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Exploitation of Avalanche Photodiodes for Thomson Scattering Diagnostics in Tokamaks

M. Aftanas

Charles University Prague, Faculty of Mathematics and Physics, Prague, Czech Republic.

P. Belsky, P. Bohm, V. Weinzettl, J. Brotankova

Institute of Plasma Physics, AS CR, v.v.i., Association EURATOM/IPP-CR, Prague, Czech Republic.

R. Barth, H. van der Meiden

Institute for Plasma Physics, Rijnhuizen, Ass. EURATOM / FOM, the Netherlands.

Abstract. The COMPASS tokamak, originally from UKAEA, Culham laboratory, U.K., will be reinstalled at Institute of Plasma Physics, Prague. The scientific programme is focused mainly on the investigation of the edge plasma region with high temperature and density gradients called pedestal. Many innovations will be done and new diagnostics have to be constructed. One of the key diagnostics is an incoherent Thomson scattering for measurements of electron temperature T_e and density n_e with a high spatial resolution. Several construction options are considered. In this paper a possibility of using a Nd:YAG laser in combination with a detection system based on Avalanche Photodiodes is discussed.

Introduction

Thomson scattering is one of direct diagnostic methods for measuring the electron density n_e and temperature T_e of plasma. It became a standard tool for diagnosing high temperature plasmas in tokamaks. Theory of Thomson scattering (TS) was described first by J.J. Thomson at beginning of the 20th century. If the wave vector of incident electromagnetic radiation is much longer than the plasma Debye length, the radiation is scattered on free electrons. The scattered power is given by incoherent summation over the scattered power of the individual electrons. The scattering spectrum reflects the electron velocity distribution, from which the local electron temperature and density can be determined *[Thomson 1897, Thomson 1906, Barth 1998]*.

In many fusion devices, Thomson scattering diagnostic is used only for the central region of plasma column. Measurements at the plasma edge are much more demanding, because both T_e and n_e are lower by an order of magnitude, and consequently the intensity of the scattered light is low. The construction of TS systems is based on different lasers *[Beurskens 1999]*, mainly on Neodym-Yag or ruby laser and combined with several detection systems. Avalanche photodiodes (APD) or Charged-Coupled Devices (CCD) are used for the detection of the scattered light. The Table 1 summarizes status of the TS diagnostics on European tokamaks.

Table 1. Overview of TS on major European fusion devices.

Facility	Location	LASER (energy and wavelength)	Detection system
ASDEX-Upgrade	Germany, Garching	Nd-Yag (1064nm, 2J)	APD
JET	UK, Culham	Nd-Yag (1064nm, 5J), Ruby (694nm, 3J)	APD
MAST	UK, Culham	Nd-Yag (1064nm, 1,2J)	APD
RFX	Italy, Padova	Nd-Yag, Ruby (694nm, 15J)	APD
TCV	Switterland,Lausanne	Nd-Yag (1064nm, 1,8J)	APD
TEXTOR	Germany, Julich	Nd-Yag, Ruby (694nm, 10-12J)	CCD
TJ-II	Spain, Madrid	Ruby (694nm, 10J)	CCD

High resolution TS at the plasma edge is exploited at majority of above mentioned facilities.

The main aim of current design studies at IPP Prague is to select a most suitable combination of the laser and of the detection system to fulfil the scientific programme at the reinstalled COMPASS tokamak.

Theory

A typical arrangement of the TS diagnostic in a tokamak is schematically shown in Figure 1.

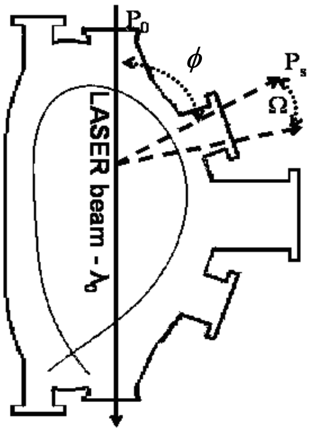

Figure 1. Poloidal cross-section of a tokamak vessel with a layout of TS diagnostics. The vertical laser beam is shown together with a scattered beam to the solid angle *Ω*.

