Performance Evaluation of ITER Thomson Scattering Systems

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Abstract. Electron temperatures in ITER of up to 40keV and densities of up to several times 10^{20} m^{-3} are expected. Thomson Scattering is a proven technique for making these measurements. Successful deployment of such a system requires that all components maintain adequate performance throughout the lifetime of the experiment. The parameters accessed by ITER lead to very different operating conditions from existing devices. These range from a high dose neutron environment to in-vacuum mirrors and the extremely long plasma discharges. This paper will assess the expected performance of the proposed systems and highlight critical areas.

1. Introduction

Thomson scattering (TS) systems are being designed to be integrated to ITER where the electron temperatures expected are substantially higher than any existing tokamak [1], [2]. This diagnostic technique is needed for a wide range of physics studies, and some real-time plasma control, so high accuracy and, especially, high reliability is needed. The specified errors in such systems are generally between 5% and 10%. Their successful deployment requires that all components maintain adequate performance throughout the lifetime of the experiment or some other appropriate time-scale. This time-scale can be different for different parts of the system; where immediately accessible components can in principle have short maintenance intervals (as little as weeks for out of machine areas), while less accessible components may be required to have very long intervals (~5-10 years for some in machine components). The parameters accessed by the development of ITER lead to very different operating conditions from present devices. Amongst the new challenges are the high dose neutron environment, in-vacuum mirrors and the extremely long plasma discharges.
The main systems being considered for ITER cover the divertor region (provided for ITER by the Russian Federation - RF), the mid-plane core (provided to ITER by the EU) and the edge plasma (Provided to ITER by Japan - JA). Two general techniques are available to get spatial information – LIDAR [1] using time-resolved detection of backscattered light from very short laser pulses, and imaging systems where the laser beam is viewed from an angle. Detailed measurement requirements are given in the ITER Diagnostics Table of Requirements [3] and in [4]. To support the measurements of the data to the highest temperatures, work to examine the robustness of TS theory for ITER operating scenarios has been carried out. A performance assessment of the various systems is also given. Key items in all the systems

will be the lasers used to illuminate the plasma and efficiency of light collection and detection. For the light collection, the first mirror must endure challenging conditions. A generic approach to this problem is being addressed by [5]. For the light detection, suitable detectors are required. This is specifically important to the LIDAR [1]. The imaging systems have less demanding bandwidth and detector requirements but need high space resolution and accuracy, in the presence of strong background light in the divertor especially. The necessity to measure low-temperature (T_e~ 1eV) TS profiles in the divertor and efficient tuning-out of stray light at the lasing wavelength requires a spectral analyser with special features.The design of these systems for ITER requires urgent R&D in many areas. In this paper we focus on the optics, lasers and detectors and do not address the engineering aspects.

2. High Temperature Thomson Scattering Theory Review

Incoherent Thomson scattering has become a reliable electron temperature and density diagnostic for modern tokamaks. In these devices, temperatures exceeding 10 keV have been achieved and temperatures as high as 40 keV are predicted for next step devices. At these temperatures, the electron velocities are a substantial fraction of the velocity of light causing two relativistic effects to become significant. Firstly, a ‘blue shift’ in the scattered spectrum which increases with temperature is obtained. As a result, the spectrum is no longer symmetric about the incident wavelength nor is it symmetric about the position of the shifted peak. Secondly, there is a change in the polarisation of the scattered light which results in a reduction of the spectral intensity [6], [7] in the laser polarisation.

