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New High Resolution Thomson Scattering System for the COMPASS Tokamak

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Abstract. The COMPASS tokamak is being re-installed at IPP Prague after its transfer from Culham, U.K. Within the innovation, new diagnostics will be constructed, including a High Resolution Thomson Scattering System measuring electron temperature (T_e) and electron density (n_e) profiles. Scientific programme of the COMPASS tokamak is focused on the pedestal studies, thus the main stress will be laid on the edge part of the system.

Introduction

Thomson Scattering (TS) system is a powerful technique capable to measure electron temperature (T_e) and electron density (n_e). It does not disturb the plasma enabling local measurements and even profiles of these parameters. A limitation of this diagnostic is its construction complexity connected with a low scattering cross-section. A new high resolution TS (HRTS) system is now being designed for the COMPASS tokamak, following the re-installation of the machine at IPP Prague from Culham, United Kingdom.

The COMPASS tokamak (COMPact ASSembly) [*Pánek*, 2006] is a single-null divertor tokamak. With its parameters (major radius 0.56 m, minor radius 0.2 m, plasma current $\sim$ 300 kA, toroidal magnetic field 1.2-2.1 T and pulse length up to 1 s), it is the smallest tokamak with a clear H-mode and ITER- relevant geometry. The re-built COMPASS is equipped with a unique set of copper saddle coils for resonant perturbation techniques. ITER-relevant plasma conditions will be achieved by a new heating system based on two neutral beam injectors (2 x 300 kW). Another heating will be performed by re-deployed LH system (400 kW). 60 ports are available in COMPASS for diagnostic purposes.

The scientific programme proposed for the COMPASS tokamak will benefit from the unique features of COMPASS tokamak and consists of two main projects, both highly relevant to ITER: edge plasma physics (H-mode studies, plasma-wall interaction) and wave-plasma interaction studies (e.g., parasitic lower hybrid wave absorption in front of the antenna, lower hybrid wave coupling in detached plasmas) [*Pánek*, 2006].

The new HRTS system is supposed to contribute to this scientific programme by detailed measurements of the profiles of electron temperature and density.

Outline of TS system

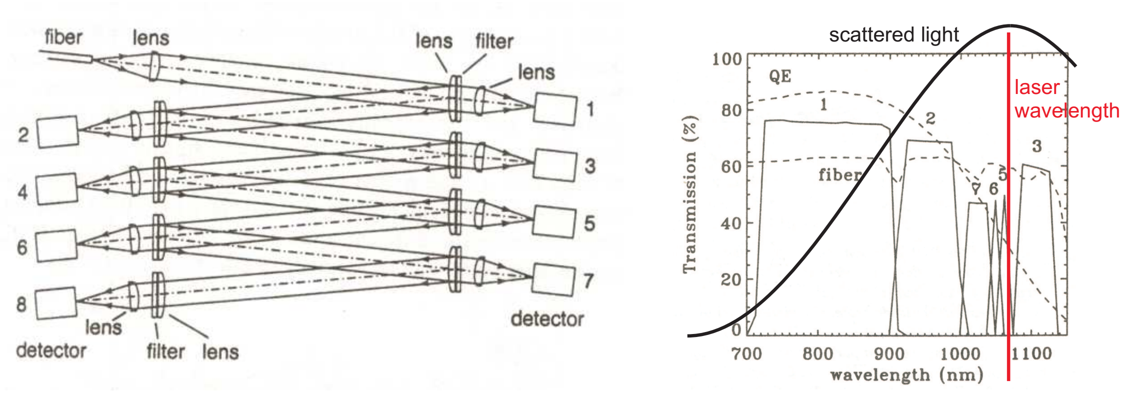
Thomson Scattering [*Barth*, 1998] is based on measurement of light scattered on electrons in plasma. A coherent light from a monochromatic laser beam is injected into the plasma and scattered by free electrons. A Doppler shift appears in the scattered light because of the thermal motion of the electrons. The measured spectrum is Gaussian for a Maxwellian electron velocity distribution. The electron temperature can then be determined from the width of the broadened laser line and the electron density can be determined from the absolute intensity of the detected spectra.

