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Generation of a Plasma Neutron Source for Monte Carlo Neutron Transport Calculations in the Tokamak JET

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Abstract

The connection between plasma physics and neutronics is crucial for the understanding of the operation and performance of modern and future tokamak devices. Namely neutrons, one of the primary carriers of information on the plasma state, represent the basis for various plasma diagnostic systems as well as measurements of fusion power, tritium breeding studies, evaluations of tokamak structural embrittlement and the heating of water inside the fusion device's walls. It is therefore important that the birth of neutrons in a plasma and their transport from inside the tokamak vessel to the surrounding structures is well characterized. In the paper a methodology for the modelling of the neutron emission on the tokamak JET is presented. The TRANSP code is used to simulate the total neutron production as well as 2D neutron emission profiles for a JET plasma discharge. The spectra of the fusion neutrons are computed using the DRESS code. The computational results are analysed in an effort to create a plasma neutron source generator, which is to be used for Monte Carlo neutron transport computations.

Keywords:
Plasma neutron source, Monte Carlo method, JET, TRANSP, DRESS.

1. Introduction

The majority of modern neutron transport computations in support of fusion experiments is performed with the Monte Carlo method (Čufar et al., 2017). The initial step of a simulation is the creation of a source neutron, the characteristics of which are sampled on the basis of the system's physical model. Tokamak plasma is a toroidal neutron source, with the probability of neutron emission being strongly dependent on several key parameters, such as the electron and ion temperatures and the neutral beam injection system heating power. The connection between plasma physics and neutron transport computations is crucial for understanding the basics of the tokamak fusion power evaluation, since accurate knowledge of the neutron source results in better understanding of the response of the tokamak's neutron diagnostic systems (Jarvis and Conroy, 2002). In order to study the relation between neutron emission, diagnostics response and its uncertainty it is necessary to improve the generic source models used in computations so far. In the paper the initial step of creating a detailed plasma neutron source for Monte Carlo neutron transport calculations is presented, based on the use of the state-of-the-art plasma transport code TRANSP (Goldston et al., 1981) and the neutron spectrum computation code DRESS (Eriksson et al., 2016). The diagnostic data of a baseline DD discharge of the JET tokamak is used as input for the TRANSP/NUBEAM ion orbit code (Pankin et al., 2004), which computes the fast ion distribution function and evaluates the beam-target fusion reactions that govern neutron production. Plasma simulations present the basis for the evaluation of the neutron spectra from the DD and DT fusion reactions which are performed with the DRESS code. Upon obtaining the neutron emissivity profile and spectra through combining the thermal and fast ion neutron production in the JET vacuum vessel, the generation of a Monte Carlo neutron source description is discussed.

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2. JET plasma discharge

JET is currently the largest operating tokamak device with an aspect ratio of approximately 3, the fusion plasma being confined in the vacuum vessel by magnetic fields of up to 4 T and plasma currents of up to 5 MA. Since 2011 the tokamak has been equipped with the so-called ITER-like wall made of beryllium and tungsten, materials which are of interest for future fusion devices. The plasma auxiliary heating system consists of two neutral beam injectors (NBI) with a total injected deuterium beam power of 34 MW and four ion cyclotron resonance heating (ICRH) antennas with a power of up to 10 MW. For this study a representative deuterium JET discharge 92436 has been chosen, the plasma parameters of which are shown in Figure 1 for a time interval between 46 s and 57 s. The electron density (n_e) and temperature (T_e) measurements, performed with the high resolution Thomson scattering diagnostics (HRTS), are shown in the upper panel of Figure 1. It can be seen that during the discharge the average values of the parameters were $n_e \sim 7 \cdot 10^{19}$ m^{-3} and $T_e \sim 6$ keV. During the discharge both the NBI and ICRH systems were used for the heating of the plasma, their average total power being approximately 27 MW and 4 MW, respectively. The bottom graph displays the measurements of neutron rate as detected by the ex-vessel time resolved neutron yield monitor (KN1) and corrected by a calibration factor to obtain the total neutron emission from the plasma (Syme et al., 2014).

