
EFDA–JET–CP(04)01/05

R. Pasqualotto, P. Nielsen, C. Gowers, M. Beurskens, M. Kempenaars,
T. Carlstrom, D. Johnson and JET-EFDA Contributors

High Resolution Thomson Scattering for JET

High Resolution Thomson Scattering for JET

R. Pasqualotto^{1,2}, P. Nielsen, C. Gowers³, M. Beurskens⁴, M. Kempenaars⁴,
T. Carlstrom⁵, D. Johnson⁶ and JET-EFDA Contributors

¹*EFDA-CSU Culham, Culham Science Centre, Abingdon, OX14 3DB, UK*

²*Consorzio RFX - Associazione Euratom-Enea sulla Fusione, Corso Stati Uniti 4, I-35127 Padova, Italy*

³*EURATOM-UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK*

⁴*FOM-Rijnhuizen, Ass. Euratom-FOM, TEC, PO Box 1207, 3430 BE Nieuwegein, NL*

⁵*General Atomics, P.O.Box 85608, San Diego, California 92186-5608, USA*

⁶*Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA*

Preprint of Paper to be submitted for publication in Proceedings of the
15th HTPD Conference,
(San Diego California, USA 18-22 April 2004)

“This document is intended for publication in the open literature. It is made available on the understanding that it may not be further circulated and extracts or references may not be published prior to publication of the original when applicable, or without the consent of the Publications Officer, EFDA, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK.”

“Enquiries about Copyright and reproduction should be addressed to the Publications Officer, EFDA, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK.”

ABSTRACT.

A new Thomson scattering system is being developed for JET, with 15 mm spatial resolution and a foreseen accuracy for temperature better than 15% at a density of 10^{19} m^{-3} . This resolution is required at the internal transport barrier and edge pedestal and it can not be fully achieved with the present LIDAR systems. The laser for this system is Nd:YAG, 5 Joule, 20 Hz. Scattering volumes from $R= 2.9 \text{ m}$ to $R= 3.9 \text{ m}$ are imaged onto 1 mm diameter fibres, with F/25 collection aperture. Two fibres are used per scattering volume. Using optical delay lines, three scattering volumes are combined in each of the 21 filter polychromators. The signals are recorded with transient digitisers, which allow the combined time delayed signals to be resolved. Knowledge of the time delay between signals allows the use of correlation techniques in determining signal levels. The AC output of the amplifier is used, which tolerates a higher level of background signal without affecting dynamic range. The noise resulting from plasma light is determined directly.

INTRODUCTION

A new High Resolution Thomson Scattering (HRTS) diagnostic is being developed for the Joint European Torus (JET) with the purpose of better resolving the steep gradients of electron temperature (T_e) and density (n_e) at the plasma edge and at the Internal Transport Barrier. This is a conventional 90° geometry system, which measures profiles with up to 63 points along the outer radius of the plasma ($R = 2.9\text{-}3.9 \text{ m}$) at 20 Hz, with a resolution of 15 mm. It will complement the existing main and edge Light Detection and Ranging (LIDAR) systems, which have limited spatial resolution of respectively 120 and 80 mm. The recently upgraded edge system achieves equivalent 15 mm resolution in the mid-plane with flux surface mapping, but with limited spatial coverage [1].

1. SYSTEM DESCRIPTION

The components of the system and their positions inside the Torus Hall are shown in Fig.1. The Nd:YAG laser is a custom laser, built from existing commercial laser modules. [2] The laser will have a single oscillator and two amplifier branches, which produce two parallel beams closely apart. The energy per pulse in one polarisation is 5 Joule at a repetition rate of 20 Hz. The laser is situated in the roof-laboratory above the JET Torus Hall. The double laser beam is combined with the Edge LIDAR laser beam and enters the Torus Hall through the same penetration. The beams from the two systems are 10 cm apart once they reach the Torus mid-plane. The HRTS beam is then directed by a mirror to enter the Torus through a window on the main pumping port and aimed slightly downwards to strike the inner vessel wall at the mid-plane. A beam dump made of a stack of vertical stainless steel blades is installed here. The double beam size is 30 mm x 15 mm at the input window and 15 mm x 7 mm at the dump.

