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SOLENOIDAL DETECTOR NOTES

Transformers in the SDC Coil

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Abstract : Transformers in a LAr calorimeter at the SDC will have to survive in a magnetic field. We have studied the problem both experimentally and by numerical simulation.

1. INTRODUCTION

The SDC calorimeter surrounds an open superconducting coil which produces a large fringe field as shown in Figure 1. Such a field would saturate the material of a pulse transformer or any other device using ferromagnetic material. Transformers are needed to allow fast readout calorimeter modules with large capacitance. They also serve to reduce the electronic noise due to the detector capacitance.

Any SSC calorimeter must satisfy rather stringent requirements. Independently of the type of detector, the high luminosity of up to $10^{34} cm^{-2} sec^{-1}$ requires fine segmentations and/or tolerance of high rates. The large energy deposited in a typical event of interest puts stringent requirements on linearity and resolution at large energies. The requirements which a calorimeter at the SSC should satisfy can then be summarized as follows:

1) A stochastic resolution of $(0.2 - 0.25)/\sqrt{E}$ for EM showers and $(0.5 - 0.7)/\sqrt{E}$ for hadrons. Here E is measured in GeV.
2) An asymptotic resolution at large energies of $1 - 2\%$ for EM showers and $2 - 3\%$ for hadrons. Also, a linearity of $\leq 5\%$ after corrections.
3) A timing resolution of ≤ 10 nsec, and sufficient segmentation and speed so that event pileup does not degrade the performance even at a luminosity of $10^{34} cm^{-2} sec^{-1}$.

4) Radiation tolerance to 10–20 Mrad/year in the forward ($\eta \geq 3$) region. The neutron flux produced by the calorimeter should be tolerable ($\leq 10^{34}$neutrons/cm^{-2}/year; this requirement practically eliminates Uranium as an absorber material).

5) Transformers should survive a field of 0.7 Tesla, which is the maximum field value at the location of any calorimeter elements. However, the electromagnetic (EM) modules have sufficiently low capacitances so that they could be read out without transformers. The maximum field in the region of the hadron calorimeter (HAD1, HAD2) is less than 0.5T.

If one uses LAr as a calorimeter medium, the high radiation level presents no problem. However, speed, linearity and tolerance of magnetic fields are questions which have to be solved. We discuss here our results.

2. FAST READOUT OF A LAR CALORIMETER

At the SSC individual crossings will be spaced 16 nsec apart. This compares poorly with the typical electron drift time of 400–600 nsec. The Helios detector at CERN has shown that one can clip the output pulses and still obtain adequate signal/noise behavior. However, Helios has individual strips as readout units, with the preamplifiers being mounted inside the liquid on the side of the detector.

This arrangement will not work well in a 4π detector where hermeticity is of paramount value. We have studied an arrangement for the central barrel detector which combines fast readout risetimes with excellent hermeticity. In a typical detector design, many layers of readout gaps are connected to a $1-2\Omega$ impedance readout line. If adequate care is taken to eliminate stray inductances, then the connection to the low impedance line is effectively a short piece of a line of somewhat higher impedance–in our example 10Ω. The 1Ω line, as shown in Figure 2a, is terminated by a transformer. The amplifier input in this case is simulated by a resistor.

The pulse transformer has to be of high quality. One wants as high primary and

secondary inductances as possible, because this minimizes parallel noise due to the transformer[1]. On the other hand, an imperfect transformer presents (in series with an ohmic impedance) an inductance of value $(1-k)L_1$, where $k = \sqrt{L_{12}/L_1 L_2}$ is the coupling coefficient. Figures 2b and 2c show how critical it is that the transformers be of high quality. A suitable compromise is to build transformers with $(1-k) \leq 0.002$ and L_1 of the order of 3–5 μ Henry.

Typical pulse transformer cores consist of ferrite toroids. Transformers suitable for LAr operation must have a low loss factor at 2–6 MHz, and a high permeability in the same frequency range even at cryogenic temperatures of $\approx 85K$. High permeability, wide bandwidth and slow temperature dependence are to some extent contradictory requirements, and so the best available material, Philips $3D3$[2], has at liquid Argon temperatures a permeability of only 280, and a loss factor of $\approx 10^{-4}$ in the desired frequency range. We have performed detailed studies of toroidal transformer performance in a magnetic field. These studies were done both at room and LN2 temperatures. All transformers were wound on 3D3 toroidal cores of 1/2" and 3/8" diameter.

In a magnetic field ferrite toroids become saturated; the effect on the transformer is that all inductances (both mutual and selfinductances) decrease. Figure 3 illustrates the behavior of such a transformer in a magnetic field. Note that even at no field, the permeability of the transformer has dropped by a factor 3 when it is cooled down. Whether at room temperature or at low temperatures, the transformer performance starts to deteriorate if an ambient field of 0.02 Tesla lies in the plane of the toroid. If the field is perpendicular to the plane of the toroid, much higher fields (about 0.13 Tesla) are required before one notices any reduction in transformer performance.

Shielding of transformers is possible if they are enclosed in ferromagnetic material. In Figure 4 we show the behavior of a transformer inside a steel pipe; the external field was perpendicular to the pipe axis. Again one sees a reduction of permeability at zero field. However, the deterioration with magnetic field starts at the same field value for both

temperatures.

