Progress of development of Thomson scattering diagnostic system on COMPASS[a)]

P. Bilkova,[1,b)] R. Melich,[1] M. Aftanas,[1] P. Böhm,[1] D. Sestak,[1] D. Jares,[1] V. Weinzettl,[1] J. Stöckel,[1] M. Hron,[1] R. Panek,[1] R. Scannell,[2] and M. J. Walsh[2,3]
[1]*Institute of Plasma Physics AS CR, v.v.i., Association EURATOM/IPP.CR, Za Slovankou 3, Prague 8 182 00, Czech Republic*
[2]*Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, United Kingdom*
[3]*ITER Organization, CS 90 046, St Paul lez Durance Cedex 13067, France*

(Presented 17 May 2010; received 17 May 2010; accepted 27 August 2010; published online 27 October 2010)

A new Thomson scattering diagnostic system has been designed and is being built now on the COMPASS tokamak at the Institute of Plasma Physics ASCR in Prague (IPP Prague) in the Czech Republic. This contribution focuses on design, development, and installation of the light collection and detection system. High spatial resolution of 3 mm will be achieved by a combination of design of collection optics and connected polychromators. Imaging characteristics of both core and edge plasma collection objectives are described and fiber backplane design is presented. Several calibration procedures are discussed. The operational deployment of the Thomson scattering diagnostic is planned by the end of 2010. [doi:10.1063/1.3494378]

I. INTRODUCTION

Thomson scattering (TS) is widely applied in the field of high-temperature plasma diagnostics for highly localized measurements of the electron temperature and density in the plasma.[1] Two multipoint Thomson scattering (TS) diagnostics with high spatial resolution one focused on the core plasma (core TS) and one on the edge plasma (edge TS) are being developed on the COMPASS tokamak. The COMPASS tokamak, originally from CCFE Culham, United Kingdom, has been reinstalled in IPP Prague, Czech Republic.[2] The first plasma was achieved in December 2008. TS on COMPASS is based on a set of two Nd:YAG lasers (1064 nm, 30 Hz, and 1.5 J each), two objectives collecting the light from both the core and edge plasma regions and number of polychromators equipped by Avalanche photodiodes (APDs) and spectral filters. Both conceptual and detailed designs of most parts of the diagnostic[3] as well as procurement phase were finished in 2009. In this paper, progress in development of TS (focusing on assembling and testing of particular items) is summarized. The detailed description of port plug structure and unique design of collection objective are given for both the core TS and the edge TS diagnostics. Procedures of polychromator tests including the spectral calibration are described and results are shown.

II. PORT PLUG STRUCTURE

The port plug is made from 316L type stainless steel. Vacuum window at the tokamak side is bonded to the stainless steel. For protection of the vacuum window, a knife-edge shutter has been implemented (see Fig. 1). The shutter can be manipulated from the side port by a cat-tail mechanism. The objective will be placed inside the port freely and fixed to the movable trolley (see Fig. 1). For alignment purposes, a cross-table is implemented that allows adjustment in both vertical direction (10 mm) and horizontal direction (10 mm). Rotation around the vertical axis is also possible. Figure 2 shows mechanical structure holding the collection lenses.

III. COLLECTION OPTICS

Two separate collective objectives have been designed to focus scattered light from the core and the edge plasma regions (core and edge objective) onto backplanes where inputs of optical fibers bundles are placed (Fig. 3). The goal of the optical design was to accommodate to geometry of tokamak ports used for TS diagnostics. The edge diagnostics port is inclined at 20° with respect to an observed plane. The edge collective objective observes up to 55° above its optical axis from finite distance while still keeping high input F/# to collect enough light and maintaining resolution capabilities. The design work also involves studies to avoid any vignetting or physical contact with tokamak construction where expected movements during the shots are up to 1 mm.

The core objective focuses light from the field of view (FOV) of 240 mm chord (from −30 to 210 mm above the midplane). The light is imaged on 24 fiber bundles (1.23×2.65 mm^2 cross-section) corresponding to 24 spatial points. The edge objective observes a FOV of 100 mm (200–300 mm above the midplane) and images the collected light on 32 fiber bundles (2.42×1.23 mm^2 cross-section) corresponding to 32 spatial points. The objective is designed so

[a)]Contributed paper, published as part of the Proceedings of the 18th Topical Conference on High-Temperature Plasma Diagnostics, Wildwood, New Jersey, May 2010.

