Dual-laser wavelength Thomson scattering at Wendelstein 7-X[a)]

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(Presented 17 April 2018; received 3 May 2018; accepted 20 June 2018; published online 15 October 2018)

This paper presents the approach of the dual-laser wavelength Thomson scattering (TS) system for the Wendelstein 7-X stellarator. The dual-laser wavelength TS method is based on two lasers with different wavelength fired quasi-simultaneously. This method has two advantages compared to a single laser wavelength TS system. First, the dual laser availability allows an in-situ spectral calibration and secondly, higher electron temperatures can be measured without any change of the spectral filter set-up of the polychromators. The W7-X dual-laser wavelength TS concept is based on high power lasers: a set of standard Nd:YAG lasers with λ=1064 nm wavelength and a Nd:YAG laser with λ=1319 nm wavelength newly developed for this application. This laser uses a different transition line with 34% efficiency compared to the main 1064nm Nd:YAG line. Simulations of the expected performance of the new dual-laser wavelength system show, that electron temperatures up to T_e =15 keV can be measured compared to the original design parameter up to Te=10 keV. The in-situ spectral calibration can be performed using a range of temperatures from 1keV to 10 keV using TS measurements of the 1064 nm versus 1319 nm TS simultaneously.

I. INTRODUCTION

Dual-laser wavelength Thomson scattering is an upcoming technique based on two lasers with different wavelength being fired quasi-simultaneously. This method was proposed by Smith[1] et al. in 1997 for self-calibration of a Thomson scattering (TS) system. The first review of dual-laser calibration of TS systems in ITER and RFX-mod was published by L. Giudicotti and R. Pasqualotto[2] in 2014. For RFX-mod, reverse field pinch plasmas, the combination of a Nd:YAG (λ=1064 nm) and a Nd:YLF (λ =1053 nm) laser was chosen, to measure the sensitivities of the spectral channels. At W7-X the basic TS system[3,4] includes a pulsed, high power Nd:YAG laser with λ=1064 nm, together with five interference filter polychromators for spectral analysis of the scattered light in the near infrared region between λ=750-1061 nm. The system is able to measure T_e up to approximately 10 keV within an error of ~10%, depending on n_e and background light. This system will be equipped with an additional Nd:YAG laser with λ=1319 nm, so that the peak of the TS spectrum shifts up by 1319-1064=255 nm. This has two advantages: First, the dual laser availability allows also an in-situ spectral calibration. Secondly, higher T_e >10 keV can be measured as the peak of the TS spectrum shifts to shorter wavelengths. This avoids the polychromators having to cover λ<750 nm, where line emission and Bremsstrahlung increase strongly. This is important for W7-X in case of the so-called electron root confinement studies where temperatures up to 15 keV can be expected.

[a)]Contributed paper published as part of the Proceedings of the 22nd Topical Conference on High-Temperature Plasma Diagnostics (HTPD 2018) in San Diego, CA, USA.
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Unfortunately, no experimental data can be shown yet, where the λ=1319 nm laser has been applied for TS on a plasma. This paper will discuss the layout of the double laser set-up, its benefits, and demonstration for its use as an in-situ calibration method. A detailed description of the TS system layout and TS data analysis in W7-X can be found in the literature[3,4,5].

