Conceptual Design of the Best TOF Neutron Spectrometer for Fuel-Ion Ratio Measurements at ITER

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Measurements of the core plasma fuel ion density ratio \( \frac{n_T}{n_D} \) is required for safe and efficient burning plasma operations at ITER. However, this measurement is difficult and very few working techniques have been demonstrated. One candidate method to obtain the fuel-ion composition is neutron emission spectroscopy, specifically, measurement and analysis of the DT neutron spectrum of neutral beam heated plasmas. However, none of today’s fully implemented neutron spectrometer techniques fulfils all requirements for such measurements at ITER and a suite of instruments will most probably be required.

In [1] the \( \frac{n_T}{n_D} \) measurement was demonstrated using data from the magnetic recoil proton (MPR) spectrometer acquired during JET DT operations in 1997. Due to size and weight constraints, the MPR is however not possible to interface at ITER. Instead, a back elastic scattering time-of-flight (BestTOF) spectrometer is presented here. The goal of the BestTOF design is to obtain a spectrometer that fulfils all requirements for fuel ion density measurements in a broad range of operational conditions at ITER. The technique takes advantage of the well-established (forward) time-of-flight method, while exploring the favourable conditions of \((n, d)\) scattering in the backward direction (i.e., around 180°) regarding cross section and kinematics. This is achieved by introducing deuterium-based scintillators as first, in-beam scatterers in the design.

Aside of size and weight, the requirements of the instrument are a high efficiency and count rate capability to be able to acquire the counting statistics required for performing the analysis; to fulfil the ITER requirements on accuracy, precision and time resolution this means at least several 100 kHz rate of useful counts. The spectrometer also needs an energy resolution of 4% or better. Furthermore, the signal to background at the high-energy side of the DT emission \( (E_n > 14 \text{ MeV}) \) must be at least 1000.

In this paper we show that the BestTOF design fulfils all of the above mentioned requirements while also being light and compact enough for installation at ITER. The BestTOF is also proposed to be a part of the complete high resolution neutron spectrometer system at ITER.

References
Conceptual design of a BackTOF neutron spectrometer for fuel ion ratio measurements at ITER


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Abstract. In this paper we present a conceptual design of a back scattering neutron time of flight spectrometer (BackTOF) for use at ITER. The BackTOF is designed to fulfill the requirements set by measuring the fuel ion ratio in a burning plasma using the information in the neutron spectrum.

1. Introduction

Neutron emission spectroscopy (NES) in fusion research can provide information on several important plasma parameters, including an estimate of the fuel ion ratio in the core of a burning plasma [1]. The method in [1] relies on separating the supra-thermal DT emission due to beam-target reactions from the thermonuclear DT emission. The estimate of the fuel ion ratio is, today, the primary motivation for considering a High Resolution Neutron Spectrometer (HRNS) at ITER. Several HRNS techniques have been employed previously for measuring the DT neutron emission, see e.g. [2,3]. However, none of the presently demonstrated systems fulfill all requirements of a HRNS at ITER simultaneously. The main requirements for a HRNS at ITER are:

- A relatively compact size and low weight; the entire spectrometer should fit within roughly 1 m³,
- An intrinsic energy resolution (prior to any unfolding techniques) of 4% or better combined with an efficiency of several times 10⁻⁵ or better,
- A count rate capability of useful counts of at least several 100 kHz.
- The signal to noise ratio in the spectrum should be at least 1000,
- The spectrometer should be able to withstand the harsh environments close to a burning fusion plasma. This concerns both magnetic fields in the order of one Tesla as well as strong neutron radiation.

The required efficiency and count count-rate capabilities stem from the fact that about 10’000 counts are needed in a neutron spectrum to perform the analysis necessary for an nt/nd measurement [4]. To achieve the desired time resolution at ITER (100 ms) would require a total count rate of 100 kHz. But, in order to perform the measurement at lower than maximum fusion power, an efficiency several times this is needed. A similar discussion can be made for the count rate capability. A count rate of 100 kHz is enough to reach the time resolution required by ITER. However, to obtain a dynamic range in the measurement a count rate capability of several 100 kHz is required.

Further, the burning plasma conditions at ITER will result in a beam-target emission with an intensity of only a few percent in relation to the thermonuclear emission. The signature of the beam-target emission can be found on the high-energy side of the thermonuclear emission, around 17 MeV [4]; this means that any interference from the thermonuclear emission, either in the response function or from a background, should not exceed 1/1’000. Otherwise the determination of the beam-target fraction will be impeded.

We present in this paper a conceptual design of a back scattering neutron time of flight spectrometer (BackTOF) that aims to fulfill all requirements for measuring the fuel ion ration
at ITER. The BackTOF was first conceptually studied in [5], but no detailed investigation of the response function was made. Recent advancements in data acquisition systems, in particular the simultaneous readout of pulse amplitude and timing, are also important for the operation of a BackTOF at high count rates.

