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Edge and core Thomson scattering systems and their calibration on the ASDEX Upgrade tokamak

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Abstract

A new 10 channel Thomson scattering (TS) system was installed on the ASDEX Upgrade tokamak, to measure radial profiles of electron density and temperature at the plasma edge with high radial resolution. Together with the already existing TS system, which is now used for the core plasma, electron density and temperature profiles extending from the edge to the core are now obtained in a single discharge. The TS systems are relatively calibrated by an optical parametric oscillator.

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I. INTRODUCTION

Since the early years of ASDEX Upgrade (AUG) a 16 channel "Vertical Thomson Scattering" (VTS) diagnostic [1] exists, which was used to measure electron density and temperature profiles alternatively in the core plasma with a spatial resolution of 25 mm, or in the edge plasma with a resolution of around 3 mm. For obtaining complete profiles of electron density and temperature a discharge had to be run twice with the same parameters, but with the VTS system set to the core, or edge position. A second Thomson scattering (TS) system with 10 spatial channels has been installed on the AUG tokamak, to measure radial profiles of electron density and temperature only at the plasma edge. It is designed to have practically the same high spatial resolution as the VTS system, although in a slightly different geometry. The VTS system is then used for measuring profiles only of the core plasma.

The spectral analysis of the Thomson scattered light is done on AUG by polychromators, which consist of four spectral channels. The signal amplifiers of the detectors have two outputs, a fast AC coupled branch for measuring the scattered light pulses of the laser (pulse duration 10 ns), and a slow DC coupled branch for measuring the plasma light level. A standard technique for performing the relative spectral calibration of a polychromator is using a cw tungsten lamp as a light source together with a spectrometer for tuning the wavelength. This has the disadvantage that only the slow DC, and not the fast AC branch of the signal amplifier can be calibrated. As a spectrally broad light source delivering short pulses, which resemble the scattering pulses very closely, a super-continuum light source is used for glass fiber coupled polychromators [2]. This light source, however, is not strong enough to perform a parallel calibration of the polychromators installed on the AUG tokamak. For years an optical parametric oscillator (OPO) is used here, which has not yet been documented.

The paper is organized as follows: The new edge TS system, together with improvements to the alignment stability, and the data evaluation, are described in section II. Details of the relative calibration of the polychromators with an OPO can be found in section III. Examples of measured profiles are presented in section IV.

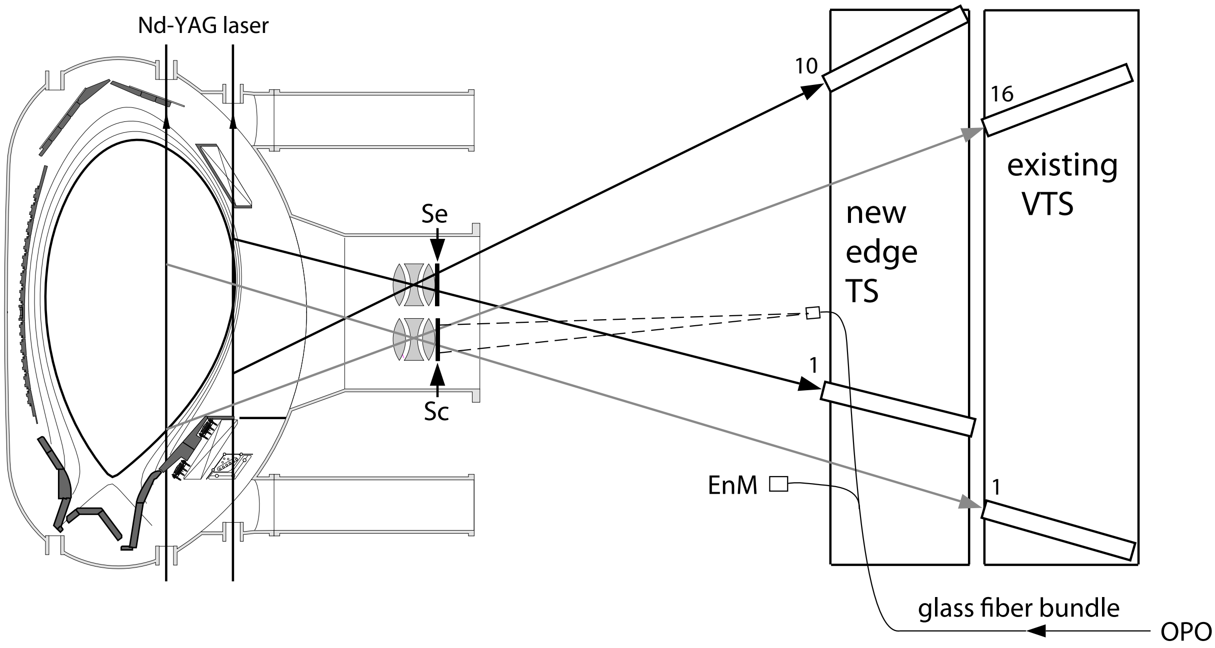

FIG. 1. Poloidal cross section of the scattering geometry, together with the setup for the relative calibration with an OPO.

