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INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

INPE-5946-PRE/2088

POLOIDAL FIELD LEAKAGE OPTIMIZATION IN ETE

Carlos Shinya Shibata
Antonio Montes

Trabalho aceito para apresentação no Encontro Brasileiro de Física de Plasmas, 3., Águas de Lindóia, 04-06 de dez. 1995

INPE
SÃO JOSÉ DOS CAMPOS
1996

Publicado por:

Divisão de Ensino e Documentação - DED

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ABSTRACT - A very simple but efficient numerical algorithm is used to minimize the Ohmic coil field leakage into the plasma region of the tokamak ETE. After few iterations the code provides the positions and the currents required for two pairs of compensation coils. Resulting optimum field intensity distribution is presented and commented.

INTRODUCTION

Among the principal issues to be considered in the project of a tokamak, the correct specification of the compensation coils takes an important role. Due to the finiteness of the central Ohmic coil extent, there will always be a field leakage into the plasma region, thus reducing the efficiency of the transformer coupling effect. This leakage, if not adequately corrected, can generate MHD instabilities related to the presence of magnetic islands [1,2] or even inhibite the discharge breakdown. In order to optimize the plasma current induction by reducing this error field in the tokamak ETE [3], a simple but efficient numerical code was written to calculate the position and the current required for the compensation coils. The algorithm is based on the successive minimization process of the average poloidal field over the plasma cross section, and the results obtained are within the tollerance range cited by some authors [4,5].

NUMERICAL ALGORITHM

Considering circular coil loops placed coaxially to the machine major axis, carrying a purely toroidal current I, the generated field will be purely poloidal by symmetry, $\vec{B} = B_r(r,z)\hat{e}_r + B_z(r,z)\hat{e}_z$, and by direct integration of the Ampere's Law the cylindrical components B_r and B_z can be expressed in terms of the complete elliptical integrals. This will be the field due to a single loop coil, while for a realistic configuration with N_c coils, each of them built up by an $N_r \times N_z$ single loop arrangement, the total field is obtained by summing up algebrically the contributions due to all current elements. Denoting by B_{ij} this total field intensity at a given point (r_i, z_j), we can then introduce an average poloidal field over the plasma cross section defined as:

$$<B> = \frac{1}{m \times n} \sum_{i,j} B_{ij} \qquad (i = 1, m;\ j = 1, n)$$

where now the summation is performed over the $m \times n$ points of a rectangular grid covering the center of the plasma column.

Although the code supports up to 5 pairs of fixed coils in addition to the central inductive solenoid, we consider here a simpler configuration, composed by a fixed 2-layers-130-turns Ohmic coil ($I_{\Omega} = 20\,kA/\text{turn}$, $I_{\Omega}^{tot} = 5.2\,MA$), and 2 pairs of "free" compensation coils: the first one at $(r_1, \pm z_1)$ and carrying a current I_1, and the second one at $(r_2, \pm z_2)$ and carrying a current I_2 — this forming the basic configuration (BC). Next, we construct 12 adjacent configurations (AC's) by varying one by one the parameters (r_1, z_1, I_1) and (r_2, z_2, I_2), respectively by small amounts $(\pm\Delta r_1, \pm\Delta z_1, \pm\Delta I_1)$ and $(\pm\Delta r_2, \pm\Delta z_2, \pm\Delta I_2)$. The average poloidal field $<B>$ corresponding to each of these perturbed configurations is then compared to that calculated for the initial configuration; the compensation coil arrangement that has generated the minimum-$<B>$ is taken as being the new BC. This process is continued until all the 12 AC's result in values for $<B>$ greater than that for the BC - and so a local minimum-$<B>$ configuration is found. Successive simulations showed that the number of iterations required for stabilization and the attained final configuration depend strongly on the initial conditions and on the sizes of the perturbations (i.e, on the distances from BC to the AC's).

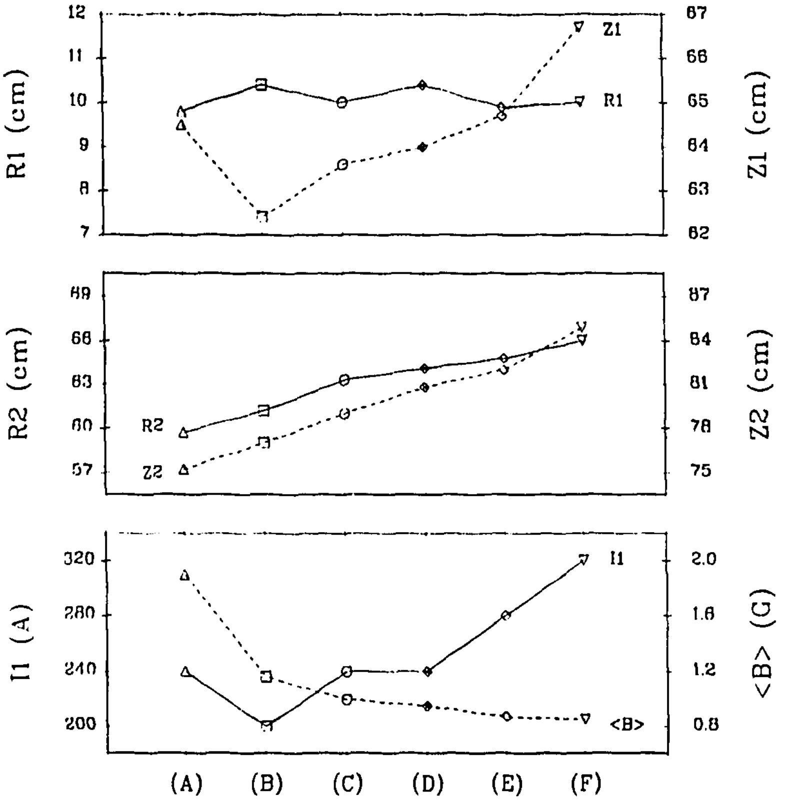

Figure 1. Parameters relative to 6 different final stages of local minimum-$<B>$ configurations.

