Title
SHIELDING EFFECT BY THE THIN IRON TUBE

Author
Hosoyama, K.

Publication Date
1983-06-01

LBL-16303
UC-20b c.2

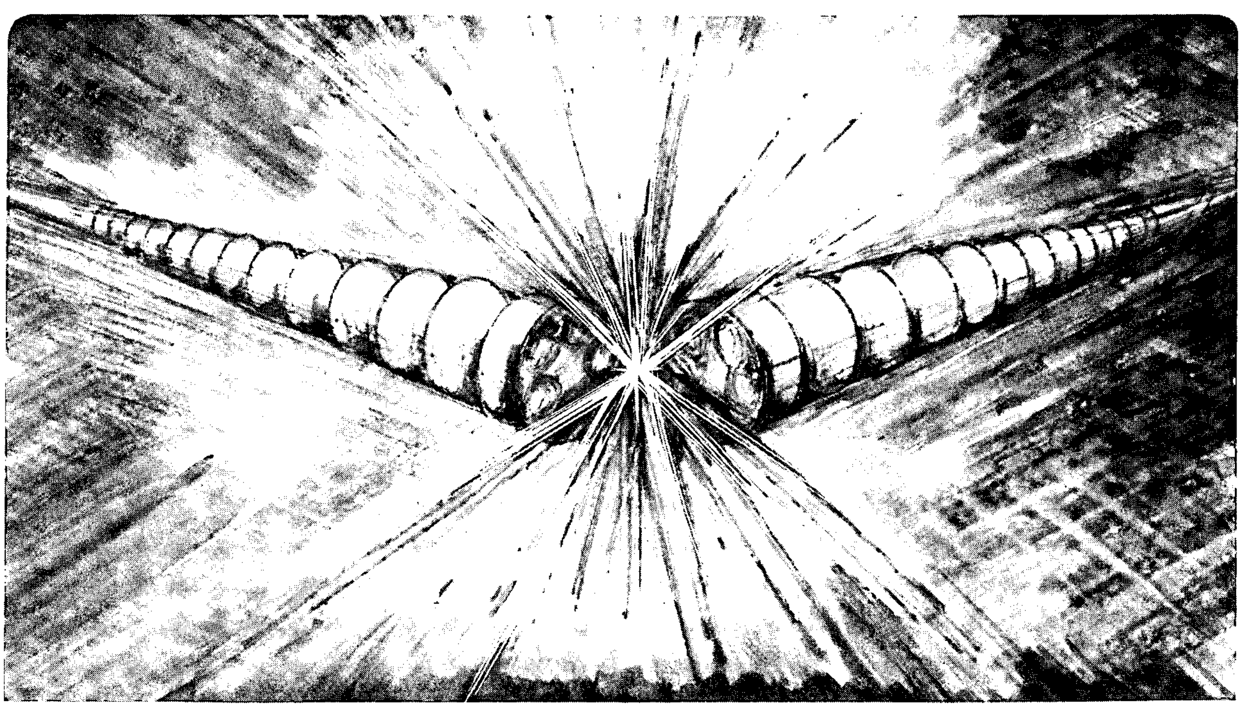
Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

SHIELDING EFFECT BY THE THIN IRON TUBE

K. Hosoyama

June 1983



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

SHIELDING EFFECT BY THE THIN IRON TUBE*

K. Hosoyama

Introduction

Due to an imperfection of electrical joint and the hysteresis loss in the self-correction coil, the current in the self-correction coil decays. Because of this self-correction current decay, during the magnet operation, we must reset and refresh the self-correction current at some time intervals. The reset of the self-correction current is performed by heating up a part of the self-correction coil and making a normal part and dumping the self-correction current to zero and after that cool down again to make the superconducting state under the high multipole components free condition. If we perform the reset procedure of self-correction coil at higher multi-components not free condition then these higher multi-components will be trapped by self-correction coils. From this point of view we must notice the following fact that after excitation of the main coil, even in the zero current in the mail coil, there exists the residual magnetic field due to the persistent current in the main coil superconducting wires. Especially in the case of high field magnet (8T ~ 10T), because a lot of superconductor is used to produce high magnetic field, the effect of residual higher multipole components is a severe problem.

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U. S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

To get the higher multi-components free space in the coil, we insert a thin iron tube inside the main coil, outside the self-correction coil. (See Figure 1.) At very low magnetic field, even if we use a thin soft iron tube, we will be able to get enough shielding effect. On the other hand, at very high magnetic field, the iron tube will saturate completely and its permeability μ decreases from about 4000 μ_0 to lower than 2 μ_0. This means the iron shielding tube becomes compltely transparent against the magnetic flux at high field.

We discuss here the shielding effect of a thin iron tube in very low field and very high field, by a simple analytical calculation and saturation effects of a thin iron tube in medium magnetic field by the numerical calculation using the computer code "POISSON".

Analytical Solution of Shielding Effect by Iron Tube

To estimate the shielding effect of thin iron tube, we make a simple model. Figure 1 shows the shielding iron tube, main coil and self-correction coil. For simplicity, we assume a current sheet at $r = R$ for main coil and iron $(\mu = \infty)$ sheild at $r = b$ for a return Yoke and a thin iron tube, inner radius a_1 and outer radius a_2, permeability μ for shielding of higher multi-components at very low magnetic field. The self-correction coil is installed inside the iron tube.

If we assume the permeability $\mu = \text{constant}$ in the shielding iron, we will be able to calculate the shielding effect analytically. (See Appendix.)

We define the shielding factor F as follows:

$$F = \frac{B_0 \text{ (without iron tube)}}{B_0 \text{ (with iron tube)}} \qquad (1)$$

LBL-16303
SUMAG-96

SHIELDING EFFECT BY THE THIN IRON TUBE*

Kenji Hosoyama

June 1983

Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U. S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

where B_0 is the magnetic flux density inside the iron tube.

The magnetic flux density B_0 in the center area of this model magnet is expressed as follows:

$$Br(r,\theta) = -A_n^I \sin(n\theta) \tag{2}$$

$$B\theta(r,\theta) = -A_n^I \cos(n\theta) \tag{3}$$

where the coefficients A_n^I are given, (see Appendix.)

$$A_n^I(\text{without iron tube}) = \frac{\mu_0 I_0}{2nR^{n-1}} \left\{1 + \left(\frac{R}{b}\right)^{2n}\right\} \tag{4}$$

$$A_n^I(\text{with iron tube}) = \frac{\mu_0 I_0}{2nR^{n-1}} \left\{1 + \left(\frac{R}{b}\right)^{2n}\right\}$$

$$\times \frac{4}{2\left\{1 + \left(\frac{a_1}{a_2}\right)^{2n}\right\} + \left(\frac{\mu}{\mu_0} + \frac{\mu_0}{\mu}\right)\left\{1 - \left(\frac{a_1}{a_2}\right)^{2n}\right\} - \left(\frac{\mu}{\mu_0} - \frac{\mu_0}{\mu}\right)\left\{\left(\frac{a_2}{b}\right)^{2n} - \left(\frac{a_1}{b}\right)^{2n}\right\}} \tag{5}$$

From the Eqs. (1) ~ (5), we get the following equation for shielding factor F.

$$F = \frac{2\left\{1 + \left(\frac{a_1}{a_2}\right)^{2n}\right\} + \left(\frac{\mu}{\mu_0} + \frac{\mu_0}{\mu}\right)\left\{1 - \left(\frac{a_1}{a_2}\right)^{2n}\right\} - \left(\frac{\mu}{\mu_0} - \frac{\mu_0}{\mu}\right)\left\{\left(\frac{a_2}{b}\right)^{2n} - \left(\frac{a_1}{b}\right)^{2n}\right\}}{4} \tag{6}$$

where

a_1: inner radius of iron shielding tube

a_2: outer radius of iron shielding tube

R: radius of main coil current sheet

b: radius of iron ($\mu=\infty$) shielding Yoke

and we assumed the current distribution

$$i(\theta) = I_0 \cos(n\theta) \tag{7}$$

for the main coil current sheet, n is the multipolarity of magnetic field discussing.

Shielding Effect at Low Field

At very low field, because of no saturation effect in the iron tube, we can calculate the shielding factor F by using Eq. (6). Figure 2 shows permeability dependence of the shielding factor F of Eq. (6), where iron tube inner radius a_1 = 2.5 cm, main coil current sheet radius R = 4 cm, iron ($\mu = \infty$) shielding Yoke radius b = 5 cm was assumed, n = 1,2,3,5 represent the dipole, quadrupole, sextupole and decapole fields respectively. From Figure 2 it is clear that we can get more shielding effect for higher multipole magnetic field.

