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Poloidal variation of high-Z impurity density due to hydrogen minority ICRH on Alcator C-Mod

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Abstract

In the Alcator C-Mod tokamak, strong, steady-state variations of molybdenum density within a flux surface are routinely observed in plasmas using hydrogen minority ion cyclotron resonant heating. In/out asymmetries, up to a factor of 2, occur with both inboard and outboard accumulation depending on the major radius of the minority resonance layer. These poloidal variations can be attributed to the impurity's high charge and large mass in neoclassical parallel force balance. The large mass enhances the centrifugal force, causing outboard accumulation while the high charge enhances ion-impurity friction and makes impurities sensitive to small poloidal variations in the plasma potential. Quantitative comparisons between existing parallel high-Z impurity transport theories and experimental results for $r/a < 0.6$ show good agreement when the resonance layer is on the high-field side of the tokamak but disagree substantially for on-axis and low-field side heating. Ion-impurity friction is shown to be insufficient to explain experimental results and the accumulation of impurity density on the inboard side of flux surface is shown to be due to a poloidal potential variation from magnetic trapping of non-thermal cyclotron heated minority ions. Parallel transport theories are extended to account for cyclotron effects and revised models agree with experimentally measured impurity density asymmetries to within ~50%.

I. INTRODUCTION

The presence of impurities in fusion plasmas is known to be a challenge because of power loss in the core from radiation and fuel dilution. Still, tokamaks use impurities to maintain radiative divertors and mantles to protect plasma facing components [1] and impurity ions that are not fully-stripped of electrons can be used to diagnose kinetic properties of plasmas. Whether used as tracers or viewed as contaminants to be eliminated, their presence is ubiquitous and the physics of high-Z impurity transport in tokamaks is still not completely understood [2]. Much effort has been focused on characterizing cross-field impurity transport [3] and as the community moves towards validation [4] of gyrokinetic modeling of the turbulence thought to be responsible [5,6], it is important to include all relevant physics. When calculating force balance along the field, the large mass and high charge of impurity ions are expected to cause variations of the impurity density on a flux surface [7,8,9,10]. Both neoclassical [10,11,12] and anomalous cross-field transport [13] have proven to be sensitive to the magnitude and direction of these asymmetries. Substantial poloidal variation can also lead to systematic errors when interpreting data from diagnostics sensitive to impurity emission. It is thus of interest to have a validated model for parallel impurity transport as part of the larger understanding of impurity transport in tokamaks.

Prior investigations on JET [14] and AUG [15] into high-Z impurity density asymmetries have focused on neutral beam-heated plasmas where centrifugal effects due to externally applied torque can lead to toroidal flows exceeding the impurity thermal velocity, $v_{\phi,z}/v_{th,z} \geq 1$. In these cases, the large mass of the impurities enhances the centrifugal force, causing accumulation on the outboard or low-field side (LFS) of a flux surface. In Alcator C-Mod [16] deuterium plasmas using hydrogen minority ion cyclotron resonant heating (ICRH), toroidal rotation rates up to ~ 20 kHz have been observed, despite no external momentum input, and such a LFS accumulation is expected for intrinsic molybdenum. Measuring the two-dimensional impurity density profile reveals that indeed such in/out asymmetries exist in C-Mod plasmas with the poloidal variation, $\tilde{n}_z/\langle n_z \rangle$, up to 0.3, yet measurements are not always in quantitative agreement with predictions based solely on centrifugal force. In some cases the sense of the asymmetry is even reversed, with accumulation on the inboard or high-field side (HFS) of a flux surface, indicating another physical mechanism is at work.

Impurity asymmetries have not been thoroughly investigated in wave-heated plasmas. The use of cyclotron heating is predicted to play a role in the parallel impurity force balance by creating a poloidally varying electrostatic potential by magnetically trapping electrons (ECRH) or ions (ICRH) [17, 18] on the LFS. The high charge of the impurities magnifies any small potential variation caused by this trapping, and they respond in Boltzmann-like manner with $\tilde{n}_z/\langle n_z \rangle \sim \exp(-Ze\tilde{\phi}/T_z)$. In JET, Ni laser blow off into a

plasmas using hydrogen minority ICRH showed a $\sim 10\%$ HFS accumulation that was shown to be qualitatively consistent with estimates of magnetic trapping of minority ions [19]. Using toroidal field scans to modify the location of the minority resonance layer, C-Mod experiments discussed here demonstrate conclusively an impurity asymmetry linked to ICRH and show measurements can be explained quantitatively by highly charged molybdenum ions interacting with a steady-state poloidal potential variation due to trapped minority ions.

In Section II, the physics of parallel impurity transport is briefly reviewed and current theories are extended to include effects due to cyclotron heating. Section III describes the experiments performed on the Alcator C-Mod tokamak and the diagnostic tools used to measure and model the asymmetries with Section IV discussing the data analysis techniques. Section V presents the experimental results, demonstrating the link between the changes in the asymmetries and the ICRH heating. Section VI discusses the impact of these observations while Section VII summarizes the findings.

II. THEORETICAL BACKGROUND

Existing parallel impurity transport theories solve the coupled continuity and parallel force balance equation for a collisional (Pfirsch-Schlüter) high-Z impurity for both collisional [7] and collisionless (banana) [8] main ions. In addition to inertial forces, ion-impurity friction has also been identified as a mechanism to sustain an impurity pressure gradient along the fields. While thought to be a major influence for low-Z impurities in the pedestal of C-Mod [20], it will be shown in Section V that ion-impurity friction cannot explain the observations of molybdenum asymmetries. The poloidal variation of n_z can be found by solving the 1-D partial differential equation, (25) in [8], in the trace, $n_z Z^2/n_i \ll 1$, limit

$$\frac{\partial n}{\partial \theta} = n g (1 + \gamma b^2) + g \gamma \frac{K_z}{\langle n_z \rangle u} b^2 + n \frac{\partial M^2}{\partial \theta} \quad (1)$$

where $b^2 = B^2 / \langle B^2 \rangle$, $n = n_z / \langle n_z \rangle$, K_z is found from the integral constraint that $n(0) = n(2\pi)$ and $\langle \dots \rangle$ denotes the standard flux-surface average. The coefficients u , g and γ are gradient driven terms related to ion-impurity friction and main-ion poloidal flow and can be found in [7] and [8] for the respective collisionalities. The M^2 term is combination of the centrifugal force on the impurities and the force from the electrostatic potential variation arising from the weaker poloidal asymmetry of the main ion density also caused by centrifugal force.

$$M^2 = \frac{m_z \omega_z^2 R^2}{2T_i} \left(1 - \frac{\omega_i^2}{\omega_z^2} \frac{Z m_i}{m_z} \frac{T_e}{T_e + T_i} \right) \quad (2)$$

where ω_z and ω_i are the impurity and main-ion toroidal rotation frequencies, respectively. Note the theory in [7] assumes $\omega_z = \omega_i$, though they should differ by the difference in their diamagnetic flows which is a non-negligible correction to (2) for plasmas of interest.

The effect of wave heating on the poloidal potential variation has previously not been included in these theories. To evaluate the impact on the impurity asymmetry, a minority species is included in calculating the electrostatic potential variation on a flux surface. As discussed in [19], a cyclotron heated species can be modeled with a bi-Maxwellian distribution characterized by a temperature anisotropy, $T_\perp/T_\parallel > 1$. The parallel force balance equation for a species with an anisotropic but diagonal pressure tensor and a poloidally varying electrostatic potential,

$$\hat{b} \cdot (\nabla \cdot \bar{P} + n_m Z_m \nabla \tilde{\phi}) = \nabla_\parallel p_\parallel + \frac{p_\parallel - p_\perp}{B} \nabla_\parallel B + n_m Z_m \nabla_\parallel \tilde{\phi} = 0 \quad (3)$$

taking the temperatures to have zero parallel gradient, becomes,

$$\begin{aligned} \nabla_\parallel \left(\ln(n_m) + \ln(B^\eta) - \frac{Z_m \tilde{\phi}}{T_\parallel} \right) &= 0 \\ \frac{n_m}{\langle n_m \rangle} &= \frac{\langle B^\eta \rangle}{B^\eta} \exp\left(-\frac{Z_m \tilde{\phi}}{T_\parallel} \right) \end{aligned} \quad (4)$$

where, n_m is the minority ion density, $\eta = T_\perp/T_\parallel - 1$ and B is the magnitude of the magnetic field. Including the minorities in quasi-neutrality does not modify the structure of differential equation (1). Assuming a small hydrogen minority fraction, $f_m = n_m/n_e \ll 1$, $Z_m = 1$ and that $e\tilde{\phi}/T_e$ is small, (2) becomes

$$M^2 = \frac{m_z \omega_z^2 R^2}{2T_i} \left(1 - \frac{\omega_i^2 Z m_i}{\omega_z^2 m_z} \frac{T_e}{T_e + T_i} \right) - Z f_m \frac{T_e}{T_e + T_i} \left(\frac{\langle B^\eta \rangle}{B^\eta} - 1 \right) \quad (5)$$

This model assumes that the effect of the waves is to establish an anisotropic minority distribution that slows down on electrons and ions without impacting the parallel force balance of ions or impurities. Collisional processes will equilibrate temperatures along the field and between ion species. Using this ansatz requires that Z_m and f_m remain small enough that minority-impurity friction is not important.

