Numerical Calculations of Steady State Microwave Plasma Parameters

by

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The work described here was motivated by a desire to predict the plasma parameters in the ELMO Bumpy Torus presently under construction at Oak Ridge. The basic method is a zero-dimensional computer calculation in which the particle and power balance equations are simultaneously solved. In the course of the development of the computer code, it became apparent that it could be applied to any steady state cylindrical plasma such as a mirror or a large aspect ratio torus. In fact, with only minor modifications, the technique can be extended to time dependent plasmas as well.

Shown below are the three differential equations that are simultaneously solved.

$$\frac{dn}{dt} = \frac{n}{\tau_{IONIZ}} - \frac{n}{\tau_{DIFF}}$$

$$\frac{dT_e}{dt} = \frac{P_{\mu w}}{nV} - \frac{T_e - T_i}{\tau_{ei}} - \frac{T_e}{\tau_{DIFF}} - \frac{30}{\tau_{IONIZ}}$$

$$- \left.\frac{dT_e}{dt}\right|_{BREM} - \left.\frac{dT_e}{dt}\right|_{SYNCH}$$

$$\frac{dT_i}{dt} = \frac{T_e - T_i}{\tau_{ei}} - \frac{T_i}{\tau_{DIFF}} - \frac{T_i}{\tau_{cx}}$$

The first is a particle balance equation. The electron and ion densities are assumed equal. Particles are produced by ionization and lost by diffusion. The ionization time is approximated by a complicated analytic function of electron energy. The electrons and ions are assumed to be Maxwellian. The neutral pressure outside the plasma is specified explicitly, and the pressure inside the plasma is calculated using the mean free path for neutral atoms. Both thermal and Franck-Condon neutrals are considered. Various diffusion mechanisms have been considered including neo-classical and Bohm.

The electrons are heated by microwaves. The heating is assumed to be 100% efficient so that the heating rate is just the input microwave power divided by the number of particles. Energy is lost from the electrons through Coulomb collisions with the ions, through diffusion to the walls, through excitation and ionization of neutrals, and by Bremsstrahlung and synchrotron radiation. The electrons are assumed to lose 30 eV of energy per ionization to the background neutrals. The neutral gas is assumed to be hydrogen, and impurities which may be liberated from the walls have been neglected.

The ions are heated by collisions with electrons and cooled by diffusion to the walls and by charge exchange with neutrals. These three equations are solved by successive iteration. The initial conditions are set arbitrarily, and the iteration proceeds until a steady state is reached. The microwave power can then be slowly increased in time so as to maintain a steady state. This is done by requiring that dT_e/dt be less than 1% of $P_{\mu w}/nV$. The density and the electron and ion temperature can then be plotted as a function of microwave power.

Fig. 1 shows a typical result for the ELMO mirror device with classical diffusion into the loss cone. The ambipolar electrostatic potential has been included, but the method by which this was done will not be discussed. The density and electron temperature increase monatonically with power while the ions remain cold. In the real experiment, most of the stored energy is in a relativistic component of electrons, and these have been ignored in the computer calculation. The numbers agree within about a factor of two with the parameters of the cold plasma component actually observed in ELMO.

Fig. 2 shows how the electrons are losing energy as a function of microwave power. Diffusion dominates the losses over most of the range except at low power where the temperature is low and collisions with neutrals are important.

Fig. 3 shows the result for the ELMO Bumpy Torus assuming neo-classical diffusion. We assume a stable equilibrium with a density gradient scale length equal to the minor radius of the torus. Ambipolar potentials have also been neglected. We don't take the numbers too seriously, but there are some interesting features such as the discontinuity at 50 kW that marks the transition into the collisionless regime.

Fig. 4 shows where the energy is lost for this case. The dependences are a bit complicated, but note that none of the loss mechanisms, except perhaps bremsstrahlung, are negligible over the whole range.

Fig. 5 shows the result of adding Bohm diffusion to the neo-classical diffusion in the Bumpy Torus. The density is considerably lower, and the electron temperature runs away when the microwave power reaches about 30 kW.

