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Incoherent and Collective Thomson Scattering for the Determination of Electron and Ion Properties in Low-Temperature Plasma

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Abstract

In this lecture an overview of applications of incoherent Thomson scattering (TS) as well as collective Thomson scattering (CTS) will be given. These are the most accurate methods for measuring the electron and ion properties, because the method is direct and non-intrusive. A CTS system based on the fundamental wavelength of a seeded Nd:YAG laser, being developed for the high density, low-temperature plasma of the linear plasma generator Magnum-PSI will be described also. The small Debye length of dense low temperature plasma enables application of CTS at relatively short laser wavelength. The combination of this CTS system and existing incoherent TS system enables determination of electron density and temperature as well as ion temperature and plasma velocity of the near surface plasma. In this lecture, the theoretical background and experimental challenges of the work will be given along with some examples that demonstrate the capabilities of such systems.

Keywords Thomson scattering · Linear plasma generator · Low temperature plasma

Introduction

Successful operation of the ITER tokamak requires divertor operation in a plasma regime, wherein the heat flux to the divertor plates remains below the technological limits of the plasma-facing components, i.e. maximum power load of 10 MW/m² at the surface of the actively cooled tungsten monoblocs. To reduce these power fluxes gas seeding scenarios are applied to cool the plasma and remove momentum, which leads to a so-called detached plasma state inside the divertor of the tokamak. The detached plasma state is governed by particle recycling and ion-neutral friction in the near surface plasma, leading to cooling and temperature gradients along the magnetic field lines [1]. At temperatures below 1 eV, volume recombination processes will participate in the reduction of ion flux to the target. However, detailed understanding of the involved mechanisms is still missing and given that DEMO will put much more stringent demands on the divertor

power exhaust, reliable predictions of divertor operation are mandatory [2]. To investigate these conditions in detail, this research will be carried out in the high-flux linear plasma generator Magnum-PSI [3], unique in its ability to produce ITER-relevant divertor plasma conditions, characterized by a very high plasma density (10^{18} m^{-3} – 10^{21} m^{-3}), while providing excellent diagnostic access.

The focus of the current work is to provide a full picture of the electron and ion properties of the near-surface plasma in an ITER-relevant divertor regime through detailed diagnosis, and to deliver input for modelling. All available diagnostics will be deployed for this purpose, including an upgraded collective Thomson scattering (CTS) for unambiguous measurement of the ion properties. The CTS diagnostic was developed and tested at the forerunner of Magnum-PSI, Pilot-PSI [4].

Sheath and presheath research require TS and CTS measurements close to the surface, and sets extreme demands on stray light suppression, which is one of the biggest challenges for these diagnostics. Simultaneously a minimum measurable electron temperature of 0.2 eV is required, which makes it even more difficult to comply to these demands.

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In Sect. 2 a brief overview of the linear plasma generator Magnum-PSI will be given, followed by Thomson scattering theory treated in Sect. 3. In Sect. 4 the systems will be described, which are used for the linear plasma generators in DIFFER, as well as the applied instrumentation for stray light suppression. In Sect. 5, the capabilities will be demonstrated with some example measurements, finalized by a summary.

High Flux Linear Plasma Generator Magnum-PSI

Magnum-PSI (see Fig. 1) [3] is built for plasma-surface interaction studies under high particle fluxes and for developing alternative power exhaust schemes such as for example liquid metal divertor configurations. Magnum-PSI consists of a cascaded arc source [5], a superconducting magnet with a bore diameter of 130 cm that can generate an axial magnetic field of up to 2.5 T and an advanced target manipulator arm that allows for plasma incidence angles from 90° down to angles as small as 3° (the angle between inclining magnetic field and surface) for mimicking ITER divertor conditions at the divertor plates. Materials can be exposed to stationary plasma fluxes of up to $10^{25}/\text{m}^2\text{s}$ and transient plasma pulses (duration typically 0.5–1 ms) corresponding to ELM-like power loads of max $1 \text{ GW}/\text{m}^2$. In the latter case a pulsed current of up to 2 kA was superposed on the base current (typically 100–200 A) of the cascaded arc source [6]. The electron density and temperature can reach values up to $2 \times 10^{21} \text{ m}^{-3}$ and 7 eV (pulsed: $6 \times 10^{21} \text{ m}^{-3}$, 15 eV), respectively. The cascaded arc source consists of a tungsten cathode, a stack of five water-cooled metal floating plates and an anode that forms a 30–50 mm long discharge channel. The pressure inside

Fig. 1 Linear plasma generator Magnum PSI. Inside the target exchange and analysis chamber, targets are mounted on a target manipulator (length 5 m) to insert the targets in the plasma exposure chamber, which is located within the superconducting magnet

the source is approximately 10^4 Pa at gas flows in the range of 4–7 SLM.

