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ABSTRACT

MAST-U is equipped with a Super-X divertor, which aims to reduce heat flux to the target and promote detachment. Measurements of plasma electron density and temperature in the Super-X chamber offer insight into the processes at work in this type of divertor. First data have been obtained from the MAST-U divertor Thomson scattering diagnostic designed to measure these quantities. Following a Raman scattering calibration in nitrogen, the diagnostic operated over a number of plasma pulses in the first physics campaign. Electron density and temperature measurements have been taken in attached and detached conditions as the strike leg moved through the field of view of the diagnostic. The system operated with a dedicated 30 Hz laser with timing synchronized to seven similar lasers installed in the core Thomson system. Electron densities in the range of 1×10^{18}–5×10^{19} m^{-3} have been measured by the system throughout these regimes. Although the system was specified to measure from 1 to 40 eV, electron temperatures in the Super-X divertor in the first campaign were low, and measurement down to 0.5 eV has been critical, particularly close to the detachment front. This generation of polychromator has been designed with increased stray light rejection compared to those used in the core system. This has proved successful with very low levels of stray light observed.

I. INTRODUCTION

MAST-U completed its first physics campaign in 2021. One of the goals of these experiments was to characterize the Super-X divertor[9] and study the mechanisms behind the detachment process. To diagnose the closed Super-X divertor, a dedicated Thomson scattering system[1] was installed to measure electron density and temperature in the Super-X chamber to offer further insight into the operation of this configuration.

During the first campaign, a single 1.6 J 30 Hz laser was used with timing synchronized[2] to seven similar lasers installed in the core Thomson system.[3,4] Due to the digitization capacity available, seven polychromators were used for the first operation of the diagnostic. The location of these measurements can be seen in Fig. 1, where the red points are those used in the first campaign and the black points are additional spatial points that will be used in the second campaign. The collection optic[8] allows a field of view ranging from 1.05 to 1.45 m along the major radius. There is space for 66 fibers in the collection optic, which allows space for upgrading the diagnostic in the future.

Alignment of the collection optics was established during the first Raman calibration. A back illumination of the fibers during the calibration can be seen in Fig. 2. Following calibration, a good signal level was observed down to ~1×10^{18} m^{-3} and 0.5 eV. A concern prior to the campaign was laser damage to the in-vacuum mirror[1] as this would stop the operation of the system. The in-vacuum mirror was inspected after the campaign and no damage was observed. This was achieved by moving the focusing lens further away from the vessel to increase the size of the laser beam as it reaches the in-vacuum mirror. A concern of doing this was an increased beam size is more likely to interact with the hole in the divertor tile and become a source of stray light. The impact of this was less than expected

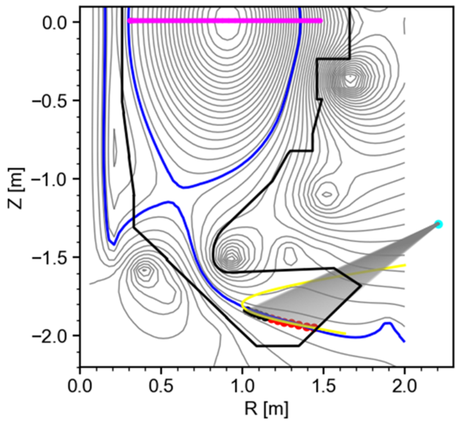

FIG. 1. Core (magenta) and divertor (red and black) spatial points with divertor collection cell (cyan) and laser (yellow) with separatrix (blue) from MAST-U plasma shot 45465 equilibrium at 0.5 s in Super-X divertor configuration.

with minimal stray light observed over the campaign due to the stray light mitigation techniques implemented in the design of the polychromators.

II. RAMAN SCATTERING CALIBRATION

Absolute signal calibration is important for a divertor-based Thomson system, especially with the Super-X allowing for the development of advanced operating scenarios. Raman scattering requires a number of spectral channels close to the laser wavelength with high rejection of light outside the intended pass band. This requirement is met by a laser line filter to remove the 1064.1 nm Nd:YAG wavelength and OD6 light rejection filters, manufactured by Alluxa. During commissioning, we found the stray light performance of these polychromators to be an improvement compared to the polychromators in the core system due to the filters.

