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Upgrades and application of FIT3D NBI-plasma interaction code in view of LHD deuterium campaigns

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Abstract. This work presents a novel upgrade of FIT3D neutral beam-plasma interaction code, part of TASK3D-a transport suite of codes, and its application to LHD experiments in the framework of the preparation to the first deuterium experiments in LHD. The NBI system will be upgraded to D injection and efforts have been recently put to extend LHD modelling capabilities to D operations. The implemented upgrades for FIT3D to enable D NBI modelling in D plasmas are presented, with a discussion and benchmark of the models used. In particular, the beam ionization module has been modified and a routine for neutron production estimation has been implemented. In recent LHD campaign, He experiments have been run to help the prediction of main effects which may be relevant in future LHD D plasmas. Identical H/He experiments showed similar electron density and temperature profiles, while a higher ion temperature with He majority has been observed. In order to investigate the causes of this behaviour, the upgraded FIT3D code is used to evaluate the NBI power deposition with different plasma composition. Although a better fast ion confinement in He is noted, the NBI power deposition appears to be unaffected, suggesting that intrinsic plasma transport properties and not heat deposition plays a key role.

1. Introduction

1.1 LHD device and NB system: preparation for D operation

LHD (Large Helical Device) [1], run at NIFS (Japan), is a toroidal helical device (heliotron) for plasma confinement capable of current-free operations. LHD is the largest helical device in the world, together with the recently built W7-X stellarator. It is equipped with superconducting coils which enables long pulses achieving steady state regimes. The peculiarity of this device is the pair of helical coils which, together with 3 poloidal coils, provide the complex non-axisymmetric 3D magnetic field. LHD started plasma operations in 1998, and the goal is to study reactor-relevant plasmas in helical configuration, in order to offer an alternative way to tokamaks in the path towards commercial fusion reactors.

High β (5.1%), high density (1.2 x $10^{21}$$m^{-3}$), high ion temperature (10keV) and long pulses (3200s) have been separately reached [1] in hydrogen experiments. In order to explore reactor relevant conditions, a first D campaign is foreseen from 2017 [2] and big efforts have been undertaken at NIFS for the preparation of D operations.

While in other magnetic configurations the isotope effect has been widely studied (e.g. for JET [3],[4] or JT60-U [5],[6] as tokamaks and for RFX-mod [7] as reversed field pinch), for helical configurations the presence of the isotope effect is still an open field of discussion, and limited data are available [8]: this is one of the reasons that led to the decision of starting a D campaign at LHD. In addition to the study of the isotope effect, the main objectives of the LHD D campaign are very reactor-oriented and consist in the exploration of high-performance plasmas by confinement improvement and the demonstration of the confinement capability of high-energy ions, relevant for burning plasmas in helical configurations.

Consistently with this plan, the neutral beam injection system will be upgraded to D injection. External heating in LHD is essential since the ohmic power contribution is missing. Among the installed heating systems, NBI is the most powerful, and most of the experiments rely on NB heating. Currently LHD is equipped with 5 hydrogen neutral beam injectors: 2 perpendicular positive-NBIs (40-50 keV, up to 12MW) and 3 tangential (co- and counter-injection) negative NBIs (180-190 keV, up to 16MW). Figure 1 shows a sketch of the NBI system, while injection parameters are listed in table 1.

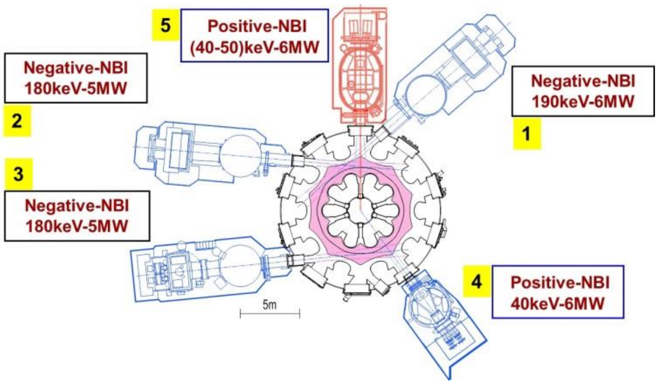

Figure 1. View of the 5 hydrogen LHD NBIs, with the corresponding line numbers.

