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High resolution Thomson scattering on the COMPASS tokamak - extending edge plasma view and increasing repetition rate

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ABSTRACT: The Thomson scattering (TS) diagnostic system on the COMPASS tokamak consists of separate collection optics for core and edge plasmas. Till now, the adverse orientation of the viewport available for the edge TS limited the investigated plasma scenarios to those, where H-mode plasma pedestal was possible to be observed. The vacuum vessel port has been recently modified and directed more to the plasma edge. To bridge the time for designing and manufacturing a new lens, the so far used edge TS collection lens was tilted and the fibre bundles rearranged to comply with the new geometry. However, the full potential of the new port is utilized only by the newly designed and manufactured lens. Comparison of performance of the collection lenses before and after the viewport modification is presented. Apart from the edge collection system upgrade, the laser system was extended by two lasers with parameters similar to the original two, thus increasing the repetition rate of the TS system to 120 Hz or allowing to obtain four profiles with tight timing in order to measure fast transient events in the plasma.

KEYWORDS: tokamak; Thomson scattering; LAPD18.

[**] *See H. Meyer et. al. Nuclear Fusion FEC 2016 Special issue (2017)*

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1. Introduction

The Thomson scattering (TS) diagnostic system was put into operation shortly after the COMPASS tokamak re-installation in Prague. Since then it has undergone several upgrades. The most notable upgrades are presented here: increase of number of lasers and change of edge plasma viewport and collection optics.

The COMPASS tokamak (R = 0.56 m, a = 0.18 m, B_T = 0.8–2.1 T, κ = 1.6, plasma current up to 400 kA, NBI (neutral beam injection) heating 2 × 400 kW) can produce plasma discharges in H-mode (high confinement) regime with different types of ELMs (edge localised modes) [1]. The scientific programme of the COMPASS tokamak is focused on the edge plasma; the set of the installed diagnostics corresponds to this objective [2]. One of the investigated topics is a study of pedestals – a transport barrier formed in the tokamak plasma edge region in the H-mode regime. This study is important for future fusion machines like ITER [3], [4] and the Thomson scattering diagnostic system, measuring electron temperature and density profiles, plays a key role in it. The COMPASS tokamak already contributes to the multi-machine database of pedestal parameters [5], [6]. The presented upgrades allow enlarging the operational space of plasma scenarios covered well with the TS measurements and improving the statistics of the measured data by increasing signal-to-noise ratio of the measurements and increasing the repetition rate of the TS system.

After this introductory chapter, the second chapter gives an overview of the COMPASS TS system. The upgrades are presented in the third chapter, explaining technical details of increasing the number of lasers, modification of the tokamak port for the edge TS and a new edge TS collection lens.

2. Overview of the Thomson scattering diagnostic on the COMPASS tokamak

The TS system for the COMPASS tokamak was designed and built in 2008-2010 years during the tokamak installation [7] and started its operation in 2011 [8]. Since the beginning, it was designed to have two separate collection optics (both sharing one laser beam); one observing the edge plasma region with high resolution (~a/100), the second extending the measured profiles to the middle of the plasma. The first measurements used only the core TS lens, the edge lens was installed later [9]. Couple of modifications and upgrades were done on the system since its installation. The aim of this chapter is to summarise briefly the above mentioned papers and describe the recent state of the system (figure 1), including the upgrades presented in detail in the following chapter.

