A neutral beam injection source for the TORIC/SSFPQL package

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Introduction

The iteration loop between the ion-cyclotron (IC) full–wave TORIC code and the surface-averaged kinetic Fokker-Planck (FP) SSFPQL solver has been implemented to simulate the close interplay between IC generated fast-ion tails and IC wave propagation and absorption [1]. In many fusion devices an important high-energy ion population can be generated and sustained by neutral beam injection (NBI). Synergetic effects can be expected when simultaneously applying NBI and IC heating. To address these effects, a NBI source and a fast particle loss term have been recently added to SSFPQL [4].

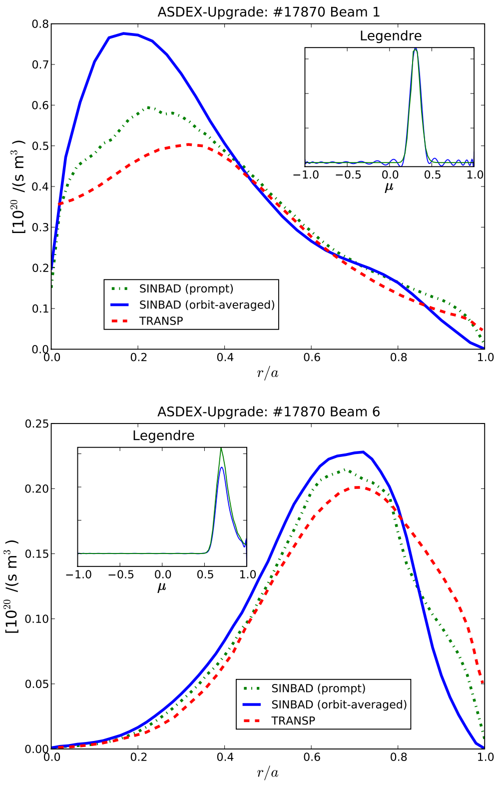

Figure 1: Deposition profiles calculated with SINBAD for a radial (A) and a tangential (B) sources. The inset shows the Legendre polynomial reconstruction used in SSFPQL.

In a first step the NBI source for SSFPQL has been obtained from the Monte Carlo code (MC) FAFNER [2]. The MC approach is very detailed in describing the particle trajectories but very noisy: SSFPQL needs a smooth source with more angular information. The NBI deposition profiles can be accurately calculated also with a beam model, which is faster and is not affected by the statistical noise typical of MC codes. To exploit this advantage, the beam-model routine SINBAD [3] has now been interfaced with SSFPQL.

Interface with SINBAD

SINBAD is a fast beam deposition routine based on a simplified but nevertheless rather accurate "narrow" beam model. The main simplification consists in assuming "pointsize"sources, as justified by the distance between sources and plasma boundary, much longer than the source width. Nevertheless, SINBAD takes into account important beam geometry features, such as beam divergence and focusing, relevant in the plasma core where the plasma section is comparable with the beam width. SINBAD determines the NBI deposition profiles as functions of the pitch angle $\mu_v = v_{\parallel}/v$ (here parallel and perpendicular refer to the direction of the local confining magnetic field), and performs the expansion of the deposition profiles in Legendre polynomials of μ_v. The coefficients of this expansion are transferred to SSFPQL and used to build the NBI source in the Fokker-Planck equation [4]. Optionally, SINBAD averages the initial deposition profile along the first guiding-center drift orbit of each newborn ion. In this way orbit broadening effects and prompt losses are taken into account. When used as source in the FP equation, the beam deposition profiles should not be orbit-averaged. In the case of a surface-averaged FP solver like SSFPQL, however, averaging over the first orbit can be regarded as a rough approximation for finite banana-width effects in the beam source. In converting SINBAD to a Fortran 90 module for TORIC-SSFPQL package, we have extended it to take into account standard numerical tokamak equilibria as those used in TORIC. In addition, the orbit-average routine has been rewritten from scratch to integrate the Morozov-Solov'ev equation for the same numerical equilibrium [5].

