EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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DIFFERENTIATED-EFFECT SHIMS FOR MEDIUM FIELD LEVELS AND SATURATION. THEIR USE IN MATCHING THE BENDING STRENGTH OF AN ACCELERATOR'S MAGNETS AT TWO FIELD LEVELS

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ABSTRACT

The arrangement of shims on the upstream and downstream ends of magnets may be based on the independent effects of variations in the geometric length and degree of saturation at the edges of the poles. This technique can be used to match the bending strength of an accelerator's magnets at two field levels (medium fields and maximum fields) and thus save special procedures (mixing the laminations, local compensation for errors by arranging the magnets in the appropriate order) and special devices (for instance, correcting dipoles) solely for correcting bending strengths at low field levels.

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1. INTRODUCTION

The effect of shims placed on the upstream and downstream ends of a magnet may vary with the field level. Nevertheless, there is a correlation between the effects of shims at medium-field and saturation levels if only the thickness of these shims is varied.

On the other hand, the errors in the bending (or focusing) strength of magnets at the same field levels may be unrelated or else related by a law which differs from that governing the effects of correcting shims. Therefore, in order to correct these errors at two field levels, two parameters have to be adjusted: the geometric length (thickness of the shims) and the degree of saturation at the edges of the poles (notches).

2. STANDARD TECHNIQUE FOR CORRECTING GEOMETRIC LENGTH

According to this technique, the pole length is extended in the direction of the beam. The technique may be used to enlarge the useful aperture of a given magnet, i.e. the region in which the bending strength is acceptable. In the case of a group of magnets, the technique may be used to balance the bending strengths at a particular field level.

Figure 1 illustrates how the homogeneity of the SPS correcting dipoles is adjusted. The homogeneity of these C-shaped magnets, expressed as

$$\frac{\Delta C}{C} = \frac{\int B_r \, d\ell - \int B_0 \, d\ell}{\int B_0 \, d\ell}$$

where B_r represents the field level in the plane of symmetry at a distance r from the centre, has been improved

i) by placing shims on the upstream and downstream ends (curve B);

ii) by channelling the flux by placing thin, and hence saturated, laminations parallel with the beam, along the coils and on the open side (curve C).

The geometry of the ends of the CERN SPS dipoles is shown in schematic form in Fig. 2: a variable number of shims 1.5 mm thick may be placed between a detachable end-piece and the yoke itself. The pole length (6.2 m), and hence the total flux, is thus increased without adding to the average cross-section of the return yoke.

The field level in the iron increases by ΔB_f, at least near the upstream and downstream ends. This increase of ΔB_f has a significant effect on the field level in air B_a only near the saturation level.

If the dipoles were short, the ΔB_f increase would be nearly uniform in the yoke in the longitudinal direction, and the variation of the field level in air could be expressed as

$$\frac{dB_a}{B_a} = -\left(\frac{dS_a}{S_f}\right) \Big/ \left(\frac{e}{E}\frac{\partial B}{\partial H}\frac{1}{\mu_0} + \frac{S_a}{S_f}\right)$$

with the mean values

S_a, S_f: cross-sections exposed to the flux

e, E : magnet gap, length of the lines of force in the iron.

For an increase of $\Delta \ell$ in the length of a magnet which has a bending strength of

$$C = \int_{-\infty}^{+\infty} B \, d\ell ,$$

the effect of the shims would be

at medium fields: $$\frac{\Delta C}{C} = \frac{\Delta \ell}{\ell}$$

at saturation: $$\frac{\Delta C}{C} = \frac{\Delta \ell}{\ell}\left[1 - \left(1 \Big/ \frac{e}{E}\frac{\partial B}{\partial H}\frac{1}{\mu_0} + \frac{S_a}{S_f}\right)\right] .$$

This simple formula still seems to hold for the long SPS dipoles:

Field	Calculated	Measured
1.0 T	2.4×10^{-4}	2.0×10^{-4}
1.8 T	1.6×10^{-4}	1.25×10^{-4}
Ratio	0.66	0.63

The measurements also showed that the effect of the shims was proportional to their total thickness, at least for shim thicknesses of up to 15 mm (Fig. 3, straight line A).

3. VARIATION IN THE DEGREE OF SATURATION AT THE EDGE OF THE POLES

This variation may be produced in different ways by making notches either in the pole face or at the upstream end of the magnet near the edge of the pole (Fig. 4). The calculation of the fringe field in the axial plane of a dipole with a notch 20 mm deep and Y = 25 mm wide on the upstream side gives a relative reduction in the bending strength of 14.6×10^{-4} at 1.8 T, whereas the bending strength remains unchanged at 1.0 T. The effect of the third dimension is ignored [MAGNET program[1]), result shown in Fig. 5].

The experimental results shown in Fig. 3, curve B, for a notch 22 mm deep and with different Y values, reveal a smaller relative decrease in bending strength: 9.0×10^{-4} at 1.8 T and at Y = 25 mm with a negligible effect at 1.0 T (1.0×10^{-4}).

4. COMBINED EFFECTS OF SHIMS AND NOTCHES: CORRECTING A MAGNET'S FIELD

It may be seen that, by using a combination of shims and notches, it is possible to make combined corrections of the bending strengths at medium and maximum field levels. Points such as M in Fig. 3, whose coordinates are the possible corrections at medium-field and saturation levels, fall within straight line A for the shim corrections and curve B for the notch corrections.

In order to ensure that all the magnets in an accelerator have the same bending strengths at two field levels, the range of possible corrections must cover the natural spread of the C values. This spread is shown in Fig. 6 for the A-type SPS dipoles.

The standard deviations of the distributions are 6.3×10^{-4} at 1.0 T and 6.9×10^{-4} at 1.8 T with a correlation of r = 0.75 between the two measurements[2]).

