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ABSTRACT

This paper presents the results of calculations on the forces acting on each coil of the ATLAS Barrel Toroid, with the presence of the End Cap Toroids, the Solenoid and the Tilecal iron yoke.

The aim of these calculations, made by using an analytical 3D code and finite elements 2D and 3D codes, is the knowledge of the intensity and the distribution of the forces in the coil of the Barrel Toroid in order to reproduce the same situation in the test coil B0 by means of suitable blocks of iron installed around the coil (magnetic mirror). A few iron configurations for the magnetic mirror are presented and the resulting forces are compared with the forces on the Barrel Toroid. The iron configuration with the highest performance/cost ratio is proposed.

1. - INTRODUCTION

The L.A.S.A. (Laboratorio Acceleratori e Superconductività Applicata) is involved in the ATLAS Collaboration for the design and construction of the model of a superconducting coil of the main magnet of the detector. The model, called B0, has several purposes, like to verify the

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1. - INTRODUCTION

The L.A.S.A. (Laboratorio Acceleratori e Superconductività Applicata) is involved in the ATLAS Collaboration for the design and construction of the model of a superconducting coil of the main magnet of the detector. The model, called B0, has several purposes, like to verify the design choices, the construction capabilities, the operational behaviour of the large superconducting coil. Among these purposes, there is the test of the B0 magnet by reproducing, if possible, the same force distribution existing in the Barrel Toroid when the whole magnet system is in operation.

In order to achieve this goal a suitable distribution of iron blocks is foreseen in the lower side of the B0 coil. These iron blocks act as a magnetic mirror and can produce an external force whose intensity and distribution is very similar to the one acting on the Barrel Toroid coils.

As a first step, the calculation of the forces acting on the Barrel Toroid coils has been carried out by assuming the up to date geometry and a perfect symmetry of the whole magnet system. In a second step the B0 coil with different magnetic mirrors has been considered in order to find the best performance/cost ratio.

The calculations have been carried out with analytical 3D codes and difference and finite element 2D and 3D codes in order to have in some cases a cross check of the results.

2. - MAIN PARAMETERS OF THE MAGNET SYSTEM AND CALCULATION APPROACH

The magnet system consists of 3 superconducting toroids in air and 1 superconducting thin solenoid with an iron yoke (Fig. 1).

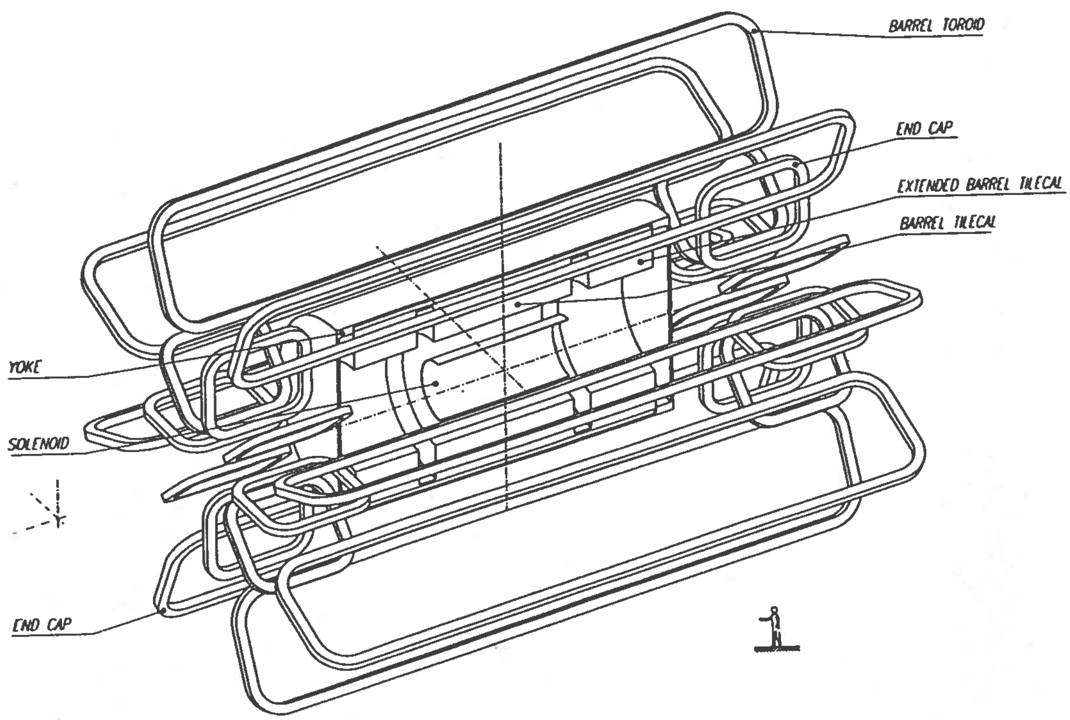

FIG 1 - Magnet system of ATLAS

Each toroid consists of eight flat coils assembled radially and symmetrically around the beam axis. The first toroid, called Barrel Toroid (in the following referred as BT) has 8 coils with a length of about 25 m and an overall diameter of about 20 m. The Table 1 shows the main parameters of the BT coils [(1)].

TABLE 1 - Main parameters of the BT coils

	Warm	Cold
Innermost radius of innermost conductor edge (m)	4.876	4.878
Outermost radius of outermost conductor edge (m)	9.854	9.836
Longitud. pos. of most forward conductor edge (m)	12.474	12.422
Radius of curvature of conductor (inner) (m)	1.000	0.996
Conductor width with insulation (mm)	57.8	57.57
Conductor height with insulation (mm)	12.8	12.75
Insulation thickness between neighb. pancakes (mm)	0.5	~0.5
Central plate thickness (mm)	52	51.8
Number of turns	2x2x30	2x2x30
Operating current (A)		20500

Two End Cap Toroids (in the following ECTs) are inserted in the barrel at each end of the BT. They have a length of about 4.4 m and an inner bore of 2.4 m and an outer diameter of about 10 m. The ECT coils are rotated by an angle of 22.5^{o} with respect to the BT coils. The main geometrical and physical parameters of the ECT coils are summarized in the Table 2 [(1)].

TABLE 2 - Main parameters of the ECT coils

	Warm	Cold
Innermost radius of innermost conductor edge (m)	1.210	1.205
Outermost radius of outermost conductor edge (m)	5.009	4.988
Longitud. position of most inward conductor edge (m)	7.955	7.959
Longitud. position of most forward cond. edge (m)	12.305	12.291
Radius of curvature of conductor (inner) (m)	0.6	0.5985
Conductor width with insulation (mm)	41.5	41.33
Conductor height with insulation (mm)	12.5	12.45
Insulation thickness between neighb. pancakes (mm)	0.5	~0.5
Central plate thickness (mm)	52	51.8
Number of turns	2x2x29	2x2x29
Operating current (A)		20000

In the inner bore of the detector a thin superconducting solenoid is inserted. At 4.5 K, it has a length of 5.3 m, an inner radius of 1.218, an outer radius of 1.250 m and a magnetomotive force of 9.4 MAt (2).

The solenoid is surrounded by the tilecal which can be divided in two parts:

1. The innermost part of the tilecal (the barrel part) has a complex structure, because it is made of solid blocks of iron glued with iron spacers, inside of which the scintillators will be placed. The barrel part has a length of 5.638 m, an inner radius of 2.259 m and an outer radius of 3.86 m. At each end of this structure (0.63 m far from each edge) there are two extended barrel parts, with a length of 2.650 m, same radii of the barrel part and similar material composition.
2. The outermost part of the tilecal consists of two steel support tubes of 12.2 m in length. the first tube has an inner radius of 3.86 m and an outer radius of 3.94 m. The second support tube has an inner radius of 4.13 m and a thickness of 10 cm. The gap between these support tubes will be filled with air or steel with very low stacking factor (~0.17) (2).

The calculation of the forces in the BT coils with 3D code (like TOSCA or MAFIA) requires a very large number of meshes in order to describe in details the complex geometry of the magnet system. For this reason at L.A.S.A. a different approach to the problem has been preferred.

Because the forces on each BT coil are due mainly (~90%) to the BT and ECT coils in air, whereas the contribution of the solenoid and tilecal yoke to the total force is limited to about 10%, these contributions have been calculated separately.

