Proposal to Construct an Antiproton Source for the Fermilab Accelerators

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Abstract

We propose to build a small storage ring for the accumulation of antiprotons produced in an external target. Stochastic and electron cooling will be used to reduce the transverse and longitudinal phase space of the antiprotons. The dynamics of stochastic and electron cooling will also be studied in this storage ring using circulating protons. The cooled antiprotons can be re-injected into the main ring or energy doubler ring; after simultaneous acceleration along with a proton bunch the accelerator will become a colliding pp machine with a center of mass energy range of 300-2600 GeV. Luminosities in the range $10^{29} - 10^{32}$ cm$^{-2}$sec$^{-1}$ are expected.
Introduction

The technological advances in the understanding of the cooling of the transverse and longitudinal phase space of R.F. bunched beams as well as the availability of an intense source of anti-protons at Fermilab, the Fermilab main ring and Energy Doubler ring, have encouraged us to explore once again the old question of building a proton anti-proton storage ring. The physics possibilities of such storage rings operating in the 300-2600 GeV center of mass range are truly enormous. Near the top of the list of physics possibilities is certainly the production and observation of the \( W^0 \) intermediate vector boson through the process

\[
\overline{p} + p \rightarrow W^0 + X \\
\rightarrow \mu^+ + \mu^-
\]

However, the collision of intense beams of matter and antimatter at extremely high center of mass energies is more than likely to involve completely undreamed of physics. We therefore think the physics frontier is justification enough for such a venture. In our feasibility study, although not entirely complete, we have uncovered no conceptual problems to building such a machine at Fermilab. The cost of the \( \overline{p} \) cooling ring is modest on the scale of planned storage rings. We therefore propose that this machine be constructed at the earliest possible date at Fermilab and that one or more long straight sections be instrumented for physics experiments. The proposal submitted at this time focusses on the conceptual design of this machine. A more complete proposal for the construction of the cooling ring will be submitted in the near future.
2. **Physics in Hadron - Anti-hadron Collisions**

The possibilities of observing the production and decay of a very high mass (~100 GeV) intermediate vector boson are reason enough to construct such a machine. In addition for the highest energy option the average parton-antiparton collision has an energy in excess of the weak interaction unitarity limit, therefore the ultimate nature of weak interaction may be decided with this machine.

The study of purely hadronic \( \bar{p}p \) interactions will be of great interest. For example the measurement of the total \( \bar{p}p \) cross section at such high energies will surely be of interest. However it would be of no use to further catalogue the physics projects since the most interesting discovery to be made would almost certainly not appear on any list made at this time. This is, in fact, the main reason for building the machine.

3. **General Scheme for Collecting and Cooling Anti-protons**

The general scheme for obtaining a high intensity, cooled anti-proton beam is as follows:

1. 3.5 GeV/c antiprotons are produced by an intense, R.F. bunched beam from the main accelerator. The beam energy should be above 50 GeV but need not be above 100 GeV.

2. The \( \bar{p} \)'s are transported into the accumulator ring by a special transport system that matches the phase space.

3. The antiproton bunch is initially cooled in transverse and longitudinal phase space by stochastic cooling similar to that operated at the ISR.

4. The \( \bar{p} \) bunch is moved into a parking orbit and another
The $\bar{p}$ bunch is injected. This operation is carried out a few thousand times yielding $10^{10}$-$10^{12}$ antiprotons.

5. The antiprotons are decelerated to a momentum of 350 MeV/c. Stochastic cooling keeps the beam stable.

6. An intense electron beam is turned on with the electrons traveling with the same velocity as the $\bar{p}$ and in the same direction. Approximately 1 amp/cm$^2$ is used. The antiproton beam phase space is cooled further to a very small value.

7. The antiproton beam is accelerated up to 9.0 GeV/c.

8. The antiprotons are extracted into a transport system and carried back to the main ring.

9. The $\bar{p}$ are injected into the main ring and a pulse of $5 \times 10^{10}$ - $5 \times 10^{12}$ protons are obtained in the main ring and all accelerated up to 50 GeV/c.

10. For higher luminosity ($\sim 10^{30}$-$10^{31}$ cm$^{-2}$sec$^{-1}$) requirements some additional R. F. bunching is required.

11. The $p$ and $\bar{p}$ are accelerated to 200 GeV and collide at one or more long straight sections.

12. For operation of the energy doubler as a $\bar{p}p$ storage ring the $\bar{p}$ are first accelerated to 400 GeV/c and transferred to the energy doubler and coast in the "normal" direction. Protons are injected into the main ring, accelerated through transition, R. F. bunched (optional) accelerated to 400 GeV/c and injected into the energy doubler. The $\bar{p}$ and $p$ beams are then accelerated to 1000-1300 GeV/c and collide. The main ring continues to
operate normally and continues to fill the p cooling ring for the next injection.

Before discussing in detail the scheme for cooling the transverse and longitudinal oscillations of the p beam we first briefly review the status of the theory for the cooling of massive particle beams in storage rings and accelerators.