In the large aspect ratio, circular limit using (5) for M^2 in (1) and assuming weak radial gradients ($g=0$ limit), the $m=1$ cosine density can be shown to reduce to

$$\frac{\tilde{n}_z}{\langle n_z \rangle} = 2 \frac{r}{R_o} \cos \theta \left[\frac{m_z \omega_z^2 R_o^2}{2T_i} \left(1 - \frac{\omega_i^2 Z m_i}{\omega_z^2 m_z} \frac{T_e}{T_e + T_i} \right) - \frac{Z f_m}{2} \frac{T_e}{T_e + T_i} \left(\frac{T_\perp}{T_\parallel} - 1 \right) \right] \quad (6)$$

where the tilde indicates the poloidally varying component, $n_z = \langle n_z \rangle + \tilde{n}_z$. For molybdenum in a C-Mod deuterium plasma, $\langle Z \rangle \sim 32$. When $f_m \sim 5\%$, $T_e \approx T_i$, and $\omega_i \sim \omega_z$, a temperature anisotropy of

$T_{\perp}/T_{\parallel} \sim 2.7$ in the minority temperature will have as much an impact on the asymmetry as a toroidal flow of order the thermal velocity, $v_{\phi,z}/v_{z,th}$. This effect acts opposite to the centrifugal effect, pushing the impurities to the HFS and in the low-flow or high P/n_e limit ($\eta \gg 1$) the effects of minority temperature anisotropy can be expected to dominate the asymmetry physics.

III. DESCRIPTION OF EXPERIMENTS

In Alcator C-Mod plasmas where hydrogen minority heating is employed, intrinsic molybdenum from plasma facing components is commonly observed at fractions of 10^{-4} to 10^{-3} and makes up the majority of the radiated power loss. In order to gain insight into the parallel impurity transport physics driven by ICRH, the flux-surface variation of this radiation is observed as the hydrogen minority, D(H), resonance layer is scanned. The heating is provided by x2 two-strap antennas at 80 and 80.5 MHz and a single four-strap antenna at 78 MHz using $(0, \pi, \pi, 0)$ phasing [21]. A toroidal field of $B_t = 5.4$ T places all frequencies approximately on-axis and over consecutive discharges, the toroidal field is scanned from 4.2 T to 6.2 T, moving the resonance layer from the HFS to the LFS, as shown in Figure 1. The ICRH power, ~ 3 MW, and antenna mix is kept constant and the line-averaged electron density is held fixed at $\sim 1.8 \times 10^{20}$ [m $^{-3}$] using cryopumping. The plasma current is 1.1 MA in discharges with $B_t > 4.4$ T and reduced to 1.0 MA in those with smaller toroidal field in an effort to maintain a $q_{95} > 3$. All plasmas exhibit sawtooth activity and are therefore presumed to have $q_0 < 1$. As the D(H) resonance location is scanned, the electron and ion temperature profiles do not stay constant, nor does the toroidal rotation profile but all are measured. Upper single null plasmas in the unfavorable ∇B drift direction are used allowing for high P_{ICRH}/n_e by avoiding H-mode and plasma shape is held constant over the B_t scan. For on-axis heating, I-mode [22] plasmas are obtained while for sufficiently off-axis heating, plasmas remain in L-mode.

Profiles of the electron density and temperature are measured using Thomson scattering with additional T_e measurements from electron cyclotron emission [23]. Spatially resolved, high resolution spectra from Ar $^{16+}$ line emission are measured using a spherically bent crystal spectrometer where tomographic techniques are used to find the local temperature and toroidal rotation [24]. The viewing geometry of the diagnostic weights approximately equally the inboard and outboard sides of the plasma. So in/out asymmetries in the Ar $^{16+}$ density are expected to have little impact on the measurements. Main-ion and impurity temperatures are assumed to be equal because $\tau_{iz}/\tau_E \ll 1$ for the plasma volume under investigation. The main-ion density is calculated from the electron density profile assuming a flat dilution profile based on Z_{eff} calculated from neoclassical conductivity [25]. The low-Z and high-Z

constituents of Z_{eff} are determined from neutron rate and radiation, respectively. The hydrogen to deuterium fraction, typically measured using the isotope shift in Balmer alpha, is unavailable for these USN plasmas so $n_m/n_e \sim 4\%$ is assumed throughout. Example kinetic profiles for $r/a < 0.9$ for both LFS and HFS off-axis heated discharges are shown in Figure 2 and are used in Section V to compare predictions from theory to experimental measurements. The difference in toroidal rotation between LFS- and HFS-heated plasmas is currently not understood, but the x-ray spectroscopy-based measurement in Figure 2d is confirmed by looking at the sawtooth pre-cursor frequency and assuming it comes from the $q=1$ surface. The midplane emissivity profile is determined by Abel inverting the line-integrated brightness profiles measured using two separate pinhole camera each using a single 22-channel, unfiltered AXUV diode array [26]. One camera views from $0.44 < R < 0.89$ [m] and the other from $0.65 < R < 0.92$ [m] and tangency radii for each are indicated in Figure 1. Each camera is independently aligned and calibrated, and consistent brightness profiles are observed in regions where the views overlap.

IV. ANALYSIS TECHNIQUES

The midplane emissivity profile, $\epsilon(R)$, can be determined from the AXUV diode arrays independent of any equilibrium reconstruction. EFIT [27] is used to find the poloidally varying part of the impurity density,

$$\frac{\tilde{n}}{\langle n_z \rangle} = \frac{\epsilon_{LFS} - \epsilon_{HFS}}{\epsilon_{LFS} + \epsilon_{HFS}} \quad (7)$$

where the ϵ_{LFS} and ϵ_{HFS} are the emissivities on the same flux surface for $R > R_o$ and $R < R_o$, respectively. The use of (7) assumes that all of the emissivity is due to molybdenum radiation. Soft x-ray and VUV spectroscopy [28] are used to identify the impurities present in the plasma and radiation modeling using cooling curves [29,30] indicates that approximately 80 % of the emissivity is due to molybdenum. The physics under investigation is expected to produce smaller or negligible asymmetries for lighter, low-Z impurities and so (7) will slightly underestimate the poloidal variation of the molybdenum density. In addition (7) takes the moments of the electron distribution, n_e and T_e , as constant on a flux surface, which is accurate only for low main-ion Mach number plasmas, $M_i^2 < 0.1$. It also assumes parallel heat conduction will force poloidal symmetry of T_e . The in/out asymmetry has been measured to be zero within error bars during Mo laser blow-off injection into Ohmic plasmas where $v_{\phi,z}/v_{z,th} \ll 1$ in agreement with theoretical predictions. In ICRH-heated plasmas, asymmetry measurements are taken during steady-state portions of the discharge more than 200 ms after the RF is turned on.

The pressure anisotropy of the minority ions is calculated via the TRANSP suite [31] of codes using spline fits to measured electron density and temperature profiles and ion temperature profiles output from regularized inversions of x-ray crystal spectroscopy data. The ICRF modeling in TRANSP outputs the parallel and perpendicular stored energy from which $p_{\perp}/p_{\parallel} = E_{\perp}/2E_{\parallel}$ and is assumed to equal T_{\perp}/T_{\parallel} .

The impurity density variation predicted by theory is found by solving the 1D nonhomogenous linear differential equation (1) using an integrating factor approach. Poloidal gradients are determined using flux surface geometry from EFIT and integrals are performed numerically. Outputs from this code have been verified against analytical predictions in various limiting cases. Solutions using M^2 from (2) and (5) are computed separately to isolate the ICRH effects.

V. RESULTS

The midplane emissivity profiles for a $B_t=6.0$ T (LFS-heated) plasma are plotted in Figure 3a against major radius and in Figure 3b versus normalized minor radius, r/a . Good agreement between the two independently measured emissivity profiles (AXA and AXJ) is demonstrated in the region of overlap. In the core plasma, the emissivity for $R > R_0$ is less than for $R < R_0$ on the same flux surface but this trend reversed for $r/a > 0.6$. Figure 4 uses (7) to calculate the in/out asymmetry from the AXUV diode measurements and the radial profiles of $\tilde{n}_z/\langle n_z \rangle$ are plotted for the discharges shown in Figures 1 and 2. Differences in the measured asymmetry profiles are observed during the toroidal field scan, most notably when the D(H) resonance is on-axis or the LFS and $\tilde{n}_z/\langle n_z \rangle < 0$.