The first contribution, due to the BT and ECT coils in air, has been calculated with an analytical 3D code, developed at L.A.S.A.. The error in this contribution has been valued less than 1%. The second contribution, due to the tilecal yoke, was evaluated by means of the MAFIA code (3D code), by simplifying the description of the magnet system. In this case the error can be of the order of 10%.

As a consequence the forces acting in the BT coils are known with a maximum error of about 2%.

This error level can be accepted in order to carry out an engineering design of the magnets and to simulate the force distribution in the B0 model.

3. - FORCE CONTRIBUTION DUE TO COILS IN AIR

In order to separate the different contributions of the elements which compose the BT and ECT system, the following configurations have been considered:

- single coil of BT;

- whole BT;
- BT + ECTs.

The study of the forces produced by a single coil of BT is useful in order to separate the contributions due to internal and external forces: in fact the configuration of a single coil produces the self-field only, and the coil is subjected to internal forces only. Moreover this study allows to compare the force distribution in the full scale coil in respect to the scaled B0 coil.

For the calculation of the forces a 3D analytical code has been used. It calculates the forces by using the Laplace's formula for linear wires with circular cross section. When the corner of the calculation mesh is inside a wire, the current intensity of this wire is reduced of the factor:

$$k = \frac{\pi \cdot d^2}{S}$$

where d is the distance of the corner from the wire axis and S is the surface of the wire cross section.

Each curved section of the coils (90° span) has been described with 20 chords.

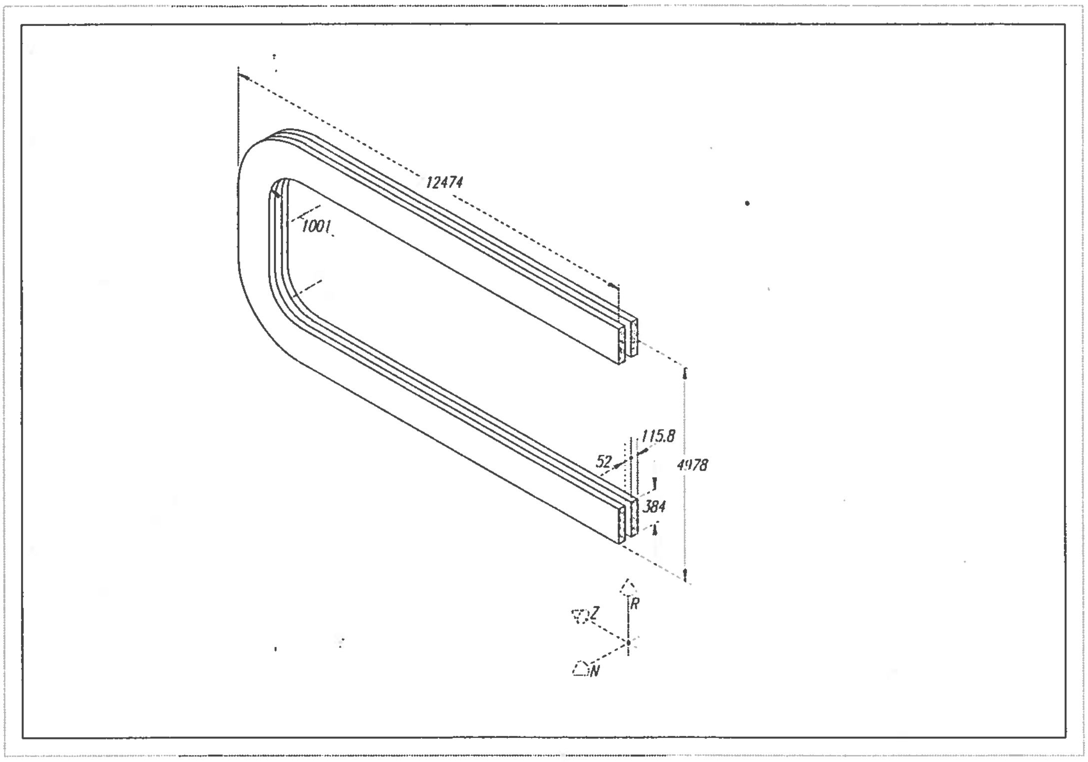

FIG 2 - Coordinate system and symbols used (dimensions at room temperature)

The coordinate system and the symbols used in the presentation of the results are shown in the Fig. 2. In particular the specific forces are presented in the graphs as a function of the length of the path from the centre of the inner long side of the coil up the centre of the opposite side (outer long side).

3.1. - Single coil of BT

The Fig. 3 shows the components of the specific force (the radial component F_R, the axial component F_Z and the modulus of the total specific force $F_T = \sqrt{F_R^2 + F_Z^2}$) for the single coil of the BT.

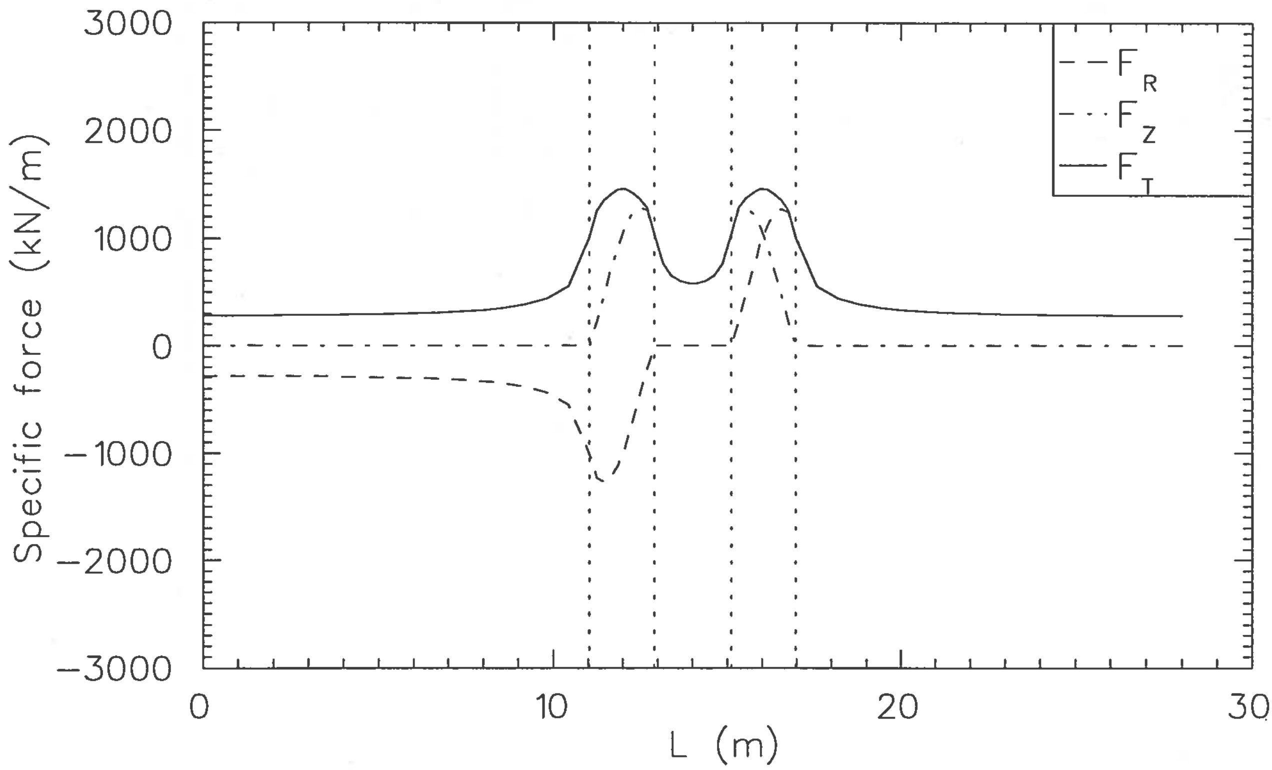

FIG 3 - Specific forces vs. the length measured along half coil of the single BT coil configuration.

The force distribution is symmetric and obviously the net force on the coil is null. The dashed vertical lines in the graph delimit the regions of the round corner of the coils. In this zone the total specific force increases of about a factor 4 (~1250 kN/m) in respect to the force acting on the straight axial side (~275 kN/m). The increment in this region is due to the radial side of the coil and to the circular shape of the corner.

