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ABSTRACT

Accurate simulations of Neutral Beam Injection (NBI) in tokamak plasmas are vitally important for the analysis of present experiments since NBI is a main heating and current drive tool used in many tokamaks. Different numerical techniques including Monte-Carlo (MC) simulations of beam particles and the solution of the Fokker-Planck (FP) equation for the beam particle distribution function are used in different codes. Although the full two-dimensional MC simulations include detailed particle physics, they are computationally expensive while the procedure based on the solution of 1D FP equation is fast and frequently used in transport codes for the modelling of tokamak scenarios. Here the NBI modules based on the MC technique (NUBEAM module [1] routinely used in TRANSP code [2]) and FP technique (NBI module [3] originally included in ASTRA code [4]) are compared for a number of JET discharges with different confinement properties.

1. EXPERIMENTAL SCENARIOS AND PLASMA MODEL

The JET discharges selected for analysis (Table I) include deuterium H-mode plasmas performed at different density and q_{95}, a hybrid scenario (HS), discharge with sustained Internal Transport Barrier (ITB) and reversed q-profile and an equilibrium configuration with current hole (CH) where an ITB was also produced. The H-mode plasmas performed in a broad density range have been chosen to test the cases of central (low density) and off-axis (high density) beam deposition. As a consequence, these plasmas are characterised also by a very different fractions of trapped beam particles. The NBI simulations (tangential deuterium beams are applied to these plasmas) are performed during 1.5-2s of the stationary phase for H-mode plasmas and the ITB discharge, while the simulation time is reduced to 1s of a nearly stationary phase for the CH shot since the strong reversed shear configuration was transient.

The 1.5D transport code ASTRA is used for these simulations. For adequate comparison of two modules (using the same equilibrium and plasma profiles) the NUBEAM package, extracted recently from the TRANSP code [1] and included in the NTCC module library (http://w3.pppl.gov/NTCC) has been implemented in the ASTRA code. The NBI simulations of JET discharges are performed with experimental temperatures, electron density, toroidal rotation and effective charge profiles. The current density profile is taken from TRANSP simulations where the current diffusion equation is solved with the neoclassical conductivity and bootstrap current from NCLASS. The NUBEAM module takes into account the ambipolar radial electric field, which is also calculated by TRANSP. The concentration of neutral atoms is an input parameter for the NBI package while the NUBEAM uses the neutral data from NTCC FRANTIC module used in also in TRANSP. The plasma equilibrium is simulated in the ASTRA code with the beam driven current and fast ion pressure from the NBI module. With these assumptions both modules are simulated simultaneously in the same ASTRA run so that they use the same equilibrium and plasma profiles as input.

The physics included in the NBI and NUBEAM packages describing the penetration of neutral beams, the beam-plasma interaction and beam particle losses is described elsewhere [1] and will not be repeated here. The list of assumptions used in both codes is also summarised in Ref.1.

2. SIMULATION RESULTS

The compared parameters are the NBI power absorbed by electrons (P_{BE}) and ions (P_{BI}), total absorbed power (P_{BE} +P_{BI}), total number of the fast ions in the plasma (N_{FST}), and rotation torque (T). The global values of the above quantities are compared in Table II and Fig.1 and the profiles for some of them illustrating typical cases are shown in Figs.2 - 4. The simulations show that the NUBEAM and NBI modules agree quite well for total heating power and fast particles number (within 7%) at low q_{95} ($q_{95} \leq 4.1$) (Table II). Profiles of the past particle density and absorbed power for such scenarios is also in a good agreement meanwhile the power fraction absorbed by ions is systematically higher (up to 16%) and fraction absorbed by electrons is systematically lower in the NBI module of ASTRA than in NUBEAM. It means that NUBEAM systematically obtains lower ion heating and higher electron heating in comparison with the analytical solution of the FP equation [5] used for the energy fractions calculations in the stationary NBI solver of ASTRA.

