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BEAM OPTICS STUDIES ON THE ANTIPROTON ACCUMULATOR

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Summary

The CERN Antiproton Accumulator (AA) was designed to accumulate 6 x 10^{11} antiprotons per day, using the stochastic cooling technique[1]. Its construction was completed within two years and the first beam circulated in early July 1980[2]. This paper describes the conceptual design of the lattice and how multipole shim corrections were applied to develop the large betatron and momentum design acceptances. We also report how a sequence of such corrections, based on optics studies with proton beams, have been applied to the point that the machine is now approaching design performance.

Theoretical Concept of the AA Lattice

The lattice is of the separated function type with 12 FODO focusing periods, each with a phase advance of 68°. This configuration was chosen to keep γ_{tr} below the γ of the 3.5 GeV/c antiprotons injected.

The superperiodicity is 2 since we require two long straight sections where α_p is zero for the momentum cooling kickers and for the injection/ejection septum. Figure 1 shows one half superperiod. The dispersion must rise rapidly within the first 90° of phase advance between septum and injection kicker, for at the injection kicker the injected beam and the stack must be separated by a movable shutter. There are two types of bending magnet with a strength ratio 5 : 8, chosen to give the best α_p variation[3].

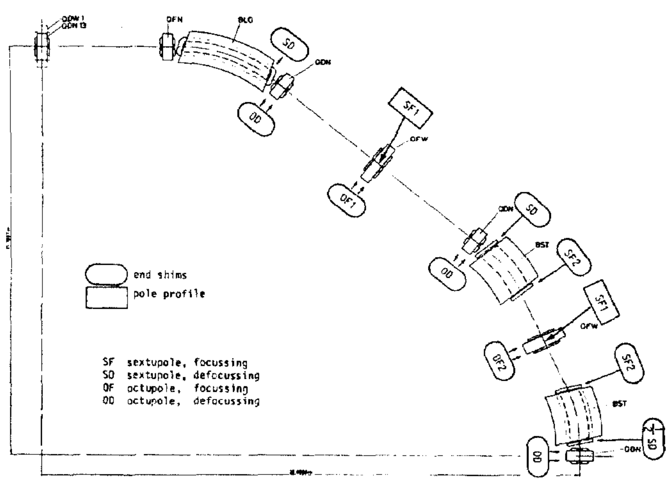

Fig. 1 - One half superperiod of the AA ring lattice, showing where different families of shims may be applied to give sextupole and octupole correction.

One of the unusual features of the design is its large momentum acceptance, over 6%, needed to accept 1.5% of the spectrum of $\bar{p}$'s from the production target and to allow the various gymnastics of precooling, stacking and accumulation to take place at different revolution frequencies. Another requirement is that the transverse acceptance must be large, 100 π mm.mrad in each plane, to collect enough $\bar{p}$'s. To provide such large betatron acceptances yet avoid the influence of high order betatron resonances on a stored beam whose momentum is modulated first by synchrotron motion and later by cooling, is a challenging task, and it is largely this which has prompted the sequence of corrections described below. Fortunately, intensity dependent instabilities are likely to be of minor importance in this machine and one can aim to keep the Q-spread small.

Another special requirement is that dispersion α_p must be zero within tight tolerances in the long straight section over the whole momentum acceptance to avoid transverse heating of the beam by momentum cooling. The increase of betatron amplitude in τ hours is given by

$$\Delta a = \frac{n\alpha_p}{T} \left(\frac{\gamma}{\gamma+1}\right) \sqrt{f_r PZ\tau} \simeq \alpha_p \sqrt{\tau/360}$$

where:
- n is the number of cooling cavities
- Z their impedance
- P the power they deliver to the beam
- T the kinetic energy of the $\bar{p}$'s
- γ the relativistic mass ratio
- f_r the revolution frequency

The tolerance on α_p is 5 cm.

Beam Measurements and Corrections

Needless to say, first beam tests with the uncorrected machine showed significant departures from design optics. Fortunately these departures had been anticipated and methods of correction prepared, as described below.

The use of two types of bending magnets to shape α_p leads to a tight tolerance on their relative strength if the orbit of the central momentum particle is to be on the axis of the long straight sections. The short bending magnets have a trim supply which is adjusted to make the average of the beam position zero at these critical locations. Computer control provides a simultaneous compensation of the average bending field to make the mean of all pick-ups zero. Radial and vertical adjustments of the position of certain quadrupoles, selected by a "most efficient corrector" algorithm[4], bring peak-to-peak orbit distortions to 3.2 mm horizontally and 1.4 mm vertically.

The spectrum analysers used for measuring transverse Schottky signals[5] allow rapid and automatic measurements of Q_H and Q_V over the whole aperture. Figure 2 shows such a measurement together with x*, the radial position where α_p should be zero, as a function of momentum. These measurements were made before corrections were applied.