II. DOUBLE WAVELENGTH SYSTEM LAYOUT

Nd:YAG lasers are the working horse in many TS systems worldwide, because the lasers are robust. The wavelength (λ =1064 nm) is in the near infrared region were plasma background light is low and sensitive detectors[5] (silicon avalanche diodes) for the detection of the scattered light are available. The well-known λ =1064.14 (1064) nm transition provide the lowest threshold of laser lines in Nd:YAG crystals[4] and is therefore widely used; the W7-X TS diagnostic is now equipped with three such lasers[3]. In our dual-laser wavelength application the λ=1318.8 (1319) nm Nd:YAG transition was chosen. The relative performance of this line is 34% compared to the λ=1064 nm line[6]. Because there are until now no commercial λ=1319 nm high power Nd:YAG laser on the market, a development order was given to a laser company. At the time of writing the following laser performance at λ =1318.8 nm was achieved requiring the suppression of the stronger λ =1064 nm radiation. The laser output energy E=0.72 J using an oscillator and three amplifier steps. The pulse length t=15 ns, the beam diameter d=12 mm and the repetition frequency f=10 Hz. This should be compared to our λ=1064 nm lasers with tunable E=0.6-2.4 J, t=10 ns, d=12 mm and f=10 Hz.

A schematic layout of the set-up is given in figure 1. The detailed geometry of the laser beam path of the W7-X TS system includes 10 mirrors. The main optical components exist of a high reflectivity (HR) and high anti reflecting (AR) coated beamsplitter/combiner in order to overlay and separate the double wavelengths at respectively the start and end of the laser beam path; a set of HR coated mirror, and a tripple AR coated lens. Figure 2 shows the coating characteristic of a) the beamsplitter/combiner and b) the laser mirrors. The lens coating characteristics are not shown but also feature AR<0.1% for 1064 nm and 1319 nm. All coatings are specified to withstand laser power densities up to 10 J/cm^2.

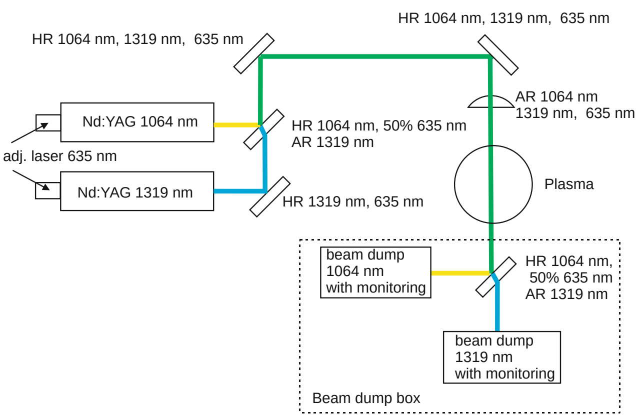

Figure1: Schematic layout of the W7-X TS system with the double wavelength lasers implemented. The 1064 nm and 1319 nm lasers are overlayed with a beam combiner using a 1064nm HR and 1319 nm AR coating (50% coating for each 635 nm alignment lasers). Subsequently 10 mirrors (only 2 shown) with a triple 1064 nm, 1319 nm and 635 nm HR coating are used to guide laser beams to the plasma. A +4 m focal length lens with triple 1064 nm, 1319 nm and 635 nm AR coating is used to focus the laser beams. At the exit the beam combiner is used as beam splitter to separate the two wavelength in order to allow the measurement of the laser energy and alignment monitoring for each laser.

