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Abstract

The Fermilab antiproton Accumulator has been modified for use in a medium energy experiment. The experiment is conducted with circulating antiproton beam of momentum between 6.7 GeV/c and 3.7 GeV/c colliding with protons from an internal gas jet. Antiprotons are accumulated at the normal momentum of 8.9 GeV/c and then decelerated to the appropriate energy. It is necessary to cool the beam continually during the time it is colliding with the gas jet. The experiment requires new provisions for the control of magnet power supplies and low level rf system and modifications of the cooling system and high level rf systems to permit variable energy operation. Transition must be crossed to decelerate the beam below 5 GeV/c; because the deceleration is very slow, transition can not be crossed in a conventional manner. This paper will describe the required changes to the Accumulator and operating experience with protons.

I Introduction

The availability of intense antiproton beam at precisely defined energy in the Fermilab $\bar{p}$ Accumulator opens the possibility of studying the spectrum of charmonium states in a threshold production experiment[1],[2] without the limitation that applies in e^+e^- collisions to photon quantum numbers ($J^{PC} = 1^{--}$) in the final state. A stochastically cooled beam of about 10^{11} $\bar{p}$ colliding with a hydrogen jet with area density of $\sim 1.5 \times 10^{14}$ cm^{-2} provides a luminosity of 10^{31} cm^{-2}s^{-1},[3] permitting precise measurements of states for which few data exist and a sensitive search for states as yet unobserved.[4],[5] The states of interest and corresponding Accumulator parameters are shown in Table 1. Resolution for the resonance mass is $\Delta M_R = \Delta E_{\text{beam}}\, m_p/M_R \approx 300$ keV rms.[2]

The Accumulator is a 474 m circumference storage ring[6] designed to stack and stochastically cool a beam of $\sim 5 \times 10^{11}$ $\bar{p}$'s at 8.9 GeV for the Tevatron colliding beam program. To use this facility for the experiment during fixed target running it has been necessary to generate smooth ramps for about ninety devices including main bend bus, three quadrupole busses, three quad shunts, four sextupole busses, skew quads, and more than sixty trim elements. The variety of natural time constants in these circuits and the fact that the so-called large quads and bending magnets are well into saturation at design energy requires high setting rates to maintain precise control of Accumulator lattice parameters even though the deceleration proceeds at only about 20 MeV/s. It was possible to meet these control needs primarily through software by the addition of an auxiliary frontend computer as described in a companion paper[7].

The stochastic cooling system is essential to counteract the growth of beam emittance and loss of energy arising from repeated traversal of the gas jet. A new set of momentum cooling electrodes has been installed on the central orbit of the Accumulator and computer setable delays have been installed to permit cooling at any desired energy. Variable energy operation also required the addition of mechanical tuners to the 53 MHz rf cavities and a programmable frequency synthesizer to the low level rf system.

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II Accumulator Operating Mode

During fixed target running the Main Ring injects beam into the Tevatron approximately once per minute. The Main Ring cycle is only a few seconds long, and the rest of the Tevatron cycle is used to run Main Ring cycles for $\bar{p}$ production without impact on the fixed target operation. First the Accumulator is run in its design mode[6] to accumulate the $\sim 10^{11}$ $\bar{p}$ wanted for the experiment. Then the stacking rf, beam transport lines, and Debuncher ring are turned off.

The beam which has been accumulated at the core orbit has already been cooled. Cooling can be continued as long as necessary to facilitate adiabatic capture by the 53 MHz rf system for transfer to the central orbit. The control of the rf system is then taken over by the auxiliary frontend computer which executes a deceleration sequence to the desired energy or to just above transition, whichever is greater. The deceleration can be stopped at any point if it is necessary to debunch and recool. For good efficiency the deceleration rate is ~20 MeV/s.

Transition crossing is effected by changing the transition energy of the ring. The beam is debunched, and then a special set of ramps acting only on the quad busses increases γ_t by one unit. Beam is cooled both immediately before and after this so-called γ_t-jump. Below transition the beam is again captured with the 53 MHz rf system now at harmonic number 86 instead of h = 84. A new set of ramps is executed to complete the deceleration to the desired energy.

