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Advanced Thomson scattering system for high-flux linear plasma generator

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An advanced Thomson scattering system has been built for a linear plasma generator for plasma surface interaction studies. The Thomson scattering system is based on a Nd:YAG laser operating at the second harmonic and a detection branch featuring a high etendue ($f/3$) transmission grating spectrometer equipped with an intensified charged coupled device camera. The system is able to measure electron density (n_e) and temperature (T_e) profiles close to the output of the plasma source and, at a distance of 1.25 m, just in front of a target. The detection system enables to measure 50 spatial channels of about 2 mm each, along a laser chord of 95 mm. By summing a total of 30 laser pulses (0.6 J, 10 Hz), an observational error of 3% in n_e and 6% in T_e (at $n_e = 9.4 \times 10^{18} \text{ m}^{-3}$) can be obtained. Single pulse Thomson scattering measurements can be performed with the same accuracy for $n_e > 2.8 \times 10^{20} \text{ m}^{-3}$. The minimum measurable density and temperature are $n_e < 1 \times 10^{17} \text{ m}^{-3}$ and $T_e < 0.07 \text{ eV}$, respectively. In addition, using the Rayleigh peak, superimposed on the Thomson scattered spectrum, the neutral density (n_0) of the plasma can be measured with an accuracy of 25% (at $n_0 = 1 \times 10^{20} \text{ m}^{-3}$). In this report, the performance of the Thomson scattering system will be shown along with unprecedented accurate Thomson-Rayleigh scattering measurements on a low-temperature argon plasma expansion into a low-pressure background. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4768527>]

I. INTRODUCTION

The tokamak ITER¹ is presently under construction and aims at producing 10 times more fusion power than the external heating power. A very important, unresolved issue is the fact that 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 and transient loads (~ 1 ms) caused by edge localized modes of more than 1 GW/m².

This paper deals with the divertor simulator Magnum-PSI (Magnetised Plasma Generator and NUmerical Modeling for Plasma Surface Interaction)² for materials testing with very large output power (up to 40 MW/m²) and ion and radical fluxes ($4 \times 10^{24} / \text{m}^2 \text{ s}$). The development of new materials which can withstand high heat fluxes and high fluxes of radicals in a chemically aggressive atmosphere is also essential in many new technologies as for new energy sources, in anti-abrasive and anti-corrosive applications and for space re-entry purposes.³

Magnum-PSI, will be equipped with a superconducting magnet that can generate an axial magnetic field of maximum 2.5 T. The machine is temporarily equipped with a conventional coil system that generates a magnetic field of up to

1.9 T. A wall-stabilized cascaded arc produces a 100 mm diameter hydrogen, argon or helium plasma jet;⁴⁻⁶ it can be operated continuously or in pulsed mode. The first generation sources (45 kW) generate a power density of 40 MW/m² corresponding to an ion flux of $\Gamma = 1 \times 10^{21} \text{ s}^{-1}$ within a diameter of 2 cm at the target. The electron density and temperature of the plasma can reach values above $5.0 \times 10^{21} \text{ m}^{-3}$ and 5 eV, respectively.

The plasma jet is confined by an axial magnetic field and is transported over a distance of about 1.5 m to a target. Three roots blower stages (total pump capacity 52 500 m³/h) are implemented and a skimmer between source and target chamber allows for differential pumping; this is necessary to maintain a low ambient pressure (~ 1 Pa) during high particle and energy flux generation.

Optical emission spectroscopy is applied to measure impurity concentrations and plasma velocity (using the Doppler shift of an atomic line). ITER relevant diagnostics like laser induced desorption spectroscopy (LIDS),⁷ laser induced ablation spectroscopy, and laser induced breakdown spectroscopy (LIBS) are under development on Magnum-PSI.

In this paper, an incoherent Thomson scattering (TS) system is described that will be used as a control tool for the plasma conditions. The construction of the TS system for Magnum-PSI has been finished and first experiments have been performed. The application of a laser injection system

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with efficient stray light reduction aperture system and a detection system consisting of a high f -number ($f/3$) high spectral resolution transmission grating spectrometer has shown to result in extremely low electron density and temperature limits of below $1.0 \times 10^{17} \text{ m}^{-3}$ and 0.07 eV, respectively. A fiber bundle (length 40 m) based detection system allows for sampling of 50 spatial channels of about 2 mm each. In addition, the 35 m long laser beam line is fully remotely controllable by using piezo-based actuators combined with a video camera system. A global description and design requirements of the TS system are given in Sec. II. The laser beam line and the detection branch are described in Secs. III and IV, respectively. The system performance is reported in Sec. V, and finalized in Sec. VI with measurements on an argon plasma expansion in the absence of a magnetic field. In Sec. VII, the results are summarized and discussed.

