RAYIC - A Numerical Code for the Study of Ion Cyclotron Heating of Large Tokamak Plasmas

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IPP 4/216 Februar 1984

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Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Max-Planck-Institut für Plasmaphysik und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

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IPP 4/216

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Abstract

The code RAYIC models coupling, propagation and absorption of e.m. waves in large axisymmetric plasmas in the ion cyclotron frequency domain. It can be used both to investigate the waves behaviour, and as a source of the power deposition profiles for use in transport codes.

The present user manual, after a brief summary of the physical model, presents the structure of RAYIC, the complete list of input-output variables (calling sequence), and some examples of the output which can be obtained from the code.

§ 1 - INTRODUCTION

RAYIC is a numerical code developed for the study of Ion Cyclotron Heating of large Tokamak plasmas. It combines a careful application of the Eikonal approximation (ray tracing and power transport) with a 3-D semi-analytic solution of Maxwell equations near the antenna and around singular layers (ion cyclotron and two-ion hybrid resonances). Thus the code can be used to obtain detailed information both on the propagation of the waves and on the power deposition profiles, under a large range of conditions.

The present report is intended as "user manual" for the code. The physical model on which the code is based has been discussed in two previous reports /1, 2/, and will therefore be only briefly summarized in Section 2. Section 3 describes the structure of the code. Section 4 presents the complete list of input variables which must be specified to run a case, and describes the output and the plots which can be obtained. Finally, Section 5 describes the reference runs which are built in the code. A few comparisons with similar codes /3, 4/ will be made in Section 2.

§ 2 - The model

The core of RAYIC is a ray-tracing subroutine, which follows the propagation of the fast Alfvén wave in an arbitrary axisymmetric configuration

$$X = X(\psi, \vartheta) \qquad Z = Z(\psi, \vartheta) \tag{1}$$

(X,Z) are cartesian coordinates in the meridian cross-section, $(0 \leq \psi \leq 1)$ labels magnetic surfaces, and ϑ is the poloidal angle (Fig. 1). The metric of the (non-orthogonal) coordinates ψ, ϑ, φ, and the expression for the static magnetic field components in terms of the toroidal current density and the shape of the magnetic surfaces are detailed in /1/, Section 5.

The plasma dispersion relation is written in the warm plasma approximation, neglecting the electron inertia:

$$H(\omega, \vec{k}) = A n_\perp^4 - B n_\perp^2 + C = 0 \tag{2}$$

The expressions for A, B, C in terms of $n_\parallel$ and the plasma parameters are given in /1/, Eqs. (2) to (5). To cope with arbitrary plasma cross-sections, the ray equations are written in an explicitly covariant form,

$$\begin{aligned} d\psi/d\tau &= \partial H/\partial \tilde{k}_\psi & d\vartheta/d\tau &= \partial H/\partial \tilde{k}_\vartheta \\ d\tilde{k}_\psi/d\tau &= -\partial H/\partial \psi & d\tilde{k}_\vartheta/d\tau &= -\partial H/\partial \vartheta \end{aligned} \tag{3}$$

where $\tilde{k}_\psi$, $\tilde{k}_\theta$ are the covariant components of the wave-vector; the independent variable is then changed to the wave phase $\sigma(\psi,\vartheta) = \int (\tilde{k}_\psi d\psi + \tilde{k}_\theta d\vartheta)$ by dividing Eqs. (3) throughout with

$$\mathcal{D} = \frac{d\sigma}{d\tau} = \tilde{k}_\psi \frac{\partial H}{\partial \tilde{k}_\psi} + \tilde{k}_\theta \frac{\partial H}{\partial \tilde{k}_\theta} \qquad (4)$$

The explicit form of the equations thus obtained, and the relations between the covariant and physical components of $\vec{k}$ are given in /1/, Section 6, Eqs. (1) to (28). The choice of σ as independent variable minimizes the number of derivatives to be evaluated, scales all variables automatically in the most natural way, and makes it easy to visualize wavefronts and ray pencils. It has moreover the advantage that breakdowns of the Eikonal approximation are automatically detected /6/.

The power transport equation takes into account ion cyclotron damping at the fundamental and at the first harmonic, and electron Landau and Transit Time damping (Ref. /1/, Section 6, Eqs. (29) to (31), and Section 4, Eqs. (10) to (14)).

The initial conditions for the ray and power transport equations are provided by a 3-D plane layered model of the antenna, described in /1/, Section 7. This model assumes

that the current distribution in the antenna is known (numerical codes for the self-consistent evaluation of the antenna loading and current distribution are available /5/). The output of the antenna subroutine consists of the spectral distribution of the radiated power among partial waves with different toroidal wavenumber n_φ, and, for each n_φ, the distribution of the power flux across a wavefront in the poloidal direction.

It is appropriate to recall here that we consider this decomposition of the radiated field in partial waves uniform in the toroidal direction

$$\vec{E}(\vec{r}) = \sum_n \vec{E}_n(\psi,\vartheta)\, e^{i(n_\varphi \varphi + \sigma_{n_\varphi})} \qquad (5)$$

as essential, to deal with the fact that in this direction the antenna is always much shorter than the wavelength, both in vacuum and in the plasma (this is not the case in the poloidal direction, due to the large refractive index in the plasma). Recently, the Authors of Ref. /3/ have shown numerically that at least in a plane-layered geometry with uniform or linear profiles of $n_\perp^2$, ray tracing applied to the field as a whole gives a good approximation to the exact solution even in the diffraction-dominated limit. Nevertheless, in the absence of a general proof of this rather surprising result, we prefer to avoid what amounts to a systematic violation of the indetermination principle. Note that the computer time requirements of the two approaches

are comparable: the need for scanning the toroidal wavenumber n_φ is compensated by the fact that for each n_φ we have to follow only a few rays in one meridian cross-section, ignoring the φ-coordinate altogether.

Integration of the ray equations is interrupted when the ray reaches a cut-off or a resonance. In the first case it is possible to instruct the code to resume integration, assuming specular reflection of the wave at the interruption point. It is not recommended, however, to follow the rays for more than two or three transits, since standing wave effects cannot be taken into account by the antenna model.

Integration is also interrupted when for some species

$$\left| \frac{\omega - n\Omega_{ci}}{k_{//} v_{thi}} \right| \leq 2 \qquad (n=1,2) \tag{6}$$

Inside a layer defined by this inequality, ray tracing fails because of the large antihermitean part of the dielectric tensor. The complex dispersion relation, however, shows that $\vec{k}$ and the field polarization vary little within the layer. Thus the ray is assumed to cross the Doppler-broadened cyclotron resonance along a straight segment; only the power transport equation is integrated within the layer, interpolating linearly between the values $\vec{k}$ and polarizations at the entry and exit points.

This procedure usually gives excellent agreement with analytic estimates /2/. It fails however if the resonance is too broad ($\Delta k_{\parallel}/k_{\parallel} \gtrsim 0.2$), or if the ray arrives on the resonance at grazing angle ($k_Z >> k_X$): in this case the integration cannot be resumed. It also fails in a more fundamental way if the cyclotron resonance is too close to a wave singularity (two-ion hybrid resonance or confluence with a Bernstein wave near $\omega = 2\Omega_{ci}$) not smeared off by sufficient Doppler broadening of the cyclotron resonance. In this case, ion cyclotron absorption is first evaluated assuming constants $\vec{k}$ and polarizations, then the wave resonance is treated as if well separated from the cyclotron resonance. This procedure is only qualitatively justified; it applies however only to a narrow transition range of $k_{\parallel}$-values, so that no large uncertainty in the global power balance is thereby introduced. (The most difficult case is pure second harmonic heating at temperatures well below 1 keV).

The evaluation of power deposition at two-ion hybrid resonances is based on a study of these singularities, described in Ref. /2/. The amount of power in the reflected and transmitted Alfvén waves, and the amount coupled to the slow (acoustic or Alfvén) wave is evaluated using analytic expressions given in this Reference (Section 5). It is moreover assumed that the slow wave is rapidly absorbed, and the corresponding power is distributed between

the different species of particles in proportion to the antihermitean part of the dielectric tensor. As long as the wave resonance is well separated from cyclotron resonances, therefore, most of this power goes to the electrons. As $k_{\parallel}$ increases, ion cyclotron absorption sets in, until the wave resonance is smeared out altogether.

No attempt is made to restart ray tracing after encountering a wave resonance. In view of the limited applicability of ray-tracing to multiple transit situations, we have not considered worth-while implementing the complicated reinitialization required for this purpose (in particular, both a transmitted and a reflected ray should be followed in most cases). However the power absorbed from the transmitted or reflected wave at the nearby fundamental resonance of the minority ions (and/or first harmonic of the majority) is taken into account in the power balance, using analytic estimates given in Ref. /2/.

In some cases, particularly in plasmas with circular cross-section, almost anastygmatic focusing of the ray pencil near the centre of the plasma is observed. This does not imply a break down of the Eikonal approximation, except that in reality the diameter of the illuminated region cannot be smaller than about one wavelength. When this focalization occurs near a resonance, therefore, straight application of ray tracing leads to a sharp localization

of the power deposition which is artificial to some extent. To avoid this, it is possible to instruct the code to smear out the power deposited by each ray at resonances (both cyclotron and hybrid) over a region one wavelength in diameter, with a Gaussian profile. This smoothing also helps to reduce possible jumpiness of the calculated power deposition profiles arising from the fact that only a finite number of rays can be followed.

The limitations of the model are well known /1-2/. In the first place, it is obviously necessary that the plasma be large and dense enough to accomodate at least a few wavelengths. In addition, the power balance is only reliable if absorption is sufficiently strong, since no account can be taken of selective eigenmode excitation. Even in the presence of such modes, however, RAYIC can give information on the wave propagation, and estimates correctly the single-transit absorption for each partial wave separately.

For the moment, no attempt has been made to couple RAYIC with the solution of the appropriate quasilinear Fokker-Planck equation /4/, and damping is evaluated for Maxwellian distribution functions. It is however possible to simulate suprathermal populations, by introducing for example two minority species with identical masses and charges, but different temperatures and concentrations. Work to complete the code in this sense is planned.

§ 3 - The code

RAYIC has been conceived so that it can be easily used either as an independent code or as part of a larger package, e.g. a Tokamak transport code. To facilitate coupling with other codes, all input parameters for a run of RAYIC have to be specified by the user program before calling RAYIC itself, whereby complete freedom is left on how the specification is implemented. In the standard form, the "user" is a MAIN program, in which the required parameters are entered by FORTRAN statements. With this MAIN as a guideline, it should be easy to construct the interface subroutine to couple RAYIC to another code. For the same purpose, the input variablles are collected together in a few labeled COMMONs (together with the output variables) and are not altered during execution by RAYIC. In addition, the profile variables (densities, temperatures, current density) have to be specified at the points of a discrete mesh rather than as analytic functions (of course it is possible to obtain these discrete representation from analytic expressions, as it is done in the standard version). The continuous and smooth profiles required for ray integrations are produced within RAYIC by cubic spline interpolation. In practically all cases, moreover, spline interpolation runs faster than direct evaluation from analytic expressions.

RAYIC is divided into three essentially independent parts, namely the ray-tracing package proper, including the treatment of singular layers, and two auxiliary packages, dealing with the antenna and with the graphical output, respectively. In this way, it should be easy to modify the antenna model, if required. Adapting the code to the plotting software available at different computer installations should also be reasonably easy.

The modular structure of RAYIC also allows adapting the code to other frequency ranges. Thus a complete version for Lower Hybrid waves (RAYLH) and a simpler version (circular plasma cross-section only) for electron cyclotron frequencies are available.

RAYIC is written in standard FORTRAN, compatible with both the H and 77 versions. It is about 9500 lines in length, including comments, and has 34 subroutines and 7 functions (plus 3 user-defined functions, cf. Section 4). It uses about 1100 kbyites memory when running on a CRAY1 computer. No auxiliary storage (disk, magnetic tapes) is required.

Always on a CRAY1, the CPU time required by a typical run (11 values of n_φ , 8 rays for each n_φ) is about 30 sec. It decreases to 5 to 10 secs for a run exploring only one value of n_φ , but with a substantial amount of graphical output. Included in these times is the evaluation of the antenna.

The predictor-corrector subroutine which integrates the ray equations chooses the step to keep accuracy (relative) better in principle than 10^{-6} (10^{-4} for the power transport equation). One has further to check the accumulated error after a relatively long integration; this is done by comparing the dispersion polynominal H, Eq. (2), to its largest term:

$$\varepsilon = \left| H \Big/ \mathrm{Max}\left(An_\perp^4, Bn_\perp^2, C\right) \right| \qquad (7)$$

ε is typically less than 10^{-9} at the starting point (where $\vec{n}$ is evaluated by a rapidly convergent Newton iteration) and usually remains well below 10^{-5} throughout. It might become somewhat larger if ray tracing is pursued too close to a singular surface or a cut-off, where the Eikonal approximation breaks down anyhow.

We proceed now to a brief description of the principal subroutines of RAYIC. A complete alphabetic list of all subroutines, each with a short description, and with all calls, is given in Appendix 2.

a) Initialization. The first subroutine called by RAYIC is normally INITAL, which evaluates the required dimensionless parameters, sets initial values for the control and output variables, and monitors the following tasks by calling the appropriate subroutines:

a) evaluation of the metric coefficients associated with the MHD equilibrium (METRIN);

b) normalization of the profiles (n, T, B_θ) and evaluation of the coefficients for spline interpolation (PROFIN, CUBSPL);

c) establishing the position of singular layers (CYTWIN);

d) evaluation of the antenna spectrum and radiation pattern (ANTIC)

If one of the three reference runs is required, the call to INITAL is preceeded by a call to subroutine STANDP, which enters the corresponding data (cfr. Section 5). After the initialization is completed, the main parameters characterizing the run are printed out by subroutine OUTRUN, which also provides the final output at the end of the run.

b) Ray tracing is monitored by subroutine RAYPAT, whose first task is to establish the initial position, wave-vector and power transported for each ray, thereby initializing the dependent variables. RAYPAT then let the ray be advanced by successive (user-specified) increments $\Delta\sigma$ of the independent variable, by calling the ordinary differential equation integration subroutine HPCSD. This procedure is continued until either all power is absorbed, or a failure of the Eikonal

approximation is detected (by subroutine OUTPUT, cfr. below). If this failure is due to a low-density cut-off or a cyclotron resonance layer, the appropriate re-initialization is performed (in the second case by calling subroutine CYCRES), and integration is restarted; otherwise the next ray is initialized.

HPCSD is a second-order predictor-corrector subroutine, written by Dr. O.Debarbieri. It needs two user-defined subroutines, which have to be declared as external by the user modulus. The first (here DERHIC) has to provide the rhs of the differential equations

$$\frac{dy_j}{dx} = f_j(x, y_1, \cdots y_N) \qquad (8)$$

DERHIC first evaluates the metric at the point reached by the integration (by calling COORDS);then the plasma parameters there (PROFIX, which in turn uses the cubic-spline subroutines INTERV and VALSPL), the physical components of the wavevector (WAVECT), and finally the dielectric tensor and its derivatives, field polarization and damping (DISPIC). With these elements, it evaluates the r.h.s. of the ray and power transport equations.

The second (here OUTPUT), monitors the integration for accuracy, occurrence of reflections or singularities, etc., and prints partial results when required. It also ensures that the power absorbed since the last step is distributed between the various species (by calling subroutine ABSORB) and that partial results are stored for subsequent graphical display (by calling OUTGRA).

If a failure is detected, OUTPUT calls subroutine TIHRES, which checks whether this is due to a two-ion hybrid resonance, and, if this is the case, evaluates the appropriate power balance. Note that enabling the code to recognize wave resonances was one of the major difficulties. In some very special cases (e.g. hybrid resonances involving impurity minorities with very localized density profiles) it might still happen that such an occurrence is not properly recognized. In principle, this should not happen in any physically relevant situation.

c) The evaluation of the field radiated by the antenna is performed by subroutine ANTIC. The field is Fourier decomposed in partial waves with space dependence $\exp i(n_\varphi \varphi + k_\theta y)$, and for each component (n_φ, k_θ) the surface impedance of the plasma is evaluated by integrating the full wave Maxwell

equations in a cold plasma with the appropriate density profile, but neglecting curvature (slab 3-dimensional model). The integration is performed again by the predictor-corrector subroutine HPCSD, with subroutines FUANTY and OUTANT as externals. For each n_φ, all partial waves k_θ are explicitly summed to find $E_\theta(n_\varphi, y)$, $B_z(n_\varphi, y)$, and thereby the distribution of Poynting flux on the asymptotic wavefront.

This procedure fails if a wave resonance $n_\parallel^2 = \varepsilon_{xx}$ occurs within the near-field region. In this case ANTIC prints a message, and returns control to INITAL, which fills the lacking information with model functions:

$$P(n_\varphi) = C \cdot \left(\frac{\sin n_\varphi (w/R)}{n_\varphi (w/R)} \right)^2$$

$$P_\psi(n_\varphi, \vartheta) = C \left(\frac{\sin hy}{hy} \right)^2 \qquad (9)$$

where w and h are the width and half-height of the antenna element, respectively. This makes it possible to obtain information on the subsequent behaviour of the waves, although the power balance is obviously meaningless in this case.

d) Details on the possibilities offered by the graphical output package will be given in Section 4,e). The package consists of subroutines OUTGRA (interface with the main package), GERGRA (execution of the plots), GRAPHS (opening a new page and drawing one curve) and PLOPSI (specially devoted to displaying the MHD configuration.

It must be noted that GERGRA, GRAPHS and PLOPSI by necessity contain calls to plotting subroutines (for drawing axes, printing numbers and symbols, drawing continuous curves between arrays of points, etc.) which are installation-dependent. Normally only these calls (marked by comments) have to be modified when RAYIC is to be installed on a new computer site. In some cases, two additional calls might be necessary, to open and close the plot file respectively. It is recommended to place these calls in the user program, respectively before and after the call to RAYIC.

