MAGNET SYSTEMS

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1. INTRODUCTION

Despite the coming of age of superconductivity, as exemplified by the Energy Doubler at Fermilab and the HERA Project at DESY, there is a continuing requirement for conventional, iron-cored magnets. These might be for an accelerator or a storage ring or just a single magnet for special application. Thirty years ago, pole profiles were designed with the aid of conducting paper, and one or more prototypes were considered essential in order to guarantee that the desired field quality would be forthcoming. Nowadays, we have computer programmes to help us, and their accuracy is such that in most cases no prototype at all is required; provided that a small amount of correction is allowed for at the pole ends, a considerable amount of time and money can be saved by their use.

A large proportion of those people involved with accelerators are liable to be asked to design a magnet at some stage in their careers, and a description of the process is given below, including useful formulae and rules-of-thumb, in the hope that some time can be saved in the learning process. The problem is to design a magnet in which correction for the higher poles present in the end-fields are corrected in the pole profile.

2. INITIAL DESIGN

I will take as an example one of the quadrupoles required for the AC (antiproton collector) ring which is to be commissioned at CERN in 1987[1]. The given parameters were as follows:

Effective length (L_{eff}) = 0.75 m
Central gradient (g_o) = 6.47 T/m
Sextupole component (G'/G_o) = 0.617 m^{-1}, where

$$G' = \frac{d^2}{dx^2} \int B_z ds$$

$$G_o = \frac{d}{dx} \int B_z ds$$

The good field region was ± 160 mm (H) by ± 33 mm (V). Within this region the ultimate requirement was that $\Delta G/G_o \sim 1 \times 10^{-3}$, where

$$\Delta G = \left(\frac{d}{dx} \int B_z ds\right)_x - \left(\frac{d}{dx} \int B_z ds\right)_o$$

Other restraints were that the overall length should be as short as possible and the current I should be about 2000 A, while the available cooling water pressure was to be 10 Bar with a maximum allowable temperature rise ΔT = 20 °C.

After making allowance for a vacuum chamber containing a beam position monitor, the inscribed radius r was fixed at 132 mm. The ampere-turns required for a quadrupole is

$$NI = g_o r^2/2\mu_o$$

and N was chosen to be 27 turns per pole.

The effective length of a quadrupole can be expressed as

$$L_{eff} = L_{iron} + \alpha r,$$

where α is a factor which depends on the geometry of the coils at the pole ends. If the coil ends are close to the pole-tip, $\alpha \sim 0.8$, but if they are withdrawn as in a saddle-type coil, then α approaches unity. Our initial guess for α was 0.85, as we wanted the coils to be of the race-track type for ease of manufacture.

The pole contour (without the sextupole term) is given by the hyperbola

$$xz = r^2/2$$

and is terminated by shims - small 'growths' of steel to extend the good field region. An initial guess has to be made as to the pole width - this is very dependent on the quality and extent of the good field region required. It is not necessary to have extra pole-width in order to allow for the subsequent inclusion of higher-order poles.

Having now approximate dimensions for the pole, the length and resistance of the conductor can be calculated and the coolant flow determined. This can be derived from the formula

$$\Delta P = \ell\left(8qa^{-1.334}\right)^{1.79}$$

where ΔP = pressure drop (Bar)
ℓ = flow path length (m)
q = litres/min
a = flow area (mm^2)

The water temperature rise is given by

$$\Delta T = 0.06\ (I^2R)/4.2q$$

The working current density is determined by balancing the running costs of the magnet against the capital cost, and will vary from country to country. If possible, the coolant hole size should be adjusted so that there is at the most one water circuit per coil.

Knowing now the dimensions, we fit the coils round the pole, allowing for packing, insulation and growth due to winding inaccuracies. The two dimensional field (B_z along the horizontal median plane) will be roughly as shown in Fig. 1, with the peak field occuring approximately at the start of the shim, x_s. An estimate of the total flux which has to return through the yoke is given by

$$\phi = gx_s\ (x_s + x_p)/2$$

and the width of the return yoke

$$w = \phi/B$$

where the field B in the return leg would typically be 1.4-1.5 Tesla. The width w must be large enough to accept the end field flux.