Predictions from parallel transport theory which includes only inertial and ion-impurity friction forces are compared to the measurements, taking into account changes in the background plasma as shown in Figure 2. Inboard accumulation, $\tilde{n}_z/\langle n_z \rangle < 0$, is allowed in cases of strong ion-impurity friction, but modeling using experimental profiles shows that for all regions, $\tilde{n}_z/\langle n_z \rangle$ should remain positive inside of $r/a \sim 0.8$. The measured and modeled profiles in the $B_t=4.4$ T, HFS heated plasma are shown in Figure 5 and reasonable agreement is found for $r/a < 0.7$. This demonstrates the ability to sustain a large, $\tilde{n}_z/\langle n_z \rangle \sim 0.3$, high-Z impurity density asymmetry caused by centrifugal force without any externally applied momentum. This same comparison is made in Figure 6 for the $B_t=6.0$ T, LFS heated plasma. While the experimental results agree within the uncertainty to modeling at $r/a \sim 0.8$, a large discrepancy is observed for $0.3 < r/a < 0.65$, where the ICRH power is expected to be deposited on the LFS.

The mechanism thought to contribute the HFS accumulation is due to a poloidal electric field

created by magnetically trapped minority ions whose non-thermal distribution function is sustained by absorption of cyclotron waves. For large power per particle, P_{ICRH}/n_e , resonance localization [18] should increase the perpendicular energy of the minority ions, further trapping them until their banana tips are at the D(H) resonance layer. As this layer is scanned from LFS to HFS by changing the toroidal field, resonance localization will move the orbits from deeply trapped (LFS-heating) to trapped orbits that are nearly passing (HFS-heating). It would be expected, qualitatively, that HFS heating would have less impact on parallel impurity transport. In Figure 7, measured asymmetries at $r/a \sim 0.15, 0.45$ and 0.75 are plotted for the full toroidal field scan. Far off-axis, $r/a \sim 0.75$, the asymmetry is relatively independent of the resonance layer and small variation is likely due to shot-to-shot changes in ω_z , T_e and T_i . Near the magnetic axis, $r/a \sim 0.15$, the sign of $\tilde{n}_z/\langle n_z \rangle$ is driven negative as the resonance layer is moved through the region; while further off-axis, in both LFS and HFS-heated cases, the core moves towards symmetry, $\tilde{n}_z/\langle n_z \rangle = 0$. For mid radius, $r/a \sim 0.45$, the asymmetry response differs. As the resonance layer is scanned to the LFS, $\tilde{n}_z/\langle n_z \rangle$ decreases, eventually becoming negative, similar to on-axis heating. As the layer is scanned towards the HFS, $\tilde{n}_z/\langle n_z \rangle$ becomes more positive, even as the resonance layer passes through $r/a \sim 0.45$. These trends are qualitatively consistent with the resonance localization arguments.

The differences between the measured and modeled asymmetries can also be shown to be linked to ICRH dynamically. When the input power is ramped down during 1.40-1.42 seconds, prior to the current and field ramp down at 1.5 seconds, the measured asymmetry profiles change quickly, moving much closer to the (ICRH-free) profiles shown in Figures 5 and 6. Cross-field transport, $\tau_E \sim 30$ ms, is marginally slower than the fast-ion slowing down time, 20 ms, while the parallel impurity equilibration time is faster than both, ~ 1 ms. We postulate that when the ICRH is removed, pitch angle scattering reduces T_\perp/T_\parallel , and the parallel impurity equilibrium is modified before the background plasma changes significantly, relaxing the asymmetry profiles back to their steady-state values. Figure 8 shows the time history of $\tilde{n}_z/\langle n_z \rangle$ at $r/a \sim 0.2$ and 0.5 in the HFS-heated plasmas and in Figure 9, this is shown for the LFS-heated case for $r/a \sim 0.5$ and 0.7 . The largest change is near the D(H) resonance in the LFS-heated case, where an initial $\tilde{n}_z/\langle n_z \rangle \sim -0.15$ changes to slightly positive. All show better agreement with modeling in the 10's of ms after the ICRH power is removed. Also evident from the time history plots in Figure 8 is a periodic modulation of the asymmetry correlated to sawtooth crashes. The only major modulation in the observed kinetic profiles is in T_e which has a weak effect on the asymmetry so it is thought that the impurity asymmetry modulation is due to fast-ion transport driven by the sawtooth perturbation.

In order to provide more quantitative theoretical comparison, the pressure anisotropy from

TRANSP simulations is used to model the poloidal potential variation. Figure 10 and 11 compare the measured $\bar{n}_z/\langle n_z \rangle$ profiles to solutions of (1) using M^2 from (5) which includes minority trapping effects. There is little change in the asymmetry for the HFS-heated case but a large impact for the LFS-heated case is predicted. By including the minority heating effect, $\bar{n}_z/\langle n_z \rangle$ is driven below zero reproducing the inboard accumulation seen in the LFS-heated plasma. In Figure 11, modeling predicts an asymmetry much stronger than is observed when using the TRANSP output. By artificially reducing the strength of the ICRH force by 0.4 in the modeling, good quantitative agreement can be obtained. The sensitivity of the asymmetry to the minority fraction, both directly in (5) via f_m and implicitly in the TRANSP-based temperature anisotropy is a possible explanation for the quantitative discrepancy.

VI. DISCUSSION

Having a validated theory of parallel impurity transport is important in accurately interpreting information from modern tokamak diagnostics. The soft x-ray crystal spectroscopy technique used on C-Mod to get core velocity and temperature profiles is also being planned for use on ITER [32] where neutral beam penetration at energies favorable for traditional charge exchange diagnostics is weak. The ITER spectrometer will use intrinsic tungsten used in the divertor. These impurity ions will experience large asymmetries due to expected intrinsic rotation [33] and the mix of planned ion and electron cyclotron heating techniques. Profile coverage is limited and a validated model of the poloidal variation will be critical to obtain accurate rotation and temperature profiles. Additionally, soft x-ray tomography is sometimes used [34,35] to aid in equilibrium reconstructions by assuming surfaces of constant emissivity are also flux surfaces. In plasmas where in/out asymmetries are expected, this can lead to systematic errors in the Shafranov shift.

Results presented in Section V demonstrate the sensitivity of the parallel transport of high-Z impurities to the poloidal electric field generated by ion cyclotron heating, suggesting measurements of $n_z(\theta)$ as general diagnostic technique to infer E_θ . The radial force balance equation is often used in a similar manner to determine the radial electric field [36]

$$E_r = \frac{-1}{Zn_z} \frac{\partial p_z}{\partial r} - v_{z,\theta} B_\phi + v_{z,\phi} B_\theta \quad (8)$$

where n_z , $\partial p_z/\partial r$ and $v_{z,\theta}$ and $v_{z,\phi}$ are all measured. In this case the poloidal electric field can be found from the parallel force balance equation, ignoring ion-impurity friction, via

$$E_\theta = \hat{b} \cdot \nabla \theta \frac{T_z}{e} \left[\frac{1}{Zn_z} \frac{\partial n_z}{\partial \theta} - \frac{m_z \omega^2}{2ZT_z} \frac{\partial R^2}{\partial \theta} \right] \quad (9)$$

Instead of radial pressure gradients and v_z being measured to find E_r , the parallel gradients and toroidal rotation, ω_z , can be used to find E_θ . The presence of a poloidal electric field could impact cross-field transport by imparting a radial $E_\theta \times B_\phi$ drift. At $r/a \sim 0.45$ using the modeling shown in Figure 11 for the LFS-heated plasma that best matches experiment, this results in drift velocity that varies over the flux surface $\sim v_d \sin\theta$ with $v_d \sim 3.5$ m/s as shown in Figure 12. No significant flux-surface averaged, radial particle flux will occur unless the density also had a non-zero up/down asymmetry. In this work, the main focus has been in/out asymmetry driven by minority heating and centrifugal force and future work will focus on ion-impurity friction effects which are responsible for the up/down asymmetry.

Neoclassical theories have shown that a poloidal potential variation $e\tilde{\phi}/T_e \sim \epsilon$ can impact transport by causing electrostatic trapping which complements the magnetic trapping inherent to the tokamak. It was shown that radial electron transport can, in some cases, be enhanced by a factor of 2 as $e\tilde{\phi}/T_e$ rises to $\sim 4\epsilon$ [11]. The bootstrap current can also be influenced by this modification to trapping with enhancement or reductions on the order of 20-30% depending on the sense of the asymmetry and impurity content [12]. For the C-Mod case described above, the potential variation, $e[\phi(\theta) - \phi(0)]/T_e$ is plotted in Figure 12 where it is demonstrated to be much smaller than necessary to impact neoclassical transport. These results demonstrate that high-Z impurity asymmetries can be used as a sensitive tool for measuring very small changes in the poloidal electric field. Large asymmetries, $\tilde{n}_z/\langle n_z \rangle \sim 1$, can act as an indicator of when neoclassical poloidal electric field effects need to be included in transport modeling.

Recent work studying the impact of poloidal asymmetries on anomalous radial impurity transport has shown that HFS accumulation of impurities can lead to a reduction or even a reversal of the impurity density zero flux gradient scale length [13]. The C-Mod measurements presented here show asymmetries, $\tilde{n}_z/\langle n_z \rangle \sim -0.15$, at the level where cross-field transport could be affected and examples of $\tilde{n}_z/\langle n_z \rangle \sim -0.25$ have been observed in more recent in C-Mod plasmas. Future studies of asymmetry-induced turbulent impurity transport will require a more complete measurement of the poloidal variation of impurity density rather than just the in/out asymmetry. The existing tools [37,38] used to model the parallel transport for use with gyrokinetic codes include poloidal asymmetries driven by centrifugal force but do not include any poloidal electric field effects generated from cyclotron heating. Some extensions to these tools may be necessary to complete validation exercises for high-Z impurity transport in cyclotron-heated plasmas.

