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DOCUMENTATION OF THE HIGH BETA STABILITY CODES HBT AND HBTAS AT JET

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ABSTRACT

The ideal magnetohydrodynamic stability code HBT (High Beta Tokamak) has recently been extended to include arbitrary non up-down symmetric plasma shapes. Both the HBT and the new asymmetric version, called HBTAS, have been installed at JET. The HBT and HBTAS codes can be used to study the ballooning mode stability properties (exact) and the low-n mode stability (in the high-β approximation) of JET discharges. In this report both codes are described in some detail. The equations and the numerical methods used are given. Further, how to use HBT(AS) in general and specifically for the study of actual JET discharges is explained. Detailed descriptions of all the input and output parameters of HBT(AS) are given in the appendices.

I. INTRODUCTION

The HBT (High Beta Tokamak) code is an ideal magnetohydrodynamic equilibrium and stability code developed at the FOM Institute for Plasma Physics 'Rijnhuizen' by J.P. Goedbloed [1] and coworkers. Originally it was used for high-β optimization studies. However, HBT can equally well be used for the study of the MHD stability properties of actual JET discharges.

In the near future the JET configuration will be changed to a divertor geometry with a single x-point plasma shape. Also during past high-β operation, single x-point plasma shapes were used. To be able to investigate the MHD stability properties of these plasmas, HBT has been extended to include arbitrary non up-down symmetric plasma shapes. Both the new code, called HBTAS, and HBT have been installed at JET. Results of a study of the stability properties of JET high-β discharges with HBT and HBTAS are discussed in an accompanying report [2].

In this report, the codes HBT and HBTAS are described in some detail. In section II and III respectively, the equations used in the equilibrium and in the low-n and ballooning mode stability computations are given. Also the numerical methods that are applied in HBT and HBTAS are discussed. For up-down symmetric equilibria, the plasma boundary and the position of the magnetic axis can be specified before the actual equilibrium calculation. This can be exploited through the use of a conformal mapping which maps the plasma boundary onto a circle and the magnetic axis onto the origin of the circle. In this computational plane the actual equilibrium computation becomes much easier and more accurate. In the case of a general non up-down symmetric plasma shape the magnetic axis cannot be chosen freely and an additional iteration is needed to determine the position of the magnetic axis. Both the up-down symmetric equilibrium and the new non up-down symmetric equilibrium are discussed in sec. II.A and B. The conformal mapping is described in sec. II.C. In sec. II.D the results of a test of the asymmetric equilibrium with an asymmetric Soloviev equilibrium are given.

The parts concerning the stability of low-n modes and of ballooning modes are presented in sec III A and B respectively.

The remaining part of this report contains an explanation of the use of the HBT and HBTAS codes at JET. In sec. IV a general description of the codes is given in terms of the four modules (see fig. 4.1) of HBT(AS) and the necessary input parameters. A full list of all input and output quantities is given in the appendices. In sec. V the interface of HBT with IDENTC,

the main source of equilibrium data at JET, is given. It describes the relation between IDENTC output parameters and HBT input parameters. An example of a complete run of HBT using IDENTC data is presented in appendix F. To be able to use experimentally measured equilibrium profiles like for example a pressure profile as measured by the LIDAR diagnostic, (sec. V.B), HBT(AS) has the facility to specify the input profiles through the coefficients of a spline interpolation of an arbitrary profile. This is described in appendix G.

EQUILIBRIUM

A. NORMALIZATION

The force balance equation, $\nabla p = \mathbf{j} \times \mathbf{B}$ in a plasma in toroidal geometry is given by the Grad- Shafranov equation

$$R \frac{\partial}{\partial R}\left\{\frac{1}{R}\frac{\partial \Phi}{\partial R}\right\} + \frac{\partial^2 \Phi}{\partial Z^2} = \mu_0 R j_\phi \,, \tag{2.1}$$

where Φ is the poloidal flux, J_ϕ is the toroidal current density, R is the distance from the axis of symmetry, and Z is the vertical coordinate. The toroidal symmetry also allows the right-hand side of Eq. (2.1) to be written in terms of two flux functions, with the pressure $p(\Phi)$ and a diamagnetic profile $f(\Phi) = RB_\phi$:

$$R j_\phi = - R^2 \frac{dp(\Phi)}{d\Phi} - \frac{1}{2\mu_0}\frac{df^2(\Phi)}{d\Phi} \,. \tag{2.2}$$

The formulation of the equilibrium problem of finding $\Phi(R,Z)$ in terms of physical quantities contains two trivial scaling parameters, viz. the vacuum magnetic field B_0 and the scalelength a (the minor radius of the torus) of the problem. They just provide the dimensions of the physical quantities but do not enter the problem otherwise. Similarly, the total poloidal flux $2\pi(\Phi_1 - \Phi_0)$ will only enter as a scaling parameter normalizing the J_ϕ and B_ϕ profiles. This scaling is accounted for by the parameter $\alpha = a^2 B_0/(\Phi_1 - \Phi_0)$. The two arbitrary profiles $p(\Phi)$ and $f(\Phi)$ can then be normalized as follows:

$$P(\psi) = \left(\frac{\mu_0 \alpha^2}{\varepsilon B_0^2}\right) \cdot p(\Phi) \,, \quad F^2(\psi) = \frac{\varepsilon \alpha^2}{a^2 B_0^2}\left(f^2(\Phi) - R_0^2 B_0^2\right) \,, \tag{2.3}$$

where the normalized flux $\psi = (\Phi - \Phi_0)/(\Phi_1 - \Phi_0)$ will now play the role of a radial coordinate. The other physical parameters can then be scaled as:

$$B_\phi = B_0 \cdot \frac{1}{1+\varepsilon x}\left[1 + \frac{\varepsilon}{\alpha^2} \cdot F^2(\psi)\right]^{1/2} \,,$$

$$\mathbf{B}_p = \frac{\varepsilon B_0}{\alpha} \cdot \frac{-1}{1+\varepsilon x} \nabla\psi \times \mathbf{e}_\phi \,,$$

$$j_\phi = \frac{\varepsilon B_0}{\mu_0 \alpha a} \cdot \frac{-1}{\varepsilon}\left[(1+\varepsilon x)P'(\psi) + \frac{FF'(\psi)}{1+\varepsilon x}\right] \,,$$

$$j_p = \frac{\varepsilon B_0}{\mu_0 \alpha^2 a} \cdot \frac{FF'(\psi)}{1+\varepsilon x} \left[1 + \frac{\varepsilon}{\alpha^2} \cdot F^2(\psi) \right]^{-1/2} \nabla\psi \times \mathbf{e}_\phi \,, \tag{2.4}$$

where the dimensionless coordinates $x \equiv (R-R_0)/(a)$ and $y \equiv Z/a$ are exploited.

At high β, the two profiles $P(\psi)$ and $-1/2\, F^2(\psi)$ only differ $O(\varepsilon)$ from each other. Therefore, it is expedient to define a new flux function:

$$G(\psi) = \frac{1}{\varepsilon} \left[P(\psi) + \tfrac{1}{2} F^2(\psi) \right] . \tag{2.5}$$

The Grad-Shafranov equation then becomes

$$\psi_{xx} + \psi_{yy} - \frac{\varepsilon}{1+\varepsilon x} \psi_x = A \left[\Gamma(\psi) + Bx(1 + \tfrac{1}{2}\varepsilon x)\, \Pi(\psi) \right] , \tag{2.6}$$

where we have separated the amplitudes from the shapes of the derivatives of the flux functions G and P by defining the unit profiles:

$$\tfrac{1}{2} AB\, \Pi(\psi) = - P'(\psi) \,, \qquad A\, \Gamma(\psi) = - G'(\psi) \,, \tag{2.7}$$

with $\Pi(0) = \Gamma(0) = 1$. In our method of solution, to be elaborated below, the parameters A and B will become eigenvalues of the problem.

B. NUMERICAL SOLUTION

Numerical solution of Eq. (2.6) requires the specification of boundary conditions. Here we consider a fixed and given shape of the plasma boundary. The boundary condition at the plasma-vacuum interface, i.e. $\mathbf{B}\cdot\mathbf{n} = 0$, then becomes:

$$\psi = 1 \quad \text{at the plasma boundary} \,. \tag{2.8}$$

With this boundary condition specified, Eq. (2.6) can be solved in the interior of the plasma boundary. If Eq. (6) is rewritten in the form

$$\Delta\psi = f(\psi, x, y) \,, \tag{2.9}$$

it can be considered as a kind of Poisson equation. When f is independent of ψ and the plasma boundary is circular, Eq. (2.9) can easily be integrated. Fourier transforming:

$$\psi = \sum_{m=0}^{M}{}' \psi_m(s)\, e^{imt} \,,$$

$$f = \sum_{m=0}^{M}{}' f_m(s)\, e^{imt} \,, \qquad \text{where } x + iy = s e^{imt} \,. \tag{2.10}$$

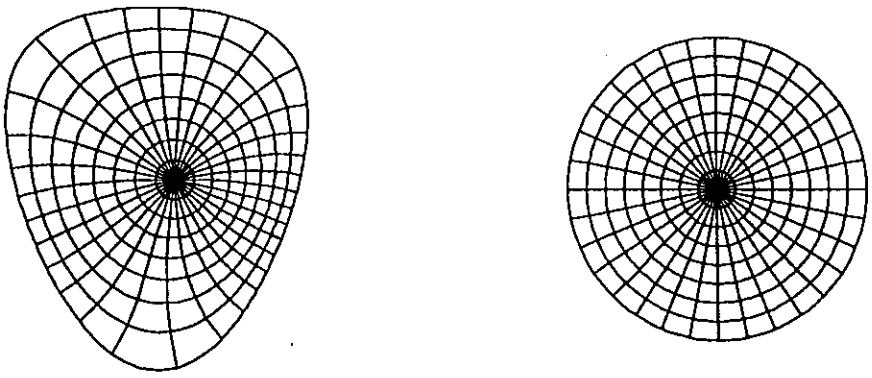
Equation (2.9) is then solved by

$$\psi_m(s) = 2\,\delta_{m0} + s^m \int_1^s ds'\, s'^{-(2m+1)} \int_0^{s'} ds''\, s''^{\,m+1}\, f_m(s'') \,, \qquad (2.11)$$

where the boundary condition $\psi(s=1) = 1$ is satisfied.

The limitation of a circular plasma boundary can be removed by the use of a conformal map. We apply a coordinate transformation with an analytical function, such that the arbitrary plasma boundary is mapped onto a circle in the new coordinate plane.

$$z = \sum_{m=0}^{M} \phi_m\, w^m$$



Physical plane Computational plane

Fig. 2.1 Conformal mapping

In the mapped (s,t) plane Eq. (2.9) then becomes

$$\Delta\psi = h^2 f(\psi, s, t) \,, \qquad (2.12)$$

where $h(s,t) \equiv |dz/dw|$ is the scale factor of the conformal mapping. Again, if f is independent of ψ, Eq. (2.12) can be solved as before.

In the general case, where f does depend on ψ, Eq. (2.12) can be solved with a Picard iteration:

$$\Delta\psi_{n+1} = f(\psi_n(s,t), s, t) \,, \qquad (2.13)$$

where the solution (2.11) is exploited at each step. In principle, this solves the Grad-Shafranov equation. However, the representation of nested flux surfaces by means of a Fourier series and exploiting a coordinate system with a shifted origin with respect to the magnetic axis, is not very accurate. The accuracy of the solution can be greatly enhanced by specifying the position of the magnetic axis forehand and using a conformal mapping which maps this point onto the

origin of the computational plane. Moreover, the behaviour of the solution $\psi(s,t)$ near the magnetic axis will be known analytically, viz.: $\psi_0(s) \sim s^2$, $\psi_1(s) \sim s^3$, and $\psi_m \sim s^m$ $(m \geq 2)$. Thus, the equilibrium quantities on the magnetic axis can be calculated very accurately.

For a general non up-down symmetric plasmashape, however, specifying the position of the magnetic axis yields three additional boundary conditions:

$$\psi(R_M, Z_M) = 0\,, \quad \frac{\partial\psi}{\partial R}(R_M,Z_M) = 0\,, \quad \text{and} \quad \frac{\partial\psi}{\partial Z}(R_M,Z_M) = 0\,, \tag{2.14}$$

and apparently no degrees of freedom left to satisfy them.

In the case of up-down symmetric plasmas $[\psi(R,Z) = \psi(R-Z)]$, when the condition $\partial\psi/\partial Z = 0$ is trivially satisfied, the two additional degrees of freedom can be obtained if the values of A and B in Eq. (2.6) are not specified forehand but are treated as eigenvalues of the problem. Thus, instead of the usual procedure of specifying the total pressure and the diamagnetic profile, only the shape of the profiles is specified whereas the absolute magnitudes are implicity given by the position of the magnetic axis.

Still restricting the discussion to up-down symmetric equilibria, the computation proceeds as follows. With a given position δ_x of the magnetic axis, the calculation of a computational grid centered at the magnetic axis has to be done only once, after which the equilibrium can be calculated (see Fig. 2.2a). At each step of the iteration (2.11) the values of A and B then follow from the condition that s = 0 be the magnetic axis, so that the m = 0 and m = 1 harmonics should satisfy :

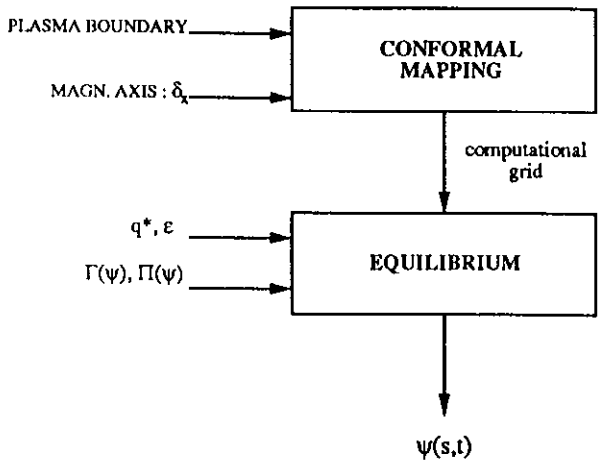


Fig. 2.2a Flow diagram of the symmetric equilibrium

$$\psi_0(s=0) = 2 - A \int_0^1 ds' \; \frac{1}{s'} \int_0^{s'} ds'' \; s'' f_0(s'') = 0\,, \tag{2.15}$$

$$\frac{\partial\psi'}{\partial s}(s=0) = -\frac{1}{2} A \int_0^1 ds' \, (1-s'^2) f_1(s') = 0\,, \tag{2.16}$$

where both ψ_m and f_m are real. Notice that Eq. (2.15) provides the value of A explicity and Eq. (2.16) provides the value of B implicitly through the function $f_1(s)$.

In the general non up-down symmetric case, the Fourier coefficients ψ_m and f_m are complex. Condition (2.16) should then be satisfied for both the real and imaginary part. Because no more constants are available to be used as an eigenvalue, the position of the magnetic axis can then no longer be specified in advance. Therefore, an extra iteration loop is needed to determine the value of the vertical coordinate of the magnetic axis, δ_y, for which both the real and imaginary part of condition (2.14) give the same value for B.

During the iteration on δ_y, we have a situation similar to the one we had before the magnetic axis was mapped onto the origin of the computational plane. The equilibrium iteration will converge to a solution with the magnetic axis approximately at the correct position (i.e., not yet on the origin of the computational plane). This converged equilibrium then gives a new estimate of δ_y. This value then is returned to the conformal mapping, after which a new equilibrium iteration can be started (see Fig. 2.2b). This procedure is repeated until both the real and imaginary part of condition (2.16) yield the same value for B.

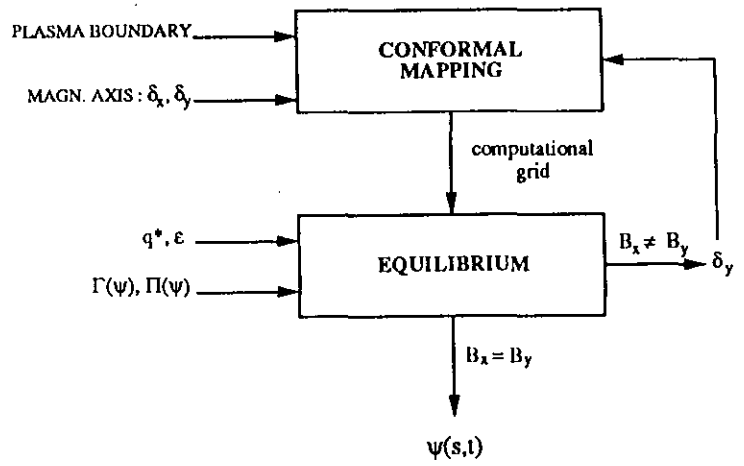


Fig. 2.2b Flow diagram of the up-down asymmetric equilibrium

C. THE CONFORMAL MAPPING [3]

The aim of the mapping is to transform a specified but arbitrary shape of the plasma boundary into a circle and to map the magnetic axis onto the origin of the computational plane. In order to preserve the Laplacian of the left-hand side of Eq. (2.9) this mapping must be conformal so that the mapping function is an analytical function. Here we describe the mapping for an arbitrary non up-down symmetric plasma shape.

A possible choice of the function that maps the physical z-plane onto the computational w plane is given by:

$$z = \sum_{m=0}^{M} \phi_m \, w^m = \sum \phi_m \, s^m \, e^{imt} . \tag{2.17}$$

Let the plasma boundary in the z-plane be represented by $z_B = f(\theta) e^{i\theta}$. In the w-plane the plasma boundary is then represented by a circle of radius s = 1. On the boundary, Eq. (2.17) becomes

$$z_B(\theta) = f(\theta) \, e^{i\theta} = \sum \phi_m \, e^{imt} . \tag{2.18}$$

If the relation $\theta(t)$ is known on the boundary, the coefficients ϕ_m of the mapping will be the Fourier components of $f(\theta(t))e^{i\theta(t)}$. Therefore, the mapping problem will be solved if the boundary correspondence function $\theta(t)$ is known.

A relation between θ and t is obtained from the function

$$h(w) = ln \frac{z(w)}{w} . \tag{2.19}$$

On the plasma boundary this becomes

$$h(e^{it}) = ln \left(\frac{f(\theta(t))^{i\theta(t)}}{e^{it}} \right) = ln \; f(\theta(t)) + i \, (\theta(t) - t) . \tag{2.20}$$

Expressing the boundary values of the real and imaginary parts of the analytic function h(w) by means of the Fourier series

$$\begin{aligned} Re\,(h(t)) &= \sum_{m=0}^{M} \, (\, a_m \cos mt + b_m \sin mt) , \\ Im\,(h(t)) &= \sum_{m=0}^{M} \, (- b_m \cos mt + a_m \sin mt) , \end{aligned} \tag{2.21}$$

the following iteration scheme is obtained for the boundary correspondence function $\theta(t)$:

$$\begin{array}{ccccc} \theta_i^n & \rightarrow & ln \, \{ f(\theta_i^n) \} & \overset{FFT}{\rightarrow} & a_m , \, b_m \\ \uparrow & & & & \downarrow \\ (\theta_i^{n+1} - t_i) & & \overset{FFT^{-1}}{\leftarrow} & & - b_m , \, a_m \end{array} \tag{2.22}$$

where $\theta_i \equiv \theta(t_i)$. If the plasma shape is up-down symmetric, the coefficients ϕ_m in eq.(2.17) become real and the coefficients b_m are zero. It is to be noted that the relations (2.21) can also be expressed in the form of an integral equation which is known as the Theodorsen equation.

Once the boundary correspondence function $\theta(t)$ is known, the coefficients ϕ_m of the mapping function are easily calculated.

D. AN ANALYTIC TEST CASE

In the previous paragraphs the method of solution of the Grad-Shafranov equation was given. It was explained how both the conformal mapping and the equilibrium problem can be solved by means of Fourier transformations. Combined with the use of a computational grid with the origin on the magnetic axis, the resulting algorithms are fast and accurate through the use of the fast Fourier transform. In this section some examples and tests of the convergence rate and of the accuracy of the equilibrium are given.

