

Laser system for high resolution Thomson scattering diagnostics on the COMPASS tokamak^{a)}

P. Bohm,^{1,2,b)} D. Sestak,¹ P. Bilkova,¹ M. Aftanas,¹ V. Weinzettl,¹ M. Hron,¹ R. Panek,¹ L. Baillon,³ M. R. Dunstan,⁴ G. Naylor,⁴ and M. J. Walsh⁵

¹*Institute of Plasma Physics AS CR, v.v.i., EURATOM IPP.CR, Za Slovankou 1782/3, 18200 Prague 8, Czech Republic*

²*Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University, Břehová 7, 11519 Prague 1, Czech Republic*

³*Ecole Nationale Supérieure d'Arts et Métiers, 51000 Châlons en Champagne, France*

⁴*EURATOM/CCFE Fusion Association, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, United Kingdom*

⁵*ITER Organization, CS 90046, 13067 St. Paul lez Durance Cedex, France*

(Presented 17 May 2010; received 17 May 2010; accepted 19 May 2010; published online 4 October 2010)

A new Thomson scattering diagnostic has been designed and is currently being installed on the COMPASS tokamak in IPP Prague in the Czech Republic. The requirements for this system are very stringent with approximately 3 mm spatial resolution at the plasma edge. A critical part of this diagnostic is the laser source. To achieve the specified parameters, a multilaser solution is utilized. Two 30 Hz 1.5 J Nd:YAG laser systems, used at the fundamental wavelength of 1064 nm, are located outside the tokamak area at a distance of 20 m from the tokamak. The design of the laser beam transport path is presented. The approach leading to a final choice of optimal focusing optics is given. As well as the beam path to the tokamak, a test path of the same optical length was built. Performance tests of the laser system carried out using the test path are described.

[doi:10.1063/1.3460450]

I. INTRODUCTION

The COMPASS tokamak, originally from CCFE, Culham, U.K., was reinstalled in Prague, Czech Republic.¹ First plasma was achieved in December 2008. COMPASS is a small tokamak ($R=0.56$ m, $a=0.2$ m, $BT=0.8-2.1$ T, $k=1.6$), but the shape of the plasma is ITER-like, thus experiments on COMPASS can be used for scaling of ITER modeling. COMPASS scientific program is focused on H-mode and pedestal studies. This is reflected in selection of diagnostics and their parameters.² One of the diagnostics is Thomson scattering (TS) system.³

TS for COMPASS facilitates two Nd:YAG (yttrium aluminum garnet) lasers of 30 Hz repetition rate and 1.5 J pulse energy each as source of intense radiation for scattering. The scattering region inside the plasma is divided into two parts: edge at 200–300 mm above midplane with spatial resolution of up to 3 mm and core at –30 to 210 mm above midplane with spatial resolution of 10 mm. The scattered light from both regions is collected by custom designed lenses and relayed by fiber bundles out of the tokamak area and into a number of polychromators. These polychromators divide the light into five spectral channels (using a set of filters), light from each of these channels is then imaged onto an Avalanche Photo Diode (APD) where it is converted to an elec-

trical signal. From each polychromator four of the five spectral channels are digitized, channels are chosen according to selected electron temperature range at corresponding spatial point. Signals from all 28 polychromators are digitized using a 120 channel 1 GS/s ADC system.

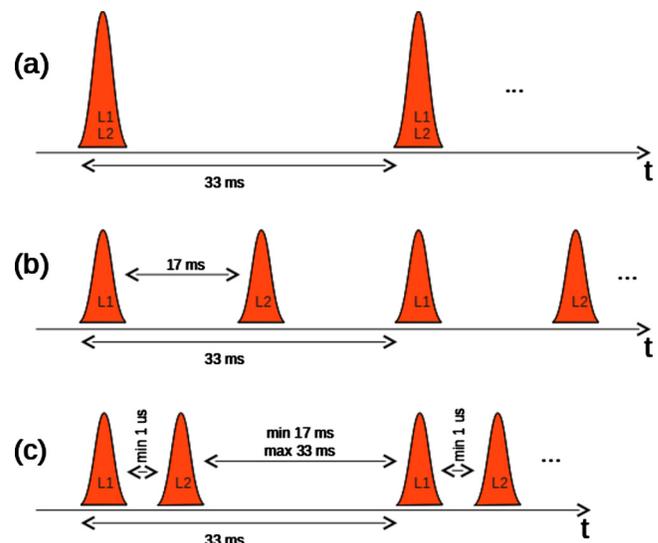


FIG. 1. (Color online) Laser operating modes.

^{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)} Electronic mail: bohm@ipp.cas.cz.