The scattered light is collected through an upper main vertical port. The distance of this port to the the collection efficiency only of the inner positions, which already benefit from higher density. Edge positions on the other hand would be vignetted anyway by the base of the long narrow port.

[3] The window assembly is in fact a double window tube made of two wedged windows about 50 mm apart with an interspace at controlled pressure for JET vacuum safety. The tube is welded onto a 400 mm diameter flange which can be remotely handled. To protect the window against plasma deposition the assembly has a simple mechanical shutter on the plasma side.

An optical bench above the window holds an imaging lens and two motorised mirrors (Fig. 3a). Following the window is a plano-convex fused quartz lens of 3 m focal length. The lens images the scattering volumes to the Torus Hall nearest wall. Two mirrors after the lens direct the image towards the wall and rotate it from vertical to horizontal. The precise control of the tilt of these two mirrors allows the final alignment of the collection system. The lens is the only refractive element in the primary collection system. The chromatic aberration resulting from the lens causes a slight blur of the image, which is acceptable. The thickness of the lens is similar to the thickness of the windows: radiation darkening is not an issue for this thickness of quartz in the expected radiation fluxes for JET plasmas.

The optical bench is supported off the transformer limbs. This is partially to avoid the thermal and vibrational motions of the vessel and partially not to load the vertical port with this weight. The weight could break the port in case of a disruption. It also protects the optics against the forces induced during a disruption. The transformer limbs do move a small amount during a discharge but much slower. This motion causes a slight movement of the image on the wall. The motion can be in either upwards or downwards direction, depending on the time during the discharge. Two phenomena play a role, the magnetostriction of the transformer yoke and the thermal expansion of the central column. The resulting movement of the image is estimated to be always less than 4 mm, which is within the tolerance of the optical system. Four stepper motors are used to align the mirrors. The magnetic field strength at the position of the mirrors is estimated in some cases to exceed 0.3 Tesla, which is more than can be accepted for the motors. The motors are therefore placed about 1 m above the table where the field strength is much less. The motors operate the mirrors through long shafts connected with suitable flexible joints.

A 5 m long optical bench is mounted on the Torus Hall wall. It holds 126 (can be expanded to 150) tightly spaced small mirrors and an equal number of optical fibres (Fig. 3b). The mirrors are 30° off-axis paraboloidal rectangular mirrors 30 mm wide x 40 mm high. The fibre ends are located near the focal point of the mirrors. The distance to the wall is about 15 m and the image magnification is $M \sim 4$. The mirrors are arranged on a circle of about 15 m radius such that the axis of each mirror telescope is pointing to the imaging lens. The scattering volumes from $R=2.9$ m to $R=3.9$ m are imaged onto the mirrors and each mirror in turn images the lens onto its own fibre. Two fibres form a single scattering volume. The spatial resolution in the plasma is therefore 15 mm.

The viewing port allows in principle observation of the plasma inside $R=3.0$ m (Fig.2), but scattering measurements inside this radius would be limited mainly by higher background plasma light level from the divertor, which can be up to 50 times more intense particularly during ELM's. [4].

The fibres are fed to 21 filter spectrometers through a small existing penetration in the Torus Hall wall. Each spectrometer receives 6 fibres, each scattering volume being defined by two fibres. To distinguish between the three scattering volumes, the signal of two of the fibres is delayed by 50 ns and the signal of another two fibres by 100 ns. The delays are accomplished by a number of patch fibres. This grouping seems a good compromise between spatial resolution and acceptable signal to noise ratio. If the signal level is too low it will be possible to combine more fibres with the same delay albeit at the sacrifice of spatial resolution.

The fibres are 1 mm diameter hard clad fibres with a numerical aperture of 0.37. The fibre size is slightly larger than the image of the collection lens: nominal image size is 0.8 mm diameter. In fact the image is wedge shaped being the size of the aperture of the port in the radial direction and only about half this size in the toroidal direction, making alignment slightly less critical. The numerical aperture is somewhat better than immediately required by the solid angle given by the system. Measurements of transmission vs angle of incidence indicate that this is necessary to minimise transmission losses. To minimise the insertion loss of the patch fibres the connection will be made using a small drop of index matching fluid. Tests have shown that this reduced the insertion loss from 10% to about 5%.

