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AND CORRECTIVE MEASURES USING SKEW QUADRUPOLES AND SEXTUPOLES

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Introduction

The Antiproton Accumulator, AA, was designed to have a nominal transverse acceptance on the injection orbit of 100 π mm.mrad in each plane. The transverse phase-space density of antiprotons just after injection had been predicted by tracking antiprotons from the production target into the Accumulator. The inner regions of phase-space in XX' and YY' were expected to be of uniform density with some decrease towards the acceptance limits due to fall-off in antiproton production with angle and depth of focus restrictions at the target. A rectangular machine aperture was assumed.

In practice, although the phase-space density is as predicted out to transverse acceptances of about 40 π mm.mrad in each plane, the rate of depletion with increasing acceptance is greater than that given by this simple model. This is illustrated in Fig. 1 where the predicted horizontal antiproton betatron amplitude

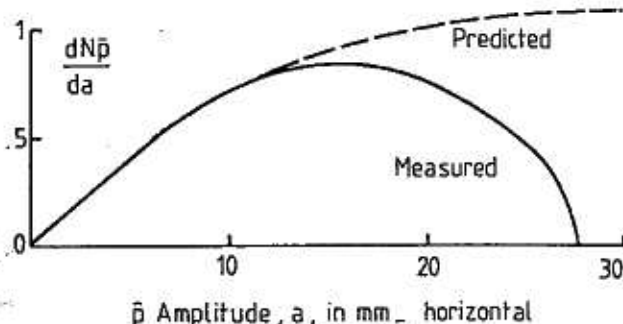


Fig. 1 - Antiproton amplitude distributions; predicted and measured.

distribution in a zero momentum dispersion region of the AA is compared to a typical measured distribution. The understanding and correction of the effects producing the paucity of particles at large amplitudes is the subject of this report. It has become particularly

important in view of the project to add to the AA an antiproton collector ring having an acceptance of 200 π mm.mrad in each plane.

Techniques for Measuring \bar{p} Amplitudes and Yield

Antiproton yield is measured by integrating the longitudinal Schottky noise signal from the circulating antiprotons just after injection and cross calibration against a d.c. current transformer using more intense beams of protons or antiprotons¹. With careful use this technique gives a precision of $\pm 2\%$ and, as it is relatively slow, it measures the antiproton yield after the resonant and coupling losses following injection have occurred.

In one of the zero dispersion regions of the AA a set of internal beam scrapers and an array of scintillation counters are used to measure the amplitude distributions of circulating antiprotons. The output from the counters, which monitor the secondary radiation from a horizontal or vertical scraper as it is driven at constant speed through the beam after injection, is fed into a multi-channel scaler. Computerized reconstruction of the amplitude distributions and calibration against the beam current transformer is provided. In this way the antiproton yields (the integrals of the amplitude distributions) can be measured over a larger dynamic range than is possible with the Schottky scan.

Calibration

Although the position of the scrapers during amplitude scans is known to ± 0.1 mm, the proportionality between the rate at which antiprotons strike the scraper as it moves and the counting rate had to be tested. This was done by scraping a high intensity proton beam (mis-steered at injection to give large horizontal betatron amplitudes), again using the current transformer as the reference monitor and the entire AA operating with reverse electrical polarity to preserve the directional sense of antiprotons. As Fig. 2 shows there was good agreement between the amplitude distributions measured by the counters and by the transformer

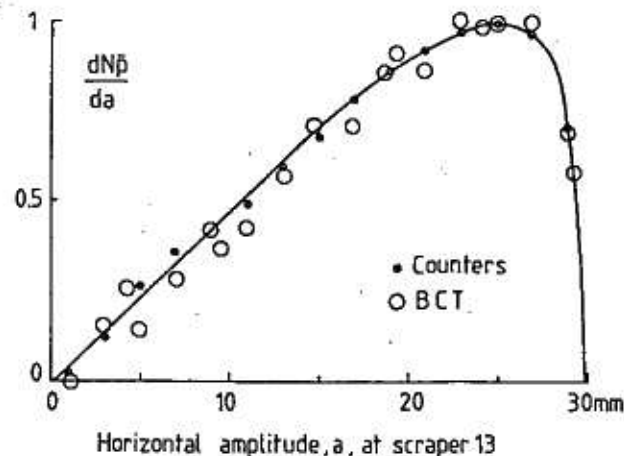


Fig. 2 - Amplitude distribution measured by counters and beam current transformers.

