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Design and development of five-channel interference filter polychromator for SST-1 Thomson scattering system

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ABSTRACT

Five-channel interference filter polychromator is designed and fabricated for measuring electron temperature and density from Thomson scattered spectrum of SST-1 tokamak plasma. The instrument is designed for measuring electron temperature in the range of 20 eV–3 keV and electron density of 10^{18}–10^{19} m^{-3}. Optical ray tracing software, Zemax is used for simulating and optimizing the optical design. Each polychromator is a stand-alone unit with field programmable gate array (FPGA) based controller unit for easy operation, monitoring of the temperature variation of the instrument and communicating to a central personal computer (PC). The control unit also protects the avalanche photo diode (APD) detectors from damage due to high current flow, sets the slow channel gain and switches on the biasing power supply. Characteristics of the present polychromator design are relatively high signal throughput and variable bandwidth selection of filters combined with a stable, low cost and relatively simple configuration. Filter selection, arrangement order of filters, statistical error analysis, mechanical and optical design and estimation of electron temperature and density are discussed in this article. The fabricated filter polychromator is tested for its image quality, optical alignment, and integrated performance.

1. Introduction

Thomson scattering (TS) diagnostics is considered as one of the most reliable methods for measuring spatial and temporal profiles of the electron temperature (T_e) and density (n_e) of tokamak plasma [1–5]. However, the low TS cross-section (6.653×10^{-25} cm^2) of electron makes it a difficult diagnostic to carry out measurements accurately. Innovations in high throughput spectral resolving system, high-gain detectors and large laser energy with higher repetition rates have helped the TS diagnostics to attain higher levels of accuracy and temporal resolution. Grating polychromators have been used for resolving the spectrum of scattered photons in many tokamaks [1,6,7] even though it has drawbacks such as low efficiency, difficulty in making variable spectral channel width, bulky size and high coast. The present Thomson scattering system uses multichannel interference filter polychromator [8–10] for spectral sampling and measurement of Thomson scattered spectrum. As the SST-1 TS system [11] is designed for multi point imaging (27 spatial points at a time) along horizontal and vertical cords and in the diverter region of SST-1, the size and cost of polychromator is required to be minimized for a cost effective operation. Here, we present in detail the design and performance testing of five-channel interference filter polychromator. The electron temperature range of SST-1 plasma is in the range of 20 eV (divertor or edge plasma) to 3 keV (core region). A five-channel filter polychromator design is opted for SST-1 Thomson scattering diagnostics, out of which one channel at the laser wavelength, will be used for the Rayleigh calibration.

2. Design of filter polychromator

2.1. Filter selection

The fundamental wavelength of Nd:YAG laser (1064 nm) is used as the source for SST-1 TS system. The lower wavelength region of Thomson scattered spectrum is used for estimating electron temperature and density. In a filter polychromator, the collected TS spectrum is divided into different bands using interference filters. The pass band selection of interference filter is based on the temperature range to be measured and the shape of the scattered spectrum. For an incoherent Thomson scattering, the scattered power P_{sc} within a solid angle $d\Omega$ and wavelength interval $d\lambda_s$ is calculated by using the equation [12].

$$P_{sc} d\lambda_s d\Omega = \frac{p_i r_0^2 \, d\Omega n_e L c}{2\pi^{1/2} a \sin(\theta/2)\lambda_i} \left\{ 1 - 4\frac{\Delta\lambda}{\lambda_i} + \frac{c^2 \Delta\lambda^3}{4a^2 \lambda_i^3 \sin^2(\theta/2)} \right\} \exp\left(-\frac{c^2 \Delta\lambda^2}{4a^2 \lambda^2 \sin^2(\theta/2)} \right) \cdot d\lambda_s \pi \quad (1)$$

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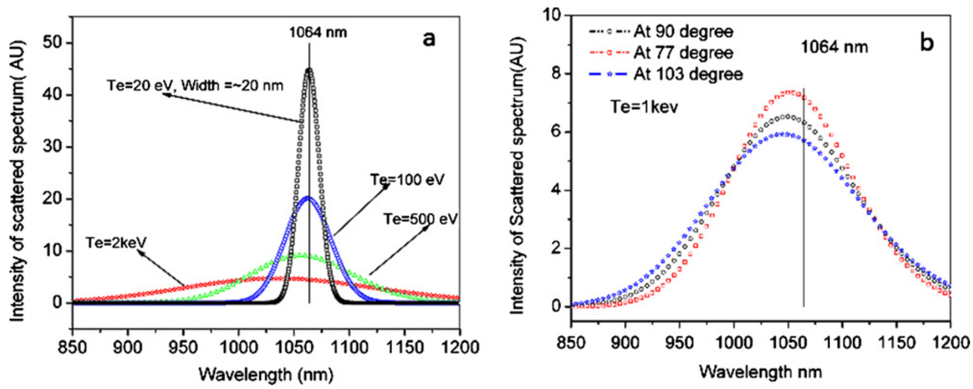

Fig. 1. (A) The Thomson scattered spectrum at different temperatures, the filters were selected on the basis of this spectrum. The lower range to be measured is 20 eV, which corresponds to a 20 nm width. (B) The collection angle dependence of Thomson scattered spectrum at 1 keV.