RESULTS AND COMMENTS

Applying the code for six different but close initial conditions, a set of six local minimum-$<B>$ configurations were obtained. In all these iteration processes, the step-sizes in coil coordinates $(\Delta r, \Delta z)$ were kept fixed to 1 mm, and the perturbations in the current were $\Delta I = 20\,kA$, which is the designed value of the current per turn for the experiment. The final stages for these six configurations are shown in Figure 1, denoted by (A) to (F) and represented by different symbols. Comparison between the top and the middle frames indicates a greater displacement of the compensation coil #2. From the last frame it is clear that this outward going tendency of the coil #2 is accompanied by successive increasing of the current intensity in the compensation coil #1, and that all these effects combined provide a sequence (A) → (F) of improving minimum-$<B>$ configurations.

Next, we concentrate our focus on the configuration (F), which corresponds to the arrangement with an $(N_r \times N_z) = (2 \times 130)$ turns Ohmic coil, plus the compensation coil #1 (CC1) with (2×8) turns coil at $r_1 = 10.0\,cm, z_1 = \pm 66.7\,cm$, and the compensation coil #2 (CC2), a (2×1) turns coil at $r_2 = 66.0\,cm, z_2 = \pm 84.9\,cm$. The current in all the coils is $I = 20\,kA/\text{turn}$, so, $I_1^{tot} = 320\,kA$ and $I_2^{tot} = 40\,kA$. Among the cases considered before, this is the one providing the best result, $<B> = 0.85\,G$. Then, in order to analyse the effect of any small perturbation on the field intensity distribution in the plasma region, 8 configurations around (F) were considered by shifting the CC1 radial coordinate each time by an amount of only 1mm, to both sides. The resulting $<B>$ values are given in the Table 1, which shows increasing values of the averaged error field as CC1 is moved away from the configuration (F), reproduced as the case #4. This fact is also confirmed by the constant-$|\vec{B}|$ curves sequence in Figure 2, where it is evident the rapid degeneration of the leakage field compensation due to small radial displacements in CC1.

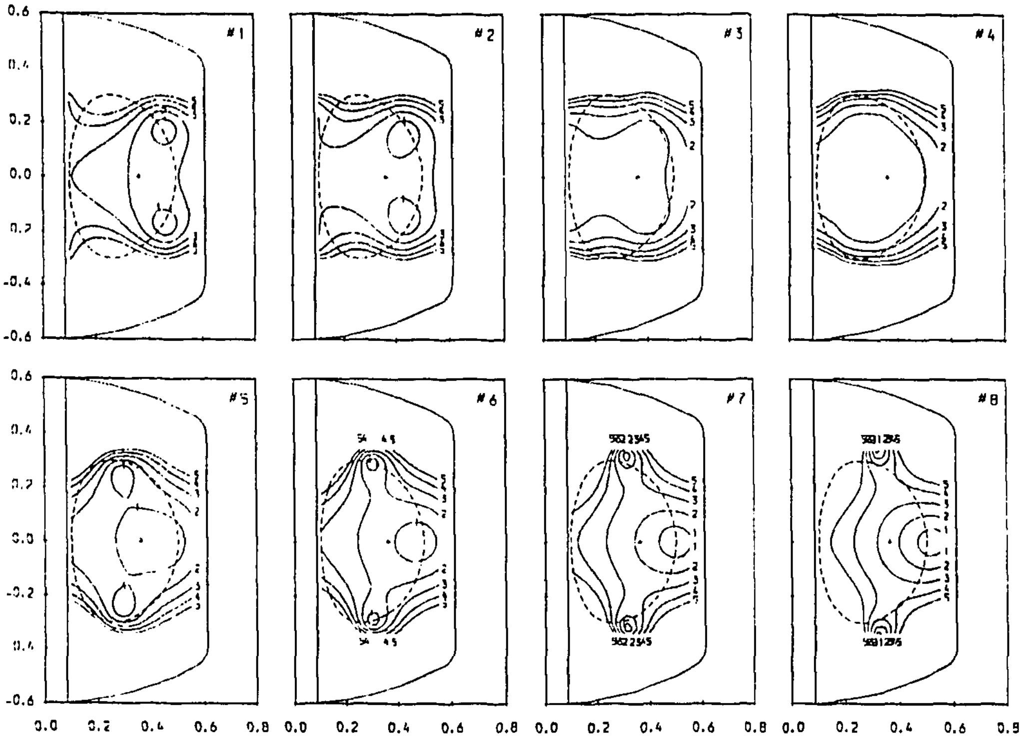

Figure 2. Constant-$|\vec{B}|$ curves for the sequence given in Table 1; case ♯4 correponds to the configuration (F) in Fig.1.

A more detailed view of the configuration (F) is given in Figure 3: the left frame shows the constant poloidal flux contours, whereas the right picture is the same of the case ♯4 in Figure 2; notice the high order null with $|\vec{B}| \leq 2.0\,G$ around the magnetic axis. The effectiveness of the optimized compensation coils becomes more evident from the radial profiles (at z=0) of the uncompensated (Ohmic coil only) and compensated magnetic fields, given in Figure 4.

Since ETE is expected to operate at $B_o \simeq 4kG$, one has for the later case the ratio $<B>/B_o \simeq 2.5 \times 10^{-4}$, which is within the admissible range cited in the literature [1,2]. Furthermore, despite the simplicity of the compensation coils arrangement, the results obtained here are as good as those found in other spherical tokamak designs with more sophisticated coil arrangements [4,5], thus demonstrating the usefullness of the code.