II. DIAGNOSTIC SETUP

The new edge TS system is placed closer to the torus than the VTS system, resulting in a modified scattering geometry. The light is imaged directly into the newly designed polychromators of the edge TS system. Thus mirrors in front of the polychromators, which are used for aligning the VTS system, are no longer needed.

A. Scattering geometries of the core and edge TS systems

The scattering volumes of both the new edge TS, and the VTS system have a length of 25 mm. They are imaged directly through air to the polychromators to maximize the amount of observed scattered light (fig. 1). For the VTS system the poloidal plane is also the plane of observation. The plane of observation for the new edge TS system is inclined by 4 degrees with respect to the poloidal plane (fig. 2). Thus the images of the scattering volumes of both TS systems are separated in the toroidal direction by about 24 cm, so that the entrance slits of the VTS polychromators are not shadowed by the polychromators of the edge system which are located at smaller major radii, than the VTS polychromators.

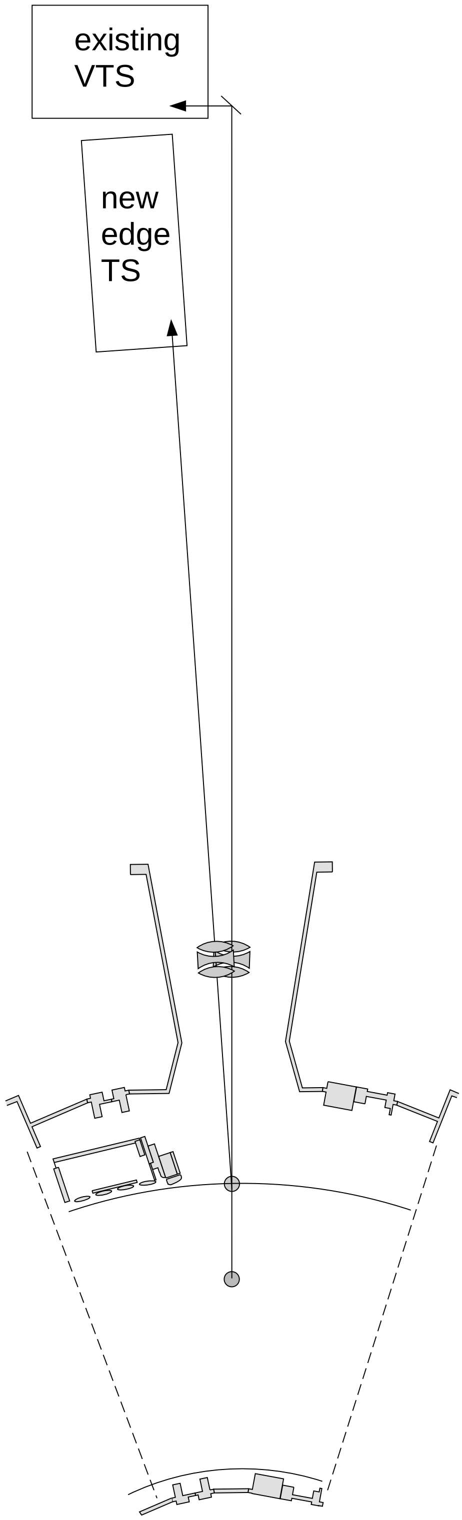

FIG. 2. Scattering geometry, toroidal cross section.

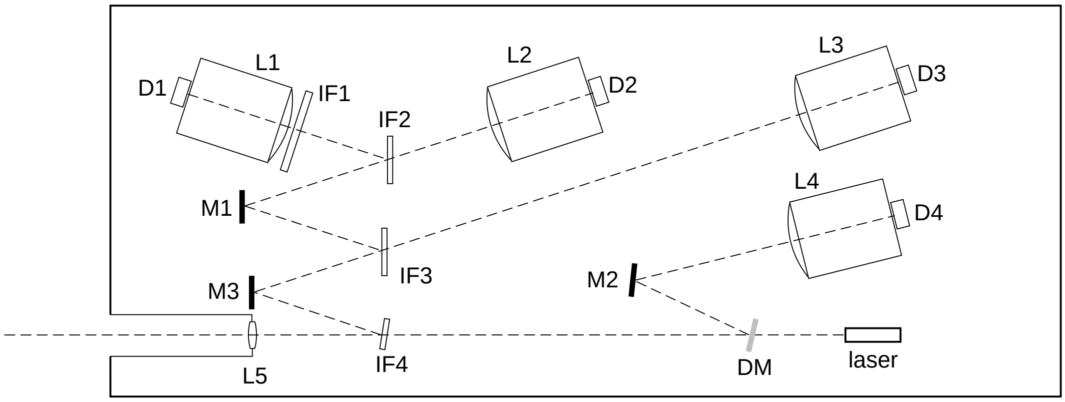

FIG. 3. Schematic of the polychromator of the new edge TS system.