If we use the soft iron for shielding tube, the permeability of soft iron will be about 4000 μ_0 at low magnetic field. (See Figure 4.) For the dipole magnetic field, (n = 1), shielding factor F are 15, 30, 55 for iron tube thickness t = 0.25, 0.5, 1.0 mm respectively. For the sextupole magnetic field (n = 3), shielding factor F are 58, 110, 200 for iron tube thickness $t = 0.25, 0.5, 1.0$ mm respectively. Because the main component of residual magnetic field due to the persistent current in the superconductor is sextupole, the shielding factor F for $n = 3$ is important. If we use the thickness $t = 0.25$ mm soft iron tube, the sextupole component decreases to 1/58 inside the iron shielding tube.

Figure 3 shows the iron tube thickness dependence of shielding factor F for two materials: $\mu = 4000\ \mu_0$ typical soft iron and $\mu = 12000\ \mu_0$ Permayllo® cases. If we expect shielding effect $F = 30$ for sextupole component $(n = 3)$, from the Figure 3, the thickness of iron tube required are about 0.13 mm and 0.04 mm for $\mu = 4000\ \mu_0$ soft iron and $\mu = 12000\ \mu_0$ Permayllo® case respectively.

Magnetic Flux Density in the Iron

In the discussion of shielding effect above, we assume the permeability μ of iron is constant. But by the saturation effect of iron (see Figure 4), permeability μ starts decreasing at about 1 Tesla. Because the iron tube in the magnetic field absorbs almost all magnetic flux lines, especially in the case of low magnetic field (see Figure 7(b),(d)), the magnetic flux density B in the iron tube becomes high values even in low external magnetic field. Figure 5 shows the maximum magnetic flux density B_{max} in the iron tube against external dipole $(n = 1)$ magnetic field. If we set $B_{max} = 10^4$ Gauss (1 Tesla) for a critical value of saturation, the external magnetic field B_0 (without iron tube) corresponding to this will be about 40 Gauss for $t = 0.25$ mm case. This means that if we use the 0.25 mm thickness soft iron tube, then up to 40 Gauss of external magnetic field we can get the shielding effect discussed above without saturation effect. Considering the fact that the strength of residual magnetic field by the persistent current in the superconducting wire is about 20 Gauss, this 0.25 mm thickness soft iron tube gives us enough shielding effect.

Shielding Effect at High Field

If the permeability μ approaches to μ_0, this corresponds to complete saturation of iron tube in very high magnetic field, the shielding factor F will approach to 1. This means that under the high magnetic field the iron tube becomes transparent against the magnetic flux. Figure 6 shows the shielding factor F at low permeability μ values. For the higher magnetic field B (more than 5T), because the permeability μ is less than $2\mu_0$ (see Figure 4), the shielding factor F is about 1.001 for t = 0.5 mm case (see Figure 6). That is this shielding tube has no effect for high magnetic field.

Saturation Effect of Iron Tube

We discussed the shielding effect by iron tube at very low magnetic field (less than $B_{external} \approx 40$ Gauss) and at high magnetic field (higher than $B_{external} \approx 4T$) by using a simple analytical calculation. Because of saturation effect in the iron tube, higher multipole error field, especially sextupole and decapole are produced between about 40 Gauss and 4T. Of course self-correction coils inside the iron shielding tube cancel out these error fields, but it is very important to know the strength of these higher multipole components. We discuss here about the saturation effect of thin iron tube in the medium magnetic field. We use the computer code "POISSON" to take into account the saturation effect of iron.

Calculation by the Computer Code "POISSON"

The geometry used for the "POISSON" is same as for the analytical calculation (see Figure 1). Figure 7(a) shows the triangular mesh for the numerical calculation of "POISSON".

Results of Numerical Calculations

(1) Field Profile

To get the idea of how to magnetic field penetrate into the iron tube, we show the magnetic field profile of different excitation stage (see Figure 7(b)~(k)).

At very low excitation current (total current = 100 A), the iron shielding tube does not saturate and shields the external magnetic field (see Figure 7(b)). Because of no saturation inside the iron, magnetic field lines inside the shielding tube are completely parallel (see Figure 7(c)). According to the increase of excitation current, the iron tube begins to saturate and saturation effect appears (see Figure 7(e)). At very high excitation current, the iron tube saturates so much that shielding effect decreases; the magnetic flux lines penetrate into the inside of the iron tube easily and field uniformity is improved again (Figures 7(j),(k)).

(2) Excitation Curves

Figure 8 shows the magnetic field strength B_0 at center (inside the shielding iron tube) as a function of main coil total current. At low excitation current, the magnetic field B_0 is very low by the iron tube shielding effect, but according to the increase of excitation current, the saturation effect in the iron starts and magnetic flux penetrate into the inside of iron tube rapidly and continues until iron tube reaches to the enough saturation.

(3) Coefficients of Sextupole and Decapole by the Saturation Effect of Shielding Effect

Figure 9 shows the sextupole and decapole coefficients b_2, b_4 of magnetic field inside the iron shielding tube against excitation current. We define the sextupole and decapole coefficients b_i following manner:

$$B = B_0 \; 1 + b_1 x + b_2 x^2 + b_3 x^3 + b_4 x^4 + \ldots$$

$$x : [\mathrm{cm}]$$

where b_1, b_2, b_4 are coefficients for quadrupole, sextupole, decapole, respectively.

At low excitation current, there is no saturation in the iron tube so we can expect the enough shielding effect. But according to the increase of excitation current, large sextupole b_2 and decapole b_4 components appear due to the saturation of iron shielding tube and continue until the iron tube reaches to the enough saturation.

To check the thickness dependence of it, we calculate three cases (t=1.0, 0.5, 0.25 mm). By using the "POISSON", it is difficult to calculate the very thin iron tube case. So that, for easy to calculate, instead of direct solution of $t = 0.5$, 0.25 mm shielding tube, we change the stacking factor of iron shielding tube from 1.0 to 0.5 and 0.25 in the $t = 1$ mm shielding iron tube geometry.

By reducing the thickness of iron tube, sextupole component b_2 and decapole component b_4 peaks shift to lower excitation current, but these strengths do not change so much.

From Figure 9 we can estimate the required maximum capacity of self-correction coil to correct the sextupole due to the saturation; at 0.1 T sextupole coefficient b_2 are $5x10^{-2}$, $2.5x10^{-2}$, $1,2x10^{-2}$ for t=1, 0.5, 0.25 mm respectively, these b_2 values are comparable to $1x10^{-3}$, $0.5x10^{-3}$, $0.24x10^{-3}$ due to the error field at the 5 T.

Conclusion

To get the higher multipole components free space in the coil, it is very useful to use the thin soft iron tube. From the standpoint of complete shielding, it is better to use the rather thick shielding tube (about 1 mm), but from the standpoint of saturation effect of iron tube it is better to use the thin shielding tube. If we choose the t = 0.125 mm soft iron for shielding tube, we will get the enough shielding effect. ($F \approx 25$ for sextupole $n = 3$) and equivalent b_2 value at 5 T due to the saturation effect will be about $1.2x10^{-4}$. If we assume the $\Delta B/B_0 = 10^{-3}$ at $r = 2$ cm for the amount of correction by self-correction coil at 5 T due to the error field then the b_2 value will be $2.5x10^{-4}$. The self-correction current due to saturation effect of shielding tube is about a half of the current due to the error field. And if we take into account the fact that in the case of saturation effect of shielding tube the self-correction coil works at very low field, we will be able to expect higher critical current I_c there, that is the saturation effect of the 0.125 mm thick shielding iron tube is easily corrected by the self-correction coil.

FIGURE CAPTIONS

Figure 1. The geometry of self-correction coil, shielding iron tube and main coil.

Figure 2. Permeability dependence of shielding factor F at low magnetic field.

Figure 3. Shielding iron tube thickness dependence of shielding factor F at low magnetic field.

Figure 4. Magnetic flux density B dependence of permeability μ of soft iron.

Figure 5. Maximum magnetic field B_{max} in the iron tube.

