OPERATION OF THE FERMILAB ACCUMULATOR FOR MEDIUM ENERGY PROTON-ANTIPROTON PHYSICS

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Abstract

The Fermilab Antiproton Source Accumulator Ring was built primarily as an 8 GeV storage ring to meet the needs of the Tevatron proton-antiproton collider program. Recently the Accumulator has been used to provide lower energy beams interacting with a gas jet target at center of mass energies in the charmed particle region. This paper summarizes the status of the accumulator as a source of medium energy proton-antiproton interactions.

Physics Motivation and History

The Fermilab Accumulator was built primarily as an antiproton collection and storage device for operation of the Tevatron collider. However, it was realized during the construction of the source that the Accumulator could also be a tool for studying medium energy antiproton interactions[1]. Specifically, it was planned to study resonant production of the various charmonium states by decelerating the antiproton beam to the proper energy and colliding it with an internal gas jet target. A similar experiment[2] was performed at the CERN ISR.

Deceleration was first attempted in September 1987. By January 1988 the beam had been decelerated through the transition energy. Work resumed in August 1989, after a long collider run, when a proton beam was decelerated with 100% efficiency to 4 Gev/c. In March 1990, the first antiproton beam was decelerated.

Deceleration Technique

Although it was recognized that the antiproton source could be used for medium energy physics during the construction, no system or subsystem was built or modified to make deceleration possible. It was subsequently decided[3] that it would be easiest to implement deceleration via software control utilizing the existing digital interfaces to the power supplies. The deceleration is managed by a separate PDP-11 computer dedicated to the purpose. The computer program sequentially changes the settings of the various ramped devices according to interpolation of an input file (ramp table). It was particularly attractive to employ a computer generated ramp because of an existing but unused port in the serial CAMAC link. Thus, the ramp could be implemented with no additional hardware and leave the existing control system unmodified.

There are a number of limitations on the deceleration rate: the amount of r.f. voltage available and the maximum voltage of the magnet power supplies. The use of a computer generated ramp does not unduly compromise the deceleration rate: the standard rate is 20 MeV/sec. The update frequencies for the various devices are given in Table I. We rely on the natural time constants of the power supplies to filter the steps generated by the digital ramp. The r.f. is digitally synthesized from a 10 MHz reference oscillator and is therefore extremely agile. The discontinuities in the ramp caused by the 60 Hz update frequency are digitally filtered to smaller steps at a 20 kHz frequency by a dedicated 68000 microcomputer in a VME crate. The filter time constant is chosen to be approximately equal to the step response time constant of the dipole bus. The r.f. voltage can be ramped but is usually left constant.

TABLE I. Update Frequency of the ramped devices

Device type	Quantity	Update Frequency (Hz)
Frequency	1	60
Dipole Bus	1	60
Quadrupoles	4	60
r.f. voltage	1	60
Sextupole	5	7.5
Skew Quads	2	7.5
Octupoles	2	7.5
H trims	8	0.5
V trims	24	0.5
Dipole Shunts	30	0.5
Damper timing	4	0.5
Total	82	5.7 (average)

The entire system is operated without any beam feedback circuits. We intend to implement a phase feedback loop for the r.f. system in the near future and may later employ a radial position feedback system. The lack of feedback loops makes it difficult to compensate for the hysteresis of the magnets. Great care is therefore taken in starting the machine from a standard magnetic field configuration: the magnets are ramped three times to their standard currents after each deceleration.

The stochastic cooling systems are used to improve the beam lifetime - just as they are used during collider operation. The presence of the gas jet and the lower energy makes the cooling systems even more crucial, however. The stochastic cooling systems also allow the possibility of repairing the emittance growth which may occur during the deceleration. The stochastic cooling systems were modified to include a binary system of delay lines that has a total range of $\Delta T = 128$ nsec. This range accommodates beam velocities of $\beta > .85$. A special stochastic cooling difference pickup was added to the core cooling system to allow momentum cooling on the central orbit. Simulations of the cooling system performance cooling system suggest that beam momentum spreads of $\Delta P = 0.5$ Mev/c (σ) are possible.

The transition energy is crossed using a γ_t jump technique. The beam is debunched at an energy just above transition ($\eta = 1/\gamma_t^2 - 1/\gamma^2 = .004$). Then the four quadrupole busses are changed so that γ_t rises and $\eta = -.004$. The beam is rebunched and deceleration continues. The γ_t change is gradually removed as deceleration continues and the normal lattice is restored.

