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SDC
SOLENOIDAL DETECTOR NOTES

MAGNETIC TRANSFORMERS FOR THE SDC

I. Horvath, F. Lobkowicz, G. Osborne, J. Soong

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I. Horvath, F. Lobkowicz, G. Osborne, J. Soong
University of Rochester, Rochester N.Y. 14627

We have investigated the problem of shielding magnetic transformers in the field of an SDC magnetic coil. In particular our conclusions are:

1) The "long coil" option, with a field of 2 Tesla, makes it impossible to use magnetic transformers in the end plugs. The central barrel would presumably be in a zero field and so no shielding is necessary there.
2) The "short coil" option will make it possible to use magnetic transformers in most places, with the possible exception of some of the EM section in the endcap. In the following we justify these conclusions.

1. Transformer Manufacture

We have studied a wide range of transformer ferrites; we come to the conclusion that the Philips 3D3 material - used in Helios - is still the best material if one requires good behavior at large frequencies and low temperatures. It has a magnetic permeability $\mu = 750$ at room temperature; at LN2 temperature this drops to a value $\mu = 275$. Its loss factor is $\tan \delta = 0.015$ at 1 MHz.

If one wants to use toroid transformers, then obviously a smaller transformer requires less iron for shielding in a magnetic field. Unfortunately other considerations put a lower limit to the transformers size:

(i) Smaller transformers require more turns to reach the same selfinductance. Philips makes 3D3 toroids of OD = 0.5", 0.375", and 0.23". The respective number of turns required to reach a self inductance of 500 μHy at low temperatures is:

OD	# of turns
0.5"	57
0.375"	64
0.25"	97

Note that the transformer coil - in particular the primary wiring - adds at least 2mm to the overall diameter.

(ii) The minimum secondary inductance of 300-500 μHy is given by noise considerations; the parallel resistance

$$R_p = \frac{\omega L_2}{\delta}$$

should be $\geq$ 50 kΩ at frequencies of ν = 2-6 MHZ.

(iii) The coupling factor $k = L_{12} / \sqrt{L_1 L_2}$ of the transformer should be very close to unity. Any deviation produces an inductive termination of the order of (1-k) L_1 where L_1 is the primary inductance of the transformer. As Figures 1 and 2 show, such an inductive termination significantly increases the rise time. Note that while a damping resistor R_D reduces the initial ringing, it also introduces a serial resistance which is scaled up by the transformer and contributes to the serial noise.

Helios uses Toroidal transformers of 0.52" outer diameter, with 55 turns forming the secondary winding. The typical (1-k) is $1\text{-}2 \times 10^{-3}$ and the total primary-to-secondary capacitance is ~ 15 pF. We have built transformers of only slightly lower quality onto 3/8" diameter toroids, with $(1\text{-}k) \sim 2\text{-}3 \times 10^{-3}$ after rounding the sharp corners of the commercial toroids. We believe it will be extremely difficult to build much smaller transformers; somewhere between an OD of 0.3 and 0.4" one hits a "brick wall". In consequence we believe that any shielding tubing for magnetic transformers should have an ID of at least 0.5", and a value of 0.6" seems more conservative.

2. Transformers in Magnetic Field

The tranformer reacts to an external magnetic field by saturation. We measure the effect by measuring the change in secondary selfinductance. Any external magnetic field is most dangerous if it lies in the plane of the toroid. In Figure 3. we show the response of a 3D3 toroid to such an external field. One notes that while the initial

selfinductance at low temperatures is reduced, the saturation process is also somewhat slower. Figure 4. shows the same measurement inside a magnetic shield. Again one sees that the transformer behavior deteriorates at very similar fields at room and LN2 temperatures. From Figure 3. we then conclude that a parallel field of 200 Gauss will begin to affect the performance of the transformer.

We have also investigated the effect of a magnetic field perpendicular to the plane of the transformer torus. We find no transformer degradation at a field of 1 kGauss and a 50% loss of L_2 at 1.3 kGauss. We assume in the following that the transformer orientation is always such that the field does maximum damage.

3) Shielding against a magnetic field.