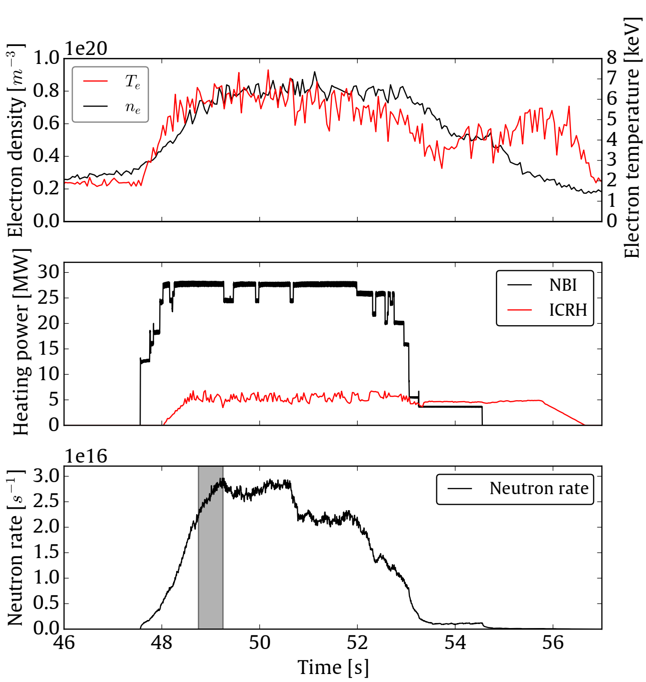

Figure 1: Basic plasma parameters for JET shot 92436 – the line averaged electron density and temperature are shown in the upper panel, followed by the heating power and the neutron rate measured by ex-vessel fission chambers in the bottom. The grey area denotes the time window used for averaging of TRANSP fast ion distribution and neutron emission computations.

3. TRANSP/NUBEAM plasma calculations

The time dependent plasma transport code developed at Princeton Plasma Physics Department, TRANSP, in combination with the neutral beam injection fast ion module NUBEAM and Bosch-Hale DD/DT cross sections (Bosch and Hale, 1992), has been used to model the neutron production during JET discharge 92436 with toroidal symmetry. The plasma simulation was initiated at 47 s into the JET shot and discontinued at 55 s, while the averaging time window for the NUBEAM fast ion distribution function computations was set to 0.5 s. Due to a relatively high electron density the TRANSP calculation was performed with the assumption that the ion temperature is equal to that of electrons, i.e. $T_i = T_e$ (Weisen et al., 2017). Additionally both toroidal plasma rotation and anomalous radial diffusion of fast ions were omitted (Baranov et al., 2009). The plasma was presumed to be externally heated only with the NBI system, neglecting the ICRH in order to study the fast ion behaviour and neutron production in a beam heated plasma. The total neutron rate computations were performed at 25 ms time intervals in order to average out temporal fluctuations, the same being done for the KN1 fission chamber measurements – the comparison of neutron rates (NR) is presented in Figure 2.