Table 1. Parameters of NB lines in LHD.

Beam line #	Name	Accelerated ions	Injection	E_{NBI} - P_{NBI}
1	Ctr1	H^-	tangential	190 keV – 6 MW
2	Co2	H^-	tangential	180 keV – 5 MW
3	Ctr3	H^-	tangential	180 keV – 5 MW
4	Pb4	H^+	perpendicular	40 keV – 6 MW
5	Pb5	H^+	perpendicular	40-50 keV – 6 MW

Tangential NBIs locally drive current, but thanks to the opposite injection directions, LHD can be run in net current-free regimes. For D injection, NB lines ”Pb4” and ”Pb5” will be upgraded to 9MW by rising the NB energy respectively to 60keV and 80keV. This increase is driven by the idea of providing more ion heating in D operations, in order to reach higher ion temperature relevant for reactor studies. The 3 tangential NBIs will be upgraded to D injection but will keep the current energy and power [9].

1.2 NBI modelling at LHD: FIT3D tool

The analyses of LHD discharges are routinely performed by TASK3D-a tool [10] [11], which is an integrated transport suite developed for the analysis of LHD helical plasmas in 3-D magnetic configurations. The complex combination of injection trajectories in a non-axisymmetric device with different NB energies makes NBI modelling crucial for experiment analyses. FIT3D [12] is a code integrated in TASK3D-a for NBI-plasma interaction modelling and it has been developed to evaluate radial profiles of NB absorbed power, beam pressure, beam particle source, induced momentum and driven current. It is composed by three routines: a Monte Carlo routine which calculates the fast ion birth profile for H NBI taking into account the beam trajectories, a Monte Carlo routine which follows the newly-born fast ions for a time interval shorter than the energy slowing-down time, but longer than the time scales of orbit effects and a routine which evaluates analytically a steady-state solution of the fast ion Fokker-Plank equation without taking into account orbit effects. In order to follow the dynamics of fast ion slowing down, FIT3D code is coupled to another routine, which computes the power transfer from fast ions to plasma during the slowing down process. Other NBI codes have been used to model selected LHD experiments as for instance Monte Carlo codes GNET [13] and MORH [14], but they are not integrated in TASK3D-a for usual analyses.

2. Upgrades of FIT3D for the analysis of D injection in D plasma

In preparation of the D campaign, TASK3D-a code is being upgraded to allow the analyses of LHD D experiments in the near future. Within this task, FIT3D NBI code has been reviewed in order to identify the necessary modifications and implementations to enable a correct and complete modelling of D injection in D plasmas with multi-impurities. The first intervention regards the neutral beam ionization which has been upgraded for D operations. Since the non-negligible fusion reactions in D plasmas, the second intervention deals with the implementation of a routine which estimates neutron and fusion power production from D-D fusion reactions, including thermal plasma and beam-plasma sources. Beam-beam reactions have been neglected in this work, but studies are underway [15] and we leave discussions on this topic to further work. The above mentioned code GNET has been used also for the prediction of the confinement of 1 MeV tritons [16] produced by D-D fusion reactions.

2.1 Deuterium neutral beam ionization in deuterium plasmas

A population of Monte Carlo test particles is used to calculate the ion birth profile. The physics of the beam ionization is condensed in the so-called "beam stopping cross section" $\sigma_s=1/(n_e\lambda)$ where n_e is the plasma density and λ is the e-folding beam intensity decay length. Currently, FIT3D code uses an analytical formula proposed by Janev [17] for σ_s. The formula takes into account the ionization by plasma electrons and ions, charge-exchange process, ionization by impurities (He, C, O, Fe) and a cross section enhancement due to multistep ionization (ionization from excited states). It takes as input the atomic mass *u* of the beam particles, the beam energy, plasma density, electron temperature and the impurity concentrations. This formula is originally evaluated for H injection in H plasmas, in a NBI energy range between 100 and 10^4 keV/u. Considering LHD H NBIs, the two positive NBIs are out of this range. In case of D beams, E_{NBI}/u will be less than 100 keV/u for all the NB lines, resulting outside of the range of Janev's σ_s fit. For this reason the more recent beam stopping cross section fit by Suzuki [18] has been implemented: it consists of a more precise fit (see the reference paper for comparisons with Janev's fit) for the ionization cross sections, which includes more impurities (He, Li, Be, B, C, N, O, Fe) and it is calculated for a wider E_{NBI}/u range (from 10 to 10^4 keV/u). Moreover different fitting coefficients are provided in case of H, D and T background plasmas, while previously it was not possible to distinguish different background plasmas. In figure 2 we can appreciate the difference between the two cross section fits for D injections at LHD energies. At typical LHD temperatures the resulting difference is ~10% at low density, up to more than 30% at high density.