Measurements were obtained by firing the laser into the gas-filled vessel and measuring the scattered signal collected at each polychromator. Even though it was not used, the filter with a central wavelength of 1061 and 2 nm bandwidth (1061/2 nm) does overlap with a portion of the anti-Stokes spectrum.[5,7] Due to the narrow bandwidth, the signal-to-noise ratio in that channel was considerably lower (~17% compared to ~7%) than in the 1057/5 and 1047/15 nm filters; thus, this channel was neglected. For both of these channels, there is only an anti-Stokes contribution as there is no transmission beyond the 1064.1 nm laser wavelength.

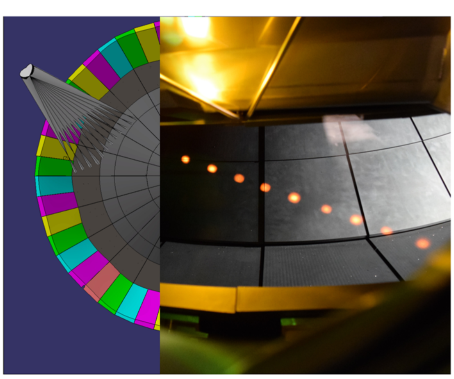

FIG. 2. A top-down CAD view of MAST-U showing 12 fiber projections for the divertor Thomson system (left) and a view into the lower Super-X chamber from the collection window showing the back-illuminated fiber projections and divertor tiles (right).

The Raman signal measured in the divertor system was determined for each laser pulse from a Gaussian fit to the scattered signal. For each gas calibration, the laser was fired for 1 s, so the average of these fits to the scattered signals is taken to determine the Raman signal for the given pressure, similar to that seen in Fig. 3. To account for variations in energy between the bank of lasers used in the calibration, each of the signal values was normalized by their respective laser energy. This was repeated for each of the recorded pressures so that the linearity of the pressure scan and the associated uncertainty could be determined.

There is some variation in the collected transmission across the collection cell due to vignetting at the outboard side of the cell because of the closed baffle of the divertor. Characterizing this vignetting with Raman scattering enables the density measurements, particularly at the edge of the collection cell, to account for this reduction in the scattered light collected. Another Raman calibration will be carried out before the second physics campaign. This will coincide with the addition of five additional polychromators.

III. SCATTERED SIGNAL FITTING

The laser energy for the first campaign was reduced to 0.8 J by altering the Q-switch delay as a precaution to preserve the in-vacuum mirror.[1] The duration of the laser pulses at this energy is ~10 ns full width at half maximum (FWHM). Scattered signals are fitted on embedded computers as part of the data acquisition to generate a Gaussian fit with a mean 1-sigma of 12 ns, which corresponds to a FWHM of 28 ns. The difference in Gaussian width between the core and divertor signals seen in Fig. 3 is due to the altered Q-switch delay.

An example of fitted signals for a ~1 eV plasma can be seen in Fig. 4. Signal is measured in the 1057/5 and 1061/2 nm channels due to the temperature of the plasma at this location. The 1047/15 and 1017/45 nm channels see no signal as they have central wavelengths farther away from the Doppler-shifted light collected from the plasma. At such low temperatures, a negligible signal in these channels is collected even with a significantly broader bandwidth, as expected.

Once the Gaussian fits have been produced, these integrals are used in a subsequent fit to the analytical Selden function.[6] The density values produced from this fit are obtained from a calibration constant determined via rotational Raman scattering, as described in Sec. II.

IV. RESULTS

A goal of the first MAST-U physics campaign was to study the detachment threshold in the Super-X divertor. A 600 kA flattop plasma current scenario was established that diverted the strikepoint