To test the accuracy of the general non up-down symmetric equilibrium, we compare the results of HBTAS with an analytical non up-down symmetric equilibrium. To that end we have generalized the well-known Soloviev equilibrium [4] by adding asymmetric terms:

$$\psi(x,y) = \left[x - \tfrac{1}{2}\varepsilon\,(1-x^2)\right]^2 + \frac{2}{\varepsilon}\left(1-\tfrac{1}{4}\varepsilon^2\right)\frac{b-c}{b\,c}\left[x-\tfrac{1}{2}\varepsilon\,(1-x^2)\right](y-\delta_y) + \frac{1-\frac{1}{4}\varepsilon^2}{1-\tau}\left[(1+\varepsilon x)^2-\tau\right]\frac{(y-\delta_y)^2}{b\,c}, \qquad (2.23)$$

where ε is the inverse aspect ratio, $\sqrt{bc}$ is the ellipticity, $(b-c)/\sqrt{bc}$ is a measure of the up-down asymmetry, and τ measures the triangularity. The parameter δ_y represents the freedom of a rigid shift in the vertical direction, which may be transformed away by the choice of the coordinates. Two examples of the flux contours of a non up-down symmetric Soloviev equilibrium are shown in Figs. 2.3.

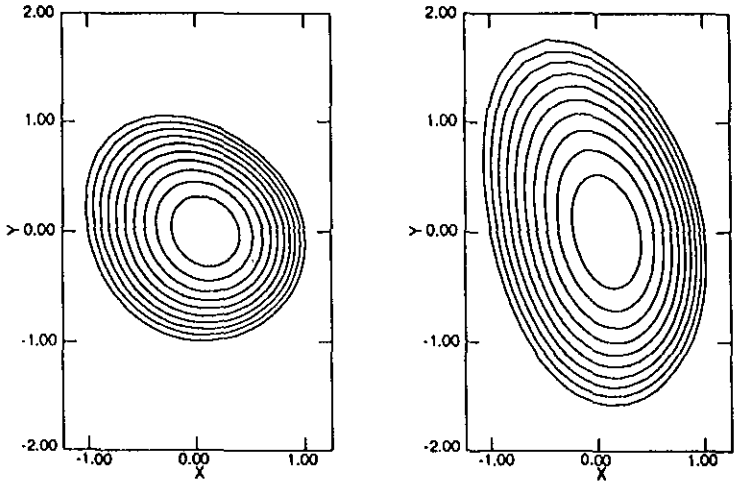


Fig. 2.3 Flux contours of two asymmetric Soloviev equilibria , ellipticity = 1.0 and 1.8

The error in the numerical solution of the Soloviev equilibrium by HBT is defined by

$$\text{Error} = \frac{1}{N} \frac{\sum_{i,j} \left[\psi(x_{ij},y_{ij}) - y_{solov}(x_{ij},y_{ij})\right]^2}{\sum_{i,j} \left[\psi(x_{ij},y_{ij}) + y_{solov}(x_{ij},y_{ij})\right]^2} . \tag{2.24}$$

In Fig. 2.4a the relative error is shown as a function of the number of radial grid points (IINT) for the two examples of Fig. 2.3. From this figure it is clear that with the same number of radial grid points and Fourier harmonics, the near circular equilibrium has a higher accuracy than the equilibrium with a large ellipticity. This is an obvious consequence of the fact that near circular equilibria can be represented with fewer harmonics after conformal mapping than elliptical equilibria. However, by increasing both the number of radial grid points and the number of Fourier harmonics, an arbitrarily accurate result can be obtained. This is again illustrated in Fig. 2.4b, where the relative error is shown as a function of the number of harmonics for the two cases.

An example of the convergence rate of the general non up-down symmetric case is shown in Fig. 2.5a. Here we have plotted the difference in the flux at all grid points between two consecutive equilibrium iterations as a function of the number of iterations. At the points where the difference increases, a new value for the position of the magnetic axis is calculated and the mapping is recalculated. This small increase shows that little accuracy of the solution is lost when the position of the magnetic axis is updated. Also plotted in Fig. 2.5b is the difference in the two values of B.

Thus also in the case of up-down asymmetric equilibria, by recalculating the conformal mapping with the origin of the coordinate system on the magnetic axis during the equilibrium iteration, an accurate equilibrium solution can be obtained.

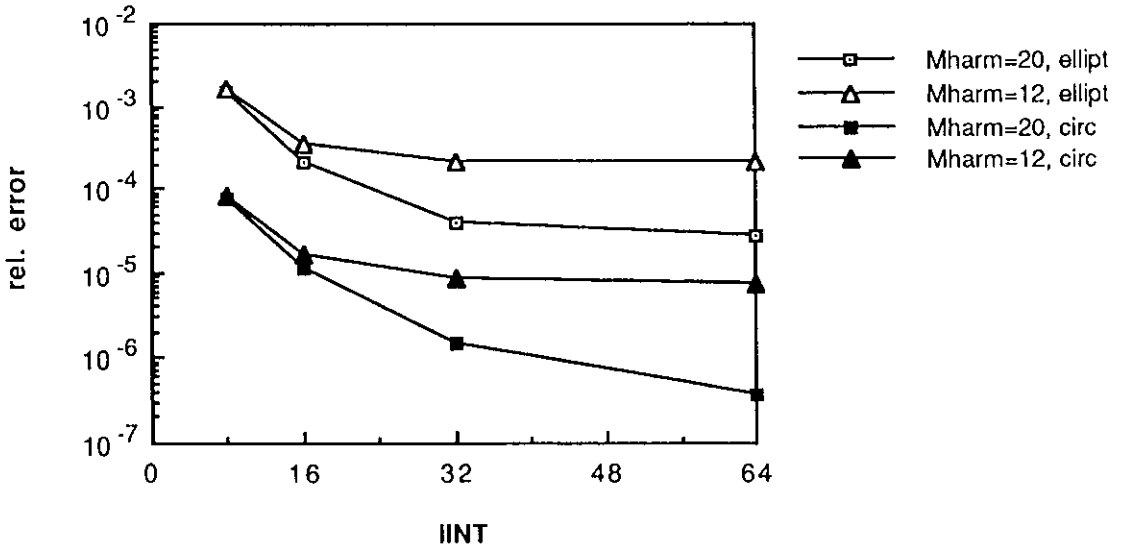


Fig. 2.4a The relative error of the equilibrium compared to a Soloviev equilibrium for a circular (black dots) and an elliptical case (white dots) as a function of the number of radial gridpoints. Mharm is the number of fourier harmonics.

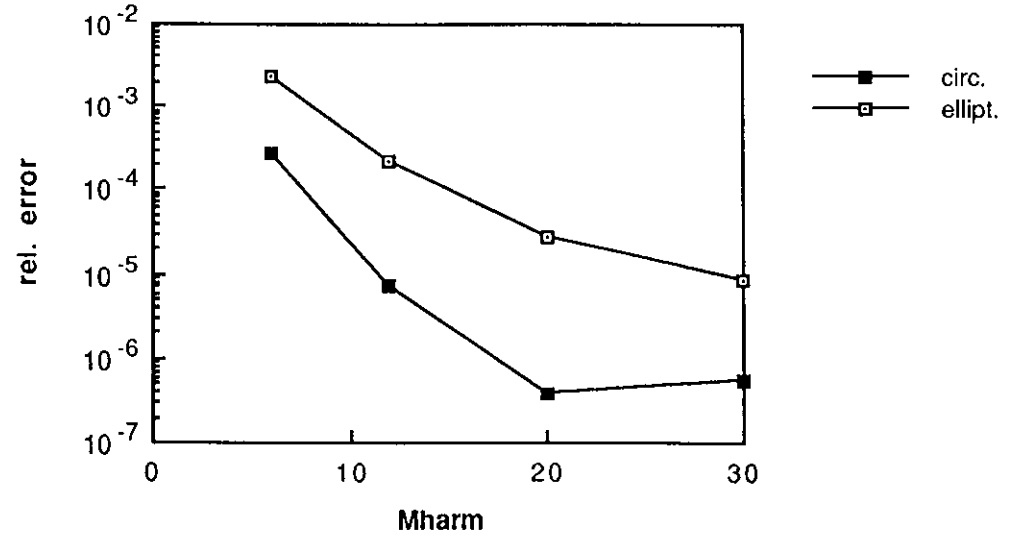


Fig. 2.4b The relative error in the equilibrium as a function of the number of fourier harmonics

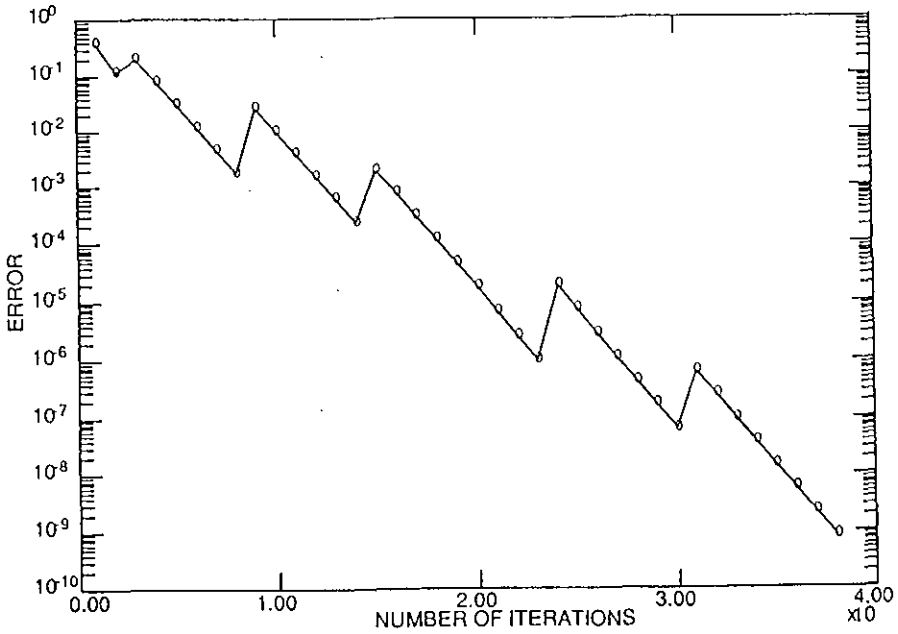


Fig. 2.5a The error in the equilibrium iteration as a function of the number of iterations for an elliptical plasma shape ($\kappa = 1.8$)

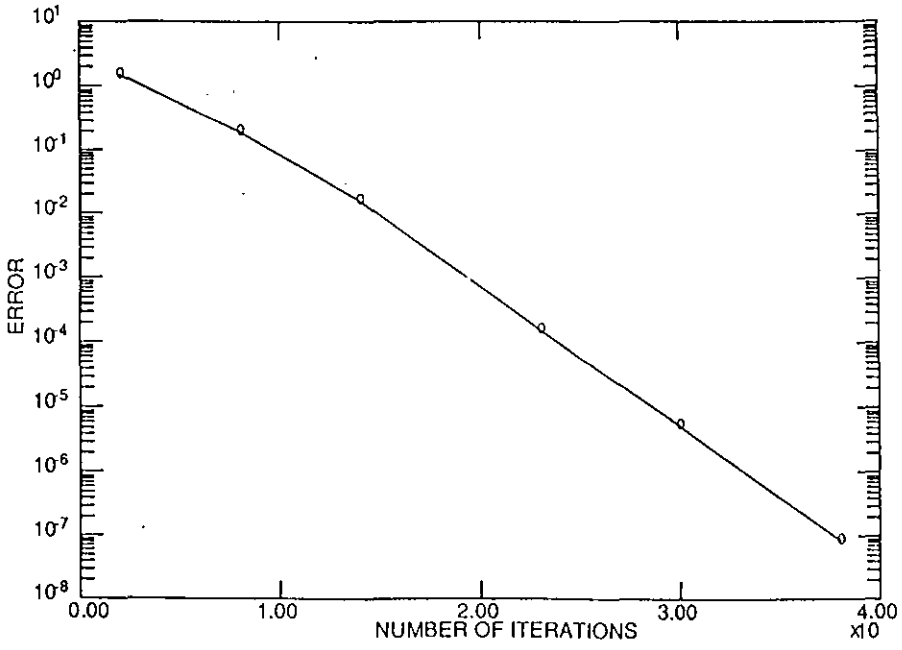


Fig. 2.5b The difference in the two eigenvalues B_x and B_y at each iteration

III. STABILITY

A. LOW-N STABILITY

The low-n global stability analysis in HBT exploits the high-β tokamak ordering, which leads to a description in terms of one scalar unknown, viz. the stream function S(s,t). This quantity is represented in terms of global radial expansion functions and Fourier harmonics in the poloidal angle. The techniques used have been extensively described in Ref. [5], which dealt with the extension HIBAT of HBT. Since there is no point in reproducing all expressions here, the reader is refered to that paper for technical details on this part of HBT.

B. BALLOONING STABILITY

1. General equations

In the limit of highly localized modes, i.e. large toroidal mode numbers and large perpendicular wave vector, the contributions of the plasma compression and of the parallel current density to the change δW of the potential energy of the perturbations tend to zero. As a result, in the remaining part of δW the flux only appears as an implicit parameter so that δW only depends on the poloidal angle. Thus by taking the limit, the problem of minimizing δW is reduced from a two dimensional problem with the flux and the poloidal angle as variables, to a one dimensional problem for each flux surface involving the poloidal angle only. The remaining terms in the potential energy are the stabilizing term of the field line bending and the destabilizing term of the pressure gradient [6].

Then, δW can be written as :

$$\delta W(\psi) = \int_{-\infty}^{\infty} dt\; k_t^2 J \left[\left(\frac{k_n^2}{k_t^2} + 1\right) \left(\frac{1}{JB}\frac{\partial X}{\partial t}\right)^2 - \frac{2RB_p}{B^2}\frac{dp}{d\psi}\left(\kappa_n - \kappa_t \frac{k_n}{k_t}\right) X^2 \right], \quad (3.1)$$

where

$$k_t = nB/RB_p, \quad \text{and} \quad k_n = nRB_p \int_{t_0}^{t} \frac{\partial}{\partial \psi}\left(\frac{JB_\phi}{R}\right) dt'$$

are the two components of the perpendicular wave vector. Here, J is the Jacobian, B is the total magnetic field with B_p and B_ϕ as poloidal and toroidal components, κ_n and κ_t represent the normal and tangential curvature components, and t_0 is a free parameter to be discussed later. Eq. (3.1) has been derived by means of the so called ballooning transformation [7] which circumvents problems with the poloidal periodicity of the eigenfunction. This is done by replacing the analysis of periodic eigenfunctions over the domain $0 < t < 2\pi$ by a summation over quasi eigenfunctions which are non-periodic and extend over the domain $-\infty < t < \infty$.

Minimizing $W(\psi)$ leads to a standard Sturm-Liouville equation:

$$(PX')' + (Q - \omega^2 R) X = 0 , \tag{3.2}$$

where

$$P = (k_n^2 + k_t^2) \frac{1}{JB^2} , \quad Q = -\frac{2JRB_p k_t^2}{B^2} \frac{dp}{d\psi} \left(\kappa_n - \kappa_t \frac{k_n}{k_t}\right) , \quad R = \rho J P .$$

The value of the parameter t_0 is determined by the next order in the $n^{-1/2}$ expansion of δW. This yields the condition that the energy minimum must be minimized with respect to t_0 :

$$\frac{\partial W(X_0)}{\partial t_0} = 0 , \tag{3.3}$$

or, equivalently, the growth rate resulting from the Sturm-Liouville equation must have a minimum at the appropriate value of t_0.

The asymptotic form of the ballooning equation (3.2) for large t, after averaging over the periodic behavior of the equilibrium quantities, can be written as :

$$\frac{d}{dt} \left(t^2 \frac{dX}{dt}\right) + D_M X = 0 , \tag{3.4}$$

where D_M is the coefficient of the well known Mercier criterion [8]. The latter criterion states that D_M must be smaller than $\frac{1}{4}$ for stability with respect to interchanges. This criterion also determines the asymptotic behavior of X at large t. For $D_M < \frac{1}{4}$, proper behavior of X is obtained: $X \sim t^{-1/2-\sqrt{1/4 - D_M}}$. However, for $D_M > \frac{1}{4}$ the eigenfunctions are oscillatory and infinitely many negative eigenvalues ω^2 exist [9]. Thus, the Mercier criterion is a necessary condition for ballooning stability.

2. Numerical solution; the Suydam method

In the majority of cases where ballooning mode stability is calculated, one is only interested in the sign of the energy minimum: stable or unstable. A possible method to determine the sign of δW is the Suydam method which has been implemented in HBT. This method is based on a simple finite difference approximation of δW and was originally

developed by Suydam to calculate the marginal stability of an axisymmetric cylindrical plasma column [10]. The method provides a fast and easily implemented way to determine the ballooning stability.

For convenience we write the potential energy as :

$$\delta W = \int_{-\infty}^{\infty} \left[P(t) \left(\frac{dX}{dt}\right)^2 + Q(t)\, X^2 \right] dt \,. \tag{3.5}$$

Approximating this expression with centered finite differences and truncating the integration interval at some large t, δW can be written as

$$\delta W = \sum_{-n}^{n} A_{i,j}\, X(t_i)\, X(t_j) \,, \tag{3.6}$$

with $$A_{i,i} = \frac{1}{\Delta t}\left(P_{i+1/2} + P_{i-1/2}\right) + \frac{\Delta t}{4}\left(Q_{i+1/2} + Q_{i-1/2}\right) \,,$$

$$A_{i,i+1} = A_{i+1,i} = -\frac{P_{i+1/2}}{\Delta t} + \frac{\Delta t}{4} Q_{i+1/2} \,,$$

$$A_{i,j} = 0 \quad \text{for all other i, j combinations .}$$

By rearrangement of terms, the expression for δW can be simplified to

$$\delta W = \sum_{-n}^{n} \alpha_i\, Y^2(t_i) \,, \qquad \alpha_0 = A_{00} \,, \qquad \alpha_i = A_{i,i} - \frac{A_{i-1,i}^{\,2}}{\alpha_{i-1}} \,. \tag{3.7}$$

It is clear from Eq. (3.7) that the determination of the sign of the minimum of δW reduces to the calculation of the sign of the α_i coefficients. This procedure is quite fast and works with a large mesh size Δt, even when the eigenfunction has a singular point inside the interval [..].

In [11] it was shown that the position t_i where the coefficient α_i becomes negative is of the order of the halfwidth of the eigenfunction, i.e. $\alpha_i < 0$ occurs before the slowly decaying part of the eigenfunction. This greatly reduces the angular domain over which the coefficients have to be evaluated. Also, there is a clear correlation between the value of t_i where $\alpha_i = 0$ and the growth rate of the eigenmode. Thus, considering a finite domain in t is equivalent with neglecting modes with very small growth rates.

To calculate the growth rates and eigenfunctions, the ballooning equation (3.2) must be solved. Since this is a standard Sturm-Liouville equation without singular points, it can be solved by a shooting method. The shooting method that is implemented in HBT discussed is [12].

