Synthetic diagnostic for the JET scintillator probe lost alpha measurements

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J. Varje[1], V. Kiptily[2], P. Sirén[1,3], H. Weisen[4] and the JET contributors[*]

[1] Department of Applied Physics, Aalto University, P.O. Box 11100, 00076 AALTO, Finland
[2] CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK
[3] VTT Technical Research Centre of Finland, P.O. Box 1000, 02044 VTT, Finland
[4] SPC, station 13, EPFL, 1015 Lausanne, Switzerland
[*] See the author list of "Overview of the JET preparation for Deuterium-Tritium Operation" by E. Joffrin et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 27th Fusion Energy Conference (Ahmedabad, India, 22-27 October 2018)

Abstract

A synthetic diagnostic has been developed for the JET lost alpha scintillator probe, based on the ASCOT fast ion orbit following code and the AFSI fusion source code. The synthetic diagnostic models the velocity space distribution of lost fusion products in the scintillator probe. Validation with experimental measurements is presented, where the synthetic diagnostic is shown to predict the gyroradius and pitch angle of lost DD protons and tritons. Additionally, the synthetic diagnostic reproduces relative differences in total loss rates in multiple phases of the discharge, which can be used as a basis for total loss rate predictions.

Quantifying the losses of energetic ions, such as fusion products and neutral beam injection (NBI) and ion-cyclotron radiofrequency heating (ICRH) ions, is important in fusion devices both for performance and machine protection, as lost ions reduce heating efficiency while increasing the loads on the first wall. Measuring fast ion losses is also one of the few techniques which directly measure properties of the fast ion distribution function, without resorting to inference from other diagnostics. Direct measurement of these losses using fast ion loss detectors (FILD) is a common technique for studying fast ions under various plasma phenomena, including magnetic perturbations and MHD instabilities which induce additional transport [1-5].

The JET tokamak is equipped with a scintillator-based lost alpha diagnostic probe [6] which directly measures lost fast ions, including 3.5 MeV fusion alphas. The energy range extends up to 1.4 MeV for tritons and 4 MeV for protons in typical JET operating scenarios. Light emitted as the collimated particles hit a scintillator plate inside the probe is detected, both with fast photomultiplier tubes as well as CCD imaging. These are then mapped to the gyro radius and pitch angle of the incoming particles. Synthetic diagnostics using particle trajectory following can be used to interpret these measurements and determine the origin of the losses, as well as map them to the fast ion distribution function.

In this paper we present a synthetic diagnostic workflow for the JET lost alpha scintillator probe based on the Monte Carlo orbit-following code ASCOT [7], previously applied to similar FILD studies for other tokamaks, including AUG [8] and ITER [9], and validate it with experimental measurements at JET. First the components of the synthetic diagnostic calculation chain and their operation is presented. After this, the predicted losses are compared to measurements during a JET discharge with varying plasma conditions. Finally, the results and future applications in the upcoming JET campaigns are discussed.

ASCOT-based synthetic scintillator probe

The synthetic diagnostic for the lost alpha scintillator probe is based on the ASCOT orbit-following code [7] and the fusion source integrator AFSI [10]. ASCOT is first used to calculate the slowing-down distribution of NBI ions, generated using the beamlet-based NBI source code BBNBI [11]. The particles are followed until they thermalize, as defined by energy below 1.5 times the local ion temperature, or until they leave the plasma, and during slowing-down their distribution is collected.

This distribution function is then used a reactant distribution in AFSI, which is used to calculate the thermonuclear, beam-thermal and beam-beam fusion source. The code uses a Monte Carlo algorithm to calculate the 4D source distributions, including anisotropic velocity distribution and energy spectrum, for the fusion products. These distributions are then used to calculate the neutron rate as well as sample markers representing the charged fusion products such as DD protons and tritons or DT alphas. The markers are weighted such that the density of markers in volume is constant, which increases the number of markers close to the edge of the plasma and thus the statistics of the losses.