In Figure 5 we show the measurement of the shielding effect as one thickens the steel. Again the secondary selfinductance is used as a measure of transformer behavior. We also show the effect of adding another 0.25mm layer of NETIC inside the steel. As one can see, the effect is quite small because NETIC saturates at already very low external fields.

In Figure 6 we show the magnetic field measured inside the same two pipe arrangements described in Figure 5. We measure the maximum of the B–field inside the shield; this maximum value occurs at 90° relative to the external field. The natural variable is t, the ratio of the material thickness to the inner radius. During these tests we sometimes used two concentric pipes, and because of radius tolerances there was always air between the pipes. The t–value listed here are the total thickness of steel divided by the innermost radius.

One might ask whether two concentric pipes with vacuum between them make a better shield than a single pipe of the same thickness. We claim that this is not the case and present Figure 7 in evidence. It shows the calculation of $\vec{B}$ inside and outside two concentric cylinders. The field is largest along the line AA', and there it is parallel to the steel surfaces. This implies that $\vec{H}$ and not $\vec{B}$ is continuous there when one moves along a radius. Therefore $\vec{H}$ on the outer edge of the inner shell is nearly the same as at the inner edge of the outer shell. But then also $\vec{B}$ is the same in the two shields; the B–field "jumps over" the gap. Indeed, one has lost because the space between the two shells could have been also filled with iron, thus allowing the B–flux to be distributed over a larger area. The maximum field value, and therefore saturation effects, would be reduced.

Any hollow ferromagnetic structure not only shields the region inside, but also increases the field on its outer surface. For simple surfaces such as spheres or cylinders, the effect is easily calculated as long as the material is not in saturation. If one inserts a ferromagnetic sphere into a large homogeneous field, the local maximum field is tripled

and the total B-flux into the sphere is

$$\Phi = 3\pi r_2^2 B_o,$$

where r_2 is the outer radius of the sphere and B_o the magnetic field at infinity. For a cylinder with axis perpendicular to the field, the local maximum field is doubled and the total flux per unit length is

$$\Phi = 4 r_2 B_o,$$

where r_2 is the outer radius of the cylinder and B_o again the field at infinity. The same simple calculation also allows an estimate of when the steel will saturate.

Assume that the cylinder or the sphere are hollow and have inner radius r_1. In the absence of any saturation,the magnetic field flux will be maximal at the 3 o'clock point A in Figure 7. The maximum field can be estimated by the condition that the whole flux has to pass through the iron cross section. One then obtains

$$B_{max} = 3\frac{(1+t)^2}{t(2+t)} B_o \tag{1}$$

for the sphere, and

$$B_{max} = 2\frac{1+t}{t} B_o \tag{2}$$

for a cylinder, where in both cases again $t = (r_2 - r_1)/r_1$ is the ratio of material thickness to the inner radius. A reasonable upper limit for B_{max} is about 2 Tesla if one wants no penetration of the field inside the hollow material. Figure 8 shows calculations (crosses) and measurements (circles) of external fields (at infinity) if the inside field is never to exceed 0.02 T for a cylinder made out of mild steel. The measurements (circles) are labelled by the number of separate layers used to obtain the total thickness. As experiment and detailed calculation shows, and as the above estimate already indicates, there is little advantage in layering the material.

We also show (dashes) the approximate fit obtained for B_o from Eq. 2 with $B_{max} = 1.95T$. The approximation is excellent for smaller values of t, and even for $t = 3$ the deviation is less than 5%.

The above calculations are valid only for a single sphere or cylinder with the mag field perpendicular to its axis. With the many shields necessary for a calorimeter in a magnetic detector such as the one proposed by SDC, the problem is more serious since the large amount of individual steel units starts to distort the whole magnetic field pattern. The problem is potentially particularly serious in the central calorimeter barrel, where a long row of nearly touching shields could effectively "short out" the magnetic flux return path, increasing the field in the neighborhood of each shield and driving it into saturation. It is therefore necessary to space the shields away from each other as far as possible. Since their overall size is a multiple of the inner radius, the problem decreases if one can reduce the transformer size. Note that it is only the ratio of the outer to the inner radius which affects the shielding quality; thus reducing the size of the inner opening leads to a reduction of the outside dimensions in the same ratio.

We are presently experimenting with transformers with "binocular cores" which are manufactured by several suppliers. Unfortunately, Philips, which produces the toroidal cores, does not as yet produce binocular cores out of the same material, and is unlikely to do so unless given a large order. Nevertheless, we have found materials which at room temperature have similar properties to 3D3, and for which binocular cores are readily available. We are comparing binocular and toroidal cores made out of such material. Initial results indicate that it is possible to make high quality transformers out of binocular cores. Since these cores are not only easier to wind, but also much smaller than toroids, we are reasonably confident that one can produce transformers with outer diameters of 0.3" or possibly even a bit less.

ACKNOWLEDGEMENTS

This research is being funded by the US Department of Energy, and individual physicists working on this project are also being supported by the US National Science foundation.

REFERENCES AND FOOTNOTES:

1. For a more detailed discussion of fast readouts in ionization calorimeters see e.g. V. Radeka and S. Rescia, NIM A265, 228– 242 (1988).
2. This MnZn ferrite material has been designed specifically for pulse transformers.
3. The two pipes were kept approximately concentric using aluminium spacers.

