Thomson scattering on low and high temperature plasmas

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Thomson scattering on low and high temperature plasmas

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de rector magnificus, prof.dr.ir. C.J. van Duijn, voor een commissie aangewezen door het College voor Promoties in het openbaar te verdedigen op maandag 14 februari 2011 om 16.00 uur

door

Hendrikus Johannes van der Meiden

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Dit proefschrift is goedgekeurd door de promotoren:

prof.dr. A.J.H. Donné
en
prof.dr. N.J. Lopes Cardozo

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Violence is the last refuge of the incompetent
Salvor Hardin

From Isaac Asimov’s Foundation series

Aan mijn lieve vader, moeder,
Yulia, Roel, Igor en Rik
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Samenvatting

Een wereldwijd ontwikkelingsprogramma is opgezet om de tokamak ITER te realiseren, om energie te produceren door middel van beheerste kernfusie. ITER bestaat uit een vat dat ongeveer de vorm heeft van een autoband, waarin een heet plasma van waterstofisotopen wordt opgesloten in een sterk magnetisch veld. Fusie-energie kan worden geproduceerd als het plasma op een temperatuur van ongeveer 100 miljoen graden gebracht wordt bij een deeltjesdichtheid van ongeveer $10^{20}$ m$^{-3}$.

Voordat een betrouwbare en efficiënte fusie-energiecentrale gerealiseerd kan worden moeten nog wel enige obstakels overwonnen worden. Ten eerste dient de opsluiting van het plasma geoptimaliseerd te worden, zodanig dat het verlies van warmte en deeltjes ten gevolge van instabiliteiten zo klein mogelijk is. Instabiliteiten in het magneetveld kunnen leiden tot verslechtering van de opsluiting van het plasma. Door deze instabiliteiten ontstaan magnetische eilanden (ook wel genoemd ‘tearing modes’) in het magnetische veld dat het plasma normaliter opsluit. Bij verschillende tokamak-experimenten wordt dit onderzocht, tevens wordt er apparatuur ontwikkeld, om de groei van de magnetische instabiliteiten te observeren en te beheersen. De mechanismen die ten grondslag liggen aan het ontstaan van interne transportbarrières worden bij deze experimenten ook onderzocht; dit zou kunnen leiden tot een verbetering van de opsluiting van het plasma. De erosie ten gevolge van de hoge plasmafluxen en de corresponderende vermogensbelasting op de divertorcomponenten (10 MW/m² (continu) en > 1 GW/m² (gepulst) ten gevolge van ELM’s (Edge Localized Modes)) is het tweede obstakel dat moet worden opgelost. De lineaire plasmageneratoren Pilot-PSI en z’n opvolger Magnum-PSI zijn speciaal ontworpen om de plasma-wand interactie bij deze hoge vermogensbelasting te bestuderen. Het derde obstakel, dat bij deze experimenten onderzocht wordt, is de opname van te veel tritium in het ITER wandmateriaal tijdens plasma-wand interactie.

Dit proefschrift beschrijft de ontwikkeling van Thomsonverstrooiingssystemen die gebruikt worden om zowel snelle fenomenen in tokamakplasma’s alsook om het quasicontinue plasma van lineaire plasmageneratoren te bestuderen. Thomsonverstrooiing is de beste methode om de dichtheid ($n_e$) en elektronentemperatuur ($T_e$) van een plasma te meten: de nauwkeurigheid van de in dit proefschrift behandelde systemen is over het algemeen beter dan 3 - 4% en 4 - 8% voor respectievelijk $n_e$ en $T_e$. Fundamenteel gezien is Thomsonverstrooiing de acceleratie van een elektron ten gevolge van een elektromagnetische golf met als direct resultaat het uitstralen van een golf met dezelfde frequentie als die van de oorspronkelijke golf; ofwel elastisch verstrooiing van een elektromagnetische golf aan een elektron. Het uitgestraalde licht is Doppler-verschoven ten gevolge van de snelheid van het elektron. Verstrooiing van het licht op een ensemble van elektronen resulteert in een spectrum dat de snelheidsdistributie van de elektronen weerspiegeld. Hieruit kunnen $n_e$ en $T_e$ worden bepaald. Als de afmeting van de invallende golf langer is dan de Debye-lengte, dan wordt het licht collectief verstrooid door de elektronen die zich
in de Debyewolk van bijvoorbeeld een ion bevinden. Dit principe heet collectieve Thomsonverstrooiing, en kan worden gebruikt om de ionentemperatuur te meten.

De eerste uitdaging in dit proefschrift was het ontwikkelen van een snel repeterend Thomsonverstrooiingssysteem voor de TEXTOR tokamak (Jülich, Duitsland). Een intra-cavity robijnlaser is ontwikkeld die een pulstrein van 30 laserpulsen van ~15 J kan genereren met een herhalingsfrequentie van 5 kHz. Het laser systeem werkt als een normale oscillator, maar in dit geval met een cavity-lengte van 18 m, waarbinnen zich het plasma bevindt. Tevens is een snel detectiesysteem ontwikkeld, bestaande uit CMOS camera’s gekoppeld aan een set van vier aan elkaar gekoppelde lichtversterkers. Bij een elektronendichtheid van \( n_e = 2.5 \times 10^{19} \text{ m}^{-3} \) konden \( n_e \) en \( T_e \) (in het bereik: 50 eV - 5 keV) profielen worden gemeten over de volle plasmadiameter van 900 mm (ruimtelijke resolutie 7.5 mm), met een herhalingsfrequentie van 5 kHz en met een nauwkeurigheid van respectievelijk 4% en 8%. De hoge achtergrond aan plasmalicht bleek het grootste probleem te zijn in het ontwerp. Tengevolge van de lange laser-cavity is de laserpuls behoorlijk lang (ongeveer 1 \( \mu \text{s} \)) en moet er een detectietijdsvenster toegepast worden van overeenkomstige lengte. Dit laatste resulteert in een veel hogere achtergrond aan plasmalicht dan bij enkel-puls Thomsonverstrooiings-systemen gebruikelijk is (laserpuls typisch 10 ns). Desalniettemin kan door toepassing van een combinatie van hoge laserpulsenergie (> 12 J/puls), het meten van de plasmalichtbijdrage, en door het detectietijdsvenster nauwkeurig af te stellen, een betrouwbaar en snel-repeterend Thomson-verstrooiingssysteem worden gerealiseerd. De grootste sprong in de ontwikkeling is gemaakt door een hoge dope robijnstaaf te vervangen door een met een lage dope (0.03% Cr\(^+\)). Hierdoor wordt het pomplicht afkomstig van de flitsbuizen homogener over de staafdoorsnede geabsorbeerd, waardoor de efficiëntie van laserlichtgeneratie met een factor 1.5 is verbeterd. Tevens heeft dit de divergentie van de laser bundel verkleind, waardoor de collectie-efficiëntie voor licht aan de observatiezijde beter is geworden. De diagnostiek maakte het bijvoorbeeld mogelijk om gedurende 2.2 ms, en met een herhalingsfrequentie van 5 kHz, de evolutie van het dichtheidsprofiel in roterende magnetische eilanden te bestuderen. Tevens kon de dynamica van interne transportbarrières gemeten worden door de tijdsevolutie van de \( T_e \) profielen te meten.

De tweede uitdaging was om een Thomsonverstrooiingssysteem te ontwikkelen voor de plasma generator Pilot-PSI, gebaseerd op een frequentieverdubbelde Nd:YAG laser. Het strooilichtniveau van het bestaande systeem op Pilot-PSI kon worden geminimaliseerd door het toepassen van een speciaal koolstof diafragsysteem in de vacuümbundellijn. Dit maakt Thomsonverstrooing mogelijk op een afstand van slechts 17 mm van een target dat door een hoog-vermogen plasmabundel wordt bestraald. De gevoeligheid van het detectiesysteem is met meer dan een factor 5 verbeterd door een Generatie III lichtversterker aan de bestaande ICCD camera te koppelen. De minimale dichtheid en temperatuur die met het systeem kunnen worden gemeten, bedragen respectievelijk \( 4 \times 10^{19} \text{ m}^{-3} \) en 0.2 eV. Dit kan door het signaal afkomstig van 30 opeenvolgende laserpulsen
(0.35 J/puls bij 10 Hz) te accumuleren. In plaats van meerdere Pilot-PSI boogontladingen
is er nu nog maar één enkele ontlading nodig om een accuraat $T_e$- en $n_e$ profiel te meten.
Het Thomsonverstrooiingssysteem is momenteel de hoofddiagnostiek in het Pilot-PSI
onderzoek en heeft aan de basis gestaan van veel ontdekkingen; de metingen gaven onder
meer inzicht in de magnetisatie-eigenschappen van het plasma en indicaties voor viskeuze
ionenverhitting werden gevonden. Tijdens ELM simulatie-experimenten, kon met enkel-
puls Thomsonverstrooing (0.35 J verstrooingsenergie) de tijdsevolutie van het gepulste
plasma gemeten worden.

Hierop volgend is een geavanceerd Thomsonverstrooiingssysteem ontworpen en
geconstrueerd voor Magnum-PSI. Dit systeem is ook gebaseerd op een frequentiever-
dubbelde Nd:YAG laser gecombineerd met een 35 m lange, op afstand gecontroleerde,
laserbundellijn. Het detectiesysteem is gebaseerd op een zogenaamd hoog-etendue
‘transmissieroosterspectrometer’. Het systeem is zodanig ontworpen dat $n_e$ en $T_e$ profielen
gemeten kunnen worden over een 100 mm diameter plasmabundel met een ruimtelijke
resolutie van 1.5 mm. De minimale dichtheid en temperatuur die met dit systeem kunnen
worden gemeten, bedragen respectievelijk $9\times10^{18}$ m$^{-3}$ (bij gebruik van 30 laser pulsen van
elk 0.55 J, 10 Hz) en < 0.15 eV. De eerste metingen laten zien dat de ontwerpspecificaties
gehaald zijn.

De laatste jaren werd de behoefte aan een nauwkeurige methode voor ionen-
temperatuurbepaling in de plasmabundel van de lineaire plasmageneratoren steeds groter.
Daarom is een haalbaarheidsstudie gestart om te beoordelen of collectieve
Thomsonverstrooing bij Magnum-PSI toegepast kan worden om de ionentemperatuur ($T_i$)
 en bovendien de macroscopische snelheid van het plasma te bepalen. Deze methode is
gebaseerd op verstrooing aan de elektronen die zich in de Debyewolk van een ion
bevinden. De conclusie van deze studie is dat $T_i$ en de macroscopische snelheid bij $n_e =
5.0\times10^{20}$ m$^{-3}$ (testparameters: $T_i = 2.5$ eV, resolutie 2.4 mm) met een nauwkeurigheid van
respectievelijk 10% en 15% gemeten kunnen worden. Dit kan worden bereikt door door
de fundamentele golflengte van de Nd:YAG laser te gebruiken en door het signaal van 10
laserpulsen van elk 1.2 J te accumuleren. Het voorgestelde systeem kan worden gebruikt
om te onderzoeken of viskeuze verhitting de oorzaak is van het feit dat $T_i$ veel hoger is
dan $T_e$ in de gemagnetiseerde plasmajet van Pilot-PSI en Magnum-PSI (optische emissie-
spectroscopie geeft alleen een indicatie hiervan). Bovendien, kunnen collectieve
Thomsonverstrooiingsexperimenten op Magnum-PSI aantonen dat dit een goede methode is
om $T_i$ in de ITER divertor te bepalen. Op het ogenblik zijn hiervoor nog geen goede
technieken beschikbaar.
Worldwide research is ongoing, to develop and build the tokamak ITER to generate energy based on controlled nuclear fusion. The principle design concept of ITER is a donut-shaped vessel wherein the fusion fuel, a hot plasma of hydrogen isotopes, is contained by high magnetic fields. The fusion power can be produced at a plasma temperature of ~100 million degrees C and density of ~10^{20} m^{-3}.

In order to realize turn key fusion energy plants, a number of issues need to be addressed. Firstly, the control of the bulk plasma to prevent outflow of heat and particles due to instabilities, needs to be improved. Subject of research on many present-day tokamaks is the formation of magnetic islands (so-called tearing modes) due to instabilities in the magnetic field that confines the plasma. Tools to monitor and prevent growth of magnetic islands are therefore very important. Additionally, the mechanisms underlying the occurrence of confinement-friendly internal transport barriers have to be studied. This research can lead to improved plasma performance. The second issue that has to be addressed, is the erosion due to the high power load (10 MW/m2 (continuous) and > 1 GW/m2 (transient) due to Edge Localized Modes (ELMs )) on plasma facing components of the ITER divertor. The linear plasma generators Pilot-PSI and Magnum-PSI have been built to study plasma-wall interaction during these power loads. This research includes the third issue; tritium retention build-up in wall material.

This thesis describes the development of Thomson scattering systems to study fast plasma phenomena in tokamaks as well as to study the quasi-continuous plasma of linear plasma generators. Thomson scattering is the most accurate method for measuring the electron temperature ($T_e$) and density ($n_e$) of a plasma: the accuracies of the systems described in this thesis are better than 3 - 4% and 4 - 8% for $n_e$ and $T_e$, respectively. Basically, Thomson scattering is the process of acceleration of electrons due to an electromagnetic wave and as a consequence emission of radiation with the same frequency as that of the incoming wave, i.e. the wave is scattered elastically. The re-radiated light is Doppler shifted due to the velocity of the electron. Scattering on an ensemble of electrons results in a spectrum that resembles the electron velocity distribution, from which $T_e$ and $n_e$ can be retrieved. If the size of the incident wave is larger than the Debye length, then the light is collectively scattered by electrons, i.e. also by electrons bunched in the Debye cloud of an ion. This so-called collective Thomson scattering can be utilized to measure the ion temperature ($T_i$).

The first research challenge was the development of a high repetition rate Thomson scattering system for the TEXTOR tokamak (Jülich, Germany). A so-called double-pass intra-cavity laser was developed that generates a burst of 30 laser pulses of ~15 J each (with a repetition rate of 5 kHz). The system operates like a laser oscillator with the plasma as part of an 18 m long cavity. A fast detector equipped with CMOS cameras
coupled to an image intensifier stage was developed. At a repetition rate of 5 kHz and a density of \( n_e = 2.5 \times 10^{19} \text{ m}^{-3} \), density and temperature (range: 50 eV - 5 keV) profiles could be measured along the full plasma diameter of 900 mm long, with a spatial resolution of 7.5 mm. Coping with the plasma light background turned out to be the biggest issue: due to the long cavity and the laser pulse is relatively long (~1 \( \mu \text{s} \)) and a large detector gate window is required, resulting in a much higher plasma light contribution compared to single-pulse Thomson scattering systems. Nevertheless, a combination of high laser pulse energies (~12 J/pulse), careful plasma light monitoring and effective detector gating proved to be the solution to realize a reliable high repetition rate Thomson scattering system. The main step in laser development was the replacement of a high dope ruby rod by one with a low dope (0.03% Cr\(^{3+}\)), leading to a homogenous absorption of the pumping light from the flash lamps over the ruby rod cross section. The pumping-to-probing efficiency was improved by a factor of 1.5 and a significant minimization of the laser beam divergence, resulting in a better imaging efficiency of the viewing system. The diagnostic system enabled to record rotating magnetic islands during 2.2 ms with a repetition rate of 5 kHz, revealing the detailed density profile evolution inside the islands. Confinement properties of transport barriers were studied by measuring the time evolution of the \( n_e \) and \( T_e \) profiles.

A second challenge was to develop a Thomson scattering system for the Pilot-PSI linear plasma generator, based on a frequency-doubled Nd:YAG laser. The stray light contribution of the system already existing at Pilot-PSI could be significantly reduced by application of a special carbon aperture system in the vacuum laser beam line, which enabled Thomson scattering measurements at a distance of 17 mm from a target surface exposed to a high power plasma beam. The sensitivity of the detector system was improved by more than a factor of 5 by application of a Generation III image intensifier at the front of the existing ICCD detector. The lower density and temperature limit of the system is \( 4 \times 10^{19} \text{ m}^{-3} \) and 0.2 eV, respectively. To achieve these values, the signal from 30 laser pulses (0.35 J/pulse, 10 Hz) needs to be accumulated. Instead of multiple Pilot-PSI discharges, now only one discharge is required to obtain accurate \( n_e \) and \( T_e \) profiles. This diagnostic has become a working horse for Pilot-PSI research and revealed different properties of the hydrogen plasma jet such as plasma confinement and indications for ion viscous heating. During ELM simulation experiments, single pulse TS measurements were successfully performed; using only 0.35 J scattering energy the time evolution of the plasma could be measured on shot to shot base.

Subsequently, an advanced Thomson scattering system was designed and constructed for Magnum-PSI. This system features a frequency-doubled Nd:YAG laser, equipped with a 35 m long remotely-controllable laser beam line and a high etendue spectrometer based on a transmission grating. The system is designed to measure electron density and temperature profiles of a plasma column of 100 mm in diameter with a spatial resolution of 1.5 mm and features a lower density limit of \( 9 \times 10^{18} \text{ m}^{-3} \) (using 30 laser pulses of 0.55 J each, 10 Hz).
First measurements at Magnum-PSI show that the design specifications are met and that on virtue of the high light collection power of the detection system even $n_e$ and $T_e$ profiles of the argon plasma expansion could be measured accurately at densities of $5 \times 10^{18} \text{ m}^{-3}$ and temperatures below 0.15 eV.

In recent years the need arose for an accurate method to determine the ion properties in the plasma jet of the linear plasma generators. Therefore, the author initiated a feasibility study to find out whether CTS can be performed on Magnum-PSI to measure $T_i$, and moreover the macroscopic velocity of the plasma. It was demonstrated that $T_i$ and the macroscopic velocity can be measured with an accuracy of 10% at $n_e = 5.0 \times 10^{20} \text{ m}^{-3}$ (test case: $T_i = 2.5 \text{ eV}$, resolution 2.4 mm) and 15%, respectively. This can be achieved by accumulating 10 laser pulses of 1.2 J each, using the fundamental wavelength of a Nd:YAG laser. The proposed system may be used to prove that viscous heating of the ions in the plasma is the main cause for the ion temperature being much higher than the electron temperature in the magnetized plasma jet of Pilot-PSI and Magnum-PSI. Moreover, CTS experiments on Magnum-PSI can possibly prove that this technique is a viable ion temperature determination method for the ITER divertor; presently there are no good candidate techniques for ITER available.
CHAPTER 1

Introduction

In the twentieth century the energy consumption on Earth has grown significantly [1]. Fast growing economies of highly populated countries like China and India will enhance the demands for energy spectacularly. This implies that Earth’s non-renewable resources like coal, oil and gas will be exhausted within a few hundred years in case we don’t succeed to convert our energy supply to non-fossil fuel sources. Since the industrial revolution 200 years ago, mankind has been releasing additional amounts of greenhouse gases into the atmosphere, which trap more heat, enhancing the natural greenhouse effect. The consequences can be catastrophic [2].

Fortunately, there is hope; energy saving programs and renewable energy sources based on for example wind, solar, hydro- and geothermal power are being developed. It is expected that within 50 years, energy sources based on nuclear fusion will become available to generate large amounts of energy for big cities and industrialized areas. The process of nuclear fusion continues already for about 5 billion years in the core of the sun and proves to be a reliable source of energy. It is based on fusion of light nuclei forming a heavier nucleus, however with a mass which is less than the sum of the masses of the original nuclei. The loss in mass is, according to Einstein’s energy-mass equation \( E = mc^2 \), released in the form of energy. On Earth deuterium (D) and tritium (T) are used as fusion nuclei; the process yields helium and highly energetic neutrons (see Fig. 1.1). Deuterium is in inexhaustible amounts available in Earth’s oceans, and the conditions required for fusion of deuterium and tritium are technically feasible.

In fusion devices a plasma, the fourth state of matter, can be produced, by ionization of deuterium and tritium. If the temperature of the plasma is such that the kinetic energy of the nuclei is high enough to overcome the repelling electrostatic forces, then fusion of the nuclei is possible due to the strong nuclear force. To produce and confine the plasma at the required temperature (~100 million degrees C) and density (~\(10^{20}\) m\(^{-3}\)) a device called tokamak had been proposed, which was developed in Russia in the fifties of the last century (the name is an acronym for ‘Toroidalnaya KAmera MAgnitnaya Katushka’). A toroidal magnetic field within a donut-shaped vessel ensures confinement of the charged particles. Since then, many tokamak devices were built. In the United Kingdom the Joint European Torus (JET, operational since 1983) was constructed as the result of a Europe-wide collaboration. In 1997, a total of 16 MW of fusion power was produced with a total input power of 24 MW (\(Q = 0.65\)). The worldwide fusion research resulted in an international collaboration to realize ITER (International Thermonuclear
Experimental Reactor and is also the Latin word for ‘The way’), which will produce 10 times more power than the injected power ($Q = 10$).

![Fusion reaction between deuterium and tritium.](image)

**Fig. 1.1:** Fusion reaction between deuterium and tritium.

### 1.1 Outstanding issues to be addressed in the design of ITER

Although in present-day tokamaks the necessary plasma confinement requirements are sufficient to achieve fusion conditions (see Fig. 1.2), plasma control will be necessary to assure stable operation with low energy losses and to prevent disruptions which lead to high induced forces on the vessel components.

ITER will produce 500 MW of fusion power. During operation, all particles including helium (the fusion product) and other impurities are passing the scrape-off layer, a two centimetre thick plasma layer at the edge of the plasma, with a power flux of about 1 GW/m². Ninety percent of the power is radiated isotropically, but the remainder is transported to the divertor (see Fig. 1.3) that has to exhaust these particles and corresponding power fluxes. The incident power flux on the divertor plates is reduced to about 10 MW/m² (corresponding to $10^{24}$ ions/m²s at about 10 eV plasma temperature), because the particle flux intersects the plates at large angles (relative to the normal of the plates). One of the main challenges is the development of divertor plates, which can withstand these power loads during many years of ITER operation at a typical pulse length of 400 s.
Due to Edge Localized Modes (ELMs) the peak power load at the divertor plates can even transiently exceed values above 1 GW/m² during a few ms. Enormous efforts are being invested in material research. Carbon-fibre composites, tungsten and other materials are proposed as high heat flux components.

Besides the power load itself, erosion and tritium inventory build-up (less than 0.7 kg tritium is allowed within the ITER vessel) in the surfaces of the divertor components are issues to be solved.

Diagnostics have to be developed to investigate the involved underlying mechanisms of the different issues, but also systems are needed for monitoring purposes. For investigating the underlying mechanisms of the different issues Thomson scattering (TS) is an indispensable tool; the development of TS systems for these specific aims is the subject of this thesis.

1.2 Linear plasma generator
To simulate the ITER relevant divertor plasma conditions and to investigate the underlying erosion mechanisms of plasma facing surfaces, a linear divertor simulator Magnum-PSI (MAGnetized plasma generator and NUMerical modeling for Plasma Surface Interaction) is being built at Rijnhuizen [4, 5]. It will consist of a linear plasma generator, a superconducting magnet to generate a continuous axial magnetic field of 3 T to confine
the plasma beam and a target manipulator system (see Chap. 2). It is expected that the device will generate $> 10^{24}$ ions/m$^2$s within a 100 mm plasma beam diameter.

The forerunner of Magnum-PSI, Pilot-PSI (Fig. 1.4) is operating since 2005 [6]. It is smaller in dimension and consists of a conventional coil system to generate the axial magnetic field (0.4 - 1.6 T), but it can provide particle fluxes up to $10^{25}$ ions/m$^2$s within a full beam diameter of about 25 mm.

![Plasma exposure of a target in linear plasma generator Pilot-PSI.](image)

**Fig. 1.4:** Plasma exposure of a target in linear plasma generator Pilot-PSI.

### 1.3 Thomson scattering

Thomson scattering is a diagnostic method for measuring electron temperature and density (profiles) with high accuracy [7, 8, 9]. The technique is suited for measuring with high spatial resolution and some systems even with high repetition rate [10]. A legendary demonstration of TS as a reliable diagnostic tool was given in 1969 by a British/Russian team to verify the (at that time) astonishing claim that the tokamak T4 produced a plasma in the temperature range of 0.3 - 1 keV [11].

Basically, Thomson scattering is the process of acceleration of electrons due to an electromagnetic wave and as a consequence emission of radiation with the same frequency as that wave, i.e. the wave is scattered elastically. The observer will see this radiation Doppler shifted when the electron is moving. If charge shielding effects are absent, then an ensemble of electrons will radiate Doppler broadened light with intensity proportional to the number of scattered electrons. When the length of the scattering volume is known, the electron density can be determined. At non-relativistic electron velocities, the electron temperature is proportional to the square of the width of the Gaussian spectrum.

*At the time this thesis was finished the Magnum-PSI machine and several diagnostics were ready, but the magnet was not yet delivered*
Due to the relatively high mass of the ions ($m_i \approx 1800 m_e$), their contribution to the scattered power may be neglected, because ions suffer only negligible acceleration in the oscillating electromagnetic field of the laser. Despite this, with collective TS (CTS) it is possible to measure the ion properties. In that case the scale length of the incident wave approaches that of the size of the shielding cloud around each ion, and thus the light is scattered by the collective of electrons in the shielding cloud reflecting the velocity of the ion (the corresponding spectrum is called ion feature).

This shielding cloud has a scale length, the so-called Debye length $\lambda_D$, and is given by

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{e^2 n_e}},$$  

(1.1)

where $\varepsilon_0$ is the permittivity of vacuum, $e$ is the electron charge, $k_B$ the Boltzmann constant and $n_e$ and $T_e$ are given in (m$^{-3}$) and (K), respectively.

Although TS is a relatively old diagnostic method, most TS systems described in this thesis feature remarkable steps forward in development. This was necessary to make them compatible with fast and slow plasma phenomena occurring in high and low density plasmas, respectively, often at a high plasma light background.

1.4 Objectives
The first objective of this thesis is related to the control of the bulk tokamak plasma. A fast repetitive TS system is necessary to measure the time evolution of magnetic islands and transport barriers in the tokamak TEXTOR (Forschungszentrum Jülich). $T_e$ (range: 50 eV - 5 keV) and $n_e$ profiles have to be measured over the full plasma diameter of ~1 meter with a spatial resolution of less than 1 cm and an accuracy better than 10%. The approach is based on an intra-cavity laser system to generate high laser energy per pulse to cope with the expected high plasma light background and a cutting-edge fast 2D detector. This work is described in Chapter 5 and published in [10].

The next objective concerns the development of TS systems for low temperature high density plasmas of the linear plasma generators Pilot-PSI and Magnum-PSI. At Pilot-PSI an existing system based on a Nd:YAG laser operating at the second harmonic has to be improved concerning dynamic range; the densities in Pilot-PSI can be varied over three orders of magnitude. The system, operating at relatively low scattering energy (0.4 J/pulse, 10 Hz) has to be capable to measure $T_e$ and $n_e$ profiles within one plasma discharge of 4 s and has to enable even single-pulse TS measurements in case the cascaded arc source is operating in pulsed mode [12]. These requirements set high demands on detection sensitivity and plasma light background reduction; the application of high-quality image-intensifier techniques was the first development step here. Because the profiles have to be measured in the vicinity of a target surface a novel stray light reduction concept has to be applied in the vacuum laser beam line. The development of this system is described in Chap. 6 and was published in [7].
INTRODUCTION

For Magnum-PSI the requirements on sensitivity are much stronger concerning lower
detection and temperature limit of $< 1 \times 10^{19}$ m$^{-3}$ and $< 0.1$ eV, respectively. Because a laser
chord of about 100 mm length has to be sampled, the demands on light collection power
are even stronger. This means that the total light collection power of the Magnum-PSI
system has to be enhanced by almost one order of magnitude compared to that of the
Pilot-PSI TS system. The proposed starting point here is the application of a high f-number
transmission grating spectrometer. The development of this system is described in Chap. 7
and will be published in 2011 [13].

At Pilot-PSI, the need arose for a diagnostic that measures accurately the ion temperature
and the axial velocity of the plasma jet. For optical emission spectroscopy (OES) such a
reference is highly desirable to confirm the assumption that the Doppler-broadened light
originating from the neutrals represents the velocity distribution of the ions. OES
measurements at Pilot-PSI have given ion temperatures up to 2.5 times the electron
temperature [14, 15]. Ion viscous heating is the proposed cause for this temperature dis-
crepancy. To tackle this problem in the future on Magnum-PSI, the author employed a
feasibility study concerning a possible application of CTS on this device, i.e. enabling
measurement of ion temperature and macroscopic velocity of the plasma jet. The
approach here is, to apply forward CTS and vary the scattering angle such that it matches
the conditions for high signal yield corresponding to the ion feature. This approach
incorporates the application of an injection seeded Nd:YAG laser operating at the
fundamental wavelength (1064 nm) combined with an electron bombarded Charged-
Coupled Device (EBCCD), which is cutting-edge technology. This study is described in
Chap. 8 and [16].

1.5 This thesis

This thesis involves the application of TS on high and low temperature devices. In Chapter
2 the tokamak TEXTOR and linear plasma generators Pilot-PSI and Magnum-PSI are
described. An overview of TS theory is given in Chapter 3 comprising incoherent, collective
TS and the theoretical description required for hot plasmas. Chapter 4 is dedicated to
design considerations concerning TS systems in general. The development of the Multi
Pulse TS (MPTS) system for TEXTOR, based on an intra-cavity ruby laser, including a
collection of first measurements is presented in Chapter 5. In Chapter 6 the performance
of the TS system of Pilot-PSI is presented followed by a description of the design of the TS
system of Magnum-PSI in Chapter 7. A study concerning a possible application of collective
Thomson scattering on Magnum-PSI is the subject of Chapter 8. Chapter 9 finalizes this
thesis with an evaluation and valorisation of this work.

1.6 Publications

The author of this thesis contributed to different research disciplines; microwave tech-
nology, molecular physics, surface physics and Thomson scattering on high and low
temperature devices. The list is divided in journal and conference contributions (only first
author contributions to main conferences are given).
Journal contributions

- ‘Thomson scattering system for Magnum-PSI’.  

- ‘Collective Thomson scattering for ion temperature and velocity measurements on Magnum-PSI: a feasibility study’.  

- ‘Production of high transient heat and particle fluxes in a linear plasma device’.  

- ‘Construction of the plasma-wall experiment’, Magnum-PSI ‘.  

- ‘Thomson scattering system on the TEXTOR tokamak using a multipass laser beam configuration’.  

- ‘Rotation of a strongly magnetized hydrogen plasma column determined from an asymmetric Balmer-beta spectral line with two radiating distributions’.  

- ‘Optimization of the output and efficiency of a high power cascaded arc hydrogen plasma source’.  

- ‘High sensitivity imaging Thomson scattering for low temperature plasma’.  

- ‘PSI research in the ITER divertor parameter range at the FOM PSI-lab’.  

- ‘10 kHz repetitive high-resolution TV Thomson scattering on TEXTOR: Design and performance (invited)’.  

- ‘Electron cyclotron resonance heating on TEXTOR’.  

- ‘Overview of core diagnostics for TEXTOR’.  

- ‘10 kHz repetitive high-resolution TV Thomson scattering on TEXTOR’.  

- ‘Electron cyclotron resonance heating on TEXTOR’.  

- ‘Calibration procedure and data processing for a TV Thomson scattering system’.  

- ‘Filamentation in the RTP tokamak plasma’.  
• ‘New diagnostics for physics studies on TEXTOR-94 (invited)’.

• ‘Test of a periodic multipass-intra-cavity laser system for the TEXTOR multiposition Thomson scattering diagnostics’.

• ‘A high spatial resolution double-pulse Thomson scattering diagnostic; description, assessment of accuracy and examples of applications’.

• ‘Application of band-stop filters for the 30-200 GHz range in oversized microwave systems’.

• ‘High-resolution multiposition Thomson scattering for the TJ-II stellarator’.

• ‘Structures in $T_e$ profiles: High resolution Thomson scattering in the Rijnhuizen tokamak project’.

• ‘Electron thermal transport in RTP: filaments, barriers and bifurcations’.

• ‘A high resolution multiposition Thomson scattering system for the Rijnhuizen Tokamak project’.

• ‘Double pulse Thomson scattering system at RTP’.

• ‘Sub-eV electron-spectroscopy in ion-atom collisions’.
• ‘Detection of low-energy hydrogen-atoms from a tokamak plasma by means of H⁻ formation on tungsten surfaces’.

