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P Siren et al.

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Synthetic neutron camera and spectrometer in JET based on AFSI-ASCOT simulations

Paula Sirén,[a] Jari Varje,[b] Henri Weisen[c] and Tuomas Koskela[d] and JET contributors[*]

[a] *VTT Technical Research Centre of Finland, P.O Box 1000, 02044 VTT, Finland*
[b] *Aalto University, P.O. Box 11100, 00076 Aalto, Finland*
[c] *SPC, station 13, EPFL, 1015 Lausanne, Switzerland*
[d] *NESRC, Lawrence Berkeley National Laboratory, Berkeley, CA 94720*

E-mail: paula.siren@vtt.fi

ABSTRACT: The ASCOT Fusion Source Integrator (AFSI) has been used to calculate neutron production rates and spectra corresponding to the JET 19-channel neutron camera (KN3) and the time-of-flight spectrometer (TOFOR) as ideal diagnostics, without detector-related effects. AFSI calculates fusion product distributions in 4D, based on Monte Carlo integration from arbitrary reactant distribution functions. The distribution functions were calculated by the ASCOT Monte Carlo particle orbit following code for thermal, NBI and ICRH particle reactions. Fusion cross-sections were defined based on Bosch-Hale model and both DD and DT reactions have been included.

Neutrons generated by AFSI-ASCOT simulations have already been applied as a neutron source of the Serpent neutron transport code in ITER studies. Additionally, AFSI has been selected to be a main tool as the fusion product generator in the complete analysis calculation chain: ASCOT - AFSI - SERPENT (neutron and gamma transport Monte Carlo code) – APROS (system and power plant modelling code), which encompasses the plasma as an energy source, heat deposition in plant structures as well as cooling and balance-of-plant in DEMO applications and other reactor relevant analyses.

This conference paper presents the first results and validation of the AFSI DD fusion model for different auxiliary heating scenarios (NBI, ICRH) with very different fast particle distribution functions. Both calculated quantities (production rates and spectra) have been compared with experimental data from KN3 and synthetic spectrometer data from DRESS code. No qualitative differences have been observed. In future work, AFSI will be expanded for synthetic gamma diagnostics and additionally, AFSI will be used as part of the neutron transport calculation chain to model real diagnostics instead of ideal synthetic diagnostics for quantitative benchmarking..

KEYWORDS synthetic diagnostics; neutrons; Monte Carlo integration.

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1. Introduction

In current experimental devices, neutrons primarily indicate the achieved fusion power. Additionally, due to safety aspects, the total neutron production has to be monitored during the plasma operation and in reactor applications, neutron damage should be estimated. In order to connect plasma physics simulations and scenario modelling to these real effects, synthetic diagnostics for neutron production are needed.

The main purpose of synthetic diagnostics is to interpret measured data and filter out non-physical effects. They are also used in the calibration of real systems, scenario development and the analysis of experiments when the measured data is not available. Additionally, in the case of neutrons, simulated production rates are important also in the preparing of experiments, since the fixed neutron budget cannot be overcrossed due to safety limits set by nuclear safety authority.

In this paper, implementation of synthetic neutron diagnostics, including production rate and spectrum, based on the AFSI Fusion Source Integrator is described. A synthetic neutron camera and spectrometer are qualitatively validated with experimental data from the JET neutron camera (KN3) and synthetic time-of-flight spectrometer (TOFOR) in selected discharges.

The structure of this paper is as follows: In the second section the experimental background and fusion neutrons in JET are introduced. The main tool AFSI is presented in Chapter 3and the most important results in synthetic neutron camera and spectrometer and comparison with the experimental data are discussed in Chapter 4. The work is concluded in Chapter 5 with the discussion of possible error sources, challenges and future updates.

2. Fusion neutrons in plasma experiments

The principle of the modelling of neutron and gamma transport in materials is mainly similar both with neutrons produced by fission and fusion reactions. However, the effects in materials are different due to the energy spectrum of neutrons. In DD fusion, the energy is mainly on the order of magnitude of 2-3 MeV depending on the kinetic energies of reactants, which enable more threshold reactions and longer mean free paths for neutrons in the materials. In addition, the materials in fusion devices are different, so various reactions which are not relevant in fission reactors, are observed in fusion applications.

Fusion reactions which produce neutrons can be divided into several groups based on the energy or source of reactive particles. Typically, they are divided into three groups: thermal particle reactions, thermal-fast particle reactions and fast particle reactions. In current devices, with the exception of the DT campaign in JET, the majority of neutron population is produced in DD reactions between fast and thermal particles. However, all reaction types can contribute significantly to the total production rate and they are required in the validation of the computational methods. In forthcoming reactor-relevant tokamaks, thermal reactions dominate the neutron production due to the smaller fraction of fast particles. It has to been noted that, thermal-fast and fast particle reactions can be important due to the different energy spectra of emitted neutrons. The highest energies of neutrons are achieved in the reaction due to RF heated particles. Additionally, in thermal-fast and fast particle reactions, the neutron distribution is strongly asymmetric on the poloidal cross section, which can be seen the production rate in different lines of sight in the neutron camera.