[b)]Author to whom correspondence should be addressed. Electronic mail: bilkova@ipp.cas.cz.

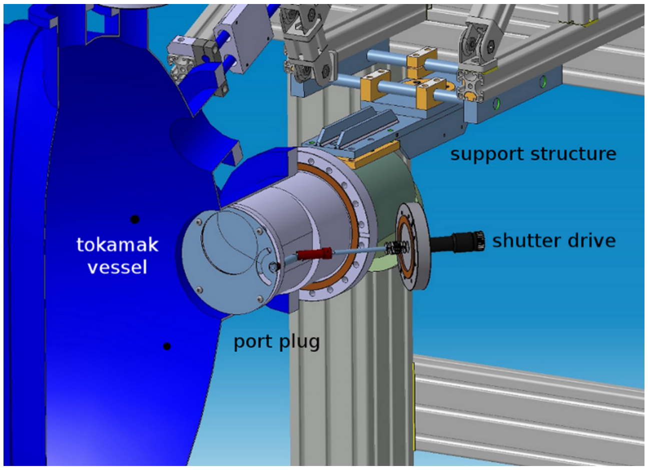

FIG. 1. (Color online) The core port plug equipped by a knife-edge shutter. 3D visualization.

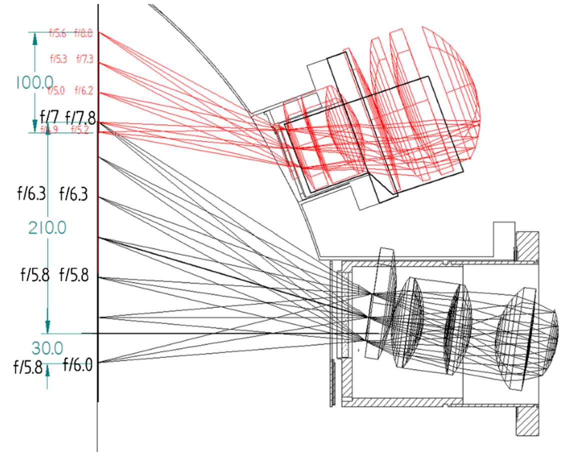

FIG. 3. (Color online) The core and the edge (upper) collection objectives. F/# numbers varying along the vertical axis corresponding to selected spatial points are shown.

that additional 30 mm of observation area can be applied below current FOV. The input to the optical collection fibers are mounted in a spherical holder with 71 mm radius for the core TS and 109 mm radius for the edge TS.

The optical designs of both core and edge collection objectives were done by ZEMAX software to provide a detailed inspection of imaging capabilities. Both objectives have been checked with respect to all main type of optical aberrations (monochromatic and chromatic, on-axis and off-axis) and with respect to proposed spatial resolutions (10 mm spatial resolution for core objective and 3 mm for edge objective). Those analyses show that the most limiting aberration is the image distortion when off-axis objects are imaged with different magnifications. The analysis of image distortion for core objective is provided in Fig. 4. The image of each fiber bundle in the tokamak can be seen. The spatial resolution varies between 8.1 and 12.4 mm and the core objective has 35% image distortion. Similar analysis has been provided for edge objective with conclusion that image distortion is 34%. The spatial resolution varies from 3.1 mm (at a point closest to the optical axis of the objective) to 4.6 mm (the most distant point from the optical axis).

The geometry of the ports together with the need to collect as much light as possible force both objective designs to employ a novel off-axis lens design. That places a high demands on the precision of mechanical parts and also on the lens assembly because the lenses need to be rotationally oriented with respect to each other.

Objective F/# varies as the function of FOV (Figs. 3 and 5). Image F/# is 1.76 for the entire FOV and almost matches fiber F/1.75. Fibers will be placed on circle with such a radii that shade each other only slightly even for the most off-axis fields. Color aberration on the most off-axis fiber has such values that different wavelength images cross from one fiber to another only minimally.

Both objectives are optimized for wavelength range 0.75–1.06 μm. Due to low number of collected photons, antireflection coatings on all optical surfaces are necessary. The lens edges as well as inner side of the tube are blackened in order to avoid any reflected light. Two broadband wiregrid polarizers are used in front of the optical fiber backplane to reduce randomly polarized plasma background light.