4. Use of the Ring for Electron and Stochastic Cooling

Stochastic cooling has been successfully tried out on the ISR and electron cooling has been tested in Budker's Laboratory. We, therefore, have strong evidence that the general principles behind these cooling techniques are correct. In detail, however, there is still a great deal to be learned about stochastic cooling and electron cooling, especially as it applies to the problem of collecting and cooling a large bite in p phase space in order to construct a p injector for Fermilab. It appears that the same cooling ring that is used to store and cool the p's could be used to study these cooling processes using the copious beams of protons available from secondary targets. We would therefore propose to construct the cooling ring at the earliest possible date and carry out detailed studies of the cooling phenomena. A practical fallout from the electron cooling study might be the measurement of the e⁻ capture cross sections for the production of energetic H atoms. Such atoms can be useful in the heating of plasmas.

The cooling ring is therefore to be constructed in a flexible way with a variable range of parameters that would allow a detailed study of three dimensional stochastic cooling and electron cooling.
5. Cooling of Betatron Oscillations

About ten years ago, Budker\(^1\) proposed electron cooling as a way to increase the phase space density of antiprotons stored in a small storage ring. He pointed out that the cooling process could replace the synchrotron radiation damping of \(e^+, e^-\) storage rings and permit high luminosity \(p\bar{p}\) colliding beams. About five years later, Van der Meer\(^2\) in an unpublished note, pointed out the possibility of cooling the betatron motion in a storage ring with a wide band electronic feedback loop based on the detection of the microscopic fluctuations of the position of the beam. Experimental evidence of successful electron cooling and of stochastic cooling have been recently reported at Novosibirsk\(^3\) and at CERN\(^4\). Recently, Cline, McIntyre and Rubbia\(^5\) have pointed out that the high energy rings at CERN and at FNAL could be transformed into a \(p\bar{p}\) storage ring of about 600 GeV in the center of mass. Finally the projected Energy Doubler\(^6\) at FNAL could give access to the fantastic energy of 2000 GeV in the center of mass.\(^7\)

The present paper concentrates on a realistic scheme of producing \(\bar{p}\)'s with sufficient phase space density to reach luminosities in excess of \(10^{30} \text{sec}^{-1} \text{cm}^{-2}\) at 600 GeV in the center of mass. The main step is repetitive accumulation with no increase of total phase space. The antiproton yield in a realistic collecting channel increases sharply over the energy interval 1.5-4 GeV/c and this contrasts with the increase of electronic cooling times (\(\sim \beta^3\gamma^5\)) and the technological difficulties of a high energy, high current electron cooling beam (about 100amps dc at 750 keV). A comparatively simpler and faster accumulation scheme is proposed. It can operate
at higher antiproton momenta and is based on betatron damping with a low signal (10 V) feed-back loop.

Accumulation can be repeated until about a few times $10^{10}$ particles are stored. At this point, the damping time becomes increasingly long and the main stack must be separated from the newly injected beam. A two-stage accumulation scheme is proposed to reach higher numbers of antiprotons. Final operations are required in order to adjust the beam parameters to the injection in a storage ring.

6. **Production of Antiprotons**

Antiprotons must be produced in a high density target bombarded by the proton beam. In order to achieve a reasonable yield, the antiproton channel collects negative particles produced around the forward direction ($0^\circ$ production angle). The main beam is then conveyed to a beam dump. The useful duration of the proton burst is about four times the revolution of the storage ring ($4 \times 600 \text{ ns} = 2.4 \mu\text{s}$). Some R.F. manipulations in the main accelerator may be required in order to achieve the largest possible number of protons in this time period.

The target is an iridium rod, 4.4 cm long. Following a calculation by Ranft\textsuperscript{8} one gets an overall target efficiency of 1.3. The total energy lost in the target can be as large as $10^5$ Joules at each pulse and it leads to an instantaneous evaporation. An automatic replacement device must be provided. Care must be taken that the radioactive debris are safely handled.