Conference contributions
• ‘Collective Thomson scattering for ion temperature measurements on Magnum-PSI: a feasibility study’.
  H.J. van der Meiden, 14th International Symposium on Laser Aided Plasma Diagnostics, Castelbrando, Treviso, Italy, September 2009 (invited)

• ‘Multi-pulse 20 kHz TV Thomson scattering with high spatial resolution on TEXTOR-94’.

• ‘10 kHz repetitive high-resolution TV Thomson scattering on TEXTOR: Design and performance’.

• ‘Multi-pulse 20 kHz TV Thomson scattering with high spatial resolution on TEXTOR-94’.

• ‘Resonance two-photon electron spectroscopy of the triplet states of molecular hydrogen’.
  H.J. van der Meiden, W.B. Westerveld and A. Niehaus, Najaarsvergadering van de sectie atoomfysica en quantumelektronica, Lunteren, The Netherlands, November 1993
References

2. International Climate Change Partnership (ICCP).
CHAPTER 2

Research devices

The Thomson scattering systems described in this thesis were applied on the tokamak TEXTOR [1] and the linear plasma generators Pilot-PSI and Magnum-PSI. For TEXTOR a high repetition rate TS system was developed based on an intra-cavity ruby laser system for measuring fast plasma phenomena. Pilot-PSI [2] and Magnum-PSI [3] are quasi-continuous experiments that make it possible to accumulate TS data from 1 - 30 laser pulses using low energy lasers (0.4 - 0.7 J/pulse). This chapter provides background information about these different experimental devices. In Sec. 2.1 and 2.2 the TEXTOR tokamak, and the linear plasma generators Pilot-PSI and its successor Magnum-PSI are described, respectively.

2.1 TEXTOR tokamak

A schematic presentation of a tokamak is shown in Fig. 2.1. Toroidal field coils generate a toroidal magnetic field ($B_\phi$). Capacitor banks are discharged over the primary transformer coil and at the secondary side a plasma current is generated. The current through the plasma itself generates a poloidal magnetic field ($B_\theta$), and this along with the toroidal field results in a helical magnetic field line configuration as depicted in Fig. 2.1. The magnetic winding number $q = m/n$ is defined as the number of toroidal windings ($m$) a field line requires to describe a single winding in the poloidal direction ($n$). If $q$ has a rational value, so-called rational surfaces are formed; in this case $m$ and $n$ are integers, the magnetic field lines close onto themselves after $m$ toroidal and $n$ poloidal turns. Diffusion of charged particles perpendicular to the magnetic flux surfaces (energy loss) is in principle only possible by collisions with other particles. This energy transport is called (neo-) classical diffusion. However, the magnetic topology can be disturbed by for instance the formation of magnetic islands on the rational surfaces, leading to a much higher transport of energy out of the hot plasma core. To prevent these magnetic instabilities, detailed studies are required to understand the underlying mechanisms. Monitor and control methods have to be developed for suppressing these instabilities.

This is one of the aims of the physics program of the tokamak device TEXTOR (Fig. 2.2). The basic machine parameters are: major radius $R_0 = 1.75$ m, minor radius $a = 0.46$ m, magnetic field $B_0 \leq 2.8$ T, and plasma current $I_p \leq 0.8$ MA. Depending on the loop voltage, the plasma can be sustained for at maximum 10 s.

The induced plasma current results in ohmic heating with a power of up to 0.5 MW and the electron temperature and density reached are typically 1 keV and $4 \times 10^{19}$ m$^{-3}$,
respectively. Ohmic heating becomes less effective due to the fact that the plasma conductivity drops at high temperature. Therefore, TEXTOR is equipped with additional heating techniques: Electron Cyclotron Resonance Heating ($P_{\text{ECRH}} > 0.8$ MW) generated by a gyrotron, Ion Cyclotron Resonance Heating systems ($2 \times 2$ MW) and two Neutral Beam Injection devices (1.5 MW each). With these additional heating schemes the electron temperature and density reach values up to 3 keV and $1 \times 10^{20}$ m$^{-3}$, respectively.

The Dynamic Ergodic Divertor, a device that dynamically modifies the local magnetic field structure [4], is used to study plasma-wall interaction and to study several magnetic instabilities. The TEXTOR machine and the plasma parameters are listed in table 2.1.

![Fig. 2.1: Schematic presentation of a Tokamak](image1)

![Fig. 2.2: Inside TEXTOR](image2)

**Table 2.1: Main machine parameters of TEXTOR**

<table>
<thead>
<tr>
<th>Basic parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius</td>
<td>$R$ 1.75 m</td>
</tr>
<tr>
<td>Minor radius</td>
<td>$a$ 0.46 m</td>
</tr>
<tr>
<td>Plasma volume</td>
<td>$V$ 7 m$^3$</td>
</tr>
<tr>
<td>Toroidal magnetic field at $R$ (Normal operation)</td>
<td>$B_0$ 1.5 - 2.9 T (2.25 T)</td>
</tr>
<tr>
<td>Pulse length</td>
<td>$\Delta t$ &lt;10 s</td>
</tr>
<tr>
<td>Plasma current (normal operation)</td>
<td>$I_p$ 0.2 - 0.8 MA (0.35 MA)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heating</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohmic</td>
<td>$P_\Omega$ 0.3 - 0.5 MW</td>
</tr>
<tr>
<td>ECRH</td>
<td>$P_{\text{ECRH}} &gt; 0.8$ MW</td>
</tr>
<tr>
<td>ICRH</td>
<td>$P_{\text{ICRH}} 2\times2$ MW</td>
</tr>
<tr>
<td>NBI</td>
<td>$P_{\text{NBI}} 2\times1.5$ MW</td>
</tr>
<tr>
<td>Current drive (ECCD)</td>
<td>$I_{\text{ECCD}}$ 25 - 50 kA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Plasma parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop voltage</td>
<td>$V_l$ 1 V</td>
</tr>
<tr>
<td>Electron temperature</td>
<td>$T_e$ 1.0 - 3.0 keV</td>
</tr>
<tr>
<td>Electron density</td>
<td>$n_e$ 0.5 - $10\times10^{19}$ m$^{-3}$</td>
</tr>
<tr>
<td>Ion temperature</td>
<td>$T_i$ 1.0 - 4.0 keV</td>
</tr>
<tr>
<td>Effective ion charge</td>
<td>$Z_{\text{eff}}$ 1.5</td>
</tr>
</tbody>
</table>
Many diagnostics are applied at TEXTOR, an overview of these can be found in [5], a few are mentioned here as background information to accommodate the reader.

Several radiometer diagnostics are used to determine the electron temperature using heterodyne detection of electron cyclotron emission (ECE) [6]. They are based on the fact that electrons in the plasma radiate at the cyclotron frequency and a number of its harmonics. Normally the plasma is optically thick for second harmonic radiation. This implies that the radiation intensity is proportional to $T_e$. Because the toroidal magnetic field strength varies from inner (high field side) to outer side (low field side) with $1/R$, the ECE frequency will per definition have the same proportionality; hence, the temperature is in principle determined locally along the minor radius. The TEXTOR TS system is used for extra cross calibration of the ECE diagnostics.

To determine the line-integrated electron density along a chord through the plasma, an interferometer is used. It is based on the fact that if a wave (IR/microwave beam) passes the plasma, it will experience a phase shift due to the change of refraction index, which is proportional to $n_e$ integrated along the chord of the beam through the plasma. By counting the phase fringes the line-averaged density can be determined. The interferometer diagnostic at TEXTOR has a time resolution of up to 20 kHz. Multiple interferometer beams [7] are applied to retrieve the electron density profile by means of numerical Abel inversion techniques. This diagnostic is used as cross reference to check the absolute density determination of the TEXTOR TS system.

A collective TS (CTS) diagnostic is operating successfully to measure the fast ion population; the measured fluctuations originate from scattering on the electron wakes drawn by the fast (MeVs) ions. The scattering configuration is set such that the so-called scattering parameter, $\alpha$, is much larger than unity (probing frequency 110 GHz (ECRH beam)), i.e. the scale of the scattering wave is much larger than the Debye length [8]).

Since 2003, a high resolution TS system with high repetition rate based on incoherent TS is operating successfully at TEXTOR and is dedicated to the study of fast phenomena [9]; details will be given in Chapter 5. This system is also used as an absolute reference for other diagnostics.

2.2 Pilot-PSI & Magnum-PSI

2.2.1 Pilot-PSI

The Pilot-PSI device is schematically shown in (Fig. 2.3). A wall stabilized DC cascaded arc (Fig. 2.4) produces the plasma. The source allows producing hydrogen, helium, argon plasmas and mixtures of these species. A discharge current is drawn between a set of 3 cathodes and the nozzle, which serves also as the anode. The typical discharge parameters are a gas flow of 2 standard litre per minute (slm; 1 slm = 4.5×10^{20} particles/s) and a discharge current between 100 and 300 A. This requires an arc voltage of approximately 200 V (depending on the magnetic field strength). The plasma is exhausted into the 0.4 m diameter vacuum vessel that is kept at a background pressure of 1 - 10 Pa during operation by a set of roots pumps (total pumping speed of 2×10^3 l/s). An axial magnetic field from 0.4 T (< 3 minutes; limited by the cooling of the coils) up to 1.6 T (< 4 s) confines and guides the
plasma to the target at 0.56 m downstream the source. TS is performed at either ~40 mm downstream of the source nozzle or at a distance of 17 mm in front of the target surface.

Pilot-PSI allows exposing targets even beyond ITER relevant divertor conditions, namely particle fluxes of up to $10^{25}$ ions/m²s are possible. However, at these conditions the full width of the hydrogen plasma beam is rather small, in the range of 15 mm. The trajectories of erosion products can exceed several centimetres at ITER relevant conditions. This means that study of redeposition processes during a hydrogen beam exposure of carbon targets is not possible.

Fig. 2.3: Schematic side view of the Pilot-PSI vessel and the positions of TS observation.

Fig. 2.4: Cascaded arc: the current is drawn between the cathode and nozzle

### 2.2.2 Magnum-PSI

Magnum-PSI (see Fig. 2.5) differs from the Pilot-PSI experiment by the fact that it is a CW experiment with the capability to generate a plasma beam with a full diameter of 100 mm. By virtue of a superconducting magnet, a CW axial magnetic field of max 3 T can be generated allowing for plasma-surface investigation in conditions that are similar to those in the ITER divertor. The main machine parameters are described in table 2.2.

The Magnum-PSI machine (see Fig. 2.5 from left to right) consists of a source chamber with skimmer (to remove the neutrals by differential pumping), a plasma heating chamber, a target chamber (plasma exposure vessel) and a target exchange and analysis chamber. A target manipulator is used for moving the target of interest (dimension 60×12 cm²) over a distance of about 5 m from the target chamber to the target exchange and analysis chamber maintaining vacuum conditions to preserve target surface conditions. In the target chamber a plasma beam dump is used to control the duration of the exposure.
Fig. 2.5: Magnum-PSI. The axial magnetic field generated by the superconducting magnet confines the plasma until it impinges on a target. After plasma exposure, the manipulator arm transports the target to the target exchange and analysis chamber to perform detailed ex-situ analysis of the surface and deeper layers.

Table 2.2: Main parameters of Magnum-PSI

<table>
<thead>
<tr>
<th>Basic parameters</th>
<th>( I_p )</th>
<th>( P_{source} )</th>
<th>( P_{vessel} )</th>
<th>( R )</th>
<th>( B_0 )</th>
<th>( \Delta t )</th>
<th>( n_e )</th>
<th>( T_e )</th>
<th>( P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma source current (^1)</td>
<td>(&lt; 800 \text{ A})</td>
<td>(&lt; 120 \text{ kW})</td>
<td>(&lt; 1 \text{ Pa})</td>
<td>(0.5 \text{ m})</td>
<td>(&lt; 3 \text{ T (cw)})</td>
<td>Pulsed/continuously</td>
<td>(0.01 - 5 \times 10^{21} \text{ m}^{-3})</td>
<td>(\text{max } 7 \text{ eV})</td>
<td>More than (40 \text{ MW/m}^2)</td>
</tr>
<tr>
<td>Power input (^1)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Gas flow rate</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Background pressure during operation</td>
<td>(P_{vessel})</td>
<td>(&lt; 1 \text{ Pa})</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Vessel radius</td>
<td>(R)</td>
<td>(0.5 \text{ m})</td>
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<tr>
<td>Length of plasma jet (distance between source and target)</td>
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<tr>
<td>Axial magnetic field (superconducting magnet)</td>
<td>(B_0)</td>
<td>(&lt; 3 \text{ T (cw)})</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Pulse length</td>
<td>(\Delta t)</td>
<td>Pulsed/continuously</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Electron density (at 15 mm distance from target)</td>
<td>(n_e)</td>
<td>(0.01 - 5 \times 10^{21} \text{ m}^{-3})</td>
<td></td>
<td></td>
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<tr>
<td>Electron temperature (at 15 mm distance from target)</td>
<td>(T_e)</td>
<td>(\text{max } 7 \text{ eV})</td>
<td></td>
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<tr>
<td>ELM simulation mode ((&gt;10 \text{ kA superposed on arc current plateau during } 0.5 \text{ ms}))</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Electron density during ELM pulse simulation mode</td>
<td>(n_e)</td>
<td>(\text{max } 2 \times 10^{22} \text{ m}^{-3})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron temperature during ELM pulse simulation mode</td>
<td>(T_e)</td>
<td>(\text{max } 8 \text{ eV})</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Transient power flux on target</td>
<td>(P_{Transient})</td>
<td>(2 \text{ GW/m}^2) during (0.5 \text{ ms}) (target value)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**Heating**

ICH | Still in development

Ohmic (different schemes are possible)

The design is still ongoing, different prototypes are in use; only an estimate is given.

A typical Magnum-PSI measurement session consists of the following elements:

**Installation of sample:** A sample is installed on the target holder of the target manipulator in the target exchange and analysis chamber.
Pre-exposure phase: Characterization of the target of interest before exposure to the plasma beam. The target is investigated with surface characterization diagnostics like X-ray Photoelectron Spectroscopy (XPS) and Auger Electron Spectroscopy (AES). After that, the target manipulator transports the sample to the target chamber (a plasma dump is blocking the plasma jet to prevent uncontrolled exposure of the target).

Tuning phase: The plasma source is started and tuned to the desired plasma beam conditions. TS (inside the source chamber), calorimetry and a few spectroscopic diagnostics are used to control the temperature, density and purity of the plasma jet.

Exposure phase: If the plasma conditions are as desired, the plasma dump goes down and the exposure of the target by the plasma jet begins. During the exposure, the plasma conditions are monitored (using for instance TS in the target chamber) and adjusted and in case extra plasma heating is required, ohmic or additional heating will be applied. Diagnostics are applied for measuring the plasma condition and for monitoring target surface composition and structure during the plasma exposure.

Post-exposure phase: After exposure the sample can be retrieved and analyzed in the target exchange and analysis chamber. If it is apparent that a longer exposure is required it can be inserted again in the plasma, else it will be removed from the target exchange and analysis chamber and analyzed outside the Magnum-PSI area with additional surface characterization diagnostics.

2.2.3 Diagnostics at Pilot-PSI and Magnum-PSI

Several diagnostics, like TS, optical emission spectroscopy and calorimetry are used as control instruments, and a short description of these diagnostics is given here. Several diagnostics are shared between Magnum-PSI and Pilot-PSI.

At Pilot-PSI and Magnum-PSI, the ion temperature is determined by measuring the fluorescence of the excited neutrals. By measuring the $H_\beta$ light, the ion temperature can be determined from the Doppler line broadening. This diagnostic is a line-averaged measurement and needs Abel inversion to retrieve local temperature values. A drawback of this optical emission spectroscopy is that it is still not clear how well the excited neutrals represent the ion properties [10].

A multi-wavelength pyrometer is used for both experiments to measure the surface temperature of the targets of interest.

Overview spectrometers are used and have a repetition rate of about 10 Hz, which makes them very suitable for monitoring impurities, and thus they are used to yield an interlock in the case the arc source is malfunctioning.

Colour-monitor cameras are applied at Pilot-PSI and Magnum-PSI to keep a general overview of the plasma beam during operation.

Laser Induced Fluorescence system (LIF; H(n=2) → H(n=3)) is being developed on Pilot-PSI [10, 11]. Investigations are ongoing concerning the coupling between H(n=2) and the ions.

Langmuir probes are used to measure the plasma potential, electron temperature and density. A disadvantage of probes is that due to their physical presence they can dis-
turb the plasma properties. Nevertheless, variants of these probes can provide a treasure of fundamental information about the plasma, especially the relation between $E \times B$ drift, plasma potential and plasma rotation [12].

A TS system is operating successfully at Pilot-PSI [13] and a fully upgraded and improved system has been installed at Magnum-PSI ([14] and see Chap. 7). At Magnum-PSI TS will be used as a real-time control diagnostic: every 7 seconds an $n_e$ and $T_e$ profile is delivered and the plasma conditions can be tuned to the desired $n_e$ and $T_e$ by varying the source current or gas flow.

Magnum-PSI will be a test bed for diagnostic tools proposed in the ITER divertor for probing dust and tritium inventory. For this purpose, speckle interferometry, laser induced ablation spectroscopy (LIAS), laser induced desorption spectroscopy (LIDS) and laser induced breakdown spectroscopy (LIBS) will be applied.

As mentioned above, outside the Magnum area, the exposed samples will be investigated with several surface characterization diagnostics like X-ray Photoelectron Spectroscopy (XPS) and Auger Electron Spectroscopy (AES). XPS and AES provide information (composition, structure) about the upper atomic monolayers (a few dozens thick). Of course also Thermal Desorption Spectroscopy (TDS) is implemented.

### 2.2.4 Control and data acquisition

The requirements concerning the control and data acquisition system for Magnum-PSI differs from that of most tokamak experiments:

- **At Magnum-PSI, a single exposure can take a long time, maybe up to a whole day.** This means that signals may need to be recorded over a very long time. This sets high demands on storage rate and size of the database. Typical tokamak shots have a duration of 10 - 100 sec; only for a short time the demands on the storage rate and database size are high.
- **A tokamak shot consists usually of a pre-programmed sequence of events.** This may not be the case at Magnum-PSI, where for instance a human operator may anticipate to what is actually happening during the experiment.
References

Thomson scattering

Thomson scattering (TS) is basically the process of acceleration of electrons due to an electromagnetic wave and as a consequence emission of radiation with the same frequency as the incoming wave, i.e. the wave is scattered elastically [1]. This process can be applied as a non-intrusive method to determine the electron temperature and density with high accuracy and high spatial resolution. Scattering by electrons whose motions are correlated with each other can also occur; this enables fluctuation measurements (to identify turbulence) and measurements of the plasma frequency.

A simple experimental TS setup is shown in Fig. 3.1. An electromagnetic wave from a laser with wave vector $k_0$ (frequency $\omega_0$) is incident on the plasma. Electrons will oscillate in the electric field of the laser beam and reradiate this light with a Doppler shift due to the velocity of the electrons (corresponding to the velocity component parallel to the differential wave vector $k$). After the light is dispersed by a spectrometer it is imaged onto a camera. The collected number of photons and the width of the spectrum represent the electron density ($n_e$) and temperature ($T_e$), respectively.

Fig. 3.1: General Thomson scattering scheme.
In this chapter the general TS theory is described using the description given by [1, 2, 3] in an attempt to give a brief coherent overview. The required analytical expression for isotropic relativistic electron velocity distribution is given in Sec. 3.6.

3.1 Thomson scattering principle: scattering on a single electron

The following conditions are assumed for the single electron case (see Fig. 3.2):

- Only the electron velocity \( v_e \) components parallel to \( k \) are observed in the spectrum of the scattered light;
- The Compton effect, i.e. the momentum transfer from photon to the scattered electron, is negligible;
- Relativistic effects are ignored; electron velocity \( v_e \ll c \), with \( c \) the speed of light;
- The scattering volume dimension \( r_j \) is much smaller than the distance between scattering volume and observer \( |R| \).

![Fig. 3.2: Scattering geometry and definition of parameters. An electron with charge \( e \) and mass \( m \) is located at position \( r_j \). The observer is located at position \( R \) with \( |r| \ll |R| \).](image)

If an electromagnetic wave (with wave vector \( k_0 \)) and with frequency \( \omega_0 \)

\[
E = E_0 \cos \left( k_0 \cdot r_j - \omega_0 t' \right),
\]

is incident on a moving electron (with index \( j \) and velocity \( \mathbf{v} \)), the electron will accelerate according to

\[
m_e \frac{dv}{dt'} = eE_0 \cos \left( k_0 \cdot r_j (t') - \omega_0 t' \right).
\]

The observer is located at a distance \( |R| \) from the electron and in order to determine the contribution of the resulting electrical field at this location, the re-radiated field (by the
electron) emitted in the past at the retarded time \( t' \) has to be taken into account according to

\[
t' = t - \frac{|R - r_j(t')|}{c} = t - \frac{R - r_j(t') \cdot s}{c},
\]

with \( s \) the unit vector in the direction of observation. As mentioned at the start, it is assumed that \( |r_j(t')| \ll |R| \).

In approximation the trajectory of the electron can be given as

\[
r_j(t') = r_j(t' = 0) + vt',
\]

assuming that the displacement of the electron \(|v| t'\) is much smaller than \(|R|\). By substituting equation 3.4 in 3.3 the following equation can be derived for the retardation time

\[
t' = t - \frac{R / c + r_j(0) \cdot \hat{s}}{1 - \hat{s} \cdot \beta},
\]

with \( \beta = \frac{v}{c} \).

Using equation 3.4 and 3.5 and the fact that \( k = \omega / c \) (thus \((\omega_0 - k_0 v) = \omega_0 (1 - \hat{i} \cdot \beta)\)) the argument in equation 3.1 becomes

\[
k_0 \cdot r_j(t') - \omega_0 t' = k_0 \cdot r_j(0) - (\omega_0 - k_0 v) t'
\]

\[
= k_0 \cdot r_j(0) - (1 - \hat{i} \cdot \beta) \omega_0 t'
\]

\[
= k_0 \cdot r_j(0) - \frac{(1 - \hat{i} \cdot \beta) \omega_0 t}{1 - \hat{s} \cdot \beta} + \frac{(1 - \hat{i} \cdot \beta) k_0 R}{1 - \hat{s} \cdot \beta} - \frac{(1 - \hat{i} \cdot \beta) k_0 r_j(0) \cdot \hat{s}}{1 - \hat{s} \cdot \beta}.
\]

According to [4] the electric field emitted by an accelerated charged particle (\( \beta \ll 1 \)) is given as

\[
E_s(R,t) = \frac{e^2}{4\pi \varepsilon_0 c R} \left[ \hat{s} \times (\hat{s} \times \hat{\beta}) \right]_{\parallel},
\]

where \( \varepsilon_0 \) is the dielectric constant in vacuum.

After substituting equation 3.2 and 3.6 in equation 3.7 the emitted electrical field can be written as

\[
E_s(R,t) = \frac{e^2}{4\pi \varepsilon_0 c^2 R} \left[ \hat{s} \times (\hat{s} \times E_0) \right] \cos \left[ k_s R - \omega_s t - (k_s - k_0) \cdot r(0) \right].
\]

This means the charge radiates the Doppler shifted electromagnetic wave with frequency

\[
\omega_s = \frac{(1 - \hat{i} \cdot \beta) \omega_0}{1 - \hat{s} \cdot \beta} \quad \text{and} \quad k_s = (\omega_s / c) \hat{s}.
\]
Using equation 3.9 one can derive the well known equations for the Doppler shift and differential wave vector \( k \):

\[
\Delta \omega = \omega_s - \omega_0 = \mathbf{k} \cdot \mathbf{v} \quad \text{with} \quad \mathbf{k} = \mathbf{k}_s - \mathbf{k}_0. \tag{3.10}
\]

The electron sees in its frame of reference the incident wave Doppler shifted (\( \omega' = \omega_0 - \mathbf{k}_0 \cdot \mathbf{v} \)) due to its velocity relative to the source of radiation. The re-radiated wave with same frequency \( \omega' \) will be observed in the laboratory frame (direction \( \mathbf{k}_s \)) with a Doppler shifted frequency (\( \omega_s = \omega' + \mathbf{k}_s \cdot \mathbf{v} \)), i.e. the scattered wave is double Doppler shifted.

The magnitude of the scattering vector \( k \) is defined as (see Fig. 3.2):

\[
k = |\mathbf{k}| = \frac{4\pi}{\lambda_0} \sin \left( \frac{\theta}{2} \right). \tag{3.11}
\]

with \( \theta \) the scattering angle between \( \mathbf{k}_0 \) and \( \mathbf{k}_s \). Here it is assumed that \( \mathbf{k}_s = \mathbf{k}_0 \).

Using the definition of the Poynting vector and equation 3.8 the power emitted by the electron per unit solid angle \( d\Omega \) (through the area \( R^2 d\Omega \)) can be written as [1]:

\[
\frac{dP_s}{d\Omega} = \varepsilon_0 c R^2 |\mathbf{E}_s|^2, \tag{3.12}
\]

resulting in

\[
\frac{dP_s}{d\Omega} = \frac{e^4}{16\pi^2\varepsilon_0 c^3 m^2 R} \left[ \hat{s} \times \left( \hat{s} \times \mathbf{E}_\omega \right) \right]^2 \cos^2 \left[ k_s R - \omega_s t - (k_s - k_0) \cdot \mathbf{r}(0) \right]. \tag{3.13}
\]

From equation 3.13 it follows that the power scattered by ions is much smaller than that of electrons by a factor of \( \left( M_{ion}/m_e \right)^2 \) and is therefore negligible.

The time averaged power emitted by the electron can be given by

\[
\overline{\frac{dP_s}{d\Omega}} = r_e^2 \varepsilon_0 c \frac{E_\omega}{2} |\hat{s} \times (\hat{s} \times \mathbf{e})|^2
\]

\[
= r_e^2 I_{in} |\hat{s} \times (\hat{s} \times \mathbf{e})|^2, \tag{3.14}
\]

with \( \mathbf{e} \) the unit vector in the polarization direction of the incident field \( \mathbf{E}_{\omega} \), \( r_e \) the classical electron radius defined as

\[
r_e = \frac{e^2}{4\pi\varepsilon_0 m_e c^2} = 2.82 \times 10^{-15} \text{ m}, \tag{3.15}
\]

and \( I_{in} \) the incident power given by \( I_{in} = \varepsilon_0 c E_{\omega}^2/2 \).

Using the vector product according to figure 3.1, equation 3.14 can be written as

\[
\overline{\frac{dP_s}{d\Omega}} = r_e^2 I_{in} \left( 1 - \sin^2 \theta \cos^2 \varphi \right). \tag{3.16}
\]
From this it follows that the differential Thomson scattering cross-section on a single electron is given as

$$\frac{d\sigma_T}{d\Omega} = r_e^2 \left(1 - \sin^2 \theta \cos^2 \varphi \right).$$  \hspace{1cm} (3.17)

Using the angle $\psi$ between $k_s$ and $E_0$, equation 3.17 can be converted to a simpler form:

$$\frac{d\sigma_T}{d\Omega} = r_e^2 \sin^2 \psi.$$  \hspace{1cm} (3.18)

For low temperature plasmas the angular variation of the scattering cross-section can be represented by an oscillating dipole (see Fig. 3.3).

The state of polarization of the incident wave is normally chosen such that $\psi = 90^\circ$; the differential cross-section corresponds in that case exactly to the square of the classical electron radius given by

$$\frac{d\sigma_T}{d\Omega} = r_e^2$$  \hspace{1cm} (3.19)

The total Thomson scattering cross-section is obtained by integrating Eq. 3.18 over the full solid angle and is given as

$$\sigma_{Ts} = \frac{8}{3} \pi r_e^2 = 6.65 \times 10^{-29} \text{ m}^2.$$  \hspace{1cm} (3.20)

The very small value of the Thomson cross-section, which is the ratio between the total scattered power to the incident power, means that powerful lasers and sensitive detection systems have to be used.
3.2  Thomson scattering on a plasma: general considerations

The following additional conditions are assumed for scattering on a plasma consisting of ions and electrons:

- A plane electromagnetic wave scatters on an ensemble of \( N \) electrons;
- The number \( N \) electrons, with position of each electron \( r_j(t_j) \) in the scattering volume, will not change within the duration of the laser pulse;
- The ensemble of electrons occupies a volume large compared to the wavelength of the incident wave;
- The dimension of the scattering volume is much smaller that that of the distance \( (R) \) between scattering volume and observer, i.e. each electron will equally contribute to the observed radiation.

Using these conditions the total scattered electric field at the observer \( E_{s}^{\text{tot}} \) can be determined. It consists of the vector sum of the scattered field of the individual electrons within the scattering volume

\[
E_{s}^{\text{tot}} = \sum_{j=1}^{N} E_j.
\]  

(3.21)

Using equation 3.12 the time averaged scattered power per solid angle at the observer can be described as [1]:

\[
\frac{dP}{d\Omega} = \varepsilon_0 c R^2 \left( \sum_{j=1}^{N} \sum_{l=1}^{N} E_i \cdot E_j \right).
\]

(3.22)

Separating equation 3.22 in terms with \( j = l \) and \( j \neq l \), this equation can be represented by summation of an incoherent and coherent part as

\[
\frac{dP}{d\Omega} = \varepsilon_0 c R^2 \left[ \frac{N}{2} E_s^2 + 2N(N-1)\langle E_j \cdot E_l \rangle_{w_{ij}} \right].
\]

(3.23)

The first term is just the sum of the individual contributions from \( N \) electrons randomly distributed over the scattering volume \( V \) (incoherent scattering); the magnitude of this term is linear with the electron density \( (n_e = N/V) \). The average electromagnetic field due to the second term will be zero, if the particles have random positions; in that case no correlation occurs. However, if the positions of the electrons in the scattering volume are correlated (density fluctuations organized by for instance ion acoustic waves and/or the plasma frequency) then the phases of the scattered waves are correlated (collective scattering). Because \( N >> 1 \), the \( N^2 \) dependence of the coherent term can lead to considerable enhancement of the scattering power. Of course not all electrons participate in the collective motion of plasma waves and thus \( N \) corresponds only to the electron density within the fluctuations.
3.3 Thomson scattering and influence of Debye length

The quantity \(2\pi/k\) (with \(k = |k|\)), is the scale length for scattering, and it determines the scale or resolution on which phenomena are viewed in a scattering experiment. This means that the combination of laser wavelength and scattering angle (see Eq. 3.11) selects directly the spatial Fourier component of the electron density distribution for which the wave vector is \(k\), i.e. the detector will view only the corresponding frequency spectrum.

Correlated interactions between the plasma electrons only occur at or above a certain scale length, the so-called Debye length \(\lambda_D\):

\[
\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{e^2 n_e}},
\]

where \(k_B\) is the Boltzmann constant, and \(n_e\) and \(T_e\) are given in \((m^{-3})\) and \((K)\), respectively. Because there are no plasma modes with wavelengths less than the Debye length, an undisturbed spectrum is expected, i.e. it will reflect the pure electron velocity distribution. And the intensity is linear with the number of scattered electrons, i.e. in accordance with the first term of Eq. 3.23.

As mentioned before, whether coherent effects influence the scattering process depends on the ratio between \(\lambda_D\) and the dimensions of the scattering wave. This relation is described by the scattering parameter [2]:

\[
\alpha = \frac{1}{k\lambda_D}.
\]

If \(\lambda_D \gg \lambda_0/(4\pi \sin(\theta/2))\), the scattering process can be considered as incoherent scattering; the incident wave “sees” the individual electrons. However, if \(\lambda_D \leq \lambda_0/(4\pi \sin(\theta/2))\), the incident wave sees a collective of charges (within \(\lambda_D\)) and the scattering process needs to be treated as collective scattering. The two situations are illustrated in Fig. 3.4.