IV. OPTICAL FIBERS

The scattered light focused by collection lenses is then relayed over 20 m to polychromators via bundles of optical

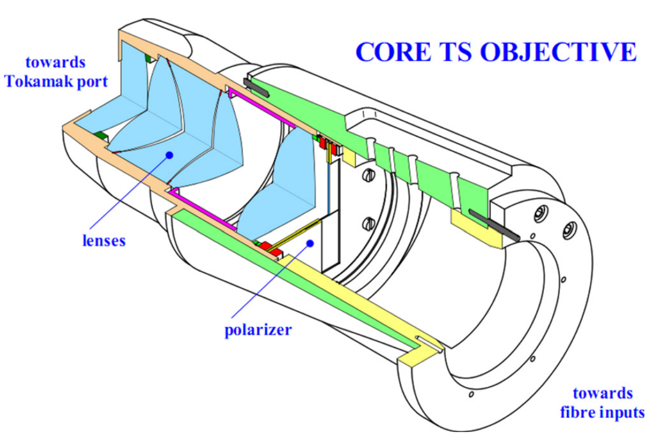

FIG. 2. (Color online) Objective mechanics supporting collection lenses of the core TS.

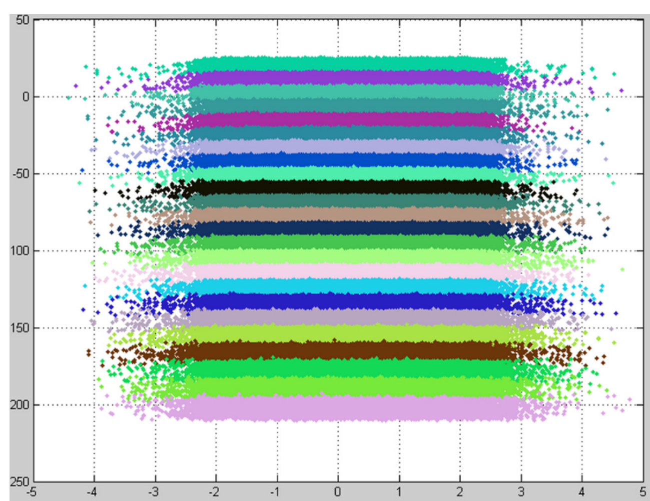

FIG. 4. (Color online) Image of the fiber bundles as imaged by the objective into the vessel (core TS). Horizontal axis: horizontal dimensions (mm). Vertical axis: vertical dimensions (mm).

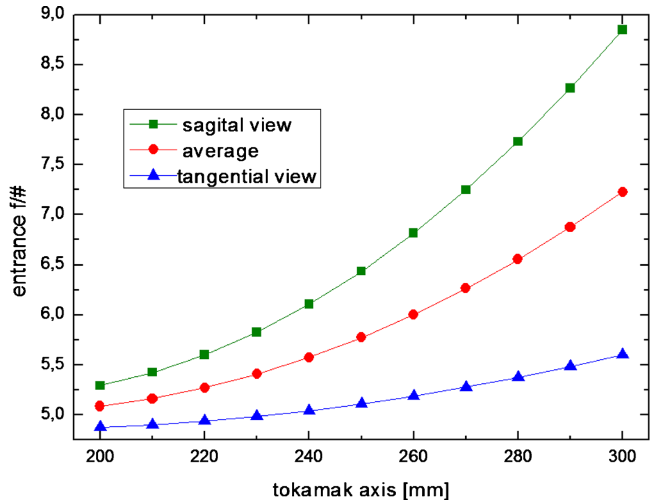

FIG. 5. (Color online) Entrance F/# changing along the vertical axis in tokamak.

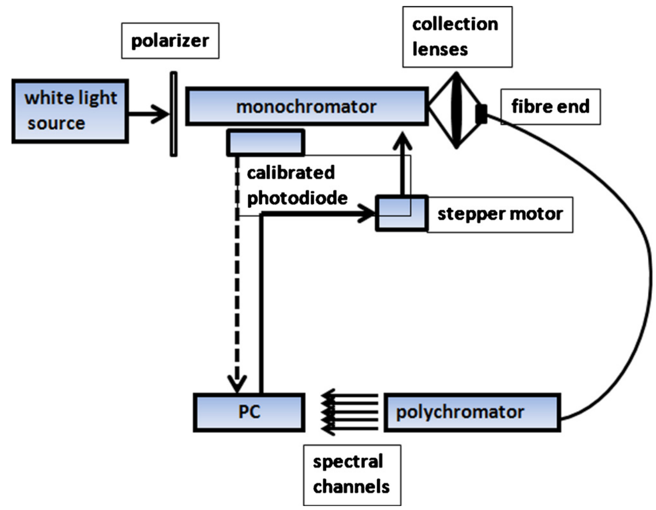

FIG. 7. (Color online) Experimental setup of spectral calibration of polychromators.