2. The Backscattering TOF Spectrometer

2.1. Design Principles

In a neutron time of flight spectrometer (TOF), information on the neutron energy is typically obtained from the time difference between elastic scattering in two sets of organic scintillator detectors. The first scattering takes place in the primary detector set (D1), and the secondary detector set (D2) subsequently catches a fraction of the neutrons that first scattered in the D1.

The back scattering time of flight spectrometer (back TOF) works in a similar way as the traditional forward scattering TOF [6]. The difference is that the traditional TOF relies on forward scattering on hydrogen in the D1, while the backTOF relies on backwards scattering on deuterium. The need for a deuterated D1 comes from the fact that neutron scattering on hydrogen cannot produce a backscattered recoil neutron since their masses are about equal. See figure 1 for a geometrical description of the two configurations.

The dash-dot circle in the forward TOF design in figure 1 is the constant time of flight sphere, on which all scattered neutrons will have the same time of flight from D1 to D2 independently of the scattering angle \( \alpha \) [6]. The D2 detector is positioned as closely as possible to this sphere. To maximize the angular coverage for a given size of a D2 detector, the angle \( \alpha \) should be chosen as small as possible. However, \( \alpha \) cannot be too small or the energy deposition in the D1 would not be large enough to yield a significant signal. Typically, a scattering angle around 30\(^\circ\) is chosen, and the neutron recoil energy is therefore \( E_{n'} \approx 0.75 \cdot E_n \). In a backward scattering TOF spectrometer, the scattering angle is close to 180\(^\circ\), and the recoil energy is \( E_{n'} \approx 0.11 \cdot E_n \).

![Geometry of a forward scattering TOF (left) and a backward scattering TOF (right). The symmetry axes are shown with dash-dot lines.](image)

The efficiency of a TOF spectrometer is given by the fraction of the incoming neutrons that scatter in the D1, into the solid angle covered by the D2, times the catching efficiency of the D2. Design parameters that affect the efficiency are the area and thickness of the D2 (\( A_{D2} \) and
$dx_{D2}$, respectively) as well as the distance from the D1 to the D2 ($L$). Increasing $A_{D2}$ or decreasing $L$ results in an increased solid angle covered by the D2, and hence a higher efficiency. Similarly, increasing $dx_{D2}$ increases the catching efficiency of the D2, which also results in a higher total efficiency.

The main contribution to the resolution of a TOF spectrometer is the fact that, due to the finite size of the D1 and D2 detectors, there is no 1:1 mapping from incoming neutron energy to flight time, $t_{TOF}$. Instead, there is a distribution of flight times, which is typically simulated with Monte Carlo codes. The main contributing factors are how well the D2 detector follows the constant TOF sphere in a forward TOF, the thickness of the D2 and the light transport in the D2. Since the velocity of a neutron (assuming classical kinematics) scales as $\sqrt{E}$, the energy resolution of the spectrometer scales as $dE/E = 2 \frac{\sigma_{TOF}}{<t_{TOF}>}$, where $\sigma_{TOF}$ is the standard deviation of flight times from incoming mono-energetic neutrons, and $<t_{TOF}>$ is the mean value of the flight times. Increasing $dx_{D2}$ results in a higher $\sigma_{TOF}$ and hence degraded resolution. Similarly, decreasing $L$ reduces $<t_{TOF}>$ and degrades the resolution as well. This illustrates the trade-offs between efficiency and resolution that have to be made when designing a TOF spectrometer. To improve the efficiency of a forward TOF without sacrificing the resolution requires a scale up of the constant TOF sphere.

The forward scattering TOF is well suited for measurements of neutrons from the DD reaction with energies around 2.5 MeV. Consider a typical example; assuming a flight path of 1.25 m, the energy of the recoil neutron is around 1.9 MeV, which gives a $<t_{TOF}>$ of 65 ns. A well-designed spectrometer will have a $\sigma_{TOF}$ of about 2 ns, and the energy resolution then becomes $2/2/65 = 6\%$, which is acceptable for analysis of the DD emission. However, for 14 MeV neutrons $<t_{TOF}>$ is reduced to 27 ns, and the energy resolution degrades to 14\%, which is not acceptable for analysis of the DT emission. These figures are representative of the TOFOR spectrometer [6] in operation at JET.

On the other hand, in the backscattering geometry, a 180-degree scattering of a 14 MeV neutron results in a recoil energy of 1.6 MeV. With a 125 cm flight path this gives a resolution of 5.5\% if $\sigma_{TOF}$ is 2 ns. For 14 MeV neutrons, this is almost three times better than forward scattering spectrometer despite the same physical dimension of the instrument. Further, since the angular dependence of $E_d'$ in Eq. 1b is minimized for angles around 180°, the geometrical contribution to $\sigma_{TOF}$ is typically smaller for a backscattering geometry, and the energy resolution can be expected to improve further compared to the forward TOF.

