Thomson Scattering Diagnostics on the CASTOR Tokamak

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Introduction

Thomson Scattering is a powerful diagnostic which is applied at almost every magnetic confinement device. Depending on the experimental conditions different plasma parameters can be diagnosed. When the wavelength of the incident light is much smaller than the Debye length, the total scattered power is obtained by an incoherent summation over the scattered powers of individual electrons. The scattering spectrum in this case reflects the electron velocity distribution, from which local values of the electron temperature and density can be derived.

Physical principle

Thomson Scattering (TS) enables measurement of many plasma parameters. We will engage in the measurement of electron temperature (T_e) and density (n_e).

Scattering of the monochromatic electromagnetic radiation on hot electrons in a plasma leads to a spectral broadening of the scattering spectrum due to the Doppler effect. If the wavelength of the applied light is well bellow the Debye length, the TS process is incoherent. The Debye length in thermonuclear plasmas $\lambda_D \sim 3x10^{-5}$ m, while the wavelength of ruby laser (used for measurement of T_e and n_e) is ~ $7x10^{-6}$ m). If the electron velocity distribution is Maxwellian, the measured spectrum is of the gaussian shape. From its width we determine the electron temperature. From absolute intensity of the measured light we can determine the electron density.

The mathematical framework of TS theory is rather complicated. Therefore we will just briefly resume the basic ingredients.

Without going into details we will give the results of the electromagnetic theory which describes the scattered power P_S as follows:

$$P_S = P_0 \frac{d\sigma_T}{d\Omega} \sin^2 \phi \cdot n_e \cdot \Delta L \cdot \Omega \cdot S(k,\omega), \tag{1}$$

where P_o is the incident power, $\frac{d\sigma_T}{d\Omega}$ is the differential scattering cross section of TS, ϕ is the angle between the incident wave amplitude and the direction of the scattered field direction, ΔL is the length of scattering volume, Ω is the solid angle. The dynamic formfactor $S(k,\omega)$ describes the frequency shifts resulting from the electron motion.

The contribution from electrons in each velocity interval must be integrated over the electron velocity distribution, $f(v)$, to determine the net contribution to the spectrum of the scattered light in each frequency interval.

$$S(\vec{k},\omega) = \int_{-\infty}^{\infty} f(v_k) \cdot \delta[\omega_0 - \omega_S(v)] dv_k , \tag{2}$$

in which the δ-function takes care of the fact that each velocity leads to Doppler-shifted, frequency

$$\omega_S(v) = \omega_0 + \vec{k} \cdot \vec{v} . \tag{3}$$

Therefore, the theoretical scattering spectrum will have the same profiles as $f(v)$. When $f(v)$ along $\boldsymbol{k}$ is a Maxwellian distribution

$$f(v_k) = \frac{1}{v_{Te}\sqrt{\pi}} \exp\left[-\left(\frac{v_k}{v_{Te}}\right)^2\right] \tag{4}$$

with thermal velocity:

$$v_{Te} = \sqrt{2k_B T_e / m_e} \quad . \tag{5}$$

The dynamic formfactor becomes:

$$S(\lambda_S) = \frac{1}{\Delta\lambda_e\sqrt{\pi}} \exp\left[-\left(\frac{\lambda_S - \lambda_0}{\Delta\lambda_e}\right)^2\right] \tag{6}$$

in which k_B is the Boltzmann constant, λ_0 and λ_S are the wavelengths of the incident and the scattered radiation, respectively.

Equation (6) predicts that the TS spectrum will have a gaussian shape with a 1/e width:

$$\Delta\lambda_e = 2\lambda_0 \frac{v_{Te}}{c} \sin\frac{\theta}{2} = \frac{2\lambda_0}{c} \sin\frac{\theta}{2} \sqrt{\frac{2k_B T_e}{m_e}} \tag{7}$$

which is

$$\Delta\lambda_e(nm) = 1.94\sqrt{T_e(eV)} \tag{8}$$

for $\lambda_0 = 694.3$ nm (ruby laser) and $\theta = 90°$. The width of the scattering spectrum is proportional to the square root of the T_e, e.g. for $T_e = 1000$ eV one finds $\Delta\lambda_e \sim 61$ nm.

In conclusion, assuming a Maxwellian velocity distribution, TS enables determination of T_e from the shape of the scattering spectrum, according to Eq. (8) and n_e from the total scattered power, using Eq. (1).

Till now we have assumed that the thermal velocity is small compared to the speed of light. When this is not the case, relativistic effects have to be taken into account, leading to two phenomena: On one side there is a small decrease of the classical Thomson cross section due to the mass defect by a factor $1/\gamma^2$. The other effect, much more important, is called the "head-light" effect, which means that for an observer, the electron radiates preferentially in the forward direction. It results in a so-called blue shift of the scattering spectrum. Impact of relativistic effect on the shape of scattered spectra is shown in Figure 1 [2].

