LIDAR Thomson Scattering diagnostic for STEP

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Introduction

Incoherent Thomson Scattering (TS) is an established diagnostic method used on most magnetic confinement fusion devices. Two different approaches have been adopted: conventional TS and LIDAR[1]. Conventional system so far has been used on all the machines, while LIDAR (alongside another conventional TS system) has only been implemented on JET tokamak [2,3]. That diagnostic was operated routinely for almost 40 years and had undergone several modifications, including use of different types of short pulse lasers, detection systems (photomultipliers, streak camera) and different lines of sight for core and edge measurements [4]. Despite the success achieved at JET, this method was not yet used anywhere else.

In the LIDAR TS a short laser pulse (~300ps) is fired into the plasma, and the scattered light is collected from the same access port using 180° backscattering. Spatial resolution is achieved by the speed of light time-of-flight separation. While the laser source and the detectors in LIDAR are more technologically challenging than in a conventional system, significantly reduced requirements for plasma access, optics alignment and resistance of the optical components to the neutron damage makes LIDAR concept better suited for burning plasma devices.

STEP is the UK programme to design and build a prototype fusion reactor which should demonstrate net electricity production and tritium self-sufficiency. A comprehensive set of diagnostics, compatible with harsh environment of a fusion reactor is being developed for STEP. LIDAR Thomson Scattering is also being considered, especially for the initial phases of STEP commissioning and operation when the physics model of STEP plasma will be validated. Some of STEP LIDAR design considerations will be described here.

Design constraints

Since the LIDAR concept is naturally favourable for large fusion devices, an extensive design work has been done for ITER LIDAR diagnostics which has identified a number of design solutions and key challenges [5-7].

Detectors for LIDAR Thomson scattering must be able to accept large etendue, have sufficiently short response time (300ps) and have high quantum efficiency (QE). Multi-channel plate photomultipliers (MCP-PMT) with GaAsP or GaAs photocathodes were found to be the closest to satisfy all these requirements simultaneously, although their detection wavelength range is limited to λ<850nm. MCP-PMT Hamamatsu detectors were used in JET LIDAR system (with Ruby laser λ=692nm) from 2011 [3] and until the end of JET operations in 2023.

Laser energy and pulse duration: both values are constrained by the laser induced damage threshold of the optical components, which changes with the duration of the laser pulse as $1/\sqrt{t}$. JET LIDAR system used 300ps laser pulses which is matching the MCP-PMT detectors response time. Nd-YAG lasers with pulse energy E=5J and pulse duration t=300ps are being offered on the market [8]. With these characteristics, the laser spot diameter on any of the optical mirrors in the beam path is limited to at least d~25mm diameter.

Spatial resolution of LIDAR TS is determined by the total response time of the acquisition system, which is a combination of the laser pulse duration, detector response time and the bandwidth of the digital acquisition:

$$\tau = \sqrt{\tau_{laser}^2 + \tau_{det}^2 + \tau_{DAQ}^2}. \tag{1}$$

DAQ solutions matching the time response of the other components (3.3GHz or 300ps) are already available. The spatial resolution of such a system will be $l = 0.5 * c * \sqrt{3} * 300ps \sim 8cm$ which is sufficient to measure core plasma profile of STEP but not sufficient to resolve the pedestal region.

Scattered light collection optics

The main challenges for the collection optics design are the first mirror which must face the plasma and survive the heat, neutron and charge exchange particles fluxes, and the radiation shielding. ITER is the closest available comparator to STEP in terms of diagnostic challenges, therefore for the initial assessment it is assumed that the first mirrors solution is similar to those implemented (and eventually tested) in ITER conventional TS systems [9,10]. In LIDAR system the first mirror can be much further recessed behind the first wall for better shielding from the incoming plasma radiation. For the simulation, we take the size of the first wall aperture of d=10cm diameter, first mirror of 20cm dimeter placed 2.5 metres behind the first wall. First two mirror surfaces are Rhodium and likely an in-situ mirror cleaning method will be implemented. The rest of the optical system is assumed to consist of 20 surfaces with high performance interference mirror (or anti-reflection for windows and lenses) coating and 2% signal loss on each of them. The light will have to be guided through a labyrinth to limit the neutron streaming, the final design will made once the machine configuration will finalize and will be a compromise between the etendue needed to transmit scattered light from a long radial extent of the laser beam and radiation shielding.