The beam transport after the target must collect the largest
# Table 1

Parameters of the $\overline{p}$ Focusing Front End

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal $\overline{p}$ momentum</td>
<td>3.0 GeV/c</td>
</tr>
<tr>
<td>Maximum accepted angles</td>
<td></td>
</tr>
<tr>
<td>(a) Vertical plane</td>
<td>$\theta_V$</td>
</tr>
<tr>
<td>(b) Horizontal plane</td>
<td>$\theta_H$</td>
</tr>
<tr>
<td>Parameters of first doublet: $(Q_1, Q_2)$</td>
<td></td>
</tr>
<tr>
<td>-free distance to first lens</td>
<td>2.5 m</td>
</tr>
<tr>
<td>-gradient of first lens $(Q_1)$</td>
<td>690 Gauss/cm</td>
</tr>
<tr>
<td>-gradient of second lens $(Q_2)$</td>
<td>560 Gauss/cm</td>
</tr>
<tr>
<td>Useful half-apertures of each lens $(Q_1, Q_2)$</td>
<td></td>
</tr>
<tr>
<td>(a) Vertical</td>
<td>120 mm</td>
</tr>
<tr>
<td>(b) Horizontal</td>
<td>280 mm</td>
</tr>
<tr>
<td>Values of the $\beta$ function at the target location</td>
<td></td>
</tr>
<tr>
<td>(a) Vertical plane</td>
<td>$\beta_V^*$</td>
</tr>
<tr>
<td>(b) Horizontal plane</td>
<td>$\beta_H^*$</td>
</tr>
<tr>
<td>Emittances of the accepted beam</td>
<td></td>
</tr>
<tr>
<td>(a) Vertical plane</td>
<td>$22.5 \pi 10^{-6}$ rad m</td>
</tr>
<tr>
<td>(b) Horizontal plane</td>
<td>$90 \pi 10^{-6}$ rad m</td>
</tr>
<tr>
<td>Maximum accepted momentum spread</td>
<td>$\frac{\Delta p}{p}$</td>
</tr>
<tr>
<td>Target material and length</td>
<td>Iridium rod, 4.4 cm</td>
</tr>
<tr>
<td>Target efficiency</td>
<td>$n_T$</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Maximum field gradient</td>
<td>690 Gauss/cm</td>
</tr>
<tr>
<td>Current</td>
<td>1130 A</td>
</tr>
<tr>
<td>Voltage</td>
<td>145 V</td>
</tr>
<tr>
<td>Resistance at 50 C°</td>
<td>0.13 Ohm</td>
</tr>
<tr>
<td>Power consumption</td>
<td>162 KW</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>1100 mm</td>
</tr>
<tr>
<td>Weight of copper</td>
<td>1.15 t</td>
</tr>
<tr>
<td>Weight of iron</td>
<td>10 t</td>
</tr>
</tbody>
</table>
possible fraction of $\bar{p}$'s produced. We have considered only standard quadrupoles, i.e., we have excluded the use of pulsed lenses and/or superconducting elements. A possible design is shown in Fig. 2. The main parameters of the critical front end of the $\bar{p}$ focusing channel are listed in Table 1. The first quadrupole doublet of lenses is taken from a realistic design (the storage ring DORIS). Parameters are given in Table 2. A drawing of the lens is shown in Fig. 3. In order to accommodate the required emittances, the aperture must be as large as $52 \times 24 \text{ cm}^2$. Subsequent lenses are necessary to match the $\bar{p}$ beam to the betatron functions of the ring. Bending magnets move the residual proton beam to a beam dump and match momentum compactions. The whole beam transport is pulsed only for a short period during each injection cycle.

The yield of antiprotons produced in the momentum interval $3 < p < 4 \text{ GeV/c}$ and in the forward direction for an incident proton energy $E_p = 23.1 \text{ GeV}$ on a lead target has been measured by Dekkers et al.:

$$\frac{d^2N}{dpd\Omega} = 2 \times 10^{-2} \text{ GeV}^{-1} \text{s}^{-1} \text{ster}^{-1} \text{(int. p)}^{-1}.$$ 

Since the acceptance of the injection channel is relatively large, the variation of yield with the angle of production must be taken into account. The following parameterization has been assumed for the invariant cross section:

$$E \frac{d^3N}{dp^3} = e^{-6p} f(p||).$$

Integration up to an angle of $\theta_M$ from the forward direction gives
\[
\frac{dN}{dp} = 1.93 \times 10^{-4}(1 - e^{-6p_0M}) \text{ GeV}^{-1}(\text{int. } p)^{-1}
\]

The fraction of the accepted \( \bar{p} \)'s as a function of \( \theta_M \) is displayed in Fig. 4. For \( \theta_M = 30 \times 10^{-3} \) rad., about 40\% of \( \bar{p} \)'s are collected and \( \frac{dN}{dp} = 7.72 \times 10^{-5} \text{ GeV}^{-1}(\text{int. } p)^{-1} \). Assuming \( \Delta p = 2.0 \times 10^{-2} \), i.e., \( \Delta p = 60 \text{ MeV/c} \), we get \( N = 4.63 \times 10^{-6}(\text{int. } p)^{-1} \) \( \bar{p} \) (at \( E_p = 23.1 \) GeV). Including target efficiency (1/3) and the corrections due to the finite target length (0.9), we arrive at the figure: \( N = 1.53 \times 10^{-6} \) \( \bar{p} \) (incident \( p \))^{-1} (at \( E_p = 23.1 \) GeV). For incident protons of \( E_p \geq 60 \) GeV, we assume a yield 2.5 times larger, i.e., \( N = 3.84 \times 10^{-6} \) \( \bar{p} \) (incident \( p \))^{-1}.

The FNAL accelerator, at the time of the proposed experiment, probably will have reached the design intensity of \( 5 \times 10^{13} \) ppp. One turn ejection will then give \( 6.36 \times 10^{12} \) protons over the 4 turns of the storage ring. We can hope to accumulate about \( 2.44 \times 10^7 \) \( \bar{p} \)'s at each injection pulse. This is only 10\% of the available protons from the accelerator. Schemes are possible, in which bunching at low frequency is used to increase considerably the useful number of antiprotons. We shall not consider these improvements at the present stage.