B. Polychromators of the new edge TS system

The scattering volume is imaged into the entrance slit of the polychromator (fig. 3). A relay lens (L5) in the entrance slit then images the main objective lens to the objective lenses (L1 to L4) in front of the detectors (D1 to D4), which give a demagnified image of the entrance slit on the detector.

Silicon avalanche photo-diodes with integrated hybrid amplifier [3] with a rectangular light sensitive area of 1 mm $\times$ 7 mm are used as detectors. Each avalanche photo-diode is temperature stabilized by heating the detector to 29 degrees Celsius to ensure constant absolute and spectral sensitivity: Due to the slight heating of the detector only a very small amount of additional heat is produced in the polychromator. Thus no active cooling of the polychromator is needed.

Four spectral channels are used in the polychromator. The spectral ranges are determined by interference filters (IF1 to IF4 in fig. 3). Metallic mirrors (M1 to M3) are used to fold the optical paths, which makes the polychromator more compact. For alignment purposes a diode laser is coupled onto the optical axis of the polychromator by a dielectric mirror (DM), which transmits the visible light of the alignment laser and reflects the near infrared spectral range passing to the detector.

C. Laser beam lines

For the new edge TS system 6, and for the core TS system 4 Nd-YAG lasers (pulse energy below 1 J, pulse duration 10 ns) at 20 Hz repetition rate each [4] are used respectively. The lasers of the edge and core TS systems are not fired simultaneously to avoid cross talk between both TS diagnostics. The laser light of each TS system is transferred via four mirrors from the laser laboratory, which is outside the torus hall, to the tokamak, over a distance of about 20 m. To achieve acceptable stability all mirrors are mounted either on the concrete wall, or floor of the hall. The lasers are focused by a lens (f= 4 m), which is also mounted on the concrete floor of the torus hall, to the center of the AUG torus, where the scattering volumes are located. Here the lasers of the edge TS system have a radial distance of 2.7 mm. The actual spatial resolution of the TS system in the outer mid-plane of the plasma is determined by mapping the scattering volumes (length 25 mm) with a magnetic equilibrium to this spatial position. For the edge TS system several scattering volumes, which are close to the outer mid-plane of the plasma, are nearly tangential to the magnetic flux surfaces. In this case radial resolutions down to the diameter of a focused laser of about 2.7 mm are obtained.

Behind the focusing lens the laser beam diameter shrinks and increases the risk of damaging the vacuum window to the torus. Double Brewster windows are therefore used where the lasers enter the torus.

The lasers are aligned to the center of the focusing lens below the machine and to a field stop on top of the machine. The field stop on top of the machine is connected to the upper optical bench (UOB), which is movable in the toroidal direction to compensate for movements (flexure, thermal expansions) of the joist structure holding the vacuum vessel and the solenoids. A fix-point for the UOB is defined by a reference laser beam: A laser is mounted to the wall of the torus hall. The target position of the reference laser beam on the opposite wall of the torus hall is feedback controlled. Thus the position of the reference laser beam is fixed to the torus hall (fig. 4): A two segment detector attached to the UOB senses the position of the reference laser. Control signals are then derived to drive an electrical motor to keep the UOB aligned to the reference laser and thus the torus hall. Both the main objective lenses, and the polychromators of the two TS systems are fixed to the concrete floor of the torus hall. Thus shifts of the torus in the toroidal direction, which can be of the order of several millimeters in the sector where the TS diagnostics are located, have no influence on the alignment of the TS systems.

For each TS system a fraction of the laser light is reflected into a glass fiber by a glass plate, which is located behind the focusing lens. These laser monitor signals are then fed to