The probing light source for the COMPASS TS is formed by four Nd:YAG lasers. The lasers are flash-lamp pumped, 1064 nm wavelength, about 1.5 J output energy each, 30 Hz repetition rate each. The Q-switched laser pulse width is about 7 ns. The output beams are not combined co-linearly into a single beam, but they are put close to each other (in a row) with aid of D-shaped mirrors not far from the laser output, where the beams are still of small diameter (10-11 mm) and the beam profile is close to a top-hat shape. Then the beams are led from the laser room to the tokamak hall by reflections on 4 flat mirrors, covering overall distance of 20 m to the focusing lens located in proximity of the entrance vacuum window [10]. The axes of the beams are slowly converging to cross on the focusing lens. The focusing lens (f = 2.8 m) creates a narrow beam in the observed TS region (1.3 – 3.0 mm beam diameter). The entrance vacuum window is oriented under the Brewster angle to minimise losses on the surface without need of anti-reflex coating. The laser beam passes through the tokamak vertically, i.e. the measured TS profiles are oriented along the z-axis. The beam continues through a vacuum pipe under the tokamak and is terminated in a beam dump composed of stainless steel knife blades. The distance of the beam dump from the tokamak vessel is 2 m, providing sufficient time of travel for the possible stray light from the beam dump to the collection lenses to be distinguished from the TS signal.

The scattered light is collected by two collection lenses (figure 2). The lens observing the core plasma (“core TS”) is looking through an equatorial port of 150 mm inner diameter. The observed region spans from z = -15 mm to z = 213 mm with 9 – 12 mm spatial resolution, the F-number is F/5.9. The second collection lens (“edge TS”) covers range 210 – 320 mm, where the edge of the plasma is located in plasma scenarios with a divertor configuration. To resolve the pedestal gradient, the edge TS spatial resolution is below 4 mm and F/5.0 provides sufficient signal-to-noise ratio. The vacuum viewports can be covered with shutters, which protect the windows e.g. during tokamak vessel walls boronisation. Both the core and edge TS lenses are mounted on a common support structure, which allows fine adjustment of the optics and to retract the lenses for maintenance on the tokamak ports and ex-vessel TS optics adjustment (figure 1).

The collected scattered light is coupled into fibre bundles consisting of polymer silica cladding fibres with F/1.75, 210 μm cladding diameter and 200 μm core diameter. The fibres are assembled into the bundles, each bundle defining one spatial point of the TS measurement. The core TS fibre bundle has 11 rows (vertical direction, along the laser beam) and 6 columns, the bundle imaged by the core TS lens is about 8 mm high and 4 mm wide (this width accommodates the laser beam size + laser pointing stability). The edge TS fibre bundle has 6 rows and 10 columns, its image in the scattering region is about 3.5 mm high and 6.9 mm wide. Two fibre bundles are coupled into one detection unit; the two spatial points are resolved by difference in signal arrival time, caused by the different fibre bundle length (20 m vs. 33 m) – this technique is called “duplexing”.

The core TS system has 24 spatial points (i.e. dedicated fibre bundles) and the edge TS system 30 points. Two fibre bundles in the core TS and two in the edge TS are “split fibres” –

fibre bundles divided into halves. The ratio of the signals in the left and right halves gives a feedback of the collection optics versus laser beam alignment.

The scattered light is spectrally analysed in 29 polychromators. The polychromator is a cascade of 5 spectral filters; the light transmitted through each filter is detected by a fast avalanche photodiode (APD). The polychromators optics, chassis and electronics were designed by TS team on the MAST tokamak (Culham Centre for Fusion Energy, [11]), the filters wavelengths were optimised for the COMPASS TS. The on-board electronics not only amplify the signal from APD, but compensate the APD gain drift with temperature and divide the signal into "fast" signal (high-pass filter at 200 kHz) containing the scattered signal and "slow" signal (low-pass filter at 200 kHz) containing the background light.

The fast data acquisition system (DAQ) for recording the temporal evolution of the scattered signal has 120 channels with 1 GS/s sampling rate and 8-bit resolution. The number of fast DAQ channels allows to digitize 4 spectral channels from each polychromator. The slow signal from the polychromators is digitised in 192 channels data acquisition system with 500 kS/s and 16-bit resolution. The collected data are saved in the tokamak central database (CDB – COMPASS DataBase) and post-processed by the automated script.