7. The Storage Ring

The main features of the lattice of the storage ring can be reasonably well defined by simple considerations. The first choice is the momentum of the antiprotons, which has been somewhat arbitrarily set to 3.8 GeV/c as a compromise between size, cost and performance. This, in turn, leads to two possible choices of the
Table 3
Main Parameters of the Cooling Ring

I. Lattice and Orbit Parameters

- Nominal momentum \( p_0 \) : 3.8 GeV/c
- Guide field \( B_0 \) : 12.0 K Gauss
- Curvature radius (magnetic) \( \rho \) : 10.66 m
- Average radius \( R \) : 34.8 m
- Number of periods \( N \) : 16
- Period structure \( 0/2 \ BBDFDBB0/2 \)
- Period length \( L_p \) : 16.54 m
- Number of bending magnets/period : 4
- Quadrupole gradient for \( v = 1.75 \) :
  - \( F \) : 690 G/cm
  - \( D \) : 480 G/cm
- Quadrupole gradient for \( v = 2.25 \) :
  - \( F \) : 157 G/cm
  - \( D \) : 157 G/cm
- Nominal length of F-quadrupole : 0.75 m
- Nominal length of D-quadrupole : 0.5 m
- Nominal length of bending magnet : 2.09 m
- Length of interelement gap : 1.0 m
- Free length in empty semi-period : 8.0 m
- Nominal working point \( \nu \left\{ \nu_x = 1.84 \right\}^* \nu_y = 1.68 \} = 2.25
- Total transition energy/rest energy \( \gamma_t \) : 1.9
- Phase advance/period \( \mu \) : 81°
- Maximum \( \beta \) value in F-quadrupole \( \bar{\beta}_H \) : 22.97 m
- Minimum \( \beta \) value in F-quadrupole \( \bar{\beta}_V \) : 9.45 m
- Maximum \( \beta \) value in D-quadrupole \( \bar{\beta}_V \) : 14.88 m
- Minimum \( \beta \) value in D-quadrupole \( \bar{\beta}_H \) : 8.78 m
Table 3 (cont.)

- Maximum of momentum compaction \( \dot{a}_p \) 8.78 m
- Minimum of momentum compaction \( \dot{a}_p \) 5.65 m

*Basic structure - long straight section at 1 integer each \( 2v_x \) and 1/2 integer each \( 2v_y \), thus \( v_x = 5.84 \) and \( v_y = 3.68 \) for this machine with 4 long straight sections.

II. Dipole Magnets

- Number of units 32
- Nominal length 2.09 m
- Gap height 100 mm
- Useful width 225 mm
- Lamination height 50.8 cm
- Lamination width 155 cm
- Core weight (packing fraction 0.96) 13.4 tons
- Copper weight 2.0 tons
- Number of turns 120
- Conductor dimension 43 x 14.25 mm²
- Cooling hole 6 m dia
- Ampere turns 100,000
- Nominal current 850 A
- Current density 500 amp/sq in
- Power losses 18 KW
- Resistance 7.2 x 10⁻³ Ohm
- Voltage drop/unit 11.4 volts
### Table 3 (cont.)

#### III. Quadrupole Lenses
- Number of units: 20
- Field gradient: 250 Gauss/cm
- Current: 285 A
- Voltage: 7.5 V
- Power consumption: 2.13 KW
- Magnetic length: 590 mm
- Number of turns/coil: 25
- Conductor dimensions: 11 x 11 mm²
- Cooling hole (φ): 4 mm
- Iron weight: 820 Kg
- Copper weight: 140 Kg

#### IV. Main Power Supply
- Bending magnets
  - (a) Voltage: 250 V
  - (b) Current: 1580 A
- Quadrupole lenses (2 separate supplies for D and F)
  - (a) Voltage (each supply): 82 V
  - (b) Current: 285
- Total installed power for magnets: 500 KW
Table 3 (cont.)

**V. Correcting Elements**

- Sextupoles 16
- Octupoles 16
- Bending magnets for orbit correction 32
- Skew Quadrupoles (45°-tilt) 2
- Pick-up stations (for R.F. bunched beam only) 40

**VI. Vacuum System**

- Ring average pressure (90% H₂, 10% N₂) 10⁻¹⁰ Torr
- Number of ion pumps 40
- Number of rotary pumps 5
- Chamber wall thickness 2 mm
- Bake-out heating elements and thermal insulation thickness 7 mm
- Temperature of bake-out 350°C
- Inner vacuum chamber apertures
  - (a) Vertical 80 mm
  - (b) Horizontal 225 mm
transition energy $Y_t$ (in units of the rest mass) which must be kept as far as possible from the working point: $Y_t \gg 3$ and (b) $Y_t \ll 3$. Alternative (b) is preferred because stochastic damping requires the largest possible randomizing effect from the momentum spread.