The contour plot of the range of defects which can be corrected has been superimposed on the spread figure. This plot is obtained from the correction plot shown in Fig. 3 by means of symmetry. Since the shim and notch corrections can be made at both ends of the magnet, the contour has been expanded by a factor of two. All magnets whose point M lies within the contour may be corrected so as to bring M to the origin O of the axes. In other words, within the limits of measurement accuracy, all the magnets can be given the same bending strength at 1.0 T and 1.8 T.

5. DETAILED INVESTIGATION OF THE RANGE OF DOUBLE CORRECTIONS FOR THE SPS DIPOLES

5.1 Combined variation of the number of shims and the width of the notches

The effects were measured accurately for notch widths Y ranging from 0 to 30 mm and a number of shims N ranging from 0 to 10, i.e. 0-15 mm. Figure 7 shows the range of corrections which can be obtained by modifying the upstream end only. If both ends are adjusted, the range of corrections is doubled. The corrections move the error points to the origin of the axes.

5.2 Variation in the number of shims N and the gap X between the shims and the yoke when Y ≠ 0

Use may also be made of notches of variable width X on the pole face as shown in Fig. 4.

The magnets' errors at 1.0 T and 1.8 T (Fig. 8) constitute the coordinates of their reference points. The correction moves these points to the origin of the axes, if these points lie on the grid shown in the figure for Y = 30 mm. The range of possible corrections falls within the range of corrections made by varying N and Y when X = 0, except for the right-hand part which is an extension (combined reduction of the bending strengths at 1.0 T and 1.8 T).

5.3 Effects of varying X and Y at constant N (N = 5), Fig. 9

The range of possible corrections falls within the range possible by varying Y and N.

6. CONCLUSION: USEFULNESS OF SHIM AND NOTCH CORRECTIONS

By making combined use of shims and notches on the upstream and downstream ends of dipole magnets, it is possible to obtain independent correction effects at medium field levels and at saturation. The process may be used to correct the bending strength of a wide-aperture magnet by introducing the necessary shims and notches to compensate for the errors measured along the aperture.

Moreover, the range of possible corrections fully covers the region over which the bending strength of a large number of magnets is naturally spread at these two field levels. It is thus possible to match the bending strength of all the magnets in an accelerator or beam line.

In the case of the SPS dipoles, corrections of up to 40×10^{-4} and 20×10^{-4} were easily achieved at bending strengths of 1.0 T and 1.8 T, respectively, by means of shims and notches. The method was used only for a certain number of dipoles. It had been planned to use shims for corrections at 1.0 T and to mix the magnets in the ring in order to make the bending strengths of each half-period the same at 1.8 T, since the magnets were not corrected at this field level. This method produced excellent results[3], but it was necessary to adjust about one hundred magnets by making shim and notch corrections.

By applying a systematic double correction, it would be possible to save magnet mixing for correcting the closed orbit at injection.

The yokes of the SPS dipoles were made from laminations grouped into seven categories according to the measured coercive field[4]. By using the same lamination mix for each magnet, the measured spread of bending strengths at 0.045 T was reduced to a standard deviation of 6×10^{-4}. This value also holds at 1.8 T, and so magnet mixing, which gave good results at 1.8 T, may also be used at 0.045 T.

If all the magnets were corrected not only at 1.0 T but also at 1.8 T, one or more of the following methods could be used at the injection field level:

- lamination mixing
- magnet mixing
- iron or iron-free orbit correcting devices.

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2) A. Riche, Updated measured magnetic properties of the SPS magnets 363 MBA, 391 MBB, 108 QF, 106 QD, SPS/MA/Int. 76-7, May 1976.

3) R. Billinge, Magnet mixing to reduce the high field closed orbit distortion, CERN Lab. II MA/74-1 (1974).

4) R. Billinge, Developments in magnet technology, CERN Lab. II/MA/75-1 (1975), and Proc. 5th Internat. Conf. on Magnet Technology, Rome, 1975 (Lab. Naz. CNEN, Rome, 1975), p. 3.

Figure captions

Fig. 1 : Aperture field corrections for a C-shaped dipole.

Fig. 2 : Dipole end shims.

Fig. 3 : Correction using shims (A) and correction using notches (B).

Fig. 4 : Variation in the saturation at the edge of the pole.

Fig. 5 : Calculated effect of a notch.

Fig. 6 : Contour of the range of defects which can be corrected.

Fig. 7 : Correction of defects by variation of N and Y (X = 0). (Correction at one end only.)

Fig. 8 : Correction of defects by variation of N and X (Y = 30 mm). (Correction at one end only.)

Fig. 9 : Correction of defects by variation of X and Y (N = 5). (Correction at one end only.)