Due to the Doppler effect, scattering of laser wave on free electrons yields spectral broadening of the laser line. The scattered power P_S can be estimated as follows *[Donné 1994, Franke 1997]*:

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

where P_0 is power of the incident electromagnetic radiation, $d\sigma_T/d\Omega$ is the differential scattering cross section, n_e is the electron density, ΔL is the length of the scattering volume, Ω is the solid angle corresponding to the observed volume, $S(k,\omega)$ is the dynamic formfactor which describes the frequency shift resulting from the electron motion and ϕ is the angle between incident and scattered wave. In thermal equilibrium, the factor *S* is given by the Maxwell distribution *[Barth, 1998]*:

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

where λ_0, λ_S are the wavelengths of incident and scattered radiation. The width of the spectrum $\Delta\lambda_e$ is given by the expression:

$$\Delta\lambda_e = 2\lambda_0 \frac{a}{c} \sin\frac{\theta}{2} = \frac{2\lambda_0}{c} \sin\frac{\theta}{2} \sqrt{\frac{2k_B T_e}{m_e}} \tag{3}$$

The above formula shows how the electron temperature is determined from the width of the scattered spectrum.

Number of scattered photons

A key parameter for the design of a TS detection system is the number of scattered photons, which is calculated using expression (1) for the expected geometry of an experiment. We have developed software for estimation of this value for arbitrary radial profiles of T_e and n_e. As an input parameter for current calculations, the radial profiles of T_e and n_e measured on the COMPASS tokamak in the Culham laboratory were used (see Figure 2.a).

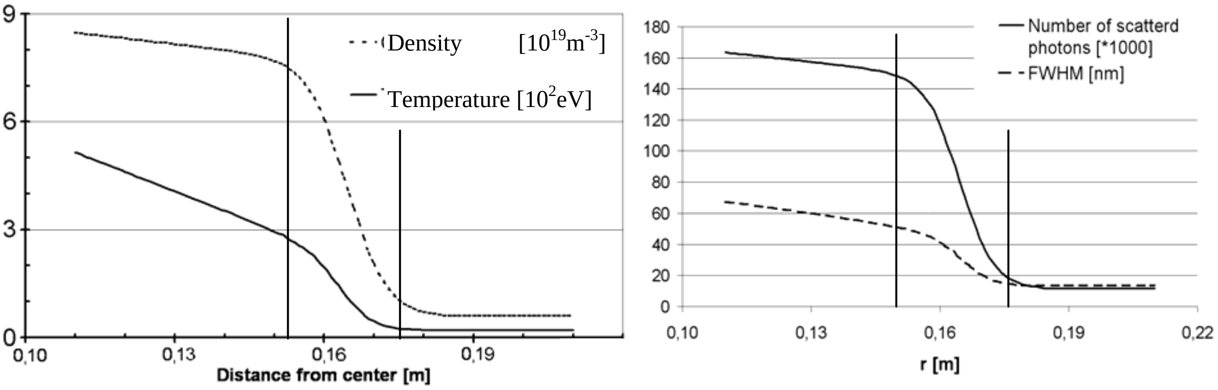

Figure 2.a Radial profiles of the electron temperature and electron density measured in Culham laboratory. **2.b** The total number of scattered photons and the halfwidth of the spectrum as a function of radius for 5J laser. The region of pedestal is marked by vertical lines.

The radial profile of the total number of scattered photons is plotted in Figure 2.b together with the halfwidth of the spectrum. It should be stressed out that the investigated part of the radial profile contains high density and temperature gradients where the TS signal drops significantly. The total number of scattered photons is still acceptable at all radii, while the halfwith implies severe requirements on the detection system.