II. DESIGN REQUIREMENTS AND GENERAL DESCRIPTION

The central part of Magnum-PSI consists of the source chamber (vessel diameter 600 mm), on which the cascaded arc plasma source is mounted, and the target chamber (vessel diameter 500 mm) that hosts the target during plasma exposure (see Figure 1). Both chambers are placed within the inner bore of a superconducting magnet. In the same figure, the TS laser beam lines are shown. The laser beam lines reach source and target chamber through diagnostic ports in the vessel of the superconducting magnet. Thomson scattering is the most accurate method for measuring n_e and T_e of a plasma.^{8,9} The design requirements and general description for this TS system are given here.

The laser room of Magnum-PSI and the Magnum-PSI machine are located in different parts of the laboratory. This requires a 34 m long laser beam line that has to be controlled remotely since, during operation, the entrance to the Magnum-PSI hall is limited for safety reasons. The magnetic stray field can be up to 1 T close to the magnet and multiple lasers are operating simultaneously in the Magnum-PSI hall.

For maintenance purposes, the magnet of Magnum-PSI is mounted on a rail system that allows for a translation along its axis. In case the magnet has to be translated, laser injection and dump tubes that penetrate the magnet have to be removed within a few hours. Moreover, coupling and decoupling of the tubes have to be done from outside the magnet. Both these requirements set high demands on the mechanical design.

TS can be performed at two locations. First, close to the cascaded arc output, to determine the plasma conditions before the actual exposure (in which case a plasma dump is inserted between source and target). Second, just in front of the target, to measure the plasma conditions during plasma exposure.

To allow for quasi-real time monitoring of the plasma jet conditions, the TS system has to provide every 10 s T_e and n_e profiles. Because there is also time required for camera read-out and data acquisition, the recording time (time required for accumulation of the scattered light) is set to 3 s. The TS system can also be applied for dedicated research, in which longer recording periods can be used to achieve high accuracy, even at extremely low density.

The accuracy of the Magnum-PSI TS system should at least be equal to that of the TS system that operates at the forerunner of Magnum-PSI, the linear plasma generator Pilot-PSI,¹⁰ i.e., accuracies of 3% and 6% for n_e and T_e ,

FIG. 1. The 34 m long TS laser beam line together with the target chamber and source chamber of Magnum-PSI. The laser beam alignment is monitored by cameras and controlled by mirror mounts equipped with piezo-based actuators.

respectively. It should be noted that Magnum-PSI can generate low and high power loads on the target and that n_e may vary by three orders of magnitude. Furthermore, the plasma diameter will be about three times larger than that of Pilot-PSI, i.e., a laser chord of 90–100 mm length is required. In addition, at Magnum-PSI, the need arose to investigate the plasma at the edge of the jet, where T_e can be even below 0.1 eV. These requirements together set the minimum measurable n_e and T_e to $n_e < 10^{18} \text{ m}^{-3}$ and $T_e < 0.1 \text{ eV}$. The maximum measurable T_e should be $T_e > 7 \text{ eV}$.

As in tokamaks, a low background density of molecular hydrogen is essential to avoid beam particle losses due to anomalous recombination of ions by molecular exchange processes as molecular activated recombination.^{5,11} Thus, neutral density (n_0) profile measurements are essential to verify the design of the vacuum system of Magnum-PSI; differential pumping is used to reduce the neutral density near the target. The TS system should allow for n_0 measurements for $n_0 > 10^{20} \text{ m}^{-3}$; this sets high demands on plasma and stray light reduction as well as on the dynamic range of the detector.

The spatial resolution of the system is chosen to be about 2 mm; this is excellent for distinguishing the different gradients in the n_e , T_e , and n_0 profiles.

III. LASER BEAM LINE

Most laser beam line components of the 34 m long TS laser beam line are mounted on the concrete floor of the Magnum-PSI hall for good stability. For this reason, the laser beams enter the Magnum-PSI vessel from below.

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 (diameter 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 h, stayed within a full angle of $17 \mu\text{rad}$. This implies that the laser, in combination with a $M = 4$ beam expander, can be pointed at one spot at a distance of 34 m for several hours with an accuracy of better than 0.15 mm. The beam expander reduces the laser beam divergence from 0.5 mrad to about 0.13 mrad. The resulting 38 mm diameter laser beam is guided from the laser room to the Magnum-PSI vessel by multilayer mirrors. After mirrors M3 and M5 (see Figure 1), 3.2 m plano-convex lenses are installed to focus the beam to a spot size of about 0.5 mm at the plasma centre. After passing the plasma, the beam is dumped via a top mirror on a laser dump. Mirror M3 is controlled by a pneumatic cylinder to enable TS in source and target chamber in an alternating way (switching period a few seconds).

