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Modeling of Synergy Between 4th and 6th Harmonic Absorptions of Fast Waves on Injected Beams in DIII-D Tokamak

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Abstract. In recent moderate to high harmonic fast wave heating and current drive experiments in DIII-D, a synergy effect was observed when the 6th harmonic 90 MHz fast wave power is applied to the plasma preheated by neutral beams and the 4th harmonic 60 MHz fast wave. In this paper, we investigate how the synergy can occur using ORBIT-RF coupled with AORSA. Preliminary simulations suggest that damping of 4th harmonic FW on beam ions accelerates them above the injection energy, which may allow significant damping of 6th harmonic FW on beam ion tails to produce synergy.

INTRODUCTION

Fast Alfvén waves (FWs) in the ion cyclotron range of frequencies are one of the main auxiliary plasma heating and current drive methods in present tokamak experiments and ITER. In previous DIII-D experiments, various frequencies of FWs (4th harmonic 60 MHz, 5th harmonic 83 MHz, 6th harmonic 90 MHz and 8th harmonic 116 MHz) were separately applied to the plasma preheated by injected deuterium beams. Experiments have indicated that damping of the 4th harmonic FW on beam ions was much stronger than that of the 6th or 8th harmonic FW under similar conditions [1]. As evidence, larger stored energy and stronger neutron emission rates were measured in the 4th harmonic experiments compared to those measured in the 6th and 8th harmonic cases. Fast ion D_α (FIDA) [2] spectroscopy also confirmed stronger acceleration of beam ions in the 4th harmonic heating cases. Quantitative understanding of this moderate to high harmonic FWs damping on beams has been an important theoretical issue over the past years. For this, the finite-orbit-width 5-D Monte Carlo code ORBIT-RF [3] coupled with the 2-D linear full wave code AORSA [4,5] has been used. Simulations reproduced experimental observations such as FIDA signals in phase space and real space and neutron reaction rates [3].

In recent DIII-D experiments, synergy is observed when 6th harmonic FW is applied to the plasma preheated by neutral beams and 4th harmonic FW. The measured neutron rate from the two combined FWs is much stronger than the sum of that from separate 4th and 6th harmonic FW [6]. Theoretically, significant damping of the 6th harmonic FW on beam ions is possible when substantial fast ion population above the injection energy (tails) is present, which is due to $k_\perp \rho_i \geq 1$ ($k_\perp$ is the perpendicular wave number, and ρ_i is the fast ion Larmor radius). Therefore, if the 4th harmonic FW accelerates injected ions to well above the beam injection energy, significant damping of the 6^{th} harmonic FW on beam ion tails can occur, which may lead to synergy. Currently, ORBIT-RF does not allow two frequencies of FWs simultaneously to model experiments with combined FWs. Therefore, in this paper, the effect of beam tails on synergy is investigated by performing three simulations: (1) neutral beam (NB) only, (2) NB + 6^{th} harmonic 90 MHz and (3) NB accelerated by 4^{th} harmonic 60 MHz + 6^{th} harmonic 90 MHz. Synthetic FIDA signals and neutron reaction rates are computed for each case and compared.

SYNERGY EXPERIMENTON DIII-D

Figure 1 shows time traces of experimental data during the combined 60 MHz and 90 MHz FWs heating [6]. In this discharge, neutral beam injects 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, the 60 MHz FW (~1.0 MW) is coupled to the plasma preheated by neutral beam (NB). After a few hundred ms, the 90 MHz FW (~1.5 MW) power is added [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 period of 400 ms. This is larger than the sum of neutron reaction rates measured individually from separate pulses of 60 MHz and 90 MHz in a similar target plasmas [6]. This synergy is also observed in the stored plasma energy.