Spectral channels configuration and performance analysis

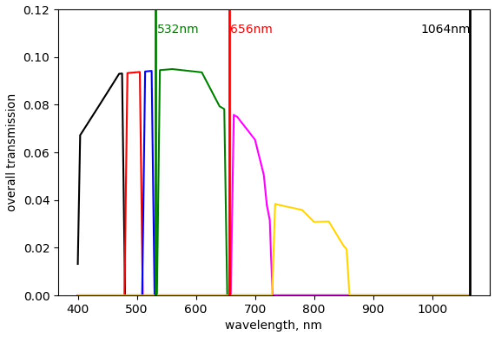

Figure 1: STEP LIDAR spectral channels

Limited spectral range of the available detectors and large spectral broadening of the backscattered Thomson light makes it necessary to use dual laser Thomson scattering system. Fundamental and 2nd harmonic (1064nm and 532nm) Nd:YAG lasers is the only viable combination, also from the availability and cost point of view. On Figure 1 the configuration of six spectral channels for the dual laser system is shown. GaAsP cathode detectors are used for the spectral channels in the range of 400-720nm, and the longest wavelengths λ>720nm requires IR enhanced version GaAs with somewhat reduced QE. Detector options for a shorter wavelength channel 300-400nm do exist but in this analysis they were not yet considered. For the performance analysis, Nd:YAG lasers with 5J pulse energy at 1064nm and 3J at 532nm were used [8], with assumed 10% energy loss in transit to the plasma. The two lasers are fired separately along the same chord with a sufficiently short time delay to assume constant plasma conditions. 1064nm is fired first to avoid detector saturation with stray light. Overall transmission including QE of the detectors is shown on Figure 1, it assumes the collection optics assembly described above and additionally the transmission is divided by two to account for unforeseen losses. Two STEP plasma scenarios are used for analysis: “ramp-up” with low density and high temperature and the “flattop” burning plasma. Kinetic profiles are taken from the plasma integrated modelling simulations. For the Bremsstrahlung calculation, Z_{eff} was set to 2 for the whole profile and additional enhancement factor of 2 applied to the intensity of the plasma radiation to account for reflections and line emission. In the considered plasma scenarios, the measurement uncertainty due to statistical noise is found well below 5%, as shown on fig.2

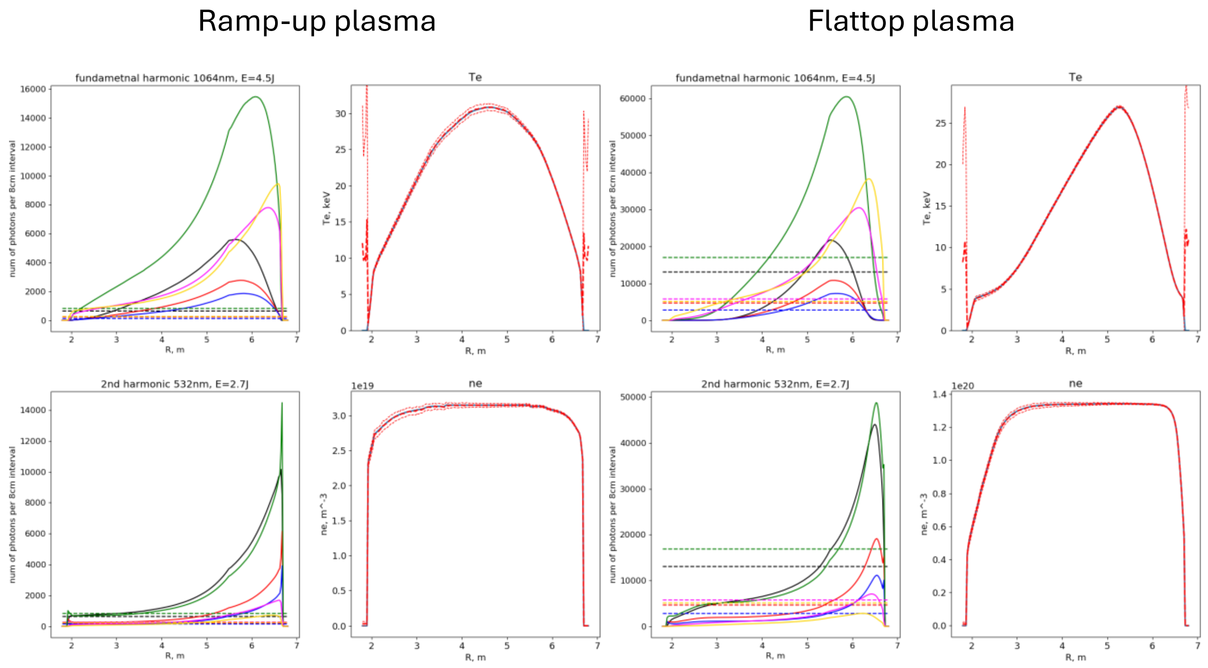

Figure 2: performance simulation results: number of photoelectrons per spectral channel for both lasers (dashed line represents the Bremsstrahlung level) and corresponding Te and ne profiles with uncertainty intervals

Spectral self-calibration using dual-colour laser

In addition to providing measurements for the full range of electron temperatures using a relatively narrow spectral range, dual colour laser scheme has a capability of self-calibration - correction of spectral calibration errors and/or drifts due to degradation of the optical components. This is achieved by minimizing the average residuals – discrepancies between the measured and the fitted signals over a sufficiently large dataset. This is equivalent to finding the minimum of the following expression:

$$\chi^2 = \sum_j \sum_i w_{1,i}\,(n_{e,j}F_{1,i}(T_{e,j}) - \gamma_i S_{1,i})^2 + \sum_i w_{2,i}\,(n_e\gamma_0 F_{2,i}(T_{e,j}) - \gamma_i S_{2,i})^2 = min \tag{2}$$

Here the index ‘j’ represents various TS measurements, made either at different radial positions or for different laser pulses, and γ_i is the unknown systematic error in the absolute sensitivity of particular spectral channels. Additionally, γ_0 represents the uncertainty in relative efficiency of the TS light collection for two lasers.