A. Mechanical design and construction of the TS vacuum system

As described in Sec. II, the TS system should allow for fast dismounting from the Magnum-PSI machine. Therefore, a special mechanical vacuum coupling has been developed for the TS vacuum system. The vacuum tubes of the TS system can be coupled and decoupled to the Magnum-

FIG. 2. Remote coupling of the TS input tubes to the target and source chamber 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.

PSI vessel from outside the magnet. This is illustrated in Figure 2.

B. Laser 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. These windows, therefore, are mounted under the Brewster angle at the end of long vacuum tubes, at large distance from the plasma centre.

After the laser beam passes the Brewster input window (located at 165 cm below the plasma centre), the stray light from this window is first collimated by a so-called critical aperture of $\varnothing = 11 \text{ mm}$ (see Figure 3). A subcritical aperture of $\varnothing = 24 \text{ mm}$ collimates the stray light originating from scattering from the edges of the critical aperture. As a result, the stray light is collimated such that it entirely fits in the $\varnothing = 100 \text{ mm}$ output tube. The laser and stray light beams pass the output window, located at about 240 cm above the plasma centre, and are guided via a mirror onto a laser dump.

C. Alignment system

The laser beam line is remotely controlled by mirror units equipped with piezo-based actuators (PZA12, Newport). The mirror boxes feature an alignment utility that consists of a simple non-synchronized complementary metal oxide semiconductor camera that records the pulsed laser light (FWHM 12 ns) from a diffuser screen; a very small fraction of the laser beam that passes through the multilayer mirror. In this way, the position and shape of the main laser beam are measured real-time.

FIG. 3. Layout of the stray light reduction system used in the source chamber. Stray light from the entrance window is mainly collimated by an 11 mm diameter aperture at 63 cm below the plasma centre (at $z = 0$ mm).

IV. DETECTION BRANCH

For each TS location, the TS light originating from the corresponding laser chord is imaged onto a fiber array by a viewing system (see right inset of Figure 1). At the target location, a lens (AF Nikkor 85 mm $f/1.8D$) images the 95 mm long laser chord onto a linear fiber array of 59 fibers (40 m length, 26.7 mm input height, array format 59×1 ; CeramOptek UV400/424P). The magnification of the setup is $M = 0.267$, but can be enhanced in case Magnum-PSI is operated with a smaller diameter plasma beam. The viewing system at the source chamber has the same magnification as that of the viewing system used at the target chamber making use of another lens (AF DC-Nikkor 135 mm $f/2D$). For both locations, the size of the spatial elements in the plasma is about 2 mm and the viewing f -number is larger than $f/11$. The scattering angle along the full chord length varies between 84.7° and 95.3° , a variation that is taken into account in the data analysis.

A. High etendue spectrometer

The TS light collected by the viewing systems is relayed by the fiber bundles to the input of a transmission grating spectrometer. This spectrometer features a high etendue (with f -number of $f/3$) and high wavelength dispersion and is equipped with an ICCD camera (PI-max 1300, Princeton Instruments). The required fiber array is selected by a motorized fiber array exchanger (see Figure 4), combined with an entrance slit (25×0.6 mm²). The fiber arrays are curved to correct for spectral line curvature (see Sec. V A); 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 $>95\%$ between 515 and 545 nm) is placed at the entrance.

The high etendue spectrometer¹² is equipped with a holographic transmission grating. This allows collection of light with low vignetting values since the lenses can be installed

FIG. 4. Schematic top view of the spectrometer. A fiber exchanger enables selection between TS measurements in front of the target and close to the plasma source. For normal situations, the dispersed light is imaged directly onto the ICCD. In case the viewing dump in the target chamber is made non-functional, an intermediate image with a 532 nm mask (consisting of a 0.8 mm narrow black strip) will be applied.

very close to the grating. Transmission gratings feature a low stray light contribution, because they exhibit, in contrast to reflection gratings, a negligibly low number of micro-defects. Using the configuration shown in Figure 4, the detector cannot detect light originating from reflections at lens surfaces.

At the optical axes of the spectrometer, the dispersion of the light originating from the slit obeys in approximation the following grating equation:¹³

$$\frac{d\lambda}{dx} \approx \left(\frac{\lambda_0}{f} \right) \left(\frac{\cos \theta_2}{\sin \theta_1 + \sin \theta_2} \right). \quad (1)$$

Here, f is the focal length of the spectrometer lenses and λ_0 the central wavelength of the grating that determines the grating groove frequency

$$\nu = \frac{\sin \theta_1 + \sin \theta_2}{\lambda_0}. \quad (2)$$

The incident angle θ_1 and diffraction angle θ_2 are both about 61° and are defined as shown in Figure 4. Using these numbers a calculated average dispersion of about 0.4 nm/mm was found.

The dispersed TS light is imaged onto the filmless (Uni-gen II) photocathode (window antireflection coated) of the ICCD camera. The 25 mm diameter “Generation III” image intensifier is fiber optically coupled to a front-illuminated CCD (1340×1300 pixels, pixel size 20 μ m square, 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%.