Another relevant consideration is the radial aperture associated with the momentum spread of the beam at injection. The average radial displacement $\langle \Delta r \rangle$ around the orbit and the fractional momentum error $\frac{\Delta p}{p}$ are related by the average value of the momentum compaction function $\langle \alpha p \rangle$:

$$\langle \Delta r \rangle = \langle \alpha p \rangle \frac{\Delta p}{p}$$

The transition energy in turn is connected to $\langle \alpha p \rangle$ by the relation:

$$Y_t = \sqrt{R/\langle \alpha p \rangle}$$

where $R$ is the average radius of the ring. A reasonable choice is $\langle \alpha_p \rangle = 4 \text{ m}$, corresponding to a radial aperture allowance of 8 cm for $\Delta p/p = 2\%$. Since $R = 2p = 32 \text{ m}$, $Y_t = 2.00$. Furthermore, we can relate $Y_t$ to $v$ the number of betatron oscillations/turn because of the relatively exact expression $Y_t = v$. Taking $v$ values equally distant from integer and half integer resonances gives quantized values of $v = 1.25, 1.75, 2.25, 2.75$ and so on. The value $v = 2.25$ is the one suggested by the previous considerations. The number $N$ of equal cells around the circumference of the ring is related to $v$ by the betatron phase advance/cell, $\mu = v/2\pi N$.

For optimized designs, the phase advance has a value approximately around $\pi/2$, giving $5 < N < 15$. Lower values of $N$ are preferable since (a) we can get the largest straight sections for given values of $R$ and $p$ and (b) we can exploit the characteristic shape modulation of the size due to the strong focusing in order to
optimize the apertures of the components around the ring. Several possible alternatives of the initial parameters have been considered.

The main parameters of an example ring are given in Table 3. A schematic drawing of the ring is shown in Fig. 1a. A possible magnet and vacuum chamber design is shown in Fig. 1b.

8. Injection and accumulation

The injection is performed in four turns in order to collect the longest possible proton burst from the accelerator (Fig. 4b). Since the diameter of the ring is ~200m, this corresponds to an injection time of 2.4 ms. Injection of the new beam must not disturb the main stack already present in the ring. The vertical plane is preferred since in this way the stochastic damping is not affected by radial effects due to momentum spread. The injection procedure is as follows:

(i) a pair of fast (~50 ns risetime) kickers produce a vertical bump of few centimeters in order to bring the injection septum within the aperture of the ring. The bump however leaves enough aperture around the equilibrium orbit, so that the main stored beam does not hit the septum. (See Fig. 5)

(ii) The new beam is injected through the septum and four turns are stored before the first injected particle reaches the septum. At this moment the bump is quickly turned off (~50 ns decay time) and the injected beam appears in the phase space diagram as a halo around the old stack (Fig. 6).

(iii) After a few milliseconds to let \( \pi^- \), \( K^- \), etc. decay, the betatron cooling is turned on and it collapses the newly injected beam on the old stack (Fig. 7a,b,c,d,e). Note that the old stack is continuously damped, thus correcting the inevitable phase space blow-up due to the injection procedure.
The stochastic damping parameters\textsuperscript{10} are summarized in Table 4. Figure 8 shows the expected stacking time as a function of the number of antiprotons present in the ring. Note that the large momentum spread is necessary in order to randomize the sample in a few turns.\textsuperscript{2} If C is the circumference of the orbit,
\[
\frac{\Delta C}{C} = \left(\frac{1}{\gamma^2} - \frac{1}{\gamma_t^2}\right) \cdot \frac{\Delta p}{p}.
\]
For $C = 200\text{m}$, $\frac{\Delta p}{p} = 10^{-2}$, $\gamma_t = 2.0$, and $\gamma = 3.6$, we get $\Delta C = 0.35 \text{m/revolution}$, which is just adequate.

If, for instance, instead $\frac{\Delta p}{p} \sim 10^{-3}$, according to Monte Carlo simulations we expect an increase of about 7 times in the cooling time.

The horizontal betatron motion is almost certainly weakly coupled with the vertical one by the presence of parasitic fields. It is therefore advisable to damp both modes of oscillations. This can be done very simply by increasing the coupling of the two modes with a skew quadrupole.

9. **Damping of momentum spread**

After a few times $10^{10}$ particles are accumulated in the ring, the stacking time becomes quite long and it is advisable to remove the main beam. At this point we propose to reduce the momentum spread with stochastic momentum damping. The main parameters of the momentum damping\textsuperscript{10} are listed in Table 5. The main feature of momentum damping is that its rate becomes progressively slower as
### Table 4

