A Thin Foil Proton Recoil Spectrometer for DT neutrons using annular silicon detectors

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Abstract

The use of the Thin-foil proton recoil spectrometer (TPR) to measure DT neutrons has been studied previously [1] and is a well established technique for neutron spectrometry [2]. Recently the TPR spectrometer has been put forward as one of the techniques in the high resolution neutron spectrometer system in ITER [3]. The main focus of this study is to investigate the TPR efficiency and resolution by the use of annular solid state detectors and find near optimal designs for 14 MeV neutron detection from DT plasmas.

A Python code was developed for the purpose of calculating efficiency and resolution as a function of spectrometer parameters. The code also calculates the response functions for the selected designs. An optimisation was done regarding the foil thickness, distance from a foil to the detector and distance between detectors using a pareto plot analysis. An investigation was made into how the detector segmentation would influence the spectrometer resolution and efficiency.

The results presented include the selected spectrometer design with calculated resolution, efficiency and count rates. The results show that spectrometer efficiency is below 0.01% for resolution better than 5%. Moreover the detector segmentation gives a significant improvement of the spectrometer resolution.

Introduction

DT fusion plasmas produce neutrons with a mean energy of 14 MeV. The neutrons escape the confined plasma and their energy spectra can be used to determine plasma parameters like temperature. One of the possible methods for neutron spectroscopy is thin-foil proton recoil (TPR) technique which has good energy resolution and potential for background separation [1, 3]. A Python code was used to optimise the TPR design for 14 MeV neutron spectroscopy at different resolutions. By varying several of many geometrical parameters two near-optimal designs were found and the spectrometer response functions were calculated. These designs were then used for fuel ion temperature determination in ITER-like conditions.

Neutrons in Fuel Ion Temperature Measurements

Neutron measurements in plasma diagnostics can be used in fuel ion temperature, ratio or density determination. For example, the fuel ion temperature can be determined from the neutron energy spread. This can be achieved by using neutron spectrometers. For a required temperature precision, typically 10%, the measurement time τ depends on both spectrometer resolution and efficiency. The statistical method used in this paper required a spectrometer response function and is described in detail in [4].

Thin-foil Proton Recoil Spectrometer

The spectrometer consists of a thin polyethylene foil as a neutron-to-proton converter and two silicon detectors as depicted in Figure 1. In TPR design a collimated neutron beam leaving plasma impinges on the the polyethylene foil. Some of the neutrons then elastically scatter in the foil and transfer some energy to the protons. The recoil proton energy relates to neutron energy: $E_p = E_n \times cos(\theta)^2$, where θ is scattering angle. Depending on the θ, the protons may hit the annular telescope detector consisting of $\Delta E - E$ detectors. The fuel ion temperature can then be inferred from the proton energy spectra. The spectrometer is designed to cover the energy range of 10 - 20 MeV which is of interest for DT fusion plasmas.
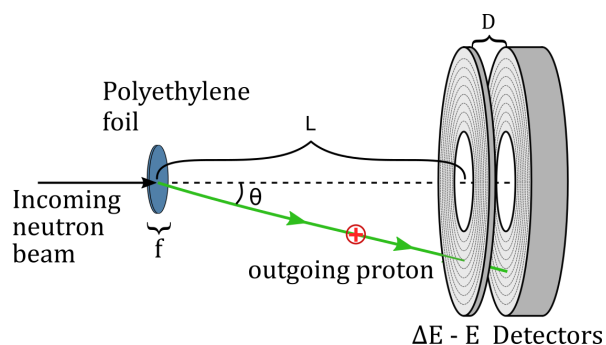
Figure 1: *Scheme of thin film proton recoil spectrometer. f - foil thickness , D - distance between detectors, L - distance from foil to ΔE detector.*

The two detectors in consideration are readily available segmented annular silicon detectors with a radial division of 16 strips. The detector inner and outer radius is 24 and 48 mm respectively. The use of two detectors allows for coincidence measurements which reduces the background signal. Radial segmentation of the detectors allows increased count rates and possibly improve the spectrometer resolution.

Efficiency and Resolution Calculations

The spectrometer performance is affected by multiple geometrical parameters, for example the increase of foil thickness f would degrade the resolution and improve the efficiency. We have selected to investigate three of them: L, f , D as shown in Figure 1. A Python 3 code was developed to determine the efficiency and resolution by varying the selected parameters. The resolution was calculated for two detector configurations, segmented and non-segmented. In the segmented configuration the detector strips are processed independently. In addition to that the

code produces a neutron response function which then can be used to fold with different neutron spectra to estimate the detectors performance.

The code considers perpendicular neutron beam impinging on the polyethylene foil, then calculates n,p scattering in the foil and estimates the subsequent proton energy loss in polythene and Si detectors. Dedicated libraries were used for proton stopping power in silicon and polyethylene [5] and the neutron elastic cross section [6].