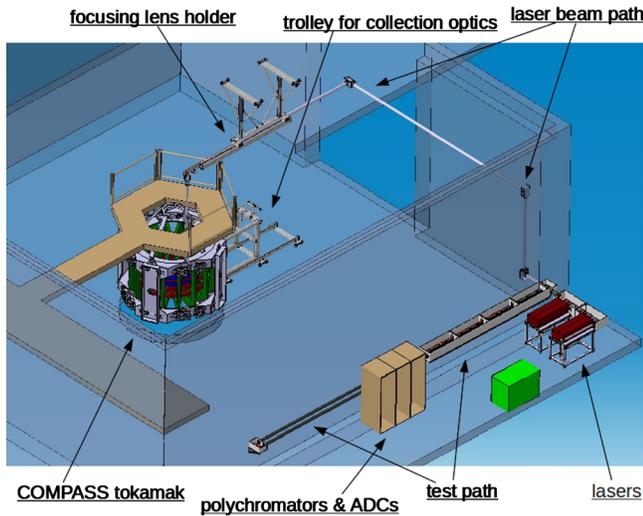


FIG. 2. (Color online) Laser beam path design—three-dimensional view.

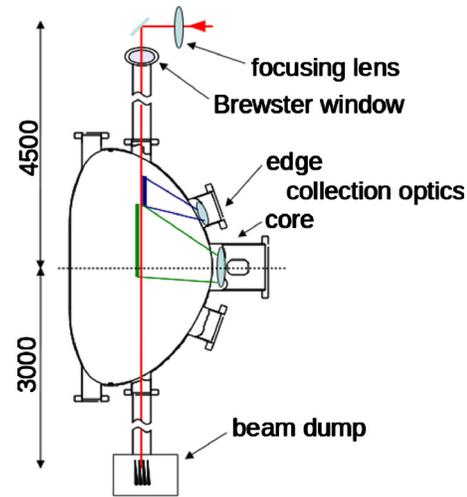


FIG. 4. (Color online) Laser passing through the tokamak—cross-section.

II. LASER SYSTEM DESIGN

A. Two lasers

A high energy laser source is needed for TS, since the TS effect has a very small scattering cross-section. Calculations of necessary laser energy for sufficient collected scattered photons were performed.³ To obtain the desired performance of the TS system in the pedestal region, laser pulse energy should be 3 J. This will be achieved by using two Nd:YAG lasers, each laser with 1.5 J pulses (polarized) at wavelength of 1064 nm and a repetition rate of 30 Hz.

Besides the regime when both lasers are fired simultaneously [Fig. 1(a)], the lasers can be fired independently when electron density is high enough to collect a sufficient number of scattered photons or when higher statistical error of measurement does not matter. Then the laser system can operate with double (60 Hz) repetition rate [Fig. 1(b)] or in “double-pulse” mode with arbitrary pulse separation from 1 μs to 16.6 ms [Fig. 1(c)]. The double-pulse mode allows observation of fast events in the plasma, like an evolution of the pedestal profiles during edge localized modes.

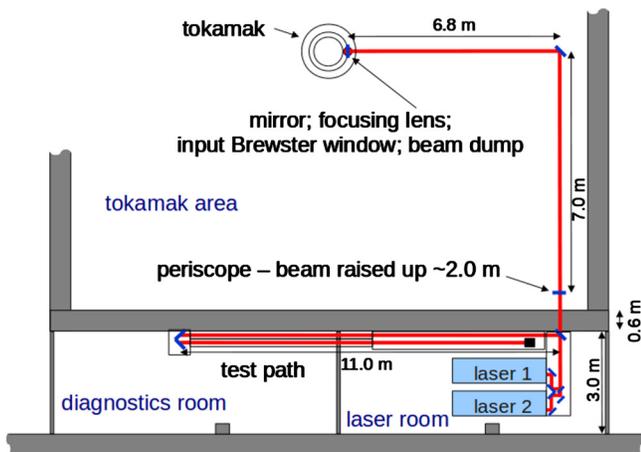


FIG. 3. (Color online) Laser beam path design—top view sketch.

B. Laser beam path

The laser system is located outside the tokamak area (Figs. 2 and 3). This allows easy access to the lasers and the possibility of carrying out adjustments during tokamak operations. The location of these lasers (outside the area) does mean that there is 20 m between the lasers and the focusing lens located above the tokamak vessel. The focused beams enter the tokamak vessel from the top via a Brewster vacuum window and through a pipe which has a number of apertures to reduce the stray light (Fig. 4). Once the laser beams have passed through the vessel they fall onto a laser beam dump located at the bottom of the vessel, this beam dump consists of a number of stainless steel blades (Fig. 5).