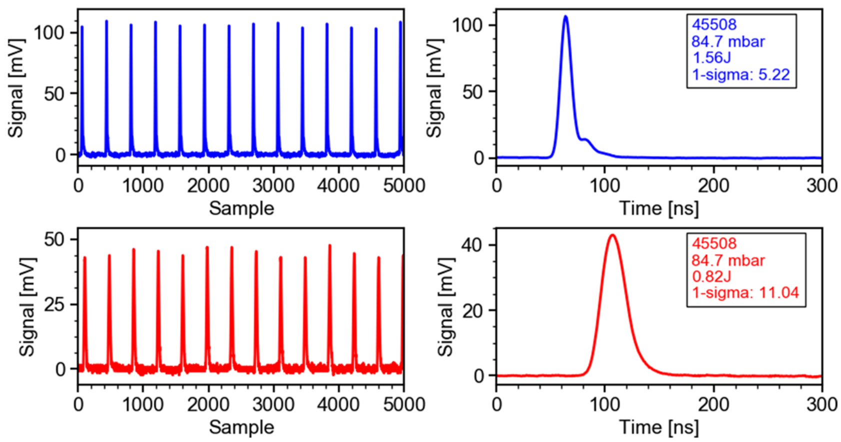

FIG. 3. Comparison of Raman scattering signal level between a core (blue) and divertor (red) polychromator for 84.7 mbar with 1.52 and 0.82 J of laser energy, respectively.

out to the Super-X divertor tile from ~400 ms before ramping down to a safe stop at ~850 ms.

Adjustments were made to the divertor coils in this scenario to align the strike leg with the divertor Thomson laser line, as seen in Ref. 1. This allowed the system to measure the electron properties of the strike leg. It was found that with a strike point sweep during the Super-X phase, Langmuir probe measurements could still be made with a good signal-to-noise ratio while also obtaining Thomson profiles close to the strike leg. This aided comparison between the two diagnostics.

With a plasma scenario established, it allowed quantities such as magnetic flux expansion, elongation and the gas fueling rate and location to be changed to see how these affected the detachment threshold. With a new gas system on MAST-U, the gas injection is controlled by applying a voltage to a piezoelectric element. Results from a midplane gas fueling scan will be presented in this work.

During an experiment, a predefined gas waveform is applied throughout the plasma pulse. Typically, this was a constant fueling rate from ~300 ms as can be seen in Fig. 5, but the system does allow for a gas ramp within a single pulse. For these results, only plasmas with a constant fueling rate are discussed. With a constant rate, this allows a fueling scan to be carried out over a number of subsequent pulses by changing the gas waveform.

Starting at a low rate of fueling for shot 45443, the divertor was observed to be attached based on spectrometry measurements of the Fulcher band emission and the absence of electron–ion recombination. After increasing the gas fueling to the level seen in 45461, there is a noticeable increase in the line averaged density through the core of the device. At this density, there were some signs of detachment measured by the spectroscopy systems. The gas fueling was increased further in 45463 and there were signs of electron–ion recombination, and the location of Fulcher band emission had moved away from the target. These signatures are indicative of detachment.

During the detachment process, it is expected that the density will increase with the upstream density until the characteristic roll-over point is reached. Beyond this point, the density in the divertor would be expected to drop with a continued increase in the upstream density. This is what was observed from the divertor Thomson system in Fig. 5. The expected density increase between 45443 and 45461 is observed before further increases in upstream density cause a drop in the divertor density seen in 45463.

Throughout this process, it is expected that the divertor temperature continually decreases with the increasing upstream density and this is what was observed. This is particularly evident in 45463 where the electron temperature near the divertor target is so cold

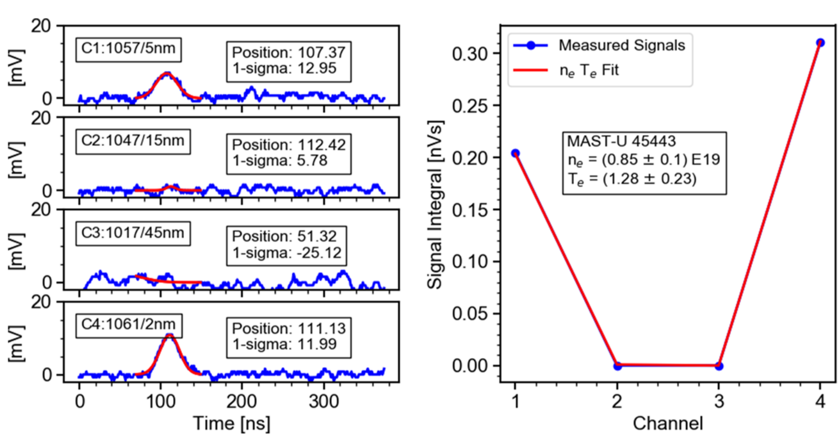

FIG. 4. Scattered signals from MAST-U plasma 45443 at 479 ms (left) and the associated fit to produce electron density and temperature values (right).

