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ABSTRACT

Existing tokamaks such as DIII-D and future experiments like ITER employ both NB injection (NBI) and ion-cyclotron resonance heating (ICRH) for auxiliary heating and current drive. The presence of energetic particles produced by NBI can result in absorption of the Ion cyclotron radio frequency (ICRF) power. ICRF can also interact with the energetic beam ions to alter the characteristics of NBI momentum deposition and resultant impact on current drive and plasma rotation. To study the synergism between NBI and ICRF, a simple physical model for the slowing-down of NB injected fast ions is implemented in a Monte-Carlo rf orbit code. This paper presents the first results. The velocity space distributions of energetic ions generated by ICRF and NBI are calculated and compared. The change in mechanical momentum of the beam and an estimate of its impact on the NB-driven current are presented and compared with ONETWO simulation results.

MODELING OF STEADY-STATE SLOWING DOWN OF NB INJECTED FAST IONS

Assuming that the injected neutral particles are all ionized by the background plasma in the equatorial plane, Z=0 ($\vec{v} \bullet \theta_p = 0$), an initial source rate of fast ions generated due to NB injection, $S(E_b,\ \xi,\ \psi,\ \theta)$, is calculated with the given NB injection power (P_{NB}), beam ion energy (E_b) and tangential radius (R_T) in phase space. Here the pitch of particle is given by $\xi = v_{//} / v = (B_T R_T)/(BR)$ [1]. The weightings of each test particle (fast ions), W_k (k=1,n: n is a total number of test particles), is calculated using the relation, $W_k = S \times t / n$, in order to represent the real number of fast ions generated from NB source. These injected energetic ions will lose their energy and momentum to the background plasma ions and electrons through pitch-angle scattering and drag [2], and eventually will be thermalized. To model a steady state slowing-down regime of NB injected fast ions, the thermalized fast ions ($<1.5T_i$) are re-injected into the plasma at the birth energy with a source rate compatible with P_{NB}. The weightings of re-injected fast ions are readjusted to be consistent with the constant input power.

SIMULATION OF ICRH INTERACTION WITH NBI

A D-H plasma is simulated with the plasma and heating parameters shown in Table 1. For the simulation of interaction of minority ions with ICRF wave, the wave zone is set to a wedge model in the poloidal cross section [2]. To relate the electric field magnitude (only left-hand component, E_+, is considered in this work) to the absorbed rf power, $|E_+(r)|^2 = (1 - r^2/a^2)$ is modeled [2]. The background minority H ions are modeled initially as Maxwellian distribution. Fast ions are produced by ICRF minority heating, and are subsequently slowed down by Coulomb collisions. They are then re-injected within their initial phase space to achieve steady state. Concurrently a neutral H beam is injected in tangential direction (on DIII-D, R_T =104 cm). The energy of resultant H ions is assumed to be mono-energetic with a full energy 80 keV (half and third energy ion beams are ignored in this work). Therefore, the ICRF wave will be simultaneously interacting with thermal minority ions from Maxwellian background as well as the energetic tail minority ions from NBI. To model the NB fast ion source properly, two kinds of ions produced by different heating methods are treated as two different groups of Monte Carlo test particles where they are separately coupled with background plasma through the slowing-down collisions and pitch angle scattering. The simulation was followed for a few slowing-down times to reach a steady-state solution. For the preliminary results presented here, typically 1000 test particles were used to represent the background ions (500) and NB injected fast ions (500).

Table 1 Input Parameters for Simulations.

Plasma Parameters		RF Heating	NB Heating
$T_D(0)$ =3.0 keV	$B_t(0)$ = 18.6 kg	P_{RF} = 3 MW	P_{NB} = 8.0 MW
$T_H(0)$ =2.0 keV	a = 50 cm	f_{RF} = 34.5 MHz	E_{NB} = 80 keV
$T_e(0)$ =3.0 keV	R_{maj} = 186 cm	n_ϕ = 7.0	R_T =104 cm
$n_e(0)$ =1.0×10^{14} cm^{-3}	n_H/n_D = 0.04		

Case With ICRF Only Fast Ions. The ICRH alone simulation is first done with the plasma and rf heating parameters in Table 1. With f_{RF} = 34.5 MHz, a fundamental cyclotron resonance surface is located at $(R - R_0)/a \approx$ -0.51 on the high-field side. Figure 1 shows the energetic ion distribution [Fig. 1(b)] evolved from initial Maxwellian distribution [Fig. 1(a)] in velocity space. A strong energetic tails up to 80 keV are seen due to the interaction of resonant background H minority ions with the ICRF wave.

Case With ICRF + NBI. Almost all the injected fast ions have gone through one thermalization within two slowing down times. For the plasma parameters in Table 1, the slowing down time of NB injected H ions is about 70 ms. At this time, a steady state is reached by NB injected fast ions and an energetic tail is formed. The ICRF wave is turned on at the end of two slowing-down times and the simulation continues for one additional slowing down time. Figure 2(a) shows the initial distribution of test minority ions (Maxwellian + mono-energetic) in velocity space. Figure 2(b) shows the energetic ions distribution generated due to the interaction

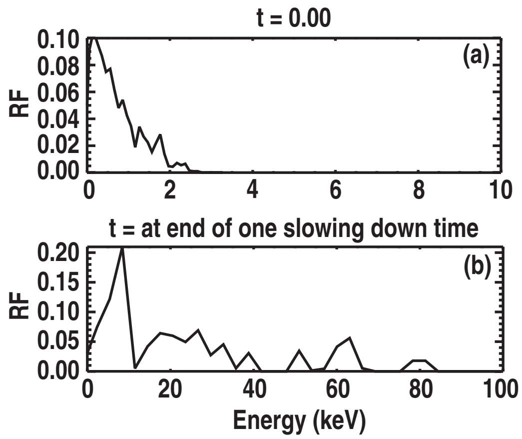

Figure 1. Distribution of energetic ions excited from thermal ions by ICRF.