A central triggering unit was designed and built for the TS system [12]. It synchronises the lasers in respect of each other, controls their operation during the experiment, triggers the fast DAQ, creates time stamps in the central tokamak DAQ to pair the time axis of TS and tokamak and synchronises the TS timing to tokamak $t = 0$. The variable timing allows to set arbitrary delays between individual lasers, i.e. the TS system can run in 120 Hz mode (lasers delayed equally) or 30 Hz 4-pulse burst mode. When two lasers are fired simultaneously (laser output pulse timing jitter is <1 ns), the probing laser pulse is doubled and signal-to-noise ratio of TS measurement improves. The triggering unit hardware is based on FPGA (field-programmable gate array).

3. Upgrades of COMPASS TS

3.1 Lasers

The TS system was equipped with two lasers since its installation, now their number was increased by two new lasers. The overall repetition rate was increased from 60 Hz to 120 Hz, or 4 instead of 2 subsequent plasma profiles can be measured with variable TS timing. This improves statistics of measurements, e.g. the pedestal parameters scaling studies can be based on twice more data-points. Increased number of fast subsequent measurements can better cover temporal evolution of studied fast transient events (e.g. ELMs).

The two new lasers have the same output parameters as the two old lasers (see previous chapter). But since the manufacturer is different and now the beam path has to accommodate more laser beams, couple of modifications to the overall laser combining, control and beam path were necessary, the description follows.

Increased number of laser beams passing through the vacuum pipes before and after entering the tokamak requires tighter alignment of the individual beams. This resulted in changing the round shaped mirrors, on which the beam of one laser is directed along the passing beam of a second laser, for D-shaped mirrors, which allow closer positioning of the reflected and passing beams.

Originally, both beams from two lasers were terminated on an automated movable beam dump in the laser room, before entering the tokamak hall. This beam dump limits the exposure time of the optics in the tokamak hall, Brewster vacuum window and beam dump under the tokamak. New arrangement of 4 laser beam combination is located in proximity of the movable beam dump. The motion of this beam dump could disturb the alignment and material sputtering from the beam dump would degrade the optical surfaces of the combining mirrors. Therefore, now individual automated shutters are mounted on the laser outputs.

The electronics of the old lasers did not limit the external triggering. To keep the laser operation with the external triggering safe, the repetition rate had to be carefully controlled by the triggering unit itself [12]. The new lasers have an internal control mechanisms in the digital controller, which does not allow to deviate from the nominal repetition frequency by more than 10%. This was not compatible with original way of re-synchronisation of the lasers to tokamak time, when, after receiving a trigger pulse from the tokamak, the laser sequence was held on for up to one laser pulse and resumed at a correct time. Now, this time shift is distributed to 10 laser pulses within the 10% repetition rate tolerance. Apart of this, the different time constants of optimal delay between flash lamp and Q-switch triggers and also delay of optical laser output after these triggers had to be taken into account when modifying the triggering unit programme.

After solving the above described issues, the new lasers were successfully implemented and the increased repetition rate can be exploited in coming experimental campaigns.

3.2 Edge TS port

The available port for the edge TS was directed to the core plasma (figure 1), which made the optical design of the collection lens challenging [9]. The resulting edge TS system worked, but the available field of view proved to limit the variability of plasma scenarios to only those, where the pedestals were well covered.

Therefore, the tokamak port was modified. First, the original port was cut out with a robotic laser welding machine, also taking away a piece of the tokamak vessel surrounding the port tube. Then a stainless steel patch was welded on the tokamak vessel. The new port was welded precisely, being positioned on the patch.

This changed not only the angle of axis of the port from -20° to 0°, but also the inner diameter of the port from 100 mm to 150 mm (figure 2). The port is now directed straight to the edge plasma region. The bigger port diameter allows to collect more scattered light. The original port required fitting the vacuum window onto an insertion with an integrated window shutter, which further limited the window size to 60 mm diameter and made the shutter design complicated, and thus less reliable. Now the vacuum window can be a standard viewport with clear diameter of 130 mm and the shutter is also a standard product without any reliability issues. Another benefit of the horizontal orientation of the port is accessibility. The angled port with the collection lens located inside the diagnostic port plug required moving the lens under the angle when retracting the table with both core and edge TS lenses. The edge TS lens had to be mounted on an angled travel mechanism, which had a negative effect on the structure stability. Now the lens is fixed directly onto the support structure of both TS lenses.