Table 1
Major parameters used for numerical calculation.

Pulse width	10 ns
Focused laser beam diameter	2 mm
Imaging length	10 mm
Laser pulse energy	1.6 J
Input wavelength	1064 nm
Solid angle	5×10^{-3} str
Scattering angle	77–110°

where p_i is the incident laser power, n_e is the electron density, L is the scattering length, c is the light velocity, θ is the scattering angle, λ_i is the incident laser wavelength, $\Delta\lambda$ is the shift in scattered wavelength, r_0 is the classical electron radius and $a^2 = 2KT_e/me$. The filter polychromator disperses TS scattered spectrum into bands, by sequential, selective band transmission and reflection with the help of band pass filters and precise optical alignment. For using the instrument in the entire temperature range of SST-1 (20 eV–3 keV), with in acceptable limit of errors, the filter selection has a critical role. The numbers of photons reaching the detectors is calculated by the above equation using the parameters of SST-1 Thomson scattering system given in Table 1. For temperature range up to 3 keV and for $\theta = 90°$ TS spectrum has a nearly Gaussian shape and electron temperature is proportional to the width of the spectrum [12]. Fig. 1(a) shows the 90° TS spectrum at different electron temperatures. The TS spectrum broadens nearly 20 nm for plasma with electron temperature of 20 eV, which gradually increases to 180 nm for 3 keV plasma (for Nd:YAG laser operating at the fundamental wavelength). Therefore, narrow pass bands are opted near the laser wavelength to accommodate more filters to improve the accuracy of lower electron temperature measurements. As the lower wavelength region of the scattered spectrum has very low fluence as shown in Fig. 1a, filters with large pass bands are chosen for this region to improve the signal to noise ratio. The filter selection is optimized with the statistical error analysis for the expected range of electron temperature and is discussed in Section 2.6. Table 2 gives the central wavelength and pass bandwidths of all the filters used in present design, finalized after carrying out error analysis for different set of filters possible in the expected range of wavelength.

Table 2
The center wavelength and bandwidth of filters used in the design. The filters are designed to have steep fall in transmission at either side of its transmission band so as to avoid overlapping of band between the filters width.

Filter number	Center wavelength (nm)	FWHM (nm)
1	1064	2
2	1058	8
3	1048	12
4	1030	18
5	960	120

For a multipoint Thomson scattering system the scattering angle has to be considered while calculating the electron temperature. In SST-1 Horizontal TS, the collection angle varies from 77° to 103°. Fig. 1(b) shows the Thomson scattered spectrum for electron temperature at 1 keV corresponding to three different scattering angles. As the scattered spectrum changes significantly with collection angle and hence, it becomes an important parameter for the estimation of the temperature and density profiles accurately. Fig. 2 shows the ratio of counts between the channels for two different collection angles as a function of temperature. The significant difference between the ratios suggests the requirement of incorporation of the angle while calculating the temperature profile.

2.2. Mechanical design

The important aspects in the mechanical design of filter polychromator were the stability of instrument, easiness in alignment and calibration, size of instrument and cost effectiveness. In the present design, two thick aluminum alloy (B 51S) bars (width 20 mm, depth 80 mm) precisely aligned and fixed parallel (10 arc minutes) to each other using another two aluminum bars forming a rigid fixture. This fixture is fixed on an optical breadboard of dimension 420 mm × 800 mm. Interference filters (diameter 50.8 mm)

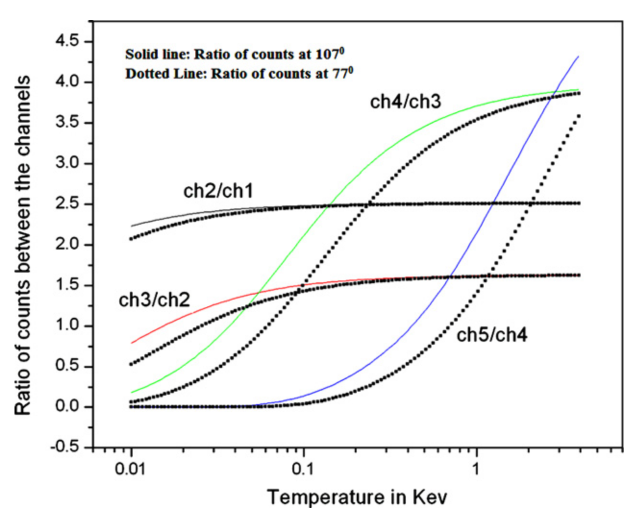

Fig. 2. Ratios for the counts of channels in filter polychromator for two different angles of collection. Solid line is the ratio for 107° angle of incidence and the scattered one is for 77°. This illustrates the importance of angle while calculating the temperature profile.