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Integrated modelling driven fusion research – coupling of plasma and neutron transport codes

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Introduction

Neutron measurements play a crucial role in the operation of modern fusion devices – they are the foundation for predicting fusion power, monitoring and extrapolating the performance of plasma scenarios, as well as tritium breeding and fast ion physics studies [1]. The work presented in the paper has mainly been driven by the need for a better understanding of the properties of fusion neutrons emitted from D and DT plasmas at the JET tokamak, calling for a strengthening of the coupling between plasma modelling and neutron transport codes. We present findings addressing the following interconnected key objectives: *(i)* Establish whether changes in neutron emission properties, arising from perturbations in plasma conditions, affect fusion power measurements at JET and experimentally validate the neutron emission modelling; *(ii)* Compare neutron emission modelling results stemming from different methodologies and computational chains in order to cross-validate plasma modelling codes; *(iii)* Demonstrate the importance of precise neutron yield measurements for modelling support of T and DT operations at JET and ITER.

Neutron emission modelling

In the last decade the development of fusion modelling suites has progressed largely, with significant effort invested into code coupling. Such integrated modelling frameworks enable a wholesome approach to interpretive and predictive analyses of complex and correlated phenomena in fusion research, ranging from plasma physics to concept fusion power plant performance [2]. In the paper we give an overview of the recent progress in the coupling of plasma and neutron transport codes, its experimental validation, and comment on the parallel development of methodologies for modelling of realistic plasma neutron sources. These comprise state-of-the-art plasma transport, two-body kinetics and neutron transport codes – specifically we will compare two recently developed computational chains, TRANSP-DRESS-MCNP [3] and ASCOT-AFSI-SERPENT [4], presenting the most comprehensive modelling work undertaken on this subject to date. Neutron emission properties of several JET D and mixed D-^{3}He plasma discharges were modelled in detail through interpretative plasma simulations, focused on scenarios using NBI and RF systems for externally heating the plasma. The modelling results were compared with neutron diagnostics measurements of the fission chambers (neutron yield), neutron camera (emissivity profile), time-of-flight spectrometer (energy spectrum) and neutron activation system (energy spectrum). In the following chapter the response of the activation system modelling is highlighted, since it is based on the use of the full TRANSP-DRESS-MCNP computational chain, together with a short description of code benchmarking results.

Experimental validation and benchmarking

Two different types of discharges were chosen for the experimental validation of neutron emission modelling – namely baseline-like, due to high NBI+RF auxiliary power and similarity to neutron calibration plasma conditions, and three-ion scenarios, due to the presence of a prominent MeV-range fast ion tail. The fast ion pitch-energy distributions for the two discharges are shown in Fig. 1. The baseline-like distribution on the left-hand side exhibits the NBI source of fast ions at energies around 100 keV, positive pitch of 0.5 to 0.6, the slowed-down ions and indications of ions accelerated through the 2nd harmonic D RF resonance, which is not the dominant heating mechanism. On the other hand one can see an evolved fast ion tail in the right-hand side graph, extending up to energies of 4 MeV, the consequence of a favourable ion-ion hybrid resonance layer positioned at the magnetic axis.

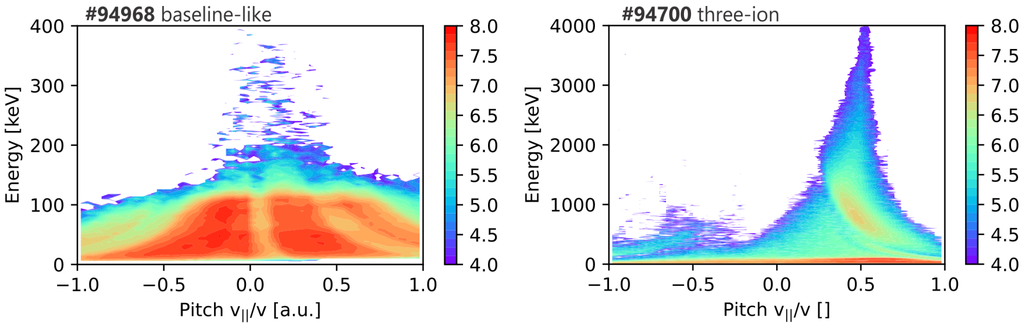

Figure 1: Pitch-energy fast deuteron distribution functions ($\log_{10}$ cm^{-3}) for the baseline-like (left) and three-ion discharge (right), plotted for ions located in the vicinity of the magnetic axis.

