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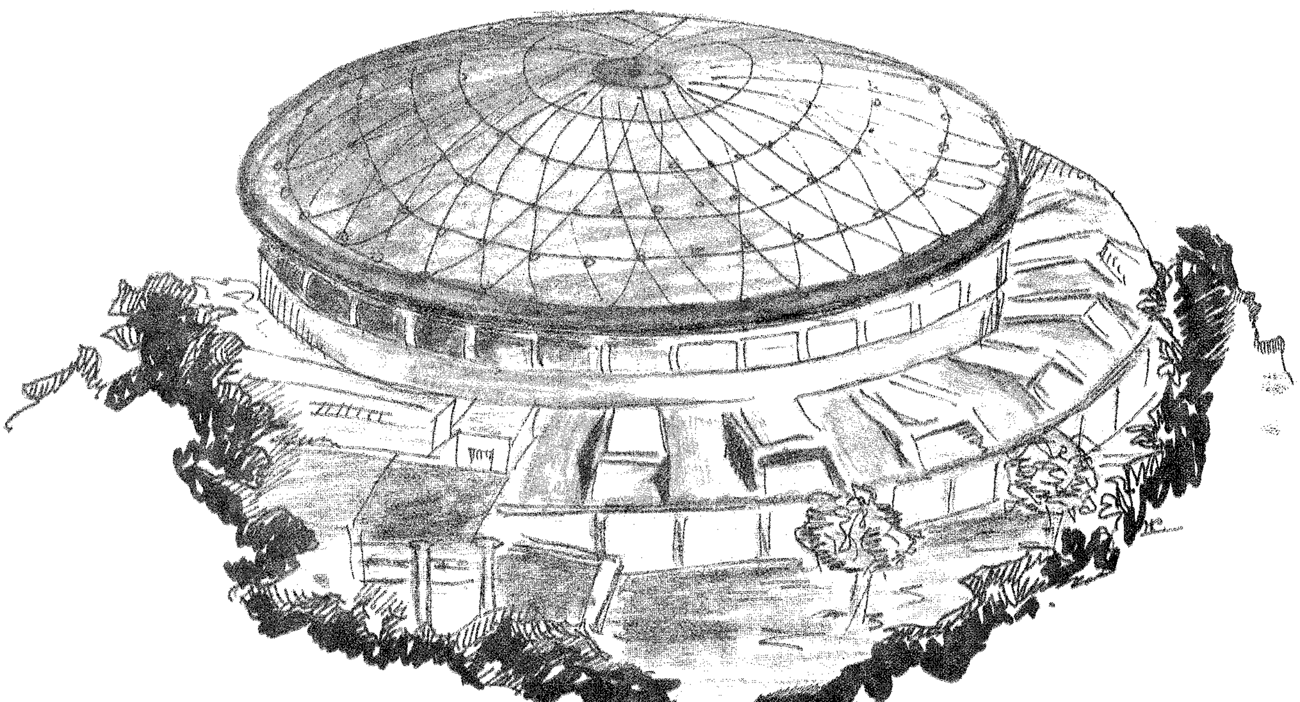

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Preliminary electromagnetic and cryogenic calculations of SMASH superconducting coil

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Abstract

In this note we want to describe preliminary evaluations on the superconducting coil of SMASH, pointing out some problems about the electromagnetic and cryogenic design.

Introduction

The following parameter list for the future detector has been prepared by Dr. M. Piccolo:

Coil radius	1.3	m
Length	2.65	m
Field at the center	1.	Tesla
Field uniformity for $r \leq 1.$ m and $|z| \leq 1.$ m	≈ 1 %	

where r is the radial coordinate of our cylindrical coil and z is the axial direction. Moreover, the radial component of the field, B_r, must satisfy the condition:

$$\int B_r * dz \leq 200 \text{ [Gauss * m]}$$

where the integration is made at r=0.9 m and the range of integration is $0. \leq z \leq 1.$ m.

The questions posed were:

1. Field uniformity;
2. Stored energy;
3. Static magnetic forces;
4. Tolerances on coil positioning;
5. Stresses due to coil misalignment;
6. Electrical characteristics of the coil;
7. Power supply characteristics;
8. Fringe fields.