![Fig. 3.4: Schematic presentation of scattering by electrons in a Debye sphere for a) non-collective Thomson scattering and b) collective Thomson scattering.](image)

For wavelength scales larger than the Debye length, it is expected that some plasma resonant modes like the plasma frequency will appear as peaks in the frequency spectrum.
of corresponding $k$. In case $\alpha \ll 1$ no long range electric fields organize the electrons into waves, and therefore the positions of the electrons are uncorrelated. The spectrum will originate from purely incoherent TS (so-called electron feature) and for a thermal equilibrium plasma the shape will be a Gaussian centred around the laser frequency (see Fig. 3.5: spectrum at for instance $\alpha = 0$). The half width of the Gaussian reflects the temperature of these electrons. In case $\alpha \gg 1$ the scattering process can be referred as purely coherent TS (so-called ion feature). The spectrum will consist of one centred peak and two satellites (see Fig. 3.5: narrow peaks at $x_i = 0$). The half width of this centred peak represents the ion temperature. This width is approximately the square root of the mass ratio of the ions and the electrons smaller than that of the incoherent case (for a hydrogen plasma 42 times smaller), i.e. the scattered electric field originating from the electrons bunched in the Debye sphere of the ions will be observed. The measured satellites are associated with the plasma frequency, i.e. the electron density can be obtained from the spectral position of these peaks (see Sec. 3.4). If $\alpha = 1$ contributions of both the electron and ion feature are expected (see Fig. 3.5: spectrum at $\alpha = 1$). The electron feature has a flat minimum in the centre and the peak in the middle shows the ion feature, which relative half width reflects again the ion temperature. The shape of the spectrum is described by the scattering form factor $S(k, \omega)$, which will be treated in next section.

Fig. 3.5: Schematic shape of TS spectra at different values of $\alpha$, adapted from [6].
3.4 Scattering form factor

Equation 3.10 shows that only the velocity component of the electrons parallel to \( k \) is observed in the spectrum of the scattered light. Summation of the \( E_s \) fields (see Eq. 3.21) from \( N \) electrons and using the definition of the Poynting vector, the average power reaching the detector in the direction of \( k \) can be given by

\[
P_s = P_L \Delta L n_e \Omega \frac{d\sigma_T}{d\Omega} \int_{-\infty}^{\infty} S(k, \omega) d\omega,
\]

where \( P_L \) is the incident laser power, \( \Omega \) the solid angle of the viewing system, \( \Delta L \) the length of the scattering volume \( V \) and \( n_e = N/V \). \( S(k, \omega) \) is the scattering form factor, which describes the shape of the frequency spectrum, and is given by [2]

\[
S(k, \omega) = \frac{1}{2\pi N} \int_{-\infty}^{\infty} d\tau \exp(i\omega\tau) \sum_{j} \cos[k \cdot (r_j(t) - r_j(t + \tau)) - \omega_0 \tau].
\]

This expression can be written in a more appropriate form as follows, assuming an ensemble of electrons at positions \( r_j(t) \) with density

\[
n(r, t) = \sum_{j} \delta(r - r_j(t)),
\]

and its spatial Fourier transform

\[
n(k, t) = \sum_{j} \exp(k \cdot r_j(t)),
\]

the following quantity can be given by

\[
n(k, t) n^*(k, t + \tau) \exp(-i\omega_0 \tau) = \sum_{j} \cos[k \cdot (r_j(t) - r_j(t + \tau)) - \omega_0 \tau],
\]

where the asterisk denotes the complex conjugate.

The expression at the right side of Eq. 3.30 is equal to that of Eq. 3.27; therefore the scattering form factor can be represented by

\[
S(k, \omega) = \frac{1}{2\pi N} \int_{-\infty}^{\infty} d\tau \exp(i(\Delta \omega)\tau) \bar{n}(k, t) n^*(k, t + \tau),
\]

here \( \Delta \omega = \omega - \omega_0 \) is the frequency shift. The spectrum of the scattered radiation is thus the temporal Fourier transform of the autocorrelation function of the spatial Fourier component of the electron density fluctuation corresponding to the selected wave vector \( k \) [2]. The desired wave vector is selected by the choice of laser wavelength and scattering angle (see Eq. 3.11).

In Appendix 3.A the calculation of the scattering form factor is described, with the following result:

\[
S(k, \omega) = \left[ \frac{1 - G_s(\omega/k)}{[1 - G_s(\omega/k) - G_r(\omega/k)]} \right]^2 F_s(\omega/k) + \left[ \frac{G_r(\omega/k)}{[1 - G_s(\omega/k) - G_r(\omega/k)]} \right]^2 F_r(\omega/k),
\]
Here $F_e(v)$ and $F_i(v)$ are the zero-order velocity distribution functions for the component of electron velocity along the $k$ direction normalized to unity, and which are called the ion and electron feature.

3.5 **Salpeter approximation**

For a plasma in thermodynamic equilibrium the one-dimensional velocity distributions are given by

$$F_e = \frac{n}{\pi^{1/2} \nu_e} e^{-(\nu/v_e)^2}, \quad (3.33)$$

and

$$F_i = \frac{n}{Z \pi^{1/2} \nu_i} e^{-(\nu/v_i)^2}, \quad (3.34)$$

with $\nu_{e,i} = \left(\frac{2k_B T_{e,i}}{m_{e,i}}\right)^{1/2}$, \quad (3.35)

the average thermal speed of the particles.

Substituting Eq. 3.33 and 3.34 into Eq. 3.32 and introducing a dimensionless variable $x_{e,i} = \Delta \omega/k \nu_{e,i}$, Eq 3.32 can be converted to:

$$S(k, \omega) d\omega = \frac{n[1 - G_e]^2 e^{-x_e^2} dx_e}{\pi^{1/2} \left(1 - G_e - G_i\right)^2} + \frac{Zn |G_e|^2 e^{-x_i^2} dx_i}{\pi^{1/2} \left(1 - G_e - G_i\right)^2}, \quad (3.36)$$

with $Z$ the ion charge number, the term $1 - G_e - G_i$ the dielectric coefficient of the plasma, and $F_{e,i}$ the velocity distribution functions for the component of the velocity parallel to $k$ and normalized to unity for electrons and ions, respectively. The wavelength scale of the electron feature is defined by $x_e = (m_i/m_e)^{1/2} x_i$.

The screening integrals $G_e$ and $G_i$ can be represented by [2]:

$$G_e = -\alpha^2 w(x_e), \quad (3.37)$$

and

$$G_i = -\alpha^2 \frac{Z T_e}{T_i} w(x_i), \quad (3.38)$$

with $w(x_{e,i})$ the plasma dispersion function (see Fig. 3.6), which is tabulated by [7], and can be written as a summation of a real part $Rw(x_{e,i})$ and an imaginary part, the so-called Landau term $Iw(x_{e,i})$:

$$w(x_{e,i}) = Rw(x_{e,i}) + Iw(x_{e,i}), \quad (3.39a)$$

$$Rw(x_{e,i}) = 1 - 2x_{e,i} \exp\left(-x_{e,i}^2\right) \int_0^{x_{e,i}} \exp\left(t^2\right) dt, \quad (3.39b)$$
\[ I_w(x_{e,i}) = \pi^{1/2} x_{e,i} \exp \left( -x_{e,i}^2 \right). \]  
\[ \text{(3.39c)} \]

The real part of \( W(x) \) can be approximated by the following Taylor series:

\[ R_w(x_{e,i}) = 1 - 2x_{e,i}^2 \left( 1 - \frac{2}{3} x_{e,i}^2 + \frac{1}{15} x_{e,i}^4 + \ldots \right) \quad \text{for } x_{e,i} < 1, \text{ and} \]

\[ R_w(x_{e,i}) \approx -\frac{1}{2x_{e,i}} \left( 1 + \frac{3}{2x_{e,i}^2} + \frac{15}{4x_{e,i}^4} + \ldots \right) \quad \text{for } x_{e,i} \gg 1. \]
\[ \text{(3.40)} \]

**Fig. 3.6**: The plasma dispersion function [7], consisting of a real and imaginary part.

For a given frequency shift \( \omega \) the difference in scale between \( x_e \) and \( x_i \) is very large. Using this fact, Salpeter derived a simpler expression for the dynamic form factor [8]. In case \( T_e \) and \( T_i \) are not too different, the following condition is valid:

\[ x_e/x_i = \omega_i/\omega_e = \left( m_i T_i/m_e T_e \right)^{1/2} \ll 1. \]

In that case the dynamic form factor can be separated in two terms, each of which is a function of either \( x_e \) or \( x_i \) alone. This means for instance that in case \( |x_i| \sim 1 \) then \( |x_e| \ll 1 \).

First, consider the area between \( |x_i| < 1 \) and the area where \( |x_i| \gg 1 \), then the imaginary part of \( w(x_i) \) becomes negligible. Then, using Eq. 3.36 and approximations Eq. 3.40 and Eq. 3.41 it follows that \( G_i \ll G_e \) and \( G_i \ll 1 \). In that case \( G_i \) in the first term of Eq. 3.36 can be neglected (except for the case that \( |x_i| < 1 \)).

In case \( |x_i| < 1 \) (and thus \( |x_e| \ll 1 \)), the first term of Eq. 3.36 becomes negligible and \( G_e = \alpha^2 \) (see Eq. 3.40). Executing all approximations in Eq. 3.36, valid for the different frequency domains that scale with \( x_{e,i} \), the dynamic form factor can be formulated as:

\[ S(k, \omega) d\omega \equiv S_e(k, \omega) d\omega + S_i(k, \omega) d\omega, \]
\[ = \Gamma_\alpha (x_e) dx_e + Z \left( \frac{\alpha^2}{1 + \alpha^2} \right)^2 \Gamma_\beta (x_i) dx_i, \quad (3.42) \]

where \( \Gamma_{\alpha, \beta} \) are the well known Salpeter functions defined as

\[ \Gamma_\alpha (x_e) = \frac{\exp(-x_e^2)}{\left|1 + \alpha^2 w(x_e)\right|^2} = \frac{\exp(-x_e^2)}{\left(1 + \alpha^2 - 2\alpha^2 x_e \exp(-x_e^2) \int_0^x \exp(t^2) dt \right)^2 + \pi \alpha^4 x_e^2 \exp(-2x_e^2)} \quad , \quad (3.43) \]

and

\[ \Gamma_\beta (x_i) = \frac{\exp(-x_i^2)}{\left|1 + \beta^2 w(x_i)\right|^2}, \quad (3.44) \]

with

\[ \beta^2 = \frac{Z \alpha^2}{1 + \alpha^2} \frac{T_\alpha}{T_i}. \quad (3.45) \]

The spectra corresponding to electron feature \((S_e)\) and ion feature \((S_i)\) are presented in Fig. 3.7 a and b, respectively.

**Fig. 3.7:** a) Calculated shape of the electron feature as a function of the normalized wavelength and for different values of \(\alpha\). b) Calculated shape of the ion feature for different values of the ratio \(T_e\) over \(T_i\) at \(\alpha = 1.6\) \((Z = 1)\). Remark: \(x_e = \sqrt{m_e/m_i} x_i\).
Fig. 3.8: Calculated electron and ion feature contributions as function of $\alpha$ and electron-ion temperature ratio in case $Z = 1$. Remark: although $S_i$ is approximately equal to $S_e$ when $\alpha \approx 1.3$, even then only a small fraction (~5%) of $S_e$ will contribute to the narrow spectrum of $S_i$.

Integration of the form factor gives the expression for the expected relative contributions originating from the ion and electron feature as a function of the scattering parameter $\alpha$:

$$\int_{-\infty}^{\infty} S(k, \omega) d\omega = S_e(k) + S_i(k) = \frac{1}{1 + \alpha^2} + \frac{Z\alpha^4}{(1 + \alpha^2)^2(1 + \alpha^2 + Z\alpha^2 T_e/T_i)}.$$  \hspace{1cm} (3.46)

The separate contributions are shown in Fig. 3.8.

3.5.1 Electron and ion feature

In Fig. 3.7a and 3.7b the spectra of the electron and ion features are plotted as function of the normalized wavelength. When $\alpha \approx 0$, the electron feature (Eq. 3.42) will reflect the classical Maxwellian electron velocity distribution.

In both scattering contributions resonances can be found. In the region $x_e > 1$, the spectrum of the electron feature shows satellites. Here, the denominator of the first term of the electron feature goes to zero: $1 + \alpha^2 R \nu(x_e) = 0$ (in fact, the dielectric coefficient of the plasma becomes zero). It can be shown that the frequency shift of the resonances, $\Delta \omega_e$, corresponds to the electron plasma frequency $\omega_p$ and is given by:

$$\Delta \omega_e = \sqrt{\omega_p^2 + \frac{3 k_B T}{m_e} k^2}.$$  \hspace{1cm} (3.47)

This enables to determine $n_e$ since $\omega_p \propto \sqrt{n_e}$ and thus to make an absolute calibration of the sensitivity of the system. However, according to Eq. 3.46 the intensity goes down for higher values of $\alpha$. 
Using approximation Eq. 3.40 a similar solution can be found for the ion feature term in Eq. 3.42 (assuming $\alpha \geq 1$ and $Z = 1$). The peaks in this spectrum correspond to the ion acoustic resonance given in practical form by:

$$\Delta \omega_i = k \sqrt{\frac{k_BT_e + 3k_BT_i}{m_i}}. \quad (3.48)$$

These resonances are visible if $T_e \geq T_i$. For the plasma condition where $T_e \ll T_i$ the spectrum has a near-Gaussian shape (see Fig. 3.7b) reflecting the pure Maxwellian velocity distribution of the ions with $T_i$ corresponding to half 1/e-width ($\Delta \lambda_{1/e}^i$) given by:

$$\Delta \lambda_{1/e}^i \approx \frac{2\lambda_e}{c} \sin \left(\frac{\theta}{2}\right) \left(\frac{2k_BT_i}{m_i}\right)^{1/2} \text{[nm]}, \quad (3.49)$$

where $T_i$ is given in K.

In this case the width of the spectrum will be very narrow, because ion acoustic resonances are absent.

If $\alpha \ll 1$, the contribution from the ion feature is negligible (see Eq. 3.46) and the electron feature term of Eq. 3.42 is can be approximated by

$$S(k, \omega) \approx \frac{2\pi^{1/2}}{k\nu_e} \exp \left(-\frac{x_e^2}{2}\right). \quad (3.50)$$

Only the contribution from scattering on individual electrons of the spectrum will be measured (see Fig 3.3 and 3.4 for the case with $\alpha = 0$). From the half 1/e-width $\Delta \lambda_{1/e}$ of this incoherent spectrum, $T_e$ can be derived and is given in practical form as:

$$\Delta \lambda_{1/e} = \frac{2\lambda_e}{c} \sin \left(\frac{\theta}{2}\right) \left(\frac{2k_BT_e}{m_e}\right)^{1/2} \text{[nm]}, \quad (3.51)$$

where $T_e$ is given in K.

### 3.5.2 Influence of impurities on the spectral shape of the ion feature

Evans [9] modified Salpeter’s theory to include the influence of small amounts of impurities to the shape of the spectrum. In Fig. 3.9, spectra of the ion feature for a hydrogen plasma are shown as a function of several impurity concentrations $n_j$. For small impurity levels, the impurity peaks scale approximately with $n_j Z_j^2$, where $\overline{Z}_j$ is the mean charge of the impurity species $n_j$ [9, 10]. The impurity concentration of a plasma can be measured by collective Thomson scattering if information about the mean charge of the plasma is available from for instance spectroscopy.
3.6 Hot plasmas: relativistic effects

An analytical expression for relativistic TS spectra was given by M. Mattioli [11] for an isotropic relativistic Maxwellian velocity distribution [11, 12]:

\[
F(\lambda) = \frac{1}{2\sqrt{\pi} \sin(\theta/2)} \frac{\lambda_0 p_1 X(p_1)}{\lambda} Y(\Lambda) \exp \left[ -\frac{Z(\Lambda)}{p_1^2} \right],
\]

(3.52)

with:

\[
\Lambda = \frac{\lambda_0}{\lambda} \quad \text{(normalization parameter)},
\]

(3.53)

\[
p_1 = \frac{1}{c} \sqrt{\left( \frac{2k_B T_e}{m_e} \right)},
\]

(3.54)

(the ratio between thermal velocity and the speed of light),

\[
Y(\Lambda) = \frac{2 \sin(\theta/2) \Lambda^4}{\sqrt{(1 - 2\Lambda \cos \theta + \Lambda^2)}},
\]

(3.55)

\[
X(p_1) = 1 + \frac{15}{16} p_1^2 + \frac{105}{512} p_1^4,
\]

(3.56)

and

\[
Z(\Lambda) = \frac{\sqrt{(\Lambda - 2 \cos \theta + \Lambda^{-1})}}{\sin(\theta/2)} - 2.
\]
Here, \( c \) denotes the speed of light, \( k_B \) the Boltzmann constant, \( m_e \) the electron rest mass and \( r_e \) the classical electron radius. The scattering angle \( \theta \) corresponds to the angle between the incident laser beam and the observation direction.

In the classical case, i.e. when the thermal velocity is much smaller than the speed of light (\( p_1 \ll 1 \)), this function reduces to:

\[
F_{ci}(\lambda) = \frac{1}{2\sqrt{\pi} \sin(\theta/2) \lambda_0 p_1} \exp\left[\frac{(\lambda - \lambda_0)}{2\sin(\theta/2) \lambda_0 p_1}\right]^2, \tag{3.57}
\]

which is a Gaussian distribution normalized such that the integral equals to one.

In Fig 3.10 the theoretical spectra for this relativistic velocity distribution are shown. At high electron temperatures a blue shift occurs and additionally the scattering power in the direction of the observer will be enhanced (head light effect) [1].

![Theoretical spectra for a relativistic Maxwellian velocity distribution of the electrons diagnosed with a ruby laser (694.3 nm) under a scattering angle of 90°](adapted from 13).

### 3.A Appendix

In this appendix the dynamic form factor as given in Eq. 3.32 will be derived. The so-called dressed test particle model [2] is used for determination of \( n(k,t) \): the spatial Fourier transform of the electron density fluctuation, has to be determined. The essence of this model is that each charged particle in the plasma (electrons, as well as ions) is used as test particle, taking into account the Debye shielding effects. The resulting electric field originating from each test particle is calculated for the observer at distance \( R \). For determination of the electron density fluctuations \( n(k,t) \), plasma kinetic theory is required. Here the one-particle distribution functions \( f_e(r,v,t) \) and \( f_i(r,v,t) \) for electrons and ions, respectively, are introduced. These functions give the probability of finding a particle in volume element \( dr \) centred about the position vector \( r \) and in a volume element \( dv \) in velocity space. The distribution functions \( f_e(r,v,t) \) and \( f_i(r,v,t) \) are normalized to the total number of electrons \( N \) and the total number of ions \( N/Z \), respectively.
The starting point is the Vlasov equation, also called the collisionless Boltzmann equation. The plasma can be assumed to be sufficiently warm, i.e. the collision time is long compared to the interaction time with the internal electric field of the plasma.

\[
\frac{df_e(r,v,t)}{dt} + v \cdot \nabla f_e(r,v,t) - \frac{e}{m_e} E(r,t) \nabla_v f_e(r,v,t) = 0 \quad (3.A1)
\]

\[
\frac{df_i(r,v,t)}{dt} + v \cdot \nabla f_i(r,v,t) - \frac{Ze}{m_i} E(r,t) \nabla_v f_i(r,v,t) = 0 \quad (3.A2)
\]

The propagation of small amplitude waves are considered here, thus it is appropriate to use distribution functions defined as a stationary part \(f_{0,e,i}(v)\) and \(f_{1,e,i}(r,v,t)\) describing the small perturbation due to the wave: \(f_{e,i}(r,v,t) = f_{0,e,i}(v) + f_{1,e,i}(r,v,t)\).

Including the internal electric field resulting from each charged particle the Vlasov equations can be given as:

\[
(v - v_0) \nabla f_{1e}(r,v) - \frac{e}{m_e} E(r,t) \nabla_v f_{0e}(v) = 0, \quad (3.A3a)
\]

\[
(v - v_0) \nabla f_{1i}(r,v) - \frac{Ze}{m_i} E(r,t) \nabla_v f_{0i}(v) = 0. \quad (3.A3b)
\]

The internal electric field resulting from each particle is given by Poisson’s equation

\[
\nabla \cdot E(r,t) = 4\pi e \int \left( Z f_{1i}(r,v) - f_{1e}(r,v) \right) dv + 4\pi q \delta \left[ r - (r_0 + v_0 t) \right]. \quad (3.A3c)
\]

Taking the spatial Fourier transform of equation 3.3a and introducing the electrostatic potential \(\varphi(r,t)\) where \(E = -\nabla \varphi\), the following expression for the electrons can be derived:

\[
f_{1e}(k,v) = -\frac{e}{m_e} \frac{\varphi(k,t) k \cdot \nabla_v f_{0e}(v)}{k \cdot (v - v_0)}. \quad (3.A4a)
\]

Following the same procedure for equation 3.3b gives:

\[
f_{1i}(k,v) = \frac{Ze}{m_i} \frac{\varphi(k,t) k \cdot \nabla_v f_{0i}(v)}{k \cdot (v - v_0)}. \quad (3.A4b)
\]

Using the fact that \(\nabla \cdot E = \nabla^2 \varphi\), Eq. 3.3c can be written as

\[
k^2 \varphi(k,t) = 4\pi e \int \left( Z f_{1i}(r,v) - f_{1e}(r,v) \right) dv + 4\pi q \exp \left( ik \cdot (r_0 + v_0 t) \right), \quad (3.A4c)
\]

After inserting 3.4a and 3.4b in 3.4c follows:

\[
\varphi(k,t) = \frac{4\pi q}{k^2} \frac{\exp \left( ik \cdot (r_0 + v_0 t) \right)}{1 - G_e - G_i} = \frac{4\pi q}{k^2} \exp \left( ik \cdot (r_0 - v_0 t) \right), \quad (3.A5a)
\]

with

\[
G_e(v_0) = \frac{4\pi e^2}{m_e k^2} \int \frac{k \cdot \nabla_v f_{0e}(v)}{k \cdot (v - v_0)} dv, \quad (3.A5b)
\]

and
Here $\varepsilon$ is the dielectric coefficient of the plasma with $G_i$ and $G_e$ the so-called ‘screening integrals’ for the electron and ion test particle, respectively.

The Fourier transform of the electron density fluctuation or ‘shielding cloud’ associated with the test particle can be found by substituting 3.5a into 3.4a and integration over velocity space:

$$n_j(k, t) = \int f_{1e}(k, v) dv = \left( \frac{q_j}{e} \frac{G_e(v_{0j})}{\left[ 1 - G_i(v_{0j}) - G_e(v_{0j}) \right]} \right) \exp \left( ik \cdot (r_{0j} + v_{0j}t) \right). \quad (3.6)$$

This is the Fourier transform of the electron density fluctuation associated with the $j$th test particle. The total electron density of the plasma is obtained by applying Eq. 3.6 on all test particles $q_j$, taking the charge value $-e$ for an electron and $+Ze$ for an ion. In addition, the ‘self-fluctuation’ of the test particle itself must be included if it is an electron:

$$n(k, t) = \sum_{j=1}^{N_{\text{electrons}}} \left( \frac{1 - G_i(v_{0j})}{\left[ 1 - G_i(v_{0j}) - G_e(v_{0j}) \right]} \right) \exp \left( ik \cdot (r_{0j} + v_{0j}t) \right) - \sum_{j=1}^{N_{\text{electrons}}} \sum_{\ell=1}^{N/2} \left( \frac{G_e(v_{0\ell})}{\left[ 1 - G_i(v_{0\ell}) - G_e(v_{0\ell}) \right]} \right) \exp \left( ik \cdot (r_{0\ell} + v_{0\ell}t) \right). \quad (3.7)$$

For $n(k, t)$ the autocorrelation function $\langle n(k, t)n^*(k, t+\tau) \rangle$ can be determined and after rearranging the terms, the dynamic form factor Eq. 3.31 can be expressed as a function of the screening integrals:

$$S(k, \omega) = \frac{1}{N} \left[ \sum_{j=1}^{N_{\text{electrons}}} \left( \frac{1 - G_i(v_{0j})}{\left[ 1 - G_i(v_{0j}) - G_e(v_{0j}) \right]} \right) \delta \left( \Delta \omega + k \cdot v_{0j} \right) \right]^2 + Z^2 \left[ \sum_{\ell=1}^{N/2} \left( \frac{G_e(v_{0\ell})}{\left[ 1 - G_i(v_{0\ell}) - G_e(v_{0\ell}) \right]} \right) \delta \left( \Delta \omega + k \cdot v_{0\ell} \right) \right]. \quad (3.8)$$

The sums are evaluated by converting them to integrals over configuration and velocity space weighted by the zero-order distribution functions, which are assumed separable in the Cartesian coordinates of velocity. If we denote $F_e(v)$ and $F_i(v)$ the zero-order velocity distribution function for the component of electron velocity along the $k$ direction normalized to unity, the following equation can be obtained for the dynamic form factor:

$$S(k, \omega) = \left( \frac{1 - G_i(\omega/k)}{\left[ 1 - G_i(\omega/k) - G_e(\omega/k) \right]} \right)^2 F_e(\omega/k) + \left( \frac{G_e(\omega/k)}{\left[ 1 - G_i(\omega/k) - G_e(\omega/k) \right]} \right)^2 F_i(\omega/k). \quad (3.9)$$
References

Design considerations

In this chapter the main elements required for designing a reliable and sensitive Thomson scattering diagnostic is treated. The procedure from specification until realization of a TS system is described. The required calibration procedures are described as well. In Fig. 4.1 the basic setup of an incoherent TS system is presented as a starting point.

An electromagnetic wave from a laser with wave vector \( \mathbf{k}_0 \) (frequency \( \omega_0 \)) is incident on the plasma. Electrons will oscillate in this field and reradiate Doppler-shifted light due to their velocity. The light is detected within a solid angle centred around \( \mathbf{k}_s \) and relayed by a lens system or a fibre bundle to a spectrometer. In the spectrometer the light will be dispersed in wavelength and imaged onto a detector.

Fig. 4.1: General Thomson scattering scheme.
4.1  Requirements & design choices

4.1.1  General considerations

Three main TS system configurations are in use nowadays.

First, high spatial resolution systems based on intensified 2D imaging detectors. The Doppler broadened light is relayed to a spectrometer (see Fig. 4.2) and a grating disperses the light that subsequently is imaged onto an Intensified Charged Coupled Device (ICCD; a CCD coupled to an image intensifier). Some of these types of systems are equipped with Complementary Metal Oxide Semiconductor (CMOS) cameras to allow for measuring $T_e$ and $n_e$ profiles with high repetition rate during a burst of laser pulses [1].

Second, high repetition TS systems based on a filter spectrometer [2] (see Fig. 4.3). These are often combined with Avalanche Photo Diodes (APD). APDs combine very well with the fundamental wavelength of the Nd:YAG laser; the quantum efficiency around 1064 nm is higher than 80%. The repetition rate is realized by applying multiple Nd:YAG lasers, each of which can have a repetition rate of 20 - 50 Hz.

Third, a special variant is the Light Detection And Ranging TS (LIDAR-TS) system [2]. The scattered light of a short (~300 ps) laser pulse travelling through the plasma is detected in backward direction. The measurement position can be retrieved from time of flight of the laser pulse. The spatial resolution is determined by the physical length of the laser pulse and the temporal response of the detection system. For a typical LIDAR system the spatial resolution is in the range of 50 - 100 mm, which implies that this method is mainly of interest for large-scale fusion devices as JET and ITER. The repetition rate is mainly determined by the laser itself. Spectral analysis is performed with a filter spectrometer based on fast Micro-Channel Plate photomultipliers.

In general a TS diagnostic needs two vessel ports for injection and dump of the laser. The scattering angle is mostly at 90 degrees, which implies that one port is used for viewing the scattered light. Thus minimal three ports are required for a standard TS system. Additionally, at the opposite side of the viewing system, a viewing dump inside the vessel is used to absorb the laser stray light. LIDAR-TS, which is based on backward TS requires only one vessel port (a laser/viewing dump is required at the opposite side).

Because in this thesis only TV imaging TS systems are treated, the focus of the remainder of this chapter is only on those systems.

![Fig. 4.2: 2D imaging TS system: Littrow spectrometer equipped with ICCD camera.](image)

![Fig. 4.3: Filter spectrometer equipped with APD detectors, adapted from [4].](image)
4.1.2 Required laser power and detection efficiency

For the basic design, there are important requirements concerning minimum detectable density limit and tolerable observational error. This sets demands on for instance the size of the viewing solid angle as can be seen from the scattering formula, Eq. 4.1. Here, the TS signal is expressed in number of photoelectrons, \( N_{pe} \), detected at the photocathode of the detector, which could be a CCD or an avalanche photodiode or an image intensifier followed by a CCD or CMOS camera.

\[
N_{pe} = \frac{E}{h \nu_0} \Delta L \Omega n_e \frac{d\sigma_T}{d\Omega} \tau_{overall} \eta_{first\ detector},
\]

(4.1)

with \( n_e \) the electron density of the plasma.

### Table 4.1: Main parameters of a Thomson scattering system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Units</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy per laser pulse entering the scattering volume</td>
<td>( E )</td>
<td>J</td>
<td>mirrors and divergence limiter cause losses of ~10%</td>
</tr>
<tr>
<td>f-number of the viewing lens</td>
<td>( f/nr )</td>
<td>rad</td>
<td>this depends on the linear etendue of the detector</td>
</tr>
<tr>
<td>Solid angle</td>
<td>( \Omega )</td>
<td>sr</td>
<td>( \Omega = \frac{\pi}{4} (f/nr)^2 )</td>
</tr>
<tr>
<td>Length of the scattering volume along laser chord</td>
<td>( \Delta L )</td>
<td>m</td>
<td>of the order of ( 10^{-2} ) m</td>
</tr>
<tr>
<td>Differential Thomson scattering cross section</td>
<td>( d\sigma_T/d\Omega )</td>
<td>m²/sr</td>
<td>7.94×10⁻³⁰</td>
</tr>
<tr>
<td>Transmission from scattering volume till first photocathode of detector</td>
<td>( \tau_{overall} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective quantum efficiency detector</td>
<td>( \eta_{first-detector} )</td>
<td>%</td>
<td></td>
</tr>
</tbody>
</table>

Given a certain laser energy, the viewing f-number has to be chosen such that the desired minimum \( n_e \) can be measured with an acceptable observational error \( \left( \sigma_{n_e} = 1/\sqrt{N_{pe}} \right) \) at the required spatial resolution (size of spatial element).

4.1.3 Laser wavelength

The choice of laser wavelength is mainly determined by the sensitivity range of detectors. Most commercially available detectors like (I)CCD cameras operate with high quantum efficiency in the visible light range and match very well with the wavelength of a ruby (694.3 nm) or a frequency-doubled Nd:YAG laser (532 nm). In the TS systems described in this thesis, Generation III (Gen III) image intensifiers, equipped with a GaAsP photocathode, were applied. The quantum efficiency (QE) of these image intensifiers ranges to 50%, but the effective QE is about 25% due to the noise figure (noise due to the electron multiplication process and the loss of photoelectrons inside the image intensifier).

For incoherent TS the line width of the laser is no issue, but for collective TS this needs special attention, because the expected spectral widths corresponding to an ion temperature of about 2 eV (a typical lower value for the bulk ion temperature in Pilot-PSI and Magnum-PSI) are in the range of 0.1 nm. Therefore, collective TS has to be performed
with a laser that has a linewidth of 0.1 cm\(^{-1}\) (\(-0.003\) nm); sufficiently narrow to probe the ion feature. In that case, the spectral resolution of the detection system has to be in the same range.

### 4.1.4 Spatial resolution

All TS systems treated in this thesis measure \(T_e\) and \(n_e\) profiles with high spatial resolution; typically with a spatial element size of about 1 - 2% of the plasma diameter.

Depending on the required spatial resolution and number of spatial elements along the laser chord, the relay fibre configuration (fibre array type and size) and magnification of the viewing system has to be defined. The (spatial) resolution of the spectrometer device has to comply with these requirements, i.e. detector pixel size and quality of imaging optics has to be taken into account.

### 4.1.5 Plasma light background and noise

For Thomson scattering diagnostics the plasma light background can be severe and measures have to be taken to reduce its impact on the Thomson scattering measurements. Application of image intensifiers (or photomultipliers/avalanche photodiodes) that can be gated with a time window tightly centred around the laser pulse is in most cases an efficient solution to realize good background suppression. The image intensifier is coupled with lens systems or fibre optics onto the chip of a CCD or CMOS camera. An additional advantage of image intensifiers is the fact that, by virtue of the high photon gain, the noise of the CCD/CMOS camera becomes insignificant, i.e. detection setups are configured such that every photoelectron produced at the first photocathode (of the image intensifier) will generate about 100 - 300 counts at the CCD/CMOS device. This has to be compared with the noise level of the CCD, which is nowadays in the range of 1 - 2 counts rms. In this thesis the focus is on Thomson scattering system with spectrometers featuring Intensified Charged Coupled Devices (ICCD).