In addition, Magnum-PSI is equipped with a high-power Nd:YAG laser (LASAG FLS 352-302) for generating thermal heat pulses of 0.1–3 ms, corresponding to transients of approximately $1 \text{ GW}/\text{m}^2$, during plasma exposure.

To minimize recombination losses of the plasma beam a low background pressure is maintained between 0.1 and 0.5 Pa. For this purpose differential pumping between the source and target exposure chamber is applied with a total effective roots blower pump capacity for hydrogen of about $60,000 \text{ m}^3/\text{h}$.

These capabilities discerns Magnum-PSI from its forerunner Pilot-PSI, which was equipped with a conventional pumping system and copper coils for generating the axial magnetic field.

The electron density (n_e) and temperature (T_e) were measured by Thomson scattering in front of the source and at variable distance from the target (see Fig. 2) [7]. For measuring the heat load on the target, calorimetry is applied together with infrared thermography. The latter was performed by measuring the surface temperature by a fast IR camera (FLIR SC7500MB) and a SpectroPyrometer (FAR, model FMPI) combined with material heat conductivity calculations. Emission spectroscopy was used for monitoring of impurities as well as plasma velocity measurements (Doppler shift) [8].

In Fig. 2 the obtained parameters for stationary plasma are shown. On March 21 2018, Magnum-PSI set a new world record for longest plasma exposure of tungsten plasma facing components [9]. The achieved plasma

Fig. 2 n_e and T_e values in the beam center as function of magnetic field (Lines of constant ion flux (solid) and power flux (dashed)). For stationary plasma power fluxes of up to $q = 50 \text{ MW}/\text{m}^2$ are achieved [3]

fluence, realized in only 18 h, is equivalent to a full year of high power fusion operations in ITER.

Thomson Scattering

Thomson scattering is a nonintrusive diagnostic method for measuring unambiguously n_e and T_e of a plasma. 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 [10–13]. 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. Scattering of an electromagnetic wave from a plasma volume, containing randomly distributed electrons will result in cancelation of the measured electric field ($E_j \propto \exp[-i\phi_j]$, with j the electron indices and ϕ_j the phase of the scattered wave), i.e. each phase is present at the detector. However, the number of particles in this volume is governed by Poisson statistics, which means that the electric field will originate from pure electron density fluctuations. Therefore, the measured E-field strength at the detector is proportional to $\sqrt{N}$, with N the number of electrons, resulting in a scattered light intensity that scales linearly with N .

A polarized electromagnetic wave $\mathbf{E} = \hat{\mathbf{i}}E_0e^{i(k_0r_j - \omega_0t)}$ incident on *one* electron (see Fig. 3) causes an acceleration of that electron according to

$$\dot{\mathbf{v}}(t) = \hat{\mathbf{i}} \frac{e}{m_e} \left[E_0 e^{i(k_0r_j - \omega_0t)} \right] \Big|_{t'=t-\frac{R}{c}} \quad (1)$$

The dipole electric field E received by the observer s is given by

Fig. 3 An electromagnetic wave (wave vector $\mathbf{k}_0$, frequency ω_0) is incident on a moving electron (index j , velocity $\mathbf{v}$). The electron will accelerate along polarization vector $\mathbf{E}_0$. The electron is located at position $\mathbf{r}_j$. The observer is located at position $\mathbf{R}$ ($|\mathbf{r}| \ll |\mathbf{R}|$)

$$\mathbf{E}_s(\mathbf{R}, t) = -\frac{e^2}{4\pi\epsilon_0 c^2} \left[\frac{1}{R} \hat{\mathbf{s}} \times (\hat{\mathbf{s}} \times \dot{\mathbf{v}}(t')) \right] \Big|_{t'=t-\frac{R}{c}} \quad (2)$$

Note that, to find the field at the detector, we have to evaluate $d\mathbf{v}/dt$ a later time t at the detector, which is related to the earlier time t' at the electron as $t' = t - \frac{|\mathbf{R}-\mathbf{r}(t')|}{c}$. The term $|\mathbf{R}-\mathbf{r}(t')|$ is replaced by S for simplicity. S is approximately equal to $|\mathbf{R}|$, because $|\mathbf{r}(t')| \ll |\mathbf{R}|$ (see Fig. 3).