Main Parameters of Betatron Stochastic Damping

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pickup aperture</td>
<td>30 cm</td>
</tr>
<tr>
<td>Pickup length</td>
<td>50 cm</td>
</tr>
<tr>
<td>Pickup bandwidth</td>
<td>from 100 MHz to 400 MHz</td>
</tr>
<tr>
<td>Equivalent sample length</td>
<td>50 cm</td>
</tr>
<tr>
<td>Noise figure of amplifier</td>
<td>3 db</td>
</tr>
<tr>
<td>Pickup importance</td>
<td>120 ohm</td>
</tr>
<tr>
<td>Number of pickup elements</td>
<td>16</td>
</tr>
<tr>
<td>Deflector</td>
<td></td>
</tr>
<tr>
<td>Deflector length (code unit)</td>
<td>50 cm</td>
</tr>
<tr>
<td>Number of units</td>
<td>4</td>
</tr>
<tr>
<td>Deflector aperture</td>
<td>30 cm</td>
</tr>
<tr>
<td>Deflecting power</td>
<td>$4.75 \times 10^{-8}$ rad/volt</td>
</tr>
<tr>
<td>Cooling parameters at $\bar{p}$</td>
<td>$2.5 \times 10^7$ $\bar{p}$</td>
</tr>
<tr>
<td>Antiproton current</td>
<td>6.6 $\mu$A</td>
</tr>
<tr>
<td>Number of $\bar{p}$'s in sample</td>
<td>$1.4 \times 10^4$</td>
</tr>
<tr>
<td>R.M.S. rise at end cooling cycle</td>
<td>1.0 cm</td>
</tr>
<tr>
<td>R.M.S. fluctuation in average position</td>
<td>84 $\mu$</td>
</tr>
<tr>
<td>R.M.S. signal from 16 pickups</td>
<td>59.1 mA</td>
</tr>
<tr>
<td>R.M.S. noise from 16 pickups</td>
<td>565 nA</td>
</tr>
<tr>
<td>Cooling time at optimum gain</td>
<td>11.4 sec</td>
</tr>
<tr>
<td>R.M.S. deflection angle (at optimum gain)</td>
<td>$5.74 \times 10^{-8}$ rad</td>
</tr>
<tr>
<td>Total R.M.S. voltage</td>
<td>11.55 V</td>
</tr>
<tr>
<td></td>
<td>3.49 V</td>
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<tr>
<td>Parameter</td>
<td>Value</td>
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<tr>
<td>Pickup aperture</td>
<td>30 cm</td>
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<tr>
<td>Pickup length</td>
<td>75 cm</td>
</tr>
<tr>
<td>Pickup bandwidth</td>
<td>from 100 to 200 MHz</td>
</tr>
<tr>
<td>Sample length</td>
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<tr>
<td>Number of pickup elements</td>
<td>16</td>
</tr>
<tr>
<td>R.F. cavities</td>
<td>10</td>
</tr>
<tr>
<td>R.F. cooling impedance</td>
<td>100 Ω</td>
</tr>
<tr>
<td>Cooling parameters at</td>
<td></td>
</tr>
<tr>
<td>Number of $\vec{p}$ in sample</td>
<td>$2.5 \times 10^{10}$ $\vec{p}$</td>
</tr>
<tr>
<td>R.M.S. momentum spread</td>
<td></td>
</tr>
<tr>
<td>(a) at beginning</td>
<td>$0.84 \times 10^{-2}$</td>
</tr>
<tr>
<td>(b) at end cooling</td>
<td>$0.84 \times 10^{-3}$</td>
</tr>
<tr>
<td>R.M.S. fluctuation of energy</td>
<td>3200</td>
</tr>
<tr>
<td>R.M.S. signal from pickup</td>
<td>7.56</td>
</tr>
<tr>
<td>R.M.S. noise from 16 pickups</td>
<td>565 nA</td>
</tr>
<tr>
<td>Cooling time (inverse rate) of optimum gain</td>
<td>(335) 187 sec 1300 sec</td>
</tr>
<tr>
<td>R.M.S. voltage in each cooling</td>
<td>(184 V) 220 V 32 V</td>
</tr>
<tr>
<td>Power in each cavity</td>
<td>(340 V) 84 kV 84 W</td>
</tr>
<tr>
<td>Beam invariant area</td>
<td>36 eV sec 3.6 eV/sec</td>
</tr>
</tbody>
</table>
\[ \frac{\Delta p}{p} \] diminishes because of the corresponding increase of the de-randomizing time of the sample.\(^2\) It is impractical to reduce the momentum spread to less than about \( \frac{\Delta p}{p} \approx 2 \times 10^{-3} \) full width. This corresponds to an invariant phase area of the beam of 3.6 eV sec, which is still much too large to be injected in the main ring. We propose at this point to capture adiabatically the beam with R.F. of the lowest harmonic number (h=1) and to decelerate it until it reaches approximately 350 MeV/c, corresponding to about 60 MeV kinetic energy. The relative beam sizes will increase by the factor \((\beta \gamma)^{1/2}\) which is about 3.16. The available apertures should then be sufficient. The momentum spread will also increase to about \(7 \times 10^{-3}\) after adiabatic debunching. Assuming some blow-up in the debunching process, it is probably appropriate to assume that the beam will have a forward relative momentum spread \(\frac{\Delta p}{p} = 10^{-2}\) at \(p = 350\) MeV/c.

The minimum R.F. voltage required to capture at \(p = 3.0\) GeV/c a beam of area \(A = 4\) eV-sec and \(h = 1\) is easily calculated. It is

\[ V_0 = 7280\, \text{Volt} \quad \text{at} \quad f_0 = 1.7\, \text{MHz}. \]

At the value \(p = 350\) MeV, these figures change to:

\[ V_0 = 1748\, \text{Volt} \quad \text{at} \quad f_0 = 580\, \text{KHz}. \]

One simple cavity of the type PPA (drift tube) is amply sufficient in order to provide the required voltage.