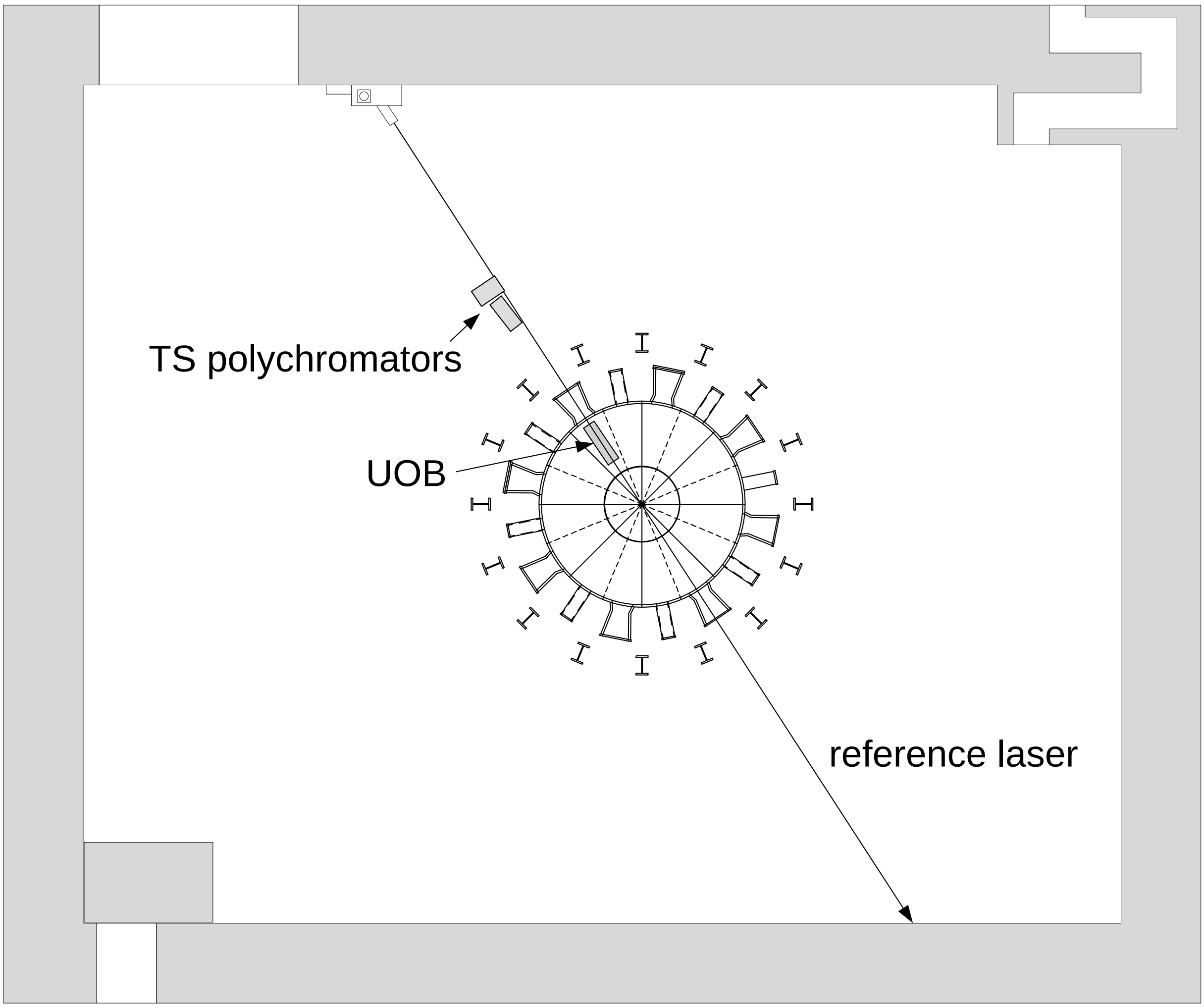

FIG. 4. A reference laser spanning between the walls of the AUG torus hall is used to keep the upper optical bench (UOB) fixed in space relative to the concrete walls.

each of the Avalanche photo-diodes by splitting the glass fibers.

A signal proportional to the laser energy is obtained by coupling a fraction of the laser light into an integrating sphere [5], which is located in the UOB.

D. Data acquisition

A 500 ns long time-trace around the scattering signal and the laser monitor signal is acquired for each of the spectral channels with transient digitizers [6] (sampling rate 1 GSamples/s, low-pass filter frequency 250 MHz). The digitized data are transferred to the memory of a workstation immediately after the acquisition of the 500 ns time window has

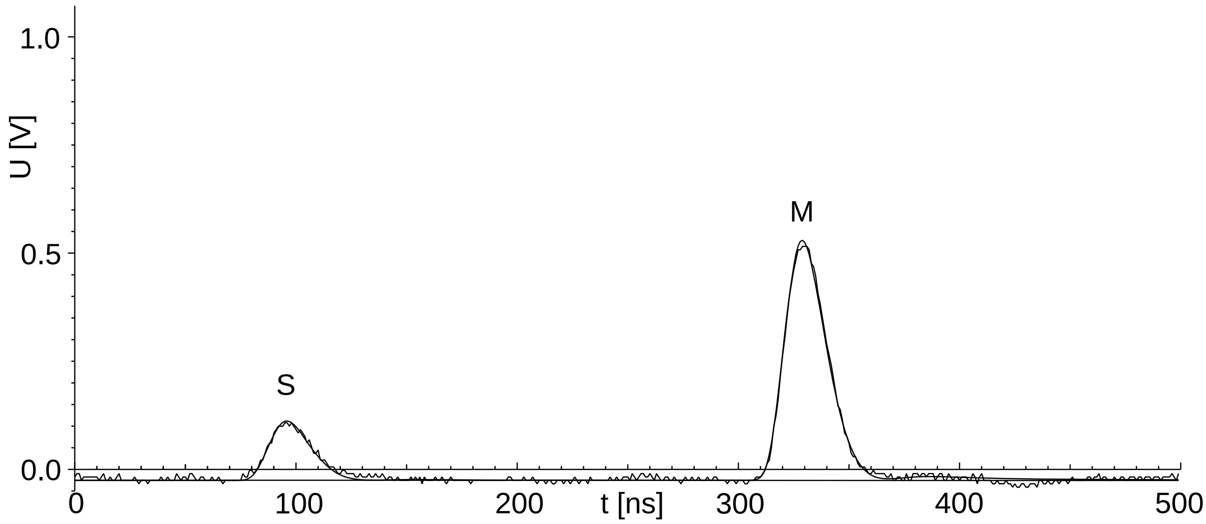

FIG. 5. Typical scattering (S), and laser monitor (M) signals and their fits.