The broadening of the laser line is higher at bigger angles of scattering. As seen in Fig. 4, that would be achieved with the laser passing through the vessel from the bottom. This setup was rejected on behalf of opposite direction. The collection optics are looking upward, possible collected laser stray light will be minimized when the laser does not illuminate the upper part of tokamak vessel (i.e., not looking into the beam dump).

Both the laser beams are polarized horizontally; when firing the lasers simultaneously, it is not possible to combine the beams into a single colinear one. Therefore, the beams are located above each other at the beginning of the beam path (laser room), the centers are separated by 20 mm. The

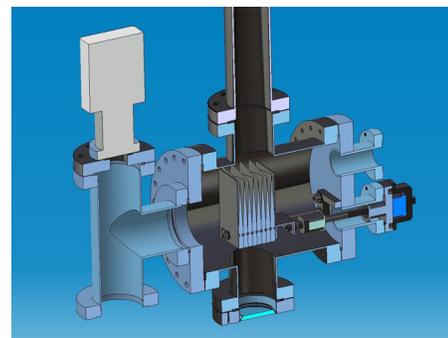


FIG. 5. (Color online) Beam dump in vacuum.

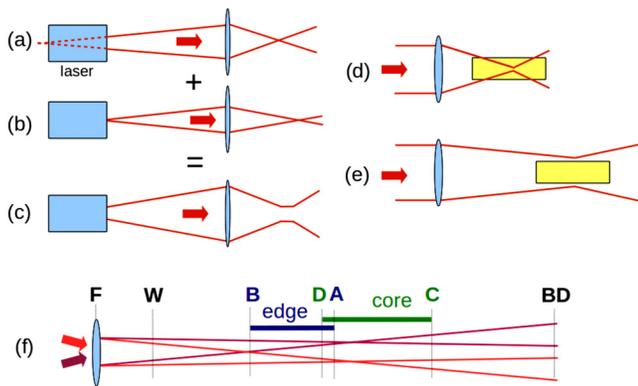


FIG. 6. (Color online) Focusing the beam. (a) Ideal geometrical focusing of uncollimated beam. (b) Effect of beam quality divergence. (c) Sum of effects (a) and (b) gives estimate of the beam diameter. (d) Examples of too short focal length lens (rectangle shows the observed region). (e) Examples of too long focal length lens (rectangle shows the observed region). (f) Sketch of two laser beams crossing on the lens and important positions along the beam after focusing, described in Table I.

two beams cross on the focusing lens, it means they are slowly converging to each other.

The mirrors used along the beam path were chosen to withstand the high energy load, the damage threshold is 10 J cm^{-2} at 1064 nm wavelength and 7 ns pulse duration. To minimize energy loss, reflectivity of the mirrors is $>99\%$, reflectivity for alignment He–Ne laser is 70% . The most of the mirrors in the laser path reflect at p-polarization, but when the beam height has to be changed, mirrors are reflecting at s-polarization. The mirrors have to be optimized for both polarizations.

C. Focusing lens

For optimal laser beam shape in the scattering region inside the plasma, the laser beam is focused by a positive lens. Focal length is given by length and width of the scattering region, beam parameters like diameter on the focusing lens and divergence and by mechanical possibilities of the tokamak. The overall length of the viewing chord on COMPASS TS is 330 mm . The width of the laser beam should be minimized along the whole region of this viewing chord. The width of the region, from which light is collected, should be minimized to minimize the collected background light. The laser beam has to fit into this width, including tolerance for the laser beam shift. For both edge and core regions the width of observed region in the plasma is 5 mm .