§ 4 - Input-output of the RAYIC code

The Input-output variables of RAYIC are collected together in a few labelled COMMONS, reproduced in Table I. In this section, we describe these variables in sufficient details to facilitate running the code. An alphabetic list of these variables with a short explanation is also given in Appendix I.

a) The equilibrium configuration

The MHD equilibrium configuration is described parametrically in the form (1), with

$$X(\psi,\vartheta) = \left[\sum_{m=1}^{M}\left(\sum_{n=1}^{N} b_X(m,n)\,\psi^n\right)\cos(m-1)\vartheta\right]\cos\vartheta$$

$$Z(\psi,\vartheta) = \left[\sum_{m=1}^{M}\left(\sum_{n=1}^{N} b_Z(m,n)\,\psi^n\right)\cos(m-1)\vartheta\right]\sin\vartheta \qquad (10)$$

with $M \leq 5$ and $N \leq 3$. From the point of view of the user, this amounts to specify the two arrays b_X (= = BTPX(5,3)) and b_Z (= BTPZ(5,3)). Equations(10) are sufficiently general to cover most analytic approximations to the solutions of the Grad-Shafranov equation (for the case of circular or elliptic plasmas, cfr. also below). Actually, in most cases, Eqs. (10) contain much more parameters than required: the code automatically sets M and N to the lowest values really used, thus avoiding to sum lines or columns which contain only zeros.

To define the MHD equilibrium completely, one has also to specify the toroidal radius R_T (=RTORUS), the toroidal magnetic field B_0 (=BZERO), and the ϑ-averaged current density profile $J_\varphi(\psi)$ (=PJAVG(101)) (for the last quantity, crf. b)).

For consistency with common practice, R_T is defined as the distance of the geometric centre of the plasma from the vertical axis, and B_0 is the magnetic field at this point. On the other hand, Eqs. (10) put the origin of X,Z at the magnetic axis; the position of the latter and the plasma radius and ellipticity are evaluated by the code using the identities

$$a = \frac{1}{2}\left[X(1,0) - X(1,\pi)\right] \tag{11}$$

$$e = Z\left(1, \frac{\pi}{2}\right)/a \tag{12}$$

$$\Delta = \frac{1}{2}\left[X(1,0) + X(1,\pi)\right] \tag{13}$$

It is possible to normalize the coefficients b_X and b_Z in two different ways. If NRMRAD = 0, they have to be given in meters. If NRMRAD = 1, they can be arbitrarily normalized (i.e. up to a common factor), and the user must specify the plasma radius a (=RPLASH), in meters.

If it is desired to enter the arrays b_X and b_Z directly, the control parameter NEQUIL has to be set equal to zero. For simple circular or elliptic cross-section, however, it is possible to shortcircuit this procedure, by putting NEQUIL = 1. One has then to specify, in addition to a and R_T, also the shift of the magnetic axis Δ (=RSHIFT, meters) and the ellipticity e (=POLASP, dimensionless). The few non-vanishing elements of the arrays b_X and b_Z are in this case evaluated by the code.

b) The plasma

Up to 8 ion species are allowed (NSPEC $\leq$ 8). Each species must be characterized by its mass A_i (=ATM(8)) and charge Z_i (=AZI(8)) in atomic units. It is moreover required to specify which ion species is to be considered as reference species (MAINSP, crf. below).

The density and temperature profiles and the toroidal current density J_φ have to be specified at equidistant points of a discrete mesh in ψ:

$$\psi_j = (j-1)\,\Delta\psi \qquad (14)$$

The number of points in the mesh (NPROF) should lie between 11 and 101. The required arrays are:

$$
\begin{aligned}
n_e(\psi_j) &\Rightarrow \text{PNE}(101) && (\text{cm}^{-3}) \\
T_e(\psi_j) &\Rightarrow \text{PTE}(101) && (\text{keV}) \\
n_i(\psi_j) &\Rightarrow \text{PNI}(101,8) && (\text{cm}^{-3}) \\
T_i(\psi_j) &\Rightarrow \text{PTI}(101,8) && (\text{keV}) \\
J_\varphi(\psi_j) &\Rightarrow \text{PJAVG}(101) && (\text{arbitrary units})
\end{aligned}
\qquad (15)
$$

(for convenience, the mesh array ψ_j = PPSI(101) is also included in the input-output variables, but needs not be initialized by the user).

Two options are offered for the normalization of the profile functions (15). If the control integer IPROEQ is set to zero, all tables (except for the density of the reference ion species MAINSP and J_φ) have to be separately specified in physical units. In this case, the code ensures charge neutrality by evaluating the density profile of the reference species. Alternatively, if IPROEQ = 1, only the density and temperature profiles of the electrons, and the temperature profile of the reference ion species need to be specified, and can be arbitrarily normalized. In this case, one has to enter also the central values of $n_e(0)$ (=DENC), $T_e(o)$ (=TEMPEC) and $T_i(o)$ (=TEMPIC(8)), as well as the central concentrations $\nu_i = n_i(0)/n_e(0)$ (=ACONC(8)). In this case, ion density profiles are taken to be proportional to the electron density profile, and ion temperature profiles are taken pro-

portional to the temperature profile of the reference species. Charge neutrality is ensured by reevaluating the concentration of the reference species. When several species are present, taking IPROEQ = 1 makes the code run somewhat faster. Because of the role of the reference species in ensuring charge neutrality, it is recommended to choose this species to coincide with the "majority" species. For convenience, the values $n_i(0)$ (=DENIC(8)) are also included in the input-output commons, but need not be specified by the user.

The current density profile $J_\varphi(\psi)$ can always be entered in arbitrary units. It is therefore required to specify the total toroidal current I_0 (=TCURR, Ampères).

c) The_waves_

The h.f. waves are characterized by the applied frequency f (=FREQCY, hz), the total power coupled P_0 (=POWER, MW) and by the geometric and electric characteristics of the antenna.

The frequency f can be entered in two ways. If the control integer IRESP is set equal to zero, f has to be given in hz. If IRESP is a positive integer, on the other hand, the frequency will be chosen by the code so that ion species IRESP has the (NHARH-1)-cyclotron

harmonic at a distance X_{Res} (=XRES) from the geometric centre of the device.

P_o (=POWER) is the total power launched by the antenna, in MW. When running RAYIC alone, i.e. not coupled e.g. with a transport code, it is advisable to choose P_o = 1 MW, and to interpret the results as normalized "per MW coupled".

For the evaluation of the power spectrum in n_φ and of the poloidal distribution of Poynting flux, the antenna is assumed to consist of N_a (NANTS) elements, uniformly spaced around the torus. Each element is a rectangular strip of width w_a (=WIDTH) in the toroidal direction, and length $2h_a$ (h_a = HEIGHT) in the poloidal direction; it is mounted with its centre at an angle $\vartheta = \vartheta_a$ (=THANTN, deg; e.g. ϑ_a = 0 for antennas centered at the outer equatorial position). The distance from the plasma d_p (=DISTAP) and from the wall d_w (=DISTAW) have also to be specified (all dimensions in meters). As already mentioned, the position of the Faraday shield is assumed to coincide with the plane of the strip. Different elements can be excited with a phase difference $\Delta\phi$ (=DPHASE, degs.)

The current distribution in each element of the antenna is assumed to have the form (the same in all elements)

$$J_y(y,z) = C f(y) \cdot g(z) \qquad (16)$$

and the user is required to provide the complex Fourier transforms of f(y) and g(z) according to the definitions

$$\tilde{f}(n_y) = \int_{-h_a}^{+h_a} dy\, f(y)\, e^{i n_y \frac{\omega}{C} y}$$

$$\tilde{g}(n_\varphi) = \int_{-w_a/2}^{+w_a/2} dz\, g(z)\, e^{i n_\varphi \frac{z}{R_T}} \qquad (17)$$

(we recall that y is in the poloidal, z in the toroidal direction). The format of these function is described in Subsection f. The constant C is <u>not</u> required, since the radiated spectrum is normalized to POWER.

Note that for $\Delta\phi = 0^o$ or $\Delta\phi = 180^o$ symmetry imposes strict selection rules on n_φ: thus for $\Delta\phi = 0^o$ only partial waves with $n_\varphi = 0, \pm N_a, \pm 2 N_a$, etc., for $\Delta\phi = 180^o$ only partial waves with $n_\varphi = \pm N_a/2, \pm 3 N_a/2$, etc. are excited. Since $w_a << c/f$, moreover, the n_φ spectrum is rather broad, and hardly affected by $\Delta\phi$. To get rapidly an idea of the spectrum, it is possible to stop RAYIC just after the evaluation of the antenna, by setting JOUTA = -1. Detailed information on the coupling is then printed. The other options for JOUTA are JOUTA = 1, in which case the same antenna information is printed, and then RAYIC proceeds to ray tracing, and JOUTA = 0, in which case only a short summary of the antenna parameters is printed.

It is not always useful to follow all partial waves, particularly when the above selection rules apply. Thus RAYIC can be instructed to follow only partial waves with n_φ given by

$$n_\varphi = n_{\varphi 1} + (J-1)\,\Delta n_\varphi \qquad J=1,\dots N_\varphi \qquad (18)$$

where $n_{\varphi 1}$ (=NPHI1), Δn_φ (=JUMPHI) and N_φ (=NUMPHI) have to be specified by the user. If $\Delta\phi = 0^\circ$ or 180° and $\vartheta_a = 0^\circ$ or 180°, the symmetry $(n_\varphi, \vartheta) \leftrightarrow (-n_\varphi, -\vartheta)$ allows to consider only positive values of n_φ. The necessary renormalization when $\Delta\phi = 0^\circ$ is automatically carried out by the code. It is also necessary to specify the number of rays to be followed for each n_φ (NTHIN). NUMPHI cannot exceed 51 and NTHIN cannot exceed 11; typical choices are NUMPHI = 11 with JUMPHI = 4, and NTHIN = 8.

Finally, one must specify the maximum number of reflections allowed to each ray (MAXREF), and whether smoothing of the power deposition is required (ISMOOT = 1) or not (ISMOOT = 0).

d) Control of the output

Several options are offered for the printed output: assigning to the integer IPRINT values from 0 to 3 increases the amount of information printed. The normal

choice is IPRINT = 1. In this case, all the globel parameters (MHD configuration, central densities, temperatures and concentrations, frequency, antenna dimensions; location of resonances and cut-offs in the equatorial plane) are first printed. If NUMPHI = 1, detailed information on each ray is printed at intervals DEXKPR of the independent variable σ (actually DEYKPR = $\Delta\sigma/2\pi$, i.e. intervals are measured in wavelengths), namely, in successive lines:

a) $\sigma/2\pi$, ψ, ϑ, X, Z, the power transported

b) $n_{\parallel}$, $n_{\perp}$, n_{ψ}, n_X, n_Z

c) $\omega/k_{\parallel}v_{the}$, the power deposited in the electron since the last step (only if $|\omega/k_{\parallel}v_{the}| \leq 5$)

d) $(\omega-n\Omega)|k_{\parallel}v_{thi}$ and the power deposited in the ion species i since the last step (only if $|\omega-n\Omega)/k_{\parallel}v_{thi} \leq 5$ for n=1 or 2).

If NUMPHI > 1 this information is given only at the initial and final position for each ray. In all cases, moreover, a message is printed at particular occurrences (resonances, reflections, etc.) At hybrid resonances moreover the optical thicknesses η_1, η_2 (Ref. /2/ Eqs. (67)), the reflection, transmission and absorption coefficients, and the power deposited in each species are given (coupling to slow or acoustic waves is included in the absorption coefficient).

Finally the power balance is displayed: first the power deposition profiles (W/cm^3, versus ψ); then the balance for each partial wave n_φ (only if NUMPHI > 1), finally the global balance.

If IPRINT = 0, all information on ray-tracing is skipped, and only the run parameters and the power balance are printed.

With IPRINT = 2 one obtains, in addition to the global run parameters, the output of the matrices b_X and b_Z, and the density, temperature and poloidal magnetic field profiles versus ψ; moreover information on rays is supplemented by elements of the dielectric tensor, polarizations and accuracy.

Finally when IPRINT = 3, all details are printed each time HPCSD has completed one integration step. This choice is included for testing, but should be used only exceptionally, since it gives rise to extremely long outputs.

The graphical output is executed if the integer IGRAPH is set equal to unity. It consists of up to 18 plots, as follows. A first page presents a summary of the run parameters. Then, if the integer IPLOPR is set equal to 1, normalized profiles of $n_e(\psi)$, $T_e(\psi)$, $T_i(\psi)$ for i = MAINSP, and of the safety factor $q(\psi)$ (MHD definition) are given.

If NUMPHI = 1, it follows a plot of the rays and wavefronts in the meridian cross-section, and up to 14 plots of various quantities along the rays. The user chooses which of these plots are executed by setting equal to unity the appropriate entry of the two-index array IPLOXY(I,J), $1 \leq I \leq 2$, $1 \leq J \leq 7$, according to the following table:

first index I =	1	abscissa is $\sigma/2\pi$
	2	ψ
second index J =	1	ordinate is $n_\perp$
	2	$n_\parallel$
	3	n_ψ
	4	m_θ
	5	n_X
	6	n_Z
	7	Power transported.

Thus IPLOXY(2,1) = 1 causes the display of $n_\perp(\psi)$, IPLOXY(7,2) = 1 the display of the transported power versus phase, etc.

If NUMPHI > 1, the amount of output (and storage memory) for these plots would become too large; thus it is not possible to obtain detailed plots in this case. The suggested procedure is to run a complete case (scanning n_φ) first, to obtain the power balance; then, if it appears interesting, to run a few typical values of n_φ separately, to visualize ray

behaviour. Actually all quantities except power deposition depend only weakly on n_φ.

The last graph (executed also if NUMPHI > 1) is a plot of the power deposition profiles (versus ψ) for electrons and ions.

A set of such plots for a single partial wave is presented in Figs. 2 to 19.

e) Output variables

The principal output variables from RAYIC are the power deposition profiles $W_e(\psi)$ (= PWE(101)) and $W_i(\psi)$ (= = PWI(101,8)). They represent averages over each magnetic surface, and are given in W/cm^{-3}. For convenience in subsequent use of these arrays, they are collected in a separate COMMON, labelled /OUTPIC/.

In addition, the following quantities have been included among the input-output COMMON variables, since they can be useful to understand the details of the energy balance:

The array of values $n_\varphi(J)$ (Eq. (10); =NPHI(51)); for each n_φ, the power coupled $P(n_\varphi)$ (normalized to POWER taking into account symmetry of the spectrum if required; =PWCPL(51)) and the power still not absorbed at the end point of all rays (=PWTRA(51)).

The angular position of the starting points of the NTHIN rays (= THSTRT(11)) and the fraction of power flux attributed to each ray (normalized separately to unity for each value of n_φ). Of course all these values are evaluated by RAYIC, and need not to be initialized by the user.

f) User-defined functions

The user is requested to provide three functions, to specify the shape of the initial wavefront and the current distribution in the antenna elements.

f1) FUNCTION PSIWFR(THETA,DPSDTH) must define the shape of the first wavefront,

$$\psi = \psi_w(\vartheta) \tag{19}$$

($\psi_w \Rightarrow$ PSIWFR; $\vartheta \Rightarrow$ THETA, in radiants). Moreover, to enable RAYIC to evaluate the direction of $\vec{k}$ at the starting point of each ray, the derivative $\partial\psi_w/\partial\theta$ (= DPSDTH) is also required).

Strictly speaking, $\psi_w(\vartheta)$ should follow from the evaluation of the asymptotic field of the antenna (and should in principle be a different function for each value of n_φ). However, the antenna model neglects the curvature of the real geometry. What is more im-

portant, there is always some ambiguity in the definition of a wavefront from an "exact" field distribution. This ambiguity is irrelevant within the Eikonal approximation, but becomes in principle unavoidable as soon as one tries to use shaping of $\psi_w(\vartheta)$ to simulate diffraction effects. For this reason, and unless there are documented grounds for a different choice, it is recommended to put simply

$$\psi_w(\vartheta) \equiv \psi_0 \qquad \frac{\partial \psi_w}{\partial \vartheta} = 0 \tag{20}$$

f2) The complex functions FUNCTION CFUNJY(ZNY) and FUNCTION CFUNJZ(NPH). must define the complex Fourier transforms of the current distribution in each antenna elements, according to the definitions (8) and (9) above. The arguments are n_y (= ZNY,real) and n_φ (= NPH,integer).

§ 5 - Test runs

Three test runs are available, and can be obtained by setting the integer JSTAND equal to 1, 2 or 3 respectively. The parameters for these runs are entered through the subroutine STANDP, and override any other parameter entered by the user.

The three runs have in common the JET-like equilibrium MHD configuration of Figs. 1 and 3, and the density and temperature profiles of Fig. 2; moreover, they share the following set of parameters:

BZERO	= 3.45 T	RTORUS	= 3 m
RPLASM	= 1.2 m	TCURR	= $5 \cdot 10^6$ A
DENC	= $5 \cdot 10^{13}$	TEMPEC	= 1.7 keV
NANTS	= 4	DPHASE	= 0
THANTN	= 0.	WIDTH	= 0.4 m
HEIGHT	= 0.8 m	DISTAP	= 0.05 m
DISTAW	= 0.1 m	POWER	= 1 MW
NEQUIL	= 0	IRESP	= 0
MAXREF	= 1	ISMOOT	= 1
NUMPHI	= 1	NPHI1	= 0
JUMPHI	= 4	NTHIN	= 8
IPRINT	= 1	CIGRAPH	= 1
IPLOPR	= 1	JOUTA	= 0
IPROEQ	= 1	NPROF	= 41

a) JSTAND = 1 - 2 % He_3^{++} in a H^+ plasma.

The other parameters are as follows:

NSPEC	= 2	MAINSP	= 1
ATM(1)	= 1	AZI(1)	= 1
ATM(2)	= 3	AZI(2)	= 2
ACONC(2)	= 0.02	TEMP C(1)	= 1.7 keV
TEMPIC(2)	= 5.1 keV	FREQCY	= $35 \cdot 10^6$ Hz

The energy balance is as follows:

Power coupled	1.000 MW
Absorbed	0.4451 MW
by the electrons	0.07834 MW
by He_3^{++} ions	0.3667 MW

The deposition profiles are given in Fig. 20, and the power balance as a function of n_φ in Fig. 21 (only $n \geq 0$ are shown).

b) JSTAND = 2 - pure D^+ plasma, $\omega = 2\Omega_D$.

The other parameters are as follows

NSPEC = 1	MAINSP = 1
ATM(1) = 2	AZI(1) = 1
TEMPIC(1) = 1.7 keV	FREQCY = $50 \cdot 10^6$ Hz.

The power balance is

Power coupled	1 MW
Absorbed	0.2714 MW
by the electrons	0.08764 MW
by D^+ ions	0.1837 MW

The deposition profiles are given in Fig. 22, and the power balance as a function of n_φ in Fig. 23.

c) JSTAND = 3 - 5 % H^+ in a D^+ plasma.