II.1 Deceleration

Originally it was supposed that one could calculate ramps from magnet measurement data which could be optimized by small corrections. However, this effort was frustrated not only by the inadequacy of the excitation curves but also by the complication of the differing time constants on the different busses. Therefore, an iterative empirical approach was adopted in which corrections were made by taking beam measurements in steps of about 40 MeV of deceleration and correcting the ramps at each step.

Both of the Accumulator rf systems, one operating at 53 MHz and one at 1.2 MHz, provide sufficient bucket area (> 20 eVs) above transition but marginal bucket area at the lowest energies of interest (~ 10 eVs). The 53 MHz system is used at present because the beam position monitor electronics is designed for this frequency. This permits the measurements needed to make the stepwise correction of the ramps. A recent improvement to the 1.2 MHz system has increased the voltage a factor of four from 0.7 to 3 kV. Because both systems are driven by the same lowlevel system, there is the option to use either; the 1.2 MHz system may be used in the future to provide greater bucket area.

The 53 MHz system provides a maximum of 40 kV over a bandwidth of about one rotation harmonic, *viz.*, 600 kHz. This is entirely adequate for deceleration to transition at h = 84 without cavity tuning. Because there has been beam loss from bunch growth in results so far, a constant $V_{rf} = 19$ kV has been used to transition. To avoid retuning the cavities, the beam is bunched and decelerated below transition at h = 86. The voltage program corresponds roughly to a starting bucket area of 10 eVs smoothly increasing to 12 eVs by 3.6 GeV/c.

II.2 Transition crossing

The design value of the transition energy for the Accumulator is 5.1 GeV corresponding to transition gamma $\gamma_t = 5.43$. Conventionally beam is accelerated across transition rapidly before the bunches break up. In the Accumulator the deceleration rate is limited by the rate at which bus currents can be changed. To date rates in excess of 20 MeV/s have been less efficient. This rate is not fast enough for crossing transition without major disruption of the bunches. The γ_t-jump alternative has been adopted.[8] The beam is debunched 0.3 GeV above transition; γ_t is then raised at constant bend field until the beam is 0.6 GeV below the new transition energy.

Simulation of beam behavior in longitudinal phasespace shows no pathology for synchronous deceleration at 100 MeV/s for $|\eta| > 10^{-4}$. Fig. 1 shows that γ_t is changed gradually from its design value of 5.43 to 5.05 during the deceleration from 8.9 to 5.02 GeV where the beam is debunched and cooled. At this energy $\eta = 0.004$, chosen to give adequate cooling rates before transition is crossed. Next γ_t is raised in 30 s to 6.05 giving $\eta = -0.008$. During this transition jump the betatron tunes are kept constant to avoid beam loss. The γ_t is increased by changing the lattice for lower dispersion in the high dispersion sections and negative dispersion in the "zero dispersion" sections as illustrated in fig. 2. A change of one unit in γ_t requires a change of 9% in the current in the large quadrupoles. The beam is then recooled and recaptured for further deceleration. The choice to cool both immediately before and after transition is based on operational experience. Because the beam pipe is small in the "zero dispersion" straight sections, beam loss there limits the useful size for the γ_t-jump.

II.3 Energy calibration

The resonance masses are measured by the beam energy at which production is maximum. The most accurate way to measure the beam energy is to use the mass of the Ψ and Ψ', which are known to 0.1 MeV/c^2. Because the width of the Ψ is only 0.063 MeV/c^2, it is advantageous to calibrate the beam energy as well as possible to minimize the search time. The known energy and the beam circulation frequency establishes the Accumulator circumference. The energy for other resonances can then be determined by controlling the closed orbit and comparing the NMR reading from a bending magnet at the new point to that at the Ψ or Ψ' resonance.