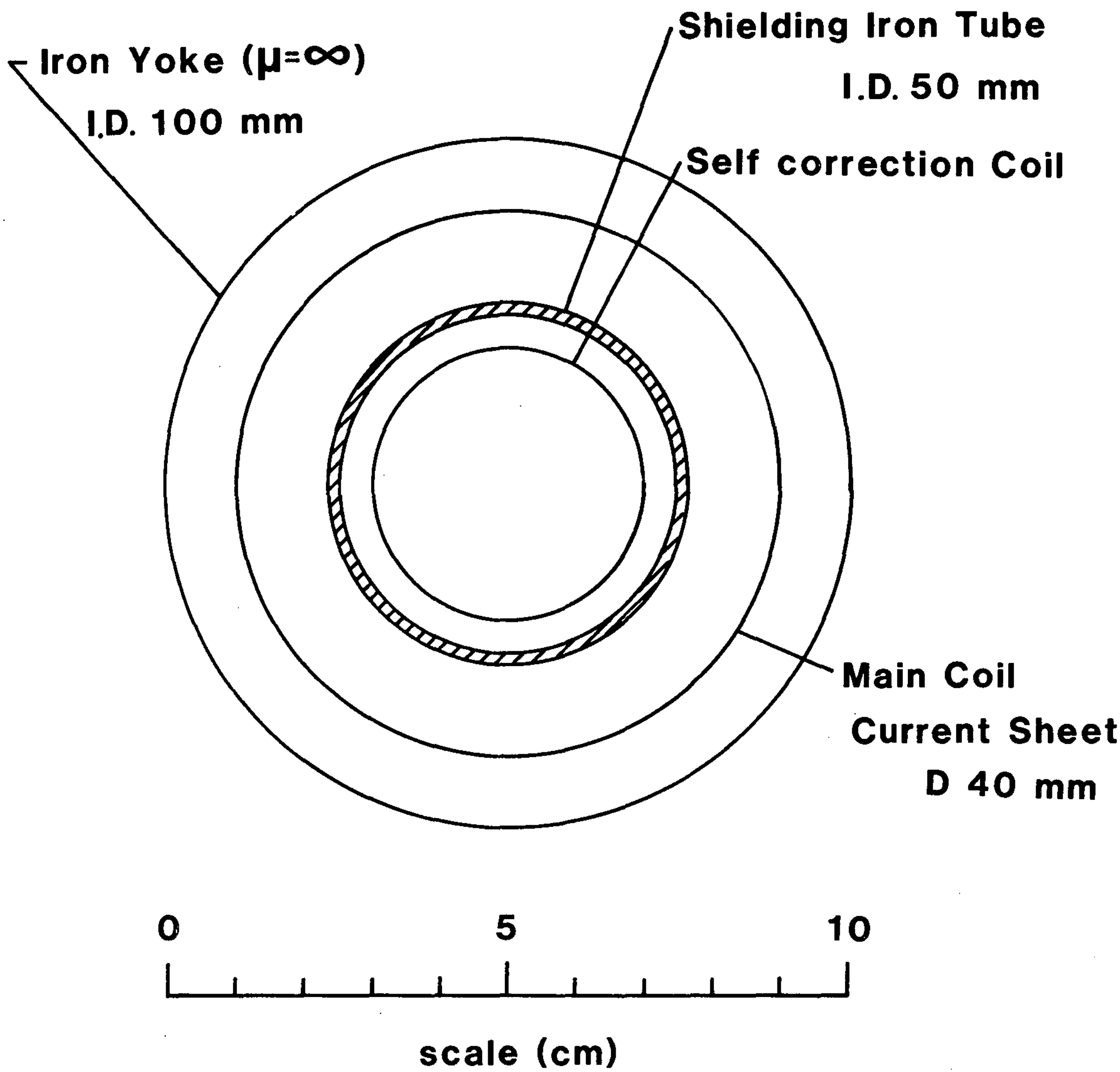
Figure 6. Shielding factor F at high magnetic field.

Figure 7. (a) Triangle mesh for numerical calculation.

(b)~(k) Magnetic flux line in the magnet.

Figure 8. Excitation curves (magnetic field strength inside the iron shielding tube against the total current in the main dipole coil).

Figure 9. Excitation current dependence of sextupole and decapole coefficients b_2 and b_4 by the saturation of iron shielding tube.



