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NUMERICAL MODELING OF THE EBT-S
ION-CYCLOTRON HEATING EXPERIMENT

J. L. Sperling, S. Hamasaki,
H. H. Klein and N. A. Krall

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NUMERICAL MODELING OF THE EBT-S ION-CYCLOTRON HEATING EXPERIMENT

To determine the effect of ion-cyclotron heating on EBT-S plasma parameters, a one-dimensional, time dependent neoclassical model of plasma particle and energy transport was used. Previously this code has been successfully checked against EBT-1 experimental results and has been used to predict EBT-P plasma parameters¹. The interested reader is referred to Reference 1 for the code details and the code results for both EBT-1 and EBT-P.

For EBT-S the code was run with the following parameters.

$B_0 = 0.7$ tesla (axial field at the midplane)

$B_0 = 1.4$ tesla (axial field at the throat)

$R_T = 150$ cm (major radius)

$a = 15$ cm (minor radius at the midplane)

The radially dependent magnetic field of Reference 1 was used for the calculations described below. Electron and ion heating by waves was modeled by assuming various power deposition profiles in the plasma. Two different deposition profiles were actually used in the calculations. For the first profile (see Figure 1), power deposition is assumed proportional to density for both the electron and ions (i.e., $P_i, P_e \propto n$). For the second profile (see Figure 2), the energy deposition is evaluated at the center of each cell with the following weighting, $P_i, P_e \propto n (1 - V/V_{TOT})^{-1}$

¹ELMO Bumpy Torus Proof of Principle, Phase I - Project Definition Study, Final Report - Volume II Appendices, McDonnell Douglas Astronautics Co., St. Louis, Missouri, Appendix A.

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where V and V_{TOT} are the plasma volume contained within a radial surface and the total plasma volume, respectively. Hence, for the first heating profile and relatively constant density across EBT, heating is relatively uniform across the plasma, while for the second profile there is preferential heating toward the outside of the plasma.

Two important results are evident upon examination of Figures 3-22. First, ion power leads to improved plasma parameters (i.e., electron temperature, ion temperature, density and energy confinement time). Second, plasma parameters are much more strongly dependent on the magnitude of the total power input to the plasma rather than the power deposition profile (see Figures 19-22). However, the uniform profile (Figure 1) results in somewhat higher electron temperatures but lower densities than the more outwardly peaked profile (Figure 2).

Specifically, Figures 3, 5, 7, 9, 11, 13, 15, 17, 19-21, indicate that even a small amount of ion heating can have a significant effect on plasma densities and temperatures. All these figures have a total electron power deposition in the plasma of 10 kW; however, Figure 3 corresponds to no ion power, while Figures 5 and 7 are with 2 kW of ion power but with the different power deposition profiles. The presence of this small amount of ion power results in an increase in central density from 2.4 to over $3 \times 10^{12} \text{ cm}^{-3}$, an increase in electron temperature from 500 eV to 730 and 650 eV and a more than doubling of ion temperature from 70 eV to 160 eV. The energy confinement time is also almost doubled from just under 10 msec to roughly 18 msec (Figure 22).

Further increments of ion power to 5, 10 and 20 kW for fixed electron power of 10 kW leads to additional improvement in plasma parameters. With 10 kW of ion power, a central density of roughly $4 \times 10^{12} \text{ cm}^{-3}$ (the cutoff density for 18 GHz microwaves) can be attained (see Figures 13 and 15). With 20 kW of ion power, densities of $4.5 \times 10^{12} \text{ cm}^{-3}$, in excess of the 18 GHz cutoff, are predicted (Figure 17). Energy confinement time seems to be maximized for power levels of roughly 5 or 10 kW (Figure 22); however, because of the density increase, the quantity $n\tau_E$ increases with ion power over the entire range studied.

In all cases the self-consistent ambipolar electrostatic potential associated with the transport corresponds to a radially inward electric field (Figures 4, 6, 8, 10, 12, 14, 16, and 18). The ambipolar electrostatic field in the outer plasma regions where the plasma products are larger is found to increase with ion power.

