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Electron temperature (T_e) measurements by Thomson scattering system

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Abstract. Thomson scattering technique based on high power laser has already proved its superoirity in measuring the electron temperature (T_e) and density (n_e) in fusion plasma devices like tokamaks. The method is a direct and unambiguous one, widely used for the localised and simultaneous measurements of the above parameters. In Thomson scattering experiment, the light scattered by the plasma electrons is used for the measurements. The plasma electron temperature is measured from the Doppler shifted scattered spectrum and density from the total scattered intensity. A single point Thomson scattering system involving a Q-switched ruby laser and PMTs as the detector is deployed in ADITYA tokamak to give the plasma electron parameters. The system is capable of providing the parameters T_e from 30 eV to 1 keV and n_e from $5 \times 10^{12}\mathrm{cm}^{-3}$–$5 \times 10^{13}\mathrm{cm}^{-3}$. The system is also able to give the parameter profile from the plasma center ($Z = 0$ cm) to a vertical position of $Z = +22$ cm to $Z = -14$ cm, with a spatial resolution of 1 cm on shot to shot basis. This paper discusses the initial measurements of the plasma temperature from ADITYA.

Keywords. Thomson scattering; plasma diagnostics.

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1. Introduction

Incoherent Thomson scattering [1] is a well known diagnostics method useful for the measurements of basic plasma parameters. The process of scattering is that the plasma free electrons in the oscillating field of the incident radiation are accelerated and hence they radiate. Since the electrons have thermal velocity, the scattered radiation will be Doppler shifted from the incident laser wavelength. ADITYA [2] is a medium size tokamak with a major radius (R) of 75 cm, minor radius (a) of 25 cm, plasma current (I_p) of $\sim$ 250 kA, electron density $\leq 5 \times 10^{13}\mathrm{cm}^{-3}$ and electron temperature ≤ 1 keV.

This paper briefly gives the main components of the ADITYA Thomson scattering system (ATS) that are described along with the initial measurements. This system is devoted to the measurements of plasma electron temperature and density. The ATS uses a 10J ruby laser with a pulse duration of about 20 ns. The high power laser requirement is because of the very small cross-section of Thomson scattering ($\sim 6 \times 10^{-26}$ cm^{-2}, i.e, *the classical electron radius square*). The method also need a very careful elimination of stray light to increase the signal to noise ratio. On each laser pulse, the scattering from a single element will be collected, dispersed into 10 different wavelength bands to perform the analysis.

2. Theory

The main advantage of this diagnostics technique lies in its well developed theory behind it for any conditions of the plasma. In the case of incoherent scattering, the total scattered power is the simple sum of the scattered powers from each individual electron present in the observed scattering volume. For the assumption of electrons with simple Maxwellian velocity distribution, the scattered power at right angles to the incident wave and polarization vectors of the laser beam is given by Selden Model [3],

$$P(\lambda)\Delta\Omega\Delta\lambda = \frac{\Delta\Omega\Delta\lambda}{\lambda_L} r_0^2 \pi^{-1/2} n_e L P_L \frac{c}{\nu} y_1 \mathrm{e}^{[-(c/\nu)^2 y_2]} \tag{1}$$

with,

$$y_1 = 2^{-1/2}(1 - 3.5x + 7.6x^2 - 13.3x^3), \tag{2}$$

$$y_2 = \frac{x^2}{2}(1 - x) \tag{3}$$

and

$$x = \frac{\lambda - \lambda_L}{\lambda_L}, \tag{4}$$

where λ_L = laser wavelength (nm), λ = scattered wavelength (nm), ν = mean thermal velocity of electrons $\left[= (\frac{2KT_e}{m_e})^{1/2}\right]$ (cm/sec), c = speed of light (cm/sec), L = scattering length (cm), P_L = power of the laser beam (Watts), $\Delta\Omega$ = solid angle of observation (Sr), n_e = local electron density (cm^{-3}), T_e = local electron temperature (eV).