IV. DESCRIPTION OF THE CODE

The HBT code is divided into four modules, CONFIG, EQUIL, STAB, and BALON (Fig. 4.1), corresponding to the conformal mapping, the equilibrium iteration, the low-n stability, and the ballooning stability calculation, as described in the previous section. The input variables for each module are all specified in three NAMELISTs, one for the geometrical and physical quantities, NAMELIST/VARn/, one for the print switches, NAMELIST/PRIn/, and one for

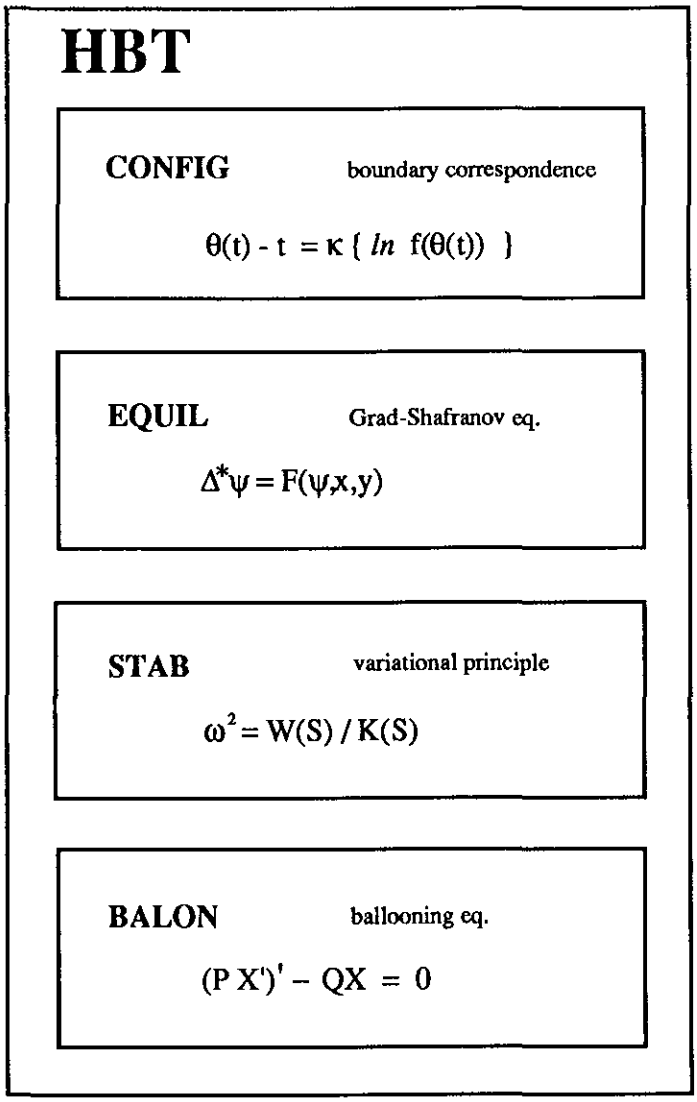


Fig. 4.1 Structure of the code

the plot switches, NAMELIST/PLOn/, where n is the number of the module (n = 1: CONFIG; n = 2: EQUIL, n = 3: STAB; n = 4: BALON). Default values are provided for all input quantities. An overview of the meaning of all the input variables and control switches is given in Appendix A of this report, which reproduces the extensive comment section of the code. The meaning of the main output quantities is explained in Appendix D. The execution of any module of the code can be skipped by making MODEn = 0 in the corresponding namelist VARn.

The shape of the plasma cross-section and the pressure and diamagnetic functions are specified through input parameters in NAMELIST/VAR1/. The shape of the plasma boundary can be specified through the coefficients of the parametric form (this option is selected with the namelist variable ICROSS = 1) :

$$x = \cos(\theta + C \sin\theta + D \sin 2\theta)$$

and

$$y = \frac{b}{a} \sin(\theta + E \cos\theta + F \cos 2\theta), \tag{4.1}$$

where x and y are the cartesian coordinates centered at the geometric center and normalized to the half-width of the plasma cross-section. The coefficients are given by the input parameters: PAR1 = b/a, PAR2 = C, PAR3 = D, PAR4 = E, PAR5 = F, respectively. In HBT proper, which deals with up-down symmetric equilibria, the coefficients E and F are zero. In the up-down asymmetric version HBTAS, the plasma shape can be given by either specifying the coefficients E and F or by means of B-spline coefficients of the radius as a function of the poloidal angle (see appendix G).

There is an option in the code to run Soloviev equilibria for parametric studies and for comparison of results with other codes. In this case, one has to choose ICROSS = 2 in NAMELIST/VAR1/ and the Soloviev exact solution of the Grad-Shafranov equation will be obtained. The code then overwrites the free functions $\Gamma(\psi)$ and $\Pi(\psi)$ with 1 and automatically fixes the shape of the plasma cross-section to correspond to the $\psi = 1$ flux surface of the Soloviev equilibrium. If one chooses ICROSS = 3, the same plasma cross-section will be used, but the code does not overwrite $\Gamma(\psi)$ and $\Pi(\psi)$, so that a new class of equilibria is obtained which may be used to investigate classes of equilibria close to the Soloviev equilibrium (e.g., to find out about the effect of shear).

The profile functions $\Gamma(\psi)$ and $\Pi(\psi)$ of Eq. (2.7) are specified in a normalized form as profiles of unit amplitude on the unit interval $0 \le \psi \le 1$, where the normalized flux function ψ is chosen to have the values 0 at the magnetic axis and 1 at the plasma boundary, respectively. The relationship between the normalized profiles and the toroidal current density j_ϕ is obtained from the expressions (2.4) and (2.6) of Sec. IIA:

$$j_\phi = \frac{\varepsilon B_0}{\mu_0 a \alpha} \frac{A}{1+\varepsilon x} \left[\Gamma(\psi) + Bx(1+\tfrac{1}{2}\varepsilon x)\,\Pi(\psi)\right], \qquad (4.2)$$

where A and B are the eigenvalues of the equilibrium problem and α is the poloidal flux between the plasma boundary and the magnetic axis, as discussed in Sec. IIA. The function $\Pi(\psi)$ is the normalized pressure gradient and $\Gamma(\psi)$ is the gradient of the normalized diamagnetic decrement. In the current version of the code, the profile functions can be specified in six different forms, depending on the values of the profile switches IPAI and IGAM, as shown in Table I.

Table I.
Unit Profiles

IGAM	$\gamma(\psi)$	IPAI	$\pi(\psi)$
1	$(1+a_\gamma\psi+b_\gamma\psi^2+c_\gamma\psi^3+d_\gamma\psi^4)^{e_\gamma}$, where $1+a_\gamma+b_\gamma+c_\gamma+d_\gamma = 0$	1	$(1+a_\pi\psi+b_\pi\psi^2+c_\pi\psi^3+d_\pi\psi^4)^{e_\pi}$, where $1+a_\pi+b_\pi+c_\pi+d_\pi = 0$
2	$(1-\psi)(1+a_\gamma\psi+b_\gamma\psi^2+c_\gamma\psi^3+d_\gamma\psi^4+e_\gamma\psi^5)$	2	$(1-\psi)(1+a_\pi\psi+b_\pi\psi^2+c_\pi\psi^3+d_\pi\psi^4+e_\pi\psi^5)$
3	$(1-\psi^{e_\gamma})(1+a_\gamma\psi) + b_\gamma[\psi(1-\psi)^2]$	3	$(1-\psi^{e_\pi})(1+a_\pi\psi) + b_\pi[\psi(1-\psi)^2]$
4	$d_\gamma[1+a_\gamma\psi+b_\gamma\psi^2+c_\gamma\psi^3 - (1+a_\gamma+b_\gamma+c_\gamma)\psi^4]^{e_\gamma} + (1-d_\gamma)\pi(\psi)$	4	$[1+a_\pi\psi+b_\pi\psi^2+c_\pi\psi^3 - (1+a_\pi+b_\pi+c_\pi)\psi^4]^{e_\pi}$
5	B-spline coefficients of the diamagnetic profile (see Appendix G)	5	B-spline coefficients of the pressure profile (see Appendix G)
6	not in use	6	B-spline coefficients of the pressure gradient profile (Appendix G)

$$\Gamma(\psi) = \Gamma_1 + (1-\Gamma_1)\,\gamma(\psi)\,; \quad \gamma(0) = 1,\ \gamma(1) = 0\,;$$

$$\Pi(\psi) = \Pi_1 + (1-\Pi_1)\,\pi(\psi)\,; \quad \pi(0) = 1,\ \pi(1) = 0$$

(Γ_1 and Π_1 allow for finite current density or pressure gradient at the plasma boundary).

The major equilibrium quantities are specified in NAMELIST/VAR2/. The inverse aspect ratio ε, the shift of the magnetic axis with respect to the geometric center of the plasma cross-section normalized to the minor radius δ, and the "cylindrical safety factor" q^*, can be varied

from EPS1 to EPS2, DEL1 to DEL2, and QS1 to QS2 in NEPS, NDEL, and NQS values, respectively. The parameter q^* is a measure of the total toroidal current I_ϕ, and is defined by :

$$q^* = \frac{aLB_0}{\mu_0 R_0 I_\phi}, \tag{4.3}$$

where a is the minor radius, L is the poloidal circumference of the plasma boundary, B_0 is the vacuum magnetic field at the geometric plasma center, and R_0 is the major radius. The possibility of running HBT in the exact or in the high-β tokamak mode imposes some constraints on the choice of the parameters, as described in the sequel.

After convergence of the equilibrium calculation , the values of $\varepsilon\beta_p$ (EBETPL), <B> (BETAA), q_0 (Q0), q_1 (Q1), and α (ALFA) are printed out, where q_0 and q_1 are the values of the safety factor at the magnetic axis and at the plasma boundary, respectively. The quantity α (defined above Eq. (2.3)) is related to q^*. The profiles of the flux function ψ (PSI), the flux contours in the physical z-plane, and the profiles of the pressure (P), the toroidal current density j_ϕ (JTOR), the poloidal field B_p (BPOL), the toroidal field B_ϕ (BTOR), and the safety factor q may be plotted by activating the switches L22 to L29 in NAMELIST/PLO2/.

The relevant quantities for the global stability analysis are specified in NAMELIST/VAR3/. Here, one has to keep in mind that the module STAB is based on the high-β ordering for which neither ε nor q^* explicitly appear in the normalized equilibrium equation [1,13, 14]. In this case, it can be shown that the magnetohydrodynamic energy functional can be written in the form $\delta W = \delta W^{(0)} + nq^*.\delta W^{(1)} + (nq^*)^2.\delta W^{(2)}$, where $\delta W^{(0)}$, $\delta W^{(1)}$, and $\delta W^{(2)}$ do not depend on ε and q^* [14,15]. Thus, varying ε is meaningless in the high-β ordering, and in the stability analysis q^* appears as a measure of both the toroidal current and the poloidal mode number because $m \sim nq^*$. To bring out the different roles played by q^*, it is indicated by QS in the equilibrium part and by QSTAR in the global stability part. The scanning range of QSTAR is specified by QSTAR1 and QSTAR2 with NQSTAR values.

The module STAB can also be run using the σ-stability concept [16], that is, a lower cut-off value σ for the square of the growth rate of the mode is specified à priori. Both σ and the square of the frequency of the mode, ω^2, are normalized to the square of the poloidal Alfvén frequency, $\omega_A^2 = \varepsilon^2 B_0^2/(\mu_0 \rho \alpha^2 a^2)$, where ρ is the mass density of the plasma. In the output, the NEV lowest eigenvalues OMSQ = ω^2/ω_A^2 are printed for each value of QSTAR, where NEV is an input parameter. Furthermore, marginal values of QSTAR for stability can be calculated by choosing LMARG = 1. The eigenvalues and the related flow fields can be plotted by activating the switches L32 to L34 in NAMELIST/PLO3/.

The effect of a conductive wall on the stability of the global model can be simulated by imposing a circular wall concentric with the plasma boundary in the transformed computational

plane. The radius of the wall normalized to the plasma radius (in the transformed plane) is specified by the parameter WALL.

The input parameters to run the ballooning module are specified in NAMELIST/VAR4/. The easiest way to run BALON is to simply check the ballooning stability on each of the NPSI flux surfaces from PSI1 to PSI2. In this case, the fast finite-difference method described in section 3B, is employed. For each value of the flux function PSI, the values of all relevant flux-averaged quantities, including the shear parameter (SHEAR), $s = 2(\psi/q)(dq/d\psi)$, and the pressure gradient parameter (GPAR), $\alpha = -4\,\mu_0(q^{*2}/\epsilon B_0^2)\,\sqrt{\psi}\,(dp/d\psi)$, are printed, together with the value of the Mercier parameter D_M ($D_M < 1/4$ for stability) and a message concerning the ballooning stability.

If the surface is found to be unstable, the value of the extended poloidal variable for which the energy functional becomes negative is printed out; otherwise only the message 'BALLOONING STABLE' is written. The ballooning equation (3.2) can also be solved directly by a shooting routine calculating the growth rate by activating the switch NSHOOT. In this case, the data for the shooting routine is written on a temporary file, DABAL, which has to be allocated beforehand (see Appendix E). The basic difference between the "exact" and high-β tokamak versions of the ballooning equation is that the poloidal part is neglected in the expression for the normal curvature [11]. It turns out that the poloidal curvature term in the ballooning equation depends explicitly on q^*. Thus, to allow for the possibility to verify the effect of the poloidal curvature on the ballooning stability, the scan in q^* in the module BALON is made independent of the scan in the equilibrium part. For this reason, q^* is re-labelled QST and a scan from QST1 to QST2 in NQST steps can be made. However, for JET discharges one is usually interested in evaluating the ballooning stability for actual equilibria, i.e., for specific values of ϵ and q^* given by IDENTC. In this case, QST1, QST2, and NQST should be made equal to QS1, QS2, and NQS, respectively.

A summary of the different options to run HBT is given in Table II. An example of a complete HBT run is given in Appendix F. Note that the input variables used in all NAMELIST's are explicitly written in the output file and can also be written on the front page of the plots by activating the switch L11.

Table II.
Options to run HBT

exact equilibrium and ballooning stability		high-β equilibrium, global and ballooning stability	
/VAR2/	MODE2 = 1 EPS1 = ε_1 EPS2 = ε_2 NEPS ≠ 0 QS1 = q^*_1 QS2 = q^*_2 NQS ≠ 0	/VAR2/	MODE2 = 1 EPS1 = 0 EPS2 = 0 NEPS = 0 QS1 = 1.0 QS2 = 1.0 NQS = 0
/VAR3/	MODE3 = 0	/VAR3/	MODE3 = 1 QSTAR1 = $(nq^*)_1$ QSTAR2 = $(nq^*)_2$ NQST ≠ 0
/VAR4/	MODE4 = 1 QST1 = q^*_1 QST2 = q^*_2 NQST ≠ 0	/VAR4/	MODE4 = 1 QST1 = 1.0 QST2 = 1.0 NQST ≠ 0

V. INTERFACING WITH EXPERIMENTAL JET DATA

A. CONNECTION WITH IDENTC

The easiest way of obtaining input data for HBT needed to reconstruct JET equilibria is to use IDENTC output. The shape of an up-down symmetric cross-section of the plasma is parametrized in IDENTC as :

$$\begin{aligned} R &= R_m + a\cos(\theta + \gamma \sin\theta), \qquad \gamma = \arcsin(\delta_t), \\ z &= z_m + E\, a \sin\theta, \end{aligned} \tag{5.1}$$

where R_m, z_m, a, E, and δ_t are output parameters (see Table III). Comparing with the parametrization used in HBT given in Eq. (4.1) we notice that there is a one-to-one correspondence between the two codes for symmetric configurations ($z_m = 0$), i.e.,

$$b/a = E, \qquad C = \arcsin(\delta_t), \qquad D = 0. \tag{5.2}$$

IDENTC also gives the two values of the major radius where the last closed magnetic surface crosses the equatorial plane, R_E and R_W, where $R_W < R_E$, from which a and R_0 follow:

$$a = \frac{R_E - R_W}{2}, \qquad R_0 = \frac{R_E + R_W}{2}, \tag{5.3}$$

while $\epsilon = a/R_0$. The equilibrium configuration is fully determined by these quantities. Note that the quadrangularity parameter D of HBT is not used in IDENTC. Although this parameter is actually vanishingly small for most shapes of the plasma cross-section, we find that in highly elongated JET X-point configurations the form of the last closed magnetic surface is better represented by considering $D \neq 0$. For up-down asymmetric plasma shapes, the plasma shape can be given in the form of B-spline coefficients where IDENTC provides the coordinates of the boundary curve R_i and Z_i (see appendix G). It is to be noted that in the case of X-point plasmas the values given by IDENTC for the elongation and triangularity can be incorrect. In that case, both parameters may be obtained from a plot of the flux surfaces.

The position of the magnetic axis can also be obtained from IDENTC. However, instead of using this data to specify the value of δ for HBT, we recommend to make a scan to obtain the correct value. This is so because the computation of the position of the magnetic axis in IDENTC is not accurate enough to match the HBT accuracy requirements. For fixed profiles and for a given form of the plasma cross-section, the value of δ is directly related to the value of the Shafranov beta,

$$\beta_I = \frac{8\pi S\langle p\rangle}{\mu_0 I_p^2} \ , \tag{5.4}$$

where S is the area of the plasma cross-section and <p> is the average pressure. The correct value of δ is then the one which gives the same value for β_I in HBT and IDENTC (or $\varepsilon\beta_I$ = EBETPL in HBT) for a given value of q^*. To calculate the value of q^* (Eq. (4.2)), the values of I_p, B_0, and $2\pi ae$ (length of the circumference of the plasma cross-section) can also be directly obtained from the IDENTC output.

The connection between the profile parameters of both codes follows from the expressions for the toroidal current density. In its standard version, IDENTC uses

$$j_\phi = \frac{\lambda}{\mu_0}\left[b_t \frac{R}{R_0}\hat{A}(\psi) + (1-b_t)\frac{R_0}{R}\hat{B}(\psi)\right], \tag{5.5}$$

with the two profiles

$$\hat{A}(\psi) = (1-\psi) + a_1(1-\psi)^2 \ , \tag{5.6}$$

$$\hat{B}(\psi) = (1-\psi) + b_1(1-\psi)^2 \ . \tag{5.7}$$

Comparing with the expression for j_ϕ used in HBT, Eq. (4.2), it follows that the proper choice of the profiles (Table I) is given by IGAM = IPAI = 1, $\Gamma_1 = \Pi_1 = 0$, and

$$a_\pi = -\frac{1+2a_1}{1+a_1}; \qquad b_\pi = \frac{a_1}{1+a_1}; \tag{5.8}$$

$$a_\gamma = -\frac{1+2b_1+2b_t(a_1-b_1)}{1+b_1+b_t(a_1-b_1)}; \qquad b_\gamma = \frac{b_1+b_t(a_1-b_1)}{1+b_1+b_t(a_1-b_1)}. \tag{5.9}$$

The constants A and B (Eq. (2.7)), which are calculated as eigenvalues of the equilibrium problem in HBT, are directly related to the profile parameters of IDENTC, i.e.,

$$\begin{aligned} \frac{A}{\alpha} &= \frac{a_1}{\varepsilon B_0}\left[1+b_1+b_t(a_1-b_1)\right], \\ B &= 2\varepsilon\frac{b_t(1+a_1)}{1+b_1+b_t(a_1-b_1)} \ . \end{aligned} \tag{5.10}$$

Recently, IDENTC has been modified to allow for the specification of experimental pressure profiles. In this case the function $\Pi(\psi)$ has to be chosen to fit the experimental profile on the ψ-grid, as discussed in the next section.

A summary of the connection between IDENTC and HBT parameters is given in Table III.

Table III.
Connection between IDENTC and HBT parameters

Input parameters

IDENTC	NDBPLOT (output)	HBT (input)	NAMELIST
E	IDC-ELONG (Eq. (5.1))	PAR1 (Eq. (4.1))	VAR1
δ_t	IDC-TRIAN (Eq. (5.1))	PAR2 = arcsin (δ_t)	VAR1
-	-	PAR3 = 0	VAR1
a_1	IDC-A1 (Eq. (5.6))	API, BPI (Eq. (5.8))	VAR1
b_1	IDC-B1 (Eq. (5.7))	AGA, BGA (Eq. (5.9))	VAR1
b_t	IDC-BTAN (Eq. (5.5))	CPI = DPI = 0 ; EPI = 1.0	VAR1
		CGA = DGA = 0 ; EGA = 1.0	VAR1
		PAI1 = GAM1 = 0	VAR1
		IGAM = IPAI = 1	VAR1
R_E	IDC-REAST (Eq. (5.3))	EPS1 = $(R_E-R_W)/(R_E+R_W)$	VAR2
R_W	IDC-RWEST		
-		DEL1, DEL2 (scan)	VAR2
I_p	IDC-IPLASMA	QS1 (Eq. (4.3))	VAR2
B_T	IDC-BTORO		
$2\pi ae$	IDC-CONTOUR		

Output parameters

IDENTC	NDBPLOT (output)	HBT (output)
β_2	IDC-BETAAVER	EBETPL = $\varepsilon\beta_I$
$2\pi\Phi_0$, $2\pi\Phi_1$	IDC-PSIAXIS, PSIBOUND	ALFA (Eq. (2.3))
q_0, q_1	IDC-QAXIS, QBOUND	Q_0 , Q_1
		B (Eq. (5.10))

To check the agreement between the equilibria calculated by the two codes, it is useful to compare the values of α (Φ_0 and Φ_1 are given by IDENTC), q_0, q_1, and B calculated by HBT with those that follow from the IDENTC output. Unfortunately, the value of A given by Eq.