To summarize, the transport code results suggest that ion power can be used to increase the plasma parameters in EBT-S. The results are relatively insensitive to the power deposition profile. For the power levels used, the electron temperature is greater than the ion temperature and the ambipolar electrostatic field is radially inward. Temperature and density profiles are rather flat across most of the plasma cross section and only vary rapidly near the plasma edge. Also, the magnitude of the ambipolar electrostatic field in the outer regions of the plasma increases with ion power.

Figure Captions

- Figure 1. Representative example of a power deposition profile proportional to density (power deposition per unit volume in arbitrary units, $\bar{P}$, vs. radius).
- Figure 2. Representative example of a power deposition profile peaked toward the outside of the plasma (power deposition per unit volume in arbitrary units, $\bar{P}$, vs. radius).
- Figure 3. Density and temperature profiles in units of 10^{12} cm^{-3} and 100 eV vs. radial distance in centimeters for the power deposition profile of Figure 1. The total electron and ion power deposition rates are $P_e = 10 \text{ kW}$ and $P_i = 0 \text{ kW}$, respectively. The neutral flux is 1.5×10^{17} particles per 2π per second per sector.
- Figure 4. Electrostatic potential in volts vs. radial distance in centimeters for the power deposition profile shown in Figure 1. The total electron and ion power deposition rates are $P_e = 10 \text{ kW}$ and $P_i = 0 \text{ kW}$, respectively. The neutral flux is 1.5×10^{17} particles per 2π per second per sector.
- Figure 5. Same as Figure 3 but $P_i = 2 \text{ kW}$.
- Figure 6. Same as Figure 4 but $P_i = 2 \text{ kW}$.
- Figure 7. Same as Figure 3 but $P_i = 2 \text{ kW}$ and the power deposition profile is given by Figure 2.
- Figure 8. Same as Figure 4 but $P_i = 2 \text{ kW}$ and the power deposition profile is given by Figure 2.
- Figure 9. Same as Figure 3 but $P_i = 5 \text{ kW}$.
- Figure 10. Same as Figure 4 but $P_i = 5 \text{ kW}$.
- Figure 11. Same as Figure 3 but $P_i = 5 \text{ kW}$ and the power deposition profile is given by Figure 2.

- Figure 12. Same as Figure 4 but $P_i = 5$ kW and the power deposition profile is given by Figure 2.
- Figure 13. Same as Figure 3 but $P_i = 10$ kW.
- Figure 14. Same as Figure 4 but $P_i = 10$ kW.
- Figure 15. Same as Figure 3 but $P_i = 10$ kW and the power deposition profile is given by Figure 2.
- Figure 16. Same as Figure 4 but $P_i = 10$ kW and the power deposition profile is given by Figure 2.
- Figure 17. Same as Figure 3 but $P_i = 20$ kW and the power deposition profile is given by Figure 2.
- Figure 18. Same as Figure 4 but $P_i = 20$ kW and the power deposition profile is given by Figure 2.
- Figure 19. Electron density (10^{12} cm^{-3}) vs. ion power (kW) for $P_e = 10$ kW and neutral flux (1.5×10^{17} particles per 2π per second per sector). Solid lines are for the power deposition profile, Figure 1, and broken lines for the profile Figure 2.
- Figure 20. Electron temperature (10^2 eV) vs. ion power (kW) for $P_e = 10$ kW and neutral flux (1.5×10^{17} particles per 2π per second per sector). Solid lines are for the power deposition profile, Figure 1, and broken lines for the power Figure 2.
- Figure 21. Ion temperature (10^2 eV) vs. ion power (kW) for $P_e = 10$ kW and neutral flux (1.5×10^{17} particles per 2π per second per sector). The power deposition profiles of Figure 1 and Figure 2 result in essentially the same ion temperatures.
- Figure 22. Energy confinement time (msec) vs. ion power (kW) for $P_e = 10$ kW and neutral flux (1.5×10^{17} particles per 2π per second per sector). Solid lines are for the power deposition profile shown in Figure 1 and the dotted lines are for the deposition profile Figure 2. Between $P_i = 2$ and 10 kW the energy confinement time for both deposition profiles is the same.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16

Figure 17

Figure 18

Figure 19

Figure 20

Figure 21

Figure 22