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Measurements

A beam of uniform transverse phase-space density has a triangular amplitude distribution as in Fig. 2. In this case the beam had large amplitudes in one plane only. For antiproton beams with simultaneous large amplitudes in both planes the distributions are more like that shown in Fig. 1. This is mainly due to the machine aperture being effectively elliptical instead of rectangular. However, there is also some depletion in the particle distribution at large amplitudes within the ellipse, due to effects discussed below. The fact that the observed distribution is a machine effect and is not due to a shortage of antiprotons at large transverse momenta can be demonstrated by injecting antiprotons and then, using the injection kicker as a full-aperture asynchronous kicker, kicking the beam horizontally in an attempt to reproduce the triangular distribution of Fig. 2. Whatever the kick given to the antiprotons, the large-amplitude part of the distribution after the loss of particles resulting from the kick is always the same, although with large enough kicks there remain no particles with zero amplitude. This is demonstrated in Fig. 3.

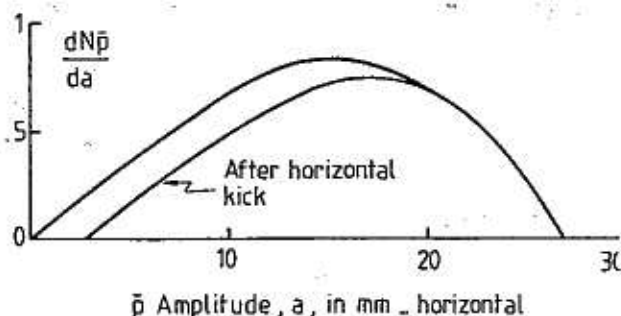


Fig. 3 - Antiproton amplitude distributions before and after horizontal kick.

The so-called soft aperture limit which this represents can be modified by changing the machine tune and the strengths of its skew quadrupole and sextupoles. In Fig. 4 the change in horizontal amplitude distribution, and antiproton yield, with change in horizontal tune parameter, Q_h , is demonstrated. Many comparisons of this sort have been made²⁻⁴ enabling us to increase significantly the yield at large amplitudes but without being able to compensate fully the effects producing losses from the corners of the aperture.

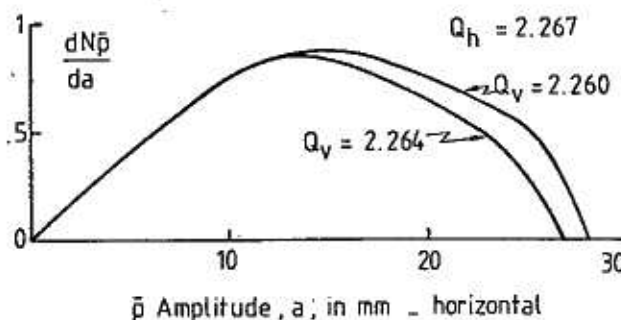


Fig. 4 - Antiproton amplitude distributions for different vertical tunes.

Analysis

Linear coupling⁵ is well understood. The phenomenon is apparent when there are skew quadrupole errors in the guide field and becomes particularly

serious near second order difference resonances like $Q_h - Q_v = 0$. It can transfer energy from the horizontal betatron motion into the vertical plane. The amplitude of the vertical motion grows at the expense of the horizontal motion. After a fraction of the energy has been transferred it flows back again, oscillating between the two planes. A particle which is injected with the maximum amplitude that can be accepted by a rectangular vacuum chamber in both planes may circulate for a few turns in the corner of the chamber but will hit the wall as one or other of the amplitudes grows at the expense of the other.

Fortunately, it is the average skew quadrupole which drives this effect and not a higher Fourier component of the azimuthal distribution. Provided the betatron phase advances do not overtake each other by more than a few tens of degrees one may expect to compensate the driving term with a single, judiciously placed skew quadrupole. This has been done in the accumulator by observing the vertical betatron sidebands with a spectrum analyzer while exciting horizontal betatron motion. The results agree with simple yield optimization. They also show that, while the compensation needed is momentum dependent, its variation from injection orbit to stack is only 20%.

Non-linear coupling is less well understood, but began to appear in particle simulation with programs such as PATRICIA⁶ and MAD⁷ as a raggedness of the smooth elliptical trajectory which one might expect a particle to describe in betatron phase space. In animated real-time tracking, the motion appears stable and harmonic within an outer and an inner ellipse which include the unperturbed trajectory. The effect, colloquially called "wambling" but more correctly "nutating", is seen to exchange energy between betatron planes in exactly the same way as linear coupling. It occurs in even the simplest simulation in which the only departure from linearity is a sextupole error.