finished. In this way the high costs for large amounts of fast memory in the transient digitizer modules are saved.

E. Pulse fit

For improved signal-to-noise ratio, the scattering signals are evaluated by making fits to the signal pulses [7]. Fitting of the scattering signal pulses started [7] with a model pulse constructed from the convolution of a Gaussian function, resembling the electrical current pulse $I_d(t)$ collected by the detector, with a first-order low-pass filter. This was sufficient to fit noisy signals. With lower noise levels, and especially for larger laser monitor signals, where a slight ringing at the end of the signal pulse is observed, this model is no longer adequate. The electrical circuit of the pre-amplifier integrated in the housing of the photo-detector could not be analyzed. To approximate the observed shape of the signal pulse more closely, now a model pulse is used, which is a convolution of a modified electrical current pulse $I_d(t)$ with the impulse response function of a fourth-order low-pass filter. In angular frequency space ω the amplitude response of this low-pass filter is described by $A(\omega) = 1./\Pi_{n=1}^{2}(1. + i\ a_n\alpha\omega - b_n\alpha^2\omega^2)$ with $a_n = 2b_n sinh(\gamma) cos((2n-1)\pi/4)$, $b_n = 1/(cosh^2(\gamma) - cos^2((2n-1)\pi/4))$, and α as a frequency axis scaling factor. The parameter γ is constant for all spectral channels, $\gamma = 5$. The parameter α is adjusted for each spectral channel individually, $\alpha = 0.7\ -\ 1.4$. The choice of the coefficients a_n and b_n was inspired by the design of Chebyshev filters [8].

The time evolution of the detector current pulse $I_d(t)$ is now modeled by a cubic exponential function for the fast rise, and by a Lorentzian function for the slower fall-off of the pulse. The time constant τ_G for the cubic exponential function is laser dependent and varies between 10 ns to 12 ns. The time constant for the Lorentzian function is found to be constant, $\tau_L = 7\ ns$, for all lasers and spectral channels.

In the fitting procedure first the best fit to the large laser monitor signal is determined by varying the position of the model pulse in time. The scattering signal, which can be small, is then fitted with a model pulse, which is set at a known constant amount of time before the laser monitor signal (see fig. 5).

III. CALIBRATIONS

For determining the electron temperature from the signal ratios of the several spectral channels a relative calibration must be performed. An absolute calibration of the detectors is necessary for obtaining the electron density.

A. Relative calibration

The relative calibration method must fulfill several purposes: (a) The line-width of the tunable monochromatic light source must be smaller than the edge steepness of > 1 nm of the interference filters, which are used in the spectral channels. (b) The relative calibration of all the polychromators of each TS system should be done in parallel, to save time. (c) A calibration signal pulse should be used, which resembles the TS signal pulse very closely, so that the same signal paths and data acquisition can be used both for the TS measurement, and the calibration.

As a spectrally tunable light source an optical parametric oscillator (OPO) [9] is used. It is pumped by a seeded frequency tripled Nd-YAG laser [10] with a repetition rate of 10 Hz. The output of the OPO reaches pulse energies of up to 12 mJ, in the wavelength region of interest of 750 nm to 1064 nm, and has a line-width $< 4\ cm^{-1}$, which is sufficient for the calibration purposes, mentioned above.

The OPO laser is located outside the torus hall. The laser light is transported by a glass

