FERMILAB ENERGY DOUBLER: $\bar{p}p$ at 2 TeV

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Introduction

Construction of the Energy Saver/Doubler has started. This project will not only provide Fermilab with a 1 TeV fixed target program, but will also produce colliding beams of 1 TeV protons on 1 TeV antiprotons. To collect a sufficient number of antiprotons to have a $\bar{p}p$ luminosity of greater than 10^{30} cm^{-2} sec^{-1}, accumulation over many accelerator pulses is required. Accumulation requires "cooling" of the antiproton beam. The cooling and accumulation schemes proposed at Fermilab and CERN will be discussed.

Energy Saver/Doubler

The Energy Saver/Doubler is a superconducting accelerator. Operation of the accelerators will require a power level 40 megawatts less than present. The energy will be $\sim$ 1 TeV with greater than 2 x 10^{13} protons per pulse (> 1 cycle/minute). Future improvements should provide $\sim$ 5 x 10^{13} ppp at a cycle time of $\sim$ 40 seconds. A string of 25 magnets was tested at 90 GeV with 1.25 x 10^{13} protons in a single pass in February, 1979. The energy doubler beam is 25 inches below the present main ring. Figure 1 is a picture of the magnets in the tunnel.

Fig. 1. Main Ring Tunnel. Upper magnets are Main Ring magnets and lower magnets are Energy Doubler magnets.

The lattice [1] is necessarily similar to the Main Ring and requires 774 dipoles and 216 quadrupoles. At this time 6 of 990 magnets have been installed in the final location. Installation of the machine is scheduled to be completed by the end of 1981. Start-up of the accelerator will be in 1982. The magnet has a cold bore and warm steel. A cross section of the dipole magnet is shown in figure 2.

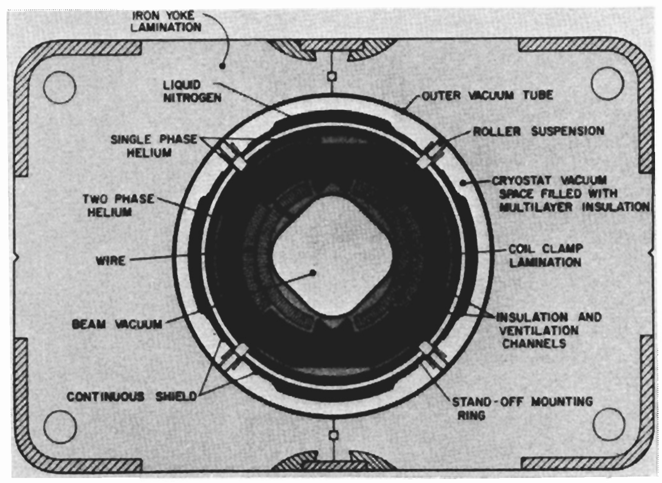

Fig. 2. Cross section of Energy Doubler dipole magnet.

Figure 3 illustrates the measured value for higher harmonic errors in the fields of 16 dipoles. The expected deviations for the distributions are shown. Correction elements up to and including octopole are incorporated in the lattice.

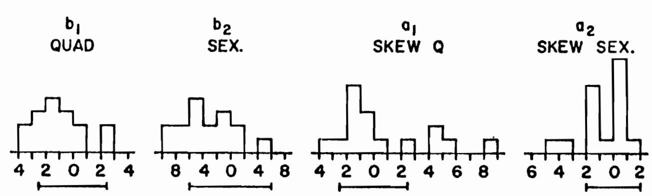

Fig. 3. Magnetic coefficients for 16 Energy Doubler dipole magnets in units $\Delta B/B$ at 1" x 10^{-4}.

Figure 4 shows the quench current and ac loss for the 16 magnets. The lower quench current for some of the magnets is understood and will be corrected for future magnets.

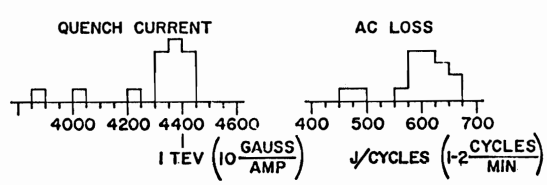

Fig. 4. Quench current and ac loss for 16 Energy Doubler dipoles.