Parasitic light from the laser is used to trigger the programmable timing generator (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.

TABLE I. TS system parameters.

Laser energy at the scattering volume integrated over 20 pulses including 85% beam line transmission	E_{laser}	$11 \pm 0.3 \text{ J}$
Typical measurement time (20 pulses at 10 Hz)		2 s
Solid angle at magnification $M = 0.267$ at viewing side.	Ω	$6.2 \times 10^{-3} \text{ sr}$
Length of scattering volume (corresponding to CCD pixels)	ΔL	$2 \times 10^{-3} \text{ m}$
Differential Thomson scattering cross section	$d\sigma_T/d\Omega$	$7.94 \times 10^{-30} \text{ m}^2/\text{sr}$
Differential Rayleigh scattering cross section (532 nm, Ar)	$d\sigma_R/d\Omega$	$5.4 \times 10^{-32} \text{ m}^2/\text{sr}$
Differential Rayleigh scattering cross section (532 nm, Ar ⁺)	$d\sigma_R^+/d\Omega$	$2.12 \times 10^{-32} \text{ m}^2/\text{sr}$
Transmission viewing system (including vessel window)	τ_{view}	0.86
Transmission fiber bundle including surface reflections	τ_{fiber}	0.84
Throughput spectrometer for average polarization (measured)	$\tau_{\text{spectrometer}}$	0.33
Transmission band pass filter including edge effects of the slit	η_{Bfilter}	0.85
Quantum efficiency image intensifier of ICCD including noise factor 1.6	η_1	0.2 at 532 nm
Quantum efficiency photocathode		0.5 at 532 nm
Conversion efficiency counts per photoelectron (counts/photoelectron)	S_{ICCD}	80
Transmission tandem lens coupling system (presently not installed)	τ_1	0.93
Spatial resolution ICCD (measured)		$< 35 \mu\text{m}$

B. Stray light reduction for the detection branch

To minimize the stray light originating from the opposite vessel walls, carbon viewing dumps are installed at the side opposing the viewing systems. In addition, the stray light originating from the output window (at 2.4 m distance from scattering volume) could be reduced by a factor 2 by switching the image intensifier gate window off, just before the stray light arrives. However, in case the target is oriented such that it blocks the line of sight to the viewing dump, a tremendous amount of stray light can enter the spectrometer. In case it is necessary, this problem can be solved by placing a mask at the output of the spectrometer to block the laser stray light (see Figure 4). A Rodenstock tandem lens system (f 95/1.2) can be used to relay the light from the intermediate image to the ICCD camera.

V. 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

$$\tau_{\text{overall}} = \frac{h\nu_0 S_{\text{Rayleigh}}}{S_{\text{ICCD}} E_{\text{laser}} \Delta L \Omega n_{\text{argon}} \eta_1 (d\sigma_R/d\Omega)}, \quad (3)$$

with the parameters as explained in Table I.

Rayleigh scattering was performed at an argon vessel pressure of $n_{\text{argon}} = 49.3 \text{ Pa}$. The measured Rayleigh signal S_{Rayleigh} integrated over multiple spatial elements with length $\Delta L = 6.8 \text{ mm}$ (96 CCD pixels in position direction) was determined. Substituting this value and the system parameters given in Table I in Eq. (3) results in an overall transmission of $\tau_{\text{overall}} = 0.20 \pm 0.03$.

A. Spectral and spatial resolution

The relatively large input slit produces a spectral line curvature in the detector plane. This is due to a path difference between rays originating from the outer vertical edges and the centre of the slit. This is compensated for by using

a curved slit at the entrance of the spectrometer. To test the spectral resolution and to perform a spectral calibration of the spectrometer, a semiconductor laser (532 nm) and a neon spectral lamp were simultaneously used to illuminate the input array of the fiber bundle. By translating the output fiber array in perpendicular direction relative to one of the entrance slit edges (partially blinding the fibers), the effective fiber width was reduced to about $20 \mu\text{m}$. As a result of the spectral calibration an average dispersion of $7.609 \times 10^{-3} \text{ nm/pixel}$ (0.38 nm/mm) was found (see Figure 5), and agrees quite well with the calculated value of 0.4 nm/mm given in Sec. IV A. At this setting, the spectral resolution is about 0.038 nm (5 pixels FWHM; see, for instance, neon line at 533.08 nm). The resolution of the image intensifier itself is about $35 \mu\text{m}$ (2 pixels), which means that the contribution of the lens system to the spectral resolution is small.

