JAYCOR

J510-80-001

CONF-800707--24

THEORETICAL STUDIES OF EBT

MASTER

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

May 1980

Paper to be presented at IAEA, Brussels Conference, 1980

P.O. Box 370 - 1401 Camino Del Mar • Del Mar, California 92014 • 714/453-6580

THEORETICAL STUDIES OF EBT*

S. HAMASAKI, H. H. KLEIN, N. A. KRALL, J. B. McBRIDE and J. L. SPERLING
JAYCOR, Del Mar, California

Scaling EBT to Proof-of-Principle

We have used a one-dimensional time dependent model of plasma particle and energy transport to predict the performance of an EBT experiment large enough to test confinement scaling in a parameter range (n, T, τ, etc.) close to reactor conditions. Such a device is referred to as EBT-P. The model is based on a computer code [1] which uses the magnetic field lines as the basis for the coordinate system, and so includes some EBT geometrical effects, with neoclassical transport [2] perpendicular to the surfaces of constant pressure. The geometry is self-consistent, i.e., the plasma pressure reacts on the magnetic field. The transport equations in this system are defined in terms of α, ψ and χ, by $\underset{\sim}{B} = \nabla\alpha \times \nabla\psi$, $\nabla\alpha \cdot \nabla\psi = 0$, and $\underset{\sim}{B} \times \underset{\sim}{\chi} = 0$. In terms of a flux surface average defined by

$$<A> = \partial[\int_V d^3x\, A]/\partial V \quad ,$$

where V is the volume contained within a ψ surface, the transport equations become

$$\frac{\partial}{\partial t} <n> + \frac{\partial}{\partial V} <\Gamma\cdot\nabla V> = <S>$$

$$\frac{3}{2}\ \frac{\partial <p_j>}{\partial t} + \frac{\partial}{\partial V} <Q_j\cdot\nabla V> = <S_j>$$

$$4\pi \frac{\partial p}{\partial V} + \frac{\partial\psi}{\partial V}\ \frac{\partial}{\partial V} K \frac{\partial\psi}{\partial V} = 0$$

$$<\dot{\psi}> = <ch_\alpha E_\alpha> \quad , \qquad K = (\oint Bdl)\ (\oint dl/B)$$

where h_α are the metric coefficients and K is geometric. The transport coefficients include both the collisional and plateau regimes. The model has been benchmarked against ORNL calculations [3] of EBT-1 performance.

In the present application, point model scaling estimates which indicate $\tau_E \propto R_T^2/R_C^2$, p(power in) $\propto R_T^3$ is used to estimate the R_T, R_C required to confine 10^{13} cm^{-3} at 1 keV with about 1 MW of input power. This leads to the machine parameters used in this study: B_o = 14 kG, R_T = 550 cm (major radius), a = 32 cm (midplane), a = 20 cm (mirror throat), N = 36 sectors, β_A = 0.4 (annular beta), R_C = 22 cm (midplane radius of curvature). Given these baseline values for the geometry, the 1-D model is used to calculate the performance parameters n, T_i, T_e, τ_E vs. the direct electron heating (e.g., ECRH), direct ion heating (e.g., beams or ICRH) and neutral particle influx, Figs. 1 and 2. We conclude that the plasma quality improves in all respects by increasing the electron or ion power deposition, as well as by optimizing the neutral influx. More significantly, direct ion heating allows at least one additional set of operating states, of higher density and temperature than available using an equal input of electron heating above. These equilibria states have negative ambipolar fields, just as in EBT-1.

---

*Supported in part by the U.S. Department of Energy and in part by subcontract to McDonnell Douglas Corporation.