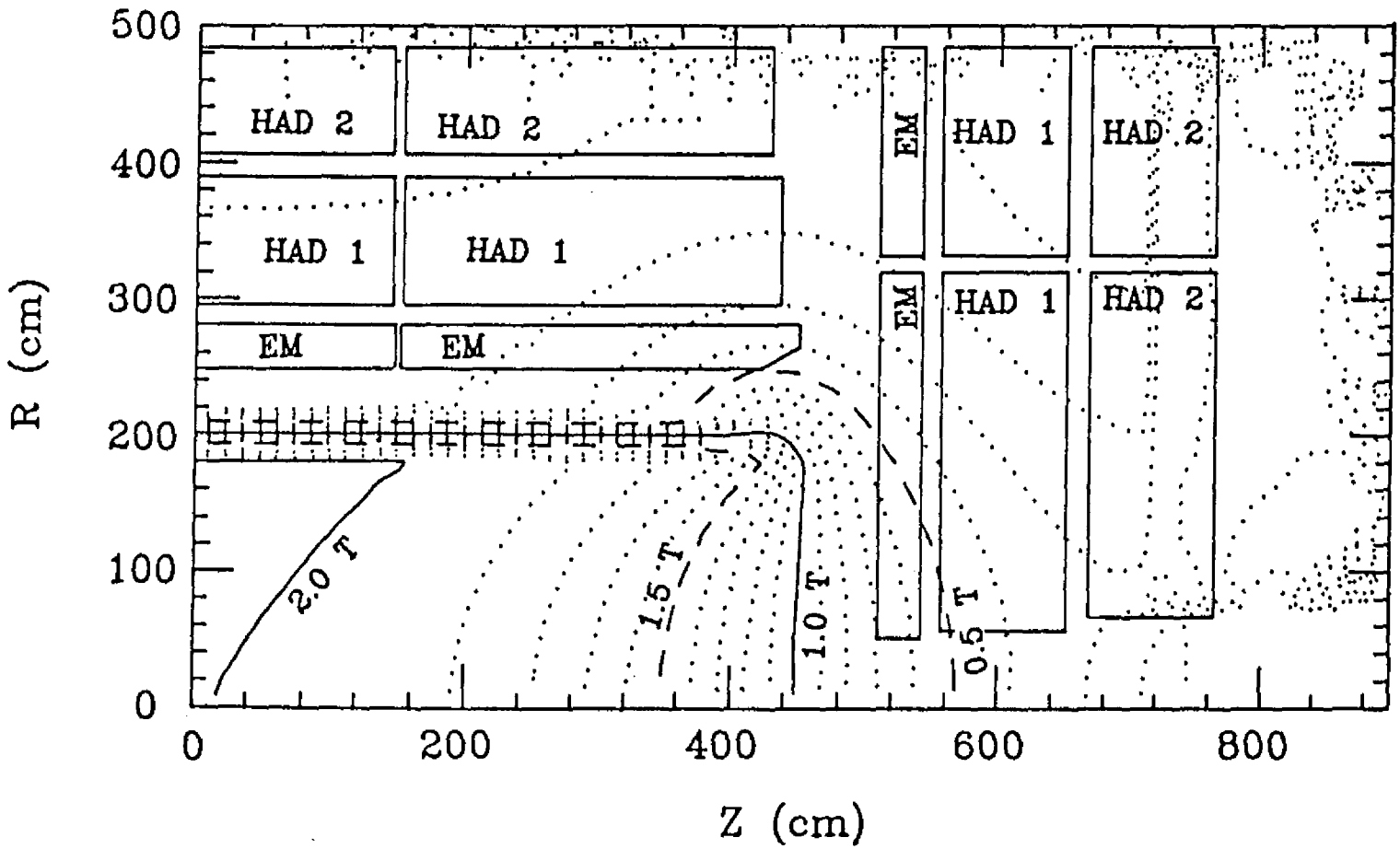

Figure 1: The magnetic field of the SDC superconducting coil, and the arrangement of calorimeter modules.