The Thomson cross-section is of the order of $10^{-30}m^2$, hence a high-power laser and an extremely sensitive detection system are always required in all TS diagnostics to overcome the global noise (stray light from laser, the light emitted by plasma itself, and the noise of detector) affecting the measurements. In order to minimize the noise level, a pulsed laser with pulse length of $\cong 10 \div 20$ns is used and the detection system is open just for this short time.

Two types of lasers are commonly used as a source of the primary light for TS: a ruby laser or a Nd-YAG laser. Ruby lasers (λ=694.3 nm) can supply high energy but cannot provide repeated pulses. Nd-YAG (or Nd-glass) lasers can provide both a high repetition rate and high energy. Further, Nd-YAG lasers can be operated either at their first harmonic (λ=1064 nm), in the near infrared region (NIR), or at their second harmonic frequency (λ=532 nm), in the green visible region. For our new system, we are considering these two frequencies of Nd-YAG laser.

The scattered light from each spatial element must be collected and separated into different wavelength bands. It is realized by two basic types of detection systems: spectrometer with cascade of spectral filters with avalanched photodiodes (APD) or CCD camera. The convenience of using one or the other of these two systems is mainly related to the wavelength of the detected light.

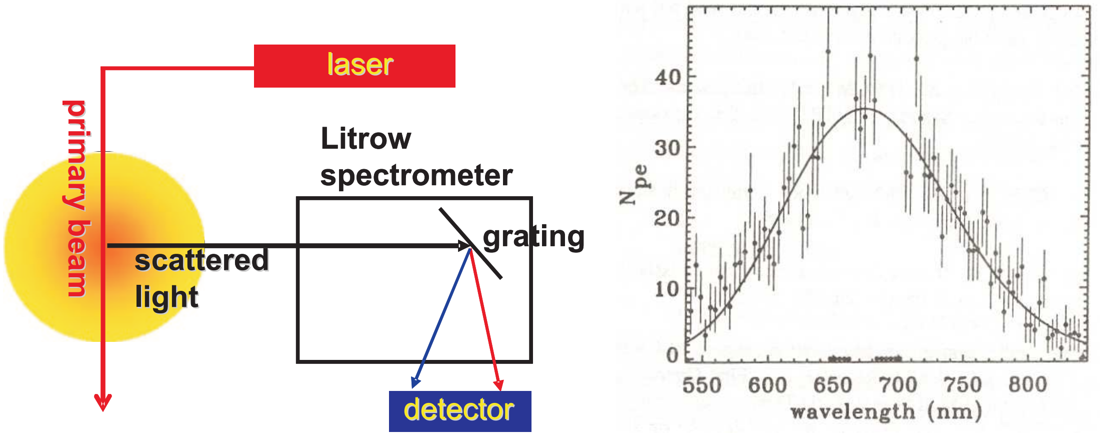
Spectral filters with APDs are used for the NIR region due to the efficiency of the photodiodes. The light collected from one spatial point is divided by means of a cascade of spectral filters with specially designed transmissivity as is shown in Fig. 1b. Behind each filter, an APD is installed as in Fig. 1a. The obtained sensitivity is the highest among the detection systems currently used in TS. However, for large systems with high number of spatial channels, this system becomes to be large and difficult to handle since for every spatial point, one cascade is needed. Another disadvantage is a limited number of spectral channels.



(a) (b)

Figure 1. Schema of detection system using APDs. a) Cascade of spectral filters with photodiodes. b) Example of transmissions of the spectral filters, optical fibres and quantum efficiency (QE) of the APDs [*Barth*, 1998]compared to scattered spectrum.

Spectrometer with CCD is a compact solution consisting of a Littrow spectrometer. Light collected from the whole chord is dispersed by a grating and subsequently projected onto a chip of CCD camera as is shown in Fig. 2a: spatial channels correspond to pixels in one direction and the wavelength is spread in the second one. Since the number of pixels can be large, high wavelength and spatial resolution can be obtained. The main disadvantage of this solution is lower sensitivity as compared with the option of using APDs. Moreover, gating may become a difficult item. While for the visible region, gating can be performed by using an intensifier, there is no equivalent system in the NIR region. An example of measured data is shown in Fig. 2b.