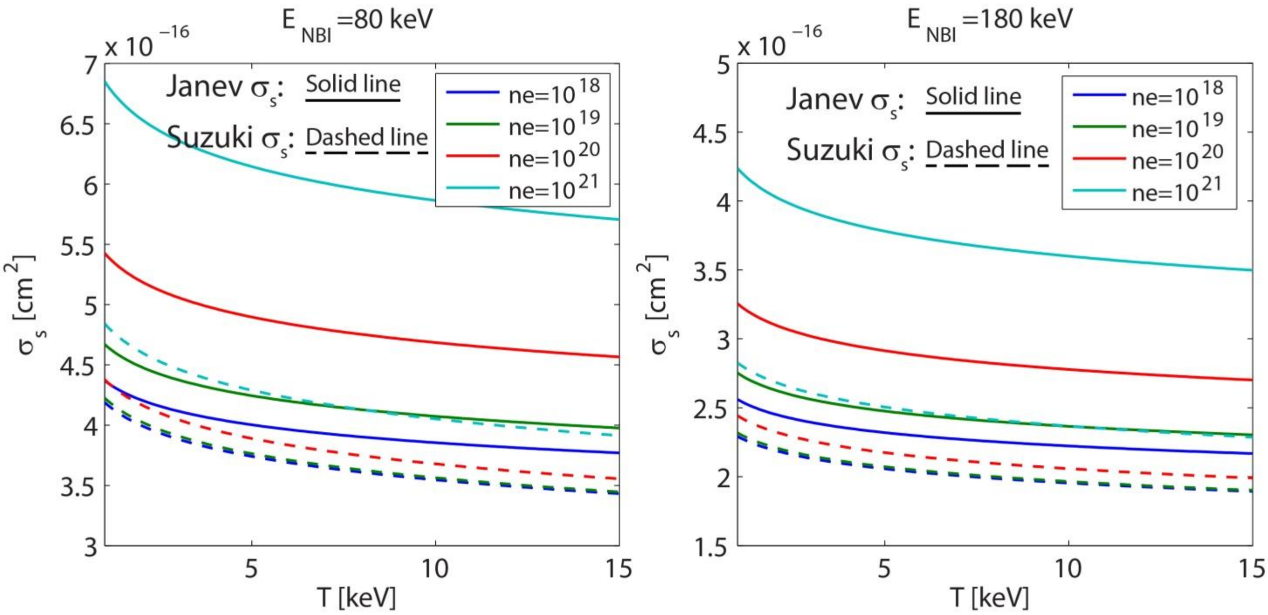

Figure 2. Comparison of Janev (solid line) and Suzuki (dashed line) ionization cross sections for D plasma with D NBI, for two different LHD NB energies at different plasma temperature and density values (Z_{eff}=1.5, C as representative impurity).

2.2 Neutron rate and fusion power source estimation for D plasma with D NBIs

For future LHD D operations, neutron production from D-D fusion reactions will be relevant. The estimation of fusion reactions is important also for D operation licencing, in addition to the evaluation of the fusion power source in the plasma.

For these reasons a routine which evaluates the neutron rate and fusion power source produced by D-D fusion reactions both from thermal plasma and from beam-plasma interaction has been implemented. The two branches (with very similar probability) of D-D fusion reactions are:

D + D → p (3.02MeV) + T (1.01 MeV) [reaction 1]

D + D → n (2.45 MeV) + ^{3}He (0.82 MeV) [reaction 2]

The first reaction produces only charged particles which are confined and heat the plasma. The second reaction produces ^{3}He particles which are confined in the plasma and neutrons which are insensitive to the magnetic field and escape the plasma. The sources of fusion products for thermal plasma and beam-plasma D-D reactions are respectively $S_{th} = {}^1\!/_2\, n_D{}^2\langle\sigma v\rangle$ and $S_{b-p} = n_D n_b\langle\sigma v\rangle$, where n_D is deuterium plasma density, n_b is NB fast ion density and $\langle\sigma v\rangle = \iint f_i f_j \sigma \cdot v_{ij} dv_i dv_j$ is the reactivity of reaction 1 or 2.