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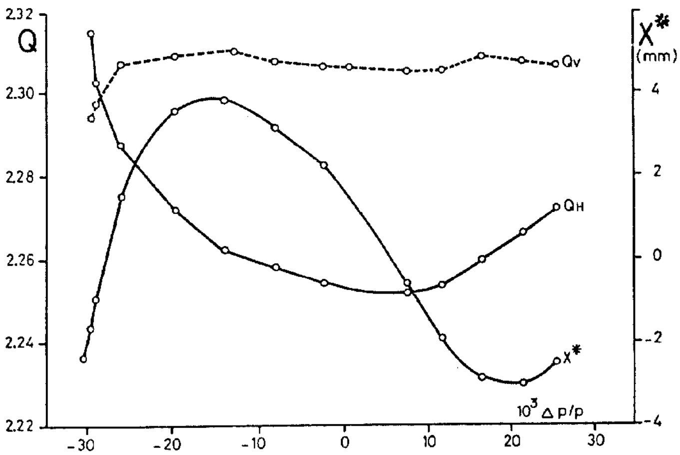

Fig. 2 - An early measurement of Q_H, Q_V and x*, the position of the beam where α_p should be zero

The Q_V variation was not far from tolerance but Q_H required substantial correction. There is a weak slope to the Q plots whose origin is a sextupole component which was anticipated from magnet measurements. There are also higher order terms which are partly due to the wide quadrupole's edge effect, proportional to $\alpha_p \alpha_p{}' (\Delta p/p)^2$. Other departures from predicted behaviour may well be due to the fact that flat quadrupoles had been modeled in design calculations by their integrated gradient and not their gradient distribution along the beam.

The next step was to compute modifications to the shape of the ends of quadrupole magnets. The modifications were applied by adjusting the pattern of soft-iron washers, mounted along the end faces near the pole tips. Since the modifications were intended to flatten the three curves, Q_V, Q_H and x* simultaneously, three kinds of pattern were required. One pattern was applied to D quadrupoles in non-zero α_p locations, and the other two to two sets of wide F quadrupoles. The various possible families are indicated in Figure 1. A system of three equations with three unknowns was solved by a perturbation method[6] to derive a gradient error curve for each kind of quadrupole. Subsequently, direct calibration in the machine of the effect of gradient perturbations on Q and x* led to a refined correction procedure. For a relative gradient error of the form:

$$\ell_o \frac{G^{(n)}}{G} \frac{x^n}{n!}$$

a first approximation to the distribution of washers is:

$$\ell(x) = k\frac{G^{(n)}}{G} \ell_o \frac{x^n}{(n+1)!}$$

where k is an efficiency factor of order 1.6 to 1.7.

Present Performance Compared with Theory

Figures 3 and 4 show the results of the most recent Q and x* measurements, now that about five iterations to this correction procedure have been applied.

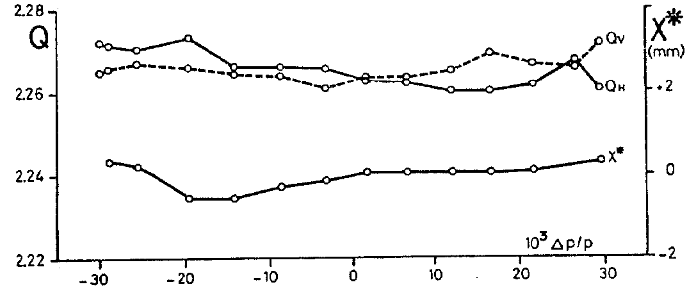

Fig. 3 - Q_H, Q_V and x* after correction

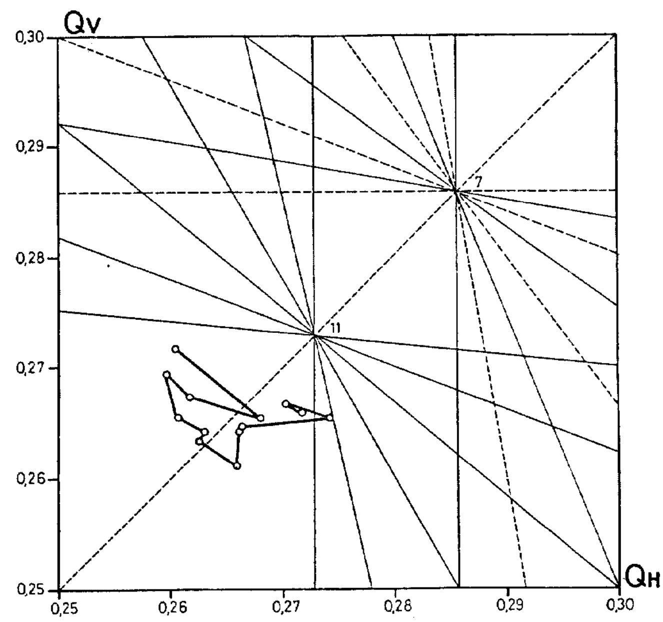

Fig. 4 - The present working line plotted in a Q diagram where all dangerous neighbouring resonances are shown

