APERTURE STUDIES FOR THE FERMILAB AP2 ANTI-PROTON LINE*

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Abstract

The AP2 beamline transports anti-protons from the production target to the Debuncher ring. The observed aperture is smaller than that estimated from linear, on-energy optics. We have investigated possible reasons for the aperture limitation and have identified possible sources, including residual vertical dispersion from alignment errors and chromatic effects due to very large chromatic lattice functions. Some experiments have already been performed to study these effects. We present results of the experimental and theoretical studies and possible remedies.

INTRODUCTION

The AP2 beam line at Fermilab transports anti-protons from the target where they are produced to the Debuncher ring. To first order, the distribution of incoming particles is flat transversely and longitudinally. In addition the incoming beam has only about 1% anti-protons. The remainder is pions and other particles that decay along the line and during the first few turns in the Debuncher. This complicates measurements of beam parameters.

The line was originally designed to have an acceptance of 20π mm mrad in both transverse planes and an energy acceptance of $\pm 2.0\%$ [1]. Currently the acceptance of the Debuncher is larger than this and, after some upgrades, will be 35π mm mrad. However, measurements of the AP2 line show a transmission of 29π mm mrad in the horizontal and 17π mm mrad in the vertical plane.

If the acceptance of the line could be increased to 35π mm mrad in both planes this would significantly increase the anti-proton yield into the Debuncher, which, in turn, would lead to a significant gain in the overall performance of the Tevatron. Previous studies investigating causes for the restricted aperture mainly considered linear, on-energy optics and no imperfections. We have looked at alignment and field errors and also off-momentum optics, which are important as the energy spread of the beam is large.

Figure 1 shows the lattice functions for the nominal lattice. From this one can calculate the beam envelopes and compare them to the apertures. This is shown in Fig. 2. In the area around the momentum collimator (which is fully open), located near 170 m at the peak of the horizontal dispersion, the beam is scraping slightly in the horizontal plane.

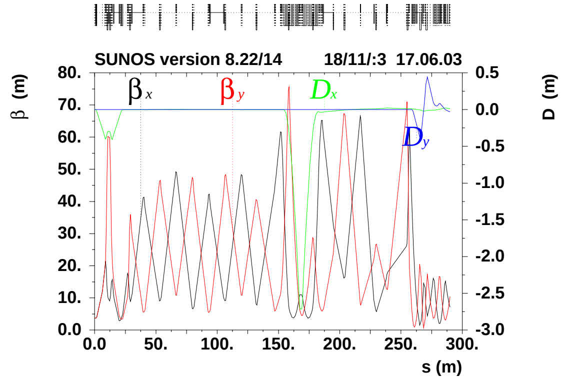

Figure 1: Nominal lattice of the AP2 beam line calculated with MAD [2].

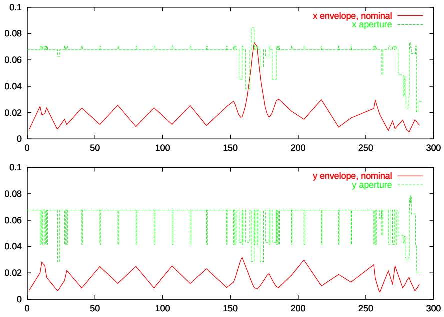

Figure 2: Beam envelopes (in m) for 40π mm mrad emittances and 4.5 % full width energy spread Aperture restrictions, where known, are indicated.

POSSIBLE SOURCES OF APERTURE RESTRICTION

Mismatch

The position of the lithium lens is adjusted on transmission so the upstream end of the line should be reasonably matched. The match into the Debuncher is more questionable, but we do not believe that it is cause for concern.

Random Errors

The following errors were considered: alignment errors (transverse and longitudinal (0.5 mm), roll, yaw and pitch (10 mrad)) and field strength errors (1%).

Using MAD [2], ten different seeds of machine errors were studied without attempting to correct anything. The uncorrected orbits are typically in the range of several cm (peak excursion), so the orbit in the real beam line can be assumed to be significantly better than that. The resulting β-beat can be as high as 50%.