fibers (polymer cladding silica type, 210/230 μm diameter). The fibers are hexagonally close packed in bundles. The fiber bundles have been designed for both efficient collection of the scattered light and good stability of the output signal in relation to possible laser misalignment.[3] At the collection cell end, the cross-section of fiber bundle is a rectangle while at the polychromator end fibers form a circle of 3 mm diameter. Each fiber bundle consists of two separate arms with rectangular cross-sections at the collection cell end that are combined and randomized at the circular end (see Fig. 6). Scattered light from two adjacent spatial points in a plasma travels by the two arms to a single polychromator. Signals from both points are distinguished by different length of bundle arms (one arm is 13 m longer) causing a signal delay of 64 ns. This duplexing technique has been applied because of budget constraints since it reduces the number of polychromators by a factor of 2. In addition, one specific fiber bundle has been designed for control of lasers alignment. The bundle has one rectangular input and one circular end. At the rectangular input it is vertically divided into two parts. By comparing signals from both parts information about laser beam alignment can be obtained.

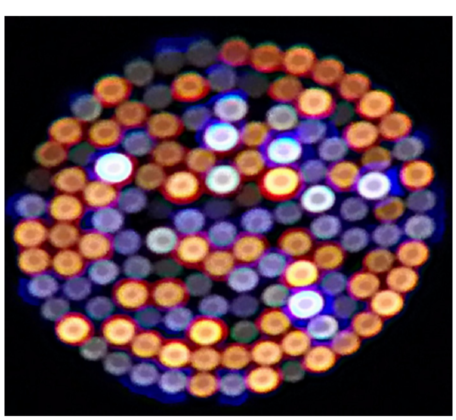

FIG. 6. (Color online) Randomized circular end of fiber bundle (two rectangular fiber bundle inputs were illuminated by different colors light sources).

V. POLYCHROMATORS

The scattered light is spectrally analyzed in 29 polychromators.[4–6] The light is analyzed by a set of five spectral filters and detected by Avalanche photodiodes. Parameters of spectral filters (central wavelength and bandwidth) have been determined[3] to enable measurement of electron temperatures in the range of 10 eV to 5 keV. A polychromator spectral calibration is performed using the optical setup illustrated in Fig. 7. Monochromator Oriel Cornerstone 260 with a grating line density 1200 mm^{-1} and blaze wavelength 100 nm equipped with a silicon detector (400–1100 nm range) is used. A calibrating light was halogen Mikropack HL-2000-FHSA light source (360–2000 nm). The light from the monochromator is passed through an optical fiber bundle. The calibrating light is then passed through the polychromator where it is split by the optical filters. The polychromators electronics produce fast and slow measurement of the light seen by each APD. The calibrating light is measured from the slow output. It is then turned into a measured voltage by the APDs. A power calibration is performed

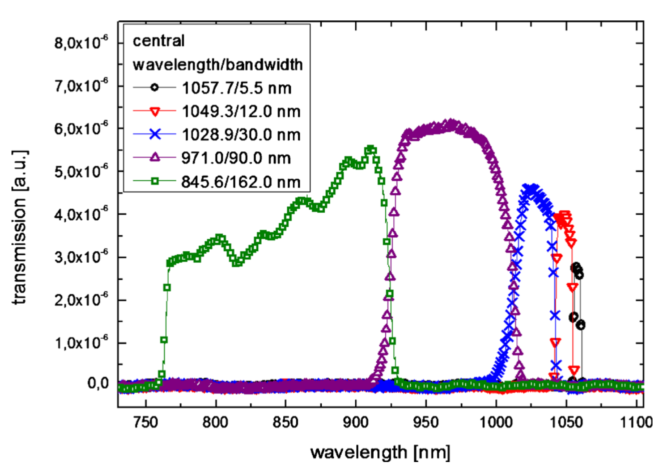

FIG. 8. (Color online) Spectral transmission of polychromator filters measured by a setup shown in the Fig. 7. The measured values have been calibrated by a white light source spectral output curve provided by a manufacturer.