Figure (1) shows the deposition profiles for the radial source 1 (60 keV, frame A) and the tangential source 6 (93 keV, frame B) calculated with SINBAD for an ASDEX-Upgrade like plasma (reference discharge is # 17870 with only Deuterium, central $T_e \approx 4$ keV, $n_e \approx 8 \times 10^{19}\mathrm{m}^{-3}$, $B \approx 2$ T and 2.5 MW of NBI at only full energy). For comparison Fig. (1) also shows the deposition profile calculated with the TRANSP code. The agreement is good in the outer part of the plasma, but somewhat less in the plasma core. Moreover, in comparison with TRANSP results, the shining through radiation predicted by SSFPQL is lower for beam 1 and higher for beam 6. This can be explained in terms of the different stopping rate coefficients used in the two codes (as shown in figure (2.5) of [6]), and will be investigated further in the future. When weighted with the specific volume, however, the agreement in the outer plasma region matters much more than in the plasma core. In both cases of Fig. (1) the neutral beam was injected in the direction of the toroidal magnetic field: the newborn ions drift towards the plasma inner side and the drift is larger for trapped ions. As a consequence, the orbit-averaged profiles show

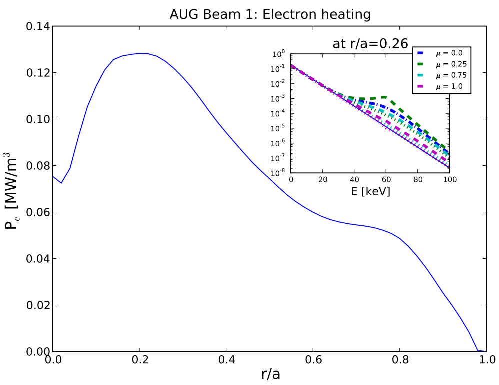

Figure 2: Power collisionally transferred from NBI fast ions to electrons calculated by SSFPQL. The inset shows the Deuterium distribution function at the maximum of the NBI deposition and for different values of μ_v. Dashed and dotted lines refer to positive and negative values of μ_v.

a depletion in the peripherical region in favour of a central peaking, more visible in the case of source 1, which is oriented more radially. In the case of counter-injection the orbit-averaged profiles are lower along the whole radial profile because of higher prompt losses. When used as source in SSFPQL, SINBAD predicts about one fourth of the total NBI power is absorbed by electrons, with the deposition profiles shown in figure (2). In this case $E_{\rm crit} \approx 18\ T_{e[\rm keV]}$; this favours electron heating in the cooler plasma periphery.

The inset of figure (2) shows the distribution function calculated with SSFPQL at the maximum of the ionization profile. The effects of NBI are visible around the injection energy 60 keV, particularly for low μ_v since the orientation of beam 1 is almost radial. When fast ions are reactant of nuclear reaction with neutron yield, such as Deuterium, the extent of fast-ion tail can be estimated from the neutron rate. The neutron rate predicted with SSFPQL for this case is about 1.5×10^{15} neutrons/sec in good agreement with 1.55×10^{15} calculated with TRANSP code.