If for TS and Rayleigh scattering measurements the full width of the fiber array ($\sim 400 \mu\text{m}$) is used at the spectrometer

FIG. 5. A 532 nm semi-conductor laser and a neon lamp illuminated simultaneously the fiber array (output fiber width $\sim 20 \mu\text{m}$). The spectrum at spatial position pixel 510 shows from left to right the dominant lines 532 nm (even some laser modes are visible) and the neon lines: 533.08 nm, 534.11 nm, and 534.33 nm.

FIG. 6. (a) A 532 nm semi-conductor laser and a neon lamp illuminated simultaneously the input fiber array. The full fiber width ($400 \mu\text{m}$) was used. (b) Spectrum corresponding to a track at spatial position pixel 510 of the image shown in Figure 6(a).

entrance, the spectral resolution is about 0.137 nm (18 pixels FWHM); the spectral performance is shown in Figures 6(a) (image) and 6(b). This width corresponds to a minimum measurable temperature of about 0.06 eV (assuming a Maxwell-Boltzmann electron velocity distribution¹⁰) where it has been assumed that the smallest detectable line width is twice the spectral resolution. In addition, it can be seen in Figure 6(a) that the spectral line curvature is corrected for sufficiently. If about $270 \mu\text{m}$ of the fiber array is covered by the slit edge, the width of the instrumental line profile (broadening of the spectrum due to the spectrometer) is reduced to 8 pixels (0.063 nm). Note that the line width of the Nd:YAG laser of the TS system ($\sim 0.01 \text{ nm}$) is significantly narrower and is not taken into account. As a result, the minimum measurable temperature is reduced to a theoretical electron temperature of below 0.01 eV . This setting will be used for testing the T_e measurement accuracy, described in Sec. VI B. Given the spectral resolution, the spectral range of the spectrometer is 10.2 nm , which is sufficient to measure T_e up to 11 eV (assuming a half $1/e$ -width of 5 nm).

The spatial resolution of the detection branch was determined by measuring the resolution of the spectrometer and viewing system separately. A uniformly emitting light source (Labsphere, USS-800C-35R) was used for illuminating the fiber array at the viewing side; in this way the output fiber array, consisting of 59 fibers (fiber cores were interspaced by about $60 \mu\text{m}$, mainly due to the space required for cladding and jacket), could be used as a test object for the spectrometer. The resulting image, shown in Fig. 7(a), reflects in horizontal direction the broad Planck spectrum and vertically the modulation due to the individual fibers that are aligned in the output array. Note that, at the time of measurement, only 54 fibers were used; 5 fibers were blocked by a mount of the band pass filter. In Figure 7(b), a slice corresponding to wavelength pixel 750 is shown; it can be seen that the spatial resolution of the spectrometer is 24 pixels, mainly determined by the fiber size. This means that the spectrometer can measure maximum 54 spatial elements, each sampled by 24 pixels. The resolution of the viewing lens was found to be less than $60 \mu\text{m}$ (at magnification 0.267); five $70 \mu\text{m}$ diameter

FIG. 7. (a) Input fiber array was illuminated by a uniformly emitting light source. The individual fibers can be identified in the spectrum. (b) This is a slice corresponding to wavelength pixel 750.

pinholes, distributed over 100 mm object height, were used as test objects and imaged onto a CCD camera. As a result, due to this magnification and viewing system resolution, each $400\text{ }\mu\text{m}$ diameter fiber (at the viewing side) corresponds to a spatial element of about 2 mm at the location of the plasma.

B. Relative and absolute calibration

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

Rayleigh scattering on argon has been used to calibrate the absolute sensitivity of the TS system and also to check the alignment between the laser beam and the fiber array.

C. Influence of inverse bremsstrahlung

The detector system allows for measurements of electron temperatures even below 0.1 eV. However, the laser beam is focused to a spot size of about 0.5 mm, resulting in a power density of about 23 GW/cm^2 (2.8 MJ/m^2). At these power densities one has to take into account that electron heating could occur due to the process of inverse bremsstrahlung. Under the assumption that the heat is not conducted away during the laser pulse, the fractional increase in T_e can be calculated according to Ref. 14. Assuming an electron temperature of $T_e = 0.1\text{ eV}$ and an ion density of $n_i = 1.0 \times 10^{19}\text{ m}^{-3}$ (assuming $n_e = n_i$), a temperature rise of less than 1% is found at a laser wavelength of 532 nm. Hence, plasma heating by inverse bremsstrahlung is negligible. The chosen test ion density is realistic, because at the low test temperature the ionization degree of the plasma is very low. The calculated temperature rise is lower than the measurement accuracy of the TS system. Moreover, in Ref. 15 no temperature rise due to laser heating was found experimentally.

VI. PLASMA MEASUREMENTS

In order to demonstrate the capabilities of the TS system, the expansion properties of an argon plasma jet were measured in the absence of an axial magnetic field (see Figure 8). Currently, a provisional viewing dump was installed that reduces stray light for the radial positions between -50 mm and $+15\text{ mm}$.