In general, it can be assumed, as is the case for most Thomson scattering diagnostics, that the incident wave electric field $\mathbf{E}_i$ is perpendicular to the scattering plane and only the component of scattered field along the direction of $\mathbf{E}_i$ is measured. The incoherent Thomson scattered power per unit solid angle per unit angular frequency can be written as [7]

$$\frac{d^2P}{d\Omega_s\, d\omega_s} = r_e^2 \int \langle S_i \rangle d^3\mathbf{r} \int \left| 1 - \frac{(1-\cos\theta)\beta_e^2}{(1-\beta_i)(1-\beta_s)} \right|^2$$
$$\times \left| \frac{1-\beta_i}{1-\beta_s} \right|^2 \left(1-\beta^2\right) f(\beta)\, \delta(\mathbf{k}\cdot\mathbf{v}-\omega)\, d^3\boldsymbol{\beta}$$

where r_e is the classical electron radius, $\langle S_i \rangle$ is the mean incident Poynting vector, θ is the scattering angle, β_i and β_s are the components of the electron velocity ($\boldsymbol{\beta}$) in the direction of the incident and scattered radiation wave vectors, respectively, β_e is the component along the direction of the incident electric field, $\mathbf{k} = \mathbf{k_s} - \mathbf{k_i}$, and $\omega = \omega_s - \omega_i$ where $\mathbf{k_s}$, $\mathbf{k_i}$, ω_s, and ω_i refer to the wave vectors and angular frequencies of the scattered and incident radiation, respectively, and $f(\beta)$ is the relativistic electron velocity distribution.

Sometimes, the first term in the velocity integral, namely, the

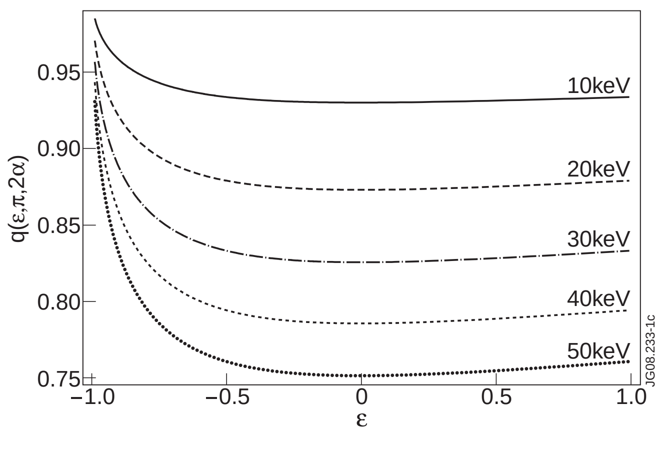

FIG. 1: Depolarization term as a function of normalized wavelength shift for LIDAR scattering at different electron temperatures.

depolarisation term is ignored in order to derive an analytical formula, which is acceptable for low temperature plasmas where its value is approximately unity. At high temperatures, however, this approximation is no longer valid as can be seen in Fig. 1, where the case for LIDAR scattering is examined. It shows a significant decrease from unity as the temperature increases, reaching a value of approximately 0.8 at 40 keV. For this reason, the depolarisation term must be included in the analysis of data from high temperature plasmas [8].
For electron temperature measurements by incoherent Thomson scattering (TS), a Maxwellian electron velocity distribution is usually assumed to interpret the scattered spectrum. However, recent experiments [9], [10] have suggested that this assumption may be violated in the presence of electron heating, which can generate fast electrons leading to a high energy tail in the electron distribution function. It has been suggested that the deviation of the distribution function from a Maxwellian is the reason for the observed discrepancy between Thomson scattering and electron cyclotron emission temperature measurements during heating. In some cases T_{eTS} can be up to 15-20% lower than T_{eECE} [9]. However, if one determines the electron temperature ignoring the presence of the high energy electrons, it would cause one to overestimate the electron temperature and as a result, the discrepancy cannot be purely due to the effect of high energy electrons on the TS diagnostic [11]. Other experiments have implied the presence of a non-Maxwellian electron bulk distribution because of additional heating and this may yet prove to cause such a discrepancy [10]. As much higher temperatures for the ITER plasma are expected, the urgency to thoroughly investigate the cause of this temperature discrepancy is of paramount importance.