The neutron emission modelling results - such as the ion distribution functions, emissivity profiles and neutron spectra were used to propagate realistic neutron source properties in neutron transport simulations. Due to the differences in the fast deuteron distributions, the energy spectra of neutrons exhibited different levels of anisotropy. The baseline-like case DD neutrons were emitted with spectral shapes similar to a broadened Maxwellian, due to D-NBI ion broadening. On the other hand the three-ion cases display large anisotropy effects, the fast ion tail induced fusion resulting in emission of neutrons with energies up to 5 MeV, as shown in the left-hand side graph of Fig. 2. It was found that these spectral anisotropies, resulting from different physics mechanism driving the discharges' fusion performance, can be detected by using the multi-foil activation technique [3, 1]. This means we use Indium and Aluminium foils, based on ^{115}In(n,n')^{115m}In and ^{27}Al(n,p)^{27}Mg activation reactions (cross section shown in Fig. 2), to probe the shape of the spectrum. Based on the different energy thresholds of the two reactions, we can detect the anisotropy effects of a fast ion tail on the neutron spectrum – e.g. the spectral difference denoted in the left-hand side graph by a shaded green area. The reaction are sensitive to additional neutron sources, like triton burnup DT and ^{9}Be(D,nγ)^{10}B neutrons, which were modelled realistically as well. The sensitivity is expressed by calculating the ratio of Al/In activation, which was compared to activation measurements shown on the right panel of Fig. 2. The horizontal axis of the graph represents the ratios of the integral neutron yields for three-ion over baseline-like discharges. A good agreement of the activation ratio for three-ion over baseline-like pulses is observed for both measurements, with the relative discrepancies of the order of 1 %. One can observe that measured and computed ratios have values above unity – this means that the relative ^{27}Al(n,p) activation in the three-ion #94700 is indeed larger due to the anisotropic effects of the RF fast deuteron tail on the neutron spectrum. The difference in the modelled spectra exhibited in Fig. 2 is experimentally validated. Additionally, it can be seen that the measured and calculated ratios increase from #94968 and #94969. While the relative activation of Indium in the two baseline-like discharges stays approximately constant, Al-27 activation is highly sensitive to the triton burnup neutrons. While there is little difference in the Al activation due to the DD peak shape in the baseline-like discharges, the DT neutron contribution is a factor of 1.5 higher in the highest performing #94968. This means that Al/In activation is larger for #94968, which results in a lower computed ratio.

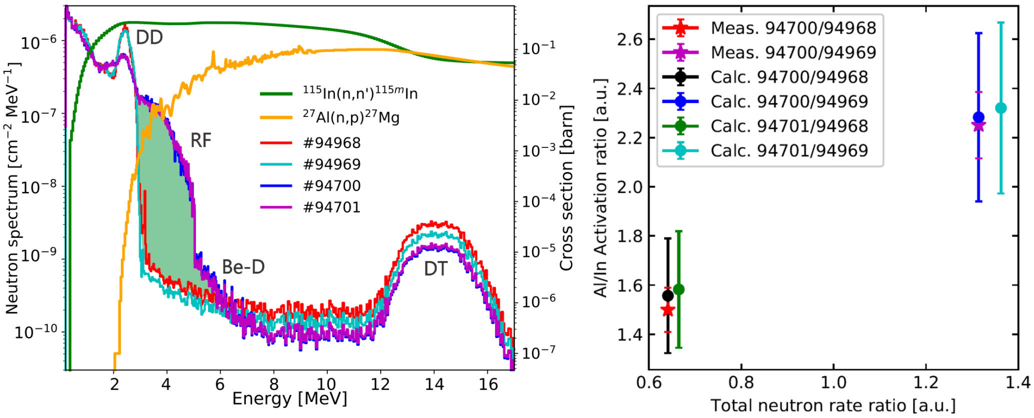

Figure 2: *Left:* Normalized total neutron energy spectra computed in the neutron activation system for the baseline-like and three-ion pulses. Denoted are the contributions from the DD, T burnup DT, and ^{9}Be(D,nγ) fusion, as well as the neutron anisotropy stemming from the fast ion tail in the three-ion scenario. Added are the cross sections for the ^{115}In(n,n')^{115m}In and ^{27}Al(n,p)^{27}Mg neutron activation reactions. *Right:* Comparison of the measured (stars) and calculated (circles) ratios of ^{27}Al(n,p)/^{115}In(n,n') neutron activation, with their estimated uncertainties. On the x-axis are the ratios of the total neutron yields for individual discharges.

