Progress in Development of Thomson Scattering Systems for ITER

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Abstract. Electron temperature and density are important indicators of plasma performance as well as key components in transport analyses. Therefore, they need to be measured with good spatial and temporal resolution in the ITER plasma. The resolution and accuracy required vary with the region of the plasma and with the plasma scenario. Four different Thomson scattering arrangements capable of measuring T_e, n_e profiles at the respective locations in Core, Edge, SOL near the X-point, and Divertor outer leg regions have been conceptually designed. The target requirements for each of the diagnostics are challenging while the environment in which the diagnostics are to be implemented is much harsher than on present day devices. In what follows, Thomson scattering diagnostic evaluation in plasma research/operations and the details of the implementation in ITER are presented and discussed. Special consideration is given to the challenges and status of the existing designs.

1. Introduction

Thomson scattering is a proven diagnostic technique capable of reliable and robust measurement of the profiles of electron temperature and density independent of plasma scenario. There are two ways to provide spatial resolution: either the laser beam is crossed with the collected light cone (conventional Thomson scattering) or the spatial origin of the scattered light is determined by a time-of-flight LIDAR principle. Both principles are envisaged for Thomson Scattering in ITER. They will provide instruments capable of measuring T_e and n_e profiles repetitively, during burn lengths ranging from 400 s (reference) to 3000 s (steady state). The diagnostic systems involved are classified in part by the operational role of their measurement in control, [1] but will, in any case, always used to characterize the plasma behaviour and performance. In particular measurements of T_e profiles for core and divertor plasmas, needed for many physics studies, are required for advanced plasma control.

2. Thomson scattering system for the plasma core

The Thomson scattering system for the plasma core [2] will be an implementation of the LIDAR technique. A layout of the front end in equatorial port plug is shown in FIG. 1.

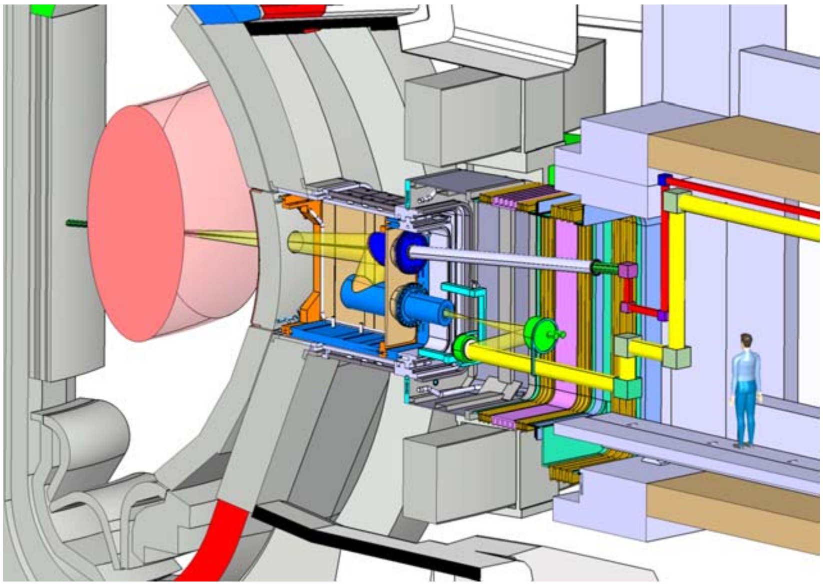

FIG. 1. Outline schematic of the port plug area LIDAR design for ITER.

The transmitted and collected light are carried through a neutron shield by an optical relay system to a dedicated area in the diagnostic hall. Steering mirrors are included in the design to maintain alignment against relative movements of the tokamak and the building. In dealing with fine structure in T_e and n_e profiles, such as internal transport barriers, the system should provide about 7 cm resolution (a/30) at a rapid measurement rate. The target requirement for time resolution is about 10 ms (100 Hz pulse repetition rate). The core temperature should be measured with 10% accuracy to enable a useful determination of the stored energy and to support the analysis of the plasma performance.
The present target requirements [1] are summarized Table I.

