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SPECIAL INJECTION REGION QUADRUPOLE FOR THE CERN ANTIPROTON COLLECTOR RING

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Abstract

In the ACOL injection region, a special combined function magnet has been built. It is composed of two semi-quadrupoles, one acting on the circulating beam, the other on the injected beam. Each semi-quadrupole has a neutral pole. The angle between magnetic axes is equal to 7.85° .

Both semi-quadrupoles are positioned such that they act also as dipoles, each giving a deflection of 18 mrad. The field and the gradient must track with those of the other quadrupoles in the collector ring. The mechanical design, the magnet computation and the measurements are described.

Introduction

The CERN Antiproton Accumulator (AA) has been upgraded by the addition of an Antiproton Collector Ring (AC) [1]. The latter is concentric with the AA and had to be accommodated inside the walls of the existing building. For this reason and because it is a storage ring with 200 μ m.mrad acceptance, several stringent constraints had to be satisfied.

Among 56 quadrupoles, 16 are displaced to participate in the bending field made up of 24 dipoles. A special injection region has been designed to inject and extract antiprotons. Some magnets for these purposes are also used as ring lattice magnets to store the beam. One ring dipole, BHSS2, has a hole in its core where the injected beam passes. A special shield has been added around the vacuum chamber to minimize the effect of magnetic flux when the injected beam crosses the dipole core. One ring quadrupole, QFC54, with combined functions, has a large aperture with a strong field at the edges and acts simultaneously on the injected and circulating beam. One special quadrupole, QDC53, with combined functions, is designed with two semi-quadrupoles. One (QDC53-I) belongs to the injection lattice and another one (QDC53-A) belongs to the ring lattice where the circulating and ejected beams pass through it.

Fig. 1 shows a layout of this region. The design and results on QDC53 are presented.

Fig. 1: Layout of special ACOL injection region

Design

The AC being a storage ring with a very large acceptance, a strong focusing lattice was designed consisting of 56 ring quadrupoles divided into seven families.

The family QDN5, which includes QDC53, is composed of eight defocusing quadrupoles, displaced in the horizontal plane by 51.2 mm in order to give a bending angle of 18 mrad. The pole profile designed for this family includes a 12-pole component to compensate the pole-ends effects. The injection channel has the same focusing structure as the AC ring but the geometry is different. This explains that magnets, which must fulfill the same functions for the injected and circulating beams, have special structures (Fig. 2).

Two defocusing semi-quadrupoles were designed. Each magnet has a neutral pole (i.e. a mirror plate at $x=0$) to close the magnetic flux. The angle of 7.85° between magnetic axes has been calculated from injection line and ring lattices.

Figure 2 shows a top view with geometrical data concerning the different beams.

Fig. 2: Injected, ejected and circulating beams in QDC53

To keep a symmetry, the injection line lattice was designed with a defocusing quadrupole, QDC53-I, having the same characteristics as QDC53-A; i.e. horizontal bending angle and gradient. Then the current could come from one power supply to feed both semi-quadrupoles.

Another constraint is due to the ejected beam. It should pass through QDC53-A before going into the ejection septa. The pole profile designed for QDN5 family allows an aperture large enough just to accept this beam. The consequences were: i) an increase of good field region for the integrated gradient compared to quadrupoles of the family QDN5; ii) to impose conditions for the ejected beam according to the kick received in QDC53-A and to the limit in the aperture at the ends of this semi-quadrupole.

All shimming had to be done by adjusting the pole-lengths according to the saturation effects and the mirror plate effects.

Table 1 gives the main parameters requested for the QDNS family. Each semi-quadrupole must track with them.

Beam rigidity at 3.5752 GeV/c	11.92558	T.m
Focusing strength	0.47535	m ⁻²
Deflection angle	+0.018	radian
Central orbit position	+0.0512	m
Effective gradient length at x=0	0.738	m
Nominal gradient at x=0	5.668	T/m
Integrated gradient	4.1836	T
Integrated magnetic field on circulating and injected beam	0.21442	T.m
Integrated magnetic field on ejected beam	0.41451	T.m
Deflection angle for ejected beam	0.0348	radian
Nominal current	1851.3	A
Turns/pole	15	

Aperture requirements	Horizontal plane	Vertical plane
QDC53-A	-18 < X < +115 mm	-48 < Y < +48 mm
QDC53-I	18 < X < 88 mm	-48 < Y < +48 mm

Table 1

Saturation effects

Saturation effects were calculated for all seven families. Because some defocusing and focusing quadrupoles contribute to the bending field, it was decided to build only one power supply which feeds current to all quadrupoles of the AC machine. The nominal current was fixed by averaging the gradient of narrow quadrupoles (3 families).