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The biggest problem caused by the machine errors is residual vertical dispersion due to vertical misalignment of the quadrupole magnets. Dispersion values of more than 0.5 m have been observed in a number of seeds. The dispersion is a possible source of aperture restrictions, as the nominal energy spread of the beam is $\pm 2.25\%$ and the energy distribution is (to first order) flat. In addition, in most seeds the dispersion pattern is such that one has a particularly large vertical dispersion in the injection kicker, which has the smallest vertical aperture (see Fig. 2; the kicker is the last element in the line).

In all the seeds, at least some scraping occurred somewhere in the line, mainly in the injection kicker. However, this is for the uncorrected case so in the real machine the orbit excursions will be smaller. Nevertheless, the residual orbit excursions could still produce a significant amount of dispersion at some places, as local orbit bumps are not necessarily closed in dispersion. Usually, large local orbit bumps are rare in transport lines, however this line has a small number of corrector magnets that tend to be at similar phase advances, so it is possible to inadvertently introduce a local orbit bump of some amplitude while trying to optimize the line. The occurrence of π-bumps has been observed in simulating the orbit correction of the beam line, so it cannot be excluded for the real beam line.

Multipole Errors

Due to the large emittance, a significant fraction of the beam particles travel through the magnets at large amplitudes. We therefore plan to add multipole errors in future studies. This might require measuring the multipole fields on several of the magnets in the line (so far only one of each type of magnet has been measured), especially the three quadrupole magnets in the injection channel, where the injected beam travels far off center.

Off-Momentum Lattice

Figure 3 shows the chromatic β-functions as defined in [2]. The chromatic β-functions are rather large, especially at the end of the line, which means that they are not matched well into the Debuncher ring (as rings tend to have fairly small chromatic β-functions). This is also visible looking at the β-functions for particles with a momentum deviation of 2%, which show a β-beat of the order of 50%. As the energy distribution in the beam is flat (to first order) this leads to a large mismatch for a significant fraction of beam particles.

In general, experience with other beam lines has shown that the chromatic β-functions should be smaller than 5 [3]. Experience from other machines [3, 4] has also shown that the chromatic lattice functions need to be matched at both ends of a transfer line for beams with a significant energy spread.

The fairly large chromaticity (-10 in both planes) also indicates possible problems for off-momentum particles.

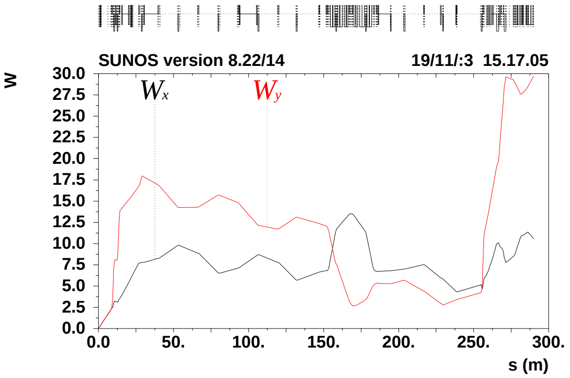

Figure 3: Chromatic β-functions of the AP2 beam line calculated with MAD [2].

Energy Error in the Debuncher Ring

Since the maximum momentum aperture in the line is 4.5% total width, a significant fraction of particles could be lost if the energy of the Debuncher were significantly different from the central energy transmitted by the AP2 line, as the energy acceptance of the Debuncher is 4.6%.

The absolute energy acceptances of the Debuncher and the line have been measured. They agree well.

Misalignment of a Small Aperture

There is always the possibility that a small aperture like the kicker or the septum is misaligned and therefore restricting the acceptance of the line. This has not been studied yet and might be difficult to determine due to the scarcity of corrector magnets.

TRACKING STUDIES

Tracking a Grid of Particles

For starters, a number of particles, having different initial amplitudes (all angles were zero), were tracked through the line. This was done for no energy deviation and for $\pm 2.25\%$ energy deviation. Figure 4 shows the phase space coordinates of the particles at the end of AP2. Due to chromatic effects the particles end up at very different places in phase space depending on their energy.