TABLE I: TARGET REQUIREMENTS

Parameter	**Range or coverage**	**Spatial resolution**	**Time resolution**
T_e n_e	0.5 – 40 keV $3\ 10^{19}$ - $3\ 10^{20}$ m^{-3}	7 cm (a/30)	10 ms (100 Hz)

The central part of the burning plasma has the highest temperature (up to T_e ~40 keV). In these conditions relativistic effects have a pronounced effect on the blue wing of the spectra. FIG. 2 shows Thomson scattering spectra for two laser wavelengths. The accessible spectral window for light collection, from 350 nm to 850 nm, is marked in the figure. It is determined by window radiation-induced absorption, that is mostly pronounced in UV region, and lack of suitable detectors at wavelengths above 850 nm. Plasma deposition on mirrors can only aggravate the already challenging problem of accessing wavelengths below about 350 nm. It is seen in Fig.2 that spectral power measurements in the wavelength range 350 nm - 850 nm could resolve temperatures from 5 keV up to 40 keV, with a laser wavelength of 1064 nm.

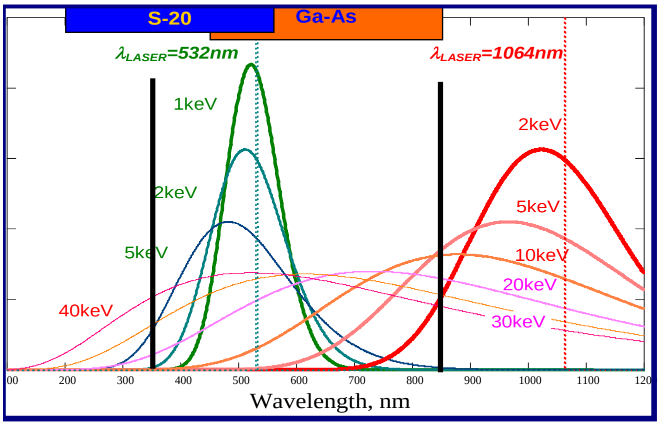

FIG. 2. Scattered spectral power density for Nd:YAG fundamental and 2nd harmonic wavelengths. Inserts show matching of different wavelengths to the spectral response of two types of photocathodes (S-20, GaAs).

For temperatures below ~5 keV, the use of the second harmonic Nd:YAG laser wavelength (532 nm) may be possible, as can also be seen from FIG. 2. Since it is difficult to cope with the full temperature range of an ITER plasma using a single laser wavelength, the spatial profile along the chord would be merged from two profile measurements, one for the high temperature core and the other for the “low temperature” edge. If suitable detectors are developed for the wavelength region 850 – 1060 nm all spectral measurements could be made with a single laser wavelength at 1064 nm.

3. Thomson scattering system for the plasma edge region

The understanding of the edge pedestal characteristics is crucial for characterizing the confinement and stability properties of the core plasma and for quantifying the effect of the ELM energy load on the divertor. It is important to make T_e, n_e measurements at the top of the pedestal, but also the pedestal widths for temperature, density and electron pressure. This will allow identification of the underlying physics and to improve further the scaling laws for confinement [3]. The edge, with much steeper gradients in the reference H-mode plasma, should be measured with a spacing of just 0.5 cm (midplane equivalent) between measurements, at about 20 locations. In order to meet this specification, a conventional Thomson scattering system is planned for the upper edge region taking an advantage of the natural flux expansion in this area which is typically up to a factor of three. The provisional target requirements [1] are contained in Table II.

TABLE II: TARGET REQUIREMENTS.

Parameter	Range or coverage	Spatial resolution	Time resolution
T_e n_e	0.05 - 10 keV $5\ 10^{18} – 3\ 10^{20}\ m^{-3}$	0.5 cm	10 ms (100 Hz)

The target requirements would be met by using a specially designed Nd:YAG laser of high output energy (5J) and high repetition rate (100Hz). It becomes possible to realize the unique performance of this laser by use of an sophisticated laser scheme [4] as shown in FIG. 3. At present design solutions are being sought to satisfy the stringent engineering requirements on safety and maintainability. In a recently developed diagnostic arrangement of the in-vessel collection optics the transparent vacuum window, most of the lenses and fibre guides have been moved away from the port plug to withstand the hostile plasma environment.