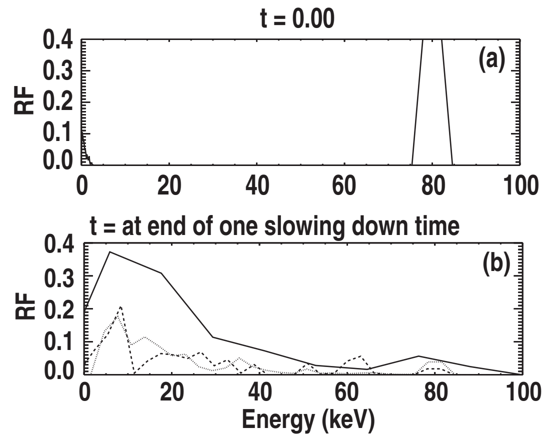

Figure 2. Distribution of energetic ions from NB energetic ions by ICRF.

with ICRF wave (from interactions with both the background and NB injected ions). Due to the resonant heating of NB injected energetic ions with ICRF wave, it is seen that an enhanced tail with energies up to 100 keV are generated (solid line). A slowing down distribution for NBI without ICRF is also plotted [Fig. 2(b) dotted line]. The dashed line is for ICRF only.

THE NET NB ION DRIVEN CURRENT

It is well known [3] that a directed NB with a net momentum can generate a current when the Z_{eff} of the bulk ions is different from the Z of beam ions. To study the impact of ICRF on NB current drive (NBCD), the net current generated by energetic beam ions can be calculated from momentum balance between NB injected fast ions and background electrons. Defining $\Delta M_{f \to \varepsilon} \equiv \sum \Delta$ (momentum transfer from fast ions to electrons), v_f (steady state fast ion mean velocity) is obtained by [4].

$$v_f(\psi) = \frac{\Delta M_{f \to e}(\psi)}{n_f(\psi) m_f} \left[1 + \frac{Z_f^2}{Z_{eff}} \right] \quad . \tag{1}$$

Including the opposite contribution due to electrons and accounting for toroidal trapping effect, the net NB ion driven current can be expressed as [5],

$$J_{net} = J_f + J_i + J_e = e n_f v_f Z_f \times \left\{ 1 - \frac{Z_f}{Z_{eff}} + 1.46 \varepsilon^{\frac{1}{2}} \left(\frac{Z_f}{Z_{eff}} - \frac{Z_{eff}}{Z_f} \frac{m_f}{m_i} \right) A(Z_{eff}) \right\} \quad . \tag{3}$$

where $A(Z_{eff})$ is 1.36 for $Z_{eff} = 2$ [6] and ε is the inverse aspect ratio, $\varepsilon = r / R$. Figure 3(a) shows the net NB ion driven current (A/cm^2) calculated from ORBIT-RF at the end of two slowing down time (before the ICRF wave is turn on). Here the solid line is J_f (A/cm^2) and the dotted line is J_{net} using (1) for v_f. This result is cross-checked using the definition on a flux surface, $v_f(\psi) = \int d^3 v_{//}(\psi) f_f(\bar{v})$ [the dashed line (J_f)]. The two calculations agree qualitatively, however, because of finite size orbits, a larger number of test particles to cover the phase space might be needed to achieve better agreement. In Fig. 3(b), a ONETWO transport code calculation using similar plasma and NB heating parameters is displayed. A reasonable agreement is obtained with the momentum balance approach. For this particular case, the change in NBCD due to the addition of ICRF is insignificant.

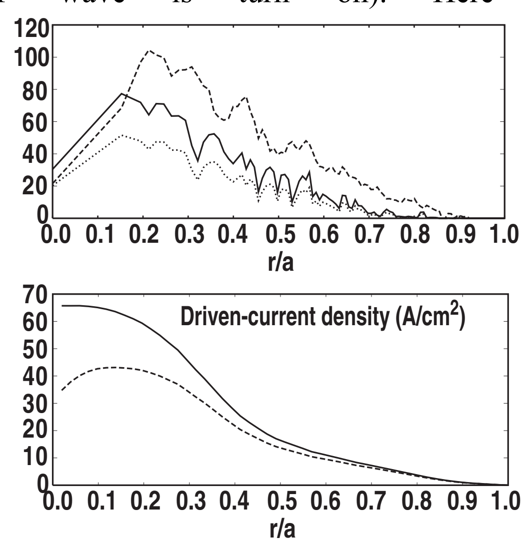

Figure 3. NB ion driven current density from (a) ORBIT-RF [solid and dashed lines, net (dotted)] and (b) ONETWO [solid, net (dashed)] in A/cm^2.

FUTURE WORK

Preliminary results in the modeling of ICRF interaction with NBI appear qualitatively as expected. Since the number of test particles used is relatively too small to achieve satisfactory statistics in these first simulations using a single processor, adaptation of the code to parallel processors will be required to increase the number of test particles for quantitative benchmarking. Further progress will also be made by coupling a full wave solver to ORBIT-RF to describe self-consistent ICRF wave propagation. In addition, the interaction of minority ions with ICRF at higher harmonics is planned in order to model the actual experiments on DIII-D.

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