At this stage we can also estimate the inductance, a parameter of interest with regard to the power supply. This is

$$L = 8N\phi L_{eff}/I$$

Unfortunately, the running of this design on a 2D magnet programme showed that the flux at the root of the pole was about 2.0 Tesla, at which level saturation effects in the steel are dominant. A re-design (see Fig. 2), in which the pole length was much reduced, necessitated the use of saddle-shaped coils which are more expensive and significantly increase the electrical resistance and water flow path length. The magnet also became larger, but some of this increase in size was counteracted by making the pole assymetrical about the 45° line, taking advantage of the small vertical size of the good field region.

The next section briefly describes the magnet programmes used.

3. MAGNET PROGRAMMES[2-5)]

3.1 Two dimensional

MAGNET is very easy to use and set up. It is fast and can employ a very fine mesh, but it assumes left-right symmetry and therefore cannot be used for a quadrupole containing a sextupole component.

PE2D takes longer to set up, but is easy to use and makes no left-right assumptions unless asked to. It will calculate eddy-current distributions and losses. MAGNET and PE2D have been compared for the same problem and agree in field gradient to 1 or 2 parts in 10^3.

To use PE2D, the magnet is divided into 4-sided regions, for each of which is specified the:

a) coordinates
b) material
c) current density
d) μ-value (for linear calculations)
e) number of subdivisions for each side
f) B-H curve.

A fine mesh (5-10 mm) is required in and near the areas of interest, ie the pole face, the shims and the air gap. The programme generates a triangular mesh (see Fig. 3) using (at RAL) a PRIME computer, and it is then submitted to a main frame for non-linear iteration. Typically 12 minutes of CPU time are required for the non-linear solution of 180° of quadrupole with quadratic elements. A post-processor on the PRIME is used to obtain fields, contours, eddy losses, etc.

3.2 Three dimensional

TOSCA was written before PE2D and parts of it are not as user-friendly as that programme. It uses a square, rather than a triangular mesh, which is sometimes inconvenient for quadrupoles. It is capable of handling quite complicated magnets ($\sim$ 40,000 nodes) but the way in which the problem is meshed is extremely important. It is recommended that users learn about the programme on a small programme first so as not to waste a lot of CPU time. TOSCA can be used in 2D mode, which has a very much quicker turn-round, and this also is recommended as a means of deriving a satisfactory mesh (by comparing the results with the 2D programme).

Fields can be calculated to various degrees of accuracy, the most accurate being very expensive but seldom required. For a 180° quadrupole plus sextupole (∿ 20,000 nodes), typical CPU times are as follows:

Integration over the coils	1400 s
Iterations (∿ 22)	3600 s
Field calculation (4800 values)	900 s

The coils are represented by arcs and straight sections. The total number of conductors, which heavily influence CPU time, was seven in this case.

Where parts of the magnet are tending towards saturation (such as the shims) it is very important to use a B-H curve which represents accurately the steel to be used. The packing factor should also be allowed for by, for instance, multiplying the B values in the B-H curve by the estimated packing factor.

4. POLE PROFILE ADJUSTMENT

Returning now to the problem, this is run in 2D (non-linear, 90°) and the shims adjusted to obtain the required field quality. If possible the pole-width is reduced, thus enabling the magnet to be reduced in size, and the field in the return yoke is also checked. We now run TOSCA in the 2D mode, and adjust the mesh to get good agreement with the 2D programme results, at the same time bearing in mind the ultimate size of the problem which will have to be run in 3D.

We now go through the following steps:

a) Run in 3D and adjust the core length to get the desired L_{eff}

b) Plot $\Delta G/G$ versus x,z (see Fig. 4). The allowed poles for an assymetric quadrupole are 4, 8, 12, 16 etc.

c) Calculate the 8 and 12-pole coefficients and multiply by L_{eff}/L_{iron}.

d) Change the signs and include in the pole profile (see Sec. 5).

e) Check the new profile in 2D.

f) Run the new profile in 3D and check $\Delta G/G$ versus x,z is flat in the central region (Fig. 5).

g) Now introduce the sextupole component into the profile; this requires that 180° of the quadrupole is described in both programmes. Again we multiply the required sextupole component by L_{eff}/L_{iron} (Fig. 6).

h) Run in 2D to check, and adjust the shims (Fig. 7)*).

i) Run in 3D. Adjust the sextupole component if necessary and optimise the shims (Fig. 8)*).