Any hollow magnetic material will produce a large attenuation of the field until it saturates. However, it also attracts field lines and thus the field at the outer steel surface will be larger than at infinity.

Fortunately, an easy analytical calculation allows one to estimate this effect. Outside the steel the magnetic field is the gradient of a potential ϕ with $\nabla^2\phi = 0$. Thus for a cylinder (Field perpendicular to cylinder)

$$\phi = B_0 \left(r - \frac{a^2}{r}\right) \cos\theta = B_0 \left[x - \frac{a^2 x}{x^2 + y^2}\right] \qquad (1)$$

where a is the cylinder outer radius. For a sphere one has

$$\phi = B_0 \left(r - \frac{a^3}{r^2}\right) P_1(\cos\theta) = B_0 z \left[1 - \frac{a^3}{(x^2+y^2+z^2)^{3/2}}\right] \qquad (2)$$

In both cases B_0 is the field (in x- or z- direction) at infinity. In either case the maximum field on the surface is

$$B_{max} = 2\, B_0 \quad \text{for a cylinder}$$

$$= 3\, B_0 \quad \text{for a sphere}$$

For the following we assume cylindrical geometry. One should note that this is true only if the external magnetic field is approximately perpendicular to the cylinder axis. Fortunately, this will naturally be true in the end caps where the fields are largest.

We have investigated the question whether a single shield is better than multiple shields if one keeps the outermost diameter (and of course the innermost diameter) the same. A single shield provides a maximum of steel which can "shunt" the magnetic field lines. A multiple shield provides attenation at each step, since only the field lines "leaking in" have to be caught and shunted aside by the next inner layer. However, a multiple shield provides less steel if the outer diameter is to stay the same. Figure 5 gives examples how rapidly the field penetrates inside; We show measured maximum field values inside a single shield and inside a double shield of approximately double the total steel thickness. As one can see, once the field becomes measurable, it grows very rapidly. The abscissa is the magnetic field at infinity, calculated from the measured value on the outer surface (we simply divided by two).

Figure 6 shows what value of a "field at infinity" one can tolerate for single shields of various thickness. The parameter "Tir" is the total thickness of steel if the most inside radius is equal to unity. Thus "Tir=1" means, e.g., a single shield of outer diameter equal to twice the inner diameter:

$$OD = (1+Tir)ID$$

Some measured values are also shown. One should note that the calculated magnetic field inside is the maximum value which occurs at 3 and 9 o-clock relative to the direction of the field. The field falls off further inside.

In Figure 7 we illustrate why double shields are no better, and indeed slightly inferior, to single shields of equal total thickness. The magnetic field collected in twice the area around the tube has to be

shunted through the steel. The narrowest cross section in the overall field direction is at 3 o'clock relative to the external field, and thus $\vec{B}$ in the steel is maximal there. However, at that spot $\vec{B}$ is also parallel to the steel surface and therefore it is the H-vector which is continuous. Thus $\vec{H} = \vec{B}/\mu$ is continous across the gap and the $\vec{B}$-field in the inner cylinder is practically the same as in the outer cylinder. One has mainly lost a bit of steel cross section - namely the gap itself.

Finally, Figure 8 shows a magnetic field map calculated by Nobu Unno. The arrangement is for a short coil with flux return as shown in the EOI. Also shown are the locations of the calorimeter modules. If one accepts the results of Figure 6, according to which one can certainly shield 5 kGauss and probably 6-7 kGauss, then the only area of concern would be the large η-region. Even there, however, the field is nowhere larger than 7 kGauss and the hadronic sections are in fields of 5 kGauss or less.

We should estimate here the effect of an inhomogeneous magnetic field. From Eq (1), one concludes that the stray field falls off like r^{-2}. Thus at a distance of 3-4 times the outer shield radius the effect of the shield is 10% or less. One can turn this argument around: as long as the original field gradient (without the shield) was only a few percent over the outer diameter of the shield, the shielding effect should be unchanged.

