Finite Larmor radii effects in fast ion measurements as demonstrated using neutron emission spectrometry of JET plasmas heated with 3rd harmonic ICRF

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Abstract

This paper demonstrates how the finite Larmor radii (FLR) of fast ions can affect fast ion measurements by studying data from the neutron time-of-flight spectrometer TOFOR. Neutron spectra were calculated from a model of the fast ion velocity distribution for a JET experiment with 3rd harmonic ICRF heating of deuterium beams. It was found that FLR effects need to be considered to get a good description of the data, if the Larmor radius of the fast ions are comparable to the width of the field of view of the instrument. This applies not only to results from neutron spectrometry but also to other types of fast ion diagnostics.

Introduction

In a magnetically confined fusion plasma, "fast ions" refer to sub-populations of ions that have much higher energy than the thermal bulk plasma. Examples include helium ions produced in the d(d,n)^{3}He and d(t,n)^{4}He fusion reactions as well as ions produced by external heating systems, neutral beam injection (NBI) and ion cyclotron radio frequency (ICRF) heating. It is important to understand the behavior of fast ions in order to have a well performing fusion reactor, and great effort goes into the theoretical and experimental investigation of this subject [1].

Neutron emission spectrometry (NES) provides one way of diagnosing fast ions, since the neutron spectrum from the d(d,n)^{3}He reactions contains information about the deuterium distribution in the plasma [2]. In this paper the neutron time-of-flight spectrometer TOFOR [3] is used to diagnose fast ions in this way.

In the analysis of fast ion diagnostics data it is normally assumed that the entire Larmor orbits of the ions are visible to the measuring instrument. However, this approximation may be invalid if the Larmor radii of the fast ions are comparable to the width of the field of view of the

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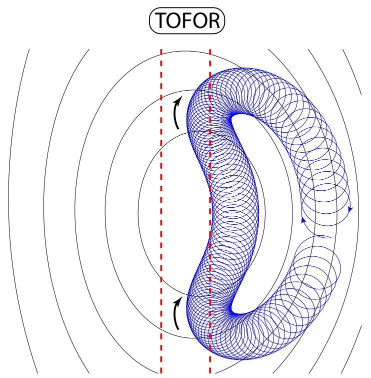

Figure 1: A trapped 2 MeV deuteron in JET. The red lines mark the field of view of TOFOR.

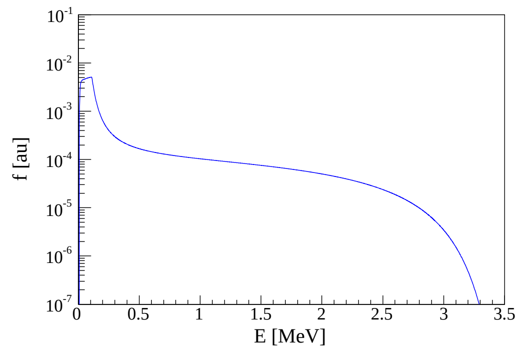

Figure 2: Calculated fast ion energy distribution for JET pulse #74946.

instrument. Figure 1 shows the orbit of a trapped 2 MeV deuteron in JET (the toroidal B-field is around 2.3 T). The field of view of TOFOR is also indicated and the turning point of the orbit is just at the outer edge of this region. It is clear from this figure that only a part of the Larmor gyration will be visible to TOFOR. This will affect the shape of the measured neutron spectrum, as discussed in the subsequent sections. The effect has been previously observed in [7, 8, 9] and this work is part of a systematic investigation of these effects.

A JET experiment was studied to investigate this finite Larmor radius (FLR) effect. Deuterons in the MeV range were produced by adding to 1.7 MW of deuterium NBI, 4 MW of ICRF heating at a frequency corresponding to the 3rd harmonic cyclotron frequency of deuterium. The 3rd harmonic deuterium resonance layer was located close to the outer limit of the field of view of TOFOR, creating fast deuterons with orbits similar to that in Figure 1. A model of the fast ion distribution, previously used in [4], was extended to include FLR effects. The neutron emission predicted with this model was then compared with measured TOFOR data.

Modelling

In a fusion reaction producing a neutron and a residual product of mass m_r, the neutron energy can be calculated from classical kinematics as

$$E_n = \frac{1}{2}m_n v_{cm}^2 + \frac{m_r}{m_n+m_r}(Q+K) + v_{cm}\cos\theta\left(\frac{2m_n m_r}{m_n+m_r}(Q+K)\right)^{1/2}, \tag{1}$$

where v_{cm} is the center of mass speed, Q the released fusion energy, and K is the relative kinetic energy of the reactants. θ is the angle between the center of mass velocity and the neutron emission direction in the center of mass frame. The neutron energy spectrum can be calculated by integrating this expression over the reactant velocity distributions, one of the reactant species being the thermal background plasma and the other the fast ions.