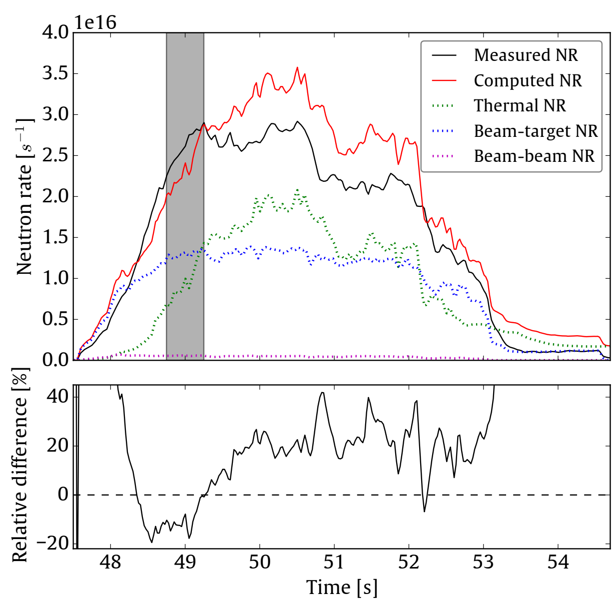

Figure 2: Comparison of measurements (KN1 fission chamber) and TRANSP computations of total neutron emission for JET shot 92436. The computed neutron counts are further divided into contributions from thermal, beam-target and beam-beam fusion reactions. The relative difference between the computed and measured total neutron emission is shown in the bottom panel. The grey area denotes the time window used for averaging of TRANSP fast ion distribution and neutron emission computations.

The TRANSP neutron rate calculations are divided into contributions from thermal, beam-target and beam-beam fusion reactions. One can observe that the neutron production due to beam induced plasma heating and fast ion population is significant and is of the same order compared to that resulting from fusion of bulk thermal ions. The relative difference between the computed and measured neutron rates is shown in the bottom graph, where it can be seen that the time evolution of emission is comparable, whereas the calculation overestimates the neutron rate. It is shown that the average discrepancies are of the value of ~ 20 %, with similar results being presented in previous work (Baranov et al., 2009; Weisen et al., 2017). The scale has been adjusted to display the difference in the central part of the discharge, while the discrepancies at the start and end of the NBI heating are larger, i.e. of the order of 100 %.

4. JET neutron emission computations

In order to model the neutron emission in JET, where the number of fusion reactions caused by fast ions is comparable to that of thermal ions, an insight into the fast ion distribution function $f_{fi}\,(E,p,R,Z)$ is imperative. The NUBEAM code enables the computation of the distribution function f_{fi} for a limited amount of time intervals with a fixed width, providing information on the energy E, pitch angle $p = v_{\|}/v$ and position of the fast ions, defined by the JET major radius R and z-axis Z. The computations described below were performed for a time interval 49.75 s $\leqslant t \leqslant$ 50.25 s, which is denoted by the grey areas in Figures 1 and 2. TRANSP, being a 1.5D code, considers plasma quantities constant over toroidal flux surfaces and deals with the square root of the normalized toroidal magnetic flux, $\sqrt{\psi_{TN}}$, as its spatial variable. The function f_{fi} however can not be treated as a toroidal flux surface averaged quantity since fast particle orbits can deviate from the flux surfaces (Gorelenkov et al., 2014). Therefore NUBEAM calculations can be mapped on to an irregular 2D spatial grid. Although the grid is aligned with the toroidal flux surfaces, it introduces a division of $\sqrt{\psi_{TN}}$ radial zones into areas equally spaced in the poloidal angle fixed to the magnetic axis. The total number of plasma zones N_{mc} is defined by the radial resolution of the grid N_{fb} through:

$$N_{mc} = \sum_{i=1}^{N_{fb}} 4i\,.$$

An example of the irregular grid is shown in Figure 3, where the limiter of the JET tokamak is denoted black and the equilibrium plasma boundary red. The black dots represent a 220 plasma zone grid defined by $N_{fb} = 10$, whereas all of the computations presented in the paper were performed using a detailed mesh with $N_{fb} = 40$ and 3280 plasma zones.

The fast ion density n_{fi} was computed for the specified time interval by integrating the fast ion distribution function over both ion energy and pitch angle:

$$n_{fi} = \int_0^\infty \int_{-1}^{1} f_{fi}\,(E,p,R,Z)\;dE\,dp\,,$$

with the resulting profile displayed in Figure 3. It can be seen that in addition to the central part of the fast ion population located around the magnetic axis, there is also a significant number of fast ions on the outboard side of the tokamak. These trapped particles can contribute to the neutron emission considerably, causing its profile to shift from the magnetic axis toward the outer plasma boundary. The fast ion distribution function was then used to derive the neutron emission profile – to further analyse the effect of neutral beam heating on the neutron emission, the NUBEAM module was used to obtain both the toroidal flux surface average profile as well as the neutron emission profile mapped on to the irregular grid. The results are shown in Figure 4.