Case	CC1 r (cm)	CC1 z (cm)	$<B>$ (G)
♯ 1	9.70	± 66.70	4.73
♯ 2	9.80	± 66.70	3.08
♯ 3	9.90	± 66.70	1.53
♯ 4	10.00	± 66.70	0.85
♯ 5	10.10	± 66.70	2.37
♯ 6	10.20	± 66.70	4.11
♯ 7	10.30	± 66.70	5.89
♯ 8	10.40	± 66.70	7.69

Tab.1 - Error fields for slightly perturbed configurations around (F).

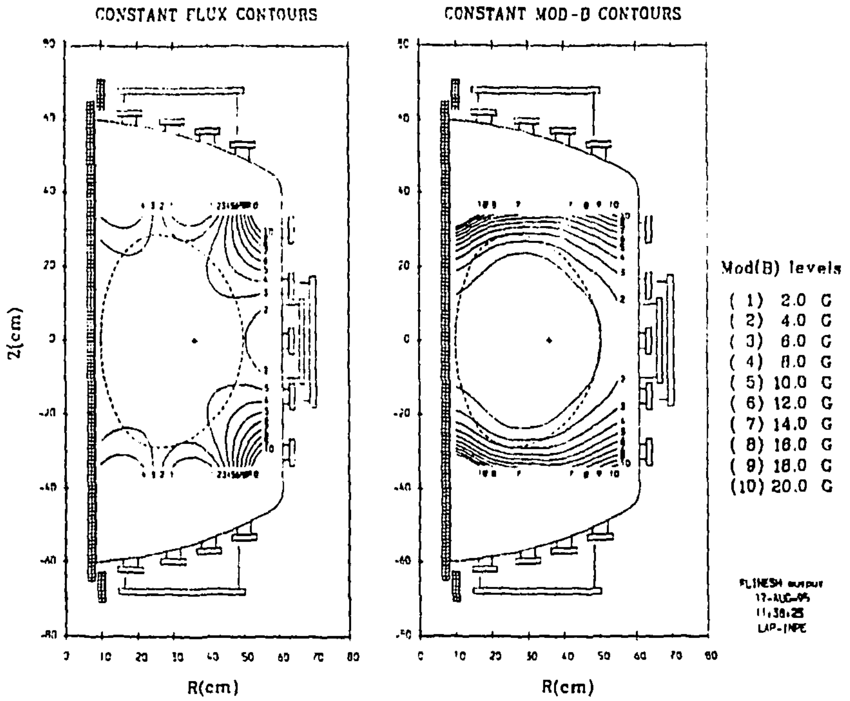

Figure 3. Constant poloidal flux and constant-$|\vec{B}|$ contours for the optimum configuration (F).

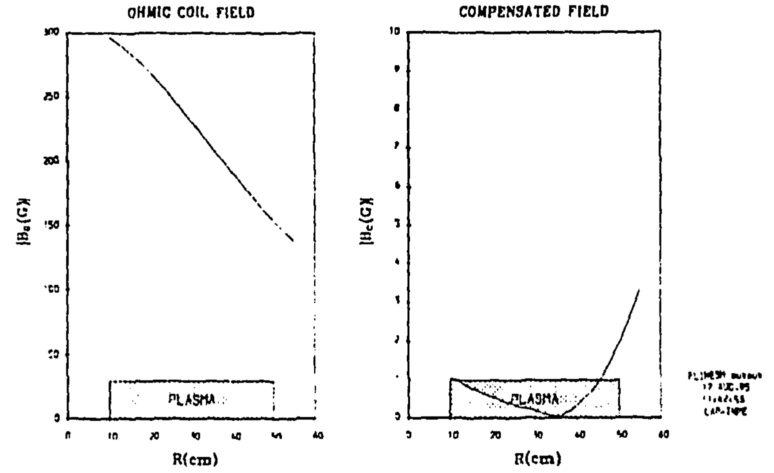

Figure 4. Ohmic (left) and compensated (right) field radial profiles.

REFERENCES

[1] Morris, A.W. *Plasma Phys. Contr. Fusion* 34 (1992) 1871.

[2] Todd, T.N. *"How to build a tokamak"*, in: *"Plasma Physics - An Introduction Course"*. R.O Dendy (Editor), Cambridge University Press, 1993.

[3] Ludwig, G.O. *et el*, this proceedings.

[4] Menard, J. *et al*, *"Ohmic heating error field correction in CDX-U with application to PSTX"*. 35th APS-DPP Meeting, Nov. 1993, St. Louis, Missouri.

[5] McCool, S.C. *et al*, *"The USTX Proposal"*. University of Texas at Austin, Fusion Research Center Report ‡468, May 1995, Austin, Texas.