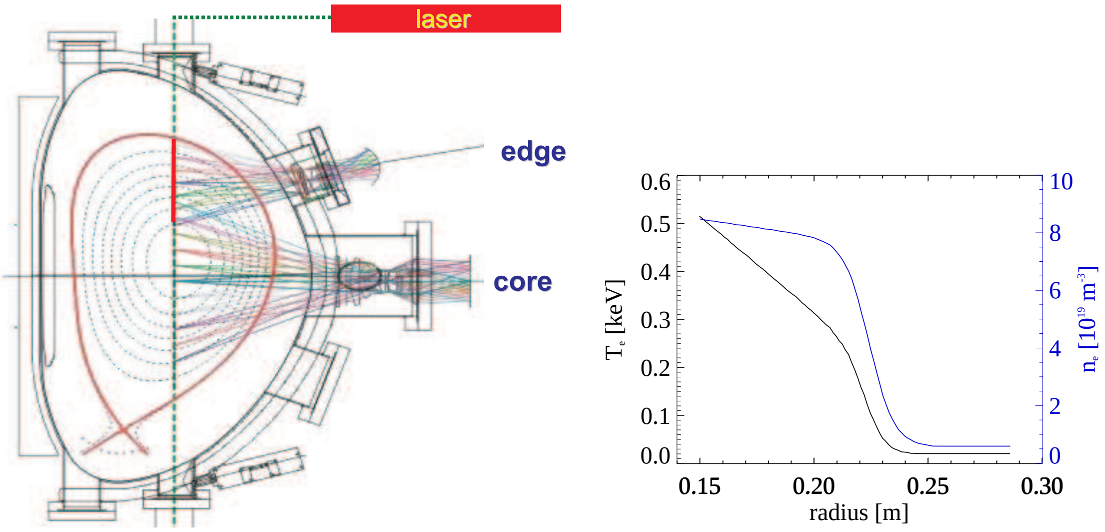


(a) (b)

Figure 2. Detection system using spectrometer with CCD camera. a) Brief schema. b) Example of measured data from tokamak RTP [*Barth*, 1998]. Data in the region around laser wavelength and H_α must be cut off.

The high resolution TS system for COMPASS

T_e and n_e profiles will be measured along a vertical chord as depicted in Fig. 3. The whole chord is too long to be visible by single collecting optics, thus two separate detection systems will be built: one for the edge and the other for the core plasma. For the edge system, spatial resolution 3 mm is required along a chord of 18 cm, which gives 60 spatial channels. For the core system, only 10 mm of spatial resolution is required along 400 mm, which gives 40 spatial channels. The required time resolution, as assigned by the repetition rate of the laser, will be $20 \div 30$ Hz.



(a) (b)

Figure 3. a) Layout of the TS system for COMPASS tokamak, locations of edge and core detection system. b) Expected profiles of electron temperature and density. Data are from previous measurements at Culham.

Since the scientific programme is focused on the studies of pedestal plasma, the priority will be given to the construction and implementation of the edge detection system. The typical plasma parameters expected to be measured are: n_e=1 × $10^{19}m^{-3}$ and T_e=20 ÷ 40 eV for the edge plasma and n_e=10 × $10^{20}m^{-3}$ and T_e=1 keV for the core.

The diagnostic parameters quoted above are rather challenging, thus our TS system will require solutions derived from top notch laser and detection system technologies. The requirement of high spatial resolution implies small scattering volumes and consequently small number of detected photons. Especially in the measurements at the plasma edge, the number of photons detected in the furthest channels (see Fig. 2b) will be comparable to the noise. Furthermore, the gradients of T_e and n_e in the pedestal region tend to be are rather steep as shown in Fig. 3b, hence the detection system is required to have a high dynamic range.