Inserting Eq. 1 and the formula for the classical electron radius $r_e = \frac{1}{4\pi\epsilon_0} \frac{e^2}{m_e c^2}$ in Eq. 2 gives the electric field at the detector originating from *one* electron:

$$\mathbf{E}_s(\mathbf{R}, t) = r_e \left(\frac{E_0}{R} \sin(\psi) \right) \left[e^{i(k_0r_j - \omega_0t)} \right] \Big|_{t'=t-\frac{R}{c}} \quad (3)$$

Here we used the fact that $\hat{\mathbf{s}} \times (\hat{\mathbf{s}} \times \dot{\mathbf{v}}(t'))$ describes dipole radiation, and thus $\sin(\psi)$ [14] is used instead. In Fig. 4 it is shown that the E-field is at maximum when the detector is located at $\psi = 90^\circ$.

The power radiated by an ensemble of electrons is given by the pointing vector $\mathbf{P}_s = \frac{1}{\mu_0} [\mathbf{E}_s \times \mathbf{B}_s] = \epsilon_0 c |\mathbf{E}_s|^2$ and the time averaged power emitted through surface $S^2 d\Omega$ assuming $R \sim S$ gives the differentially radiated power

$$\begin{aligned} \frac{d\mathbf{P}_s}{d\Omega} &= \epsilon_0 c \overline{|\mathbf{E}_s|^2} = \frac{1}{2} \epsilon_0 c r_e^2 (\hat{\mathbf{s}} \times (\hat{\mathbf{s}} \times \mathbf{E}_0))^2 \\ &= \frac{1}{2} \epsilon_0 c r_e^2 E_0^2 \sin^2(\psi) \end{aligned} \quad (4)$$

Dividing Eq. 4 by the power of the incident beam $P_{inc} = \frac{1}{2} \epsilon_0 c E_0^2$ gives the differential cross section for TS:

$$\frac{d\sigma_T}{d\Omega} = r_e^2 \sin^2(\psi) \left(\text{maximum } \frac{d\sigma_T}{d\Omega} = 7.94 \times 10^{-30} \text{ m}^2 \text{ sr}^{-1} \right) \quad (5)$$

The dimensions of the observed scattering wave characterized by k ($k = |\mathbf{k}| \frac{4\pi}{\lambda_0} \sin(\frac{\theta}{2})$) is given by $2\pi/k$, wherein λ_0 is the laser wavelength, θ the scattering angle between incident wave ($\mathbf{k}_0$) and scattered wave ($\mathbf{k}_s$) (see Fig. 3). The ratio between the size of the observed wave and the Debye

Fig. 4 Polar plot of emitted radiation. The TS radiation pattern is like a dipole, perpendicularly to the laser polarization the highest TS signal can be expected

length λ_D ($\lambda_D = \sqrt{\frac{\epsilon_0 k_B T_e}{e^2 n_e}}$) is the so-called scattering parameter α ($\alpha = \frac{1}{k\lambda_D}$).

If $\alpha \ll 1$ then the individual electrons can be observed (see Fig. 5), and the measured spectrum will resemble the velocity distribution of the electrons, which will have a Gaussian shape for a Maxwellian velocity distribution. The width of the spectrum represents T_e and the integral of the full Gaussian corresponds to n_e .

If α is close to 1 or higher the electron density fluctuations on the scale of the Debye length can be observed, this method is called collective Thomson scattering (CTS) (see Fig. 6). The electron density fluctuations correlated with the movement of the ions can be detected, i.e. the ion temperature and ion velocity can be measured.