In this note only questions N° 1,2,3,6,7,8 will be answered. Point 4. is delegated to mechanical engineers, and point 5. will be answered by using a three-dimensional code, still in course of acquisition.

As it will be afterwords pointed out, the geometry has been lightly changed, and new answer will be given for this second version of the coil.

Magnetic calculations

A preliminary mechanical project has been developped by B. Dulach and his group [Ref. 1]; Fig. 1 and 2 show the mechanical lay-out. From this first drawing we started using a rough simplification, with the following assumptions :

1) the iron around the coil has been simplified as a continous medium, the thickness of which is the sum of the single slabs (total thickness 0.85 m);
2) the superconducting coil is considered as a cylinder, where the current is uniformly distributed over the cross-section of the cylinder;
3) the iron is not considered to have an octagonal section, but a circular one, the inner radius of which is the same of the minimum distance from the solenoid axis.

The first of these simplifications is done because of the need of very long time to prepare a data set with the iron in slabs, compatibly with the maximum allowed number of mesh points of POISSON code (40000 points) [Ref. 2]. Therefore this kind of geometry will be analysed successively. The second semplification is due to the fact that, at the moment, the coil is not defined. In any case, in the second version studied, we have assumed a thickness of 0.05 m, rather than 0.3 m as in the first runs, for a better fit of the thin solenoid. The third simplification is due to the POISSON code, which allows to solve problems with revolution symmetry, using cylindrical coordinates r (radius) and z (axis of the solenoid). Fig. 3 shows the geometry "seen" by POISSON. The figure has to be reflected on the plane -z;r, and to be obviously rotated around z axis.