The correct focusing forces for QDC53 were achieved by adjusting the effective length taking into account the saturation effects for family QDNS.

The classical relation between the ampere-turns and the gradient for an infinite permeability has been modified as follows

$$nI = \frac{r^2}{2\mu_0} g \frac{f_{\infty}}{f}$$

where r is the inscribed radius of the quadrupole, and where $f = g \cdot l_g$ and $f_{\infty} = g_{\infty} \cdot l_{\infty}$. g_{∞} and l_{∞} are the gradient and the effective length for an infinite permeability, g and l_g are the gradient and the effective length for the real permeability.

From 3D calculations (where the real BH-curve is introduced), the components B_y versus x are given, together with the integrated gradient. Then g and l_g are deduced. Two runs were performed at two different currents. A polynomial fit for the ratio f_{∞}/f versus integrated gradient was made. According to the requested focusing strength and the results of this fit, the effective length was found to be $l_g = 0.731$ m at $x = 0$ and pole length of 0.667 m for a current of 1882 A.

Two-dimensional and three-dimensional work was carried out. The figure 3 shows the flux line distribution when a 2 mm gap is introduced between the neutral poles of QDC53-A and QDC53-I.

There is no significant difference, with respect to other quadrupoles, to the field distribution seen by the beam but much more flux passes down the neutral pole rather than across it.

The highest magnetic field $B = 1.28$ T was found at $x = -5$ mm and $y = 300$ mm for a neutral pole 85 mm thick. The gradient was 5.65 T/m with a current of 1831 A.

Fig. 3: Flux line distribution into QDC53-I

Construction

Firstly, the magnet was assembled and measured as a normal QDNS. Then it was split into two parts. On each base quadrant of QDC53-A and QDC53-I, three special feet were welded and machined. The parallelism between the plane defined by the three feet and the plane defined by the reference surface of the core quadrant is less than 0.05 mm.

The neutral pole is composed of two plates each 45 mm thick. One plate is bevelled for ease of mounting and to allow some clearance for adjustments. Neutral poles were mounted on each semi-quadrupole. Each half magnet was placed on a special base plate such that the errors in the x , y and z planes were minimized with respect to each other and a 2 mm air gap was left between the two independent neutral poles. However, radially it was not possible to place both two ton half semi-quadrupoles on the base plate and accurately achieve an angular position of 7.85°. Therefore a mechanical push/pull system had to be foreseen to enable radial positioning. This was dimensionally checked using dowel holes pre-machined into the top of each neutral pole.

The median plane and the respective heights could be measured from two precise surfaces machined at the ends of each neutral pole. The tilt of each semi-quadrupole is checked from two small positioning targets mounted at the top of each quadrant.

Two large positioning targets are mounted on QDC53-A at the top of neutral pole and are in the same plane as the inner face of it where $x=0$. These were used for installation in the AC ring. Fig. 4 shows both semi-quadrupoles with their respective neutral poles.

An alignment fixture was designed to be placed inside each semi-quadrupole to enable an optical control. The dimensional precision is better than 0.01 mm. It was used to align QDC53-A and QDC53-I on the common plate and also on the magnetic measuring system to align the semi-quadrupole prior to any magnetic measurements.

Fig. 4: Semi-quadrupoles mounted with their respective neutral poles.