For the assumption,

$$\mathrm{e}^{-[Dx^2(1-x)]} = (1 + Dx^3)\mathrm{e}^{(-Dx^2)} \tag{5}$$

with,

$$D = \frac{1}{2}\left(\frac{c}{\nu}\right)^2 = \frac{127.5}{T_e(\mathrm{KeV})}. \tag{6}$$

Equation (1) can be written as

$$P(\lambda)\Delta\Omega\Delta\lambda = \frac{\Delta\Omega\Delta\lambda}{\lambda_L} r_0^2 n_e L P_L S(T_e, x), \tag{7}$$

where,

$$S(T_e, x) = \left(\frac{D}{\pi}\right)^{1/2} y\mathrm{e}^{-(Dx^2)}, \tag{8}$$

$$y = 1 - 3.5x + 7.6x^2 + (D - 13.3)x^3. \quad (9)$$

The eq. (1) also included the relativistic effects up to the first order (valied up to 25 KeV) and finite transit time effects. Equation (7) has been used for the calculation of the expected scattered photons.

The scattered spectrum is Gaussian in shape and resembles the electron velocity distribution of the plasma. The half width at half maximum (HWHM) of this spectrum is directly linked with the electron temperature and is given by the following equation,

$$\Delta\lambda_{1/e}(A^0) = 4 \times 10^{-3}\lambda_i(A^0)\sin(\theta/2)[T_e(\mathrm{eV})]^{(1/2)}. \quad (10)$$

For 1.0 eV plasma, HWHM comes out to be about 3 nm, which shows the need of high spectral resolution to measure low temperatures.

3. Description of the system

The ATS uses a ruby laser system with PMTs as the detector using a conventional imaging system. In this section the major sub-systems of the set-up is given in brief.

3.1 *Laser input*

The light source, which is the Q-switched ruby laser has a maximum energy of about 10 J, pulse duration 20 ns and divergence of about 1.2 mrad. The laser is kept at about 7 m distance from the machine for its safe operation against the electromagnetic and RF interferences results from the machine. The gaussian beam is directed into the machine through the drift tube at the bottom vertical port of the machine using a high energetic mirror with high reflectance ($>$ 99.9%). The drift tube consists of a set of knife edged apertures which help in reducing the stray light as well as to direct the beam to a desired accuracy.

The gaussian beam is made narrow by focussing it along the desired plasma chord (i.e, through the plasma center) using an AR coated plano-convex lens (of $f = 1.2$ m) with high trasmission ($>$ 99.9%). The size of the beam waist at the focal plane (plasma center) is about 1.5 mm and it is about 2.5 mm at the plasma periphery. The pencil like beam is aligned to the desired chord with an accuracy better than 0.25 mm. The beam exits through another drift tube at the top port which also have knife edged apertues. The exit beam is perfectly dumped inside the vacuum vessel itself on a set of colour glass filters mounted at Brewster angle.

3.2 *Collection optics*

The 90° scattered photons from the scattering volume are collected through the radial port, using a F/5 optical system, consisting of an achromatic objective lens. The image produced by the objective lens is fed to the spectrometer using a set of field and relay lenses. The entire imaging optics is designed such that it will view only a single element of 1 cm with a magnification of 1:1. The viewing optics arrangement is also such