(5.10) cannot be directly checked, because the parameter λ is usually not provided in the IDENTC output. However, λ is related to α and it suffices to get the correct value for this parameter. In comparing the results of HBT with IDENTC, one should note that the value of q_0 is not always accurately calculated in IDENTC. Therefore, is is better to first make sure that the global parameters α, q^*, and β_I are in good agreement. Furthermore, when there is uncertainty about the pressure profile of IDENTC, it is advisable to check the value of β_I against the MHD (MG2.BTI) and diamagnetic (MG2.BET) values provided in the PPF.

Appendix F gives an example of a HBT run using IDENTC data.

B. INPUT OF EXPERIMENTAL EQUILIBRIUM PROFILES

For some situations of practical interest, viz., pellet fuelled discharges with strong additional heating, the pressure profiles strongly deviate from the usual Gaussian shape. These highly peaked profiles are rather poorly represented by the polynomial expressions used in the standard version of IDENTC. For this reason, IDENTC has recently been modified to allow for the specification of the pressure profile as a set of values at discrete values of the major radius. These 'experimental' pressure profiles can be constructed from the LIDAR diagnostic for the electron density and the temperature profiles (or, with a far better time resolution, from the electron cyclotron emission for the temperature and from the laser interferometer for the electron density). The ion temperature profile can be obtained from the charge exchange diagnostic. In some cases, the q profile can be derived from the mode activity on the soft x-ray measurements. Also, equilibrium profiles resulting from transport codes like TRANSP or ESCO are usually not available in a simple polynomial expression. Hence, input of profiles which are given in a pointwise fashion is desirable.

To facilitate the input of such arbitrary pressure and diamagnetic profiles, HBT has been extended with the possibility to read the profiles from a file containing the coefficients of a B-spline interpolation of the experimental profiles. A separate program SPLINE is then used to create the input files for HBT. A detailed description of the use of spline input is given in appendix G.

APPENDIX A:
DESCRIPTION OF HBT AND MEANING OF THE INPUT VARIABLES

HBT contains a fairly extensive in-code documentation of the overall structure of the program and of the meaning of the different NAMELIST input parameters. The relevant parts of the code are reproduced here for the convenience of the user. The lines have been numbered using the UPDATE convention which facilitates an easy referencing and discussion of modifications. The lines HBT.13 - 85 contain notes on the four different modules, HBT.277 - 328 gives the NAMELIST input parameters and those default values that are not specified in the BLOCK DATA subprogram (discussed in Appendix C), whereas HBT.320 - 852 provides a complete description of the meaning of all the input parameters.

