

A STRONG FOCUSING BENDING MAGNET FOR THE CERN ANTIPROTON COLLECTOR

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Abstract

ACOL, the CERN Antiproton Collector, includes 56 quadrupoles, some of which are offset with respect to the closed orbit in such a way that they bend the beam. We discuss one of these magnets which accommodates two offset beams both bent the same direction such that this magnet is best described as a strong focusing bending magnet. The field near the edge of the aperture reaches 1.7 T i.e. a value where permeability varies considerably. This fact and the superposed gradient made the design a bit difficult. A design in some respect similar to a Morpurgo magnet has been adopted in which the conductors come so close to the useful field area that they participate in shaping the field. This made the magnet compact but required high current densities. Finally, the 3 D field has been computed with the TOSCA code and the ends of the magnet shaped as wedges (not perpendicular to the orbit) in order to make both the gradient and the effective length independent of the beam position. Practical construction and field measurements are also discussed.

Introduction

The CERN Antiproton Accumulator (AA) is currently being upgraded by a second storage ring of higher acceptance, the Antiproton Collector (ACOL, which is built in the small space around the AA ring inside the wall of the existing building. For this and optical reasons eight quadrupoles are displaced towards the centre of the ring such that they help to bend the beam into a closed orbit. Most of the 56 wide and narrow quadrupoles have been described elsewhere¹ but here we describe the QFC 54 (= quadrupole, focusing, combined function, #54) in the injection region which is offset by about 78 mm such that it combines the function of bending by 30 mrad and focusing. Its aperture includes also the injected beam which enters at an angle and is bent more strongly and therefore requires aperture up to approximately $x = 270$ mm. Quadrupole 54 is a "half-quadrupole" in which the vertical symmetry plane $x = 0$ of the field is replaced by an iron boundary serving as left backleg. It is a combined function magnet like old synchrotron magnets of CERN PS and ISR or Brookhaven AGS. However, it has a higher gradient $g = 6.4$ T/m which is maintained up to 1.7 tesla at the edge of its wider aperture.

The Pole Profile

Since this magnet is both part of the ACOL storage ring and of the injection channel optics calculations had been done under the assumption that the bending length ℓ_B and gradient length ℓ_G have the same nominal value:

$$\ell_B = \frac{1}{B_0} \int B dz, \quad \ell_G = \frac{1}{G_0} \int G dz$$

Therefore these lengths had to be made equal. It is known from old synchrotron magnets PS and AGS that the gradient length is considerably (7 cm) shorter than the bending length and there is a relation²:

$$\ell_G = \ell_B + \frac{B}{g} \frac{d\ell_B}{dx}$$

where g is the gradient and B the field on the orbit position X_0 and $d\ell_B/dx$ is negative because the effective length and fringe fields decrease versus x as the gap under the hyperbola becomes narrower. Thus in order

Table I

ACOL MAGNET QFC 54	
PARAMETER LIST	
beam rigidity at 3.5752 GeV/c	11.92558 T*m
focussing force	0.38263 m ⁻¹
deflection angle	0.030 radian
ACOL beam position (angle/force)	78.4 mm
inject. beam position	215 mm \pm 56 mm
aperture requirements	27 < x < 271 mm
	-28 < y < +28 mm
effective length (gradient)	0.724 m
measured gradient	6.430 T/m
field on injected beam	1.36 T
field at aperture limit x=270 mm	1.7 T
current	1851.3 A
turns/pole	21
conductor size	10mm x 10mm
current density (5MM hole)	23. A/mm ²
hyperbola equation	$x \cdot y = 7588$ mm ²
core length	680 mm
core length incl neutral pole	820 mm

to obtain the expected deflections for both orbit and injected beam the gradient had to have a constant specified value and the iron length had to be varied to make $d\ell_B/dx$ constant and $\ell_B = \ell_G$. Therefore this magnet has a hyperbolic pole profile. Due to earliest aperture specifications $x_{\max} = 271$, $y = \pm 28$ mm, the profile equation is:

$$xy = 7588 \text{ mm}^2, \quad r = 123.19 \text{ mm}$$

The magnet parameters are shown in Table I.