Although somewhat counter intuitive, it can be argued that it is easier to measure the poloidal variation of the high-Z impurity than the radial impurity density profile. This is due to the necessity of accurate electron density and temperature profiles as well as atomic physics modeling to turn an

emissivity into an impurity density and constrain a 1-D impurity transport simulation. In contrast, the poloidal variation of the impurity emission can be determined from a SXR tomography diagnostic, a common tool on many tokamaks. It is suggested that future theoretical investigations into asymmetry-induced transport phenomenon produce verifiable predictions of the poloidal impurity density profile. If large asymmetries are observed along with changes in radial transport, which can be caused by a variety of mechanisms, then parallel transport may be playing a role in radial transport.

VII. SUMMARY

Large, steady-state poloidal variations of high-Z impurity density are observed in Alcator C-Mod plasmas using hydrogen minority ICRH. Both inboard and outboard accumulation of molybdenum on a flux surface have been observed with $|\tilde{n}_z/\langle n_z \rangle|$ up to 0.3. Parallel impurity transport theories that include only centrifugal and ion-impurity friction forces, cannot explain ICRH-heated C-Mod results. Significant disagreement occurs on flux surfaces with cyclotron-heated energetic minority populations when the resonance layer is located at $R \geq R_0$. In these cases, inboard accumulation of molybdenum is observed. By measuring asymmetries during shot-to-shot scans of the minority resonance layer and examining the transient asymmetry response after removing the ICRH power, the link to cyclotron heating is firmly established. The effect is attributed to a poloidal potential variation sustained by magnetically trapped minority ions. Extensions to parallel impurity transport theory including this effect are derived, and compared to the measured asymmetries. Using this extended theory with minority pressure anisotropy based on TRANSP, inboard accumulation of molybdenum is predicted whose radial profile shape agrees qualitatively with experiments. The magnitude of the asymmetry matches measurements to within $\sim 50\%$, which is likely within the uncertainty in the minority population.

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FIGURE CAPTIONS

FIGURE 1: EFIT equilibrium reconstruction of the typical plasma shape used in this experiment. The major radii of resonance layers for hydrogen minority ICRH are plotted for $B_t=4.4, 4.7, 5.4$ and 6.0 T. Tangency radii of the midplane AXUV diode arrays (open and closed circles - offset for clarity) are also plotted.

FIGURE 2: Radial profiles used in asymmetry modeling; (a) electron density, (b) electron temperature, (c) ion temperature and (d) toroidal rotation frequency.

FIGURE 3: Example AXUV emissivity profiles plotted against major radius (a) and normalized minor radius, r/a (b), demonstrating the presence of both inboard and outboard impurity accumulation for a LFS-heated plasma.

FIGURE 4: The poloidal varying impurity density profiles derived from the AXUV diode emissivity data for various ICRH resonance layer locations shown in Figures 1 and 2.

FIGURE 5: Comparison of measured (solid blue) and modeled (dashed black) impurity density asymmetries with no minority heating effects for a $B_t=4.4$, HFS-heated plasma. Data are close to agreement for $r/a < 0.7$.

FIGURE 6: Comparison of measured (solid red) and modeled (dashed black) impurity density asymmetries with no minority heating effects for a $B_t=6.0$, LFS-heated plasma. Data show disagreement between $0.3 < r/a < 0.65$ in the vicinity of the minority resonance layer.

FIGURE 7: At various r/a locations, the magnitude of the poloidal impurity density asymmetry versus toroidal field. $B_t=5.4$ puts the layer nominally on-axis with $B_t > 5.4$ T and $B_t < 5.4$ T being LFS- ($r/a > 0$) and HFS-heating ($r/a < 0$), respectively.

FIGURE 8: Time evolution of the measured impurity density asymmetry at $r/a=0.2$ and 0.5 (c) for a HFS-heated plasma. As the ICRH power (a) is ramped down faster than the energy confinement time only small changes in the electron temperature (b) are observed for the kinetic profiles but the measured asymmetries approach the modeling in Figure 5. Also evident is the modulation of the asymmetry by

sawteeth.

FIGURE 9: Same as Figure 8 but for $r/a=0.5$ and 0.7 in the LFS-heated plasma. The measured asymmetries relax to the modeling shown in Figure 6 with a much larger change in magnitude and a reversal of the direction of the asymmetry.

FIGURE 10: Comparison of measurements (solid blue) with modeling (black dashed) including the effects due to minority heating for a HFS-heated plasma. Including the minority does not have a significant impact as expected from resonance localization but still reduces the discrepancy between the measurement and modeling.

FIGURE 11: Comparison of measurements (solid red) with modeling (black broken lines) including the effects due to minority heating for a LFS-heated plasma. Including the minority has a large impact on the modeling but predicts a larger asymmetry than observed (dashed). Scaling the magnitude of the ICRH effects to 40% (dash-dot) shows good quantitative agreement.

FIGURE 12: Poloidal variation of the electrostatic potential, $e[\phi(\theta)-\phi(0)]/T_e$ (left axis) and the resulting $E \times B$ drift velocity (right axis), calculated at $r/a=0.45$ from modeling shown in Figure 11 that best agrees with the measurements.