The attractive specific force F_N between the two sections of the coils is about constant (the variation is within ± 2 %) and has an average value of 1210 kN/m (corresponding to a pressure of 0.31 daN/mm^2).

The numerical values of the specific forces are reported in the Table 6.

3.2. - WHOLE BT

The toroidal magnetic field of the whole BT produces on the BT reference coil an increase and a dissymmetric distribution of the specific force, as shown in the Fig. 4. In particular the forces in the inner straight axial side increase from about 280 to about 850 kN/m whereas the ones in the outer side increase only up to about 570 kN/m.

The maximum specific force in the round corner reaches about 1600 kN/m. The attractive force F_N between the two sections is almost unchanged because of the symmetry of the BT configuration: the little difference (about 0.2%) between the single coil and whole BT F_N forces, is due to the radial component of the magnetic field produced by the other coils of the BT (this component is not null because each section of the reference coil is displaced in average of about 0.08 m from the symmetry plane of the reference coil).

The resultant force is directed radially towards the detector axis and its value (about 6200 kN) is reported in the Table 8 for a comparison with the resultant forces of the magnet in the various configurations.

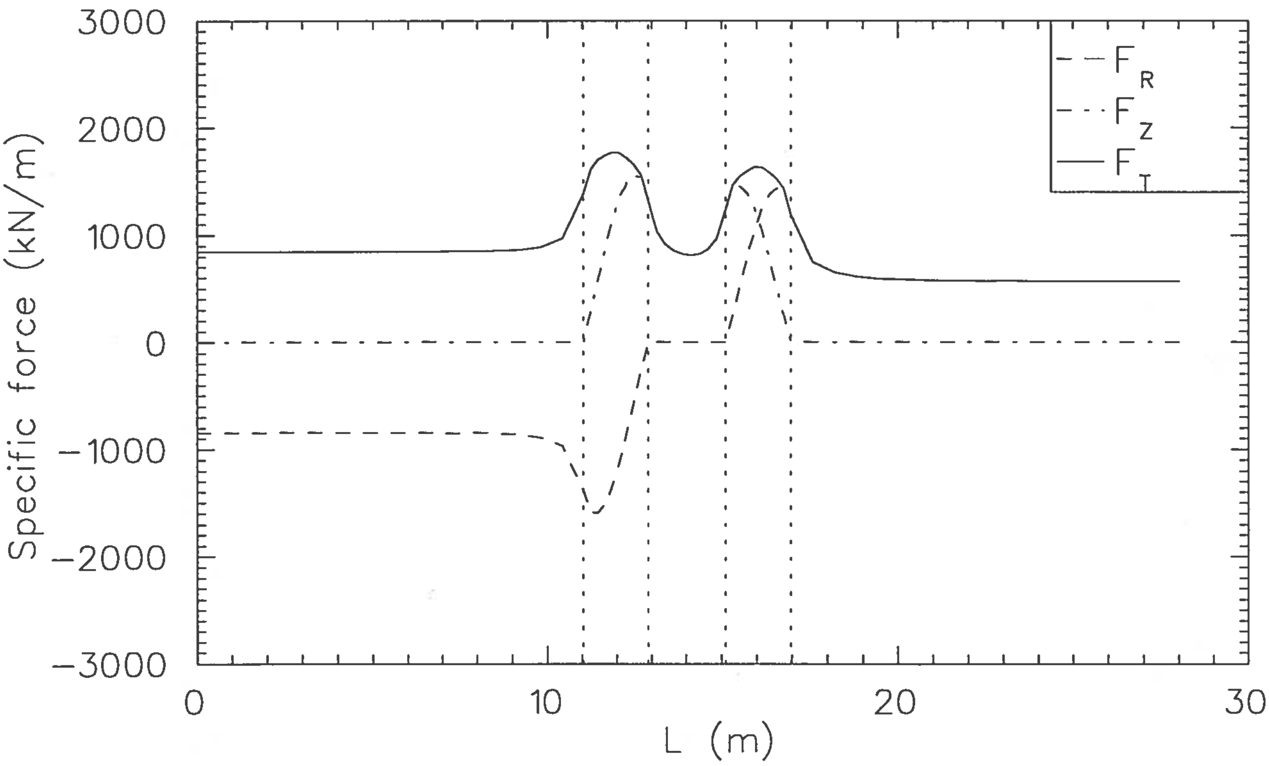

FIG. 4 - Specific forces vs. the length measured along half BT coil in the whole BT configuration.

3.3. - BT + ECTs

As for the previous cases the graph of Fig. 5 shows the distribution, along the BT reference coil, of the specific force F_R, F_Z and F_T, when also the End Cap Toroids are excited at the maximum current intensity.

It is possible to see that the presence of the ECT coils produces a strong dissymmetry in the specific forces that will be difficult to reproduces in the B0 coil.

The main contribution of the ECT coils is confined between z > 6 m and R < 8 m (6 m < L < 15 m in Fig. 5). The maximum value of the total specific force (F_T = 2070 kN/m) is reached at L = 12 m, corresponding to the beginning of the curved corner. The resultant radial force on the BT reference coil is about 1100 ton.

The difference between the integral of the axial specific force for the BT+ECTs configuration and the one of the whole BT configuration represents the attractive force between the reference coil BT and one ECT. From the calculated values for the up to date geometry and magnetomotive force of the toroids, a total attractive force of about 240 ton is obtained.

The ECT magnetic field has a little effect in the F_N force acting on each section of the BT reference coil: the specific force F_N increases only of a few percent in respect to the previous cases in the region z > 6 m and R < 8 m.

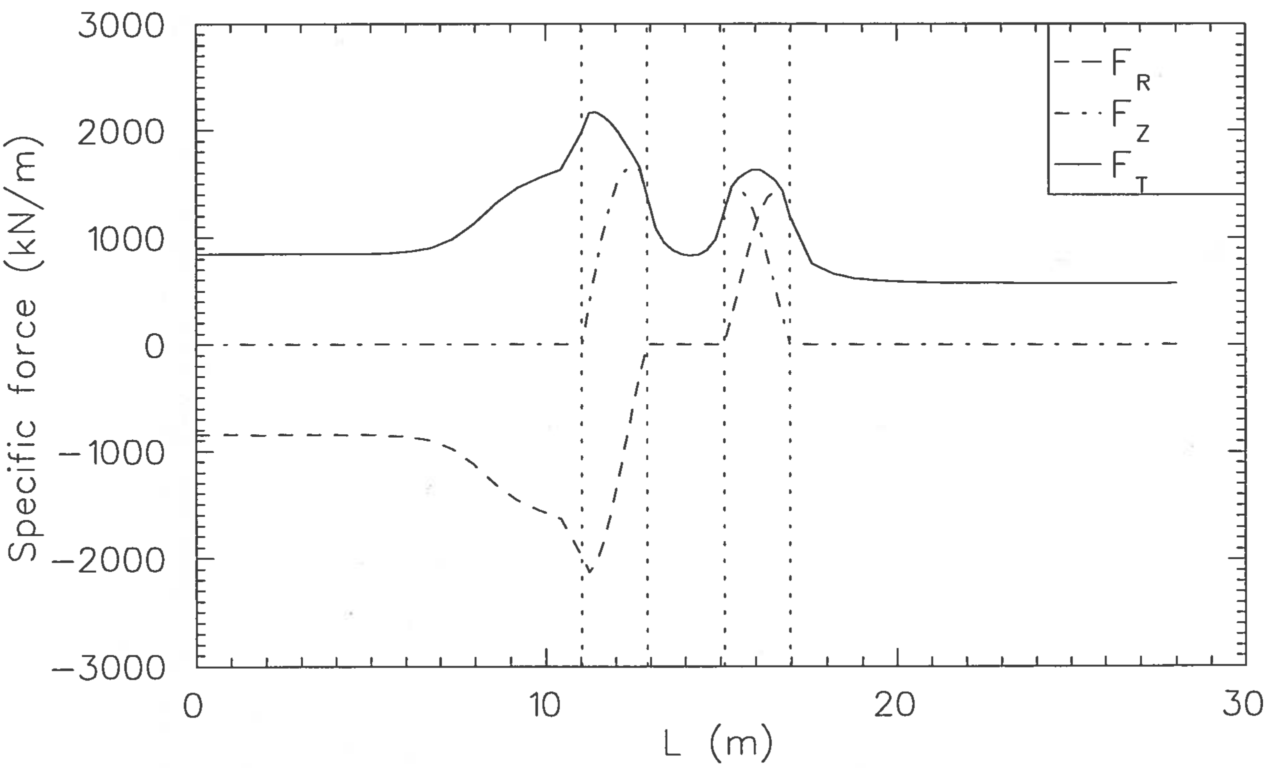

FIG. 5 - Specific forces vs. half perimeter of a BT coil in the configuration BT + ECTs.