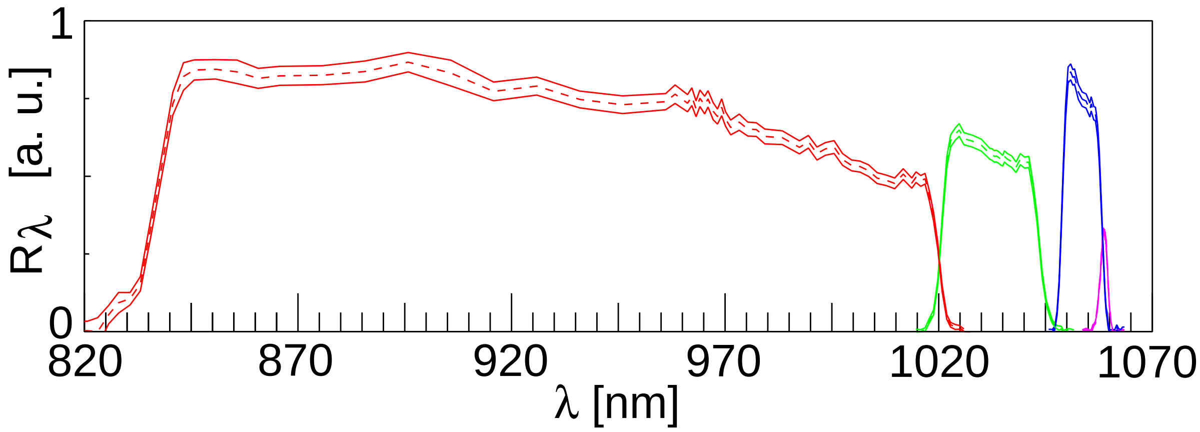

FIG. 6. (Color online) Responsivities R_λ (broken lines), together with their error bands (solid lines) of the four spectral channels in a polychromator versus wavelength λ, which are obtained with the OPO laser system.

fiber bundle near to the polychromators installed in the torus hall. The glass fiber bundle is then split into two parts: one part is fed to an energy monitor (EnM in fig. 1), the other part is imaged to one of the objective lenses of each TS system. The objective lenses are covered with a circular plate each (Se, Sc), made from spectrally flat diffuse reflecting polytetrafluoroethylene (PTFE) plastic, which acts as a volume reflector (see fig. 1). Such a material is also commonly used e. g. in integrating spheres.

As a laser energy monitor a fast Germanium PIN photo-diode [11] is used. Its spectral calibration in the wavelength range of interest, of 750 nm to 1064 nm is simple, because the spectral response of the Germanium PIN photo-diode depends here only linearly on the wavelength of the irradiated light. So only a small number of wavelengths is necessary for a calibration over the full range of wavelengths of interest. The Germanium PIN photo-diode is cross-calibrated with an absolutely calibrated, but slow energy meter [12]. Although the sensitivity of the Germanium PIN photo-diode is much smaller than the sensitivity of the Silicon avalanche photo-diode, which is used in the polychromators, large signal pulse amplitudes are obtained by coupling a sufficiently high amount of OPO laser light to the detector.

The emission wavelengths of the OPO laser are chosen such that the resolution is higher (below 1 nm) for the transmission edges of the filters, than for the transmission flattops of the filters (about 5 nm). For the two spectral channels nearest to the Nd-YAG laser line the responsivity is also measured at the wavelengths corresponding to the spectral lines of the Raman spectrum of nitrogen, which is important for the absolute calibration of the TS diagnostic. In this way on the order of 100 wavelengths are chosen and laid down in a list. In the automatic data acquisition procedure, a master PC reads the wavelengths from the pre-defined list of calibration wavelengths and sends them to the OPO PC, which controls the position of the crystal in the OPO laser. The master PC sends the wavelengths also to the workstations, which read the wavelength and the scattering signal pulse data from the transient digitizers after each OPO laser trigger. Thus for each trigger the wavelength of the OPO radiation is stored together with the scattering signals in the calibration shot file. In this way the signal pulse data are always consistent with the wavelength data of the OPO radiation, also in the case when some data were acquired due to spuriously occurring triggers. The data acquired due to spurious triggers do not fit into the regular timing scheme of the OPO laser, which is running at a fixed repetition rate, and are thus automatically recognized by the evaluation software and sorted out. For each OPO wavelength typically on the order of 40 laser pulses are acquired.

With the relative calibration the responsivities of the spectral channels, $R_\lambda = Q_\lambda / W_\lambda$, are determined. Here Q_λ is the charge measured by the detector of a spectral channel, and W_λ is the energy of the light pulse with wavelength λ irradiating the polychromator, which is measured by the calibrated Germanium PIN photo-diode. The multi photon processes necessary for generating the OPO emission give rise to variations of the OPO output power of the order of 10%. These variations modulate the signal amplitudes of both the Silicon Avalanche photo-diodes, and the Germanium PIN photo-diode. The responsivity is therefore estimated by $R_{\lambda,e} = (R_{\lambda,Ge-PIN}/n_p)\Sigma_{i=1}^{n_p}(Q_{Si-Av,i}/Q_{Ge-PIN,i})$. Here $Q_{Si-Av,i}$ and $Q_{Ge-PIN,i}$ are the charges per light pulse measured by the Silicon Avalanche, and the Germanium PIN photo-diode, respectively, $R_{\lambda,Ge-PIN}$ is the responsivity of the Germanium PIN photo-diode, and n_p is the number of OPO laser pulses acquired at the wavelength λ. In the formula for $R_{\lambda,e}$ variations of the OPO output power cancel out, which results in a smaller error of the determined responsivity. A typical result for the responsivities R_λ of the four spectral channels in a polychromator is shown in figure 6.