We learn⁸ that this wambling is none other than intersection of the line, which is the perturbed stable trajectory in four dimensional phase space, projected on a single two dimensional phase plane. It is rather as if one had sliced a ball of string in half. Ando⁹ has shown how it may be compensated to first order if the sextupole patterns (suitably weighted with beta values) are chosen to have zero vector sum in the phase variables:

$$\begin{aligned} 3Q_h \\ Q_h + 2Q_v \\ Q_h - 2Q_v \\ Q_h \end{aligned}$$

We have found that there is also a second order perturbation of the betatron phase space which excites the frequency $2Q_h - 2Q_v = 0$ which can be predicted to cause a sudden increase in wambling when the working point is within 0.02 of the main diagonal¹⁰. This seems to predominate in the AA (and incidentally in contemporary SSC lattices). We have managed to predict strengths of sextupoles which compensate this in simulation for on-momentum particles¹¹ and these agree with experiments where a single sextupole whose strength is within a factor 2 of theory improves beam survival after injection by 20%¹².

Improvements due to Sextupoles

During early 1984, it was possible to procure an ex-ISR sextupole for installation in the zero dispersion section 24 of the AA. Studies¹² carried out with this sextupole indicated improvements in both injection yield as well as in the global performance

figure of merit given by the accumulation yield and stacking rates. While a skew quadrupole in the zero dispersion section 1 of the AA compensates the linear coupling to a large extent, these studies vindicated the hypothesis that the effect of non-linear stopbands close to the AA working region would be reduced, and a greater fraction of the large amplitude particles collected.

The encouraging results led to the installation of another ISR recuperated sextupole in the diametrically opposite, second non-dispersive section 13 of the AA. Various experiments¹³ were carried out with one-at-a-time and coupled strategies to find the optimum combined settings for these 2 sextupoles.

The experiments gave a 20% improvement in the global accumulation yield and a somewhat smaller increase of 12% in the injection yield (Fig. 5), using both the sextupoles for correction of the non-linear coupling resonance, the nearest being $2Q_v - 2Q_h = 0$.

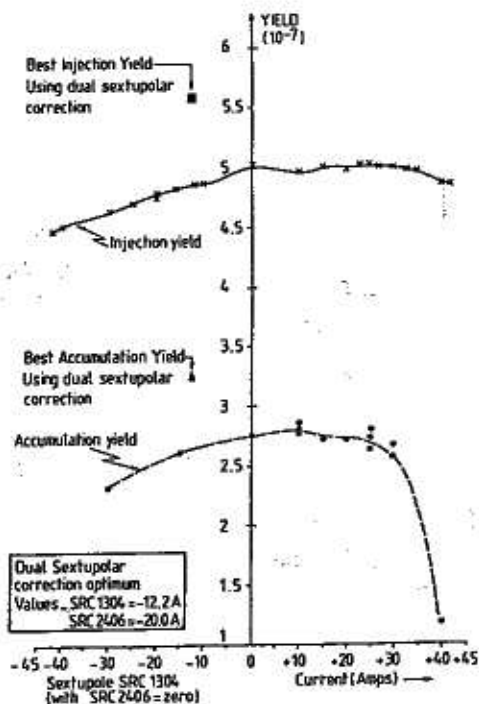


Fig. 5 - Antiproton injected yield and rate of accumulation per pulse (accumulation yield) versus current in sextupole SRC 1304.

Conclusion

The Antiproton Accumulator has the unusual feature that it is designed to accept any antiprotons which fall within the aperture of its rectangular vacuum chamber. By careful orbit correction one may achieve acceptances within 20% of the ideal figure. However, techniques which measure the two dimensional projection of the tenuous cloud of injected antiprotons reveal that the particles which simultaneously have maximum excursions in both planes are lost soon after injection. Manipulation of a skew quadrupole and a normal sextupole consistently improve the yield of antiprotons accepted and seem to help avoid losses from the corners of the distribution.

Simulation and second order perturbation theory strongly point to coupling as the reason for the losses. We have decided that without a formidable armoury of multipoles it is unrealistic to attempt to compensate such coupling completely and in the design of the new ACOL ring we calculate yield on the basis of an elliptical rather than a rectangular beam. However, even elliptical beams may require a larger physical aperture than might be calculated from linear theory. For this reason we suggest that the results are relevant to any machine interested in attaining maximal dynamic aperture.

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