3.3 Edge TS lens

A new collection lens for edge TS was designed and built to fully exploit the possibilities of the new edge TS port. To bridge the time gap between new port modification and new port manufacture, the old lens was used in combination with the new port. Design of the new lens and comparison of performance of 3 set-ups (old port + old lens, new port + old lens and new port + new lens) are described in this chapter and compared in figure 3.

The old lens was designed for the adverse geometry of the old edge TS port [9]. It consisted of 7 lens elements, some of them made of high refractive index glass SF6 to reach the required field of view far from the tokamak port axis. For the same reason, the lens elements were not axisymmetric. This design reached quite far in the edge plasma region, but the imaging quality was decreasing with the distance from the optical axis, and the magnification of the lens was increasing, as can be seen in figure 3a). It means the spatial resolution of the edge TS system was decreasing with *z* position, going from 3.5 mm at $z = 200$ mm to 6.0 mm at 284 mm. Moreover, the field of view turned out to be not sufficient for all plasma scenarios and limited reliable pedestal observations to smaller plasmas only [6].

After the tokamak port modification described in the previous chapter, the old lens was used in a configuration improving the field of view and imaging quality. The imaging quality was improved by using the field of view closer to the optical axis – the lens was tilted from original -20° angle to -10° vertically, at which angle the F/# was measured to be most evenly distributed over the field of view. The lens magnification was designed for a different imaging distance than the new port allowed, which limited the reached resolution. But in figure 3a) it can be seen that the field of view was dramatically improved. The last spatial points (i.e. with highest *z*) were not useful since their viewing lines intersected with the tokamak chamber.

The new lens design was optimised for the new tokamak port. The design F/# was not limited by the available aperture of the optics, but in the whole field of view only by the F/# of the fibres and required magnification. The available geometry does not require compromises in imaging quality or F/# of the optical design. This even allowed such optimisation, like using 2 off-the-shelf lenses out of 6 total, the rest is custom made, but the costs were further cut down by designing them as two pairs of same lenses. The mechanics of the lens housing is simpler and lighter than in the one of the previous collection lens, which helped to lower the possible eddy currents (the lens is located in between the tokamak poloidal and toroidal field coils). The optical fibre holder was 3D-printed in the institute (polylactic acid (PLA) material), which again cut down the cost significantly (compared to conventional machining from aluminium alloys) and sped up the manufacture. Standard optomechanics are used as an adjustable support of the fibre holder, which may allow later upgrade to motorised tracking of alignment of the fibres in respect to the laser beam.

New collection lens field of view covers the required region in the edge plasma with very constant spot size (3.6 – 3.8 mm); the spots are well defined and do not get blurred and overlap, unlike in the case of upper most points of the old lens (fig. 3a)). To evaluate the practical F/#, data from Raman calibrations are compared in figure 3b). The signals in the upper most points are comparable for both old and new lens with the new port. But is should be taken into account, that the resolution was improved. This is illustrated in figure 3c), where the Raman signal was normalised to the spatial point size (i.e. graph c) is graph b) divided by a)). Now the effective improvement achieved with the new lens and the new port is obvious.

4. Summary

All above described COMPASS TS upgrades were successfully implemented. The new lasers increased repetition rate of the TS system. The challenging tokamak port modification, which allows better observation of the edge plasma, was performed. The new edge TS collection lens increased the signal-to-noise ratio and improved quality of the electron temperature and density profiles measurements. The system is prepared to provide more and better data in the coming experimental campaigns.