The filter spectrometers will be delivered by General Atomics [5] (GA), while the amplifiers for the detectors will be provided by Princeton Plasma Physics Laboratories (PPPL), a modified version of their standard model. [6] The spectrometers are 4 channel filter polychromators. The design is fairly standard and used at a number of experiments around the world. There will be two sets of filters. Seven spectrometers will be fitted with filters suitable for low temperatures (50 eV – 5 keV). The remaining spectrometers will have filters to allow measurements of 500 eV - 20 keV. Stray light suppression is better than 10⁵. The detectors are avalanche photodiodes (APD) with good spectral sensitivity even at the laser wavelength.

The transimpedance amplifiers provide two outputs: a DC output for plasma background light and an AC output for scattering signals, with a gain respectively of 10⁴ and 10⁵ V/A. Both are 50 Ω outputs. The bias voltage of the APD will be preset to a nominal avalanche gain of 75 via an internal potentiometer. The AC channel has a lower frequency cut-off corresponding to 5 μs, allowing a high level of background light without affecting the dynamic range. The upper frequency limit is such to allow the recording of three time-delayed signals, 50 ns apart, each with a pulse width of about 15–20 ns.

The AC output is fed into 1 GS/s, 150 MHz, 8 bit transient recorders. [7] The use of transient recorders allows determination of the three time-delayed signals and the level of background noise without knowing the actual DC level. Fitting to a known response function allows a more accurate determination of the signal level and directly gives the error estimate of the signals. [8] The DC outputs will be recorded by a slower recording system. This signal is used to assure that the system is within dynamic range.

2. PERFORMANCE SIMULATION

The potential performance of the HRST diagnostic has been evaluated by computing the expected measurement errors of T_e and n_e (fig. 4). This is done by deriving the expected signal levels at a given temperature and by calculating their uncertainty on the basis of the photoelectron statistics, the plasma background light variation and the detector noise. A number of parameters determine the signal level. The overall transmission of laser and collection is estimated 0.2. The laser produces 5 J/pulse. The collection optics achieve a solid angle of F/25. Density is set to $1 \times 10^{19} \text{ m}^{-3}$. The detector-amplifier noise is defined by the excess noise factor F and by the noise equivalent number of photoelectrons in a 100 ns time slice, [9] set respectively at 3 and 50. The background signal is considered not relevant. In these conditions and with the selected transmission functions it turns out that the expected relative errors of T_e and n_e are respectively 7-13 % and 4-7 %.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to Bill Baker of Consorzio RFX for the helpful collaboration on the critical issue of the design and procurement of the collection window.

REFERENCES

- [1]. M. Kempenaars et al., this conference
- [2]. Quantel SA, Les Ulis Cedex, France
- [3]. R. Pasqualotto, P. Nielsen, Proceedings Intern. Conf. On "Advanced Diagnostics for Magnetic and Inertial Fusion", Varenna, 3-7 settembre 2001
- [4]. C. Gowers et al., Proceedings Intern. Conf. On "Advanced Diagnostics for Magnetic and Inertial Fusion", Varenna, 3-7 settembre 2001
- [5]. T. N. Carlstrom et al., Rev. Sci. Instrum. **63**, 4901 (1992)
- [6]. D. W. Johnson et al., Rev. Sci. Instrum. **72**, 1129 (2001)
- [7]. Le Croy model PXD-114
- [8]. B. Kurzan et al., Plasma Phys. Control. Fusion **46**, 299 (2004)
- [9]. R. Pasqualotto, P. Nielsen, L. Giudicotti, Rev. Sci. Instrum. **72**, 1134 (2001)

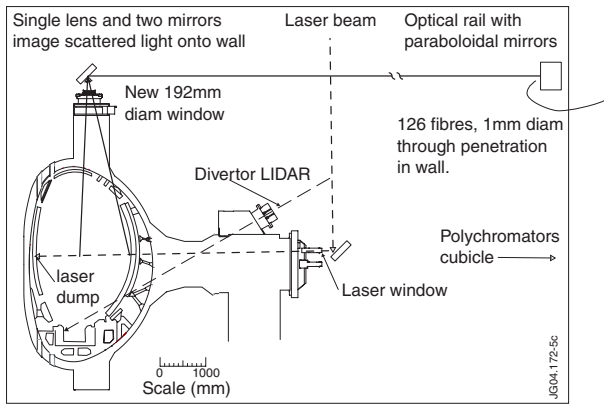


Figure 1: General layout of the HRTS system components in Torus Hall.