XBL 837-10596

Fig. 1

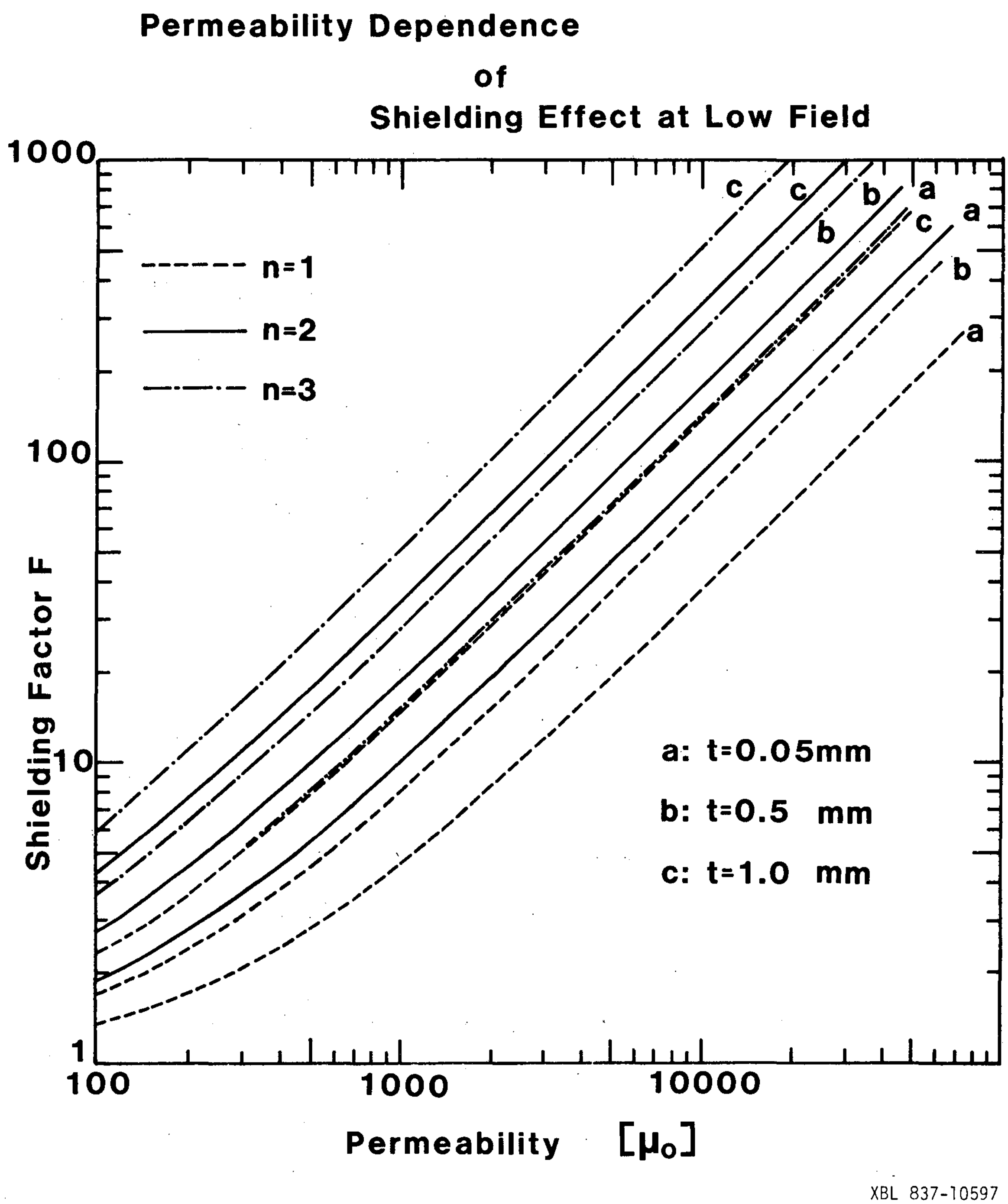
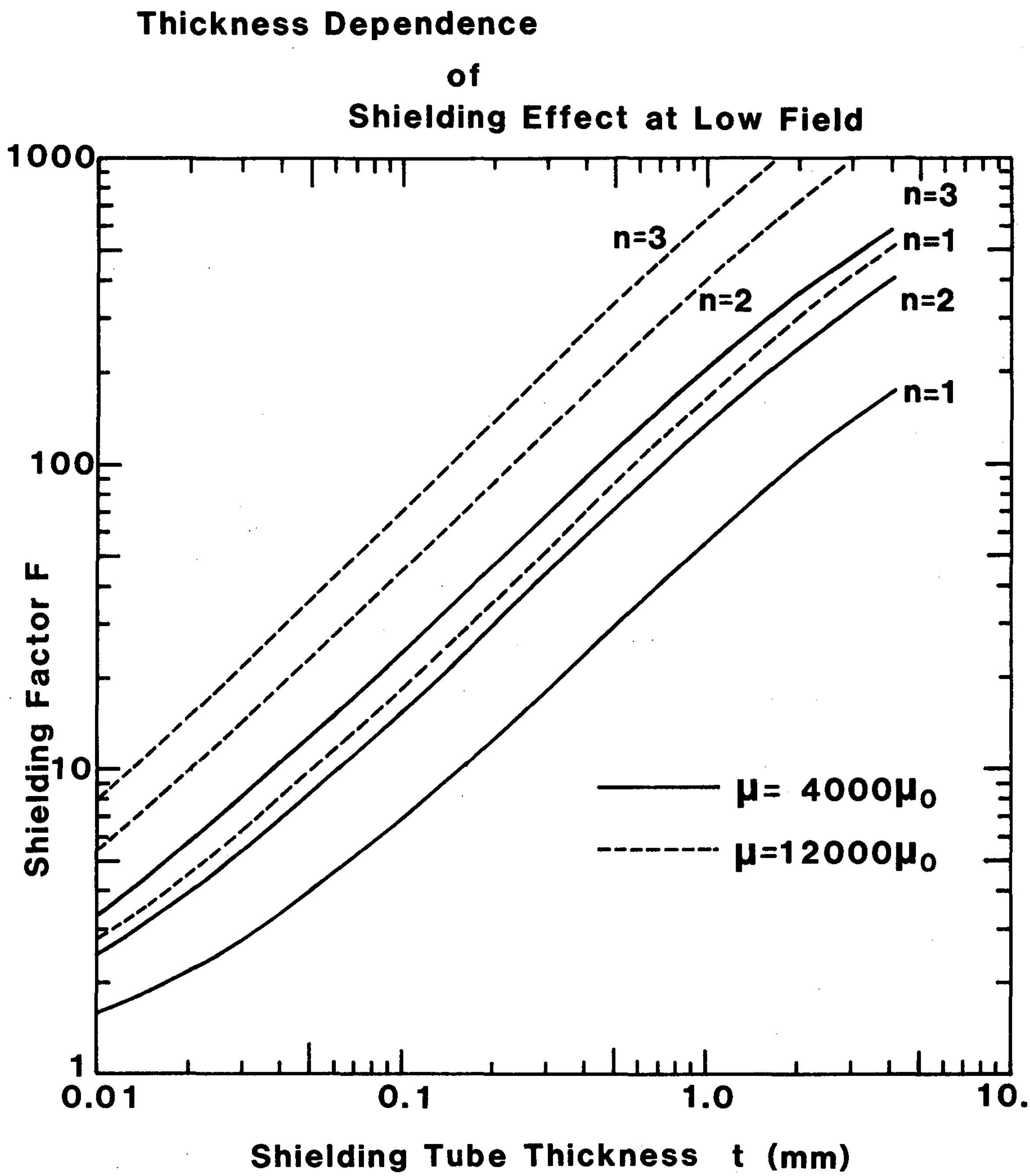
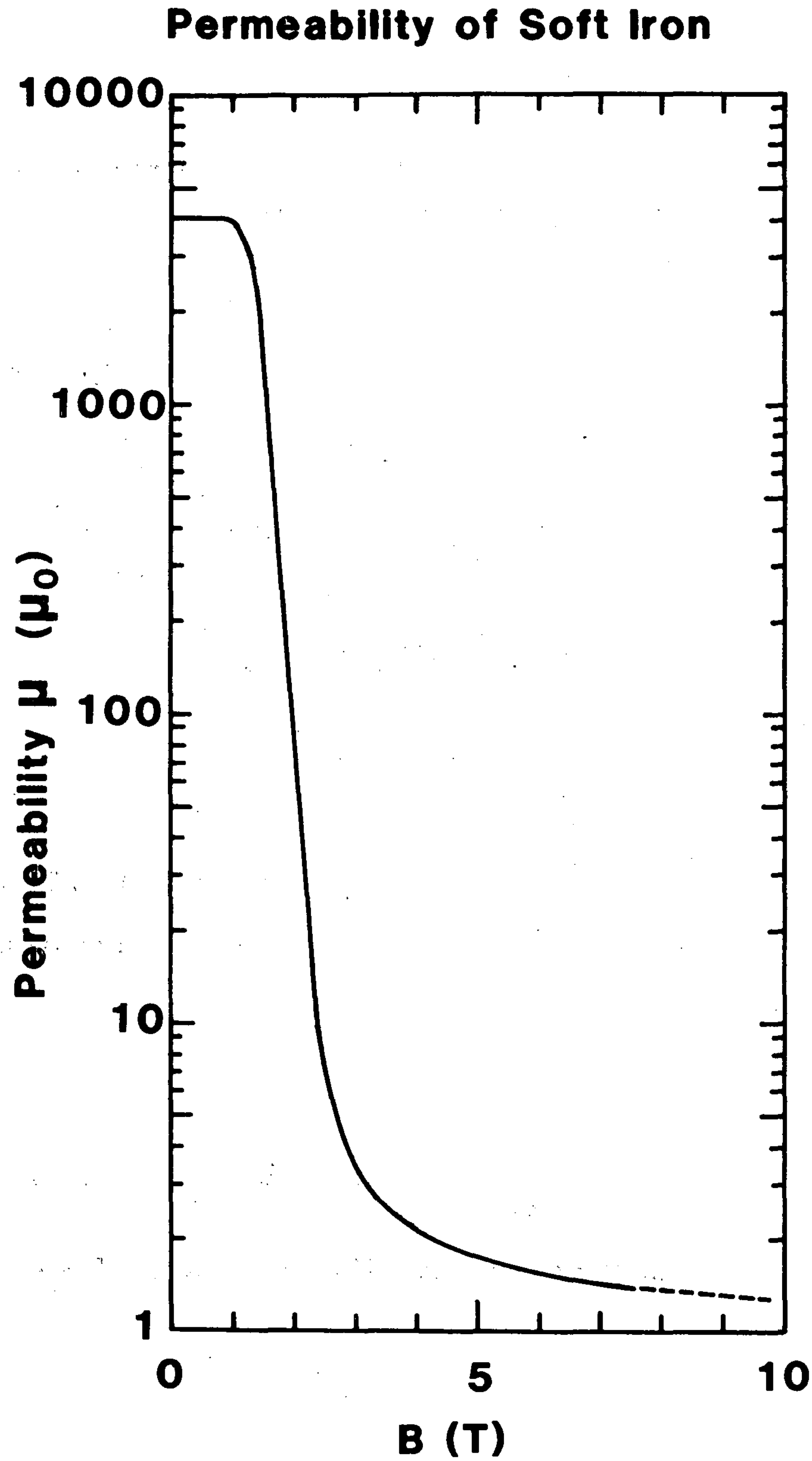

Permeability Dependence
of
Shielding Effect at Low Field
n=1
n=2
n=3
a: t=0.05mm
b: t=0.5 mm
c: t=1.0 mm
Shielding Factor F
Permeability [μo]
1000
100
10
1
100
1000
10000
a
b
c
XBL 837-10597