Electron Ring Heating

The confinement, heating and stability of the hot electron annulus which gives mhd stability to EBT involves a complex interplay of many physical effects. We concentrate on one of these effects, the balance between a relativistically correct heating rate and classical energy loss processes. The heating calculation emphasizes the role of second harmonic heating and relativistic effects in the steady state ring temperature, and includes the effects of mode polarization, and spectra and the spatial location of microwave cutoff and resonance regions. Lacking in the calculation is a self-consistent determination of the wave amplitude and spectrum, and a calculation of spatial transport out of the ring region, i.e., the plasma density and microwave field level are treated as known parameters. The approach is quasi-linear [4], and gives the heating rate in the annulus as

$$\frac{dW}{dt} = \frac{\pi \omega_p^2 m_o}{8\omega} \sum_k \sum_n \int p_\perp \, dp_\perp \int dp_z \, \delta\left[p_z - \frac{m_o}{k_z}(\gamma\omega - n\Omega_o)\right]$$

$$|\vartheta|^2 \left[\frac{n\Omega}{p_\perp}\frac{\partial f_o}{\partial p_\perp} + \frac{k_z}{m_o \gamma}\frac{\partial f_o}{\partial p_z}\right]$$

$$\vartheta \equiv p_\perp E^- J_{n-1}(b)\, e^{i\psi} + p_\perp E^+ J_{n+1}(b)\, e^{i\psi} + 2\, p_z E_z J_n(b)$$

which includes the resonance condition (in the δ-functions), the relativistic mass shift which shifts the location of cyclotron resonance at high energies, the polarization (E^+, E^-), and higher harmonic contribution through $J_n(b)$, $b \equiv kp_\perp/m_o\Omega_o$. Classical loss processes include synchrotron radiation, bremmstrahlung, and velocity drag. The cutoff conditions are $\omega \neq \omega_p/(1 - \Omega_e/\omega)^{1/2}$ for the extra-ordinary mode. Figs. 3 and 4 show the competition between ring heating and drag by the background. Ring equilibrium would occur when the heating curve crosses the drag curve. Figure 3, where resonance is at $R \approx 8.9$ cm, suggests that a ring thickness of about 2 cm is reasonable, in that the high energy component has difficulty overcoming drag for further off-resonant points. Fig. 4 shows that the ordinary mode (primarily first harmonic) is ineffective at heating cold plasma, but becomes competitive with 2nd harmonic extraordinary mode heating at high temperature. Heating by 1st harmonic extraordinary mode would be even larger at low temperature, but requires a penetration mechanism, e.g., mode conversion at the mirror throat. In summary,

- Second harmonic heating is not sufficient to start up the ring if it must compete with drag by a 10^{12} cold background. Lower bulk density during startup (to reduce drag) or mode conversion (to allow the more effective 1st harmonic extraordinary mode to penetrate) would give the required preheating of the ring.

- Localized rings of thickness 1-2 cm and temperatures of several hundred keV in the range of EBT-1 parameters are predicted by ECR heating with microwave fields $\sim$ 100 V/cm (consistent with the input power level), if the startup problem is assumed solved.

---

[1] KLEIN, H. H., BYRNE, R. N., J. Comp. Physics 32 (1979).
[2] HAZELTINE, R. D., KRALL, N. A., KLEIN, H. H., CATTO, P. J., Nucl. Fusion 19 (1979).
[3] JAEGER, E. F., HEDRICK, C. L., Nucl. Fusion 19 (1979) 443.
[4] KENNEL, C. F., ENGLEMANN, F., Phys. Fluids 9 (1976) 2377.