The declarations of COMMON blocks have been omitted here since this would not interest the general user. The expert user, however, will notice that the lines HBT.88 - 92 contain the PARAMETER statements determining the maximum sizes of the different arrays used in the computation. The sizes given here represent a conservative use of HBT, restricting the use of central memory as much as possible. Extending the memory for improved resolution may be done by changing the PARAMETER declarations of JMAX0, etc. and adapting NCOM5, NCOM6, and NCOM7 to values consistent with the expressions found in the respective COMMON blocks. Needless to say: this should be done with care.

```
      PROGRAM HBT                                                       HBT .   1
      IMPLICIT REAL*8 (A-H) , REAL*8 (O-Z)                              HBT .   2
C                                                                       HBT .   3
C     ***************************************************************** HBT .   4
C     *    EQUILIBRIUM AND STABILITY OF A DIFFUSE HIGH-BETA TOKAMAK    * HBT .   5
C     *      ADDITIONAL FORTRAN LIBRARIES NEEDED: HGOLIB, PPPLIB.      * HBT .   6
C     ***************************************************************** HBT .   7
C                                                                       HBT .   8
C     * PRESENT VERSION OF THE PROGRAM:                                 HBT .   9
      CHARACTER VERSION*(*)                                             HBT .  10
      PARAMETER(VERSION='45')                                           HBT .  11
C                                                                       HBT .  12
C     ****************** GENERAL COMMENTS ****************************** HBT .  13
C     *                                                                 * HBT .  14
C     * 1. IN PART1 (THE MODULE CONFIG) THE BASIC CONFIGURATION IS SET,* HBT .  15
C     * I.E., THE SHAPE OF THE PLASMA CROSS SECTION IS PRESCRIBED AND   * HBT .  16
C     * THE TWO ARBITRARY EQUILIBRIUM FUNCTIONS ARE SPECIFIED.          * HBT .  17
C     * BY MEANS OF A MOEBIUS TRANSFORMATION                           * HBT .  18
C     *        Z(ZETA)=(DEL+ZETA)/(1+DEL*ZETA)                         * HBT .  19
C     * THE MAGNETIC AXIS IS MAPPED ONTO THE ORIGIN OF THE ZETA-PLANE. * HBT .  20
C     * BY MEANS OF AN ADDITIONAL NUMERICAL CONFORMAL MAPPING ZETA(W)   * HBT .  21
C     * THE PLASMA REGION IS MAPPED ONTO THE UNIT DISK IN THE W-PLANE   * HBT .  22
C     * WITH THE IMAGE OF THE MAGNETIC AXIS AT THE CENTER.              * HBT .  23
C     * DEL IS THE SHIFT OF THE MAGNETIS AXIS IN THE PHYSICAL Z-PLANE. * HBT .  24
C     * THE COMPUTATIONS ARE PERFORMED IN THE W-PLANE WHERE THE POLAR   * HBT .  25
C     * REPRESENTATION W=S*EXP(I*T) IS USED.                            * HBT .  26
C     * THE COMPUTATIONAL GRID IS GIVEN BY S(I), I=1,..,IINT, AND       * HBT .  27
```

```
C     * T(J), J=1,..,JPTS.                                              * HBT .  28
C     * FOURIER HARMONICS IN THE ANGLE T ARE LABELLED BY M=1,..,MHARM.  * HBT .  29
C     * THE TWO ARBITRARY EQUILIBRIUM FUNCTIONS ARE DERIVED FROM THE    * HBT .  30
C     * NORMALIZED UNIT PROFILES GAM(PSI) AND PAI(PSI):                 * HBT .  31
C     *        GAM=GAM1+(1-GAM1)*SMLGAM(PSI),                           * HBT .  32
C     *        PAI=PAI1+(1-PAI1)*SMLPAI(PSI),                           * HBT .  33
C     * WHERE  SMLGAM(0)=1, SMLGAM(1)=0,                                * HBT .  34
C     *        SMLPAI(0)=1, SMLPAI(1)=0.                                * HBT .  35
C     * THEY ARE RELATED TO THE PROFILES G(PSI) AND P(PSI) BY           * HBT .  36
C     *        DG/DPSI=-A*GAM(PSI),                                     * HBT .  37
C     *        DP/DPSI=-.5*A*B*PAI(PSI),                                * HBT .  38
C     * WHERE THE DIAMAGNETISM QQ(PSI)=P-EPS*G AND THE PRESSURE P(PSI)  * HBT .  39
C     * ARE THE USUAL FUNCTIONS ENTERING THE GRAD-SHAFRANOV EQUATION.   * HBT .  40
C     * IN OUR FORMULATION, THE AMPLITUDES A AND B ARE EIGENVALUE       * HBT .  41
C     * PARAMETERS THAT FOLLOW FROM THE REQUIREMENT THAT PSI=0 AT THE   * HBT .  42
C     * MAGNETIC AXIS AND PSI=1 AT THE PLASMA SURFACE.                  * HBT .  43
C     * EPS IS THE INVERSE ASPECT RATIO.                                * HBT .  44
C     *                                                                 * HBT .  45
C     * 2. IN PART2 (THE MODULE EQUIL) THE EQUILIBRIUM IS DETERMINED    * HBT .  46
C     * FOR BOTH THE HIGH-BETA TOKAMAK APPROXIMATION (INDEPENDENT OF    * HBT .  47
C     * EPS AND THE NORMALIZED CURRENT PARAMETER QS) AND FOR THE GENE-  * HBT .  48
C     * RAL CASE WHERE BOTH EPS AND QS ENTER.                           * HBT .  49
C     * THE EQUILIBRIUM IS ITERATED UNTIL THE MEAN SQUARE ERROR OF THE  * HBT .  50
C     * VALUES OF PSI(I,J) AT SUBSEQUENT ITERATIONS IS SMALLER THAN     * HBT .  51
C     * THE VALUE OF THE INPUT PARAMETER ERROR OR WHEN THE NUMBER IT    * HBT .  52
C     * OF ITERATIONS EXCEEDS NIT.                                      * HBT .  53
C     *                                                                 * HBT .  54
C     * 3. IN PART3 (THE MODULE STAB) THE GLOBAL STABILITY IS ANALYZED  * HBT .  55
C     * FOR THE HIGH-BETA TOKAMAK APPROXIMATION ONLY. HERE, THE PARA-   * HBT .  56
C     * METER QSTAR=QS (APPROXIMATELY) ENTERS INDEPENDENTLY TO LEADING  * HBT .  57
C     * ORDER. THE STABILITY ANALYSIS IS PERFORMED FOR A WALL SITUATED  * HBT .  58
C     * AT A CIRCLE S=WALL CONCENTRIC TO THE IMAGE OF THE PLASMA SUR-   * HBT .  59
C     * FACE IN THE W-PLANE.                                            * HBT .  60
C     * STABILITY IS ANALYZED BY MEANS OF ANGULAR HARMONICS LABELED     * HBT .  61
C     * M=M1,..,M2 AND RADIAL POLYNOMIALS N=0,..,NN,                    * HBT .  62
C     * SO THAT THE ENERGY MATRIX W CONSISTS OF THE ELEMENTS            * HBT .  63
C     * (M)*(N),(MU)*(NU) = (M1,..,M2)*(0,..,NN),(M1,..,M2)*(0,..,NN).  * HBT .  64
C     * THE EIGENVALUES OMSQ(NE) ARE LABELED WITH NE=1,..,NEV, WHERE    * HBT .  65
C     * NEV.LE.(M2-M1+1)*(NN+1).                                        * HBT .  66
C     * STABILITY IS DETERMINED BY THE LOWEST EIGENVALUE NE=1.          * HBT .  67
C     * THE CONFIGURATION IS TERMED SIGMA-STABLE IF OMSQ(1).GT.-SIGMA.  * HBT .  68
C     *                                                                 * HBT .  69
C     * IN SUBROUTINE ANASTA A FURTHER ANALYSIS OF THE GLOBAL STABI-    * HBT .  70
C     * LITY IS PERFORMED BY CALCULATING THE EIGENFUNCTIONS CORRESPON-  * HBT .  71
C     * DING TO THE LOWEST EIGENVALUES NE=1,..,NEF, WHERE NEF.LE.NEV.   * HBT .  72
C     *                                                                 * HBT .  73
C     * 4. IN PART4 (THE MODULE BALON) THE LOCAL BALLOONING STABILITY   * HBT .  74
C     * IS ANALYSED FOR EITHER THE HIGH-BETA TOKAMAK APPROXIMATION OR   * HBT .  75
C     * FOR THE EXACT CASE. IN THE FIRST CASE STABILITY IS INDEPENDENT  * HBT .  76
C     * OF QSTAR, IN THE LATTER CASE THE PARAMETER QST=QS (OF THE       * HBT .  77
C     * EQUILIBRIUM PART) APPEARS.                                      * HBT .  78
C     * CALCULATIONS IN THE BALLOONING PART ARE PERFORMED ON A NON-     * HBT .  79
C     * ORTHOGONAL PSI-T GRID.                                          * HBT .  80
C     *                                                                 * HBT .  81
C     * IN SUBROUTINE SHOOT AN ALTERNATIVE ANALYSIS OF THE LOCAL        * HBT .  82
C     * BALLOONING STABILITY IS PERFORMED BY SHOOTING FOR THE EIGEN-    * HBT .  83
C     * VALUES.                                                         * HBT .  84
C     ******************************************************************* HBT .  85
C                                                                         HBT .  86
C1    * COMMON BLOCKS FOR COMPUTED VARIABLES:                           HBT .  87
      PARAMETER(JMAX0=512,MCMAX=255,                                    HBT .  88
     A          IMAX=100,JMAX=256,MMAX=63,                             HBT .  89
     B          M1MIN=-6,M2MAX=14,NNMAX=12,ISTEP=2,JSTEP=2,            HBT .  90
     C          NPLMAX=20,JMAX2=256,MMAX2=63,                          HBT .  91
     D          NCOM5=149331,NCOM6=64608,NCOM7=80955)                  HBT .  92
                                                                              .
                    (COMMON statements omitted)                             .
                                                                            .
C                                                                       HBT . 234
C2    * COMMON BLOCKS FOR NAMELIST INPUT VARIABLES:                     HBT . 235
                                                                            .
                    (COMMON statements omitted)                             .
                                                                            .
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C                                                                       HBT . 277
C3    * NAMELIST INPUT:                                                 HBT . 278
      NAMELIST/VAR1/RUN,NOTE,IO,IOD,                                    HBT . 279
     A              GAM1,IGAM,AGA,BGA,CGA,DGA,EGA,                      HBT . 280
     B              PAI1,IPAI,API,BPI,CPI,DPI,EPI,                      HBT . 281
     C              ICROSS,PAR1,PAR2,PAR3,JPTS0,MCM,ERRCM,NITCM,MODE1   HBT . 282
      NAMELIST/PRI1/N11,N12,N13,N14,N15,N16,N17,N18,N19,                HBT . 283
     A              N15A,N15B,N15C,N15D,N15E,N15F,N15G,N15H,N15I,       HBT . 284
     B              N17A,N17B,N18A,N18B,N19A,N19B                       HBT . 285
      NAMELIST/PLO1/L11,L12,L13,L14,L15,KRAD,LANG                       HBT . 286
      NAMELIST/VAR2/EPS1,EPS2,NEPS,DEL1,DEL2,NDEL,QS1,QS2,NQS,          HBT . 287
     A              IINT,JPTS,MHARM,ERROR,NIT,                          HBT . 288
     B              NPRE,IMIX,NMIX,AMIX,BMIX,MODE2                      HBT . 289
      NAMELIST/PRI2/N21,N22,N23,N24,N25,N26,N27,N28,N29,N210,N211,N212, HBT . 290
     A              N23A,N23B,N24A,N24B,N24C,N24D,N24E,N24F,N24G,       HBT . 291
     B              N25A,N25B,N26A,N26B,N26C,N28A,N28B,N28C,            HBT . 292
     C              N210A,N210B,N211A,N211B,                            HBT . 293
     D              N212A,N212B,N212C,N212D,N212E,N212F,N212G           HBT . 294
      NAMELIST/PLO2/L21,L22,L23,L24,L25,L26,L27,L28,L29,                HBT . 295
     A              L21A,L21B,L21C,KCON                                 HBT . 296
      NAMELIST/VAR3/WALL,QSTAR1,QSTAR2,NQSTAR,M1,M2,NN,LE,NEV,          HBT . 297
     A              LMARG,SIGMA,NEF,NAPHI,MODE3                         HBT . 298
      NAMELIST/PRI3/N31,N32,N33,N34,N35,N36,N37,N38,N39,N310,N311,N312, HBT . 299
     A              N313,N31A,N31B,N31C,N31D,N31E,N31F,N31G,N31H,       HBT . 300
     B              N31I,N31J,N31K,N31L,N31M,N31N,N31O,N31P,            HBT . 301
     C              N35A,N35B,N312A,N312B,N313A,N313B                   HBT . 302
      NAMELIST/PLO3/L31,L32,L33,L34,L35,                                HBT . 303
     A              L31A,L31B,L31C,L32A,L32B,L33A,L33B,NCON,AMP         HBT . 304
      NAMELIST/VAR4/NPOL,PSI1,PSI2,NPSI,QST1,QST2,NQST,T0,TBB,TBF,DBT,  HBT . 305
     A              JPTS2,MHARM2,ERROR2,NDABAL,                         HBT . 306
     B              NSHOOT,MODO1,MODO2,TX1,TX2,NTX,ALAM1,ALAM2,NLAM,    HBT . 307
     C              XF,NX,ABSER2,MODE4                                  HBT . 308
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     B              N41A,N41B,N41C,N42A,N42B,N42C,                      HBT . 311
     C              N43A,N43B,N43C,N44A,N44B,N44C                       HBT . 312
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      DATA          N10  /0/                                            HBT . 316
      DATA          L10  /0/                                            HBT . 317
      DATA          EPS1,EPS2,DEL1,DEL2,QS1,QS2                         HBT . 318
     A             /  0.,  0.,  .1,  .1,  1., 1./                      HBT . 319
      DATA          MODE2/1/                                            HBT . 320
      DATA          N20  /0/                                            HBT . 321
      DATA          L20  /0/                                            HBT . 322
      DATA          MODE3/0/                                            HBT . 323
      DATA          N30  /0/                                            HBT . 324
      DATA          L30  /0/                                            HBT . 325
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C     *  CGA,DGA,EGA  NOTICE: THERE MAY BE A RESTRICTION ON THE CHOICE * HBT . 344
C     *                OF THE CONSTANTS, DEPENDING ON THE CLASS IGAM.  * HBT . 345
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C     * IPAI         - CLASS OF THE PROFILE FUNCTION PAI CONSIDERED.  * HBT . 347
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C     *  CPI,DPI,EPI  NOTICE: THERE MAY BE A RESTRICTION ON THE CHOICE * HBT . 349
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C     *                SHOULD NOT EXCEED JPTS0/2-1.                      * HBT . 367
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C     *                PUTED BY LIBRARY SUBROUTINE MAPIN1.               * HBT . 369
C     * NITCM        - MAXIMUM NUMBER OF ITERATIONS FOR MAPIN1.          * HBT . 370
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C     * NDEL         - NUMBER OF DEL VALUES.                             * HBT . 377
C     * QS1,QS2      - RANGE OF CURRENT PARAMETER QS TO SCAN.            * HBT . 378
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C     * IINT         - NUMBER OF RADIAL INTERVALS S(I);                  * HBT . 380
C     *                SHOULD BE EVEN.                                   * HBT . 381
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C     *                SHOULD BE A POWER OF 2.                           * HBT . 383
C     * MHARM        - NUMBER OF FOURIER HARMONICS, LABELED BY M;        * HBT . 384
C     *                SHOULD NOT EXCEED JPTS/2-1.                       * HBT . 385
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C     *                PERFORMED, I.E., THE MEAN SQUARE ERROR (AMSQER)   * HBT . 387
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C     * NPRE         - NUMBER OF STEPS IN DEL FOR PRE-ITERATION.         * HBT . 390
C     * IMIX .NE. 0  - GENERALIZED MARDER-WEITZNER SCHEME FOR ITERATION  * HBT . 391
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C     * MODE2 = 0    - SKIP EXECUTION EQUIL.                             * HBT . 396
C     *                                                                  * HBT . 397
C     * - NAMELIST/VAR3/ FOR STAB:                                       * HBT . 398
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C     *                GIVING EIGENVALUES + EIGENVECTORS;                * HBT . 408
C     *         = 1    EIGEN1 (CALLING F01AGF,F02AVF OF NAG),            * HBT . 409
C     *                GIVING EIGENVALUES ONLY;                          * HBT . 410
C     *         = 2    EIGEN2 (CALLING F01AJF,F02AMF OF NAG),            * HBT . 411
C     *                GIVING EIGENVALUES + EIGENVECTORS.                * HBT . 412
C     * NEV          - NUMBER OF LOWEST EIGENVALUES TO BE PRINTED,       * HBT . 413
C     *                LABELED BY NE.                                    * HBT . 414
C     * LMARG = 1    - COMPUTE SIGMA-MARGINAL STABILITY VALUES OF QSTAR.* HBT . 415
C     * SIGMA        - CUT-OFF FOR THE GROWTH RATE OMSQ(1) USED IN THE   * HBT . 416
C     *                CRITERION FOR SIGMA-STABILITY: OMSQ(1).GT.-SIGMA.* HBT . 417
C     * NEF          - NUMBER OF EIGENFUNCTIONS COMPUTED, CORRESPONDING  * HBT . 418
C     *                TO LOWEST EIGENVALUES LABELED BY NE.              * HBT . 419
C     * NAPHI        - NUMBER OF TOROIDAL ANGLES FOR WHICH SKSI AND      * HBT . 420
C     *                SETA ARE COMPUTED.                                * HBT . 421
C     * MODE3 = 0    - SKIP EXECUTION STAB.                              * HBT . 422
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C     *                                                               * HBT . 423
C     * - NAMELIST/VAR4/ FOR BALON:                                   * HBT . 424
C     * NPOL         - NUMBER OF POLYNOMIALS TO FIT EQUILIBRIUM DATA;  * HBT . 425
C     *                SHOULD NOT EXCEED IINT.                        * HBT . 426
C     * PSI1,PSI2    - RANGE OF PSI VALUES TO SCAN.                   * HBT . 427
C     * NPSI         - NUMBER OF PSI VALUES.                          * HBT . 428
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C     * NQST         - NUMBER OF QST VALUES.                          * HBT . 430
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C     *                BALLOONING EQUATION.                           * HBT . 432
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C     *                SUYDAM METHOD.                                 * HBT . 434
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C     *                CALCULATE COEFFICIENTS OF BALLOONING EQUATION; * HBT . 437
C     *                HAS TO BE A POWER OF 2.                        * HBT . 438
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C     * MODO1  = 0   - BALLOONING EQUATION IS REWRITTEN IN A FORM     * HBT . 446
C     *                EQUIVALENT TO THE SCHROEDINGER EQUATION BEFORE * HBT . 447
C     *                INTEGRATING;                                   * HBT . 448
C     *        = 1     BALLOONING EQUATION IS INTEGRATED IN THE ORIGINAL* HBT . 449
C     *                FORM (THIS FORM IS RECOMMENDED).               * HBT . 450
C     * MODO2  = 0   - USES APPROXIMATE FORM OF THE POTENTIAL, WITH    * HBT . 451
C     *                C1=CONST, FOR INTEGRATION. IN THIS CASE, THE   * HBT . 452
C     *                BALLOONING EQUATION BECOMES EXACTLY EQUIVALENT * HBT . 453
C     *                TO SCHROEDINGERS EQUATION.                     * HBT . 454
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C     *                BEFORE SHOOTING FOR DIFFERENT VALUES OF ALAM.  * HBT . 457
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C     * NLAM         - NUMBER OF ALAM VALUES.                         * HBT . 460
C     * 0.,XF        - RANGE OF T WHERE THE EIGENFUNCTION IS CALCULATED.* HBT . 461
C     * NX           - NUMBER OF STEPS IN T (EXCLUDING T=0.)          * HBT . 462
C     * ABSER2       - ABSOLUTE ERROR FOR ODE.                        * HBT . 463
C     * MODE4 = 0    - SKIP EXECUTION BALON.                          * HBT . 464
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C                                                                       HBT . 466
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C     * N13(CMAP)   - "CROSS-SECTION IN THE MAPPED ZETA-PLANE", GR(J) * HBT . 473
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C     * N15B        - "ITERATION", IMAP                               * HBT . 477
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C     * N19          - "GRID IN THE W-PLANE"                                  * HBT . 496
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C     * N23B         - F2NUL,F2(I,J)                                          * HBT . 505
C     * N24(CALPSI)  - "FOURIER TRANSFORMED ARRAYS"                           * HBT . 506
C     * N24A         - F1TRNL,F1TR(I,M)                                       * HBT . 507
C     * N24B         - F2TRNL,F2TR(I,M)                                       * HBT . 508
C     * N24C         - B                                                      * HBT . 509
C     * N24D         - FFNUL,FF(I,M)                                          * HBT . 510
C     * N24E         - GFNUL,GF(I,M)                                          * HBT . 511
C     * N24F         - A                                                      * HBT . 512
C     * N24G         - PSIFNL,PSIF(I,M)                                       * HBT . 513
C     * N25(ITERA)   - "RESULT OF THIS STEP OF THE ITERATION"                 * HBT . 514
C     * N25A         - PSI(I,J)                                               * HBT . 515
C     * N25B         - IT,ERROR,AMSQER,ABSER                                  * HBT . 516
C     * N26          - "SOLUTION"              (AFTER ITERATION)              * HBT . 517
C     * N26A         - FFNUL,FF(I,M)                                          * HBT . 518
C     * N26B         - GFNUL,GF(I,M)                                          * HBT . 519
C     * N26C         - PSIFNL,PSIF(I,M)                                       * HBT . 520
C     * N27          - PSI(I,J)                                               * HBT . 521
C     * N28(PAREQ)   - "PHYSICAL QUANTITIES"                                  * HBT . 522
C     * N28A         - BPOL(I,J)                                              * HBT . 523
C     * N28B         - P(I,J)                                                 * HBT . 524
C     * N28C         - JTOR(I,J)                                              * HBT . 525
C     * N29(PAREQS)  - BTOR(I,J)                                              * HBT . 526
C     * N210(PSICON)- "FLUX CONTOURS IN THE Z-PLANE"                          * HBT . 527
C     * N210A        - XX(K,J)                                                * HBT . 528
C     * N210B        - YY(K,J)                                                * HBT . 529
C     * N211(SSQCON)- "S**2 CONTOURS IN THE Z-PLANE"                          * HBT . 530
C     * N211A        - XSSQ(K,J)                                              * HBT . 531
C     * N211B        - YSSQ(K,J)                                              * HBT . 532
C     * N212(EQUAR)  - "EQUILIBRIUM PROFILES"                                 * HBT . 533
C     * N212A        - XXX(I)                                                 * HBT . 534
C     * N212B        - YPSI(I)                                                * HBT . 535
C     * N212C        - YP(I)                                                  * HBT . 536
C     * N212D        - YJTOR(I)                                               * HBT . 537
C     * N212E        - YBPOL(I)                                               * HBT . 538
C     * N212F        - YQ(I)                                                  * HBT . 539
C     * N212G        - YBTOR(I)                                               * HBT . 540
C     *                                                                       * HBT . 541
C     * - NAMELIST/PRI3/ FOR STAB (CALLS TO DIAG3A,DIAG3B,DIAG3C):           * HBT . 542
C     * N31(COEF)    - "COEFFICIENTS ENTERING THE STABILITY",                 * HBT . 543
C     *                U1F(I,M)-U10F(I,M),V1F(I,M)-V6F(I,M)                   * HBT . 544
C     *                (DISTINGUISHED BY SWITCHES N31A-N31J,N31K-N31P)        * HBT . 545
C     * N32          - UF(M)                                                  * HBT . 546
C     * N33(POLYN)   - "POLYNOMIALS",                                         * HBT . 547
C     *                X(I,M,N),Y(I,M,N),Z(I,M,N)    (NO CALL TO DIAG3)       * HBT . 548
C     * N34          - ANORM(MIND,N,NU)            (NO CALL TO DIAG3)       * HBT . 549
C     * N35(W1W2)    - "MATRICES W1 AND W2"                                   * HBT . 550
C     * N35A         - W1(MIND,N,NU)  FOR SINGLE MIND IF N35A=MIND;           * HBT . 551
C     *                               FOR ALL MIND (!) IF N35A.GE.99          * HBT . 552
C     * N35B         - W2(MIND,N,NU)  FOR SINGLE MIND IF N35B=MIND;           * HBT . 553
C     *                               FOR ALL MIND (!) IF N35B.GE.99          * HBT . 554
C     * N36(INDCS)   - "CONNECTION BETWEEN INDICES IC AND N,M"                * HBT . 555
C     * N37(WEIGEN)  - ("DO LOOP ON QSTAR",IQSTAR,) QSTAR,                    * HBT . 556
C     *                W(IC,JC)                                               * HBT . 557
C     * N38(STAB)    - "HARMONIC CONTENT",SIG(IC,NE)                          * HBT . 558
C     * N39(ANASTA)  - ("DO LOOP ON NE",NE)                                   * HBT . 559
C     * N310(EIFUN1)- ZETA(II,JJ)                                             * HBT . 560
C     * N311(EIFUN2)- ("DO LOOP ON APHI",IAPHI,) APHI                         * HBT . 561
C     * N312         - "NORMAL AND TANGENTIAL DISPLACEMENTS"                  * HBT . 562
C     * N312A        - SKSI(II,JJ)                                            * HBT . 563
C     * N312B        - SETA(II,JJ)                                            * HBT . 564
C     * N313(EIFUN3)- "HORIZONTAL AND VERTICAL FLOW COMPONENTS"               * HBT . 565
C     * N313A        - VX(II,JJ)                                              * HBT . 566
C     * N313B        - VY(II,JJ)                                              * HBT . 567
C     *                                                                       * HBT . 568
```

```
C     * - NAMELIST/PRI4/ FOR BALON (CALLS TO DIAG4):                    * HBT . 569
C     * N41(INTPLN) - "EQUILIBRIUM INPUT ARRAYS",                       * HBT . 570
C     *               FF(I,M),GF(I,M),PSIF(I,M)                        * HBT . 571
C     *               (DISTINGUISHED BY THE SWITCHES N41A,N41B,N41C)    * HBT . 572
C     * N42         - "POLYNOMIAL COEFFICIENTS",                        * HBT . 573
C     *               CF(IC,M),CG(IC,M),CPSI(IC,M)                     * HBT . 574
C     *               (DISTINGUISHED BY THE SWITCHES N42A,N42B,N42C)    * HBT . 575
C     * N43(INTPLN, - "DIFFERENCE OF REEVALUATED AND INPUT ARRAYS",     * HBT . 576
C     *       CHECK)  DFF(I,M),DGF(I,M),DPSI(I,M)                      * HBT . 577
C     *               (DISTINGUISHED BY THE SWITCHES N43A,N43B,N43C)    * HBT . 578
C     * N44(CHECK)  - "REEVALUATED ARRAYS",                             * HBT . 579
C     *               FF(I,M),GF(I,M),PSIF(I,M)                        * HBT . 580
C     *               (DISTINGUISHED BY THE SWITCHES N44A,N44B,N44C)    * HBT . 581
C     * N45(BALSTA) - "DO LOOP ON PSI",IPSI,PSI,                        * HBT . 582
C     *               CC(IJ,II)                                        * HBT . 583
C     * N46         - (EPS,"DO LOOP ON QST",IQST,QST,ALPHA,)            * HBT . 584
C     *               CA(IJ,II)                                        * HBT . 585
C     * N47         - CBL(IM,II),QW                                     * HBT . 586
C     * N48(SUYDAM) - "SUYDAM PARAMETER NEGATIVE",                      * HBT . 587
C     *               I,NT,TN(NT),ALP,KP2,GP2,A01,A11                  * HBT . 588
C     * N49(SHOOT)  - INPUT DATA FROM FILE DABAL, I.E.,                 * HBT . 589
C     *               "EQUILIBRIUM PARAMETERS", GAM1,IGAM,ETC.         * HBT . 590
C     *               "BALLOONING PARAMETERS", PSI1,PSI2,ETC.          * HBT . 591
C     * N410        - DATA RELATIVE TO EACH FLUX SURFACE FROM           * HBT . 592
C     *               FILE DABAL, VIZ., PSI,GPAR,QST,ETC.              * HBT . 593
C     * N411        - CBL(IM,II)                                        * HBT . 594
C     * N412        - "EQUIVALENT POTENTIAL",TX,VP,VP0,VP-VP0,C1/C10,   * HBT . 595
C     *               TMN,VPMN,TMX,VPMX,T0MN,VP0MN,                    * HBT . 596
C     *               T0MX,VP0MX,T1MX,V1MAX          (CALL TO POT)     * HBT . 597
C     ********************************************************************* HBT . 598
C                                                                         HBT . 599
C     *************** COMMENTS ON SWITCHES FOR PLOTTING ***************** HBT . 600
C     *                    (OPERATIONAL IF NI.NE.0)                       * HBT . 601
C     *                                                                   * HBT . 602
C     * - NAMELIST/PLO1/ FOR CONFIG:                                      * HBT . 603
C     * L11(HBT)    - WRITE NAMELIST INPUT ON FIRST GRAPH.                * HBT . 604
C     * L12(HBT)    - WRITE CONCISE OUTPUT ON LAST GRAPH.                 * HBT . 605
C     * L13(GRIDAR) - PLOT GRID IN THE Z-PLANE.                           * HBT . 606
C     * L14         - PLOT GRID IN THE ZETA-PLANE.                        * HBT . 607
C     * L15         - PLOT GRID IN THE W-PLANE.                           * HBT . 608
C     * KRAD        - NUMBER OF RADIAL GRID CURVES TO BE PLOTTED.         * HBT . 609
C     * LANG        - NUMBER OF ANGULAR GRID CURVES TO BE PLOTTED.        * HBT . 610
C     *                                                                   * HBT . 611
C     * - NAMELIST/PLO2/ FOR EQUIL:                                       * HBT . 612
C     * L21(ITERA)  - PLOT FF(I,M),GF(I,M),PSIF(I,M)                      * HBT . 613
C     *               (DISTINGUISHED BY THE SWITCHES L21A,L21B,L21C).     * HBT . 614
C     *               PLOTS FOR SINGLE VALUES OF M WHEN L21A/B/C=M;       * HBT . 615
C     *               ALL M (!) PLOTTED IF L21A/B/C.GE.99.                * HBT . 616
C     * L22(PSICON) - PLOT FLUX CONTOURS IN THE Z-PLANE.                  * HBT . 617
C     * L23(SSQCON) - PLOT S**2 CONTOURS IN THE Z-PLANE.                  * HBT . 618
C     * KCON        - NUMBER OF CONTOURS TO BE PLOTTED.                   * HBT . 619
C     * L24(EQUAR)  - PLOT PSI(X).                                        * HBT . 620
C     * L25         - PLOT P(X).                                          * HBT . 621
C     * L26         - PLOT JTOR(X).                                       * HBT . 622
C     * L27         - PLOT BPOL(X).                                       * HBT . 623
C     * L28         - PLOT Q(X).                                          * HBT . 624
C     * L29         - PLOT BTOR(X).                                       * HBT . 625
C     *                                                                   * HBT . 626
C     * - NAMELIST/PLO3/ FOR STAB:                                        * HBT . 627
C     * L31(STAB)   - PLOT POLYNOMIALS X(I,M,N),Y(I,M,N),Z(I,M,N)         * HBT . 628
C     *               (DISTINGUISHED BY THE SWITCHES L31A,L31B,L31C).     * HBT . 629
C     *               PLOTS FOR SINGLE M=L31A/100, N=MOD(L31A,100)        * HBT . 630
C     *               (E.G., IF L31A=605: X(I,M=6,N=5) IS PLOTTED);       * HBT . 631
C     *               FOR ALL M IF L31A=99.., ALL N IF L31A=..99;         * HBT . 632
C     *               FOR ALL M, ALL N (!) IF L31A.GE.9999.               * HBT . 633
C     *               SIMILARLY FOR L31B/C.                               * HBT . 634
C     * L32(EIFUN1) - PLOT AMPLITUDE ZETA OF THE EIGENFUNCTION.           * HBT . 635
C     *               L32A: 3D PLOT, L32B: CONTOUR PLOT                   * HBT . 636
C     *               (FOR L32=1 BOTH OPTIONS ARE REALIZED).              * HBT . 637
C     * L33(EIFUN2) - PLOT CONTOURS OF THE COMPONENTS S*KSI AND S*ETA.    * HBT . 638
C     *               L33A: 3D PLOTS, L33B: CONTOUR PLOTS.                * HBT . 639
C     *               (FOR L33=1 BOTH OPTIONS ARE REALIZED).              * HBT . 640
C     * L34(EIFUN3) - VECTOR PLOT OF THE FLOW FIELD VX,VY:                * HBT . 641
```

```
C     *        = 1    PLOT (NO DATA WRITTEN),                              * HBT . 642
C     *        = 2    WRITE DATA ON FILE "DHBT" (NO PLOT),                 * HBT . 643
C     *        = 3    PLOT + WRITE DATA ON FILE "DHBT".                    * HBT . 644
C     * NCON         - NUMBER OF FLUX CONTOURS ON WHICH THE FLOW FIELD      * HBT . 645
C     *                IS TO BE PLOTTED.                                    * HBT . 646
C     * AMP          - AMPLITUDE OF THE LARGEST VECTOR.                     * HBT . 647
C     * L35(STAB)    - PLOT OMSQ(1)+SIGMA VERSUS QSTAR.                     * HBT . 648
C     *                                                                     * HBT . 649
C     * - NAMELIST/PLO4/ FOR BALON:                                         * HBT . 650
C     * L41          -                                                      * HBT . 651
C     ********************************************************************** HBT . 652
C                                                                           HBT . 653
C4    * START PROGRAM.                                                      HBT . 654
```

APPENDIX B:
MODIFICATION FOR HBTAS (ASYMMETRIC EQUILIBRIA)

The up-down asymmetric code HBTAS has been written in complete accordance with the conventions used in HBT. Hence, despite substantial changes in the main part of the program, the number of modifications refering to the documentation and input parameters discussed in Appendix A is minimal. In principle, only the additional parameters PAR4, PAR5 (discussed in Sec. IV), and PAR6 (reserved for future extensions, but presently not in use) describing the plasma cross-section are needed. The pertinent changes are given below, again using UPDATE conventions.

```
*IDENT MOD45AS                                                          MOD .   1
*/                                                                      MOD .   2
*/ MODIFICATIONS OF HBT FOR UP-DOWN ASYMMETRIC EQUILIBRIA.              MOD .   3
*/                                                                      MOD .   4
*DELETE HBT.11                                                          MOD .   5
      PARAMETER(VERSION='45AS')                                         MOD .   6
*INSERT HBT.281                                                         MOD .   7
     C           PAR4,PAR5,PAR6,                                        MOD .   8
*INSERT HBT.360                                                         MOD .   9
C     * PAR4-PAR6   - ADDITIONAL PARAMETERS FOR ASYMMETRIC EQUILIBRIA. * MOD .  10
```