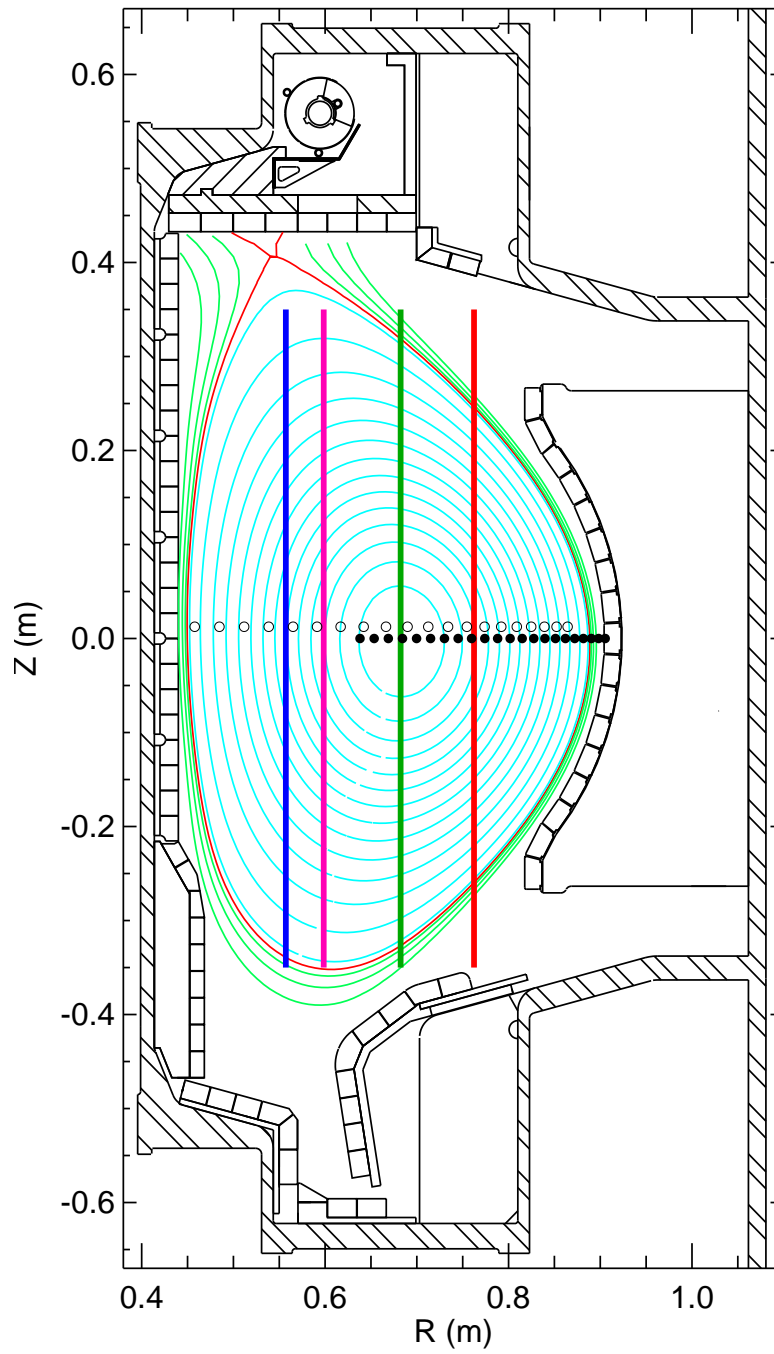


FIGURE 1

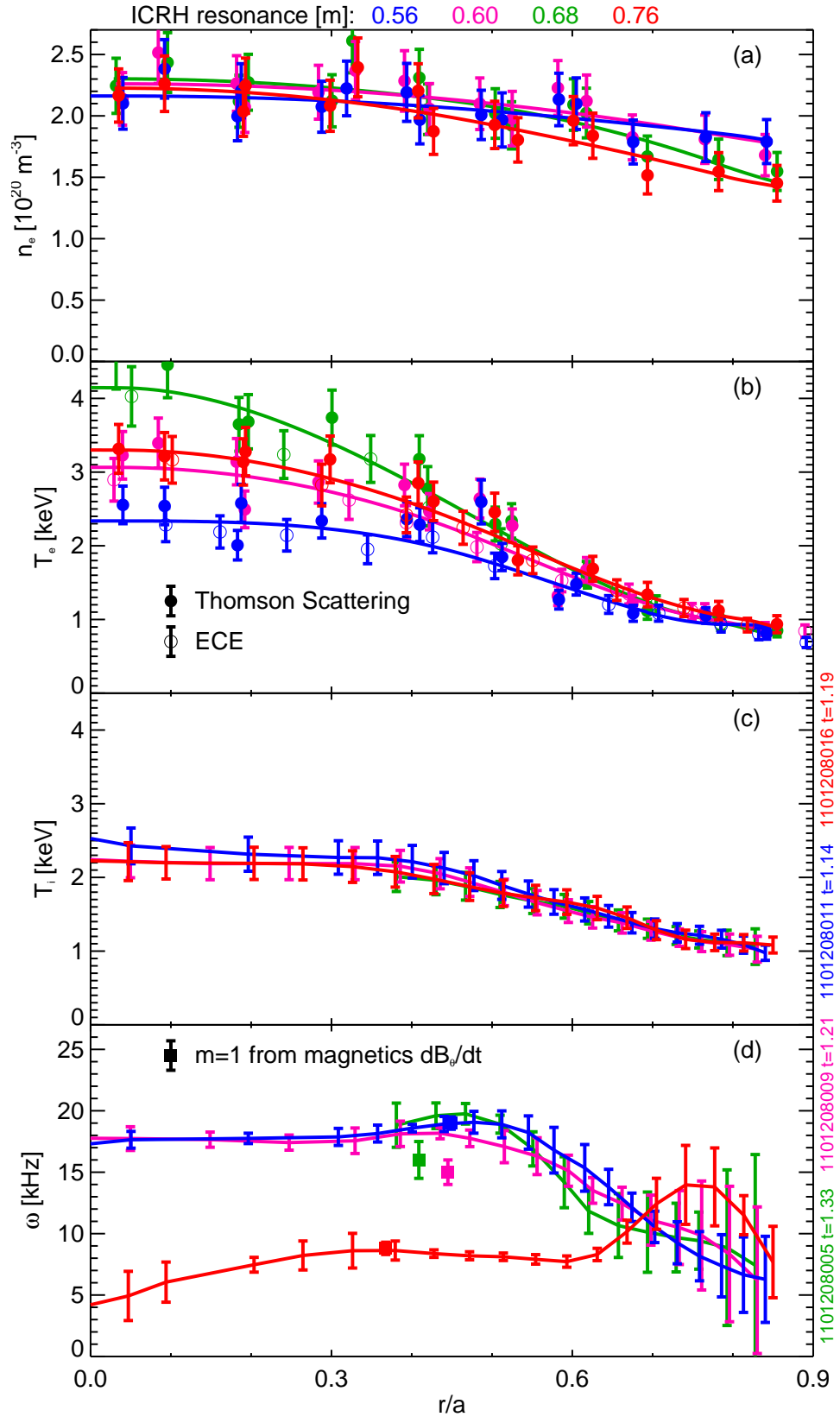


FIGURE 2

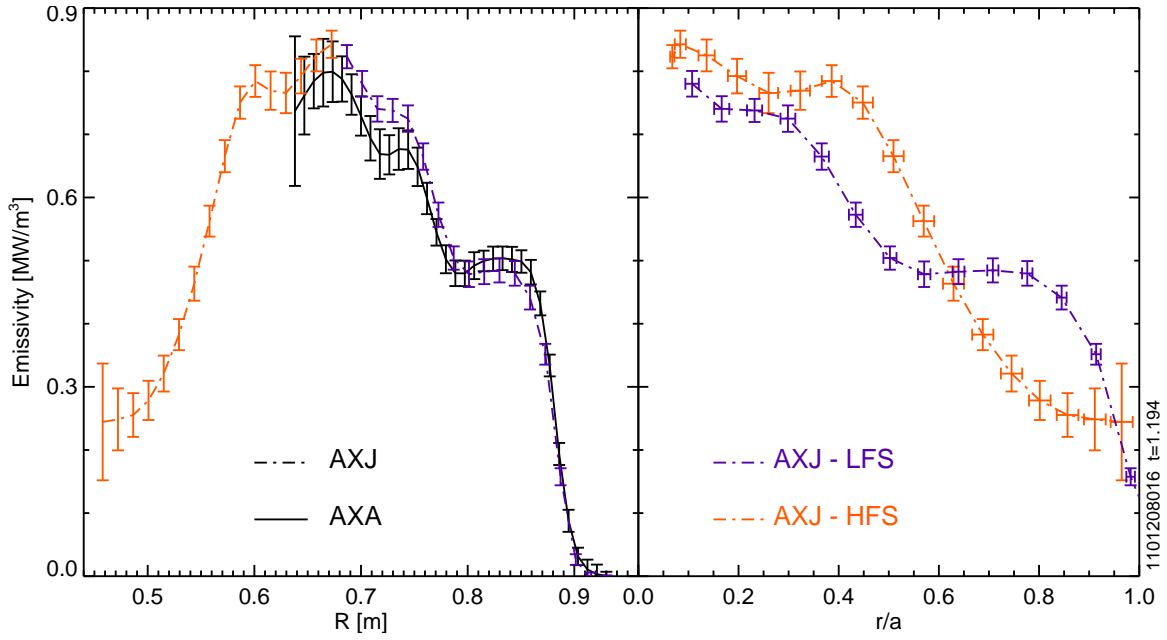


FIGURE 3