4. - FORCES AND TORQUES DUE TO THE SOLENOID AND TILECAL YOKE

In this paragraph the contribution of the solenoid and the tilecal is considered in the calculation of the forces and torques acting on the BT reference coil. The calculation has been made with an analytical approach and a numerical approach, in order to obtain a cross check of the values.

4.1 Analytical approach

In the following the interactions between the BT reference coil and the solenoid-tilecal structure will be calculated by means of simple models, able to give a rough evaluation of the forces and torques acting on the BT coils. This approach is useful because it gives an integral description of the interactions and it allows a check of the results obtained with the 2D and 3D numerical codes.

Two operating situations have been considered:

1. the solenoid is switched off and the BT reference coil is supplied at the maximum magnetomotive force [i.e. $(NI)_c = 2.46 \cdot 10^6$ At];
2. the solenoid is switched on at the maximum magnetomotive force [i.e. $(NI)_s = 9.4 \cdot 10^6$ At] and also the BT reference coil is operating at the maximum magnetomotive force.

When the solenoid is switched off, the iron of the tilecal yoke is magnetized by the toroidal field of the BT (the magnetization intensity is directed normally to the solenoid axis) and the interaction between the iron and the BT reference coil consists only in a radial attractive force.

When the solenoid is switched on, the iron is magnetized by the solenoid field (directed along the solenoid axis) and by the toroidal field of the BT. In this case the BT reference coil is subjected to a radial attractive force and to a torque produced by the fringing field of the solenoid-tilecal complex.

For the engineering design of the BT and for the preliminary design of the B0 magnet, it is not sufficient to know the resultant force and the resultant torque acting in the BT reference coil but it is necessary to know the distribution of the forces along the sides of the BT reference coil because the coil and casing are not a stiff structure.

4.1.1. - Case 1: solenoid switched off

A rough evaluation of the additional force produced by the tilecal iron can be obtained with the method of the image currents. Obviously, because this method requires the knowledge of the relative permeability of the iron in the operating conditions, it is possible to define only an upper limit for the attractive force.

The specific radial force on the axial sides of the BT reference coil is given by:

$$\frac{dF_R}{dz} = G\frac{\mu_0 (NI)_c^2}{2\pi D}\left[\frac{Ly/2+z}{\sqrt{(Ly+z)^2+D^2}}+\frac{Ly/2-z}{\sqrt{(Ly-z)^2+D^2}}\right]$$

whereas the total radial force is expressed by:

$$F_R = G\frac{\mu_0 (NI)_c^2}{\pi \cdot D}\left[\sqrt{\left(\frac{Lc+Ly}{2}\right)^2+D^2}-\sqrt{\left(\frac{Ly-Lc}{2}\right)^2+D^2}\right]$$

where:

$$G = s_f\left[\frac{\mu_r-1}{\mu_r+1}\right]$$

being s_f the stacking factor of the iron yoke and μ_r the relative permeability coefficient of the iron in the operating conditions;

$(NI)_c$ is the magnetomotive force of the BT

D is the distance between the real and image currents

Lc is the length of the axial side of the BT coil

Ly is the length of the tilecal yoke

z is the distance along the axial side of the BT reference coil measured from the symmetry plane.

In the geometry of the BT reference coil and tilecal yoke it is reasonable to assume for the stacking factor the value $s_f = 0.7$ and for the magnetic permeability coefficient a value in the range $\mu_r = 2 \div 3$ (the magnetic field produced by the BT coil at the yoke surface of the tilecal is high: $H \approx 4 \cdot 10^5$ At/m).

The total radial force due to the tilecal yoke (when the solenoid is switched off) is in the range:

$$F_R = 2500 \div 3800 \text{ kN}$$

that represents 20-30% of the force due to the interaction between the coils of the BT and ECT system. These data justify for more detailed calculations with numerical codes.

In the Fig. 6 the force distributions along the two axial sides of the BT reference coil are presented for the case $\mu_r = 2$.

4.1.2. - Case 2: solenoid switched on

In principle the radial force due to the tilecal yoke should decrease with the solenoid switched on, because the relative permeability of the iron is lowered by the magnetic field of the solenoid. It is not easy to find a suitable and simple model to describe this situation. But the lack of a model is not a problem because for the engineering design of the BT and B0 magnets it is possible to assume the results obtained in the previous case (this choice is conservative from the point of view of the magnet safety).

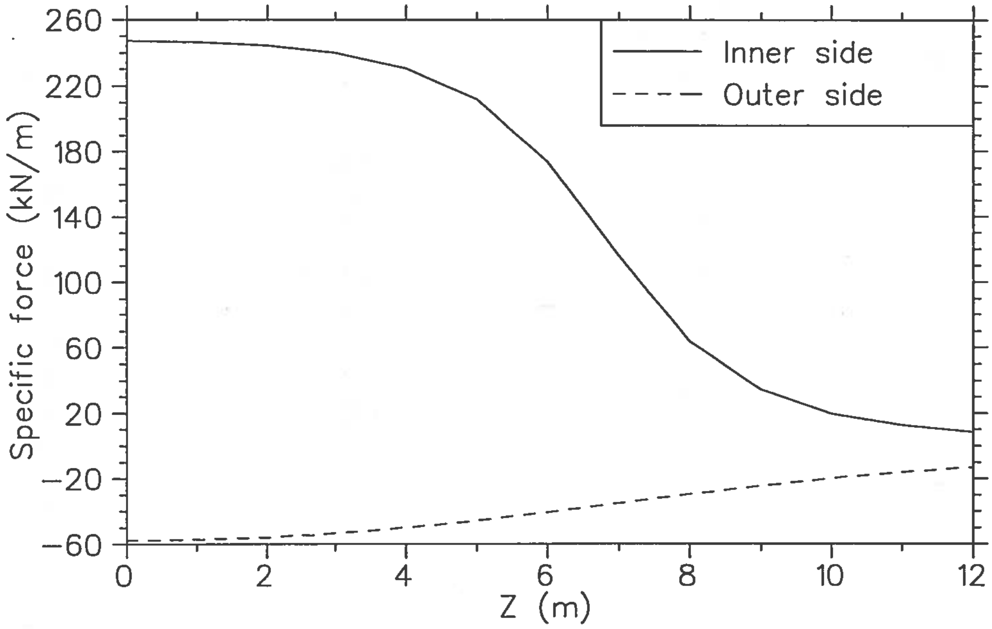

FIG. 6 - Radial specific forces due to the iron yoke along the two axial sides of the BT reference coil.

Concerning the torque acting on the BT reference coil a rough evaluation can be obtained by considering the solenoid, the tilecal yoke and the reference coil as magnetic needles.

The reference coil needle is directed perpendicularly to the other two and their magnetic moments are given respectively by:

$$m_s=(NI)_s S_s \qquad m_c=(NI)_c S_c \qquad m_y=-Ms_f S_y L_y/\mu_0$$

where S_s, S_c and S_y are the surfaces of the solenoid, the BT reference coil and the tilecal yoke, M is the intensity of magnetization of the iron and L_y the length of the tilecal yoke.

With this assumptions the maximum torque on the BT reference coil is given by:

$$\tau = \frac{\mu_0}{4\pi} \cdot \frac{(m_s + m_y) \cdot m_c}{R^3}$$

where R is the distance between the solenoid axis and the coil axis.

As in the previous case there is a large indetermination in the evaluation of the magnetic moment of the tilecal yoke (because the structure is complex and it is difficult to estimate the value of M) whereas the magnetic moments of the solenoid and the reference coil can be calculated with reasonable precision.

