Modeling of Large Orbit Fast Ion Distribution Evolution with Multiple Frequency Fast Wave Heating

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Synergy Experiments

In recent moderate to high harmonic fast wave (FW) heating and current drive experiments in DIII-D, a synergistic effect was observed in neutral beam (NB) fast ion population when 6th harmonic 90 MHz FW power was applied to the plasma preheated by NBs and 4th harmonic 60 MHz FW. Figure 1 shows time traces of experimental data indicating a synergy during combined 60 MHz and 90 MHz FW heating [1]. In this discharge, NBs inject 1.2 MW (time-averaged) of 80 keV deuterium beams into the plasma. The major radius of the magnetic axis is R_0=1.75 m, the minor radius is a=0.6 m, the toroidal magnetic field is B_0=1.94 T and the beam tangency radius is 1.15 m. Around 4400 ms, 60 MHz FW power (P_{exp} ~ 1.0 MW) is coupled to the plasma preheated by NB alone. After a few hundred ms, 90 MHz FW power (P_{exp} ~ 1.3 MW) is additionally coupled to the plasma [Fig. 1(a)]. Figure 1(c) indicates that the measured neutron emission rate (mostly from beam-plasma reactions) increases by a factor of two during the two-frequency FW heating. This increase is larger than the sum of neutron rates measured individually from separate pulses of 60 MHz and 90 MHz in similar target plasmas [2].

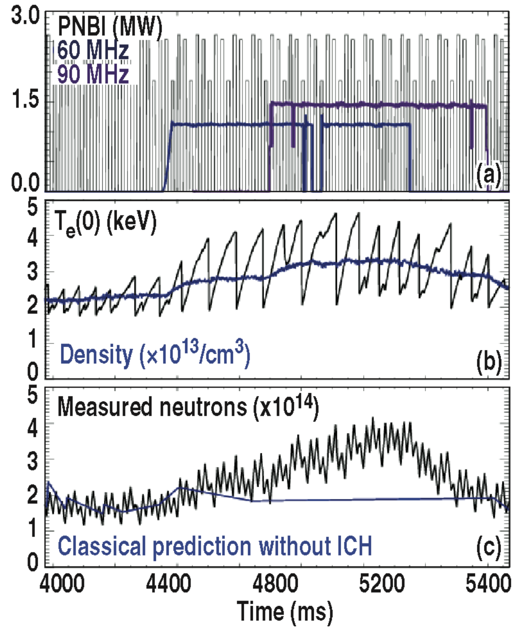

Fig. 1. Synergy experiment indicating increase of neutron emission rate during the two-frequency FWs heating.

In Fig. 2, enhancement of fast ion D_α (FIDA) signals measured at each chord of vertical and tangential FIDA systems [3] is plotted. Here, the enhancement is defined as the ratio of measured FIDA signals between NB+FW and NB alone. Due to statistical constraint for fast ion signals collected with the current FIDA spectroscopy system, the fast ion energy is integrated over wavelengths corresponding to 30~60 keV. Standard background subtraction by beam modulation is performed. Measurements for vertical FIDA signals are performed over 10 ms intervals: (1) for NB + 60 MHz, 4560 ms ≤ t ≤ 4569 ms, (2) for NB + 60 MHz + 90 MHz, 5040 ms ≤ t ≤ 5049 ms. As shown in Fig. 2(b), the statistics on the vertical FIDA signals are poor and the error bars are usually large since the diagnostic uses an integration time of 5 ms. The tangential system uses a 1 ms integration time over the 10 ms interval in which the measurements are performed, so better statistics are obtained. Figure 2(b) shows that the vertical FIDA signals display a significant increase during combined 60 MHz + 90 MHz heating compared to that during 60 MHz heating alone. Whereas, Fig. 1(c) indicates during these measured time periods that measured neutron rates are increased by ~25% for 60 MHz alone and ~50% for 60 MHz + 90 MHz. However, the tangential FIDA signals show insignificant changes. The difference between the vertical and tangential FIDA results is not well understood. It motivates the simulation study described next.