APPENDIX C:
DEFAULT VALUES OF THE NAMELIST INPUT DATA

HBT contains a BLOCK DATA subprogram preceding the main program in which representative values of the NAMELIST input parameters are fixed. Hence, the program will also run if none of these values is overwritten in the INPUT file. Of course, actual runs will have a non-empty INPUT file overwriting the default values. Should the user wish to minimize the number of parameters to be specified in a series of runs, the place to insert his typical choice of representative parameters is in this BLOCK DATA subprogram. Of course, this implies that the program has to be recompiled.

```
C*********************************************************************** DATA.  1
C* BLOCK DATA STATEMENTS TO INITIALIZE VARIABLES IN THE COMMON BLOCKS  * DATA.  2
C* CHR, VR1, PR1, PL1, VR2, PR2, PL2, VR3, PR3, PL3, VR4, PR4, PL4.    * DATA.  3
C*********************************************************************** DATA.  4
      BLOCK DATA                                                        DATA.  5
      IMPLICIT REAL*8 (A-H) , REAL*8 (O-Z)                              DATA.  6
                                                                           .
                    (COMMON statements omitted)                            .
                                                                           .
      DATA           PAI0,GAM0/2*0./                                  DATA. 48
      DATA           RUN,NOTE,IIN,IO,IOD                              DATA. 49
     A              /' ', ' ', 10,20, 20/                             DATA. 50
      DATA           GAM1,IGAM,AGA,BGA,CGA,DGA,EGA                    DATA. 51
     A              /  1.,   1,-1., 0., 0., 0., 1./                   DATA. 52
      DATA           PAI1,IPAI,API,BPI,CPI,DPI,EPI                    DATA. 53
     A              /  1.,   1,-1., 0., 0., 0., 1./                   DATA. 54
      DATA           ICROSS,PAR1,PAR2,PAR3,JPTS0,MCM,ERRCM,NITCM      DATA. 55
     A              /     1,  1.,  0.,  0.,  256,120,1.E-5,   20/     DATA. 56
      DATA           N11,N12,N13,N14,N15,N16,N17,N18,N19 /9*0/        DATA. 57
      DATA           N15A,N15B,N15C,N15D,N15E,N15F,N15G,N15H,N15I /9*0/ DATA. 58
      DATA           N17A,N17B,N18A,N18B,N19A,N19B /6*0/               DATA. 59
      DATA           L11,L12,L13,L14,L15,KRAD,LANG                    DATA. 60
     A              /  0,   0,   0,   0,   0,   10,   16/             DATA. 61
      DATA           NEPS,NDEL,NQS                                    DATA. 62
     A              /   0,   1,   0/                                  DATA. 63
      DATA           IINT,JPTS,MHARM,ERROR,NIT                        DATA. 64
     A              /  50,   64,    8,1.E-5, 10/                      DATA. 65
      DATA           NPRE,IMIX,NMIX,AMIX,BMIX                         DATA. 66
     A              /   0,    0,    0,   0.,   0./                    DATA. 67
      DATA           N21,N22,N23,N24,N25,N26,N27,N28,N29 /9*0/         DATA. 68
      DATA           N210,N211,N212 /3*0/                             DATA. 69
      DATA           N23A,N23B,N24A,N24B,N24C,N24D,N24E,N24F,N24G /9*0/ DATA. 70
      DATA           N25A,N25B,N26A,N26B,N26C,N28A,N28B,N28C /8*0/     DATA. 71
      DATA           N210A,N210B,N211A,N211B /4*0/                    DATA. 72
      DATA           N212A,N212B,N212C,N212D,N212E,N212F,N212G /7*0/   DATA. 73
      DATA           L21,L22,L23,L24,L25,L26,L27,L28,L29               DATA. 74
     A              /  0,   0,   0,   0,   0,   0,   0,   0,   0/     DATA. 75
      DATA           L21A,L21B,L21C,KCON                              DATA. 76
     A              /   0,    0,    0,   10/                          DATA. 77
      DATA           WALL,QSTAR1,QSTAR2,NQSTAR,M1,M2,NN,LE,NEV        DATA. 78
     A              /100.,    1.,    1.,     1,-3, 7, 6, 1,  1/      DATA. 79
      DATA           LMARG,SIGMA,NEF,NAPHI                            DATA. 80
     A              /    0,    0.,   0,    0./                       DATA. 81
      DATA           N31,N32,N33,N34,N35,N36 /6*0/                    DATA. 82
      DATA           N37,N38,N39,N310,N311,N312,N313 /7*0/            DATA. 83
      DATA           N31A,N31B,N31C,N31D,N31E,N31F,N31G,N31H /8*0/    DATA. 84
```

```
 DATA          N31I,N31J,N31K,N31L,N31M,N31N,N31O,N31P /8*0/          DATA. 85
 DATA          N35A,N35B,N312A,N312B,N313A,N313B /6*0/                DATA. 86
 DATA          L31,L32,L33,L34,L35                                    DATA. 87
A             /  0,  0,  0,  0,  0/                                  DATA. 88
 DATA          L31A,L31B,L31C,L32A,L32B,L33A,L33B,NCON,AMP            DATA. 89
A             /   0,   0,   0,   0,   0,   0,   0,  10, .2/          DATA. 90
 DATA          NPOL,PSI1,PSI2,NPSI,QST1,QST2,NQST,T0,TBB,TBF,DBT      DATA. 91
A             /   9, .02,  1.,  50,  1.,  1.,   0,0., 0.,100.,.1/    DATA. 92
 DATA          JPTS2,MHARM2,ERROR2,NDABAL                             DATA. 93
A             /   64,     8, 1.E-9,     0/                           DATA. 94
 DATA          NSHOOT,MODO1,MODO2,TX1,TX2,NTX,ALAM1,ALAM2,NLAM        DATA. 95
A             /     0,    1,   1,-20.,20., 41,   0.,  -1.,   6/      DATA. 96
 DATA          XF ,NX,ABSER2                                          DATA. 97
A             /20.,20,1.E-10/                                        DATA. 98
 DATA          N41,N42,N43,N44,N45,N46,N47,N48 /8*0/                  DATA. 99
 DATA          N49,N410,N411,N412 /4*0/                               DATA.100
 DATA          N41A,N41B,N41C,N42A,N42B,N42C /6*0/                    DATA.101
 DATA          N43A,N43B,N43C,N44A,N44B,N44C /6*0/                    DATA.102
 DATA          L41 /0/                                                DATA.103
 END                                                                  DATA.104
```

APPENDIX D:
OUTPUT PARAMETERS

In the OUTPUT of HBT the computed variables appear with names that are self-explanatory in most cases. For the convenience of the user the meanings of all these variables are given below. The output of an actual run is given in Appendix F.

1) Conformal mapping:

ITCM	-	number of iterations for conformal mapping to each prescribed accuracy ERRCM.
TEST	-	accuracy of the conformal mapping on output.

2a) Equilibrium (q* independent parameters):

IT	-	number of iterations for equilibrium to each prescribed accuracy ERROR.
ABSER	-	absolute error of the flux function on output.
AMSQER	-	absolute mean square error of the flux function on output.
A	-	eigenvalue A of the Grad-Shafranov equation (Eq. (5.10)).
B	-	eigenvalue B of the Grad-Shafranov equation (Eq. (5.10)).
QSW	-	$\tilde{q}^* \equiv q^*/\alpha$.
Q0W(*)	-	$\tilde{q}_0 \equiv q_0/\alpha$ (preliminary value, corrected for q^* dependent part below).
Q1W	-	$\tilde{q}_1 \equiv q_1/\alpha$
EBETPL	-	$\varepsilon\beta_p \equiv 4\pi q^{*2} <\beta> S/(\varepsilon C^2)$.
BETAAW	-	$<\tilde{\beta}> \equiv <\beta> \cdot \alpha^2/\varepsilon$.
BETA0W	-	$\tilde{\beta}_0 \equiv \beta_0 \cdot \alpha^2/\varepsilon$.
ELL	-	ellipticity of the magnetic surfaces at the magnetic axis.
ELONG	-	normalized elongation of the plasma circumference: $C/2\pi a$.
AREA	-	dimensionless area of the plasma cross-section: S/a^2.
VOLUME	-	dimensionless plasma volume: V/R_0a^2.
PVOLAR	-	$(\int pdV)/(\int pdS/S)$: factor to correct area averaged $<\beta>$ to volume averaged value.
AEFF	-	$a_{eff} \equiv \sqrt{<\beta>/\beta_0}$: effective plasma radius
BPOLIN	-	$B_p(s=1, t=\pi)$: measure of the poloidal variation of B_p.

2b) Equilibrium (q* dependent parameters):

QS - q^* (Eq. (4.3)).
ALFA - α (Eq. (2.3)).
Q0W - $\tilde{q}_0 \equiv q_0/\alpha$.
Q0 - q_0.
Q1 - q_1.
BETAA - $<\beta>$.
BETA0 - β_0.
BTORNL - $B_\phi(s=0)/B_0$.

3) Global stability (all quantities: high-β approximation):

QSTAR - q^*.
Q00 - q_0.
Q11 - q_1.
BETA0OE - β_0/ε.
BETAOE - $<\beta>/\varepsilon$.
OMSQ - ω^2: growth rate.
SIGMA - $\sigma \equiv -\omega^2_{\text{cut-off}}$: cut off for the growth rate to be considered for marginal stability.

4) Ballooning stability:

PSI - ψ.
PAI - value of profile $\Pi(\psi)$.
GAM - value of profile $\Gamma(\psi)$.
P - $p(\psi) \equiv p(\psi)/p_0$.
G - $G(\psi) \equiv (P(\psi) + \frac{1}{2} F^2(\psi))/\varepsilon$ (Eq. (2.3)).
GPAR - $-(4\mu_0 q^{*2}/\varepsilon B_\phi^2)\sqrt{\psi}\, dp/d\psi$.
QST - q^*.
RBTOR - $RB_\phi/(R_0B_0)$.
Q - q.
QW - $\tilde{q} \equiv q/\alpha$.
DQWDPS - $d\tilde{q}/d\psi$.
SHEAR - $2\,(\psi/q)\,(dq/d\psi)$.

DM	-	Mercier parameter D_M (Mercier criterion: $D_M < -1/4$).
"ALPNEG"	-	ballooning unstable for ... values of TN.
TN	-	angular measure for ballooning instability.

APPENDIX E:
THE USE OF HBT (JCL PROCEDURES)

In this appendix the JCL procedures to run HBT and HBTAS on the JET IBM system are given.

The example JCL procedure to run HBTAS which is printed below can be found in the file : JETLIB.EXAMPLES.CNTL. The dataset FT10F001 is the input file containing the namelist input variables, FT20F001 is used for written output, SPLINP and SPLINF are respectively the input files for the spline coefficients of the $\Pi(\psi)$ and the $\Gamma(\psi)$ profiles (see also appendix G). The files CINP, OHBT, COUT1, COUT2, DHBT and DABAL are temporary storage files. The plot output is written to JETUID.HBTGRID.LIST (FT41F001).

```
//XXXHBT   JOB ( ), 'G.HUYSMANS'
//         PRTY=7,
//         MSGCLASS=X,
//         NOTIFY=*,
//         TIME=(10,00),
//         REGION=4096K
/*JOBPARM LINES=50
//*************************************************************
//* AUTHOR : G.HUYSMANS
//* DATE   : 29/03/90
//*
//* SUBMITTED FROM : JETLIB.EXAMPLES.CNTL(HBT)
//* SAMPLE JCL TO RUN THE MHD STABILITY CODE, HBT
//*
//* NOTES :
//* 1.  BEFORE SUBMITTING THIS JCL, CHANGE <JETUID> TO YOUR OWN UID
//* 2.  JETUID.HBT.OUTPUT SHOULD HAVE THE FOLLOWING ATTRIBUTES:
//*     RECFM=VBA,LRECL=137,BLKSIZE=6300
//*
//*********************************************************************
//GRID      EXEC GH80NEW,DSN='JETUID.HBTGRID.LIST',NUMRECS=300
//*
//R         EXEC PGM=HBTAS
//STEPLIB   DD   DSN=JETLIB.HBT.LOAD,DISP=SHR
//FT06F001  DD   SYSOUT=*
//FT10F001  DD   DSN=JETLIB.HBT.DATA(S10766),DISP=SHR
//SHAPE     DD   DSN=JETLIB.HBT.DATA.(SHP766C),DISP=SHR
//FT20F001  DD   DSN=JETUID.HBT.OUTPUT,DISP=OLD
//SPLINP    DD   DUMMY
//SPLINF    DD   DUMMY
//CINP      DD  DNS=&&CINP,DISP=(NEW,DELETE),UNIT=TEMP,
//              DCB=(DSORG=PS,LRECL=133,BLKSIZE=13300,RECFM=FBA),
```

```
//              SPACE=(TRK,(1,5))
//OHBT      DD  DNS=&&OHBT,DISP=(NEW,DELETE),UNIT=TEMP,
//              DCB=(DSORG=PS,LRECL=133,BLKSIZE=13300,RECFM=FBA),
//              SPACE=(TRK,(100,100))
//COUT1     DD  DNS=&&COUT1,DISP=(NEW,DELETE),UNIT=TEMP,
//              DCB=(DSORG=PS,LRECL=133,BLKSIZE=13300,RECFM=FBA),
//              SPACE=(TRK,(1,5))
//COUT2     DD  DNS=&&COUT2,DISP=(NEW,DELETE),UNIT=TEMP,
//              DCB=(DSORG=PS,LRECL=133,BLKSIZE=13300,RECFM=FBA),
//              SPACE=(TRK,(1,5))
//DHBT      DD  DNS=&&DHBT,DISP=(NEW,DELETE),UNIT=TEMP,
//              DCB=(DSORG=PO,LRECL=80,BLKSIZE=6300,RECFM=FB),
//              SPACE=(TRK,(1,5))
//DABAL     DD  DNS=&&DABAL,DISP=(NEW,DELETE),UNIT=TEMP,
//              DCB=(DSORG=PS,LRECL=137,BLKSIZE=6300,RECFM=VBA),
//              SPACE=(TRK,(1,5))
//FT41F001 DD  DNS=JETUID.HBTGRID.LIST,DISP=SHR
/*
```

This JCL file will run the asymmetric version of HBT, i.e. HBTAS. To run the symmetric version HBT, one has to replace the line :

```
//R         EXEC PGM=HBTAS
```

by :

```
//R         EXEC PGM=HBT
```

Note : For more information about the use of HBT on the IBM contact : C. Nardone (phone no. : 4975)

APPENDIX F:
COMPLETE EXAMPLE: ANALYSIS OF DISCHARGE #20272

In this appendix we will describe a complete example of HBT. For this we reconstruct the IDENTC equilibrium of the high-β discharge #20272 with HBT and compare the output quantities of both codes. The ballooning stability of this equilibrium is calculated and the complete output of the equilibrium and ballooning calculation are given. To show the complete output of a low-n stability run, the equilibrium is changed to an equilibrium in the high beta approximation , i.e.with zero inverse aspect ratio and $q^* = 1.0$ and calculate the stability of the n=1 mode.

The relevant output of the fit of IDENTC to both the magnetic signals and a pressure profile from the LIDAR diagnostic is shown in table IV. The input parameters for HBT calculated from the IDENTC output with the equations of sec. V are shown in the same table. Also shown in table V is the comparison of the output quantities of both IDENTC and HBT. The value of δ, the shift of the magnetic axis is found after a sqan in δ, such that the value of β_l is the same for both codes. The difference in the values of the output parameters is caused by the difference in plasma shape.

The complete output of HBT of a ballooning calculation for two different values of the total pressure is shown below. The output file starts with the complete namelist input file. Also shown are the plots of the equilibrium profiles.

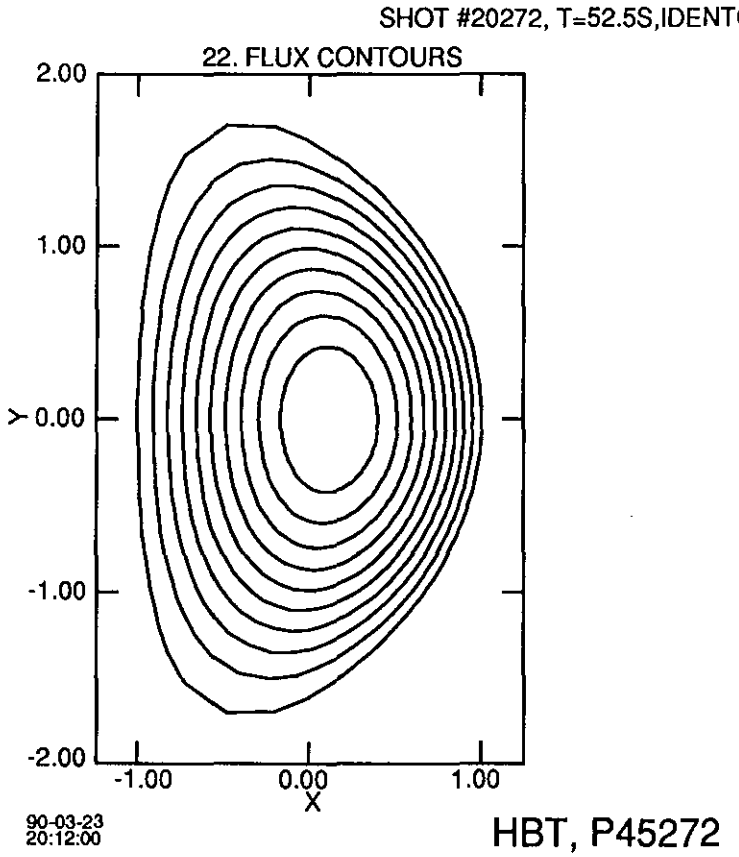
Table IV.
Input and output parameters for shot #20272

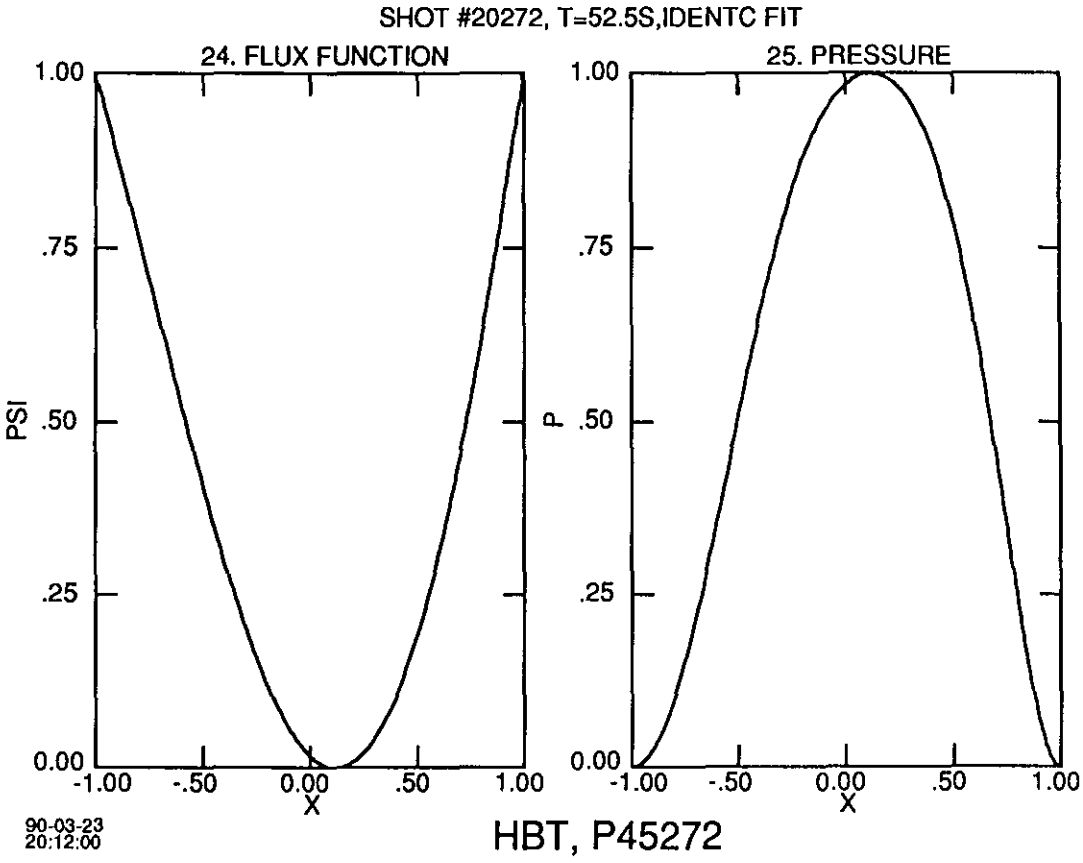
IDENTC	Value calculated for HBT
E = 2.0529*)	PAR1 = 1.72 ; PAR2 = 0.38 ; PAR3 = 0
δ_t = 0.5006*)	
a_1 = − 0.7783	a_π = − 0.432 ; b_π = − 0.568
b_1 = 16.481	a_γ = 2.511 ; b_γ = − 3.511
b_t = 0.97594	$c_\pi = d_\pi = 0$; $e_\pi = 1.0$
	$c_\gamma = d_\gamma = 0$; $e_\gamma = 1.0$
	PAI1 = GAM1 = 0
RE = 4.082 m	IPAI = IGAM = 1
RW = 1.862 m	a = 1.110 m ; R_0 = 2.972 m
I_p = 2.062 MA	ε = 0.373
B_0 = 1.222 T	
e = *)	q^* = 1.706
Φ_0 = − 0.441 Wb	
Φ_1 = − 5.659 Wb	α = 1.813
RMAG = 3.12 m	
	δ = 0.148
IDENTC	**Output value of HBT**
β_I = 0.652	δ = 0.1208
q_0 = 1.060	β_I = 0.652
q_1 = 4.022	q_0 = 1.068
α = 1.813	q_1 = 4.13
	α = 1.856

