FEASIBILITY STUDY FOR USING THE FNAL ANTIPROTON SOURCE AS A LOW ENERGY $\bar{p}$ P COLLIDER

Mike Church, Fermilab, Stephan Maury, CERN

During The Fermilab fixed target program, the Antiproton Accumulator is available for internal experiments. We have investigated the possibility of using this machine as a $p\bar{p}$ collider in the energy range of 8.9 to 2.2 GeV. This would require upgrades to the current RF systems, the addition of stochastic cooling systems for the protons, and the installation of electrostatic separators. We calculate luminosities in the range of 10^{28} cm^{-2}sec^{-1} at a single interaction region with beam intensities of 4×10^{11} and a beam-beam tune shift of .0015.

I. INTRODUCTION

The lattice of the Accumulator [1] has been designed to accept the injection of antiprotons every few seconds at an energy of 8.9 GeV. These are then momentum stacked and stochastically cooled. The antiprotons are accumulated over a period of several hours to obtain a dense core of antiprotons prior to extracting a high intensity beam towards the Main Ring and Tevatron (Fig. 1). The lattice parameters for one sector of the ring are shown in Fig. 2.

In addition to the standard operation mode described above, we study the possibility of operating the Accumulator in the collider mode, $p\bar{p}$. We also discuss the possibility of decelerating beam in the Accumulator as low as 2.2 GeV.

II. TUNE SHIFT AND LUMINOSITY

In collider mode, 4×10^{11} antiprotons are stacked and cooled in about 8 hours. Then, 4×10^{11} protons are injected in the opposite direction using the current antiproton extraction line. The main parameters to know in this option are the tune shift and the luminosity. To get an upper limit on the luminosity, we assume head-on collisions of proton and antiproton bunches. We consider a round Gaussian beam [2,5] with n particles per unit length and with a density distribution

$$\rho(r) = \frac{ne}{2\pi\sigma^2} e^{\frac{-r^2}{2\sigma^2}} .$$

The Lorentz force on one particle at a radius r is

$$\overline{F}_r = e(E_r \pm \beta c B_\phi)\hat{r} .$$

The positive sign corresponds to a particle in the other beam and the negative sign to a particle in the same bunch. The radial electric field E_r and the magnetic induction B_ϕ can be obtained from Gauss' theorem and Ampere's law respectively. Then,

$$F_r = \frac{ne^2}{2\pi r\varepsilon_0}(1\pm\beta^2)(1-e^{-\frac{r^2}{2\sigma^2}})$$

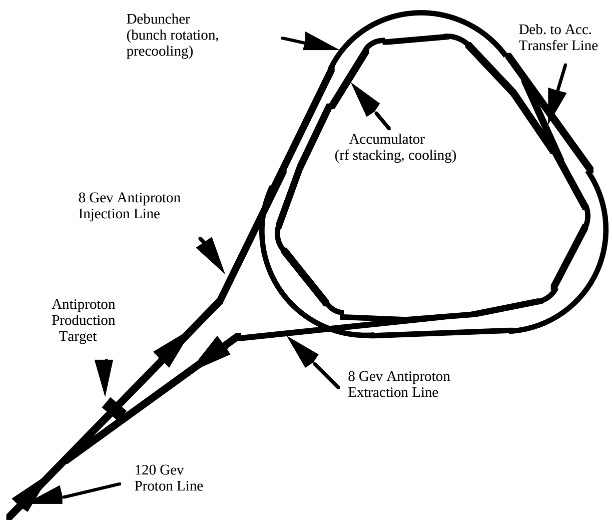

Figure 1: Antiproton Source Layout

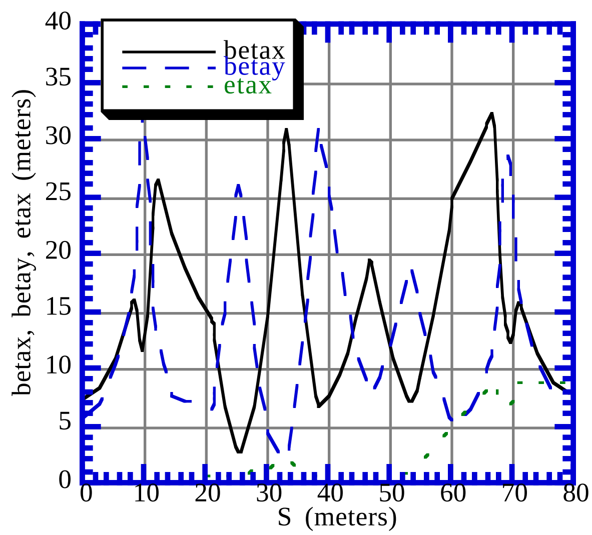

Figure 2: Accumulator lattice -- 1/6th of ring

Intrabeam scattering, Coulomb collisions between particles in the same bunch (negative sign), is counteracted by the stochastic cooling. For particles in the other beam, the effect of electric and magnetic fields is additive. We define an equivalent magnetic field B_{eq} which gives the same force:

$$B_{eq} = \frac{F_r}{e\beta c} = \frac{E_r}{\beta c} + B_\phi$$

$$= \frac{ne}{2\pi r \varepsilon_0 \beta c}(1+\beta^2)(1 - e^{-\frac{r^2}{2\sigma^2}}).$$