Results & Discussion

The Python code results were processed for all detector configurations to find a maximum efficiency for each resolution (Figure 2A). The Figure 2B and 2C describe the detector geometry where all the points are related to Figure 2A by the label on the markers. The letter labelled points correspond to segmented detector and the numbered ones to non-segmented. The black dots in Figure 2B and 2C mark all investigated designs.
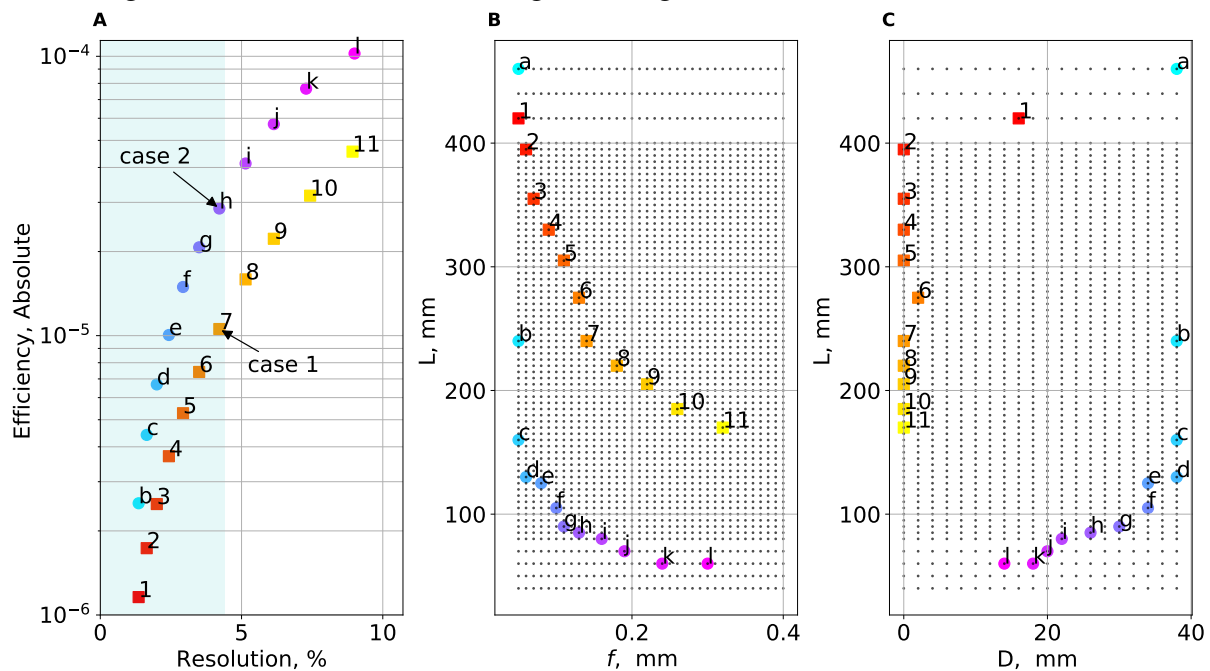

Figure 2: *Figure A - Pareto plot of efficiency vs. resolution and B,C - spectrometer geometry. Resolution was calculated assuming that detector is non-segmented (numbered) and segmented (lettered). The case 1 and 2 are selected design examples.*

From Figure 2 we see that the segmented configuration leads to higher efficiency and a more compact spectrometer for the same resolution. For the two selected designs labelled "case 1" and "case2" the efficiency for one is ~3 times as high as for the other.

We have chosen a spectrometer design with resolution < 5%, marked "case 1" in Figure 2 , and produced a detector response function. We then used the selected spectrometer design to

evaluate its performance in ITER-like conditions for various temperatures as shown in Figure 3. We considered a DT plasma and maximum power of 500 MW. The neutron emission from beam thermal reactions constitutes 1% of total neutron emission and we expect neutron rate of $10^{10} n/s$ impinging on the TPR foil.

The measurement time τ required to achieve the 10 % precision temperature measurements for the different plasmas is shown in Figure 3.

Conclusions

The system is capable of measuring ion temperatures with 10 % precision for measurement time below 25 ms for the selected plasma scenarios. The use of separated readout of the detector segments should decrease the measurement time by a factor of 3 and lead to a more compact spectrometer design. A
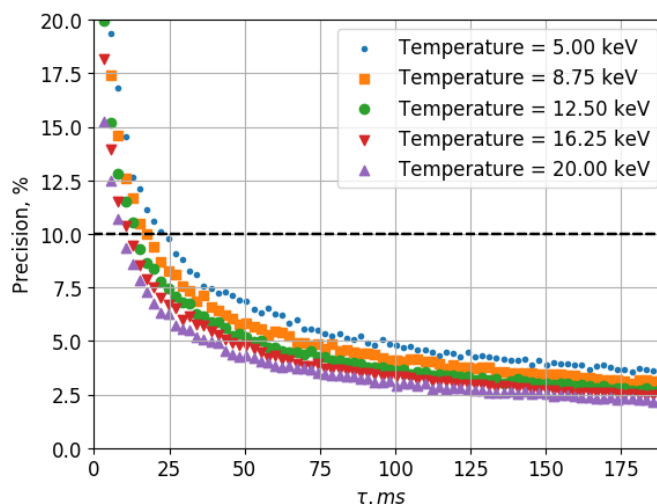

Figure 3: *Precision of ion temperature determination as a function of measurement time for five different plasma ion temperatures for case 1.*

combination of multiple TPR spectrometers can be used to improve efficiency even further as it might be necessary for lower power plasmas.

Further work is planned and includes calculation of the spectrometer response function for segmented detector, investigation of spectrometer background discrimination capabilities, count rate capability as well as ability to determine fuel ion n_T/n_D ratio. We intend to validate the simulations by using a DT neutron source.

References

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