The refrigeration system is sufficient to achieve a cycle time of less than 1 minute. The refrigeration for the Doubler is provided by a central helium plant and 24 satellite refrigerators. Figure 5 illustrates one of the 24 satellite refrigerators. Three satellites have been installed.

*Operated by Universities Research Association, Inc. under contract with the U.S. Department of Energy.

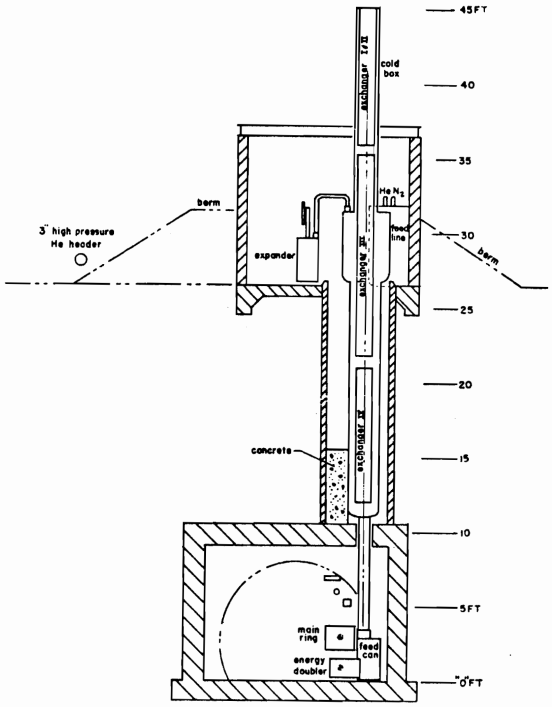

Fig. 5. Cross section of satellite refrigerator and cyrogenic feed to the superconducting magnets in the tunnel.

A complete description of the Energy Doubler is given in "The Energy Doubler Design Report".[1]

One TeV Fixed Target Program

The principal modifications for the Switchyard upgrade will be completed by the end of 1981. This schedule must be achieved to avoid interference between start-up operation of the Doubler and installation in the Switchyard. Figure 6 shows a schematic drawing of the primary proton beams and design intensities for the fixed target program.

There will be 10 primary targets. The flattop will be 10 seconds with both slow spill and multipulses ($\sim$ 1 msec duration for neutrino physics). As shown in the figure, it will be possible to deliver $\sim$ 1 TeV beam to the Meson and Neutrino laboratories at the start-up of the Doubler. Beams for the Proton laboratory and the new muon facility will come later, as will additional modifications for meson and neutrino laboratories.

FIXED TARGET

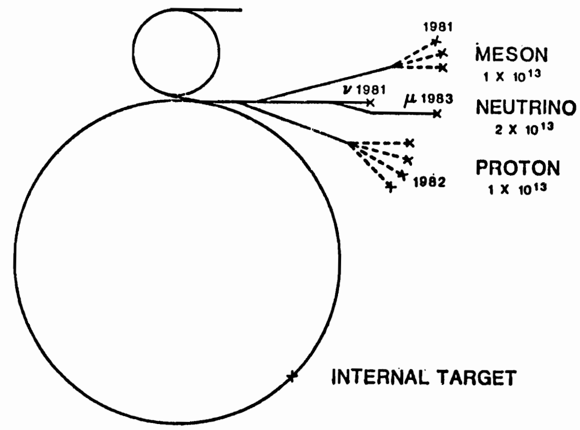

Fig. 6. A schematic drawing of the primary proton beams and design intensities for the 1 TeV fixed target program.