The other parameters are:

NSPEC	= 2	MAINSP	= 1
ATM(1)	= 2	AZI(1)	= 1
ATM(2)	= 1	AZI(1)	= 1
ACONC(2)	= 0.05	TEMPIC(1)	= 1.7 keV
TEMPIC(2)	= 5.1 keV	FREQCY	= $50 \cdot 10^6$ Hz

The power balance is

Power coupled	1 MW
Absorbed	0.7311 MW
by the electrons	0.1694 MW
by D^+ ions	0.02098 MW
by H^+ ions	0.5397 MW.

The deposition profiles are given in Fig. 24, and the power balance as a function of n_φ in Fig. 25.

Acknowledgements

We are indebted to Dr. M.Ottaviani for its invaluable collaboration on the physics of wave resonances /2/, and several other contributions and discussions about the physics of IC waves. We also thank the JET HF group for constant interest in this work, and particularly Dr. P. Lallia, for many discussions and suggestions for the improvement of the code.

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Figure Captions

Fig. 1 Geometry of the MHD configuration and definition of the variables of Section 4,a)

Figs. 2 to 19 Complete set of graphical output for a single partial wave:

1 - Summary of the run parameters
2 - Normalized profiles (n,T and safety factor)
3 - Wave rays and wavefronts
4 - $n_\perp$ versus $\sigma/2\pi$
5 - $n_\parallel$ " $\sigma/2\pi$
6 - n " $\sigma/2\pi$
7 - m_θ " $\sigma/2\pi$
8 - n_X " $\sigma/2\pi$
9 - n_Z " $\sigma/2\pi$
10 - Power transported versus $\sigma/2\pi$
11 - $n_\perp$ versus
12 - $n_\parallel$ "
13 - n "
14 - m_θ "
15 - n_X "
16 - n_Z "
17 - Power transported versus
18 - Power deposition profiles

Fig. 20 Spectral power balance for the standard run n° 1

Fig. 21 Power deposition profiles for the standard run n° 1

Fig. 22 Spectral power balance for the standard run n° 2

Fig. 23 Power deposition profiles for the standard run n° 2

Fig. 24 Spectral power profiles for the standard run n° 3

Fig. 25 Power deposition profiles for the standard run n° 3.

TABLE I - Input-output Commons of RAYIC

INPUT-OUTPUT COMMON BLOCKS FOR RAYIC		
EQUILIBRIUM PARAMETERS		
COMMON /CPLDIM/	RTORUS,	RPLASM,
+	BZERO,	TCUBE,
+	POLASP,	RSHIFT,
+	BTPX(5,3),	BTPZ(5,3),
+	NRMBAD,	JSTAND,
+	NEQUIL	
PLASMA PARAMETERS		
COMMON /CPLPAR/	DENC,	TEMPEC,
+	ATM(8),	AZI(8),
+	DENIC(8),	TEMPIC(8),
+	ACONC(8),	NSPEC,
+	MAINSP	
PROFILE TABLES		
COMMON /CPRCIC/	PPSI(101),	PJAVG(101),
+	PNE(101),	PIE(101),
+	PNI(101,8),	PTI(101,8),
+	NPROF,	IPRCEQ
FREQUENCY AND INITIAL VALUES		
COMMON /CPOWIC/	FREQCY,	XRES,
+	PCWEB,	POYNT(51,11),
+	PWCPL(51),	PWTRA(51),
+	THSTRT(11),	NPHI(51),
+	NPHI1,	NUMPHI,
+	JUMPHI,	NTHIN,
+	IRESP,	NHARM,
+	MAXREF,	ISMOOT
ANTENNA PARAMETERS		
COMMON /CANTIC/	WIDTH,	HEIGTH,
+	THANTN,	DPHASE,
+	DISTAP,	DISTAW,
+	NANTS	
CONTROL OF THE OUTPUT		
COMMON /CPRTIC/	DEVKPR,	IPRINT,
+	JCUTA,	IGRAPH,
+	IPLOPR,	IPLOXY(2,7)
OUTPUT TABLES FROM RAYIC		
COMMON /OUTPIC/	PWE(101),	PWI(101,8)

****

APPENDIX I - ALPHABETIC INDEX OF THE INPUT-OUTPUT VARIABLES OF THE RAYIC CODE.

****

(IN) = INPUT quantity normally to be explicitly entered by the USER before calling "SUBROUTINE RAYIC" (ignored in some cases, as indicated)
(--) = INPUT quantity normally entered by an indirect procedure, as indicated; can be explicitly entered by the user only at an entry point within SUBROUTINE "RAYIC", or an interior level SUBROUTINE
(OU) = OUTPUT quantity

(S) = Scalar quantity
(V1) = Vector quantity, 1 index
(V2) = Vector quantity, 2 indexes

****

(V1) ACCNC (IN) - CONCENTRATION OF ION SPECIES (NI/NE)
INDEX FROM 1 TO NSPEC
REQUIRED ONLY IF IPROEQ=1

(V1) ATM (IN) - ATOMIC MASS OF IONS (ATOMIC UNITS)
INDEX FROM 1 TO MAX(NSPEC,IRESP)

(V1) AZI (IN) - CHARGE OF IONS (ATOMIC UNITS)
INDEX FROM 1 TO MAX(NSPEC,IRESP)

(S) BZERO (IN) - TOROIDAL MAGNETIC FIELD ON AXIS, TESLA

(V2) BTPX (IN) - COEFFICIENTS OF THE REPRESENTATION OF THE FUNCTION X(PSI,THETA) (IGNORED IF NEQUIL=1)
FIRST INDEX FROM 1 TO 5 - THETA HARMONIC
SECND INDEX FROM 1 TO 3 - PSI POWER

(V2) BTPZ (IN) - COEFFICIENTS OF THE REPRESENTATION OF THE FUNCTION Z(PSI,THETA) (IGNORED IF NEQUIL=1)
FIRST INDEX FROM 1 TO 5 - THETA HARMONIC
SECND INDEX FROM 1 TO 3 - PSI POWER

(S) DENC (--) - CENTRAL ELECTRON DENSITY (CM-3)
(NORMALLY EVALUATED FROM PNE(1))

(V1) DENIC (--) - CENTRAL DENSITY OF ION SPECIES (CM-3)
INDEX FROM 1 TO NSPEC
EVALUATED FROM ACONC & DENC IF IPROEQ=1
FROM PNI(1,I) IF IPROEQ=0

(S) DEYKPR (IN) - STEP OF THE PHASE (IN WAVELENGTHS) BETWEEN PARTIAL PRINTOUTS
IGNORED IF "NUMPHI.GT.1"

(S) DISTAP (IN) - DISTANCE ANTENNA-PLASMA (METERS)
IGNORED IF "NANTS.EQ.0"

(S) DISTAW (IN) - DISTANCE ANTENNA-WALL (METERS)
IGNORED IF "NANTS.EQ.0"

(S) DPHASE (IN) - PHASE DIFFERENCE IN THE EXCITATION OF ADJACENT
ANTENNA ELEMENTS (DEGS)
IGNORED IF "NANTS.EQ.0"

(S) FREQCY (IN) - FREQUENCY (HZ)
(IGNORED IF "IRESP.NE.0", SEE BELOW)

(S) HEIGTH (IN) - HALF-HEIGTH OF THE ANTENNA ELEMENT IN THE POLOIDAL
DIRECTION (METERS)
IGNORED IF "NANTS.EQ.0"

(S) IGRAPH (IN) - CONTROL OF THE GRAPHICAL OUTPUT
IGRAPH = 1 - GRAPHS MADE
IGRAPH = 0 - GRAPHS NOT MADE
"IGRAPH" IS PUT EQUAL TO ZERO IF "NUMPHI.GT.1"

(S) IPLOPR (IN) - CONTROL OF THE PLOTS OF THE PROFILES
IPLOPR = 1 - PROFILES (NE,TE,TI,Q) PLOTTED
IPLOPR = 0 - PROFILES NOT PLOTTED

(V2) IPLOXY (IN) - LIST OF THE PLOTS TO BE MADE
IPLOXY(NXV,NYV) DIFFERENT FROM ZERO
PRODUCES A PLOT WITH VARIABLE NXV AS
ABSCISSA AND VARIABLE NYV AS ORDINATE,
ACCORDING TO THE FOLLOWING TABLE:

NXV=1	INDEP. VAR.	SEIKON (PHASE IN THE POLOIDAL PLANE)
2		PSI (MAGNETIC SURFACES LABEL)

NYV=1	DEP. VAR.	SKP
2		SKPAR
3		SKR
4		SKTH (M-THETA)
5		SKX
6		SKZ
7		SPOWER

(S) IPRINT (IN) - CONTROL OF THE OUTPUT DETAILS
IPRINT =-1 - OUTPUT SUPPRESSED
IPRINT = 0 - OUTPUT REDUCED
IPRINT = 1 - NORMAL OUTPUT
IPRINT = 2 - DETAILED OUTPUT
IPRINT = 3 - OUTPUT AT EACH CALL OF SUBROUTINE
"DERHIC" BY SUBROUTINE "HPOSD" (FOR CHECKS)
IN THIS CASE NO GRAPHS ARE MADE.

(S) IPROFQ (IN) - CONTROL OF THE ION PROFILE CHOICE
IPROFQ = 0 - SEPARATE PROFILES FOR EACH SPECIES
IPROFQ = 1 - SAME PROFILES FOR ALL SPECIES
(THIS CHOICE SAVES CONSIDERABLE COMPUTER TIME)
IF IPROFQ = 1 SPECIFY TEMPIC(I) & ACONC(I)

(S) IRESP (IN) - CONTROL OF THE FREQUENCY CHOICE
IRESP = 0 - THE FREQUENCY IS GIVEN.
IRESP > 0 - THE FREQUENCY IS EVALUATED SO THAT
FOR SPECIES "IRESP" THE "NHARM" IC HARMONIC
OCCURS AT POSITION "XRES"
IF "IRESP.NE.0" SPECIFY "NHARM" AND "XRES"

(S) ISMOOT (IN) - CONTROL OF THE POWER DEPOSITION SMOOTHING

ISMOOT = 0 - POWER DEPOSITED AT THE CLOSEST
POINT ONLY
ISMOOT = 1 - POWER DEPOSITION SMOOTHED OVER
ONE WAVELENGTH

(S) JOUTA (IN) - CONTROL OF THE OUTPUT OF THE ANTENNA EVALUATION
JOUTA = 0 - NO DETAILS ARE PRINTED
JOUTA = 1 - DETAILS ARE PRINTED
JOUTA = 2 - ALSO PX(Y) IS PRINTED
JOUTA =-1 - RAYPAT IS ARRESTED AFTER THE
EVALUATION OF THE ANTENNA

(S) JSTAND (IN) - IDENTIFIES REFERENCE RUNS (CFR 'USERMAN')
JSTAND = 0 - PLASMA PARAMETERS ENTERED BY
THE USER
JSTAND = 1,2 OR 3 - REFERENCE RUNS (USER
PARAMETERS IGNORED)

(S) JUMPHI (IN) - STEP "NPHI(L+1)-NPHI(I)"

(S) MAINSP (IN) - MAJORITY SPECIES
(CHARGE NEUTRALITY IMPLEMENTED EVALUATING
THE SPATIAL DENSITY PROFILE OF MAINSP)

(S) MAXREF (IN) - N OF REFLECTIONS FROM VERTICAL PLANES
AFTER WHICH INTEGRATION IS STOPPED

(S) NANTS (IN) - NUMBER OF ELEMENTS OF THE ANTENNA
IN THE PRESENT VERSION THE ELEMENTS ARE SUPPOSED
TO BE SYMMETRICALLY DISPOSED ALONG THE TORUS.
IF "NANTS=0" THE ANTENNA EVALUATION IS SKIPPED,
AND THE POWER IS DISTRIBUTED AMONG THE
"NUMPHI" MODES AND THE "NTHIN" RAYS
WITH A STANDARD COS SQ. LAW

(S) NEQUIL (IN) - IDENTIFIES A STANDARD EQUILIBRIUM
NEQUIL=0 - METRIC COEFFS. ENTERED BY THE USER
NEQUIL=1 - CIRCULAR OR ELLIPTIC CROSS-SECTION
IN THIS CASE SPECIFY "RSHIFT" AND "ECLASP"

(S) NHARM (IN) - ORDER OF HARMONIC (NHARM=1 AT THE FUNDAMENTAL
RESONANCE, ETC.)
IGNORED IF "IRESP=0"

(V1) NPHI (--) - VALUES OF THE TOROIDAL WAVENUMBER
INDEX FROM 1 TO NUMPHI
IN THE PRESENT VERSION THE VALUES "NPHI" ARE
EVALUATED AS
"NPHI(L) = NPHI1 + (L-1)*JUMPHI"

(S) NPHI1 (IN) - NPHI(1)

(S) NPROF (IN) - N. OF POINTS IN THE PSI-MESH
10 < NPROF < 101

(S) NRMRAD (IN) - NORMALIZATION OF THE TABLE BTP
NRMRAD=0 - BTP IN METERS - RPLASM IGNORED
AS INPUT, REEVALUATED AS OUTPUT
NRMRAD=1 - BTP ARBITRARILY NORMALIZED AS
INPUT, RENORMALIZED BY THE CODE TO RPLASM

(S) NSPEC (IN) - N. OF ION SPECIES PRESENT IN THE PLASMA
(SHOULD NOT EXCEED 8)

(S) NTHIN (IN) - N. OF RAYS IN THE POICIDAL SECTION

(S) NUMPHI (IN) - N. OF TOROIDAL WAVENUMBERS FOR WHICH
RAY TRACING IS TO BE IMPLEMENTED

(V1) PJAVG (IN) - CURRENT DENSITY AT THE MESH POINTS (ARBITR.
UNITS: IS THEN NORMALIZED TO "TCURR")
THE PRESENT CHOICE IS "PJAVG = PTE**1.5"
INDEX FROM 1 TO NPROF

(V1) PNE (IN) - ELECTRON DENSITY AT THE MESH POINTS (CM-3)
INDEX FROM 1 TO NPROF

(V2) PNI (IN) - ION DENSITY AT THE MESH POINTS (IONS/CM3)
FIRST INDEX FROM 1 TO NPROF
SECOND INDEX FROM 1 TO NSPEC

(S) POLASP (IN) - POLOIDAL ASPECT RATIO (B/A)

(S) POWER (IN) - TOTAL POWER COUPLED (MW)

(V2) POYNT (OU) - POLOIDAL DISTRIB. OF THE POWER FLUX
(EVALUATED BY SUBROUTINE PWICPL)
FIRST INDEX FROM 1 TO NPHI
SECOND INDEX FROM 1 TO NTHIN

(V1) PPSI (OU) - MESH VALUES OF PSI (EQUIDISTANT)
INDEX FROM 1 TO NPROF
PPSI(1)=0. ON THE MAGNETIC AXIS
PPSI(NPROF)=1. AT THE PLASMA EDGE

(V1) PTE (IN) - ELECTRON TEMPERATURE AT THE MESH POINTS (KEV)
INDEX FROM 1 TO NPROF

(V2) PTI (IN) - ION TEMERATURE AT THE MESH POINTS (KEV)
FIRST INDEX FROM 1 TO NPROF
SECOND INDEX FROM 1 TO NSPEC

(V1) PWCPL (OU) - POWER COUPLED TO EACH NPHI PARTIAL WAVE (MW)
INDEX FROM 1 TO NUMPHI
(EVALUATED BY THE SUBROUTINE PWICPL)

(V1) PWE (OU) - POWER DEPOSITED IN THE ELECTRONS AT THE
MESH POINTS (W/CM3)
INDEX FROM 1 TO NPROF

(V2) PWI (OU) - POWER DEPOSITED IN THE IONSS AT THE MESH
POINTS (W/CM3)
FIRST INDEX FROM 1 TO NPROF
SECOND INDEX FROM 1 TO NSPEC

(V1) PWTRA (OU) - POWER NOT ABSORBED FOR EACH NPHI (MW)

(S) RPLASM (IN) - PLASMA RADIUS, METERS
(IGNORED IF "IRESP < 0", SEE BELOW)

(S) RSHIFT (IN) - SHIFT OF THE MAGNETIC AXIS FROM THE GEO-
METRIC CENTER (METERS)

(S) RTORUS (IN) - TOROIDAL RADIUS, METERS

(S) TCURR (IN) - TOROIDAL CURRENT, AMPS

(S) TEMPEC (--) - CENTRAL ELECTRON TEMPERATURE (KEV)
(NORMALLY EVALUATED FROM PTE(1))

(V1) TEMPIC (IN) - CENTRAL TEMPERATURE OF ICN SPECIES (KEV)
INDEX FROM 1 TO NSPEC
REQUIRED ONLY IF IPROFEQ=1
FROM PTI(1,I) IF IPROFEQ=0

(S) THANTN (IN) - POLOIDAL ANGLE POSITION OF THE CENTRE
OF THE ANTENNA ELEMENT

(V1) THSTRT (--) - ANGULAR POSITION OF THE RAY STARTING POINTS
IN THE PRESENT VERSION THEY ARE UNIFORMLY
SPACED FROM "THANTN-THAPER" TO "THANTN+THAPER"
INDEX FROM 1 TO NTHIN

(S) XRES (IN) - POSITION OF THE RESONANCE (CM. FROM AXIS)
IGNORED IF "IRESP=0"

(S) WIDTH (IN) - WIDTH OF THE ANTENNA ELEMENT IN THE TOROIDAL
DIRECTION (METERS)
IGNORED IF "NANTS.EQ.0"

****

User-defined functions required by the RAYIC code

****

FUNCTION PSIWFR(THETA,ZDPSDT)

This function specifies the equation of the initial wavefront, psi = psi(theta).
The input argument is THETA (real, poloidal angle in rad.).
The return arguments are

PSIWFR = psi(theta)

(real, flux variable psi normalized between 0 on the magnetic axis and 1 at the plasma edge), and the derivative ZDPSDT (real):

ZDPSDT = d(psi)/d(theta)

The name PSIWFR cannot be altered.

==========

FUNCTION CFUNJY(ZNY)

This complex function must provide the y complex Fourier transform of the current distribution along each element of the antenna, as function of the poloidal wavenumber Ny.
It is not necessary to normalize the Fourier transform.

Input argument is ZNY (real), the poloidal wave index (c*ky/omega).
The output is the Fourier component CFUNJY, which must be declared as COMPLEX.

The evaluation of CFUNJY usually requires the parameters of of the input-output COMMONs.

==========

FUNCTION CFUNJZ(NPH)

This complex function must provide the z complex Fourier transform of the poloidal current distribution in each antenna element (all elements identical), as function of the toroidal wavenumber Nphi. It is not necessary to normalize the Fourier transform.