Because of the lack of time, the full optimisation of the shims was not carried out; we were confident that the field gradient could be linearised by means of the end shims.

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*) Since this talk was given, the quadrupole has been manufactured and measured. The measurements are included in Figs. 7 and 8. By means of adjustments to the end shims the required tolerances on L_{eff} and $\Delta G/G$ have been achieved.

5. THE INCLUSION OF HIGHER ORDER POLES

The ideal multipole field can be derived from a magnetostatic potential given by

$$\phi = \frac{1}{n} k_n r^n \sin n\theta \quad \text{where } n = \text{pole order}$$

For a quadrupole $\phi = \mu_0 NI = \frac{1}{2} k_2 r^2 \sin 2\theta$

$$= k_2 xz \text{ in Cartesian coordinates}$$

The poles follow equipotentials

$$\phi = \pm\frac{1}{2} k_2$$

$$\text{i.e. } r_o^2 = 2xz$$

If we include higher poles, we get the equation

$$\phi = \frac{k_2 r_o^2}{2} = \frac{1}{2} k_2 r^2 \sin 2\theta + 1/3\ k_3 r^2 \sin 3\theta + 1/4\ k_4 r^4 \sin 4\theta + \ldots.$$

To solve this, we convert to Cartesian coordinates and use Newton's iterative method, taking as a first approximation

$$x = r_o^2/2z$$

A neater method (because computers can handle complex numbers) is that of conformal transformation. The two methods are exactly the same in principle.

6. SOME PRACTICAL CONSIDERATIONS

6.1 Coils

6.1.1 Material

There is still no clear cut winner in the competition between copper and aluminium as a conductor material. Whereas copper has nearly twice the conductivity of aluminium it is available only in limited lengths. Aluminium can be supplied in lengths limited only by transport considerations (at least 200 m), and seems to be the preferred material for the very long dipoles required for LEP and HERA. It is not possible, of course, to have a mixture of Cu and Al conductors on the same demineralised water circuit.

6.1.2 Keystoning

This is the deformation of the cross-section when the conductor is bent. There is always the requirement to keep the overall length of a magnet as small as possible, for which small radii of curvature are indicated. Manufacturers prefer that the bending radius be greater than four times the conductor width, but it is possible to take special measures to prevent keystoning for radii smaller than this.

6.1.3 Conductor Size

The use of a high current, and thus a large conductor cross-section, results in a small number of turns, a small water coolant path length and a good packing factor.

However, difficulties may arise where the pole is not wide enough for the cross-overs from one turn to the next to take place at the ends of the magnet. The coil window may have to be enlarged to allow the cross-overs to occur within the body of the magnet.

6.1.4 Insulation

The standard insulation in use for normal applications today is glass or glass-mica tape impregnated with epoxy resin. Depending on the resin system, this can withstand up to 5 x 10^7 Grays before its flexural strength deteriorates significantly.

For DC, high-radiation-environment magnets, mineral insulated (MI) cable is generally used. However, the packing factor is not good and great care must be taken to keep the ends of the cable well sealed against moisture. Because of the metallic, protective sheath enclosing the mineral insulation round the conductor, this cable is not suitable for AC magnets.

Concrete being completely inorganic, it is extremely radiation-hard, but as in the case of MI cables will absorb moisture if allowed to. Complete canning of the coils is required, together with suitable current feed-throughs.

6.1.5 Coils for AC Magnets

The eddy power generated in a square conductor of side a, situated in a sinusoidally varying field of amplitude B, is given approximately by

$$P = (\pi B f a^2)^2/6\rho \text{ watts/m}$$

where f = frequency, ρ = resistivity, and skin effects have been neglected. Significant power losses would result if a conductor, say 1 x 1 cm^2, were used to power an AC dipole or quadrupole, since the fringe field in the region of the coil can be (locally) several kilogauss.

