Analysis of IBW-Driven Plasma Flows in Tokamaks

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Abstract. Both theory and experiment have suggested that damping of Ion Bernstein Waves (IBWs) at ion cyclotron frequency harmonics could drive poloidal flows and lead to enhanced confinement for tokamaks. However, the early analyses were based on Reynolds stress closures of moment equations. More rigorous, finite Larmor radius (FLR) expansions of the radio frequency (RF) kinetic pressure for low harmonic interactions indicated that the Reynolds stress approximation was not generally valid, and resulted in significant changes in the plasma flow response. These changes were largest for wave interactions driven by finite Larmour radius effects. To provide a better assessment of higher harmonic interactions and IBW flow drive prospects, the electromagnetic (E&M) and RF kinetic force models are extended with no assumptions regarding the smallness of the ion Larmor radius. For both models, a spectral-width approximation was used to make the numerical analysis tractable. In addition, it was necessary to include the effects of plasma equilibrium gradients on the plasma conductivity and the RF-induced momentum in order to conserve energy and momentum. The analysis of high-harmonic IBW interactions for TFTR and FTU parameters indicates significant poloidal flow shears (relative to turbulence correlation times) for power levels available in present experiments. Recent advances in all-orders calculations of E&M fields in 2-D are also discussed.

1. Introduction

Stabilization of plasma turbulence by sheared poloidal flows is a common theme in the analysis of enhanced confinement modes in tokamak discharges. A wide variety of wall conditioning techniques have been combined with plasma heating to produce such modes. Additional, more controllable, techniques for driving the needed flows would significantly aid in improving tokamak performance. IBWs have been investigated both theoretically [1,2] and experimentally [3,4,5], and have shown some promise. However, the early fluid-based analyses had limited validity, and a more complete kinetic model, valid to second order in $k_\perp \rho_i$ (ion gyroradius/perpendicular wavelength) [6], was developed in order to better understand the experiments and assess future prospects for IBW flow drive. For IBW interactions at the 2nd ion cyclotron harmonic, this kinetic model showed significantly reduced flows that were more localized in space when compared to the results from either compressible or incompressible fluid models. In order to analyze frequency regimes of interest (high harmonics and thus large $k_\perp \rho_i$), E&M and RF kinetic force models with no assumptions regarding the smallness of the ion Larmor radius [7] are required. In Section 2, a model for computing all-orders E&M fields in 1-D and 2-D is briefly described. Section 3 utilizes the results of these field calculations to examine high-harmonic IBW experiments on the TFTR and FTU experiments. The significance of these results is discussed in Section 4.

2. Electromagnetic Modeling

The electric field in the 1-D RF model [the All-Orders Spectral Algorithm (AORSA 1-D)] is represented by a Fourier series, $\vec{E} = \sum_l \vec{E}_l e^{ik_l x}$. The usual $e^{i(kz-\omega t)}$ dependence is implicit. This form allows using the Stix plasma conductivity to model the RF-induced plasma current to all orders in $k_\perp \rho_i$, namely, $\vec{J} = \sum_k \vec{\sigma}(\vec{r},\vec{k}) \cdot \vec{E}$. This plasma conductivity must be corrected to first order in ρ_i / L, where L is the equilibrium scale length, in order to account for gradients in equilibrium quantities. This correction is necessary in order to conserve energy and momentum, and is equivalent to the "odd-order" derivatives in finite difference models. The linear equations for the mode amplitudes are generated by collocation. While there is no expansion in $k_\perp \rho_i$, it is necessary to expand the expressions for the RF force in a spectral width parameter, $\delta\lambda \propto \left(k_\perp^L - k_\perp^R\right)^2 \cdot \rho_i^2$, where the superscripts L and R refer to products between the electric field that form the biquadratic expressions for energy and momentum absorption. The validity of this approximation is demonstrated by examining the same approximation in the context of energy flow and absorption. We find good agreement between $\vec{J} \cdot \vec{E}$ and the sum of spectral-width approximations for the heat-flux divergence and the local energy absorption, $\vec{J} \cdot \vec{E} = \vec{\nabla} \cdot \vec{Q} + \dot{w}$.