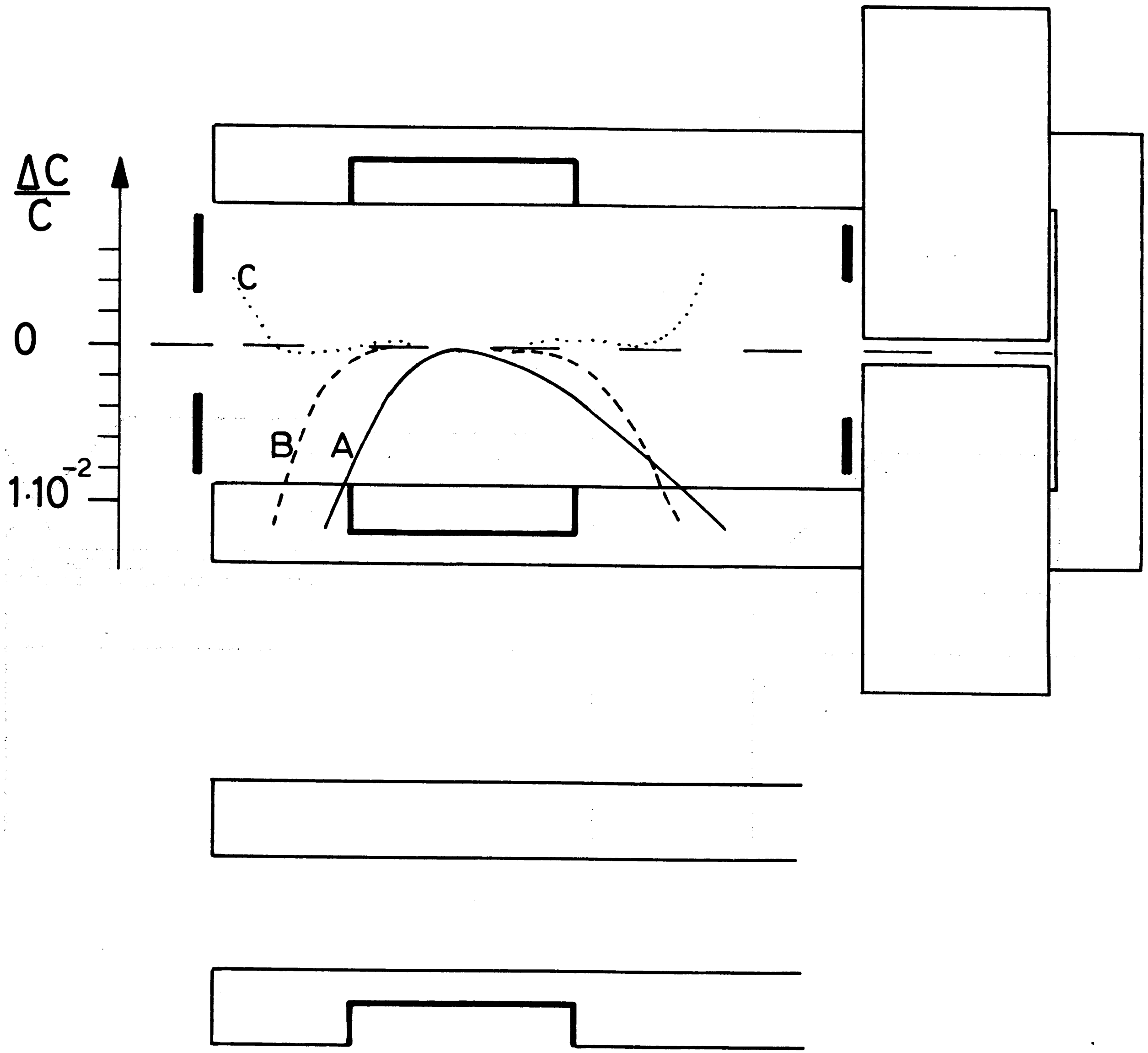


Fig. 1

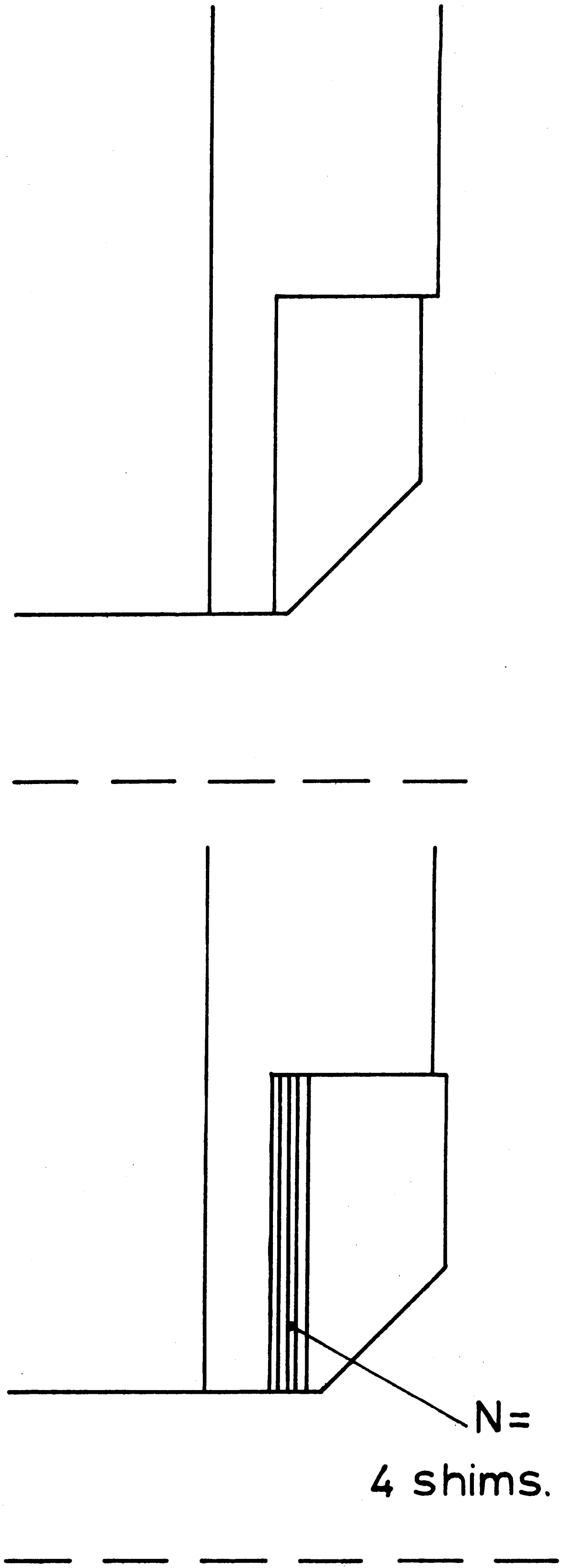
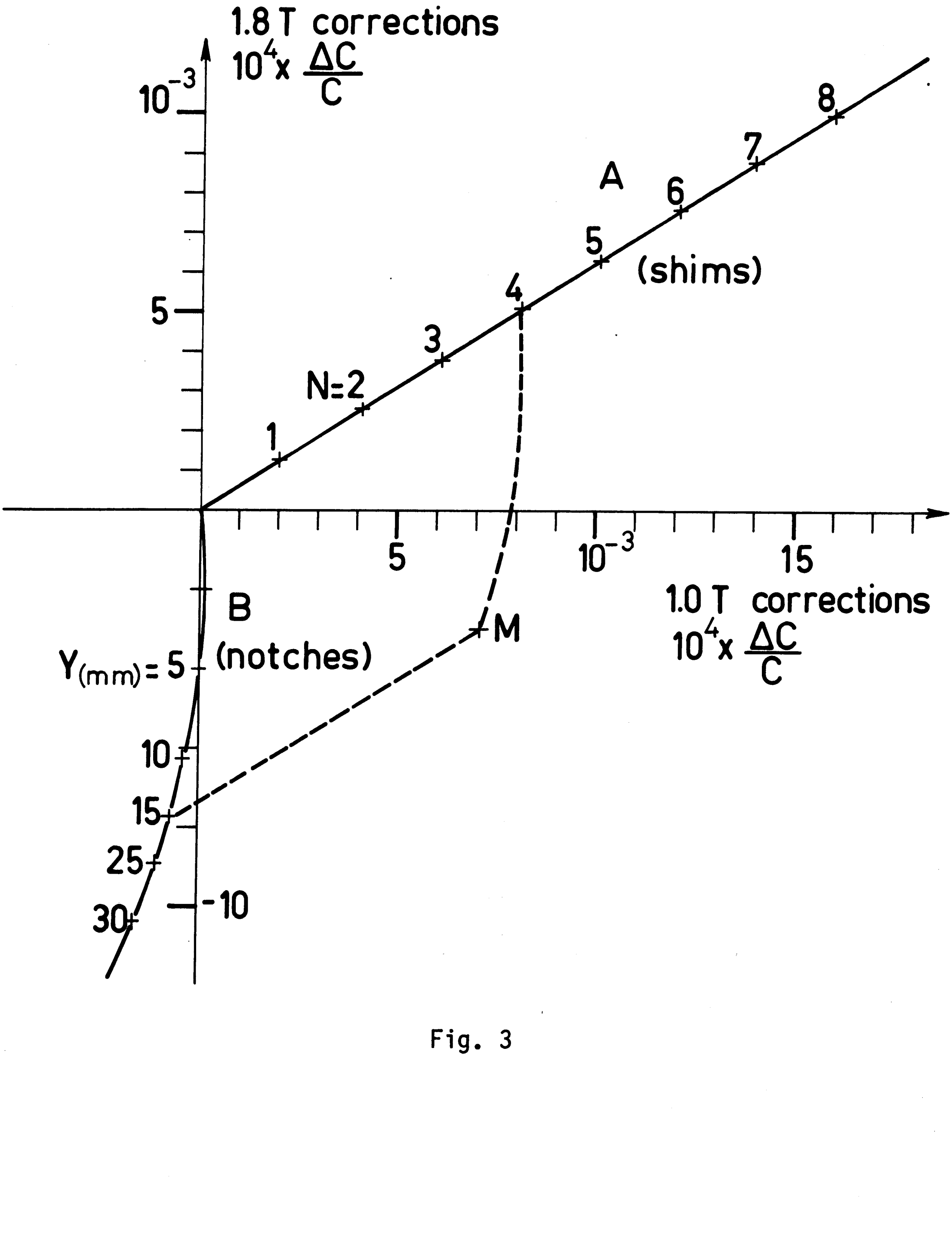


Fig. 2



1.8 T corrections
$10^4 \times \frac{\Delta C}{C}$
10^{-3}
5
A
(shims)
N=2
1
3
4
5
6
7
8
5
10^{-3}
15
1.0 T corrections
$10^4 \times \frac{\Delta C}{C}$
B
(notches)
M
Y(mm) = 5
10
15
25
30
-10