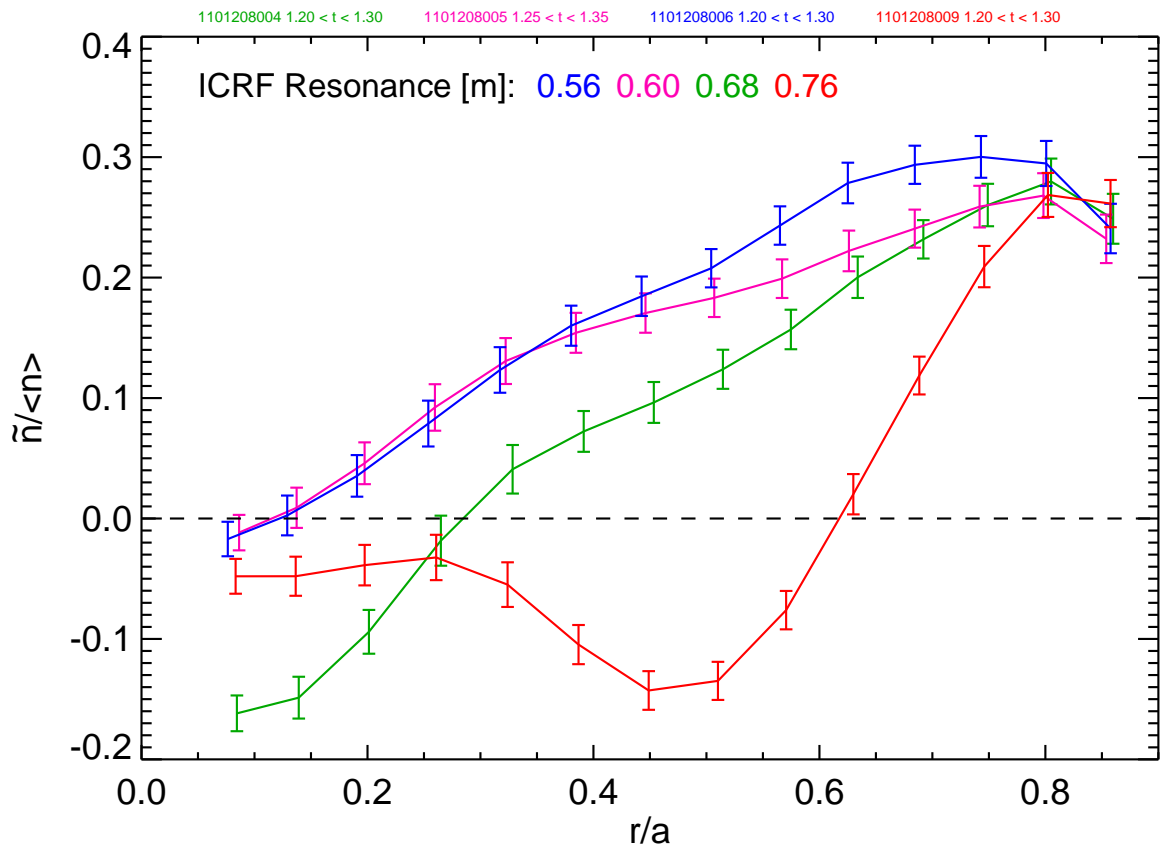


FIGURE 4

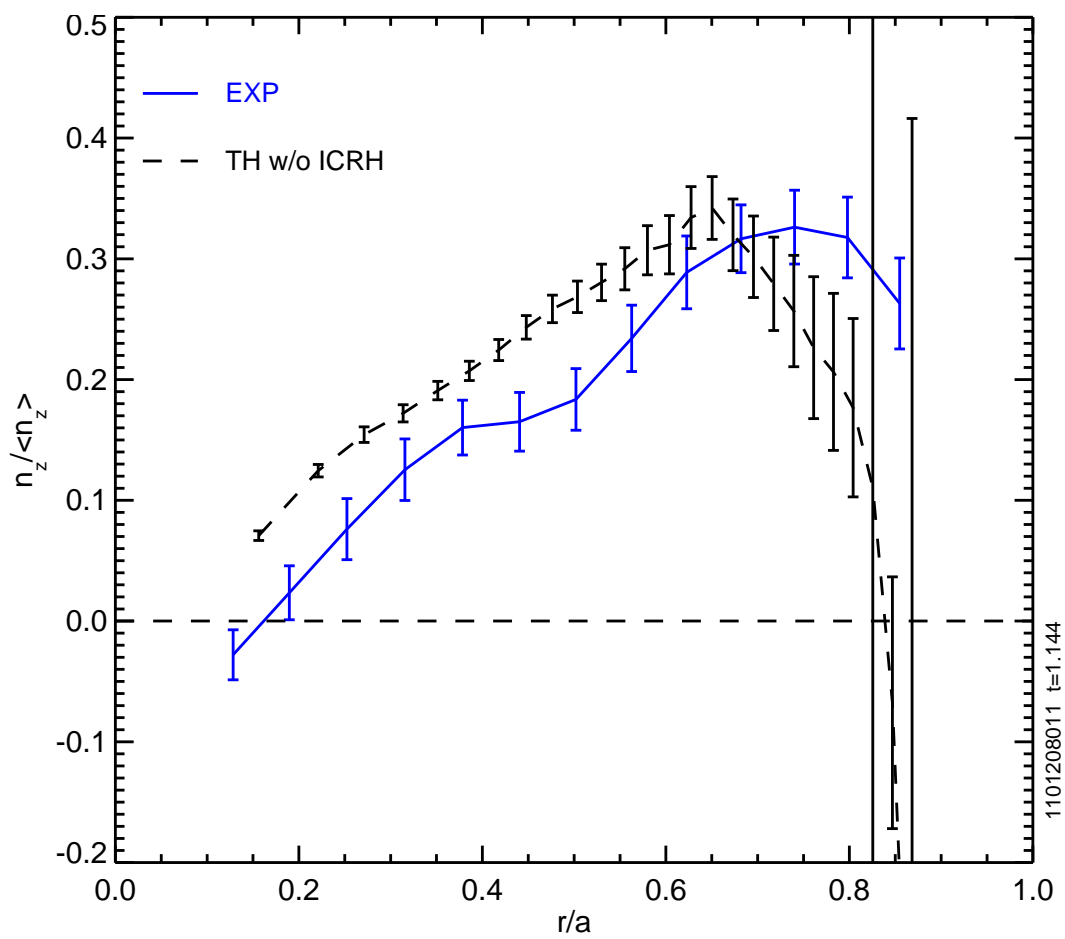


FIGURE 5

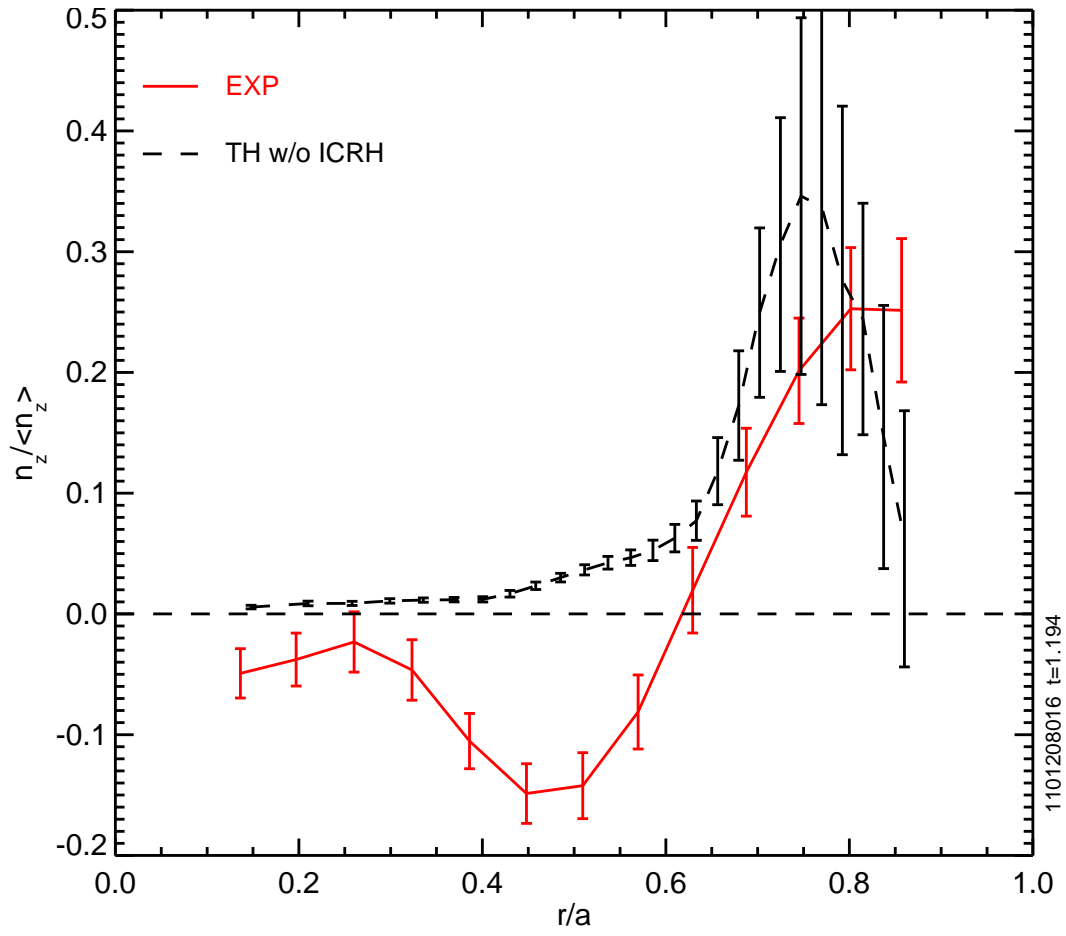


FIGURE 6