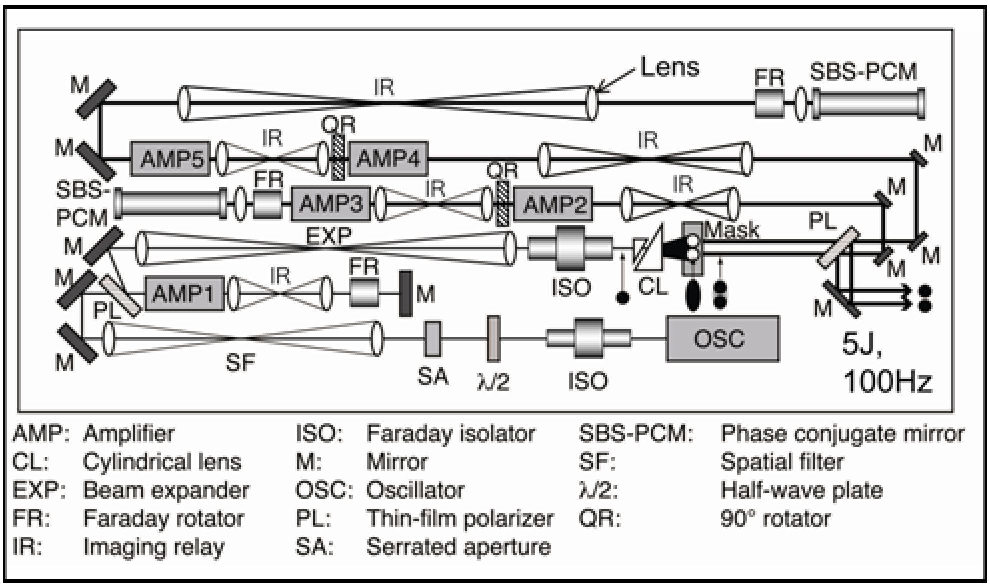

FIG.3. Laser optical design for edge Thomson scattering. High laser efficiency using Cr;Nd:YAG ceramic rods (efficiency is 2 times). Dual beam output to increase laser energy and to avoid laser damage.

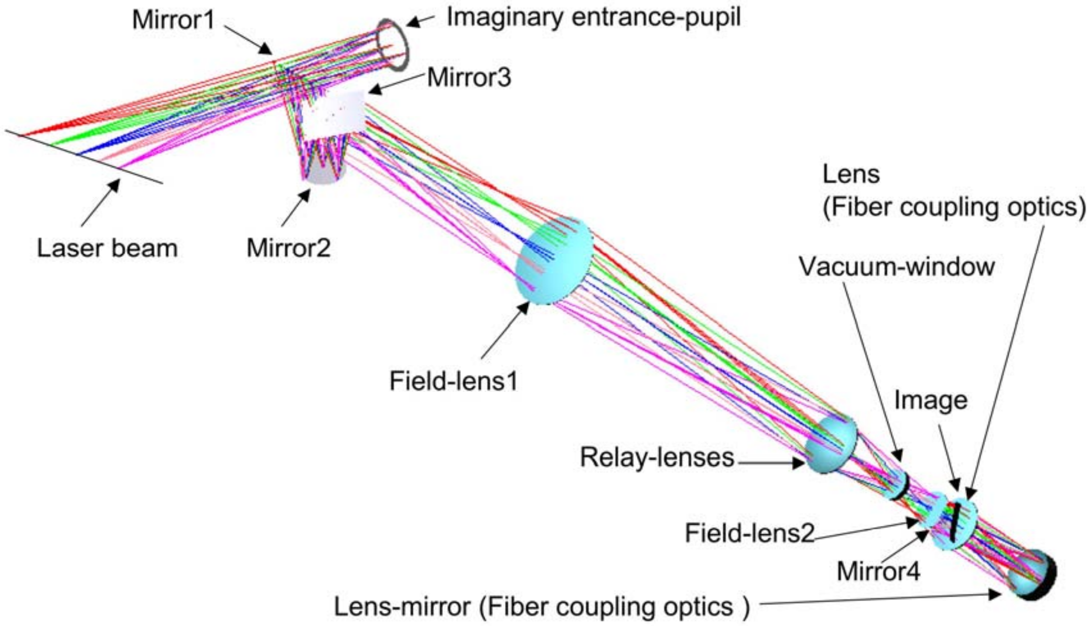

FIG. 4. Layout of in-vessel collection optics for Edge Thomson scattering.

The optical design shown in FIG. 4 gives a 60 cm field depth which corresponds to a measurement for the equivalent region of r/a > ~0.9 at the mid-plane. There is some concern about the flexibility of this scheme for scenarios with reduced plasma height, and also for situations where the pedestal moves inside r/a of 0.9. Further design improvement may be required.

4. Thomson scattering diagnostic arrangement for the X-point and the divertor leg regions.

ITER design has highlighted the fundamental need to monitor and deepen the understanding of divertor operations. The primary function of the divertor (besides enabling H-mode) is to deal with the particle and heat flux from the main plasma. A well-detached divertor plasma is essential for controlling density limits and power exhaust from the main plasma. Most studies of detachment are focused on the distinction between fully- and partially detached divertor operations [5]. The modeling of 2D distributions of the electron temperature in the divertor for various detachment scenarios are illustrated in FIG. 5.