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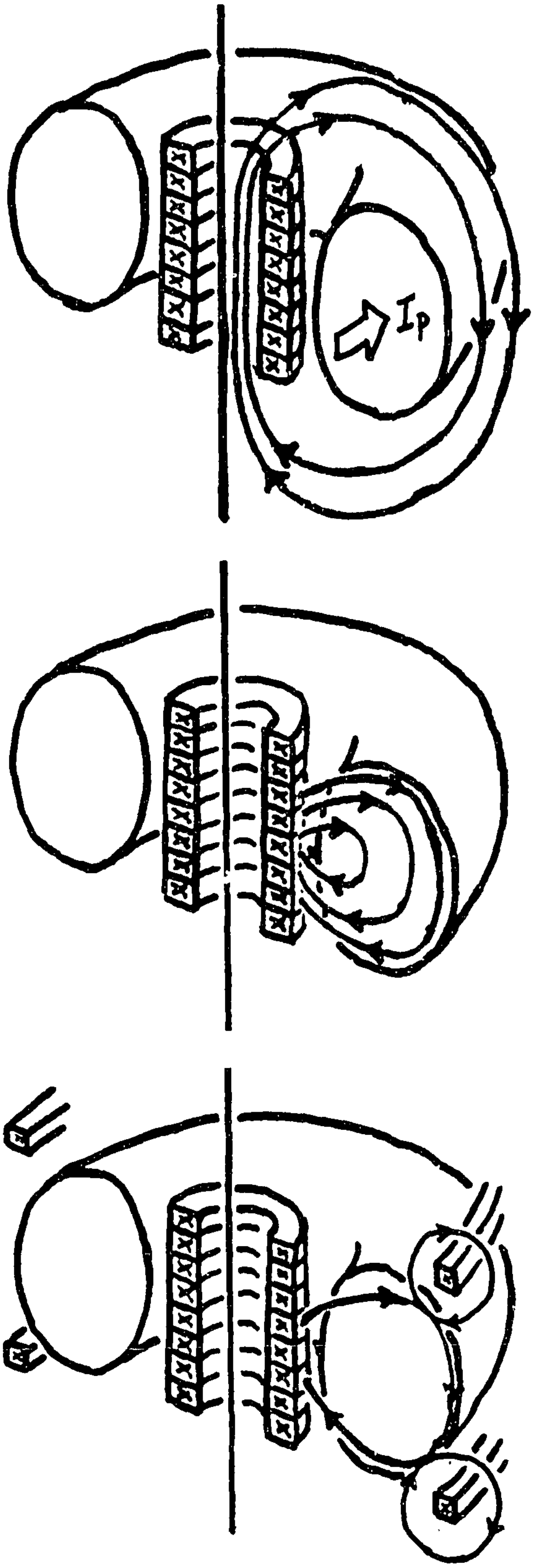
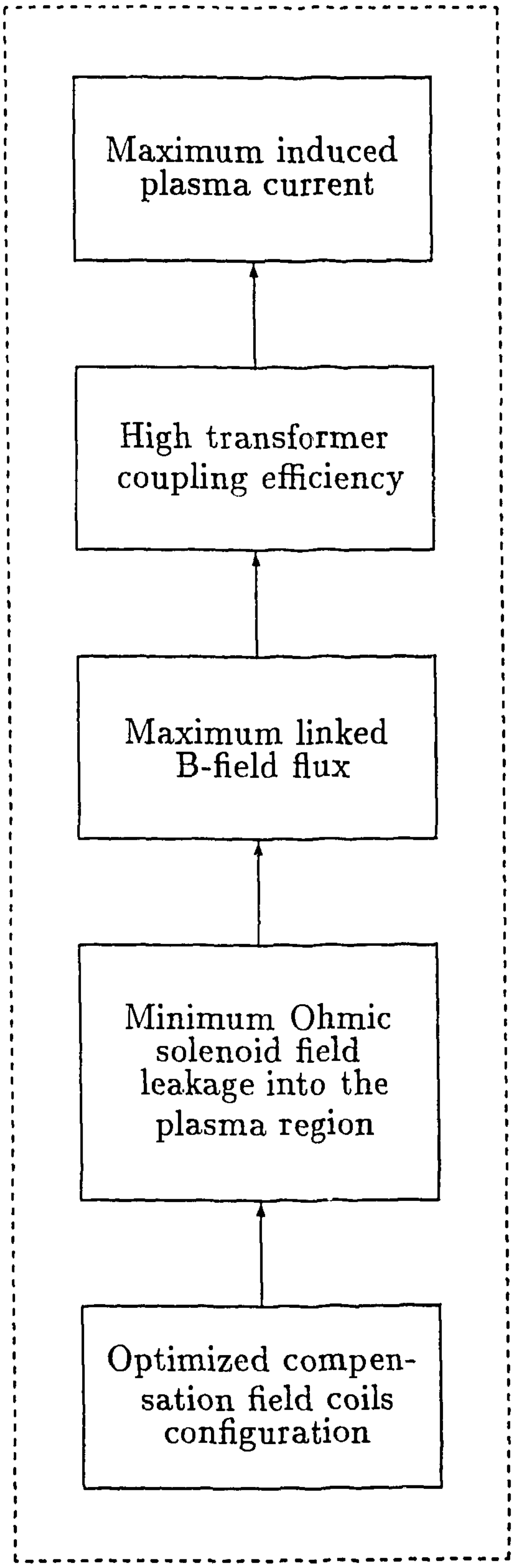
OBJECTIVE



Tokamak ETE Project



Maximum induced plasma current

High transformer coupling efficiency

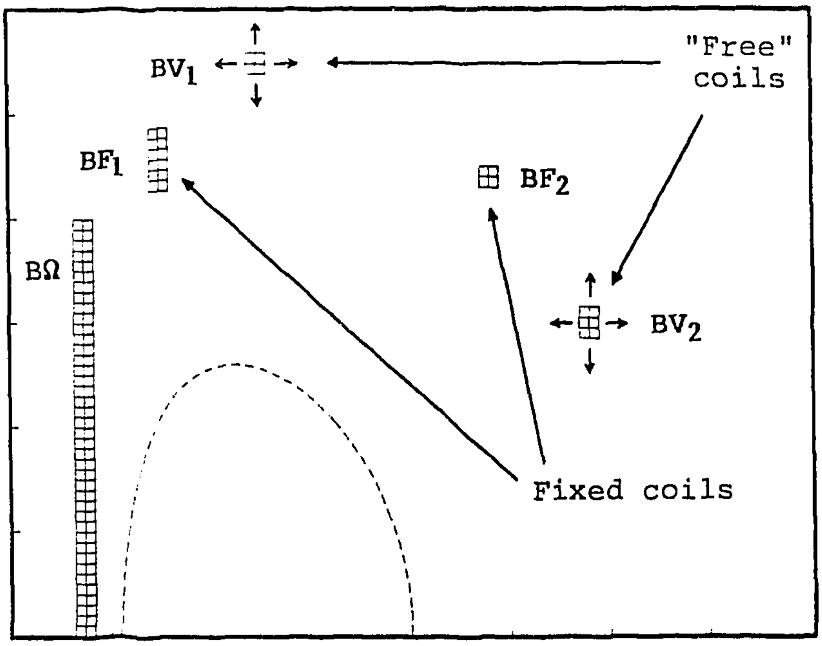
Maximum linked B-field flux

Minimum Ohmic solenoid field leakage into the plasma region

Optimized compensation field coils configuration

MAGNETIC FIELD COIL CONFIGURATIONS

- COILS



- BASE CONFIGURATION (BC)