Fig. 2



XBL 837-10598

Fig. 3



XBL 837-10599

Fig. 4

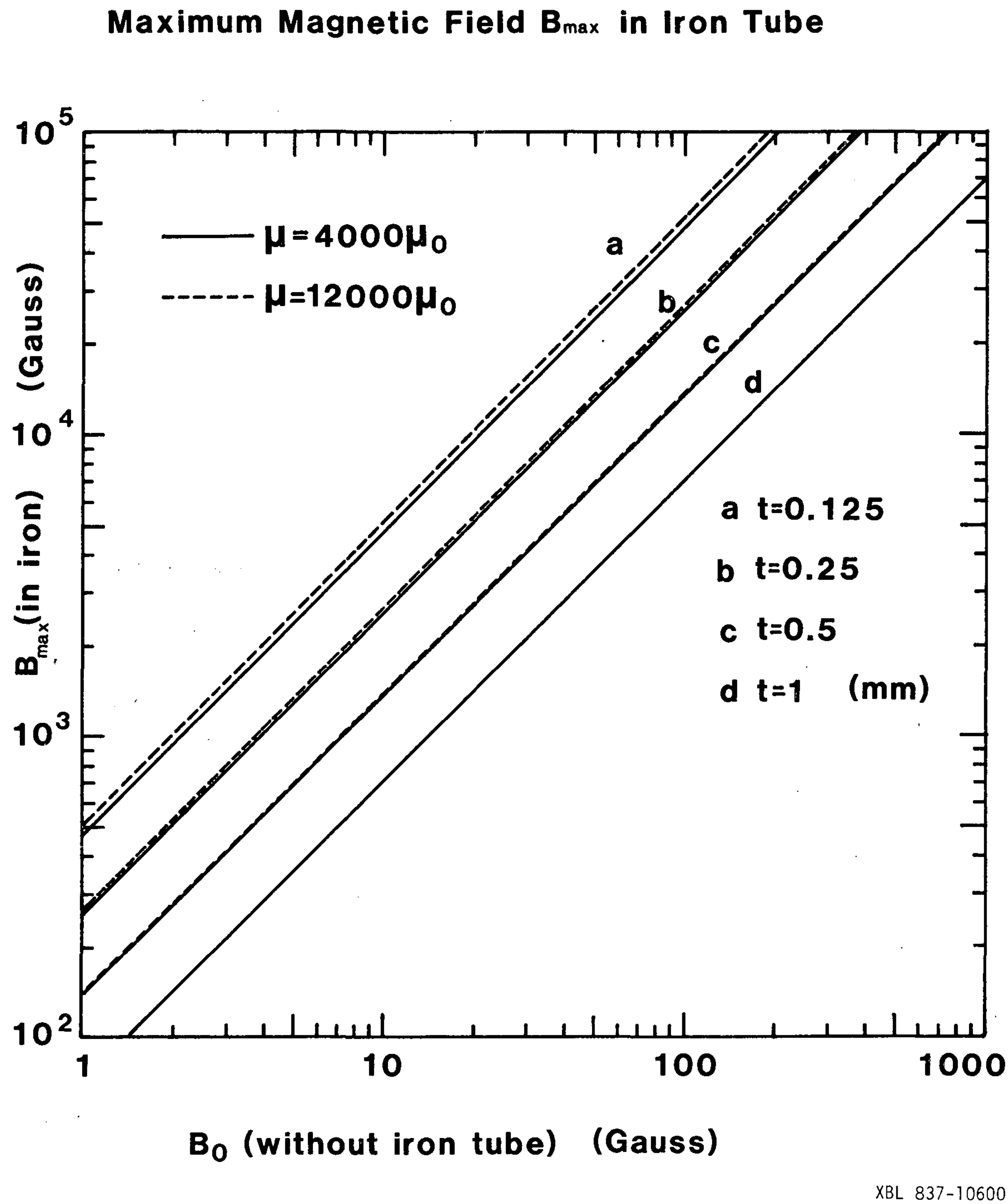
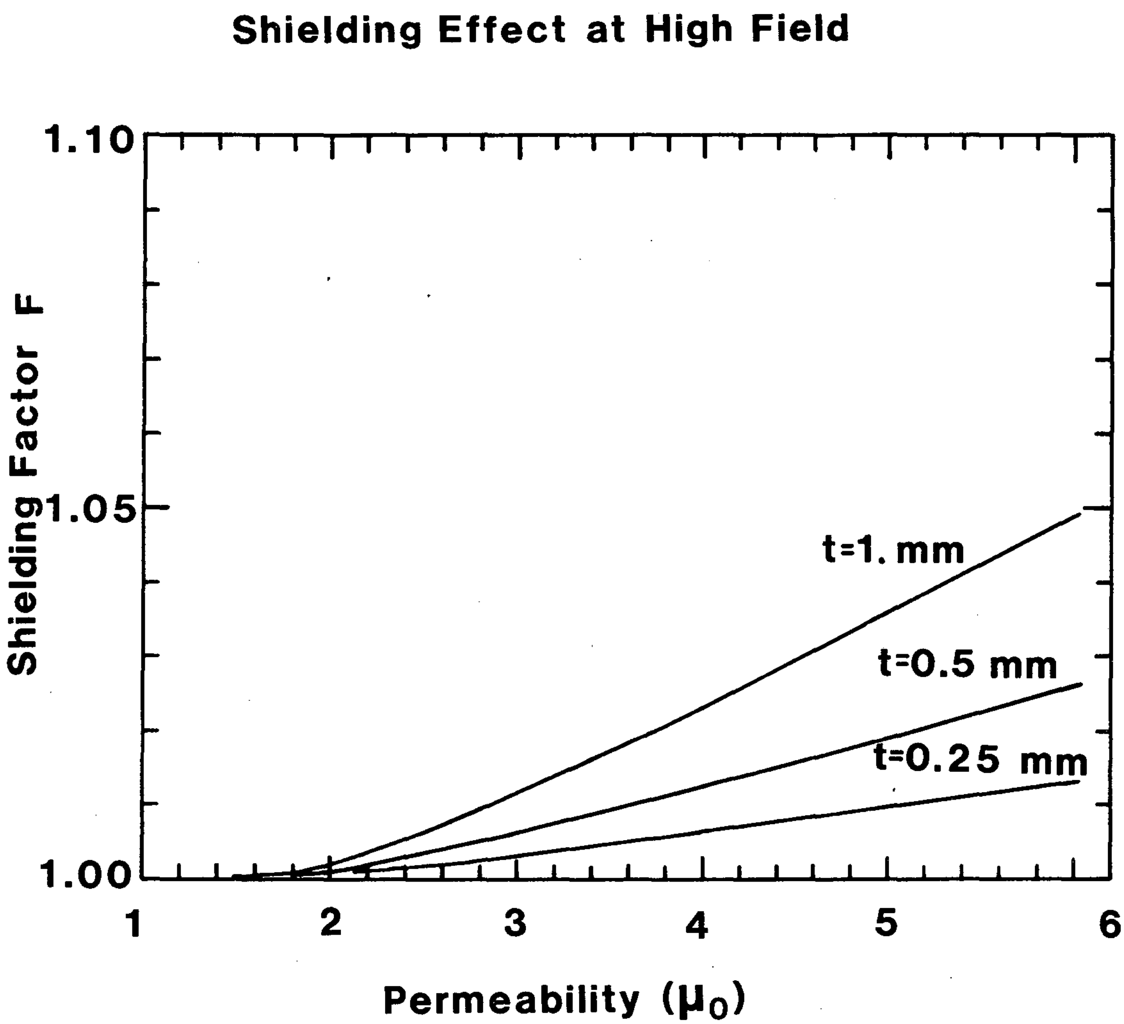
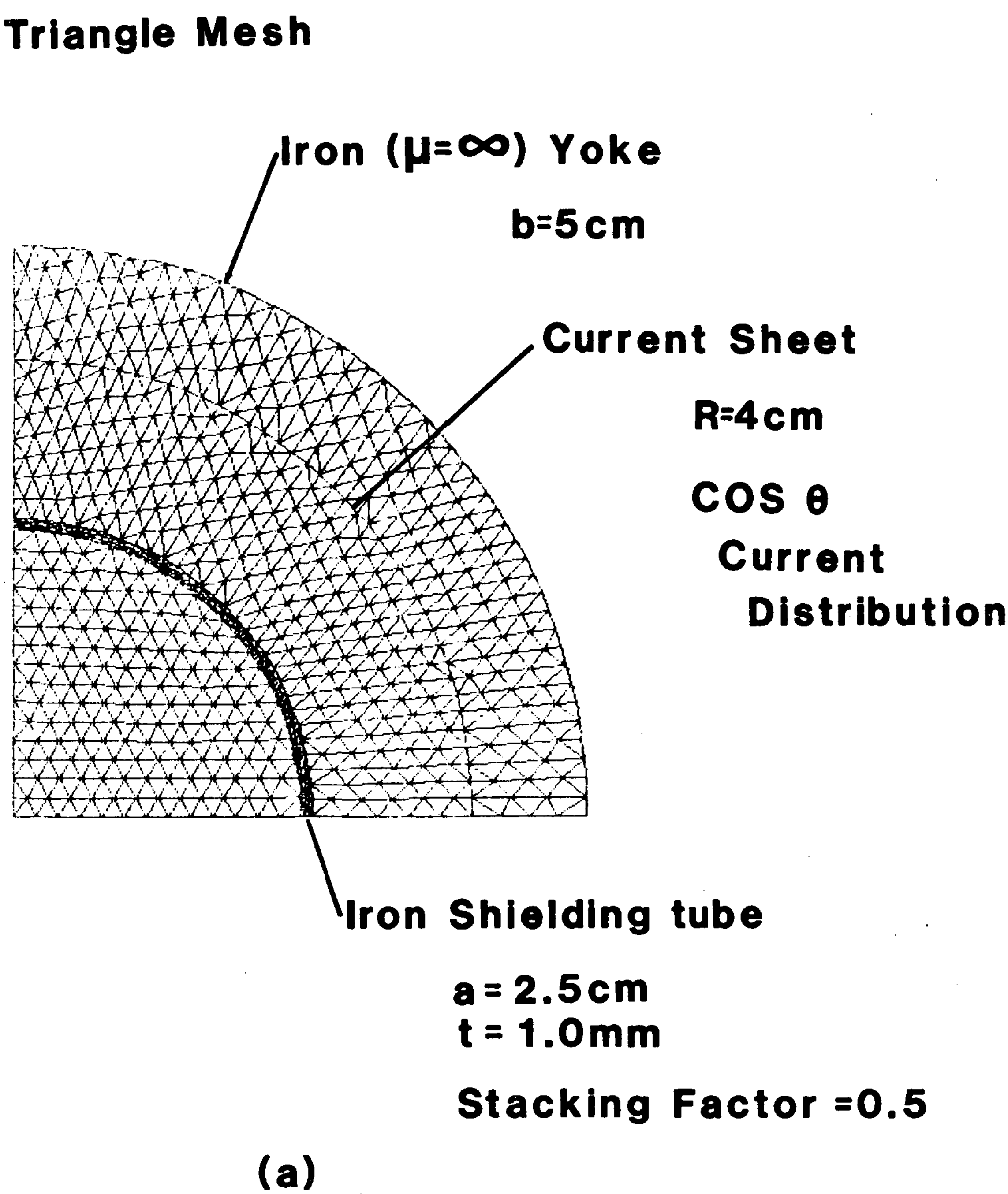