Terms inside the brackets in the equation 2 are the residuals. In the absence of systematic errors, the residuals are determined only by the quantum noise - statistical error of photoelectron count, and on average over large number of measurements should be equal to zero. Presence of systematic errors ($\gamma_i \neq 1$) increases the residuals and introduces a systematic pattern to their dependence on the electron temperature. Figure 3 left shows Monte-Carlo modelled residuals for a given calibration error [γ_i]. the minimum of χ^2 in equation 2 can be found by solving

$d\chi^2/d\gamma_i=0$. Since the fitted $T_{e,j}$ and $n_{e,j}$ themselves depend on the calibration uncertainty γ_i, finding the min(χ^2) has to be done iteratively, with re-calculation of T_e and n_e for each step. In Monte-Carlo simulations, this process was found quickly converging and pre-defined arbitrary calibration error is found with high precision after ~10 steps. Figure 3 right shows the final residuals after the calibration correction routine has been run for 10 iterations. Figure 4 shows the evolution of χ^2 during the process.

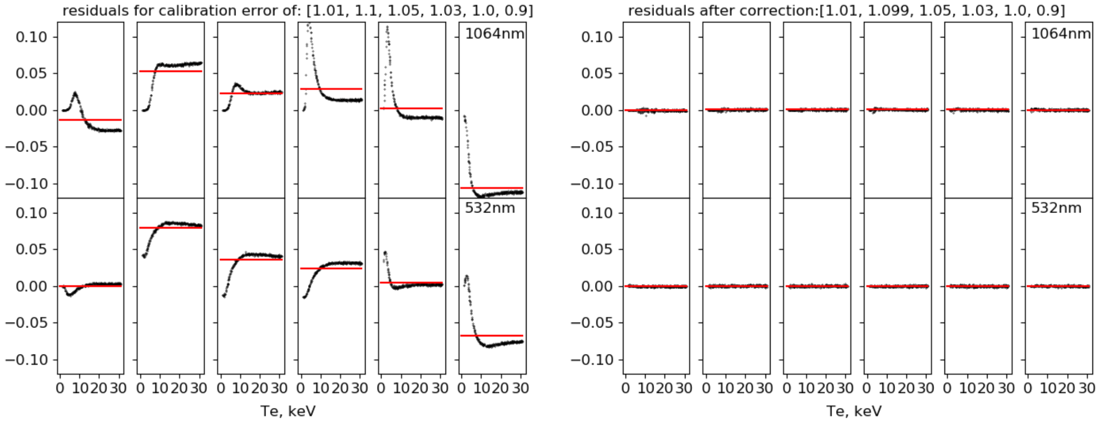

Figure 3: left – Monte-Carlo simulated residuals in 6 spectral channels for both lasers for a given calibration error, at a single radial coordinate. Right: final residuals after 10 iterations of self-calibration routine. Pre-defined calibration error found with high precision.

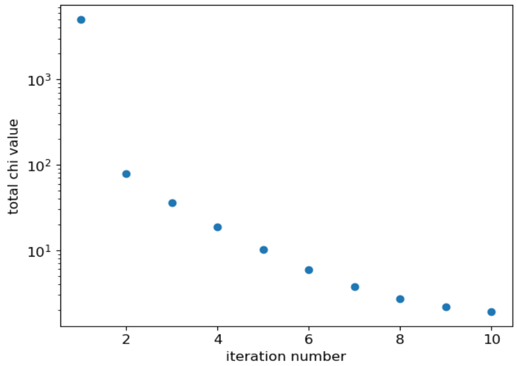

Figure 4: Evolution of χ^2 during iterative solution of equation 2

Conclusion

Initial design work for STEP LIDAR Thomson Scattering is ongoing. The design uses a dual colour scheme based on fundamental and 2nd harmonic Nd:YAG lasers and the type of detectors previously implemented and demonstrated at JET. We are exploring whether the diagnostic could provide T_e and n_e profiles in the non-active (hydrogen) plasma phase and initial D-T phase up to the establishment of routine D-T operations. As former JET Operator (2000-2023), UKAEA possesses unique experience in operating LIDAR TS system on a tokamak and therefore is well positioned to deliver a similar system for STEP.

Acknowledgement

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References

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