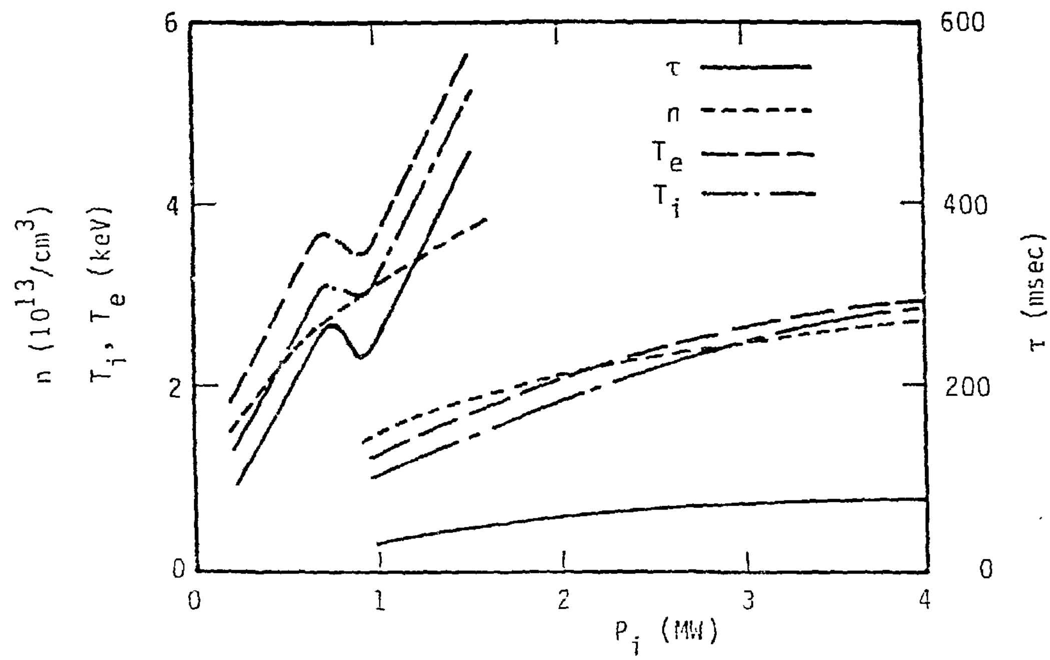

Figure 1. EBT-P performance vs. direct ion heating for 0.75 MW direct electron heating.

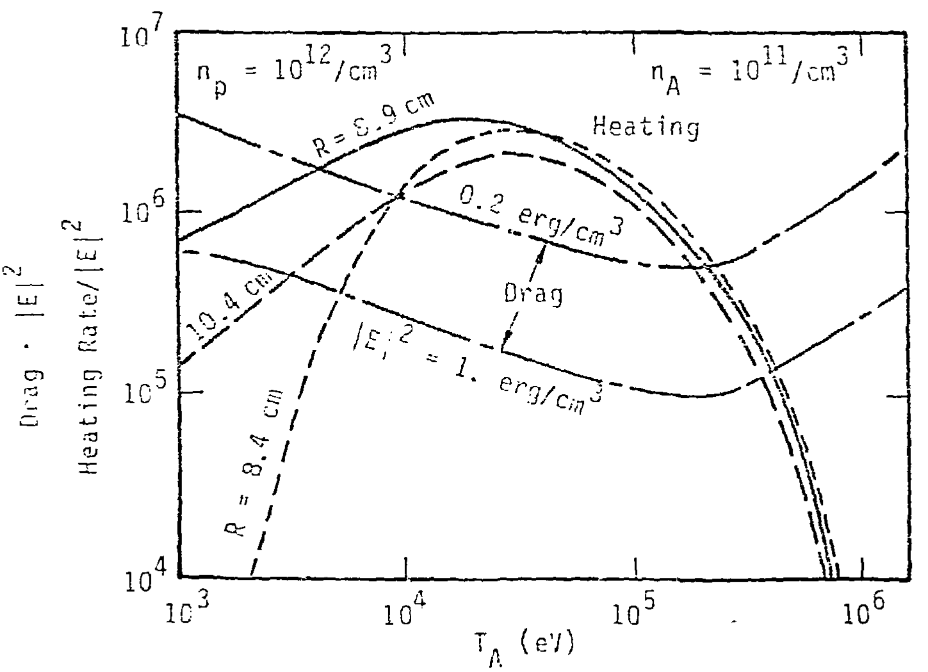

Figure 2. Plot of the line averaged RF heating rate (referred to the radius at the midplane) due to extraordinary mode and the classical power loss rate per unit volume. Heating rate is normalized to $|E|^2$.