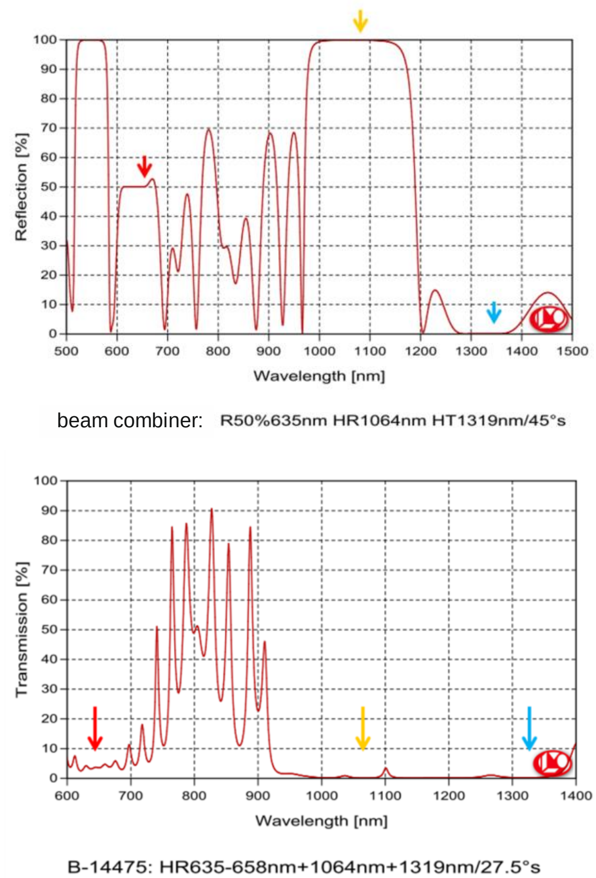

Figure 2: a) Coating specifications for the beam splitter/combiner optics showing the HR >99.9% coating for 1064 nm (yellow arrow) and AR<0.1% for 1319 nm (blue arrow). The 634nm alignment laser (red arrow) is served with a 50% reflection/transmission coating. b) Mirror coating specification with HR>99.9% for 1064/1319 nm and HR>95% for 634 nm.

The TS light is collected using two separate collection optics[3,4] viewing the inner and outer half-profiles of T_e and n_e. The light is led through multiple optical fibers to a battery of polychromators with 5 detection channels each. Light from separate spatial points is combined in one polychromators and separated using fiber-delay lines in combination with a fast transient recorder data collection[3,4], see Figure 3. The wavelength range is cut out in 5 wavelength bands[3,4] as is shown in Figure 6. In Figure 3, it is demonstrated how light from the 1064 nm and 1319 nm lasers can be combined, by time-delaying the 2nd laser by 50 ns. This way no separate detection system is required for the second laser wavelength. The 50 ns laser pulse separation is much shorter than any relevant known fusion plasma physics process

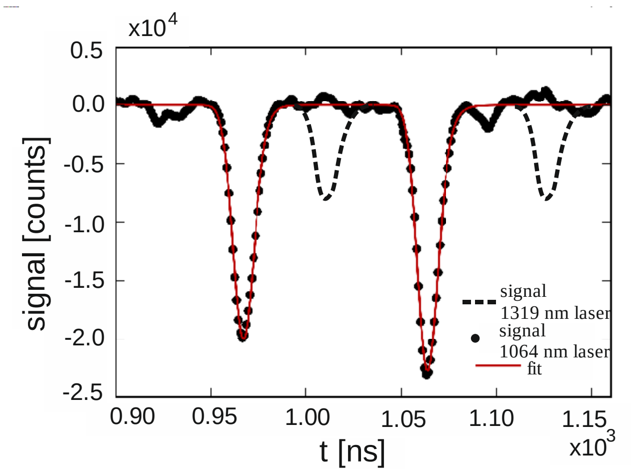

Figure 3: APD detector signals for one channel, using an AC coupled transient recorder showing the signal of the 1064 nm laser (dots with fits to the signal in red) and the expected 1319 nm signal superimposed in dashed lines and time shifted by 50 ns. In this example also a delay line (longer fibre) was used in order to allow two spatial points to be detected with one polychromators by time-separating them by 100 ns.

III. Performance analysis.

The dual laser availability facilitates an in-situ spectral calibration as well as the coverage of higher electron temperatures. For the latter, the current system with the 1064 nm laser covers a temperature range from 10 eV to 10 keV[3,4]. In principle, the temperature range can be extended by adding lower wavelength filters. However, below 750 nm the plasma background light increases significantly due to low to medium Z impurity radiation. An example is shown in figure 4. During normal plasma operation the background signals are within bounds, but in case of e.g. a plasma radiative collapse (where the radiation power exceeds the external heating power) the spectral and broadband radiation can overwhelm the TS signal.