While the present analysis focuses on 1-D, a more realistic treatment requires 2-D. The resonant surfaces that are associated with RF-induced momentum transport, e.g., harmonic resonances, are not aligned with flux surfaces, and the resulting plasma response likely has significant modifications from that obtained in 1-D. The most difficult computational hurdle for such 2-D analyses is the E&M calculation. Hundreds of modes are required for each transverse dimension, and this leads to hundreds of thousands of dense, linear equations for the unknown electric fields. Converged solutions are problematical when IBWs are either launched or generated at a mode conversion layer. The physics model for 2-D is the same as described above of 1-D, with the electric field now being described by $\vec{E} = \sum_{l,m} \vec{E}_{l,m} e^{i(k_l x + k_m y)}$. The convergence of a spectral solution for a mode conversion heating experiment on Alcator C-Mod [8] is shown in Fig. 1. In this experiment, fast waves are converted to IBW near the ion-ion hybrid resonance layer, and subsequently damp on electrons. This fully-converged solution requires 400 modes in the x direction and 100 modes in the y direction, and leads to a system of 120,000 linear complex equations for the three electric field components.

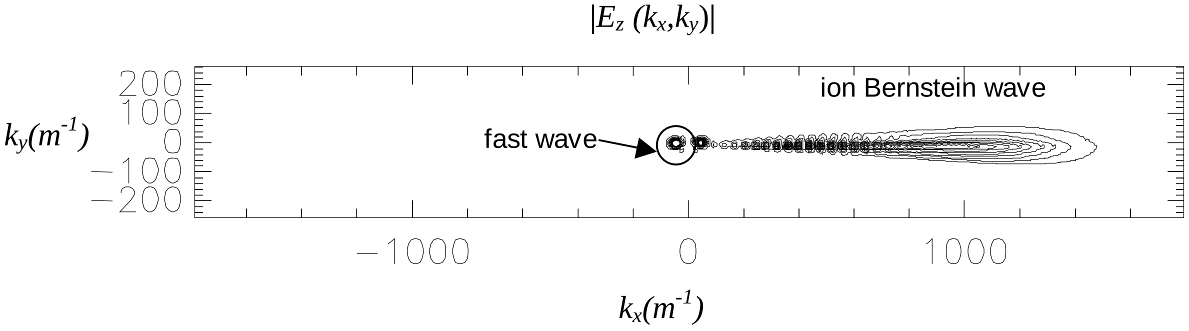

Fig. 1 Contours of E_z are shown as a function of the transverse wave numbers. There is no poloidal magnetic field for this particular analysis.

The solution to this system required almost 250 Gbytes of memory, and used 576 processors on the ORNL IBM RS/6000 SP super computer. About eight hours of clock time were required for the calculation, and a peak processing rate of 0.66 Tflops/s was achieved during the matrix factorization.

The real part of E_x is shown in Fig. 2. In addition to the mode conversion layer (minority-^3H_e) at R~0.55 m, there is a secondary mode conversion layer (majority-D) just inside the plasma edge at R~0.4 m.