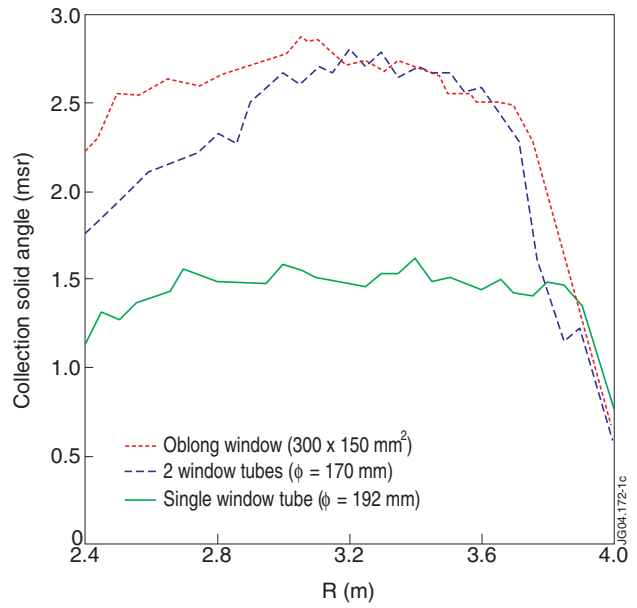


Figure 2: Solid angles of collection optics versus radial position of scattering volumes.

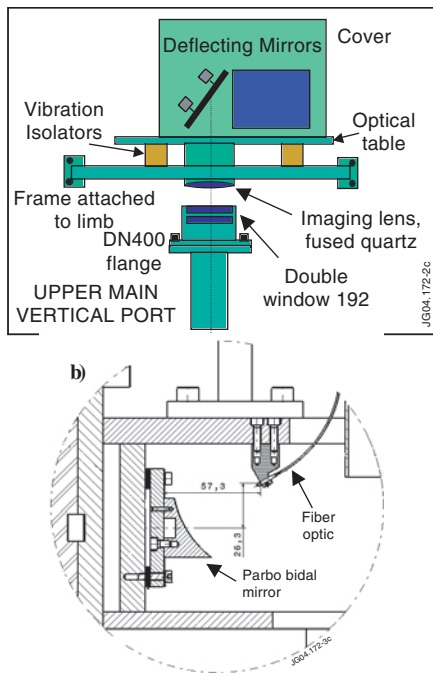


Figure 3: Schematic of the collection optics: a) on the upper vertical port, b) on the Torus Hall wall

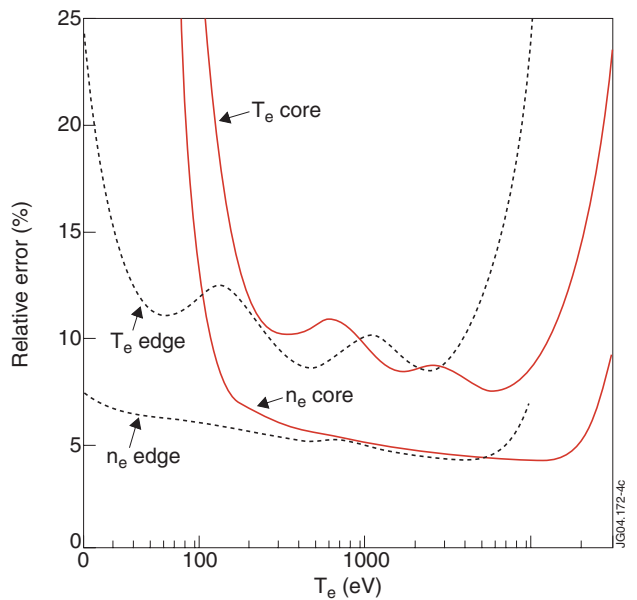


Figure 4: Expected T_e and n_e accuracy for the core and edge polychromators.