8 GEV BEAM LINE OPTICS OPTIMIZATION FOR THE RAPID ANTIPROTON TRANSFERS AT FERMILAB*.

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Abstract

Tevatron Run-II upgrade requires a significant increase of the efficiency and speed of the antiproton transfers from the Accumulator to the Recycler. The goal for the total transfer time is challenging a reduction from 1 hour down to a few minutes. Here we discuss the beam line optics aspects of this project. Results of lattice measurements and optimization are analyzed in terms of transport efficiency and stability.

INTRODUCTION

The transport of antiprotons between the Accumulator and Recycler involves 3 machines and 5 beam lines. The total length of the beam lines is over 1 km and each machine performs RF manipulations with the beam on its way. Because some of the beam lines are also used for transfers at 120GeV and 150GeV in addition to 8GeV, an initial tune up is made with the reverse proton beam prior to transporting antiprotons. The antiproton beam is sent from the Accumulator in multiple transfers, usually 5 or 6. A 2.5 MHz H=4 RF system (ARF4) is used to bunch a portion of the stack and accelerate it to the injection/extraction orbit about 140 MeV away. The extraction kicker (EKIK) then kicks this portion into the 8GeV transport line. This beam passes through the AP3, AP1, P2 and P1 beam lines on its way to the Main Injector. Main Injector RF synchronously captures the beam and decelerates it by about 40 MeV to match the Recycler ring energy.

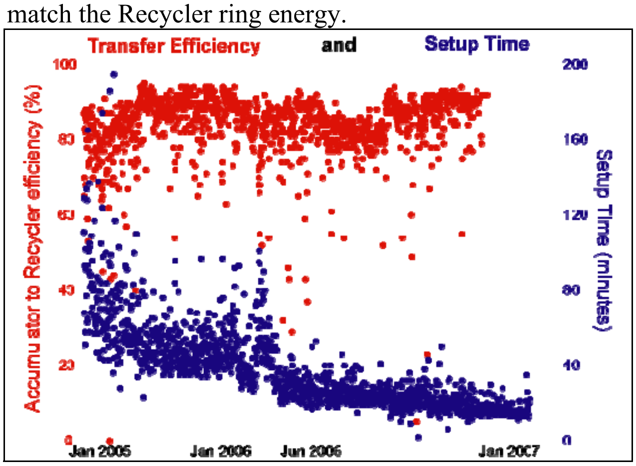

Figure 1. Accumulator to Recycler transfer efficiency and the shot set up time in 2005 through 2007. Transfer efficiency data is unavailable for the past few months but is thought to be near the historic best.

Antiprotons are then transported to the Recycler through the R22 beam line. Recycler RF forms barrier buckets to isolate the injected beam and pre-cool it before merging with the main antiproton stack. In the transfer process (shots) each machine is changing its state and mode of operation synchronously with others. The most complex transformation takes place in the Accumulator ring. It has to change from pbar accumulation (stacking) mode, where it injects antiprotons from the Debuncher and stochastically cools them into the dense core, to the transport (unstacking) mode. This process historically involved manipulation of thousands devices. Factoring in cooling the core down before the transfers, the whole process used to take more than an hour prior to 2006.

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STEPS TO EFFICIENT TRANSFERS

In order to maximize the rapid transfer efficiency good beam orbit control is required. Beam line lattice functions should be well matched to the optics of the downstream machine to avoid emittance dilution. Effective apertures should be maximized, achieved by the lattice optimization and proper beam steering. A number of hardware upgrades are needed in order to meet the goals of rapid transfers.

Magnet ramping

In 2003 the optics of the beam line was modified in order to avoid changing polarity on some magnets when switching between 120GeV and 8GeV beam line power supplies. This facilitated a faster transition between modes and improved the reproducibility of magnetic fields. The 2 sets of power supplies were originally used to improve power supply regulation. The next step is to avoid switching between power supplies. AP1 line is now being converted to single power supply operation with installation of waveform generating cards. The P1 and P2 beam lines already ramp and the AP3 beam line is dedicated to 8GeV operation.

BPM upgrade

An upgrade of the beam line Beam Position Monitor (BPM) system has been recently completed. New advanced system allows taking data at both 53 MHz (protons) and 2.5 MHz (pbars) for all transfer modes in real time. In particular it has made it possible to take good quality orbit data during antiproton transfers which have many advantages.

MI dampers

There is a transverse narrowband damper system in the Main Injector used for damping oscillations in proton beams arriving from the Booster. Switches have been installed in this system to make them bi-directional, so that they can be used for fast damping of antiproton injection oscillations in wideband mode. Installation and commissioning of the new control cards is expected to be completed in February 2007.