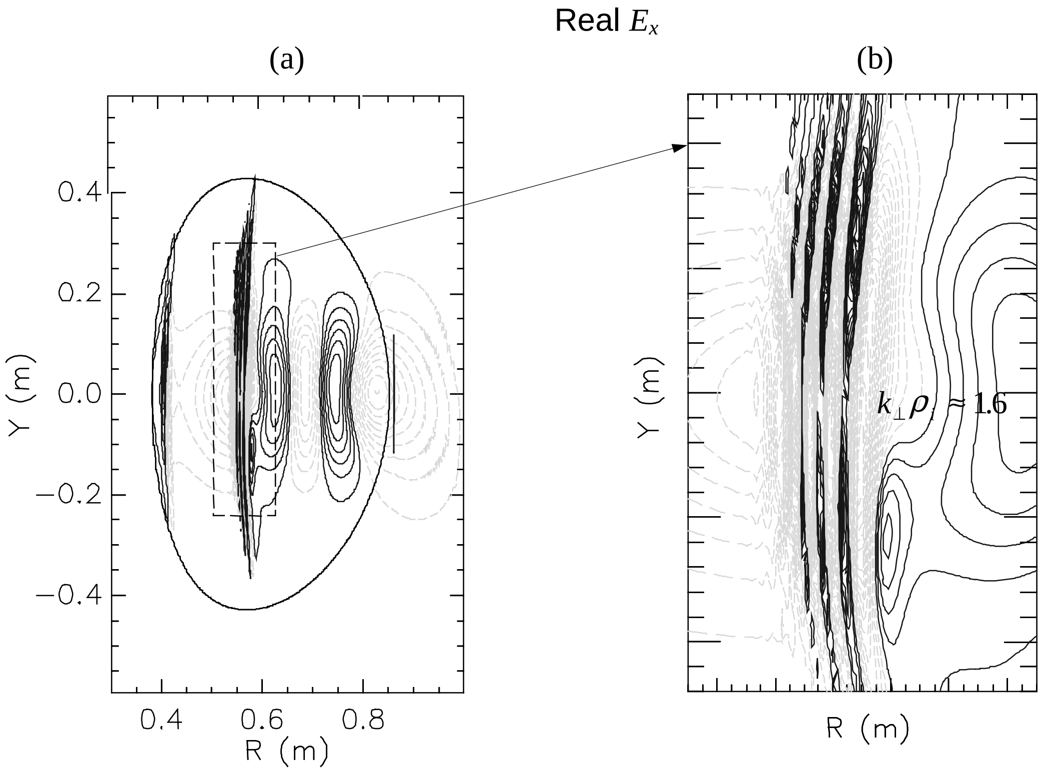

Fig. 2. Two-dimensional spectral solution for Alcator C-Mod showing mode conversion between fast waves and IBWs near the two-ion-hybrid resonance layer. Contours of E_x are shown with positive and negative values indicated by the dark and light contours, respectively. The entire cross section is shown in (a) and a blowup of the ^3H_e mode conversion layer is shown in (b).

3. Flow Drive Analysis

Poloidal flow velocities are estimated by balancing the total second-order E&M force, $\vec{F} = \left\langle \rho_1 \vec{E}_1 + \vec{j}_1 \times \vec{B}_1 \right\rangle_t - \vec{\nabla} \cdot \vec{P}_2$, where first-order quantities, denoted with the “1” subscript, refer to the first-order charge density, electric field, current density, and magnetic field, respectively, are averaged over time. The second term, $-\vec{\nabla} \cdot \vec{P}_2$, is the divergence of the second-order RF pressure tensor [7]. The divergence includes both the spatial variation of the E&M fields, and, similar to the conductivity, the variation due to the plasma equilibrium. This net force is balanced against neoclassical viscosity to arrive at the steady-state poloidal flow. Model results for the TFTR experiment are shown in Fig. 3. In this case, 360 kW power at 76 MHz is launched in deuterium (D) plasma with a tritium (T) minority using a conventional loop antenna (R = 360 cm) with the RF current in the toroidal direction. A small segment of the plasma is shown with the axis at 271 cm and plasma edge at 353 cm. Figure 3a indicates that the wave propagates in the D-majority component until it reaches the 5th harmonic tritium resonance, where it is absorbed in a ~ 1 cm-wide region for this 1-D calculation. The energy flux to the resonance, Fig. 3b, is dominated by the kinetic flux. This flux is created at the plasma surface from the Poynting’s flux as a result of the plasma-gradient driven RF currents. Neoclassical viscosity is used to balance the RF drive and obtain a steady-state poloidal velocity. Figure 3c shows the velocity that results from the absorption near the 5th harmonic T resonance. The net velocity change is about 700 m/s over a 1 cm layer.

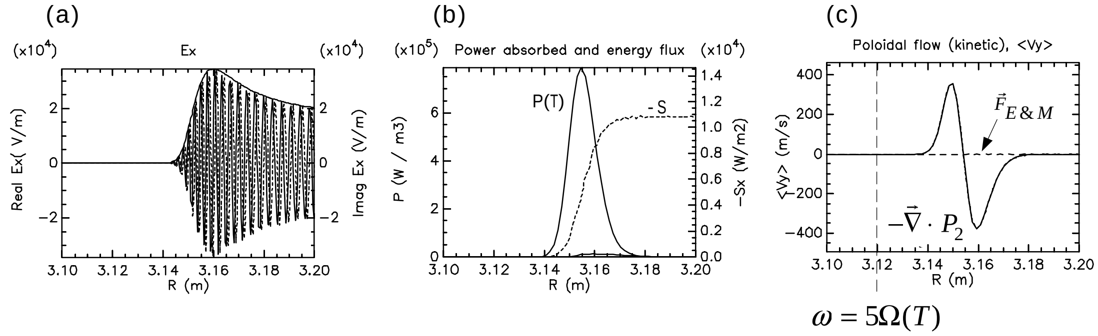

Fig. 3. IBW wave propagation in TFTR. Shown is (a) the dominant electric field E_x, (b) the energy flux S(Poynting's plus kinetic), and absorbed power P(T), and (c) the induced poloidal flow.