First, the TS system was validated concerning accuracy in n_e and T_e determination. The measurements were performed with the source parameters and plasma conditions as given in Table II. The analysis was performed using a least-mean squares fitting method, and to reduce the influence of stray light or Rayleigh scattering, the central 38 pixels around 532 nm were not used for the fit.

FIG. 8. Argon plasma expanding (at right side) in the source chamber. The background pressure $p_{\text{back}} = 15.5\text{ Pa}$. Conditions: current 100 A and gas flow 3 slm.

A. Electron density determination

During operation of Magnum-PSI, the TS system will be used as plasma condition monitoring system, delivering TS profiles every 10 s. This means that it is required that the TS system is able to record signals within a few seconds. Measurements were performed using an accumulation time of 6 s (60 laser pulses) on a plasma with $n_e = 4.7 \times 10^{18}\text{ m}^{-3}$. A typical spectrum corresponding to a spatial element of approximately 2 mm in the plasma is shown in Figure 9; the central peak at 532 nm corresponds to Rayleigh scattering. From the least-mean squares fit the accuracy in n_e was found to be $\sim 3\%$; the integrated number of photoelectrons of the spectrum is about 900 (detector sensitivity ~ 80 counts/photoelectron). This means that in 3 s (30 laser pulses), an accuracy of 3% can be reached for $n_e = 9.4 \times 10^{18}\text{ m}^{-3}$. It also means that with the same accuracy, single pulse TS measurements can be performed for $n_e > 2.8 \times 10^{20}\text{ m}^{-3}$. In the analysis procedure, collective effects, occurring in TS spectra at $n_e > 10^{21}\text{ m}^{-3}$ and at low T_e , have been incorporated to also have correct interpretation of the data at such conditions.¹⁶

Stray light measurements were performed to determine the stray light contribution in n_e equivalents to the n_e measurements. For the whole area $-50\text{ mm} < r < 50\text{ mm}$, the stray light contribution was found to be less than $9 \times 10^{16}\text{ m}^{-3}$ (in n_e equivalents). During these measurements, the laser

TABLE II. Cascaded arc source parameters and plasma conditions.

Cathode	Consists of three tungsten tips
Diameter source plates	5, 5, 6, 7, 8 mm and 9.5 mm (nozzle)
Source current and gas flow	100 A, 3 slm (slm; 1 slm = 4.5×10^{20} particles/s)
Gas type	Argon
Background pressure	$1.41 \pm 0.02\text{ Pa}$
Distance between laser chord and skimmer	125 mm

FIG. 9. Spectrum corresponding to radial position of $r = -8$ mm, z -position = 200.5 mm, and $n_e = 4.7 \times 10^{18} \text{ m}^{-3}$. TS scattered signal from 60 laser pulses was accumulated. The data points centered around 532 nm (open circles) are excluded from the fit (solid line).

chord was located at a few cm from the arc. The stray light contribution has to be subtracted from the raw TS signal. This means that only the stray light fluctuations contribute, and n_e measurements are possible well below $n_e \sim 1 \times 10^{17} \text{ m}^{-3}$; the

observational error will only be enhanced by less than a factor of 2 (thus about 6%), relative to the case of the pure TS signal.

B. Electron temperature determination

A measured TS spectrum always consists of a pure TS spectrum convoluted with the instrumental line profile of the spectrometer. Deconvolution methods can be used, but these have drawbacks concerning speed of analysis and enhancement of noise in the processed data. Therefore, the measured TS data are corrected by subtracting the width of the instrumental line profile quadratically from the fitted spectra.

To test this procedure, two TS measurements were compared, one with 400 μm and the other with 130 μm fiber width. As described in Sec. V A the latter setting for the spectrometer can be used as reference. The T_e profile measured with the 400 μm fiber width showed a structural underestimation of $< 0.008 \text{ eV}$ (5%) relative to that of the reference measurement: typical spectra corresponding to both T_e profiles are shown in Figure 10(a) (fiber width 400 μm) and Figure 10(b) (fiber width 130 μm), the local density was $n_e = 1.2 \times 10^{19} \text{ m}^{-3}$. Subtle fluctuations of the plasma conditions or small irregularities of the edge of the entrance slit (that masks a part of the fiber array) can cause such deviations. For this report, we accept this small structural deviation and this sets the lowest measurable T_e still to below 0.07 eV accepting an error of about 10% for this extreme case.

C. Plasma expansion

The expansion of an argon plasma was explored by Rayleigh-TS¹⁷ to illustrate the performance of the TS system. First, a brief description of the expansion is given. Due to the

FIG. 10. (a) Spectrum measured with 400 μm input fiber width. Central radial position $r = -13.3$ mm, z -position = 59.5 mm and $n_e = 1.2 \times 10^{19} \text{ m}^{-3}$. The data points centered around 532 nm (open circles) are excluded from the fit (solid line). (b) Spectrum measured with 130 μm input fiber width. Central radial position $r = -13.3$ mm, z -position = 59.5 mm and $n_e = 1.2 \times 10^{19} \text{ m}^{-3}$. The data points centered around 532 nm (open circles) are excluded from the fit (solid line). The narrow Rayleigh peak shows the merits of the spectrometer.