### 4.1.6 Stray light reduction

As a consequence of the very low value of the TS cross section, the ratio between scattered and incident power is typically in the range of \(10^{-14} - 10^{-15}\). This sets high demands on the sensitivity of detection systems, moreover stray light originating from the laser input windows can dominate the TS signal. The stray light contribution can be reduced by applying baffles in the vacuum laser beam line that collimate the stray light originating from especially the vacuum input windows (see Chap. 5 and 6). Furthermore, the stray light originating from the exit window can be eliminated by timing the image intensifier gate window such that it is closed before this stray light arrives at the detector. A so-called viewing dump, installed at the opposite side of the observation system, provides a black background and reduces the stray light background also significantly. If previous mentioned measures are not sufficient, notch filters can be applied at the detector side, i.e. a narrow part of the spectrum centred around the laser wavelength is cut out (see Chap. 5).
4.1.7 Collective effects
At very high densities (> $10^{22}$ m$^{-3}$) and low temperature (< 10 eV) the Debye length of the plasma becomes small and can approach the scale of the scattering wave. Here collective effects are expected and in the applied fitting functions these effects have to be taken into account according to scattering theory. If these effects have to be circumvented, a laser wavelength below 532 nm can be chosen. Enhancing the scattering angle from for instance an initial angle of 90° to 180° (backward TS) is normally not an effective solution for reducing collective effects (see Eq. 3.11 and Eq. 3.25).

4.1.8 Optical design: linear etendue & fibre transformation factor
To reach an as high as possible collection efficiency of the detection branch, the viewing angle and dimensions of the light source (laser chord) have to match the detector angle (f-number) and dimensions [2].

The linear etendue, here defined as the product of detector height ($L_2$) and the detection angle ($\alpha_2$), determines the maximum amount of light that can be detected. For a simple lens system with object height ($L_1$), viewing angle ($\alpha_1$) and image height ($L_2$) and collection angle ($\alpha_2$) the relay of light is realized most efficient if (see Fig. 4.4):

$$L_1 \alpha_1 = L_2 \alpha_2,$$

here $\alpha$ is expressed in units of radians.

For a detection branch, based on a fibre bundle relay system, with magnification of the viewing system ($M$) and fibre transformation factor ($m$) of the fibre bundle, the light relay efficiency can be expressed as

$$L_1 \alpha_1 = mL_2 \alpha_2.$$  \hspace{1cm} (4.3)

Using Eq. 4.3 the solid angle can be given as

$$\Omega = \frac{1}{2} \pi \alpha^2 = \frac{1}{2} \pi \left( \frac{mL_2 \alpha_2}{L_1} \right)^2.$$  \hspace{1cm} (4.4)

The fibre transformation factor $m$ enhances the linear etendue of the spectrometer. The advantage of this transformation factor can be demonstrated by an example. Assume the scattered light originating from a laser chord with length $L_1 = 50$ mm is detected by a detector with $L_2 = 25$ mm and $\alpha_2 = 0.33$ rad, corresponding to a linear etendue of 8.25 mmrad. For $m = 1$ the max viewing angle is then limited to about 0.16 rad. If a two times longer laser chord has to be observed with the same spectrometer, then as a consequence the viewing angle will be two times smaller and the solid angle a factor 4 smaller (see Eq. 4.3 and Eq. 4.4). Taking into account that the viewing samples are twice as large, the amount of detected light will drop by a factor of 2.
DESIGN CONSIDERATIONS

Fig. 4.4: Simple optical design scheme. Here it is assumed that the spectrometer slit has the same height as that of the detector.

Fig. 4.5: Application of a field lens at the input side of the fibre bundle assuring close to normal incidence of the head rays. This can be seen by following the chief rays (thick lines) from the object points to the fibre array; as a result of the plano-convex lens mounted on the fibre head all chief rays incline parallel to the normal of the fibre fronts.

This can be circumvented by using a fibre with transformation factor $m = 2$. In that case the viewing angle can be kept the same and the total amount of detected light is even enhanced by a factor of 2. This goes well till limitations are encountered concerning the slit width, which determines the number of spectral channels and the spectral resolution.

Attention has to be paid to the maximum acceptance angle of spectrometers and the critical angle of the fibres. The design should be realized such that the path of the chief rays originating from the laser chord follows inclining angles at normal incidence at the fibre fronts. In Fig. 4.5, a viewing system setup is shown where a field lens is used at the input side of the fibre bundle to assure that the chief rays, coming from the laser chord, are inclining at normal incidence on the fibre fronts (see also Chap. 7). Another solution is the application of a curved fibre head that is shaped such that the chief rays
incline perpendicular to the fibre fronts. Note that especially in tokamak devices, due to infrastructural complications, custom designed viewing lens systems have to be applied with special imaging properties.

4.2 Calibration
Accurate analysis can be performed only after calibration of the sensitivity of the TS detection branch; from scattering volume till detector. This calibration is split up in two steps: a relative calibration using a tungsten lamp at a known temperature to determine the spectral response, and an absolute calibration using Rayleigh scattering (on a know amount of gas) to determine the absolute sensitivity of the detection branch. Incorporating the relative calibration enables absolute determination of the electron temperature by fitting a function that represents the velocity distribution of the electrons. The Rayleigh scattering cross section on several gases is well known [5] and provides determination of the sensitivity of the complete detection system per unit of laser energy (the scattering volumes for Rayleigh and Thomson scattering are identical). If before every TS measurement Rayleigh scattering can be performed the sensitivity reduction due to polluted windows can be taken into account. This is the case at Pilot-PSI and Magnum-PSI. However, for reasons of maintaining the wall condition, at tokamak devices Rayleigh scattering can be performed mostly at a two-monthly basis or after longer periods. Within such long periods windows can become slowly polluted by so-called tokamakium and the absolute sensitivity of the system will deviate from that determined initially with Rayleigh scattering. Therefore, during plasma operation, interferometry (determines line averaged density) is used to cross calibrate the sensitivity of the TS system.

4.3 Conclusion
Even in an environment of high level background sources the diagnostic can perform excellently due to the use of narrow laser pulse widths that allow application of short detector gate windows. Together with the application of baffled laser input systems and/or notch filters for the detection systems the velocity distribution of electrons (and/or ions) can be obtained. Moreover, TS is normally a non-intrusive technique since plasma heating is negligible in all experiments described in this thesis (see chapter 7).

References
CHAPTER 5

10 kHz Repetitive High-Resolution TV Thomson Scattering on TEXTOR: design and performance

H.J. van der Meiden¹, C.J. Barth¹, S.K. Varshney¹, E. Uzgel³, T. Oyevaar¹, R. Jaspers¹, M.Yu. Kantor², D.V. Kouprienko², A. Pospieszczyk³, A.J.H. Donné¹ and TEXTOR-team³

² Ioffe Institute, RAS, Saint Petersburg, 194021, Russia.
³ Institut für Plasmaphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany.*
* partners in the Trilateral Euregio Cluster

Abstract
In late 2003 a 10 kHz multi-position Thomson scattering diagnostic with high spatial resolution became operational on the TEXTOR tokamak. In the initial phase of operation, one burst of 18 pulses of 12 J each with a repetition rate of 5 kHz could be extracted from the laser system. The installation of a low-dope ruby rod (spring 2005) resulted in a system, which can deliver higher pulse energy, and moreover a divergence of better than 0.7 mrad, leading to a big improvement in the detection of Thomson scattering photons. Furthermore, the number of laser pulses in one burst could be extended to even more than 30. The achieved laser energy of more than 15 J/pulse makes it possible to measure electron temperature and density profiles with an observational error of 8% on the electron temperature (T<sub>e</sub>) and 4% on the electron density (n<sub>e</sub>) at n<sub>e</sub> = 2.5×10<sup>19</sup> m<sup>-3</sup>, per spatial element of 7.5 mm. The viewing optics enables sampling either the full plasma diameter of 900 mm with 120 spatial channels of 7.5 mm each, or a 160 mm long edge chord with 98 spatial channels of 1.7 mm each. The system, which has recently become available for physics exploration, has already been used to study the structure of m=2 magnetic islands and the response of the plasma to off-axis electron cyclotron resonance heating.

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5.1 Introduction

The development of TV-like detectors paved the way to the design of a relatively simple and smart setup to measure simultaneously the electron temperature ($T_e$) and density ($n_e$) in plasmas at many positions along a laser chord, using a single laser pulse. The first multi-position Thomson scattering (TS) system based on such a TV-like detector was built for PLT in 1978 [1]. The development of TV Thomson scattering (TVTS) systems got a new impulse in 1994 by the introduction of a high-resolution TVTS system on the Rijnhuizen Tokamak Project [2]. Double-pulse versions of this system were installed on the TJ-II stellarator [3] and the TEXTOR tokamak [4].

The double-pulse TVTS system at the TEXTOR tokamak ($R_0 = 1.75 \text{ m}, a = 0.46 \text{ m}, B_0 < 2.9 \text{ T and } I_p < 0.8 \text{ MA}$), operated successfully from 2000 until 2001. This TS system was based on a double-pulse ruby laser ($2 \times 12 \text{ J}$) and two intensified CCD cameras for recording the scattered light. It was capable of measuring two $T_e$ and $n_e$ profiles during one discharge along a vertical chord of 900 mm length (at $R = 1.84 \text{ m}$) with 120 spatial channels of 7.5 mm each.

To study the dynamics of mesoscale structures like magnetohydrodynamic (MHD) islands and internal transport barriers in hot plasmas, one needs a repetitive system with a time resolution of < 1 ms. For this purpose, a TS system is developed. It consists of a repetitive laser and a fast detection system. The Ioffe Institute in St. Petersburg and MultiTech Ltd. designed and constructed a so-called double-pass intra-cavity laser [4, 5]. The system is operating like a normal laser oscillator, however in this case the plasma is part of an 18 m long cavity. To preserve the high spatial resolution of the diagnostic, as well as to adapt as much as possible to the existing viewing optics, the beam path of the new laser is kept the same as that of the double-pulse laser. A state of the art detector has been constructed, based on two 12-bit Phantom V7.0 complementary metal oxide semiconductor (CMOS) cameras and a special image intensifier stage.

In this paper the design aspects of the multi-pulse TVTS system (MPTS) for TEXTOR are described in Sec. 5.3 to 5.4, starting with an overview of the multi-pulse TS system in Sec. 5.2. The achieved system performance and some obtained results are presented in Sec. 5.5 to 5.8.

5.2 Basic overview of the MPTS system

The basic setup of the TEXTOR multi-pulse TVTS system is shown in Fig. 5.1. Basically, the layout of the system is comparable to that of the previous double-pulse system. The main differences are the use of (1) a multi-pulse intra-cavity ruby laser instead of a double-pulse conventional ruby laser and (2) an ultra-fast multi-frame detector instead of a combination of two single-frame intensified CCD cameras.

In the intra-cavity setup the plasma is included in the laser cavity, and the laser beam travels many times back and forth through the scattering volume, giving higher laser efficiency than is the case for a conventional laser. This photon-recycling setup enables the generation of a long train of pulses; moreover the energy of each individual pulse is typically higher than that produced by conventional high power lasers.
Scattered light is collected by a multi-element viewing lens and relayed to a spectrometer by coherent fibre bundles (not drawn in Fig. 5.1). Either the full plasma diameter of 900 mm with 120 spatial channels of 7.5 mm each, or a 160 mm long edge chord with 98 spatial channels of 1.7 mm each can be sampled.

Spectral analysis is performed by a spectrometer in Littrow configuration, covering a spectral range of 585 to 800 nm (for the full chord observation). The two-dimensional intermediate image \((\lambda, z)\) is projected onto the highly sensitive cathode of a gated image intensifier. The amplified light is recorded by two fast CMOS cameras (only one is drawn in Fig. 5.1). These cameras were selected because of their high recording frame rate of 10,900 frames/sec at an image format of 512×384 pixels and a 12-bit dynamic range.

### 5.3 Multi-pulse intra-cavity laser

At the Ioffe Institute comprehensive research has been performed on intra-cavity laser systems. The collaboration between this institute and FOM Rijnhuizen resulted in the development of a so-called double-pass intra-cavity laser with a cavity length of 18 m, as shown in Fig. 5.2 [6].

Here, the laser beam passes twice through the plasma along exactly the same path, before returning again into the lasing medium. The basic elements of the intra-cavity laser are
similar to those of an established laser oscillator. Between the flat rear mirror and the active medium (0.05% Cr⁺ ruby rod of 19 mm diameter and 200 mm length) an objective (item 2) controls the beam quality by compensating effects of thermal lensing in the ruby rod. The number of extracted pulses can be controlled by the Q-switch (item 3). The combination of the rear mirror (item 1) and the glass plate (item 6) form a short cavity to initiate laser operation. The laser beam is focused into the plasma by a lens system (item 7) and returned into the active medium by a spherical mirror (item 8).

In Fig. 5.3 a train of 20 laser pulses is shown, produced by the double-pass intra-cavity system using a saturable absorber as passive Q-switch. The application of a saturable absorber results in an irregular pulse separation, which is not preferred for systematic research of fast plasma phenomena. Therefore, an intra-cavity laser based on active Q-switching using a Pockels’ cell in combination with a polarizer has been developed. The main advantage of the active Q switch is the programmable (and, hence, more regular) time separation between pulses and, in combination with a special power supply, the possibility to extend the pulse train up to 40 pulses or more.

![Fig. 5.3: A train of 20 laser pulses produced by the double-pass intra-cavity system with an 80% saturable absorber as passive Q-switch, yielding a total probing energy of ~200 J.](image)

The final version of the double-pass intra-cavity laser system is installed inside the TEXTOR bunker [7]. Both the focusing telescope (item 7) and the spherical mirror have a focal length of 4.5 m, corresponding to the length of the entrance and exit tubes connected to the TEXTOR torus. The lens is at about 9 m distance from both cavity mirrors, which makes the system less sensitive to misalignment. The beam diameter at the in- and output windows is ~25 mm, thus limiting the power density well below the damage threshold of 250 MW/cm².

The 0.05% Cr⁺ ruby rod is pumped by six flash tubes. Each lamp is supplied with ~0.5 MW pumping power which is kept constant during the burst duration of typically 5 - 10 ms. To obtain a block wave for the pumping voltage a special power supply has been designed and constructed by MultiTech Ltd. in St. Petersburg [8].

Using an active Q-switch at a repetition rate of 5 kHz, a total probing energy of ~236 J in one burst of pulses was achieved [7]. The full width at half maximum (FWHM) of the laser pulses is 1 - 1.5 μs. Taking into account the cavity length of 18 m, the laser light
travels, corresponding to the pulse width, about 23 times up and down through the scattering volume. In other words each laser pulse within a burst has a microstructure of smaller laser pulses each with an average energy of ~ 0.6 J. The microstructure is, however, not observed by the detection system, which only observes the integrated laser pulse with total energy of ~ 15 J. The word ‘pulse’ in this article therefore refers to the integrated laser pulse. Although high probing energies are achievable with this setup, luminescence measurements at the ruby rod cross section indicated that the amplification process in the 0.05% Cr⁺ ruby rod occurs predominantly at the periphery. It is obvious, that thermal-lensing effects will occur, preventing the laser to operate with stable and low divergence. The same effect caused the pulse energy to decrease from 15 J for the first pulses, to 5 - 8 J for the later pulses in the burst.

To reduce this effect, the intra-cavity system was equipped in 2005 with a 0.03% Cr⁺ ruby rod, resulting in a laser beam divergence of less than 0.7 mrad. In Fig. 5.4 a burst of pulses is shown for the low-dope ruby rod case. Although, the flash lamp power was limited for lifetime considerations, a pulse train consisting of 22 pulses with average pulse energy of 10 - 12 J could be easily generated, without any strong degradation of pulse energy within the burst. Higher power levels up to 15 J have also been reached in trains with up to 14 - 15 pulses.

![Fig. 5.4: Intra-cavity laser operation at 5 kHz and at medium flash lamp power, using a 0.03% Cr⁺ doped ruby rod (TEXTOR Shot #100194).](image)

For comparison photographs of burn spots are shown in Figs 5.5a and 5.5b, corresponding to laser operation with a high- and low-dope ruby rod, respectively. They are measured in the vicinity of the output of the short cavity laser (rear mirror - glasses); the spread of the laser energy across the beam is very homogeneously for the low-dope rod. As a result,
about 90% of the scattered energy is concentrated within a 3.5 mm spot at the plasma centre and within a ~ 6 mm spot at the plasma edge (z = ± 450 mm). Furthermore, the application of the low-dope ruby improved the pumping-to-probing efficiency significantly by more than a factor 1.5. Therefore, it is expected that it is feasible to generate multiple (up to four) bursts with a time separation of > 0.5 s between the bursts, each with a pulse train starting with energy of more than 15 J.

Fig. 5.5a: Burn spot measured in the vicinity of the short cavity using a 0.05% Cr⁺ doped rod. Amplification occurs predominantly at the periphery of the rod.

Fig. 5.5b: Same for a 0.03% Cr⁺ doped rod. Amplification occurs homogeneously over the rod cross section.

5.4 Multi-pulse detection system

Behind the tokamak window, scattered light is collected by a multi-element viewing lens and guided to a Littrow spectrometer (Fig. 5.6) via a 28 meter long coherent fibre bundle for observation of the full plasma diameter. At the input side, the fibre array consists of 600×3 fibres, converted to 300×6 at the output side. For the edge observation a coherent bundle of 98×3 fibres is installed. Light, which enters the 260 mm high entrance slit of the spectrometer, is dispersed by a grating in Littrow setup. Using a motor-controlled rotation table different kinds of gratings can be selected covering different temperature ranges: a 600 lp/mm for 100 eV ≤ Te ≤ 5 keV, a 900 lp/mm grating for 50 eV ≤ Te ≤ 2 keV and a 1500 lp/mm grating for 5 eV ≤ Te ≤ 500 eV especially for edge TS.

Fig. 5.6: Layout of the Littrow spectrometer.
The resulting spectral image of 260×200 mm² is projected onto the cathode of a GEN III image intensifier, giving an image of 23.4×18 mm². A tandem lens system images the P46 phosphor screen onto the CMOS chip of two ultra-fast cameras with magnification M = 0.45 (see Fig. 5.7). One camera is used for detection of the Thomson scattered light up to 10 kHz, whereas the other is applied for measuring the plasma light between subsequent laser pulses. The magnification of the coupling lens is chosen such that the image of the two-part mirror (10.6×8.1 mm²) is well within the chip dimensions (11.3×8.45 mm²). The rather low gain of the GEN III intensifier and the sensitivity of the chosen CMOS camera require additional light amplification. For that purpose, a stack of three proximity-focused intensifiers is used [9]. The properties of the fast CMOS cameras and the image intensifier booster stage are described in more detail in the following subsections.

![Ultra-fast detector](image)

**Fig. 5.7:** Ultra-fast detector. Spectrally resolved light is detected by a gated GEN III image intensifier and subsequently amplified by a stack of three proximity-focused GEN I intensifiers.

### 5.4.1 Ultra-fast camera

The requirements for the ultra-fast camera(s) are very high. Both Thomson scattering and plasma light need to be recorded at the maximum rate of the laser. That means a total frame rate of 20,000 images/s should be captured with an image format of at least 250×250 pixels. The effective dynamic range should be 8 bit or higher. This requirement implies that the maximum recordable signal should be ≥ 256 times larger than twice the RMS noise of the detector, which means that statistically 95% of the noise is within one count of an 8-bit system. Two different types of cameras were tested: (1) CCD cameras with on-chip storage of the images and (2) CMOS cameras, which perform fast readout of each image and storage in a random access memory (RAM).

(1) Ultra-fast recording of subsequent images is possible with a CCD camera using on-chip storage of several images. A mask is used to blind off the storage area, leaving a pattern of regularly distributed light-sensitive pixels. The number of stored images depends on the applied mask and is about 4 to 17, depending on the type of CCD camera used. Recording speed is determined by the clock rate of the CCD chip, giving frame rates up to 500 kHz. The main disadvantage of on-chip storage is the cross talk between images in the time domain. This is due to blooming effects on the CCD chip and halo of the image.
intensifiers applied for gating. Several cameras were tested and the cross talk between the signals of subsequent images appeared to be 1 - 2 % per stored image, resulting in an accumulated image-to-image cross talk of up to 15 % (in case of 17 storage pixels).

(2) Several CMOS cameras were tested on RMS noise, linearity, blooming of the chip, cross talk of subsequent images, shutter on-off ratio (a parameter for pixel shutter quality, not described here) and sensitivity. For all cameras tested during the design phase, no blooming on chip and no cross talk could be found ($\leq 10^{-5}$). Linearity of the chips is well within the specified dynamic range of $\pm 3 \%$. In general, the sensitivity of CMOS chips can vary between 1/100 and 1/4000 count/photon @ 670 nm, which is a rather low sensitivity compared to that of cooled CCD cameras, which have typically 1/30 count/photon. One of the main advantages of the CMOS cameras is the continuous readout and storage of images, i.e. the number of sampled images only depends on the selected image format and the capacity of the available RAM. Of all tested cameras the specifications of only one, the Phantom V7, came closest to the requirements.

The Phantom V7 can store 12-bit images of $512 \times 384$ pixels (22 µm) at a frame rate up to 10.9 kiloframes per second with a remarkably high sensitivity of $\sim 1/50$ count/photon. It is found, that the image-to-image cross talk of the Phantom V7 camera is only then small enough (1.5%) when the camera is illuminated with a bias light level, corresponding to $> 270$ counts. In that case, the detector noise is about 3 counts. As a result the effective dynamic range is 9.5 bit for a noise range of 95% probability ($\pm 6$ counts). Although the Phantom V7 does not fully comply with the requested specifications it was the best available camera at the time of purchase (2003). In a standard camera memory $\sim 3400$ images of the required image format can be stored.

5.4.2 Image intensifier booster stage

Present technology of ITT Generation III intensifiers provides quantum efficiencies up to $\sim 50\%$ over a wavelength range between 580 and 850 nm, which perfectly fits our TS application. A P46 phosphor providing a decay time of $0.2 \mu s$ is chosen to circumvent cross talk between images of subsequent laser pulses, which have a minimum separation time of 100 µs. However, a P46 phosphor has a 4 to 5 times lower efficiency than the P20 phosphor used in the previous double-pulse system. The maximum obtainable gain is 1300 at the maximum Micro-Channel Plate (MCP) voltage of 1150 V. To prevent electron depletion, due to electron exhaust of the Gen III MCP, a MCP voltage of 990 V is used ($G_{ph} = 450$).

For the complete detector a conversion factor ($Q_0$) is defined as the number of counts generated by one photoelectron detected from the GEN III intensifier [10]. The value of this conversion factor determines the impact of the bit and the RMS detector noise on the observational error of the signal. The maximum value of $Q_0$ is determined by the dynamic range of the CMOS camera and the maximum electron density $n_e \leq 1 \times 10^{20}$ m$^{-3}$, at which $N_{pe} = 2 \times 10^4$ photoelectrons (pe) are distributed over one spectrum with a height of $z_{bin}$ pixels (corresponding to $\Delta L = 7.5$ mm in the plasma). Assuming a half-width of the TS spectrum of $w_{pixel}$ unbinned wavelength pixels, the amplitude of the TS spectrum of one pixel height is given by:
For $Q_0 = 80$ counts/pe, $wpixel = 170$ (half of the usable CMOS detector width) and $zbin = 4$, the amplitude $A = 2350$ counts, which is well below the maximum of 4096 counts.

The photon gain needed to realize $Q_0 = 80$ counts/pe can be found from the relation between $Q_0$, the photon gain, $G_{ph}$, the coupling lens efficiency, $T_{coupling}$, the sensitivity, $S_{det}$ (1/50 counts/photon) and the effective efficiency of the GEN III image intensifier, $\eta_1$ ($\sim 0.25$).

$$Q_0 = \frac{G_{ph} T_{coupling} S_{det}}{\eta_1}$$  \hspace{1cm} (5.2)

For the applied F/3 lens, a 50% beam splitter and a 95% transmission of the coupling lenses, $T_{coupling} = 0.013$. Inserting these values gives a required total photon gain of $G_{ph} \approx 7.7 \times 10^4$. Since, linear operation of the Generation III intensifier is well feasible at $G_1 \sim 450$, a booster stage is needed to increase the photon gain by at least another factor of ~171. This gain could be realized with a stack of three proximity-focused intensifiers equipped with S20 cathodes and P46 screens [8], operating at 12 kV and each with a gain of ~5.6.

5.5 Data analysis

In principle, data analysis is the same as for the previous double-pulse system [5], now executed multiple times, with two main differences.

First, to capture the TS photons during the full laser pulse the image intensifier needs to be gated during 1.8 $\mu$s. This discloses one of the main critical points of this diagnostic: the competition between plasma background light and the TS signal. Therefore, the background is measured additional to every laser pulse to enable correction for this.

Second, the measured TS spectrum at each position is the sum of two relativistic spectral-distribution functions, with different shapes corresponding to back- and forward scattering. The scattering angle along the full chord of 900 mm varies between 70 and 110°. However, still a two-parameter fit (depending on $T_e$ and $n_e$ values) is used to describe the spectrum since a fixed ratio between the forward and backward energy can be applied.

5.6 System performance

The number of the detected photoelectrons can be calculated from the scattering formula:

$$N_{pe} = \frac{E}{h\nu_0} \Delta L \Omega n_e \frac{d\sigma_T}{d\Omega} \tau_{overall} \eta_{intensifier} \eta_{slit}.$$  \hspace{1cm} (5.3)

Using this formula in combination with the TS system parameters described in Table 5.1, results in an expected number of photoelectrons $N_{pe} = 2190$ at a density of $1.0 \times 10^{19}$ m$^{-3}$. To compare this value with the measured number of photoelectrons, the conversion factor $Q_0$.
was determined from statistical analysis of a CMOS image with a homogeneous illumination, giving $Q_0 = 80$ counts/pe.

**Table 5.1: Main parameters of the Thomson scattering system**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy per laser pulse $E$</td>
<td>15 J</td>
</tr>
<tr>
<td>Solid angle $\Omega$</td>
<td>$1.88 \times 10^{-3}$ sr</td>
</tr>
<tr>
<td>Scattering volume (3 pixels on CMOS chip) $\Delta L$</td>
<td>$6 \times 10^{-3}$ m</td>
</tr>
<tr>
<td>Differential Thomson scattering cross section $d\sigma / d\Omega$</td>
<td>$7.94 \times 10^{-30}$ m$^2$/sr</td>
</tr>
<tr>
<td>Overall transmission till first photocathode $\tau_{overall}$</td>
<td>0.15</td>
</tr>
<tr>
<td>Effective quantum efficiency (QE=50%, noise figure=1.35) $\eta_{intensifier}$</td>
<td>0.27</td>
</tr>
<tr>
<td>Transmission through spectrometer slit $\eta_{slit}$</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Using Rayleigh scattering, the system sensitivity at an energy of 15 J, $\Delta L = 4$ pixels and $Q_0 = 80$ counts/pe, was found to be 1510 photoelectrons at a density of $n_e = 1.0 \times 10^{19}$ m$^{-3}$, which is about 30% lower than the theoretical value. The reason for this difference can be too high assumed values for the effective quantum efficiency of the image intensifier, the laser power, and/or the efficiency of the booster stage.

The expected number of detected TS photoelectrons is such, that an observational error of $< 3\%$ in $n_e$ at $n_e = 1.0 \times 10^{19}$ m$^{-3}$ is possible, if the background contribution from plasma light would be negligible. Although, in a tokamak the plasma light background can be considerable, a simple calculation shows that very accurate measurements of $n_e$ are achievable, provided that the integrated TS signal is more than two to three times higher than that of the plasma light (PL) signal.

Assume, $S_1 = TS + PL$ and $S_2 = PL$ are the signals (in number of photoelectrons) measured during and after the laser pulse, respectively. The corrected TS signal is $S = S_1 - S_2$. Using Poisson statistics one finds the error $dS$ in $S$, which can be expressed as a function of the relative error in $n_e$:

$$\frac{dS}{S} = \frac{dn_e}{n_e} \sqrt{1 + 2PL/TS},$$

with $dn_e/n_e$ referring to the observational error in the case when there is no plasma light at all, $PL=0$. 

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The signal ratio of TS and PL exceeds even a factor 3.5 (see Fig. 5.8a), which implies, that the plasma light background contributes less than 25% to the observational error in $n_e$. The image of the TS signal is shown in Fig. 5.8b. The wide and small vertical dark bands in the image correspond to the spectral ranges near the original laser wavelength (leaving the spectrometer via the slit in the two-part mirror) and the $H_\alpha$ wavelength, which is blocked by a mask on the spectral mirror (Fig. 5.6, item 7).

### 5.7 Results

The MPTS system has come into operation late 2004 and its performance has been gradually improved since then. In this section a number of typical measurement results are given.

A measured TS spectrum, corresponding to a location near the equatorial plane in the plasma is shown in Fig. 5.9a along with the plasma light spectrum in Fig. 5.9b. The solid line in Fig. 5.9a is a two-parameter spectral fit to the data. The fitted values of $T_e$ and $n_e$ are $1.015 \pm 0.056$ keV and $3.00 \pm 0.07 \times 10^{19}$ m$^{-3}$, respectively. The accuracies in the $T_e$, $n_e$ determination are $-5\%$ and $-2\%$ for the shown spectrum.
In the early operational phase of the MPTS system, using the 0.05% doped Cr⁺ rod, the pulse energy strongly degraded within a burst. For this reason it was not yet possible to follow fast processes in the plasma. However, for relatively slowly varying or stationary plasma processes it was possible to measure $T_e$-profiles with very high accuracy. In Fig. 5.10a examples are shown of $T_e$-profiles measured in ohmic plasmas and at 45 ms after switch-on of off-axis electron cyclotron resonance heating (ECRH), in an ohmic plasma and in a plasma with low-power neutral beam injection, respectively. The data from 12 individual pulses within a single burst were summed and the equivalent laser energy that was used per profile was typically ~ 220 J. The gap in the profile (plotted versus normalized plasma radius $\rho$) is due to the fact that the Thomson viewing line crosses the plasma 9 cm towards the low field side of the geometric axis. So the actual plasma centre is not seen. Fig. 5.10b gives a contour plot of the $T_e$-profile versus time relative to off-axis ECRH switch on. Here the vertical axis is the position along the Thomson laser chord. The times of Thomson measurements (except for one at 100 ms) are indicated by vertical dashed lines. The data have been interpolated. The very pronounced hollow shape of the $T_e$-profile during application of off-axis ECRH in an ohmic discharge is explained by the fact that the ohmic input power in the plasma core drops below the power lost by the electrons due to collisions with ions [10, 11].
Fig. 5.10: (a) Electron temperature profiles in TEXTOR at 45 ms after switch-on of off-axis ECRH in an ohmic discharge (red). The red bars indicate the ECRH deposition location. The black profile is measured after adding 300 kW NBI into a similar discharge. For comparison, an ohmic profile (blue) is also shown. The profiles are plotted versus the normalized minor radius $\rho$. The gap in the profile centre is due to the fact that the Thomson laser is 9 cm off-centre with respect to the geometric axis. (b) Contour plot of the electron temperature as a function of time after ECRH switch-on. The dashed lines indicate the times of TS measurement.

Summing data from consecutive laser pulses within a burst has also been used to study the $T_e$-profiles in TEXTOR plasmas with a pronounced $m/n = 2/1$ magnetic island (see Fig. 5.11a and 5.11b). In these plasmas the Dynamic Ergodic Divertor (DED) was operated in the static mode, which led to a complete locking of the island. Depending on the phasing through the DED-coils, the island could be locked such that the TS laser chord crosses the X-point at the top of the plasma, while still crossing through the (edge of) island itself at the bottom and the other way around. As is evident from Fig. 5.11 the electron temperature inside the island is rather flat, with only a rather faint peaking [11, 13].
Fig. 5.11: (a, b) Temperature profiles through different phases of a stationary \( m/n = 2/1 \) magnetic island, measured in two different TEXTOR shots with static Dynamic Ergodic Divertor (DED) operation. The island structures have a width of about 8 cm (depicted by the green lines) and are clearly seen in both shots. The profile perturbations by the islands are found to be asymmetric and are consistent with the DED coil current settings.

The real demonstration of the merits of the TEXTOR MPTS system came from plasmas with rotating \( m/n = 2/1 \) islands (see Fig. 5.12). The measurements in Fig. 5.12 were taken after installation of the 0.03% doped Cr⁺ rod with a repetition rate of 5 kHz (measurement times are indicated by the vertical dashed lines). A very strong density peaking is evident inside the island, while - as in Fig. 5.11 - the electron temperature inside the island is flattened [11]. Measurements such as the one plotted in Fig. 5.12 are now used to study the dynamics of \( m/n = 2/1 \) mode suppression in TEXTOR via ECRH and Electron Cyclotron Current Drive.