Options for the TS system of COMPASS

As a suitable reference parameter for the estimation of laser energy required for different detection systems, one can take the ratio of the scattered light to the background provided by bremsstrahlung emission from the plasma (R). For given laser energy, the higher is R the more convenient the detection system will be. Conversely, a higher laser energy may be required to achieve the same R for a given detection system. For the same energy generated in the laser pulse, R is eight times lower for the second harmonic. This is caused by: (i) efficiency of the conversion to the second harmonic (about 50%), (ii) twice lower background (from bremsstrahlung) and (iii) the fact that since the photons have half the energy, the number of them is double. Moreover, the spectral lines emitted by the plasma in NIR region are less significant. In estimating the actual performance of TS systems, the efficiency of the detectors must also be considered. The main factors spoiling the ratio R in this respect are a low quantum efficiency and long gating times.

The results from the aforementioned scenarios are summarized in Fig. 4, where the ratios R for five possible detection systems are compared. A laser (15 ns pulse length) with energy of 10 J at the first harmonic frequency and of 5 J at the second harmonic frequency, is considered as a reference for these estimations. The value R = 50 for the second harmonic was obtained by rescaling real experimental data from the tokamak T10 at Kurchatov Institute in Moscow to the conditions of COMPASS.

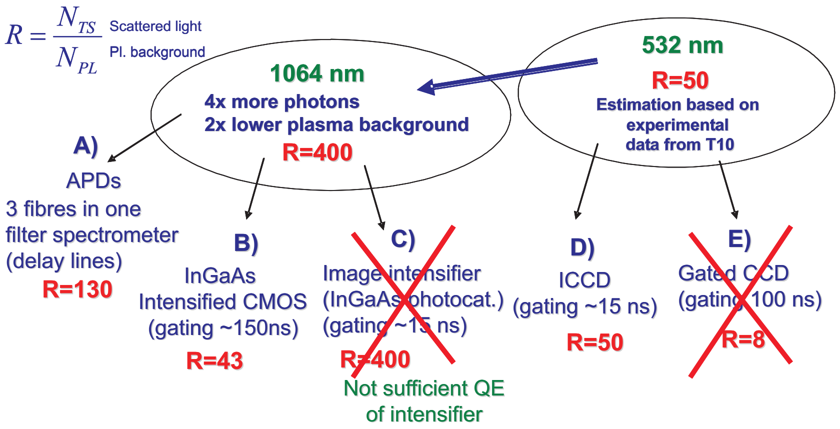


Figure 4. Schema of possible detection systems with calculated ratio R.

Standard TS systems work with detection systems A and D (Fig. 4): APD in NIR region or ICCD in visible region. Parameters of our edge detection system are at the border of possibilities of these systems. In order to improve them, we have carried out a large trade survey, looking for new technologies.

For the second harmonic, we have found a new fast CCD camera (CoolSnap Fast Camera), which can be gated with 100 ns (item E in Fig. 4). Due to high noise coming from plasma, this interval is still too long and ratio R is only 8. Therefore a standard system using an intensifier for gating is more suitable in the green region. An intensifier gated for 15 ns will give $R = 50$.

For the first harmonic, the situation is much more interesting. Until now, only APD systems were constructed, due to missing fast cameras in NIR region. Now, an intensified CMOS camera with InGaAs photocathode (LIVAR 400 Fast Camera) appeared at the market, which enables gating of 150 ns (item B in Fig. 4). This system would give ratio R=43. Another possibility is, as in the case of the second harmonic, using some slow NIR camera and an intensifier (item C in Fig. 4). With a gating of 15 ns, the ratio $R = 400$ would be obtained, which is the highest possible value. Unfortunately, the most advanced intensifiers available now have such poor quantum efficiency, that they would completely spoil the signal. The standard APD system gives ratio $R = 130$.

To conclude, excluding systems C and E, the choice is restricted to the green Nd-YAG laser and ICCD system, or NIR laser and APD or CMOS systems. What are their characteristics?