Furthermore it is clear that in this model the resultant torque τ can change sign, depending by the values assumed for the magnetic moment m_y.

By assuming that only the external cylinders of the tilecal are magnetized along the axial direction and the intensity of magnetization is in the range $M = 1.0 \div 1.5$ T, the maximum torque in the BT reference coil is:

$$\tau = +4.51 \cdot 10^4 \div -0.805 \cdot 10^4 \text{ Nm}$$

These values show that the torque is not negligible and it must be carefully considered in the design of the coil, casing, supports and vacuum chamber. From the expression of τ, it is possible to evaluate the maximum torque acting on the BT reference coil without the tilecal yoke (m_y= 0). In this case the maximum torque (τ = +2.96·10^5 Nm) is several times higher than the previous one, and probably cannot be supported by the present structure of the BT. Even if this situation will never realised, the evaluation of the maximum torque represents an useful warning for the designers and users of the magnet system.

As above mentioned, for the designers it is essential to know the specific force along the sides of the reference coil produced by the solenoid and the tilecal yoke.

The specific force F_N on the axial sides of the reference coil is given by:

$$F_N = \frac{\mu_0}{4\pi}\frac{(NI)_x (NI)_c S_x}{L_x}\left\{\frac{R}{\left[(z - L_x/2)^2 + R^2\right]^{3/2}} - \frac{R}{\left[(z + L_x/2)^2 + R^2\right]^{3/2}}\right\}$$

where:

$(NI)_x$ is the magnetomotive force of the considered component (solenoid or tilecal yoke). In the case of the tilecal yoke $(NI)_x = ML_y/\mu_0$

S_x is the surface of the considered component

L_x is the length of the considered component

R is the distance between the axis of the solenoid (or tilecal) and the axial side of the BT reference coil

z is the distance measured along the side of the reference coil from the axial symmetry plane.

The Fig. 7 and Fig. 8 show the separated contributions of the solenoid and the tilcale to the specific force F_N along the axial sides of the BT reference coil. It is important to note that the two contributions have different form factors so that the resultant torque could be negligible but the specific forces distributed along the coil can have high values.

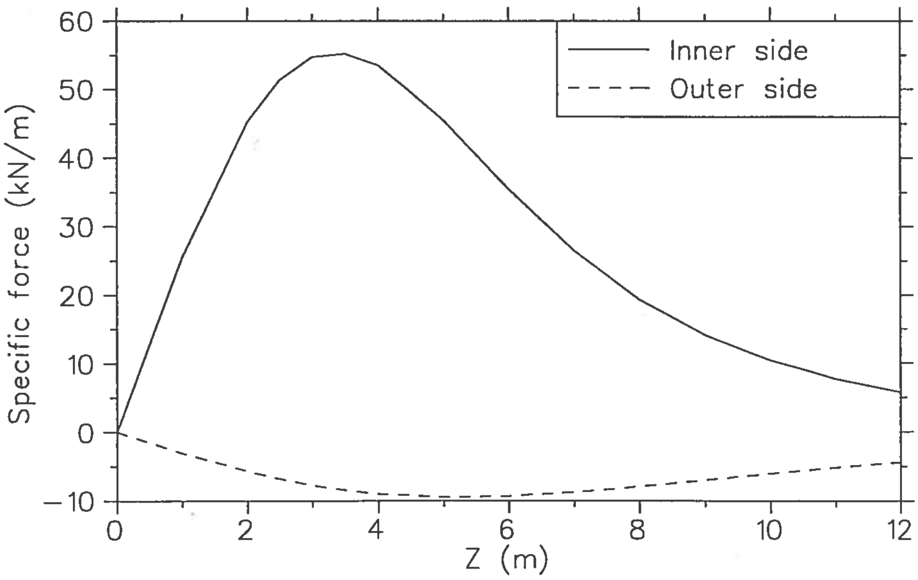

FIG. 7 - Specific force on the axial side of the BT coil due to the solenoid (analytical analysis)

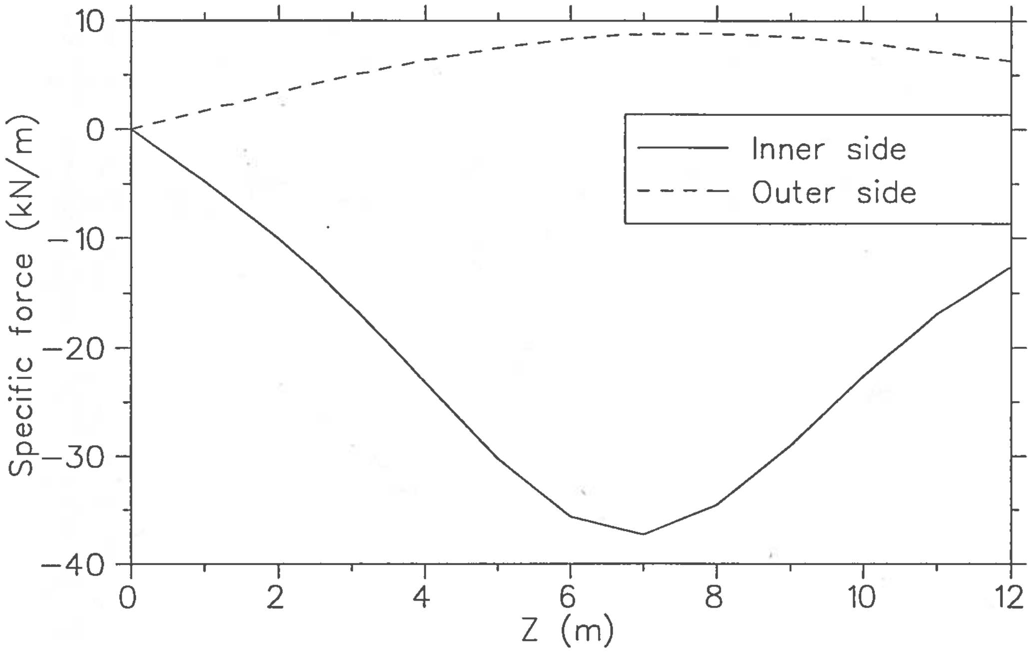

FIG. 8 - Specific force on the axial side of the BT coil due to the iron yoke (analytical analysis).

4.2. - Numerical approach

The numerical approach follows the same guidelines of the analytical approach: i.e. it examines the interaction with the solenoid-tilecal structure by considering the two cases of the solenoid switched on and switched off.

4.2.1. - Case 1: solenoid switched off

The interaction of the tilecal with the BT reference coil has been calculated with MAFIA, a 3D finite element code[3]. Because MAFIA foresees only Dirichlet boundary conditions (the magnetic field parallel to the boundary is null) or Neumann boundary conditions (the magnetic field perpendicular to the boundary is null), the problem of the solenoid switched on cannot be described. In fact the solenoid produces a magnetic field that is always perpendicular to the toroidal field in the symmetry planes of the magnet system. For this reason the calculation of the attractive force on the BT reference coil towards the tilecal has been carried out only for the case of the solenoid switched off.

As already seen, the calculation of this force is sufficient for the BT design, because it represents the strongest force in the two operational cases, and also it represents, at the maximum, only 20-30% of the total attractive force acting on the BT coil.

In order to minimise the mesh number, only 1/16 of the whole system has been described with the suitable boundary conditions. The coils of the BT and ECTs have been described by two filaments, one for each section of the coil. In the Fig. 9 half coil of the BT and two half coils of an ECT (each filament represents a section of a coil) are shown; the curved corners are represented as two segments. The cylinder in the centre represents the tilecal with the different parts.