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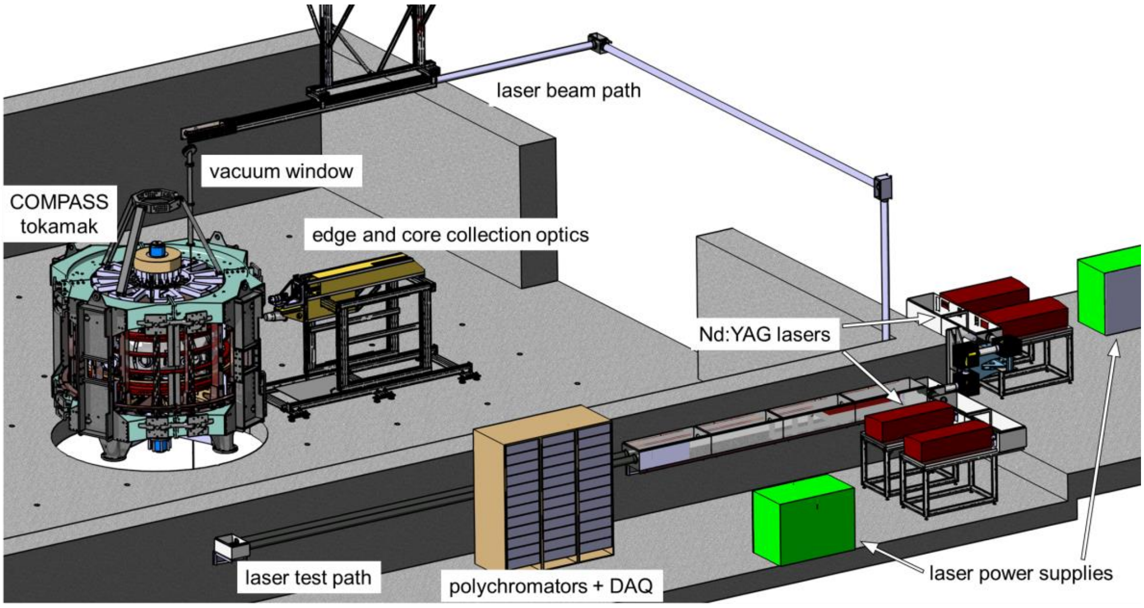

Figure 1 – Overview of the Thomson scattering system on the COMPASS tokamak. The lasers, polychromators and data acquisition are located in separate rooms outside the tokamak hall. The laser beam travels under the tokamak hall ceiling and is injected to the tokamak vertically from the top. The trolley with the collection optics is shown in a retracted position.