The ICCD system in the green region is a compact standard system, but for the edge plasma, the calculation shows that there will be a problem with noise. The problem can be solved by pushing up the power of the laser, but it will significantly increase the price of the laser. Apart of these limitations, this system can be used for both edge and core plasma.

Although complex, the APD system in NIR region is also standard. The dynamic range is poor due to limited number of spectral filters. An interesting way how to reduce the number of detectors is using delay lines: three optical fibres with different lengths from three spatial points can be led into one spectrometer. The time duration of opening the detection is longer, on the other hand, this system enables very efficient substracting of background since the photodiodes work in continuous regime. The APD system can be also used for both edge and core plasma.

Still in the NIR region, the CMOS camera is a tempting option. It has advantages of both previous systems: it is compact, it has a high dynamic range and the plasma background is low. However, the chip of the CMOS camera is too small (6 mm x 7 mm) to allow collecting the signal from the laser chord without significant losses. If we accept the cutting off a part of the collected light, the efficiency drops by a factor of two or more. Due to this reason, the CMOS camera is not suitable for the edge system, but can be easily used for the core, where the plasma density and consequently the intensity is higher.

Multi-pass system

The efficiency in signal collection can be significantly increased using a multi-pass system as in Fig. 5. The laser beam is injected to the tokamak vessel, where it is reflected by several mirrors. The detector is opened for slightly longer period, during this time, the laser beam crosses the chamber several times. This arrangement can increase the TS signal, but spoils either the spatial resolution or focalisation of the detected light. The mirrors are exposed to plasma and sputtered.

Summary and Conclusion

For TS experiments on COMPASS tokamak, several possible systems were considered and relevant parameters were calculated for both edge and core plasma studies. Solution of the edge detection system is a big challenge because its parameters touch the limit of current technology. Therefore, a thorough investigation has been carried out, seeking new solutions.

To attain the expected values of electron density and temperature (n_e=1 $\times$ $10^{19}m^{-3}$ and T_e=20 $\div$ 40 for the edge and n_e=10 $\times$ $10^{20}m^{-3}$ and T_e=1 keV for the core), two possibilities were chosen to be the most suitable: (i) Nd-YAG laser at the second harmonic frequency with Littrow spectrometers with ICCD cameras (for both core and edge systems), and (ii) Nd-YAG laser at the first harmonic frequency with Littrow spectrometer with CMOS camera (for the core) and spectral fiters with APDs (for the edge). For effective increase of the laser power, a

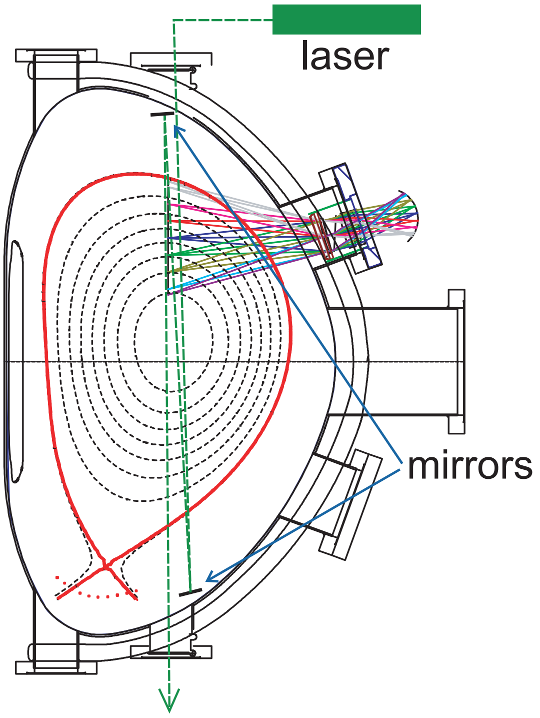


Figure 5. Schema of multi-pass system. The laser light is injected into the tokamak chamber, where is reflected by several mirrors.

multi-pass system can be used.

The two aforementioned possibilities are being investigated now. All available information is being collected and detailed parameters of each system are being calculated in order to determine the best alternative for realizing the TS system.

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