# MCF Lab: Thomson scattering data analysis

## 1 Introduction

Thomson scattering (TS) is an active spectroscopy technique where a laser is fired into a plasma and the scattered light is collected and analysed. It is an extremely important diagnostic tool in tokamak physics, allowing both the electron temperature and density to be measured across the entire diameter of the plasma with good accuracy and spatial resolution.

As the laser photons are scattered off electrons in the plasma, their frequencies are Doppler-shifted by the thermal motion of the electrons. By measuring the distribution of the frequencies of the scattered photons we are indirectly observing the velocity distribution of the electrons, allowing us to derive an electron temperature. The electron density is proportional to the total amount of photons scattered, and as such we may derive it from the observed intensity of the spectrum.

In this lab you will analyse raw spectral data from the MAST ruby laser TS system, ultimately producing a profile of the electron temperature across the whole plasma.

## 2 Calculating the scattering fraction

Estimate the fraction of photons that are collected by a lens of 30 cm diameter located 2 m from a scattering volume 1 cm long for a plasma of density $5 \times 10^{19}$ m$^{-3}$ (the cross section for Thomson scattering is $6.65 \times 10^{-29}$ m$^2$ ). Suppose this system is used to collect light scattered from a ruby laser (694.3 nm) where the laser pulses have energy per pulse of 10 J and a pulse duration of 10 ns. Estimate the total number of photons collected by the lens.

What implications might your answers have for the design of Thomson scattering diagnostic systems?

## 3 Extracting and plotting the spectrum data

Although all MAST data can be accessed through PyXPad or Python by connecting to the CCFE database, the data you will use in this lab (taken from MAST shot 17447) are stored on the VLE [1]. You will need to write your own Python script to perform the required data analysis.

Data from the ruby laser Thomson system is stored as a 2D array representing an image of the CCD detector (in `intensity.dat` or MAST channel `ats_spectra(r)/12`). Attempt to visualise this CCD data and identify which axis is wavelength and which represents spatial position within the plasma.

By using the information stored in `lambda.dat` (or `ats_wavelength(r)/12`), re-plot the spectra in terms of actual wavelength values. Select a spectrum from close to the middle of the array and display it graphically. Attempt to explain the shape qualitatively and any features present.

## 4 Data analysis: measuring $T_e$

The spectrum of scattered light power can be approximated as

$$\frac{\mathrm{dP_s}}{\mathrm{d}\lambda_\mathrm{s}}(\vec{R}, \lambda_s) \sim \exp\left[-\frac{1}{2}\left(\frac{\lambda_s - \lambda_i}{\sigma_\lambda}\right)^2\right], \tag{1}$$

where

$$\sigma_\lambda = \lambda_i \beta_\mathrm{th} \sqrt{2} \sin(\theta/2), \qquad \beta_\mathrm{th} = \sqrt{\frac{2k_b T_e}{m_e c^2}}, \tag{2}$$

and $\lambda_i$, $\lambda_s$ are the incident and scattered wavelengths respectively. Try to fit a Gaussian to one of the central spectra and obtain a measurement of the electron temperature $T_e$. Adapt your analysis to evaluate $T_e$ for all spectra, and use your results to build the electron temperature profile for shot 17447.

What are the sources of error in the spectrum data, and how can we quantify them? How can you estimate the effect of these uncertainties on your temperature measurements?

*This is the end of the assessed portion of the lab - the following extensions are not required and will not be assessed.*

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## Extension 1: The instrument function

No instrument is perfect - there will always be some level of uncertainty associated with how a piece of experimental apparatus functions. For a spectrometer like the one used in the ruby TS system, the ideal (but unattainable) case would be that a photon of a particular wavelength would always emerge from the spectrometer at exactly the same angle each time. In reality there is a distribution of angles, and therefore a distribution of possible locations on the CCD a given photon may land. This distribution is the instrument function (also sometimes called the point-spread function) and captures the statistical uncertainty associated with the apparatus itself.

For the ruby system, the instrument function is approximately a Gaussian with standard deviation $\sigma_i$. Accounting for this affect mathematically we find that the width of the observed spectrum is given by

$$\sigma_{\mathrm{ob}} = \sqrt{\sigma_\lambda^2 + \sigma_i^2}. \tag{3}$$

Using a value of $\sigma_i = 1.5 \times 10^{-9}$ m, re-calculate your temperature measurements now accounting for the instrument function.

## Extension 2: Relativistic effects

Electron temperatures in the core of high-performance MAST discharges reach several KeV. Calculate the thermal velocity for an electron in a 3 KeV plasma - consider your answer as a fraction of $c$. Larger tokamaks can achieve significantly higher electron temperatures, and ITER is expected to reach $\sim$ 25 KeV. Repeat the previous calculation for a hypothetical ITER plasma.

The spectrum given in (1) is derived in the non-relativistic limit. A useful closed-form approximation of the relativistic Thomson scattering spectrum was derived by A.C. Selden [2]. Using this result, plot the spectrum in (1) and the relativistic spectrum on-top of one-another for a MAST-like (3 KeV) plasma, and then an ITER-like (25 KeV) plasma. Qualitatively, what is the overall effect of relativity on the spectrum? Give your thoughts on whether the non-relativistic spectrum is a satisfactory approximation for the MAST and ITER cases.

Finally, replace the non-relativistic spectrum with Selden's result in your analysis of the MAST Ruby data and derive a new electron temperature profile. Discuss quantitatively the differences between your original temperature profile and that derived using the relativistic scattering spectrum.

## References


[1] `(vle.york.ac.uk)`, Fusion laboratory → MCF data lab → TS data Python files

[2] A. C. Selden *Physics Letters* (1980) 79A