3. Core Temperature and Density Measurements

The limited access in ITER means that the laser and collection optics need to be in the same port, see Fig 2. The laser entry is positioned to ensure that the critical input window is well clear of the plasma environment. The performance goals are demanding and require a fully integrated approach to the design. For example the core LIDAR system measures backscattered light which is strongly blue-shifted at the high temperatures. This has led to a

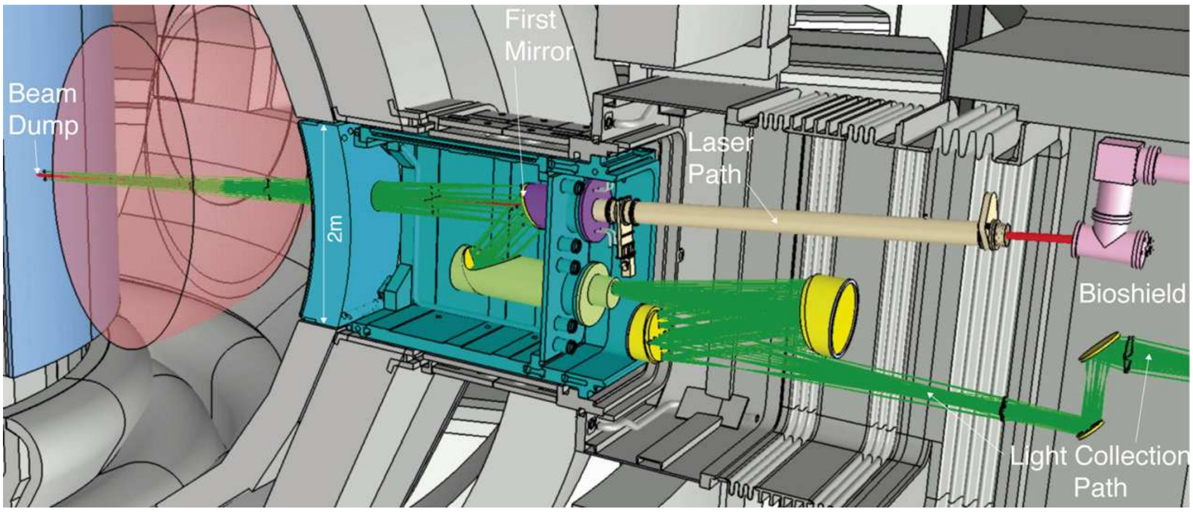

FIG. 2: Core LIDAR TS system showing the laser launcher and the light collection path from the plasma.

long wavelength laser (e.g. NdYAG at 1064nm) being favoured, and even this requires the collection optics to transmit into the near UV (~300nm ideally). This very wide spectral range has a critical effect on the optical system and the detectors, which can be met with the use of rhodium or equivalent material for the first collection mirror, and development of fast high efficiency detectors in the near infra-red (850-1300nm). At shorter wavelengths efficient fast detectors exist and need only modest improvement (some are already well proven from use on the JET LIDAR systems [12]). State of the art detectors in the >850nm near-infrared spectral region have many of the physics attributes required for use in the LIDAR system (sensitivity, area) but these are not presently developed enough for use on ITER. Two types [13] of detectors are required for this spectral range but for use in ITER LIDAR TS both require some technology advancements. The first is based on the technology of the present night vision image intensifers: by carefully controlling the composition of the ternary alloy $In_xGa_{1-x}As$ it appears possible to produce NIR photocathodes with a QE of the order of 5% up to a cut-off wavelength of l~ 1000 nm. The second is based on the technology of the transferred electron (TE) detector. These devices use an active, externally biased, InGaAsP/InP photocathode with a QE in excess of 25% up to λ=1.33 μm, but requires substantial improvements to the speed and active area to achieve the required characteristics.