2.2. Background discrimination at high count rates

The dominating background signal in all time of flight spectrometers of the type studied here is that due to random coincidences between uncorrelated neutrons. Since the neutron emission from a fusion plasma is random in time, the random background signal will appear as a flat line in the spectrum, see e.g. the discussion in [6] concerning the TOFOR spectrometer. Modern data acquisition systems can record both the timing and energy deposition of each elastic scattering in the D1; it is therefore possible to define adaptive energy intervals that can discriminate parts of the random background. See e.g. [7], where this is implemented for the TOFOR spectrometer.

Consider an example, if a coincidence between two events in the D1 and D2 detectors is recorded, there is an interval of acceptable energy depositions in the D1 that is compatible with the time difference between the two events. If the energy deposition does not fall within this interval, the coincidence can be discarded as random background. On the other hand, if the energy deposition falls within this interval, it can be either a true coincidence or a part of
the random background. The part of the random background where the energy deposition in
the D1 overlaps with the allowed energy deposition for a true event cannot be discriminated
in this way.

Figure 2 Illustration of the energy deposition a 14 MeV neutron makes as it scatters elastically on protons
(blue) and deuterons (red) as a function of scattering angle.

The efficiency of the adaptive energy thresholds to discriminate the random background
therefore scales with the width of the acceptable interval compared to the energy span of all
possible events. The backscattering TOF has very favourable properties in this regards. In
figure 2 the acceptable interval for a forward as well as a backwards-scattering TOF system is
illustrated for 14 MeV neutrons as a function of scattering angle $\alpha$. In both cases, an interval
of $\alpha = \pm 10^\circ$ is assumed. In the case of the forward TOF, the acceptable interval has a width
of 4 MeV, which is about 30% of the entire range (0 to 14 MeV). On the other hand, for the
backwards TOF the interval is only 0.4 MeV wide, or about 3% of the entire range (0 to 12.5
MeV). The possibility to discriminate the random coincidences in the backscatter TOF is
therefore enhanced by about 10 times compared with the traditional TOF. The reason is that
the geometry of the back TOF is designed around an interval in the scattering angle with very
small variations in $E_{d}'$. The opposite is true for the forward TOF.

Finally, measuring the energy deposition in the D1 detector can also be used to discriminate
multiple scattering events in a D1 detector. For example, if the 180$^\circ$ scattering of a neutron
required to reach the D2 detector is divided into two scatterings (with each than 180$^\circ$) the
total energy loss will be lower compared to a single 180$^\circ$ collision. This will result in a lower
$\tau_{\text{TOF}}$ when compared to a single scattering. This can then be discriminated since the energy
deposition in the D1 is also lower than for a single scattering.
2.3. MCNP model

In this paper, a MCNP model of a backscattering time of flight spectrometer has been used to simulate the instrument response to the neutron emission from a DT plasma. The model is based on a circular D2 detector of diameter 1.0 m and thickness 2 cm. A circular hole with diameter 15 cm is left in the middle of the D2 detector to allow for the neutron beam to reach the D1 detector. The D2 detector is further separated into 3 concentric rings. The separation of the D2 in 3 rings is in part a question of manufacturability, but it also allows for improved performance. Each ring will span a different interval of recoil angles, $\alpha$ in figure 1(b), and this will result in different lengths of the flight path ($L$), and hence different $t_{\text{TOF}}$, for the same incoming neutron energy. By compensating for this difference the energy resolution of the spectrometer can be improved somewhat. Figure 3 shows an illustration of a possible detector arrangement using hexagonal detectors. The photo multiplier tubes are assumed to be mounted on the back.

The D1 detector is separated in 5 layers along z-axis of the spectrometer, with each layer being 7 mm thick. To reduce the count rate in the D1 detectors, each layer was further divided in 4 equal parts. An illustration of a possible D1 assembly is shown in figure 3. The PM tubes are mounted on the side of each D1 detector with a light guide in between that converts the rectangular shape of the D1 detector to the circular shape of the PM tube. Two different types of MCNP simulations were made. One where only neutron histories that contain at least one scattering in the D2 detector were included in the PTRAC file and a second simulation where all neutron histories were saved to the PTRAC file. The former simulation type was used to generate the instrument response function with no random background included. In each simulation 128 million particles were launched.