The 1319 nm laser can be used to cover higher temperatures without adding an additional lower wavelength filter. It is expected that the maximum temperature can be extended up to 15 keV. A caveat is that the current 2[nd] wavelength laser has only half the laser energy compared to the main laser. This is especially an issue while high T_e>10 keV plasmas in general have low plasma density and therefore low photon-statistics. Increasing the laser energy by adding an additional amplifier may solve this issue in future. In the upcoming experiments however, we envisage adding multiple time points in order to improve the accuracy of the profile measurements, as we currently do not envisage an upgrade of the laser to energies above 0.7 J.

Simulations[4] of the system performance are given in Figure 5. The figure shows the expected errors in T_e as a function of actual temperature. With our spectral filter set-up, for the 1064 nm laser the maximum achievable temperature is limited to T_e≈10 keV (details depending on the S/N ratio in the experiment[4]). Access to higher T_e > 10 keV is not easy, even by averaging multiple measurements, as temperature and density measurements become correlated, because the Thomson spectra becomes flat at the covered spectral region[4]. An example is shown in figure 7a for T_e=20 keV. The addition of the 1319 nm laser has a clear advantage. The expected relative electron temperature errors from 1064 nm and 1319 nm lasers can be seen in Figure 5. Due to the lower laser energy, the statistical error in a single point measurement is relatively large. However, the range where errors in T_e are acceptable can be extended to higher temperatures. By averaging multiple TS measurements, temperatures up T_e≈15 keV can be accessed.

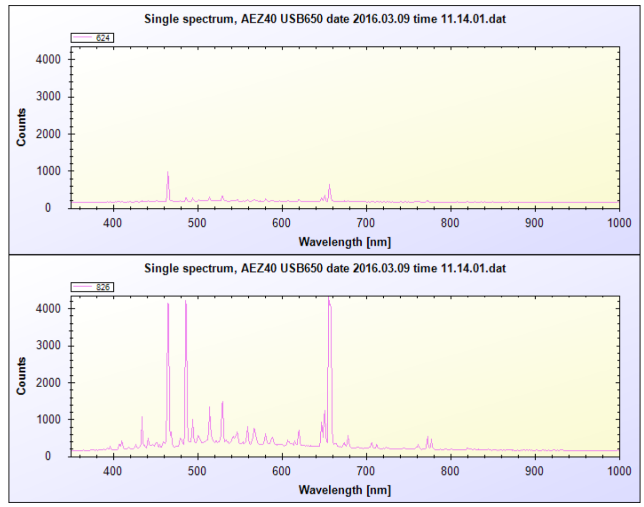

Figure 4: Example of plasma radiation from single line of sight Z_{eff} diagnostics at W7-X, during normal plasma operation (upper picture) and during radiation collapse (lower picture).

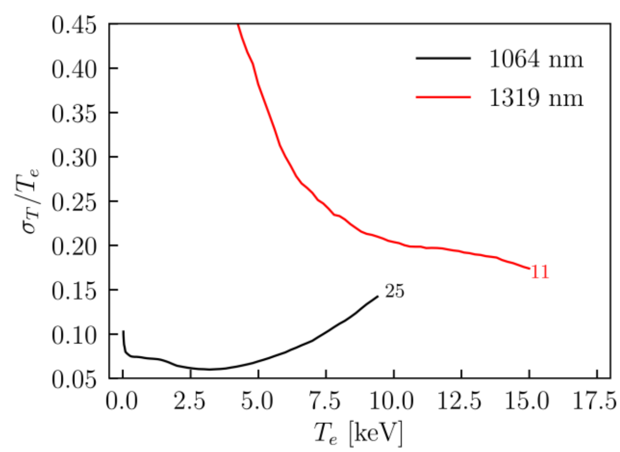

Figure 5: Statistical temperature error simulations[4] for the 1064 nm and 1319 nm laser system (for a typical experimental signal to noise ratio of S/N=25 resp. 11, i.e. lower for the 1319nm laser due to the lower laser energy). The black drawn line shows that with the 1064nm TS system, the temperature can be determined up to T_e ≈ 10 keV, be it with increasing statistical error. By adding the 1319 nm laser, the accessible temperature range is extended to T_e ≈15 keV. The statistical error rises to ~20% in this case. By adding multiple timepoints, this statistical error can be reduced.