Fig. 3

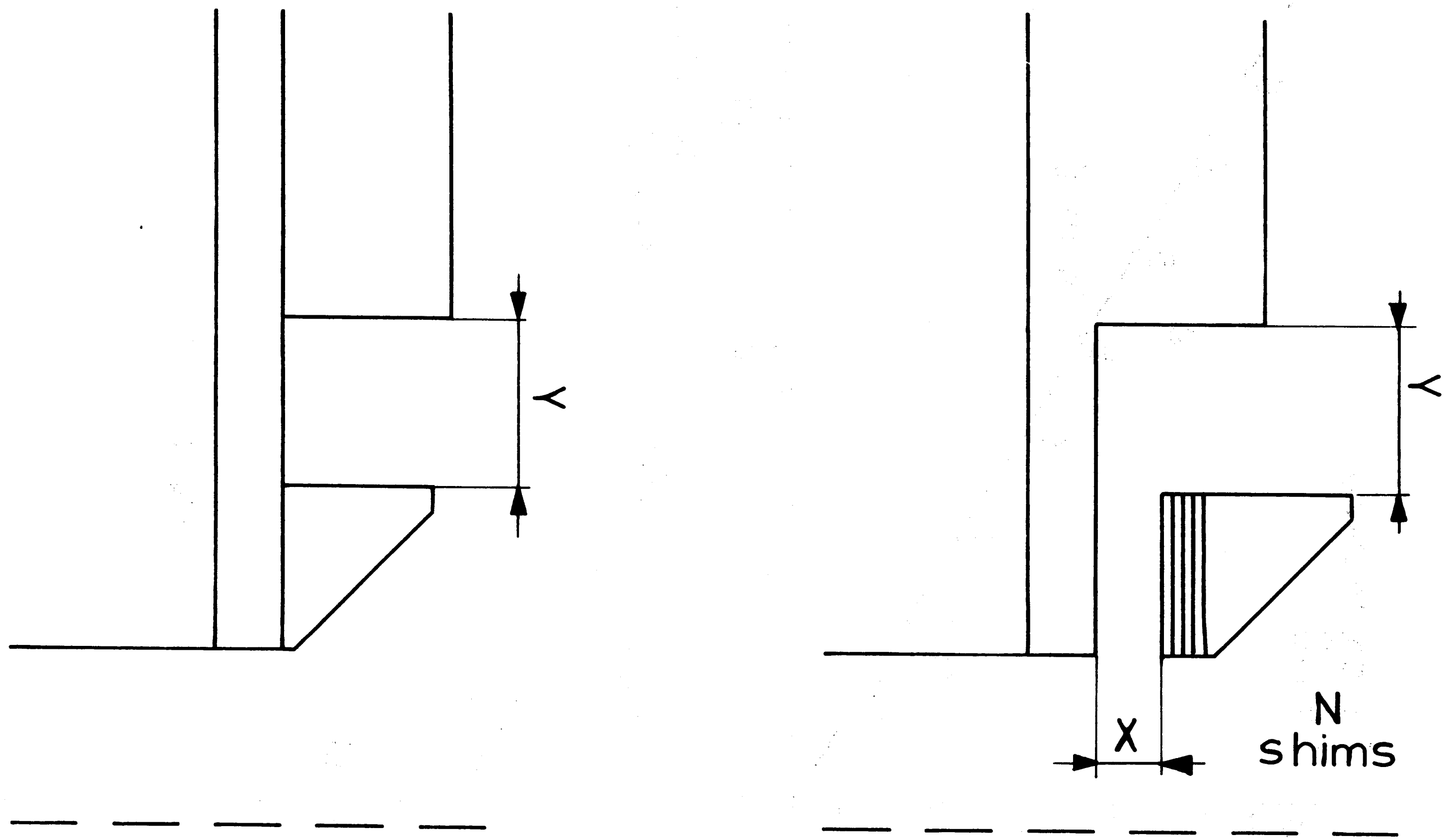


Fig. 4

