NBI modelling by upgraded TASK3D-a code in preparation of LHD deuterium campaigns

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LHD (Large Helical Device) [1] is a superconducting helical device (heliotron type) capable of studying current-less plasmas. The experiment is equipped with 5 hydrogen neutral beam injectors: 2 perpendicular positive-NBIs (40-50 keV, up to 12MW) and 3 tangential (co- and counter-current) negative NBIs (180-190 keV, up to 16MW). Currently hydrogen plasma experiments are run at LHD, but the use of deuterium (D) is planned in the future campaigns, together with the upgrade of at least 3 NBIs to D injection. In view of a helical fusion reactor it is therefore important to investigate the isotope effect and understand the energetic ion confinement in helical devices. In tokamak devices it is already known that the increase of plasma ion mass leads to better confinement properties [2,3].
Interpretative analyses of the LHD experiments are currently carried out with TASK3D-a integrated transport code [4], capable of treating hydrogen and multi-ion species plasma [5,6]. Effort has been recently put to start the upgrade of TASK3D-a code to extend the analysis capabilities to D plasmas with D NBIs. One of TASK3D-a routines is named FIT3D and it has been developed to evaluate radial profiles of NBI absorbed power, beam pressure, beam source and induced momentum. This paper presents the first upgrades proposed for FIT3D routine in order to allow the complete modelling of D NBI injection and the interaction with D plasma. Two main modifications have been proposed and here illustrated: the first regards the evaluation of the beam D particle ionization in the D plasma, while the second regards the implementation of a module which estimates the neutron rate production from D-D reactions, both from thermal and beam-plasma reactions.

Beam stopping cross section for D NBI ionization process in D plasmas

A central part of FIT3D routine is the calculation of the so-called "beam stopping cross section". The beam attenuation process is described by the stopping cross section $\sigma_s = 1/(n_e\lambda)$, where n_e is the plasma density and λ is the attenuation length. Currently FIT3D code uses an analytical formula for the beam stopping cross section proposed by Janev [7]. The formula was originally calculated for neutral hydrogen injection in H plasma; however changing the relative atomic mass of the beam particles *u* in the input E_{NBI} /u we can obtain the attenuation of a deuterium beam. Janev's formula is calculated for $100 \leqslant E_{NBI}$ (keV/u)$\leqslant 10^4$. Considering LHD hydrogen NBIs, the two positive NBIs are out of this range. In case of D beams, the beam energy divided by atomic weight of deuterium (keV/u parameter) will be less than 100 kev/u for all the NBI lines, being therefore out of the range of Janev's calculation. For this reason we proposed the use of the beam stopping cross section formula provided by Suzuki [8], which represents an updated and extended alternative to Janev's formulation. This formula is calculated for a wider E_{NBI}/u range and it uses different fitting coefficients in case of H, D and T background plasmas, while Janev did not distinguish different background plasma cases. Given the possibility of choosing D plasma background and given the wider E_{NBI}/u range of fit's validity, the use of Suzuki formulation is preferable in the analysis of D plasma and NBI with TASK3D-a tool. Figure 1 compares the beam stopping cross section for NBI D 80 keV particles (i.e. 40keV/u - typical LHD NBI energy) calculated with Janev and Suzuki formulas, with an arbitrary Z_{eff} of 1.5 and different plasma densities and temperatures. We can note some discrepancies, especially at high density: as remarked 40 keV/u is not in the range of Janev's formula.

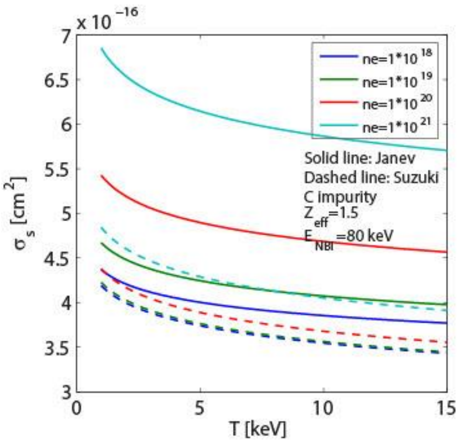

Figure 1: Comparison of beam stopping cross sections for D LHD NBI with 80 keV, calculated by Janev (solid line) and Suzuki (dashed line) formulas

Neutron production from thermal plasma and NBI-plasma fusion reactions

In D plasmas a significant neutron production is expected due to D-D fusion reactions, especially if energetic D particles are injected by the beams. D-D fusion reactions are:

1. D + D → p (3.02MeV) + T (1.01 MeV) → proton production
2. D + D → n (2.45 MeV) + ^{3}He (0.82 MeV) → neutron production