A spectral calibration is commonly performed by illuminating a diffusive white disk with a tunable monochromatic light source. The disk is placed in front of an array of collection fibers as installed in the TS set-up[3,4]. The light source is a Super Kontinuum broad-band laser[4] that is passed through a monochromator, yielding a monochromatic light source with a 0.2 nm spectral width. This light is coupled to a single fiber that is led from the calibration room to the TS set-up in the Torus Hall (TH), where it is used to illuminate the diffusive white disk. This way, all collection fibres and hence polychromators are illuminated simultaneously. By stepping the monochromator through the 750-1061 nm wavelength range the spectral shape and amplitude of the filters can be characterized. This is an important component of calibration procedure. The absolute amplitude of the polychromator's sensitivity is calibrated by means of Raman scattering[3,4] which calibrates the channels that lay in the laser wavelength vicinity (i.e. channels 4 and 5), see Figure 7. The spectral calibration as described here, combined with the Raman calibration are in principle sufficient to obtain absolute values of the plasma electron temperature and density by means of Thomson scattering.

In practice, however, it turns out that systematic deviations occur in the relative amplitude of the spectral channels that lead to errors in both temperature and density values, for an example look at Figure 6.We know the shapes of the spectral channels accurately, as they are reproducible for each spectral calibration. The amplitude however isn´t. The cause of this error is not well understood, but we assume that the white disk irradiation does not well represent the solid angle as is observed, using Thomson scattering from laser light in the plasma. Small alignment errors in the polychromator's optical layout as well as detector surface sensitivity variation can then lead to varying signal levels in the TS geometry compared to the white disk spectral calibration set-up.

Correcting alignment errors in a multiple polychromators system is an elaborate exercise. The double laser wavelength application can help to correct these[1,2]. As the two lasers follow an almost identical path through the plasma, the solid angle and intensity distribution of the collected light are identical. A relative spectral channel amplitude calibration can thus be carried out, knowing that: a) both lasers, fired quasi simultaneously ought to measure the same temperature and density for each spatial point, and b) the relative signal variation for a given temperature range must follow a fixed curve. This is demonstrated in figure 7. The spectral density function for a range of temperatures from 100 eV to 20 keV are shown for both the 1064 nm and the 1319 nm laser in figure 7a. The ratio of the signals collected in each of the channels 1-5 are plotted in figure 7b as a function of temperature. These then form the calibration curves from which the relative channel amplitude can be determined. The figure shows that for our filter set-up and choice of laser wavelength, a temperature range of 1-10 keV suffices to get the calibration information required. For W7-X this lies comfortably within the achievable plasma parameters for the core region of the plasma. Towards the cooler edge of the plasma, this temperature range is not covered, and not all channels can be calibrated simultaneosly. Due to the overlap of scattering volumes from both observation optics at the core[3], it is possible to connect each polychromator to a core fiber in order to calibrate the polychromator without influence of the profile measurement.

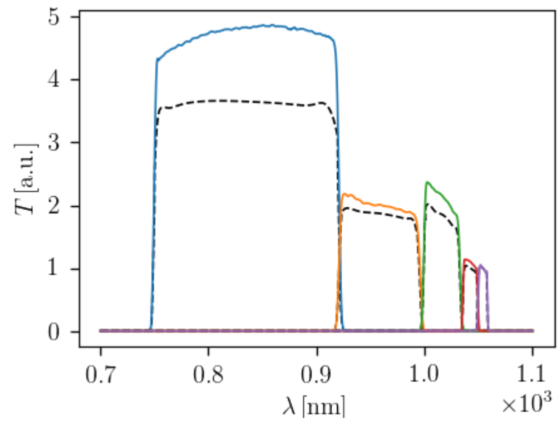

Figure 6: Reproducibility problem of the interference filters spectral calibration. These are two separate spectral calibrations with ~ 1 year time difference, separated by an intervention during which the collection optics (and white calibration disk) were removed from the port. The observed systematic deviation is expected to be due to internal polychromators miss-alignment problems, and reproducibility issues of the calibration source position and illumination.