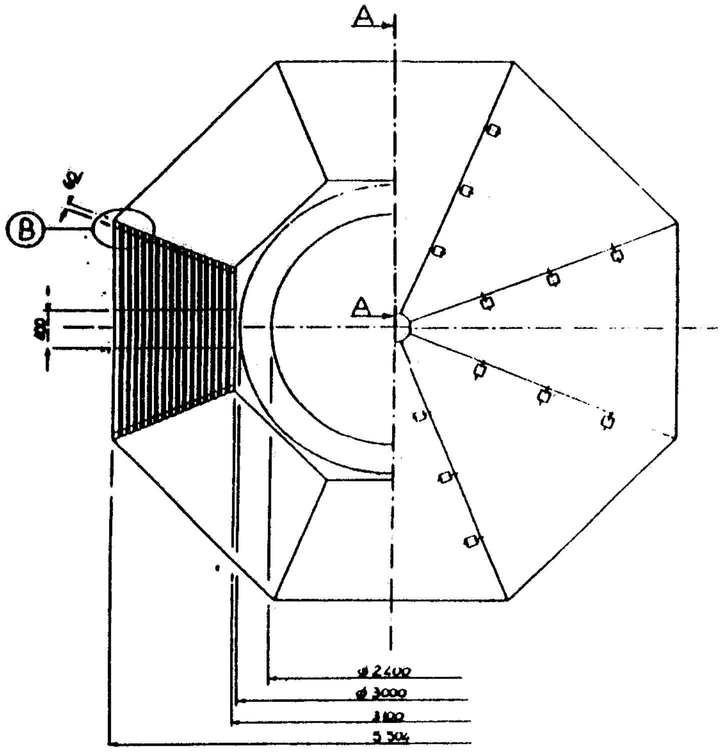

FIG. 1

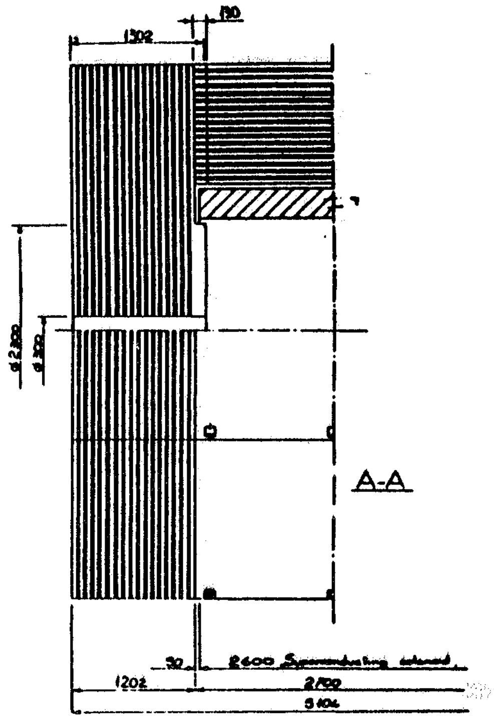

FIG. 2

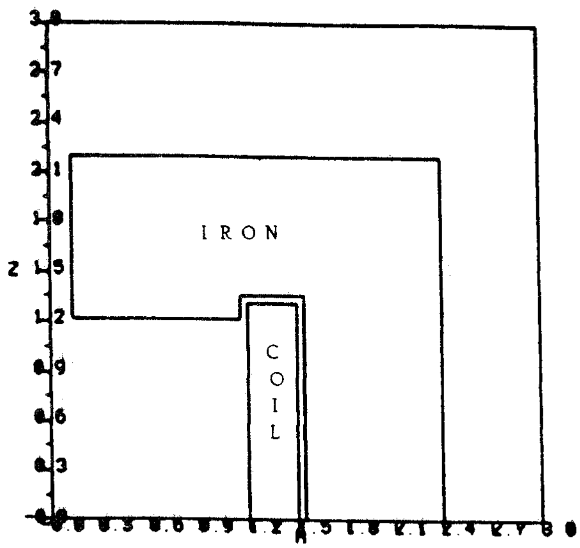

FIG. 3

A starting value of the current necessary to get a center field of 1 Tesla, can be made considering a thin solenoid (a current sheet), with radius of 1.35 m and length of 2.6 m (Fig. 1 and 2). One obtains a value of current per meter of solenoid, k :

$$k \approx B_o * (h^2+d^2)^{1/2}/(h*\mu_o); \quad [Amp/m]$$

where: B_o = Central field =1 Tesla; d = diameter of the coil = 2.7 m;
h = length of the coil = 2.6 m; μ_o = vacuum permeability = $4\,\pi\,10^{-7}$.

The value obtained is K≈1150000 Amp/m. Successive runs of POISSON indicate that, considering the reduction of the reluctance due to the iron backleg and the finite dimensions of the coil, with 855000 Amp/m, the magnetic field at the center is about 10 % greater than the desired value: ≈ 1.12 Tesla. This value of current can be considered for the superconducting cable desigr

Fig. 4 shows how the flux lines are distributed in the region. A strong tip effect, due to the pole edge, can be noticed, but it can be reduced tilting the pole as shown in Fig. 5. In other words, it will be necessary to optimize the pole profile in the final version, increasing the field uniformity. The following results, not only consider the case with the pole parallel to the r axis, but also other two cases, with the height of the pole diminished of 3 and 6 cm (curve -3 and -6 respectively). In any case the field is always greater than 1 Tesla with the same excitation current. The values calculated by POISSON are:

- pole parallel to horizontal axis	1.126	Tesla
- pole 3 cm tilted	1.115	Tesla
- pole 6 cm tilted	1.105	Tesla

Fig. 6 shows the B_z component of the field as a function of r. With a flat pole and r = 1.m, we get a variation of about 2 %, and this variation diminishes to 1.5 %, tilting the pole.

Fig. 7 shows the B_z component as a function of r, but this time at z = 1. m. The tip effect is evident. In fact with the flat pole we get an error of ≈5.5 % at r = 0.9 m, while with a 6 cm tilt we get the same error at r=0.3 m. The solution with 3 cm tilt seems to be the best , with an error of about 4 %.

Fig. 8 shows the B_z component along the z axis, only for flat and 3 cm tilted pole. The maximum is obtained at about z = 0.8÷0.9 m, with a displacement of 1% with flat pole and 2% with tilted pole. This increase is due to the pole edge near the axis, in fact tilting the pole, the angle of the pole diminishes and then the tip effect becomes stronger.