$\bar{P}P$ Colliding Beam Requirements

The goal for the Fermilab colliding beams is to have 1 TeV antiprotons on 1 TeV protons at a luminosity of greater than 10^{30} cm^{-2} sec^{-1}. This requires the Doubler to operate as a storage ring. Correction elements, DC operation, two sets of rf and low β^* sections have been included in the design of the machine.[1] A luminosity of 10^{30} cm^{-2} sec^{-1} requires approximately 10^{11} antiprotons in the Doubler.

$$L = \frac{3 N_p N_{\bar{p}} f}{\beta^* \varepsilon N_B}$$

where N_p = number of protons

$N_{\bar{p}}$ = number of antiprotons

f = revolution frequency

β^* = amplitude function

$\varepsilon = \varepsilon_o / \gamma$ = normalized emittance over γ (E/m)

N_B = number of bunches

Solve for $N_{\bar{p}}$ since the other parameters are approximately fixed.

$$N_{\bar{p}} = \frac{L\beta^* (\varepsilon_o/\gamma)}{3 f (N_p/N_B)} \sim 10^{11}$$

Achievable low β^* is 1-2 meters, normalized emittance is $\sim 10\,\pi \times 10^{-6}$ m-r, γ is 1066, f is 47 k Hertz and the number of protons per bunch is limited to about 10^{11} by instabilities. Therefore, $\sim 10^{11}$ antiprotons must be collected, bunched and accelerated in an emittance equal to or smaller than the protons. To avoid multipule interactions per bunch requires approximately 10 bunches.

Production of Antiprotons

The production of antiprotons is given by

$$\frac{dN_{\bar{p}}}{dp\,d\Omega} = \frac{1}{\sigma_o}\left(E\frac{d^3\sigma}{dp^3}\right) p_{\bar{p}} \; X \; I_p$$

σ_o = 33 mb, pp inelastic cross section

$E\frac{d^3\sigma}{dp^3}$ = .6 - .8 mb/GeV^2, $pp \rightarrow \bar{p}x$ invariant cross section at 80 GeV (fig. 7) [2]

$p_{\bar{p}}$ = $\bar{p}$ momentum

$$X = \underbrace{\frac{L}{\lambda} e^{-L/\lambda}}_{\substack{\text{absorption} \\ \sim .3}} \cdot \underbrace{\frac{L_{eff}}{L}}_{\substack{\text{depth of focus} \\ \sim .4}} = .12 \text{ target efficiency}$$

I_p = proton intensity

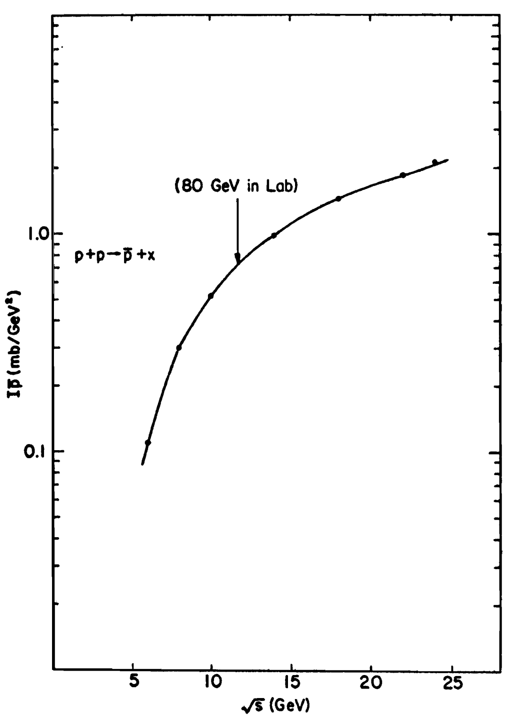

Fig. 7. Antiproton invariant cross section.

For a very large acceptance

$\frac{\Delta p}{p} = \pm 2\%$

$\Delta\Omega = 12{,}500 \times 10^{-6}$ ster.

$N_{\bar{p}} \simeq 10^9\ \bar{p}$ per pulse

For a small acceptance (booster limit)

$\frac{\Delta p}{p} = \pm .13\%$

$\Delta\Omega = 500 \times 10^{-6}$ ster.

$N_{\bar{p}} \simeq 2 \times 10^6\ \bar{p}$ per pulse.

Therefore, the limit for antiproton collection per pulse is 10^6 - 10^9 and it is necessary to accumulate over many pulses to collect 10^{11}. Accumulation requires increasing the density of particles in phase space. Liouville's theorem states that the density in phase space is a constant for an isolated system, thus entropy must be removed from the system of particles. This is referred to as particle beam cooling. This can be done utilizing dissipative forces correlated with particle motion.[3]

Enhancement of Density in Phase Space for Particle Beams

Many schemes have been developed for increasing the density in phase space (reducing beam emittance) of particle beams in circular accelerators.