The problem can usually be overcome in one of two ways:

1) Subdivide the basic conductor into 2 or 4 smaller, water cooled conductors, insulated from one another but connected in parallel. The subconductors have to be transposed in position relative to the others when going from pole to pole (in a quadrupole) or layer to layer (dipole). The manifolding for such a conductor set becomes rather extensive.
2) The conductor is formed from a bundle of individual strands, each $\sim$ 1 mm in diameter and coated with an insulator. Cooling has to be by indirect means, and therefore a low current density ($\sim$ 2A/mm^2) results. This type of coil requires a very large bending radius, leading to extra overall length of the magnet, and is expensive to make. They have been used on such accelerators as CEA, DESY and NINA.

6.2 Yokes

6.2.1 Solid

Solid cores have been used for magnets in storage rings (eg SPEAR), beam lines and for special applications (NMR). They are mechanically simple, but machining is expensive, as is good quality magnet steel, and ultra-sonic testing may be required to detect blow-holes and flaws.

6.2.2 Laminated

Laminated magnets are usually more economic to produce if more than 1 or 2 of the same design are required. The lamination thickness is determined by the stampability of the steel for slow-pulsed magnets (1.5-2 mm) or, in the case of AC magnets, by eddy current fields and core-losses (0.35-0.5 mm for 50 Hz).

6.2.3 Construction of Laminated Magnets

Slow-pulsed or DC laminated magnets are usually constructed in the fashion pioneered at Fermilab for the 500 GeV synchrotron. The laminations are stacked on a fixture between thick end plates. The stack is compressed and an angle plate pressed on and welded to the laminations and end plates. On release of the compressing force the yoke may not be perfectly straight, distortions having been introduced by the welding. This can be removed by discreet hammering of the welds.

For AC magnets, thick end plates are not allowed to cover the pole area, because of the eddy heating. Usually the poles are given a Rogowski roll-off to prevent such heating in the end laminations themselves. Epoxy resin, and perhaps insulated tie-bolts, can be used both to reduce the chances of laminations shorting together and to prevent chatter.

At Fermilab, Cornell and Argonne 'canned' combined function magnets have been constructed. The lamination stack is put in a thin stainless steel can, together with the coils, and the whole vacuum impregnated with epoxy resin. A pressurised air bag creates the aperture required for the beam. Thus no separate vacuum chamber is required and stored energies are minimised. The disadvantages of this system include the problem of high voltage feed-throughs for the coils and the quality of the vacuum, which might result in excessive pump maintenance requirements.

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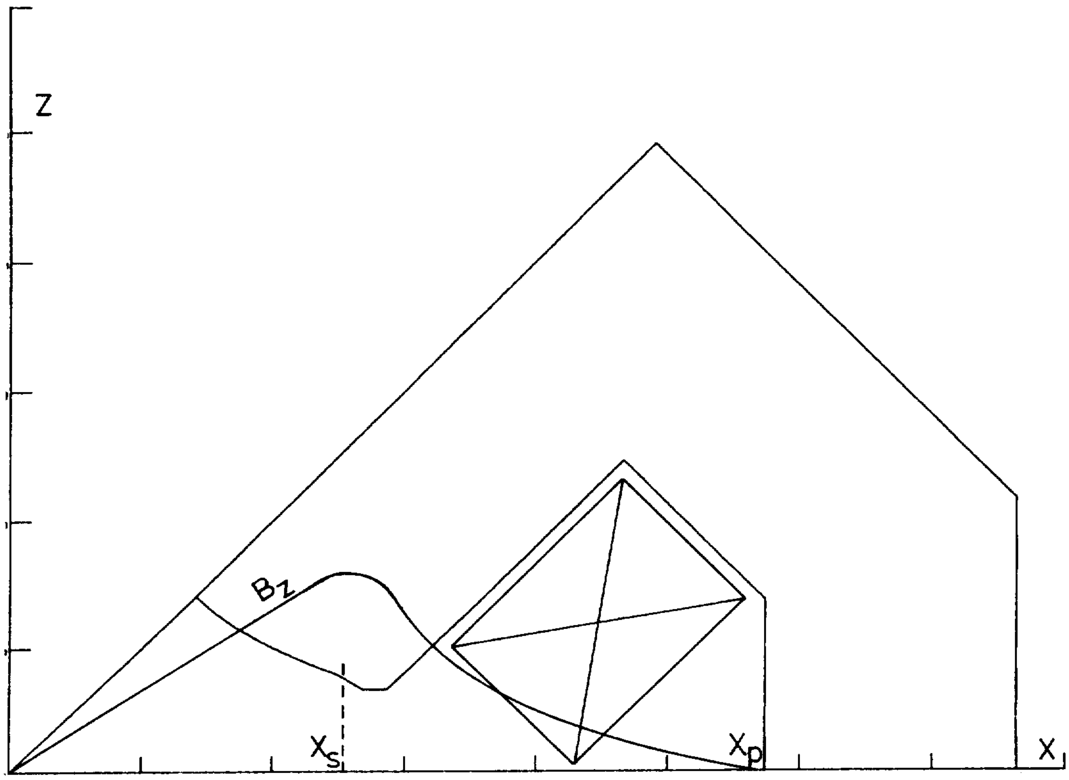