For estimating beam size around focus, Gaussian optics treatment is not necessary as the laser beams are highly multimode, i.e., not diffraction limited. Geometrical optics can be used. Basically, two aspects give the beam diameter: (1) Focusing of the beam, where the diameter linearly decreases with distance from the lens, reaching a minimum at the focus, and then increases again. If the beam is not ideally collimated, the minimum diameter is not at the focal distance after the lens, but an image of the virtual source of the beam [Fig. 6(a)]. (2) Beam divergence, given by beam quality, the beam diameter linearly increasing from the laser source and reaching zero at the laser source image position [Fig. 6(b)]. Summing the diameters from these two effects, the diameter after the focusing lens is obtained [Fig. 6(c)]. Diffraction limited beam size at the focus was neglected in the calculations, for $f=+3 \text{ m}$ it is below 0.4 mm . From this perspective, optimal focal length of the lens is a trade-off between the narrow cone of the ideal focused beam and beam diameter rising with long focal length because of divergence [Figs. 6(d) and 6(e)]. Calculations showed the optimal focal length for COMPASS TS lies around $f=+3 \text{ m}$. Finally, $f=+2750 \text{ mm}$ was chosen because of limitation by tokamak support structures. It is a plano-convex lens with antireflection coating and 2 in. (50.8 mm) diameter. Since two beams are crossing on the lens, the distance between the lasers increases the beam size in the tokamak radial direction gradually. In Fig. 6(f) is the sketch of the situation after focusing and Table I shows beam sizes at the important positions, when focusing two beams crossing on the lens. The beam size at the laser source output is 10 mm , the laser is 20 m away from the focusing lens. The beams are uncollimated (0.3 mrad divergence), feature 0.3 mrad beam quality divergence, these values were obtained from fitting the real measured beam size profile (see Sec. III). This means it easily fits into the region observed by the collection optics; on the other hand, with too narrow beam, fiber bundle throughput inhomogeneity can take effect. Therefore, position of the beam waist was shifted before the core TS region into the edge region. The edge region collection optics smooth the narrow beam over the fiber bundle.

D. Test path

A test path was designed and installed, reproducing the length of the beam path from lasers to the tokamak (Figs. 2 and 3). This allows testing the laser setting and characterization of the beam independently on the tokamak operation. Testing the beam in the test path is safer for experimental

TABLE I. Beam size after focusing estimation at important positions, as sketched in Fig. 6(f). Two beams crossing on the lens. All sizes in millimeter.

	A	B	C	D	F	W	BD
	Edge region	Edge region	Core region	Core region	Focusing lens	Input window	Beam dump
Position in tokamak	200	300	−30	210	3150	2850	−2000
Beam size, toroidal direction	0.7	0.9	1.6	0.7	22.0	19.8	16.1
Beam size, radial direction	3.7	3.8	4.7	3.6	22.0	20.1	21.3

devices, minimizing the possibility of breaking, for example, the input vacuum window on the tokamak because of misalignment of the laser. The mimic path can include the focusing lens and other optical components, like input window or apertures. When testing focusing, the beam energy has to be reduced by reflection from uncoated optical wedge. The beam profile can be observed also in the positions not accessible on the real path.

III. TESTS

The laser system was installed in October 2009. At first, the Nd:YAG lasers were aligned to He–Ne lasers and beam profile was observed over 25 m path. Tests with the focusing lens ($f=+3436$ mm) were also performed. The lasers were operated at full energy; however, the pulse energy was reduced from 1.5 J to 10 mJ by partial reflection from uncoated optical wedge to avoid electrical air break-down at the focus. Position of the beam waist was found at 4.8 m distance from the lens. The beam spots were taken on a thermal paper, and the region around the focus was scanned to compare the calculated beam size and the actual beam size. The beam diameter at the focus is approximately 0.9 mm. From the measurement beam divergence was estimated and used to specify the calculations of optimal focusing lens configuration. The beam waist diameter is narrower than was estimated from manufacturer specifications. Besides the simple method of using thermal paper, other methods like knife-edge or CCD camera analysis are planned to acquire more precise information about the beam profiles.

IV. CONCLUSION

Installation and implementation of the laser system for COMPASS TS diagnostic is proceeding. The test path has turned out to be very useful at this stage; the design of the beam path to the tokamak can be verified conveniently. The vacuum part of the beam path is designed and will be tested in the test path to optimize positions of stray light reducing apertures and beam dump position. Then the first test of TS measurements is planned in summer 2010.

ACKNOWLEDGMENTS

The COMPASS TS team would like to express thanks to MAST TS team. Also thanks to Mikhail Kantor from FOM, The Netherlands (TEXTOR tokamak in Jülich, Germany).

The work was performed in the frame of the grants of AS CR (Grant No. AV0Z20430508), GA CR (Grant Nos. 202/09/1467 and 202/08/H057), MSMT (Grant No. 7G09042), and was supported by the European Communities under the contract of Association between EURATOM and IPP.CR within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

¹R. Pánek, O. Bilyková, 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).

²V. Weinzettl, lecture on COMPASS Programmatic Conference, IPP, ASCR, v.v.i. Prague, 2–3 April 2009, available at <http://server.ipp.cas.cz/~vwei/work/diagnostics2009.pdf>.

³P. Bílková, M. Aftanas, P. Böhm, V. Weinzettl, D. Šesták, R. Melich, J. Stöckel, R. Scannel, and M. Walsh, “Design of new Thomson scattering diagnostic system on COMPASS tokamak,” *Nucl. Instrum. Methods Phys. Res. A* (in press).