Experimental Characterization of Plasma Heating with Beating Electrostatic Waves at High Wave Energy Density

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I. Introduction and Previous Work

The heating of plasmas using externally-applied radio frequency (RF) waves is an important process in many scientific and industrial applications. The use of RF waves for plasma heating has particular advantages for plasma propulsion applications in which material erosion of electrodes can severely decrease propulsion system lifetime. The ability of RF waves to impart energy to a plasma propellant for heating without requiring components that directly contact the plasma enables the design of electrodeless plasma thrusters that are not subject to the detrimental effects of electrode erosion.[1] Due to the usefulness of RF waves as a means of plasma heating, it is desirable to fully-characterize those RF heating processes that appear to be particularly effective.

One mechanism that has been shown[2,3] to be an efficient means of heating a magnetized plasma is using two electrostatic waves with angular frequencies that satisfy a beat criterion, defined as $\omega_2 - \omega_1 = n\Omega_i$, where ω_1 and ω_2 are the angular frequencies of the two electrostatic waves and Ω_i is the ion cyclotron frequency. This beating electrostatic wave (BEW) heating mechanism has been shown to be capable of heating non-resonant ions with thermal velocities that are lower than the phase velocities of the electrostatic waves. The ability of the BEW to exchange energy with ions of a spectrum of velocities is in contrast to a traditional method of plasma heating using a single electrostatic wave (SEW) that relies on a resonant energy exchange between the wave and only those ions with velocities approximately equal to the wave phase velocity.

Jorns and Choueiri recently completed an analytical and experimental investigation of BEW heating and a comparison of BEW and SEW heating.[4] They performed their analysis by considering the power, P_d, deposited by the beating waves into the plasma,

$$P_d = W_T \left(\frac{\alpha_1}{\beta_1}\eta + \frac{\alpha_2}{\beta_2}(1-\eta) + W_T \frac{\gamma_{12}}{\beta_1\beta_2}\eta(1-\eta) \right), \tag{1}$$

where W_T is the total wave energy density and η is the fraction of the total energy density in the beating electrostatic wave of lower frequency, ω_1. The other terms in Eq. 1 are characteristic of the interaction between the beating waves and the plasma and can be derived from the plasma dispersion relation for the electrostatic waves.[4] From Eq. 1, Jorns and Choueiri showed analytically that there exist distinct regimes of electrostatic wave energy density in which either BEW or SEW will provide superior heating. In particular, it was shown that there exists a threshold value of wave energy density, W_T^*, above which BEW are expected to provide superior heating. This threshold energy density, W_T^*, is defined as follows,

$$W_T^* = \left| \frac{\alpha_1\alpha_2}{\gamma_{12}} \left(\frac{\beta_2}{\alpha_2} - \frac{\beta_1}{\alpha_1} \right) \right|. \tag{2}$$

Jorns constructed the Beating Waves Experiment II (BWX II) in order to experimentally investigate the analytical predictions of BEW and SEW heating in distinct regimes of wave energy density. Figure 1 depicts a subset of the results from BWX II which show the percentage increase in ion temperature as a function of the fraction of total wave energy density in frequency ω_1. It is noted that the maximum energy density that was employed in the BWX II was only 17% of the threshold value, W_T^*. It is seen in the figure that for low wave energy densities, SEW ($\eta \approx 1$) provide superior heating, while for values of wave energy density above 10% of the W_T^* threshold, the ion temperature increase asymptotes to a constant for values of η greater than 0.2. Jorns suggested that this asymptotic behavior is likely due to a saturation of the power absorption from each SEW and does not demonstrate additional heating due to a BEW effect. BWX II was unable to confirm the superiority of BEW above the predicted threshold, W_T^*, due to limitations on the available wave power that could be introduced to the plasma.

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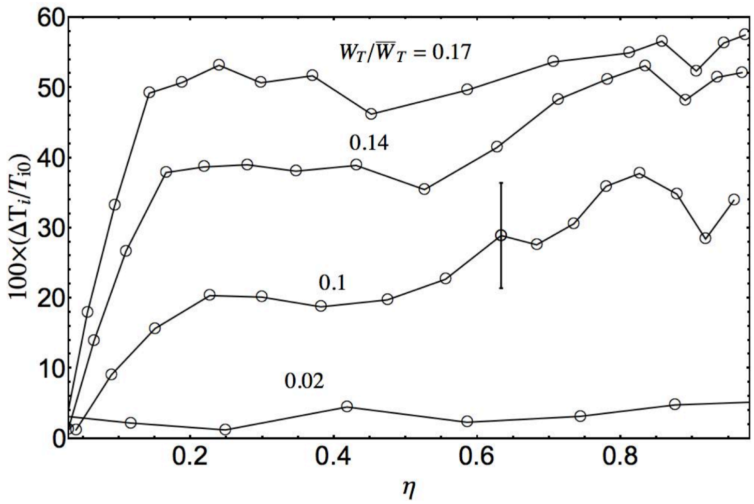

Figure 1. Fractional increase in ion temperature as a function of the fraction of total wave energy density in the first mode at ω_1. Each curve represents a case where the normalized total wave energy density, W_T/W_T^*, is constant. The threshold wave energy density, W_T^*, equals 3000 Jm^{-3} [4].

II. Future Work

Due to the potential usefulness of BEW as an efficient means of plasma heating, there is a need to experimentally verify the analytical predictions of Jorns and Choueiri pertaining to BEW superiority at high wave energy densities above the W_T^* threshold. In this paper, we will therefore present results of an experimental investigation of plasma heating using BEW and SEW of sufficiently high wave energy densities such that these experiments will be performed above the energy threshold value for BEW superiority. The achievement of the desired wave energy densities will necessarily require the implementation of an upgraded BWX II experimental setup. Among the potential improvements to BWX II that may be implemented, the design and construction of a new BEW antenna may be particularly beneficial to this effort and will therefore be attempted as a first experimental upgrade. BWX II currently employs a 40-turn strap antenna located external to the plasma. Other antenna configurations may prove to be more optimized for introducing electrostatic modes into the plasma, such as the Nagoya III for coupling to the electric field component of helicon modes and the Helmholtz coil antenna which can excite the electrostatic ion cyclotron wave. Both antenna configurations may be capable of raising the electrostatic wave energy density without requiring the use of a more powerful RF source. We may also tailor the parameters of the BWX II plasma, such as neutral density, to decrease the effect of various mechanisms that may attenuate the waves.

The ability to produce electrostatic waves of high wave energy density will also allow for the investigation of different angular frequency combinations of BEW. Previous experiments in BWX II were limited to employing only the $2\Omega_i$ and $3\Omega_i$ harmonics as this combination of electrostatic waves yielded the lowest W_T^*. The ability to introduce higher power waves into the BWX II plasma will allow us to experiment with a wider range of harmonic combinations in order to determine if there exists an optimum pairing of angular frequencies at which the largest ion temperature increase is achieved.

References

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