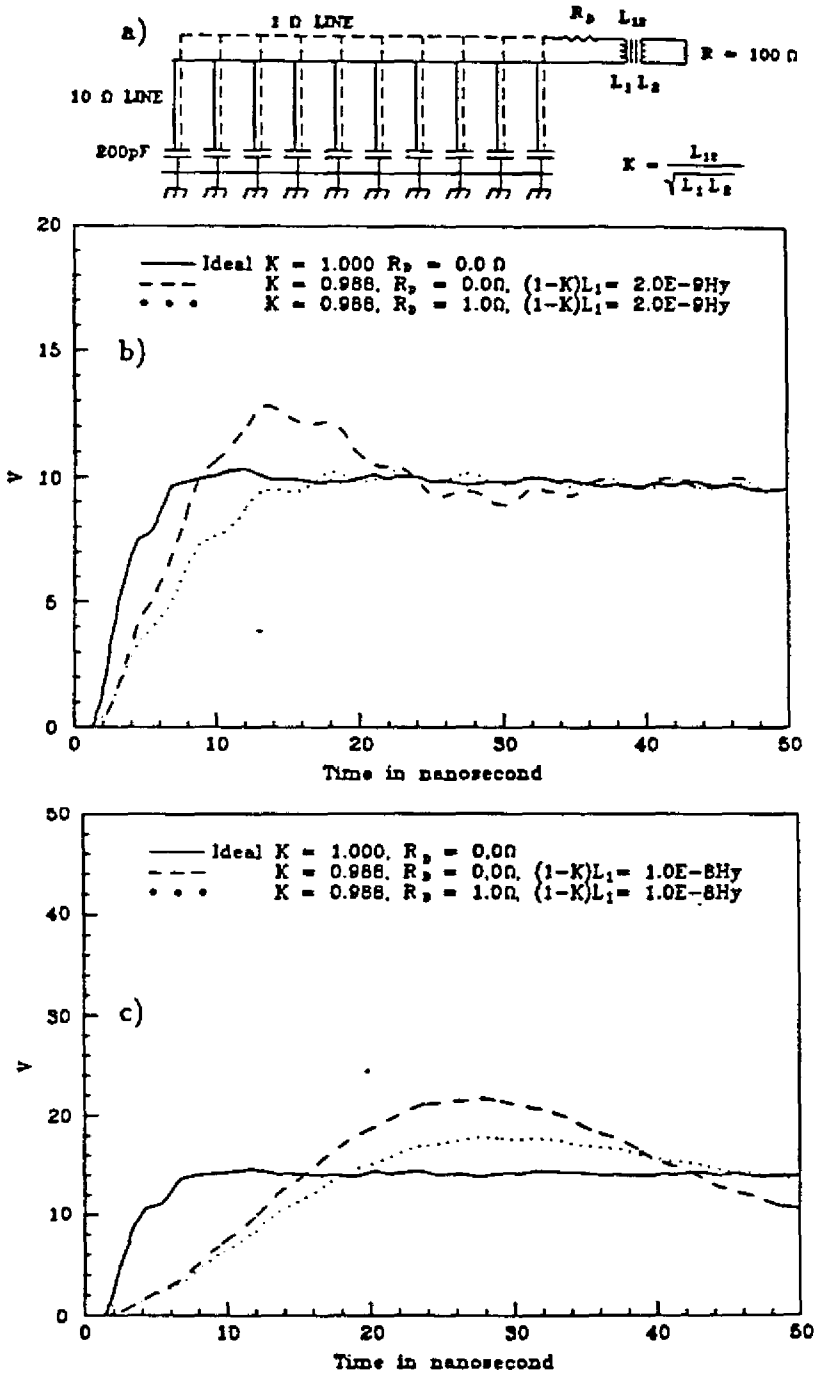

Figure 2: Equivalent Circuit for a calorimeter readout scheme. a) The basic circuit: each detector gap has a capacitance of 200pF. The transformer has a 10:1 ratio. b) Effect of imperfect coupling coefficient K on rise time in a transformer with primary inductance 1μ Hy. c) Same if primary inductance is 5μ Hy. Note effect of damping resistor R_D.