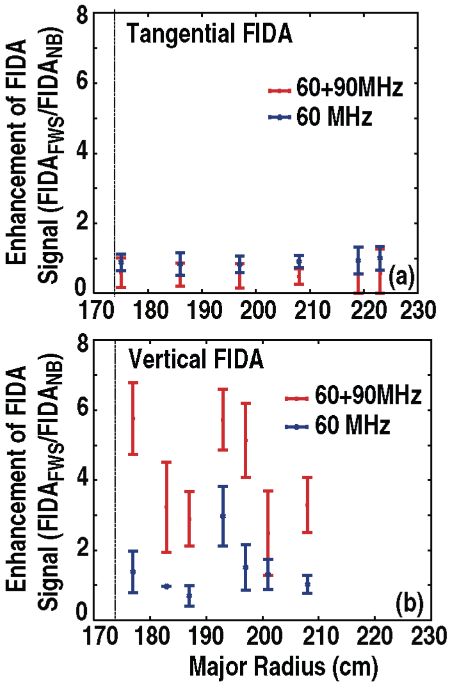

Fig. 2. Enhancement of FIDA signals measured from tangential and vertical chords during the 60 MHz alone and two–frequency FW heating.

Synergy Simulations

The 5-D finite-orbit Monte-Carlo code ORBIT-RF [4] coupled with the 2-D full wave code AORSA [5] is a comprehensive numerical model that can perform a fully self-consistent calculation of the evolution of large orbit fast ions accelerated by either a single frequency FW or multiple frequency FWs. ORBIT-RF computes the distribution of an ensemble of fast ions in velocity and physical space by solving a set of Hamiltonian guiding center equations with Monte-Carlo Coulomb collisions and quasi-linear (QL) diffusive heating. AORSA computes the spatial patterns of the FW and the normalized amplitude (amplitude per unit antenna current) by solving Maxwell's equations. Realistic FW amplitudes are computed by scaling the normalized amplitude with the experimentally determined fraction of FW power absorbed in the plasma core. These scaled FW solutions are passed to ORBIT-RF to evolve the fast ion distribution under the influence of FW injection in the plasma. In principle, ORBIT-RF and AORSA can be iterated until the results converge. For DIII-D FW heating conditions investigated in this paper, AORSA computes relatively weak single-pass absorption in the plasma, which may lead to a significant edge loss of FW power. Therefore, scaling amplitudes assuming full absorption of the FW power in the core may yield unrealistically large FW amplitudes. Investigation of simulated fast ions in a wide energy range indicates that a significant fraction of fast ions is accelerated beyond the upper energy limit of the FIDA measurement (60 keV) and is lost to the wall when FW amplitudes are scaled assuming 100% core absorption of the FW power.

As a quantitative measure of fast ions accelerated by FW, it is useful to compute neutron enhancement factor, S_n, defined as the ratio of neutron rates between NB+FW and NB alone:

$$S_n = \left(\sum_{i=1}^{nc} \langle \sigma v \rangle_i w_i \right)^{NB+FW} \Bigg/ \left(\sum_{i=1}^{nc} \langle \sigma v \rangle_i w_i \right)^{NB_{only}} .$$

Here nc is the number of Monte-Carlo fast ions, $\langle \sigma v \rangle$ is the reaction rate for the beam-plasma and w_j is the weighting of each fast ion. The diagnostic simulation code, FIDASIM [6], reads the fast ion distribution computed by ORBIT-RF/AORSA and reconstructs synthetic FIDA signals in velocity and physical space. For our purposes here, synthetic FIDA signals are also useful for alternatively understanding the acceleration of fast ions and their spatial profile. In this paper, we perform a series of simulations with varying assumed fractions of core FW power absorption (P_{abs}). Then, the fast ion distributions that yield S_n comparable to experimental enhancements are passed to FIDASIM to compare with the measured FIDA signals shown in Fig. 2.

First, NB slowing-down distribution before the FW turns on is computed by running ORBIT-RF for a few slowing down times using experimental beam parameters where Coulomb collisional orbit diffusion is turned on, but QL diffusive FW heating is turned off. To obtain a fast ion distribution with S_n comparable to the experimental neutron enhancement during the heating with 60 MHz alone (~1.25), the value of P_{abs} used to scale the FW amplitude in AORSA is reduced from 1.0 MW (full core absorption) to 0.5 MW (partial absorption). For each case, ORBIT-RF evolves the fast ion distribution self-consistently with AORSA including both QL heating and Coulomb collisions for an additional time interval of a few hundreds ms. After the 2nd iteration, S_n approaches 1.25 when P_{abs} = 0.5 MW, while S_n rises to ~1.5 when P_{abs} = 1.0 MW. The results suggest that increasing the power absorption beyond 50% up to 100% core absorption of the FW power produces highly accelerated fast ions due to large FW amplitudes, which do not contribute to the measured S_n. These fast ions are likely lost to the wall. To simulate the synergistic effect of two-frequency heating, we shall avoid the high fast ion loss regime by limiting the P_{abs} to 0.5 MW.