There is, however, a new effect in an inhomogeneous magnetic field; there will be a force on the shield tube which can become quite substantial. One can estimate an upper limit on such a force as

$$\vec{F} \cong \text{grad}\,(\vec{M} \cdot \vec{B})$$

where as a rough guess we assume B_{max} = 1.5 Tesla everywhere inside the steel to obtain

$$|\vec{M}| = \frac{B_{max}}{\mu_0} V \approx 1.2\ V \qquad (\text{Ampere} - m^2)$$

if V is the steel volume measured in cubic centimeters. Note that the gradient of B is to be measured in Tesla/meter if the final force is to be given in Newton.

4. Various questions

There are two questions on which we comment here:

a) What if the field is not perpendicular to the cylinder axis? Consider a cylinder of inner radius unity and wall thickness t, of large length, but capped off by end caps on both ends. Will the field inside be smaller if the field at infinity is parallel or perpendicular to the axis? We have not had time to do three dimensional calculations - we will do at least one or two in the next month. However, we have a crude estimate valid at inner or low faraway fields

Assume first a field perpendicular to the axis: the flux collected from twice the cylinder area 2(1+t)L (L=length) has to be shunted through a steel wall of area 2tL. Thus the maximum field in the shield is

$$B_{max} \approx 2 * B_0 \frac{2(1+t)}{2t} = \frac{2(1+t)}{t} B_0$$

Now assume that the field is parallel to the axis. The flux from three times the area $\pi(1+t)^2$ has to be shunted through a cylindrical wall of outer radius 1+t and inner radius 1. Thus for a field parallel to the axis:

$$B_{max} = 3 B_0 * \frac{\pi(1+t)^2}{\pi(1+t)^2 - \pi.1} = \frac{3(1+t)^2}{t(2+t)} B_0$$

Thus at t=1 the maximum field inside is 4 B_0 for both orientation. For thinner walls it is better to have the field axial; for thicker walls one would prefer a radial field.

b) What steel should one use? Our calculations are for mild steel with saturation at 21 k Gauss. At low temperatures such steel becomes brittle. On the other hand, 9% Nickel Steel also saturates at 21 k Gauss and has excellent mechanical properties at low temperature; it is recommended as a material for cryogenic applications because it has less internal stresses and the same yield strength as 304 stainless steel.