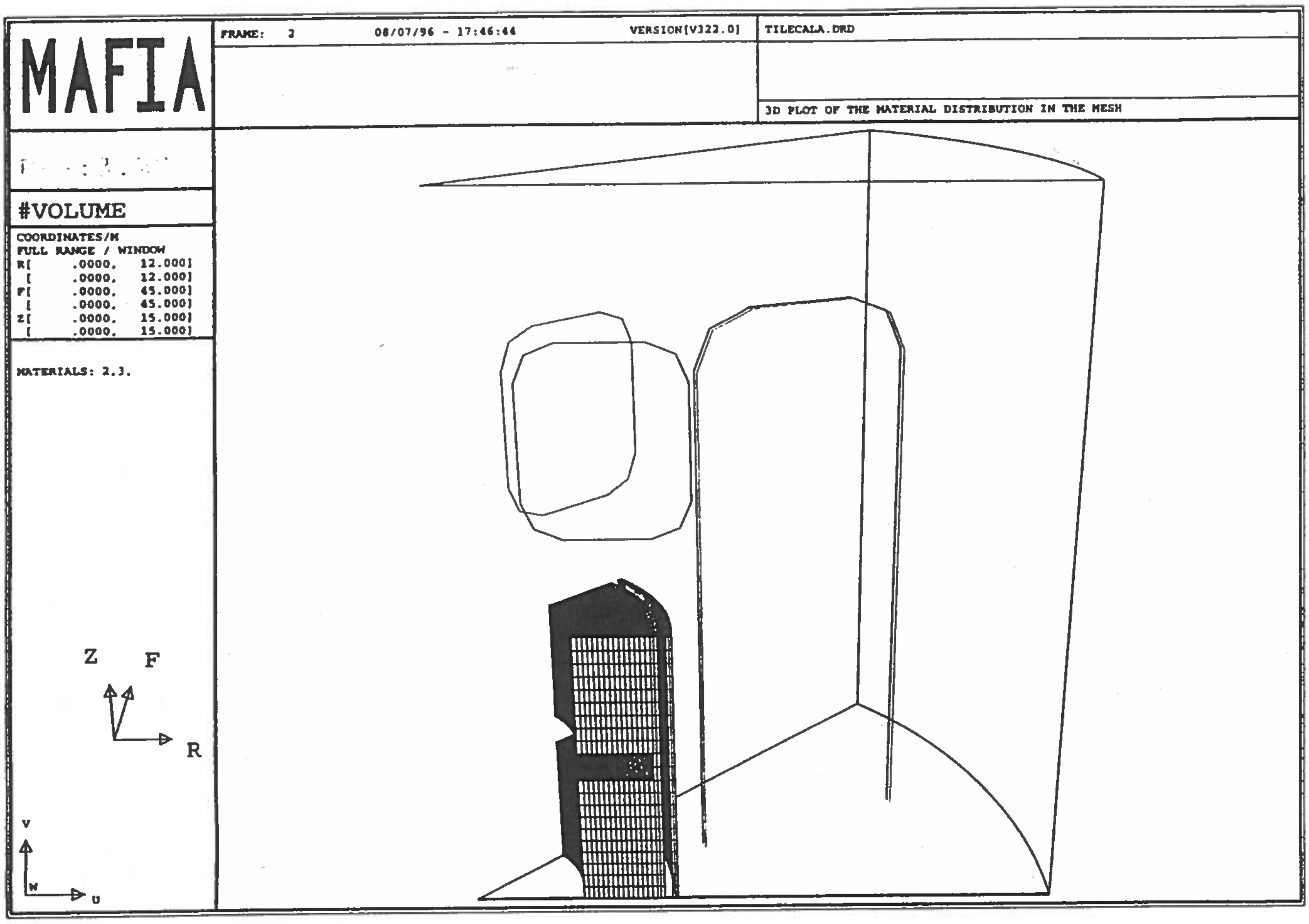

FIG. 9 - 3D representation with MAFIA of 1/16 of Tilecal, BT and ECTs

Because the tilecal is a complex structure, composed of many blocks of iron, an homogenous equivalent structure has been chosen, as described by Bergsma paper(2). The inner part of the tilecal has been considered an homogenous anisotropy material, with different magnetic permeability in r, θ and z ($\mu_r = 4480$, $\mu_\theta = 4930$, $\mu_z = 26$). The cylindrical shield is made by iron, whose magnetization curve is shown in the Fig. 10.

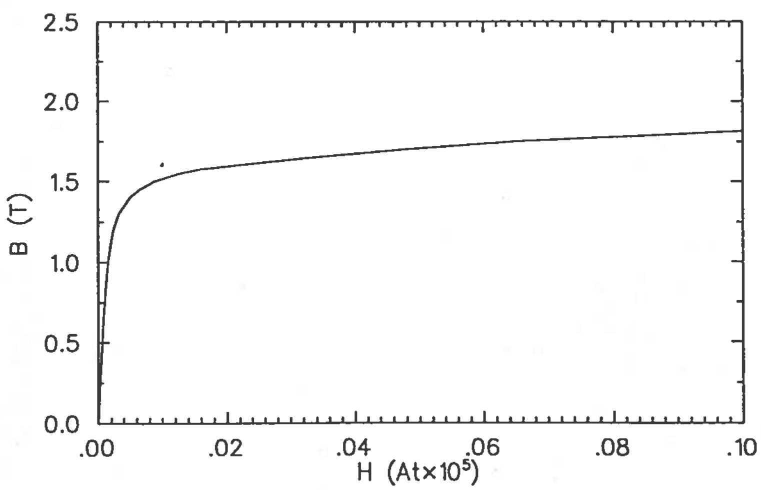

FIG. 10 - B-H curve of iron in Tilecal(2).

In the Fig. 11 the intensity of B_θ in the region with θ=0 and z=0 is plotted. It shows that the most part of the magnetic field is shielded by the most external support cylinder of the tilecal.