The field uniformity is not far from the value of 1 % at r = 1. m and z= 1. m, but some improvements can be expected taking care of modelling the pole profile, taking away the sharp edges and using a thin coil. Now we have an error of 1 % at r and z equal to 0.7 m.

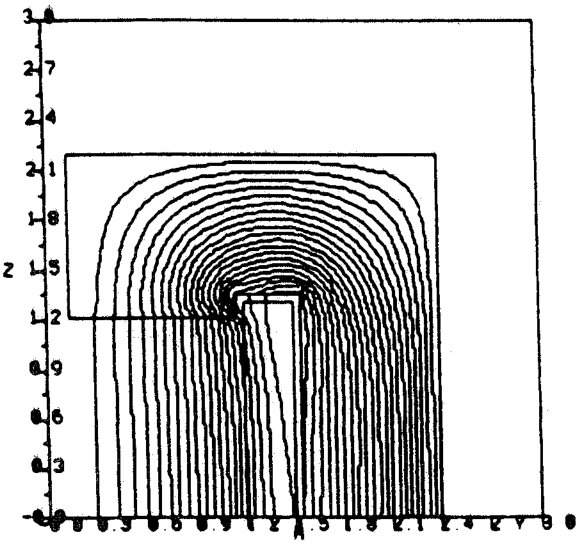

FIG. 4

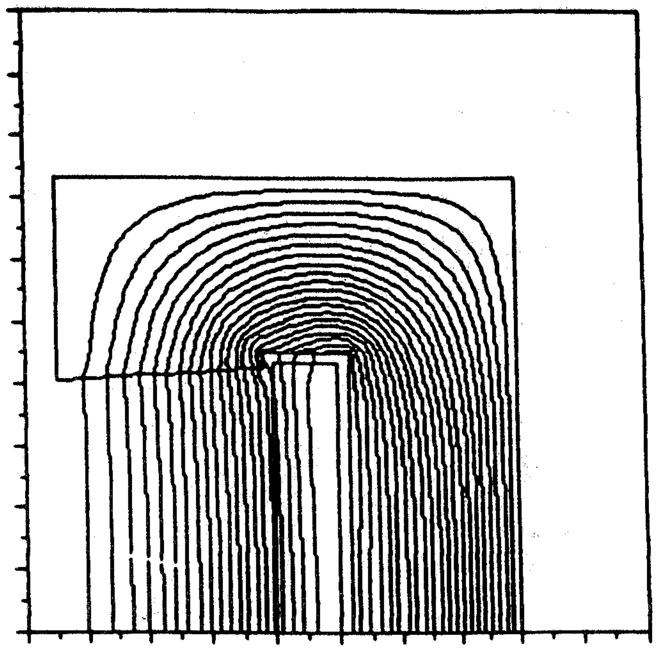

FIG. 5

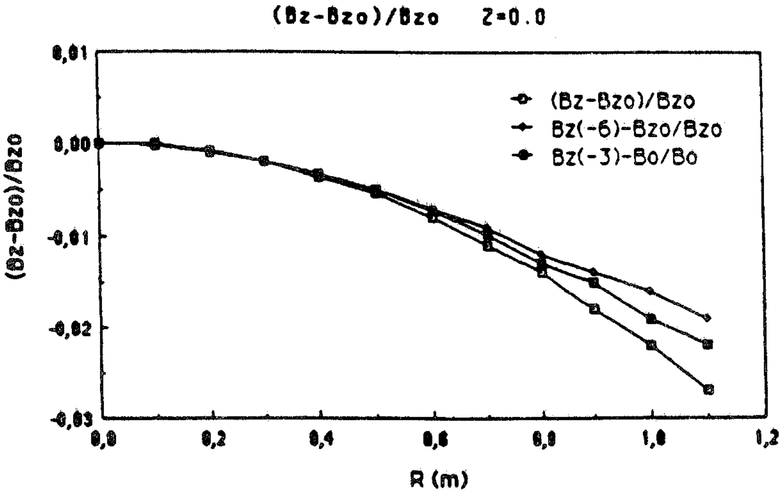

FIG. 6

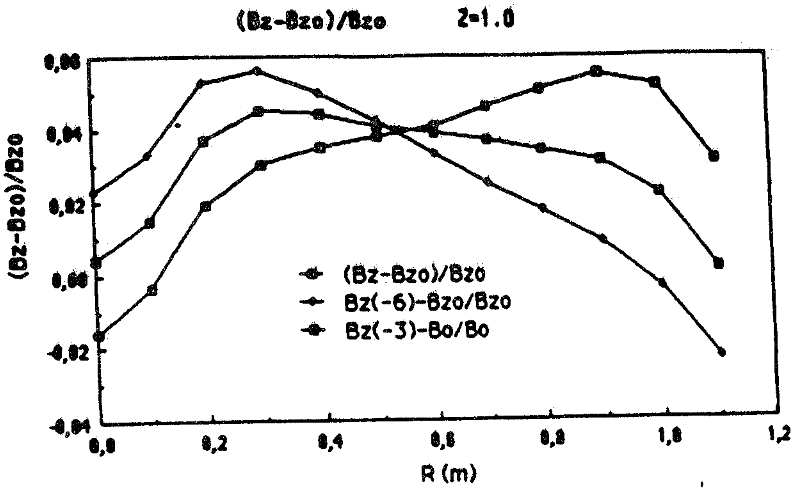

FIG. 7

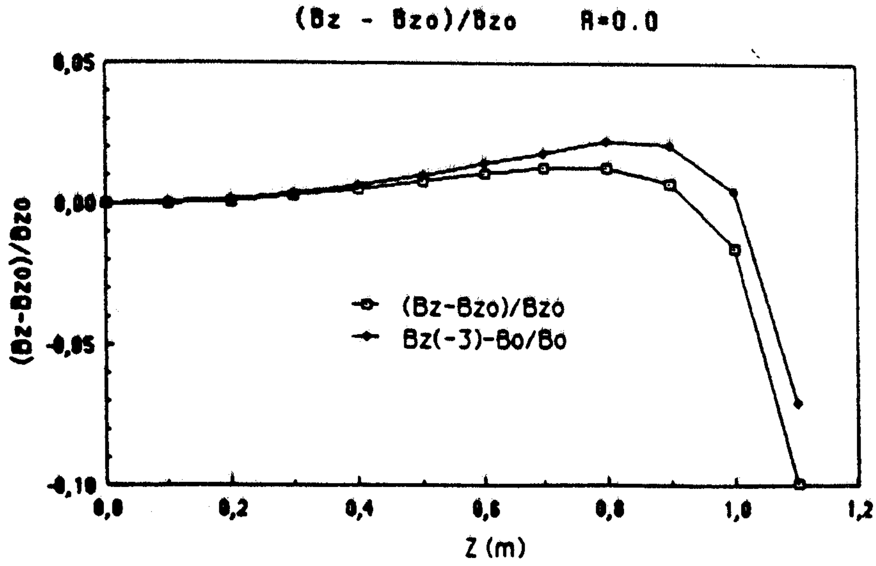

FIG. 8

Fig. 9 shows the radial component of the field Br, as a function of z, at r = 0.9 m. Tilting the pole one can improve this result. In fact the ∫B*dr, using Simpson's integration, for $0. \leq z \leq 1.$ m, is 254 Gauss*m in the case of flat pole, and 227 Gauss*m, not very far away from the requested value, with the tilted pole.

The magnetic field inside the iron is about 0.6 Tesla, while in some parts of the pole the saturation gets up to 1.3 ÷ 1.7 Tesla.

The subprogram FORCE of the POISSON's package, evaluates the stored energy, 6.7 MJoules. The forces acting on the coil are:

radial component (1/2 solenoid)	77550	kG/rad
axial component (1/2 solenoid)	6233	kG/rad

Because of the small level of saturation in the iron, the fringe field is very low. At a distance of 10 cm from the iron the maximum value found is lower than 3.3 Gauss.