Right-Hand Side Coil Design

The most difficult problem was to maintain a high gradient up to 270 mm in spite of iron saturation. This goal was achieved by bringing the right-hand side conductors as closely as possible to x_{\max} (Fig. 1) so that a very small region of field higher than $x_{\max} \cdot g = 1.7$ T is produced beyond the aperture limit. In window frame-like bending magnets one can push the field quite high by placing part of the coil in the narrow gap. This works provided that one resorts to higher current densities because the higher the current density the more rapidly the induction drops beyond the minimum gap to less dangerous values. The value of the current 1851.3 A was imposed because this magnet is

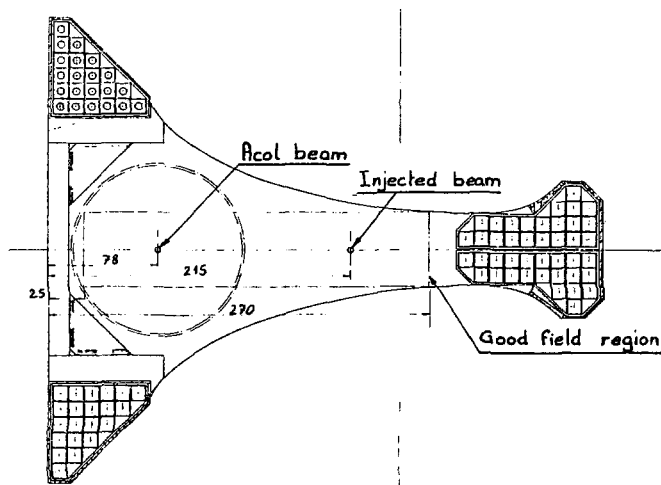


Figure 1

connected in series with all other quadrupoles. In our case two conductors 10x10 mm with their insulations and 23 A/mm² just fit into the gap. The number of turns $n = 21$ has been chosen to obtain the required gradient and the precise total strength has been adjusted by shimming iron end plates.

The standard method to limit saturation in quadrupoles is to terminate the hyperbolic pole profile as soon as possible in a shim or better shim-antishim combination which produces the steepest drop of field beyond x_{\max} . However, shims saturate. Thus we placed the first turn of the coil asymmetrically in the half-gap near the midplane. This artefact partly replaces the shim and diminishes the induction on the pole. Figure 2 shows the resulting magnet which has a small reluctance around the right-hand side coil. The remaining drop in gradient was approximately 4% and fitted best to a negative 16-pole. The hyperbolic profile was replaced by a profile which just compensates this and yields a perfectly flat gradient.