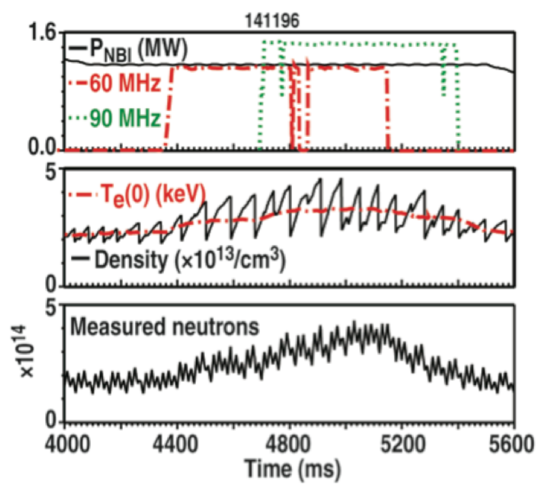

FIGURE 1. DIII-D experiment indicating synergy in neutron reaction rate when 60 MHz and 90 MHz FWs are applied simultaneously with neutral beams.

In Fig. 2, the enhancement of FIDA signals measured with each channel of vertical and tangential FIDA systems is plotted. Since absolute calibrations were not available for this discharge, FIDA signals measured for NB + 60 MHz + 90 MHz are normalized to those measured with NB only. The vertical FIDA viewing chords [2] intersect the magnetic field nearly perpendicularly, and hence is sensitive to perpendicular velocity components, while the recently installed tangential FIDA [7] intersects it more tangentially, and is sensitive to velocities along the magnetic field. As shown in Fig. 2, statistics on vertical FIDA are poor and the error bars are usually large since the diagnostic uses an integration time of 5 ms. The tangential system uses performed. Figure 2 indicates that vertical FIDA signals show a significant increase during the combined FWs phase, while the tangential FIDA signals show relative decrease during the same phase. As shown in Fig. 1(b), this discharge is strongly sawtoothing throughout both NB and NB + FWs phases. This decrease probably results from the fact that the tangential components of the fast ion population are more vulnerable to the loss due to sawteeth.

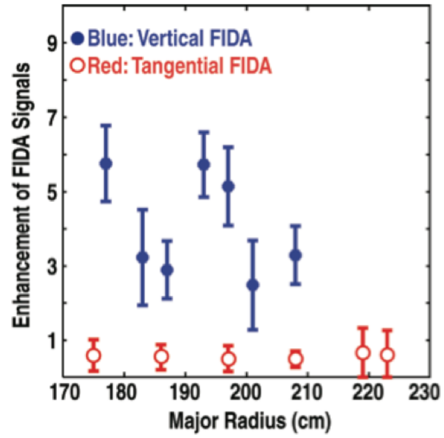

FIGURE 2. Enhancement of FIDA signals measured from tangential (open) and vertical (solid) chords during the injection period two combined 60 MHz and 90 MHz FWs with neutral beams.

SIMULATIONS

We perform three simulations to study the effect of synergy: case (1)-NB only, case (2)-NB accelerated by 60 MHz FW + 90 MHz FW and case (3)-NB + 90 MHz FW.

For case (1), the beam distribution is computed by running ORBIT-RF for a few slowing down times using experimental beam parameters where only Coulomb collisional orbit diffusion is turned on. For case (2), the computed beam distribution is passed to AORSA. Under the assumption that the experimental FW power (~1.0 MW for 60 MHz) is totally absorbed in the plasma, AORSA then computes the 60 MHz FW amplitudes and its spatial pattern. ORBIT-RF evolves the beam distribution for 100 ms with the computed 60 MHz FW fields with both quasi-linear heating and Coulomb collisions. The beam ion distribution accelerated by the 60 MHz FW is passed back to AORSA to compute the 90 MHz FW amplitudes and its spatial pattern. As indicated in previous DIII-D experiments, relatively weak single pass absorption has been observed at high harmonic frequency and high harmonic number, which led to significant edge loss of FW power [1]. Currently, AORSA does not model the edge loss. Therefore, to account for this effect when AORSA computes the 90 MHz FW, we assume that 1.0 MW FW (60% of injected 1.5 MW of the 90 MHz power) is absorbed in the plasma. This assumption seems reasonable since simulated neutron reaction rate using 1.0 MW FW power is close to the measured rate from experiment (1.5 MW FW). The beam ion distribution accelerated by NB + 60 MHz is evolved again for another 100 ms with the computed 90 MHz FW. For case (3), ORBIT-RF evolves the beam distribution separately with only the 90 MHz FW. Again, it is assumed that 1.0 MW FW is absorbed in the plasma to account for the edge loss.