The linear tune shift $\Delta\nu$ is given by

$$\Delta\nu = \frac{1}{4\pi} \cdot K \cdot \beta^* \cdot \frac{l_B}{2} \quad \text{where} \quad K = \frac{1}{B\rho} \cdot \frac{\partial B_{eq}}{\partial r}$$

where β^* is the beta function at the interaction point and $l_B/2$ is the effective length of the interaction which is half the bunch length. Putting

$$B\rho = \frac{mc\beta\gamma}{e} \quad \text{and} \quad r_p = \frac{e^2}{4\pi\varepsilon_0 mc^2} = 1.535 \times 10^{-18} m$$

gives

$$\Delta\nu = \frac{N}{B} \cdot \frac{r_p}{4\pi\sigma^2} \cdot \frac{(1+\beta^2)}{2\beta^2\gamma} \cdot \beta^*,$$

where N is the total number of particles in the beam, and B is the number of bunches. We can express the tune shift in terms of the measured emittances containing 95% of the beam. Using $\beta^* \varepsilon_{95\%} = 6\pi\sigma^2$, gives

$$\Delta\nu = \frac{3}{2} \cdot \frac{N}{B} \cdot \frac{r_p}{\varepsilon_{95\%}} \cdot \frac{(1+\beta^2)}{2\beta^2\gamma} \ .$$

The luminosity per bunch [3] is defined as the product of the number of particles per bunch (N_B) of the two beams per cross-sectional area:

$$L_B = \frac{N_B^2}{4\pi\sigma^2} = \frac{3}{2} \cdot \frac{N_B^2}{\beta^* \varepsilon_{95\%}} \quad .$$

The average luminosity is the luminosity per bunch times the collision frequency:

$$L = \frac{3}{2} \cdot \frac{N^2 f_{rev}}{B\beta^* \varepsilon_{95\%}} \ .$$

We can write the average luminosity as a function of the tune shift:

$$L = N \cdot \frac{f_{rev}}{r_p} \cdot \frac{2\beta^2\gamma}{(1+\beta^2)} \cdot \frac{\Delta\nu}{\beta^*} \ .$$

The luminosity seen by a detector is:

$$L_{\text{det}} = L \times \frac{l_{\text{det}}}{l_b}$$

where l_{det} is the effective detector length and l_b is the bunch length.

III. RF SYSTEMS

The bucket area per bunch as a function of RF voltage is

$$A = 16 \cdot \frac{E}{H\omega_{rev}} \cdot \left(\frac{\beta^2}{H\eta} \cdot \frac{eV_{peak}}{2\pi E} \right)^{1/2} \quad [4].$$

We also know that for debunched beam the phase space area is:

$$A = \beta^2 \cdot \frac{E}{f_{rev}} \cdot \frac{\delta p_{95\%}}{p}.$$

So, the voltage needed for a full bucket (bunching factor=1) is

$$eV_{peak} = \frac{\pi^3}{32} \cdot H\eta\beta^2 \left(\frac{\delta p_{95\%}}{p} \right)^2 \cdot E \ .$$

The voltage required for a bunching factor less than 1 is obtained from numerical integration of the longitudinal difference equations for particle motion in an RF bucket. With the addition of two new H=84 RF cavities in the ring, we can obtain 25 kV of DC RF voltage. At 8.9 GeV $\delta p_{95\%}/p$ can be extrapolated from measured data on σ_p, and at 2.2 GeV $\delta p_{95\%}/p$ is estimated from measurements made at 3.8 GeV.

IV. ACCUMULATOR COLLIDER PARAMETERS

Accumulator parameters, emittances, tune shifts, and luminosities are listed in Table 1 for 8.9 GeV and 2.2 GeV. At 8.9 GeV transverse emittance is extrapolated from the measured data. At 2.2 GeV transverse emittance is estimated from measurements at 3.8 GeV. We have used η=.012 at 8.9 GeV because it is already planned to modify the Accumulator lattice for Main Injector running. We have also assumed a detector length of 1 meter.