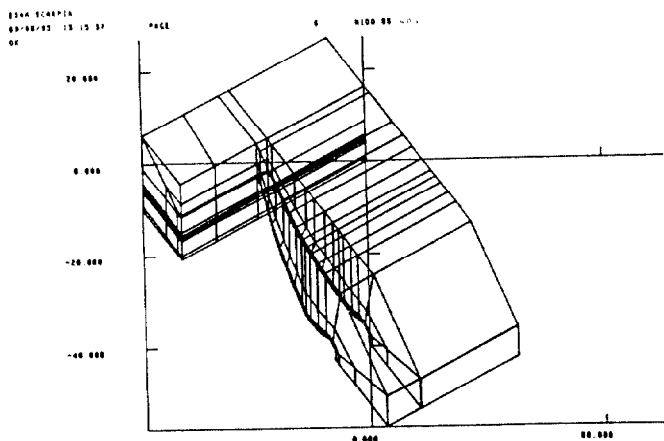


Fig. 2

Top Coil Design

The upper and lower left coil is not placed high up as usually in quadrupoles because in a half-quadrupole with neutral pole at $x = 0$ the left flux path becomes too long. Since only $y = \pm 28$ mm of the aperture is needed, we looked for a design with low coil i.e. an exact solution of the Poisson equation in coils of constant current density of such shapes that the quadrupole field is not perturbed even if the coils touch the aperture. 30 years ago, Panofsky and Hand³ built a quadrupole magnet of rectangular aperture $a \times b$ in which the 4 quadrupole coils are rectangles of width a and b such that they match to the 4 sides of the aperture. The current density and consequently also the coil areas are equal to insure balanced currents. The configuration fits into a rectangular iron window. In the following years, M. Morpurgo⁴ built a more cost effective magnet derived from the Panofsky quadrupole by observing the magnetic equipotential lines in the coils of the Panofsky magnet and replacing them by an ideal iron boundary. In this way the parts of the coil which do not contribute to the field in the aperture are cut away and hence the same fields in the aperture are obtained with less current. Our quadrupole 54 is half of a Morpurgo magnet with triangular coil on top. Without going into detail we just mention that if one limits the aperture by the top coil with lower boundary,

$$y = y_1$$

and if this coil boundary intersects the hyperbola $y = c/x$ at

$$x_1 = c/y_1$$

then the other two sides of the triangle are given by the y -axis and by the tangent to the hyperbola in (x_1, y_1) which intersects the y -axis at $2y_1$. Thus the iron boundary of this coil is given by

$$y = y_1(2 - x/x_1),$$

and the coil area is constant, $x_1 y_1 / 2 = c/2$. In our quadrupole the coil does not fit into an ideal triangle from $y_1 = 98$ to $2y_1 = 196$ mm but the fact that we have a "Pascal triangle" of 1+2+3+4+5+6 conductors helped to obtain a uniform current density which is important to obtain a good gradient uniformity. Finally a coil arrangement with very constant gradient has been computed with the 2 D finite difference program MAGNET of the CERN program library by adjusting very carefully the vertical position of this triangular coil and the iron boundary. Computations showed that coil positioning errors had to be smaller than 0.5 mm.

Three-Dimensional Field Computations

The 3-D computations have been done at RAL where the 3-D magnetic field computation program TOSCA is available. Figure 2 shows the finite element representation of half the magnet core. It was particularly difficult to enter the complicated shape of the triangular coil. One can see that the neutral pole of our magnet extends much further than the end faces of the iron core. It is a magnetic mirror for coil and air fields. The main purpose of these calculations was to determine a first approximation for the shape of the end faces of the magnet in order to obtain a constant effective length. If x , y and z are respectively the horizontal, vertical and longitudinal axes counted from the centre, then from a certain parameter $x > x_c$ the magnet had parallel end faces and for $x < x_c$ it was wedge shaped. At $x < 0$, the iron core was about 0.9 m long due to the neutral pole "mirror plate". In this way, as the gap becomes wider in the range $0 < x < x_c$ the core becomes shorter and the effective length constant if one chooses properly the wedge angle at x_c . By repeated computation of the effective length versus x and by variation of the parameters x_c and the depth of the wedge at $x = 0$, the effective length variations could be corrected in straight line approximation. We chose $x_c = 280$ mm and the depth of wedge 44 mm at $x = 0$. However, the magnet was built with detachable end plates which could be machined after measurement. Also the end plates had provision for 17 piles of washers along the pole profile which allowed to make a finer adjustment of the effective length than the straight line approximation predicted by 3-D computations.

Construction

The magnet (Fig. 3) is composed of two identical halves (upper and lower) which are assembled face to face and kept together by welded retaining plates on the outside. Although the magnet is not pulsed its core length of 0.48 m is assembled from high quality laminated steel but with two 0.100 m thick Armco end plates. About 320 laminations of 1.5 mm thickness have been piled up. The cutting of the laminations has been carried out on a LASER cutting machine because the quantity was small and the requirements of 0.02 mm precision of the pole profile in the narrow gap were tight. These tolerances could be met after several trials with good uniformity.