Fig. 1 For a symmetric quadrupole only 45° needs to be described.

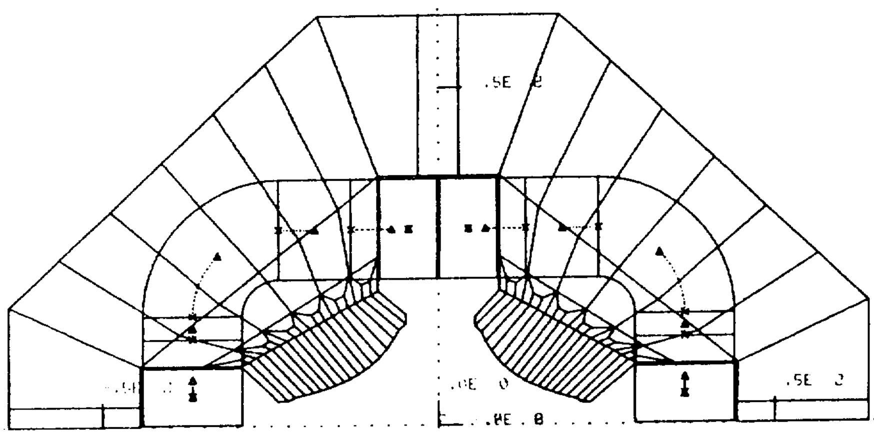

Fig. 2 An asymmetric quadrupole can be described in 90°, unless it has an odd-order pole component as shown here.

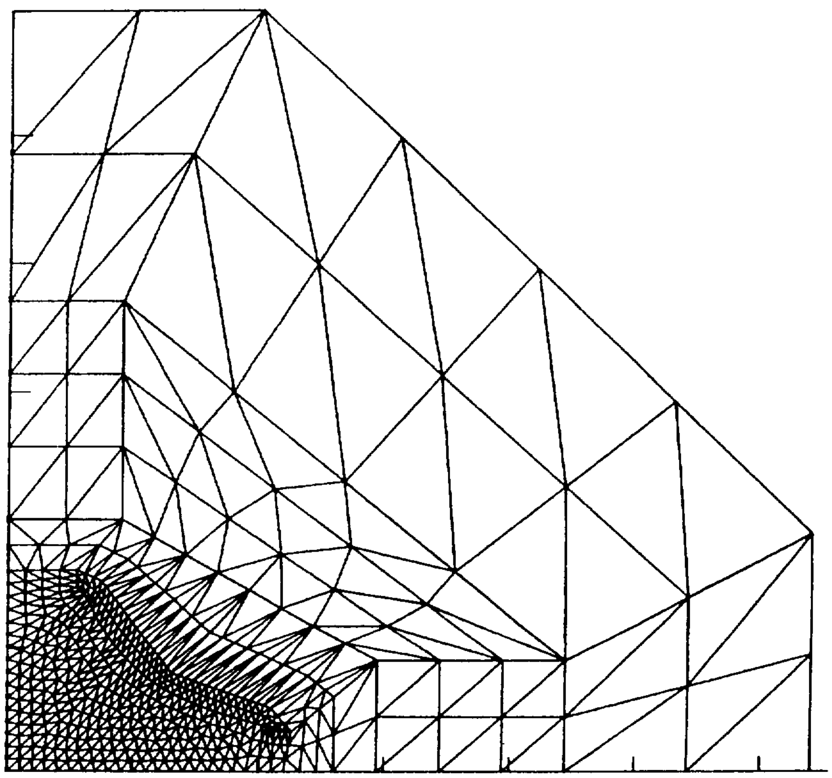

Fig. 3 An illustration of the triangular mesh used in PE2D.