E (beam energy)	8.866 GeV	2.210 GeV
N (# of particles per beam)	4×10^{11}	2×10^{11}
B (number of bunches)	84	84
η	.012	-.065
β	.9944	.9053
γ	9.449	2.355
f_{rev} (revolution frequency)	.628840 MHz	.572520 MHz
β^* (effective beta function)	3.0 m	2.6 m
$\delta p_{95\%}/p$	.0008	.0006
$\varepsilon_{95\%}$ (transverse emittance)	$.25 \times 10^{-6}\pi$	$.17 \times 10^{-6}\pi$
A (phase space area)	11.1 ev-sec	1.9 ev-sec
eV_{peak} (RF voltage)	25 kV	25 kV
bunching factor	.47	.37
bunch length	3.0 m	2.6 m
$\Delta\upsilon$ (tune shift)	.0015	.0048
L_{det} ($cm^{-2}sec^{-1}$)	$2.6\text{x}10^{28}$	$1.1\text{x}10^{28}$

Table 1: Accumulator parameters in collider mode

V. DECELERATION TO 2.2 GEV

The Accumulator has been operated successfully as low as 3.8 GeV. The passage through transition is accomplished with a γ_t jump of 1.2 units. The deceleration is accomplished in several steps, to allow for stochastic cooling in all three dimensions to counteract transverse and longitudinal emittance blow up. A deceleration efficiency to 3.8 GeV of 90% has been achieved routinely. The deceleration process has been done with an RF system on harmonic 2 with about 2.5 kV. At 2.2 GeV several issues may be of concern:

A. Stochastic Cooling

At 3.8 GeV the primary limitation to stochastic cooling has been found to be due to beam instabilities caused by trapped ions and longitudinal impedance (Keil-Schnell criterion). We expect this situation to be similar at 2.2 GeV. In cooling systems that are not gain-limited and not noise-limited (Accumulator core systems) the cooling rate is determined by the machine parameter η. At 2.2 GeV this parameter will be 4 times larger than at 3.8 GeV (in favor of better cooling). Adversely, the bad mixing (mixing from pickup to kicker) will be worse. The momentum band for effective transverse cooling in the 4-8 GHz band will be limited to approximately $\delta p_{95\%} / p = 1.0 \times 10^{-3}$ by this effect.

B. Power Supplies

Power supplies will need to be tested for stability and regulation at these low currents. At this time, there is no reason to believe they will not be well-regulated.

C. RF

In the future there will be 5 kV of H=2 RF available for bunching the beam for deceleration above 4.2 GeV. At 2.2 GeV only about half this will be available due to the fact that the cavities will be off resonance. This is adequate to completely bunch the beam provided that DC beam can be stochastically cooled to $\delta p_{95\%} / p = 1.7 \times 10^{-3}$. In operation, typical beam widths at 3.8 GeV have been $\delta p_{95\%} / p = 0.6 \times 10^{-3}$. Variable tuning capacitors could be installed on the cavities if required to increase the RF voltage at low energies.

VI. DISCUSSION

In the collider mode, new core stochastic cooling systems will be required to cool the proton beam. Two new H=84 RF cavities would need to be installed in the Accumulator for RF manipulations of the protons. Space is presently available for these additions.

In calculating the tune shift, we have assumed the beams only cross at one point in the ring (A50). This necessitates the use of electrostatic separators to separate the beams at the other zero dispersion regions (A10 and A30). We have not investigated such a system in detail, and this requires further study; however, we do not foresee any difficulty here. For example, in order to separate the beams by 4 sigma at 8.9 GeV, it would require an electrostatic 4-bump in one dimension with 4 separators, each 1 meter long, running at about 15 kV with a plate separation of 50 mm. To get a good separation in the high dispersion regions requires

$$D \bullet (\Delta p / p) \geq 2\sqrt{\beta_h \varepsilon_{95\%} + \left(D \frac{\delta p_{95\%}}{p} \right)^2}$$

where Δp is the difference in energy between the two beams and $\delta p_{95\%}$ is the beam momentum width. In the high dispersion region D=8.95 m and β_h=15.8 m, so that a separation in energy of the two beams $\Delta p / p \geq 1.7 \times 10^{-3}$ is necessary. Since the momentum aperture of the Accumulator is 1.7×10^{-2} this should pose no problem.

VI. CONCLUSION

In this preliminary feasibility study, the operation of the Fermilab Antiproton Accumulator as a $p\bar{p}$ collider from 8.9 GeV to 2.2 GeV can be envisioned with a luminosity of 2.6×10^{28} $cm^{-2}sec^{-1}$ at high energy and 1.1×10^{28} $cm^{-2}sec^{-1}$ at low energy. The beam separation scheme can easily be implemented. The beam energy can be continually adjusted from 8.9 GeV to 2.2 GeV except near the transition energy (γ_t=5.43). The operation of the Accumulator in this mode would require modest additions to the stochastic cooling systems and RF systems and an extensive R&D program to implement.

The use of LEAR as a $p\bar{p}$ minicollider for beam energies up to 2.2 Gev [6] has been contemplated since 1980 and was recently reconsidered [7], with similar assumptions as those made in the present paper.

VII. REFERENCES

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[4] "Theory of RF Acceleration", G Dome, in CERN 87-03, p110

[5] Donna Siergiej, private communication

[6] Design Study of a Facility for Experiments with Low Energy Antiprotons (LEAR), CERN-PS/DL 80-7, ch 6.4

[7] "LEAR in Collider Mode Preliminary Feasibility Study", P Lefevre, PS/DI/Note 94-09