Reactions happening among thermal plasma ions can be easily treated by the reactivity <σv> formula given by Bosch [19]. A relevant source of fusion reactions is then the interaction of NBI and plasma. In this case the integral for <σv> has to be directly calculated taking into account both plasma and beam particle velocity distribution function. The D-D fusion cross section is again taken from Bosch's work [19]. The velocity distribution function of fast ions has been obtained from Rome [20], considering the following approximations. In order to simplify the reactivity integral calculation, we decided to neglect the anisotropy in the velocity distribution function and to consider only stationary solutions, leading to an approximation depending only on particle velocity, which, in case of negligible density of background neutrals, becomes:

$$f(v) = \frac{\tau_S}{4\pi(v^3 + v_c^3)} U(v_0 - v)$$

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 e.g. [21] for definition of critical energy E_c). A Maxwellian distribution function is considered in the reactivity calculation for the (isotropic) background plasma. This model is based on a another version of FIT3D code named "FIT3D_DD" used in e.g. [16] to evaluate D-D fusion sources, but not integrated in TASK3D-a code and therefore not usable for routine analyses. In FIT3D_DD code, fusion reactions are calculated using an older formula for fusion cross section σ_{DD} proposed by Duane [22], which, according to Bosch [19], gives a less accurate extrapolation for low reactant energies.

An example of the application of the presented fusion reaction model is shown in figure 3 where the neutron source is evaluated using arbitrary but plausible density and temperature profiles for LHD: a centrally flat density profile with $n_{D,0}=3*10^{19}$ m^{-3} and a parabolic temperature profile with $T_{D,0}$=1keV. Figure 3b shows the neutron source due to the NBI line “Co2” (180keV, 4.4MW).

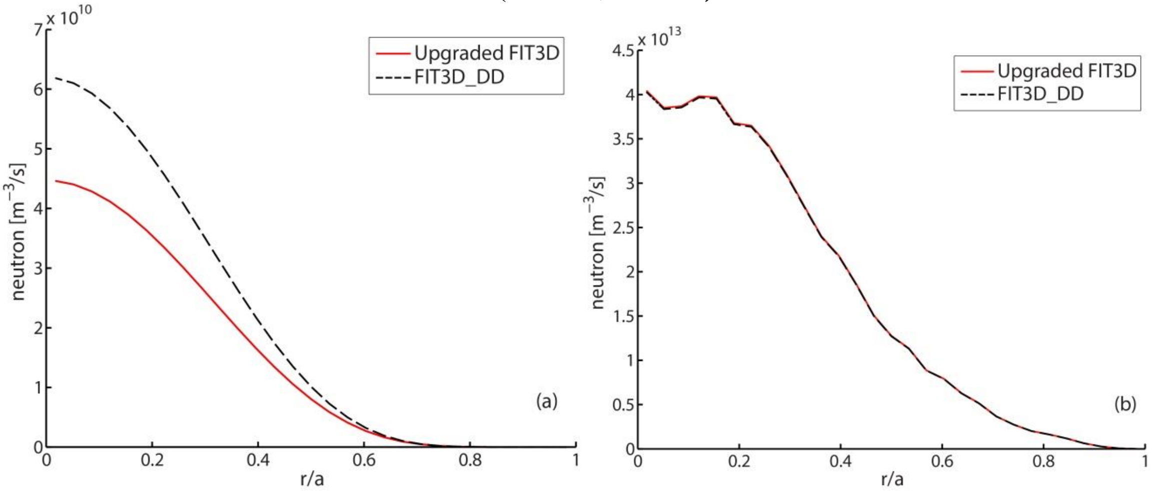

Figure 3. Neutrons from D-D thermal plasma (a) and beam-plasma (b) reactions, the latter for NBI line Co2 (E_{NBI}=180keV, 4.4 MW) with arbitrary input density ($n_{D,0}=3*10^{19}$ m^{-3}) and temperature profiles ($T_{D,0}$=1keV).