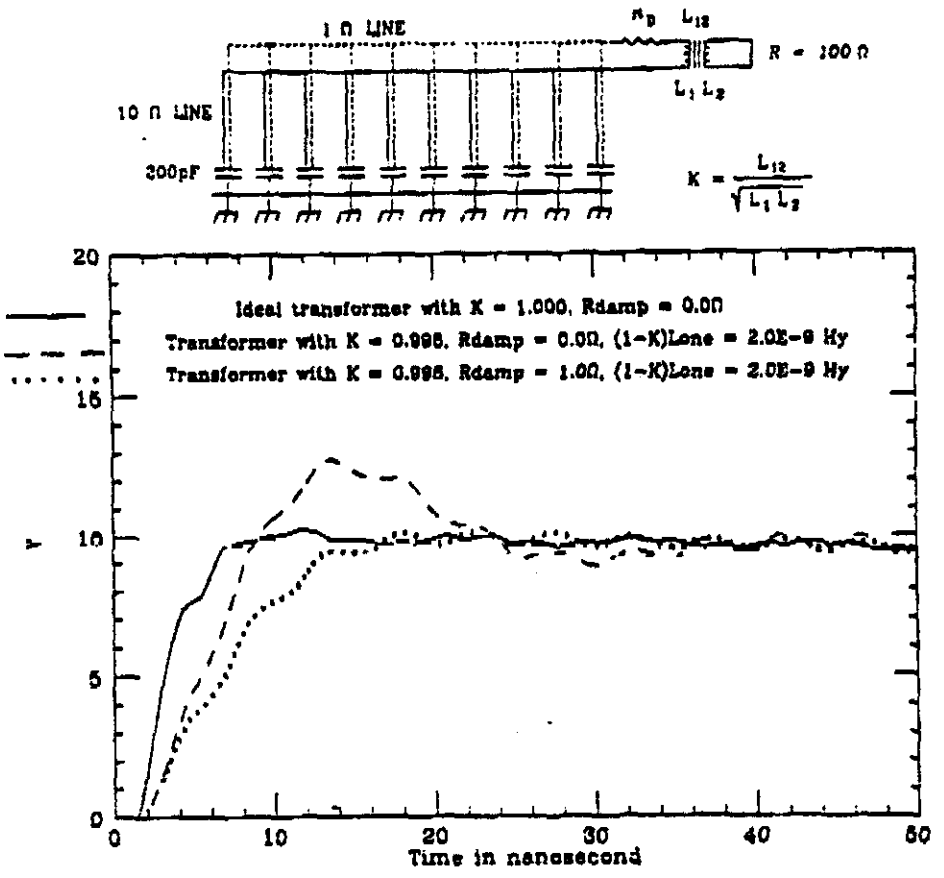

Figure 1: Effect of imperfect transformers on risetime. A damping Resistor R_D reduces ringing, but also lengthens initial risetime.

The parameters are

$$L_1 = 1\ \mu Hy, \qquad L_2 = 100\ \mu Hy$$
$$(1-k) = 0.2 \times 10^{-3}, \qquad R_D = 0,\ 1\Omega$$

Equal charge injected into each detector gap; total detector channel capacitance 2 nF.

The input current pulse has a risetime of 2 nsec.

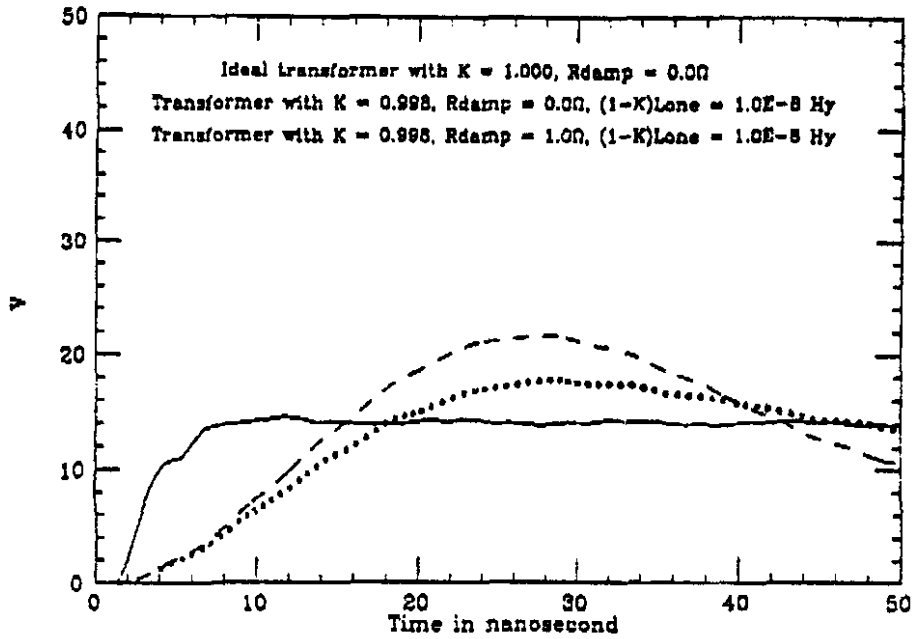

Figure 2: Same as Figure 1, except that now

L_1 = 5 μHy L_2 = 500 μHy

Note that while the perfect transformer's risetime hardly changes, the effect of k<1 is more severe.