As previously noticed, some modifications to the solenoid geometry has been made: the length increased to 3.4 m and the inner radius of the coil became 1.25 m. New runs of POISSON were performed considering a 5 cm thickness coil, with a medium radius of 1.4 m, flat pole and always the same current. Fig. 10 shows the new geometry and the distribution of the field lines. The magnetic field at the center is 1.106 Tesla, still 10 % higher than the requested value. The B_z component, as a function of r at z=0.0, is very similar to that shown in Fig. 6, but for r = 1. m, the B_z component compared with the center value is changed only 1.3 %.

Fig. 11 shows the Bz, as a function of the radius, at z = 1. m. The maximum error is 2.5 % at r = 0.5 m.

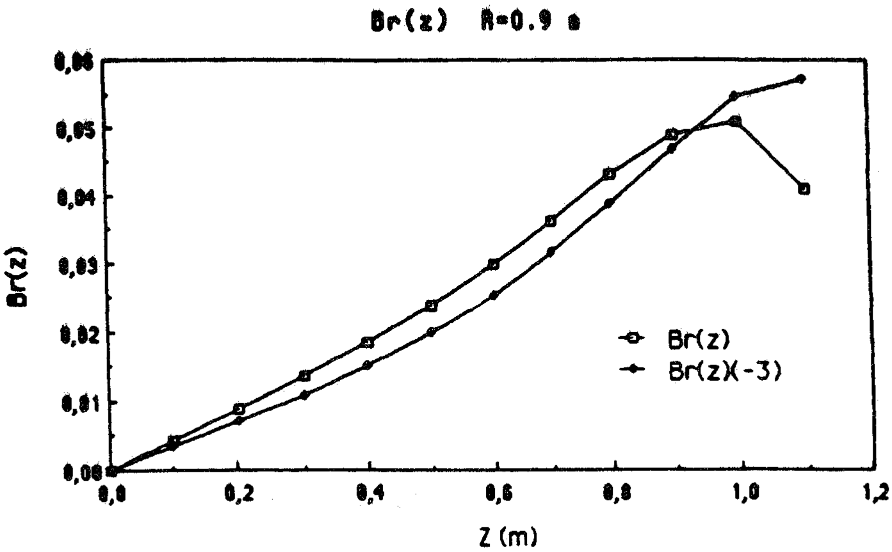

FIG. 9

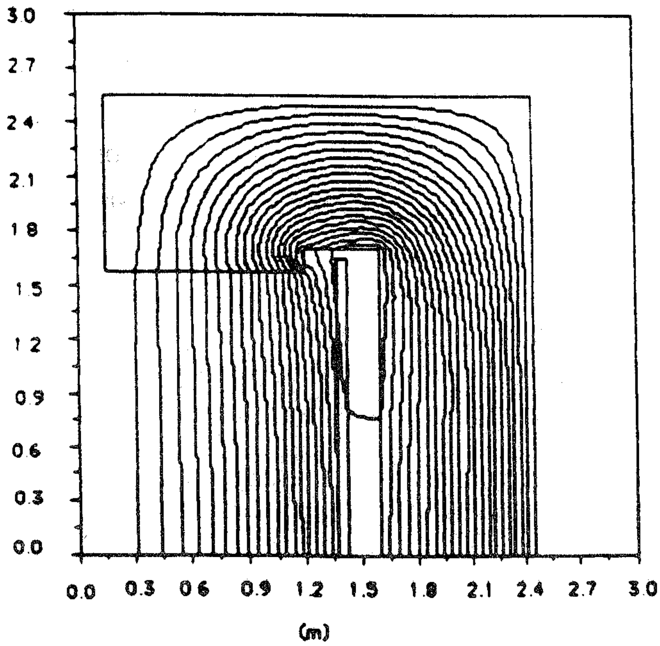

FIG. 10

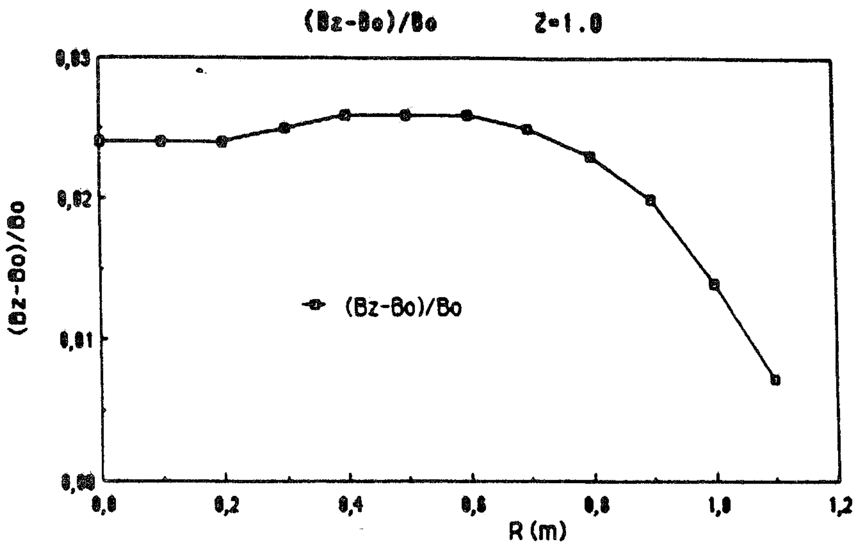

FIG. 11

Fig. 12 shows the Bz along the axis of the solenoid. It is evident the tip effect on the inner edge of the pole.

Fig. 13 shows the radial component Br at r = 0.9 m, as a function of z; the $\int B*dr$ is now 149 Gauss * m. The stored energy is 9.6 MJoules and the forces acting on the coil are:

radial component (1/2 solenoid)	105000 kG/rad
axial component (1/2 solenoid)	5480 kG/rad

The radial component corresponds to a magnetic pressure of 44117 kG/m^2.

