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Edge Thomson scattering diagnostic on COMPASS tokamak: Installation, calibration, operation, improvements^{a)}

P. Bohm,^{1,b)} M. Aftanas,^{1,2} P. Bilkova,¹ E. Stefanikova,^{1,2} O. Mikulin,^{1,3} R. Melich,¹ F. Janky,^{1,2} J. Havlicek,^{1,2} D. Sestak,¹ V. Weinzettl,¹ J. Stockel,¹ M. Hron,¹ R. Panek,¹ R. Scannell,⁴ L. Frassinetti,⁵ A. Fassina,⁶ G. Naylor,⁴ and M. J. Walsh⁷

¹*Institute of Plasma Physics ASCR, Za Slovankou 1782/3, 18200 Prague, Czech Republic*

²*Faculty of Mathematics and Physics, Charles University in Prague, Ke Karlovu 3, 121 16 Prague, Czech Republic*

³*Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University, Brehova 7, 11519 Prague, Czech Republic*

⁴*CCFE, Culham Science Centre, Abingdon, Oxon OX14 3DB, United Kingdom*

⁵*School of Electrical Engineering, Division of Fusion Plasma Physics, KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden*

⁶*Consorzio RFX, Corso Stati Uniti, 4-35127 Padua, Italy*

⁷*ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St Paul lez Durance, France*

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The core Thomson scattering diagnostic (TS) on the COMPASS tokamak was put in operation and reported earlier. Implementation of edge TS, with spatial resolution along the laser beam up to $\sim 1/100$ of the tokamak minor radius, is presented now. The procedure for spatial calibration and alignment of both core and edge systems is described. Several further upgrades of the TS system, like a triggering unit and piezo motor driven vacuum window shutter, are introduced as well. The edge TS system, together with the core TS, is now in routine operation and provides electron temperature and density profiles. [<http://dx.doi.org/10.1063/1.4893995>]

I. INTRODUCTION

The COMPASS tokamak ($R = 0.56$ m, $a = 0.18$ m, $B_T = 0.8$ – 2.1 T, $\kappa = 1.6$, plasma current up to 400 kA, NBI (neutral beam injection) heating 2×400 kW, H-mode with different types of ELMs (edge localised modes)) is in operation.^{1,2} The set of installed diagnostics corresponds to the scientific programme focus on the edge plasma.³

The high resolution multi-point Thomson scattering (TS) diagnostic has been designed to provide the electron temperature and density profiles on the COMPASS tokamak.⁴ The diagnostic consists of two sub-systems, observing core and edge plasma region. Commissioning of the core system was described earlier, including its relative (i.e., spectral) and absolute (i.e., Raman) calibration.⁵ In this paper, edge system installation is presented. The two systems (core and edge) are semi-independent—they share the laser beam (two 1.5 J@30 Hz Nd:YAG lasers, passing vertically through the plasma) and the main part of the collection lenses supports structure, but the final fitting and thus their alignment is separate. An overlap of core and edge TS systems profiles serves as a cross-check between the two systems. The edge TS required an uncommon solution of port plug vacuum window shutter—it is driven by a piezo motor. A new triggering unit for TS system is described as well.

II. EDGE TS COLLECTION LENS

The edge objective is designed as a finite conjugate system with effective focal length of 204 mm. In order to investigate the tokamak plasma up to +300 mm above its mid-plane, the lens is designed to match a field of view of roughly 51° for the object distance of about 200 mm. The wavelength range of the objective is 750–1064 nm. Due to a strong mechanical restriction inside the tokamak port, it was necessary to design it as an off-axis refractive system (see Fig. 1). The objective mechanical axis is decentred by about 11 mm, which enables to image field of view of 25° – 51° corresponding to +200 to +300 mm of tokamak plasma. The working F/# 5.1 at the lowest point of observed region increases up to F/# 8.8 at the top. The objective consists of 6 lenses in total. The first two lenses are manufactured from high refractive index glass SF6 ($n = 1.8$), to achieve the high angle of field of view. The image of the laser beam lies on an aspherical surface.

