Calibration methods for ITER core LIDAR

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Abstract. The standard technique for the relative calibration in present Thomson scattering diagnostics, can be used in ITER only if the full collection path is included in the calibration: indeed, the in-vessel optics will be exposed to neutron and gamma irradiation and particle flux, that will likely cause a distortion of the spectral transmission curve. The standard scheme would ask to position a diffuser in front of the first collection mirror, e.g. on the protective shutter, and to illuminate it with a light source nearby. Alternatively, a back illumination scheme could be used, with a more efficient retroreflector array. A completely different approach is based on TS measurements from two lasers with different wavelengths: this self-calibrating method does not require any in-vessel tool and will provide both the electron temperature and the relative sensitivity of spectral channels.

1. Introduction
In a Thomson scattering (TS) diagnostic, calibration of relative sensitivity, necessary to calculate the electron temperature $T_e$, is usually performed with a white light source coupled to a diffuser, which simulates the radiating scattering volume and illuminates all or more frequently only a reduced set of the collection optics. The relative sensitivity of the $i$-th spectral channel is calculated as the ratio of the signal from the lamp detected by that channel and the expected signal calculated as the convolution of the spectral emissivity of the lamp, the spectral reflectivity of the diffuser, the spectral transmission curve of that channel and the spectral response of collection optics; these factors are measured in advance with a calibrated tunable monochromatic light and are supposed not to change with time. If a broadband filter polychromator is used, only average changes of the collection optics transmission curve over the spectral bands of the spectrometer channels are detected and these are interpreted as modifications of the relative sensitivities. This way it is not possible to discriminate changes within each channel spectral band.

Ideally the light source should be positioned in the vacuum vessel, to include the entire collection system, while usually it is positioned just outside the collection vacuum window, so that all the collection system but the window is included in the calibration. Unfortunately the window is the element more susceptible to changes in transmission because of plasma and neutral deposition on the internal face. This is not just a change in absolute transmission, which would only affect the absolute calibration and then the estimate of $n_e$, but also a change in the transmission spectral curve which affects the relative calibration and then the estimate of $T_e$.

For ITER TS diagnostics, high accuracy and reliability are required, but operating conditions are very different from existing tokamaks: high neutron dose environment, in-vacuum mirrors and extremely...
long plasma discharges. Temperatures and densities profiles along a diameter in the midplane will be measured by the core LIDAR TS system, with spatial coverage $r/a < 0.9$, $T_e$ and $n_e$ ranges respectively of $0.5-40$ keV and $3 \cdot 10^{19}-3 \cdot 10^{20}$ m$^{-3}$ [1,2]. In this system the vacuum window is far from the plasma and not susceptible to deposition, but there are still two sources of degradation of the spectral transmission: a) two in-vessel mirrors are susceptible to plasma deposition, especially the first mirror, directly viewing the plasma; b) the high radiation level changes the optical properties of not sufficiently shielded optics, producing absorption and photoluminescence in refractive components, like the vacuum window. We then expect some degradation of the spectral transmission of in-vessel optics, probably at a high rate, with the need of frequent recalibrations.

The standard scheme would require to position a diffuser in front of the first collection mirror and to illuminate it with a light source nearby. The diffuser could be mounted on the shutter protecting the first mirror from deposition. Alternative and possibly more feasible schemes are being investigated: the internal light source can be replaced by a back illumination scheme and the diffuser could be replaced by a more efficient retroreflector array.

2. Back-illumination scheme

The basic requirement for the calibration source, either internal or external, is to produce a continuous, smooth and stable spectrum in the entire detection range of the ITER core LIDAR (from 350 nm to 1100-1400 nm). Its intensity has also to be high enough to produce a detectable signal, once attenuated by the diffuser or retroreflectors mentioned above. So far, the best candidate light source is an halogen lamp, but its use in ITER is challenging and requires to first solve few issues. The glass envelope would be darkened by the high radiation and neutron flux, changing the lamp emissivity spectrum, while a bare thoriated tungsten filament would too rapidly evaporate, thus reducing the filament lifetime. However radiation darkening might be not that severe, as the glass is thin and heats up, tending to self anneal. Two other potential problems are operation in vacuum at high temperature and in a high magnetic field. In addition lamps with highest available color temperatures (> 3000K) are required, to still have meaningful intensity level at 350-500 nm. The diffuser used with an internal source or with a back illumination scheme could be the back of the first mirror shutter coated with plasma sprayed alumina and it should be protected from plasma deposition when closed.

If the source can not be positioned next to the diffuser, this could be illuminated from outside the bioshield, with a back illumination scheme: the light is sent through the collection optics backwards, compared to the TS signal direction, then it illuminates the diffuser or a retroreflector array; the diffused or reflected light is then gathered through the collection optics again but in the forward direction this time and finally it is measured with the broadband LIDAR polychromator or a higher resolution monochromator. The diffuser, supposed Lambertian, diffuses uniformly over a $2\pi$ solid angle, while the retroreflectors send the light prevalently back along the incident direction, being much more efficient than the diffuser and thus requiring a less powerful light source.

A benefit of a flexible choice of light source is that the spectral transmission of the collection optics can be separately measured. This requires using a scanning wavelength source. It also assumes that the spectral reflectivity of the diffuser or retroreflectors is known and does not deteriorate.