Fig. 6 shows where the power is lost for this case. Ionization and diffusion are the dominant loss mechanisms with Bohm diffusion. These cases are only examples of more than 100 cases that have been run for various combinations of parameters. In particular, we have been interested in determining scaling laws for the bumpy torus configuration. We have been rather encouraged by the results, although we don't take the numbers too seriously because classical confinement seems to be the exception rather than the rule in toroidal devices. We intend now to apply the calculation to a variety of existing confinement devices and to make the calculation as realistic as possible by refining the numerous approximations that have been made. We are also in the process of developing a one-dimensional version of the code so that we can study the radial dependence of the plasma parameters.

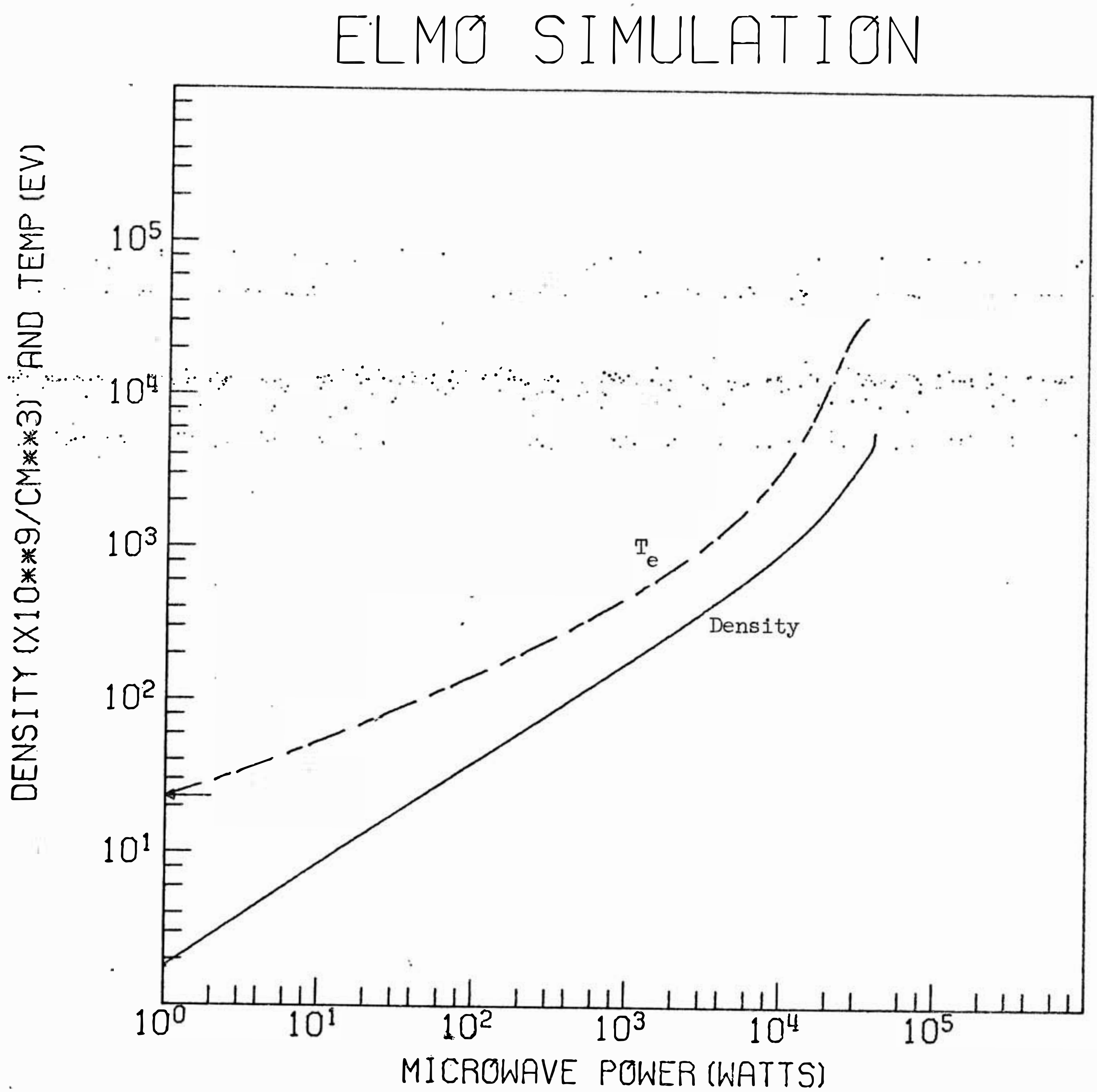
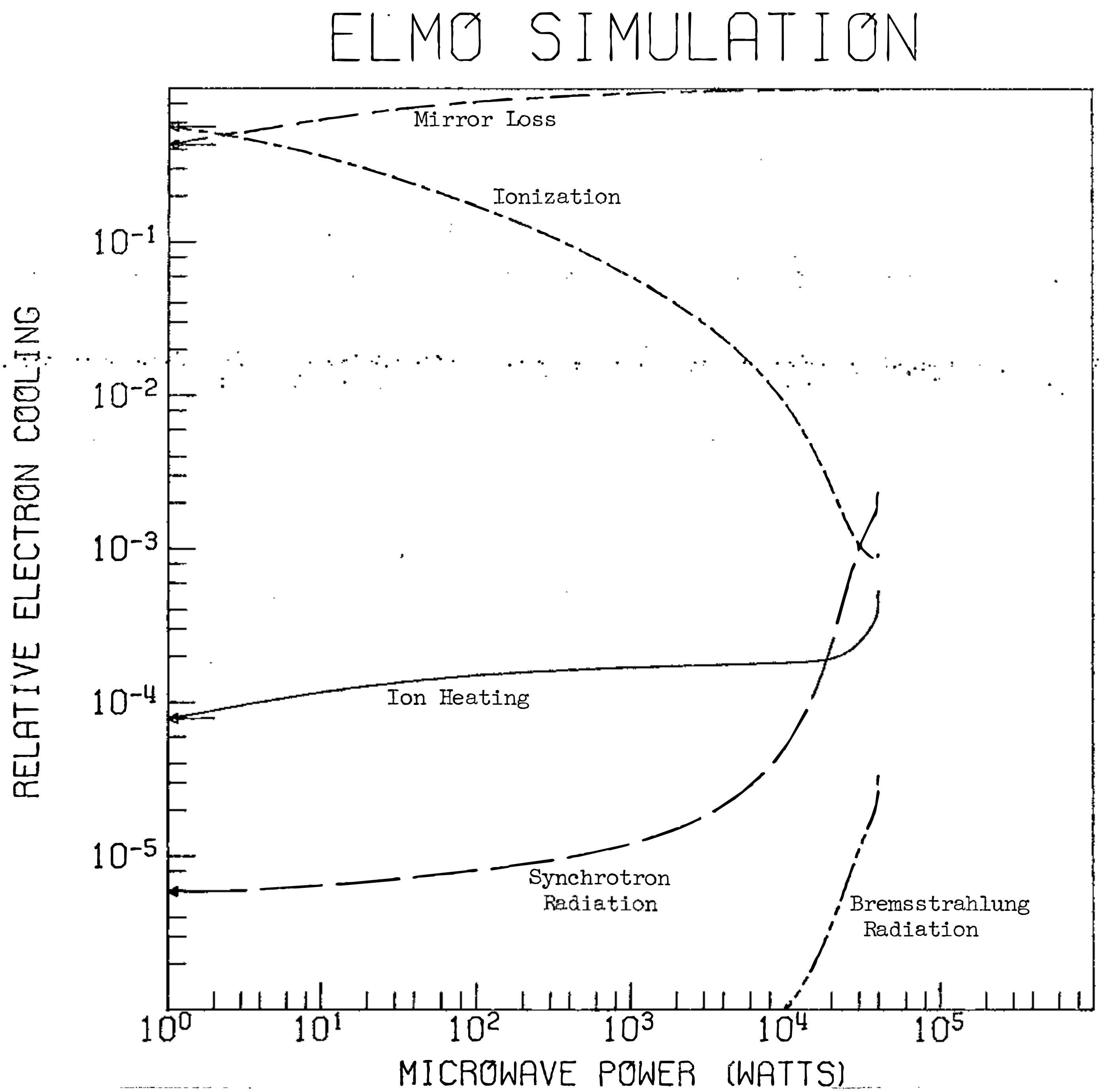
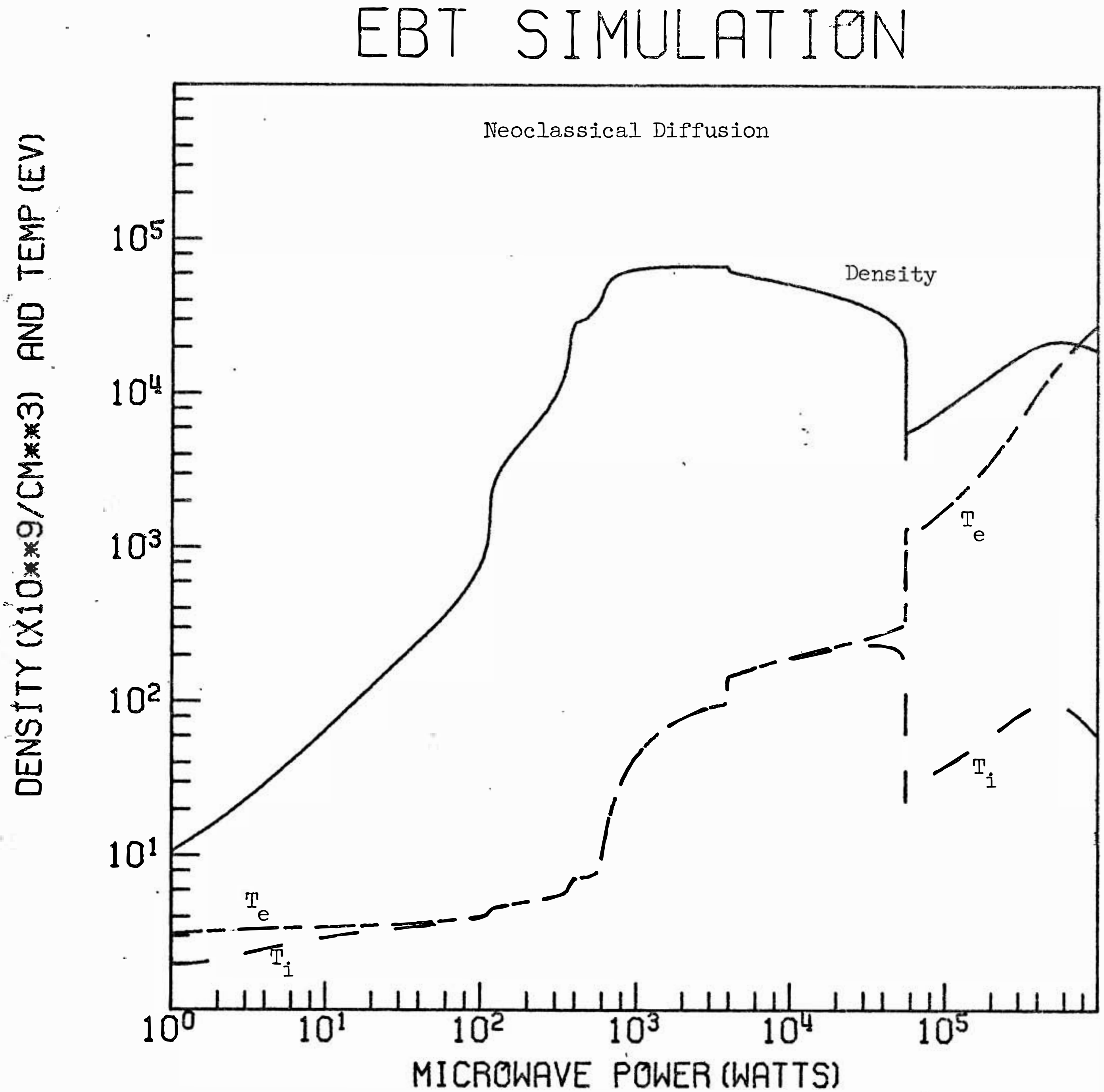