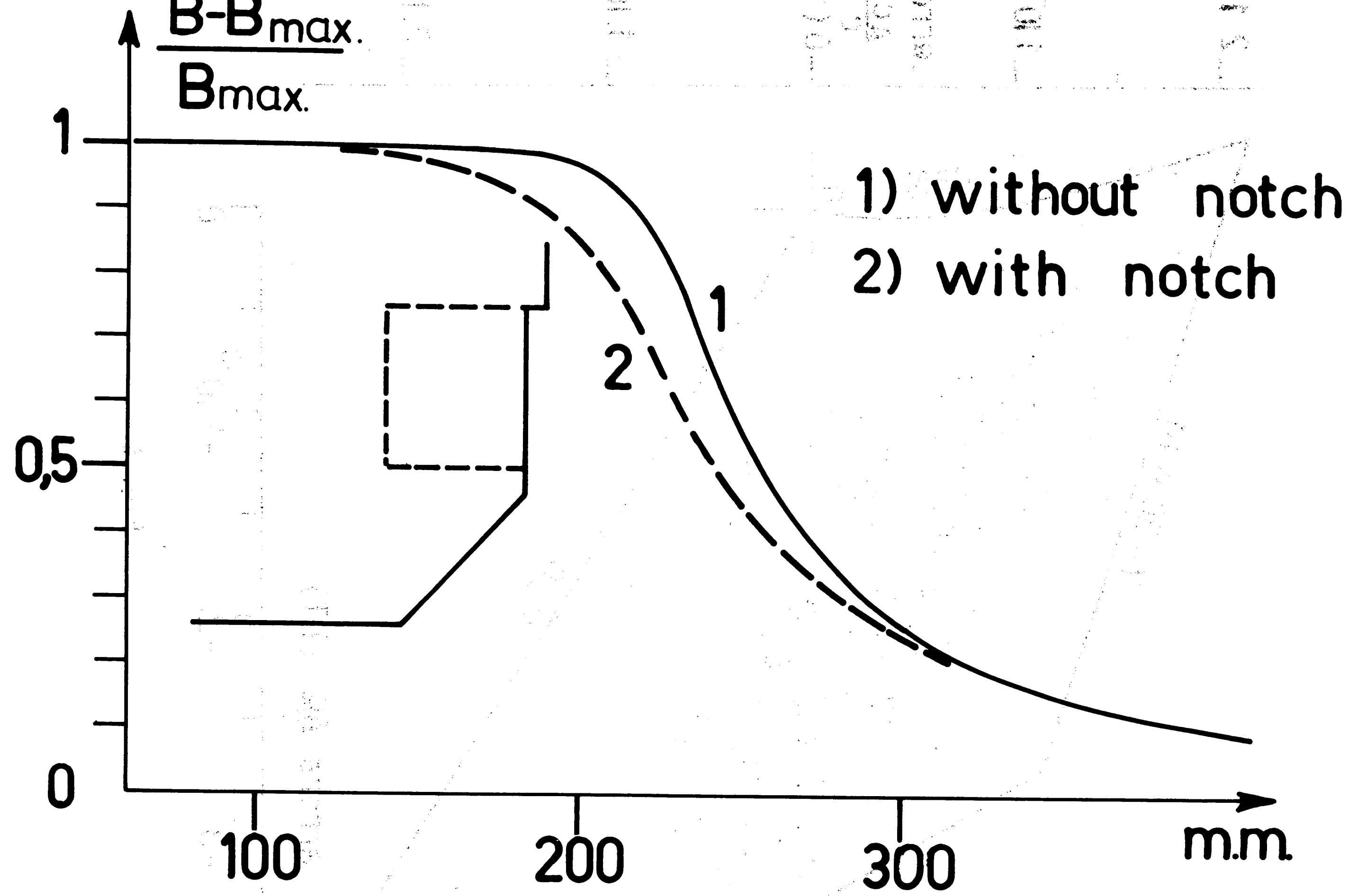
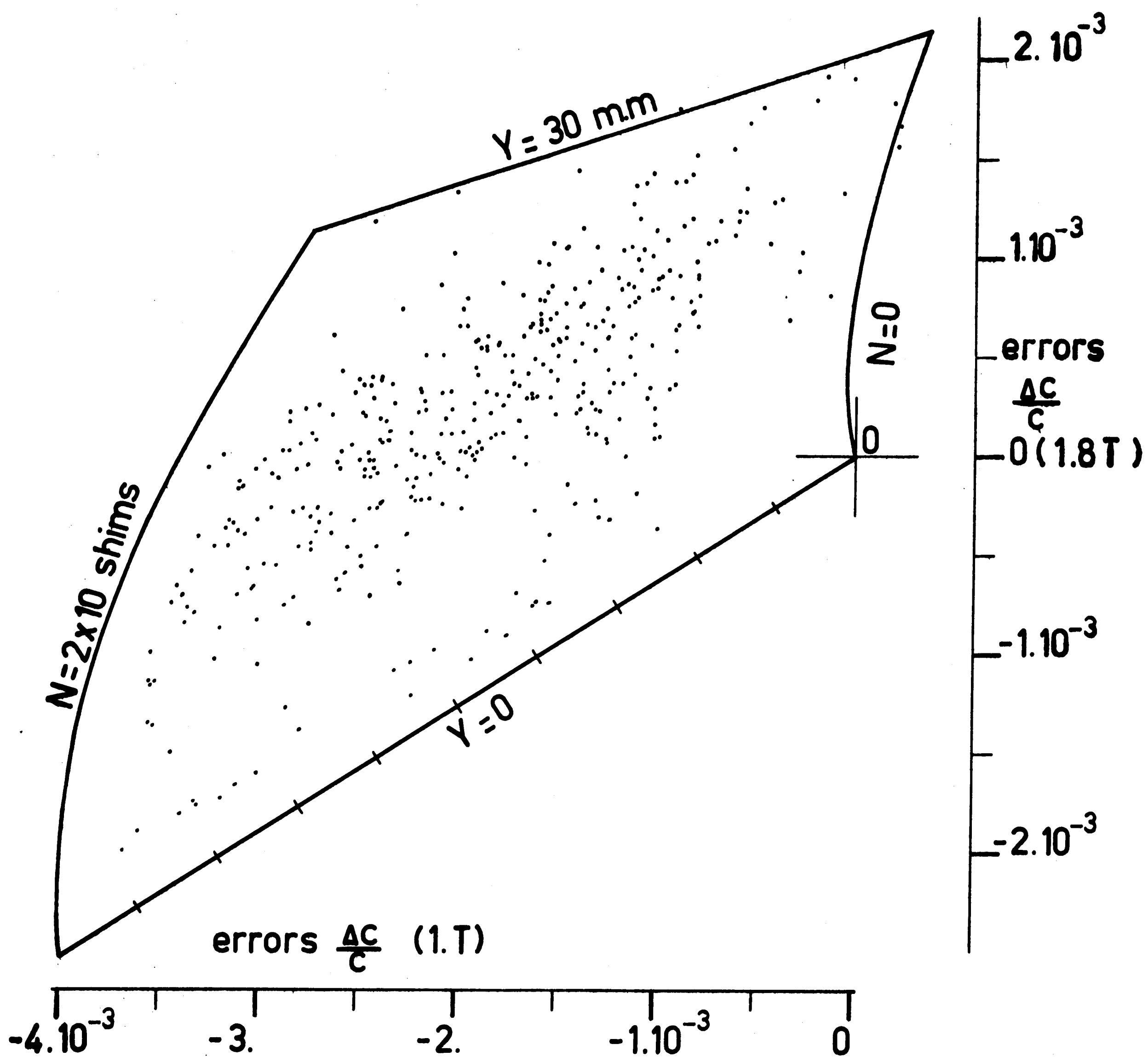