With the edge observation system, measurements have been done on modifications in the edge temperature and density gradients during passage of edge localized modes (ELMs) in H-mode discharges. These data are presently subject of analysis and cannot yet be reported here.
Fig. 5.12: Dynamics of a rotating \( m/n = 2/1 \) magnetic island made visible by the contour plots of (a) electron density, (b) electron temperature, and (c) pressure profiles measured with high-resolution multi-pulse Thomson scattering system at TEXTOR. The peaking of density and flattening of temperature within the O-point of the island is evident. The horizontal lines indicate the location of the \( q = 2 \) surface. The vertical lines indicate time points of profile measurement. The measurements have been done in a single discharge at 5 kHz repetition rate.

5.8 Summary and perspectives
After the application of the low-dope ruby rod, the expected statistical error at \( n_e \sim 2.5 \times 10^{19} \text{ m}^{-3} \) on \( T_e \) and \( n_e \) for \( 50 \text{ eV} \leq T_e \leq 2 \text{ keV} \) became \( \sim 8\% \) and \( 4\% \), respectively for the full chord observation. For edge observations the expected observational errors on \( T_e \) and \( n_e \) are \( \sim 8 \) and \( 4\% \), respectively at \( n_e \sim 10^{19} \text{ m}^{-3} \), a temperature range of \( 5 \sim 500 \text{ eV} \) and an assumed laser energy of 15 J. The edge TS observation system is ready for operation. It
will, combined with the TEXTOR dynamic ergodic divertor, provide detailed information about electron dynamics in the outer region of the plasma.

The relatively high repetition rate of the TS system enables the study of electron dynamics in hot plasmas. Examples of this have been given in Sec. VII. Thus far the system has been operated with a single CMOS camera measuring alternately the Thomson scattered light and the plasma light with the laser operating at 5 kHz. Operation of the laser at 10 kHz, albeit at somewhat lower power levels, has already been achieved in a mock up at the Ioffe Institute. In the very near future the operation of the MPTS system will be extended to three to four bursts of typically 20 - 30 pulses each at 10 kHz repetition rate. A critical issue in this respect will be the effect of thermal lensing of the ruby rod. In case this becomes significant, a possible solution would be to include phase contrast mirrors in the system [13]. The system is already planned to be used for studies of edge localized modes in $H$ modes, DED-induced structures in the edge plasma, disruptions, and internal transport barriers.

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References

High sensitivity imaging Thomson scattering for low temperature plasma

H.J. van der Meiden¹, R.S. Al¹, C.J. Barth¹, A.J.H. Donné¹, R. Engeln², W.J. Goedheer¹, B. de Groot¹, A.W. Kleyn¹,³, W.R. Koppers¹, N.J. Lopes Cardozo¹,², M.J. van de Poel¹, P.R. Prins¹, D.C. Schram¹,², A.E. Shumack¹, P.H.M. Smeets¹, W.A.J. Vijvers¹, J. Westerhout¹, G.M. Wright¹, and G.J. van Rooij¹

¹ FOM-Institute for Plasma Physics Rijnhuizen, Association EURATOM-FOM, partner in the Trilateral Euregio Cluster, P.O. Box 1207, 3430 BE Nieuwegein, The Netherlands, www.rijnhuizen.nl
³ Leiden Institute of Chemistry, Leiden University, Leiden, The Netherlands, www.surfcat.leidenuniv.nl

Abstract

A highly sensitive imaging Thomson scattering system was developed for low temperature (0.1–10 eV) plasma applications at the Pilot-PSI linear plasma generator. The essential parts of the diagnostic are a Nd:YAG laser operating at the second harmonic (532 nm), a laser beam line with a unique stray light suppression system and a detection branch consisting of a Littrow spectrometer equipped with an efficient detector based on a “Generation III” (Gen III) image intensifier combined with an Intensified Charged Coupled Device (ICCD) camera. The system is capable of measuring electron density and temperature profiles in a plasma column of 30 mm diameter with a spatial resolution of 0.6 mm and an observational error of 3% in the electron density ($n_e$) and 6% in the electron temperature ($T_e$) at $n_e = 4 \times 10^{19} \, m^{-3}$. This is achievable at an accumulated laser input energy of 11 J (from 30 laser pulses at 10 Hz repetition frequency). The stray light contribution is below $9 \times 10^{17} \, m^{-3}$ in electron density equivalents by the application of the stray light suppression system. The amount of laser energy that is required for a $n_e$ and $T_e$ measurement is $7 \times 10^{20} / n_e \, J$, which means that single shot measurements are possible for $n_e > 2 \times 10^{21} \, m^{-3}$.

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6.1 Introduction

The plasma facing components of the international fusion reactor ITER and especially the divertor wall material have to withstand particle fluxes of up to $10^{24}$ ions/m²s and power loads of up to 10 MW/m². At these high particle fluxes, the main mechanisms of erosion of wall material are chemical erosion and physical sputtering. However, redeposition of wall material, is one of the aspects of plasma wall interaction that can occur in the so-called strongly coupled regime, i.e. the mean free path for plasma ions and eroded wall material is small relative to the dimensions of the interaction region [1]. A better understanding and, ultimately, the control of the high power loads will be crucial for the realization of a fusion power plant operating in steady state.

To investigate the underlying erosion mechanisms, the linear plasma generator Magnum-PSI (MAgnetised plasma Generator and NUmerical Modeling for Plasma Surface Interaction studies) is being developed for PSI-lab at the FOM-Institute for Plasma Physics Rijnhuizen. Pilot-PSI has been constructed to develop and test the plasma source and diagnostics to be used ultimately on Magnum-PSI. It uses a so-called cascaded arc source [2] in a magnetic field of up to 1.6 T to generate intense hydrogen plasma beams. Particle fluxes of up to $10^{25}$ ions/m²s have been measured at the target that is 0.56 m downstream from the source [3]. The Thomson scattering (TS) system that is presented in this paper was designed and constructed to measure the electron density ($n_e$) and temperature ($T_e$) in the plasma. An overview of combinations of $n_e$ and $T_e$ that have been measured near the target with this system is shown in Fig. 6.1. This demonstrates that Pilot-PSI can achieve $n_e$ between $1 \times 10^{19} - 3 \times 10^{21}$ m⁻³ and $T_e$ between 0.1 - 5 eV.

![Fig. 6.1: Overview of the plasma conditions that have been measured at 17 mm in front of the target of Pilot-PSI.](image-url)
Thomson scattering is a direct and accurate method that yields both $n_e$ and $T_e$ [4]. In general the signals are low due to the small Thomson scattering cross section. High power lasers and highly sensitive detectors are needed to enhance the measured signal level as much as possible. In addition, measures have to be taken to reduce background contributions from plasma and stray light. Stray light reduction requires state of the art filters or special spectrometer configurations [5 – 7]. In the present TS system no filtering is applied and spectral analysis is performed with a Littrow spectrometer in its simplest configuration. Instead of using filter techniques, the laser stray light entering the vessel was minimized by placing the laser windows at the end of long tubes and limiting the stray light cone with special apertures. The system was developed at Pilot-PSI and optimized to measure profiles for $n_e > 5 \times 10^{18}$ m$^{-3}$ and $0.3 < T_e < 10$ eV along an observational chord of maximum 50 mm long.

The FOM-Institute for Plasma Physics Rijnhuizen has a long history in developing imaging TS systems based on Littrow spectrometers equipped with (intensified) Charged Coupled Device (CCD) and Complementary Metal Oxide Semiconductor (CMOS) cameras. The first system was applied at the Rijnhuizen Tokomak Project (RTP), which operated until 1998. Presently, similar systems are still operational at the high temperature plasma devices TEXTOR and TJ-II [8]. These systems use the ruby line (694.3 nm) as the central wavelength and feature a spectral range up to 300 nm to cover Doppler broadenings corresponding to temperatures exceeding 4 keV. This is in contrast with the spectral range of the Pilot-PSI TS system, which is 10 nm to cover a maximum temperature of 11 eV (assuming that at least the full 1/e-width of the Thomson scattered spectrum is covered).

In this paper the properties and performance of the Pilot-PSI TS system are described in Sec. 6.3 and the capabilities of the system are demonstrated by measurements performed at Pilot-PSI. The experimental details are described in Sec. 6.2 and the results in Sec. 6.4. Finally, the conclusions and an outlook are given in Sec. 6.5.

### 6.2 Pilot-PSI Experimental

The Pilot-PSI device is schematically shown in Fig. 6.2. A wall-stabilized DC cascaded arc produces the hydrogen plasma. A discharge current is drawn between a set of 3 cathodes and the nozzle, which serves also as the anode. The typical discharge parameters are a gas flow of 2 standard litre per minute (slm; 1 slm = 4.5×$10^{20}$ particles/s) and a discharge current between 100 and 300 A. This requires an arc voltage of approximately 200 V (depending on the magnetic field strength). The plasma is exhausted into the 0.4 m diameter vacuum vessel that is kept at a background pressure of 1 - 10 Pa during operation by a set of roots pumps (total pumping speed of 2×$10^3$ l/s). An axial magnetic field of 0.4 T (< 3 minutes; limited by the cooling of the coils) up to 1.6 T (< 4 s) confines and guides the plasma to the target at 0.56 m downstream the source. TS is performed at either ~40 mm downstream of the source nozzle or at a distance of 17 mm in front of the target surface, as is indicated in Fig. 6.2.
6.3 Thomson scattering system

Fig. 3 gives a schematic overview of the entire Thomson scattering system. The different elements of the system, i.e. the laser beam line, the detection branch, the data acquisition, and the overall performance are described in detail in the next sections.
6.3.1 Laser beam line and stray light suppression system

The frequency-doubled light of a 10 Hz Nd:YAG laser (LAB-170, Spectra-Physics; 0.5 J, FWHM 7 ns, divergence < 0.5 mrad) is expanded from an initial ~ 9 mm beam diameter to ~ 27 mm, which results in an improved beam divergence of ~ 0.13 mrad. The beam is focused in the centre of the Pilot-PSI vessel with an \( f = 250 \) cm singlet lens. By virtue of the low divergence, a beam waist of \( \leq 0.7 \) mm is realized in the plasma centre. A neutral density filter (OD ~ 5) located outside the vacuum at 140 cm below the plasma centre serves as a beam dump.

Undesired reflections and scattering of light at the input and output windows of the vacuum vessel are the main sources of stray light. Therefore, these are mounted under the Brewster angle at the end of long vacuum tubes, and at large distance from the plasma centre. A series of light baffles (see Fig. 6.4) collimate the cone of stray light such that it entirely fits in the \( \varnothing = 66 \) mm output tube. Firstly, a critical aperture of \( \varnothing = 11 \) mm, located 68 cm above the plasma centre, limits the stray light originating from the input window. Subsequently, a cascade of 6 mm inner diameter carbon apertures with a total height of 80 mm is applied to limit the cone diameter of the stray light originating from the edges of the critical aperture and input window. Collimation of the stray light cone diameter inside the vessel is required, since TS measurements have to be performed close to the Pilot-PSI target. This way interference of the stray light with the target surface is reduced. Furthermore, a carbon viewing dump is installed opposite of the viewing system. After these modifications, very low stray light levels are achieved; enabling TS measurements 17 mm in front of the Pilot-PSI target (see Sec. 6.3.4).

![FIG. 6.4: Layout of the stray light reduction system. Stray light originating from the entrance window is limited by a critical aperture. A 6 mm diameter cascaded carbon aperture system limits the cone of scattered light that is produced at the critical aperture.](image-url)
6.3.2 Detection system

The Doppler broadened light is collected at a scattering angle of 90 degrees by an \( f = 160 \) mm (effective f-number \( f/15 \)) viewing system. The lens system consists of two \( f = 320 \) mm achromats and images the laser chord with magnification \( M = 0.66 \) onto the entrance of a fibre bundle (15 m length, 20 mm input height, array format 48×1; CeramOptek UV400/424P). In this way 48 spatial elements in the plasma are sampled along a laser chord of 30 mm. The spatial resolution of the detection branch is 0.6 mm (corresponding to 12 CCD pixels) and is set by the fibre diameter of 400 \( \mu \)m and the magnification of the viewing system. Spectral analysis is performed with a spectrometer in Littrow configuration (see Fig. 5), covering a spectral range of 527 to 537 nm. The two-dimensional intermediate image (\( \lambda, r \)) is projected onto the highly sensitive cathode of a gated “Generation III” (Gen III) image intensifier (\( \varnothing = 25 \) mm).

![FIG. 6.5: Layout of the Littrow spectrometer.](image)

The central wavelength of this band is located around the second harmonic of the Nd:YAG laser (532 nm). Concerning sensitivity this wavelength is still suitable for a Gen III image intensifier (photocathode: extended blue GaAsP) as first amplifier. Its effective quantum efficiency is 16% and constant over the spectral range of interest. The (P43) phosphor output of the Gen III is imaged onto an ICCD camera via a tandem lens system (Rodenstock: \( f = 95 \) mm/1.2). The ICCD camera consists of a Gen II image intensifier (\( \varnothing = 25 \) mm), fibre optically coupled to the CCD (format 576×385 pixels, pixel size 22 \( \mu \)m and dynamic ADC range 16-bit) with a demagnification of 1.5. The photon gains of the Gen III image intensifier and the Gen II image intensifier are balanced such that they can operate in a linear regime free from any image depletion and noise. The first image intensifier is gated during a 30 ns long time window around each individual laser pulse to suppress plasma light, which is triggered jitter-free via a photodiode that directly samples the laser output.

The small spectral range and the choice of central wavelength constitute an important advantage of this system, i.e. a large dynamic range: atomic lines radiated by low temperature hydrogen or argon plasmas are absent in the detection band and the short image intensifier gate time of 30 ns ensures that background light contributions are small. In Sec. 6.3.4, a worst case measurement of these contributions will be given.
6.3.3 Data processing

Incoherent Thomson scattering is a direct method to determine the velocity distribution of the electrons in the plasma. Assuming a Maxwell-Boltzmann electron velocity distribution, the measured Doppler broadened spectrum can be represented by a Gaussian function with a half 1/e-width $\Delta\lambda_{1/e}$ [5] equal to:

$$\Delta\lambda_{1/e} = 2\frac{\lambda_0}{c} \sin\left(\frac{\theta}{2}\right) \left(\frac{2k_BT_e}{m_e}\right)^{1/2} \text{ [nm]}.$$  \hspace{1cm} (6.1)

Here $\lambda_0$ is the central wavelength (532 nm), $c$ is the speed of light, $\theta$ the scattering angle (-90 degrees for the present system), $k_B$ Boltzmann’s constant and $m_e$ the electron mass. Substituting these numbers in equation 6.1, $T_e$ can be determined from the half 1/e-width according to:

$$T_e = 0.452 \left(\Delta\lambda_{1/e}\right)^2 \text{ [eV]},$$  \hspace{1cm} (6.2)

where $\Delta\lambda_{1/e}$ is given in nm. At the first photocathode surface the spectra are resolved with a dispersion of 0.83 nm/mm. The minimum detectable electron temperature in this setup is determined by the input fibre diameter of 0.4 mm, corresponding to a spectral width of 0.33 nm. Setting the smallest detectable line width to twice this width gives, using equation 2, a minimal detectable temperature of 0.2 eV. The maximum detectable temperature is determined by the spectral range covered by the spectrometer. This is 10 nm, which is sufficient to measure temperatures up to 11 eV (assuming a half 1/e-width of 5 nm).

The integrated spectrum is a measure for the number of photons collected per spatial element, which is proportional to the electron density. Rayleigh scattering is performed for absolute calibration. The Pilot-PSI vessel is filled with 50 Pa of argon and the scattered signal combined with the Rayleigh cross section provides the signal (counts) per Joule per Pa. The spectral response of the detection system is determined by illuminating the viewing lens system with a tungsten lamp (at 2685 K). We follow the calibration procedures as described by Barth et al. [9].

6.3.4 Performance

The sensitivity of the entire detector $Q_0$, i.e. the number of CCD counts per photoelectron generated at the first photocathode, was determined by Rayleigh scattering. First, the measured CCD signal was related to the calculated number of photoelectrons ($N_{pe}$) produced at the first photocathode during Rayleigh scattering as:

$$N_{pe} = \frac{E}{h\nu_0} \Delta L \Omega \frac{d\sigma_R}{d\Omega} n_{\text{argon}} \tau_{\text{overall}} \eta_1 \eta_{\text{slit}}$$  \hspace{1cm} (6.3)

Table 6.1 lists the values of the various parameters for the present system. Substituting these values yields $2.0 \times 10^3$ photoelectrons per spatial element of 0.6 mm for an argon vessel pressure of 50 Pa. The measured Rayleigh signal integrated over this spatial element (height 12 CCD pixels) was approximately $8 \times 10^5$ counts. This means for the overall sensitivity: $Q_0 = 400 \pm 80$ counts/pe (where the error takes into account the uncertainty in
the values of Table 6.1). This number will be used for the determination of the observational error in $n_e$ and $T_e$.

**TABLE 6.1**: Summary of the system parameters used to calculate the number of detected photoelectrons in a Thomson or Rayleigh scattering experiment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser energy at the scattering volume integrated over 30 pulses</td>
<td>$10.8 \pm 0.3$ J</td>
</tr>
<tr>
<td>Measurement time (30 pulses at 10 Hz)</td>
<td>3 s</td>
</tr>
<tr>
<td>Solid angle, determined by grating size $100 \times 100$ mm$^2$ and magnification $M = 0.66$ at viewing side.</td>
<td>$3.5 \times 10^{-3}$ sr</td>
</tr>
<tr>
<td>Scattering volume (corresponding to 12 CCD pixels)</td>
<td>$6 \times 10^{-4}$ m</td>
</tr>
<tr>
<td>Differential Thomson scattering cross section [8]</td>
<td>$7.94 \times 10^{-30}$ m$^2$/sr</td>
</tr>
<tr>
<td>Differential Rayleigh scattering cross section at 532 nm for argon [5]</td>
<td>$5.4 \times 10^{-32}$ m$^2$/sr</td>
</tr>
<tr>
<td>Transmission through spectrometer slit</td>
<td>0.9</td>
</tr>
<tr>
<td>Overall transmission up to first photocathode</td>
<td>0.35</td>
</tr>
<tr>
<td>Effective quantum efficiency first image intensifier</td>
<td>0.16</td>
</tr>
<tr>
<td>Gain first image intensifier</td>
<td>2290</td>
</tr>
<tr>
<td>Transmission tandem lens coupling system</td>
<td>0.13</td>
</tr>
<tr>
<td>Effective quantum efficiency image intensifier of ICCD</td>
<td>0.07</td>
</tr>
<tr>
<td>Inversed sensitivity ICCD (counts/photon)</td>
<td>-0.15</td>
</tr>
<tr>
<td>CCD conversion factor (photoelectron/count)</td>
<td>10</td>
</tr>
</tbody>
</table>

The measured signal will contain contributions from plasma light, stray light and noise. In the following series of measurements, these were evaluated individually. The background signal levels were compared with the actual TS signal level for a “worst case” in which the plasma contained a high level of carbon (originating from a carbon target exposed to the plasma). This leads to more plasma radiation overall with strong radiation in the molecular band between 520 – 570 nm [10] (i.e. overlapping with the TS detection band). The different contributions originating from CCD noise, plasma light and stray light are plotted in Fig. 6.6a and 6.6b together with a TS spectrum that corresponds to a peak density of $7 \times 10^{19}$ m$^{-3}$. The TS measurements described in this paper were all performed with an accumulated laser energy of $10.8 \pm 0.3$ J (30 pulses at 10 Hz) in the scattering volume. In all these cases TS was performed at 17 mm distance from the target surface. The intensity is given in CCD counts using a pixel binning of 12 (corresponding to 0.6 mm in the plasma) and 5 in radial and wavelength direction, respectively. The integrated TS signal and background contributions are plotted in units of density equivalents in Fig. 6b. The residual CCD noise was determined by subtracting a random dark image from the average of 27 dark images. This resulted in a standard deviation of 2.5 counts (temperature CCD chip 5 °C), which shows that the CCD noise is negligible compared to the sensitivity of the detector $Q_0$. The plasma light was recorded with the normal TS triggering and gate window, but without firing the laser. In this extreme case the plasma light signal had a level of $5 \times 10^{18}$ m$^{-3}$ in density equivalents. It will be explained in Sec. 6.5 how such plasma light contributions can be further reduced. Finally, the stray light was measured by firing the laser through the evacuated vessel (0.01 Pa), again keeping all
other parameters unchanged. It is noted that a software mask was applied over 0.5 nm around 532 nm in order to eliminate the residual stray light. This spectral range is indicated by the vertical lines in the spectrum of Fig. 6.6a.

Fig. 6.6b shows that this brings the stray light contribution to below $9 \times 10^{17} \text{ m}^{-3}$ in density equivalents. This way, also any signal originating from Rayleigh scattering on the neutral particles in the beam is rejected. However, this is not an issue as the Rayleigh scattering contribution is negligibly small. The Rayleigh scattering cross section of H$_2$ is three orders of magnitude smaller than the TS cross section (at 532 nm laser wavelength), which means that the neutral density needs to be more than one order of magnitude larger than the plasma density before Rayleigh scattering becomes significant. Experiments (data not shown here) confirmed that this is indeed the case.

These ‘worst case’ measurements are also indicative for the detection limit of the system. Fig. 6.6c displays a Thomson scattering spectrum recorded just below the centre (at $r = -1.7 \text{ mm}$) of the plasma column where $n_e$ was $7 \times 10^{19} \text{ m}^{-3}$. It is seen that the signal to
FIG. 6.6: Contributions of plasma light, stray light, and CCD noise to the TS signal measured at the plasma centre for $n_e = 6.5 \times 10^{19} \text{ m}^{-3}$ and $T_e = 3.3 \text{ eV}$ in counts (a) and in density equivalents (b); TS spectrum taken below the centre of the plasma column ($r = -1.7 \text{ mm}$) where the detection limit is reached (c). Plasma operation conditions: a source current of 100 A, a magnetic field of 0.4 T, a H$_2$ gas flow of 1 slm, and a net target current of 50 A.
noise ratio is ~4. In general, this is the minimum to be able to determine the spectral width for $T_e$. The accumulated laser energy was $10.8 \pm 0.3$ J. In other words, the system requires $7 \times 10^{20}/n_e$ J laser energy for a reliable temperature and density measurement.

6.3.5 Coherent effects

Correlated interactions between the plasma electrons only occur on or above a certain scale length: the so-called Debye length $\lambda_D$:

$$\lambda_D = \sqrt{\varepsilon_0 k_B T_e \over e^2 n_e},$$

(6.4)

where $\varepsilon_0$ is the permittivity of vacuum, $e$ is the electron charge and $n_e$ and $T_e$ are given in $(\text{m}^3)$ and $(\text{K})$, respectively. Whether coherent effects influence the scattering process depends on the ratio between $\lambda_D$ and the wavelength of the incident light $\lambda_0$.

This relation is described in general by [6]:

$$\alpha = \frac{1}{k\lambda_D},$$

(6.5)

where $k$ is the magnitude of the scattering vector $\mathbf{k}$ defined as

$$k = |\mathbf{k}| = {4\pi \over \lambda_0} \sin \left(\frac{\theta}{2}\right).$$

(6.6)

If $\lambda_D >> \lambda_0/(4\pi \sin(\theta/2))$, the scattering process can be considered as incoherent scattering; the incident wave “sees” the individual electrons. However, if $\lambda_D \leq \lambda_0/(4\pi \sin(\theta/2))$, the incident wave “sees” only a collective of charges (within $\lambda_D$) and the scattering process needs to be treated as coherent scattering. The TS measurements described in this article can be considered as incoherent scattering ($\alpha < 0.1$), except for one case to be treated in Sec. 6.4.

6.3.6 Influence of the ICCD camera properties to the observational error

The performance of the complete detection system should be determined by the first amplifier. To investigate if this is also valid for our detector configuration, the individual photon to photoelectron conversion steps at the first and second photocathode and at the CCD chip are treated here. These steps are schematically depicted in Fig. 6.7. The CCD noise contribution can be neglected because the detector sensitivity $Q_0$ is almost two orders of magnitude larger. Each conversion obeys Poisson statistics, i.e. the standard deviation is equal to the square root of the number of generated photoelectrons ($N_{pe}$). In approximation, the square of the relative standard deviations of these processes are summed to find the square of the relative error in the TS signal ($S_{TS}$), i.e. the error in the electron density (see also Table 6.1):

$$\left(\frac{\sigma_{TS}}{S_{TS}}\right)^2 = \frac{1}{N_{pe,1}} + \frac{1}{N_{pe,2}} + \frac{1}{N_{pe,CCD}}$$

(6.7)
FIG. 6.7: The TS detector: conversion stages from input photons $N_{TS}\ [ph]$ to CCD counts $S_{TS}\ [cnts]$. A Gen III image intensifier is coupled to an ICCD camera with a tandem lens system. The ICCD camera consists of a Gen II image intensifier fibre optically coupled to the CCD chip. $N_{TS}\ [ph]$ corresponds to the number of collected TS photons and $N_{pe,i}$ the number of generated photoelectrons at each individual conversion step $i$. The tandem lens system consists of 2 identical Rodenstock objectives ($f = 95\ mm/1.2$). The layout of the image intensifiers is also shown, each consisting of a photocathode (PC), a microchannel plate (MCP) and a phosphor screen.

The first two terms correspond to the conversion step at the photocathode of the first and second image intensifier, respectively. The third term corresponds to the conversion step at the pixel surface of the chip. In the last stage the CCD photoelectrons $N_{pe,\ CCD}$ are converted to counts according to:

$$N_{pe,\ CCD} = S_{TS}\chi_{CCD}.$$  \hspace{1cm} (6.8)

The number of photoelectrons generated at the photocathode of the second image intensifier corresponds to:

$$N_{pe,\ 2} = \frac{S_{TS}\eta_2}{\chi_{ICCD}}.$$  \hspace{1cm} (6.9)

The number of photoelectrons generated at the photocathode of the first image intensifier can be expressed as:

$$N_{pe,\ 1} = \frac{S_{TS}\eta_1}{G_1\tau_1\chi_{ICCD}}.$$  \hspace{1cm} (6.10)

After substituting equations 6.8, 6.9 and 6.10 into equation 6.7 the following expression can be found:

$$\sigma_{TS}^2 = S_{TS}\left(\frac{G_1\tau_1\chi_{ICCD}}{\eta_1} + \frac{\chi_{ICCD}}{\eta_2} + \frac{1}{\xi_{CCD}}\right).$$  \hspace{1cm} (6.11)

Inserting the values listed in Table 6.1 yields that the first term (the photoelectron statistics at the first image intensifier) determines the observational error for more than 97%.
6.4 Results
The capabilities of the new TS system are illustrated on the basis of plasma measurements in Pilot-PSI.

**FIG. 6.8:**
(a) $T_e$ profile in case of a floating target.
(b) $T_e$ profile in case of a grounded target.
(c) A typical spectrum at a radial position -0.8 mm.
Operation conditions: source current 200 A, magnetic field 0.8 T, $H_2$ gas flow 1 slm.

**FIG. 6.9:**
(a) $T_e$ profile.
(b) $n_e$ profile.
(c) Typical TS image. The fibres can be identified easily.
Operation conditions: source current 100 A, magnetic field 0.8 T, $H_2$ gas flow 1 slm, target current 65 A.
Fig. 6.8 shows the results of measurements performed at a distance of 17 mm in front of the target. The experimental conditions were: a source current of 200 A, a magnetic field of 0.8 T, and a H₂ gas flow of 1 slm. The target was either at floating potential or grounded (Figs. 6.8a and 6.8b, respectively). Grounding the target resulted in a net target current of 24 A, which was expected to lead to additional power input.

Indeed, it is observed that the net current leads to an increase in peak $T_e$ from $\sim 1.2$ to $\sim 1.8$ eV. The $n_e$ profiles remain unchanged (peak density $9.5 \times 10^{20}$ m⁻³, data not shown). Note the observed mirror symmetry around $r = 0$ of the measured profiles. Due to fast axial rotation of the plasma jet (rotational frequencies up to 0.1 MHz as measured with optical emission spectroscopy [2, 11]) these should indeed resemble a perfect cylindrical symmetry. Thus the profiles are measured without significant distortion. This illustrates the high accuracy of the system for temperature measurements. In Fig. 6.8c, a scattered spectrum for the central fibre collected during 30 laser shots is shown. The relative errors derived from the fit are smaller than 2%.

However, at a density of about $1 \times 10^{21}$ m⁻³ and $T_e \sim 1.5$ eV small coherent scattering effects are expected to occur (see Sec. 6.3.5). At these conditions the scattering process is slightly coherent $\alpha \sim 0.2$, which means that in this case, the peak electron density is underestimated by $\sim 4\%$ and the peak electron temperature is overestimated by $\sim 8\%$ [6]. A coherent spectrum is lower in the central wavelength and has slightly broader wings than an incoherent (Gaussian) spectrum.

The second example was selected for its even more complicated, but still symmetric, features in the profile. This was obtained by reducing the source current to 100 A (other operation parameters remained the same). This led to a factor of six times lower peak $n_e$ and in case of a grounded target to a much larger net target current of 65 A. The results are shown in Figs. 6.9a and 6.9b. The corresponding CCD image is shown in Fig. 6.9c. This clearly shows the Doppler broadening in the wavelength direction and the plasma profile in the spatial direction. The separated bands along the spatial axis correspond to the individual fibres. The light around the laser wavelength in the bottom part of the image corresponds to stray light due to the interaction of the target with the primary stray light cone. The $n_e$ profile shows some deviations from symmetry. The small structures that are observed are probably artificial and are explained by small changes in the alignment of the optical systems between the TS measurement and the Rayleigh calibration. The individual fibres within the array are not perfectly in one line, and this gives rise to an additional irregularity in the overall transmission response. The $T_e$ profile is not dependent on absolute sensitivity variations and is again symmetric. It consists of two main regions; the outer regions at $r > 5$ mm are flat temperature plateaus at $\sim 0.8$ eV and in central region $r < 5$ mm, $T_e$ increases to $> 3.0$ eV (in case of a floating target $T_e \sim 1.4$ eV). The temperature excursions within the central 2 mm are only present with a strong net target current and reach $\sim 3.5$ eV.
6.5 Conclusions and outlook

Although this TS system enables integrating scattered light originating from hundreds of laser pulses, only 30 pulses of approximately 0.36 J each were integrated with a repetition rate of 10 Hz for the results shown in this paper. This integration time is sufficient to measure $n_e$ and $T_e$ profiles with a spatial resolution of 0.6 mm and an observational error of 3% and 6%, respectively, at $n_e = 4 \times 10^{19} \text{ m}^{-3}$. These decrease to 1% and 2%, respectively, at $n_e = 1 \times 10^{21} \text{ m}^{-3}$. Also in case of a high background of plasma light the system is able to match these specifications. The system requires only a few laser shots to measure these profiles in the ITER relevant regime that is accessible by Pilot-PSI, i.e. $10^{20} < n_e < 10^{21} \text{ m}^{-3}$.

For the present application, it was not necessary to further reduce plasma light contributions. Subtracting the background signals is a good method of signal correction, since at these low signal background levels, ~90% of the observational error will be determined by the Poisson statistics of the actual TS signal [12]. To reduce the plasma light contribution, the solid angle of the viewing system will be adapted to better match the acceptance angle of the spectrometer. Additionally, a band-pass filter (band width 20 nm) will be applied. It is expected that the plasma light contribution will become negligible.

At the new plasma generator, Magnum-PSI, a magnetic field (3 T) will be applied by a superconducting magnet enabling long duration target surface exposures. This feature allows the TS system to integrate enough laser pulses to sustain for even at $n_e \sim 1 \times 10^{19} \text{ m}^{-3}$ an accuracy in $n_e$ and $T_e$ of better than 3% and 6%, respectively. In fact, because the background signals will in general be low, much higher accuracies are feasible with that system.