In Fig. 3, the synthetic FIDA signals computed by FIDASIM [8] for tangential and vertical chords are compared for NB only, NB accelerated by 60 MHz + 90 MHz and NB + 90 MHz. The fast ion signal is integrated from 30 to 60 keV. Figure 3(a) shows that the computed tangential FIDA signals indicate no significant change in the three cases, which is qualitatively consistent with the measured tangential FIDA signals shown in Fig. 2. It should be noted that the decrease of measured tangential FIDA signals cannot be produced in this simulation since ORBIT-RF does not model any fast ion losses due to sawteeth instability. In Fig. 3(b), computed vertical FIDA signals are compared for the same three cases. For the NB case accelerated by the 60 MHz + 90 MHz, the signals are increased, though poor statistics are indicated in the middle region, while no significant change is computed for NB + 90 MHz. Significantly higher FIDA signals (Fig. 2 solid) are observed from NB + simultaneous combination of 1.0 MW 60 MHz and 1.5 MW 90 MHz (2.5 MW power) FWs, while the increased FIDA signals [Fig. 3(b) dashed] from the simulation are from the application of 1.0 MW of 90 MHz FW to a distribution resulting from NB preheated with 60 MHz FW. Quantitative comparison of Fig. 3 with Fig. 2 is not possible in this work. Nevertheless, our preliminary simulations show that damping of 4th harmonic 60 MHz FW on beams ions accelerates them above the injection energy, which then may allow significant damping of 6th harmonic 90 MHz FW on beams tails to produce the synergy. The synergy is also qualitatively reproduced in the computed neutron reaction rate. The neutron reaction enhancement factors (the ratio of neutron rate between NB + FW and NB only) are computed to be 1.3 for NB accelerated by 60 MHz FW + 90 MHz and 1.05 for NB + 90 MHz. Quantitative comparison of theory and experimental results will require modeling of simultaneous interaction of two frequencies of FWs and fast ion in orbit rf. This upgrade is underway.

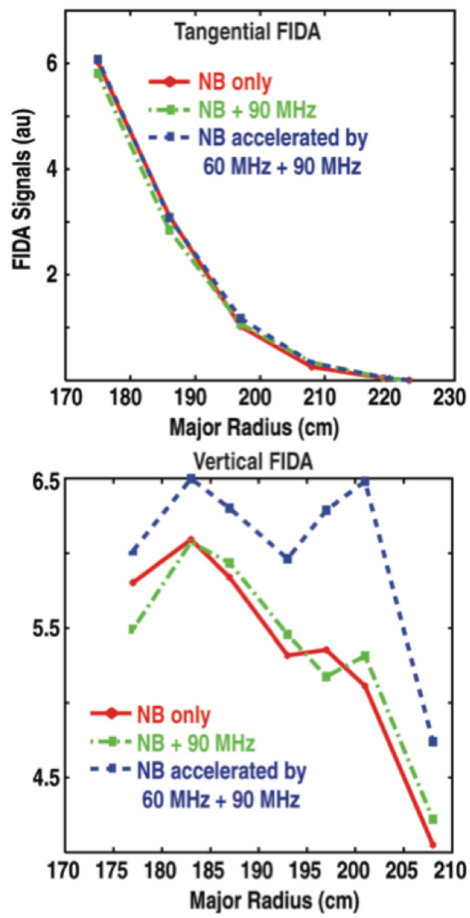

FIGURE 3. Computed FIDA signals for (a) tangential FIDA and (b) vertical FIDA for NB only (solid), NB accelerated by 60 MHz + 90 MHz (dashed) and NB + 90 MHz (chain).

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