Maximum Magnetic Field Bmax in Iron Tube
μ=4000μ0
μ=12000μ0
a
b
c
d
a t=0.125
b t=0.25
c t=0.5
d t=1 (mm)
10^5
10^4
10^3
10^2
Bmax(in iron) (Gauss)
1
10
100
1000
B0 (without iron tube) (Gauss)
XBL 837-10600

Fig. 5



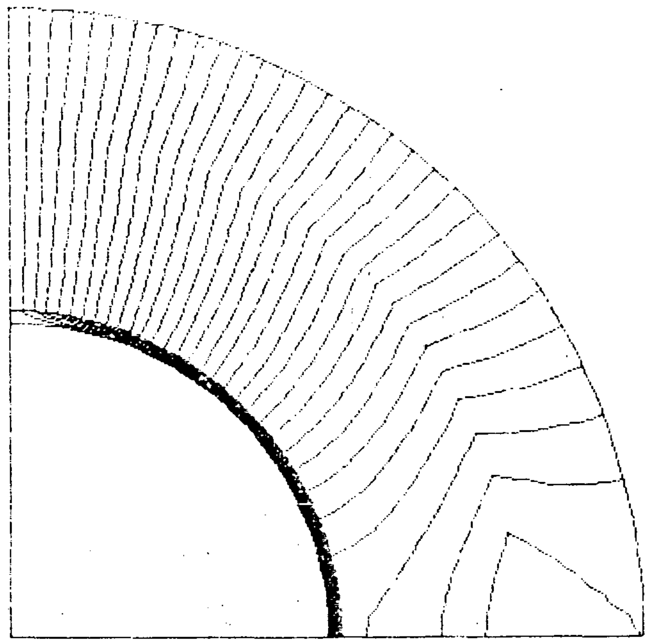
XBL 837-10601

Fig. 6



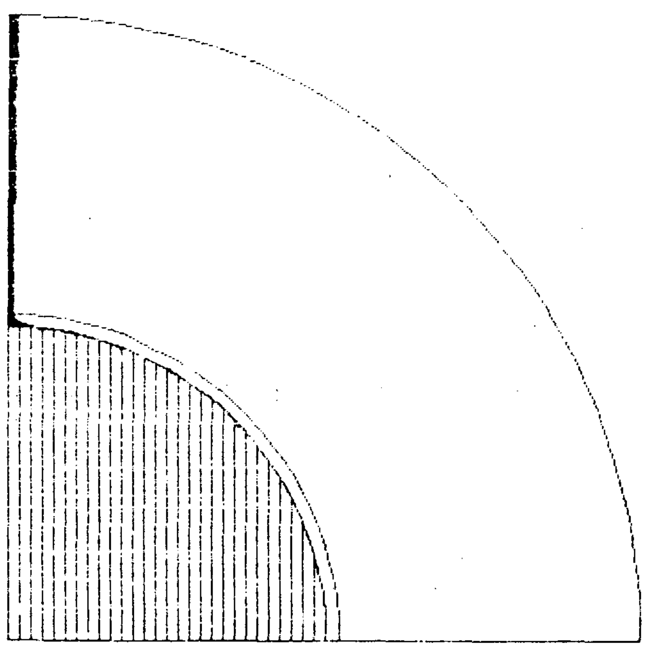
XBL 837-10602

Fig. 7(a)



100 A

(b)



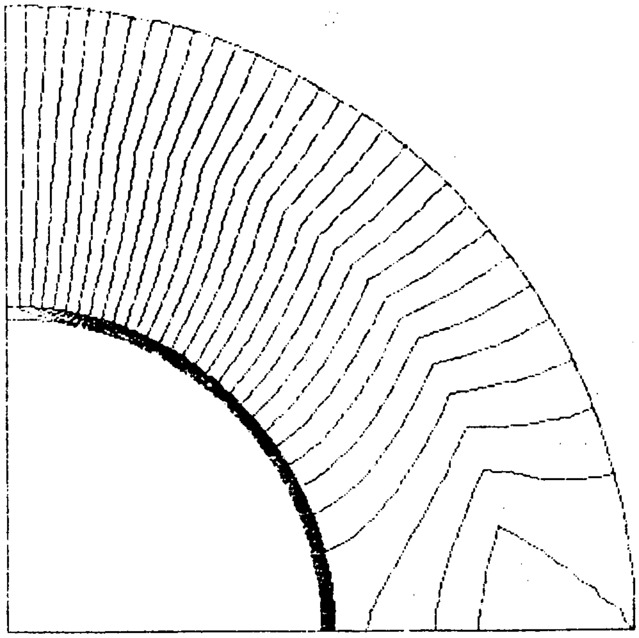
100 A

Low Field Profile

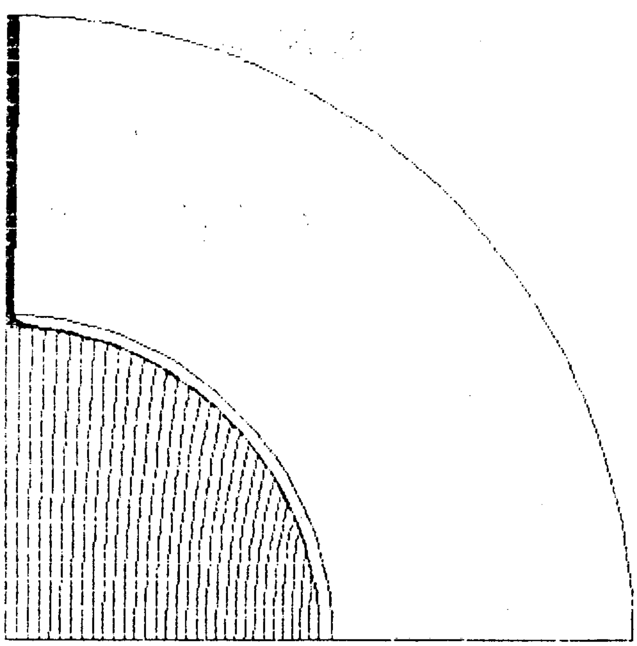
(c)

XBL 837-10603

Fig. 7(b)(c)