Acknowledgement

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References
CHAPTER 7

Thomson scattering system for Magnum-PSI

H.J. van der Meiden¹, A.J.H. Donné¹,², H.J.N. van Eck¹, P.M.J. Koelman¹, W.R. Koppers¹, A.R. Loƒ¹, N.N. Naumenko³, T. Oyevaar¹, P.R. Prins¹, J.Scholten¹, P.H.M. Smeets¹, S.N. Tugarinov⁴, P.A. Zeijlmans van Emmichoven¹ and J. Rapp¹

¹ FOM Institute for Plasma Physics Rijnhuizen, Association EURATOM-FOM, Trilateral Euregio Cluster, P.O. Box 1207, 3430 BE Nieuwegein, The Netherlands, www.rijnhuizen.nl
³ IPh NASB, Minsk, Belarus
⁴ SRC TRINITI, Troitsk, Moscow reg. Russian Federation

Abstract
An advanced Thomson scattering (TS) system has been built for the linear plasma generator Magnum-PSI (MAgnetised plasma Generator and NUmerical Modeling for Plasma Surface Interaction studies). The TS system is based on a Nd:YAG laser operating at the second harmonic, and a detection branch consisting of a 40 m long fibre relay system and a high f-number (f/3) transmission grating spectrometer. The scattered light is detected by an Intensified Charged Coupled Device (ICCD) camera equipped with a “Generation III” (Gen III) image intensifier. The laser beam line is remotely controlled by piezo-based actuators combined with simple cameras for laser beam position monitoring. The system measures electron density \(n_e\) and temperature \(T_e\) profiles of a 100 mm diameter plasma column close to the output of the plasma source or close to the target (1.2 m from the plasma source). At an electron density of \(n_e = 9 \times 10^{18} \text{ m}^{-3}\), the observational error in \(n_e\) and \(T_e\) is 3% and 6%, respectively. This was achieved by accumulating the scattering energy from 30 laser pulses (0.5 J, 10 Hz). The minimum measurable temperature is < 0.1 eV. In this report the design considerations of the system are described along with first Thomson scattering measurements.

* An abridged version of this chapter will be submitted to Review of Scientific Instruments (2011).
7.1 Introduction

The plasma facing components of the ITER divertor (a device used for exhaust of helium and impurities) have to withstand continuous heat loads of about 10 MW/m² (particle flux density higher than \(10^{24}\) hydrogen ions m\(^{-2}\)s\(^{-1}\)) and transient loads of more than 1 GW/m² caused by Edge Localized Modes (ELMs).

One of the challenges in fusion research is to develop materials that can withstand these high power loads. This type of research can be excellently done on the linear plasma generator Magnum-PSI [1]. This device is built to study both the continuous plasma-wall loads as well as the mentioned transient power loads that can be expected in the ITER divertor. To simulate these conditions a high-power cascaded arc source produces a 100 mm diameter plasma jet; it can be operated continuously and/or in pulsed mode. An axial magnetic field up to 3 T, generated by a superconducting magnet, confines and transports the plasma to the target of interest.

An advanced Thomson scattering (TS) system has been developed for Magnum-PSI to provide \(T_e\) and \(n_e\) profiles of the plasma jet during plasma exposures. Magnum-PSI can generate low and high power loads at the target. This corresponds to low and extremely high electron densities and sets high demands on the sensitivity and linearity of the TS system. Therefore, a high etendue spectrometer based on a transmission grating was applied combined with an ICCD camera. The second harmonic fundamental of a Nd:YAG laser (532 nm) matches with the maximum of the quantum efficiency curve of the Unigen II filmless photocathode of the Gen III image intensifier of the ICCD camera.

In this paper the design and performance of the TS system is described in Sec. 7.3-7.7. Preceding this, in Sec. 7.2, Magnum-PSI is described. The properties of the plasma expansion are described in Sec. 7.8 followed by first TS measurements presented in Sec 7.9; showing the ability of the system.

7.2 Magnum-PSI

The linear plasma generator Magnum-PSI features a superconducting magnet generating an axial magnetic field of maximum 3 T (see Fig. 7.1a). The bore diameter of the magnet is 1300 mm and it features 16 holes at 45 degrees interspacing in the azimuthal direction and at two axial locations which enables excellent access to the ports of the vacuum vessel. A wall-stabilized cascaded arc located in the source chamber (SC: inner diameter 600 mm) produces a hydrogen, argon or helium plasma (see Fig. 7.1b and Fig. 7.1c) [2, 3]. A discharge current is drawn between a set of 3 cathodes or a single large diameter cathode and a nozzle, which also serves as anode. Currently the typical discharge parameters are a gas flow of 4 standard litre per minute (slm; 1 slm = \(4.5 \times 10^{20}\) particles/s) and a discharge current between 100 and 300 A. The first generation sources (45 kW) will generate a power flux of 40 MW/m² corresponding to an ion flux \(I = 1 \times 10^{21}\) s\(^{-1}\) within a diameter of 2 cm at the target located in the target chamber (TC: inner diameter vessel 500 mm). The plasma jet is transported to the target at a distance of about 1.5 m, convectively (and confined) by an axial magnetic field. New generation plasma sources are being developed that can generate a power flux of 10 MW/m² within a 10 cm diameter beam. To ensure for
all cases a background pressure of below 3 Pa in the TC three giant roots blower stages (total pump capacity 52500 m$^3$/hr) are implemented. Skimmers allow for differential pumping between SC and TC and target exchange and analysis chamber. The electron density and temperature of the plasma can reach values above $5.0 \times 10^{21}$ m$^{-3}$ and 7 eV, respectively.

Besides several machine diagnostics like calorimetry, an incoherent TS system will be used as control tool for the plasma conditions. Electron density and temperature profiles are provided and stored in the database every 7 seconds. Optical emission spectroscopy (OES) is applied to measure impurity concentrations. To determine the power flux, the axial (macroscopic convective) velocity of the plasma is measured using the Doppler shift of the emission line of interest. Laser induced desorption spectroscopy (LIDS), laser induced ablation spectroscopy (LIAS) and laser induced breakdown spectroscopy (LIBS) will be applied also at Magnum-PSI. To measure the surface changes of the target, speckle interferometry is in preparation. Using Magnum-PSI as a testbed, it can be proven whether or not these diagnostics can be applied in ITER to serve as a monitor for the wall condition. Besides the mentioned diagnostics, Magnum-PSI features an extensive diagnostic park to investigate target surfaces in-situ and ex-situ.

Fig. 7.1a: Magnum-PSI. The vacuum tubing of the big roots blowers is well visible. The bore of the magnet is 1.3 m to enable sufficient diagnostic access to the target chamber.
Fig. 7.1b: Cascaded arc source used currently in Magnum-PSI. The cascaded plates have, starting from the cathode, the following diameter: 4, 4, 4, 5, 6 mm and the nozzle (diameter 7.5 mm). The current is drawn from three cathode tips (one is shown) to the nozzle.

Fig. 7.1c: Photo of argon plasma at high background pressure. Source current 100 A, flow 3 slm. Background vessel pressure was 77 Pa.

7.3 Thomson scattering system for Magnum-PSI: general description

A sensitive incoherent TS imaging system, the successor of the TS system operating at the Pilot-PSI plasma generator [4], has been installed at Magnum-PSI. The target chamber, source chamber as well as the TS laser beam line are shown in Fig. 7.2. All laser beam line components are mounted on the concrete floor of the Magnum-PSI hall for good stability. For this reason the laser beam enters the Magnum-PSI vessel from below. The 34 m long laser beam line is completely remotely controlled, because during activation of the magnet, the entrance to the Magnum-PSI hall is limited for safety reasons. The magnetic stray field is about 1 T close to the magnet if it is operating at 3 T; moreover multiple lasers are operating simultaneously in the Magnum-PSI hall.

In an alternating way TS can be performed 100 cm downstream the source output and in front of the target. $T_e$ and $n_e$ profiles can be measured along a chord length of 100 mm with a spatial resolution of 1.6 mm. The lower temperature limit is $T_e = 0.07$ eV. The accuracy in $n_e$ and $T_e$ is 3% and 6% respectively at $n_e = 9.0 \times 10^{18}$ m$^{-3}$. This is achievable at an accumulated laser energy of about 16 J (30 Nd:YAG laser pulses of 0.55 J/pulse, operating at 10 Hz, laser wavelength 532 nm). The scattering angle along the full chord length varies between $84.7^\circ$ and $95.3^\circ$, and is taken into account for the data analysis.
THOMSON SCATTERING SYSTEM FOR MAGNUM-PSI

Fig. 7.2: The 34 m long TS laser beam line together with the target chamber (at the left side) and source chamber (at the right side) of Magnum-PSI. The laser beam alignment is monitored by cameras and controlled by mirror mounts equipped with piezo-based actuators.

7.4 Laser beamline

A Spectron laser, model SL 8354, is installed in the laser room and is used as the workhorse for the TS system. The laser delivers 0.7 J/pulse within a diameter of 9.5 mm at the second harmonic 532 nm at 10 Hz repetition rate. The beam divergence is 0.5 mrad and the pointing stability, measured during a period of 3 hours, stayed within a full angle of 17 µrad. This is a remarkable good value, which implies that the laser, in combination with an \( M = 4 \) beam expander, can be pointed at one point at a distance of 34 m for several hours within a deviation of only 0.15 mm. The beam expander reduces the laser beam divergence from 0.5 mrad to about 0.13 mrad. The 38 mm diameter laser beam is guided from the laser room to the Magnum-PSI vessel by six 45° multilayer mirrors. After mirrors BL1MM3 and BL1MM5 (see Fig. 7.2), 3.2 m plano-convex lenses are installed that focus the beam to a spot size of about 0.5 mm at the plasma centre. After having passed the plasma, the beam is dumped via a 45° top mirror on to a laser dump. The laser position is also monitored at this location. Mirror BL1MM3 is controlled by a pneumatic cylinder to enable TS in the source chamber and target chamber in an alternating way.
7.4.1 Stray light reduction system
Undesired reflections and scattering of light at the input and output windows of the vacuum vessel are the main sources of stray light. Therefore, these windows are mounted under the Brewster angle at the end of long vacuum tubes, at large distance from the plasma centre. A series of light baffles (see Fig. 7.3) collimates the cone of stray light such that it entirely fits in the $\varnothing = 100$ mm output tube. The laser and stray light beams pass the output window, located at about 240 cm above the plasma centre, and are dumped via a mirror onto a laser dump. The collimation of stray light is done in two different ways for the different TS locations.

The laser input system in the source chamber consists of a conventional baffled reduction system. After the laser beam passes the input window (located at 165 cm below the plasma centre), the stray light originating from this window is first collimated by a so-called critical aperture of $\varnothing = 11$ mm, located 630 mm below the plasma centre. A sub-critical aperture of $\varnothing = 25$ mm, located 330 mm below the plasma centre collimates the stray light originating from scattering from the edges of the critical aperture.

A stronger collimation of the stray light cone diameter inside the vessel is required, since TS measurements have to be performed close to the target. Therefore, interference of the stray light with the target surface needs to be reduced. At the target chamber a critical aperture of $\varnothing = 11$ mm, located 630 mm below the plasma centre, collimates the

FIG. 7.3: Layout of the stray light reduction system used in the target chamber. Stray light originating from the entrance window is limited by a 6 mm diameter carbon aperture at 33 cm below the plasma centre. The stray light cone originating from the edges of the critical aperture is not shown, because the stray light contribution is assumed to be relatively low.
stray light originating from the input window and from reflections within the input tube. Subsequently, a 6 mm inner diameter carbon aperture, located at 330 mm below the plasma centre, is applied. This is the main collimator for the stray light originating from the edges of the critical aperture and input window.

7.4.2 Mechanical design and construction of the TS vacuum system
For the TS vacuum system two special mechanical devices have been developed in-house. Firstly, the vacuum coupling between the Magnum-PSI vessel and the vacuum tubes of the TS system (see Fig. 7.4); these flanges can be decoupled and locked from outside the magnet. This remote coupling is necessary to enable fast dismounting of the TS system in case the magnet has to be translated. Secondly, the laser input system can be translated over a total path of 40 mm along the main axis of Magnum-PSI; the large size of the upper dump tubes enables for a good stray light reduction at all positions of the laser input. This feature (not shown in Fig. 7.4) will be installed when it is required.

Fig. 7.4: Remote coupling of the TS input tubes to the TC and SC vessel. The lever, depicted in (a), is coupled to the locking ring (b) and controls the locking ring located within the magnet. In decoupled state (c), the locking ring is in downwards position; the ceramic balls rest in the grooves of the rods connected to the locking ring. In this state the input tube can be moved into the conical cylinder. If it is inserted (b), the locking ring is pushed up and the connection is locked; the ceramic balls are forced into the locking groove of the conical cylinder. Simultaneously, the O-rings are pressed against both input tube and conical cylinder for vacuum sealing.
7.4.3 Alignment system
Because the level of the stray magnetic field at some locations in the Magnum-PSI hall is higher than 1 T, and human access is not allowed during operation, remote control of the TS system is desirable. For this purpose, most multilayer mirror boxes are equipped with an alignment unit. Piezo-based actuators (PZA12, Newport) are applied to control the mirrors of the laser beam line remotely from the laser room location. The alignment units feature a very cheap complementary metal oxide semiconductor (CMOS) camera (not synchronized in time) that records the pulsed laser light from a diffuser screen. A very small fraction of the laser beam passes through the multilayer mirror and a 100 times (ND2) attenuator. Although the laser pulses have a width of only 12 ns the cameras can detect these short pulses, probably due to the fact that the pixels are not completely reset after readout; in this way the position and shape of the main laser beam can be measured in real-time.

For pre-guiding purposes the power of the main laser beam can be attenuated by using an attenuator consisting of a half wave plate combined with a polarizer. Rotation of the half wave plate, causes a rotation of the polarization of the linear polarized main laser beam and results in a reduction of the transmitted power through the polarizer. In this way, the settings of the Spectron laser can remain the same as during the TS measurements.

7.5 Detection branch
Two viewing systems (see right insert of Fig. 7.2) are used to detect the Thomson scattered light. At the target location an objective (AF Nikkor 85mm $f/1.8D$) images the 100 mm long laser chord onto a linear fibre array of 59 fibres (40 m length, 26.7 mm input height, array format $59 \times 1$; CeramOptek UV400/424P). The magnification of the setup in this case $M = 0.267$, but can be enhanced in case Magnum-PSI is operated with a smaller diameter plasma beam. The viewing system at the source chamber consists of an objective with a longer focal length (AF DC-Nikkor 135mm $f/2D$). Together with a longer object distance the magnification of this system is about the same as that of the viewing system at the target chamber. At the input face of each fibre array a field lens will be mounted to assure that the chief light rays enter the fibre tips perpendicular*. For both locations the size of the spatial elements in the plasma is about 1.6 mm and the viewing f-number is larger than $f/11$.

* Currently the field lens is not installed to keep maximum flexibility in choice of magnification.
7.5.1 High etendue spectrometer

The TS light collected by these viewing systems is relayed to the input of a high etendue spectrometer. The required fibre array (see insert in Fig. 7.5) can be selected by a motorized fibre array exchanger. The front of the fibre arrays can be translated over a certain distance transverse to the entrance slit (25×0.6 mm\(^2\)) such that a part of the cross section of the fibre array can be selected. Using this feature the instrument function of the spectrometer can be narrowed at the costs of signal yield in an approximately linear way. The fibre arrays are curved to correct for spectral line curvature (see Sec. 7.5.1); a well known effect occurring in high f-number spectrometers.

To reduce the amount of plasma light that can enter the spectrometer, a band pass filter (transmission is > 95% between 515 - 545 nm) is placed directly after the slit.

The high etendue spectrometer is equipped with a holographic transmission grating. This allows collecting of the light at large f-numbers (\(f/3\)) and with low vignetting values since the lenses can be installed very close to the grating. Transmission gratings feature a low stray light contribution, because these gratings exhibit, in contrast to reflection gratings, a negligibly number of micro defects. Using the configuration shown in Fig. 7.5 the detector cannot detect light originating from reflections from lens surfaces.

At the optical axes of the spectrometer the dispersion of the light originating from the middle of the slit obeys in approximation the following grating equation [5]: presently

\[
\frac{d\lambda}{dx} = \left(\frac{\lambda_0}{f}\right) \frac{\cos \theta_2}{\sin \theta_1 + \sin \theta_2}.
\] (7.1)

Here \(f\) is the focal length of the spectrometer lenses and \(\lambda_0\) the central wavelength of the grating that determines via equation 7.2 the grating groove frequency:

\[
\nu = \frac{\sin \theta_1 + \sin \theta_2}{\lambda_0}.
\] (7.2)

The incident angle \(\theta_1 (35^\circ)\) and diffraction angle \(\theta_2 (66^\circ)\) are defined as shown in Fig. 7.5. Using these numbers the average dispersion of the spectrometer was found to be about 0.43 nm/mm. Due to the different incident and dispersion angles the image of the gap of the slit is imaged onto the detector with a magnification depending on the ratio of these angles \(M_{\text{spectrometer}} = 1.89\).

The dispersed TS light is imaged onto the filmless (Unigen II) photocathode of an ICCD camera (PI-max 1300, Princeton Instruments). The 25 mm diameter Gen III image intensifier is fibre optically coupled to a front-illuminated CCD (1340×1300 pixels, pixel size 20 \(\mu\)m square, ADC 16-bit). The quantum efficiency (QE) of the photocathode is about 50%, but taking into account the noise factor the effective QE is about 20%. As a special feature, the input window of the photocathode is antireflection coated for a wide spectral range.
Fig. 7.5: Schematic top view of the spectrometer. A fibre exchanger enables selection between TS measurements in front of the target or close to the plasma source. For normal situations the dispersed light is imaged directly onto the ICCD. In case the viewing dump in the TC vessel is made non-functional, an intermediate image (see Sec. 7.5.2) with a 532 nm mask (consisting of a 0.8 mm narrow black strip) will be applied. Note that the actual angle between the optical axes of the input and diffraction optics is in reality 80°; for clarity the picture is drawn with an angle of 90°.

Some parasitic light from the Spectron laser is used to trigger the programmable timing generator (PTG, Princeton Instruments) that subsequently triggers the photocathode of the image intensifier. A gate window of 25 ns is applied to catch the TS photons originating from the 12 ns (FWHM) laser pulse, making the plasma light background insignificant.

7.5.2 Stray light reduction
To minimize the stray light originating from the opposite vessel walls, a carbon viewing dump is installed at the side opposing the viewing systems. However, in case the Magnum-PSI target is oriented such that it blocks the line of sight to the viewing dump, then the viewing dump function is disabled, and a tremendous amount of stray light can enter the spectrometer. Therefore a mask will be placed at the output of the spectrometer to block
the laser stray light (see Fig. 7.5). A Rodenstock tandem lens system \((f 95/1.2)\) will be used to relay the light from the intermediate image to the first cathode of the detector\(^*\).

### 7.6 System performance

To determine the overall transmission of the detection systems Rayleigh scattering was performed. Using the Rayleigh scattering formula the overall transmission is given by:

\[
\tau_{overall} = \frac{h\nu_0 S_{Rayleigh}}{\varepsilon_{ICCD} E_{laser} \Delta L \Omega n_{argon} \eta_1 \left( \frac{d\sigma_R}{d\Omega} \right)} .
\]

(7.3)

Here, it is assumed that the measured quantity \(S_{Rayleigh}\) (cnts) is equal to the product of the number of detectable photoelectrons \(N_{pe}\) times the conversion efficiency of the ICCD camera given by the factory \((\varepsilon_{ICCD} = 80 \text{ cnts/pe})\). In Table 7.1 the values for various parameters of the TS system are given. Rayleigh scattering was performed at an argon vessel pressure of \(n_{argon} = 94 \text{ Pa}\). The measured Rayleigh signal \(S_{Rayleigh}\) integrated over multiple spatial elements with length \(\Delta L = 7.2 \text{ mm}\) (96 CCD pixels in radial direction) was \(8 \times 10^6\) counts. Substituting this value and the values given in table 7.1 in Eq. (7.3) resulted in an overall transmission of \(\tau_{overall} = 0.3 \pm 0.03\).

Taking into account the transmission of the different components of the detection branch (see Table 7.1) and using the measured value for the overall transmission shows that the throughput of the spectrometer (diffraction efficiency grating including the transmission of the lenses) is \(0.46 \pm 0.05\). This corresponds to the specifications of the spectrometer \([6]\).

The spectrometer itself was tested with respect to vignetting. The input slit was illuminated by a uniformly emitting light source (integrating sphere type USS-800C-35R) from Labsphere. The signal decays symmetrically from the max value at the centre (532 nm) to half that value at the edge. This is probably caused by simultaneously the spectral response of the band-pass filter and the diffraction efficiency of the grating. The vignetting in vertical (spatial) direction is very small.

### Table 7.1: Summary of the TS system parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser energy at the scattering volume integrated over 20 pulses including 85 % beam line transmission</td>
<td>(E_{laser} = 11 \pm 0.3 \text{ J})</td>
</tr>
<tr>
<td>Typical measurement time (20 pulses at 10 Hz)</td>
<td>2 s</td>
</tr>
<tr>
<td>Solid angle at magnification (M = 0.267) at viewing side.</td>
<td>(\Omega = 6.2 \times 10^{-3} \text{ sr})</td>
</tr>
<tr>
<td>Scattering volume (corresponding to CCD pixels)</td>
<td>(\Delta L = 1.6 \times 10^{-3} \text{ m})</td>
</tr>
<tr>
<td>Differential Thomson scattering cross section</td>
<td>(d\sigma_T/d\Omega = 7.94 \times 10^{-30} \text{ m}^2/\text{sr})</td>
</tr>
<tr>
<td>Differential Rayleigh scattering cross section (532 nm, Ar)</td>
<td>(d\sigma_R/d\Omega = 5.4 \times 10^{-32} \text{ m}^2/\text{sr})</td>
</tr>
<tr>
<td>Differential Rayleigh scattering cross section (532 nm, Ar(^+))</td>
<td>(d\sigma_R^+/d\Omega = 2.12 \times 10^{-32} \text{ m}^2/\text{sr})</td>
</tr>
</tbody>
</table>

\(^*\) Currently the dispersed light is directly imaged onto the ICCD as shown in Fig. 7.5 at the right side below.
### 7.6.1 Spectral and spatial resolution

The relatively high input slit produces a spectral line curvature in the detector plane. This is due to a path difference between rays originating from the edge and the centre of the slit. This can be compensated by using a curved slit at the entrance of the spectrometer. To test the spectral performance of the spectrometer, a semiconductor laser (532 nm) and a neon spectral lamp were simultaneously used to illuminate the spectrometer slit, for this purpose the width was adjusted to 50 µm (see Fig. 7.6a and Fig. 7.6b). As can be seen the correction for line curvature is not completely accomplished, but this is sufficient for TS measurements, vertically only a limited number of pixels will be binned and this will not influence the spectral resolution. The spectral calibration is performed for each track; giving the corresponding wavelength for each individual pixel of the image. An average dispersion of 0.00878 nm/px (accuracy 0.8%) was found; this corresponds to a spectrometer dispersion of 0.439 nm/mm and is approximately the calculated value. The spectral resolution at a slit width of 50 µm is about 9 pixels FWHM, corresponding to 0.08 nm. This width is mainly due to the fact that the spectrometer features a magnification $M_{\text{spectrometer}} \approx 1.9$ and the resolution of the image intensifier (35 µm, 2 pixels).

#### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission viewing system (including vessel window) $\tau_{\text{view}}$</td>
<td>0.86</td>
</tr>
<tr>
<td>Transmission fibre bundle including surface reflections $\tau_{\text{fibre}}$</td>
<td>0.84</td>
</tr>
<tr>
<td>Transmission and diffraction efficiency spectrometer for average polarization (measured, see Sec. 7.5) $\tau_{\text{spectrom}}$</td>
<td>0.46</td>
</tr>
<tr>
<td>Transmission band pass filter $\eta_{\text{Bpfilter}}$</td>
<td>0.9</td>
</tr>
<tr>
<td>Effective quantum efficiency first image intensifier of ICCD including noise factor 1.6. $\eta_i$</td>
<td>0.2 @532 nm</td>
</tr>
<tr>
<td>Quantum efficiency photocathode</td>
<td></td>
</tr>
<tr>
<td>Conversion efficiency counts per photoelectron (counts/photoelectron) $\varsigma_{\text{ICCD}}$</td>
<td>80</td>
</tr>
<tr>
<td>Transmission tandem lens coupling system $\tau_1$</td>
<td>0.93</td>
</tr>
<tr>
<td>Spatial resolution ICCD (measured)</td>
<td>&lt; 35 µm</td>
</tr>
</tbody>
</table>

![Fig. 7.6: (a) Image: a 532 nm semi-conductor laser and a neon lamp illuminated simultaneously a 50 µm slit. (b) Spectrum corresponding to a track at a (radius) pixel 508. From left to right the dominant lines correspond to Nd:YAG, 532 nm, and the neon lines: 533.08 nm, 534.11 nm and 534.33 nm.](image)
During TS or Rayleigh scattering measurements the fibre arrays will serve as spectrometer slit. Using the full fibre diameter of 400 µm (see Fig. 7.7a and Fig. 7.7b); the fibre image projected on the ICCD camera will have a maximum width of about 700 µm (0.32 nm). This corresponds to a minimum measurable temperature of about 0.2 eV. By translating the fibre array in transfers direction relative to the entrance slit, such that about 260 µm of the fibre cross section is blinded by the slit edge, the width of the instrument function can be reduced to 0.12 nm (see Fig. 7.8a and Fig. 7.8b). The minimum measurable temperature can be reduced to far below 0.1 eV at the costs of detection sensitivity.

![Fig. 7.7: (a) A recorded image: a 532 nm semiconductor laser and a neon lamp illuminated simultaneously the input fibre array. The full output fibre diameter (400 µm) was used. (b) Spectrum corresponding to a track at pixel 508.](image)

![Fig. 7.8: (a) Similar image as shown in Fig. 7.7a, but now about 140 µm of the fibre cross section was used. (b) Spectrum corresponding to a track at (radius) pixel 508.](image)

The spatial resolution of the detection system was determined by illuminating the fibre array at the viewing side by the uniformly emitting light source. In Fig. 7.9a and Fig. 7.9b it is shown that the individual fibres of the array are well resolved for the part that corresponds to the bulk plasma, i.e. this corresponds to a spatial resolution of about 1.5 mm in the plasma.
7.6.2 Relative and absolute calibration

To measure the spectral response of the complete detection branches in the SC and TC, each viewing system was illuminated by the earlier mentioned uniform light source. The results of these spectral response measurements will be used to calculate the calibration factors of each pixel required for fitting the spectral distribution function to the TS data.

Rayleigh scattering on argon is used to calibrate the absolute sensitivity of the TS system and also to check the alignment between the laser and the fibre array of the viewing system.

7.7 Influence of inverse Bremsstrahlung on TS measurements

The detector system allows measurements of electron temperatures even below 0.1 eV. However, the laser beam is focussed to a spot size of about 0.5 mm, resulting in a power density of about 23 GW/cm² (2.8 MJ/m²). At these power densities one has to take into account that electron heating could occur due to the process of inversed Bremsstrahlung. The electron temperature can be raised due to the absorption of photons. Under the assumption that the heat has not been conducted away during the laser pulse, the fractional increase in $T_e$ is as follows [7]:

$$
\frac{\Delta T_e}{T_e} = 1.42 \times 10^{15} \left( \frac{n_i Z^2}{(k_B T_e)^{3/2}} \right) v_0^{-3} \left[ 1 - \exp \left( -E_{ph}/(k_B T_e) \right) \right] I_0
$$

(7.4)

with $n_i$ the ion density in m⁻³, $I_0$ the laser energy density in J/m², $Z$ the effective charge of the ions (assume $Z = 1$), $k_B T_e$ in eV and $E_{ph}$ the photon energy in eV (532 nm: 2.33 eV). Assuming an electron temperature of $T_e = 0.1$ eV and an ion density of $n_i = 1.0 \times 10^{19}$ m⁻³ (assuming $n_e = n_i$) a temperature rise of less than 1% is found. Hence, plasma heating by inverse Bremsstrahlung is negligible. The chosen test ion density condition is justified, because at the low test temperature the ionization degree of the plasma is very low. The
calculated temperature rise is below the measurement accuracy of the TS system. Moreover, in ref [8] no temperature rise due to laser heating could be found experimentally. If problems concerning this can be expected the plano-convex lens that focuses the laser beam at the centre of the plasma can be replaced by a cylindrical lens system resulting in a reduction in energy density due to the slab like shape of the scattering volume.

7.8 The argon plasma expansion
In order to demonstrate the capabilities of the TS system, the expansion properties of the argon plasma jet were measured in absence of an axial magnetic field∗∗. First, briefly the expansion of the argon plasma is described.

The ionization degree of the exhausted plasma is assumed to be in the range of 10 percent, this still allows treating the plasma dynamics inside the jet as that of a hot gas of heavy particles (neutrals and ions); the coupling between ions and neutrals is strong. Due to the high pressure difference between the source and the Magnum-PSI vessel, a supersonic plasma expansion is formed. In Fig. 7.10 it is shown that three main regions can be distinguished in the expansion. In the first few centimetres the plasma expands with supersonic velocity, this is the so-called zone of silence (characteristics: velocity of particles faster than local sound speed, i.e. negligible interaction with background particles). Here the macroscopic velocity of the plasma accelerates and the diameter of the plasma jet rises (rarefaction effect), and results in a $z^{-2}$ decay of the neutral density along the z-axis according to [9].

The electron temperature drops also in this zone; the random motion (thermal energy inside the source) is converted to macroscopic velocity (kinetic energy), i.e. adiabatic cooling [10]. At a certain distance the pressure in the jet becomes lower than that of the background gas and the flow has to adapt to the ambient pressure. As a result a compression shock is formed due to the collision of the moving ‘fluid’ with the background gas. The axial position of the shock depends on the background pressure [11, 12] and is here adapted in convenient units given by

$$z_M = 7.6 \times 10^{-2} \sqrt{\frac{\Phi A T_{source}}{p_{back}}} \quad [\text{m}],$$  \hspace{1cm} (7.5)

with $A$ the atomic mass number (for argon $A = 40$), $p_{back}$ the background pressure in Pa, $T_{source}$ the particle temperature in the source (in units of eV; assumed 0.7 eV), $\Phi$ the gas flow in slm. Here it is assumed that the origin of the expansion is located just at the front of the nozzle. However, because the source consists of a divergent arc channel (see Fig. 7.1b) it is expected that the origin is located about 5 - 10 mm within the source. Equation

∗∗ At the time of writing this Chapter the superconducting magnet has not yet been delivered
7.5 shows that the axial position of the shock can be decreased by enhancing the background pressure.

In the stationary shock, the density will rise due to the compression of the gas. This means that the velocity will drop due to the fact that the forward flux is conserved. Because of collisions, most of the gained kinetic energy is converted back into thermal energy; the enhanced forward flux is converted to random motion, resulting in a significant rise in temperature. At a certain point the velocity is equal to the local sound speed (shock front). After the shock, the plasma flows subsonic, and approximately isobaric and will maintain the same diameter. This means that the diameter of the jet can be adjusted by varying the background pressure $p_{\text{back}}$ [13].

It is important to note that in the expansion zone, the coupling between electrons and heavy particles is not sufficient to exchange energy, i.e. the temperature of electrons and heavy particles can evolve differently [14].

For determination of the location of the shock, $n_e$ will be used as indicator (accuracy a few mm). This is allowed because the electron density is equal to the ion density; the influence of electrical fields is neglected here.

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**Fig. 7.10:** Hot gas expansion model showing different flow regions. Velocity, density and temperature of the heavy particles along the jet axis. Picture adapted from [11]. $M$ is the ratio between the particle velocity and the local sound speed.
7.9 Measurements

The plasma expansion was explored by the Thomson system, using the source (see Fig. 7.1b and Fig. 7.1c) at 100 A source current, 3 slm gas flow and at respectively 1.4 Pa, 5.2 Pa and 22 Pa background pressure. The $T_e$ and $n_e$ profiles were measured in the source chamber as a function of the distance between the source nozzle and the TS location, using the translation utility of the cascaded arc source. The argon density ($n_0$) can be determined by measuring the Rayleigh scattering contribution in the mid part of the TS spectra (Rayleigh-TS scattering [14]). However, the TS cross section is a factor 147 times larger than that for Rayleigh scattering (532 nm) on argon. For scattering on argon ions this value is even lower (see Table 7.1). For the used measurement period, the scattering signal originating from typically 300 shots was accumulated resulting in an observational error in $n_0$ of about 50% for densities below $1.0 \times 10^{20}$ m$^{-3}$.