1) Radiation Cooling. Particles accelerated in a field radiate along their direction of motion. With proper parameters of the lattice of a circular machine, synchrotron radiation can be used to cool the beam. This is used in present electron machines to obtain high luminositites. For a proton synchrotron, the energy radiated per turn is given by

$$\Delta E/\text{rev} = .8 \times 10^{-17}\ E^4/R$$

$$= 10 \text{ eV/rev at 1 TeV.}$$

This would correspond to a cooling time of ∿ 50 days. This is too long, however for multi TeV proton machines this will become important.[4]

2) Electron Cooling. G. I. Budker, et al.,[3] at the Institute of Nuclear Physics in Novosibirsk, have proposed and developed electron cooling of heavy particles (e.g., protons). If heavy particles in a circular machine are coalesced with an electron beam of the same average parallel velocity in one of the straight sections (see figure 8), the 2 beams can be treated as a gas and will approach an equilibrium temperature. Electron beams up to a few hundred kilovolts (protons up to 500 MeV) with a temperature in their center of mass of less than an eV can readily be produced by electron guns.[5] . Typical antiproton temperatures are the order of a KeV. The cooling for such a system is given by [5]

$$\tau = \frac{C\beta\gamma^2}{j_e\eta} \frac{T_\perp T_\parallel^{1/2}}{\log\Lambda}$$

C = constant

β,γ = relativistic parameters of the antiprotons

T = temperature of the antiprotons

je = current density of the electrons

η = fraction of circumference common to electrons and antiprotons

Log Λ = coulomb logarithum

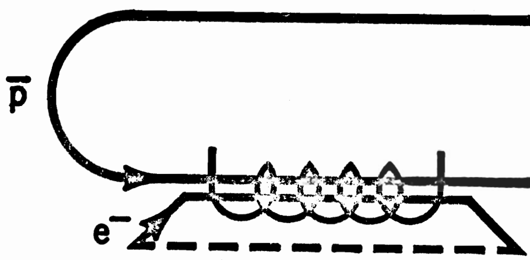

Fig. 8. Schematic drawing illustrating electron cooling.

A solenoidal magnetic field of about a kilogauss parallel to the beams is used to guide the electrons. It was found experimentally by the group at Novosibirsk[6] that with this field a smaller cooling time of up to a factor of 10 was achieved. The reason for this enhancement is that the electron is constrained (larmor radius = 10 micron) to move parallel to the magnetic field and thus remains in the vicinity of the proton for a time inversely proportional to $\Delta v_{\parallel} = v_{\parallel e} - v_{\parallel p}$ (see figure 9). A consequence of this is that as the beam cools the cooling rate increases. Cooling times obtained for protons of 50 to 80 MeV at Novosibirsk[7] and CERN[7] are less than 1 second.

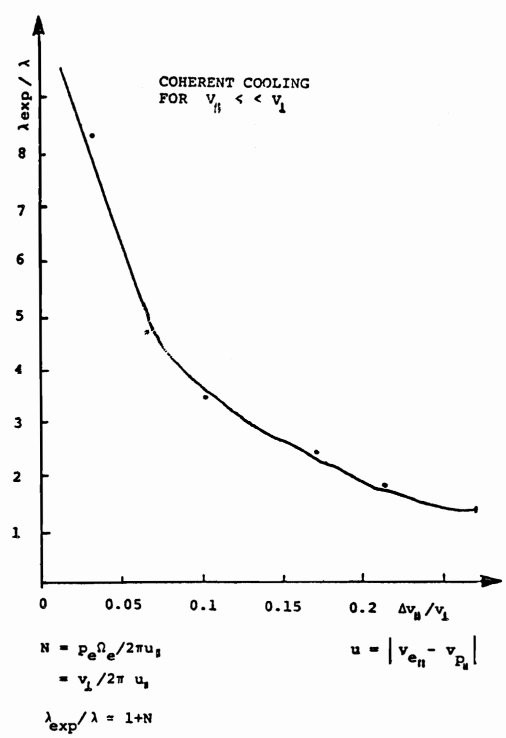

Fig. 9. Coherent Cooling for $v_{\parallel} << v_{\perp}$. See text for definition of parameters.