Two ITB scenarios and the discharge with $q_{95} = 9$ have much a larger discrepancy for NFST and total absorbed power than other analysed shots. Both electron and ion heating obtained with the NBI module are larger in these discharges (open symbols in Fig.1) and this difference comes mainly from the gradient region ($0.3 < r/a < 0.6$) (Fig.4). One of the possible reasons of this discrepancy is a scattering to the loss cone during the fast ion slowing down included in NUBEAM that allows a more accurate estimation of orbit losses. These losses are expected to be particularly strong in two ITB discharges with reversed q-profile and in discharge with $q_{95} = 9$ (q-profiles for different discharges are shown in Fig.5). In the ASTRA NBI time independent FP solver used here takes into account only first orbit analysis.

The beam torque is always underestimated with the NBI module as compared to NUBEAM and the difference between them reaches 25% at high density. The reasons for this discrepancy are under the study.

SUMMARY

The NBI parameters estimated with the NBI and NUBEAM modules have been compared for a number of JET discharges performed in a broad parametric domain. It was found that the agreement between two modules in beam density and heating power is quite satisfactory for typical JET H-mode plasmas ($n_l = (2.3\text{-}9.5)10^{19}$ m^{-3}, $q_{95} \sim 3\text{-}4$). The agreement is worse for low current and ITB plasmas where orbit losses become more important.

Finally it should be mentioned that the implementation of the NUBEAM module in the ASTRA code is an important enhancement of this code since this module opens the possibility of treating the fusion product ions and neutrons self-consistently in predictive simulations of present and “next-step” tokamaks.

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Table I: Parameters of selected JET discharges.

Pulse No	regime	Ipl, MA / Bt, T	q^{95}	$n_l*10^{19}m^{-3}$
61132	H-mode	2.35 / 1.9	2.8	2.35
61543	H-mode	1.7 / 1.5	3.75	4.4
61430	H-mode	3 / 2.5	2.82	9.5
62213	H-mode	4 / 3.14	2.72	9.2
61236	H-mode	1 / 3	9	2.35
60931	HS	1.4 / 1.7	4.1	3.4
58179	ITB	1.8 / 3	5.5 - 6	2.3
61346	CH	3 / 3.2	3	2.5

Table II: Agreement for global NBI parameters, $\Delta_X=<(X_{NBI}-X_{NUBEAM})/X_{NUBEAM}>$ (here X is the integral over the plasma volume $0.1\le r/a\le 0.9$ for sources, torque and total number of fast ions and over the whole volume for total absorbed power. Time averaging over 0.5-1s is applied to each quantity and the error bars are estimated as a maximum deviation from the mean value.

Pulse No	Δ_{NFST}, %	Δ_{PBI}, %	Δ_{PBE}, %	$\Delta_{PBE+PBI}$, %	Δ_T, %
61132	7.4±2.8	15.7±3.4	−5.9±3.4	6.3±3.2	−9.7±34
61543	3.5±2	6±3.2	−8.7±2.3	1.7±2.3	−20.7±9
61430	−0.24±2	4.6±2	−15±2	−4.3±2	−25±3.7
62213	−1.4±1.5	3.2±1.5	−12.4±2	−2.5±1.2	−25±6.2
61236	15±2.6	20±5.8	12.8±7.3	18±4.6	−3.9±24
60931*	1.7±3	7.2±4.6	−10±3.2	1.8±3.5	−10.9±12
	5.4±2.1	7.3±3.4	−6.3±3.8	3.4±3.7	−16 ±12
58179	11.6±13	17±18	14±13.8	15.8±16	−4±33
61346	17.3±4.5	18±6	11.5±6.8	18.3±5.7	−16.4±18

**Two sets of data are obtained during the low (P_{nbi}= 9MW) and high (P_{nbi}= 17.7MW) heating power plateau correspondingly.*