ARF4 modifications

Some beam loss on antiproton transfers takes place because the extraction kicker does not have a sufficiently fast rise time (it was originally designed for single bunch transfers). The leading and trailing particles in the 4 bunch train get too little and too much kick respectively. Since it is impractical to build and install a new high vacuum kicker tank in the time remaining in Run II, bunch shortening and other alternative extraction methods were considered. The simplest approach has already been implemented. The ARF4 voltage has been increased by more than a factor of 2 during antiproton transfers, resulting in shorter bunches and improved efficiency. Further modifications to ARF4 have been recently proposed to double the voltage again and, further reduce the bunch width. Since the momentum spread of the beam will grow with each increase in voltage, the beam line apertures in dispersive locations may need optimization to prevent scraping.

ORBIT CONTROL AND LATTICE MATCHING

Orbit control and lattice optimization are the key elements for achieving the best transfer efficiency. The lattice design should ensure maximum beam line aperture and the orbit should be steered to the center of that aperture. The centered orbit has been defined using quadrupole centering and local orbit bumps. This orbit has been recorded as the "reference" orbit and the normal orbit is kept as close as possible to the reference. Based on the ongoing studies and observations the reference orbit may be updated to improve aperture.

Figure 2 shows the beam size envelopes calculated with the OptiM program throughout the line for the beam with an unnormalized emittance of 1 π·mm·mrad.

The tightest horizontal aperture is located in the Accumulator extraction Lambertson magnet. In the lattice design the horizontal beta function is minimized in this location. But it is still important to carefully control the orbit in this region. In addition to the tight aperture, due to the substantial non-uniformity of the field in this magnet there is a strong skew-sextupole component which causes coupling for a horizontally displaced beam.

Currently orbit checks are carried out with reverse proton beam before every set of antiproton transfers. If necessary, orbit corrections are applied in the beam line (usually only needed once every few days). Another application then checks for injection oscillations of the proton beam in the Accumulator. Once orbit and closure are verified and corrected, operation proceeds to the shots. Kicker voltages are adjusted to compensate for the differing electric field effects on the protons and antiprotons. An offset is required on several trims to compensate for small trajectory differences between the protons and antiprotons. These corrections have been found empirically. Once the beam line tune up has been completed, orbit oscillations on the antiproton transfers are typically quite small, generally less than 0.5mm. When they are larger, closure corrections at the end of the beam line are applied by the BLT application (Beam Line Tuning) in the Main Injector. It is anticipated also that a new orbit control application will be used to calculate and apply corrections to the beam line orbit after each antiproton transfer. Such an application has been developed for the 120 GeV transport and proved to be very successful. With the improved tools and the addition of transverse injection dampers in Main Injector, the need for a routine reverse proton beam line tune up and orbit closure will be eliminated.

Lattice matching

The lattice design of the AP3-P1 8 GeV transfer lines has been greatly improved. Lattice improvements were part of the Run-IIb upgrade plan [1] and featured

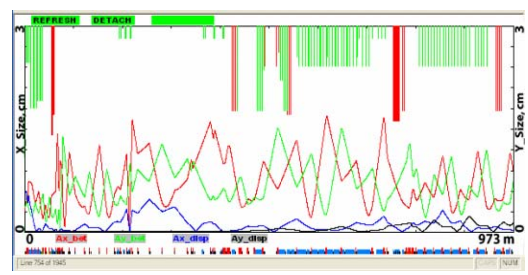

Figure 2. Beam size envelopes in the 8 GeV antiproton transport between the Accumulator and Main Injector. Red and green lines represent horizontal and vertical beam size at 95%, respectively. Vertical red and green bars in the upper part of the plot indicate the aperture limits.

substantially lower beta-functions, which resulted in more aperture room. The new lattice resulted in magnet polarities being the same for both 8 GeV and 120 GeV modes of operation. Better matching of the horizontal dispersion was also achieved. However, matching the vertical dispersion function has proven more difficult, requiring the rewiring of blocks of quadrupole groups that are bussed together. This work is planned as a future upgrade.

Lattice functions are determined using the differential orbit method [2]. Figure 3 shows a set of 4 differential orbits: 2 in the horizontal plane and 2 in the vertical plane. With the single corrector bumps separated by $\pi/2$ in betatron phase, these data sets provide enough information to fully determine all the corrections to the quadrupole designed strengths.

These corrections are found by varying all focusing elements to fit the orbit data with the calculated trajectories. Until very recently measurement of the lattice functions in the beam line could only be carried out using reverse protons from the Main Injector. This allowed a variety of intensities and frequent beam pulses. The disadvantage of this method was that the orbit variations could not be seen beyond the beam line, so it was not possible to reliably determine the errors in the few last quadrupoles of the line. This problem has been resolved with the new 2.5 MHz BPM system upgrade, mentioned above. With the differential orbits recorded with an antiproton beam moving in the opposite direction, those missing quadrupole corrections can be easily found. Correction to the quad EQ2 quadrupole gradient was found to be around 1% which makes quite significant change of the beta-functions in the antiproton direction, as it is shown in Figure 4.