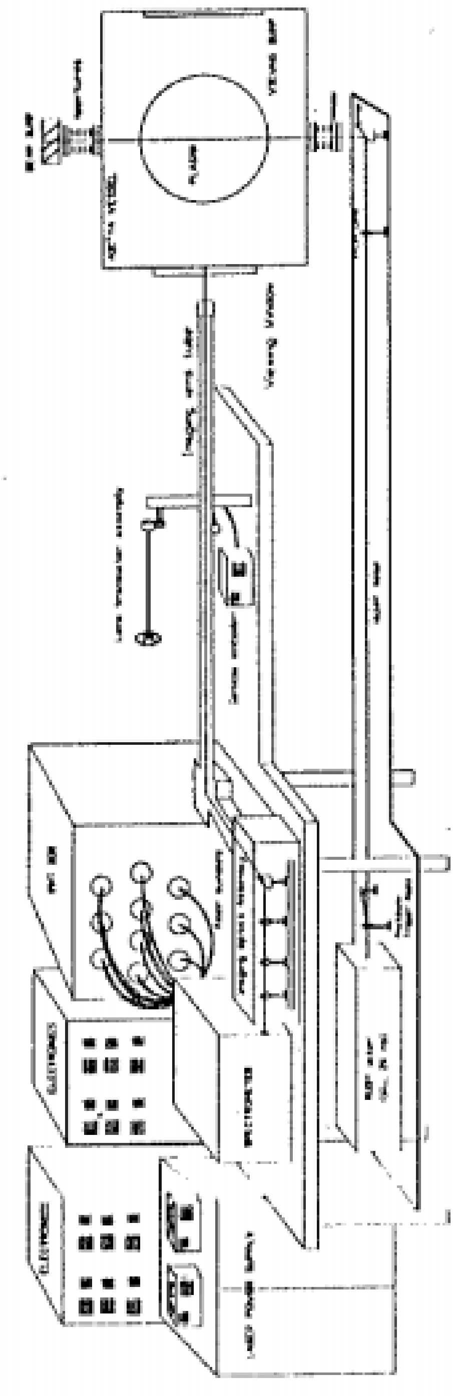

Figure 1. Aditya Thomson scattering system, a schematic view.

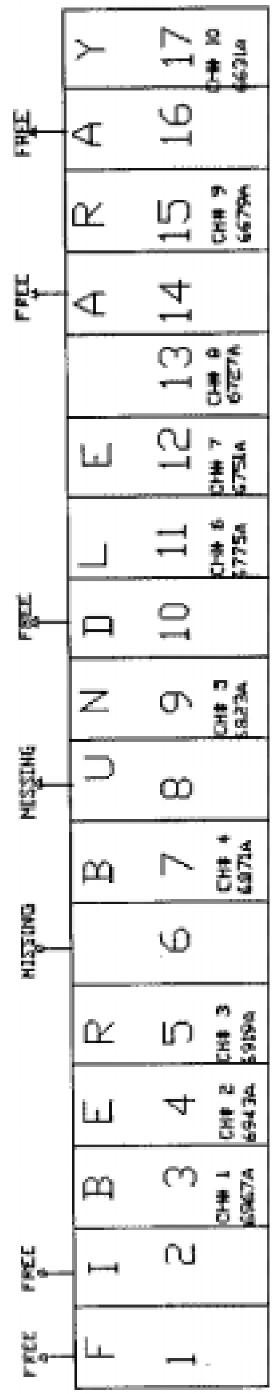

Figure 2. Schematic of the fiber bundle distribution.

that it can be scanned over the laser chord using a vertical lens translator. The exact position of the viewing element can be obtained with an accuracy better than 0.5 mm, with a well calibrated optical encoder attached along with it. The alignment of the collection optics is made to an accuracy better than 0.25 mm using a special set-up which will cut only a cm of the He–Ne laser beam passing collinear with the ruby laser beam. A carbon viewing dump mounted on the rear side of the vessel wall will further reduce the stray and plasma light, from entering into the collection optics.

3.3 *Light dispersion and detection*

The collected scattered light is dispersed into different $\Delta\lambda$-bands with a grating spectrometr (λ-Minutemen, Model SMP-310). The spectrometer with a 1200 grooves/mm grating has a resolution of 8Å/mm, magnification 1 and focal length 1 m. The exit slit of the spectrometer is replaced with a fiber bundle array, consisting of 17 rectangular bundles (each with 3×10 mm size). Ten out of the seventeen bundles, one including the laser band ($\lambda_{\rm ruby}$) and one on the higher wavelength side ($\lambda_{\rm ruby} + \Delta\lambda$) of the laser band are selected for detection and analysis (see figure 2).

The selection of the wavelength channels are made such that the system can cover a temperature range from 30 eV to 1 keV. The other end of each selected fiber bundles are coupled with a high gain photo-multiplier tube (RCA make C31034) kept inside a complete light tight shielding tube. The glass windows of the PMTs are AR coated to assure maximum transmission. The PMTs are gated and are triggered by the output of a fast photo-diode which receives a portion of the laser beam before entering into the plasma.