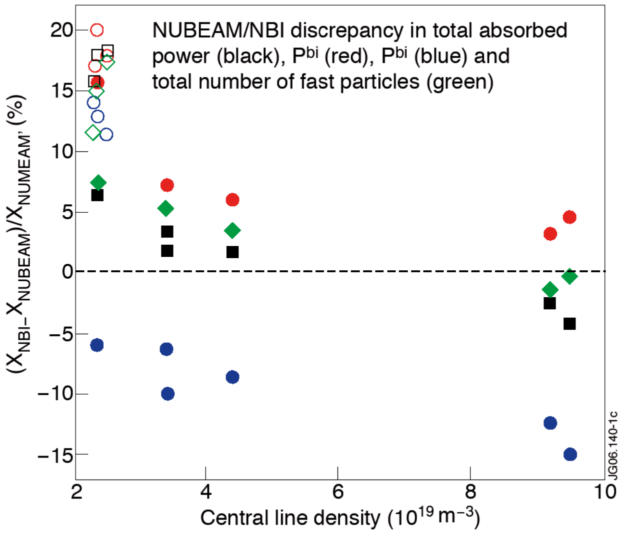

Figure 1: Difference between NBI and NUBEAM modules in total absorbed power, power absorbed by electrons and bulk ions and the number of fast particles (columns 1-4 in Table II). The results obtained for H-mode plasmas with low q_{95} and HS are shown by closed symbols, open symbols show the results for pulses 61236, 58179 and 61346.

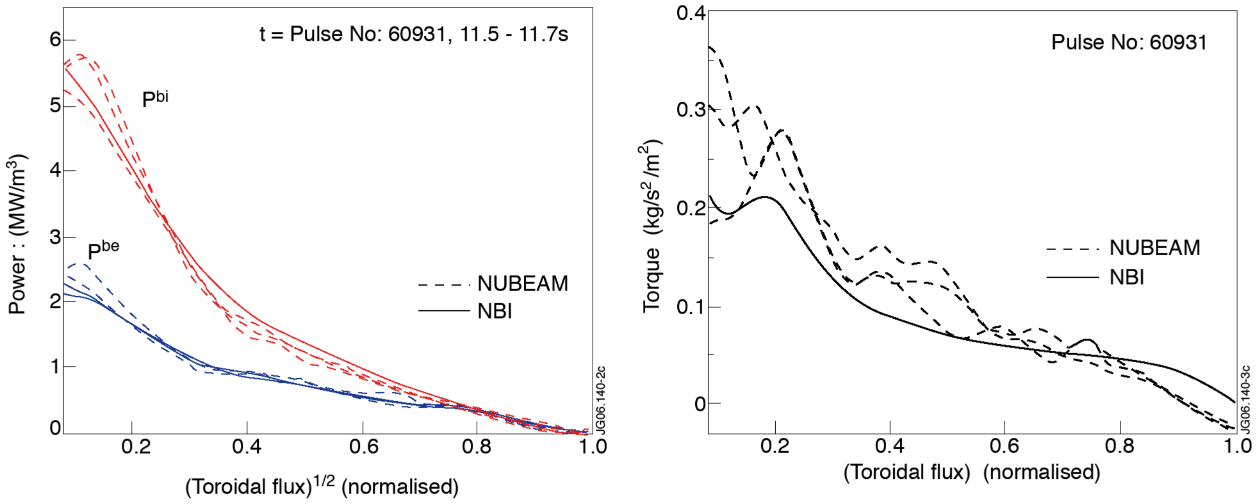

Figure 2: NBI power absorbed by electrons and ions, torque, electron source and the source of thermal (CX) neutrals simulated with NBI (solid) and NUBEAM (dashed) modules for pulse 60931. The profiles are taken with the time interval 0.1s.