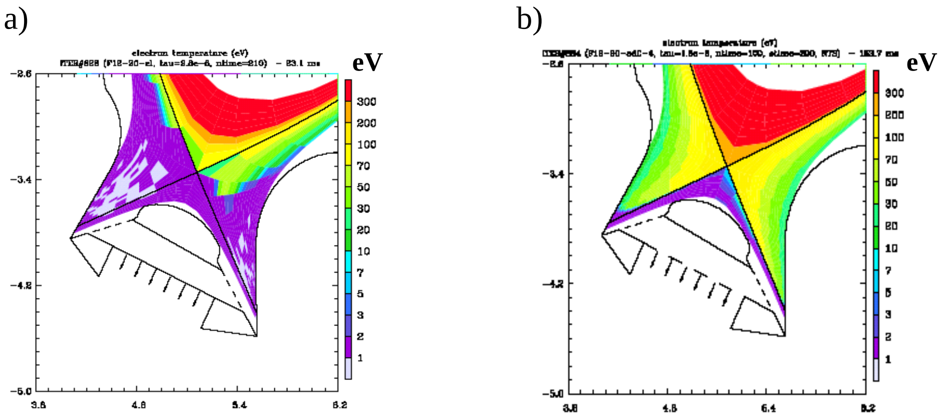

FIG. 5. 2D distribution of T_e in the divertor for two detachment scenarios. a) fully detached, b) partially detached.

Under full detachment, core confinement is degraded. A “partially detached” operating mode (i.e. detachment near the strike point on the target, but still attachment elsewhere) is preferred [6]. The highest priority for the Thomson scattering is to monitor the operating modes of the divertor by measuring T_e and n_e at an array of locations at the extent of the divertor legs. The Region near the X-point is very special. It is the region where neutral and impurity fluxes into the plasma can be high. It is important to make T_e, n_e measurements there as an aid toward interpretation of spectroscopic influxes. These in turn are used to study the impurities screening from the main plasma. The difficulty for Thomson scattering in the divertor is associated with access and survivability of optical components that have to be placed in the vicinity of this region. The problem of mirror maintenance is far more serious in the divertor than at other locations around the machine. The diagnostics should provide measurements in the X-point region and in the divertor outer leg [7] with the requirements according to Table III.

TABLE III: TARGET REQUIREMENTS.

Parameter	Range or coverage	Spatial resolution	Time resolution
T_e n_e (for the X-point region)	10 - 3000 eV 10^{19} - 10^{21} m^{-3}	~7 cm on sightline	50 ms (20 Hz)
T_e n_e (for the divertor outer leg)	0.3 - 200 eV 10^{19} - 10^{22} m^{-3}	5 cm along leg, 0.3 cm across leg	50 ms (20 Hz) 1 ms (in burst mode)

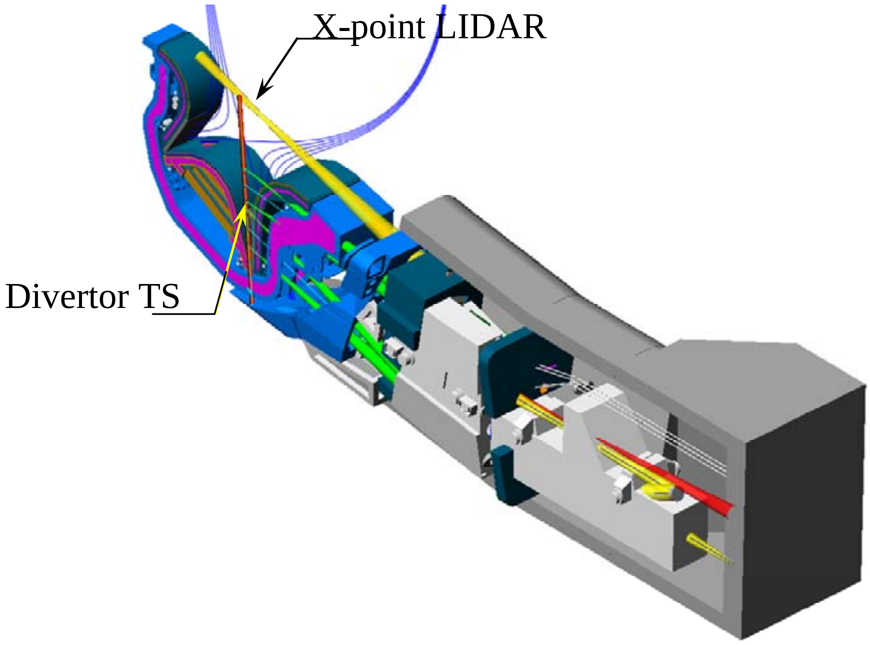

FIG. 6. Arrangement of the diagnostic racks shown as assembled in a divertor port and beam propagations in the regions near the X-point and outer divertor leg.