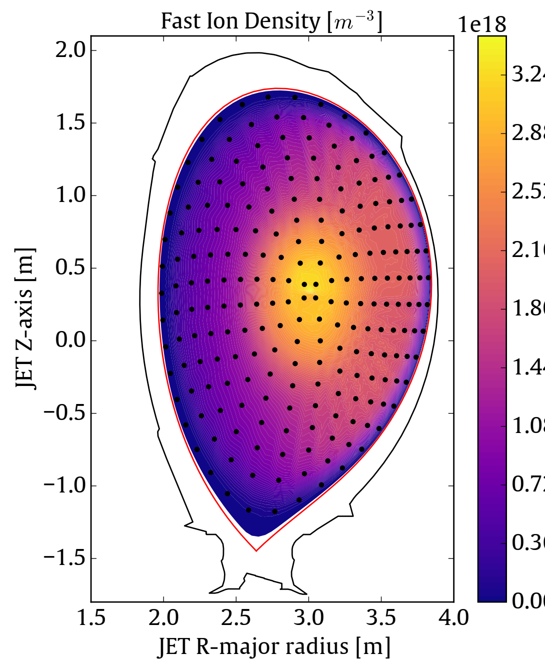

Figure 3: Fast ion density profile obtained through the computation of f_{fi} with the NUBEAM code. The irregular 2D computational grid defined by $N_{fb} = 10$ is denoted with the black dots.

The graph on the left hand-side of Figure 4 displays the neutron emission density profile (in $cm^{-3}\ s^{-1}$) enclosed within the plasma boundary, which is flux-surface averaged using the native TRANSP radial variable $\sqrt{\psi_{TN}}$. It can be observed that the profile is centred around the magnetic axis denoted by the red ×. The graph in the central panel represents the neutron profile mapped on to the NUBEAM grid. One can see that while the peak of the profile is still positioned at the magnetic axis, its top and bottom ends are displaced in the tokamak's outboard direction. The relative difference between the profiles using the NUBEAM and the TRANSP grid is shown in the graph on the right-hand side of Figure 4. An increase of the number of fusion neutrons produced at the outer plasma edge can clearly be seen when using the irregular grid mapping, corresponding to the NBI induced population of trapped fast ions. It is evident that the number of neutrons in the JET tokamak, originating from fusion reactions between bulk thermal ions, is equivalent to that arising from fusion of neutral beam ions. This is of high importance for Monte Carlo neutron transport computations since differences in the spatial and energy distribution of the plasma neutron source can significantly influence the computed response of neutron diagnostic systems.

5. Neutron spectra computations

Upon obtaining the fast ion distribution function and the neutron emission profiles, neutron spectra were calculated using the Directional Relativistic Spectrum Simulator (DRESS) code, which was developed at the Uppsala University Department of Physics and Astronomy (Eriksson et al., 2016). DRESS calculates the spectra of products emerging from two-body reactions between reactants with arbitrary velocity distributions. The code was used because it was primarily developed for the computation of neutron and charged particle spectra from the DD/DT fusion reactions and was comprehensively validated (Klimek et al., 2015). To describe the plasma as a neutron source it is necessary to compute neutron spectra on a grid which is used for mapping of the neutron emission profile – therefore the irregular grid used in NUBEAM was used as an input for DRESS. A poloidal symmetry of the neutron spectrum, with respect to the B-field orientation, is assumed. The neutron emission toroidal angle θ, aligned with the B-field, was varied from 0^0 to 180^0 to describe the anisotropic angular distribution of the spectrum. Three neutron spectra computed at a position next to the magnetic axis of the JET tokamak are shown in Figure 5. Each of the spectra was computed for a different toroidal angle θ – two of them were parallel to the magnetic field and the third perpendicular. The blue curve in Figure 5 represents the spectrum of neutrons emitted in the same direction as the B-field while the spectrum of neutrons emitted in the opposite direction is denoted by the red curve. One can observe that the two spectra, although with comparable profile shapes and maxima, display a shift in the peak energy. This occurs due to the Doppler shifting of the spectrum to higher or lower energies, depending on whether the ion is moving towards or away from the observer.