Special Software

While the hardware modification involved for the Accumulator was minor, the software development

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effort was major. The following programs were developed:

a. A Ramp Program to update the power supplies. As described above this program updates the power supplies based on the input ramp table. The ramp program must operate simultaneously with the standard control system, which has access to the same hardware through the same CAMAC interface.

b. A Ramp Editor to create and modify the ramp tables. The program supports polynomial extrapolation and interpolation of the tables to allow rapid ramp generation. Individual ramp points may be edited by hand. The ramp editor can also propagate small changes at a given point to different points in the ramp.

c. A Deceleration Sequencer to automate the deceleration process. The sequencer can be programmed to automatically perform arbitrary sequences of the following operations: 1) r.f. manipulations including capture, deposit, and moving of the beam, 2) cooling operations including turning the system on and off and setting the timing based on the revolution frequency, and 3) magnet ramping given a start and stop energy.

d. A Fast Data Logger to record the sequence of events in the deceleration. This information is usually uninteresting, but can be crucial to understanding subtle failure modes.

e. An Energy Scanning program to automatically or manually change the beam energy in very fine steps (as small as 178 keV). The stochastic cooling is monitored and the timing delays are automatically controlled. At 5 minute intervals various beam parameters are measured, a closed orbit measurement is taken and the beam energy and width are calculated. These data are sent to the experimental data acquisition system via a CAMAC link.

f. An Orbit Length and Beam Energy program that calculates the beam orbit length from the BPM radial positions. The program interpolates to find the orbit at the points between the beam monitor pickups.

Procedures for Building the Ramp Tables

The ramp tables were constructed empirically. The magnetic field measurements which had been made were not detailed enough at low energies to allow even a first guess at a realistic ramp table. The ramp table was constructed by taking the 8 GeV working point and extrapolating the energy to 0. This procedure required a large number of iterations before a working ramp table was constructed. A spare dipole magnet was put on the Accumulator bus and equipped with an NMR probe. This probe provides an accurate measurement of the relative machine energy and is used to calculate γ_t from the variation of revolution frequency with magnetic field.

Once a working ramp had been established, more careful measurements were made at approximately 500 MeV/c intervals. At each ramp point, accelerator parameters were measured and corrected until they agreed with their target values. These parameters were:

1. Closed orbit
2. Horizontal and vertical tunes (including coupling)
3. Horizontal and vertical chromaticity
4. Dispersion in the "zero" dispersion long straight section

The revolution frequency was measured for the r.f. ramp and the transverse apertures were measured as a check on the adequacy of the closed orbit.

The result of this work is illustrated in Figure 1, which shows the aperture as a function of momentum. The tunes are held constant at Q_h=6.614 and Q_v=8.611 to an accuracy of about .003. The chromaticity is approximately 0 throughout the ramp. It was not possible to completely correct the horizontal and vertical coupling because the proper correction requires a change in sign on one of the skew quadrupoles. Fast reversing switches have been installed so that it will be possible to make this correction in the future. The dispersion is held to less than 10 cm in the "zero" dispersion long straight section.

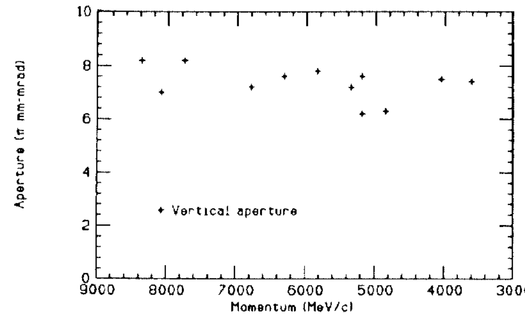

Figure 1: The vertical aperture is shown as a function of momentum. The horizontal aperture is similar except for a reduction in aperture just below the energy crossing.

A crucial element of this program was the proper functioning of the beam position monitor (BPM) system. The closed orbit system was modified to work with the h=2 r.f. system. During the early stages of this work the closed orbit system could not be used because it was tuned for h=10. The wide band turn-by-turn could be used but was not accurate enough. Improvements were made in the calibration of the preamplifier offsets. The BPM system position measurement has an undesired but significant dependence on the intensity: it was important to adjust the signal intensity to achieve the best accuracy.

Performance

Originally we used the h=84 r.f. system for deceleration. We had trouble with beam growth followed by beam loss. The beam growth appeared to occur particularly when the synchrotron frequency was equal to a multiple of the line frequency (60 Hz). We changed to an h=2 r.f. system where the synchrotron frequency range is about 10 to 30 Hz. This system has proved to be satisfactory although we notice beam dipole oscillations which are increasingly severe as the transition energy (zero synchrotron frequency) is approached.

The accumulator was operated in a short engineering run on antiprotons in March 1990. Antiprotons were accumulated at an average rate of 0.6×10^{10}/hr for periods of 10-20 hours yielding typical stack sizes of 1×10^{11}. A total of five decelerations were performed: four decelerations to the J/ψ and one to the ψ'. The beam energy was varied in the vicinity of these resonances with the scanning technique described above.