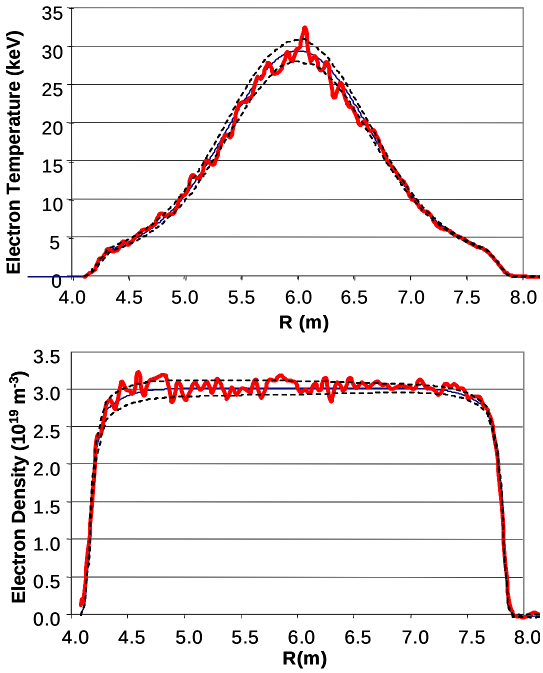

FIG. 3: Simulation of the expected performance of the core LIDAR system.

Special tools have been developed to analyse the performance of the complete system from laser to detector, with all the spectral and transmission characteristics utilised [14]. A Monte Carlo technique is used to estimate the resultant accuracy, and an example is shown in Fig 3 for the core LIDAR where a combination of a 5J, 250ps laser pulse, ~250-300ps response time detectors of 4-5 types to cover the spectral range and an optimised 6-8 channel polychromator allows the target accuracy and space resolution to be met. The ITER specification of 10ms time resolution [2] is based on several arguments (e.g. instability and transport analysis, same order as the actuator time) is a challenging target for such a high energy laser. At present, the plan is to achieve the specification by utilising a number of lasers. Estimations suggest that 15 Hz versions could be realizable; hence 7 lasers would be required. For the core LIDAR system, reliability [15] is of paramount importance and redundancy in design must be incorporated where possible. Typical operation of a multi-laser system on the MAST device has shown that out of 4 lasers, at least 1 laser was available almost 100% of the time while all 4 lasers were available >70% of the time (this corresponds to an individual laser availability of about 92% per plasma shot). Translating this simply to ITER would give 5 or more lasers available more than 98% of the time, but all 7 lasers only 56% of the time.

It has been shown by detailed neutronics studies, backed up by irradiations that even with many years of ITER operation, silica (e.g. the Russian-developed KU-1 material) retains good transmission across the spectral band for the core LIDAR, and adequately low absorption to be used as a laser window.

4. Divertor Temperature and Density Measurements

The diagnostics of Thomson scattering in the divertor (see Fig.4) offers the potential of determining localized and detailed information about key electron parameters in a most challenging domain. Monitoring of electron temperature and density for adjustment of the divertor operation mode is one of the foreground tasks for the divertor TS. The topics of high priority regarding the divertor and SOL, which also require accurate measurements of T_e and n_e, include SOL parameters, dynamic behavior of ELMs and quantitative interpretation of spectroscopic measurements. The requirements for this system are to measure temperatures between 0.3 - 200 eV at densities above 10^{19} m^{-3} every 1ms.

The graph in Fig 5 shows the error analysis for the Outer leg system with a 6-channel grating polychromator (one of two spectral devices to be used). This calculation was carried out for the following conditions: laser pulse energy 1.5 J, 2.5 ns, electron density 10^{19} m^{-3}, total optical transmission 5% and background light 200 photon/nm (assumes Bremsstrahlung radiation).