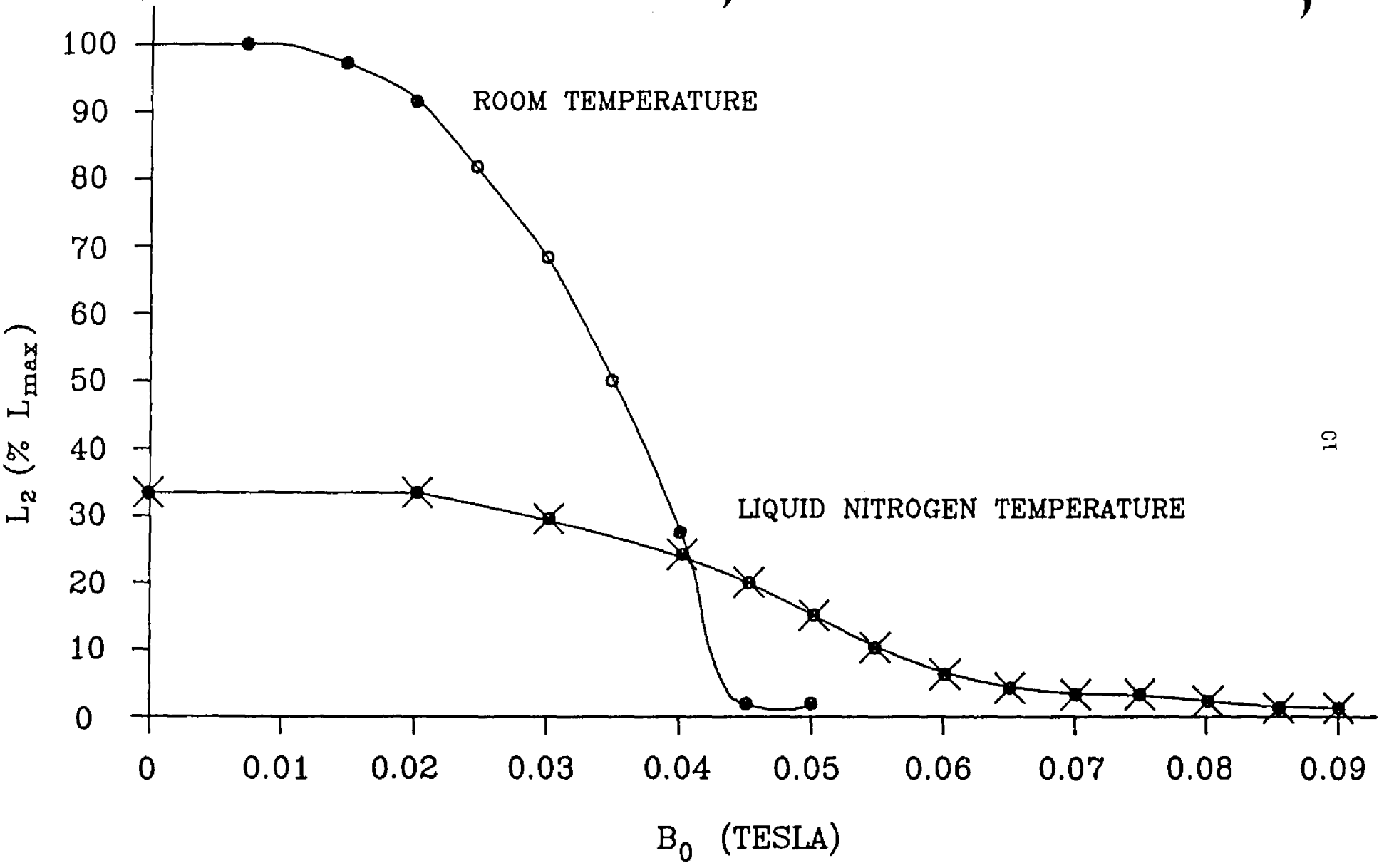

Figure 3: Effect of magnetic field on transformer behavior. The secondary inductance is used as a measure of saturation properties. Note the initial temperature dependence of L_2.

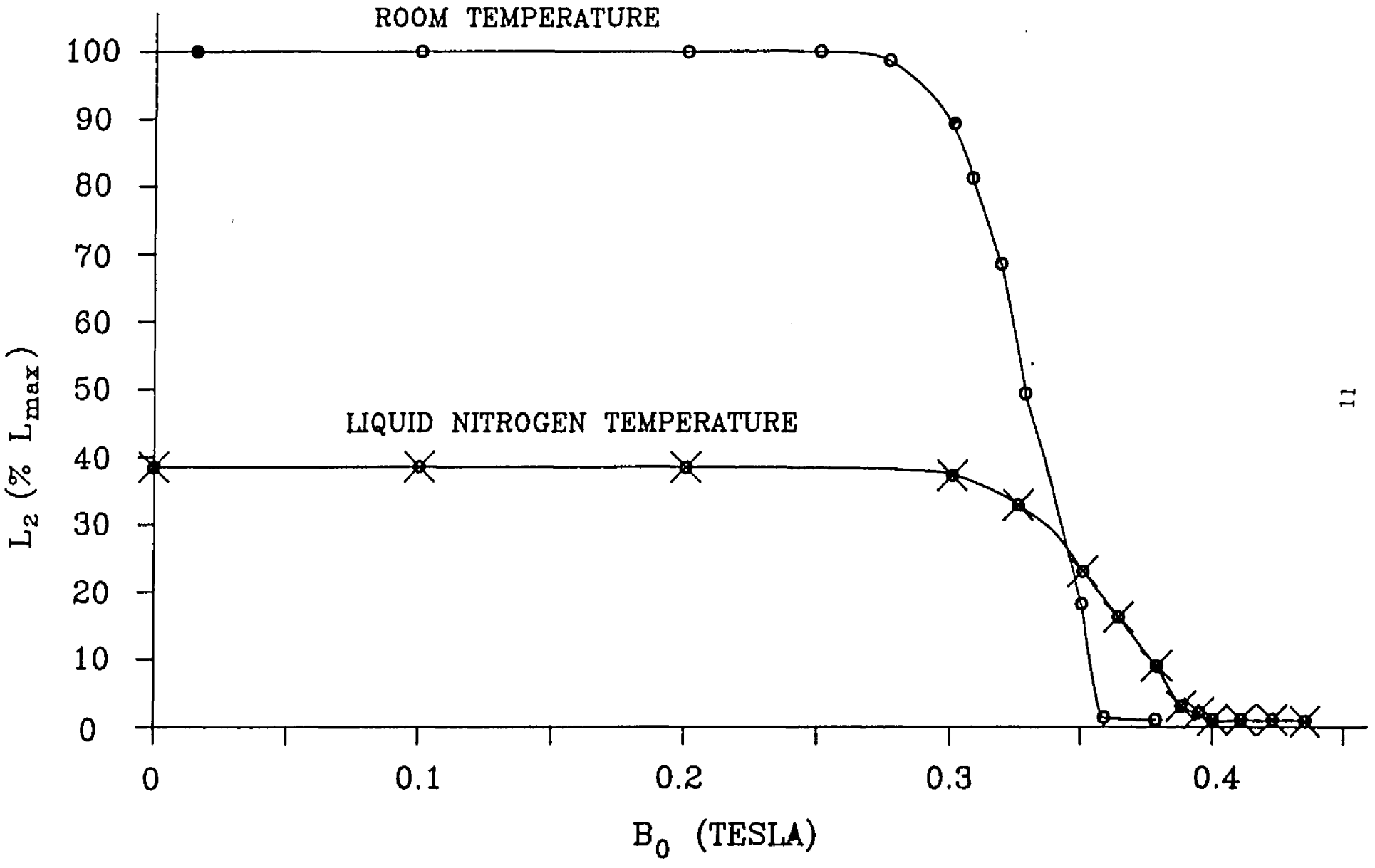

Figure 4: Behavior of the same transformer inside a shield - again at room and LN_2 temperature. Note that the situation starts at the same magnetic field at both temperatures.