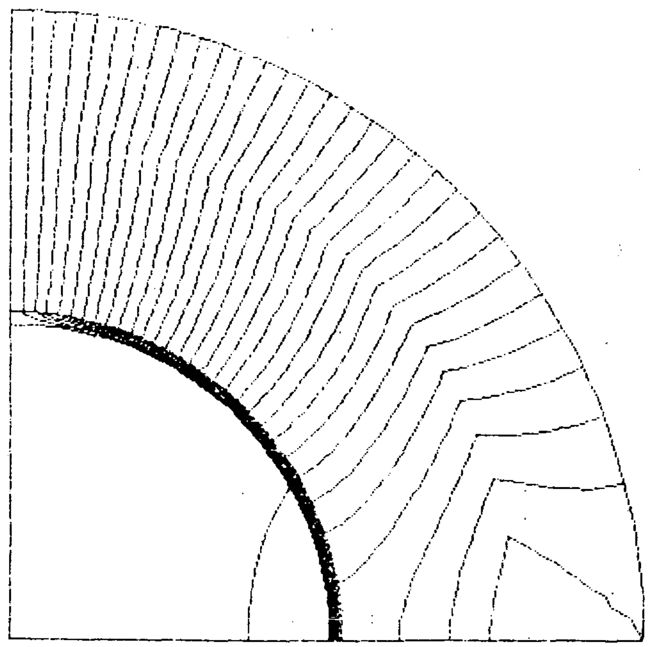
(d)



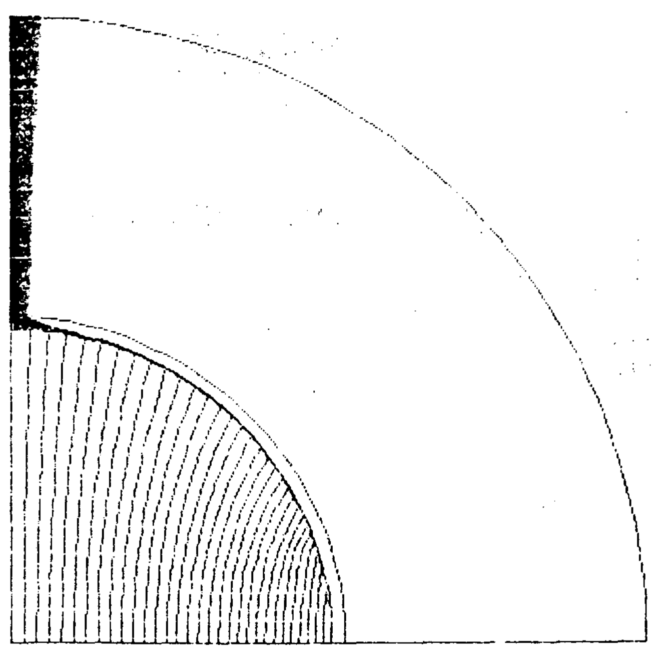
(e)

XBL 837-10604

Fig. 7(d)(e)



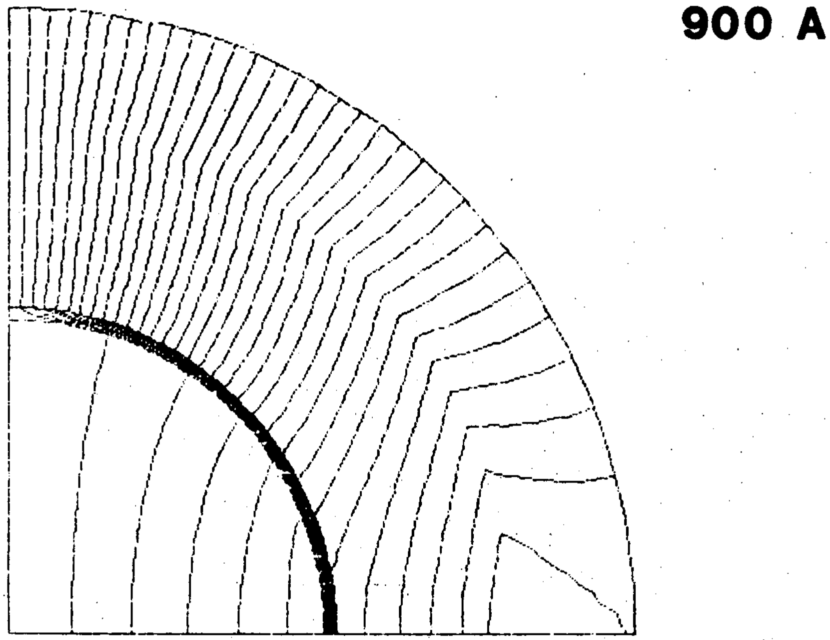
(f)



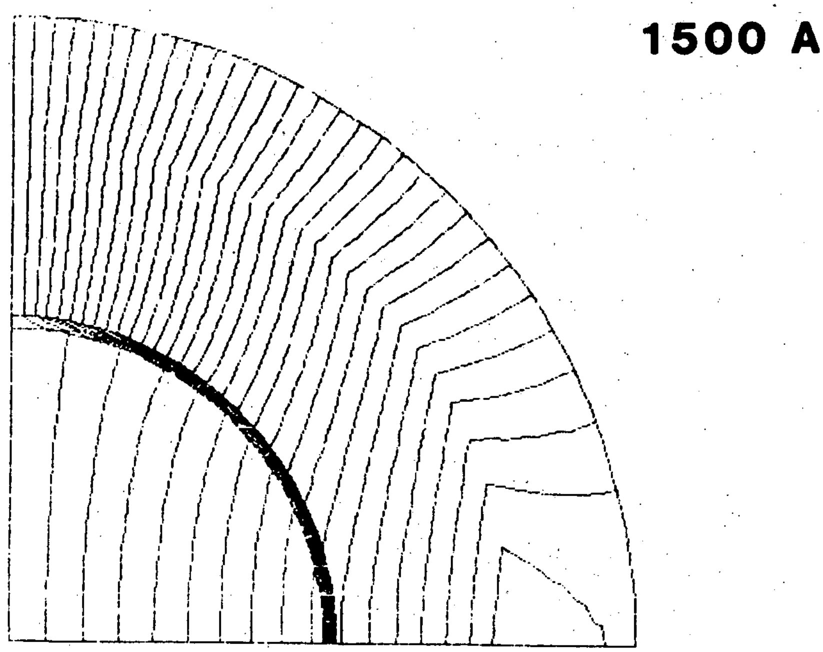
(g)

XBL 837-10605

Fig. 7(f)(g)

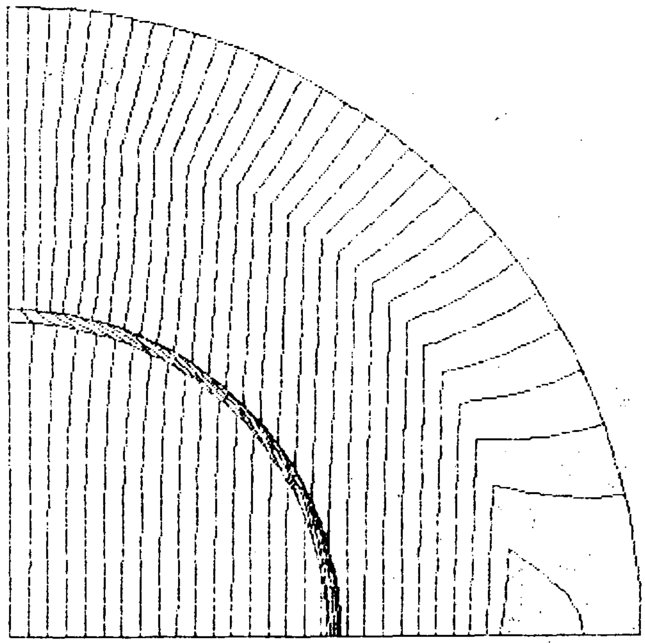


(h)