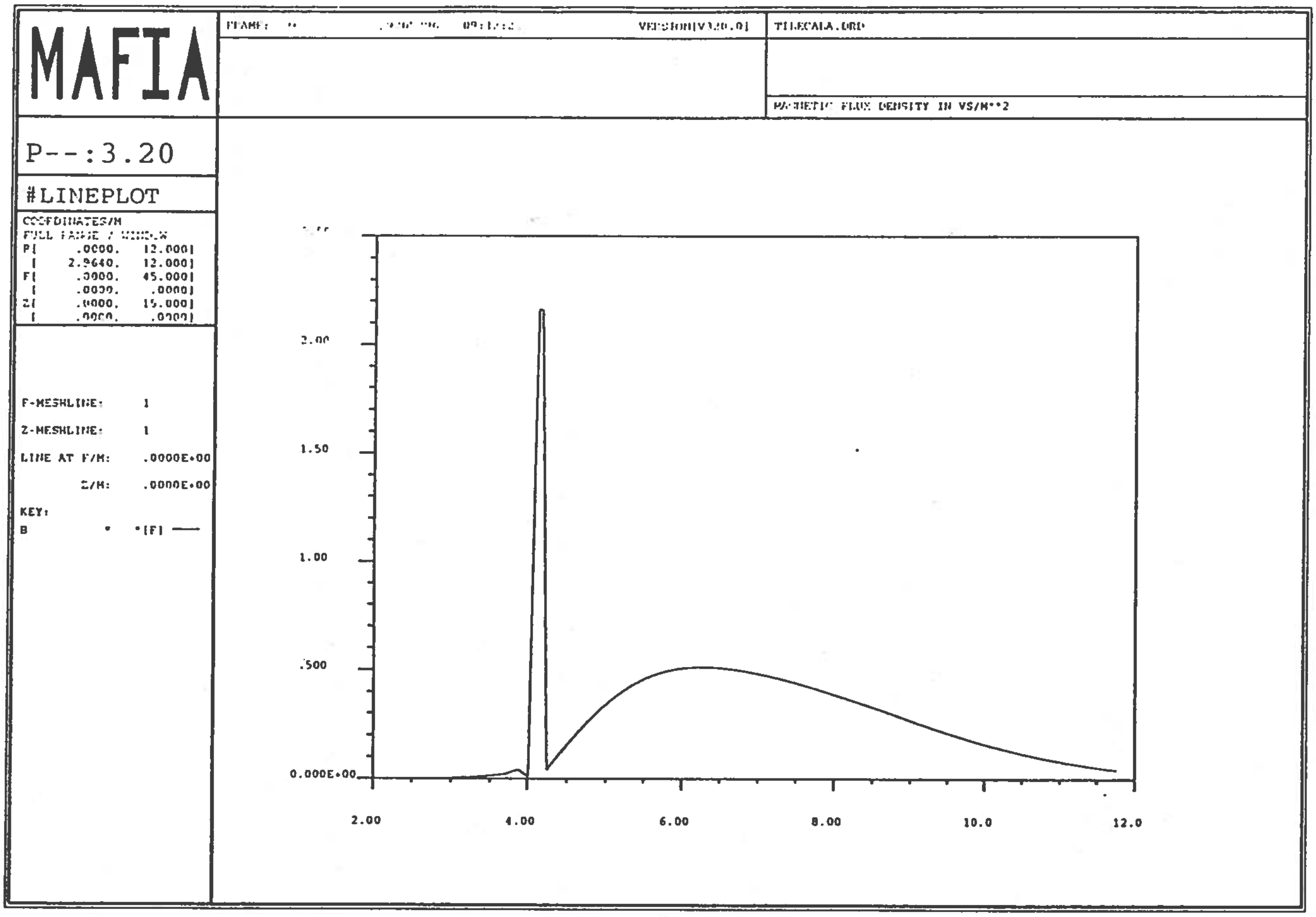

FIG. 11 - Component θ of the magnetic field B at θ=0 and z=0

The attractive force between the tilecal and the coil of the BT has been calculated by integrating the specific radial force along the coil sides. The tilecal produces a magnetic force only in the region of the innermost radius of the coils of the BT, and in the range -6.2 m < z < 6.2 m, corresponding to the length of the tilecal. The average radial specific force due to the tilecal in such region is about 110 kN/m. The total radial force due to the tilecal is about 1350 kN, with an error of ±10%.

The values of the specific force and the resultant force obtained with the 3D code are about 50-70% lower then the values obtained with the analytical approach. The discrepancy can be considered acceptable within the assumptions made in the analytical calculations.

4.2.2. - Case 2: solenoid switched on

The interaction between the BT reference coil and the solenoid tilecal system has been calculated by means of POISSON, a 2D code. In the calculation the inner part of the tilecal has been represented as an homogenous anisotropy material, with a stacking factor $s_f = 0.76$ in the radial direction and a constant permeability coefficient $\mu_r = 26$ in the axial direction. The B - H curve of the iron for the radial direction is plotted in the Fig. 10.

Three different hypothesis have been considered:

1. the outermost iron cylinders are magnetized only by the solenoid field;
2. the outermost iron cylinders are partially saturated by the magnetic field of the BT. A relative permeability coefficient $\mu_r = 50$ has been considered;
3. the tilecal has been removed.

The fringing field at the level of the inner side of the BT coil increases substantially passing from the first configuration to the third one. The Fig. 12 shows the flux lines for the second hypothesis.

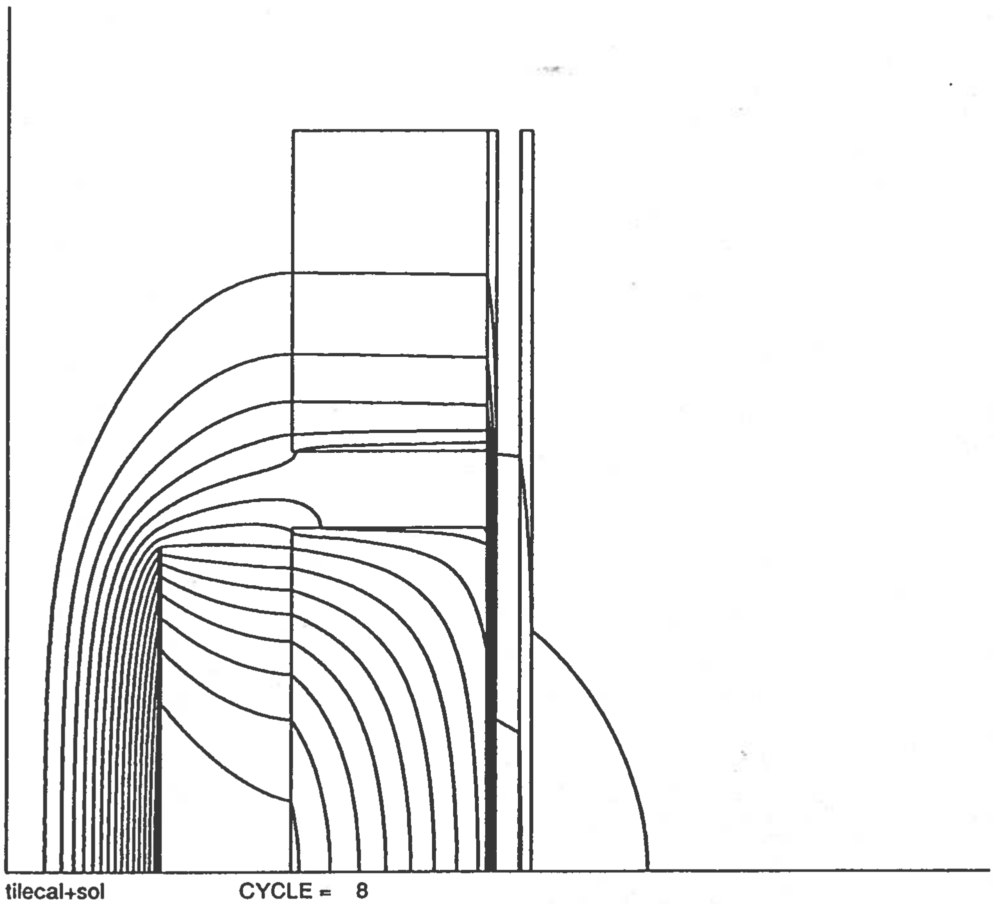

FIG. 12 - Flux lines of the field produced by the solenoid and tilecal, with the outermost support bar of the tilecal partially saturated by BT (average magnetic permeability μ_r=50)

In the Fig. 13 the specific forces produced by the solenoid along the inner side of the BT coils are plotted. It can be seen that in the first case the force is negligible, whereas in the second case the specific force is of the same order of magnitude of the specific weight of the cold mass (~8 kN/m). In the third case the specific force produced by the solenoid is quite high, and it presents a maximum of about 60 kN/m.

In the Fig. 14 and 15 the specific forces produced by the solenoid along the outer side and along the radial sides of the BT coil are shown. In these cases the forces don't seem dangerous, even if the forces produced by the solenoid without tilecal are considerable higher than the forces produced in the other two cases.

These values are substantially in agreement with the results obtained with the analytical approach and they confirm that it is not possible to excite the solenoid without the tilecal yoke. Furthermore in the design of the BT it is convenient to assume the second hypothesis (F_θ (max.) $\approx$ 10 kN/m) for conservative reasons.