BC: $B_\Omega + [BF_1 + \cdots + BF_5] + [BV_1(R_1, Z_1, I_1) + BV_2(R_2, Z_2, I_2)]$

- "PERTURBED CONFIGURATIONS" (PC's)

PC1: $B_\Omega + [BF_1 + \cdots + BF_5] + [BV_1(R_1 + DR_1, Z_1, I_1) + BV_2(R_2, Z_2, I_2)]$

PC2: $B_\Omega + [BF_1 + \cdots + BF_5] + [BV_1(R_1 - DR_1, Z_1, I_1) + BV_2(R_2, Z_2, I_2)]$

PC3: $B_\Omega + [BF_1 + \cdots + BF_5] + [BV_1(R_1, Z_1 + DZ_1, I_1) + BV_2(R_2, Z_2, I_2)]$

PC4: $B_\Omega + [BF_1 + \cdots + BF_5] + [BV_1(R_1, Z_1 - DZ_1, I_1) + BV_2(R_2, Z_2, I_2)]$

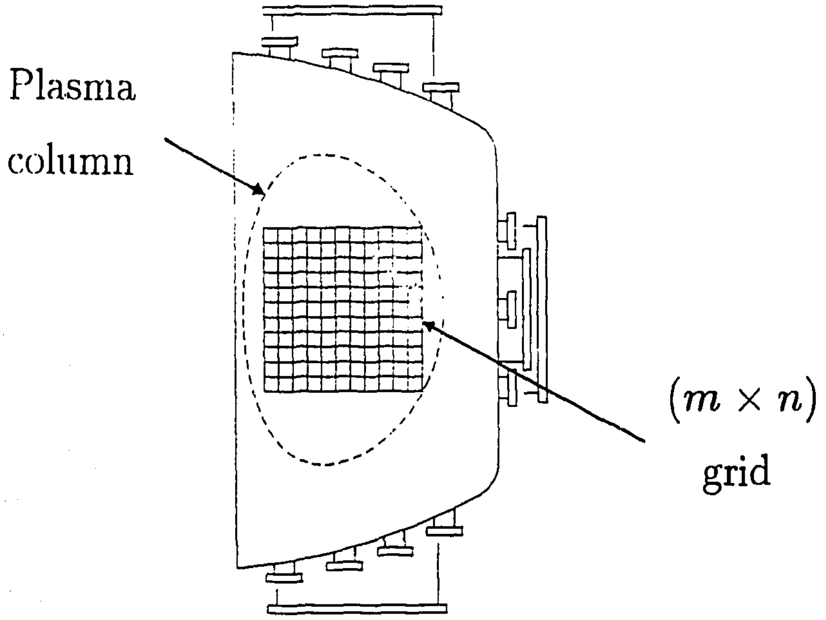
……

PC11: $B_\Omega + [BF_1 + \cdots + BF_5] + [BV_1(R_1, Z_1, I_1) + BV_2(R_2, Z_2, I_2 + DI_2)]$

PC12: $B_\Omega + [BF_1 + \cdots + BF_5] + [BV_1(R_1, Z_1, I_1) + BV_2(R_2, Z_2, I_2 - DI_2)]$