FIG. 11. On-axis n_e (dots) and T_e (open circles) as a function of axial position relative to source nozzle at $p_{\text{back}} = 1.4$ Pa. Spatial resolution about 2 mm. The solid line shows the behaviour of n_e , if it obeys Eq. (5).

high pressure difference between the source and the Magnum-PSI vessel, the plasma expands into the source chamber. The ionization degree of the expanding plasma is in the range of 5%–20%¹⁸ depending on the arc current, which allows for treating the plasma dynamics inside the jet as that of a hot gas of heavy particles (neutrals and ions) since the coupling between ions and neutrals is strong. Starting from the nozzle, the macroscopic velocity of the plasma accelerates to supersonic velocity and the diameter of the plasma jet rises linearly (rarefaction effect), and results in a z^{-2} decay of the neutral density along the z -axis.^{19,20} The electron temperature also drops in this zone; the random motion (thermal energy inside the source) is converted to macroscopic velocity (directional kinetic energy), i.e., adiabatic cooling.²¹

TS profiles of T_e , n_e , and n_0 were measured in the source chamber as a function of the distance relative to the front

FIG. 12. On-axis n_0 (dots) as a function of axial position relative to the nozzle at $p_{\text{back}} = 1.4$ Pa. Spatial element size about 4 mm (2 spatial points). The solid line shows the behaviour of n_0 , if it obeys Eq. (5).

FIG. 13. n_e , T_e profiles at $z = 53.5$ mm. Radial spatial resolution about 2 mm, 3000 laser pulses.

FIG. 14. (a) TS image (stray light subtracted) corresponding to $z = 53.5$ mm (see Figure 13). (b) Spectrum at $r = 0.85$ mm, $n_e = 1.9 \times 10^{19} \text{ m}^{-3}$. The data points centered around 532 nm (open circles) are excluded from the fit (solid line).

FIG. 15. 3D representation of radial n_e (a), T_e (b), n_0 (c) profiles, measured with TS as function of the distance to the source nozzle. The horizontal grid represents the TS data point positions (r, z). Spatial resolution about 2 mm.

of the source nozzle, using the translation utility of the cascaded arc source. The results are shown in Figures 11 and 12. The neutral density has been determined by measuring the Rayleigh scattering contribution in the mid part of the TS spectra, i.e., the fitted electron velocity distribution function has been subtracted from the measured spectrum. The Rayleigh scattering cross section (at 532 nm) for argon is 147 times lower than that for TS (see Table I). Therefore, long measurement periods (3000 laser shots) were applied to achieve accurate n_0 measurements (25% for $n_0 = 1.0 \times 10^{20} \text{ m}^{-3}$). Figures 11 and 12 show that on the axis of the jet, the measured n_e and n_0 decay approximately as z^{-2} for large z . The shock is expected at about 270 mm distance from the nozzle,¹⁸ which implies that the measurement region corresponds to the supersonic expansion zone.

For comparison with the n_e and n_0 data obtained from TS, the on-axis density as a function of the distance from the source nozzle was calculated. Instead of a divergent shaped cascaded arc source as used in the present experiment, a simplified model based on a free jet expansion of neutral gas²² was applied. It was assumed that the argon plasma exits the source at $T_e \sim 0.7 \text{ eV}$ ²⁰ (nozzle radius $r_0 = 4.75 \text{ mm}$, flow 3 slm ($\Phi = 1.35 \times 10^{21} \text{ s}^{-1}$), and that the neutral density is constant over the nozzle radius. The n_0 densities at the exit $n_{\text{res},0}$ can be estimated as^{23,24}

$$n_{\text{res},0} = \frac{\Phi}{c_0 \pi r_0^2} \quad (4)$$

with c_0 the local sound speed ($\sim 1700 \text{ m/s}$ at 0.7 eV ¹⁸). This results in a value of $n_{\text{res},0} \sim 1.2 \times 10^{22} \text{ m}^{-3}$. The on-axis n_e and n_0 at a distance z from the exit for large z is given by^{21,22}

$$n_{e,0}(z) = \frac{n_{\text{res},e,0} z_{\text{ref}}^2}{(z - z_0)^2}, \quad (5)$$