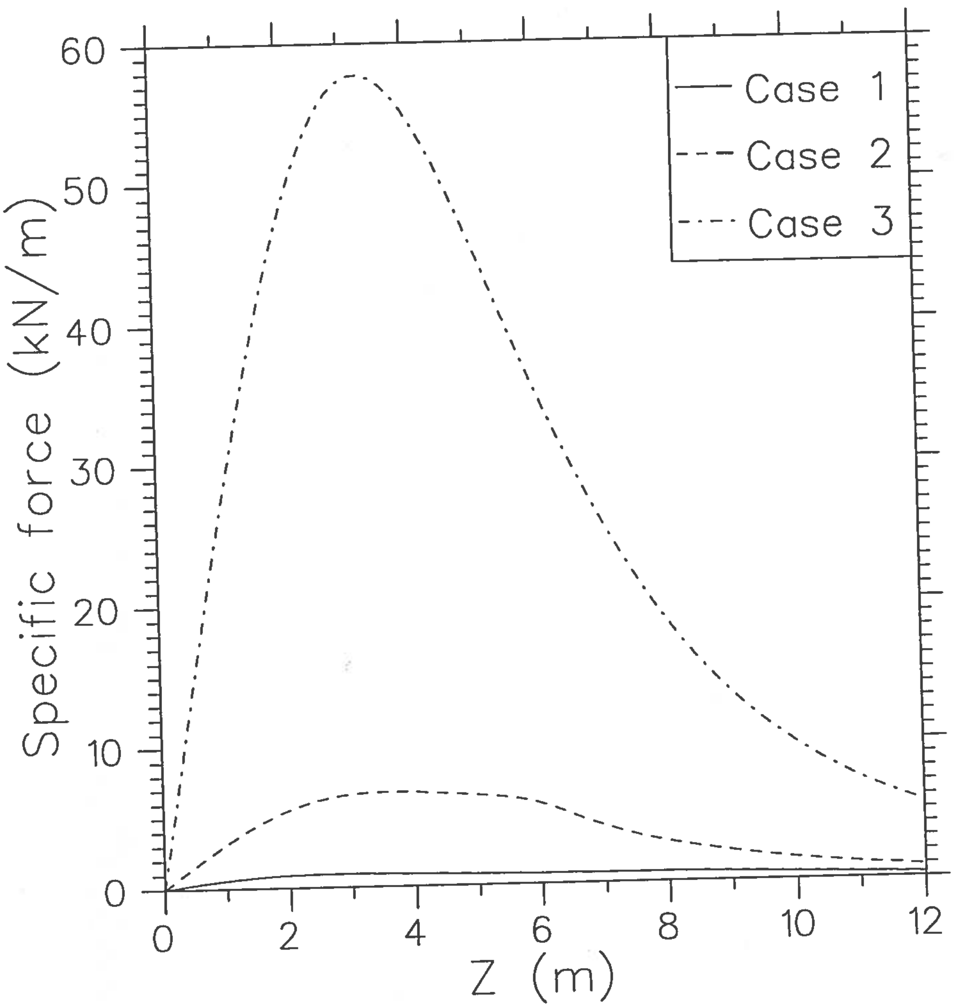

FIG. 13 - Specific forces along the inner side of the BT coil due to the solenoid.; Case 1 with iron no saturated by BT; case 2 with iron partially saturated by BT; case 3 with no iron.

TABLE 7 - (continued)

	Single coil of BT			BT			BT+ECT			BT+ECT+Tilecal		
Curve (deg)	Fr kN/m	Fz kN/m	Fn kN/m	Fr kN/m	Fz kN/m	Fn kN/m	Fr kN/m	Fz kN/m	Fn kN/m	Fr kN/m	Fz kN/m	Fn kN/m
0	0	1043	1210	0	1238	1208	0	1242	1208	0	1242	1208
10	222	1259	1208	254	1442	1206	255	1446	1206	255	1446	1206
20	468	1286	1206	529	1455	1203	531	1458	1203	531	1458	1203
30	711	1231	1204	798	1383	1202	800	1385	1202	800	1385	1202
40	937	1116	1204	1049	1250	1201	1051	1252	1201	1051	1252	1201
50	1114	935	1204	1246	1045	1201	1248	1047	1201	1248	1047	1201
60	1223	706	1204	1371	792	1202	1373	793	1202	1373	793	1202
70	1270	462	1205	1434	522	1203	1436	523	1203	1436	523	1203
80	1235	218	1208	1410	249	1206	1412	249	1205	1412	249	1205
90	1010	0	1210	1193	0	1208	1195	0	1207	1195	0	1207
Z (m)												
11.042	1010	0	1210	1193	0	1208	1195	0	1207	1195	0	1207
10.429	551	0	1221	751	0	1219	753	0	1219	753	0	1219
9.816	439	0	1223	654	0	1221	656	0	1221	656	0	1221
9.202	385	0	1224	613	0	1221	615	0	1221	615	0	1221
8.589	354	0	1224	594	0	1222	596	0	1222	596	0	1222
7.975	334	0	1225	584	0	1222	586	0	1222	586	0	1222
7.362	320	0	1225	578	0	1222	579	0	1222	579	0	1222
6.748	310	0	1225	575	0	1222	576	0	1222	576	0	1222
6.135	303	0	1225	573	0	1222	574	0	1222	574	0	1222
5.521	298	0	1225	572	0	1222	572	0	1222	572	0	1222
4.908	294	0	1225	573	0	1222	573	0	1222	573	0	1222
4.294	291	0	1225	571	0	1222	571	0	1222	571	0	1222
3.681	288	0	1225	570	0	1222	570	0	1222	570	0	1222
3.067	287	0	1225	571	0	1222	571	0	1222	571	0	1222
2.454	285	0	1225	571	0	1222	571	0	1222	571	0	1222
1.840	284	0	1225	568	0	1222	568	0	1222	568	0	1222
1.227	283	0	1225	571	0	1222	571	0	1222	571	0	1222
0.613	283	0	1225	571	0	1222	571	0	1222	571	0	1222
0.000	283	0	1225	572	0	1222	572	0	1222	572	0	1222

TABLE 8 - Total external force in the BT reference coil

Configuration	Total radial force (kN)
BT	6214
BT + ECT	10981
BT+ECT+Tilecal	12331

TABLE 9 - Specific forces on the B0 coil

	B0 in air			B0 with magnetic mirror		
Z (m)	Fr kN/m	Fz kN/m	Fn kN/m	Fr kN/m	Fz kN/m	Fn kN/m
0.000	-397	0	1224	-934	0	1224
0.175	-392	0	1224	-935	0	1224
0.350	-393	0	1224	-935	0	1224
0.525	-396	0	1224	-938	0	1224
0.700	-399	0	1224	-941	0	1224
0.875	-404	0	1224	-946	0	1224
1.050	-410	0	1224	-951	0	1224
1.225	-417	0	1224	-959	0	1224
1.400	-426	0	1224	-967	0	1224
1.574	-438	0	1224	-978	0	1224
1.749	-452	0	1224	-992	0	1224
1.924	-469	0	1223	-1008	0	1223
2.099	-490	0	1223	-1029	0	1223
2.274	-518	0	1222	-1055	0	1222
2.449	-554	0	1222	-1090	0	1222
2.624	-604	0	1221	-1138	0	1221
2.799	-677	0	1219	-1209	0	1219
2.974	-797	0	1216	-1327	0	1216
3.149	-1031	0	1209	-1557	0	1209
Curve (deg)						
270	-1031	0	1210	-1556	0	1210
280	-1254	221	1208	-1632	288	1208
290	-1288	469	1205	-1510	549	1205
300	-1238	715	1204	-1366	789	1204
310	-1127	946	1203	-1197	1005	1203
320	-948	1129	1203	-984	1173	1203
330	-719	1245	1204	-741	1273	1204
340	-474	1301	1205	-485	1333	1205
350	-225	1274	1208	-230	1302	1208
360	0	1059	1210	0	1059	1210
R (m)						
1.580	0	1059	1210	0	1059	1210
1.825	0	780	1218	0	780	1218
2.069	0	669	1220	0	669	1220
2.313	0	617	1222	0	617	1222
2.558	0	595	1222	0	595	1222
2.802	0	595	1222	0	595	1222
3.046	0	617	1222	0	617	1222
3.291	0	669	1220	0	669	1220
3.535	0	780	1218	0	780	1218
3.779	0	1059	1210	0	1059	1210

(continues)

TABLE 9 - (continued)

	B0 in air			B0 with magnetic mirror		
Curve (deg)	Fr kN/m	Fz kN/m	Fn kN/m	Fr kN/m	Fz kN/m	Fn kN/m
0	0	1059	1210	0	1059	1210
10	225	1274	1208	225	1274	1208
20	474	1301	1205	474	1301	1205
30	719	1245	1204	719	1245	1204
40	948	1129	1203	948	1129	1203
50	1127	946	1203	1127	946	1203
60	1238	715	1204	1238	715	1204
70	1288	469	1205	1288	469	1205
80	1254	221	1208	1254	221	1208
90	1031	0	1210	1031	0	1210
Z (m)						
3.149	1031	0	1210	1031	0	1210
2.974	796	0	1216	796	0	1216
2.799	676	0	1219	676	0	1219
2.624	603	0	1221	603	0	1221
2.449	554	0	1222	554	0	1222
2.274	517	0	1222	517	0	1222
2.099	490	0	1223	490	0	1223
1.924	468	0	1223	468	0	1223
1.749	452	0	1223	452	0	1223
1.574	438	0	1224	438	0	1224
1.400	427	0	1224	427	0	1224
1.225	417	0	1224	417	0	1224
1.050	410	0	1224	410	0	1224
0.875	404	0	1224	404	0	1224
0.700	399	0	1224	399	0	1224
0.525	396	0	1224	396	0	1224
0.350	393	0	1224	393	0	1224
0.175	392	0	1224	392	0	1224
0.000	392	0	1224	392	0	1224

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