Input argument is NPH (integer), the toroidal wavenumber. The output is the complex Fourier component CFUNJZ, which must be declared as complex.

The evaluation of CFUNJZ usually requires the parameters of of the input-output COMMONs.

==========

The code is provided with independent versions of these user-defined modules, for use with the reference runs. They are named

```
      FUNCTION PSIWFS
      FUNCTION CFNJZS
      FUNCTION CFNJYS
```

respectively; they can serve as guideline to the user to provide its own modules.

****

APPENDIX II - Index of the subroutine and functions of the RAYIC code

****

ABSORB (Subr): attributes the power absorbed along the ray to the different species, and monitors incidence on ion cyclotron resonance layers.
ABSORB is called by OUTPUT, CYCRES.

ANTIC(NBREAK) (Subr): provides the RAYIC package with the necessary information about the antenna. It evaluates the power spectrum over partial waves with different toroidal wavenumber n , and the poloidal distribution of the Poynting flux on the initial wavefront for each partial wave.
The argument NBREAK (output only) is returned as 0 if integration was succsessful, as 1 otherwise.
ANTIC is called by INITAL.
ANTIC calls COORDS, CYIC2, ZBFAC2, POYNTN, CFUNJY, CFUNJZ (or CFNJYS,CFNJZS).

CFNJYS(ZNY) (Func): provides the y (theta) complex Fourier spectre of the poloidal current distribution in the antenna, for the reference runs (JSTAND = 1, 2, or 3) as a function of the poloidal wavenumber Ny = ZNY
CFNJYS is called by ANTIC. The call is skipped if JSTAND = 0 (spectre entered by the USER).

CFNJZS(NPH) (Subr): provides the z (phi) complex Fourier spectre of the poloidal current distribution in the antenna, for the reference runs (JSTAND = 1, 2, or 3) as a function of the toroidal wavenumber Nphi = NPH
CFNJZS is called by ANTIC. The call is skipped if JSTAND = 0 (spectre entered by the USER).

COORDS (Subr): evaluates the cartesian coordinates X, Z, as functions of the curvilinear coordinates psi and theta, and the elements of the metric of the (psi, theta) reference frame as needed to write the ray equations.
COORDS is called by INITAL, INIWFR, DERHIC, PLCPSI, ANTIC.

CUBSPL(H,C,NPROF) (Subr): evaluates the coefficients for the cubic spline interpolation. H is the mesh step, and NPROF the number of mesh points (it must not exceed 101). C(101,4) is a two index array: as input, the first column of C must contain the mesh values of the function to be interpolated. The coefficients for the interpolation are stored in the successive three culomns of C.
CUBSPL is called by PROFIN.

CYCRES (Subr): re-initializes the ray at a transit through an ion cyclotron resonance, and evaluates the power deposited in the resonance layer.
CYCRES is called by RAYPAT.
CYCRES calls Subr. COORDS, PROFIX, DISPIC, ABSORB, OUTPUT.

CYIC2(ZNZ2) (Subr): evaluates the complex surface impedance of the plasma for plane waves of toroidal index squared ZNZ2 and varying poloidal index.
CIYC2 is called by ANTIC.
CYIC2 calls HPCSD

DERHIC(X) (Subr): provides the rhs of the ray equations needed by the predictor-corrector integrating subroutine HPCSD. The real argument X is the current value of the Eikonal function (independent variable).
DERHIC is called by RAYPAT, HPCSD.
DERHIC calls CCCRDS, PROFIX, WAVECT, DISPIC

CYTWIN (Subr): locates the position of the cyclotron resonances and two-ion hybrid resonances (for output and for use in subroutine TIHRES).
CYTWIN is called by INITAL.

DISPIC(IENTRY) (Subr): evaluates the dieletric response of the plasma:
a) the dimensionless elements of the dielectric tensor at the current position;
b) the dispersion function and its derivatives;
c) the electric field polarization and the anti-hermitean part of the dielectric tensor.

If IENTRY = 1 a), b) and c) are evaluated
If IENTRY = 0 c) is skipped
If IENTRY = -1 b) is skipped

DISPIC is called by INIWPR, DERHIC.
DISPIC calls ZETA

FUANTY(X) (Subr): provides the rhs of the differential equations for the evaluation of the surface impedance of the plasma to IC waves. The real argument X is the distance from the plasma edge.
FUANTY is called by HPCSD.

GERGRA (Subr): executes the graphical output. It is subdivided into the following sections:

ENTRY GCROSS - Plots rays and wavefronts in the poloidal cross section.
ENTRY GSCALE - evaluates the scale for the plots of the wavevector components, etc.
ENTRY GKAPPA - Executes the plots of the wavector components and of the power flux along rays.
ENTRY GTITLE - Provides the title page of the graphical output with a resumee of the run data.
ENTRY GRPROF - Plots the profiles of density, temperature, and safety factor versus psi.
ENTRY GRAPOW - Plots the profiles of power absorption.

GERGRA is called by OUTGRA.
GERGRA calls GRAPHS, PLOPSI.
In addition, GERGRA calls subroutines of a Plot library of the local computer facility.

GRAPHS (Subr): executes the plot of a curve through the array of points (X(j),Y(j)).
GRAPHS is called by GERGRA.
GRAPHS calls subroutines of a Plot Library of the local computer facility.

HPCSD (Subr): general purpose subroutine for the integration of a system of first order differential equations:

$$dy/dx = f(x,y)$$

(y and f are vectors with dimension up to 10 in the present version). HPCSD uses a predictor-corrector method of fourth order. Its use is fully described in the FORTRAN listing. This subroutine has been written by Dr. O. Debarbieri.

HPCSD is called by ANTIC, RAYPAT.
HPCSD calls FUANTY, OUTANT, DERHIC, OUTPUT.

INITAL (Subr): provides the main initialization for a run of the RAYIC program. It can be divided into the following sections:

a) check charge neutrality (density profile of the ion species MAINSP)
b) choose the frequency and normalize distances
c) enter the parameters of the MHD equilibrium
d) prepare the spline coefficients of the profiles
e) locate the ion cyclotron resonances, and the two-ion hybrid resonances and cut-offs
f) initialize the output tables

INITAL is called by RAYIC.
INITAL calls METRIN, COORDS, INVERT, CYTWIN, PROFIN, ANTIC, OUTGRA.

INIWFR (Subr): determines the normal to the initial wavefront (direction of the wavevector) and solves the dispersion relation there (modulus of the wavevector) to provide the initial values for a ray.
INIWFR is called by RAYPAT.
INIWFR calls COORDS, PROFIX, DISPIC, WAVECT.
In addition, subroutine INIWFR calls the user-defined function PSIWFR, or, if JSTAND is not zero, the code-provided function PSIWFS.

INTERV(RMX,NPROF,RX,LEFT) (Subr): determines the mesh point This subroutine determines the mesh point LEFT closest LEFT closest to point RX, in the mesh array RMX. NPROF is the number of point effectively used in the mesh.
INTERV is called by PROFIX.

INTHRM(ISPEC,ZOPXI,ZASUM) (Subr): evaluates the integral This subroutine evaluates the integral entering the in the expression for the absorption at the first cyclotron harmonics by ion species ISPEC. ZOPXI is the factor in the argument of the Zeta-function (denominator of the integrand); ZASUM is the return value of the integral.
INTHRM is called by TIHRES.
INTHRM calls ZETA

METRIN (Subr): Normalizes the tables of coefficients of the parametric representation of the MHD equilibrium, to be used in COORDS, WAVECT AND INVERT.
METRIN is called by INITAL.

OUTANT(X) Output subroutine of the antenna package. Monitors the presence of a resonance layer in the near field region of the antenna.
OUTANT is called by HPCSD.

OUTGRA(IENTRY) (Subr): interface between the Ray-tracing package and the graphical output package:

IENTRY = 1 - initializes the plot tables to zero.
IENTRY = 2 - stores the profiles of density, temperature, etc.
IENTRY = 3 - stores the position and the wavevector along the rays as integration proceeds;
IENTRY = 4 - stores the power deposition profiles.
IENTRY = 5 - monitors the execution of the graphical

output.
OUTGRA is called by INITAL, RAYPAT, OUTPUT.
CUTGRA calls GERGRA (all its entries).

OUTPUT(X) (Subr): output subroutine for the ray-tracing package. It tests for failures, reflection, absorption, and monitors storing the results for the graphical output. The real argument X is the current value of the Eikonal function (independent variable).
OUTPUT is called by HPCSD.
OUTPUT calls TIHRES, ABSORB, OUTGRA.

OUTRUN(IENTRY) (Subr): provides the printed output of the run parameters (IENTRY = 1); the printed output of the power deposition profiles (IENTRY = 2); and the output of the TIHRES subroutine (IENTRY = 3).
OUTRUN is called by RAYPAT, TIHRES.

PLOPSI (Subr): executes the plots of the plasma meridian cross-section. It draws NCOPSI equidistant magnetic surfaces (including the plasma edge) by tracing NPTHET dots equidistant in theta. The plasma edge is drawn as a continuous curve.
PLOPSI is called by GERGRA.
PLOPSI calls COORDS.

POYNTN(LPHI) (Subr): evaluates the poloidal distribution of Poyinting flux on the first wavefront for the partial wave of toroidal wavenumber LPHI.
POYNTN is called by ANTIC.

PROFIN (SUBR): transfers the density, temperature, and poloidal/toroidal magnetic field profiles from the the input arrays to private arrays of the package RAYIC and monitors the evaluation of the coefficients for the cubic spline interpolations. It also evaluates the volume between magnetic surfaces psi and psi + dpsi, the area of the psi magnetic surface, etc., to obtain the poloidal magnetic field profile from the current density profile.
PROFIN is called by INITAL.
PROFIN calls CUBSPI, CUTGRA.

PROFIX (Subr): evaluates the values of density, temperature, rotational transform, etc., at the current position psi, theta, using the spline interpolation initialized by subroutine PROFIN.
PROFIX is called by INIWFR, DERHIC.
PROFIX calls INTERV, VALSPL.

PRONES(PSI) (Func): provides the standard electron density profile for the reference runs (JSTAND = 1, 2, or 3), as a function of the flux variable PSI.
PRONES is called by STANDP.
The call is skipped if JSTAND = 0, in which case the profiles are to be entered by the USER.

PROTES(PSI) (Func): provides the standard electron temperature profile for the reference runs (JSTAND = 1, 2, or 3), as a function of the flux variable PSI.
PROTES is called by STANDP.
The call is skipped if JSTAND = 0, in which case the profiles are to be entered by the USER.

PROTIS(PSI) (Func): provides the standard ion temperature profile for the reference runs (JSTAND = 1, 2, or 3), as a function of the flux variable PSI.
PROTIS is called by STANDP.
The call is skipped if JSTAND = 0, in which case the profiles are to be entered by the USER.

PSIWFS(THETA,DPSDTH) (Func): provides the first wavefront psi(THETA) (PSIWFR), and the derivative d(psi)/d(theta) (DPSDTH), for the reference runs.
PSIWFS is called by INIWFR.
The call is skipped if JSTAND = 0, in which case the USER must provide instead FUNCTION PSIWFR(THETA,DPSDTH).

RAYIC (Subr): main subroutine for the implementation of ray tracing. It is called by the USER after input of the run parameters.
RAYIC calls STANDP, INITAL, OUTRUN, RAYPAT, CUIGRA. Subroutine RAYIC contains the only breaking point of the ray-tracing package.

RAYPAT (Subr): monitors the integration of the ray equations (loops over toroidal wavenumber and over initial theta), and the crossing of cyclotron resonances when required.
RAYPAT calls INIWFR, DERHIC, HPCSD, CYCRES, CUIGRA.

STANDP (Subr): provides a standard set of parameters for the reference runs, according to the following scheme:

JSTAND=1	2% HE3 minority in Hydrogen
JSTAND=2	pure D, 2D harmonic heating
JSTAND=3	5% H minority in Deuterium

STANDP is called by RAYIC.
The call is skipped if JSTAND = 0, in which case the run parameters are to be entered by the USER.
STANDP calls PRCNES, PROTES, PRCTIS.

TIHRES (Subr): evaluates reflection, transmission and absorption as a wavefront hits a Two-Ion Hybrid layer.
TIHRES is called by OUTPUT.
TIHRES calls INTHRS, OUTRUN.

VALSPL(H,C,I,JDERIV) (Func): returns the interpolated value VALSPL of the JDERIV-derivative (the function, if JDERIV = 0) of the mesh-function stored in the first column of the array C. I is the mesh point closest to the left, H is the distance from this point.
VALSPL is called by PROFIX.

WAVECT (Subr): evaluates the physical components of the wavevector and its derivatives in the psi, theta frame and in the 'Stix' frame.
WAVECT is called by INIWFR, DERHIC.

ZBFACT(ZNZ2) (Subr): evaluates the form factor due to the wall-plasma 'leaking guide', appearing in the expression for the power spectrum from the antenna.
ZBFACT is called by ANTIC.

ZETA(XN,ZR,DZR,WZ) (Subr): evaluates the real part of the Plasma Dispersion Function for real argument, and its derivatives as needed by the Dispersion Function of IC waves, according to the following definitions:

XN = real argument x
ZR = Re(-x*Z(x))
DZR = Re(-x*x*Z'(x))
WZ = DZR - ZR

where Z(x) is defined as in Fried and Conte.

ZETA is called by DISPIC, INTHRM.

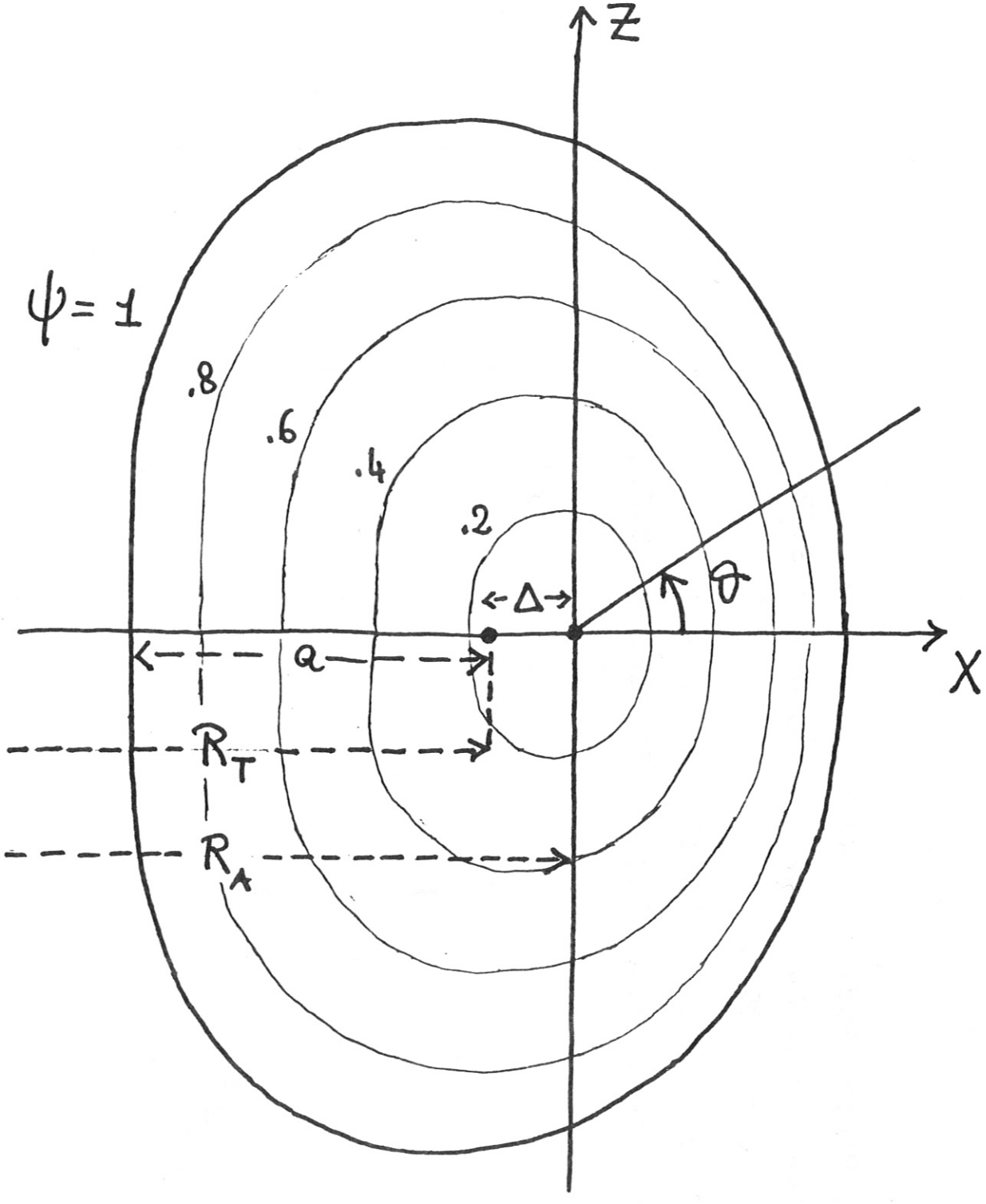


FIG. 1

Torus Radius 3.00 M, Plasma Radius 1.20 M

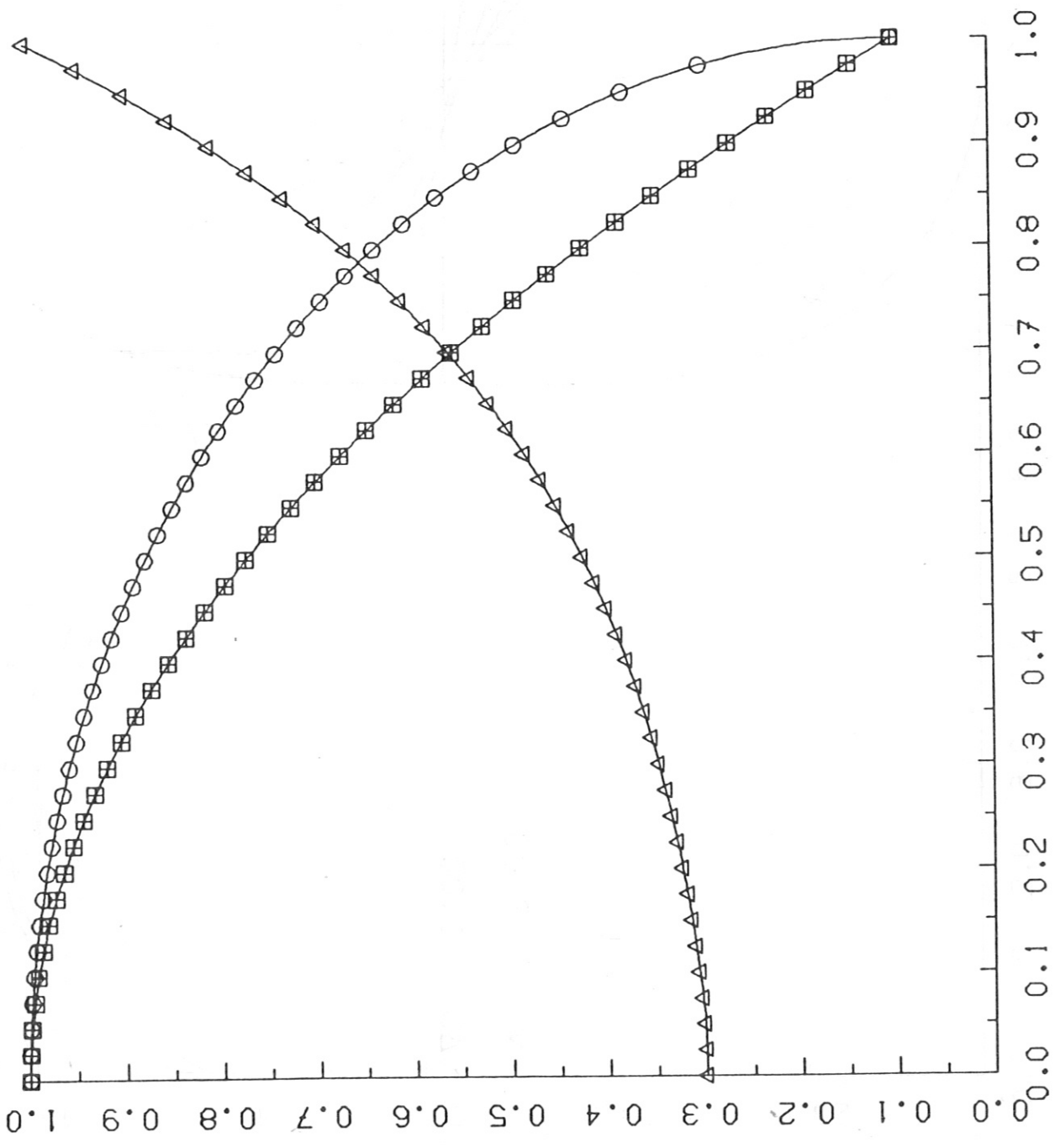
B(axis) 3.16 T, Current 5.00 Ma, Q(0) = 1.13, Q(a) = 3.77