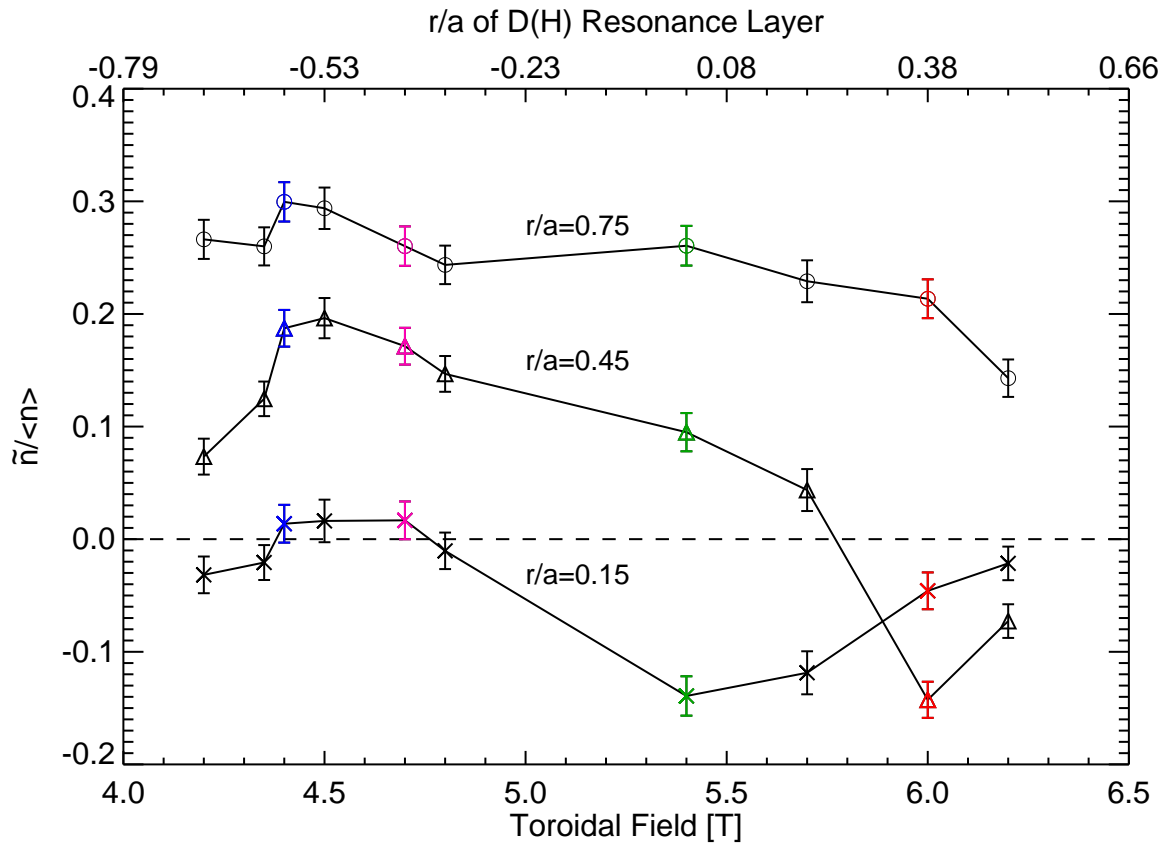


FIGURE 7

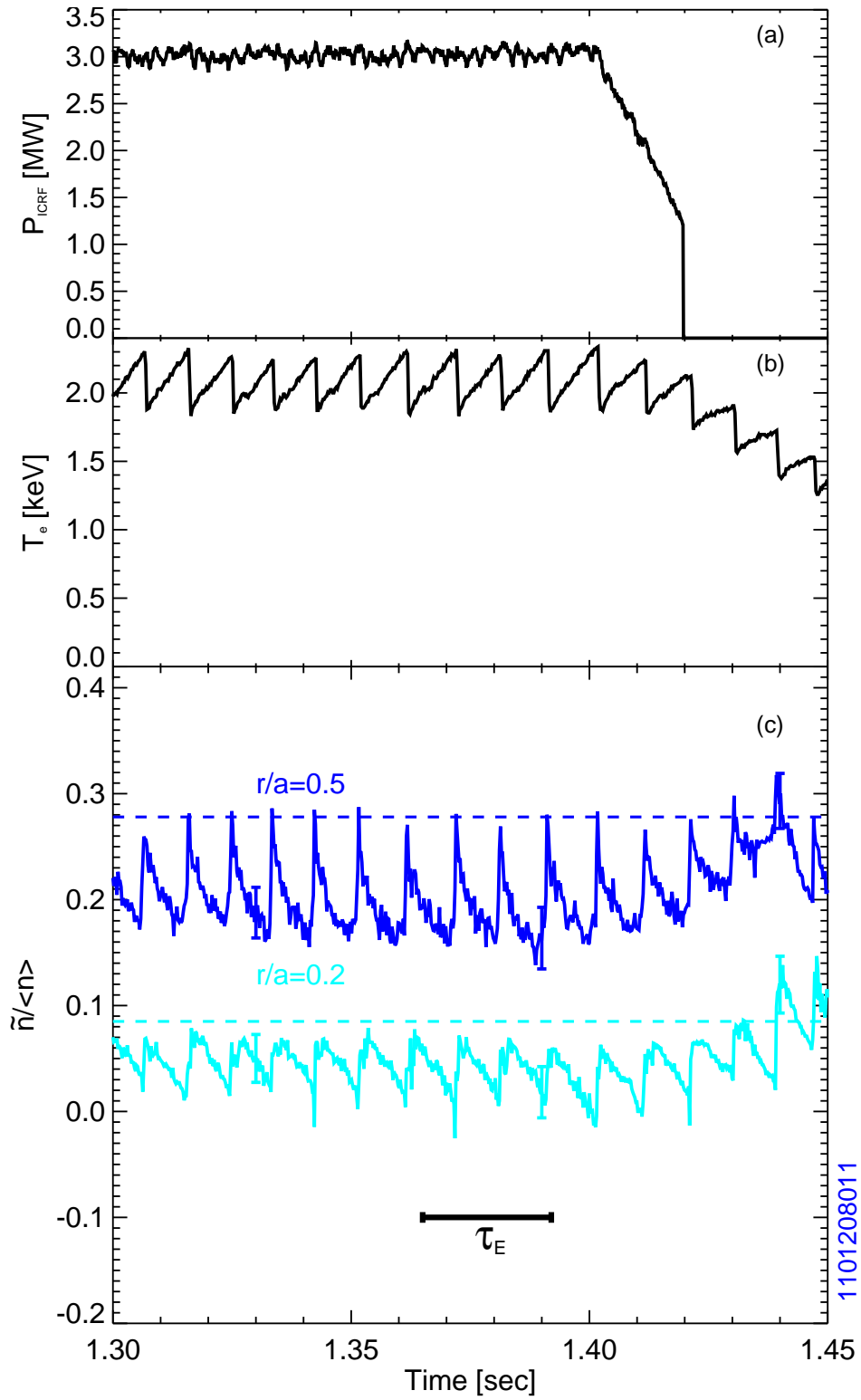


FIGURE 8

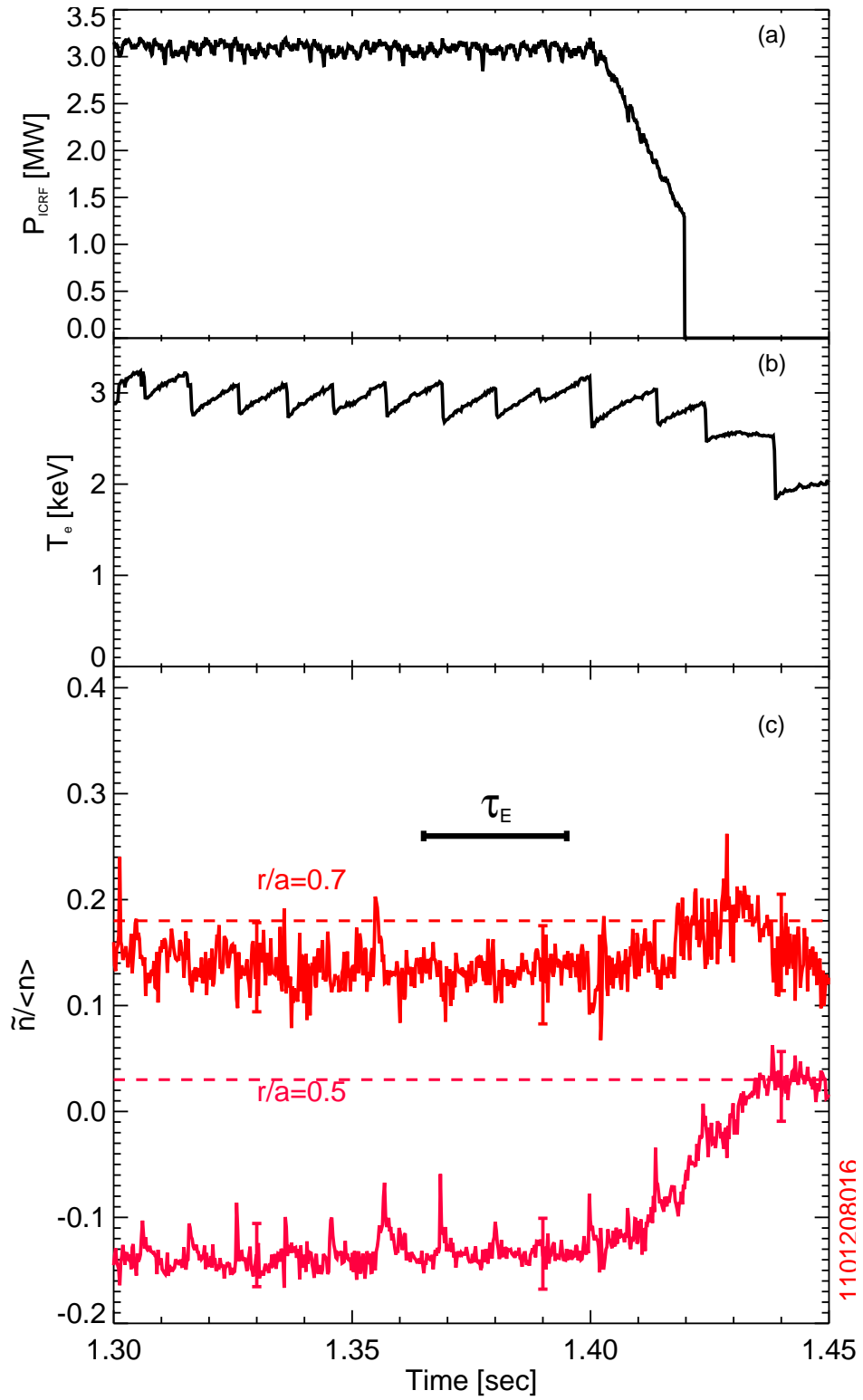


FIGURE 9