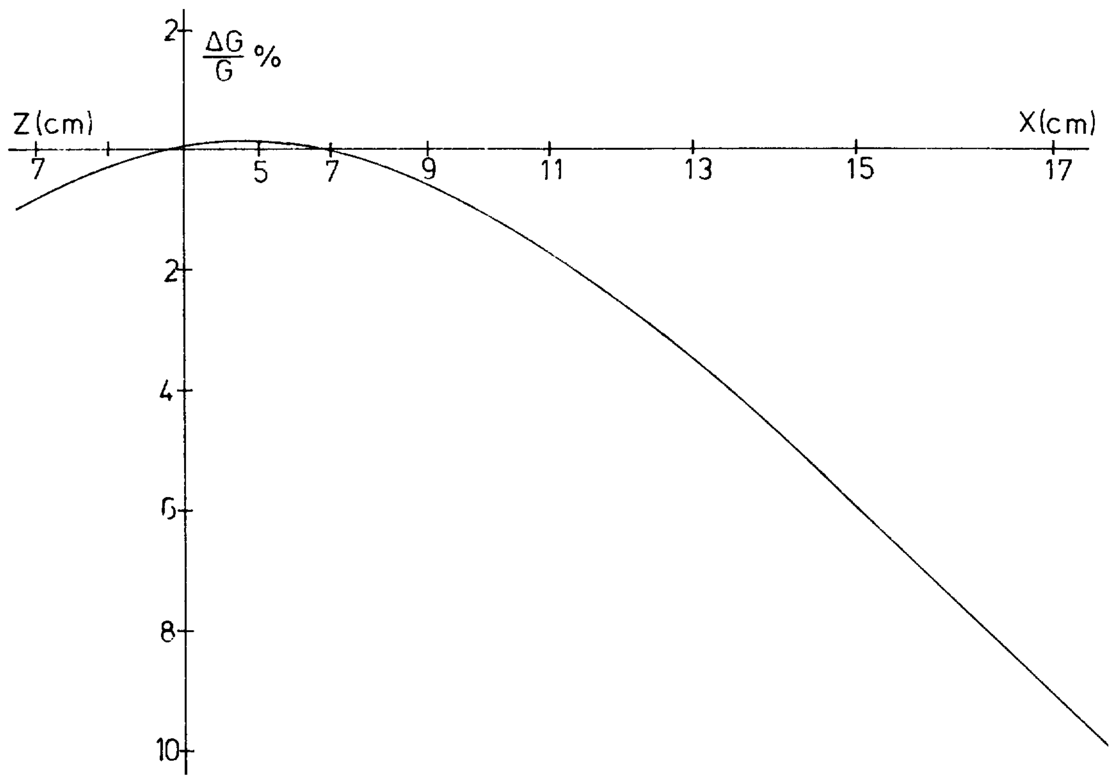

Fig. 4 The 12-pole component due to the pole ends shows up as a parabola when plotted on a quadratic scale. The 8-pole coefficient is derived from the displacement of the maximum from the ordinate.