<u>Race-track coil (1 pole)</u>	
Conductor size	15 mm x 23 mm
Hole for cooling	± 6.3 mm
Current density max.	6.4 A/mm ²
Number of turns	15
Copper length	30.2 m
Dissipated power	5865 W
<u>One quadrant</u>	
Core length (without end shims)	0.607 m
Lamination thickness	1.5 mm
Number of holes around the pole profile for washers ± 20 mm	11
<u>One neutral pole</u>	
Length	0.850 m
Height	1.110 m
Thickness	0.090 m
Magnetic permeability	5600
<u>Ensemble QDC53</u>	
Resistance	7.7 mΩ
Inductance	4.2 mH
ΔT	20°C
Water flow	17 l/min
ΔP	3.10 ⁵ Pa
Distance between neutral poles	min. 4 mm max. 81 mm
Total weight	4490 kg
Vertical movement	+4 mm -

Table 2: Main parameters

Measurements

The QDC53 was measured as a normal quadrupole and shimmed so that the variations of integrated gradient within the good field region was less than 0.2 per cent. Then it was split in two parts and mirror plates mounted. We measured both semi-quadrupoles keeping the same shimming and we found:

- i) a sextupole component (near the beam axis at $x = 51.2$ mm)

$$\int_{-\infty}^{+\infty} S dz = 0.35 \text{ T/m} \quad \text{or } K'/K = 0.084 \text{ m}^{-1};$$

- ii) a diminution of $\int_{-\infty}^{+\infty} G dz$ of about one per cent and diminution of G ($x = 51.2$, $y = 0$, $z = 0$) of 00.7 per cent.

This has been corrected by using detachable end-shims and a combination of washers at the ends of the four poles. These corrections were possible after having determined the variation of the integrated gradient when the pole length varies (1 mm gives $3.7 \cdot 10^{-3}$ T) and the perturbation of the integrated gradient given by 5 washers mounted on each 11 possible localised points at the ends of the pole. The washers distribution is visible on Fig. 4.

Figure 5 shows the results after the final shimming for both semi-quadrupoles. The homogeneity of $\int_{-\infty}^{+\infty} G dz$ versus x is plotted. The vertical coordinate is

$$\epsilon (\%) = \frac{\int_{-\infty}^{+\infty} G dz}{\int_{-\infty}^{+\infty} G dz_{\text{ref}}} - 1$$

where $\int_{-\infty}^{+\infty} G dz$ is the integrated gradient of the QDNS family. To simplify the figures, both mirror plates have been superposed and assumed infinitely thin at coordinate $x = 0$.

Fig. 5: Final integrated gradient for both semi-quadrupoles

Several holes were drilled in both neutral poles. Four holes $\varnothing$ 20 mm were used to assemble two plates forming the neutral pole and five holes $\varnothing$ 8 mm were used to support the alignment fixture. All these holes are at the level of the median plane. Because the integrated gradient was decreasing near the mirror plate (as expected), all holes were plugged. The results are shown on Figure 6.

Fig. 6: Effect on integrated gradient from holes in the neutral pole.

To analyze the saturation effects, several curves of $\int G dz$ at different currents were measured.

Figure 7 shows two curves, at current 1000 A and 1851 A (nominal). The integrated gradient changes by 0.2 per cent at the edges of the good field region for this range of current variations.

Fig. 7: Effect on integrated gradient from current variation

The integrated magnetic field was measured for both semi-quadrupoles at nominal beam positions ($x_n = 51.2$ mm). Results are in Table 3.

Table 3	QDC53-A	QDC53-I
$\int_{-m}^{+m} B dz$ (T.m)	0.21829	0.21772
$x_m = \frac{\int B dz}{\int G dz}$ (mm)	-52.1	52.0
$\Delta x = x_m - x_n $ (mm)	+0.9	+0.8

At the nominal position, the field was too high, so that the beam axis should have to be arranged to be nearer the mirror plate in order to keep the correct bending angle. The results of new magnetic measurements are given in Table 4 for the nominal current.

Central beam position from QDC53-A neutral pole	-0.0503 m
Central beam position from QDC53-I neutral pole	+0.0504 m
Measured gradient at $x=50.3$ mm	5.634 T/m
Effective length at $x=50.3$ mm	0.743 m
Integrated gradient within the good field region	4.1870 T
Integrated magnetic field at $x=50.3$ mm	0.2144 T.m
Pole length	0.657 m

Table 4

After these last measurements, the QDC53 was installed in the new AC ring where it has performed well since June 1987.

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