The fast ion energy distribution was calculated from a Fokker-Planck equation derived in [5] and previously used for NES analysis in [4]. The solution, shown in Figure 2, is the steady-state distribution for a homogeneous plasma with prescribed values for the ICRF and NBI heating powers.

The ICRF accelerates ions mainly in the perpendicular direction, thereby turning passing orbits into trapped. Furthermore, the turning points of these trapped particles are driven towards the ICRF resonance position [6]. Therefore, fast particles were assumed to occur only in a narrow region centered at the resonance position R_{res}. In the experiment studied in this paper $R_{res} \approx 3$ m, and the fast particles were assumed to be localized to the region $R = 2.92$-3.15 m.

The fast particles are mainly beam ions that have been injected at an angle of 60° to the magnetic field. Due to the ICRF acceleration in the perpendicular direction the pitch angles of these accelerated beam ions will be driven towards 90°. Therefore, the cosine of the pitch angles were assumed to be uniformly distributed between $\cos(90^\circ \pm 10^\circ)$.

Neutron energy spectra were calculated with a Monte-Carlo code, sampling the fast ion velocity distribution at different positions and calculating the neutron energy using Equation 1. The FLR effect was included by letting the fusion reaction to take place one Larmor radius away from the sampled position, in a random direction. If this emission position happened to be in the field of view of TOFOR the corresponding fusion neutron was included in the spectrum, otherwise it was neglected. For comparison, the calculations were also done without including FLR effects, i.e. also neutrons emitted outside the field of view were included in the spectrum.

Results

Figure 3 shows an example of calculated neutron energy spectra for JET pulse #74946[1]. Two spectra are presented, one including FLR effects and one where they are neglected. The spectra are also compared with the time-of-flight spectrum measured with TOFOR. It is seen that the calculated spectrum overshoots the data by almost an order of magnitude on the low energy side if FLR effects are not taken into account.

Discussion and conclusion

The results demonstrate that FLR effects can be important in fast ion measurements. The modelling could be refined by a more sophisticated spatial distribution function, but even with the quite crude assumptions made here the agreement between simulations and experiment is good.

The qualitative difference between the two calculated spectra can be explained from the fast ion orbit in Figure 1. Due to the $\cos\theta$-term in Equation 1, neutrons produced in a reaction between a fast ion and the background plasma will be up-shifted in energy if the reaction takes

[1] MHD instabilities were excited in this pulse, but they were rather weak due to the comparatively low NBI power (1.7 MW).

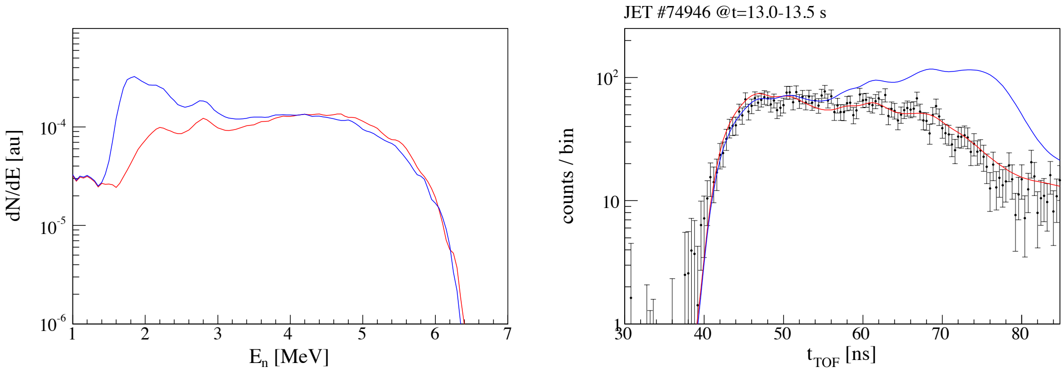

Figure 3: *Left:* Calculated neutron energy spectra, including FLR effects (red line) and without FLR effects (blue line). *Right*: The spectra have been folded with the response function of TOFOR and are compared with TOFOR data (points with error bars). The calculations overshoot the data on the low energy (long time-of-flight) side if FLR effects are not included.

place when the ion is moving towards TOFOR and down-shifted if the ion is moving away from TOFOR. In this experiment, with the resonance position at $R \approx 3$ m, a large fraction of down-shifted neutrons will be emitted outside the field of view of TOFOR, and the intensity of low energy neutrons is thus expected to be reduced due to the FLR effects, which is exactly what is seen from the calculations.

In conclusion, it has been demonstrated that it is necessary to consider FLR effects when analyzing data from fast ions measurements, if the fast ions are anisotropically distributed in the part of the plasma viewed by the measuring instrument and have Larmor radii comparable to the width of the field of view. The results apply not only to neutron spectrometry but also to other fast ions diagnostics, such as γ-ray spectroscopy and neutral particle analysis.

Acknowledgments

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