One method used to calibrate the beam energy is to exploit the relation $\Delta f/f = -\eta \Delta p/p$, where f is the beam circulation frequency and $\eta = \gamma_t^{-2} - \gamma^{-2}$. If $\Delta f = 0$, then $\gamma = \gamma_t$. Experimentally, the $\eta = 0$ point is taken as the point for which Δf is minimum. The beam is decelerated to just above transition and then debunched. The γ_t of the lattice is raised. As γ_t approaches the beam γ the frequency spread shown on the longitudinal Schottky scan gets narrower. The beam γ is measured as the γ_t for which Δf is minimum. The error on γ is determined by careful measurement of γ_t at the points where increase in Δf is just detectable. The orbit length calculated from the beam energy and the circulation frequency is 474.26 $\pm$ 0.03 m. This is in some disagreement with the design value of 474.07 m.

The second method used is to calculate the orbit length from the survey data for the Accumulator. The result is the design value; the error in the turning angle is 0.5 mrad which translates into a 0.04 m error in arc. Thus, the two results are not in agreement. One can interpret the error in turning angle to mean that the quadrupoles are not centered; it is hard to estimate the addition to the closed orbit corresponding to bending by the offset quadrupoles. The disagreement between the two results corresponds to an uncertainty of less than 0.01 GeV in absolute energy scale.

III Operational Experience

There have been about two months of proton beam test time available over the last eight months in which to develop techniques for deceleration. The major concern has been to obtain high deceleration efficiency. Therefore, beam time has been devoted to empirical improvement of current, voltage, and frequency ramps for Accumulator devices and to making measurements necessary for understanding beam dynamics and stability, *e.g.*, measurements of tunes, chromaticity, closed orbit position, γ_t, synchrotron frequency, emittances. Because the Accumulator had never before been operated below 8.9 Gev, all of these measurements are new.

These studies have been done with protons and reversed magnet polarities because protons cost far less in time and resources than antiprotons; 8.9 GeV protons can be injected directly from either Main Ring or Booster in a single 30 mA pulse (1 mA = 10^{10} p). To obtain a 30 ma stack of $\bar{p}$'s requires about 30 h of 120 GeV operation of the Main Ring. Studies were conducted with 1 – 30 mA of beam. It was generally possible to make effective measurements with as little as 0.5 mA of beam.

The initial beam injection, cooling, and rf capture is a substantially different process for protons and antiprotons; however, the amount of longitudinal cooling required for efficient capture is relevant. In fig. 1 the beam was cooled to $\Delta p/p = 0.06\%$ (FW at 10% maximum), *i.e.*, to $\sim$ 8 eVs, then captured into 15 eVs of rf bucket area. There is a beam loss of several percent after about 100 MeV of deceleration resulting from uncaptured beam hitting the beam pipe. In antiproton stacking a core width of $\Delta p/p = 0.04\%$ is typical, so this loss is not a worry.

Deceleration efficiency to 5.02 GeV/c, just above transition, has been typically 85%. The major loss appears to be associated with sidebands of 60 Hz harmonics on the rf. Although these sidebands are currently 45 dB below the rf carrier, the bunches are significantly disturbed as the synchrotron frequency passes through 60 Hz harmonics. In the 200 s taken for deceleration there is time for a fraction of the beam to diffuse to the bucket boundaries; a slow but steady beam loss is observed.

The beam was decelerated in a series of small steps $\sim$ 40 MeV each. At each step first the dipole bus was adjusted according to the radial offset, then the quad busses were adjusted to keep the tunes fixed, then the trim magnets and dipole shunts were adjusted to straighten the closed orbits, and finally chromaticity and coupling were adjusted by the sextupoles and skew quads. When a ramp value was changed all points following the previously corrected point were adjusted to make a smooth ramp including the new correction. This was a tedious and iterative process repeated many times.

At 4934 MeV/c the beam is debunched and the quadrupole currents ramped to give the γ_t-jump described in sec. II.2. In fig. 1 the horizontal excursion in the beam current curve below 4934 MeV/c shows the efficiency of the jump process. Note that for this process the momentum is simply an arbitrary independent parameter for the quadrupole current ramps unrelated to the fixed beam momentum. The momentum spread grows from about 0.2% to 1% during a γ_t-jump with 8 mA of beam current and the efficiency is about 98%. The efficiency drops to about 85% with 12 mA of beam.

