Experimental Results from Three-ion Species Heating Scenario on Alcator C-Mod*

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Abstract. Recent experiments on Alcator C-Mod using a small fraction of $^3$He added to a H(D) plasma have demonstrated efficient ion cyclotron radio frequency (ICRF) heating and indications of MeV $^3$He tail energy. Overall plasma performance on C-Mod has been observed to be dependent on ICRF absorption efficiency. For high field $B_0=8$ T discharges with D majority, $^3$He minority absorption is typically used and has low single pass absorption compared to the H minority absorption scenario. With an appropriate $^3$He fraction, we have observed strong toroidal rotation that is correlated with RF power being absorbed by thermal $^3$He ions via mode converted waves. In addition to plasma heating, ICRF can also generate high energy ions and this provides a tool to study fast ion dynamics and to check and optimize the quality of plasma confinement. For these reasons, a new three-ion ICRF scenario identified recently [Y. Kazakov et al, Nucl. Fusion 55 032001 (2015)] that has efficient RF power absorption at very low resonant ion concentrations (~1% and even below) provides an interesting operating regime for Alcator C-Mod as well as for devices such as JET, ITER and Wendelstein 7-X. This scenario works by adjusting the concentrations of the majority and two minority species to arrange that the polarization of the ICRF wave is favorable for ion heating at the location of the cyclotron resonance of a third trace species.

1. Background

In Alcator C-Mod, a recently identified [1] three ion species heating scenario the possibility of strong RF absorption at 80 MHz with a magnetic field of 8 T on $^3$He in a hydrogen-deuterium mixture. The enhancement in RF absorption is of interest for ITER because there is the potential for improved absorption based on the D:T:$(^6$Be) three-ion species scenario which avoids or reduces the need for $^3$He during the ramp-up heating phase [2]. In addition, the absorbed power per resonant particle is much higher than for standard $^3$He minority absorption, and resonant ions can be accelerated to MeV energies which is of interest for ITER in the non-nuclear phase (H:$^4$He:$^3$He scenario) and for W7-X [2].

Simulations with the 2D full wave codes TORIC [3] and AORSA [4] support the strong absorption scenario and predict that the damping of RF power by $^3$He dominates when the concentration is below 2%. The heating is efficient and localized along the $^3$He fundamental resonance with other off-axis heating due to mode conversion. The strength of the latter varies with minority concentrations. A typical magnetic geometry is shown in Figure 1 with labels shown for the mid-plane resonances of the three species (solid vertical lines) and as well as the two ion-ion hybrid
resonances (S=0, dashed vertical lines). Each hybrid layer occurs between a pair of ion species. Since the $^3$He concentration is so low (69.6% H, 30% D, 0.2% $^3$He for the example shown in Figure 1), the second hybrid layer is only separated from the $^3$He resonance by 0.4 cm in this case. This consequently puts two left hand cutoffs right in the Doppler broadened $^3$He resonance where the wave has the favorable left hand polarization of damping on ions.

As the $^3$He concentration is varied from 0 to a few percent, TORIC simulations predict a sharp rise in ion heating followed by a slow decrease. Figure 2 shows the electron and ion heating rates and predicts that above 2-3%, the heating efficiency becomes poor. Experimentally, a minimum concentration is needed for some absorption to take place, but in the simulation there is actually no minimum for a fixed Maxwellian distribution. The gradual fall-off in ion heating is due to the gradual shifting of the left-hand (L=\(n_{||}^3\)) layer away from the cyclotron resonance.

Experiments using a H:D($^3$He) three-ion scenario were carried out on Alcator C-Mod in the Fall of 2015 and Fall of 2016 campaigns with an 8 T central field and an H:D ratio of approximately 70%:30% (see also the paper by Y. Kazakov at this meeting for discussion of the JET experiments in the Spring of 2016 and applications to W7-X). The $^3$He concentration was varied over several shots controlled by gas puff duration and diagnosed with the phase contrast imaging (PCI) diagnostic [5]. Phase contrast imaging can detect the short-length waves from the mode conversion process which occurs at the ion-ion hybrid layer between two fundamental cyclotron layers. With a small amount of $^3$He in a H(D) plasma (with a large concentration of H), there are two mode conversion processes: one on the high field side of the $^3$He resonance layer and one on the low field side of the $^3$He layer. The distance between the two MC layers at small $^3$He concentrations is affected primarily by the $^3$He concentration but also by the H concentration. Analytically, the position of the two mode conversion layers is given to first order in the super minority concentration, \(c\):

\[
x_0 = \frac{a x_b + b x_a}{a + b}
\]