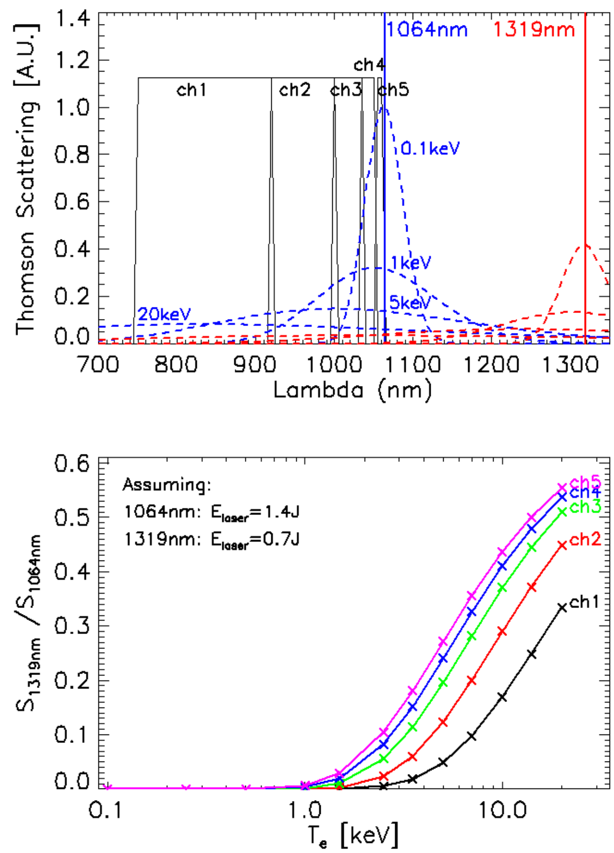

Figure 7: a) Thomson scattering spectra from both the 1064 nm (blue) and 1319 nm (red) laser, corrected for laser energy amplitude. The wavelength range for each spectral filter is indicted in black. b) Ratio of integrated signal levels for each of the five channels, as a function of temperature.

V. SUMMARY AND OUTLOOK

We have described the new dual-laser wavelength approach for Thomson scattering systems, which will be demonstrated at the Wendelstein 7-X stellarator. The dual-laser wavelength method has two advantages compared to single laser wavelength TS. First, the dual-laser availability allows an in-situ spectral calibration, secondly, higher electron temperatures can be measured with unchanged polychromators. For the W7-X TS system the both Nd:YAG laser wavelengths 1064 and 1319 nm were chosen. The shift in laser wavelength of 255 nm extends the electron temperature measurement from T_e=10 keV up to T_e=15 keV. The development of a high power Nd:YAG laser with 1319 nm was initialized. The three amplifiers steps system deliver 0.72 J at 10 Hz repetition frequency. The availability of coatings for beam combiner, beam separator and mirrors for both wavelength, plus a coating for an alignment laser, shows the capability to have an identical beam path for both laser. In the future it is planned to investigate the dual-laser wavelength and the dual-angle spectral calibration within an EUROfusion collaboration with the TS system at Wendelstein 7-X stellarator.

ACKNOWLEDGMENT

The authors wish to thank Ch. Gödeker from Laseroptik company for his calculation of the optical laser beam path components.

We also wish to thank N. Graf, InnoLas company, for his development work of the 1319 nm high power Nd:YAG laser.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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