Frequency 50.00 Mhz, Power 1.00 Mw

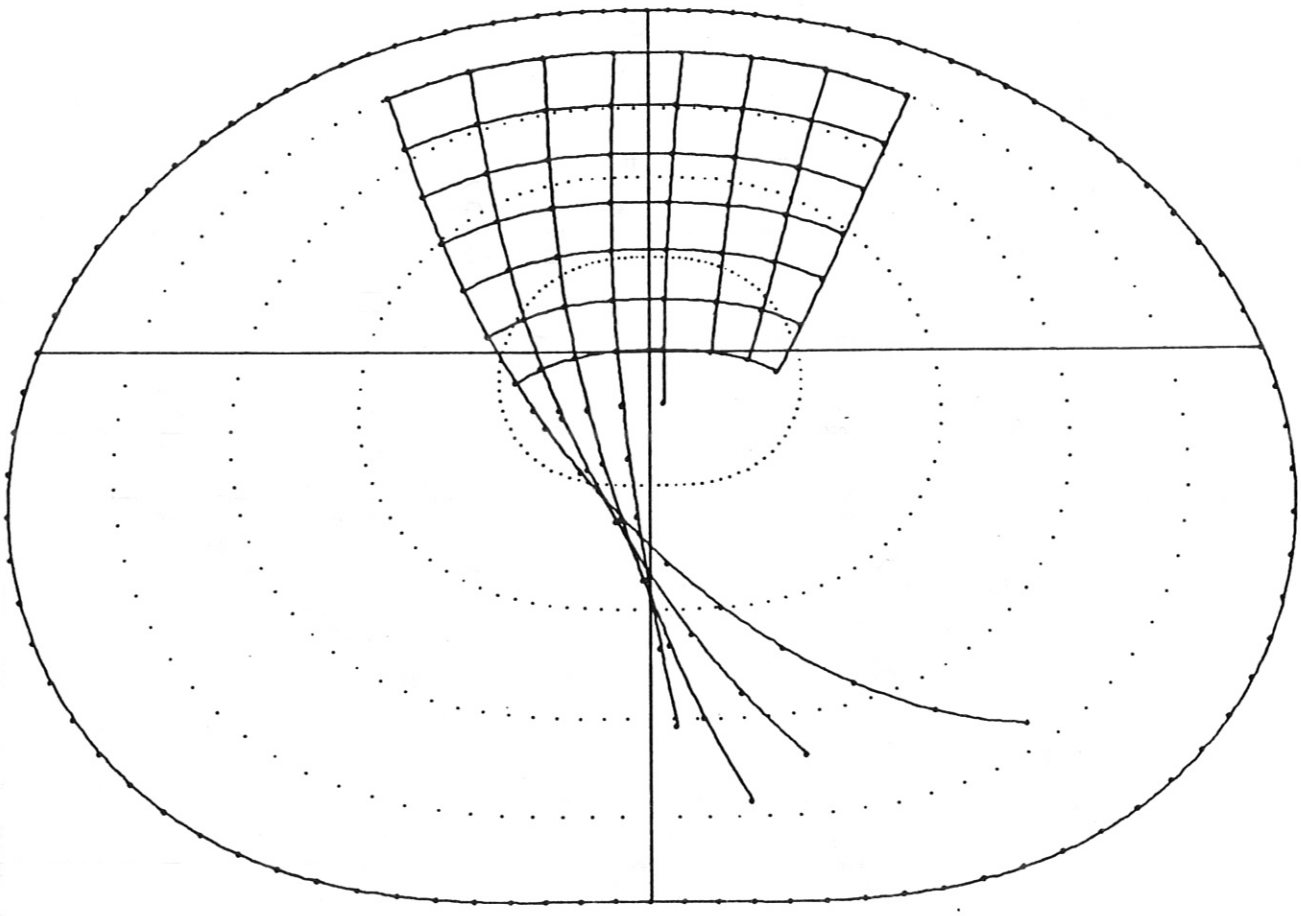
Elec: N(0) 0.50 10^{14} Cm-3, T(0) 1.70 KEV, Pw 0.09 Mw

Ions:, A 2.00, Z 1.00, Conc. 1.00, T(0) 1.70 KEV, Pw 0.21 Mw

IPP-CRAY 11.01.84 13:57:17 MAB600 J2-03 01


PROFILES
o N_e
N_0 = 0.50 10^{14}
□ T_e
T_{e0} = 1.70 Kev
+ T_i
T_{i0} = 1.70 Kev
△ Q(r)
Q(a) = 3.77
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

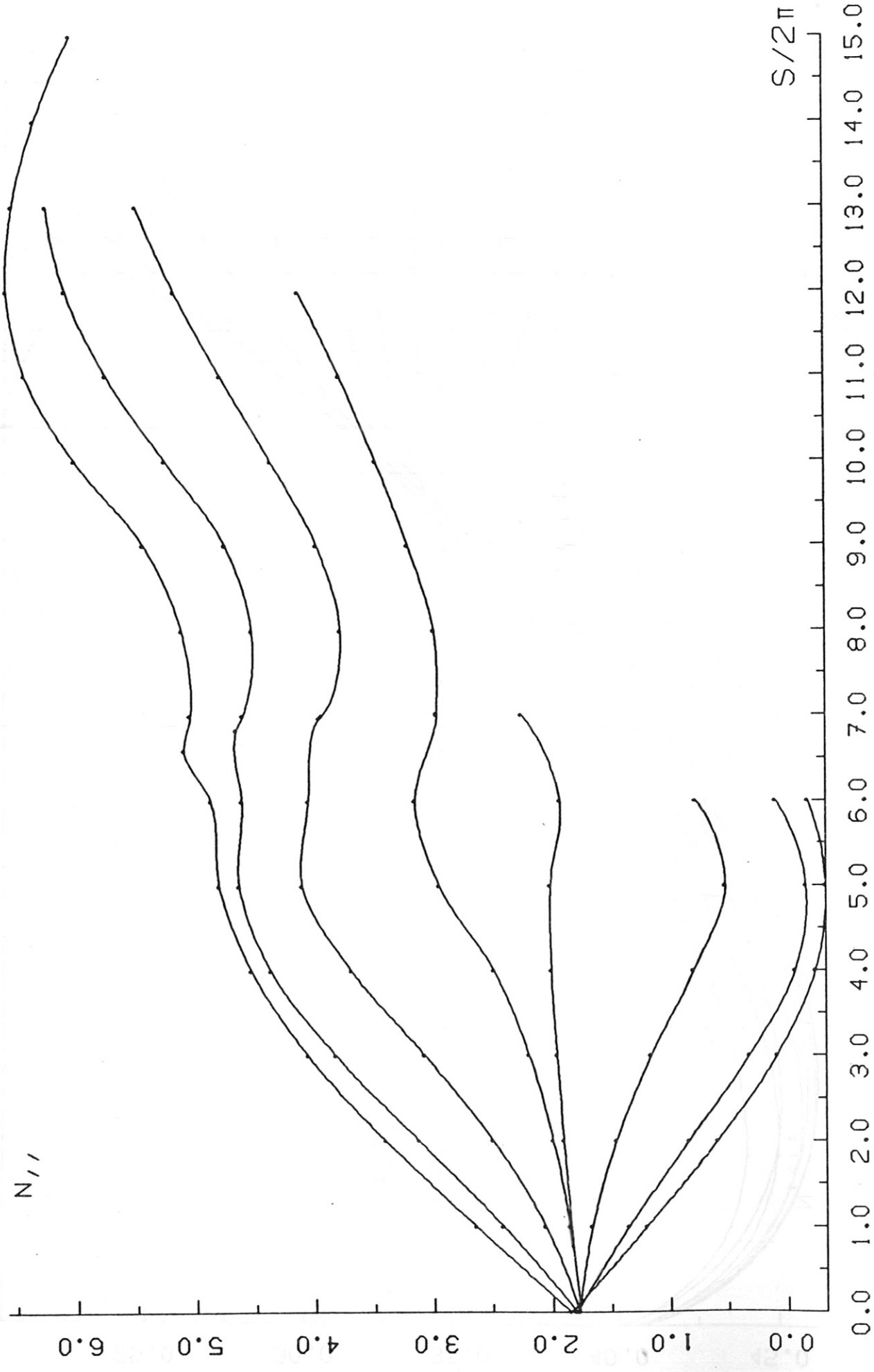
IPP-CRAY 11.01.84 13:57:17 MAB600 J2-03 03



N_ϕ = 8.00

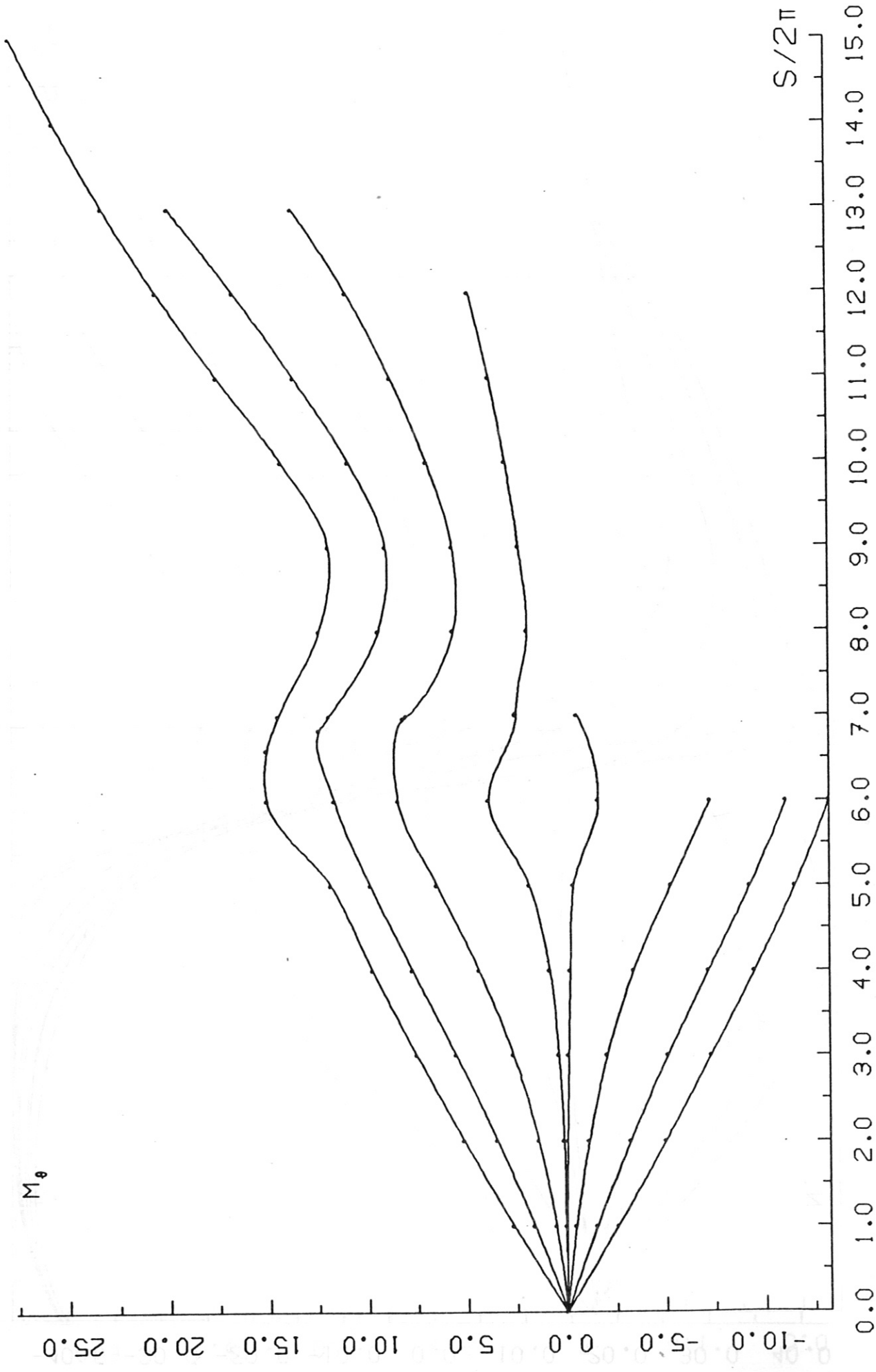
ΔS = 1.00

IPP-CRAY 11.01.84 13:57:17 MAB600 J2-03 04

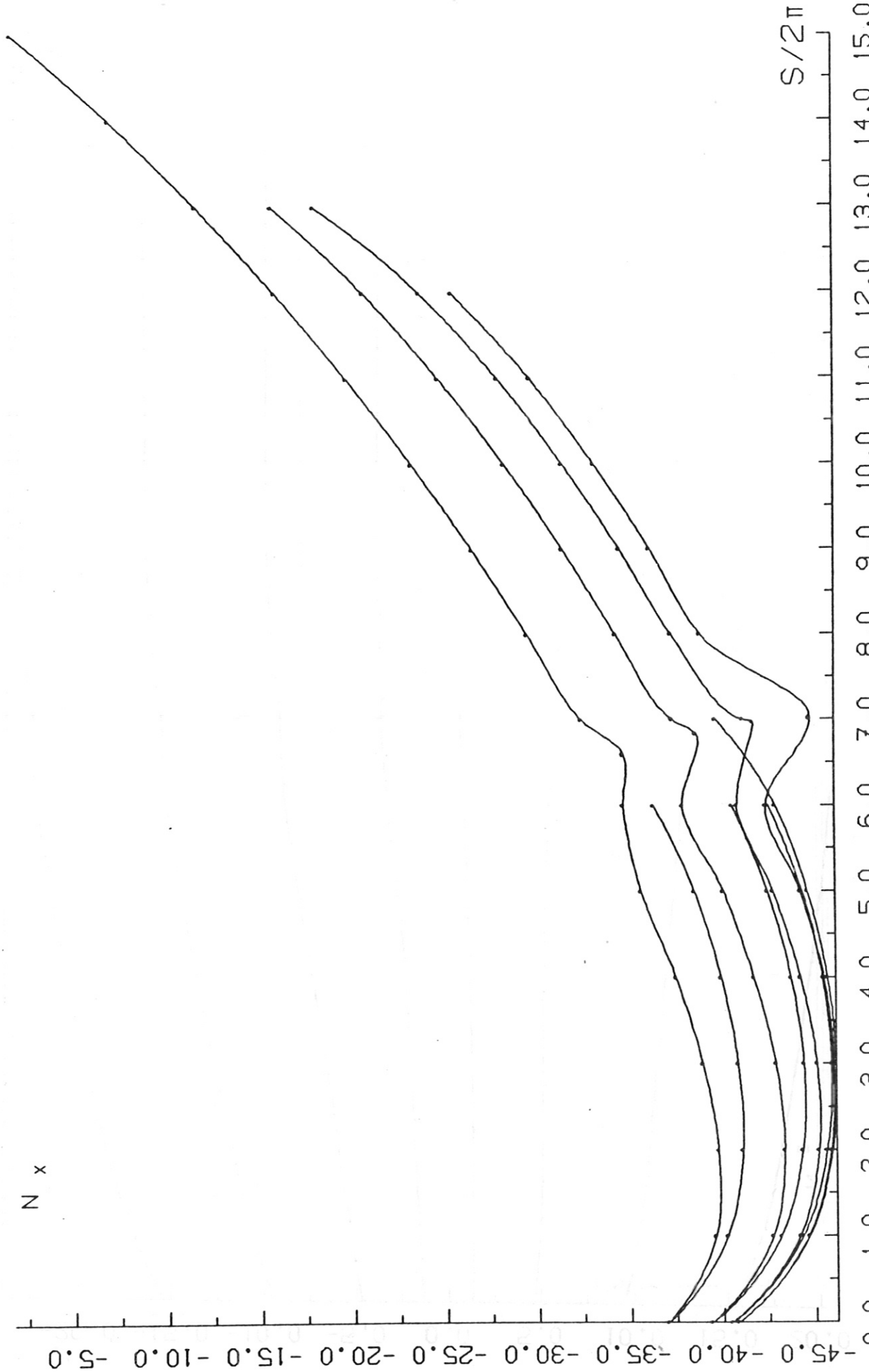

S/2π
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
N//
0.0
1.0
2.0
3.0
4.0
5.0
6.0