NO SHIELD

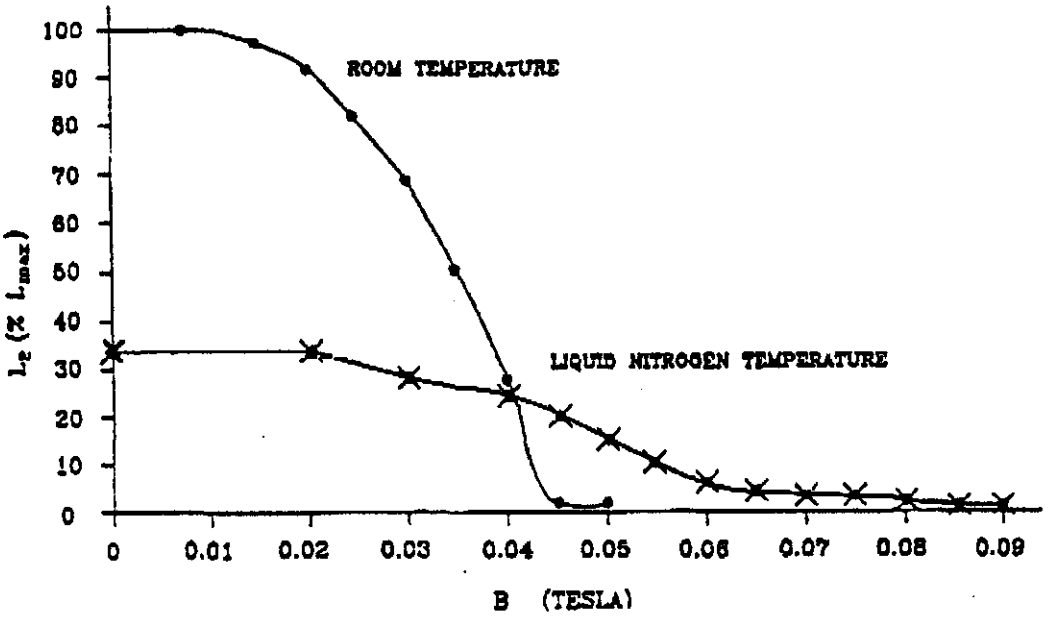

Figure 3: Response of a 3D3 toroid magnet to an external magnetic field lying in the plane of the torus.

SINGLE SHIELD

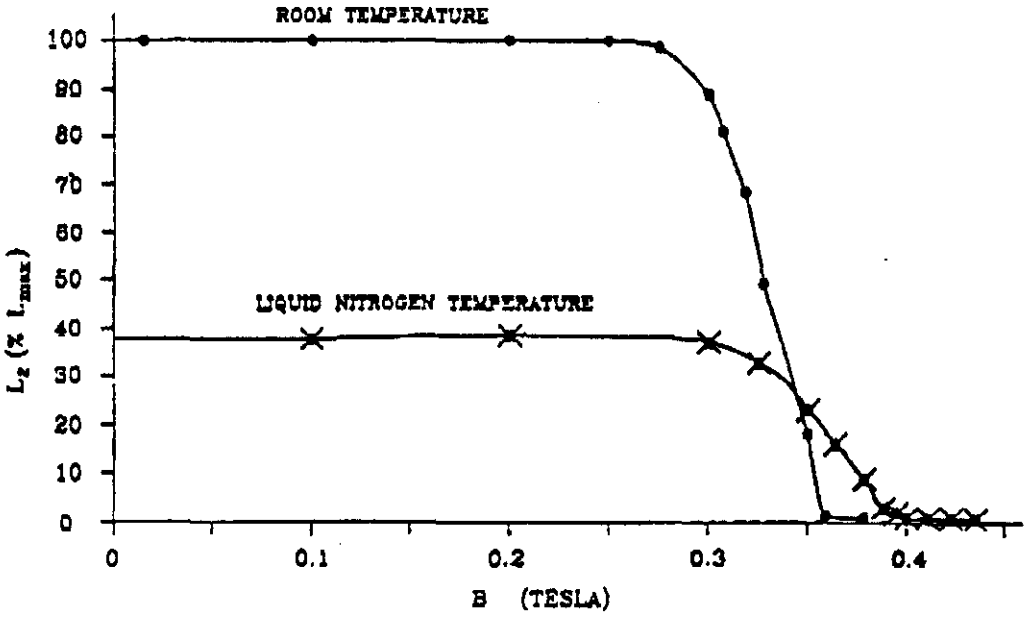

Figure 4: Response of a shielded 3D3 toroid transformer to an external magnetic field. The field is measured near the cylinder. To obtain B_0 divide by -1.6.