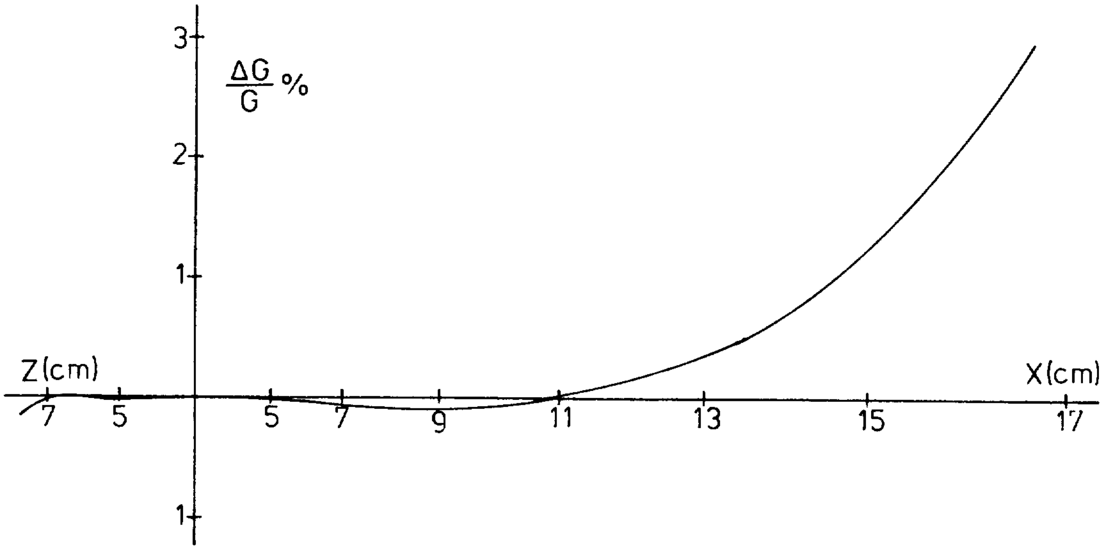

Fig. 5 With 8- and 12-pole corrections in the profile, the gradient-error curve is essentially flat in the central region. Perhaps the 12-pole correction was slightly excessive.

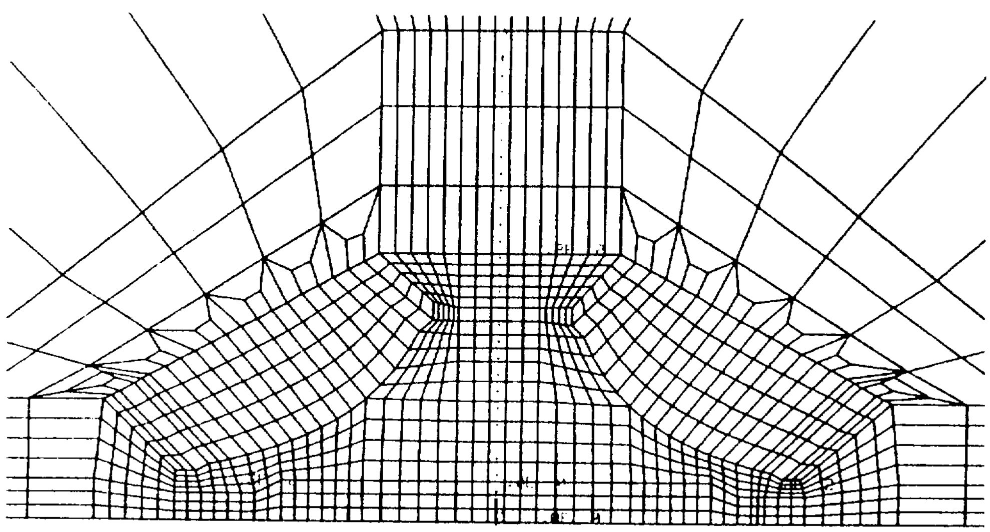

Fig. 6 The TOSCA square mesh used for this problem. The coils are put in separately and do not have to be meshed.