The number of photons from background radiation is not considered in this computation. The bremsstrahlung background radiation can be taken into account by using the semi-empiric formula *[Kunze]*:

$$\frac{dI}{d\lambda} = 1.9 \cdot 10^{-28} n_e n_i Z^2 g \frac{1}{\sqrt{kT_e}} \frac{1}{\lambda^2} \exp\left(-\frac{12395}{\lambda k T_e} \right) \qquad \left[\frac{W}{nm \cdot sr \cdot cm^3} \right] \tag{4}$$

where n_e, n_i are the electron and ion densities, Z is the effective atomic number (in this case around 2), g is the Gaunt factor ($\cong 1 - 5$; for $\lambda < 100nm$ $g=1$), λ is the wavelength.

Possible design of TS for COMPASS tokamak

The scientific programme for COMPASS tokamak is focused namely on the relatively thin pedestal region, where steep gradients of plasma parameters are met, accordingly high spatial resolution measurements of the edge plasma electron temperature and density are very important. Reliable Nd:YAG lasers have been developed for industrial applications and can be exploited to TS. The COMPASS tokamak would require the laser with the energy of 5 J and the repetition frequency 20-30 Hz.

The CCDs or APDs detectors of the scattered laser light are usually used in existing TS systems (Table 1.). In this article, we analyse exploitation of APD detectors. In contrast to CCD-based detectors which integrates signal, background radiation can be easily subtracted in APD-based systems because of a very good time resolution of the photodiodes. APDs are also more sensitive in comparison to CCDs.

Avalanche Photodiodes (APD)

APDs (Avalanche Photodiodes) are high speed and very sensitive photodiodes with a possibility to change the gain. Compare to PIN photodiodes, the APDs are more sensitive *[Primer 2005]*.

When light enters a photodiode, the electron-hole pairs are generated if the light energy is higher than the band gap energy. For Si, the band gap energy is 1.12 eV at room temperatures, so that it is sensitive to wavelengths shorter than 1100 nm. When electron-hole pairs are generated in depleted layer of a photodiode with a reverse voltage applied to PN junction, the electrons drift towards the N+ side while the holes drift towards the P+ side due to the electric field developed across the PN junction (see Figure 3.). The drift speed of these electron-hole pairs depends on the electric field intensity.

When the electric field increases to approximately 10^4V·cm^{-1}, the carries are more likely to collide with the crystal lattice and thus the drift speed saturates. If the reverse voltage is increased above 2·10^5 V·cm^{-1} some of the carriers will have sufficient energy to generate new electron-hole pairs (chain reaction).

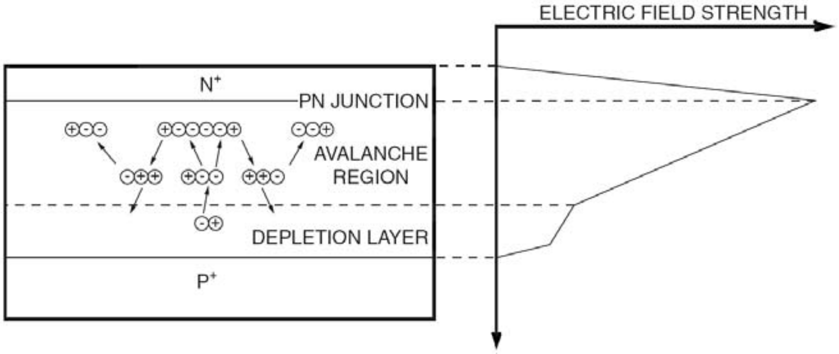

Figure 3. Schematic diagram of the avalanche process supplemented by the electric field strength values.

Thomson scattering based on Avalanche photodiodes

A possible way of an arrangement of the detection system based on APDs is an interference filters cascade (Figure 4.). The scattered light incidents the first filter, which is transparent for a specific wavelength range of the incident light (given by filter characteristics). Then it is detected by the first APD. The remaining light is reflected toward the second filter of the cascade.

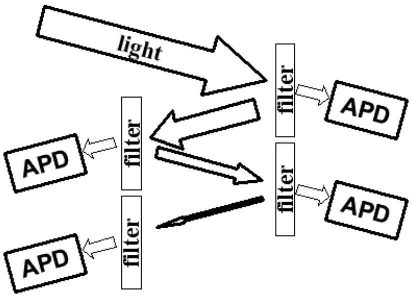

Figure 4. Cascade of interference filters for one spatial point.