Because the scale difference in velocity between ions and electrons is large, the Salpeter approximation [11, 15] can be applied describing the TS form factor $S(k, \omega)$ of the observed scattering spectrum as the sum of two separate contributions, the so-called electron feature and ion feature:

$$S = S_e + S_i = S(k, \omega) d\omega$$

$$\cong \frac{1}{\sqrt{\pi}} \Gamma_\alpha(x_e) dx_e + Z \left(\frac{\alpha^2}{1 + \alpha^2} \right)^2 \frac{1}{\sqrt{\pi}} \Gamma_\beta(x_i) dx_i \quad (6)$$

with $x_{e,i} = \Delta\omega/\omega_{e,i} = \Delta\omega/kv_{e,i}$ the normalized wavelength with $v_{e,i} = \sqrt{\frac{2k_B T_{e,i}}{m_{e,i}}}$ the average thermal speed of the particles.

Here is

$$\Gamma_\alpha(x_e) = \frac{\exp(-x_e^2)}{|1 + \alpha^2 w(x_e)|^2} \quad (7)$$

$$\Gamma_\beta(x_i) = \frac{\exp(-x_i^2)}{|1 + \beta^2 w(x_i)|^2} \quad (8)$$

$$\beta = \sqrt{Z \left(\frac{\alpha^2}{1 + \alpha^2} \right) \frac{T_e}{T_i}} \quad (9)$$

Z is the effective charge of the ions, the values are obtained from [16] and are in the range of 1–1.2 for these low temperature plasmas.

Fig. 5 Schematic presentation incoherent TS

Fig. 6 Schematic presentation CTS

The plasma dispersion function $w(x_{e,i})$, is tabulated by [17] and is described by a real $Rw(x_{e,i})$ and the Landau damping term $Iw(x_{e,i})$:

$$Rw(x_{e,i}) = 1 - 2x_{e,i} \exp(-x_{e,i}^2) \int_0^{x_{e,i}} \exp(p^2) dp \quad (10)$$

$$Iw(x_{e,i}) = -\sqrt{\pi} x_{e,i} \exp(-x_{e,i}^2) \quad (11)$$

The first term of Eq. 6 describes the electron feature: if $\alpha \ll 1$, the spectrum will resemble a Gaussian shape if the plasma exhibits a Maxwell electron velocity distribution. For understanding the dynamics, the denominator of this term can be written out and assuming that $\alpha < 0.1$, we can neglect the term with α^4 and imaginary term, giving:

$$S_e(k, \omega) \approx \frac{1}{\sqrt{\pi}} \frac{\exp(-x_e^2)}{1 + 2\alpha^2 Rw(x_e)} \quad (12)$$

Because the Rw has the highest value at $x_e = 0$ (zero Doppler shift), we can consider the case, where the influence on the spectral shape is max. It can be deduced that even if n_e varies a factor 2, the shape (amplitude) of the spectrum will vary less than 2%. This shows also the low sensitivity for n_e , in case the full electron feature will be used, it is recommendable to fit the electron feature as function of wavelength and α . But for $\alpha < 0.1$, one can neglect the second part of the denominator and the shape of the spectrum is given by a pure Gaussian. For large α , the

Fig. 7 Electron feature spectrum as a function of normalized wavelength x_e , for different α values

denominator will come in, and all the beforehand described effects are summarized in Fig. 7.

If α becomes significant (close to 1 or higher) the contribution of the electron feature (see Eq. 6) will diminish and mainly scattering from the electrons correlated with the ions S_i becomes dominant and is given by

$$S_i(k, \omega) d\omega \approx \frac{1}{\sqrt{\pi}} Z \left(\frac{\alpha^2}{1 + \alpha^2} \right)^2 \frac{\exp(-x_i^2)}{(1 + \beta^2 R w(x_i))^2 + (\beta^2 I w(x_i))^2} dx_i \quad (13)$$

If $T_e \ll T_i$ then $\beta \ll 1$, i.e. the spectrum will resemble a Gaussian shape, i.e. in case of a Maxwellian ion velocity distribution T_i can be obtained from the spectral shape (see Fig. 8).