Reactions originate in background (thermal) plasma, from beam-plasma interactions and beam-beam interactions. In order to have an evaluation of the neutron rate and fusion power production, we implemented a new routine in FIT3D code. In the present work beam-beam fusion reactions are neglected, being a minor fusion source and quite complicated to be treated. For thermal fusion reactions we decided to implement the Bosch formula for the fusion reactivity <σv> for a Maxwellian plasma [9]. Regarding the beam-plasma fusion source, the integral for <σv> has to be calculated taking into account both plasma and beam particle distribution function. D-D fusion cross section formula has been taken from Bosch [9] and the beam particle distribution function f(v) from Rome [10]. In order to simplify the Rome's formula, we decided to neglect the anisotropy in the velocity distribution function, therefore not considering any dependence on pitch angle ξ, and to consider only stationary solutions, therefore not considering any dependence on t. The resulting approximation depends only on particle velocity, takes into account slowing down of fast ions and f(v) becomes (in case of negligible density of background neutrals) $f(v) = \frac{\tau_S}{4\pi(v^3+v_c^3)} U(v_0 - v)$, where v_0 is the velocity of beam particles with energy E_{NBI} and $v_c = \sqrt{2E_c/m_f}$ is the critical velocity of fast ions with mass m_f (see Stix's paper [11] for definition of critical energy E_c). A Maxwellian distribution function is considered in the integral for the (isotropic) background plasma, and the integral calculation follows the procedure adopted for the code FIT3D_DD developed by S. Murakami and described in the work of M. Homma and S. Murakami [12], except that the fusion cross sections are calculated by the Bosch fit [9] and not by the outdated Duane's formulation [13]. The code FIT3D_DD described in [12] is not integrated in TASK3D-a, and therefore we decided to implement a fusion source routine directly in TASK3D-a. Figure 2 shows a comparison of neutron rate calculation between the code FIT3D_DD and the upgraded FIT3D routine of TASK3D-a transport analysis suite.

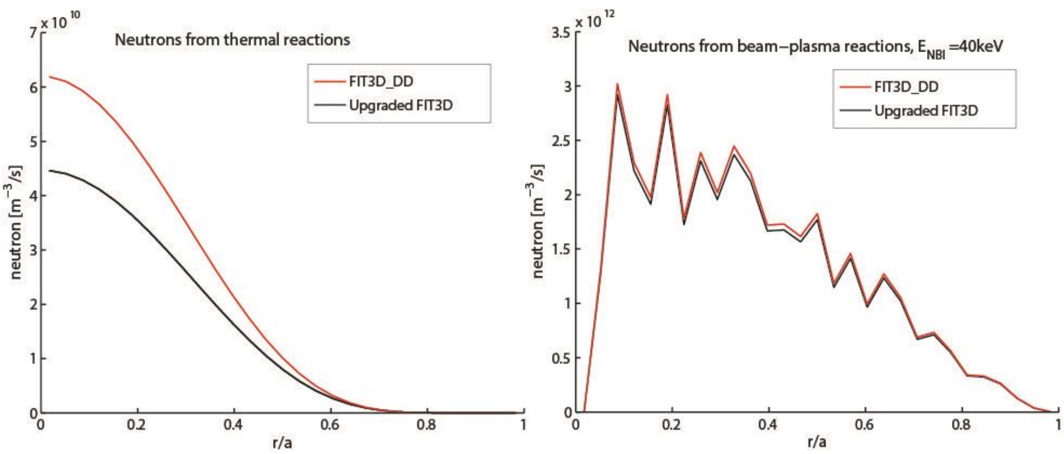

Figure 2: comparison between upgraded FIT3D code and FIT3D_DD code by S. Murakami [12] of neutron rate from thermal D plasma (left) and D NBI (40 keV) – D plasma interactions (right), obtained with arbitrary density ($n_{e,0}$=3e19 m^{-3}) and temperature profiles ($T_{e,0}$=1keV).

Conclusions

In future plans of LHD experiment, D plasma with D NBI injection discharges are scheduled in order to investigate the isotope effect and confinement properties in the path towards fusion helical reactors. Recently the upgrade of TAKS3D-a transport analysis suite has started, in order to expand the analysis capabilities for LHD experiments from H discharges to D discharges. Interaction between NBI and plasma is considerably affected by the gas change, and the present work introduces the first modifications implemented in the code in order to allow the complete modelling of D neutral beam injection in D plasma. In particular the neutral particle ionization routine has been modified, with the implementation of beam stopping cross section formula more suitable for LHD D cases. Moreover the code has been extended with the implementation of a routine which estimates the neutron rate and fusion power production both from thermal background plasma and beam-plasma interactions.

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