Similar calculations are shown for IBW experiments on FTU in Fig. 4. The FTU experiments employ a waveguide launch of 433 MHz at 350 kW. In this case, the 5th harmonic resonance of the hydrogen plasma is located just outside of the antenna, and the power is absorbed at the 4th harmonic resonance at about 1/3 of the plasma radius. The flow velocities shown in Fig. 4 are qualitatively similar to, but about a factor of ten higher than, those for TFTR with a narrower absorption layer due to the smaller Larmour radius. The RF forces in Figs. 3 and 4 were compared with those obtained from the fluid-based models with a Reynolds stress approximation for the pressure tensor. No consistent correlations were found.

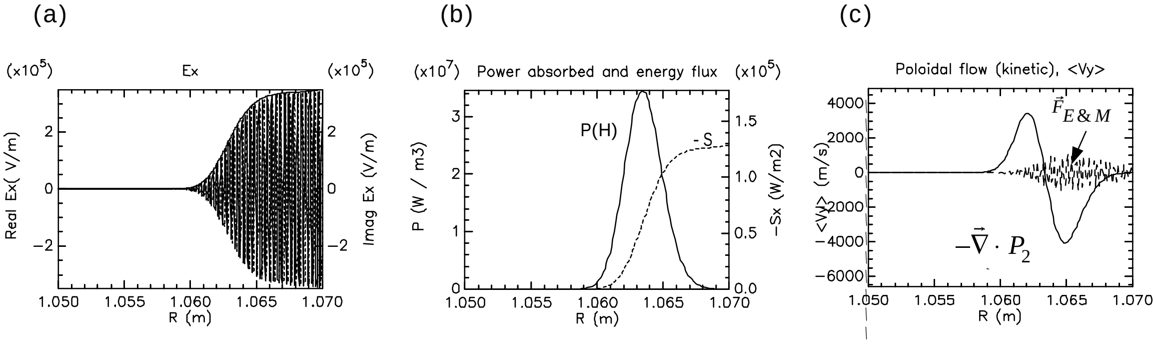

Fig. 4. IBW wave propagation in FTU. Shown is (a) the dominant electric field E_x , (b) the energy flux (Poynting's plus kinetic) and absorbed power P(H), and (c) the induced poloidal flow.

Poloidal flows are expected to affect turbulent transport when the induced velocity shear is greater than (*observed turbulence correlation time)* $^{-1}$ [9], typically ~10^5 s^{-1}. For TFTR, the estimated shear is somewhat less than this critical shear, while for FTU, the calculated shear is more than an order of magnitude larger.

4. Discussion

These flow results are in qualitative agreement with the experiments. Namely, poloidal flows are observed in TFTR with little change in confinement, whereas an improvement of about a factor of two in the core electron transport is observed in FTU. The radially-resolved velocity measurements for TFTR provide a stringent test of the present model. The most significant differences are the observation of a thicker shear layer, arguably larger flow velocities, and the induction of net poloidal momentum. Extensions to a 2-D model might lead to improvements with respect to the layer thickness, but such calculations are outside of present computational capability.

In addition to extending the analysis to 2-D, two other physics elements are likely necessary to obtain a more quantitatively correct model. First, the density moment of the second-order (in the electric field) distribution function used for the RF pressure calculations suggests nonambipolar radial particle transport that is of the same order as background rates. The resulting radial electric fields would drive additional poloidal flows. Assessing the importance of this mechanism will require integrating the RF-induced particle transport with a more complete model that allows for nonambipolar transport and appropriate mechanisms for equilibrating the resulting electric fields. The second element is the self-consistent evolution of the shear layer as a result of turbulent momentum transport. Spontaneous enhanced confinement modes can result from this interaction alone. In addition to these specific issues, modifications to RF transport rates might also be expected with more rigorous modeling of the collision operator in tokamak geometry.

In summary, the present analysis provides a more rigorous assessment of the use of high-harmonic IBW interactions to drive sheared plasma flows, and thus reduce plasma turbulence and improve confinement. Furthermore, the needed power levels are in the range of present experiments. However, the small scale lengths of these flows are apparently not consistent with experiments, and extensions to the analysis, as well as additional measurements of flow parameters, are needed.

5. Acknowledgments

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