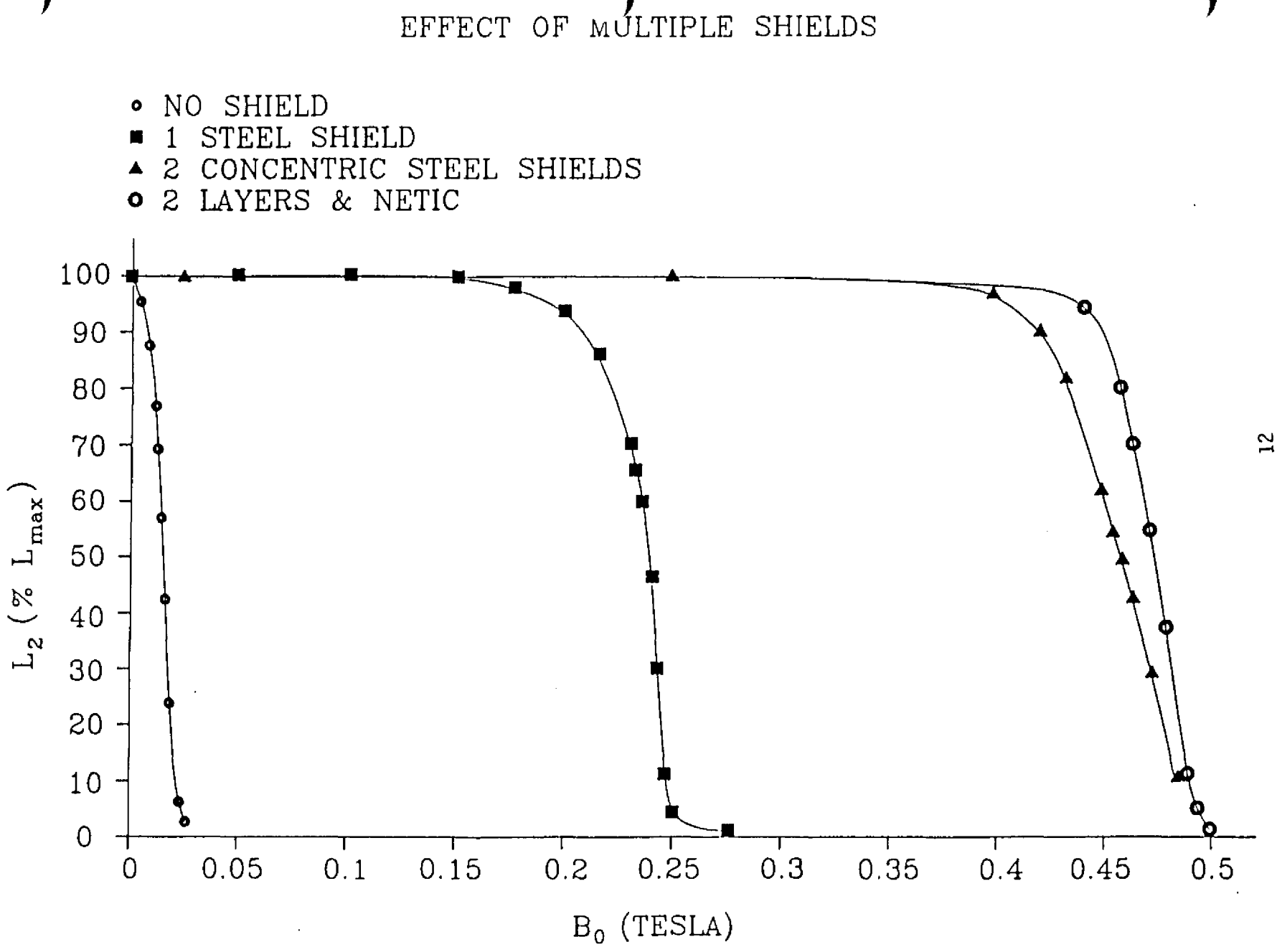

Figure 5: Effect on saturation properties of thickening the shield. Each shield layer had a thickness of 1/3 of the inner radius. Note also the small effect if another layer of NETIC is inserted around the transformer.