It can be observed that, given the arbitrary but realistic input profiles, the neutron source from beam-plasma interaction is considerably larger than thermal plasma reactions. The results are here compared to FIT3D_DD outcomes: for thermal plasma reactions the difference is relevant and can be attributed to the method used for the calculation: in FIT3D_DD the reactivity integral is in fact directly evaluated using Duane’s fusion cross section formula, while in the upgraded FIT3D we implemented the parametric formula for $<\sigma v>$ by Bosch, exempting the code to compute directly the integral. For beam-plasma reaction, the results are similar since in both codes the reactivity integral is directly calculated with the only difference of the fusion cross section formulas used, which, given the input parameters, do not differ considerably. The difference between the two codes in neutron production for beam-plasma interaction is in the order of 10^{11} m^{-3}/s and therefore not visible in the figure 3b.

3. Analysis of NBI-plasma interaction in identical H/He experiments in view of D operations

In order to prepare the D campaign in LHD, studies with the aim of predicting the LHD isotope effect are underway. In the past, in TEXT and ASDEX tokamaks, experiments were performed using helium plasma to clarify the origin of the isotope effect, since He discharges showed similar behaviours to D plasmas [23] [24]. For this reason, in the recent 18th LHD experimental campaign, similar experiments with different concentrations of H and He were executed and better ion confinement with He majority was observed [25]. In particular an increased ion temperature characterized He majority plasmas with unaffected electron temperature and density profiles. Investigations started to understand the cause of this behaviour, and an important point was to understand if the NB heat deposition (the dominant auxiliary heating) was directly contributing to the observed increased ion temperature in He majority plasma. The upgraded FIT3D code has been used to evaluate the NB power deposition of the 4 similar H/He shots (128665, 128670, 128708, 128717) at time 4.74s, when stationary conditions were reached in the discharges. The upgraded NBI code allows an accurate analysis given the newly implemented beam ionization cross section suitable also for He majority plasmas [18]. The analysed shots are characterized by similar n_e and T_e profiles, while higher T_i has been observed with He majority. Fit of experimental data are shown in figure 4.

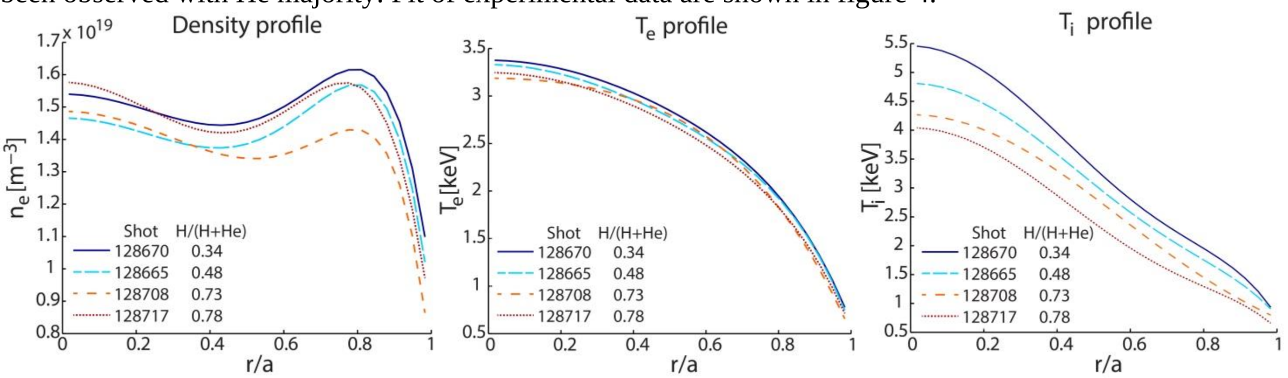

Figure 4. Experimental n_e, T_e and T_i profiles for similarity shots with different H/(H+He) concentrations.

Values of $n_H/(n_H+n_{He})$ (from now on called H/(H+He)) are reported in figure 4 for each shot. The measurement of H/(H+He) is deduced from spectroscopic measurements at the plasma periphery, and then assumed uniform in the whole plasma. Details on H/(H+He) measurement method can be found in [26]. The central ion temperature increases of more than 30% moving from 22% to 66% of He concentration.