IPP-CRAY 11.01.84 13:57:17 MAB600 J2-03 06

IPP-CRAY 11.01.84 13:57:17 MAB600 J2-03 07

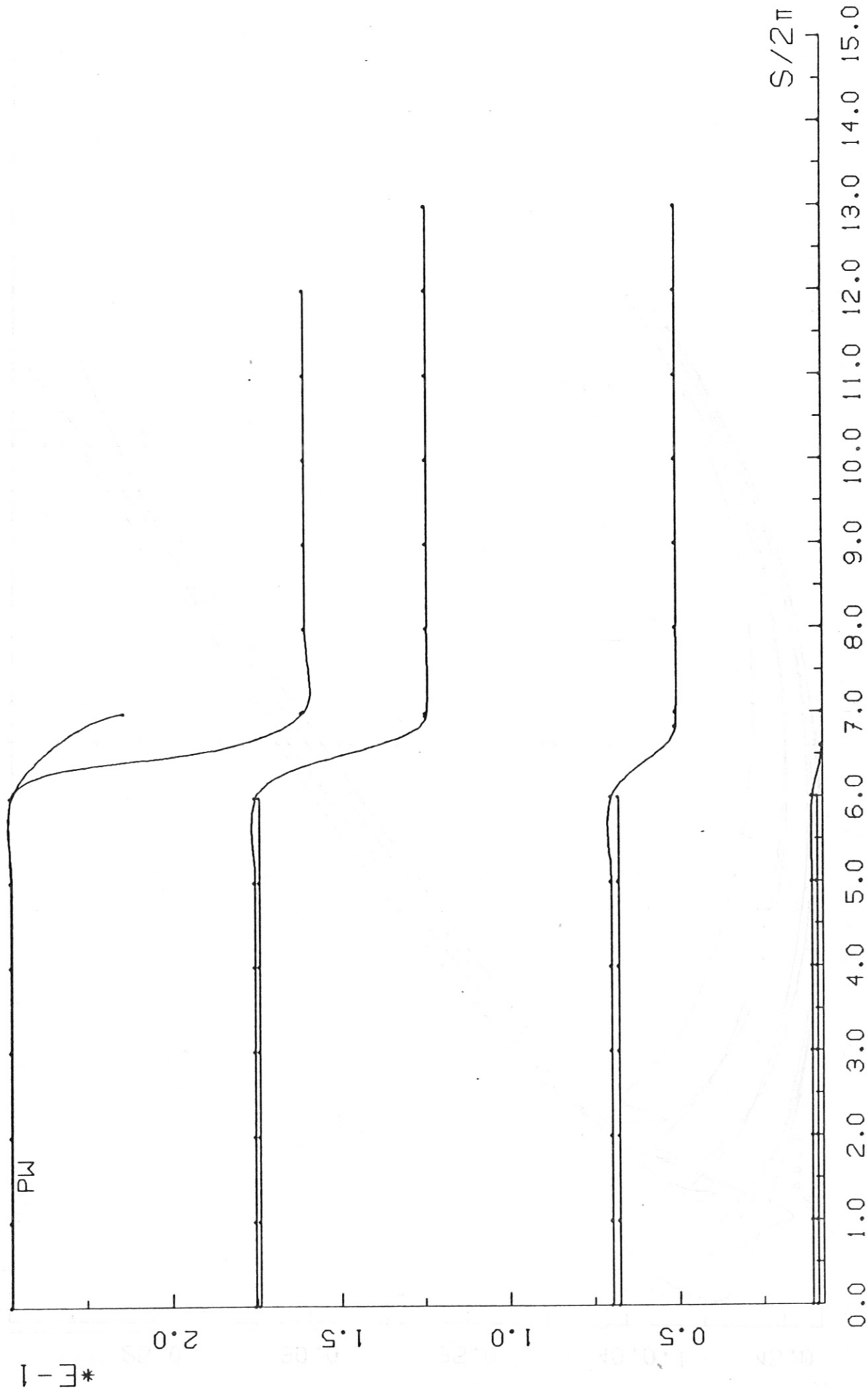


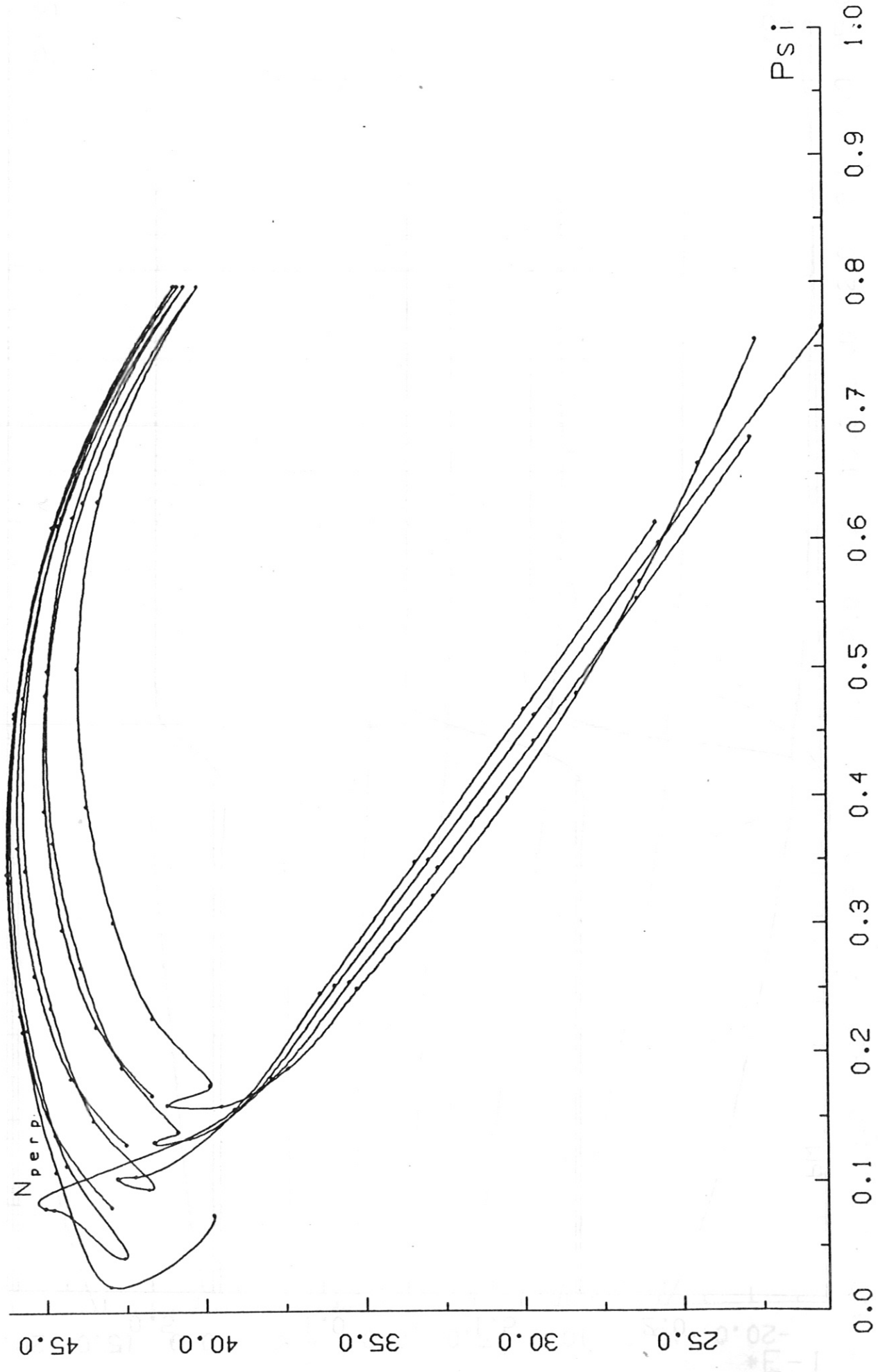
IPP-CRAY 11.01.84 13:57:17 MAB600 J2-03 08

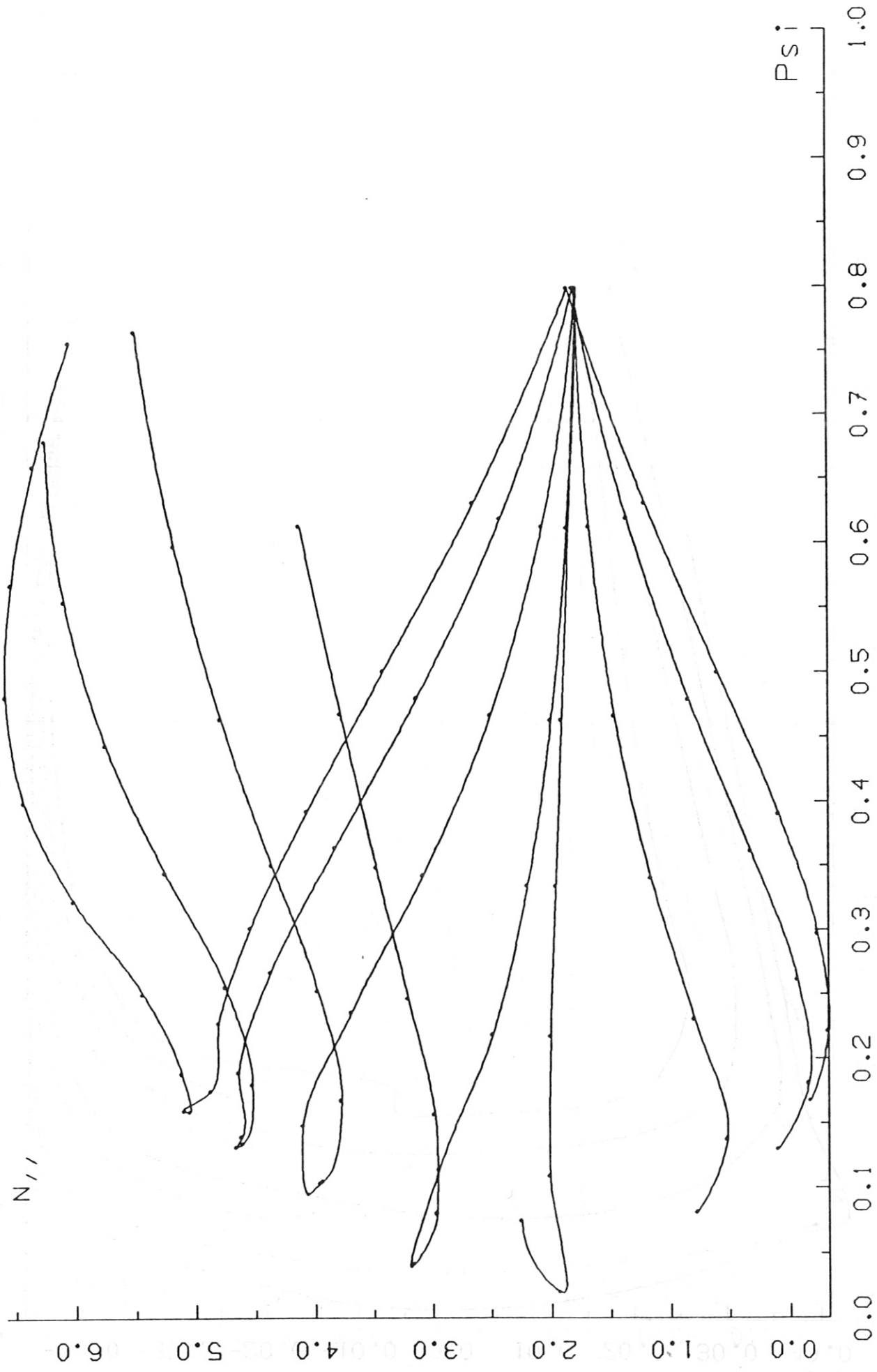


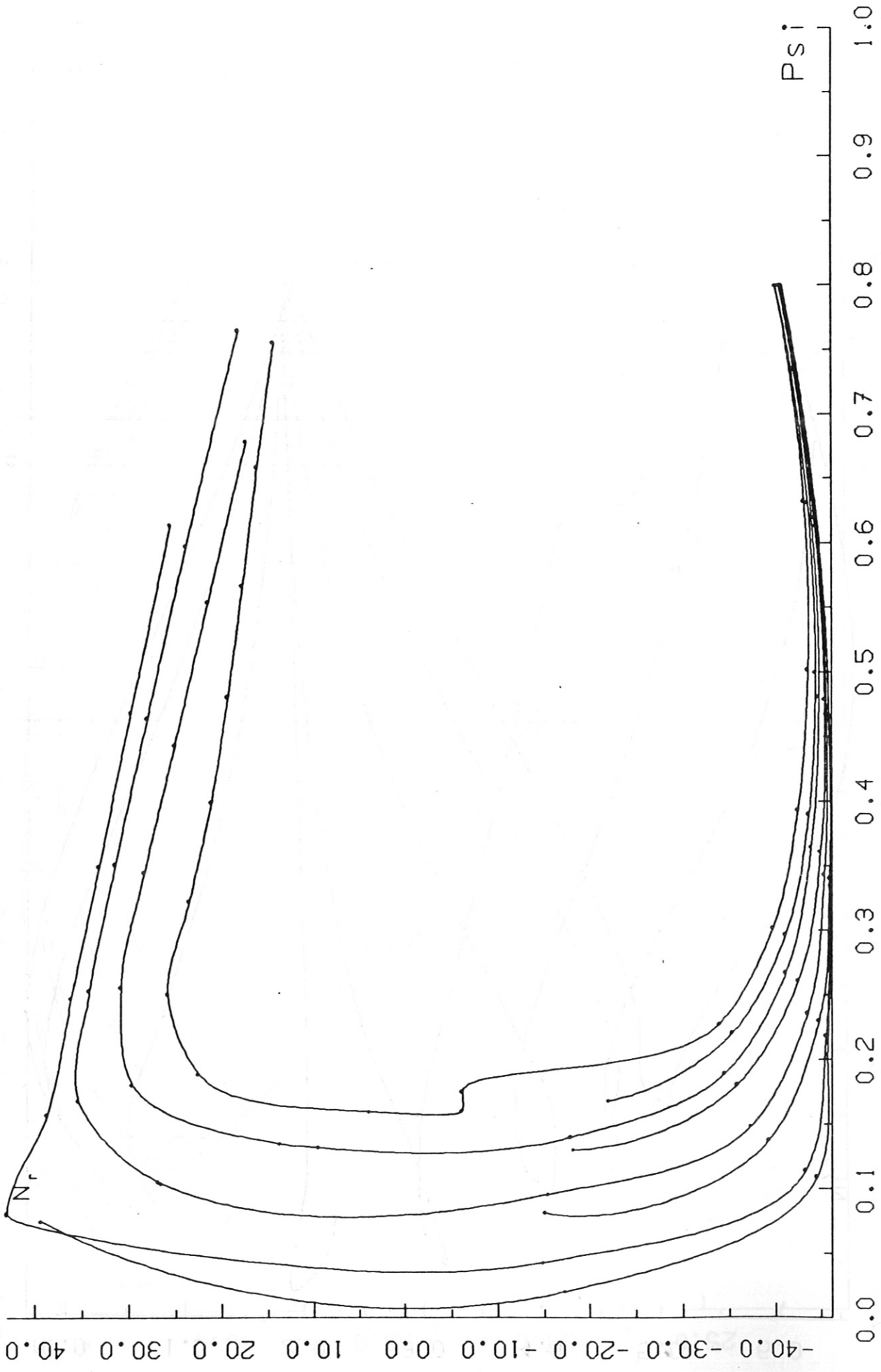
IPP-CRAY 11.01.84 13:57:17 MAB600 J2-03 09

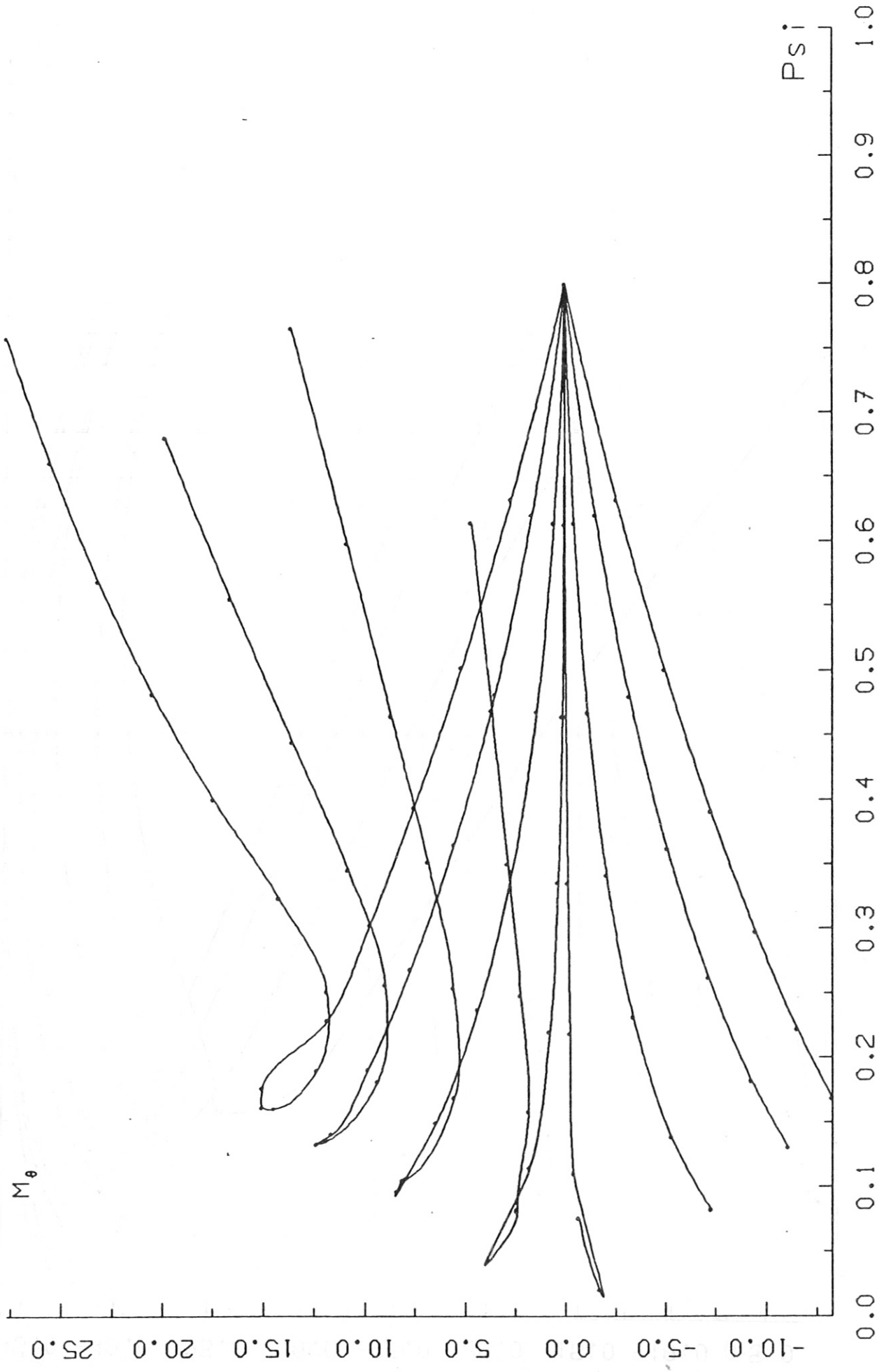
IPP-CRAY 11.01.84 13:57:17 MAB600 J2-03 10