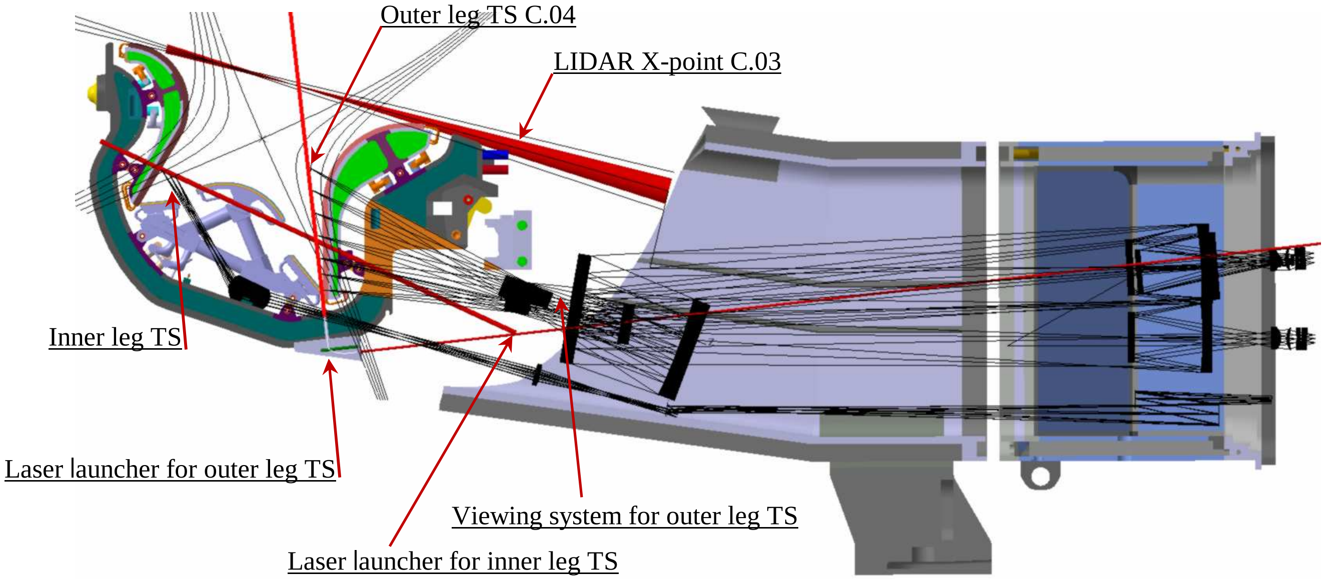

FIG 4: Divertor TS system (main system detailed in this paper is Outer leg TS C.04).

During the transition from the concept to a detailed design, significant progress has been made in the integration of the construction with the in-vessel components and the novel designs of divertor cassettes, diagnostic racks and feedthroughs in the vicinity of the divertor port closure plate. Particularly, current solutions for the rest of the divertor preclude sizable cutouts [16] in divertor cassettes and a 20mm gap between neighbouring cassettes has to be used instead. It means, unfortunately, that the X-point LIDAR (see Fig. 4) is not possible now. On the other hand, owing to a recent agreement to allocate space for the first optics (e.g., mirrors) on the port wall, a novel geometry extends the diagnostic capability also for plasmas of inner leg. The diagnostic layout is favorable both for collecting scattered light from the outer divertor leg, and for launching a probing laser beam to the inner leg from the area of the first collection mirror of the outer leg TS. The scattered light from the inner leg area will be collected by the optics located under the dome in the special mirror rack and then transmitted

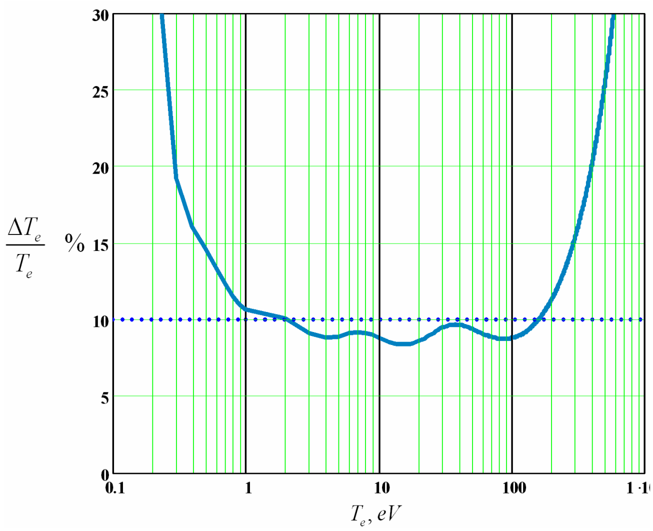

FIG 5: Error calculation for the Outer leg TS system.

from the cassette through the pumping duct in the centre of the cassette. The diagnostic design has recently been assessed and agreed.