The fusion product markers are used in another ASCOT run to simulate the losses reaching the scintillator probe. A detailed 3D wall is used to accurately map the losses, based on CAD geometry and converted to a triangular mesh. A model for the probe has been built from CAD drawings and placed in the 3D wall model (Figure 1). Instead of the actual collimator entrance in the probe with an area of only 1.2 mm^2, the losses are tallied in the flat region surrounding the entrance, with an area of approximately 2 cm x 5 cm. This is done to increase the number of the markers reaching the probe, as attempting to follow them into the collimator would require an unreasonable number of markers. For the 10 cm^2 area, approximately 1 marker in 10 000 reaches the probe. Finally, the losses to the probe are linearly mapped to the pitch angle-gyro radius grid on the scintillator plate, as calculated by the Efipdesign tool [6].

Simulated and experimental fusion product losses in JET

The synthetic scintillator probe diagnostic was tested and validated using the JET discharge #77877, where loss simulations were performed at three time points in the discharge: 44.7 s, 45.2 s and 52.5 s. The discharge is an advanced tokamak type deuterium plasma with 22 MW of NBI heating and no RF heating (Figure 2), with a central density of 4-6 $\times 10^{19}$ m^{-3} and a central electron temperature of 5-7 keV in the examined time interval.

ASCOT NBI slowing-down simulations with 100 000 markers were used to calculate the NBI fast ion distribution function. This AFSI for calculating the thermonuclear, beam-thermal and beam-beam DD proton and triton sources as well as the neutron source rate. In this discharge, the neutron rate was found to agree well with the measured total rate, verifying the AFSI source calculations (Figure 2, top).

After this, synthetic diagnostic simulations were performed for the fusion protons and tritons for the three time slices. Only first orbit losses with loss times less than 10^{-5} seconds were observed reaching the probe (Figure 3). This is due to the probe being located slightly outboard of the poloidal limiters, which effectively shadow any collisional losses from reaching the probe. Because of this, the simulation time of each marker in the synthetic diagnostic simulations could be limited to $5 \cdot 10^{-4}$ s, dramatically speeding up the simulations.

Simulations of 10 000 000 markers were performed for both species and each time slice to evaluate the total losses. In each simulation, approximately 1000 lost markers reached the probe which corresponds to a Monte Carlo uncertainty of less than 5 %. The total losses were then compared to the total photomultiplier tube current in the probe, which in turn is proportional to the total light emitted by the scintillator plate (Figure 2, bottom). The simulated losses agree well with the measured signal. A simulation with 200 000 000 markers for both species was performed to reproduce the velocity space distribution of the losses for the first time slice. The location of the maximum of the losses was found to agree with the pitch angle and gyro radius of the measured losses (Figure 4). Some fringes are seen in the synthetic signals, which is due to the larger area and different shape of the collection area compared to the actual collimator.

Finally, a simple DT extrapolation case was performed by replacing the deuterium plasma with a 50-50 mixture of deuterium and tritium. The calculation chain described above was then repeated for the DT fusion alphas in addition to the DD protons and tritons. Due to the higher DT source rate, the alpha signal eclipses the signal from the protons and tritons (Figure 5).

Conclusion

A synthetic diagnostic has been implemented for the JET lost alpha scintillator probe, based on the ASCOT code. Orbits for fusion products are followed until they intersect the probe, and the velocity space distribution of these losses is tallied. The relative loss rates to the probe in different phases of the discharge #77877 were found to be in agreement with the total measured signal from the probe. The gyro radius and pitch angle of the losses were likewise found to agree with the losses observed on the scintillator plate.

The newly developed synthetic loss probe diagnostic now provides the capability to carefully compare fast ion transport and losses predicted by ASCOT to experiments, and in particular identify discharges with non-neoclassical transport, such as turbulence and MHD induced transport. Additionally, ASCOT includes transport models for some of these phenomena, including Alfven eigenmodes (TAE) and neoclassical tearing modes (NTM), which can then be validated with experiments. Future development of the synthetic diagnostic will include both performance increasing improvements, such as backwards-in-time particle following [12], as well as more a detailed model for the probe head to refine the mapping of the losses to the scintillator plate.