6. Plasma neutron source

In order to define a plasma neutron source function ψ_{ns} for a specific time interval of a tokamak discharge, one needs to have knowledge of several key source parameters. These are the position of the birth of a neutron, defined by the JET major radius R, z-axis Z and the tokamak toroidal angle Θ. The probability of the emission of a neutron P_e at an arbitrary position inside the confines of the equilibrium plasma boundary (2D profile), which can be obtained through TRANSP/NUBEAM computations as demonstrated above, while the value of the angle Θ can be determined randomly, under the assumption of toroidal plasma symmetry, which is native to TRANSP. In the next step the direction in which the neutron was emitted θ, and its energy E has to be defined. If poloidal symmetry, with respect to the magnetic field, is assumed then the neutron emission angle θ can be defined by computing the neutron spectra at a specified number of toroidal directions equally spaced in $\cos(\theta)$, through the use of the DRESS code. The areas under the spectra computed at different angles can then be used to define the probability for the emission of a neutron in a specific direction P_θ. The vector of the B-field $\vec{b}$ at the neutron birth position needs to be known to alter the direction of $\theta = 0^0$ (perpendicular to a poloidal tokamak slice), causing it to be aligned with the magnetic field. The neutron source function can thus be written as $\psi_{ns}\ (R, Z, \Theta, P_e, P_\theta, \vec{b}, \theta, E)$, representing the basis for the description of the generation of neutrons in a tokamak plasma source.