One more problem for TS in the divertor is survivability of optical components that have to be placed in the vicinity of divertor cassettes. The life-time of optical components is expected to be limited due to contamination with carbon and beryllium-based material eroded from the beryllium wall and carbon tiles. The material eroded from the walls will accumulate in the ducts equipped with the diagnostic optical elements. As well as significantly reduced optical transmission, thin layers can dramatically change the slope of the reflectance spectra of rather low reflectivity mirrors, especially like W or Mo [17]. At the Ioffe Institute, the research and development program on preventive and cleaning techniques of in-vacuum mirrors from the plasma has been intensified recently and a significant progress achieved in pursuing the first mirror protection issue for ITER [18].

In plasma diagnostics such as Thomson scattering, a detection of the wavelength-shifted light from the laser-plasma interaction region requires a high-level of discrimination against the stray light background at the laser wavelength; this stray light may significantly exceed the Thomson scattered light in intensity. This is a particular problem in the divertor region, where stray light can occur on construction elements or on dust clouds. Special polychromators [4] being developed in the Ioffe Institute may facilitate overcoming of these limitations. The devices capable of both significant reduction of the stray light and high transmission would be beneficial for spectral analysis of such narrow Thomson scattering profiles like those occurring under the electron temperature ~ 1eV.

Table 1. *Main parameters of the laser produced in Vavilov State Optical Institute, St. Petersburg Russia*

Wavelength	1064nm
Output energy	3J
Repetition rate	100Hz
Pulse duration	10ns
Beam divergence	<0.3mrad
Efficiency	>2%
Pulse-to pulse instability	<1%
Output beam diameter	15mm
Laser head size	900x300x200mm^3

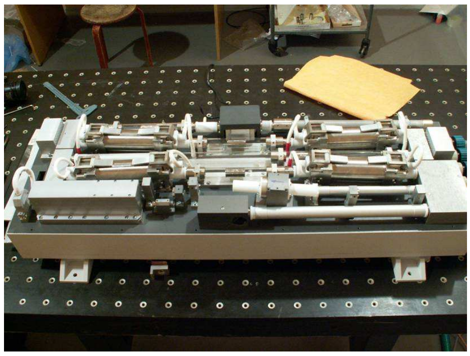

Fig 6: High brightness 3J/100Hz Nd:YAG Q-switched MOPA laser

One of the key points for all Thomson scattering ITER diagnostics is the laser capabilities. The high-performance and high-power laser systems working in steady-state and high-repetitive mode are required. An example of a high-power Nd:YAG laser design that has been completed recently is shown (see Fig.6 Table 1). To make it compatible with the ITER system, the pulse duration needs to be to 2-3ns, to reduce background light level. Development of a custom-made laser with reduced pulse duration is in progress.

5. Edge Temperature and Density Measurements

The ITER edge Thomson scattering system, whose the design is based on the YAG Thomson scattering system in JT-60U [19], requires a wide temperature range of 50 eV - 10 keV with an error of less than 10% and a temporal resolution of 10 ms. A YAG laser system with 5 J output pulse energy and a single 100 Hz repetition frequency is now being developed [20] for this system. Originally, the Edge TS system was destined to be situated in one of the ITER Top Port positions and the design of the collection optical system in the upper port plug was conducted in detail. Recently however, another proposal has been considered, wherein the measurement system is moved to the mid-plane port (see Fig. 7). This proposal aims to satisfy H-mode pedestal research, in which measurements in the region of normalized radius, *r/a* of > 0.8 is important, compared with r/a > 0.9 in the upper port design. This change will affect the designs of the collection optics system and the polychromator. A study of the errors in the systems has been carried out (see Fig. 8). In the study, polychromator designs for different configurations of laser beam and the collection optical system have been considered [21]. The main input parameters for the calculation are: pulse width of 30 ns, effective path length of the plasma along the line of sight of 4.5 m, laser diameter d = 5 mm, laser pulse energy E_i = 5 J, length of the scattering volume 10 mm, collection solid angle 0.01 Sr, a conservative effective charge number Z_{eff} = 3 and a Gaunt factor for free-free radiation of 3. The graph is for a density, n_e of $5x10^{18}$ m^{-3}. The expected H-mode density and temperature profiles of ITER [22] are used to assess the performance and a core n_e of $1.2x10^{20}$ m^{-3} and Te of 12 keV were used.