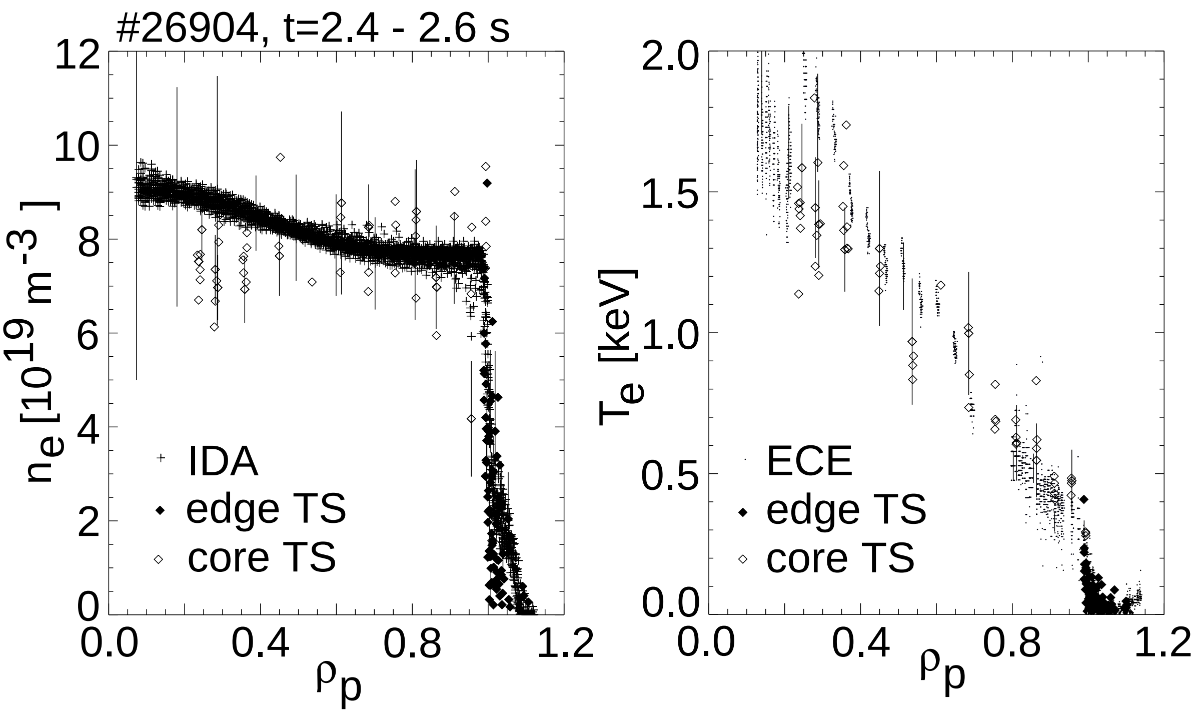

FIG. 7. Typical electron density (n_e) and temperature (T_e) profiles versus the poloidal magnetic flux coordinate ρ_P, measured by the core and the new edge TS systems. For comparison also the electron density profile determined from line integrated interferometric measurements and the Lithium beam diagnostic (IDA), and the electron temperature profile determined by ECE are shown.

B. Absolute calibration

The absolute calibration of the TS systems is done with Raman scattering in nitrogen. Here scattering signals are observed in the two spectral channels, which are nearest to the laser line.

IV. EXAMPLES OF MEASURED ELECTRON DENSITY AND TEMPERATURE PROFILES

Electron density (n_e) and temperature (T_e) data are determined by a least square fit to the scattering signals as described in [7]. A typical example for electron density and temperature profiles, which are measured by the core and edge TS systems, is shown in fig. 7. For this plot the radial and vertical coordinates of the scattering volumes in real space are mapped to