NUMERICAL ALGORITHM

- AVERAGE MAGNETIC FIELD

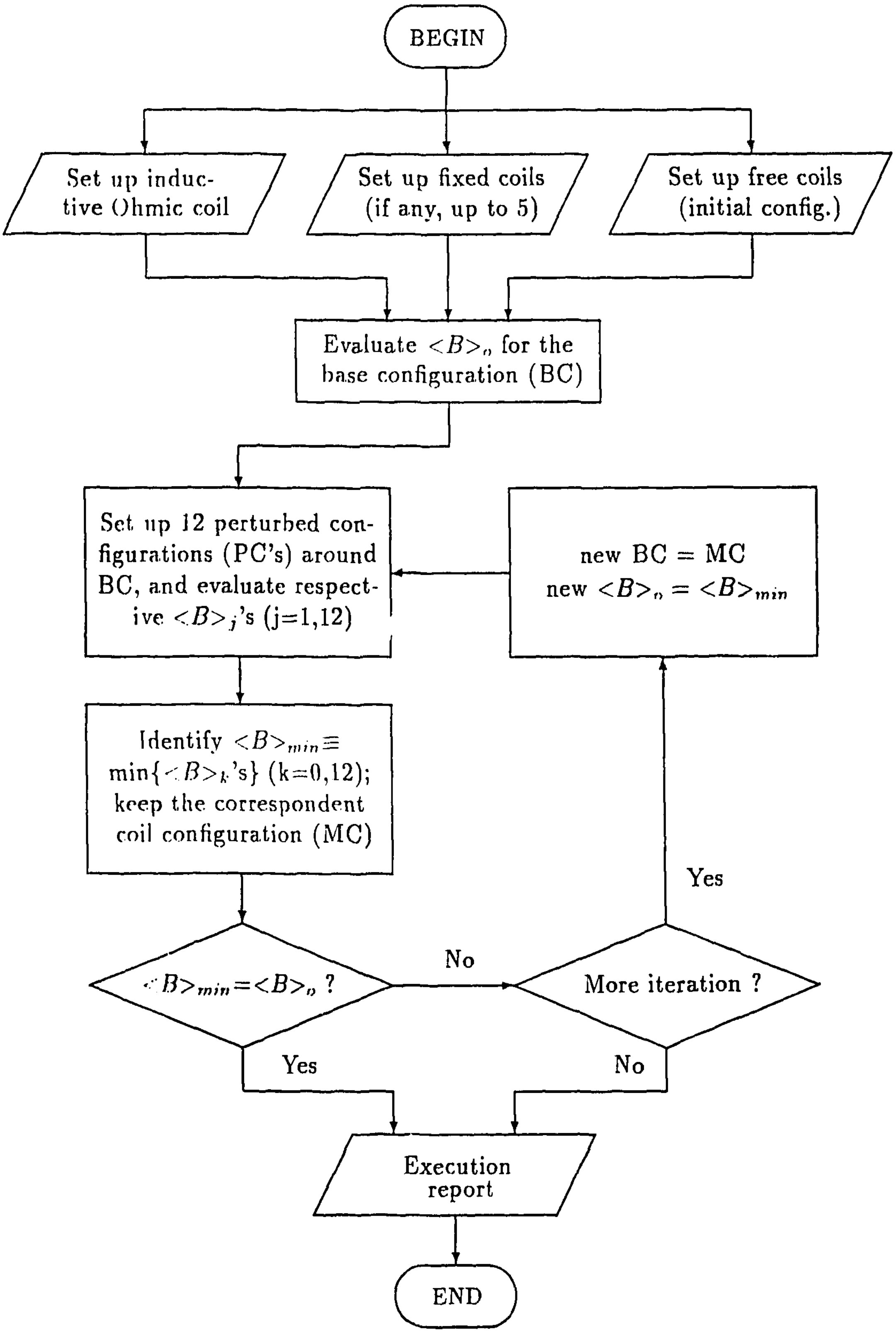


$$<B> = \frac{1}{m \times n} \sum_{\mathrm{i,j}} B_{ij} \qquad (i = 1, m;\ j = 1, n)$$

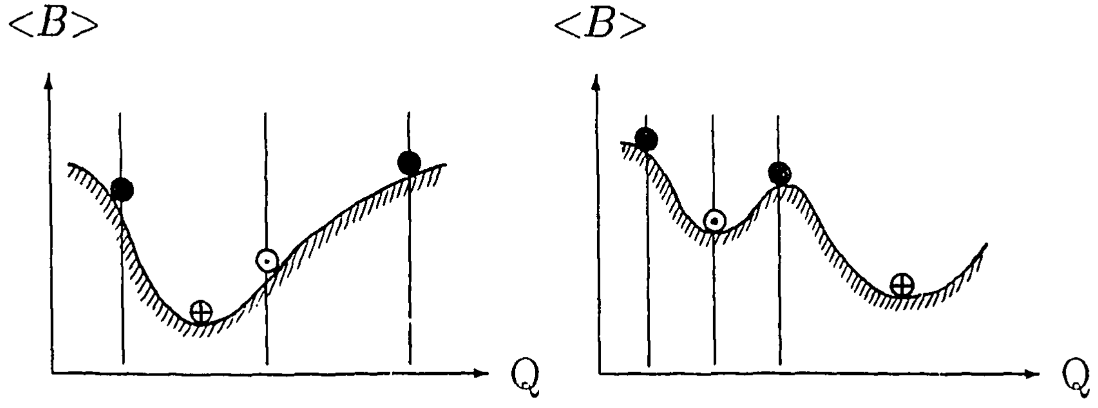
$$B_{ij} = \sqrt{B_r^2(r_i, z_j) + B_z^2(r_i, z_j)}$$

where $B_{r,z}^2(r_i, z_j)$ are the field components on the grid point (r_i, z_j) due to *all coils* (Ohmic + correction).