The dynamic behavior of Γ_β (Eq. 8) can be shown by the following assumptions: $\alpha \sim 1$, $Z = 1$ and $T_e \approx T_i$. In that case $\beta \sim 0.7$, which means that the shape of the ion feature is mainly determined by the ratio of the exponential function and the real part of the plasma dispersion function in the denominator of $\Gamma_\beta(x_i)$. Because the real part is highest at $x_i = 0$, this will result in a flattened Gaussian (see Fig. 8). For $T_e > T_i$ ion acoustic resonances become dominant marked by peaks in the periphery of the spectrum. Macroscopic velocities of the plasma can be determined from the Doppler shift of the spectrum of the ion feature [18]. The zero Doppler shift reference can be obtained from Rayleigh scattering.

For plasma conditions where $\alpha > 0.8$ (operational range for CTS in linear plasma generators $n_e \sim 0.4\text{--}1 \times 10^{21} \text{ m}^{-3}$ and $T_e \sim 1.4\text{--}3 \text{ eV}$), the contribution of the ion feature S_i is significant: $> 11\%$ of that of $S_e(\alpha = 0)$ and 36% for $\alpha = 2$. The ion feature becomes visible as a narrow peak superimposed above the much wider electron feature.

Fig. 8 Ion feature as function of normalized wavelength x_i

TS and CTS Pilot-PSI and Magnum-PSI: Performance and Instrumentation

Two examples showing the capabilities of TS and CTS systems in Magnum-PSI and Pilot-PSI are reported in this section.

TS in Magnum-PSI

During normal Magnum-PSI operation TS is performed every 3 s at about 30 mm distance from the target surface. TS can be used also at the plasma source location to monitor the upstream plasma flux. During the TS measurements signal from 30 laser pulses (each 0.4 J) are accumulated for measuring n_e and T_e profiles [7]. Single pulse TS measurements are also applied for measuring these profiles for high density transient plasma pulses (1 ms). The observational error is less than 10% in n_e . Minimum measurable temperature $< 0.1 \text{ eV}$. Very low stray light levels of typically 10% of the amplitude of the TS signal (very localized at the center of the spectrum), are obtained by collimating the stray light originating from the laser injection window (apertures shown in Fig. 9) [7, 19] and by excellent laser and stray light dumping in the dump tube applied (Fig. 10) for minimizing back reflected light. In addition at the opposite side of the viewing systems (insert Fig. 10) of the Magnum-PSI vessel a viewing dump is applied, such that the amount of vessel stray light entering the viewing system is negligible.

For normal Magnum-PSI operation the standard stray light reduction measures allows for TS measurements with negligible stray light contribution. However, sheath studies require TS measurements within the electrostatic pre-

Fig. 9 Laser stray light collimation system. The subcritical aperture is located at safe distance from the plasma. Stray light originating from the input window is collimated by the critical aperture, such that the stray light cone diameter is minimized at the entrance of the output tube. The resulting stray light from the edges of the critical aperture is collimated by the subcritical aperture and is dumped also in the output tube [7]. The dashed line depicts the center of the observation area, located at the laser beam waist

Fig. 10 Schematic view of TS and CTS beam lines in Magnum-PSI. The viewing systems for 2 locations are shown. The viewing dumps (not shown) are located at the same section, but at opposite side of the vessel

sheath of the near surface plasma, at distances less than 2 mm.

To cope with the extreme stray light levels, inherently reflected from target surface and edges, a stray light blocking system is applied inside the spectrometer [7, 20]; a mask of appropriate width is inserted at the location of the intermediate image (see Fig. 11), the stray light could be reduced by at least four orders of magnitude enabling TS measurements as close as 1.9 mm distance from the target surface. The obtained stray light reduction is 4 orders of magnitude, even better suppression is achievable by using a wider mask, at the cost of minimum measurable temperature.

These capabilities were demonstrated in Magnum-PSI [20], T_e and n_e profiles were measured as function of

distance relative to the target surface. Despite of the application of a 0.5 mm wide mask (equivalent spectral mask width ~ 0.3 nm), a minimum measurable temperature of 0.2 eV was still feasible. In Fig. 12 a recorded image is shown. The fiber modulation is recognisable, every fiber corresponds to a radial position in the plasma, the hot lip structure resembles the plasma temperature, warm in the center and cold at the edge of the beam, from this image a T_e and n_e profile can be extracted. In Fig. 13 these profiles are shown.