4. Operational testing and calibration

The operation of the system is verified by performing the Rayleigh scattering with the system, by filling the vessel with nitrogen gas for different known values of pressure. The results (see figure 3) follows the expected trend. This also assures that the stray light level is minimum, and within the acceptable level. The wavelength and intensity calibration of the spectrometer is also done by standard calibration lamps. It is found that each fiber bundle is covering a wavelength bandwidth of 24Å.

5. Signal processing and results

The PMT output are amplified twice and then digitised using CAMAC modules. The detailed paper on the description of the electronics and data acqusition of the system is given in the accompanying paper in this proceedings [4]. The final output will be in the photon integration mode and will be acquired by a computer.

In order to have a complete noise analysis, provision is also made to get the PMT output into GPIB based eight channel digital storage oscilloscope set up. The oscilloscope data is used well for the data analysis. Particularly, this paper presents the results obtained using the oscilloscope. The typical signal traces from the PMTs without and with the presence of plasma is shown in figures 4 and 5 respectively. The background plasma light is detected

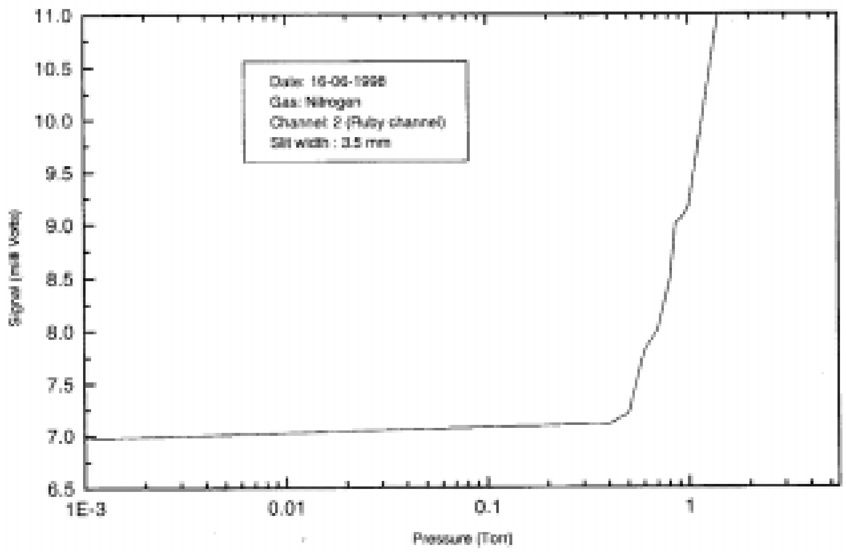

Figure 3. Rayleigh scattering for different gas pressure.

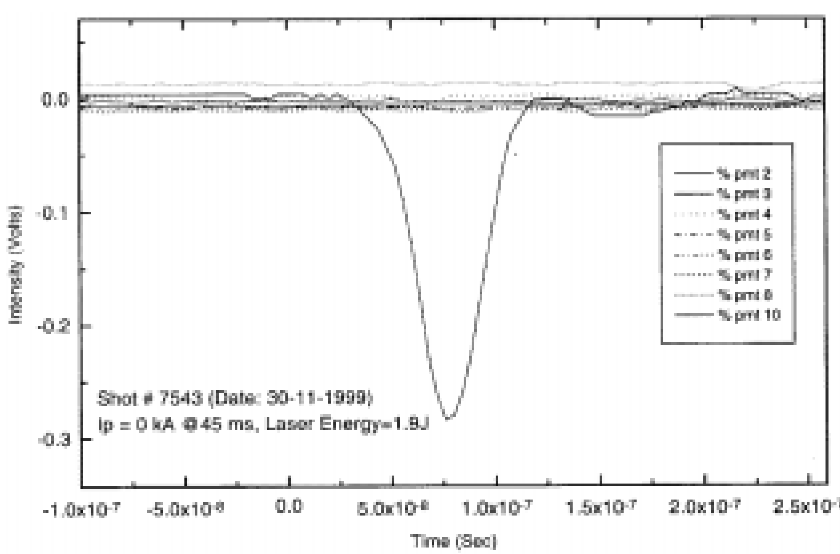

Figure 4. The scope is signal for a typical laser shot without plasma.