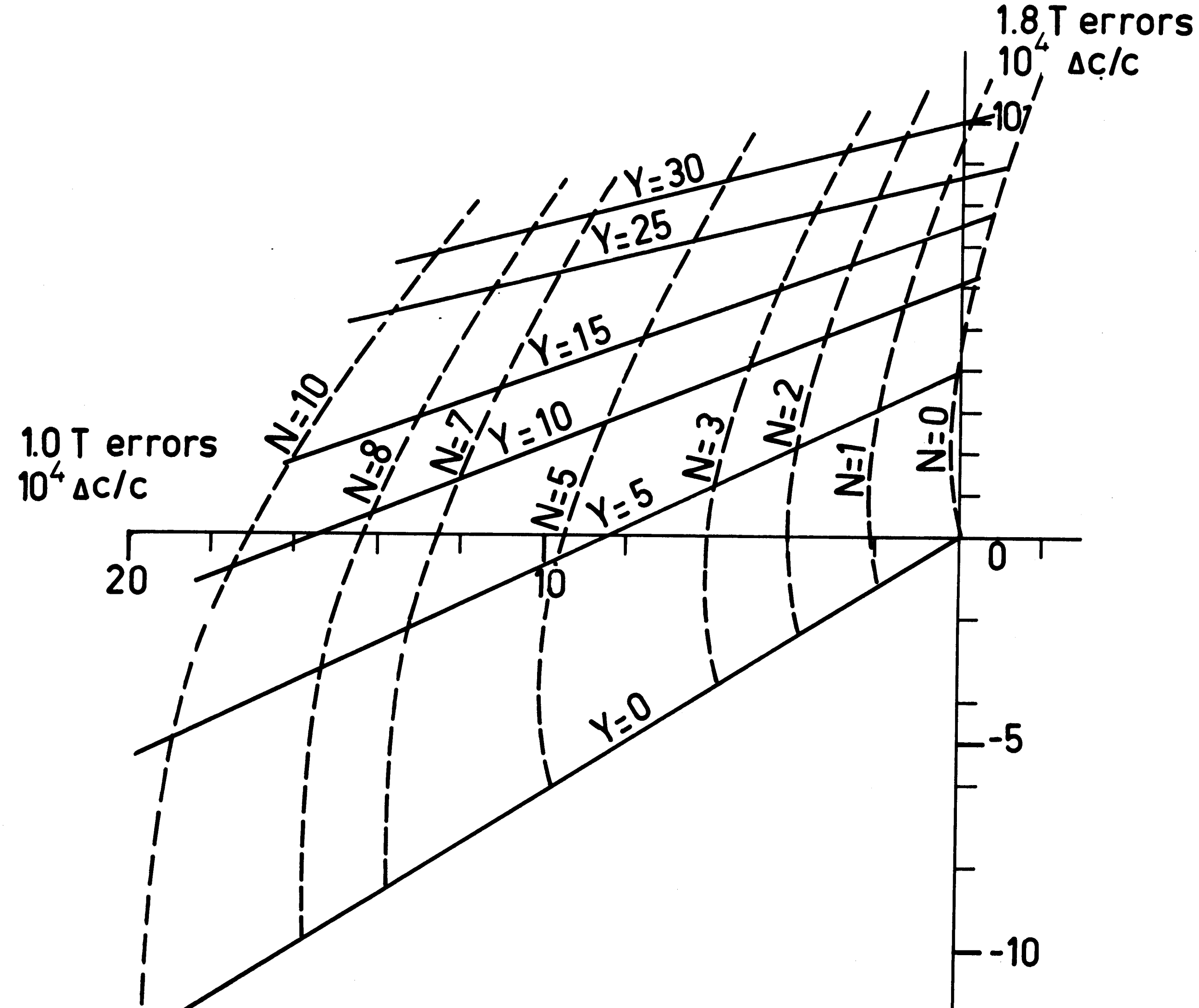