- $<B>$-MINIMIZATION PROCESS



• STEP-SIZE EFFECTS



ΔQ too big ΔQ too small

⊙ trying points ⊙ detected (false) minimum ⊕ actual minimum

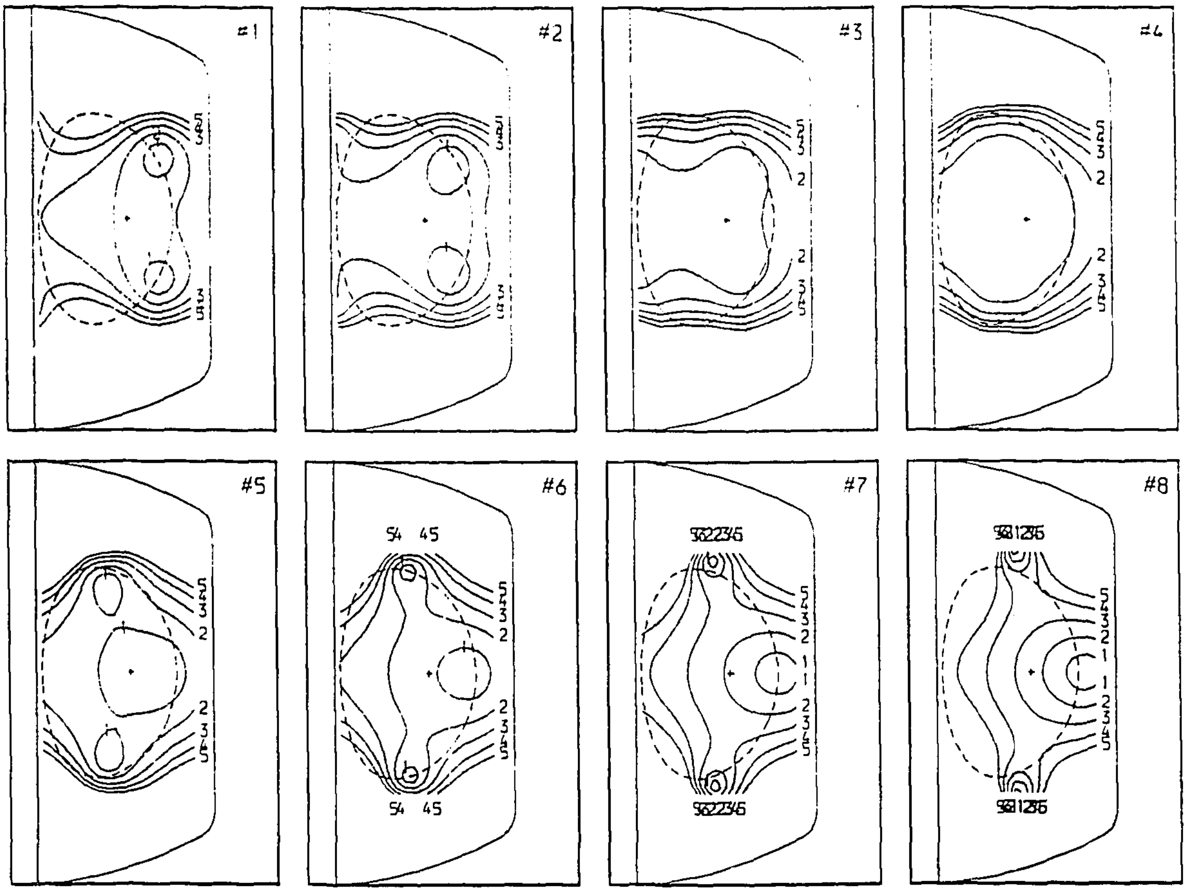
• SAMPLE RUN OUTPUT

```
-----------------------------------------------------------------
     Initial configuration -
     *  free  coil #1:  R = 10.0 cm,  Z = (+-) 70.0 cm,  I =300.0 kA
     *  free  coil #2:  R = 60.0 cm,  Z = (+-) 80.0 cm,  I = 80.0 kA
INIT CONFIG: (R=10.0, Z=70.0, I= 300.0) (R= 60.0, Z= 80.0, I= 80.0)  [cm,cm,kA]
   1  I2 low (R=10.0, Z=70.0, I= 300.0) (R= 60.0, Z= 80.0, I= 40.0) <B>=12.43 G
   2  I1 hgh (R=10.0, Z=70.0, I= 340.0) (R= 60.0, Z= 80.0, I= 40.0) <B>= 3.49 G
   3  Z2 dwn (R=10.0, Z=70.0, I= 340.0) (R= 60.0, Z= 79.9, I= 40.0) <B>= 3.26 G
   4  Z2 dwn (R=10.0, Z=70.0, I= 340.0) (R= 60.0, Z= 79.8, I= 40.0) <B>= 3.04 G
   5  Z1 dwn (R=10.0, Z=69.9, I= 340.0) (R= 60.0, Z= 79.8, I= 40.0) <B>= 2.85 G
   6  Z1 dwn (R=10.0, Z=69.8, I= 340.0) (R= 60.0, Z= 79.8, I= 40.0) <B>= 2.66 G
   7  Z1 dwn (R=10.0, Z=69.7, I= 340.0) (R= 60.0, Z= 79.8, I= 40.0) <B>= 2.49 G
   8  Z1 dwn (R=10.0, Z=69.6, I= 340.0) (R= 60.0, Z= 79.8, I= 40.0) <B>= 2.33 G
   9  Z1 dwn (R=10.0, Z=69.5, I= 340.0) (R= 60.0, Z= 79.8, I= 40.0) <B>= 2.19 G
  10  Z1 dwn (R=10.0, Z=69.4, I= 340.0) (R= 60.0, Z= 79.8, I= 40.0) <B>= 2.08 G
  11  Z1 dwn (R=10.0, Z=69.3, I= 340.0) (R= 60.0, Z= 79.8, I= 40.0) <B>= 2.02 G
  12  NoChng (R=10.0, Z=69.3, I= 340.0) (R= 60.0, Z= 79.8, I= 40.0) <B>= 2.02 G
-----------------------------------------------------------------
     Stable configuration found after  12 tries
     Final configuration -
     *  no fixed coils
     *  free  coil #1:  R = 10.0 cm,  Z = (+-) 69.3 cm,  I =340.0 kA
     *  free  coil #2:  R = 60.0 cm,  Z = (+-) 79.8 cm,  I = 40.0 kA
     Local minimum-<B> =  2.02 G
-----------------------------------------------------------------
```

RESULTS FOR ETE

- EFFECTS OF SMALL PERTURBATIONS

Exemple: slight modifications in the compensation coil radius.