ELMØ SIMULATION
DENSITY (X10**9/CM**3) AND TEMP (EV)
10^5
10^4
10^3
10^2
10^1
10^0
10^1
10^2
10^3
10^4
10^5
MICRØWAVE PØWER (WATTS)
Te
Density

Figure 1



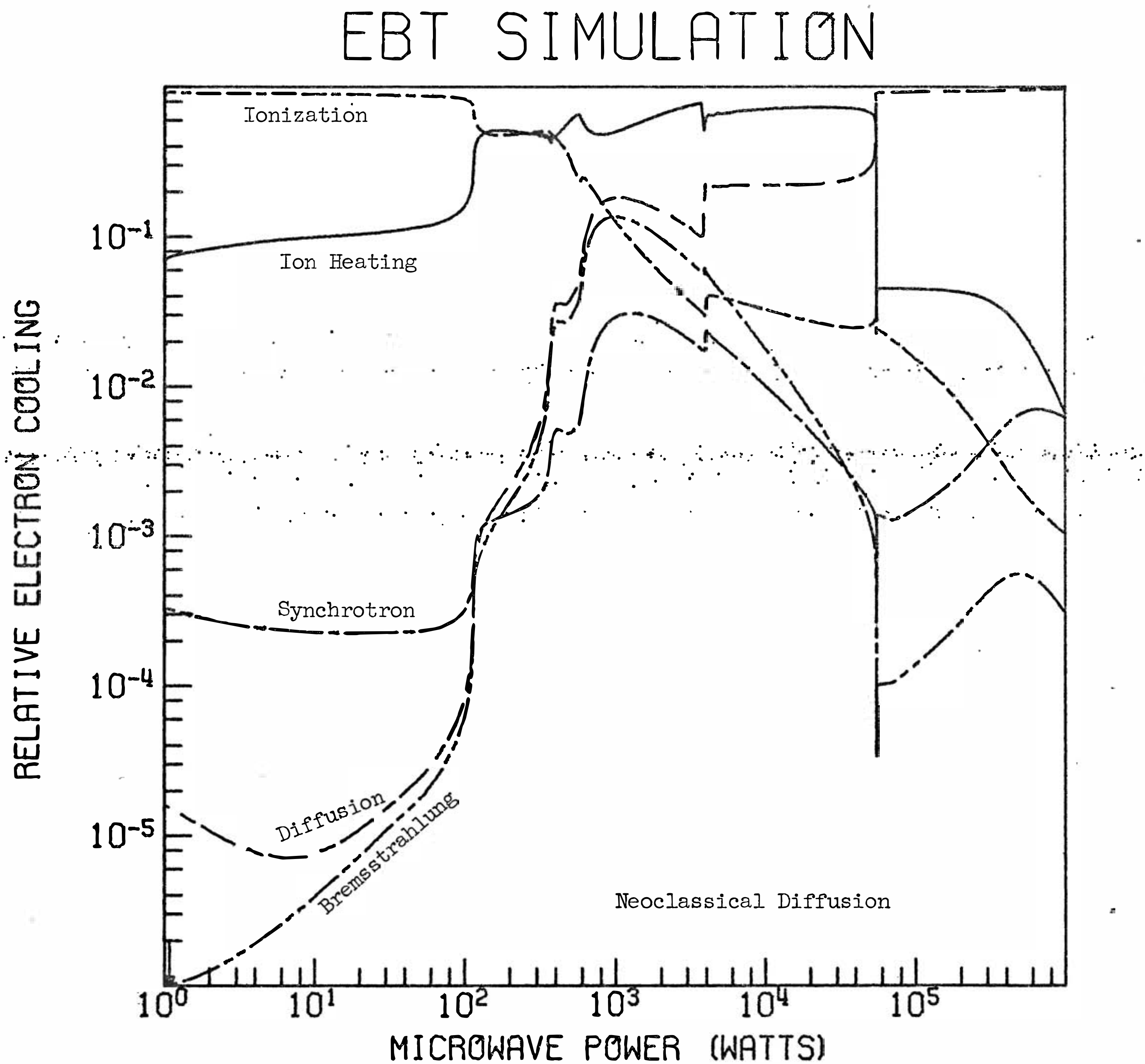
ELMØ SIMULATIØN
Mirror Loss
Ionization
Ion Heating
Synchrotron
Radiation
Bremsstrahlung
Radiation
RELATIVE ELECTRON COOLING
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
MICRØWAVE PØWER (WATTS)

Figure 2



EBT SIMULATION
Neoclassical Diffusion
Density
Te
Ti
Te
Ti
10^5
10^4
10^3
10^2
10^1
DENSITY (X10**9/CM**3) AND TEMP (EV)
10^0
10^1
10^2
10^3
10^4
10^5
MICROWAVE POWER (WATTS)

Figure 3



EBT SIMULATION
Ionization
Ion Heating
Synchrotron
Diffusion
Bremsstrahlung
Neoclassical Diffusion
RELATIVE ELECTRON COOLING
10^-1
10^-2
10^-3
10^-4
10^-5
10^0
10^1
10^2
10^3
10^4
10^5
MICROWAVE POWER (WATTS)