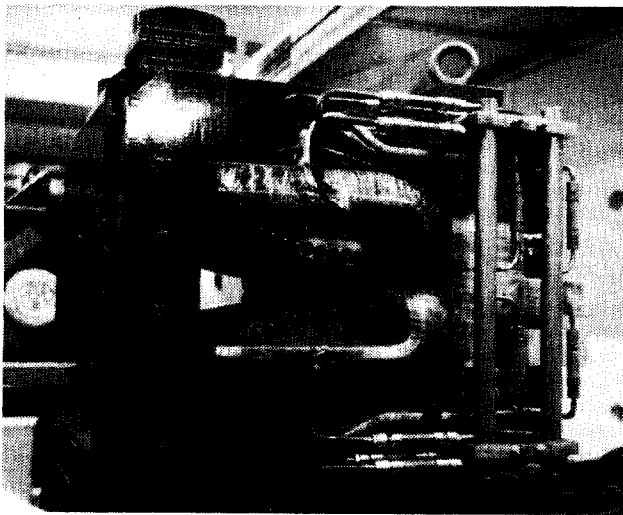


Fig. 3

The two excitation coils are wound symmetrically and connected in series. Each coil has 5 water cooling circuits fed in parallel.

Measurements

When the magnet arrived it turned out that the gradient inside the magnet rose towards the narrow gap by only 0.8%, i.e. the 16-pole term which was built into the hyperbolic profile with a peak of 4% was slightly too strong (computer runs with a lamination packing factor of 98% instead of 97% would have given the same result) (Fig. 4). Measurements also showed that the quadrupole strength $fGdz$ varied from +1.5% over -1% to a peak of +3% near the narrow gap. The drop from 1.5% to -1% near the neutral pole (= mirror plate at $x = 0$) was corrected. These mirror plates were detachable Armco steel pieces which extend the neutral pole in the z -direction. By shortening these pieces the effective length could be made constant near $x_1 = 0$. It also turned out that with the current of 1851.3 A imposed by series connection with other magnets the gradient was 6.430 instead of 6.318 initially specified. Therefore, the end faces have been machined and washers adjusted to obtain a very constant quadrupole strength of

$$fGdz = 4.5767 \text{ T}$$

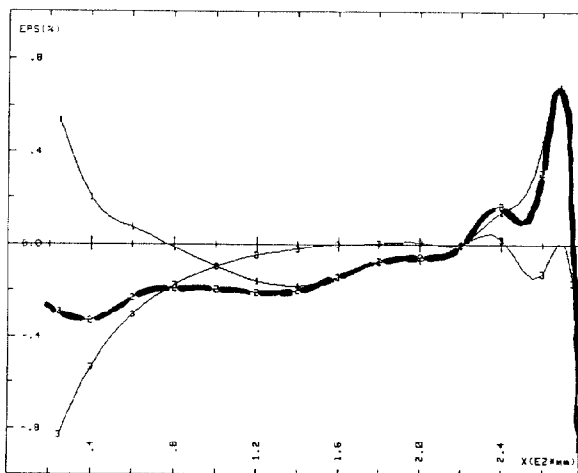


Fig. 4

and since the central gradient varies by only 0.6% near the narrow gap this ensures that also $d\ell_B/dx$ is constant and both ℓ_B and ℓ_G have the same value 726 mm (Fig. 5)

tolerances near the narrow gap are far less stringent than at the closed orbit position $X = 78 \text{ mm}$ because the injected beam traverses the magnet only once.

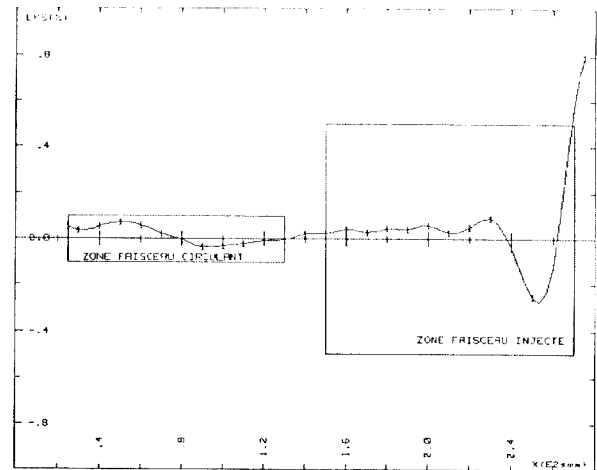


Fig. 5

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