To simulate the further evolution of fast ions accelerated by 60 MHz FW during the two-frequency FW (60 MHz and 90 MHz) heating, the fast ion distribution accelerated by 60 MHz FW with P_{abs} = 0.5 MW is passed to AORSA. AORSA computes two FW solutions corresponding to 60 MHz FW and 90 MHz FW, respectively. A series of simulations is performed to obtain the fast ion distribution that predicts S_n comparable to the experimental value (~1.5) during two–frequency FW heating. The 90 MHz FW power is reduced from P_{abs} = 1.3 MW (100% core absorption) to P_{abs} = 0.5 MW (partial absorption), while P_{abs} for the 60 MHz FW is fixed at 0.5 MW. In simulated cases, ORBIT-RF/AORSA predicts S_n = 1.25~1.4. After the 8th iteration, ORBIT-RF/AORSA result with P_{abs}(60 MHz) = 0.5 MW and P_{abs} (90 MHz) = 0.5 MW indicates S_n~1.4, which is comparable to the observed value. This increased S_n suggests a synergy on accelerated fast ions during the two-frequency FW heating compared to S_n=1.25 during single-frequency FW heating.

To compare the radial profile of accelerated fast ions with measurements, the two fast ion distributions (one with S_n~1.25 for single 60 MHz FW and one with S_n~1.4 for 60 MHz + 90 MHz FW) are passed to FIDASIM. In Fig. 3, the computed synthetic FIDA signals for tangential and vertical chords are compared for the cases with NB alone, NB + 60 MHz and NB + 60 MHz + 90 MHz. The fast ion energy is integrated in the range of 30 to 60 keV for comparisons with experimental FIDA signals. These are shown in Fig. 3. Since absolute calibrations were not available in the discharge, only a qualitative comparison is possible in this paper. For the tangential velocity component, ORBIT-RF/AORSA simulations reproduce the trend of measured FIDA signals [Fig. 2(a)], indicating that tangential components of fast ions are hardly accelerated by either a single-frequency FW or two-frequency FW. For the vertical velocity components, where vertical FIDA viewing chords intersect the magnetic field nearly perpendicularly, ORBIT-RF/AORSA predicts more enhanced FIDA signals in the two-frequency FW heating than is obtained in a single-frequency FW case, which is also indicative of synergy. This synergy comes from $k_\perp \rho \geq 1$ ($k_\perp$ is the perpendicular wave number, and ρ is the fast ion Larmor radius), which occurs since a substantial fraction of fast ions above the NB injection energy is present due to preheating by the 60 MHz FW. Therefore, the additional 90 MHz FW damps significantly on beam ion tails and produces a synergy. A more quantitative comparison is underway.

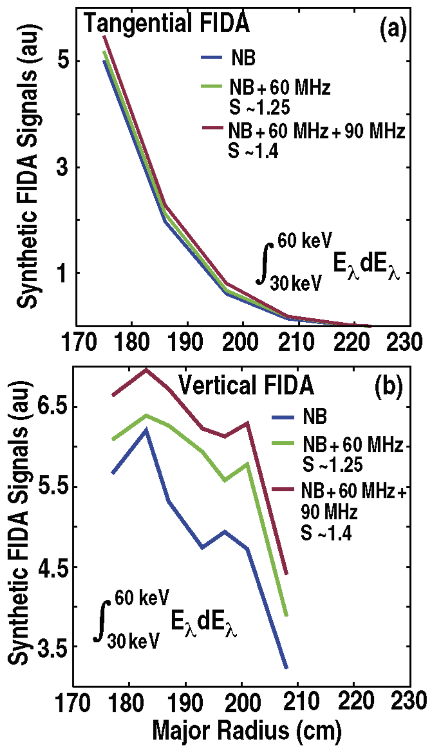

Fig. 3. Computed FIDA signals for (a) tangential FIDA and (b) vertical FIDA for NB only (blue), NB + 60 MHz (green) and NB + 60 MHz + 90 MHz (red).

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