2.1 Neutron measurements in JET

There are several neutron diagnostics systems in operation in JET. Most important of them are the fission chambers (KN1) [1] which are used to measure the total neutron production rate. Validation of simulated neutron rates against the fission chamber measurements with quantitative agreement have previously been presented in [2]. A High Spatial Resolution Neutron Camera with 10 horizontal and 9 vertical lines of sight (KN3) [3] covers the entire plasma cross section. It gives the production rate map on the poloidal cross section and is also suitable for gamma measurements. A Time of flight spectrometer (TOFOR KM11) [4] can be used to measure the spectrum in one vertical line of sight located near the centre of the core plasma.

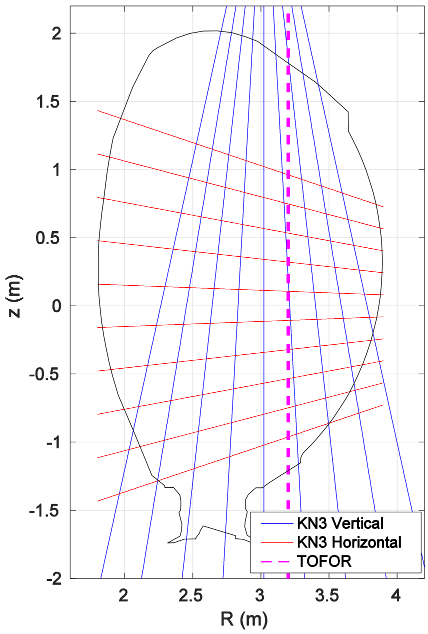

Figure 1: Geometry of JET neutron camera (KN3) and time-of-flight spectrometer

3. AFSI ASCOT Fusion Source Integrator

AFSI ASCOT Fusion Source Integrator is a modular code, which defines product distributions in 4D grid (R, z, $v_{\parallel}$,$v_{\perp}$) based on given input distributions (usually from ASCOT [5]) of reactants in DD, DT and DHe3 fusion reactions [2]. In the modelling grid, the 3D (v_x,v_y,v_z) velocity has been reduced to the parallel and perpendicular components respect to the magnetic field vector. AFSI consists of three methods: analytical, semi-analytical and Monte Carlo for solving the production rate integral

$$r_{12} = \iiint_{\boldsymbol{v}_1} \iiint_{\boldsymbol{v}_2} f_1(\boldsymbol{v}_1)\sigma(|\boldsymbol{v}_1 - \boldsymbol{v}_2|)f_2(\boldsymbol{v}_2)\,|\boldsymbol{v}_1 - \boldsymbol{v}_2| d\boldsymbol{v}_1 d\boldsymbol{v}_2$$

The AFSI Monte Carlo module was used as a source in a synthetic neutron spectrometer and camera. In the Monte Carlo model, the fusion product distribution is calculated by numerically integrating the preceding equation. It has been implemented by sampling pairs of reactant particles (1 and 2) and collecting the product distributions. Fusion product velocities in 3D are solved from energy and momentum conservation laws in the CM of mass coordinates. The cross section is based on the Bosch-Hale parametrization [6]

4. Synthetic neutron diagnostics – production rates and spectra

One of the most analysed DD fusion product record shot (#86614) [] was selected for the validation of the synthetic KN3 and the shot parameters are plotted in Figure 2a. Qualitative results from KN3 camera were available and the calculated production rates have been compared with them. AFSI-ASCOT simulations are used as a basis for synthetic neutron spectrometer, which has geometrical set-up equal to KN3 neutron camera, which is presented in Figure 1. Line-integrated neutron rates are calculated using the synthetic diagnostics along the lines of sight from AFSI simulated product distributions. This synthetic AFSI-based diagnostic was implemented as an ideal diagnostic without detector related effects, for instance scattering or attenuation.

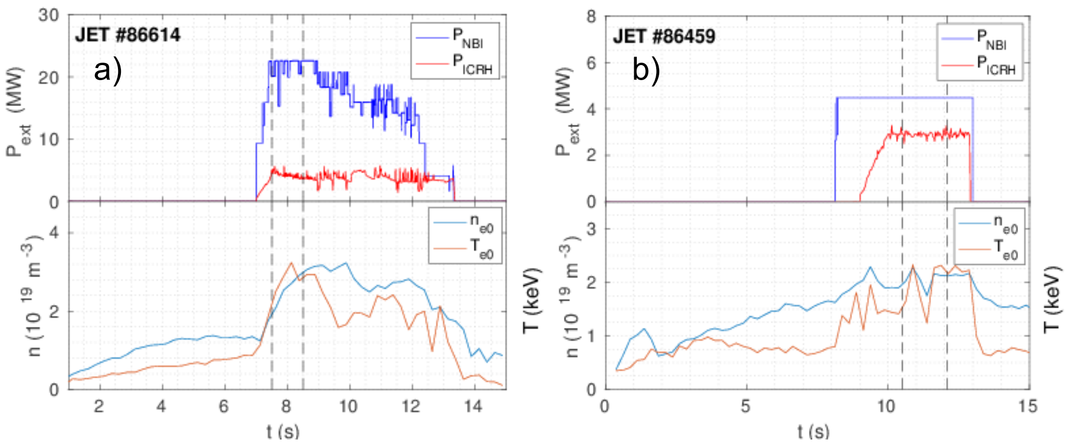

Figure 2: Plasma parameters in the validation cases a) validation for KN3 b) validation for TOFOR