![Fig. 7.11: $n_e$ and $T_e$ at $R \sim 0$ as a function of axial position relative to source nozzle at $p_{\text{back}} = 1.4$ Pa. The calculated shock is located at $z \sim 256$ mm. Conditions: flow 3 slm argon, current 100 A.](image1)

![Fig. 7.12: $n_e$ and $T_e$ at $R \sim 0$ as a function of axial position relative to the nozzle at $p_{\text{back}} = 5.3$ Pa. The dashed line depicts the calculated shock position $z_M$. Conditions: flow 3 slm argon, current 100 A.](image2)

* TS measured as function of the distance to the nozzle were never done before on a source with a divergent channel.
Fig. 7.13: $n_e$ and $T_e$ at $R$ = 0 as a function of axial position relative to the nozzle at $p_{\text{back}} = 22$ Pa. The dashed line depicts the calculated shock position $z_M$. Conditions: flow 3 slm argon, current 100 A.

The first TS measurements were performed on the plasma that expands in the SC vessel at a background pressure of 1.4 Pa. In Fig. 7.11 the TS results are shown. On the axis of the jet $n_e$ decays as $z^{-1.4}$, which is not as fast as predicted in section 7.7. Probably this is due to the fact the observation starts at $> 39$ mm after the start of the expansion, where the acceleration of the flow is reduced. According to equation 7.5 the shock is expected at 256 mm distance from the nozzle, this implies that the measurement area corresponds to the supersonic expansion zone. In Fig. 7.11 also the decay in temperature is shown and it indicates that $T_e$ has already decayed far ahead of $n_e$; this was also observed by [14].

At a background pressure of 5.3 Pa a shock in $n_e$ can be faintly seen (probably due to the long mean free path of the heavy particles), but in the temperature it is prominently visible (see Fig. 7.12). The calculated position of the shock is 132 mm. The measured shock position corresponds approximately to this value. In the same figure it is shown that the electrons are preheated ahead of the electron density. Different causes were proposed. The early jump in $T_e$ can be caused by preheating; electron thermal energy ‘leaks’ back to positions ahead of the shock front; the electron heat conductivity is large. But in [14] it was stated that the presence of the current density plays an important role; ohmic heating due to the presence of electric fields. In [15] an additional mechanism was proposed that can be associated with the fact that the mean free path for the surrounding gas is long ($> 20$ cm) in the very low $n_0$ ‘valley’ at $z$ = 90 mm. As a result, the invading background gas neutrals can heat electrons already before the actual shock occurs. More information about this preheating of electrons can be found in [16].

∗∗ Currently only a provisional viewing dump was installed that reduces stray only between -50 mm < $R$ < + 25 mm.
Clear jumps in both $T_e$ and $n_e$ can be seen in Fig. 7.13; the plasma expansion was studied at a background pressure of 22 Pa. The calculated shock position is $z = 65$ mm and the measured value is about 60 mm. At these short distances from the nozzle, deviations can become distinct; as mentioned in section 7.7, the origin of the expansion is thought to be located within the source. A second jump in $T_e$ and $n_e$ is faintly visible in the same figure at $z = 220$ mm. After the shock the flow is subsonic and isobaric; the temperature of the beam will drop due to the interaction with the surrounding gas and as a consequence $n_0$ has to rise till the background density is reached (not shown).

A three dimensional representation of $T_e$ and $n_e$ measurements is shown in Fig. 7.14 ($p_{\text{back}} \sim 5.3$ Pa) and Fig. 7.18 ($p_{\text{back}} \sim 22$ Pa). In case of a background pressure of 5.3 Pa, the fast $n_e$ decay can be seen followed by a faint shock at $z \sim 130$ mm. The radial wide extending and well pronounced shock in $T_e$ evolves in shape along the $z$-axis in about the same way as observed by [14]. In Fig 7.15 and 7.16 profiles are shown corresponding to $z = 44$ mm and $z = 124$ mm, the subtle change in shape is well visible and the fact that the measurement points are close together show that the observational error concerning Poisson statistics is very small (< 1%), even at densities below $5.0 \times 10^{18}$ m$^{-3}$; 300 laser shots were accumulated. In Fig. 7.17a an image corresponding to $z = 44$ mm is shown together with a spectrum (see Fig. 7.17b) corresponding to a radial position of $R = 7$ mm; the Rayleigh signal in the central part of the spectrum is clearly visible.

At 22 Pa background pressure the corresponding 3D plot shows in Fig. 7.18a clearly the jump in $n_e$ at $z \sim 60$ mm, but additionally a thick and broad second shock is visible between $114 < z < 264$ mm. The second shock is even more prominently visible in $T_e$ (see Fig. 7.18b). In Fig. 7.19 and Fig 7.20 subtle differences in the $T_e$ profiles corresponding to $z = 44$ and $z = 134$ mm are shown; the hollow structures in the profiles were also observed by [14]. The spectrum in Fig. 7.21b, corresponding to track 700 of the image shown in Fig. 7.21a, shows the Rayleigh contribution above the TS spectrum.
Fig. 7.14: 3D representation of radial $n_e$ (a) and $T_e$ (b) profiles as function of the distance to the source nozzle measured with TS at $p_{\text{back}} = 5.3$ Pa. Conditions: flow 3 slm argon, current 100 A.
Fig. 7.15: $n_e$ and $T_e$ profiles at $z = 44$ mm; $p_{\text{back}} = 5.3$ Pa. CCD Binning in radial direction 20 pixels, 300 laser pulses. Conditions: flow 3 slm argon, current 100 A.

Fig. 7.16: $n_e$ and $T_e$ profiles at $z = 124$ mm; $p_{\text{back}} = 5.3$ Pa, 240 laser pulses. The ‘tilt’ in the $T_e$ profile can be caused by so-called barrel shocks. Conditions: flow 3 slm argon, current 100 A.

Fig. 7.17a: TS image (stray light subtracted) corresponding to $z = 44$ mm (see Fig. 7.15).

Fig. 7.17b: Spectrum corresponding to radial position of 7 mm of the profiles shown in Fig. 7.15.
Fig. 7.18: 3D representation of radial $n_e$ (a) and $T_e$ (b) profiles as function of the distance to the source nozzle measured with TS at $p_{\text{back}} = 22$ Pa. Conditions: flow 3 slm argon, current 100 A.
Fig. 7.19: $n_e$ and $T_e$ profiles at $z = 44$ mm; $p_{\text{back}} = 5.3$ Pa, CCD binning 20 pixels along the radius, 420 laser pulses. Conditions: flow 3 slm argon, current 100 A.

Fig. 7.20: $n_e$ and $T_e$ profiles corresponding to $z = 134$ mm; $p_{\text{back}} = 22$ Pa, 300 laser pulses. Conditions: flow 3 slm argon, current 100 A.

Fig. 7.21a: TS image (stray light subtracted) corresponding to $z = 44$ mm (see Fig. 7.19).

Fig. 7.21b: Spectrum corresponding to radial position of 2.8 mm of the profiles shown in Fig. 7.19.
According to predictions described in section 7.7 the width of the jet at a background pressure of 22 Pa is narrower than that corresponding to the low background pressures. A further description of the expansion properties is beyond the scope of this chapter, but the measurements demonstrate that the TS system is an excellent diagnostic tool for studying phenomena in an expanding argon plasma jet.

7.10 Summary
The results obtained from the TS measurements on the argon plasma jet, show that the Magnum-PSI TS system is operating excellently within the design specifications. According to Rayleigh scattering the overall transmission of the detection branch is according to the requirements.

The observational error in the achieved results (~1% in $n_e$) prove that the TS system can measure within 3 seconds, $n_e$ and $T_e$ profiles (spatial resolution of 1.5 mm) at a density of $n_e = 9.0 \times 10^{18} \text{ m}^{-3}$, with an accuracy of 3% and 6%, respectively.

The performance at minimum measurable temperature, currently 0.15 - 0.2 eV, can be improved significantly by equipping the spectrometer with a grating that requires equal incident and diffraction angles; an angle $\theta_{1,2} = 60^\circ$ is proposed. This will allow for electron temperature measurements far below 0.1 eV.

This report showed clearly different features of the argon plasma expansion and gives an opportunity to study different shock phenomena. The expectation is that this system will be an excellent control tool for both low density as well as high density plasmas in Magnum-PSI.

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References

CHAPTER 8

Collective Thomson scattering for ion temperature and velocity measurements on Magnum-PSI: a feasibility study

H.J. van der Meiden

FOM Institute for Plasma Physics Rijnhuizen, Association EURATOM-FOM, Trilateral Euregio Cluster, P.O. Box 1207, 3430 BE Nieuwegein, The Netherlands, www.rijnhuizen.nl

Abstract

In this paper, collective Thomson scattering (CTS) is proposed for measuring the ion temperature and axial/rotational velocity of a plasma jet in the linear plasma generator Magnum-PSI, where ITER-relevant plasma conditions will be simulated. CTS is feasible at Magnum-PSI, because high electron densities \( n_e \) can be obtained at low electron temperatures, which means that small Debye lengths are achievable. Calculations show that CTS is possible at the fundamental wavelength (1064 nm) of a Nd:YAG laser. At this wavelength, a scattering angle of 17-35 degrees is sufficiently small to achieve a scattering parameter \( 1 < \alpha < 3 \). The estimated observational error in the ion temperature \( T_i \) is expected to be below 10% at \( n_e = 5.0 \times 10^{20} \text{ m}^{-3} \) and \( T_i = 2.5 \text{ eV} \), for a scattering volume with length of 2.4 mm using an accumulated scattering energy of 12 J (10 pulses of 1.2 J at 10 Hz). The accuracy in the determination of the axial velocity is expected to be about 15%. Setting the required accuracy for ion temperature measurements at 15%, single pulse CTS is expected to be feasible for \( n_e > 1.5 \times 10^{21} \text{ m}^{-3} \). The design considerations of the CTS diagnostic are described in this paper.

8.1 Introduction

Plasma facing components of the ITER divertor have to withstand particle fluxes corresponding to a power load of maximum 10 MW/m\(^2\). Chemical erosion and sputtering will play a major role during plasma-surface interaction and there is a necessity to understand the underlying erosion mechanisms. Therefore, the linear plasma generator Magnum-PSI...
PSI (MAgnetised plasma Generator and NUmerical Modeling for Plasma Surface Interaction studies) [1] is being built to simulate the plasma-wall conditions in the ITER divertor.

Determination of the ion properties of a hydrogen plasma is a challenging issue for diagnostics such as optical emission spectroscopy (OES). For correct interpretation other parameters such as molecular neutral density are required.

In this paper it will be shown that collective Thomson scattering (CTS) can be applied for measuring the ion temperature ($T_i$) and macroscopic velocity directly and unambiguously for this kind of plasmas.

CTS is not as established a method as incoherent Thomson scattering (TS). The latter method based on scattering by free electrons, has proven to be suited to accurately determining the electron temperature ($T_e$) and density ($n_e$) of low and high temperature plasmas [2, 3, 4].

Much information about plasma parameters can be extracted from CTS. In this type of scattering the size of the scattering wave is comparable to or greater than the Debye length of the plasma and the resulting narrow spectrum (the so-called ion feature) originates from scattering from the electrons bunched in the Debye sphere of the ions. From the spectral shape, the ratio between electron and ion temperature $T_e/T_i$, the amount of impurities [5], drift velocities between electrons and ions (current density), macroscopic plasma velocities and potentially plasma turbulence levels can be determined [6, 7, 8, 9]. In particular, the axial velocity ($v_{axial}$) and ion temperature are important plasma parameters for the determination of the particle flux load on plasma facing components.

Pilot-PSI, the forerunner of the linear plasma generator Magnum-PSI, has achieved electron densities above $4.0 \times 10^{21} \text{ m}^{-3}$ at $T_e > 3.0 \text{ eV}$. It is expected that the same plasma parameters will be achieved at Magnum-PSI. The Debye length of the Magnum-PSI plasma will be easily 100 times smaller than that of the bulk of a Tokamak plasma. The Magnum-PSI plasma conditions allow CTS performance even with lasers operating in the visible light range.

The high accessibility of the Magnum-PSI plasma generator enables implementation of several diagnostics. A very sensitive incoherent TS system is being built to measure $T_e$ and $n_e$ profiles along the full diameter of the plasma jet [10]. OES will be applied in Magnum-PSI to measure the axial velocity and ion temperature of the plasma jet. Specifically for Magnum-PSI, CTS will be an important diagnostic tool for the following reasons:

- The $T_i$ values obtained from OES on $H_{\beta}$ can be compared with those from CTS. This comparison can be used to confirm the coupling between atomic exited neutrals H ($n > 2$) and ions as proposed in [11, 12].
- OES measurements yielded ion temperatures up to 2.5 times the electron temperature [11, 12]. Ion viscous heating is the proposed cause. Accurate measurements of the ion temperature using CTS (and electron temperature by incoherent TS system), combined with measurements of axial and rotational velocity, could be used to confirm this for a better understanding of the underlying heating mechanisms.
• CTS will give valuable input for plasma simulation models (B2-EIRENE code).

In addition to being an important experiment for plasma-surface interaction studies, Magnum-PSI will be used as test bed for several ITER diagnostics. Application of a combination of an incoherent TS system and a CTS system at Magnum-PSI will result in a complete and unambiguous mapping of electron and ion properties. Ion temperature measurement diagnostics are not yet foreseen for the ITER divertor plasma. CTS experiments on Magnum-PSI can possibly prove that CTS is a viable ion temperature determination method for the ITER divertor. This is important, because presently there are no good techniques available to measure the ion temperature in the ITER divertor plasma [13].

In this article the design considerations of a CTS system for Magnum-PSI are described, comprising port access, laser requirements and detection branch. Particularly, in the last decade, low noise Near Infrared (NIR) detectors, based on a transfer electron (TE) photocathode and electron bombarded (EB) gain technology have been developed [14]. These advances in detector technology make development of a CTS system based on the fundamental wavelength of the Nd:YAG laser (1064 nm) feasible now. This hitherto never applied setup for CTS is compared with a system based on a ruby laser combined with a detection system that is equipped with an intensified charged-coupled device (ICCD) camera.

A short summary of TS theory is given in Sec. 8.2 and Magnum-PSI is described in Sec. 8.3. The design considerations of the CTS system are described in Sec. 8.4 followed by the recommended diagnostic setup and its applications given in Sec. 8.5. In Sec. 8.6, the influence of background sources originating from plasma light, Rayleigh scattering, incoherent TS and microscopic turbulence are treated. The paper concludes with a summary presented in Sec. 8.7.

8.2 Thomson scattering

The magnitude of the scattering vector \( \mathbf{k} = \mathbf{k}_s - \mathbf{k}_\theta \) (see Fig. 1) is defined as:

\[
\mathbf{k} = |k| = \frac{4\pi}{\lambda_\theta} \sin \left( \frac{\theta}{2} \right),
\]

(8.1)

with \( \theta \) the scattering angle between \( \mathbf{k}_\theta \) and \( \mathbf{k}_s \). It is assumed that \(|k_s| = |k_\theta|\), which is true if Compton effects can be neglected.
Correlated interactions between the electrons occur only on or above a certain scale length, the so-called Debye length $\lambda_D$:

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{e^2 n_e}},$$  \hfill (8.2)

with $\varepsilon_0$ the permittivity of vacuum, $e$ the electron charge and $n_e$ and $T_e$ are given in $(m^{-3})$ and $(K)$, respectively. Whether coherent effects influence the scattering process is determined by the scattering parameter $\alpha$ defined as [15]:

$$\alpha = \frac{1}{k\lambda_D}. \hfill (8.3)$$

The average scattering power reaching the observer in the direction of $k_s$ is:

$$P_s = P_L \Delta L n_e \Omega \frac{d \sigma_T}{d \Omega} \int_{-\infty}^{\infty} S(k, \omega) d \omega,$$  \hfill (8.4)

where $P_L$ is the incident laser power, $\Omega$ the solid angle of the viewing system, $\Delta L$ the length of the scattering volume and $d \sigma_T/d \Omega$ the differential scattering cross section for scattering of electromagnetic waves by a single electron defined as

$$d \sigma_T/d \Omega = r_e^2 \sin^2 \psi,$$  \hfill (8.5)

with $r_e$ the classical electron radius. In this experiment, the angle between the polarization direction of the laser and the scattering plane is $\varphi = 90^\circ$. $S(k, \omega)$ is the spectral density function or scattering form factor. Because the scale difference in velocity between ions and electrons is large (assuming $T_e = T_i$), the Salpeter approximation [15] can be
applied describing $S(k, \omega)$ as the sum of two separate contributions, each as a function of the specific normalized wavelength:

$$x_{e,i} = \Delta \omega / k \nu_{e,i} = \Delta \omega / \nu_{e,i}$$  \hspace{1cm} (8.6)

with $\nu_{e,i} = (2k_B T_{e,i} / m_{e,i})^{1/2}$ the average thermal speed of the particles.

The Salpeter approximation of the form factor is as follows:

$$S(k, \omega)d\omega \equiv \Gamma_{\alpha} (x_e)dx_e + Z \left( \frac{\alpha^2}{1 + \alpha^2} \right)^2 \Gamma_{\beta} (x_i)dx_i,$$  \hspace{1cm} (8.7)

where

$$\Gamma_{\chi} (x_{e,i}) = \frac{\exp(-x_{e,i}^2)}{1 + \chi^2 w(x_{e,i})^2} \text{ with } \chi = \alpha, \beta$$  \hspace{1cm} (8.8)

and

$$\beta^2 = \frac{Z \alpha^2 T_e}{1 + \alpha^2 T_i}.$$  \hspace{1cm} (8.9)

$Z$ is the effective charge of the ions and $w(x_{e,i})$ is the plasma dispersion function, which is tabulated by [16] and is described by a real $Rw(x_{e,i})$ and imaginary part, the Landau damping term $Iw(x_{e,i})$:

$$Rw(x_{e,i}) = 1 - 2x_{e,i} \exp(-x_{e,i}^2) \int_0^{x_{e,i}} \exp(p^2) dp,$$  \hspace{1cm} (8.10a)

$$Iw(x_{e,i}) = -\pi^{1/2} x_{e,i} \exp(-x_{e,i}^2).$$  \hspace{1cm} (8.10b)

$Rw(x)$ can be approximated by the following Taylor series:

$$Rw(x_{e,i}) = 1 - 2x_{e,i}^2 \left( 1 - \frac{2}{3} x_{e,i}^2 + \frac{4}{15} x_{e,i}^4 - \ldots \right) \text{ for } x_{e,i} < 1$$  \hspace{1cm} (8.10c)

$$Rw(x_{e,i}) = \frac{1}{2} x_{e,i}^2 \left( 1 + \frac{3}{2} x_{e,i}^2 + \frac{15}{4} x_{e,i}^4 + \ldots \right) \text{ for } x_{e,i} \gg 1$$  \hspace{1cm} (8.10d)

If $x_e \ll 1$ then $x_i \gg 1$, because $x_e / x_i \ll 1$. In this case, as follows from Eq. 8.10d, $Rw(x_i)$ and $Iw(x_i)$ both become zero, and the ion feature plays no role. Thus, outside the narrow spectral range of the ion feature the electron feature can be described by:

$$S_e(k, \omega) = \left( \frac{2\pi^{3/2}}{k \nu_e} \right) \frac{\exp(-x_e^2)}{\left( 1 + \alpha^2 Rw(x_e) \right)^2 + \left( \alpha^2 Iw(x_e) \right)^2}.$$  \hspace{1cm} (8.11)

If $x_e \ll 1$, then $Rw(x_e) \equiv 1$ and $Iw(x_e) \equiv 0$, giving the spectrum of the ion feature:
In Eq. 8.11 and 8.12, the electron and ion features are plotted as functions of the normalized wavelength as defined in Eq. 8.6. When $\alpha = 0$, the electron feature (Eq. 8.11) will reflect the classical Maxwell velocity distribution of the electrons. Eqs. 8.11 and 8.12 show where resonances in the scattering spectrum occur. In the region $x_e > 1$, the spectrum of the electron feature shows satellites. Here, the denominator of Eq. 8.11 goes to zero: $1 + \alpha^2 R w(x_e) = 0$ (in fact, the dielectric coefficient of the plasma becomes zero). It can be shown that the frequency shift of the resonances, $\Delta \omega_e$, corresponds to the electron plasma frequency $\omega_p$ and is given by:

$$\Delta \omega_e = \sqrt{\frac{\omega_p^2 + \frac{3k_B T_e}{m_e}}{k^2}}.$$  \text{(8.13)}

This enables absolute calibration of the sensitivity of the system. However, according to Eq. 8.11 the intensity goes down for higher values of $\alpha$.

A similar solution, using Eqs. 8.10c and 8.12 can be found for the ion feature (in case $\alpha \geq 1$ and $Z = 1$). The peaks in this spectrum correspond to the ion acoustic resonances given in practical form by:

$$\Delta \omega_i = k \sqrt{\frac{k_B T_e + 3k_B T_i}{m_i}}.$$

\text{(8.14)}
Fig. 8.2: a) Calculated shape of the electron feature as a function of the normalized wavelength and for different values of $\alpha$. b) Calculated shape of the ion feature for different values of the ratio $T_e$ over $T_i$ at $\alpha = 1.6$ ($Z = 1$). Remark: $x_e = \sqrt{m_i/m_e} x_i$

These resonances are visible if $T_e \geq T_i$. For the plasma condition where $T_e \ll T_i$ the spectrum has a near-Gaussian shape (see Fig. 8.2b) reflecting the pure Maxwell velocity distribution of the ions with $T_i$ corresponding to half 1/e-width ($\Delta \lambda_{1/e}$) given by:

$$\Delta \lambda_{1/e} = \frac{2 \lambda_0}{c} \sin\left(\frac{\theta}{2}\right)\left(\frac{2k_B T_i}{m_i}\right)^{1/2} \text{[nm]}. \quad (8.15)$$

In this case the width of the spectrum will be very narrow, because ion acoustic resonances are absent. In Sec. 8.4 and 8.5, this condition is used as a test case, because this sets the highest demands on the spectral resolving power of the detection devices.

Integration of the form factor over the spectrum gives the expected relative contributions originating from the ion and electron feature as a function of the scattering parameter $\alpha$

$$\int S(k, \omega) d\omega = S_e(k) + S_i(k). \quad (8.16)$$
In Fig. 8.3 the individual contributions are plotted as function of $\alpha$, and for two different $T_e/T_i$ ratio’s.

If the plasma exhibits a macroscopic velocity, then depending on the scattering geometry, the spectrum of the ion feature will show a Doppler shift, i.e. the velocity component projected on $k$ can be probed. This allows measurement of the axial and rotational velocity of the Magnum-PSI plasma beam and is treated in Sec. 8.6.

![Graph showing the form factor in case of $Z = 1$.](image)

**Fig. 8.3**: Form factor in case of $Z = 1$. Remark: although $S_i$ is approximately equal to $S_e$ if $\alpha \sim 1.3$, even then only a small fraction (~5%) of $S_e$ will contribute to the narrow spectrum of $S_i$. The spectrum of the electron feature is about 42 times wider than that of the ion feature.

Electron drift velocities ($v_d$) (a measure for current density according to $j = -e n_e v_d$) can be identified in the spectrum of the ion feature, because this affects the Landau damping strength and as a result the ion acoustic resonances in the spectrum will become asymmetric in shape [17]. However, it is more obvious to measure electron drift velocities with the incoherent TS system; the incoherent spectrum will be shifted due to this drift velocity [18]. Therefore this effect is not treated in this paper.

### 8.3 Magnum-PSI

The linear plasma generator Magnum-PSI (see Fig. 8.4) is the successor of Pilot-PSI, which has been operational since 2004. The high power cascaded arc source [19] of Magnum-PSI is specified to produce a 10 cm (full) diameter steady state plasma jet at a plasma temperature of $< 10$ eV and a hydrogen particle flux density of $10^{24}$ ions m$^{-2}$s$^{-1}$. A superconducting magnet generates an axial magnetic field to guide (and confine) the plasma to a target, over a distance of about 1.5 m. The bore diameter of the magnet is 1300 mm and features holes at 90 and 45 degrees for excellent access to the ports of the vacuum vessel (inner diameter 500–600 mm).
To enhance the temperature from about 5 eV to an electron temperature in the range of 10 eV a radio-frequency (RF) heating system is being developed. An incoherent TS system with high detection sensitivity has been designed and is being constructed (vacuum beam line depicted in Fig. 4) to measure $T_e$ and $n_e$ profiles (chord length 95 mm, resolution 1.4 mm) about 250 mm downstream of the source output and in front of the target (distance relative to target surface variable: 10 - 50 mm). The lower density and temperature limits will be about $n_e = 5.0 \times 10^{18} \text{ m}^{-3}$ and $T_e = 0.07 \text{ eV}$, respectively. The accuracy in $n_e$ and $T_e$ will be 3% and 6% at $n_e = 9.0 \times 10^{18} \text{ m}^{-3}$ if the scattering from 30 Nd:YAG laser pulses (0.35 J/pulse, $\lambda_0 = 532 \text{ nm}$) is accumulated. Magnum-PSI is equipped with a diagnostic park to perform in situ and ex situ investigations of target surfaces. Beginning 2011 the physics program of Magnum-PSI will start. More information about Magnum-PSI and the incoherent TS system can be found in [1, 10].

Fig. 8.4: Magnum-PSI. The axial magnetic field generated by the superconducting magnet confines the plasma until it impinges on a target. After plasma exposure, the manipulator arm transports the target to the target exchange and analysis chamber to make it possible to detailed ex-situ analysis of the surface and deeper layers.

8.4 CTS system for measuring ion feature

Besides geometrical factors also the compatibility between detection method and laser wavelength has to be taken into account. A boundary condition for the design was that the CTS system must consist of mainly commercially available equipment that requires negligible maintenance. This was the reason that systems based on CO$_2$ and D$_2$O lasers were not considered in this paper. This section is dedicated to the design philosophy of the CTS system for Magnum-PSI.

8.4.1 Availability of ports and scattering geometry

To keep the ports in the target chamber available for real time surface investigation and plasma diagnostics like incoherent TS and emission spectroscopy, the best suited location for the CTS viewing system is a port section about 250 mm downstream of the source (see Fig. 8.5). In a later stage ports located in the target chamber can be used to measure the plasma properties in front of the target.

The laser beam path, depicted in Fig. 8.5, is also used for the standard TS system for measurement of $n_e$ and $T_e$ profiles downstream of the source output. The laser beam line will be equipped with multi laser line mirrors, compatible with 532 nm (incoherent TS)
and the wavelength required for CTS. The laser beam can be moved within a range of 40 mm along the geometrical axes of Magnum-PSI. The neighbouring port section at the right-hand side is available (viewing system with label VS1) and it is possible to install a viewing system (VS2) at a small scattering angle $\theta_2 = 17^\circ$. Smaller angles are assumed to be unrealistic, because they position the collection system directly in the path of stray light originating from the input window and baffles. The viewing system VS1 can be used at a scattering angle range $\theta_1$ between $28^\circ$ and $41^\circ$. Different scattering geometries are possible and in the next section, it is shown that a CTS system equipped with both viewing systems VS1 and VS2 is recommendable concerning dynamic measurement range.

![Fig. 8.5: Schematic presentation of possible configurations of the CTS viewing systems in the source chamber. Laser beam location ~250 mm downstream of the source output. Due to geometrical constraints the scattering angle $\theta_1$ ranges from $28^\circ$ to $41^\circ$ ($\Delta \theta_h = 13^\circ$) for viewing system 1 (VS1). An additional viewing system as depicted as VS2 is also possible, here $\theta_2 = 17^\circ$.](image)

### 8.4.2 Laser wavelength and choice of scattering angle

The choice of laser wavelength is a trade-off between measurable spectral width (Eq. 8.15), allowable imprecision in $\alpha$ ($d\alpha$) and the value of $\alpha$; the latter determines the amount of scattered signal detected within the spectrum of the ion feature (see Fig. 8.3). The imprecision $d\alpha$ is caused by the fact that TS requires a cone collection angle $d\theta$ (see Fig. 8.1) and relative to the scattering angle $\theta$ this means that scattered light is collected over a cone of $k$ vectors, i.e. the observed spectrum will consist of contributions originating from all the $k$’s within this cone. According to [7] this introduces a systematic error ($d\lambda$) in the determination of the full 1/e-width ($2\Delta \lambda_{1/e}$) of the spectrum of the ion feature. A relative upper value of this is given by [7] (adapted for the full 1/e-width):
\[ d\lambda_{rel}^i = \frac{d\lambda}{2\Delta\lambda_{i/e}} = \frac{1}{2\sqrt{2}} \cotg \left( \frac{\theta}{2} \right) d\theta \]  

(8.17)

The relative error in the determination of \( T_i \) due to this is \( dT_i/T_i \approx 2d\lambda_{rel}^i \). It is assumed that a maximum contribution of the imprecision \( d\alpha \) to the error in the width of the spectrum of about 5% can be tolerated. According to Eq. 8.17, this implies that a scattering angle of about 17° can be applied at an effective viewing f-number of \( f/30 \). In [20] it is argued that if a theoretical spectrum was fitted, taking into account the weighted contributions from the different \( k \)'s to the spectrum, then the imprecision will be reduced to an insignificant level. In this article the upper value of this contribution (worst case scenario) will be used in the calculations.

To ensure that sufficient scattered light will be gathered within the spectrum of the ion feature, it is required that \( \alpha \geq 1 \) (see Fig. 8.3). Note that, because of the narrowness of the spectrum of the ion feature, its amplitude is much higher than that of the electron feature.

The spectral resolution of nowadays commercially available dispersive instruments like grating spectrometers is about 0.003 nm. This limit determines the number of spectral channels available for sampling of the spectrum.

The detection branch should be capable of measuring of at least five spatial points along a laser chord of 100 mm using VS1 and a single spatial point with VS2 (both with element size 2.4 mm).

If the above-mentioned boundary conditions are used a comparison can be made between a ruby and Nd:YAG laser based system with the assumption that CTS should be possible above a plasma density of about \( n_e > 5.0 \times 10^{20} \text{ m}^{-3} \) at \( T_e = 2.5 \text{ eV} \). This temperature is used as a test case, because this is the minimum bulk temperature expected for the high density plasmas in Magnum-PSI.

Table 8.1: Comparison of 2 configurations of CTS: plasma temperature 2.5 eV

<table>
<thead>
<tr>
<th>CTS based on laser type</th>
<th>Ruby (694.3 nm)</th>
<th>Nd:YAG (1064 nm)</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viewing system (see Fig. 8.5)</td>
<td>VS1</td>
<td>VS2</td>
<td>VS1</td>
</tr>
<tr>
<td>Scattering angle</td>
<td>28 - 41</td>
<td>17</td>
<td>28 - 41</td>
</tr>
<tr>
<td>Required minimum density to achieve ( \alpha \geq 1 )</td>
<td>2.55 - 5.35</td>
<td>0.95</td>
<td>1.1 - 2.3</td>
</tr>
<tr>
<td>( \alpha ) value at ( n_e = 4. \times 10^{21} \text{ m}^{-3} )</td>
<td>1.2 - 0.85</td>
<td>2</td>
<td>1.9 - 1.3</td>
</tr>
<tr>
<td>Full 1/e-width spectrum</td>
<td>0.048 - 0.07</td>
<td>0.028</td>
<td>0.075 - 0.108</td>
</tr>
<tr>
<td>Relative spectral imprecision</td>
<td>2.4 - 1.6</td>
<td>3.9</td>
<td>2.4 - 1.6</td>
</tr>
</tbody>
</table>

Remark: a very high power ruby laser (2×12 J, 20 ns) is available, but requires refurbishment and installation of two intra-cavity Fabry-Perot etalons for narrowing the laser line. Moreover, this excess of laser energy will influence the plasma due to heating of the plasma (inverse Bremsstrahlung) [7].

As can be seen from Table 8.1, a CTS system based on the ruby wavelength is not favourable for application on Magnum-PSI. Firstly, the spectral width of the ion feature (< 0.028 nm), as obtainable with the ruby variant, sets extreme demands on the resolving
power of spectrometers. Secondly, the measurable dynamic range is limited to \( > 9.5 \times 10^{20} \text{m}^{-3} \).

A CTS system based on the fundamental wavelength of an Nd:YAG laser equipped with both viewing systems VS1 and VS2 complies with the requirements; it allows one to measure the ion temperature at densities higher than \( 4.2 \times 10^{20} \text{m}^{-3} \) and the corresponding minimum spectral width can be sampled with sufficient spectral channels using commercially available spectrometers [21]. For the Nd:YAG laser based CTS system more than 20 spectral channels fit (channel width 0.003 nm) within the full 1/e-width of the ion spectral feature if configuration VS1 is used and 15 if configuration VS2 is used.