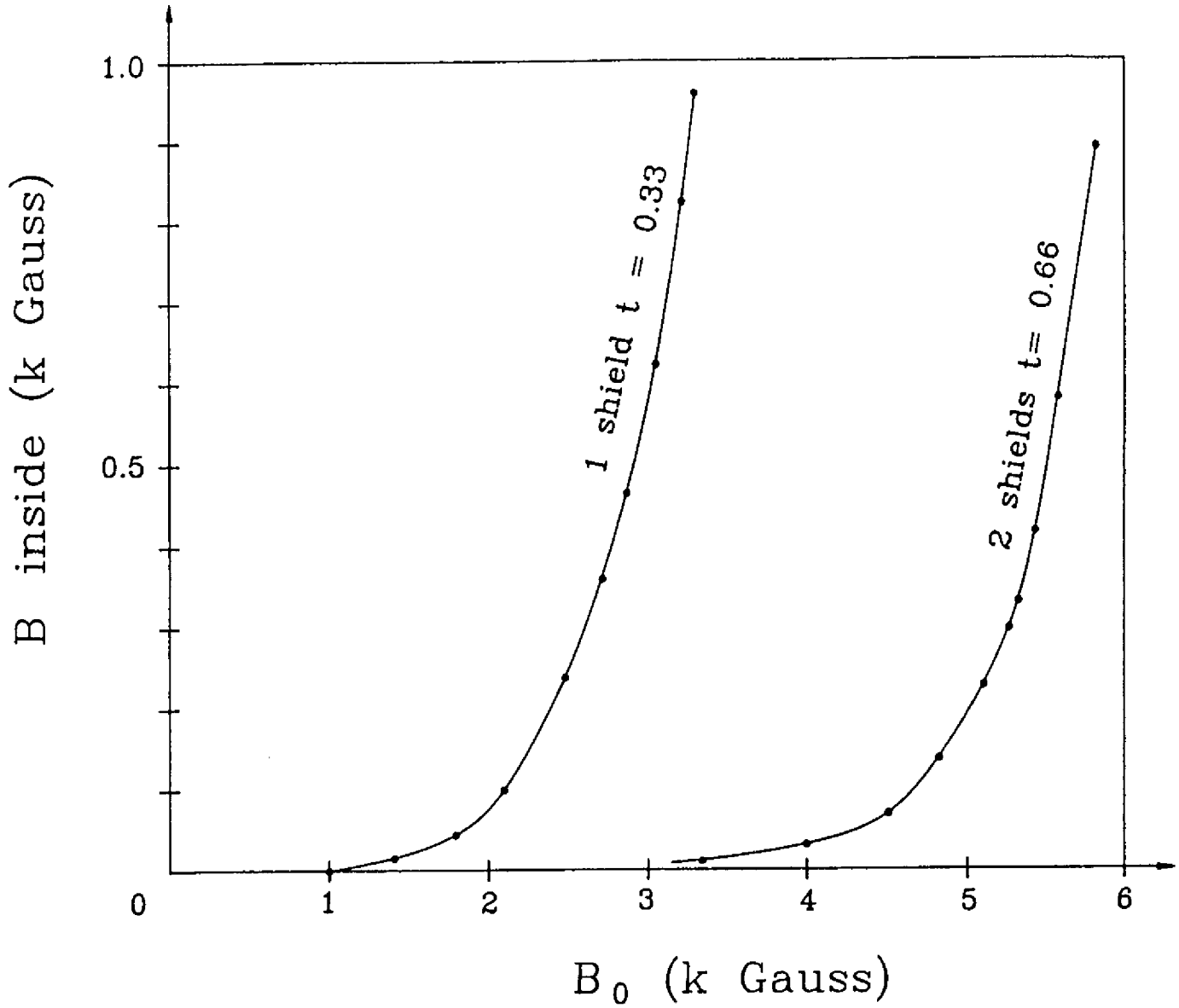

Figure 6: Measurement of magnetic field inside the single or double shield whose effects are shown in Figure 5.