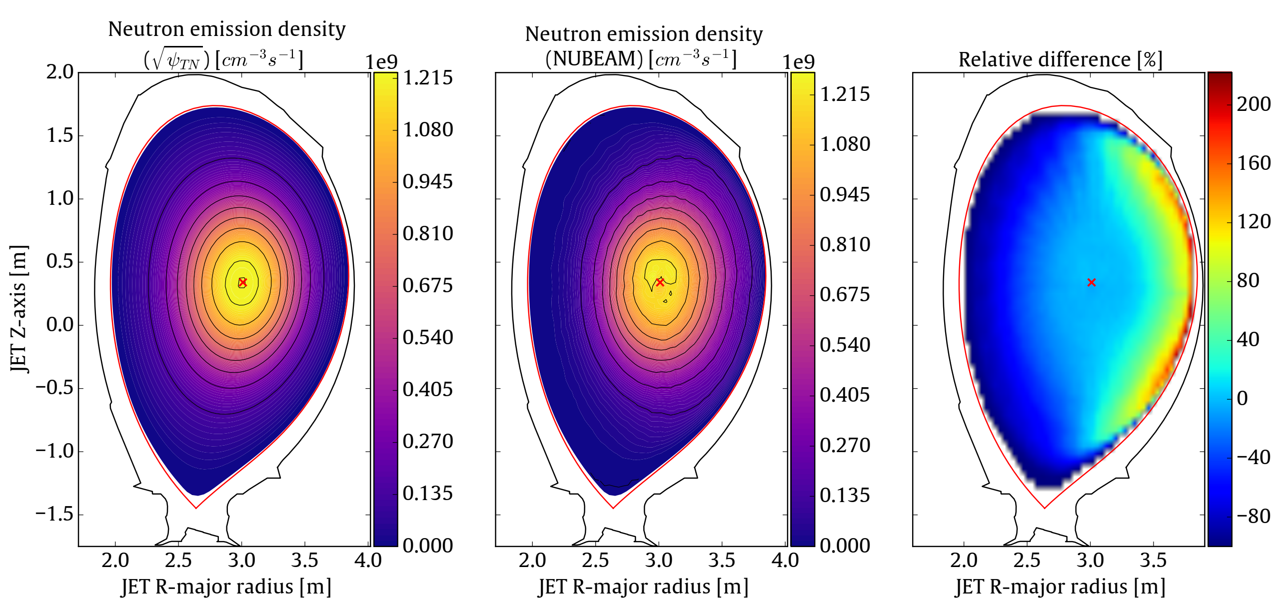

Figure 4: Comparison of TRANSP neutron emission density profile calculations performed on different computational grids – TRANSP native $\sqrt{\psi_{TN}}$ grid in the first graph and the NUBEAM Monte Carlo grid in the second. The relative difference between the two neutron profiles is shown in the last graph. The plasma magnetic axis is denoted by the red ×.

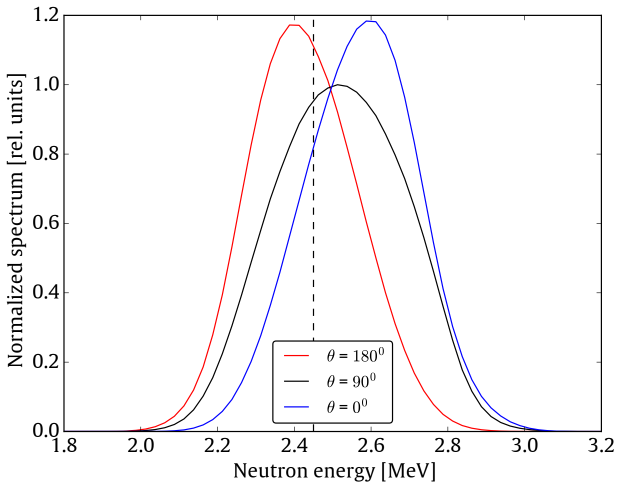

Figure 5: Neutron spectra computed with the DRESS code at the JET magnetic axis. The neutron emission angle was varied from 0^0 (direction of the magnetic field) to 180^0. The neutron spectra were normalized by the maximum value of the spectrum of neutrons emitted perpendicularly with respect to the magnetic field. The dotted line represents the 2.45 MeV DD neutron energy.

7. Conclusions

The construction of the foundations of the methodology for creating a detailed plasma neutron source generator has been presented in the paper. The possibilities of neutron emission modelling for the tokamak JET have been studied, focusing on the advanced plasma transport code TRANSP and the comprehensive model for neutral beam injection simulation NUBEAM. It has been shown that a relatively good agreement between the measured and calculated total neutron rate can be achieved, although an average 20 % overestimate can still be observed. The actions of rerunning the computations for a wider selection of JET shots with similar plasma parameters, enabling toroidal rotation simulation in TRANSP and including the ICRH plasma heating are all planned to be performed to further analyse the tokamak's neutron emission. Using the modified NUBEAM module to obtain neutron emission profiles mapped on to the irregular 2D grid, in contrast to toroidal flux surface averaging of the quantity, has proven to alter the profile shape considerably and emphasize the importance of trapped fast ions in JET. Neutron spectra at different toroidal angles and positions coinciding with the NUBEAM grid have been computed with the DRESS code, displaying emission anisotropy in the toroidal direction.

The obtained results can be combined into a function ψ_{ns}, which describes the location of the neutron's birth, together with its emission probability, direction, and energy. Although assumptions of tokamak toroidal and neutron emission toroidal angle symmetries have been made the number of source parameters remains relatively high, which might influence the performance of the plasma neutron generator code. The future challenge lies in the implementation of the program into a sate-of-the-art Monte Carlo neutron transport code in the form of a subroutine.

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