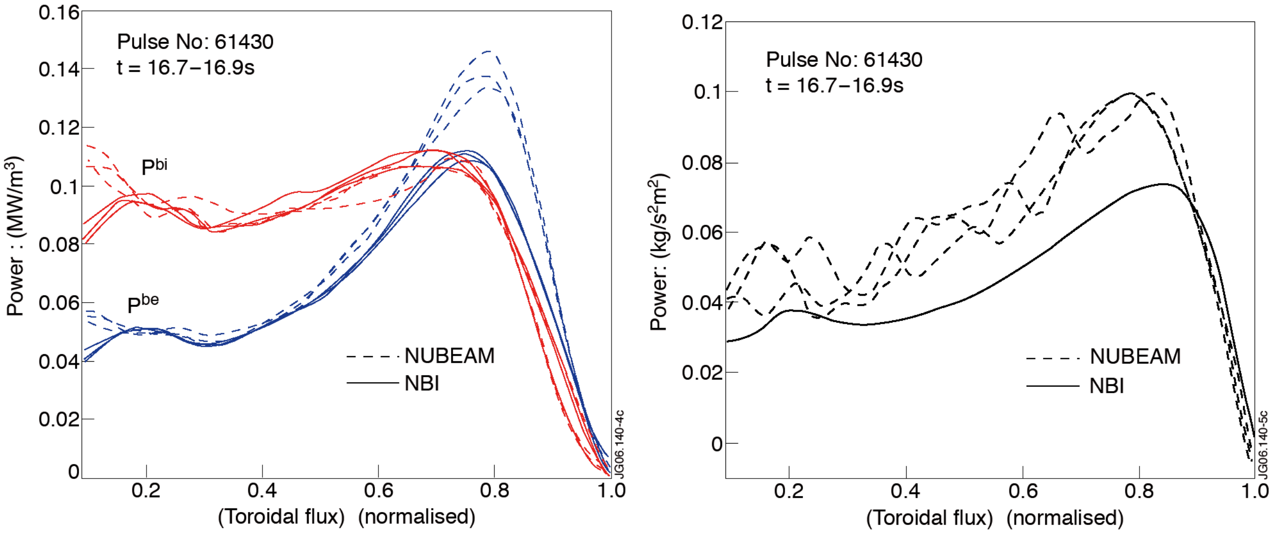

Figure 3: NBI power absorbed by electrons and ions, torque, electron source and source of thermal (CX) neutrals simulated with NBI (solid) and NUBEAM (dashed) modules for Pulse No: 61430. The profiles are taken with the time interval 0.1s.

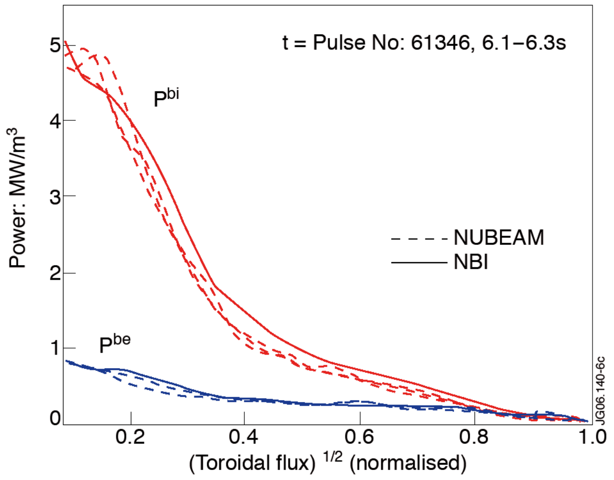

Figure 4: NBI power absorbed by electrons and ions in reversed shear pulse with ITB simulated with NBI (solid) and NUBEAM (dashed) modules. The profiles are taken with the time interval 0.1s.

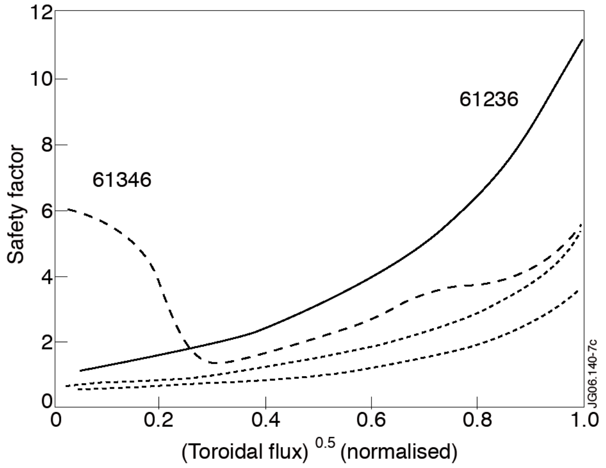

Figure 5: Safety factor profiles for CH pulse (61346, MSE measurements) and high q_{95} H-mode plasma (61236, TRANSP simulations). The q-profiles for other H-mode shots obtained in TRANSP simulations lie within the region shown by dotted curves.