In the 4 analysed shots the energy of each NB line is almost equal, while NB power is not exactly identical, especially for shot 128665 where NB line ”ctr3” is switched off, although the total NB power is similar in each shot. Figure 5 shows the NB energy and power for each line in the 4 shots. The total injected power for shots 128665, 128670, 128708 and 128717 is respectively 21.7, 22.3, 24.0 and 23.8 MW (the average total NB power in the 4 shots results $<P_{NBI}>$=22.95±1.13MW).

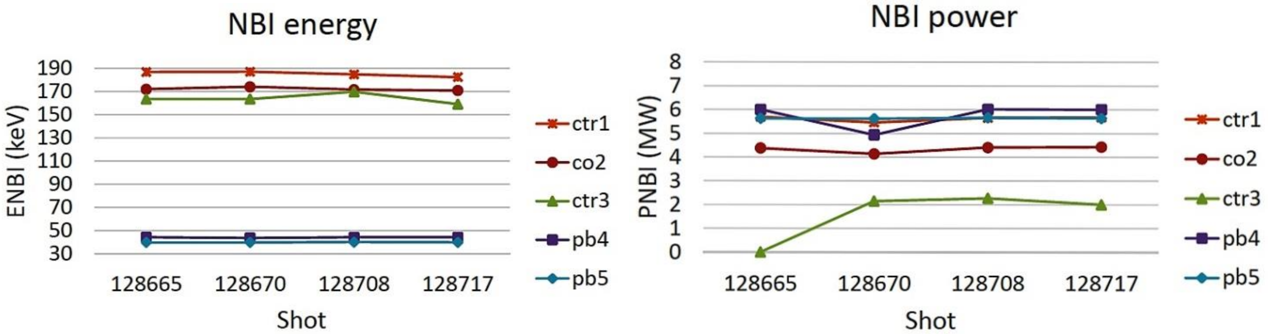

Figure 5. NB energy and power for each line in the 4 analysed shots at time 4.74s.

For the analysis we considered Z_{eff} values calculated assuming only H and He as plasma species, since the estimated concentration of other species was negligible. The resulting Z_{eff} values at time 4.74s are 1.80, 1.68, 1.43 and 1.36 for shots 128670, 128665, 128708 and 128717 respectively.

The upgraded FIT3D code has been used stand-alone to analyse NBI-plasma interaction at time 4.74s, in steady state approximation, which means considering the injection of fast particles at time 4.74s and letting the fast ion thermalize. Inputs for the code are density and electron temperature profiles and NB energy and power shown in figure 4 and 5.

The first result regards the ion birth profile which appears to be unaffected by the different plasma composition for each beam line. Beam ionization cross section indeed only slightly depends on plasma composition (see e.g. [18]). This finding confirms also the NBI-plasma interaction analysis carried out for ideal LHD plasmas with different impurities in [27]: it resulted that for H/He plasmas with a Z_{eff} change similar to the case analysed here the difference in the volume integrated ion birth rate was very little (<10%).

Fast ions are then followed by the code until the thermalization, yielding to the power deposition profile shown in figure 6, where the power densities from all the beam lines have been summed.

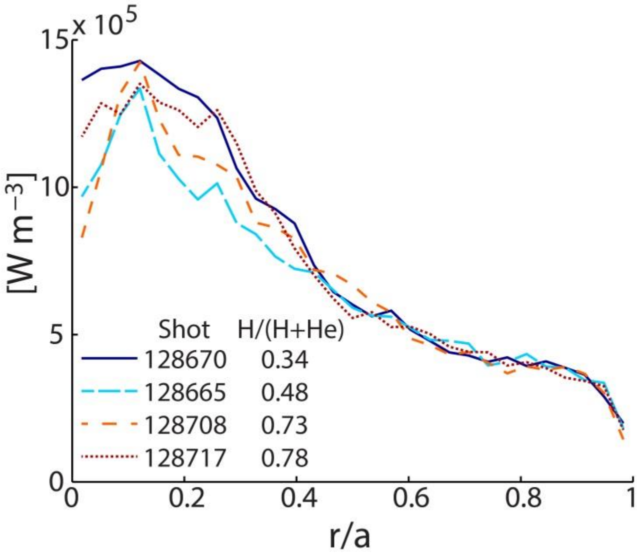

Figure 6. Total NB power deposition from all NB lines in the 4 analysed shots at time 4.74s.