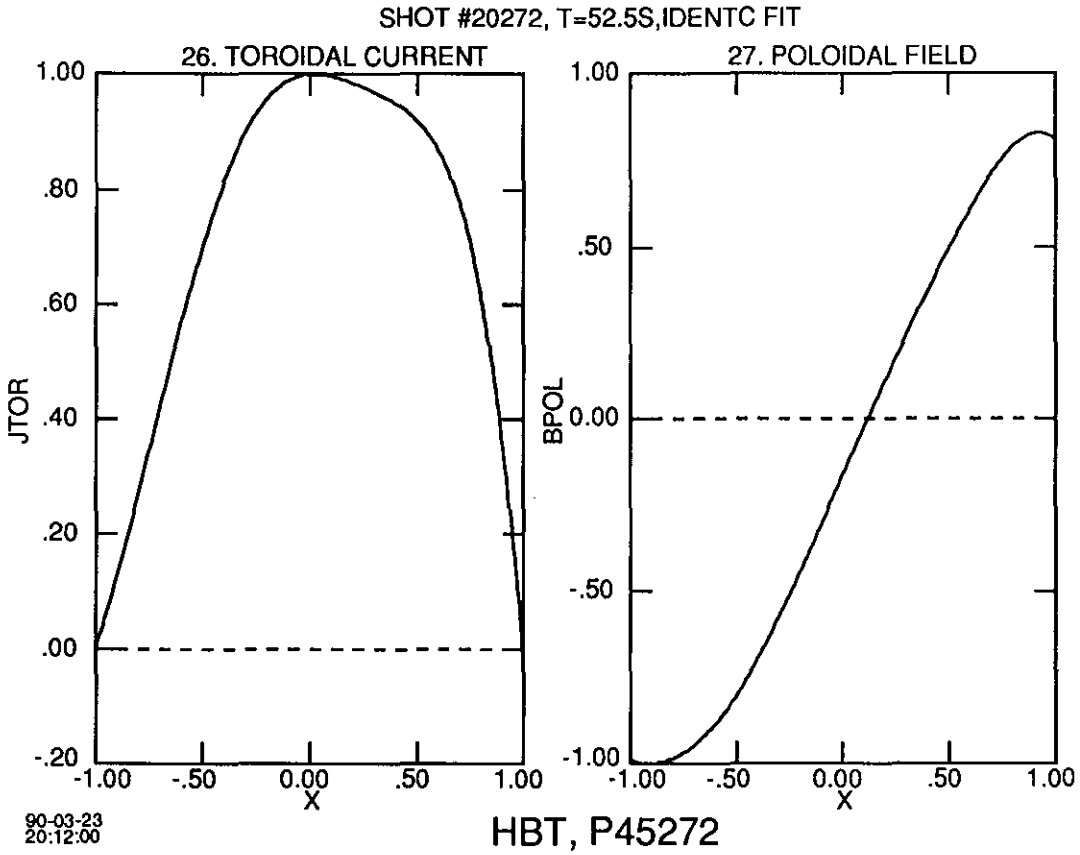
*) The values given by IDENTC for the double x-point plasma shape appear to be too large, the values used in HBT are obtained from a plot of the flux surfaces

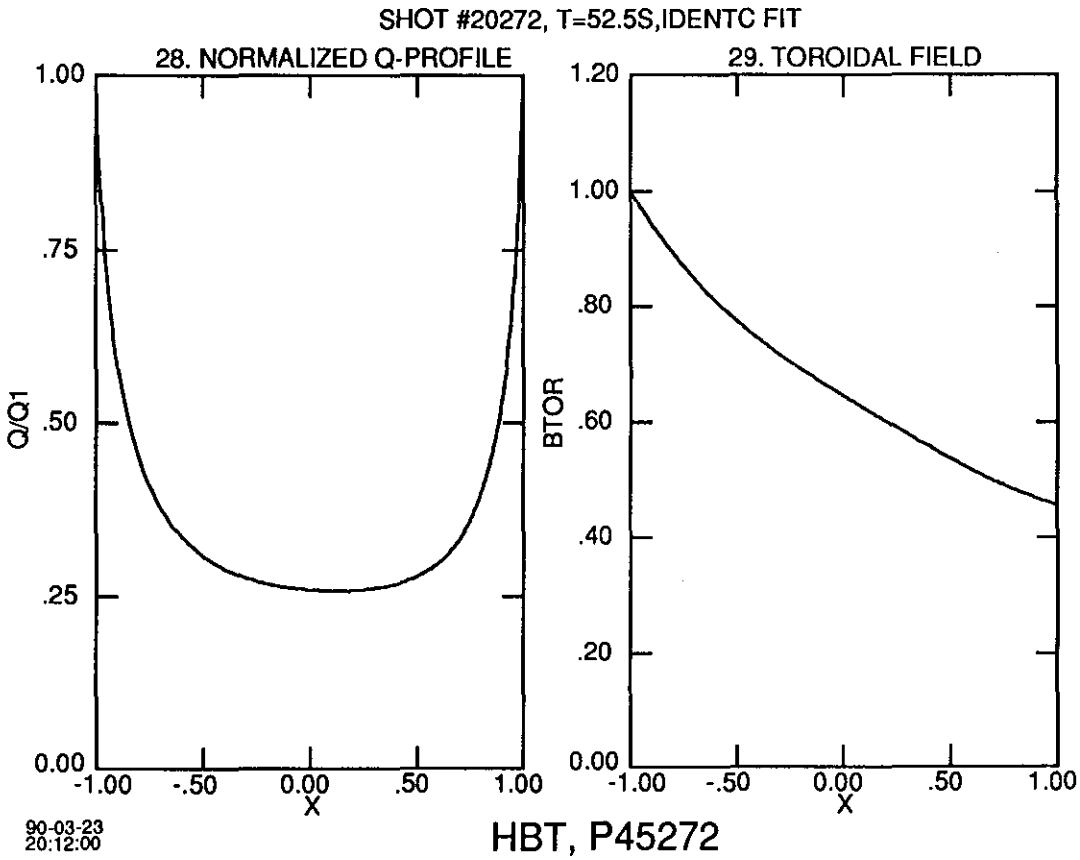
```
PROGRAM HBT
VERSION='45'


&VAR1 RUN='-', NOTE= 'SHOT #20272, T=52.5S,IDENTC FIT',IO=20, IOD=20,
      GAM1=  0.00000, IGAM= 1, AGA=  -.43200, BGA=  -.56800, CGA=  0.00000, DGA=  0.00000, EGA=  1.00000,
      PAI1=  0.00000, IPAI= 1, API=  2.51100, BPI= -3.51100, CPI=  0.00000, DPI=  0.00000, EPI=  1.00000,
      ICROSS= 1, PAR1=  1.72000, PAR2=   .38000, PAR3=  0.00000, JPTS0=256, MCM=127, ERRCM= 1.0000E-05, NITCM=100, MODE1= 1 &END
&PRI1 &END
&PLO1 &END


&VAR2 EPS1= .37300, EPS2= .37300, NEPS= 1, DEL1= .12080, DEL2= .18080, NDEL= 2, QS1=1.70600, QS2=1.70600, NQS= 1,
      IINT=100, JPTS=128, MHARM= 20, ERROR=  1.0000E-06, NIT= 25,
      NPRE=  0, IMIX=  0, NMIX=  0, AMIX=  0.00000, BMIX=  0.00000, MODE2= 1 &END
&PRI2 &END
&PLO2 &END


&VAR4 NPOL=20, PSI1=  .05000, PSI2=  .95000, NPSI=10, QST1= 1.70600, QST2= 1.70600, NQST=  1, T0= 0.00000, TBB= 0.00000,
      TBF=  50.00000, DBT=  .10000, JPTS2=128, MHARM2=30, ERROR2=  1.0000E-09, NDABAL= 0,
      NSHOOT= 0, MODO1= 1, MODO2= 1, TX1= -20.00000, TX2=  20.00000, NTX= 41, ALAM1=   0.00000, ALAM2=  -1.00000, NLAM=  6,
      XF=  20.00000, NX= 20, ABSER2=  1.0000E-10, SIGMAB=   0.00000, MODE4= 1 &END
&PRI4 &END
&PLO4 &END


PROFILES:

  GAM1  =  0.0000E+00   IGAM  =  1
  AGA   = -4.3200E-01   BGA   = -5.6800E-01   CGA   =  0.0000E+00
  DGA   = -1.7764E-15   EGA   =  1.0000E+00
  PAI1  =  0.0000E+00   IPAI  =  1
  API   =  2.5110E+00   BPI   = -3.5110E+00   CPI   =  0.0000E+00
  DPI   =  0.0000E+00   EPI   =  1.0000E+00


CROSS-SECTION:

  ICROSS=  1            D-SHAPE
  PAR1  =  1.7200E+00   PAR2  =  3.8000E-01   PAR3  =  0.0000E+00   JPTS0 =256


CONFORMAL MAPPING:

  MCM   =127            ERRCM =  1.0000E-05
  TEST  =  6.5348E-06   NITCM =100            ITCM  = 22


EQUILIBRIUM:

  EPS   =  3.7300E-01   DEL   =  1.2080E-01
  IINT  =100            JPTS  =128            MHARM = 20
  A     =  3.5728E+00   B     =  2.5294E-01
  ELL   =  1.4631E+00   ERROR =  1.0000E-06   NIT   = 25
  Q0W(*)=  5.8262E-01   BETA0W=  9.8065E-01
  ELONG =  1.3893E+00   AMSQER=  3.4487E-07   IT    = 12
  Q1W   =  2.2275E+00   BETAAW=  3.2878E-01   AREA  =  5.3066E+00
  ABSER = -4.3185E-08   PVOLAR=  1.0478E+00
  QSW   =  9.1915E-01   EBETPL=  2.4308E-01   VOLUME=  3.2196E+01
  BPOLIN=  1.7259E+00   AEFF  =  5.7902E-01

  QS    =  1.7060E+00   Q0    =  1.0681E+00
  BETA0 =  1.0618E-01   XLI   =  7.8943E-01
  ALFA  =  1.8561E+00   BTORNL=  9.8769E-01
  Q1    =  4.1344E+00   BETAA =  3.5598E-02

LOCAL BALLOONING STABILITY:

POLYNOMIAL FITTING FOR NPOL = 20

PSI1  =  5.0000E-02   PSI2  =  9.5000E-01 NPSI  = 10           QST1  =  1.7060E+00 QST2  =  1.7060E+00   NQST  =  1
T0    =  0.0000E+00   TBB   =  0.0000E+00 TBF   =  5.0000E+01   DBT   =  1.0000E-01 JPTS2 =128            MHARM2= 30
ABS ERR FOR S-FLUX:   ERROR2=  1.0000E-09
SIGMAB =  0.0000E+00

PSI   =  5.0000E-02   PAI   =  1.1168E+00 GAM   =  9.7698E-01   P     =  4.6638E-01 G     =  1.9480E+00   GPAR  =  3.8130E-01
QST   =  1.7060E+00   RBTOR =  1.0278E+00 Q     =  1.0848E+00   QW    =  5.8447E-01 DQWDPS=  1.9723E-01   SHEAR =  3.3745E-02
DM    =  3.7310E-01   BALLOONING STABLE

PSI   =  1.5000E-01   PAI   =  1.2977E+00 GAM   =  9.2242E-01   P     =  4.1157E-01 G     =  1.6083E+00   GPAR  =  7.6740E-01
QST   =  1.7060E+00   RBTOR =  1.0202E+00 Q     =  1.1282E+00   QW    =  6.0784E-01 DQWDPS=  2.7234E-01   SHEAR =  1.3441E-01
DM    = -8.5990E-02   BALLOONING STABLE

PSI   =  2.5000E-01   PAI   =  1.4083E+00 GAM   =  8.5650E-01   P     =  3.5017E-01 G     =  1.2902E+00   GPAR  =  1.0752E+00
QST   =  1.7060E+00   RBTOR =  1.0141E+00 Q     =  1.1870E+00   QW    =  6.3952E-01 DQWDPS=  3.6453E-01   SHEAR =  2.8500E-01
DM    = -1.3751E-01   BALLOONING STABLE

PSI   =  3.5000E-01   PAI   =  1.4488E+00 GAM   =  7.7922E-01   P     =  2.8536E-01 G     =  9.9768E-01   GPAR  =  1.3087E+00
QST   =  1.7060E+00   RBTOR =  1.0094E+00 Q     =  1.2651E+00   QW    =  6.8159E-01 DQWDPS=  4.8233E-01   SHEAR =  4.9536E-01
DM    = -1.3876E-01   BALLOONING STABLE

PSI   =  4.5000E-01   PAI   =  1.4190E+00 GAM   =  6.9058E-01   P     =  2.2031E-01 G     =  7.3477E-01   GPAR  =  1.4534E+00
QST   =  1.7060E+00   RBTOR =  1.0058E+00 Q     =  1.3686E+00   QW    =  7.3735E-01 DQWDPS=  6.4131E-01   SHEAR =  7.8278E-01
DM    = -1.2605E-01   BALLOONING STABLE

PSI   =  5.5000E-01   PAI   =  1.3190E+00 GAM   =  5.9058E-01   P     =  1.5819E-01 G     =  5.0557E-01   GPAR  =  1.4936E+00
QST   =  1.7060E+00   RBTOR =  1.0033E+00 Q     =  1.5074E+00   QW    =  8.1212E-01 DQWDPS=  8.6892E-01   SHEAR =  1.1769E+00
DM    = -1.0786E-01   BALLOONING STABLE

PSI   =  6.5000E-01   PAI   =  1.1488E+00 GAM   =  4.7922E-01   P     =  1.0217E-01 G     =  3.1413E-01   GPAR  =  1.4142E+00
QST   =  1.7060E+00   RBTOR =  1.0016E+00 Q     =  1.6986E+00   QW    =  9.1515E-01 DQWDPS=  1.2197E+00   SHEAR =  1.7326E+00
```

```
DM    = -8.7055E-02   BALLOONING STABLE

PSI   =  7.5000E-01   PAI   =  9.0831E-01 GAM   =  3.5650E-01   P     =  5.5433E-02 G     =  1.6450E-01   GPAR  =  1.2011E+00
QST   =  1.7060E+00   RBTOR =  1.0006E+00 Q     =  1.9754E+00   QW    =  1.0643E+00 DQWDPS=  1.8237E+00   SHEAR =  2.5704E+00
DM    = -6.4421E-02   BALLOONING STABLE

PSI   =  8.5000E-01   PAI   =  5.9765E-01 GAM   =  2.2242E-01   P     =  2.1146E-02 G     =  6.0741E-02   GPAR  =  8.4135E-01
QST   =  1.7060E+00   RBTOR =  1.0002E+00 Q     =  2.4134E+00   QW    =  1.3003E+00 DQWDPS=  3.0678E+00   SHEAR =  4.0110E+00
DM    = -4.0072E-02   BALLOONING STABLE

PSI   =  9.5000E-01   PAI   =  2.1677E-01 GAM   =  7.6980E-02   P     =  2.4817E-03 G     =  6.9181E-03   GPAR  =  3.2261E-01
QST   =  1.7060E+00   RBTOR =  1.0000E+00 Q     =  3.2527E+00   QW    =  1.7525E+00 DQWDPS=  6.8130E+00   SHEAR =  7.3866E+00
DM    = -1.3441E-02   BALLOONING STABLE
1

&VAR2 EPS=    .37300, DEL=    .18080 &END


CONFORMAL MAPPING:

  MCM   =127            ERRCM =  1.0000E-05
  TEST  =  7.8416E-06   NITCM =100            ITCM  = 27


EQUILIBRIUM:

  EPS   =  3.7300E-01   DEL   =  1.8080E-01
  IINT  =100            JPTS  =128            MHARM = 20
  A     =  3.5787E+00   B     =  4.3333E-01
  ELL   =  1.4734E+00   ERROR =  1.0000E-06   NIT   = 25
  Q0W(*)=  5.5631E-01   BETA0W=  1.6828E+00
  ELONG =  1.3885E+00   AMSQER=  6.1562E-07   IT    =  9
  Q1W   =  2.5460E+00   BETAAW=  5.4281E-01   AREA  =  5.3066E+00
  ABSER = -7.7900E-08   PVOLAR=  1.0622E+00
  QSW   =  9.6255E-01   EBETPL=  4.4061E-01   VOLUME=  3.2196E+01
  BPOLIN=  1.4538E+00   AEFF  =  5.6794E-01

  QS    =  1.7060E+00   Q0    =  9.1846E-01
  BETA0 =  1.9982E-01   XLI   =  8.4059E-01
  ALFA  =  1.7724E+00   BTORNL=  9.3151E-01
  Q1    =  4.5125E+00   BETAA =  6.4453E-02

LOCAL BALLOONING STABILITY:

POLYNOMIAL FITTING FOR NPOL = 20

PSI1  =  5.0000E-02   PSI2  =  9.5000E-01 NPSI  = 10           QST1  =  1.7060E+00 QST2  =  1.7060E+00   NQST  =  1
T0    =  0.0000E+00   TBB   =  0.0000E+00 TBF   =  5.0000E+01   DBT   =  1.0000E-01 JPTS2 =128            MHARM2= 30
ABS ERR FOR S-FLUX:   ERROR2=  1.0000E-09
SIGMAB =  0.0000E+00

PSI   =  5.0000E-02   PAI   =  1.1168E+00 GAM   =  9.7698E-01   P     =  8.0031E-01 G     =  1.9512E+00   GPAR  =  7.1758E-01
QST   =  1.7060E+00   RBTOR =  9.9135E-01 Q     =  9.3294E-01   QW    =  5.2638E-01 DQWDPS=  1.8391E-01   SHEAR =  3.4938E-02
DM    =  6.4549E+00   ALP NEG. IN  1 PTS:    1. TN=  1.7200E+01

PSI   =  1.5000E-01   PAI   =  1.2977E+00 GAM   =  9.2242E-01   P     =  7.0626E-01 G     =  1.6110E+00   GPAR  =  1.4442E+00
QST   =  1.7060E+00   RBTOR =  9.8741E-01 Q     =  9.7333E-01   QW    =  5.4917E-01 DQWDPS=  2.7413E-01   SHEAR =  1.4975E-01
DM    =  9.9029E-01   ALP NEG. IN  1 PTS:    1. TN=  9.3000E+00

PSI   =  2.5000E-01   PAI   =  1.4083E+00 GAM   =  8.5650E-01   P     =  6.0090E-01 G     =  1.2923E+00   GPAR  =  2.0234E+00
QST   =  1.7060E+00   RBTOR =  9.8579E-01 Q     =  1.0312E+00   QW    =  5.8183E-01 DQWDPS=  3.8297E-01   SHEAR =  3.2911E-01
DM    =  2.2808E-01   ALP NEG. IN  1 PTS:    1. TN=  3.7000E+00

PSI   =  3.5000E-01   PAI   =  1.4488E+00 GAM   =  7.7922E-01   P     =  4.8968E-01 G     =  9.9932E-01   GPAR  =  2.4629E+00
QST   =  1.7060E+00   RBTOR =  9.8602E-01 Q     =  1.1108E+00   QW    =  6.2675E-01 DQWDPS=  5.2190E-01   SHEAR =  5.8290E-01
DM    =  2.5654E-03   ALP NEG. IN  1 PTS:    1. TN=  3.0000E+00

PSI   =  4.5000E-01   PAI   =  1.4190E+00 GAM   =  6.9058E-01   P     =  3.7805E-01 G     =  7.3599E-01   GPAR  =  2.7353E+00
QST   =  1.7060E+00   RBTOR =  9.8763E-01 Q     =  1.2191E+00   QW    =  6.8785E-01 DQWDPS=  7.1048E-01   SHEAR =  9.2961E-01
DM    = -7.8351E-02   ALP NEG. IN  1 PTS:    1. TN=  2.6000E+00

PSI   =  5.5000E-01   PAI   =  1.3190E+00 GAM   =  5.9058E-01   P     =  2.7145E-01 G     =  5.0641E-01   GPAR  =  2.8108E+00
QST   =  1.7060E+00   RBTOR =  9.9015E-01 Q     =  1.3677E+00   QW    =  7.7165E-01 DQWDPS=  9.8412E-01   SHEAR =  1.4029E+00
DM    = -1.0440E-01   ALP NEG. IN  1 PTS:    1. TN=  2.3000E+00

PSI   =  6.5000E-01   PAI   =  1.1488E+00 GAM   =  4.7922E-01   P     =  1.7533E-01 G     =  3.1464E-01   GPAR  =  2.6613E+00
QST   =  1.7060E+00   RBTOR =  9.9309E-01 Q     =  1.5770E+00   QW    =  8.8978E-01 DQWDPS=  1.4141E+00   SHEAR =  2.0660E+00
DM    = -1.0463E-01   ALP NEG. IN  1 PTS:    1. TN=  2.4000E+00

PSI   =  7.5000E-01   PAI   =  9.0831E-01 GAM   =  3.5650E-01   P     =  9.5124E-02 G     =  1.6477E-01   GPAR  =  2.2604E+00
QST   =  1.7060E+00   RBTOR =  9.9599E-01 Q     =  1.8876E+00   QW    =  1.0650E+00 DQWDPS=  2.1699E+00   SHEAR =  3.0561E+00
DM    = -8.9937E-02   BALLOONING STABLE

PSI   =  8.5000E-01   PAI   =  5.9765E-01 GAM   =  2.2242E-01   P     =  3.6286E-02 G     =  6.0841E-02   GPAR  =  1.5833E+00
QST   =  1.7060E+00   RBTOR =  9.9838E-01 Q     =  2.3935E+00   QW    =  1.3504E+00 DQWDPS=  3.7654E+00   SHEAR =  4.7401E+00
DM    = -6.3909E-02   BALLOONING STABLE

PSI   =  9.5000E-01   PAI   =  2.1677E-01 GAM   =  7.6980E-02   P     =  4.2587E-03 G     =  6.9295E-03   GPAR  =  6.0713E-01
QST   =  1.7060E+00   RBTOR =  9.9980E-01 Q     =  3.4009E+00   QW    =  1.9188E+00 DQWDPS=  8.7598E+00   SHEAR =  8.6739E+00
DM    = -2.5071E-02   BALLOONING STABLE


PROGRAM HBT
```