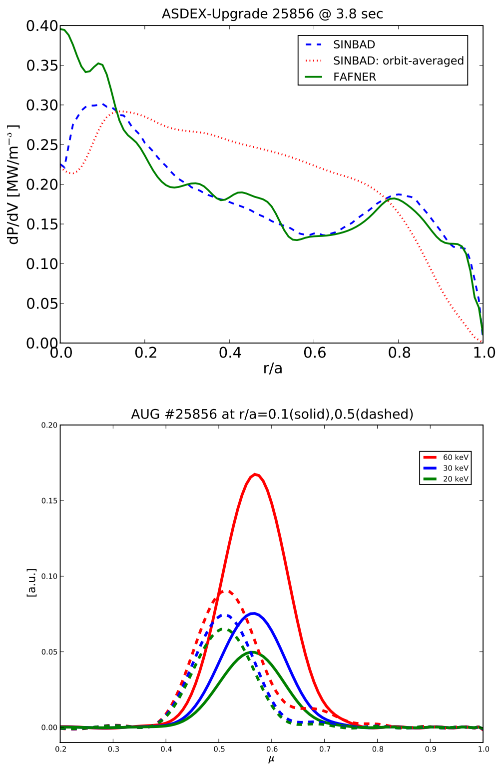

Figure 3: (A) Power deposition density profiles of NBI source 3 calculated with SINBAD and FAFNER codes. (B) Corresponding distribution in pitch angle for two radial points calculated with SINBAD.

ICRF-NBI synergy

Simultaneous application of NBI and IC heating can produce high-energy ion tails. In particular, ion heating at IC harmonics is a finite Larmor radius (FLR) effect, and, therefore, preferentially accelerates ions with large perpendicular energy, $k_\perp \rho_i \gtrsim 1$ with $k_\perp$ the perpendicular wave number and $\rho_i = v_\perp/\Omega_{\rm ci}$ the particle Larmor radius. The recent extension of SSFPQL to include a NBI source [4] allows us to take into account the effects NBI fast-ion tails in the wave propagation and absorption calculated with TORIC [1]. We apply this tool to ASDEX-Upgrade discharge 25856, for which the experimental neutron rate is available. We have analyzed the time around 3.8 sec where the plasma is characterized by a central electron temperature $T_{e0} = 2.7\,\rm keV$, density $n_{e0} = 6.8 \times 10^{13}\,\rm cm^{-3}$, confining magnetic field $B_0 = 2.6\,\rm T$ and 5% of Hydrogen in Deuterium plasma. The source 3 of NBI system was delivering 2.5 MW at 60 keV, with contributions at 1/2 and 1/3 of the full energy, carrying respectively 36% and 16.7 % of the total power. The

ICRF system was delivering a nominal 4.2 MW power at 36.5 GHz frequency, corresponding to on-axis Hydrogen fundamental heating. Figure (3.A) shows the deposition density profiles calculated with FAFNER and with SINBAD. Although they differ considerably close to the plasma axis, the difference is negligible in the global balance. Much more noticeable is the difference between orbit and not orbit averaged profiles, as already discussed. Figure (3.B) shows the μ_v–dependence of the ionization rate at $r/a = 0.1, 0.5$, calculated by SINBAD. Because of the noise of MC codes, when using FAFNER the coefficients of the expansion of NBI sources in Legendre polynomials are obtained on each magnetic surface by performing a minimum square error fitting assuming a Gaussian distribution in μ_v [4]. This excludes the possibility of describing asymmetries in the pitch-angle profiles, which are present in the μ_v-distributions calculated with SINBAD (e.g. dashed lines in fig. (3.B)). Table 1 summarizes the global results of SSFPQL with only NBI power, calculated with FAFNER, and with SINBAD with and without orbit-average. Only the results obtained with the bounce-averaged input from SINBAD differ slightly from the others. The experimental neutron rate is 3.5×10^{14} /sec, higher than that calculated with only NBI source 1.3×10^{14} /sec. When 4 MW of ICRF is considered, the predicted neutron rate, 1.7×10^{15} /sec , exceeds by far the experimental value. The reduction of synergetic effects is likely to be due to diffusive losses of fast ions during thermalization. To reproduce the experimental neutron rate the power lost by fast Deuterium ions is estimated by SSFPQL to be about 0.55 MW.

NBI source	N rate $[10^{14}]$	P_e [%]	P_D [%]	P_H [%]
FAFNER	1.35	53	43	4
SINBAD	1.34	53	43	4
SINBAD (OA)	1.58	47	48	5

Table 1: Global results of SSFPQL with only NBI source.

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