The NB power density results similar for all 4 shots both summing the contribution from all the NB lines (as shown in figure 6) and for each beam line (not shown here). This means that in the 4 analysed shots there are no relevant differences in the power deposition from NBI, regardless the H/He concentration. It is important to remember that the NB power injected at time 4.74s is a bit different among the 4 shots, as reported above. This fact might complicate any conclusion on general trends with different plasma composition, but certainly indicates that no clear differences on NB heat deposition have been observed in these LHD shots.
There are anyway hints of a better fast ion confinement with He plasmas, although they do not to influence the final power deposition. The computation of the slowing down time of fast ions (as indicated e.g. in [28]), results in a longer fast ion confinement (of ~10%) in He majority plasmas for all the beam lines. The volume integrated NB power coupled to the plasma has been computed, and it has been normalized to the injected power. The resulting normalized absorbed power is plotted in figure 7 summing on all the NB lines. In this way the effect of the different injected NB power in the 4 shots is cancelled out.

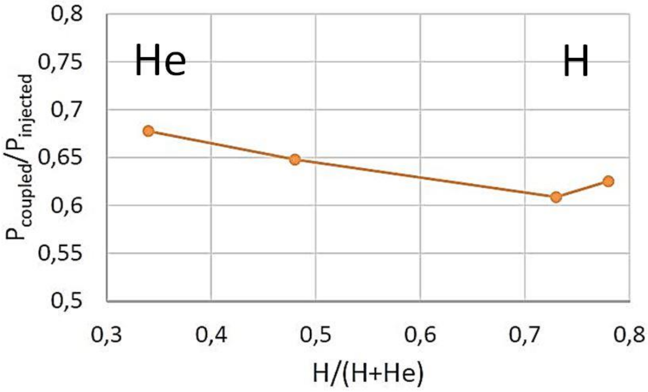

Figure 7. Integrated NB power coupled to plasma and normalized to the injected NB power. Sum of the contribution of all NB lines.

We can observe a ~10% increase of the normalized NB absorbed power going from H to He majority plasmas. It is possible to conclude that although some clues of better fast ion confinement and NB power absorption with He majority plasmas, the power deposition does not change significantly in the 4 shots analysed. The higher ion temperature with He plasmas is therefore not due to a different heat deposition from NBI.

5. Conclusions

The preparation of the first LHD deuterium campaign is ongoing and includes the review and upgrade of numerical modelling tools in order to prepare the D experiment analyses. The NBI-plasma interaction code FIT3D, part of the interpretative LHD transport analysis suite TASK3D-a, has been reviewed and upgraded in order to allow the analysis of D injection in D plasmas with multi-impurities. The upgraded FIT3D code employs an accurate beam stopping cross section suitable for D operations at typical LHD NB energies. Moreover a routine has been implemented to estimate the neutron and fusion power production from D-D reactions, both from thermal plasma and beam-plasma interaction. Beam-beam fusion reactions are at the moment not included in FIT3D, and studies on this topic are underway. These modifications allow a correct and complete modelling of D NBI in D plasmas.
The prediction of D plasma performance is a hot topic at LHD and due to the expected similar behaviour of He and D plasmas, identical H/He discharges have been run in the last experimental campaign to extrapolate D plasma performance predictions. An increased ion temperature has been observed in He majority plasmas and studies have been undertaken to understand the reason of this effect. The upgraded FIT3D is capable to analyse also He plasmas, and it has been used to investigate the role of NBI in the observed ion temperature increase. From the analysis presented, the power deposition profile is almost unaffected by the plasma composition change, although some hints on better fast ion confinement have been observed. This result is important also in view of the future D campaigns: if the heating power deposition is unaffected, the better ion confinement has to be likely attributed to intrinsic plasma transport properties. Following these results, a hypothesis to explain this effect has been proposed in [29]: the better plasma performance seems not to be due to the change of heat deposition and neoclassical transport, but it seems due to a different turbulent transport. A modified turbulent transport code tuned on these H/He experiments have then been used to

predict the performances expected in D LHD experiments [30] showing an expected increase of ion temperature of more than 20% in D plasmas with respect to H plasmas.

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