Light collected in 30 spatial points is transferred through fibre bundles into 16 polychromators.⁴ Number of spatial points is higher than number of polychromators thanks to duplexing technique—two adjacent fibre bundles are coupled into one polychromator, they are distinguished by different time of arrival of scattered light, because of fibre bundle length difference (20 m vs. 33 m). Two of the spatial points are used as split-fibre for alignment (see below). The polychromators are identical in both core and edge TS, with the same set of the spectral filters.⁶

An example of electron temperature and density profiles during a standard tokamak discharge, obtained with both core and edge TS, is shown in Fig. 2. The deuterium plasma

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^{b)}Author to whom correspondence should be addressed. Electronic mail: bohm@ipp.cas.cz

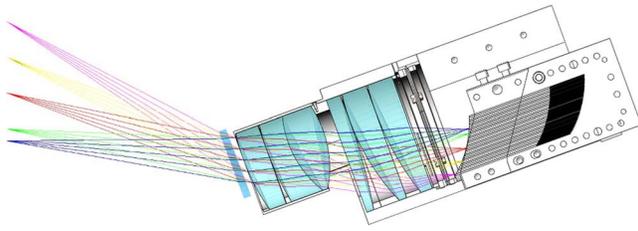


FIG. 1. The edge TS collection lens. Visualisation of a cross-section with optical rays.

was D-shaped, with toroidal field 1.15 T and plasma current 160 kA, without an additional heating.

III. SPATIAL CALIBRATION

Reliable spatial calibration is essential not only for interpretation of the measured data, but also for determining scattering angles. The scattering angle subsequently determines measured temperature: 1° error at 90° angle of scattering corresponds to approximately 2% error in determined temperature.⁷

Both the core and the edge collection lenses are mounted on a movable trolley. Travel range of the trolley allows retraction of the collection lenses from the tokamak port plugs and reconstruction of the scattering geometry outside the tokamak vessel. This arrangement enables easier alignment and spatial calibration. The spatial calibration and initial alignment of the optics is performed using fibre bundles back-illumination. Fibre bundles, normally transferring collected scattered light to the polychromators, are illuminated on the polychromator side, image of the fibre corresponds to the observed scattering region. Infrared LED diode (970 nm) is used for the purpose, as the TS system operates in NIR (760–1064 nm) and the optics are optimised for this range. Use of visible light would introduce chromatic aberrations. The calibration revealed that the core TS observes region from -16 mm to 211 mm above mid-plane. The edge TS region overlaps with core at several spatial points, ranging from 195 mm. Size of the edge TS points is 4 mm at the points closer to the plasma core, below

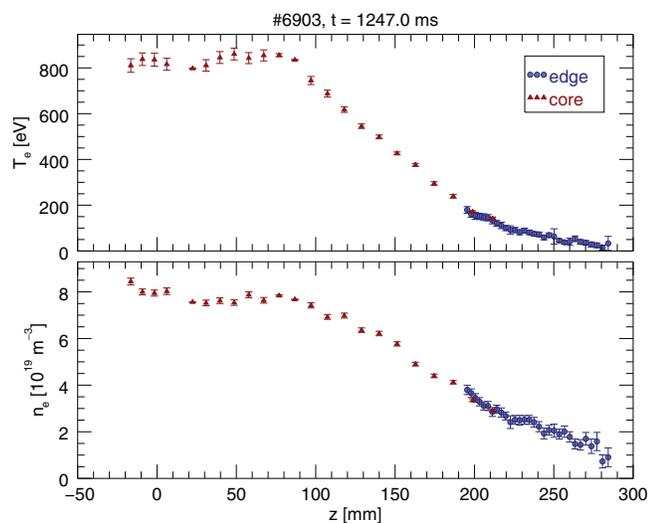


FIG. 2. Electron temperature T_e and density n_e profiles along vertical axis z , points measured with core and edge TS are distinguished.

5 mm at most of the range and rising to 6 mm at the furthest point. The furthest point observed by the edge TS in the recent setup is located at 284 mm above mid-plane. Including the point size, field of view of the edge TS reaches up to 287 mm.

The in-vessel spatial calibration was performed once to validate the above described external calibration method. A pinhole illuminated by the IR LED as a light source was moved along the laser chord inside the tokamak vessel. Recorded shape of signal in the polychromators provided spatial responsivity of the TS system, convolved with a finite size of the pinhole (1 mm). In-vessel spatial calibration validated ex-vessel calibrations within 1 mm accuracy.

IV. ALIGNMENT OF COLLECTION OPTICS

Two methods of collection optics alignment in respect to the laser beam are being used: The rough alignment with fibre back-illumination described in Sec. III and a precise alignment of the collection optics utilizing scattered signal. The second method can be used for initial alignment (during Raman calibration) and as a continuous feedback during standard TS measurements. So called “split-fibres”⁶ are used for the purpose. It is a standard fibre bundle, but divided into halves along the laser chord. Ratio of TS signal in the halves indicates alignment, it should be 1:1 when aligned. After combining the signals from both halves, the split-fibre can be included in the profile measurements similarly to a standard spatial point.