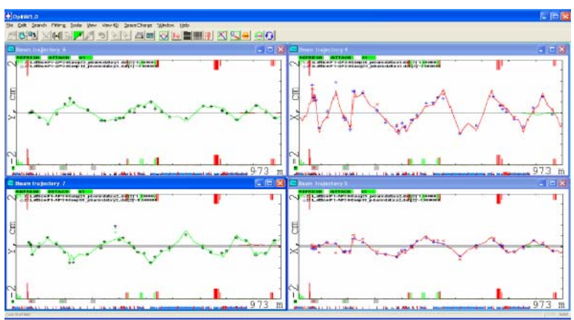

Figure 3. Four differential orbits taken with antiprotons.

Figure 4. Top and bottom plots show the change in the beta-functions (red trace – horizontal, green - vertical) in pbar direction when EQ2 quad strength is changed by 1%.

With the new measurements of the lattice functions using antiprotons, optics corrections were calculated and implemented to match the Accumulator, beam line and Main Injector. Figure 5 presents data taken with the Main Injector Ionization Profile Monitor (IPM) on the beam size turn-by-turn oscillations. Substantial oscillations in the September 29 data (blue traces) indicate an optics mismatch and transverse quadrupole oscillations of the beam size at double betatron frequency.

These oscillations eventually lead to beam emittance dilution and larger beam size, which causes losses and poor lifetime of the injected beam in the final destination- the Recycler ring. Making the optics match eliminated the beam emittance blow up and resulted in the overall transfer efficiency improvement in the end of October 2006, as it is shown in the Figure 1.

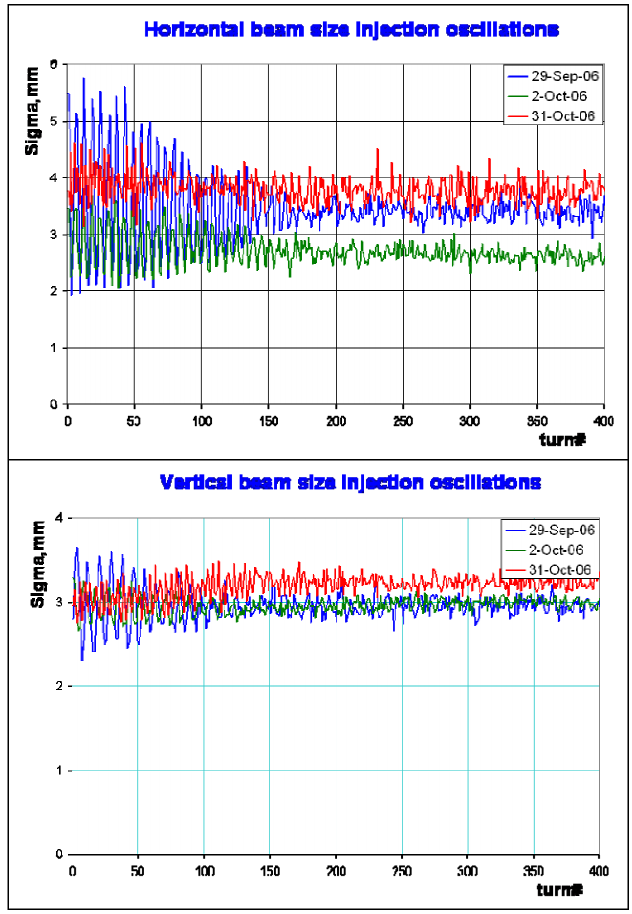

Figure 5. Main Injector IPM measurements of the transverse beam size oscillations at injection. Top and bottom plots show horizontal and vertical oscillations, correspondingly, before the optics matching (blue), after first correction (green) and after second correction (red).

CONCLUSIONS AND CURRENT PLANS

Substantial progress has been made towards fast, stable and efficient antiproton transport between the Accumulator and Recycler. While the total shot time has been reduced down to 15 minutes transfer efficiency has been maintained at the 95% level. Better dispersion matching still needs to be implemented. Orbit control application and Main Injector wideband dampers are expected to be completed soon in preparation for the elimination of the reverse proton tune up. Optics matching of the AP3-P1 line to the Main Injector has helped to maintain good antiproton transfer efficiency. The similar effort is now underway to improve optics of the R22 line between Main Injector and Recycler rings.

REFERENCES

[1] Run-IIb plans. http://www-bd.fnal.gov/doereview02/RunIIBTDR.pdf
[2] V.Lebedev et al., Measurement and correction of linear optics and coupling at Tevatron complex. ICAP-04, St. Petersburg; NIM A558 (2006), p299.