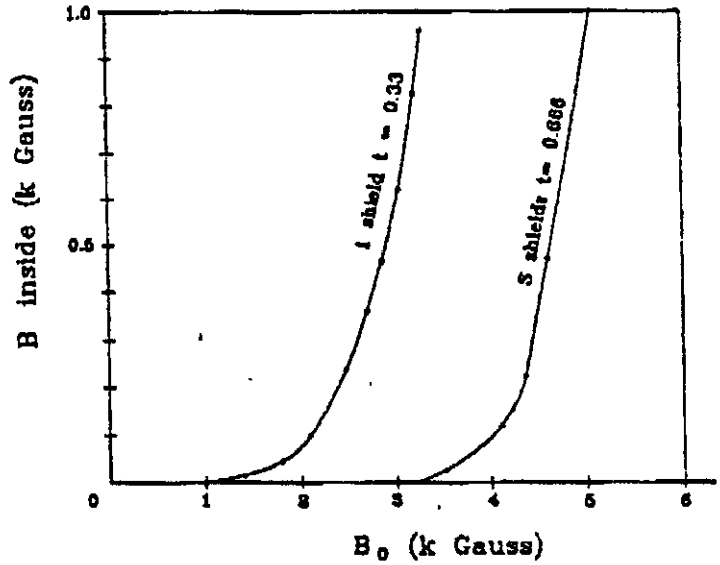

Figure 5: The field inside a single or double shield in function of field at infinity.

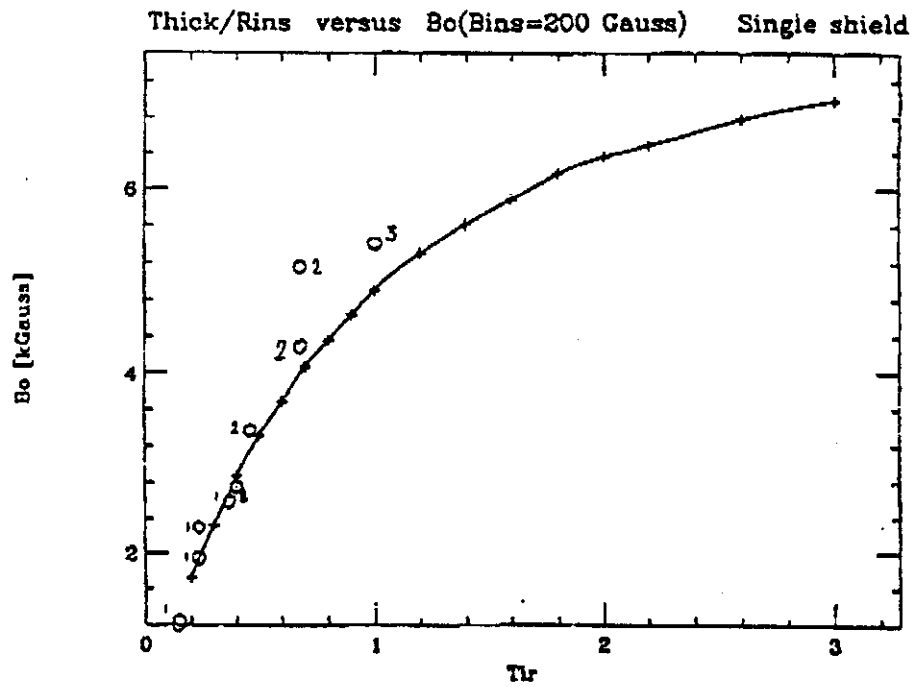

Figure 6: The field of infinity which produces a field of 200 Gauss inside a shield. Tir is the ratio of steel thickness to inner radius. The open circles denote measurements; the numbers indicate the multiplicity of the shield.