Figure 4

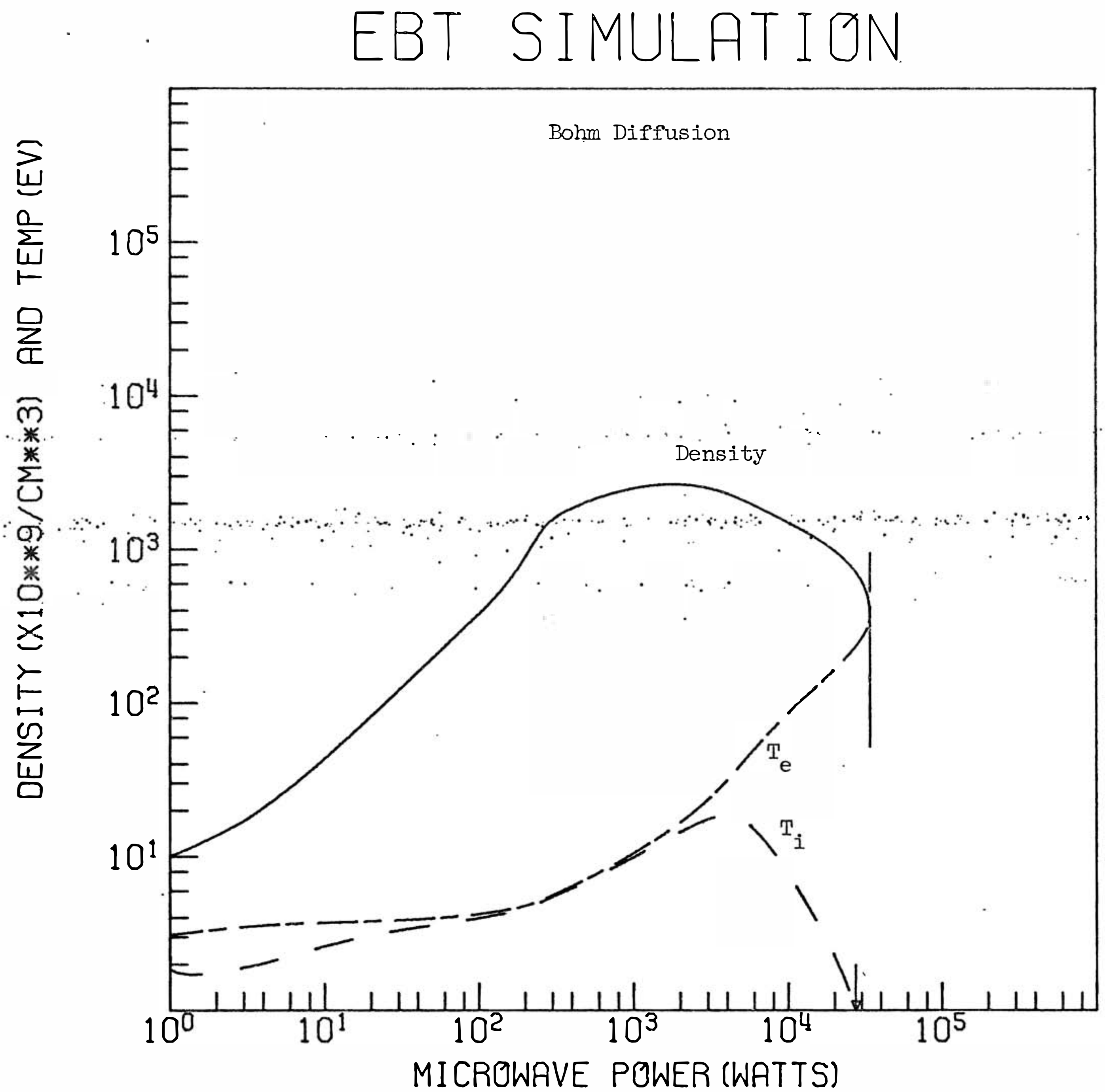

EBT SIMULATION
Bohm Diffusion
Density
T_e
T_i
DENSITY (X10**9/CM**3) AND TEMP (EV)
10^5
10^4
10^3
10^2
10^1
10^0
10^1
10^2
10^3
10^4
10^5
MICROWAVE POWER (WATTS)