Maximum was observed in the fourth channel horizontally and in the fourteenth channel vertically in the physical KN3 measurements. Also in AFSI-based production rates, the maxima are achieved in the same channels and the relative orders of magnitude is same for computational and measured values with the exception of the outermost vertical channels 12, 13 and 19. Computational values were overestimated in channels 12 and 13 and the production was underestimated in channel 19. Those differences are likely caused by detector related effects but also errors in the equilibrium reconstruction can affect the total plasma volume and production rate.

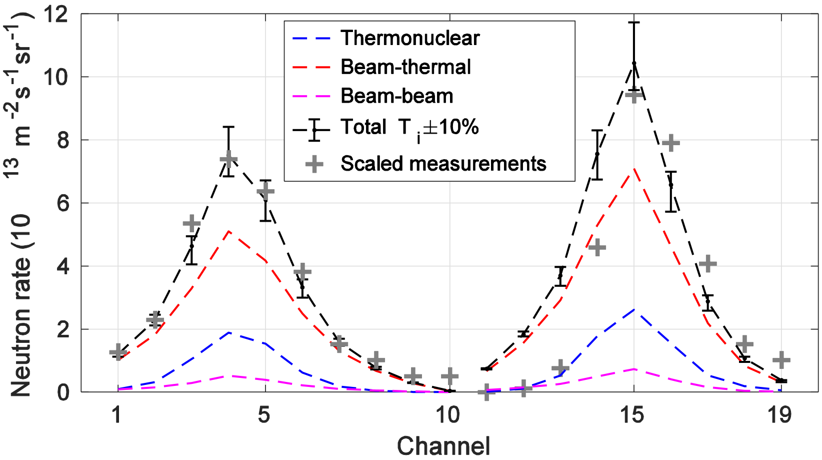

Figure 3: Total neutron production and error estimates due to uncertainty in the ion temperature profile in each KN3 channel as calculated by AFSI and compared to experimental scaled KN3 data [7].

Spectrum calculation was validated with the ICRH heated shot #86459 (plotted in Figure 2b) where the reactant distribution was strongly anisotropic. Synthetic TOFOR spectrometer is benchmarked with other synthetic Monte Carlo based diagnostics DRESS [8] presented in [9] and the distribution functions of reactive particles were given by ASCOT in both cases. The total spectrum is presented in Figure 4. The spectrum covers energies between 1.6-5.4 MeV (peaking at 2.5 and 3.0 MeV energies) which agrees qualitatively.

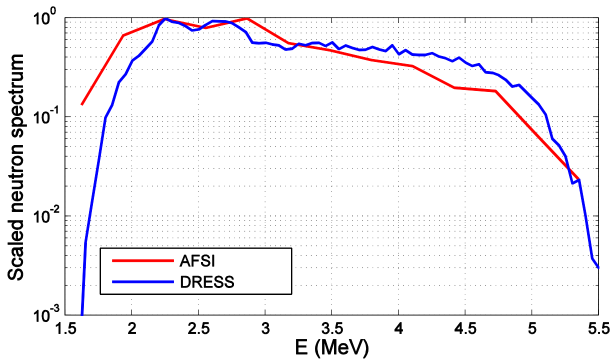

Figure 4: Neutron spectrum from the AFSI (red) and DRESS (blue) based synthetic diagnostics in ICRH-thermal particle reaction in JET #86459 t=10.5-12.1 s.

5. Conclusions

The implementation and tentative validation of synthetic neutron (and fast particle) diagnostics in JET were presented in this paper. A synthetic neutron camera (KN3) and a synthetic spectrometer (TOFOR) have been implemented by AFSI Monte Carlo module with ASCOT based input as an ideal diagnostics without detector effects. However, when AFSI is implemented as a part of calculation chain, including also neutron transport calculated by Serpent [10, 11], the tools for detector modelling are available.

The other significant issue is the quality of ion temperature data: in this simulation the assumption $T_i = T_e$ was used. The effect on the total production due to ion temperature was briefly characterised with simple sensitivity tests by repeating the simulations with the ion temperature varied by 10%. As mentioned, the KN3 experimental measurements are given as counts of the detector. The most reasonable way to do quantitative validation is by doing neutron transport calculation including the modelling of detector with tools such as the Serpent code. Synthetic KN3 camera will be expanded also for gamma production including detector related effects in near future for the extrapolation and analysis of JET DTE2 campaign [12].

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