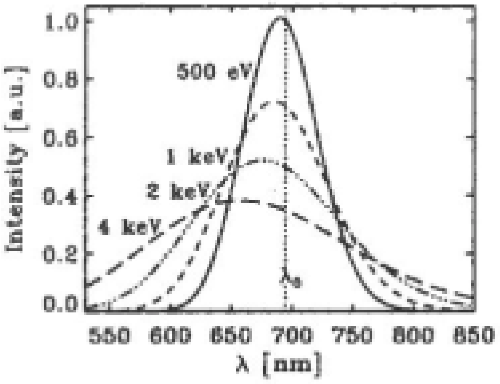

Figure 1. Theoretical relativistic scattering spectra for a plasma diagnosed with a ruby laser (694.3 nm) under a scattering angle of 90°.

It is apparent from the Figure 1 that the electrons are relativistic for high temperatures ≥ 1keV.. On the CASTOR tokamak (T_e~200 eV) this effect is not observable.

Layout of the experiments

Due to the small value of $\frac{d\sigma_T}{d\Omega} \sim 8\times10^{-30}$ m^2, the scattering yield is very low. Therefore a high-power pulsed laser is needed. Usually ruby ($\lambda = 694.3$ nm) or Nd YAG ($\lambda = 1064$ nm) lasers are used.

The monochromatic laser beam, focused by a lens or a telescope, shines through the plasma and it is scattered on free electrons. Polarization of the light is parallel to the tangent of B_{TOR}. Passing vacuum windows it generates stray light, which is reduced by a system of diaphragms and apertures and with a viewing dump. Finally, the primary beam is absorbed in a beam dump, where the monitor of the laser power is usually installed.

The light scattered at 90 degrees angle is collected by a large detection lens and then it is lead to spectrometer. Detected light is split into several spectral regions and each of them is detected. Measured data are numerically processed.

Experimental arrangement of the TS diagnostic suggested for the CASTOR tokamak is schematicly shown in Figure 2.

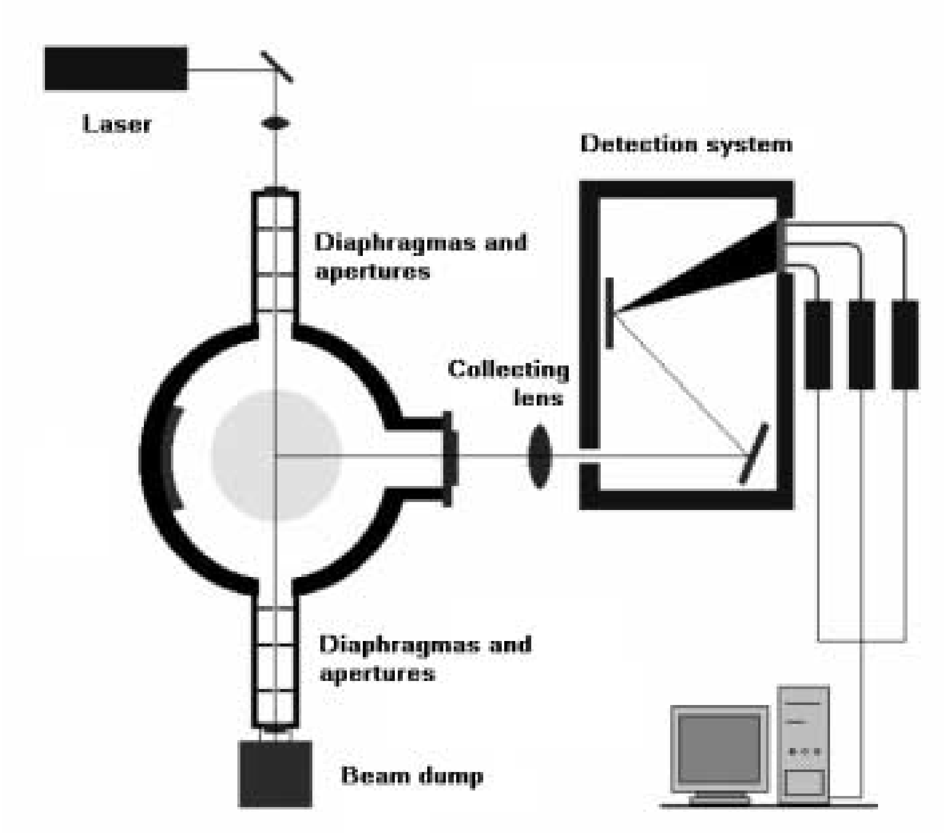

Figure 2. Layout of the experiments

Three types of detection systems for TS are usually used: the monochromator with photomultipliers, the spectral filters with avalanche photodiodes (APD) and the monochromator with an intensified CCD camera (ICCD).

Monochromator with photomultipliers is the basic method. The scattered light from one point of the plasma is dispersed in the monochromator and displayed to a fibre-optic array. Fibres lead light to the photomultipliers, where it is detected. This detection system will be used on the CASTOR tokamak.

Spectral filters with APD: (See Figure 3 [4].) The scattered light from one point of the plasma is separated into different wavelength bands by means of a cascade of interference filters (see Figure 4 [4]). Light in the channels is detected by (APD).