After the γ_t-jump it is critical to cool the beam longitudinally for recapture. We have correctly phased the stochastic cooling at this momentum and can cool effectively in all three planes. Currently $\Delta p/p = 0.07\%$ is obtained and beam is recaptured into about 56 eVs of bucket area at h = 86. In fig. 1 this recapture is seen to be about 97% efficient.

The deceleration from 4934 MeV/c to 3680 MeV/c has one difficulty in addition to the problems of deceleration above transition. To maintain constant bucket area the rf voltage must increase as $|\eta|/E$. The voltage limit of the rf cavity is reached above 3680 MeV/c. Hence there is some beam loss as seen in the sharper drop in beam current below 3900 MeV/c shown in fig. 1. The problem is partially alleviated by smoothly lowering γ_t back to 5.4 during the deceleration to 4400 MeV/c so that $|\eta|$ does not increase so fast. To date the best overall deceleration efficiency has been about 60% when starting with 8 mA of beam; the efficiency decreases with greater beam current, mainly because of loss during the γ_t-jump.

The beam lifetime has been measured to be approximately 100 h at 4.9 GeV/c and 400 h at 8.8 GeV/c. These numbers are consistent with the p^{-2} scaling expected from beam-gas multiple scattering. With the gas jet on at full intensity the lifetime drops by a factor of two.

IV Conclusion

The progress to date on the program to adapt the Accumulator to variable energy operation for direct use in medium energy physics experiments has been sufficient to establish acceptable performance for carrying out the first experiment. Beam has been decelerated to all energies required with sufficient intensity to give luminosity $\sim 10^{31}$ with good beam lifetime. By refining the techniques described above it should be possible to reach deceleration efficiency of about 80% with good reliability. Further progress in efficiency will require better understanding of beam stability. Currently no beam dampers or rf feedback loops are used. Such hardware is available; it is anticipated that further beam studies will indicate how it can be best employed.

References

[1] R. Cester,"Heavy Quarks in Antiproton-Proton Interactions", AIP Conf. Proc. No. 150(1986)p486

[2] J. Peoples, "prospects for $\bar{p}p$ Experiments in the Tev I Accumulator", in *Low Energy Antimatter*, World Scientific Publishing Co.(1986)p144

[3] C. Baglin *et al.*,Phys. Lett. **171 B**,(1986)p135

[4] P. Dalpiaz in "Proceedings of the CERN-KFK Workshop on Physics with Cooled Low Energy Antiprotons", Karlsruhe(1979)

[5] J. L. Rosner,"Heavy Quark Spectroscopy",pres. at Int'l Symp. on Lepton and Photon Interactions, held at Kyoto(19-24 Aug 1985)

[6] *Design Report Tevatron I Project*, Fermi National Accelerator Laboratory (October 1984), Chapter 5

[7] V. Bharadwaj, D. Bogert, M. Church, M. Glass, D. McConnell, W. Marsh, D. Peterson, "Computer Controls Programming for Decelerating Beam in the Fermilab Antiproton Accumulator", this conference

[8] J. Peoples, "Use of the Fermilab Accumulator for Low Energy Antiproton Experiments", in *Physics at LEAR with Low-Energy Antiprotons*, Harwood Academic Publishers(1987)