where $n_{\text{res},e,0}$ denotes the n_e and n_0 density at the source exit. In this expansion, equation z_{ref} is a reference length, $z_{\text{ref}} \sim D \times 0.806$,²² with D the nozzle diameter. The fitting parameters are $n_{\text{res},e,0}$ and z_0 with z_0 being defined as the origin, relative to the nozzle front, from which the particles seem to originate. The fitted n_e and n_0 curves, depicted as solid lines in Figures 11 and 12, show that the behaviour of the measured n_e and n_0 agrees very well with that predicted by Eq. (5). The $n_{\text{res},0}$ value for n_0 from the fit $n_{\text{res},0} = 1.1 \times 10^{22} \text{ m}^{-3}$, corresponds well with the result obtained from Eq. (4). For n_e , a $n_{\text{res},e}$ value of $n_{\text{res},e} = 1.9 \times 10^{21} \text{ m}^{-3}$ is found, which is a realistic value that corresponds to an ionization degree of the plasma of about 17%. The fits for n_e and n_0 give different values for the z_0 position: -4 mm and $+4 \text{ mm}$, respectively. The value found for n_0 is most likely influenced by the fact that the expansion is strongly rarefied: already early in the expansion, the mean free path for neutral-neutral collisions is much longer than the expansion dimensions. This leads to inflow of neutrals from the outside and thus to deceleration, and higher neutral densities^{25,26} and a z_0 position that is further downstream. Note that given the fact that z_0 position is determined from results obtained at large distance from the nozzle, the accuracy of determination of these parameters is limited.

At large distance, $z > 160 \text{ mm}$, the measured data for both n_e and n_0 depart slightly from that predicted by Eq. (5).

This is expected, because in this density valley (over-expanded region, where the on-axis jet pressure is already 30% lower than background pressure) the particle mean free path is larger than the dimensions of the jet and consequently particles from outside the jet will invade here also the plasma,^{19,20,25,26} i.e., the valley would be even deeper without invading particles. Moreover, the skimmer, located at a distance of 125 mm downstream from the TS location, will surely obstruct the flow and as a consequence n_0 and n_e will rise.

Assuming that T_e inside the arc channel was about 0.7 eV, the curves in Figure 11 show that T_e decays for the region $z < 70 \text{ mm}$ much slower than is expected on the basis of adiabatic expansion (pure adiabatic expansion: $T_e \propto n_e^{1-\gamma}$, with specific heat ratio $\gamma = 1.66$). The present measurements result in a value of $\gamma \sim 1.30 \pm 0.01$, which is within a few percent identical to that found by Refs. 18 and 21.

For $z > 140 \text{ mm}$, T_e is enhanced significantly; this behaviour can be associated with the same mechanism as described for the rise of n_e and n_0 . Although only one point at $z = 165 \text{ mm}$ was recorded, the measured T_e is in agreement with the results obtained by Ref. 18 from double Langmuir probe measurements.

In Fig. 13, n_e and T_e profiles are shown corresponding to $z = 53.5 \text{ mm}$. In Figure 14(a), the corresponding image is shown together with a spectrum (see Figure 14(b)).

Three-dimensional representations of the T_e , n_e , and n_0 measurements are shown in Figure 15 with a spatial resolution of approximately 2 mm. It should be noted how well the statistics of Figs. 15(a) and 15(b) is, which confirms the high accuracy of the n_e and T_e measurements, even for n_e below $3 \times 10^{18} \text{ m}^{-3}$.

The fact that the measured expansion properties are in agreement with Eq. (5) and the fact that the measured T_e decay is well in agreement with that found by Refs. 18 and 21 demonstrates the excellent performance of the TS system.

VII. SUMMARY AND CONCLUSIONS

The advanced Thomson scattering system built for the linear plasma generator Magnum-PSI is operational. The results presented in this report show that the specifications of the TS system comply with and even go beyond the requirements.

The TS system can measure within 3 s, with a spatial resolution of about 2 mm, n_e and T_e profiles at $n_e = 9.4 \times 10^{18} \text{ m}^{-3}$, with an accuracy of 3% and 6%, respectively. With the same accuracy, single pulse measurements can be performed at $n_e > 2.8 \times 10^{20} \text{ m}^{-3}$.

The stray light level is sufficiently low to allow for a minimum measurable density of $n_e < 1 \times 10^{17} \text{ m}^{-3}$ (6% accuracy).

The high dispersion spectrometer allows for TS measurements below 0.07 eV (10% accuracy). The spectral range of the spectrometer of 10.2 nm is sufficient for measuring T_e up to 11 eV.

In an argon plasma, neutral density profiles can be measured with a spatial resolution of approximately 2 mm and an accuracy of 25% for $n_0 = 1.0 \times 10^{20} \text{ m}^{-3}$.

The outstanding performance and the fact that the measured argon expansion properties are in agreement with the predictions, demonstrate that the TS system is not only an excellent diagnostic control tool for monitoring n_e , T_e , and n_0 for Magnum-PSI, but also for detailed exploration of plasma phenomena.

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¹See www.iter.org for information about the ITER tokamak.

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