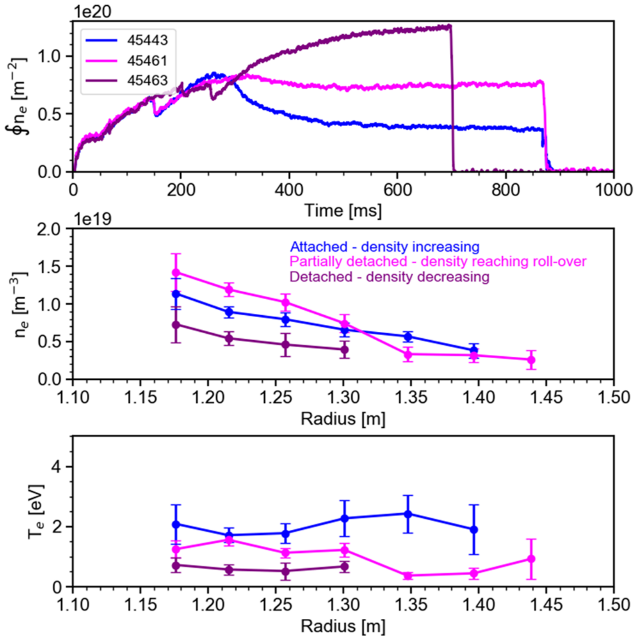

FIG. 5. Line average density and divertor density and temperature profiles at 545 ms.

that there is not enough scattered photons collected by the system to determine the electron density and temperature. Based on the polychromator specifications, it is assumed that this temperature is below 0.5 eV. Given the drop in electron temperature during the detachment process and the movement of the Fulcher band emission away from the target, temperatures of this magnitude are expected. At temperatures below 0.5 eV, an error of ~15% and ~20% was typically observed for density and temperature measurements, respectively.

V. CONCLUSIONS

The new divertor Thomson scattering system was commissioned during the first MAST-U physics campaign in 2021. Eventually, a 90 Hz diode-pumped Nd:YAG laser will operate in the system. It features eight new polychromators[1] that have shown improved rejection of stray light, which is crucial for plasma measurements down to ~0.5 eV in the Super-X divertor.

Due to the electron temperatures seen in the divertor during the first physics campaign, the signal was typically only seen in the two channels closest to the laser wavelength. Despite this, a good signal level was seen, and this is reflected in the quality of the data at these low densities and temperatures.

A Raman scattering calibration was carried out in nitrogen to commission the system. This calibration of the system enabled absolute electron density measurements to be made down to $\sim 1 \times 10^{18}$ m^{-3}. This sensitivity of electron density and temperature measurement allowed data to be collected in detached and attached plasmas as the divertor strike leg moved through the field of view of the diagnostic.

The electron density and temperature measurements were taken during a fuelling scan, that saw the divertor move from attached to detached over a number of plasma pulses. The electron density and temperature measurements were taken during a fueling scan, which showed the divertor moving from attached to detached conditions over a number of plasma pulses.

The results from this system proved to be a success for the first operation of the diagnostic; however, in the upcoming campaing, work will be carried out to implement a 90 Hz diode pumped laser to improve the temporal resolution and increase the number of spatial points to 12. With the addition of glow discharge cleaning for the divertor tiles and a cryopump to aid the control of neutral particle numbers in the divertor, it is expected that the quality of data in upcoming physics campaigns will only improve.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

J. G. Clark: Formal analysis (equal); Writing – original draft (lead); Writing – review & editing (equal). **M. D. Bowden**: Supervision (equal). **Y. Kim**: Investigation (supporting). **B. Parry**: Investigation (supporting). **E. Rose**: Conceptualization (equal); Investigation (supporting). **R. Sarwar**: Investigation (equal). **R. Scannell**: Conceptualization (lead); Supervision (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request. For further information on the MAST-U data used in II, III, and IV, please contact PublicationsManager@ukaea.uk.

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