Tracking a Set of Particles Generated by MARS

Figure 5 shows the normalized amplitude and longitudinal distributions of particles generated with MARS [5, 6] for all particles and for those that are transmitted through AP2. Only particles with initial amplitudes less than 40π mm mrad were used. However it is worrying that a significant number of particles with an amplitude smaller than 40π mm mrad are lost, mainly because they have a large energy deviation. Those particles could be transmitted if the chromatic properties of the line were improved.

To study the influence of chromatic effects, the same set of particles was tracked with the energy deviation of all

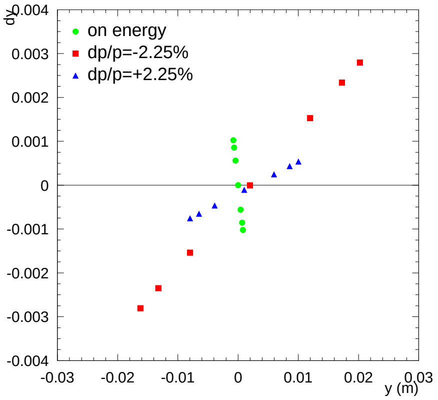

Figure 4: Final transverse coordinates (after the injection kicker) of a number of on- and off-momentum particles tracked through AP2 (calculated using MAD [2]).

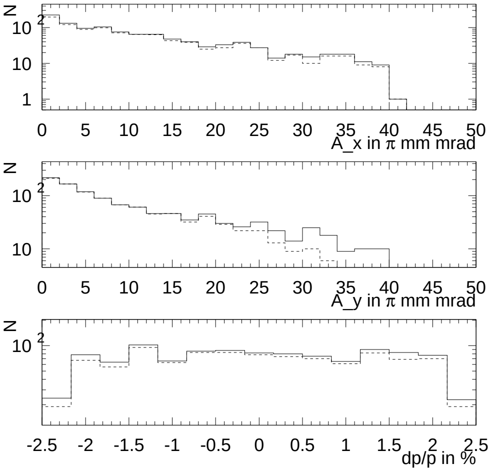

Figure 5: Initial distributions of particles generated with MARS. The solid line represents all particles with an initial amplitude smaller than 40π mm mrad, the dashed line particles that are transmitted through AP2 using the nominal lattice.

particles set to zero. In that case the transmission was increased by about 3%. As this was done using the ideal lattice we believe the effect in the real machine might be larger. In addition, this does not yet include tracking through the Debuncher.

EXPERIMENTS

Momentum Slicing

This experiment serves to determine how the transmission depends on energy by selecting slices of energy with the collimator and measuring the resulting transmission. This is done with and without bunch rotation in the Debuncher ring as this could influence the capture efficiency differently for different energies. If there is a significant amount of residual dispersion at a tight place, this experiment should show reduced transmission for off-energy particles. This experiment has been performed recently. Data analysis is still ongoing.

Measure and Correct Dispersion

Once the BPMs are available for reverse protons, one can measure the residual dispersion and from this try to infer alignment errors as well as try to correct the dispersion.

ISSUES CURRENTLY UNDER STUDY

Rematching the Lattice

One can try to rematch the lattice for better chromatic behavior. This should decrease the phase advance and chromaticity as well as the chromatic β-functions. This will of course increase the on-energy β-functions but at most places there is sufficient aperture to tolerate a moderate increase. This approach did not yield a significant gain in transmitted particles.

Therefore we are now studying adding sextupole magnets to the line. These could either be separate magnets, shims on dipole magnets or modified quadrupole magnets. We will determine where one needs to put them and what might be required to accommodate them.

If, even with sextupole magnets, the aperture is not sufficient, octupole magnets could be considered

Additional Correctors and Monitors

More correctors and monitors would definitely be helpful. Diagnosing and steering the line should be much improved if one has BPMs available at almost every quadrupole for reverse protons, which will be the case soon. It will probably allow for response-matrix type measurements, which should help in finding sources of residual dispersion and other gross machine errors.

SUMMARY

Our studies have shown that the aperture problems of the AP2 beam line are not so much a single physical aperture restriction but more a problem of chromatic effects and imperfections. We are currently working on improvements.

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