An outline schematic of the diagnostic racks planned for the divertor port is shown in FIG. 6. T_e , n_e measurements along a line-of-sight passing about 50 cm above the X-point in the reference H-mode plasma are to be performed with use of a LIDAR system with a laser beam direction tilted to the flux surfaces. This is in a region of a significant flux expansion, up to a factor of 10. The system will provide measurements with a spatial resolution of ~7 cm along the beam (equivalent to ~0.7 cm at the mid-plane) in the specified temperature and density ranges, with a lower temperature limit of 10 eV. Compared to the other Thomson scattering systems there are relatively few issues with the X-point LIDAR. The first mirror is well protected and no significant problems are anticipated with regard to erosion. However, deposition on the mirrors could occur. Another issue is the measurement of low temperature profiles at 10 eV, that suffer an excessive stray light level.

Significant effort has been focused on developing a Thomson scattering system for the divertor outer leg, [7] with a lower temperature limit of about 1 eV. The measurement lines up with the flux lines in the divertor leg. This geometry facilitates the diagnosis of proper divertor operation, especially the location of the ionization front. Due to strong inhomogeneities in the divertor, high spatial resolution is needed, especially across the divertor leg. The divertor Thomson scattering system is therefore an implementation of a conventional system. Resolutions of 5 cm along the leg and 0.3 cm across are foreseen with time resolution of about 50 ms (up to 1 ms in a burst mode). The key design features/issues is modification of the divertor cassettes to provide the access necessary and to reduce the risk of possible laser damage to the launcher underneath the cassette. Close co-operation between the diagnostic designers and the engineers working on the divertor has produced an integrated design that, in principle, satisfies the diagnostic requirements. However, the design of the divertor is under review and development and it is possible that the diagnostic designs will have to be changed to be consistent with the new divertor design.

The implementation of a number of diagnostic facilities requires substantial design effort and in some cases dedicated R&D. The generic implementation difficulty of any of the Thomson scattering systems is that during the ITER discharge, the diagnostic in-vessel mirrors are subject to erosion and deposition [8]. To some extent, heating of the mirror substrate can control the rate of plasma coating on the mirror. A significant improvement of existing cleaning methods is needed and could possibly be achieved by using a low temperature discharge in the vicinity of the mirror. Studies of the first mirror aspects and development of deposition mitigating and cleaning techniques are being pursued in a coordinated diagnostic R&D program [9].

5. Conclusions

A set of Thomson scattering diagnostics arrangements for measuring electron temperature and density profiles at the respective locations in Core, Edge, SOL near the X-point, and Divertor outer leg regions have been conceptually designed. Solutions are found to the problems of lack of access and diagnostics integration to the respective diagnostic ports. Many elements of the design still have to be completed, especially the engineering details of the components, and some further R&D is required, concerning reliability and redundancy in parts of the systems. In the core, the electron temperature and density are to be measured over the entire plasma cross-section with a spatial resolution of a/30. A LIDAR system is well suited for this measurement. In the edge, a conventional arrangement is best suited to provide the required high spatial resolution (0.5 cm radially projected to the midplane). Access through an upper port allows the measurement to be made at the top of the plasma where the physical size of the edge region is expanded due to the flux expansion. Improvement of the diagnostic flexibility is desirable to manage the plasma shape variations. For the divertor region, two systems are envisaged: one probes the plasma near the X-point while the other probes the plasma in the divertor outer leg. In the X-point region, the flux surfaces are expanded to an extent appropriate for implementing the LIDAR technique. Along the outer divertor leg, the only possibility for making T_e , n_e profile detailed measurements is conventional Thomson scattering. For validation of divertor performance models, measurements of the electron density and temperature along the divertor leg on the inboard side are of significant importance. Because of access restrictions these measurements cannot be made by conventional Thomson scattering. Various LIDAR options are currently being considered. The systems under consideration have different merits and demerits and a preferred system has not been selected. Much work is going on around the world to develop the lasers, detectors and others aspects of the Thomson scattering systems to ensure that the conceptual designs are realizable, tested and ready to be deployed to ITER.

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