During the engineering run, the E-760 detector observed the J/ψ resonance as shown in Figure 2. The horizontal scale has been slightly adjusted to make the beam energy agree with the known J/ψ mass. The [Awidth of the resonance is measured to be 0.8 Mev/c (σ) and is a measure of the beam momentum spread since the intrinsic J/ψ resonance width is negligible. The beam spread can also be measured directly from the frequency spread of the longitudinal schottky signal. These spreads also yielded a momentum spread of 0.8 MeV/c for a beam of 10^{11} antiprotons at the J/ψ. These widths are comparable to (but larger than) the estimated width of 0.5 Mev/c based on the calculated equilibrium between momentum cooling and intrabeam scattering for a $2x10^{11}$ antiproton beam. A careful exploration of the limitations to the momentum resolution of the beam has not been made.

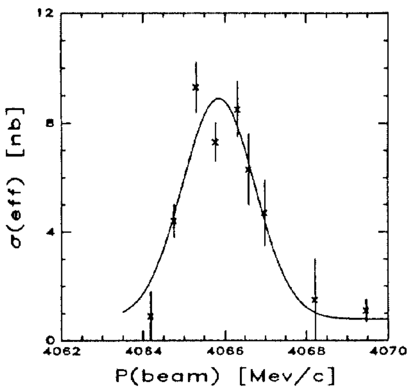

Figure 2: The J/ψ resonance was observed by the E-760 experiment while scanning the beam. These data are not fully corrected and should not be taken to be definitive.

The transverse beam size is less critical: the E-760 experiment is insensitive to beam sizes up to 3π mm-mrad. The beam size is determined by the competition between the cooling rate, which is proportional to emittance and the heating rate, which is probably dominated by multiple Coulomb scattering in the gas jet target. Figure 3 shows the beam current, lifetime and transverse emittances during data taking at the J/ψ. The oscillations in emittance were caused by a transverse instability; it was subsequently discovered that the damper had the wrong phase. Instabilities were also observed at the ψ' where η is lower. The investigation of these instabilities, particularly for higher beam currents is an important outstanding issue.

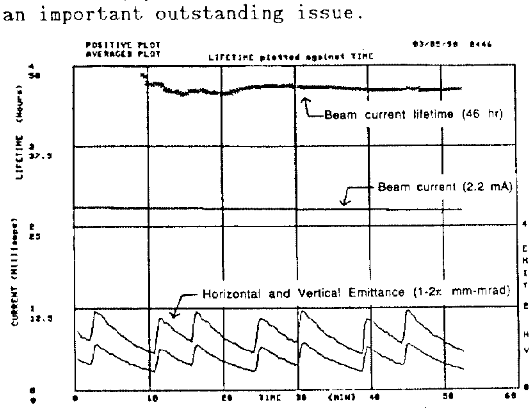

Figure 3: The on-line monitoring display of beam lifetime and emittance is shown. Oscillations in the horizontal and vertical emittance were observed with the transverse dampers set to the wrong phase.

Figure 3 also shows the beam lifetime. The observed 46 hour lifetime is typical of all the runs. The lifetime may be compared to the 400 hour lifetime observed during collider operation. The calculated beam lifetime at p=4 GeV/c in the presence of a 1 cm long gas jet with a density of $5x10^{13}$ atoms/cc is 110 hours.

Energy Calibration

A crucial issue is the energy calibration of the beam. The calibration of the energy is based on a measurement of the revolution frequency and the orbit length. With these two measurements one obtains the beam velocity:

$$v = L * f_0$$

From the velocity one can calculate the beam energy and the energy in the center of mass of the beam-target system. The revolution frequency can be measured to better than 1 Hz and the orbit length differences can, perhaps, be measured as accurately 1 mm using the BPM radial position measurements. These accuracies result in a relative resolution of 3 ppm on the beam velocity and 0.07 MeV resolution on the center of mass energy at the J/ψ. For most purposes a resolution of 1 cm in the orbit length would be satisfactory. The length of the design orbit (the one passing through center of the quadrupoles) was measured in an optical survey to be 474.068 ±.002 meters. A more accurate and more direct calibration is given by the observation of the J/ψ particle. Since the mass of the J/ψ is known, one can compute the beam velocity. Combining the beam measured velocity with the BPM radial position measurements yielded a design orbit length of 474.061 meters. The agreement between the J/ψ calibration of the length and the optical survey is quite good. The residual discrepancy may be due to systematic errors in the optical survey or in the BPM radial position measurement. However, the systematic errors in the BPM system are expected to nearly cancel when one considers the difference between two orbits. We therefore use the J/ψ calibration as a reference closed orbit with an accurately determined length and measure other orbit lengths relative to the J/ψ.

Conclusions

It has been shown that the Fermilab Accumulator can be successfully operated for medium energy proton-antiproton collisions. This instrument provides a unique window on the charmonium spectrum. Early indications suggest that antiproton deceleration can be reliable. Further work will be directed towards increasing the luminosity, the reliability, and making operations more routine. The accuracy of the energy calibration needs to be explored in more detail. And since this mode of operation is still quite new, there will undoubtedly be some unanticipated problems as well.

References

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