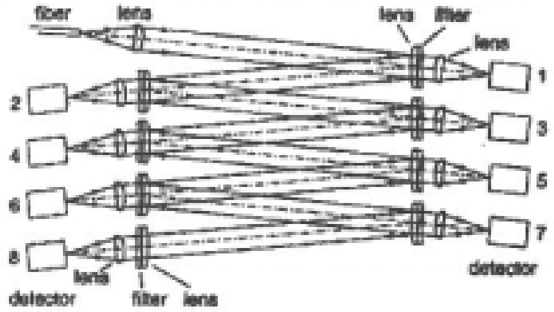

Figure 3. Example of a layout of a filter spectrometer.

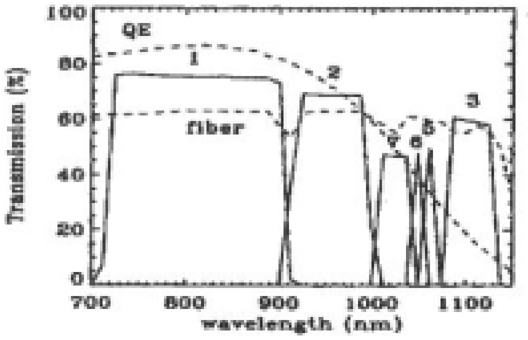

Figure 4. Schematic of a seven-channel filter polychromator. The quantum efficiency of an Avalanche Photodiode is indicated by the dotted line; the effective detector efficiency is a factor 5 lower due to the internal noise.

Monochromator with ICCD Enables to measure the whole radial profile in a single shot. The scattered light from a chord of the plasma is dispersed in the monochromator and displayed on an intensified CCD camera, as shown in Figure 5 [3].

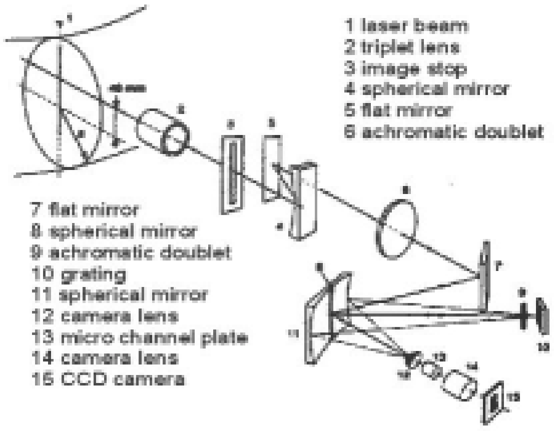

Figure 5. Schematic drawing of the system for multiposition Thomson scattering.

Calibration

Calibration is a very important issue for the TS diagnostic. The width and shape of the spectral channels of a filter spectrometer (shown in Figure 4) are calibrated by means of a tunable light source (e.g. a white light source in combination with a monochromator).

The wavelength calibration of the grating monochromator is done with the use of spectral lamps (He, Ne, Ar). The relative sensitivity of the spectral channels is calibrated by means of tungsten filament of which the emitted power as function of the wavelength is known. The absolute sensitivity of the complete system can be calibrated by filling the vacuum vessel with nitrogen or hydrogen (with known cross section for the laser light) at relatively high densities and performing Rayleigh or Raman scattering.

Status of TS-development for the CASTOR tokamak

The following components will be used on the CASTOR tokamak.

High-power laser system: A ruby pulsed laser with the wavelength $\lambda = 694{,}3$ nm, length of pulse $\tau = 10 - 20$ ns and the energy in one pulse E = 10 J. This laser system was transported to Prague from FOM Nieuwegein in the Netherlands. It was repaired and adapted, small problems eliminated and tested in operation.

Detection system: The main components were transported from CEA Cadarache in France. The collecting lens (which leds the scattered light from plasma into the monochromator) has diameter 10 cm, focal length 20 cm and transparency 75%. The monochromator is type Czerny-Turner with entrance slit 15 x 0-5mm and gratings type 70 HSM 27 1200 or 1800 lines/mm, 64x64 mm. It has dispersion 2,7 nm/mm or 1,8 nm/mm and focal length 300 mm. We have 10 pieces of lightguides and photomultipliers. Lightguides have the length of 1500 mm, input face 15 x 4,5mm and input array 15 x 45mm. Photomultipliers are the type 56 TVP with anode material S20 and quantum efficiency 3,6%. They can be gated by a short rectangular pulse.

Discussion

Calculations of efficiency of different kinds of detection were performed (number of registered photons, quantum and thermal noise …). These calculations show that the photomultiplier detection system does not enable measurement of the profiles of T_e and n_e, but only measurement of T_e and n_e in the center of the plasma column.

The best option seems to be to measure T_e and n_e in the central plasma at first using photomultipliers and to eliminate eventual problems. Later, it will be possible to extend device for the measurement of profiles of T_e and n_e. For this measurement is necessary to buy (or borrow) a new detection system, which will be able to detect the scattered light even from the plasma edge.

Conclusions

Advantages of TS diagnostics are mainly completely independence from any other measurement and the fact that it does not disturb plasma or any other diagnostics during measurement. Excellent accuracy and spatial resolution can be reached. Disadvantages are the poor time resolution and the heftiness of the device (it needs high energy laser and a good detector because of the law cross-section ~ 8×10^{-30} m^2).

References

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