In the upcoming JET campaigns the synthetic loss probe diagnostic will be applied to various plasmas for studying the transport and losses of DD protons and tritons, TT alphas, ICRH-heated MeV-range ions as well as eventual DT alphas.

Acknowledgements

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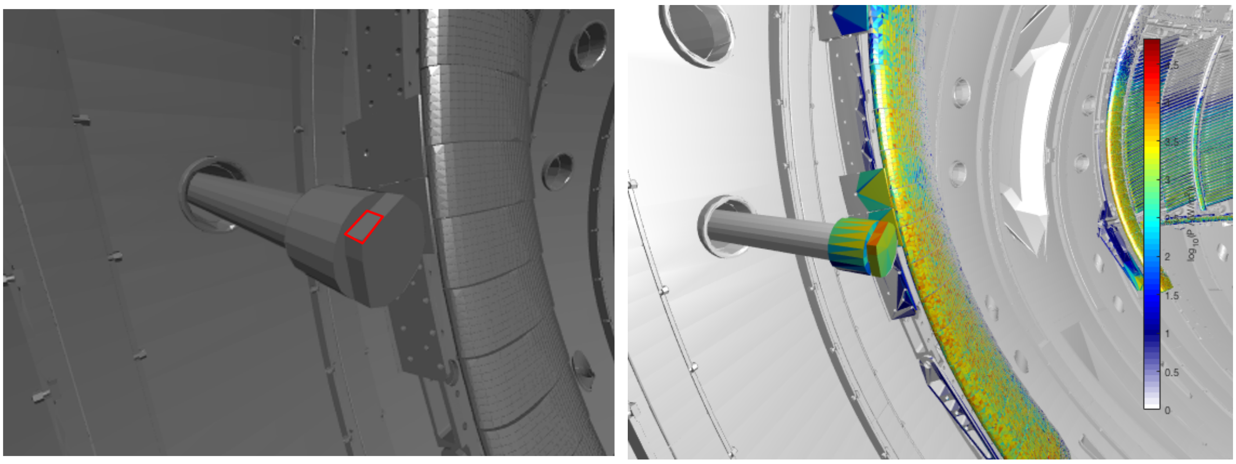

Figure 1 ASCOT model for the CAD-based first wall and the scintillator probe, region where losses are tallied is highlighted in red (left). Simulated DD proton and triton losses on the probe and limiters (right).

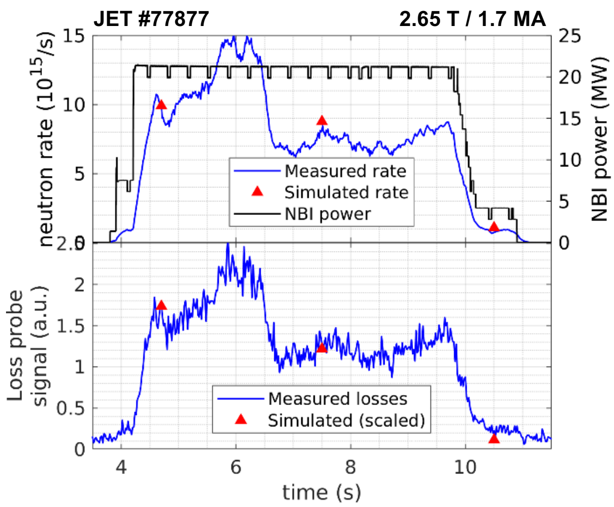

Figure 2 Simulated neutron rates match measured neutron rates at different phases of the discharge (top). Relative changes in simulated losses likewise agree with measured total photomultiplier tube signal from the probe (bottom).