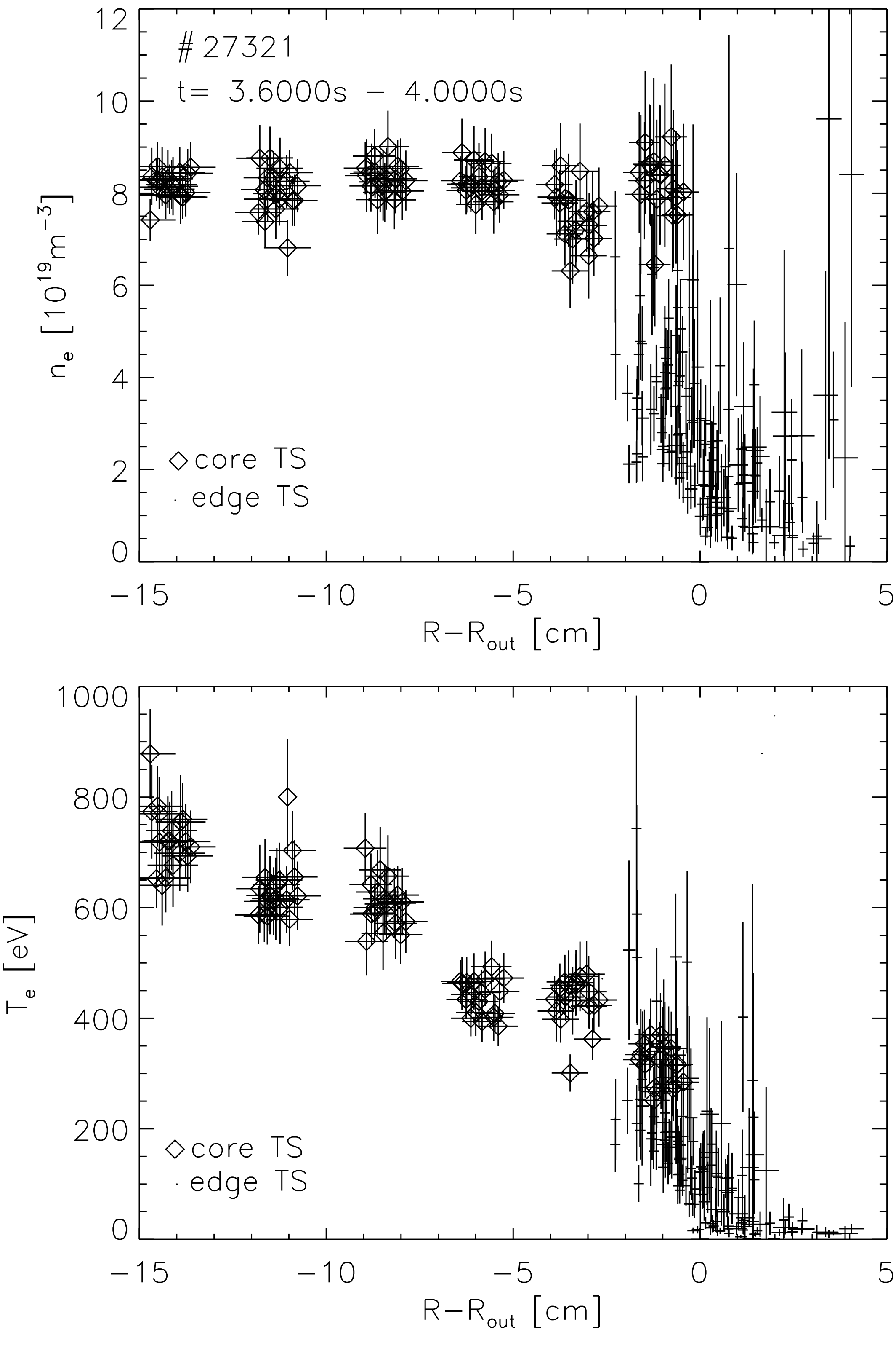

FIG. 8. Electron density and temperature profiles of the plasma edge pedestal as measured with the core and the new edge TS systems. With the high-resolution edge TS system the steep edge gradients are clearly resolved.

poloidal magnetic flux coordinates, ρ_p. For comparison also the electron temperature profile measured by electron cyclotron emission (ECE) and the electron density profile determined with integrated data analysis (IDA) [13] from line integrated interferometric measurements and the Lithium beam diagnostic are also shown. The electron temperature profiles of the TS and the ECE diagnostic agree within the error bars. The electron densities determined with IDA on open flux surfaces ($\rho_p > 1$), which is essentially determined by the Lithium beam diagnostic, are larger than the electron densities measured by the TS diagnostic, which is localized in a different toroidal position. This is often observed with strong gas puffing at high plasma densities. The electron densities measured by TS in the central part of the plasma are lower than the values determined with IDA. This discrepancy is still unresolved.

A radial scan of the plasma is typically done on ASDEX Upgrade to shift the plasma edge over the scattering volumes of the edge TS system, to obtain edge profiles with high radial resolution over a large radial range. The resulting electron density and temperature profiles of the plasma edge pedestal region are shown with higher detail in fig. 8. Edge localized modes are cut out. The positions of the scattering volumes are mapped by magnetic equilibria to the outer mid-plane of the plasma. The radial coordinate of the profiles is the major radius R relative to the outer position of the magnetic separatrix R_{out} of the plasma. The plotted radial error bars in the profiles of fig. 8 are the lengths of the scattering volumes mapped by magnetic equilibria to the outer mid-plane, or, if the scattering volumes are tangential to the magnetic flux surfaces by the laser beam diameter. Although the radial resolution of the edge TS system is about 3 mm in the steep gradient region around the separatrix, the radial positions of the edge profiles appear to be smeared out over about 1.5 cm. This is due to both the uncertainty of the radial position of the magnetic equilibrium (0.5 cm), and to fluctuations of the electron density and temperature in the steep gradient region and the scrape-off layer. This was already observed with the old VTS system [14].

V. CONCLUSION

With the new edge TS system and the older VTS system, which is now used for the core plasma, profiles of the core and edge are now obtained in a single discharge, thus saving experimental time.

ACKNOWLEDGMENTS

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