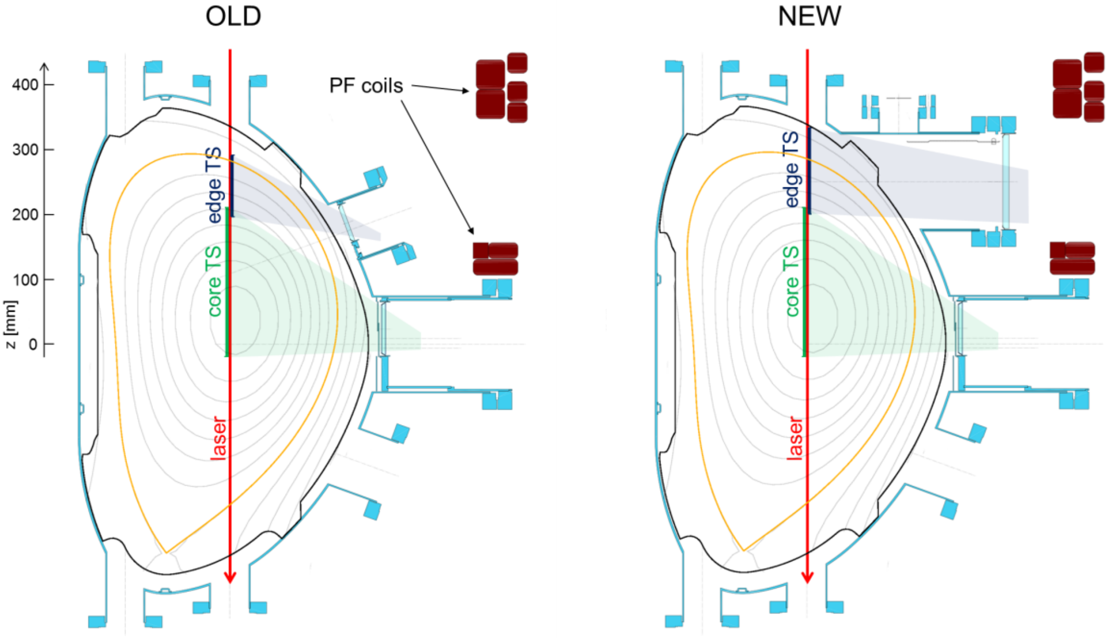

Figure 2 – Comparison of the old and new edge TS port on the tokamak cross-section. An example of magnetic surfaces reconstruction for a typical H-mode discharge is added.

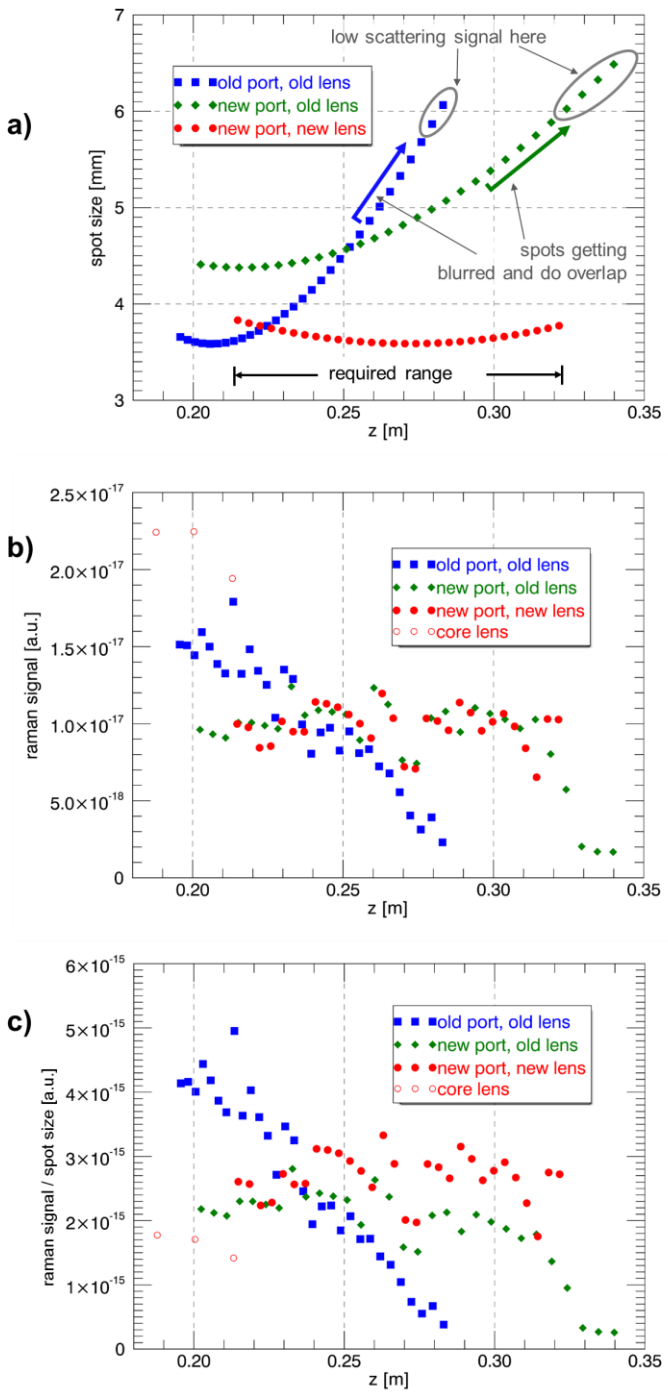

Figure 3 – Comparison of the old edge TS port with old lens, the new port with old lens and new port with new lens. a) Spatial point spotsize in dependence on the position. b) Signal strength comparison illustrated on the data from Raman calibration. c) Raman signal normalised with the spot size (i.e. graph b) devided by graph a), shows improvement of F/# of the new lens in the edge plasma region).