It can be seen that as a function of distance to the surface the bulk T_e and n_e drop monotonically when approaching the surface. It is thought that this density decay is caused

Fig. 11 Schematic picture of Magnum-PSI TS spectrometer [7, 20]

Fig. 12 Image of a typical TS measurement $n_e \sim 5 \times 10^{20} \text{ m}^{-3}$. It can be seen that the laser stray light at 532 nm is cut out. The residual stray light entering the spectrometer was removed by subtracting a recorded stray light image (measurement in empty vessel) [20]

Fig. 13 Radial Thomson scattering profiles of electron density (left) and temperature (right), obtained during a steady state hydrogen discharge in Magnum-PSI: $B = 1.2$ T, discharge current $I = 175$ A,

by plasma acceleration [20]. The drop in T_e might arise from the interaction of incoming plasma and recycled neutrals within the presheath region [20].

CTS in Pilot-PSI

The CTS diagnostic [4, 10] was developed on the Pilot-PSI linear plasma generator (was shut down end 2015), the forerunner of Magnum-PSI (see Fig. 14). It consisted of a wall-stabilized DC cascaded arc, which produced a high flux plasma beam consisting of hydrogen, deuterium, helium, neon, argon or mixtures. The typical plasma conditions are a discharge current of 200 A, gas flow 2.5 slm and an axial magnetic field of 1.2 T to confine the plasma that interacts with a tungsten target located 560 mm downstream the source.

Fig. 14 CTS beam line and detection in Pilot-PSI [4]

gas flow 7:0 slm and background pressure 1 Pa. The colors of the profiles represents the distance between TS and target surface location [20]

The CTS laser system is equipped with a 10 Hz seeded laser (Continuum DLS 8000: pulse width of 7 ns FWHM, 1 J/pulse and linewidth 0.3 pm at 1064 nm) [4]. The location of the CTS scattering volume (beam waist ~ 0.8 mm) coincided with that of the standard incoherent TS system (532 nm, scattering angle 90°) [21]. At 1064 nm α was close to 1 or higher for the plasma conditions of interest, while still permitting the use of optical detection systems with excellent signal to noise specifications. The wavelength is also chosen such that laser plasma heating due to inverse Bremsstrahlung (for $T_e > 1$ eV proportional to wavelength to the second power [22]) is negligible.

The CTS laser beam (see Fig. 14) was coupled into the laser beam line of the standard TS laser beam line by using a dichroic mirror (transmission for 532 nm and 90° reflection for 1064 nm), allowing for simultaneous TS and CTS measurements. The different scattering angles and laser wavelengths of both systems assured that the α value for TS is about 5.5 times lower than that for CTS.

Vessel stray light was mitigated by using a viewing dump at the opposite side of the viewing system (bottom vessel) and by assuring that the viewing system could not receive direct laser light scattered from the apertures located inside the laser injection system.

The Doppler broadened light was collected at a scattering angle of 30° (see Fig. 14, position scattering volume 40 mm downstream plasma source) and features a viewing system with an effective solid angle 1.9×10^{-3} sr. The collected light was relayed by a fiber bundle to a spectrometer (spectral range 1.9 nm, spectral resolution 0.0165 nm) equipped with an Echelle grating operating at the blaze angle. A special LIVAR M506 EB-camera (EBABS technology, Electron Bombarded Active Pixel Sensor) was used, which exhibited an effective quantum efficiency of about 25% at 1064 nm. Background plasma

light was suppressed by using a 200 ns detection gate window.

The CTS system was applied for measuring the rotational velocity of the plasma beam. The alignment of the scattering volume (chord length 2 mm) could at that time not be carried out accurately, which resulted in a radial alignment uncertainty of 1–2 mm relative to the plasma center. This implies that for positions above and below the plasma center, artificially reversed rotational velocities were observed [4].

For fitting the CTS data the ion feature equation (Eq. 13) (using an analytical approximation for the real part of the plasma dispersion function [23]) was used and convolved with the instrument function of the spectrometer. Fitting parameters were T_i , β , Doppler shift and signal amplitude. T_e and n_e (error bar 8% and 4%, respectively) were measured independently and simultaneously by the incoherent TS system to obtain α .

To assure low stray light levels, a viewing dump was installed at opposite side of the viewing system. In addition, a metal strip was inserted, that avoided a direct line-of-sight observation of reflected light from the laser apertures.