Figure 5

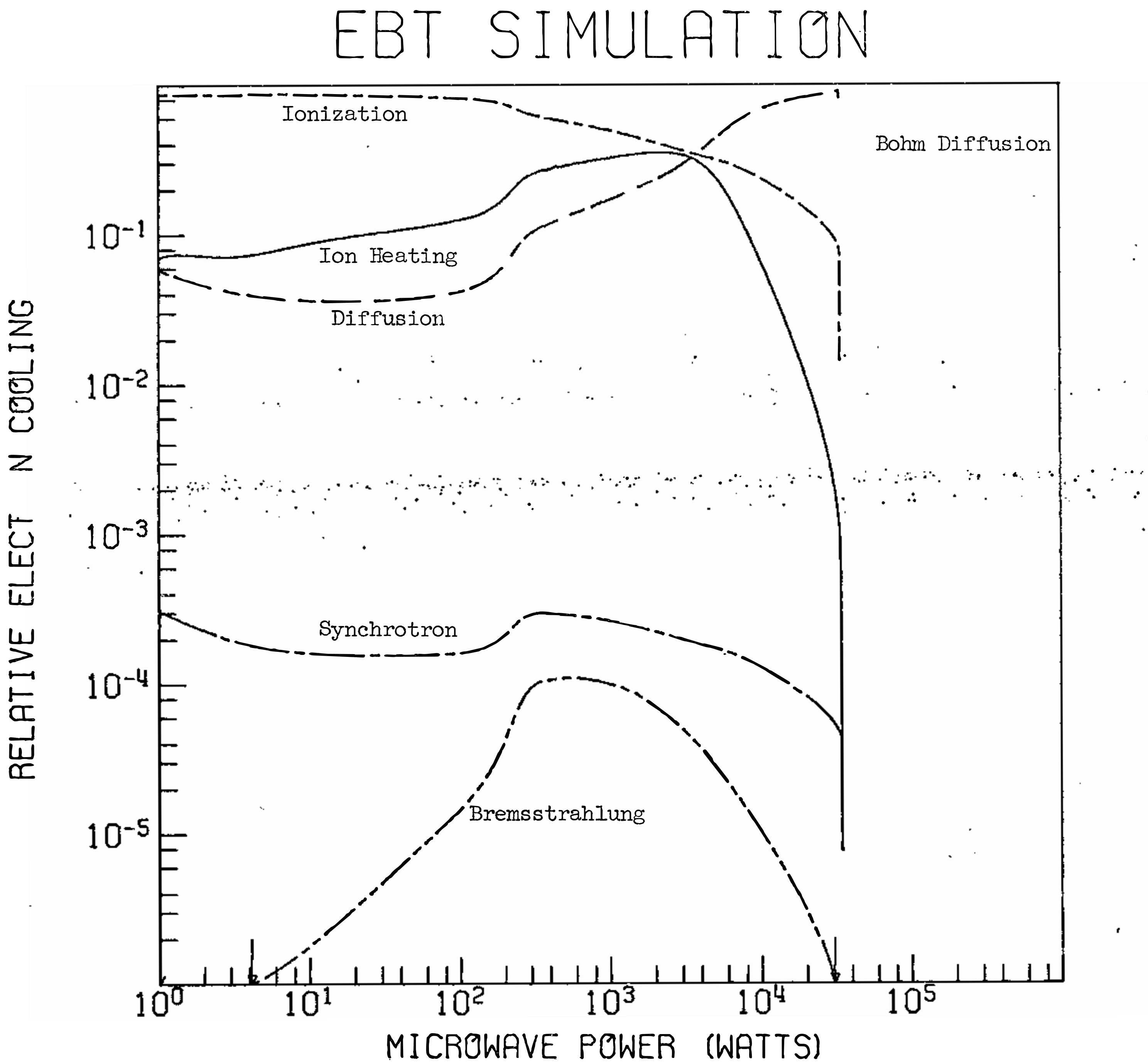

EBT SIMULATION
Ionization
Bohm Diffusion
Ion Heating
Diffusion
Synchrotron
Bremsstrahlung
RELATIVE ELECT N COOLING
MICROWAVE POWER (WATTS)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^0
10^1
10^2
10^3
10^4
10^5

Figure 6