just before and after the laser pulse and is substracted from the scattered light signal for the determination of the actual Thomson scattered light signal. The electron temperature of the plasma is calculated from the slope of the curve between $\Delta\lambda^2$ (Å^2) and logarithmic

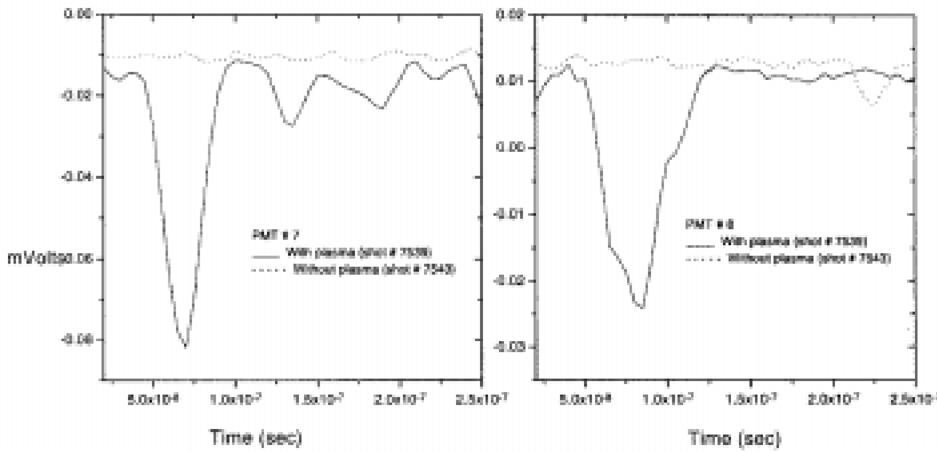

Figure 5. Example for the comparison of signals with and without plasma.

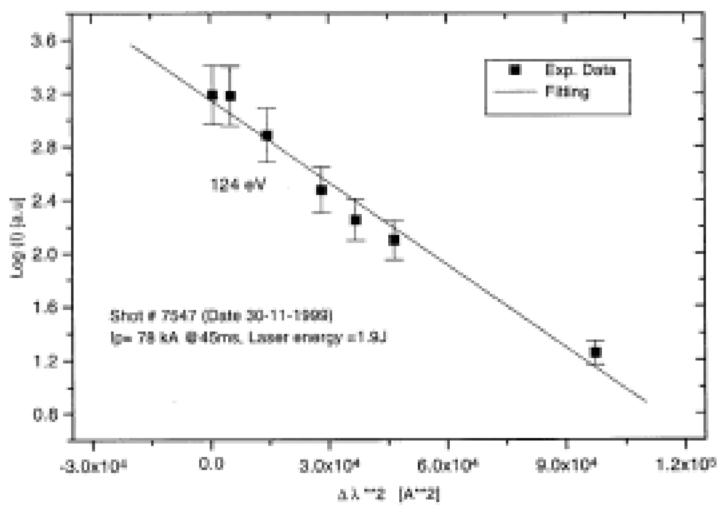

Figure 6. Electron temperature measurement of a typical plasma shot.

value of the signal in each channel. For a ruby laser system and 90° scattering geometry, the relation between the above two parameters is [1]

$$T_e = \frac{2.5723 \times 10^{-3}}{\text{Slope}} \text{eV}. \tag{11}$$

The above such plot for electron temperature measurement from the plasma centre for a typical Aditya plasma shot is shown in figure 6 and the value turned out to be 124 eV.

6. Conclusion

A Thomson scattering system based on ruby laser and PMT detector is commissioned in ADITYA tokamak. As the initial step, the operation of the system is confirmed by performing the Rayleigh scattering. All the *in-situ* calibrations required for the system are also performed. As the first part of the measurements with the system, the electron temperature of certain plasma shots have been analysed. At present, the system is tuning for the density measurements with the absolute calibration using Rayleigh scattering.

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