The latter simulation type was used to generate synthetic data that includes the random background between different uncorrelated neutrons. Since only one of the neutrons in a random coincidence needs to interact in the D2 detector, every neutron history that makes any interaction in either the D1 or the D2 detectors needs to be followed to simulate the random background. In order to keep the size of the PTRAC file manageable, the simulation was limited to 6.4 million neutron histories. A time trace of synthetic data was then constructed by adding a random starting time to each neutron history. By adjusting the range of random
starting times, different intensities of the flux on the D1 can be simulated. For example, to simulate a neutron flux at the D1 of $10^8$ s$^{-1}$, the simulated neutron histories are distributed randomly between 0 and $6.4 \cdot 10^6 / 10^8$ s = 0.064 s. Subsequently, a time of flight histogram is created from all possible coincidences in the simulated data.

3. Simulation Results

3.1. Response Function

![Response Function Graph]

Figure 4 Calculated response function from 14 MeV neutrons showing total response with no kinematic cuts (solid blue), the contributions from scattering on carbon and multiple scattering on deuterium (dash-dot green and dashed red, respectively) as well as the total response with kinematic cuts (dotted black).

In figure 4, the time of flight histogram for the simulated spectrometer response to 14 MeV neutrons is shown. The results are based on an MCNP simulation with 128 million neutron histories. The total response without the kinematic energy cuts is shown in solid blue. The main peak is located at $t_{\text{tof}} = 74$ ns, and $dt_{\text{tof}} = 1.6$ ns. The energy resolution at full width half maximum is therefore 4.3%. As can be seen, there are prominent structures at a level of a few percent on both sides of the main peak. The structures are due to neutrons colliding multiple times in the D1 detectors, either on deuterium or on carbon.

Also shown in figure 4 are separate $t_{\text{TOF}}$ histograms from histories where the incoming neutron has either scattered on carbon-12, or multiple times on deuterium in the D1. These are shown in red dashed and green dash-dot, respectively. From this analysis it is clear that the structure on the high-energy side ($t_{\text{of}} < 74$ ns) is predominantly due to neutrons scattering on carbon. The higher mass of the carbon nuclei causes the neutrons to lose less energy in the recoil compared to scattering on deuterium. Therefore they can travel the distance from D1 to D2 faster and produce a lower time of flight. Multiple scattering on deuterium in the D1 mainly shows up on the low-energy side of the main peak. Such multiple scattering typically causes a larger energy loss compared to the single scattering, and the time of flight is therefore increased.

The response function after the kinematic cuts have been applied is also shown in figure 4 in the dotted black line. The kinematic cuts are effectively discriminating the structures on both the high- and low-energy sides of the main peak, which remains near-Gaussian for at least
three orders of magnitude. Integrating the spectrum after the kinematic cuts gives an efficiency of $1.25 \times 10^{-3}$.

3.2. Background at high count rates

The results from the second simulation, including random coincidences, are shown in figure 5. It was found that the saturation load on a single D1 detector (here assumed to be 2 MHz) was reached for a total neutron flux on the D1 assembly of $2.6 \times 10^8$ s$^{-1}$. The 6.4 million events simulated are therefore equivalent to 25 ms data taking at maximum load.

The simulated spectrum contains about 8’000 true coincidence events, which are shown in solid blue. Random coincidences without adaptive energy thresholds are shown in the dashed red line. The peak signal to background is about 3. The random coincidences after the adaptive thresholds have been applied are shown in dash-dot green. As can be seen, the energy cuts are very effective at reducing the background. On the low energy side (tof > 74 ns) the signal to background is improved by a factor of 50, and on the high-energy side (tof < 74 ns) the background is discriminated entirely except for a shoulder above $t_{\text{TOF}} = 70$ ns.

![Figure 5 Simulated random background at saturation load of D1-detectors without kinematic cuts (dashed red) and with kinematic cuts (dash-dot green). True coincidences are shown as solid blue.](image)

4. Discussion and Conclusions

The back scattering time of flight spectrometer presented in this paper is one of the HRNS designs that aim to fulfil the ITER requirements at ITER. In this paper we have shown that the design

- is compact enough to fit within the 1 m$^3$ size constraint,
- can fulfill the requirement of 4% energy resolution,
- has a high enough efficiency to meet the required time resolution for performing fuel ion measurements at ITER,
- has a high enough count rate capability to (several times 100 kHz), and


- has a signal to background in the response function of about 5 orders of magnitude on the high-energy side, where the important information lies (see figure 4).

We have also shown how adaptive kinematic thresholds can be used to improve both the response function of the spectrometer, and make it near Gaussian over about 3 to 4 orders of magnitude, as well as significantly reduce the background. This is a very important observation since the spectrum in burning plasma relevant conditions will have a rather small contribution from beam-target reactions at about 1% in relation to the thermonuclear contribution.

**References**

[1] C. Hellesen et al., Nucl. Fusion 55 023005  