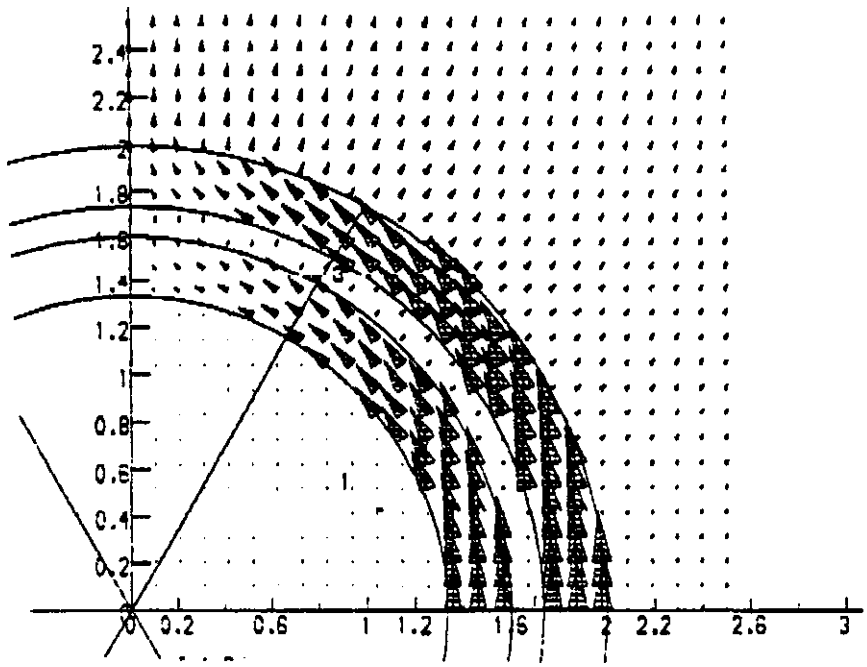

Figure 7: The B-field in a double shield. Note that the maximum field is quite similar inside the two shields.

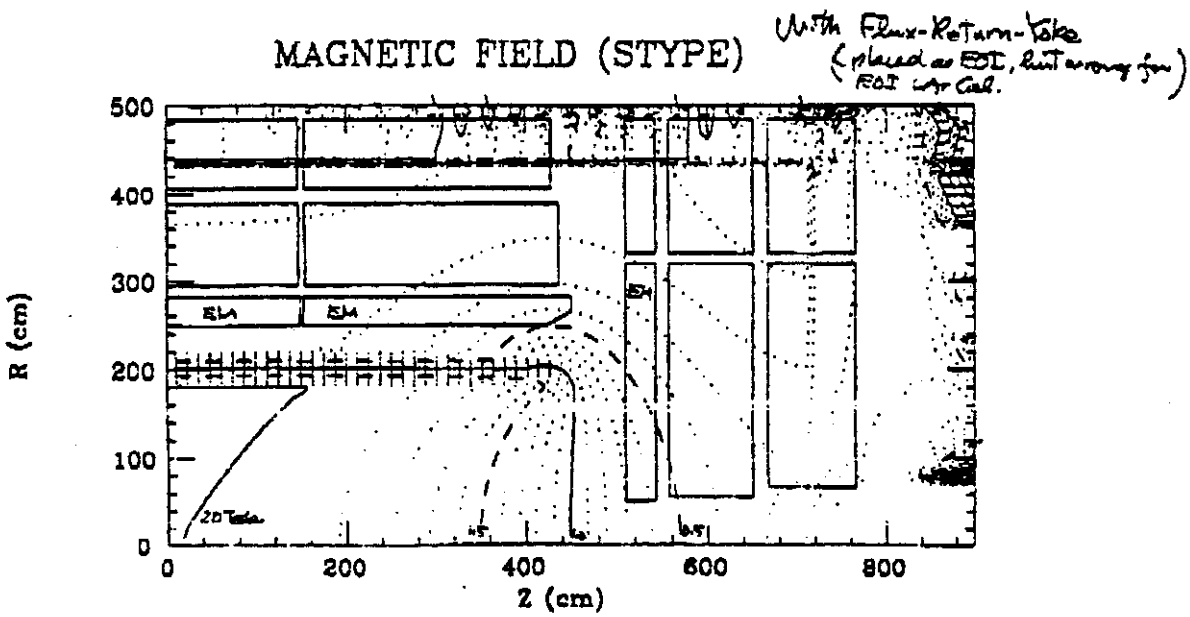

Figure 8: Magnetic field strength in the calorimeter region. The only region where the field strength exceeds 0.6 Tesla is the forward EM section.