For each spatial channel, 3 to 8 interference filters are typically used. An example of the filter selection (with 4 filters) is shown in the right panel of Figure 5. The wavelength width and transmission of individual filters were selected according to the DIII-D design *[Simonen, 1999]*.

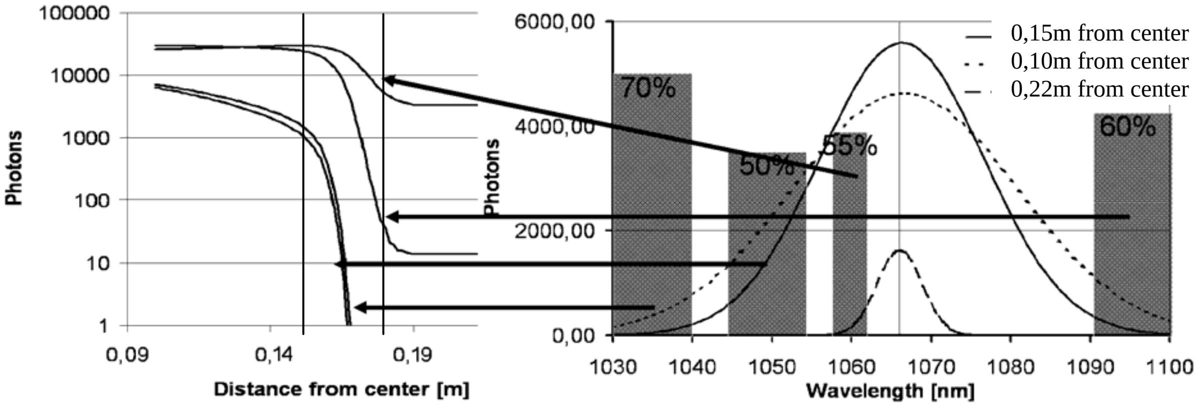

Figure 5. A possible distribution of filters with their transmissivity (right) and dependence of the signal on the distance from the centre of the tokamak (left). The region of pedestal is marked by vertical lines.

The radial distribution of the scattered photons for COMPASS tokamak predicted from profiles shown in Figure 2.a is plotted in the left panel of Figure 5. The region of interest (pedestal) is again marked by vertical lines. Figure 5 clearly shows that the selected distribution of filters cannot be used for pedestal studies because only two spectral channels are available to count a sufficient number of scattered photons in this region. Therefore, as the next step, we need to optimize the distribution of spectral filters taking into account the following: i) at least three spectral channels are required to collect sufficient signal to determine the width of the scattered spectrum, ii) the spectral width has to be selected in order to ensure that the amplitude of each spectral channel fits a limited dynamic range of the data acquisition system, iii) the system requires a uniform distribution of filters for each spatial point, since the pedestal may move according to the plasma geometry.

Conclusion

Different laser and detection options are considered for TS on COMPASS *[Brotankova, 2007]*. Final selection of the edge detection system has to be done. This decision is impacted by many factors. This article is focused on APD-based system which is a promising option because of the high sensitivity and the high temporal resolution. Further advantage is the possibility of direct subtracting the noise resulting from the background light emission from the plasma. On the other hand, the APD system has a limited number of spectral channels, which causes an uncertainty in fitting procedure and consequent determination of the electron temperature and plasma density. Another disadvantage of APD based system is its complexity, if a high spatial resolution is required. It can be solved by using a 2D matrix of APDs. However, such solution is a kind of new technology and it still requires more development.

Final design is also determined by limited financial resources available for the construction of the TS complex on the COMPASS tokamak.

In this article, the number of scattered photons and halfwidths in dependence on radius has been estimated. Calculations of precise distribution of filters with respect to moving of region of interest, i.e. pedestal will be the next step for realizing TS system based on APDs.

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