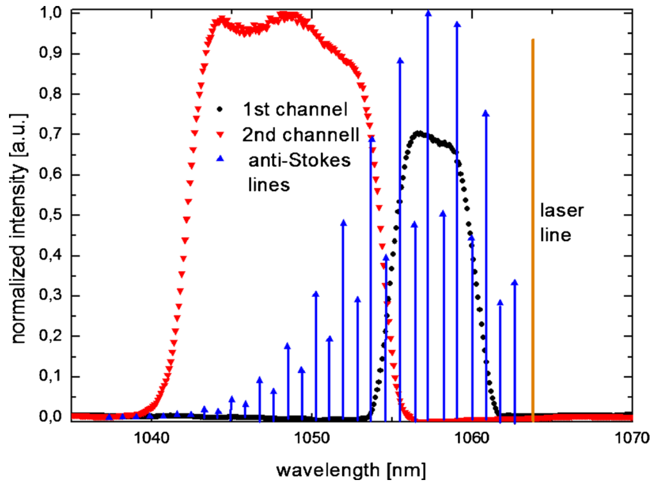

FIG. 9. (Color online) Expected Raman anti-Stokes lines from nitrogen for a vessel of 300 K temperature and normalized spectral transfer functions measured by polychromator.

by means of absolutely calibrated photodiode to measure the spectral intensity. Figure 8 shows transmission of each spectral channel of polychromator.

VI. ABSOLUTE CALIBRATION OF TS DIAGNOSTIC

Absolute calibration of the diagnostic will be performed by Raman calibration[7] at the Nd:YAG fundamental. Since the polychromator transmits blueshifted wavelengths only anti-Stokes lines (Raman lines below λ_L) are used for calibration. The COMPASS polychromators are designed with transmission filters close to the laser wavelength with very good rejection of the laser wavelength (optical density 4.8). On the COMPASS tokamak, nitrogen will be used as a calibrating gas. By iterating the nitrogen pressure and measuring the scattered signal, the system constants required for calibration can be determined. Figure 9 illustrates normalized spectral transfer function of two spectral filters of polychromator adjacent to the laser line together with expected anti-Stokes Raman lines.

The Thomson scattering diagnostic area is currently being assembled and tests performed. In the near future, port plug assembly together with collection objectives will be implemented on the tokamak and optical fibers installed in the backplane. Assembly of polychromators will be finished, calibration procedures performed and the final part of the laser beam path close to the tokamak will become operational. First tests of electron temperature measurement are planned by the end of 2010.

ACKNOWLEDGMENTS

This work, supported by Grants Nos. GA CR 202/09/1467, GA CR 202/08/H057, and MSMT LA08048, and by the European Communities under the contract of association between EURATOM and IPP.CR, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

[1] A. J. H. Donné and C. J. Barth, Fusion Sci. Technol. **49**, 375 (2006).
[2] R.Panek, O. Bilykova, V. Fuchs, M. Hron, P. Chráska, P. Pavlo, J. Stöckel, J. Urban, V. Weinzettl, J. Zajac, and F. Žáček, Czech. J. Phys. **56**, B125 (2006).
[3] P. Bilkova, M. Aftanas, P. Böhm, V. Weinzettl, D. Sestak, R. Melich, J. Stöckel, R. Scannell, and M. Walsh, “Design of new Thomson scattering diagnostic system on COMPASS tokamak,” Nucl. Instrum. Methods Phys. Res. A (submitted).
[4] Polychromators of the fourth generation developed at CCFE, Culham Science Centre, UK (original design by WSL-M. J. Walsh).
[5] R. Scannell, M. J. Walsh, P. G. Carolan, A. C. Darke, M. R. Dunstan, R. B. Huxford, G. McArdle, D. Morgan, G. Naylor, T. O. Gorman, and S. Shibaev, Rev. Sci. Instrum. **79**, 10E730 (2008).
[6] R. Scannell, M. Walsh, P. G. Carolan, N. J. Conway, A. C. Darke, M. R. Dunstan, D. Hare, and S. L. Prunty, Rev. Sci. Instrum. **77**, 10E510 (2006).
[7] R. Scannell, “Investigation of H-mode edge profile behaviour on MAST using Thomson scattering,” Ph.D. thesis, 2007.