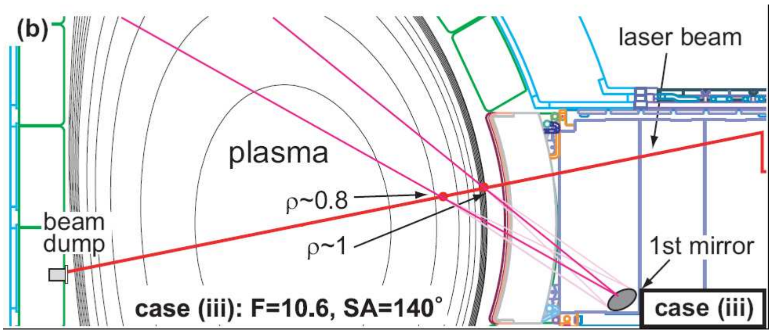

FIG. 7: Illustrations of the ITER edge Thomson scattering measurement system in the mid-plane port (showing the case when the laser is injected diagonally, for other cases see [21]).

For the mid-plane port configuration, it is concluded that be able to measure accurately the H-mode pedestal using a laser pulse energy of 5 J and width of the laser pulse is 30 ns, it is necessary to have a scattering length L of at least 10 mm.

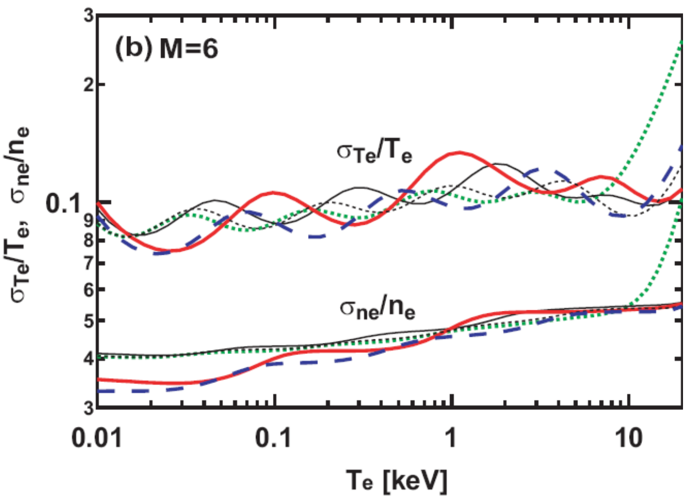

FIG. 8: Temperature dependences of the relative estimated errors in T_e and n_e for a 6 filter design. The different colours indicate different filter arrangements, including those with an optical notch filter to eliminate D_alpha emission [21] .

6. General Issues

To maintain successful continuously calibrated measurements in ITER, all the TS systems will require a range of techniques from mirror cleaning to wide-band in-situ calibrations. For example, an issue common to TS and several other optical diagnostics on ITER is the plasma facing mirror. While rhodium (as a coating) has the required spectral range for the core LIDAR, it is, like any material, subject to erosion and deposition by the plasma, causing its reflectivity and spectral response to change in time. A combination of in-situ calibration, deposition prevention and optics cleaning techniques need to be developed [5]. While the core TS system is expected to use a dielectric laser mirror, this is not possible in all of the TS systems. An assessment of in-vessel metallic mirror materials for the transmission of the laser beam used in the ITER edge Thomson scattering diagnostics has also been studied [23]. Candidate mirror materials are discussed based on a comparison between the numerical calculation and current data relevant to the laser-induced damage threshold (LIDT). Successful deployment of the TS systems in ITER will require significant offline testing to ensure an efficient transfer from the build to the tokamak.

7. Concluding remarks

Significant progress has been made around the world in several areas of the TS diagnostic development for ITER. This includes theory, laser, detector and many aspects of the system design. The modelling described above shows that, based on present estimates of the performance of individual components, in principle the systems can achieve the measurement accuracy and spatial resolution required, but with relatively little margin. Further work, backed up by testing is required in the areas indicated to ensure that reliable systems can be deployed. Critical areas such as lasers, first mirrors and detectors need to be addressed urgently.