10. **Brief Summary of the Theory of Electron Cooling**

The Novosibirsk group has demonstrated that low momentum
proton beams can be "cooled" to very small transverse dimensions ($<1\text{mm}^2$) and very small momentum spread ($<\delta p/p < 10^{-4}$). The basic idea is that the transverse and longitudinal oscillations of the proton beam are transferred to an electron beam that is injected in one of the straight sections of the storage ring. For maximum cooling efficiency the velocity of the $p$ and of the $e^-$ should be the same ($\beta_p = \beta_e$) since the coulomb scattering cross section will be a maximum.

The cooling time for a parallel $e^-$ and $p$ (or $\bar{p}$) beam is given by $(\delta\theta_e \ll \delta\theta_p)$

$$\tau = 0.5 \left( \frac{M_p}{m_e} \right) \frac{\gamma_{\bar{p}}^5 \beta_{\bar{p}}^{-3} (\delta\theta_{\bar{p}})^3}{n_e r_e c L \eta \ln (\delta\theta_{\bar{p}}/\delta\theta_e)}$$

where $r_e = \text{classical electron radius}$

$n_e = \text{electron beam density}$

$\delta\theta_{\bar{p}} = \text{bar p beam divergence}$

$\gamma = E_{\bar{p}}/m_{\bar{p}}, \beta_{\bar{p}} = (p_{\bar{p}}/E_{\bar{p}})$

$\eta = \text{cooling length/total circumference of cooling ring}$

$L = \text{cooling length (M)}$

The important features of the cooling time formula is

$$\tau \propto \frac{1}{(\text{cooling length})} \frac{\gamma_{\bar{p}}^5 \beta_{\bar{p}}^{-3} (\text{Divergence})^3}{[n_e]}$$

The $\gamma^5$ factor increases the cooling times, for reasonable electron current densities, to very long times at high $\bar{p}$ moments. [i.e., $(\bar{p}/p = 3 \text{ GeV/c}), \gamma^5 \sim 243$]

The dependence on the $\bar{p}$ beam divergence shows the desirability of precooling the $\bar{p}$ beam to reduce the divergence. Finally, the cooling time depends inversely on the cooling length and electron
beam density. It is clear that the $\gamma^5$ and (divergence)$^3$ factors dominate the cooling time and since the cooling length and electron current are linear efforts, electron cooling must be carried out at low momenta.

11. **Electron Cooling Times**

At 350 MeV/c $\bar{p}$ momenta very short cooling times can be achieved with rather modest electron beams. A schematic of the cooling straight section is shown in Fig. 9. Electrons are obtained from a large aperture electron gun (Pierce gun) accelerated to a 33 KeV and injected into the storage ring. The electron beam divergence is kept low with a small longitudinal magnetic field in the storage ring. The electrons are deflected out of the storage ring, and deaccelerated and collected in a Faraday cup. The power dissipation is kept low by good electron beam optics. An inefficiency of ~1% seems possible. The expected cooling times are given in Table 6 along with the current density and expected power dissipation. Note that the cooling times are quite short even for modest electron currents and resulting small power dissipation. The electron guns and power supply needed for the electron cooling are modest and easily obtained commercially.

We expect that the electron cooling will reduce the transverse dimension of the $\bar{p}$ beam to $\lesssim 1$ mm$^2$ and the beam momentum spread $< 10^{-4}$. The exact values depend on the residual gas scattering and the accuracy of satisfying the velocity conditions $\beta_{\bar{p}} = \beta_{e^-}$.

12. **Luminosity Estimates**

In order to estimate the luminosity we parameterize the lumi-
<table>
<thead>
<tr>
<th>Beam Size</th>
<th>$e^-$ Current/cm$^2$</th>
<th>Cooling Time</th>
<th>Power Dissipation (1% Off)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cm$^2$</td>
<td>0.1 amp/cm$^2$</td>
<td>30 sec</td>
<td>0.16 kW</td>
</tr>
<tr>
<td>10 cm$^2$</td>
<td>1 amp/cm$^2$</td>
<td>3 sec</td>
<td>15 kW</td>
</tr>
<tr>
<td>10 cm$^2$</td>
<td>0.1 amp/cm$^2$</td>
<td>30 sec</td>
<td>1.5 kW</td>
</tr>
</tbody>
</table>
nosity as a function of the number of protons and antiprotons in the machine. Figure 10 shows the resulting isoluminosity curves. The assumed emittance for the proton and antiproton beam is also given on Fig. 10.

13. Costs, Early Tests and Time Table

We have estimated the cost of the cooling ring and associated devices. The estimates are listed in Table 7. These numbers are extrapolations from previous projects known to us. Harder numbers will be available by mid summer 1976 as a more complete cooling ring design is obtained.