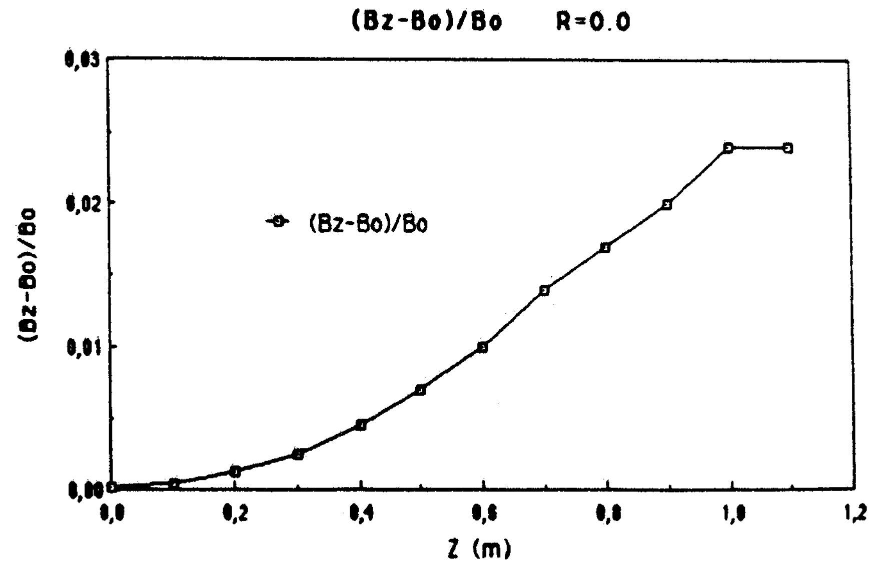

FIG. 12

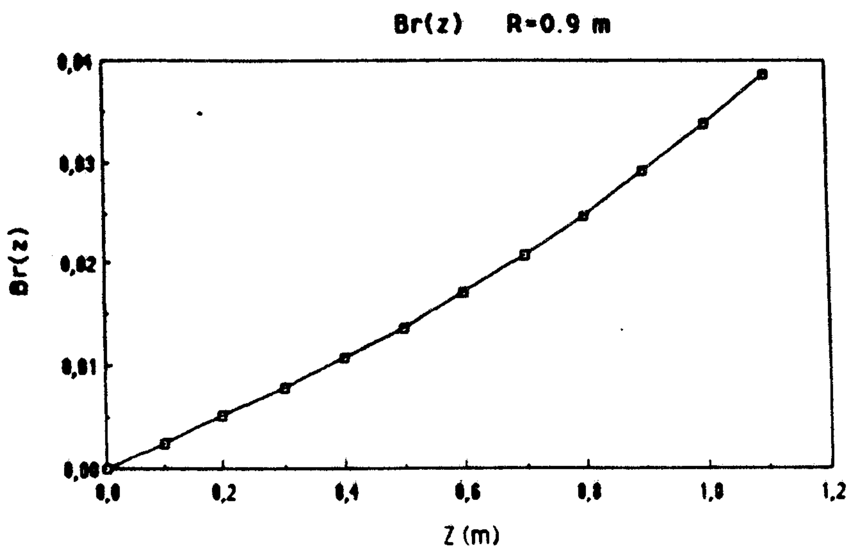

FIG. 13

Cryogenic calculations

Multifilamentary Nb-Ti cables, composed of many strands, can be easily built today, using standard technologies. In our case a 13 strand cable, each strand having 0.84 mm diameter and a Copper-Superconductor ratio of 1.8, can allow more than 11000 Amps with an external field of 1.7 Tesla. The dimensions of the twisted cable would be 4.2 * 1.7 mm^2. To obtain a better thermal stability, this cable can be welded over a Copper support, with approximate dimensions of 4.2 * 8.3 mm^2. The cable and the Copper support will reach the dimensions of 4.2 * 10 mm. Taking into account the under vacuum, epoxy resin insulation, the final dimensions of the cable will be higher, say about 4.35 * 11.35 mm^2. Such a cable can be easily wound on a cylinder, made of steel for example, with thickness of about 10 mm. One can obtain 230 turns per meter, which allow a maximum value of 2500000 Amp/m. At the desired value of Amp/m, the solenoid could be powered with a current of about 3750 Amps, a very safe value for the cable considered.

The simpler way [Ref. 3] of obtaining a stable and efficient cryogenic system for the magnet is probably the keying of an Aluminum cylinder, with thickness of 4 ÷ 5 mm, on the coil. A rectangular cross-section worm-wheel has to be welded on the cylinder, the worm-wheel having an inner diameter of ≈ 12 mm and a wall thickness of 2 mm. With these dimensions the worm-wheel allow a stable flow of the refrigerating fluid.

In the radial direction, the total dimension of the system : steel cylinder, coil, Aluminum Keying, worm-wheel, will be about 40 mm.

Obviously a superinsulated cryostat must be located around the solenoid.

Because of the horizontal positioning of the magnet, to improve the refrigerating fluid flux efficiency, the worm-wheel has to be wounded longitudinally to the axis of the cylinder, with a distance between the turns of about 10 cm.

As refrigerating fluid one can choose whether liquid Helium or supercritical Helium. The last one should have to be preferred because it can offer a more homogeneous and efficient cooling.

Power supply characteristics

The power supply will have to provide about 4000 Amps; if we suppose a total resistance of leads and power supply to coil cables of 10mΩ, the output voltage will be 40 Volts dc. With this low value of voltage and high value of current, a possibility is to use a double six-phases SCR converter, with the two bridges in parallel. If the estimated inductance of the superconducting coil is about 1.3 H, the natural ripple of such a kind of power converter will be better, at full conduction, than $1*10^{-5}$, there will not be necessity of additional filtering. The system will require a main transformer of 170 kVA, with a phase-to-phase voltage to the input of the converter of about 29 Volts.

References

1) B. Dulach - Private Communication.

2) Chr. Iselin - POISCR Solution of Poisson's or Laplace's Equation in Two-Dimensional Region; CERN T 604.

3) S. Caratti,P. Fabbricatore et al. - Design study report of superconducting solenoid for the Opal experiment. ANSALDO ING/RESE 85RO12 Sept. 1985.