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References

[1] M. J. Walsh et al, Rev. Sci. Instrum., No. 10, Vol.77, Part II, October 2006, p.10E524-1:10E525-4.
[2] A.J.H. Donné *et al*., Nucl. Fusion 47 (2007) S337 - S384
[3] A.E. Costley *et al.*, these proceedings, paper IT/P6-21
[4] G. Razdobarin, M. Walsh et al, IAEA 2006, to be published
[5] A. Litnovsky *et al.*, these proceedings, paper IT/P6-22.
[6] J. Sheffield, *Plasma Scattering of Electromagnetic Radiation* (Academic, New York,1975).
[7] I.H. Hutchinson, *Principles of Plasma Diagnostics* (Cambridge University Press, Cambridge, 1987).
[8] K. Beausang and S. L Prunty, *An analytic formula for the relativistic Thomson scattering spectrum for a Maxwellian velocity distribution*, Plasma Phys. Contr. Fusion **50**, 9 (2008).
[9] G. Taylor, J.R. Wilson *et al*, Plasma Phys. Contr. Fusion **36**, 523 (1994).
[10] V. Krivenski, E. de la Luna, G. Giruzzi,, in *29th EPS Conference on Plasma Phys. and Contr. Fusion*, *Montreux*, *June 2002*, ECA Vol. **26B**, O-1.03.
[11] O. Naito, H. Yoshida *et al*, *Relativistic incoherent Thomson scattering spectrum for generalised Lorentzian distributions*, Phys. Plasmas **3**, 4, p. 1474-1476, April 1996.
[12] M. Kempenaars, J. C. Flanagan, L. Giudicotti et al, Rev. Sci. Inst. 17th Conf. Proceedings HTPD (2008).
[13] L. Giudicotti, R. Pasqualotto, A. Alfier, M. Beurskens, M. Kempenaars, and M. J. Walsh, "Study of Fast, Near-Infrared Photodetectors for the ITER Core LIDAR Thomson Scattering", International Workshop on Burning Plasma Diagnostics, Villa Monastero, Varenna (Lc), Italy, September 24 – 28th, 2007
[14] M. Beurskens, L. Giudicotti, M. Kempenaars, R. Scannell and M.J. Walsh, Rev. Sci. Instrum. 17th Conference Proceedings HTPD (2008).
[15] G. Vayakis *et al*, Fusion Science and Technology, Vol. 53, No. 2, PP 699-750 (2008)
[16] Kochergin M.M. et al, *Interfaces for Thomson Scattering Diagnostics in the Divertor and SOL near the X-point Plasmas of ITER-FEAT*, Plasma Devices and Operations, 11, 1, 2003
[17] Mukhin E.E., et al., *Perspectives of Use of Diagnostic Mirrors with Transparent Protection Layer in Burning Plasma Experiments*, AIP Conf. Proc., v.988, p.365-369,2008 AMER INST PHYSICS ISSN: 0094-243X
[18] Mukhin E.E., et al., IT/P6-24, IAEA 2008
[19] T. Hatae, A. Nagashima, T. Kondoh et al, Rev. Sci. Instrum. 70, 772 (1999).
[20] T. Hatae, M. Nakatsuka, H. Yoshida, K. Ebisawa, Y. Kusama, K. Sato, A. Katsunuma, H.Kubomura and K. Shinobu, Transactions of Fusion Science and Technology 51, 58 (2007).
[21] S. Kajita,¤ T. Hatae, and Y. Kusama,, Rev. Sci. Instrum. 17th Conference Proceedings HTPD (2008).
[22] G. W. Pacher, H. D. Pacher, G. Janeschitz et al, Plasma Phys.Control. Fusion 46, A257 (2004).
[23] S. Kajita, T. Hatae and V. Voitsenya, Plasma Fusion Research 3, 032 (2008).