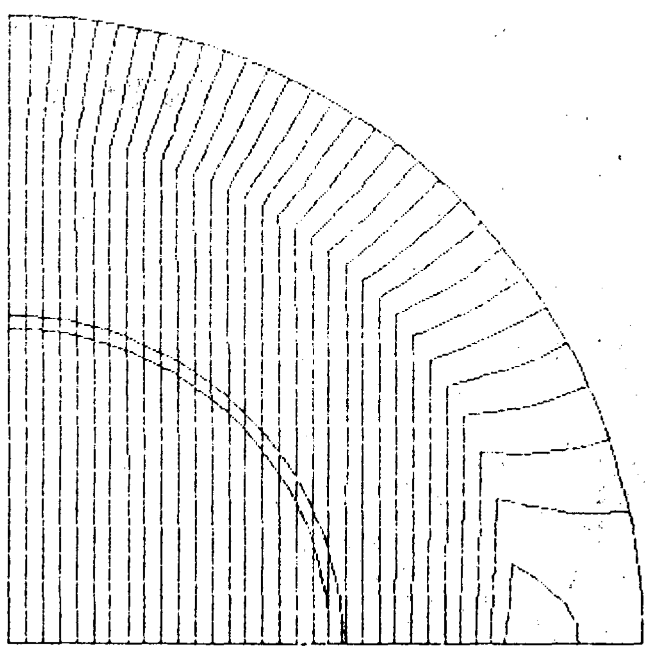


(i)

Fig. 7(h)(i)



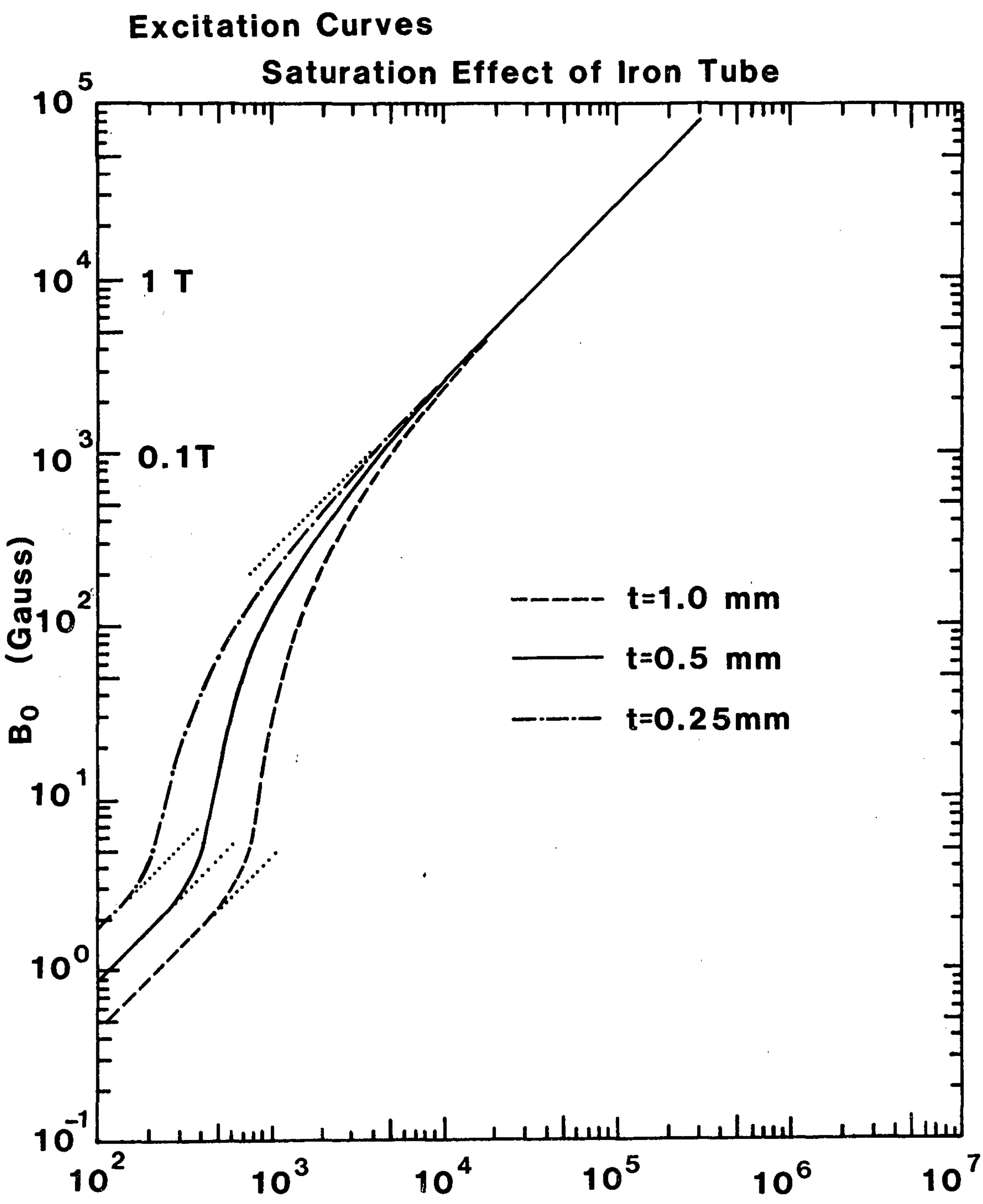
(j)



(k)

XBL 837-10607

Fig. 7(j)(k)



XBL 837-10608

Fig. 8

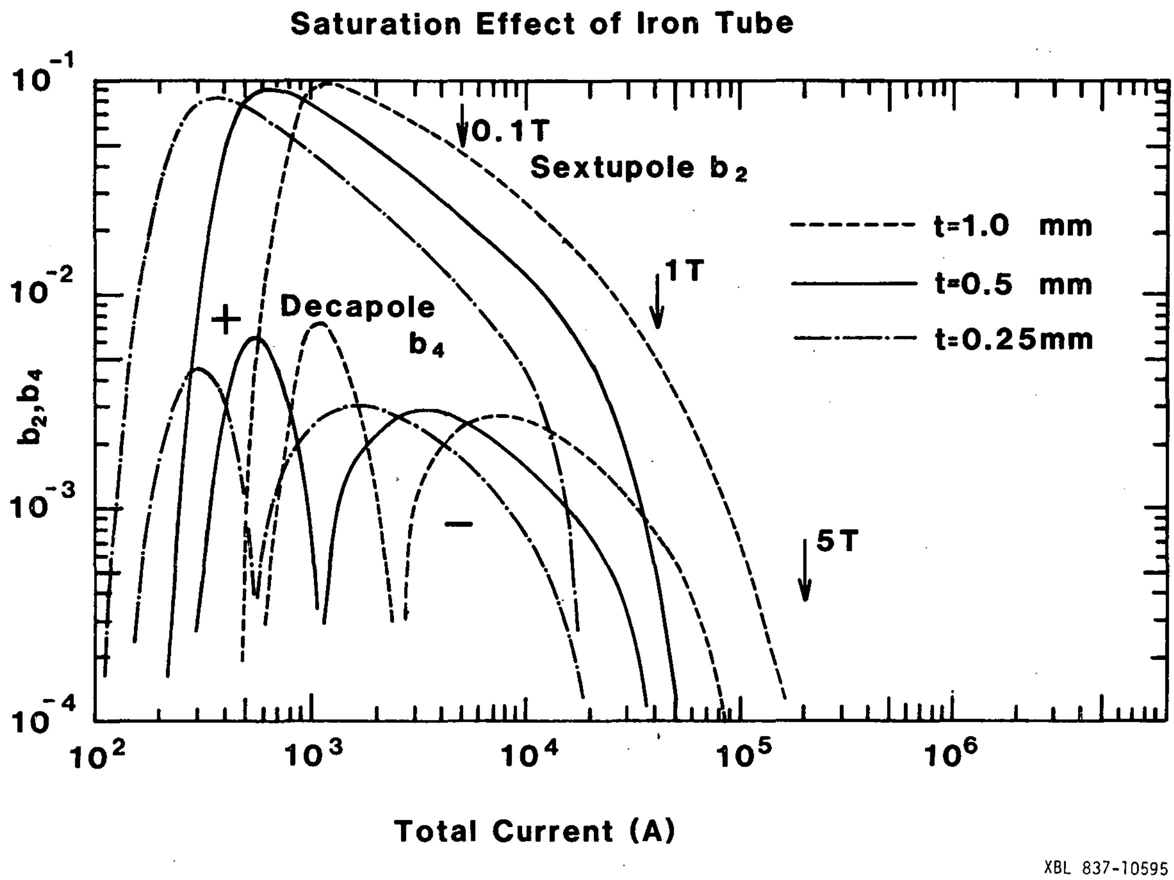

Saturation Effect of Iron Tube
10^-1
10^-2
10^-3
10^-4
b2,b4
0.1T
Sextupole b2
t=1.0 mm
t=0.5 mm
t=0.25mm
1T
Decapole
b4
+
−
5T
10^2
10^3
10^4
10^5
10^6
Total Current (A)
XBL 837-10595

Fig. 9

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720