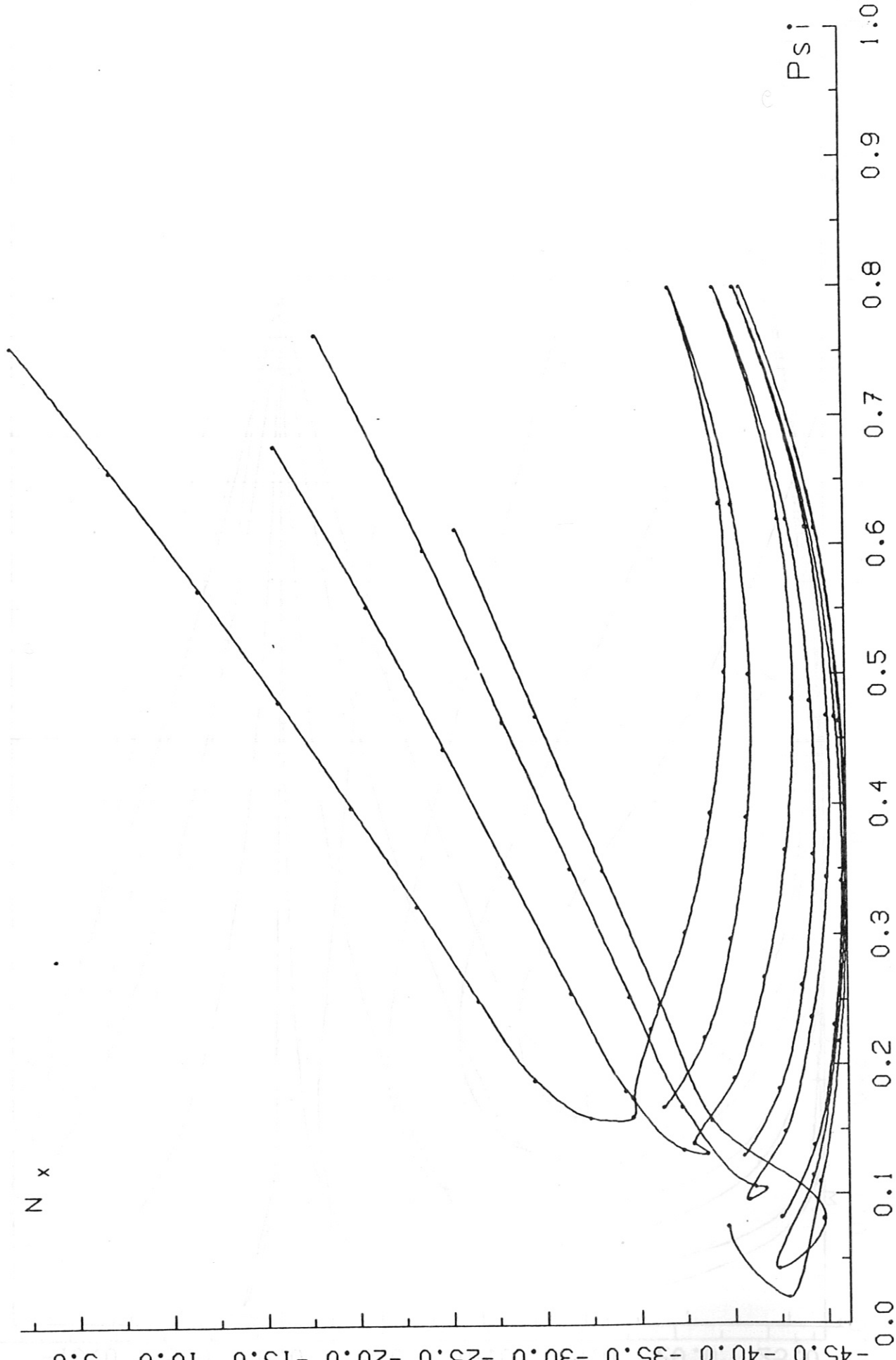


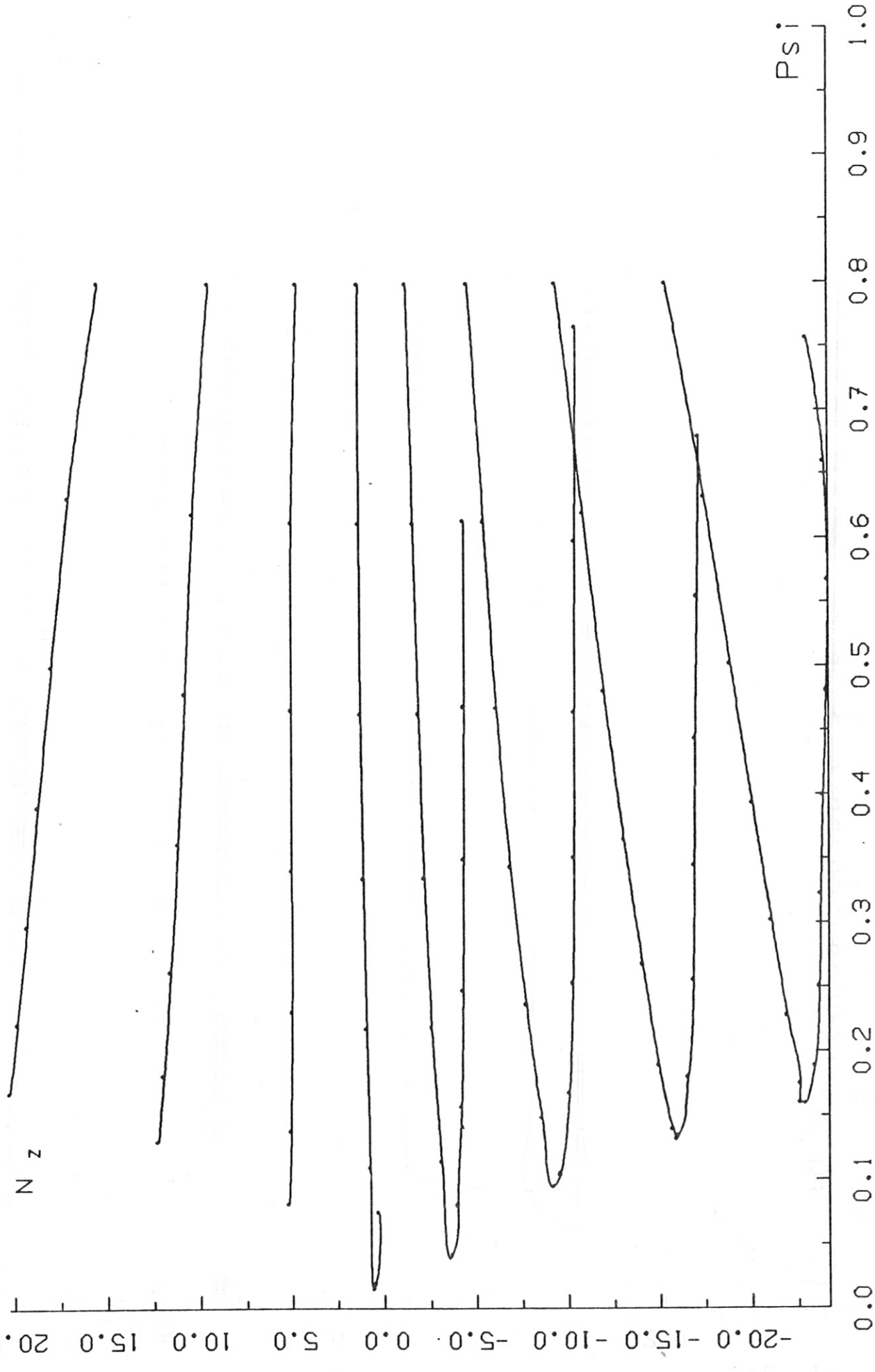

Psi
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
N perp
45.0
40.0
35.0
30.0
25.0

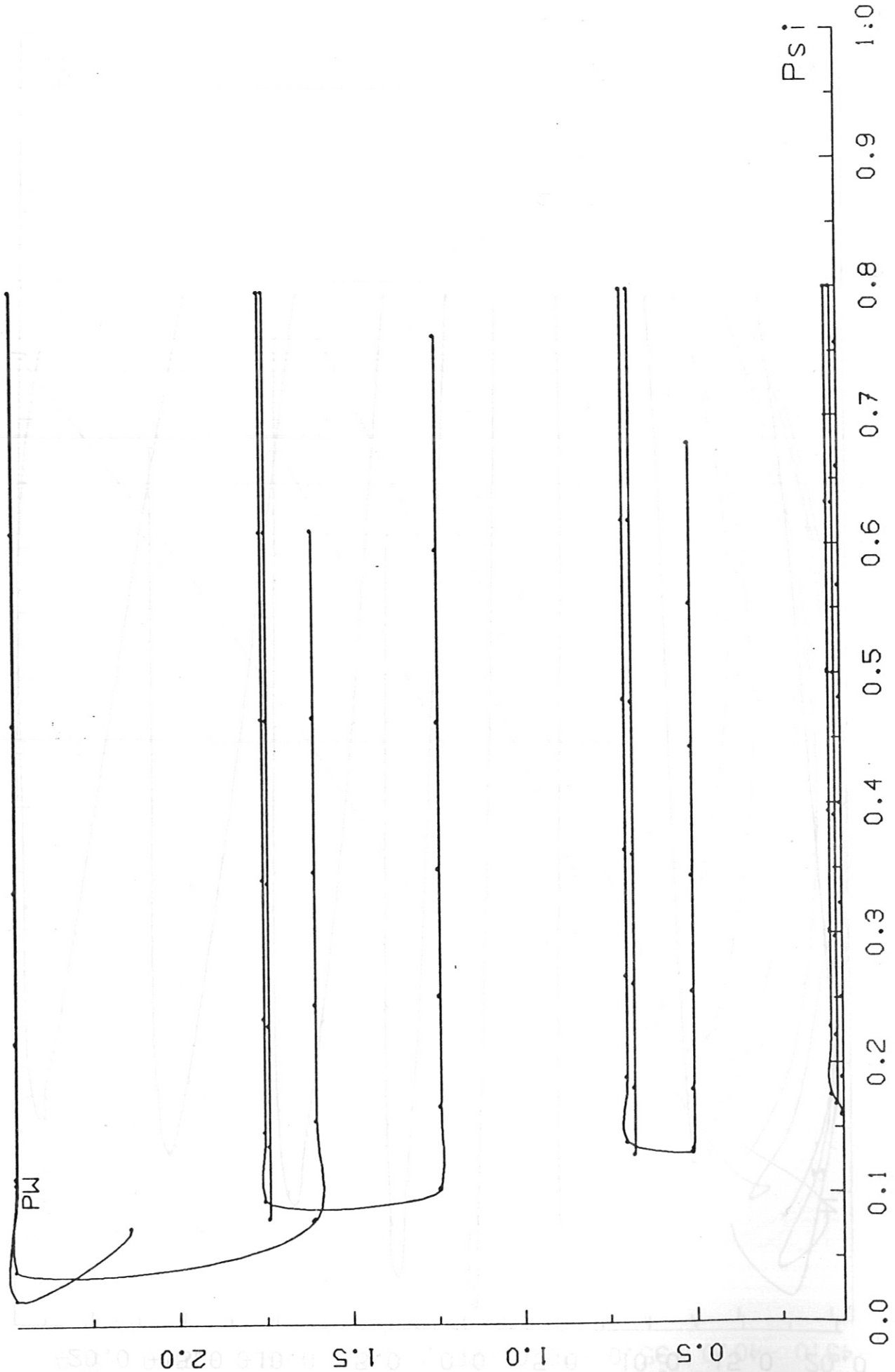

Psi
N//
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0

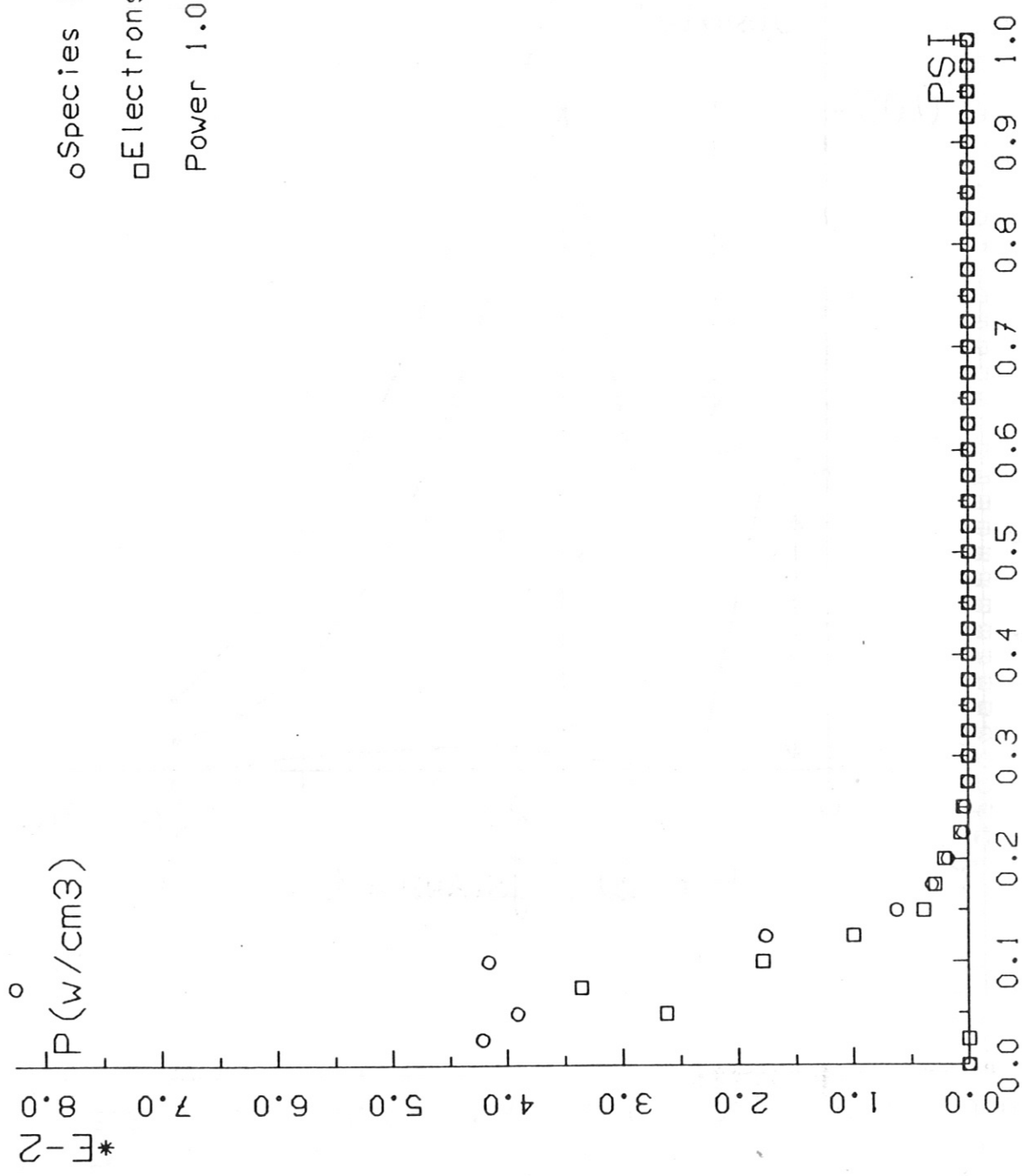

Psi
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-40.0
-30.0
-20.0
-10.0
0.0
10.0
20.0
30.0
40.0
R


Psi
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
M_θ
-10.0
-5.0
0.0
5.0
10.0
15.0
20.0
25.0


Psi
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
-45.0
-40.0
-35.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
x
N


Psi
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
N z
-20.0
-15.0
-10.0
-5.0
0.0
5.0
10.0
15.0
20.0


Psi
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.5
1.0
1.5
2.0
PW
*E-1


oSpecies 1.00
□Electrons
Power 1.00 Mw
P (w/cm3)
*E-2
PSI
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