As mentioned in the requirements, VS1 will be used for measuring about five points along the laser chord, whereas simultaneously VS2 will operate as single-point observation system. Concerning dispersive instruments both grating spectrometers and Fabry-Perot interferometers are valuable. For this project, a grating spectrometer is preferable, because it enables simultaneous recording of multiple spectra (corresponding to different spatial points in the plasma) on a CCD detector. Detection systems based on an ICCD or on a NIR detector [14] can be used for this purpose.

Summarizing the argumentation above, the Nd:YAG variant of the CTS system (combined with the NIR detector) is favourable concerning obtainable spectral width of the ion feature and the wider measurable density range; even \( \alpha \) above 3 is obtainable.

A scanning Fabry-Perot interferometer is assumed as an option for the single-point CTS configuration (VS2), in case the demands on resolving power of the spectrometer will be very high. Avalanche Photodiodes (APD) can be combined with these devices for detection of the Thomson scattered light. There are APDs available, which are optimized for 1064 nm (quantum efficiency up to 60%), but for each spatial point a special electronic circuit (to enable plasma light and TS light recording) and a fast Analog Digital Converter is required.

In next section a CTS system for Magnum-PSI is proposed that can probe the ion properties using both configurations VS1 and VS2.

### 8.5 CTS system for Magnum-PSI

As concluded in previous section, the CTS system for Magnum-PSI will be based on an Nd:YAG laser operating at the fundamental wavelength 1064 nm. The Nd:YAG laser will be equipped with an injection seeded oscillator that assures that the laser line width (\( < 10^{-4} \) nm) will be negligible relative to the spectral width of the ion feature (typical full 1/e-width 0.08 nm at 2.5 eV).

The acceptance angle of the spectrometer must be compatible with that of the viewing systems. Two factors are important for the design: firstly, the beam waist of the laser beam has to map the width of the input fibre array and secondly the width of the input slit of the spectrometer cannot be too wide in order to achieve a good spectral resolution. These two factors are in contradiction with one another, but with the relay fibre configuration shown in Fig. 6 a good solution is found. The TS light originating from a
laser chord element of beam waist 0.7 mm and length 2.4 mm will be imaged onto a fibre array with a magnification of $M_{\text{view}} = -0.25$ (with this magnification the number of required fibres per spatial element is still feasible concerning complexity). The spectrometer input side will consist of a single column fibre array (fibre core diameter 50 $\mu$m). Thus, a fibre relay transformation factor $M_{\text{relay}} = 0.25$ is applied.

![Fig. 8.6: Relay fibre configuration: multiple fibre packages are aligned along one line. Only one fibre package is shown.](image)

To keep the contribution from the spectral imprecision to the observational error as small as possible, a viewing f-number of $f/40$ is chosen. To confine the collected light, the acceptance angle of the spectrometer has to be about $f/10$ as a result of viewing f-number ($f/40$) and magnification $M_{\text{view}} = -0.25$.

The very high resolution (0.003 nm at slit width 50 $\mu$m) high f-number spectrometer ($f/10$) [21] will be equipped with an Electron bombarded Charged-Coupled Device (EBCCD) [14] and will allow for detection of multiple spatial elements.

The NIR camera consists of two key parts: an EBCCD and a TE InGaAs photocathode. The EBCCD consists of 1008×256 pixels (pixel size 26 $\mu$m square): although the factory certifies 1 strip of 1008×20 pixels, the area of the whole chip can be used. The effective quantum efficiency of the EBCCD camera is about 25$\%$ at 1064 nm and the EB gain (the number of electrons, generated by secondary emission, per photoelectron) is about 100. By virtue of the application of a back-illuminated CCD chip the NIR detector features very low noise properties. The read-out noise amounts to about 25 e; this is in contrast with other NIR detectors that suffer from noise that amounts to 1000 - 2000 e. To obtain excellent Poisson statistics for the CTS measurements (5 spatial points with VS1 and 1 spatial point with VS2) the light originating from 10 laser pulses (at a rep rate 10 Hz, 1.2 J/pulse) will be accumulated (although for $n_e > 1.5 \times 10^{21}$ m$^{-3}$ even single pulse CTS is possible).

For the proposed CTS system with scattering angles fixed to 35° and 17° for VS1 and VS2, respectively, an overview of the specifications is presented in Table 8.2.
Table 8.2: Main parameters of the proposed collective TS system:

<table>
<thead>
<tr>
<th>CTS using two viewing configurations:</th>
<th>VS1</th>
<th>VS2</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scattering angle</td>
<td>35</td>
<td>17</td>
<td>°</td>
</tr>
<tr>
<td>$T_e$ (taken as typical test case)</td>
<td>2.5</td>
<td></td>
<td>eV</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>1064</td>
<td></td>
<td>nm</td>
</tr>
<tr>
<td>Accumulated laser energy per pulse $(E)$ 10 pulses at 10 Hz</td>
<td>12</td>
<td></td>
<td>J</td>
</tr>
<tr>
<td>Length scattering volume $(L)$</td>
<td>2.4</td>
<td></td>
<td>mm</td>
</tr>
<tr>
<td>Solid angle $(f/40)$ $(\Omega)$</td>
<td>0.49×10⁻³</td>
<td></td>
<td>sr</td>
</tr>
<tr>
<td>Overall transmission up to photocathode EBCCD</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective quantum efficiency EBCCD</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slit width spectrometer (fibre diameter)</td>
<td>50</td>
<td></td>
<td>µm</td>
</tr>
<tr>
<td>Optical spectral resolution</td>
<td>0.003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density range (max $n_e$ taken as test case)</td>
<td>1.5 - 4</td>
<td>0.42 - 4</td>
<td>10²¹ m⁻³</td>
</tr>
<tr>
<td>$\alpha$ range (see Eq. 8.3)</td>
<td>1.0 - 1.52</td>
<td>1.0 - 3.1</td>
<td></td>
</tr>
<tr>
<td>Relative spectral imprecision $d\lambda_{rel}^i$</td>
<td>1.4</td>
<td></td>
<td>%</td>
</tr>
<tr>
<td>Relative ion feature contribution $(S_i(k))$</td>
<td>0.17 - 0.28</td>
<td>0.17 - 0.43</td>
<td></td>
</tr>
<tr>
<td>Full 1/e-width spectrum</td>
<td>0.08</td>
<td>0.046</td>
<td>nm</td>
</tr>
</tbody>
</table>

8.5.1 Ion temperature measurements

Using the parameters of the CTS diagnostic given in table 8.2 and the scattering formula

\[ N_{pe \text{- feature}}^{\text{ion}} = \frac{E}{h \nu_0} \Delta L \Omega n_e S_i(k) \frac{d\sigma_T}{d\Omega} \tau_{\text{overall}} \eta_{(EB) \text{ CCD}}, \tag{8.18} \]

the expected number of photoelectrons $N_{pe \text{- feature}}^{\text{ion}}$ can be calculated. For the CTS configuration that collects the TS light with VS1 at 35° about 6900 - 30000 photoelectrons are measured for the electron density range 1.5 - 4.0×10²¹ m⁻³ (spatial element of 2.4 mm) at an accumulated scattering energy of 12 J (10 pulses of 1.2 J). According to Poisson statistics, this implies an observational error below 1.2% in $n_e$ for the whole density range. Setting the relative error in $T_i$ due to statistics to twice this error gives a relative error in $T_i$ of about 2.4%.

Including the contribution in the error due to the relative spectral imprecision $d\lambda_{rel}^i$, the error in the $T_i$ determination will be about 5% for the mentioned density range. Note that it is assumed that the $T_e$ value as input for the spectral fit of the ion feature has an accuracy in the range of 3%, which is feasible for the electron densities of interest [10].

It is expected that the CTS configuration with VS2 at 17° scattering angle collects about 2000 - 46000 photoelectrons at an electron density range 0.42 - 4.0×10²¹ m⁻³. With the same logic, as used for the CTS configuration with VS1, an observational error in $T_i$ of better than 8% at 0.42×10²¹ m⁻³ is expected.
8.5.2 Axial and rotational velocity measurements

The Doppler shift of the spectrum of the ion feature is a measure of the macroscopic velocity of the plasma, i.e. this property allows measurement of the radial and axial velocity of a plasma jet. In Fig. 8.7 a vector scheme is shown for the axial velocity measurement setup, i.e. only the velocity component ($v_{\text{axial}} / B$) with its projection on $k$ is measured as a Doppler shift.

The relation between $v_{\text{axial}}$ and corresponding Doppler shift $d\lambda$ is given by:

$$\frac{d\lambda}{\lambda_0} = -\frac{v_{\text{axial}} \sin(\theta)}{c}$$  (8.19)

It is expected that the axial velocity of the bulk of the plasma column will range from 3 - 10 km/s [11, 12]. According to Eq. (8.19) this corresponds to a Doppler shift range of 0.0063 - 0.018 nm, i.e. 4 to 12 CCD pixels. The mentioned axial velocity range of the plasma is about 0.17 - 0.50 times the average thermal velocity for plasma temperature of 2.5 eV. According to [22] spectral shifts can be measured with an accuracy of better than 10% if at least 6 - 8 spectral channels are used for the fit; this error is due to the finite width of these spectral channels. An upper value of the observational error in the velocity...
determination is expected to be about 15% at a velocity of 3000 m/s and better for higher velocities. Contributions from the relative spectral imprecision $\delta \lambda_{\text{rel}}$ due to the finite viewing cone can be neglected, because this influences in approximation the spectrum of the ion feature in width symmetrically, i.e. the Doppler shift of the spectrum itself is not disturbed. To observe the rotation of the plasma beam, the scattering plane of the CTS system has to be directed perpendicularly to the plasma beam direction. The same accuracies are expected to be found for determination of the rotational velocity of the plasma jet. Rayleigh scattering will be used for determining the non-Doppler shifted reference spectrum.

8.5.3 Measurement of ionized impurities

The ion feature is in principle ideal for identification of impurities or to measure the evolution of test amounts of particles in time and space [9, 23, 24]; CTS on plasmas containing high mass particles results in high amplitude ion feature peaks, because the width of the spectrum is inversely proportional to the square root of the mass ratio of the ionized particle to be distinguished. However, for the low temperature plasmas (< 6 eV) it is impossible to distinguish other masses due to the limited spectral resolving power of the spectrometer. A drawback of this property could be that the spectrum becomes even too complicated for analysis due to too this contribution. Because the temperatures of the plasmas under consideration are low, the quantity of multiple ionized species ($Z > 1$) will be negligible. Therefore, it is expected that the measured spectrum will reflect the pure velocity distribution of the hydrogen ions.

8.5.4 Dynamic range of CTS system

In Magnum-PSI the scattering angle can be varied to enhance the width of the spectrum of the ion feature or to enhance the accuracy of velocity measurements. By reducing the scattering angle to below 17 degrees, lower plasma densities can be probed. It is foreseen to equip the viewing system with an aperture that can be varied remotely. This way the f-number of the viewing system can be varied to achieve the highest accuracy for a particular situation.

8.6 Background sources and other contributions

Background sources can, if no measures are taken, interfere significantly with the CTS spectra. By taking several measures these contributions can be minimized. In this section these measures are described and residual contributions are estimated.

8.6.1 Plasma light and detector noise

Because the spectral range of the spectrometer is about 40 times smaller than that of the current incoherent TS system operating at Pilot-PSI [25] it is expected that at 532 nm the plasma light contribution for a total detector exposure window of about 10 gate windows of 10 $\mu$s (minimum exposure time of proposed EBCCD camera) is negligible. Here we assumed that the CTS data originating from 10 laser pulses are used for a measurement.
This can be explained by the following facts. In ref [25], it was shown that the plasma light contribution in electron density equivalents was about $4.5 \times 10^{18} \text{ m}^{-3}$ for a total detection gate window of 1.8 $\mu$s. After installation of a band pass filter (width 10 nm, centred around 532 nm laser wavelength) the plasma light contribution was reduced to below $1.0 \times 10^{18} \text{ m}^{-3}$. The CTS system will probably use a total detector window of 100 $\mu$s; 50 times longer than that in ref [25]. Using these facts and taking into account that the spectrum is about 42 times narrower (and the fact that the viewing angle used will be 2.66 smaller for the CTS system), a contribution in electron density equivalents of about $2.0 \times 10^{17} \text{ m}^{-3}$ is found. In conclusion, the scattering signal to plasma light background ratio is at least five times better than that of the incoherent TS system in [25].

The noise contribution is assumed to be negligible, because the EBCCD camera features an electron multiplication gain of about 100 and the pixel binning utility will be used. Furthermore, the EBCCD is based on a back-illuminated CCD chip with very low noise properties.

8.6.2 Contribution from stray light, Rayleigh and incoherent scattered light

It is well known that the stray light contribution will become even lower at longer wavelengths. The scattering angle used for the proposed CTS system is not extremely small, i.e. the viewing system does not ‘see’ the stray light cone originating from the input window directly. Therefore, it is expected that the stray light levels can be reduced to values below that of the Pilot-PSI TS system [25] (taking into account that the viewing angle used will be 2.66 smaller for the CTS system); in theory stray light levels as low as $2 \times 10^{17} \text{ m}^{-3}$ (expressed in electron density equivalents) are feasible.

Contributions to the measured signal originating from Rayleigh scattering on the non-ionized gas of the beam can be excluded for two reasons. Experiments on the plasma generator Pilot-PSI showed that this contribution to the incoherent spectrum (at laser wavelength 532 nm) is negligible [25]. Furthermore the cross section for Rayleigh scattering decreases with the fourth power of the laser wavelength resulting in a 16 times lower Rayleigh signal (compared to 532 nm [25]) at 1064 nm. This means that during CTS measurements the signal originating from Rayleigh scattering can be completely neglected.

Some influence from incoherent scattering, the electron feature, can be expected (see Fig. 8.3). If $\alpha \sim 1$ the net contribution of the scattering signal originating from the electron feature is about 5% of that of the ion feature (assume $T_i \sim T_e$). If $\alpha$ is about 1.5 this contribution has dropped already to an insignificant level of 2.4%.

8.6.3 Micro and Langmuir turbulence

It is not expected that an influence of micro and Langmuir turbulence on the spectra can be measured. In Ref. [26, 27] it is claimed that in the plasma parameter range of interest ($n_e < 1.5 \times 10^{20} \text{ m}^{-3}$) non-thermal contributions to the ion spectral feature were never observed. Also [28, 29, 30] do not report on these non-thermal fluctuations. Because the
Magnum-PSI plasma will exhibit only slow micro and macro dynamics, it is expected that only the thermal contribution of the ion feature will be measured.

8.7 Summary
CTS is the only direct method for accurate determination of the $T_i$ and $v_i$ of hydrogen ions and additionally an excellent verification tool for optical emission spectroscopy diagnostics operating at Magnum-PSI.

A CTS system based on an Nd:YAG laser system is the best candidate concerning dynamic range and accuracy. Ion temperatures at densities even below $5 \times 10^{20} \text{ m}^{-3}$ can be determined with an accuracy in the range of 10% or better. Here also the contribution originating from incoherent scattering is taken into account. Extreme high accuracy in the determination of $T_i$ is feasible if the CTS system is utilized with a variable aperture in the viewing system; the spectral imprecision can then become even negligible and observational errors below 5% in the $T_i$ determination are feasible. Velocity measurements can be performed with an accuracy better than 15%.

The fact that Magnum-PSI is a continuous experiment, allows summing of CTS data originating from multiple pulses with 10 Hz rep. rate. This means that good statistics can be achieved for almost every plasma condition.

In this paper it is shown that a CTS system will be a complementary addition to the diagnostic park of Magnum-PSI; this will make a complete mapping of electron and ion properties of the Magnum-PSI plasma possible.

Acknowledgments
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References

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10. H.J. van der Meiden et al., To be submitted in (2011).
14. MOSIR® 950 EBCCD developed by Intevac. NIR image intensified device. Based on Intevac’s patented transfer electron (TE) photocathode and electron bombarded (EB) gain technology.
21. Spectrometers with a spectral resolution of about 0.003 nm (at slit width 50 µm) and f-number (f/5) are even constructed.
CHAPTER 9

Evaluation and valorisation

The work presented in this thesis was focused on the development of TS systems for measuring fast phenomena in high temperature plasmas (up to 5 keV) in the TEXTOR tokamak, and in low temperature (< 7 eV), high-density quasi-steady-state plasmas in the linear plasma generators Pilot-PSI and Magnum-PSI. For the latter device, also a study was performed to investigate the feasibility of collective TS (CTS) for determining the ion temperature. The main aims of this thesis as described in Sec. 1.4 were reached and are summarized in this chapter.

9.1 Multi-pulse Thomson scattering system of the tokamak TEXTOR

9.1.1 Achievements

In the period 2000 - 2005, a high repetition rate TS system was developed to study fast plasma phenomena in the TEXTOR tokamak. A so-called double-pass intra-cavity laser was developed that generates a burst of 18 laser pulses of ~12 J each, at a repetition rate of 5 kHz. A fast detector based on a CMOS camera and an image intensifier stage was developed. Temperature ($T_e$) and density ($n_e$) profiles could be measured with a time separation of 0.2 ms along the full plasma diameter of 900 mm with a spatial resolution of 7.5 mm. At a density of $n_e = 2.5 \times 10^{19}$ m$^{-3}$, $T_e$ and $n_e$ profiles were measured with an accuracy of 8% and 4%, respectively [1]. With the realized system, rotating magnetic islands (rotation frequency ~ 1 kHz) could be measured during 2.2 ms, revealing details of the density profile evolution inside the islands. Also the dynamics of internal transport barriers could be studied.

9.1.2 Outlook

In 2009 the TS diagnostic on TEXTOR was upgraded with an additional six-pass laser probing system that provided six extra passes through the plasma volume. The scattering power was increased by a factor of 3 in comparison with that of the double-pass system. The statistical errors of TS measurements were improved by a factor of 2 [2]. The new system enabled to increase the number of laser pulses in one laser burst from 18 to 40 which means a measurement period of up to 8 ms. Such a combination of measurement accuracy, repetition rate, spatial resolution and high number of spatial points was never achieved before.
After installation of an additional CMOS camera, a 10 kHz repetition rate TS system will become available. In the near future, this excellent tool will be moved from TEXTOR to the ASDEX tokamak (Munich, Germany) to continue the plasma confinement studies.

9.2 TS systems at linear plasma generators Pilot-PSI and Magnum-PSI

9.2.1 Achievements

In 2006 the existing TS system of Pilot-PSI, based on a frequency-doubled Nd:YAG laser was improved to enable accurate TS measurements within one plasma discharge (duration < 4 s). With the previous setup multiple plasma discharges were often necessary for one TS measurement. The stray light contribution of the system could be reduced significantly, enabling TS at a distance of 17 mm from a target surface under plasma exposure [3]. The sensitivity of the detector system was improved by more than a factor of 5. Using only 20 - 30 laser pulses (0.35 J/pulse at 10 Hz), the minimum measurable density and temperature of the system are $4 \times 10^{19}$ m$^{-3}$ and 0.2 eV, respectively. Many properties of the magnetized plasma jet were revealed with this system. Single-pulse (0.35 J scattering energy) TS measurements were successfully performed during pulsed mode of the cascaded arc source (ELM simulation mode) [4].

Subsequently an advanced Thomson scattering system was developed and built for Magnum-PSI [5]. This system features also a frequency-doubled Nd:YAG laser, yet equipped with a 35 m long remotely-controllable laser beam line and a high-etendue transmission grating spectrometer. The system is capable of measuring $n_e$ and $T_e$ profiles in a plasma column of 100 mm with a spatial resolution of 1.5 mm and features a minimum measurable density and temperature of $9 \times 10^{18}$ m$^{-3}$ and < 0.1 eV, respectively (accumulating 20 laser pulses, 10 Hz, 0.55 J each). During first operations of Magnum-PSI, TS was used to measure the expansion properties of an argon plasma jet, in the absence of a magnetic field. The results show that the specifications are well met. To the best knowledge of the author, concerning sensitivity and spatial resolution, this is the best performing TS system in ‘the world of low temperature plasma physics’.

9.2.2 Outlook

The TS system of Pilot-PSI is operating successfully and has revealed different properties of the plasma jet. At high electron densities ($6 \times 10^{21}$ m$^{-3}$) and low temperatures (1.55 eV), even at 90 degrees scattering angle, collective effects in the spectra were observed [6]. In Fig. 9.1a a spectrum is shown that is influenced by collective effects. The spectrum, measured in the centre of the plasma jet ($\alpha = 0.5$), has the shape of a flattened Gaussian; the central peak, the ion feature, is clearly visible. For comparison in Fig. 9.1b a spectrum is shown that corresponds to a spatial element (of the same profile) at the edge of the plasma jet. The collective effects are negligible in this case ($\alpha = 0.24$); the ion feature is absent. The latter proves that Rayleigh scattering can be excluded as a possible explanation for the central peak in the spectrum shown in Fig. 9.1a. The data is fitted according to the electron feature defined in Eq. 8.11 (using an analytical approximation
for the real part of the plasma dispersion function given by [7]). The intensity of the ion feature is according to theory (see Fig. 8.3).

After the installation of the superconducting magnet, the physics program of Magnum-PSI will start and the installed TS system will be used as a tool for control and study of the steady-state plasma jet. In addition, single-pulse TS will be applied to measure $T_e$ and $n_e$ during pulsed operation of the cascaded arc source (to simulate ELMs).

It is foreseen to equip the spectrometer of the TS system of Magnum-PSI with a transmission grating that uses equal incidence and dispersion angle, i.e. the slit will be imaged onto the ICCD camera with magnification $M = 1$. This means that the lower temperature limit of 0.07 eV can be reached using the full light collection power of the detection system; making the lower density limit $< 9 \times 10^{18} \text{ m}^{-3}$.

![Fig. 9.1a: TS spectrum measured in the centre of the Pilot-PSI plasma jet in front of a target; $n_e = 6 \times 10^{21} \text{ m}^{-3}$, $T_e = 1.55 \text{ eV}$ and $\alpha = 0.5$. Size of spatial element 0.6 mm. The ion feature peak is well visible.](image)

![Fig. 9.1b: TS spectrum measured at the edge of the Pilot-PSI plasma in front of a target; $n_e = 0.88 \times 10^{21} \text{ m}^{-3}$, $T_e = 0.92 \text{ eV}$ and $\alpha = 0.24$. Size of spatial element 0.6 mm. The ion feature is absent.](image)

### 9.3 Collective Thomson scattering

A feasibility study showed that CTS can be performed on Magnum-PSI to measure the ion temperature ($T_i$) and axial velocity with an accuracy of 10% at $n_e = 5.0 \times 10^{20} \text{ m}^{-3}$ (test case: $T_i = 2.5 \text{ eV}$, resolution 2.4 mm) and 15%, respectively [8]. It was demonstrated that this can be achieved by accumulating 10 pulses of 1.2 J each, using the fundamental wavelength of a Nd:YAG laser. These ion temperature measurements are of great importance, since for a magnetized plasma jet like Pilot-PSI and Magnum-PSI the ion temperature is thought to be much higher than the electron temperature due to viscous heating by fast rotating plasma layers ($E \times B$ drift) [9]. Possible ways to realize this diagnostic are being investigated.
The results shown in Fig. 9.1, prove that micro and Langmuir turbulence do not influence the appearance of the ion feature since the measured intensity of the ion feature corresponds to the theoretical predicted value (see Chapter 3).

The capability of CTS to distinguish between hydrogen, deuterium, tritium and helium ([10, 11, 12], see also Sec. 3.5.2) could be used to determine the concentrations of individual species in a hydrogen plasma. If the ionization state is known, this property could be used to measure the local concentrations of these species with high spatial resolution, i.e. information about migration could be obtained and can support the study on retention of these species in the divertor components. Laser induced desorption spectroscopy (LIDS) and laser induced ablation spectroscopy (LIAS) are proposed to measure tritium retention in the plasma facing components of the ITER divertor. This involves emission spectroscopy for measuring the concentrations of the impurities coming from the divertor components during laser induced heating. Instead of emission spectroscopy, CTS could be used and would be reliable in absolute sense as long as the scattering parameter $\alpha$ is larger than 1. Accessibility could be an issue; nevertheless it is worthwhile to investigate this option.

Presently there are no good techniques available to measure the ion temperature in the ITER divertor plasma [13]. CTS experiments on Magnum-PSI could show that this technique is a viable ion temperature diagnostic with application perspectives for the ITER divertor.

### 9.4 Where will Thomson scattering go from here?

Starting from the 1960s, TS became one of the most important diagnostic methods for measuring the electron temperature and density at many small and large scale plasma experiments all over the world. In this section the impact of this work and the prospects concerning TS systems is given.

#### 9.4.1 TS system development for fusion research

**High repetition rate TS systems**

The fast repetitive TS system operating in burst mode at TEXTOR (see Chapter 5) paved the road for more applications on different tokamaks. For instance, at the ASDEX tokamak such a system will be applied from 2012 onwards.

The high repetition rate feature is one of the last steps in a sequence of TS system developments. First, single point TS systems were developed in the sixties (based on detection with photomultipliers and single pulse lasers). Then, in the eighties and nineties measurements of $T_e$ and $n_e$ profiles with high spatial resolution became possible by using 2D-detectors (CCD (Charged Coupled Device)); in the nineties these were combined with
gated image intensifiers. With the developed system at TEXTOR, high spatial resolution TS measurements at high repetition rate have become feasible; it is a next step in innovation of TS systems and can lead to a new generation of TS diagnostics*. A new development on this front is, for instance, a high repetition rate laser system for MST (Madison Symmetric Torus): a Nd:YAG and Nd:glass based laser system is being realized that can generate a burst of 200 laser pulses of 1 J at a maximum repetition rate of 250 kHz [14].

**Collective Thomson scattering**

In chapter 8 it was shown that a CTS system is in principle an accurate method to measure the ion properties in the ITER divertor. Actual realization of such a diagnostic for ITER in the future is conceivable and should be investigated, taking into account the complex geometry and limited access in the ITER divertor. Magnum-PSI can then serve as a test-bed for this diagnostic.

**Using Thomson scattering as a method to measure other species in a hydrogen plasma**

Argon is sometimes mixed in the hydrogen plasma of the Pilot-PSI and Magnum-PSI plasma jet; it is thought that the higher collisionality compared to that of hydrogen softens the power load on the electrodes of the cascaded arc. The Rayleigh scattering contribution, measured during the normal TS measurements on Magnum-PSI, can be used to measure the local argon concentration and migration dynamics in the supersonic domain of the expansion close to the nozzle. Also the macroscopic velocity can be determined by measuring the Doppler shift of the Rayleigh scattered light. The feasibility of such a system will be investigated.

**Other interesting developments performed by other TS groups**

In order to measure the ion species ratio of the fusion fuel in the hot bulk plasma of ITER, a CTS system is proposed based on the detection of ion Bernstein waves (IBW) present in the spectra of the ion feature [15]. These CTS systems use mm-waves, produced by gyrotrons, and are generally used to measure the velocity distribution of the confined fast ions in hot plasmas. The IBW signature shows up in the spectrum of the ion feature as a superposed modulation that is dependent on the ion fuel ratio. Efforts to develop a proof-of-principle diagnostic have been initiated.

Currently, x-ray CTS is performed to study ultra-fast non-equilibrium collective dynamics in warm dense hydrogen [16]. The subject of interest involves moderate-to-strong inter-particle coupling which takes place at electron temperatures of several eV

*A certain temporal resolution is feasible by using multiple lasers that are fired in a cascaded sequence of pulses; but this requires extremely high financial investments compared to that for the intra-cavity system realized at TEXTOR.
and electron densities around solid density. It is present in planetary interiors, gravitationally collapsing protostellar disks and particularly during the implosion of an inertial confinement fusion capsule.

9.4.2 Developments based on Mie and Rayleigh backscattering

In the last decade, methods are developed to measure wind speed (profiles) in the troposphere. The wind speed can be obtained from the Doppler shift of the Rayleigh and/or Mie scattered light. The LIDAR (Light Detection And Ranging) principle is applied to determine the location of measurement [17].

In 2008 the Risø National Laboratory for Sustainable Energy - DTU initiated the European WindScanner Facility. Different techniques based on Rayleigh and Mie scattering are deployed at this facility [18]. The aim of this ESFRI (European Strategy Forum on Research Infrastructures) project is the mapping of the entire 3D wind and turbulence fields over complex terrain where large scale wind turbine parks are or will be located; information on the influence of the environment on the performance of the wind turbine park, but also the effects of wakes due to the mutual interaction between the turbines can be obtained. As a result of this research also the lifetime and uptime availability of the wind turbines can be improved. The ultimate goal is the improvement of the efficiency of these wind turbines.

9.5 Valorisation

The work described in this thesis contributed or may contribute in the following way to the needs of the society.

Fast camera technology

The spin-off of the work on the high repetitive TS system at TEXTOR (see Chapter 5) was a contribution in fast camera development. Tests at Rijnhuizen of a prototype of the fastest and most sensitive CMOS camera at that time (2003) showed an artefact concerning image-to-image cross talk. The company states that this development has been of great commercial value for their business (marked value more than 120 million euro). In the words of the representative: ‘The independent nature of the measurements you made on the V7 sensor provided VRI with credible, accurate and impartial results that prompted them to resolve a fundamental problem with the sensor that would have prevented the cameras being used in some very important research areas’. The ‘domino’ effect was that all subsequent produced cameras (more than 3000) were equipped with an improved chip.

This excellent camera and follow-ups are nowadays frequently applied in PIV systems (Particle Image Velocimetry) a method to measure and map in 2D the speed and behaviour of a liquid or gas. The speed is determined by measuring the velocity of the medium that is seeded with small particles which are illuminated by bright lasers against a black background. PIV is used in a huge number of Research and Development fields, from making more aerodynamically efficient cars, planes and ships to predicting the effects of building skyscrapers in cities and making more efficient wind powered turbine blades. The camera is also applied in systems to improve efficient mixing of medicines at the micron
level, analysis of asthma inhalers for more efficient inhalation and observation of the mixing and ignition of internal combustion engines to produce more efficient petrol, diesel or bio fuelled cars.

**Low cost intra-cavity lasers**

The intra-cavity laser developed at TEXTOR can lead to the development of low cost laser systems; the intra-cavity technique has shown to be very reliable in the TEXTOR TS system, also for cavities with large dimensions. The very high conversion efficiency of this type of laser enables the production of high scattering energy at low input power (required for pumping to high population inversion) and can be applied on ruby or Nd:YAG based laser systems. On the other hand, this feature makes application of low cost medium power laser systems feasible for situations where the yield of the scattering process of interest is not too critical. An application could be a monitoring system that measures the dust concentration along highways.

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Curriculum Vitae

I was born on the 16th of February 1958 in Utrecht. In 1978 I passed my examination for MTS-E (medium technical school). After military service I worked as a technician at FOM Rijnhuizen from 1980-1987 at the tokamak TORTUR. After some intermediate steps in education, I studied experimental physics at the Rijksuniversiteit Utrecht and finished this in 1992 with the master project entitled: ‘Saddle-point electrons in slow ion-atom collisions’ in the group ‘Atomm- en Grenslaagfysica’, where I continued to work as 1-year AIO on the beautiful project ‘Resonance two-photon electron spectroscopy of the triplet states of molecular hydrogen’. In 1993 I returned to FOM as research engineer in the diagnostics group of the Rijnhuizen Tokamak Project (RTP), with emphasis on microwave technology. In 1995, I became member of the Thomson scattering group. From 1998-2005 I was project leader for the TEXTOR Thomson scattering diagnostics (Forschungszentrum Jülich, FzJ). During about the same period I worked on the heliac device TJ-II on a high resolution TS system and on the detection branch of the TS system for the tokamak T10 (Kurchatov institute in Moscow). In late 2005 I became operations coordinator at the plasma generator Pilot-PSI (until 2008) and diagnostics coordinator for Pilot-PSI and Magnum-PSI. From 2009 till present I work besides this on the EFDA tasks, Speckle interferometry, LIDS (Laser Induced Desorption Spectroscopy), LIAS (Laser Induced Ablation Spectroscopy) and LIBS (Laser Induced Breakdown Spectroscopy). In parallel, I became diagnostic coordinator of the FOM-FZJ collaboration on MAGNUM-PSI. After performing a feasibility study on collective Thomson scattering at Magnum-PSI, I got the passion to write this thesis; I worked on it besides my normal working hours and finished it within 2 years.