In Figs. 15, 16 and 17 ion feature spectra are shown that were measured with CTS in stationary plasmas. The signal was obtained by averaging CTS signal from 50 laser pulses (5 s). The vertical dashed line in the figures marks the wavelength position of the laser (zero Doppler shift), measured by Rayleigh scattering. In Fig. 18 results are shown of CTS performed on a pulsed plasma generated in Pilot-PSI, which exhibited a very high n_e of $6.2 \times 10^{21} \text{ m}^{-3}$. Note that the electron feature signal cannot be observed, because this spectrum will be smeared

Fig. 15 Measured spectrum of ion feature in stationary Ne plasma. Dashed line: laser wavelength position. Rotational velocity: 600 m/s (-1 pm), $n_e = 2.71 \times 10^{21} \text{ m}^{-3}$ [4]

Fig. 16 Measured spectrum of ion feature in stationary D plasma. Dashed line: laser wavelength position. Rotational velocity: -4300 m/s (7.7 pm), $n_e = 2.04 \times 10^{21} \text{ m}^{-3}$ [4]

Fig. 17 Measured spectrum of ion feature in stationary H plasma. Dashed line: laser wavelength position. Rotational velocity: $10,400 \text{ m/s}$ (-18.2 pm), $n_e = 1.06 \times 10^{21} \text{ m}^{-3}$ [4]

out due to its ~ 43 times ($\sqrt{m_i/m_e}$) wider spectrum relative to that of hydrogen ions.

The spatial resolution of the system was 2 mm and due to this relatively long sample length, rotational velocity smoothing effects were to be expected; the plasma exhibits steep rotational v_{plasma} gradients [8] giving an indicative smoothing effect of $\sim 4000 \text{ m/s}$ for hydrogen, i.e. $\sim 7 \text{ pm}$.

The measured velocities indicated in Figs. 16, 17 and 18 are significant, which means that the scattered signal is observed a few millimeter off-axis of the plasma (in the center the rotational v_{plasma} is negligible). The accuracy of velocity determination, the shift is remarkably well visible

Fig. 18 Measured spectrum of ion feature in a pulsed D plasma. Dashed line: laser wavelength position. Rotational velocity: 5800 m/s (-10.3 pm), $n_e = 6.2 \times 10^{21} \text{ m}^{-3}$ [4]

by eye, is better than 10% for $v_{\text{plasma}} > 4000$ m/s, although it is here an averaged value. For T_i determination the accuracy is determined by Poisson statistics, but also by the mentioned velocity smoothing effect, which results in an accuracy of about 25%.

The width of the spectrum for Ne (Fig. 15) was close to that of the spectrometer instrument function, resulting in an error bar of $> 50\%$. In Fig. 16 the shape of the fitted curve of the ion feature of the D plasma resembles closely the calculated curve, for $T_e \sim T_i$ shown in Fig. 8. Because at these high densities the electron–ion relaxation time is extremely short, it is expected that $T_e \sim T_i$. Comparison of Figs. 15, 16 and 17 shows clearly that the width of the ion feature spectra is dominated by the mass of the species of the plasma, which demonstrates the ability to distinguish between different species in plasma mixtures [18, 24].

Summary and Outlook

In summary, despite of the extreme challenges concerning stray light, but on virtue of the applied stray light blocking system excellent near surface measurements could be performed in Magnum-PSI, allowing for measurements in the electrostatic pre-sheath as close as 1.9 mm.

T_i , T_e , n_e and the rotational plasma velocity were measured in Pilot-PSI by a combination of an incoherent TS system and a novel CTS system. In addition it has been shown that the different masses of the plasma species can be distinguished. The measured CTS velocities and ion temperatures are comparable with those determined by Doppler emission spectroscopy (OES) of the H_β radiation [8]. Nevertheless, dedicated simultaneous measurements

with OES and CTS will be performed in the future for validation purposes.

Currently the CTS system for Magnum-PSI is configured such that the CTS scattering plane is parallel to the magnetic field, i.e. only velocity components parallel to the magnetic field will be measured where only gentle axial velocity gradients are present, which makes smearing effects negligible. This is being deployed in Magnum-PSI for the study of plasma properties close to a plasma-exposed surface, and first results will be published in 2020.

Finally it can be noted that is in principle a good measurement technique for measuring T_i and v_{plasma} in the ITER divertor plasma [25]; up to date there is no good technique available for this task.

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