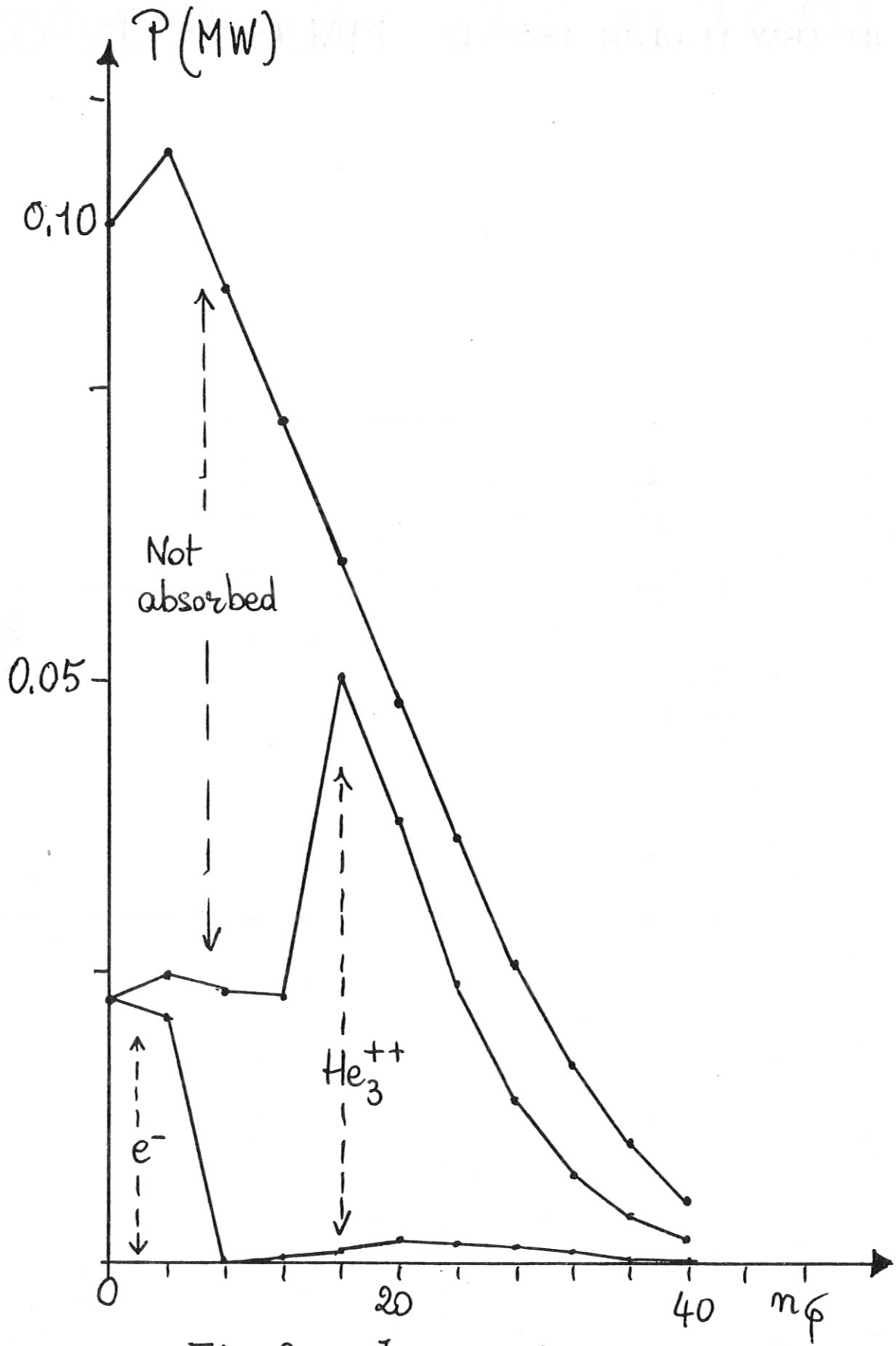


FIG 20. JSTAND = 1

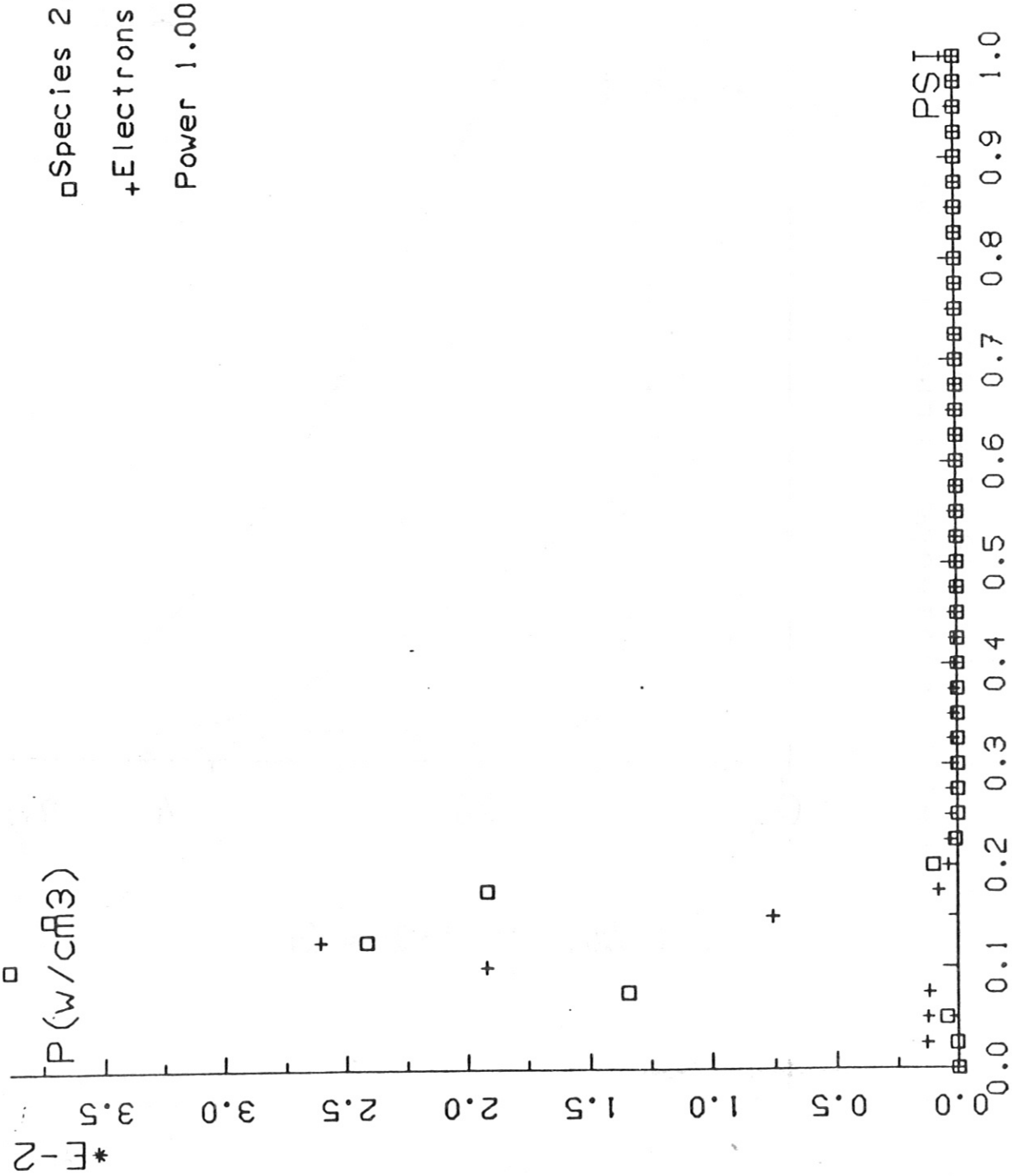

□Species 2.00
+Electrons
Power 1.00 MW
P(W/CM3)
*E-2
PSI
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Fig. 21

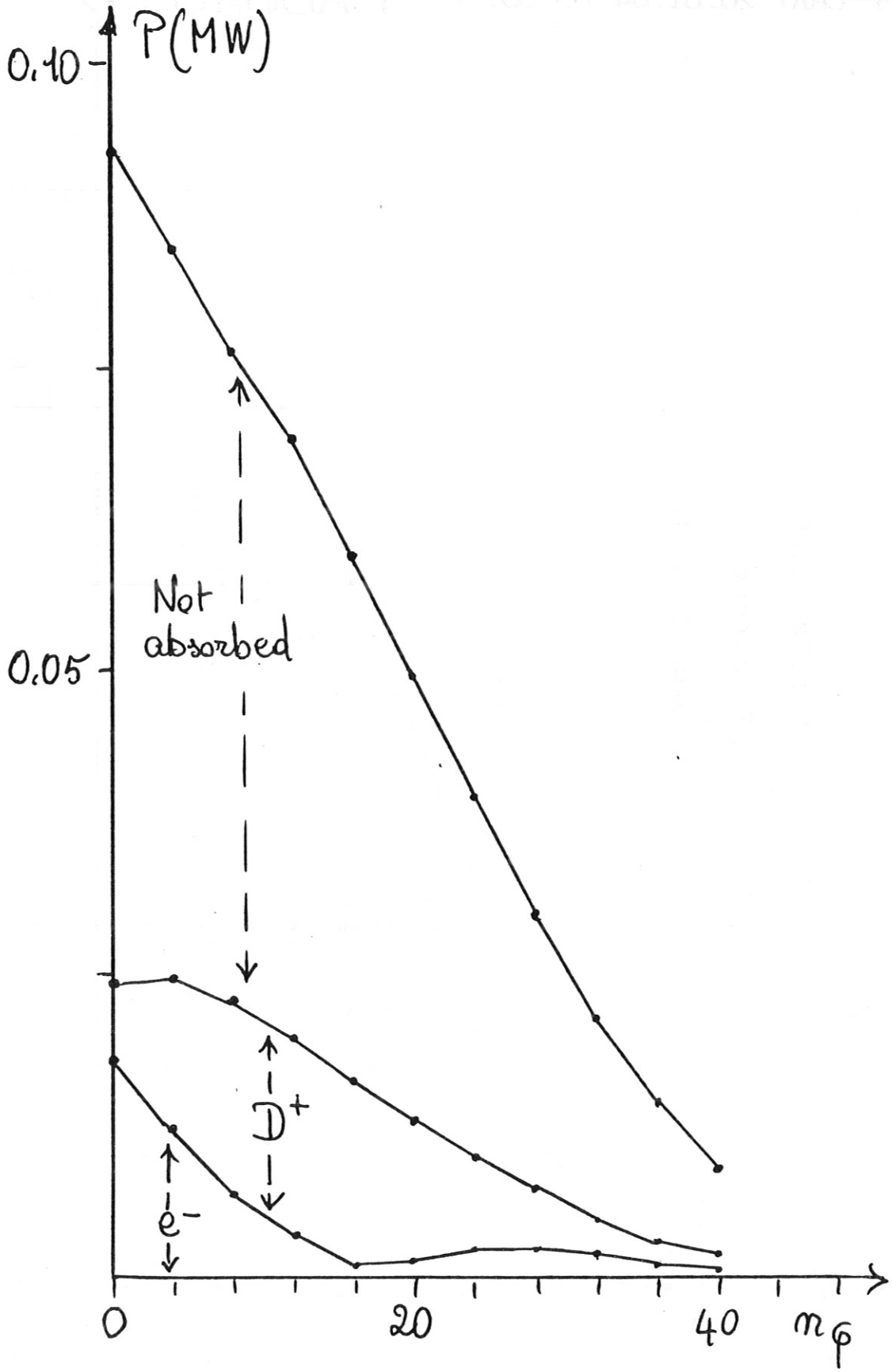


FIG 22. JSTAND = 2

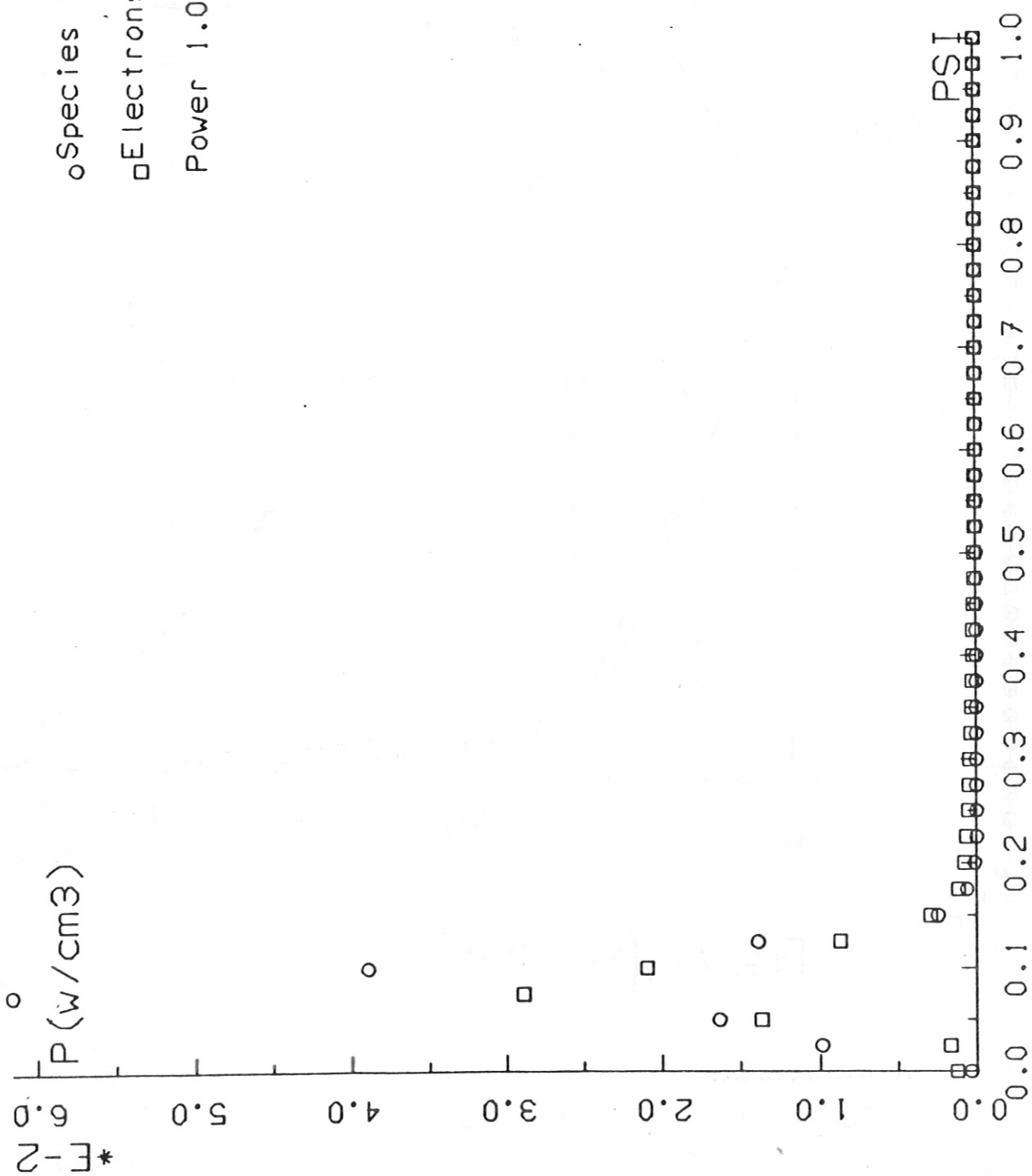

oSpecies 1.00
□Electrons
Power 1.00 Mw
P(w/cm3)
*E-2
PSI
0.0
1.0
2.0
3.0
4.0
5.0
6.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

FIG. 23

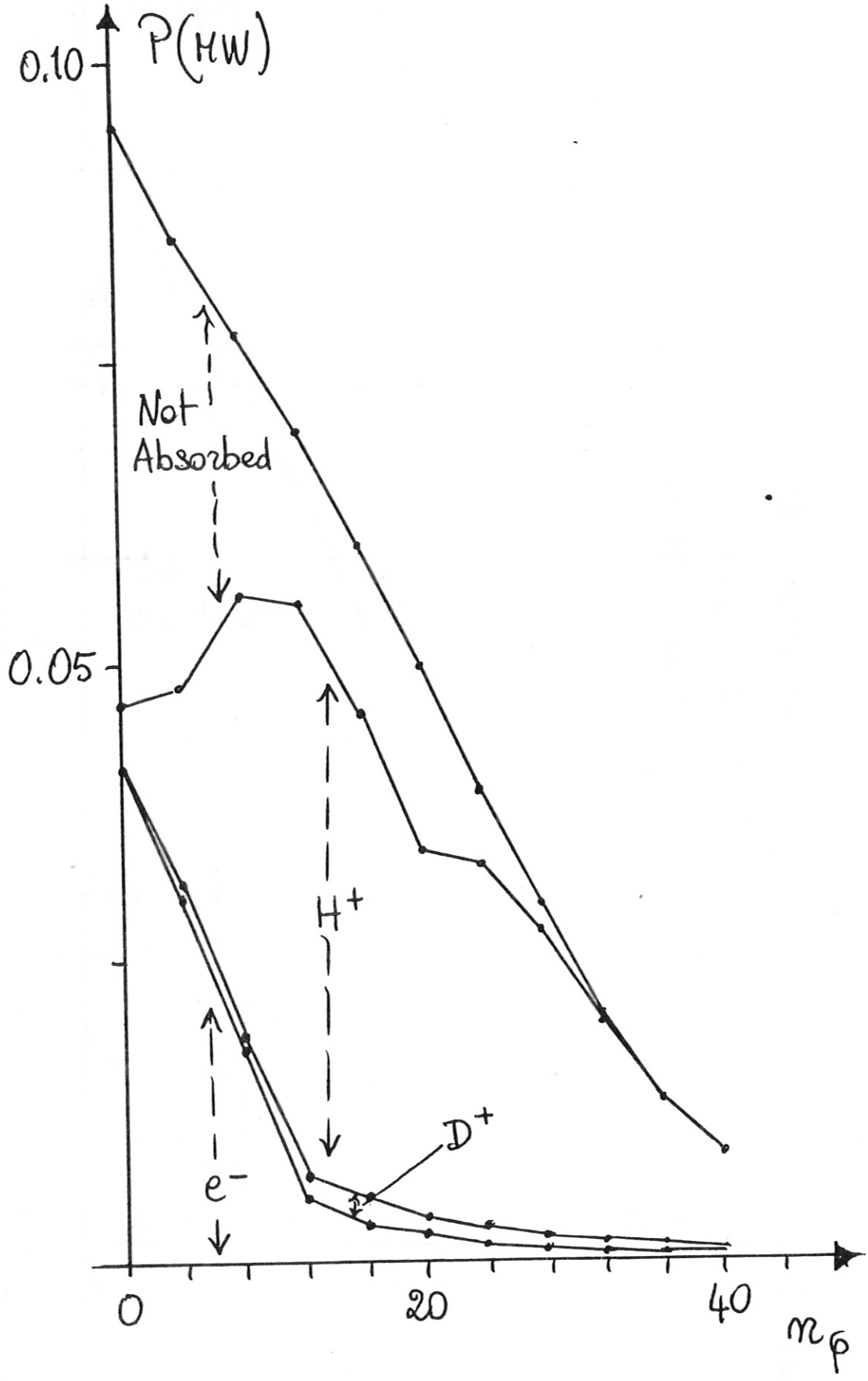


FIG. 24 JSTAND = 3

oSpecies 1.00
□Species 2.00
+Electrons
Power 1.00 MW
P(w/cm3)
*E-1
PSI
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2

FIG. 25