SHOT #20272, T=52.5S,IDENTC FIT
22. FLUX CONTOURS
2.00
1.00
0.00
-1.00
-2.00
Y
-1.00
0.00
1.00
X
90-03-23
20:12:00
HBT, P45272


SHOT #20272, T=52.5S,IDENTC FIT
24. FLUX FUNCTION
25. PRESSURE
1.00
.75
.50
.25
0.00
PSI
p
-1.00
-.50
0.00
.50
1.00
X
90-03-23
20:12:00
HBT, P45272

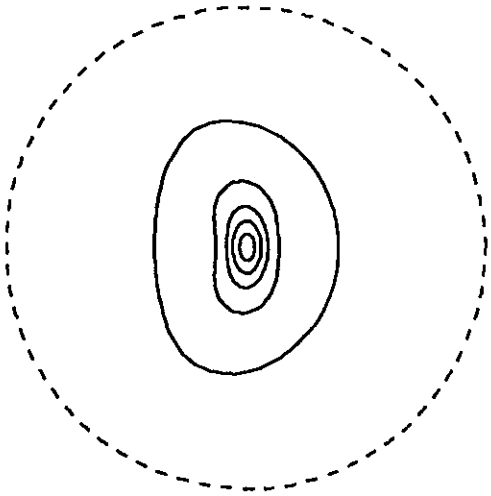

SHOT #20272, T=52.5S,IDENTC FIT
26. TOROIDAL CURRENT
JTOR
1.00
.80
.60
.40
.20
.00
-.20
-1.00
-.50
0.00
.50
1.00
X
27. POLOIDAL FIELD
BPOL
1.00
.50
0.00
-.50
-1.00
-1.00
-.50
0.00
.50
1.00
X
90-03-23
20:12:00
HBT, P45272


SHOT #20272, T=52.5S,IDENTC FIT
28. NORMALIZED Q-PROFILE
Q/Q1
1.00
.75
.50
.25
0.00
-1.00
-.50
0.00
.50
1.00
X
29. TOROIDAL FIELD
BTOR
1.20
1.00
.80
.60
.40
.20
0.00
-1.00
-.50
0.00
.50
1.00
X
90-03-23
20:12:00
HBT, P45272

Below the output of the low-n mode stability calculation of the high beta equilibrium is given. Note that NEPS=0 and NQS=0 in the high beta equilibrium option of HBT.

```
PROGRAM HBT
VERSION='45D'

&VAR1 RUN='-', NOTE='SHOT #20272, T-52.5S,IDENTC FIT', IO=20, IOD=20,
      GAM1=  0.00000, IGAM= 1, AGA=  -.43200, BGA=  -.56800, CGA=  0.00000, DGA=  0.00000, EGA=  1.00000,
      PAI1=  0.00000, IPAI= 1, API=  2.51100, BPI= -3.51100, CPI=  0.00000, DPI=  0.00000, EPI=  1.00000,
      ICROSS= 1, PAR1=  1.72000, PAR2=   .38000, PAR3=  0.00000, JPTS0=256, MCM=127, ERRCM= 1.0000E-05, NITCM=100, MODE1= 1 &END
&PRI1 &END
&PLO1 &END

&VAR2 EPS1=0.00000, EPS2=0.00000, NEPS= 0, DEL1= .12080, DEL2= .12080, NDEL= 1, QS1=1.00000, QS2=1.00000, NQS= 0,
      IINT=100, JPTS=128, MHARM= 20, ERROR=  1.0000E-06, NIT= 25,
      NPRE=  0, IMIX=  0, NMIX=  0, AMIX=  0.00000, BMIX=  0.00000, MODE2= 1 &END
&PRI2 &END
&PLO2 &END

&VAR3 WALL=   1.50000, QSTAR1= 1.70600, QSTAR2= 1.70600, NQSTAR=  1, M1=-15, M2= 15, NN=10, LE= 1, NEV= 1,
      LMARG= 0, SIGMA=  0.0000E+00, NEF= 1, NAPHI= 1, MODE3= 1 &END

&PRI3 N31= 0, N32= 0, N33= 0, N34= 0, N35= 0, N36= 0, N37= 0, N38= 0, N39= 0, N310= 0, N311= 0, N312= 0, N313= 0,
      N31A= 0, N31B= 0, N31C= 0, N31D= 0, N31E= 0, N31F= 0, N31G= 0, N31H= 0, N31I= 0, N31J= 0,
      N31K= 0, N31L= 0, N31M= 0, N31N= 0, N31O= 0, N31P= 0, N35A=  0, N35B=  0, N312A= 0, N312B= 0, N313A= 0, N313B= 0 &END

&PLO3 L31= 0, L32= 1, L33= 1, L34= 3, L35= 0, L31A=    0, L31B=    0, L31C=    0, L32A= 0, L32B= 1, L33A= 0, L33B= 1,
      NCON= 10, AMP=  2.0000E-01 &END


PROFILES:

  GAM1  =  0.0000E+00   IGAM  =  1
  AGA   = -4.3200E-01   BGA   = -5.6800E-01   CGA   =  0.0000E+00   DGA   = -1.7764E-15   EGA   =  1.0000E+00
  PAI1  =  0.0000E+00   IPAI  =  1
  API   =  2.5110E+00   BPI   = -3.5110E+00   CPI   =  0.0000E+00   DPI   =  0.0000E+00   EPI   =  1.0000E+00


CROSS-SECTION:

  ICROSS=  1            D-SHAPE
  PAR1  =  1.7200E+00   PAR2  =  3.8000E-01   PAR3  =  0.0000E+00   JPTS0 =256


CONFORMAL MAPPING:

  MCM   =127            ERRCM =  1.0000E-05   TEST  =  9.5836E-06   NITCM =100            ITCM  = 67


EQUILIBRIUM:

  EPS   =  0.0000E+00   DEL   =  1.2080E-01   IINT  =100            JPTS  =128            MHARM = 20
  A     =  3.5294E+00   B     =  4.4606E-01   ELL   =  1.4492E+00   ERROR =  1.0000E-06   NIT   = 25
  Q0W   =  5.7513E-01   BETA0W=  1.7084E+00   ELONG =  1.3892E+00   AMSQER=  8.8839E-07   IT    = 11
  Q1W   =  1.8561E+00   BETAAW=  5.6560E-01   AREA  =  5.3066E+00   ABSER = -1.1537E-07   PVOLAR=  1.0000E+00
  QSW   =  9.5810E-01   EBETPL=  4.5446E-01   VOLUME=  3.3342E+01   BPOLIN=  1.1297E+00   AEFF  =  5.7538E-01   LI    =  8.4960E-01


GLOBAL STABILITY:

  WALL  =  1.5000E+00   QSTAR1=  1.7060E+00   QSTAR2=  1.7060E+00   NQSTAR=  1
  M1    =-15            M2    = 15            NN    = 10            LE    =  2            NEV   =  1

  QSTAR =  1.7060E+00   Q00   =  1.0241E+00   Q11   =  3.3050E+00   BET0OE=  5.3884E-01   BETAOE=  1.7839E-01   OMSQ  =  2.5542E-03


PLOT: P45D-, 32

APHI=  0.0000E+00

PLOT: P45D-, 33

PLOT: P45D-, 34
      DATA WRITTEN ON FILE DHBT
      (IN ADDITION)


PROGRAM HBT
```

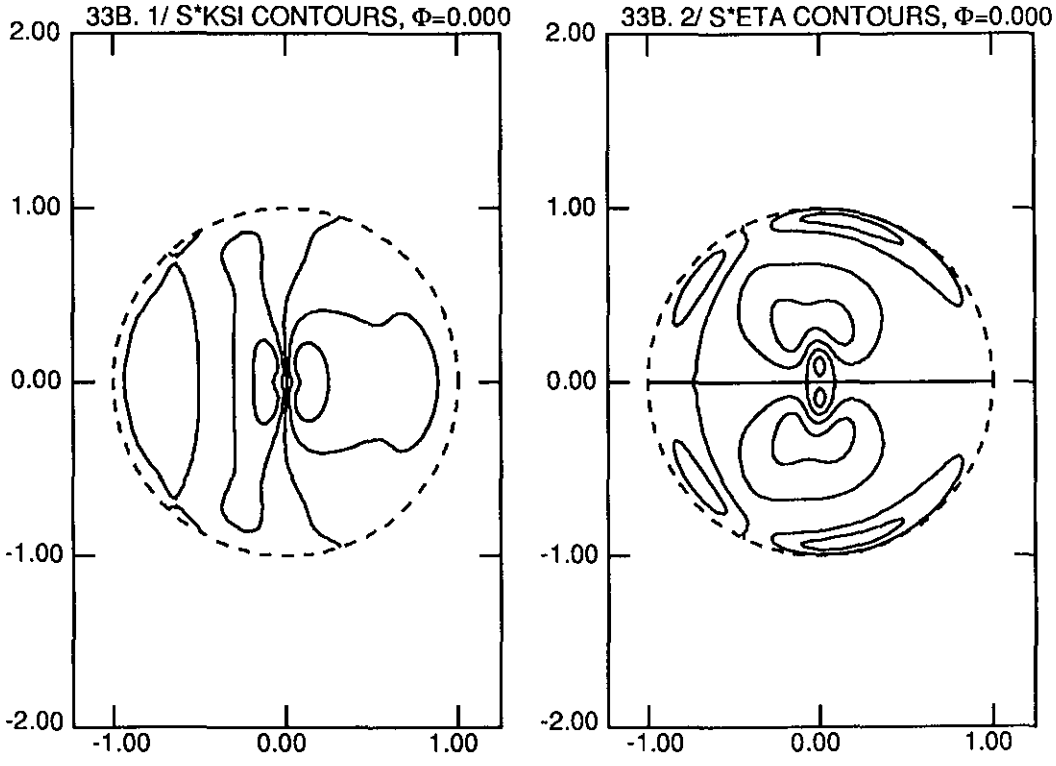
SHOT #20272, T=52.5S,IDENTC FIT
32B. ZETA CONTOURS



90-03-26
11:18:51

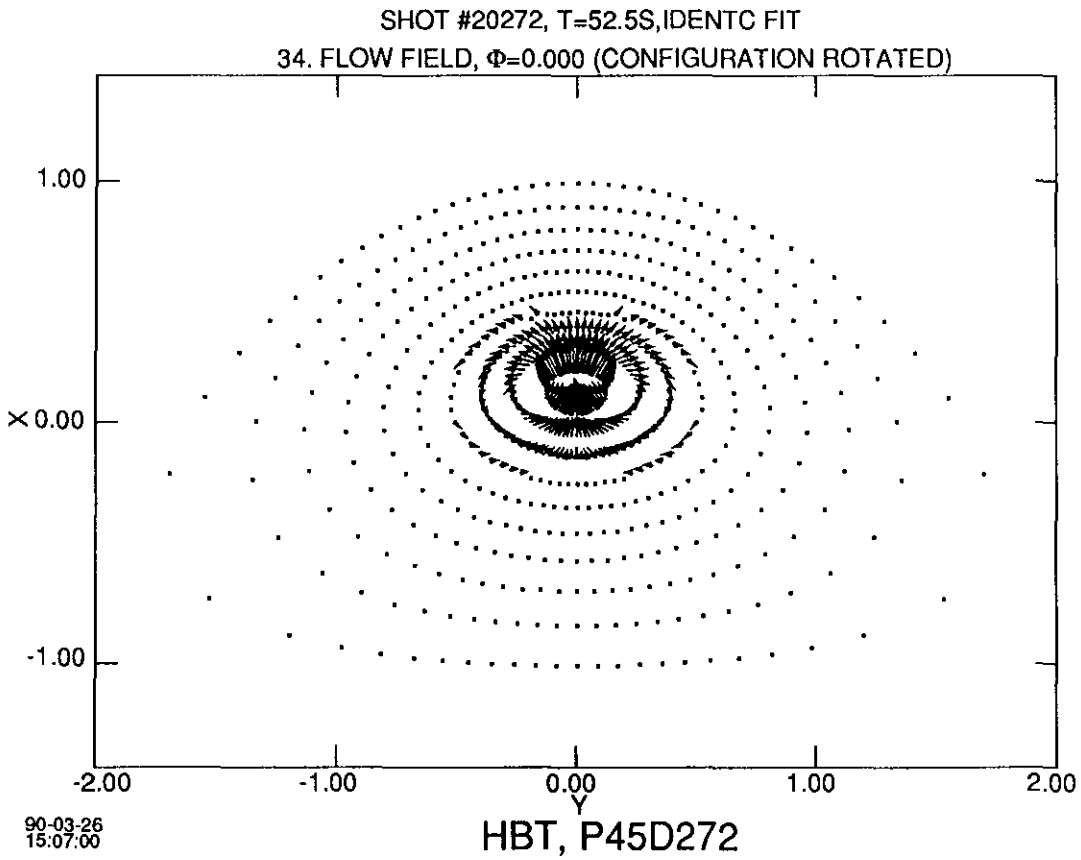
HBT, P45D272

SHOT #20272, T=52.5S,IDENTC FIT



90-03-26
11:18:51

HBT, P45D272


SHOT #20272, T=52.5S,IDENTC FIT
34. FLOW FIELD, Φ=0.000 (CONFIGURATION ROTATED)
1.00
X 0.00
-1.00
-2.00
-1.00
0.00
1.00
2.00
Y
90-03-26
15:07:00
HBT, P45D272

APPENDIX G:
INPUT OF SPLINE INPUT DATA IN HBT

To facilitate the input of profiles and plasma cross-sections which are only known at a discrete set of values, HBT and HBTAS can read input files containing the B-spline coefficients of the spline interpolation of the discrete data points. For the interpolation of the data points and the creation of the input files for HBT(AS) a separate program SPLINE is provided.

The input file with the discrete data points which is read by SPLINE must have the data ordered into two columns. For the equilibrium profiles, the first column must contain the normalized flux (see Eq. (2.4)), the column must contain the value of the specific profile. The range over which ψ must be specified is $0 \leq \psi \leq 1$, but it is advisable to specify a larger range, since ψ can become larger than 1 during the equilibrium iteration. To specify the plasma shape, the first column must contain a poloidal angle in degrees, where $\theta = 0$ corresponds to the outboard midplane of the torus. The second column must contain the radius of the plasma boundary measured from the geometric center of the plasma. The range of θ must be at least $0 \leq \theta \leq 360$. The first six lines of the input file are not read by the program SPLINE and can be used for comments. The listing of SPLINE is given below.

```
      PROGRAM SPLINE
C-----------------------------------------------------------------
C  CALCULATES THE SPLINE COEFFICIENTS OF AN ARRAY OF DATA-
C  POINTS (INTERPOLATION/FIT)  USING THE NAG ROUTINE E02BAF
C  AND WRITES THE OUTPUT TO A FILE READABLE BY HBT
C         INPUT DATA READ FROM  : SPLDATA   TAPENO : 31
C         OUTPUT WRITTEN TO     : SPLINE    TAPENO : 13
C-----------------------------------------------------------------
      REAL*8 PSI(100),PRES(100),W(100),ZK(100)
      REAL*8 WORK1(100),WORK2(4,100)
      REAL*8 C(100),SS
      INTEGER NPOINTS,NCAP7,IFAIL
      DATA (W(I),I=1,100)/100*1./

      OPEN(31,FILE='SPLDATA')
      OPEN(13,FILE='SPLINE')

      DO 30 I=1,6
        READ(31,*)
   30 CONTINUE
      I=1
   40 READ(31,*,END=50) PSI(I),PRES(I)
      WRITE(*,*) PSI(I),'     ',PRES(I)
      I=I+1
      GOTO 40
   50 CONTINUE
      NPOINTS = I-1
      WRITE(*,*) 'INTERPOLATION OR FIT ?   <I=1,F=2>'
      READ(*,*)  NFIT
      IF (NFIT.EQ.2) THEN
        WRITE(*,*) 'NUMBER OF KNOTS ?'
        READ(*,*) NKNOT
        DO 52 I=1,NKNOT
```

```
      WRITE(*,*) ' KNOT NUMBER  ',I,' ?'
      READ(*,*) ZK(I+4)
52    CONTINUE
      NCAP7=NKNOT  + 8
    ELSE
      DO 51 I=5,NPOINTS
        ZK(I)=PSI(I-2)
51    CONTINUE
      NCAP7 = NPOINTS + 4
    ENDIF
    IFAIL = 1
    CALL E02BAF(NPOINTS,NCAP7,PSI,PRES,W,ZK,WORK1,WORK2,C,SS,IFAIL)
    IF (IFAIL.NE.0) THEN
      WRITE(*,*) 'SOMETHING  IS WRONG, IFAIL = ',IFAIL
    ELSE
      WRITE(13,*) NCAP7
      DO 55 I=1,NCAP7
        WRITE(13,*) ZK(I)
55    CONTINUE
      DO 60 I=1,NCAP7-4
        WRITE(13,*) C(I)
60    CONTINUE
    ENDIF
999 FORMAT(3X,E10.4,3X,E10.4)
    END
```

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