Each collection lens is equipped with two split-fibres, to have a feedback on full chord alignment. In the core system, the split-fibres are located at the ends of the observed region, to maximise the sensitivity of alignment. In the edge, one is located at the end closer to the plasma centre, while the second is in the middle of the field of view, where reasonable plasma densities, providing sufficient signal, can be expected.

After optimisation of lens holder stability, moderate fluctuation of ratio of signals in the split-fibres was recorded during last tokamak campaigns. The fibre bundle width is designed to allow ± 1 mm tolerance of laser beam position.⁴ Alignment remained within this limit, therefore the density profiles were not affected.

V. TRIGGERING UNIT

A new triggering unit for the TS system has been developed and constructed recently.^{8,9} It is based on FPGA Xilinx Spartan 6,¹⁰ replacing its predecessor based on Microchip dsPIC microprocessor.¹¹ The triggering unit provides synchronisation of the two lasers, with choice of 30 Hz double energy regime (both lasers firing simultaneously), 60 Hz or arbitrary time delay between the two lasers. The sequence before each tokamak plasma shot comprises of laser warm-up phase with flash-lamps only, followed by the gradual output power increase. The TS triggering unit synchronises lasers timing with the tokamak clock shortly before the discharge. It also controls triggers for the TS fast data acquisition, trace of TS timing in the tokamak data acquisition and opening of the laser shutter. The hardware is prepared for receiving triggers from the plasma events.

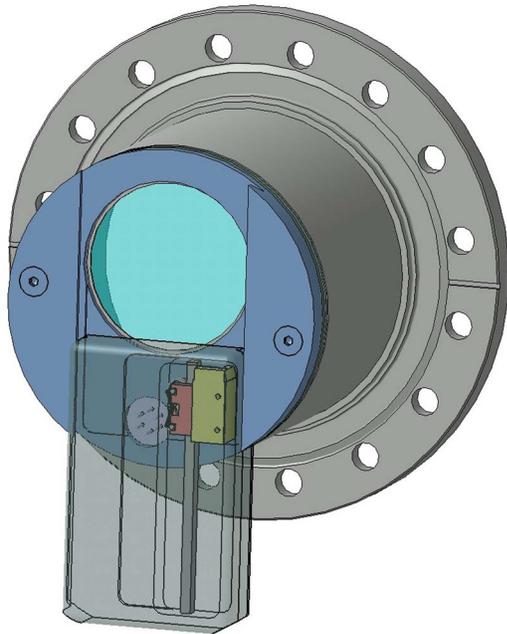


FIG. 3. Piezo motor driven vacuum window shutter on the edge TS port-plug. The shutter itself is displayed in an open position as semi-transparent, to show the driving mechanism.

VI. EDGE TS VACUUM WINDOW SHUTTER

A novel design of the vacuum window shutter has been implemented in the edge TS port-plug. To maximise the collection lens aperture, minimisation of footprints of the shutter and its driver feedthrough is desirable. It was achieved by replacing a mechanically driven blade shutter by a piezo motor driven sliding shutter (Fig. 3). The shutter is manufactured from graphite, sliding in a groove machined in a stainless steel port plug cover. The material contributes to good mobility of the shutter—it is lightweight and with low friction. The driver is the PiezoMotor's Piezo LEGS 6N linear motor.¹² It represents a compact design, requiring only 11 mm depth inside the shutter body, while providing sufficient force for movement. The 6-pin electric vacuum feedthrough puts minimum constraints on the vacuum window size and position. In addition, the electric cable passing along the collection lens in the port plug is more compact than a mechanical shutter drive feedthrough. The shutter is in operation for a year and has proven to be functional and reliable.

VII. CONCLUSION

The Thomson scattering diagnostic system on the COMPASS tokamak is now in full operation. Both core and edge systems are working routinely. Spatial calibration accuracy

was cross-checked. Stability of diagnostic alignment was improved by an upgrade of collection optics holder and is routinely checked during diagnostic operation. Variability of measurements timing was extended by a new triggering unit. The new compact edge TS vacuum window shutter serves reliably. Possibilities of a remedy to fully achieve the challenging specifications of the edge TS collection lens field of view are in investigation. In the near future, repetition rate of the TS system is planned to be increased by increase of the number of the lasers.

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- ¹²See <http://www.piezomotor.com/> for information about piezo motor manufacturer.