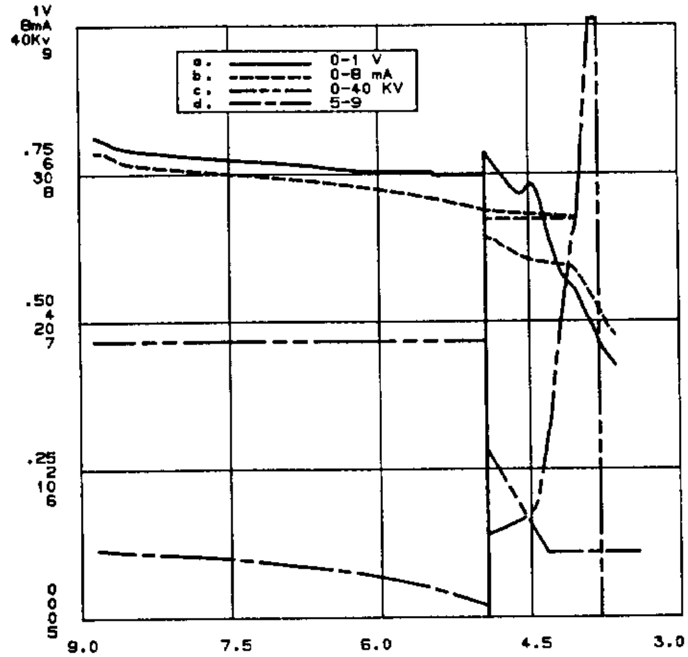

Figure 1: 53 MHz beam component (a), beam current (b), rf voltage (c), and γ_t (d) *vs.* momentum

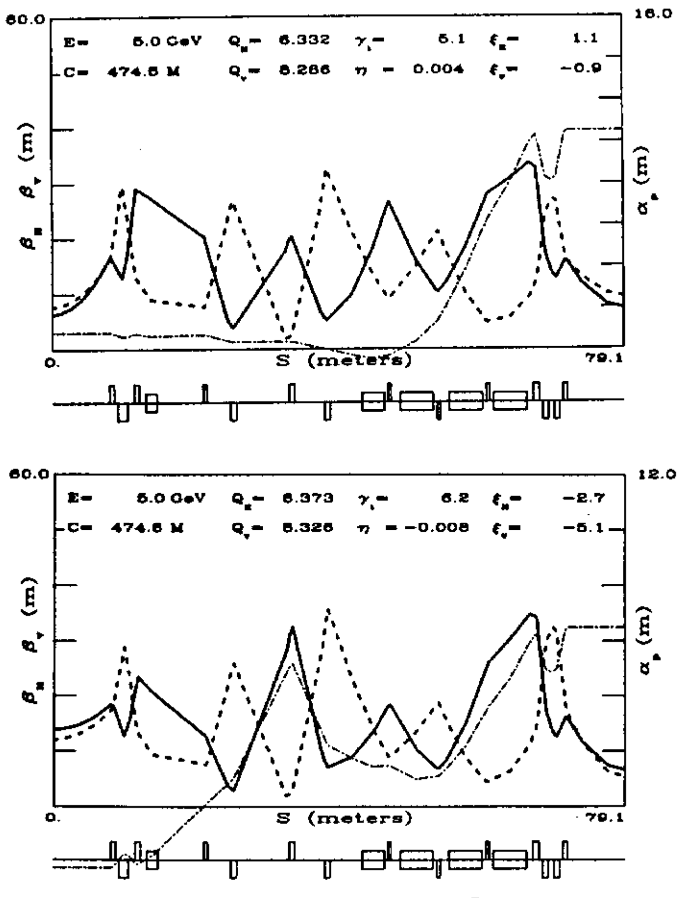

Figure 2: Lattice functions before (top) and after (bottom) γ_t-jump

State	J^{PC}	mass[a] [GeV]	p_{beam} [GeV/c]	β	γ_t	η
η_c	0^{-+}	2.981	3.679	0.9690	5.40	-.0268
ψ	1^{--}	3.097	4.066	0.9744	5.40	-.0163
χ_0	0^{++}	3.415	5.192	0.9844	5.14	.0063
χ_1	1^{++}	3.511	5.552	0.9860	5.18	.0096
$^1P_1$	1^{+-}	unobs	5.593	0.9862	5.18	.0098
χ_2	2^{++}	3.556	5.724	0.9868	5.20	.0108
η_c'	0^{-+}	3.595	5.874	0.9875	5.22	.0118
ψ'	1^{--}	3.686	6.232	0.9889	5.26	.0140
$^1D_2$	2^{-+}	unobs	6.742	0.9905	5.33	.0157
$^3D_2$	2^{--}	unobs	6.742	0.9905	5.33	.0157

(c. o. m.)

[a] Particle Data Group, "Review of Particle Properties", Phys. Lett. 170B(April 1986)

Table 1: Charmonium states and Accumulator beam parameters