The back illumination scheme has some other open issues. In principle the double pass through the collection optics should be easily taken into account, but this might complicate the measurement as the transmission should be separately measured with a higher resolution monochromator. Another possible issue is stray light: light is fed into the collection optics by inserting a beamsplitter, which gets light backwards into the collection optics from the source. This method can cause stray light into the detector, especially if a diffuser is used instead of a retroreflectors array, because of the different efficiency and because stray light can also be generated by reflections from collection optics and from the walls of the port, even though this can be minimized by imaging the porthole onto the detector. The back-illumination scheme, using an array of micro retroreflectors in front of the first mirror, is being proposed for the calibration system of the divertor impurity influx monitor [3,4]. Micro retroreflectors are necessary there, to avoid excessive losses, since a fan of parallel rays would not be
reflected back parallel by a retroreflector if imaging optics are inserted in the optical path. If the retroreflectors are sufficiently small (0.2 mm pitch), the divergence of the reflected rays and the losses are tolerable. The smaller the pupils of the optical system, the more relevant this problem is.

This scheme could be implemented also for the core LIDAR. A Zemax ray tracing model has been used to define the maximum tolerable size of the retroreflectors for the LIDAR case. A 30 mm diameter uniform source is positioned just before the spectrometer aperture, back-illuminating the collection optics. A retroreflector array is positioned in front of the first mirror and with the same diameter, retroreflectors pitch ranging from 2 to 200 mm. Fig.1 shows the incoming and reflected light through the vacuum window (in-window and out-window), and the power lost by the retroreflector array (scattered) and by the two toroidal mirrors between the retroreflectors and the vacuum window (lost). The result is that arrays with a pitch up to 20 mm can be used without significant deterioration of the performance. Using a Lambertian diffuser instead, the reflected power through the vacuum window is about 10^2 smaller.

3. Dual laser self calibration

The original Design Description Document of the ITER core LIDAR (DDD 5.5C.01) suggests to use TS measurements from two Q-switched lasers with different wavelength [5], as preferred solution for the relative calibration of the system. This method would not require any in-vessel tool, or to replicate the illumination characteristics of the TS signal and would provide both the electron temperature T_e and the relative sensitivities of spectral channels. T_e is calculated from the ratio of TS signals from the two lasers on the same spectral channel, without requiring knowledge of relative sensitivities. In addition the spectral transmission curve is obtained from comparison of measured and expected signals, once T_e has been derived. Restrictions on usable wavelength combinations apply: a) a spectral interval with significant scattered signals from both lasers, such as to have detectable signals from both lasers in at least two spectral channels, is required to get T_e; b) each wavelength of the full spectral range of interest must have a detectable signal from at least one laser to obtain the relative sensitivity of all channels. One weakness of the dual wavelength method is that it assumes small variations of transmission curve inside each channel spectral band. To resolve the transmission changes inside a spectral channel, a separate higher resolution spectrometer should be used.

The laser combination originally proposed was Ti:Sapphire (800 nm) as main laser and duplicated Nd:YAG (532 nm) as calibration laser. At least two channels have to cover the spectral range where we have detectable signals from both lasers in the same channel. If we assume that both signals are detectable if their ratio if < 20 or > 1/20, at T_e = 5 keV this spectral range is 450-750 nm, where likely two spectral channels are present. This spectral region is smaller for lower T_e and wider for higher T_e.

The present ITER requirement of measuring higher T_e (< 40 keV) than previously assumed requires a revision of the proposal, connected to a new evaluation of the optimum lasers combination.

Considering that Nd:YAG @ 1064 nm is presently being considered as a good candidate for TS measurements, possibly complemented by doubled Nd:YAG @ 532 nm for lower T_e [2], two combinations look promising for the dual laser calibration: (a) Nd:YAG @ 1064 nm + Nd:YAG @ 532 nm or (b) Nd:YAG @ 1064 nm + ruby @ 694 nm. For (a), measurable signal ratio is obtained at 10 keV in spectral range 450-800 nm, while for (b) at 5 keV in spectral range 620-950 nm. Below about 10 keV for the combination (a) and below 5 keV for (b) it is likely that the useful spectral range is too narrow to well fit two spectral channels in, thus being not sufficient to estimate T_e.
These roughly estimated threshold values did not consider the finite bandwidth of spectral channels. They have been more carefully derived with a full simulation of the TS signals in realistic conditions and with two realistic sets of six spectral channels, depending on the choice of NIR detector. The full numerical simulation confirms the results from the rough estimate (see fig.2), with operational condition of about $T_e > 8$ keV for (a) and $T_e > 3$ keV for (b). Combination (a) would have the advantage of possibly using already foreseen lasers, while (b) could be used earlier in the ITER lifetime.

![Image](attachment:image.png)

**Figure 2.** TS signals ratio (top) and relative error of calibration coefficients, derived from propagation of signal errors, (bottom) for two cases: Nd:YAG @ 1064nm + Nd:YAG @ 532nm (left) and Nd:YAG @ 1064nm + ruby @ 694nm (right)

Considering the unfamiliar and hostile ITER environment, a conservative strategy is proposed, operating both calibration methods: the back-illumination scheme being more reliable in the initial period of operation, the dual wavelength later on. In fact the dual wavelength method starts working above a threshold $T_e$, then probably some time after first day Hydrogen plasma, while the diffuser/retroreflector scheme might degrade with time loosing reliability. In addition, plasma Bremsstrahlung could play the role of internal light source, but this relies on repeated identical plasma discharges.

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### 4. References

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