The optics is now rather close to design performance. The momentum acceptance of the ring, measured for Schottky scans, agrees with theory but $\bar{p}$ capture rates are still a factor 3.5 down on calculations based on measurements of $\bar{p}$ yields from targets[7]. Figure 5 shows how the capture rate compares with theory for a simple model of constant phase space density and for a Monte Carlo calculation, taking into account horn focusing, scattering, etc. The measured $\bar{p}$ capture rate results from longitudinal Schottky signal integration. In this experiment, scrapers were used to restrict progressively the acceptance of the AA ring and we see that when the acceptance is made very small, the discrepancy with the predictions becomes much smaller. This gives us some confidence in the assumed production cross sections and suggests that some of the losses may be because the acceptance of the ring is not as high as the 100 π mm.mrad design figure. A large fraction of our work has therefore been concentrated on this problem of acceptance.

We found that although the first steps in applying the correction procedure allowed a pencil beam to be moved across the whole physical aperture of the machine without loss, a larger emittance proton beam, produced

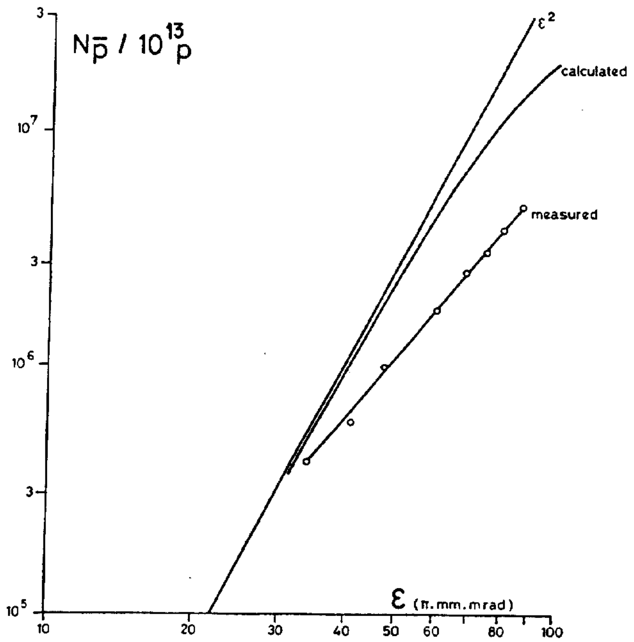

Fig. 5 - The antiprotons yield as a function of machine acceptance (emittance)

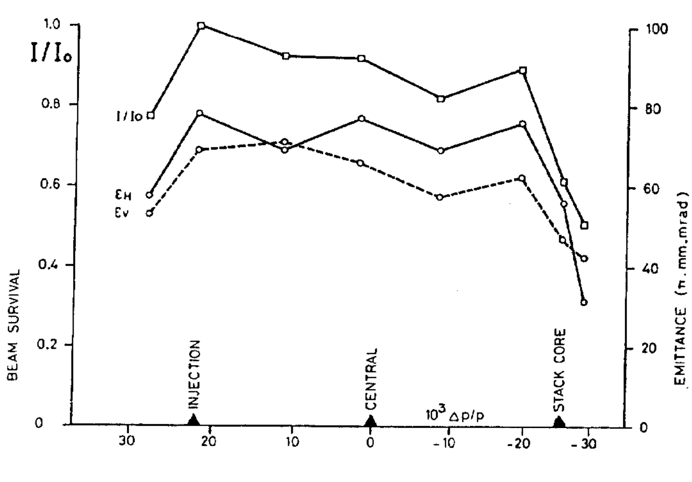

Fig. 6 - Beam survival and emittance as the dilated injected beam is moved to different momenta

by mismatching injection conditions, lost particles as it was decelerated slowly across the aperture. The losses occurred in a staircase fashion as a function of radial position. The steps in the staircase moved as the position of the working line in the Q diagram was adjusted. Losses at Q values corresponding to 11th order resonances could be seen on a time scale of less than a minute when the beam emittance exceeded 40 π mm. mrad. The present shimming scheme brings the working line to a position which is free from resonances up to 15th order.

Figure 6 shows the results of blowing up the emittance of the injected beam with a swept frequency applied through a transverse damping system at $(3-Q)f_r$. After blow up the beam is moved to another radial position and its emittances measured by moving in scrapers to touch the tails of the beam. The acceptance of the machine seems to be about 75 π mm.mrad in each plane on the injection orbit and it does not seem as if the beam meets any further acceptance limit until it is well into the stack. However, it is not certain that the beam emittance will have cooled sufficiently by the time it reaches this next restriction and we may yet have to extend the plateau of acceptance.

The reason for the 75 π limit and the further constriction at the stack, whether it be a geometrical obstruction, an orbit distortion or the influence of the higher order resonances is being vigorously sought.

Conclusions

The planned procedure for improving the optics of the AA ring by applying new patterns of shims to the pole faces according to measurements with beam, has worked out well in practice and the AA ring optics is close to the precision required. Transverse acceptances are within 60% of design values and work is under way to improve them further.

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