We have additionally cross-validated the neutron emission TRANSP-DRESS-MCNP computational chain against the alternative ASCOT-AFSI-SERPENT. In order to avoid computational bias, we used identical interpretive plasma simulation inputs in TRANSP and ASCOT, and made sure that the Monte Carlo neutron transport models of JET were computationally equivalent. For the analysis we chose several DD neutron diagnostics commissioning discharges, based on which the absolute calibration of fusion power measurements was done. These were 10 s long discharges with around 15 MW of NBI power, and no RF. Dominating the fusion performance was fusion between D-NBI and thermal ions, which means that the fast ion distribution function were calculated by beam slowing-down calculations. A comparison of the calculated neutron spectra at the position of the neutron activation system with the two equivalent methodologies is shown in the left-hand graph of Fig. 3. One can see that we obtain an excellent agreement between the MCNP and SERPENT computed realistic neutron spectra. Both spectra display a widening of the DD peak, which is the result of beam-induced double-humped and Doppler shifted spectrum of neutrons emitted.

Modelling support in T and DT operations

In addition to the important role neutron yield measurements have in assessing fusion power, they are also used as basis for calculating other important operational and modelling parameters. As an example we showcase the TRANSP analysis of a mixed protium-tritium discharge performed in the ongoing JET T campaign. The analysis served two main goals – *(i)* with data on tritium plasmas being a scarce resource, we can benchmark existing evaluations of the T(T,2n)^{4}He fusion cross section against measurements of the TT neutron rate; *(ii)* because the DT fusion cross section is 2 to 3 orders of magnitude larger than TT, residual concentrations of deuterium in the machine, as small as $n_D/n_e \sim 10^{-4}$, can produce DT neutron rates comparable to those of TT. The concentration of D can thus be determined by comparing the measured and calculated TT+DT neutron rates. The right-hand side graph of Fig. 3 shows a comparison between analytical (dashed), TRANSP calculated, and measured TT neutron rates. It shows that the use of the default cross section in TRANSP largely overestimates the neutron yield, while the new IPP evaluation matches measurements better. An additional scan was made to determine the amount of residual D, which amounted to levels of around 0.1 % to 0.5 %.

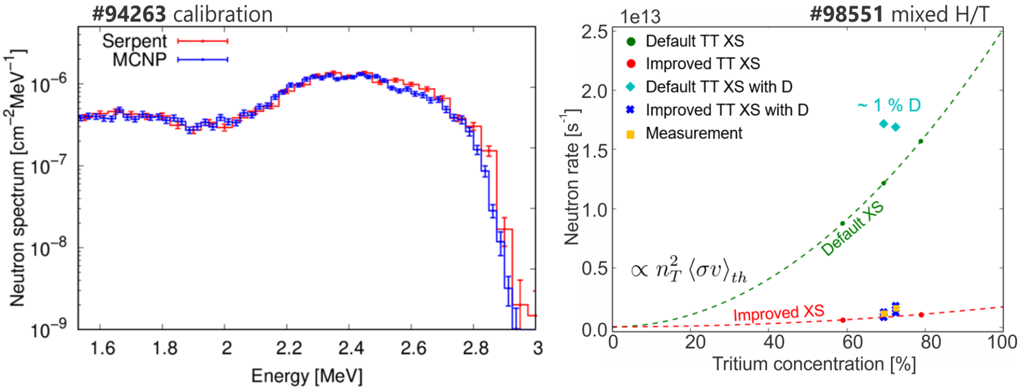

Figure 3: *Left:* Comparison of normalized neutron spectra in the neutron activation system, calculated with the TRANSP-DRESS-MCNP (blue) and ASCOT-AFSI-SERPENT (red). *Right:* TRANSP calculations of neutron rates in mixed H/T plasmas. Analytical calculations (dashed curve) and simulations (circles) are made with the default (green) and improved IPP (red) T(T,2n)^{4}He cross sections. The simulations with added trace D concentrations are compared to measurements.

Conclusions

The paper describes the developed TRANSP-DRESS-MCNP computational chain for modelling realistic neutron emission in JET plasmas, crucial for ITER modelling support. We have shown that the methodology has been experimentally verified against neutron diagnostics measurements for a variety of JET plasma scenarios. We presented the novel measurement of fast ion induced anisotropy in the DD neutron spectrum, based on the multi-foil neutron activation technique. We have additionally shown that the TRANSP based methodology has been successfully benchmarked against its ASCOT-AFSI-SERPENT counterpart for fusion power calibration JET discharges. We concluded by showcasing the importance of precise neutron yield measurements in support of JET's operation and modelling activities in the T and DT campaigns, including fusion cross section benchmarking and calculation of plasma composition.

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