Fig. 5



Y = 30 mm
N=2x10 shims
N=0
0
Y=0
2. 10^{-3}
1.10^{-3}
errors $\frac{\Delta C}{C}$
0 (1.8 T)
-1.10^{-3}
-2.10^{-3}
errors $\frac{\Delta C}{C}$ (1.T)
-4.10^{-3}
-3.
-2.
-1.10^{-3}
0

Fig. 6



1.8 T errors
10^4 Δc/c
10
1.0 T errors
10^4 Δc/c
Y=30
Y=25
Y=15
Y=10
Y=5
Y=0
N=10
N=8
N=7
N=5
N=3
N=2
N=1
N=0
20
10
0
-5
-10

Fig. 7

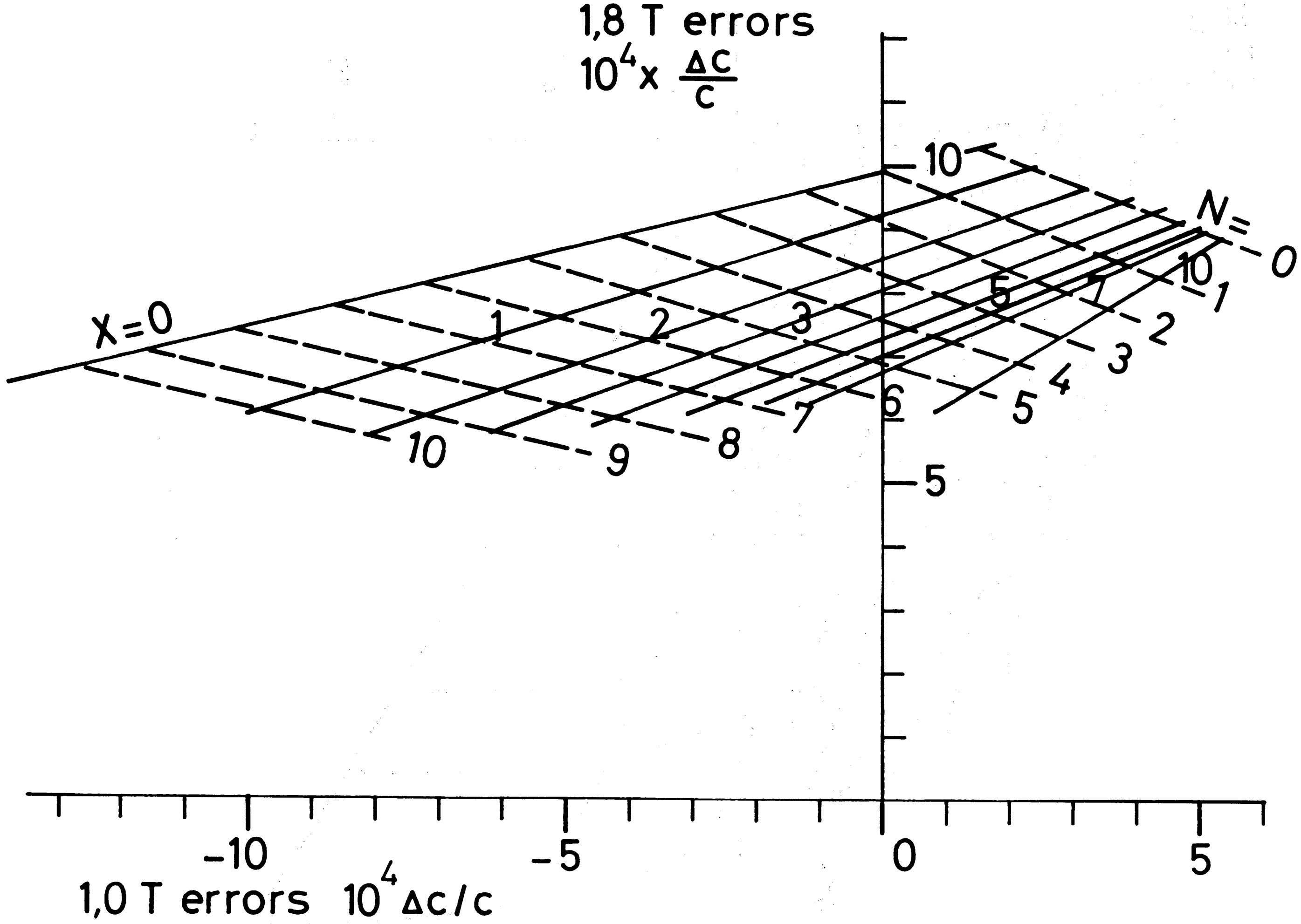

1,8 T errors
$10^4 \times \frac{\Delta c}{c}$
X=0
N= 0
1,0 T errors $10^4 \Delta c/c$
-10
-5
0
5
10

Fig. 8

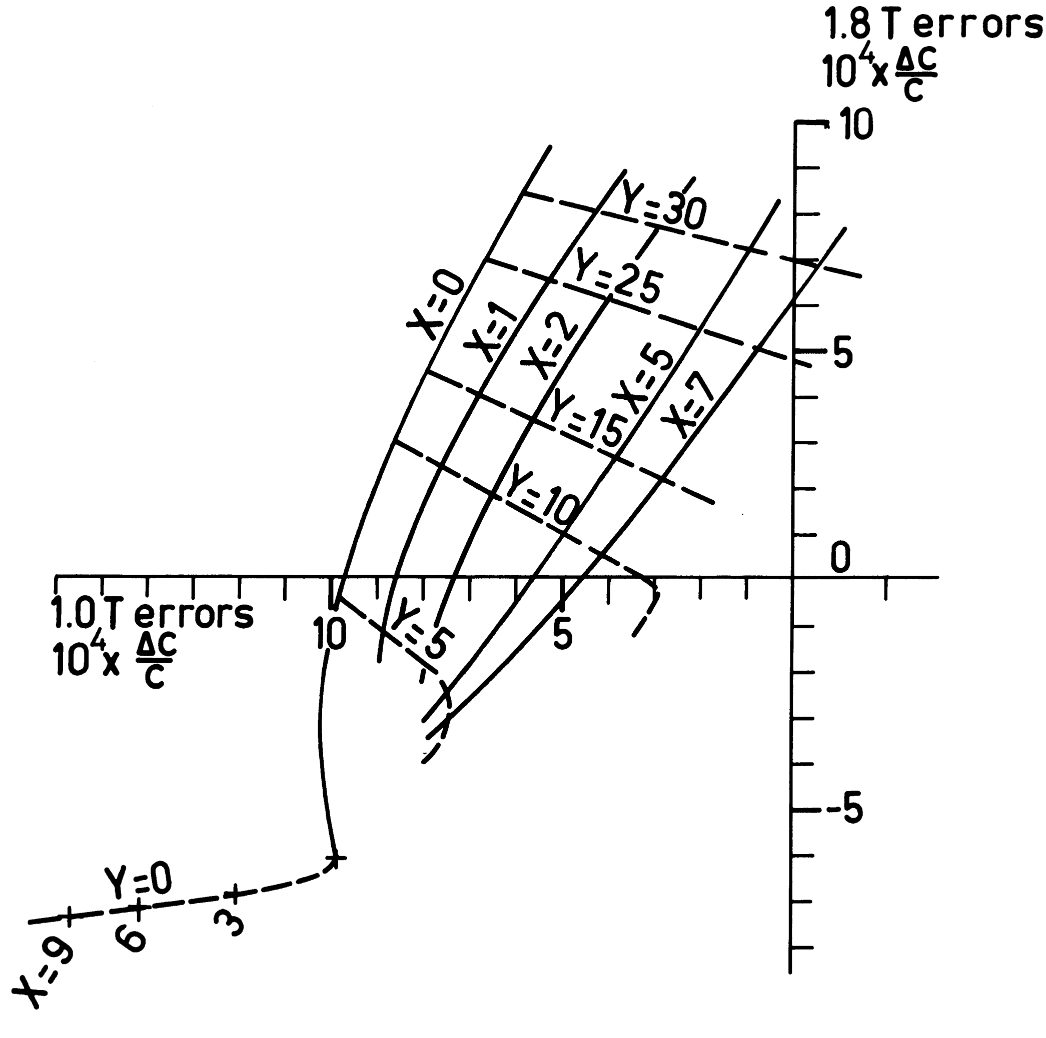

1.8 T errors
$10^4 \times \frac{\Delta C}{C}$
10
5
0
-5
1.0 T errors
$10^4 \times \frac{\Delta C}{C}$
10
5
Y=30
Y=25
Y=15
Y=10
Y=5
Y=0
X=0
X=1
X=2
X=5
X=7
X=9
6
3

Fig. 9