PBAR NOTE 552

DECELERATION AND COLLIDER MODE FOR THE FERMILAB ANTIPROTON ACCUMULATOR

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The lattice of the Accumulator [1] has been designed to accept the injection of antiprotons every few seconds at a kinetic energy of 8 Gev. These are then momentum stacked and stochastically cooled. The antiprotons are accumulated over a period of several hours to get a dense core of antiprotons prior to extracting a high intensity beam towards the Main Ring and Tevatron (Fig. 1). The parameters of the Accumulator ring on the central orbit are shown in Table 1. The lattice parameters for one sector of the ring are shown in Table 6.

momentum	8.816 Gev/c
γ	9.449
β	0.9944
circumference	474.062 meters
revolution frequency	0.628840 MHz
kinetic energy	7.9275 Gev
γ_t, transition energy	5.43
$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$	0.023

Table 1

In addition to the standard operation mode described above, we study the possibility of decelerating the beam in the Accumulator down to the lowest momentum technically acceptable. We also study the collider mode, proton-antiproton, in the Accumulator.

I. DECELERATION

The Accumulator has been operated successfully as low as 3.6 Gev/c. The passage through transition is accomplished with a γ_t jump of 1.2 units (Fig. 2). 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 3.6 Gev/c of 90% has been achieved routinely. From the current vs. momentum curves of previous decelerations, we can extrapolate to 2 Gev/c:

Bus	Current (A)
A:IB	254.3
A:QDF	53.6
A:LQ	287.0
A:QT	53.3

Table 2

The deceleration process has been done with an RF system on harmonic 2 with about 2.5 KV. The Accumulator parameters on the central orbit at 2 Gev/c are listed in Table 3.

momentum	2.00 Gev/c
γ	2.354
β	0.9053
circumference	474.062 meters
revolution frequency	0.572520 MHz
kinetic energy	1.2709 Gev
γ_t, transition energy	4.43
$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$	-.129

Table 3

Where we have distorted the lattice (1 unit in γ_t) to give a more favorable η for RF manipulations. At 2 Gev/c several issues may be of concern:

STOCHASTIC COOLING: At 3.6 Gev/c 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 2.0 Gev/c. 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 Gev/c this parameter will be 4 times larger than at 3.6 Gev/c (in favor of better cooling). Adversely, the bad mixing (mixing from pickup to kicker) will be somewhat worse. The momentum band will be limited to approximately $\delta p / p = .75 * 10^{-3}$ (95% full width) for effective transverse cooling in the 4-8 GHz band.

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.

RF: In the future there will be 5KV of H=2 RF available for bunching the beam for deceleration above 4 Gev/c. At 2 Gev/c only about half this will be available due to the fact that the cavities will be off resonance. This is adequate to bunch the beam provided that DC beam can be cooled to $\delta p / p = 2.1*10^{-3}$ (95% full width). In operation, typical beam widths at 3.6 Gev/c have been $\delta p / p = 0.6*10^{-3}$. Variable tuning capacitors could be installed on the cavities if required to increase the RF voltage at low energies.

II. COLLIDER MODE

In this mode, $2*10^{11}$ antiprotons are stacked and cooled in about 4 hours. Then, $2*10^{11}$ protons are injected in the opposite direction using the current antiproton extraction line (AP3). We choose $2*10^{11}$ because this is the number of protons that can be injected into the Accumulator in a single shot, and we choose to use equal amounts of protons and antiprotons. 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

$$\vec{F} = e(\vec{E} + \vec{v} \times \vec{B})$$

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

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:

$$2\pi r E_r = \tfrac{1}{\varepsilon_0}\int_0^r 2\pi r'\rho(r')dr'$$

$$2\pi r B_\phi = \mu_0 \int_0^r 2\pi r'\beta c\rho(r')dr' \ .$$

Then,

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

The 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

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

where β^* is the beta function at the interaction point and $l_B/2$ is the effective length of the interaction which is taken to be equal to half the RF bucket length. Putting

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

gives

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

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. Putting $\beta^* \varepsilon_{95\%} = 6\pi\sigma^2$, 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:

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

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 parameters of the Accumulator including the tune shift and the luminosity are listed in the Table 4.

	8.8 Gev/c	2.0 Gev/c
N (total number of particles)	$2*10^{11}$	$2*10^{11}$
B (number of bunches)	84	84
$\varepsilon_{95\%}$ (transverse emittance)	$.2*10^{-6}\pi$	$.2*10^{-6}\pi$
β	.9944	.9053
γ	9.449	2.355
f_{rev} (revolution frequency)	.628840 MHz	.572520 MHz
β^* (effective beta function)	8.0 m	8.0 m
$\Delta\nu$ (tune shift)	.00082	.0042
L (average luminosity)	$0.9*10^{28} cm^{-2}s^{-1}$	$0.8*10^{28} cm^{-2}s^{-1}$

Table 4

Measured emittances vs. stack size are shown in Figs. 3 and 4.

III. RF SYSTEMS

The bucket area per bunch as a function of RF voltage is [4]:

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

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 (bf=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 bunch factor less than 1 is obtained from numerical integration of the longitudinal difference equations for

particle motion in an RF bucket. The Accumulator parameters needed to bunch the beams are listed in the Table 5. For 8.816 Gev/c $\delta p_{95\%}/p$ is extrapolated from date on σ_p from Fig. 5. For 2.0 Gev/c $\delta p_{95\%}/p$ is estimated from measurements at 3.6 Gev/c.

	8.816 Gev/c	2.0 Gev/c
H (harmonic number)	84	84
$\delta p_{95\%}/p$	.0008	.0006
β	.9944	.9053
γ	9.449	2.355
E (beam energy)	8.866 Gev	2.210
η	.023	-.129
A (phase space area)	11.1 ev-sec	1.9 ev-sec
eV_{peak} (RF voltage for $bf = 1$)	10.5 KV	6.9 KV
eV_{peak} (RF voltage for $bf = 1/2$)	56 KV	43 KV

Table 5

IV. CONCLUSIONS

In the collider mode, new core stochastic cooling systems will be required to cool the proton beam. Space is available at A20 for momentum pickup and space is available at A50 for a momentum kicker. For transverse cooling, one option is the following: move the Schottky pickups at A10 and install two new transverse pickup tanks; remove two stacktail kicker tanks (thereby compromising the

stacking rate somewhat) and replace them with two transverse kicker tanks at A30. The cost of these new systems will be about .75M$.

Two new H=84 RF cavities would need to be installed in the 50 sector of the Accumulator for RF manipulations of the protons. Space is presently available. We estimate the cost of this system at 1M$. The present system is capable of running DC at about 30 KV. It is not practical to reach much higher than this without installing additional cavities -- for which there is not space in the lattice. Hence, it is probably not practical to run in collider mode with bunch factors any smaller than about 1/2.

In calculating the tune shift, we have assumed the beams only cross at one point (A50). This implies 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, but estimate the cost at 1.5M$. At the normal Accumulator operating point (tunes at .609, .607) a tune shift of up to about .005 could be tolerated.

Luminosity could probably be increased (perhaps a factor of 5?) by the addition of a low beta insert at A50, although we have not considered this option in detail. However,the relatively long bunch length spreads the interaction region away from the β_{min} point and makes the low beta insertion much less effective than it would be with a short bunch length.

References:

1. Design Report, Tevatron I Project, Sept. '94
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3. "An Introduction to the Physics of Particle Accelerators", DA Edwards, MJ Syphers in Physics of Particle Accelerators, p13
4. "Theory of RF Acceleration", G Dome, in CERN 87-03, p110
5. Donna Siergiej, private communication