The early tests of the cooling ring beyond simply making it work will concentrate on the study of stochastic and electron cooling of proton beams. We note that cooled proton beams might be useful to decrease the emittance of the protons in the main ring and increase the luminosity of the \( \pi p \) colliding beam devices. Independent of this possibility we wish to study the parameters of stochastic and electron cooling to better understand these phenomena. After the proton cooling studies we would start injecting antiprotons to study the accumulation times and characteristic cooling times as well as R. F. bunching. Finally the deacceleration of the antiprotons would be attempted and the electron cooling option.
Table 7

Estimated Cost of Cooling Ring

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost x 10^6 $</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>0.1</td>
</tr>
<tr>
<td>Electron Cooling</td>
<td>0.5</td>
</tr>
<tr>
<td>Stochastic Cooling</td>
<td>(0.5 - 1)</td>
</tr>
<tr>
<td>Dipoles</td>
<td>0.5</td>
</tr>
<tr>
<td>Quadrupoles</td>
<td>0.16</td>
</tr>
<tr>
<td>Vacuum Chamber</td>
<td>1.2</td>
</tr>
<tr>
<td>Power Supply</td>
<td>0.5</td>
</tr>
<tr>
<td>R. F. System</td>
<td>0.5</td>
</tr>
<tr>
<td>Injection</td>
<td>0.75</td>
</tr>
<tr>
<td>Extraction</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Total: 4.96 (5.46) x 10^6 $
In order to study the injection of antiprotons into the main ring we suggest that protons be used initially and accelerated the wrong direction in the main ring. We realize that the scheme of collecting, storing, cooling and reinjection protons or antiprotons into the main ring is very complex, however, we remind the reader that the scheme for obtaining $5 \times 10^{13}$ protons per pulse in the present Fermilab machine seemed extremely complex only 5 years ago, but now is taken for granted.

The tentative time table for the cooling ring is as follows:

August 1976  CP and D funding starts (??)
September 1976  Full Ring design
October 1976  First prototype dipole and quadrupole magnet construction and field map
January 1977  Bids out for dipole and quadrupole magnets and coil construction
(Allow 8 months for magnet construction)
Summer 1977  Start vacuum chamber and ion pump construction - R. F. prototype
Fall 1977  Prototype stochastic and Electron cooling devices
January 1978  Start assembly of cooling ring at Fermilab
Spring 1978  Install R. F. system
Summer 1978  Install electron cooling and stochastic cooling devices
Fall 1978  Install beam injection and extraction system
Fall 1978  First injection of protons and antiproton and study of cooling phenomena
January 1979    First injection of antiprotons into Fermilab main ring
Spring 1979    Complete detector at interaction region
Summer 1979    Start of $\bar{p}p$ colliding beam experiments
Fall 1979      Observe first $W$ production

14. **Comments**

It is expected that other people will join this effort including Rae Steining and perhaps others from Fermilab.

We wish to thank all the people who have patiently explained some of the details of cooling to us and have criticized our thinking on this subject.

We would like to especially acknowledge Drs. T. Collins, R. Herb, F. Halzen, S. Glashow, E. Picasso, G. Petrucci, N. Ramsey, L. Sulak, L. Thorndahl, L. Teng and S. Weinberg for helpful discussions and suggestions.
REFERENCES


10. For a complete description of relevant formulae see L. Thorndahl, CERN-ISR-RF 75- (Closed Distribution); December 1975.
Fig. 1b
**Magnetic Lattice and Beam Envelopes for one Quarter Storage Ring**

Acceptance: $\epsilon_h = 8 \text{ mrad cm (horizontal)}$

$\epsilon_v = 2 \text{ mrad cm (vertical)}$

---

**Fig. 2a**

Magnet lattice, beam envelopes and dispersions for one quarter storage ring ($\epsilon_h = 8\text{ mrad cm}$, $\epsilon_v = 2\text{ mrad cm}$, $\frac{\Delta P_o}{p_o} = 0.5\%$)
ANTIPROTON PRODUCTION
SCHEMATIC DIAGRAM

TARGET (4.4 cm)

PROTON BEAM

PROTON [\(\beta V = 1.8 \text{ m}\)] [\(\beta H = 20 \text{ m}\)]

\[\beta V = 0.025 \text{ m}\]
\[\beta H = 0.1 \text{ m}\]

ANTIPROTON BEAM

AMM1

BM2

Q1 Q2

PROTON DUMP

\(\vec{p}'\)

70 MOMENTUM MATCHING SECTIC AND STORAGE RIN INJECTION

Fig. 2b.
Fig. 4

ANTIPROTON MOMENTUM
\( p = 3.0 \text{ GeV}/c \)

\(-6 \rho \sin \theta (1-\epsilon)\)
FOUR TURN INJECTION SCHEME IN VERTICAL PLANE

NEARLY INJECTED BEAM

SEPTUM MAGNET

MAIN STORED BEAM

UNPERTURBED ORBIT

Fig 5
Fig 6
Fig. 7a
Fig. 7b
INITIAL PHASES: $X$

Fig. 7b
Fig. 7c PHASE SPACE Y
Fig. 7e
Fig. 7e
Fig 9
$E_{CM} = 500 \text{ GeV}$

$A_V = A_M = 10^{-5} \pi / (\beta \gamma)$

$\beta^* = 4M$

Number of antiprotons

Number of protons

Fig. 10