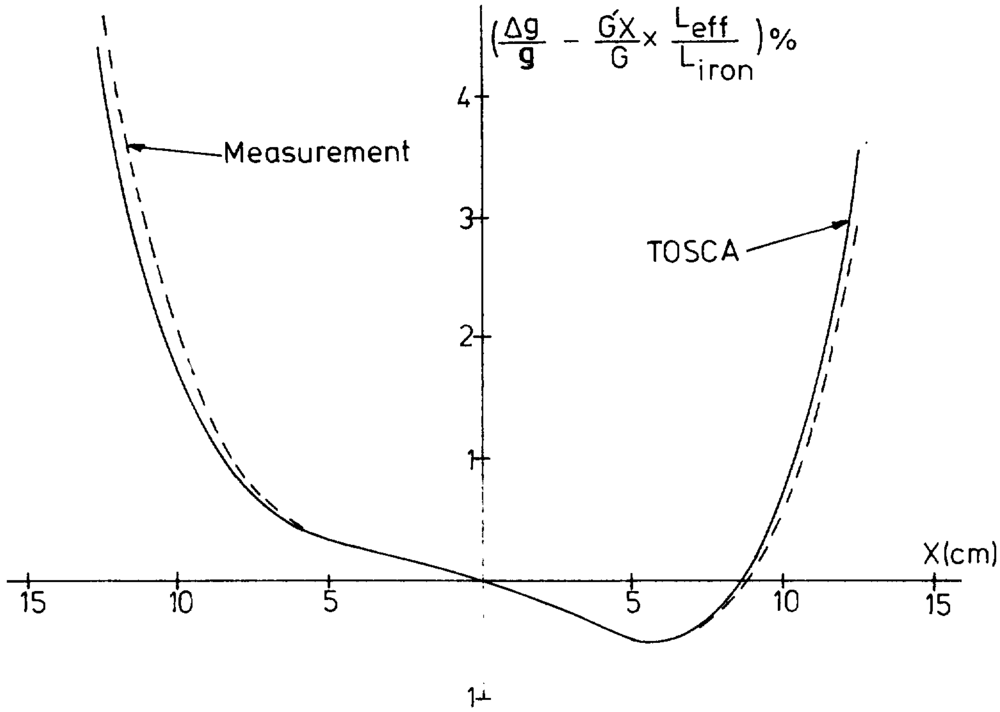

Fig. 7 The theoretical sextupole component has been subtracted in this plot of the gradient at the centre of the quadrupole.

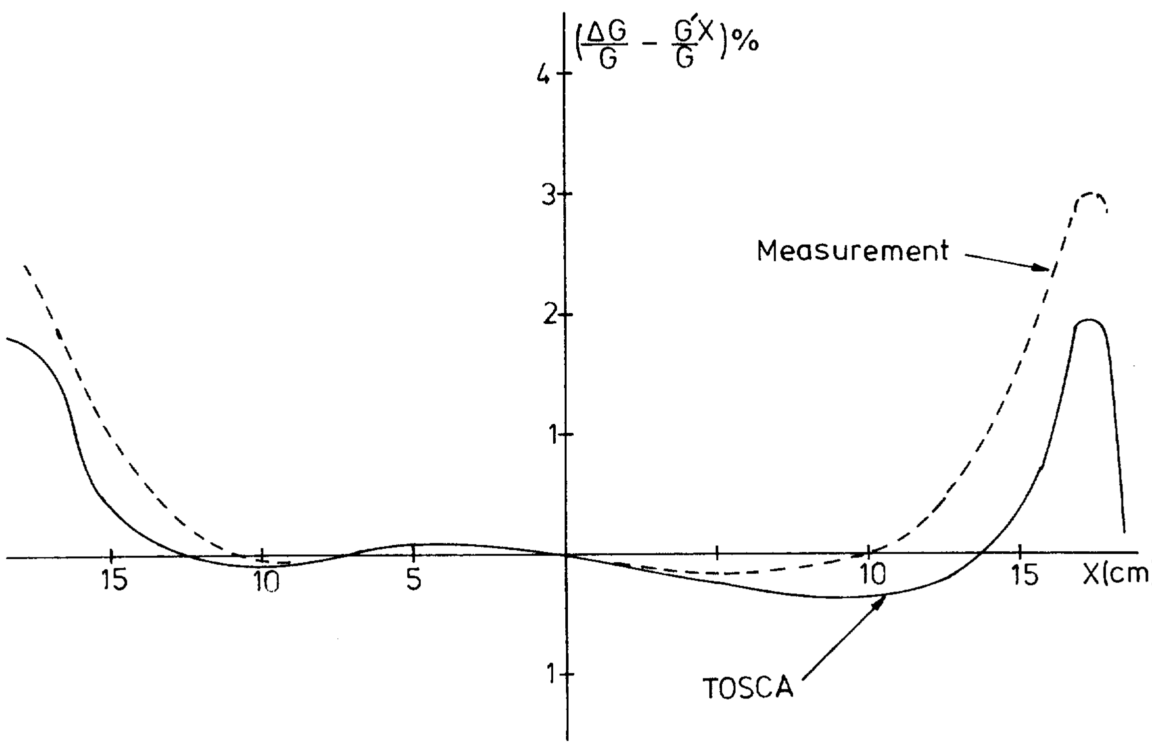

Fig. 8 Prediction and measurement of the integral gradient errors. Again the required sextupole component has been removed. The errors in the central region are small, and the good field region was easily extended by machining the end shims.