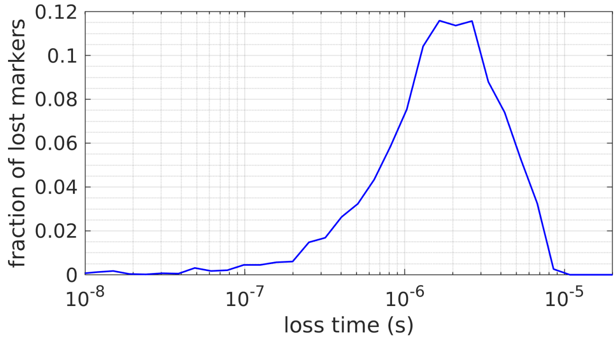

Figure 3 Loss time of particles hitting the probe indicates only first orbit losses observed (loss time < bounce time).

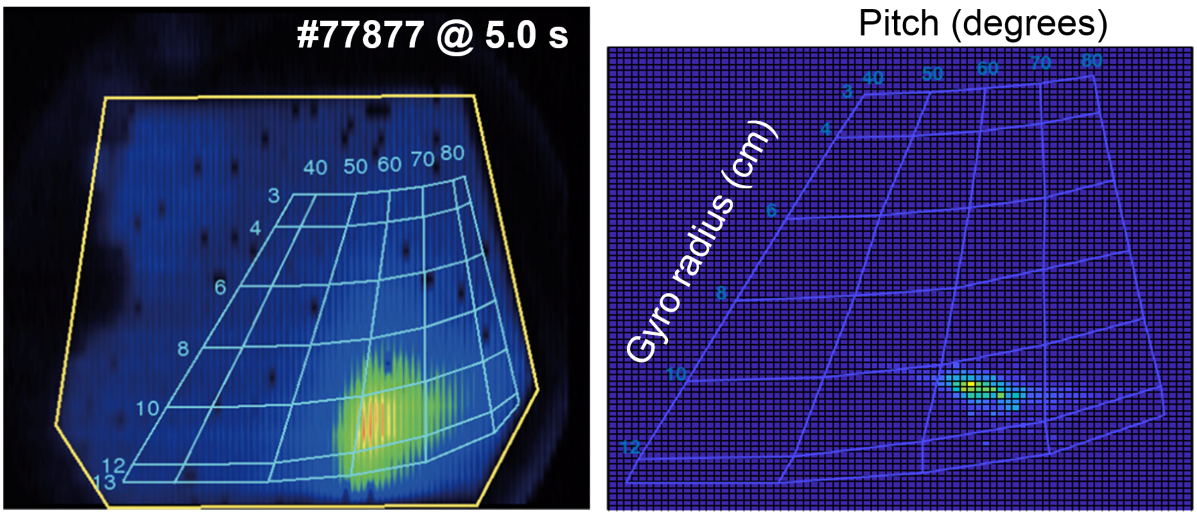

Figure 4 Measure (left) and synthetic (right) fast ion losses as mapped to the scintillator plate image.

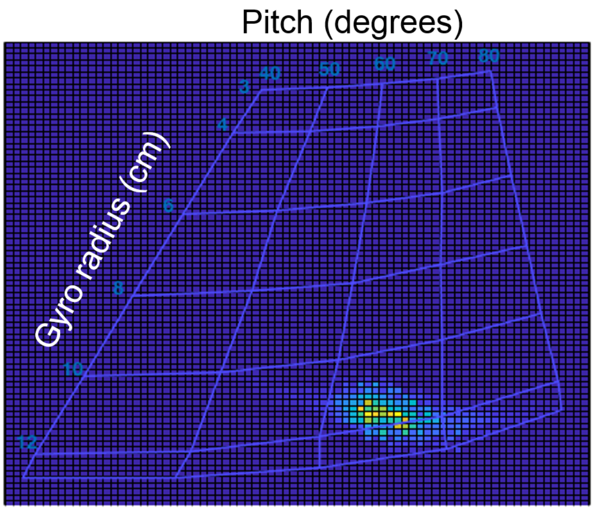

Figure 5 Synthetic fast ion loss signal for 50-50 DT case.