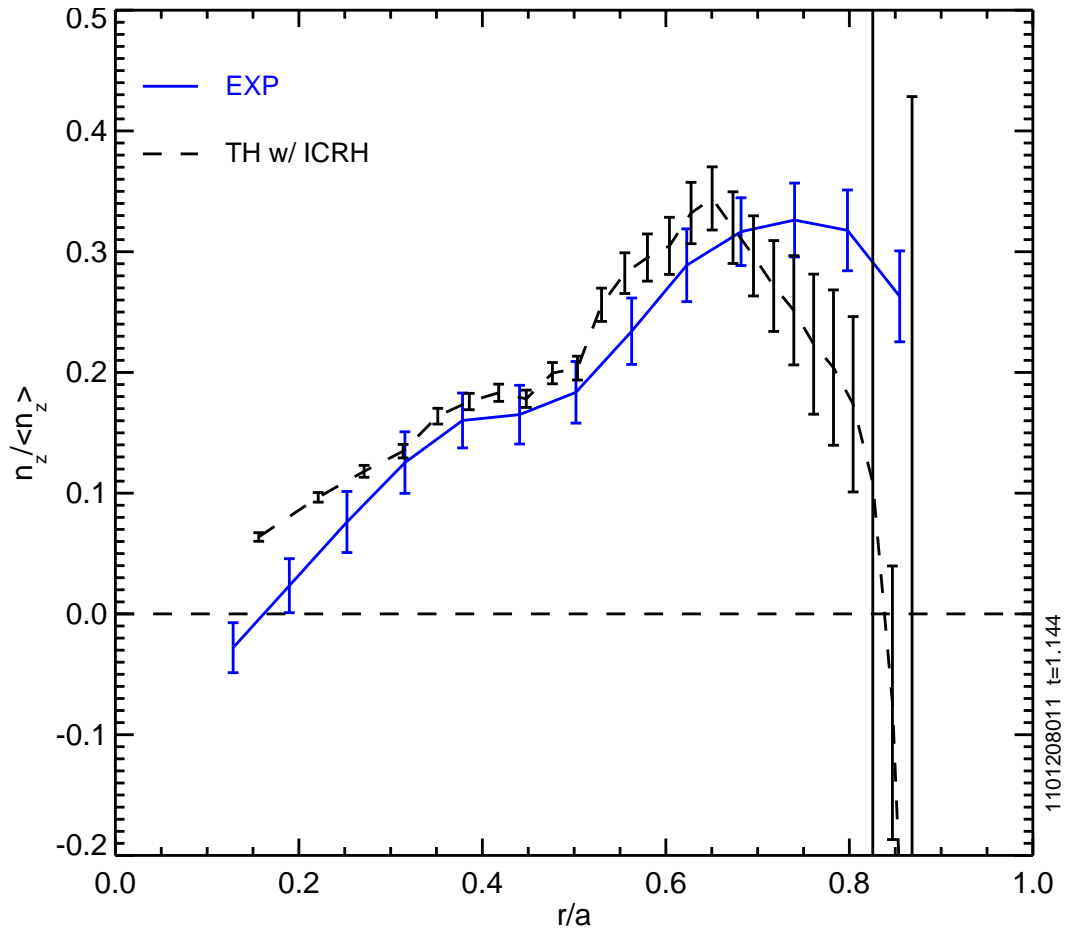


FIGURE 10

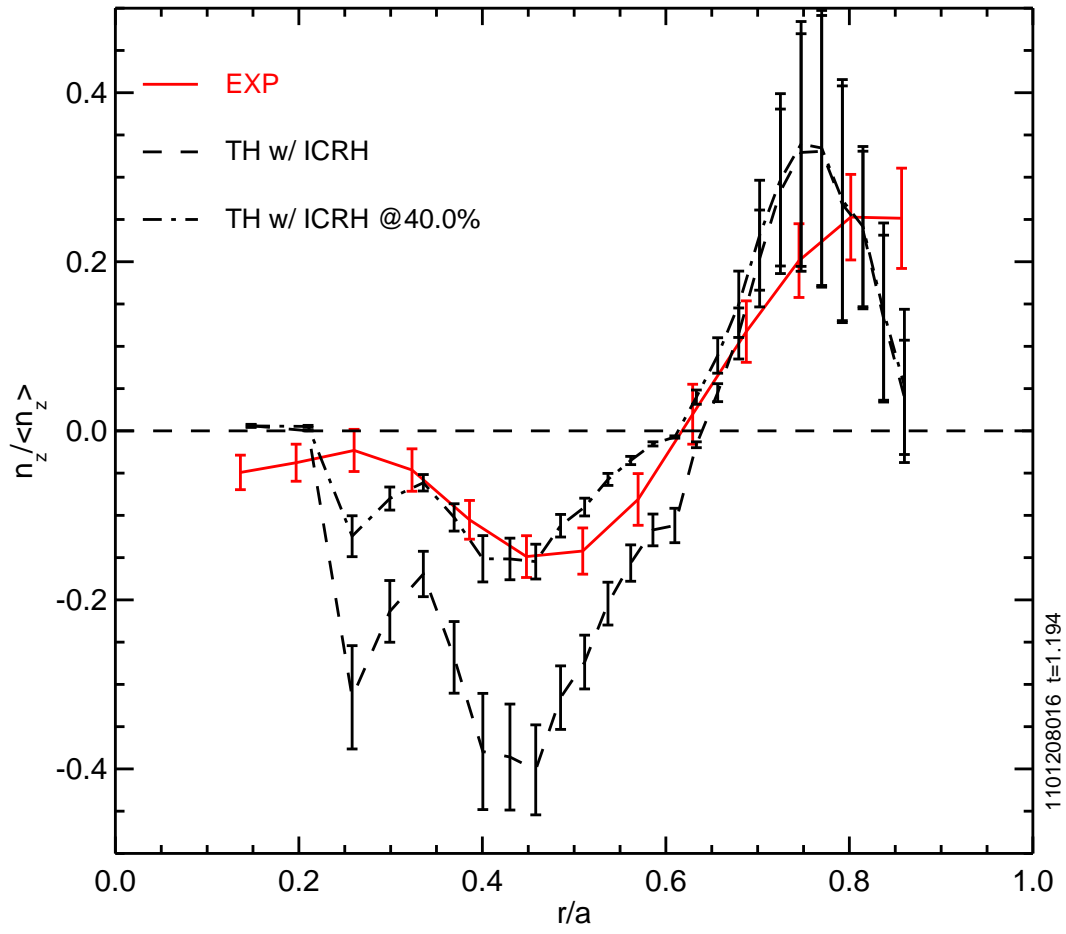


FIGURE 11

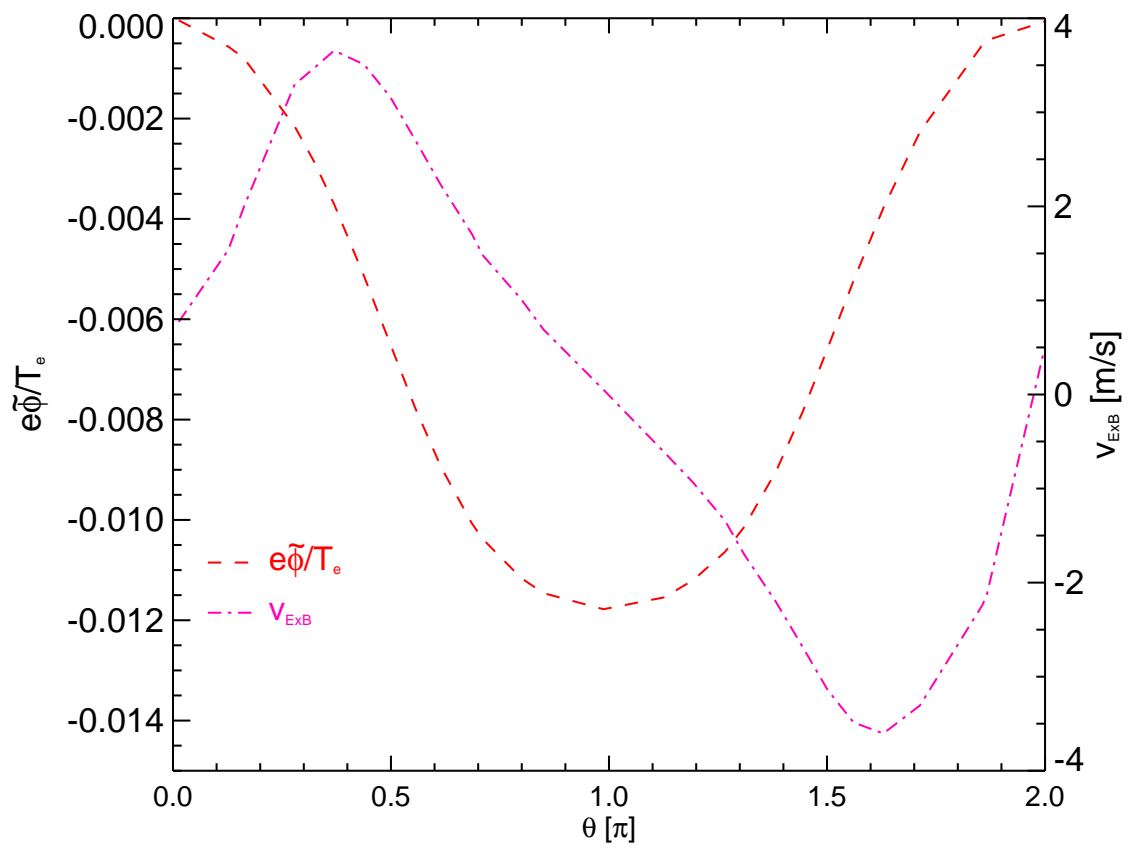


FIGURE 12