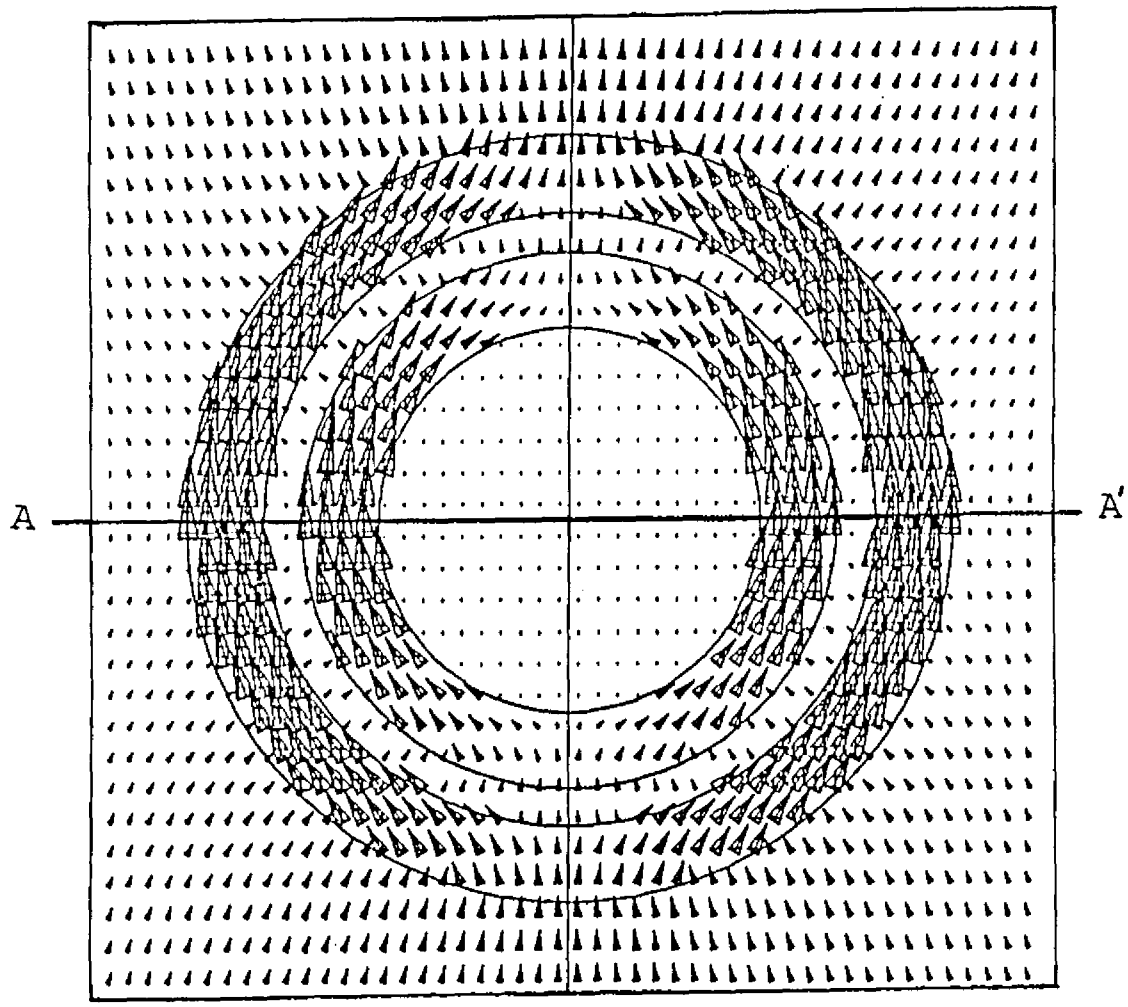

Figure 7: The magnetic field distribution in the steel and in empty space. The largest field occurs in the steel along the line AA'.

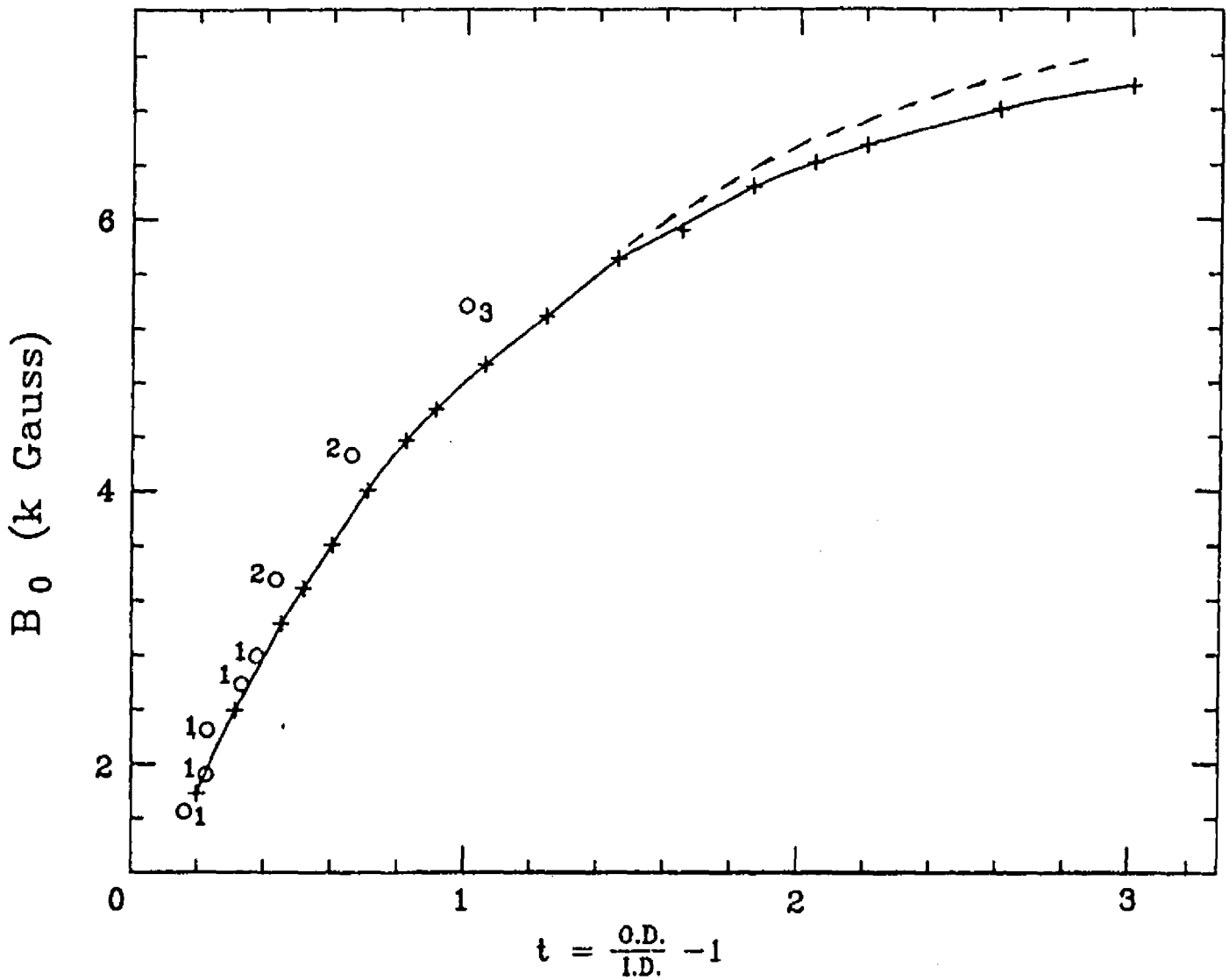

Figure 8: The maximum external perpendicular magnetic field allowed if a transformer inside a pipe of given thickness/inner radius ratio t is not to be affected. Crosses are calculations, circles are measurements, with the digit indicating the number of layers. Also shown as a dashed curve is the fit from Eq. 2.