\[
x_{\text{res1}} = x_0 + \frac{c}{x_0 - x_c} \left( \frac{a}{(x_0 - x_a)^2} + \frac{b}{(x_0 - x_b)^2} \right).
\]

\[
x_{\text{res2}} = x_c + \frac{a}{x_c - x_a} + \frac{b}{x_c - x_b}
\]

where \(a = x_a x_c, x_a = \left( \frac{\mu_a}{Z_a} \right)^2, x_{\text{res1}} = \left( \frac{eB(r_{\text{res1}})}{m_H \omega} \right)^2\) is the resonance position measured as the square of the local Hydrogen cyclotron frequency normalized to the wave frequency, \(x_a\) is the concentration of species \(a\), \(\mu_a\) is the atomic mass in units of proton mass, \(Z_a\) is the atomic number of species \(a\), \(e\) is the electron charge, \(m_H\) is the proton mass, \(B\) is the magnetic field and \(\omega\) is the wave frequency, and \(x_0\) is the hybrid resonance location for two ion species with concentrations. These formulas show that the shift of the hybrid resonances is linear in the concentration of third species and so the shift will be
small for small concentrations. We can also use these formulas to estimate the third species concentration from the measured locations of the mode conversion (MC) layers from the PCI diagnostic. Assuming that the centers of the observed MC wave correspond to the $n_e^2 = S$ layer (ion-ion-hybrid layer), the species concentration can be estimated from the cold plasma dispersion relation. Analysis of the MC locations in these shots identifies that the range of the $^3$He in these plasmas are $n_{^3\text{He}}/n_e$ from 0.4% to 2%, and $n_{\text{H}}/n_e$ from 56% to 66%. Figure 3 demonstrates the connection between the cold plasma dispersion and the PCI measurements.

2. Analysis

During the discharges, a strong increase in toroidal Alfvén eigenmode (TAE) activity coincided with the injection of $^3$He to the H(D) plasmas. Alfvénic activity is indicative of the formation of fast ions with an energy on the order of 1 MeV. Increased heating localized around the $^3$He fundamental cyclotron layer was also observed. Figure 4 shows three experimental traces that demonstrate the correlation between total coupled RF power (bottom trace) with presence of the fast wave at the $^3$He layer as measured by PCI (middle trace) with the level of TAE activity (top trace). In subsequent analysis, a synthetic PCI diagnostic using the 3D RF electric fields from AORSA will be compared to the experimental PCI data to determine the breakdown between the two competing absorption mechanisms present in mode conversion layer. These mechanisms can either heat electrons or ions or drive momentum in the ion channel. In particular, the TAE modes appear after the turn on of the RF power at 0.81 s.
The minority ion temperature is calculated using Fokker-Planck calculations from CQL3D [6] with AORSA over a range of \(^3\)He concentrations. Figure 5 shows the central ion tail temperature as calculated from a self-consistent simulation of AORSA-CQL3D. The \(^3\)He concentration is 0.4% and produces a very energetic 3 MeV tail and bulk minority temperature of 300 keV. In this simulation, finite banana orbit losses were neglected. Subsequent simulation will use finite banana width orbit loss which is expected to reduce the maximum ion energy produced in the simulations and may also moderate the tail temperature. These ion tail temperatures will be compared with theoretical calculations of Alfvén eigenmode thresholds. Figure 6 shows the presence of TAE modes during long sawtooth periods in a three ion species heating experiment in Alcator C-Mod. The long periods are necessary to allow the build up of the minority ion tail which takes 10s of milliseconds. With the frequency spectra and mode numbers identified from a combination of analysis with PCI and magnetics, we will analyze the TAE and EAE gap modes using NOVA-K [7]. With additional input on the fast ion distribution we can examine the growth rate for each mode. Using assumptions about typical damping rates of such modes, we can then estimate the lower bound on the fast ion pressure that is needed to drive these modes. This work will be presented in a future paper.

3. Conclusions

We have shown the first experimental realizations from fall 2015 on Alcator C-Mod of the three ion species heating scenario as described by Kazakov [1]. Initial results have been subsequently confirmed by experiments in 2016 on JET and Alcator C-Mod. The existence of MeV energetic \(^3\)He ions have been inferred from the presence of Alfvén eigenmodes. AORSA full wave simulations done self-consistently with the CQL3D Fokker-Planck code also support the presence of an MeV minority tail. The phase contrast imaging (PCI) diagnostic have confirmed the presence of two mode conversion layers and also provide an indirect measurement of the \(^3\)He concentration. The scenario provides an efficient way of heating the ions and the bulk plasma and has application as bulk heating in ITER at 40 MHz with \(^9\)Be-(4He)-H species mixture or as a source of pseudo-alpha population for confinement studies on W7-X.
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5. References