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♯ 3	9.90	± 66.70	1.53
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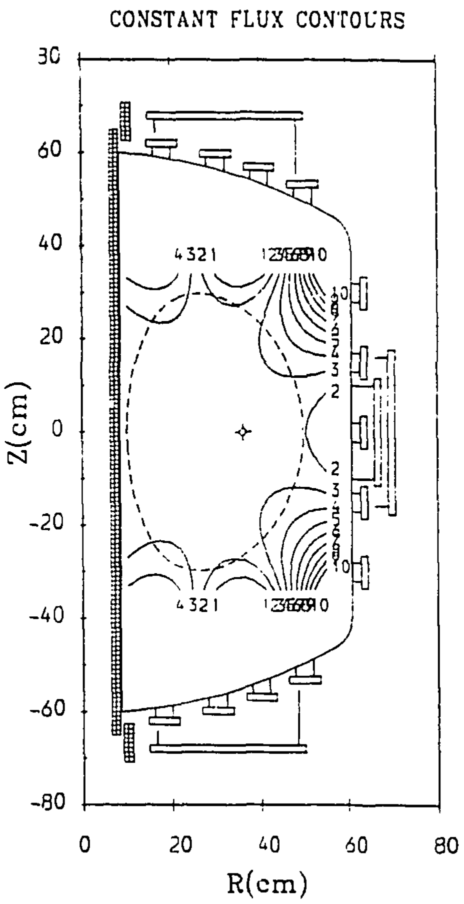
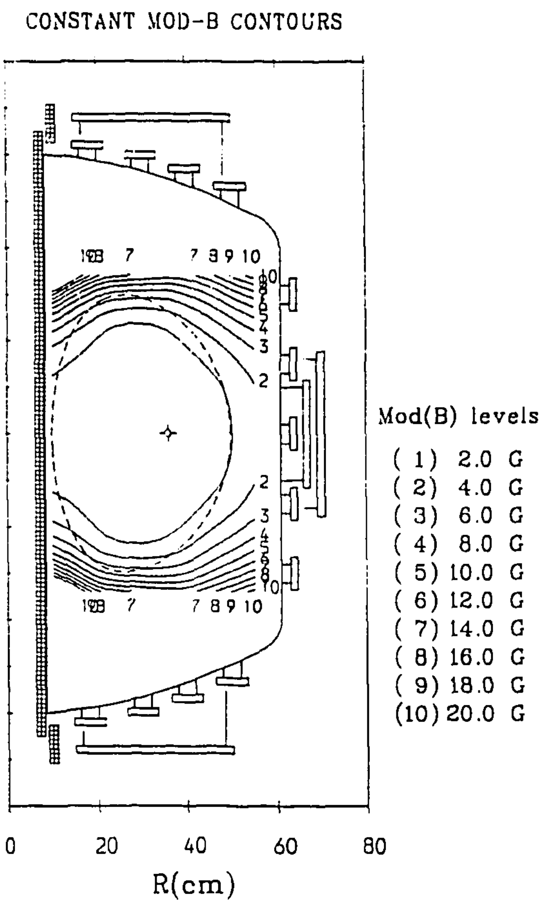
♯ 6	10.20	± 66.70	4.11
♯ 7	10.30	± 66.70	5.89
♯ 8	10.40	± 66.70	7.69

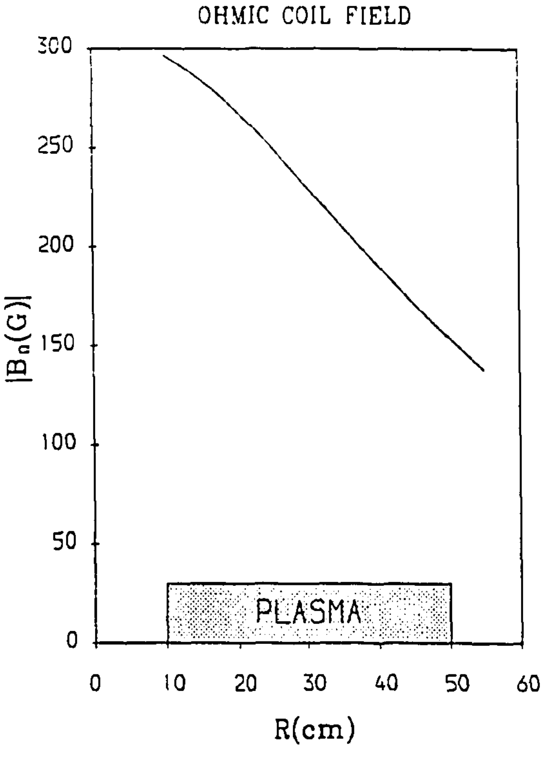
• BEST CONFIGURATION



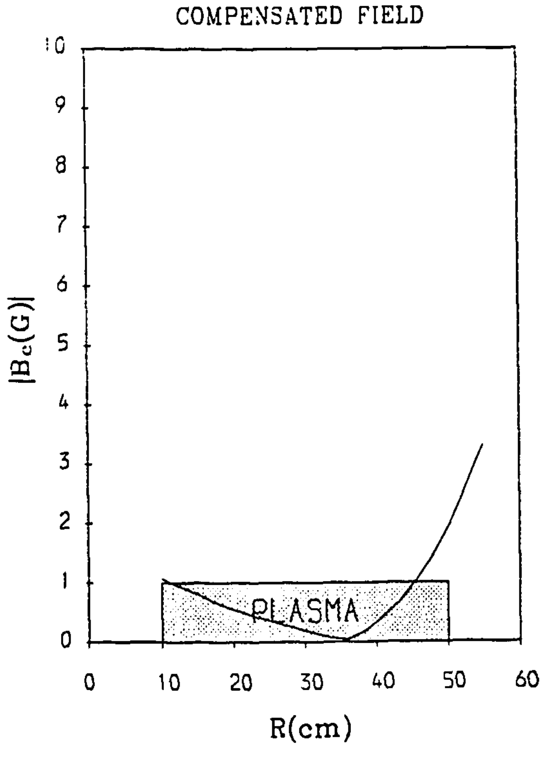
CONSTANT FLUX CONTOURS



CONSTANT MOD-B CONTOURS



OHMIC COIL FIELD



COMPENSATED FIELD

CONCLUDING REMARKS

The usefullness of the code is assured by the following issues:

- **The code is simple**: just some algebric expression evaluations are involved (B_r, B_z and $<B>$).

- **The code is transparent**: it provides a run-time report of the $<B>$-minimization process in course.

- **The code is efficient**: obtained minimim-$<B>$ value is within the admissible range cited in the literature –

  $$\frac{<B>}{B_o} \sim 2.5 \times 10^{-4} \qquad \left\{ \begin{array}{ccl} <B>_{min} & \simeq & 0.85 \; G \\ B_o & \simeq & 4.0 \; kG \; (ETE) \end{array} \right.$$

  $(<B> / B_o) \ll 10^{-3}$ [T.N.Todd, "How to build a tokamak"]
  $(<B> / B_o) < 10^{-5}$ [A.W.Morris, PP&CF 34 (1992) 1871]

- **The code is reliable**: the final compensation coils arrangement (position and current) agrees well to that obtained by a purely analytical procedure [G.O.Ludwig, private communication].

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