It is possible to utilize a circular electron machine to produce the cool electron beam (using radiation cooling for the electrons) and cool protons (antiprotons) of ∿ 100 GeV; however, the cooling time is the order of hours. This has been referred to as high energy electron cooling.[8]

3) Stochastic Cooling. S. Van der Meer, et al.[9] at CERN have proposed and developed stochastic cooling. The basic scheme is to detect a local fluctuation in a particle's position or momentum and by going across a cord intercept the particle and correct its motion (pickup→ amplify→ modify signal→ kicker). Because of the technical difference between position pickups and kickers and phase pickups and kickers the cooling times are different for transverse motion and momentum.

For transverse cooling with a pickup giving a signal proportional to the deviation which is amplified and sent to an angular kicker at the appropriate phase the cooling time is given by

$$\tau \sim \frac{2N}{W} (C + n)$$

N = number of particles

W = bandwith

C = cooling term = f (pickup, mixing)

n = noise term = f (amplifier)

For present systems of 10^7 protons at ∿ 4 GeV, cooling times of the order of 100 seconds are expected. Note as the cooling proceeds the noise term becomes more important and the cooling time increases. There is potential for innovation in discovering better devices for transverse cooling and achieving faster cooling times.

For momentum cooling CERN has developed a "filter method"[9] (see figure 10). This is possible since momentum is correlated with frequency. The filter has two important functions:

1) it cancels noise from one turn to the next, and

2) its transmission is zero at the nominal frequency (momentum) and linearly dependent on frequency near the nominal value (and harmonics). Thus, both noise and frequency are reduced near the correct value.

Stimulated by calculations made by F. Sacherer[10] computer programs with all the hardware parameters included have been written to simulate momentum cooling. Figure 11 is reproduced from a paper presented by L. Thorndahl[11] at the San Francisco Accelerator Conference on the CERN ICE experiment. Agreement between experiment and calculations is remarkable. Cooling times for 10^7 particles at 4 GeV are expected to be a few seconds.

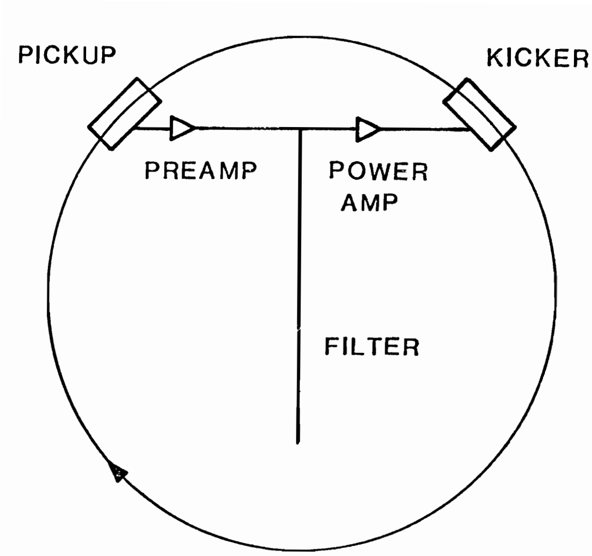

Fig. 10. Schematic layout for CERN's stochastic momentum cooling filter method.

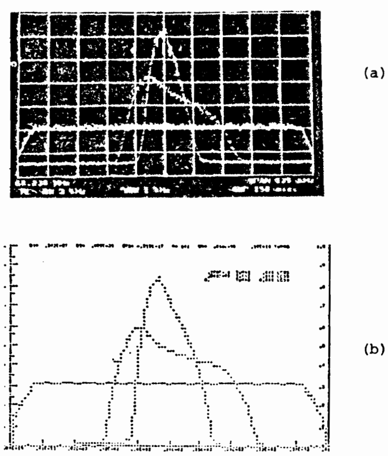

Fig. 11. (a) Observed density evolution after four and eight minutes. $7 \cdot 10^7$ protons.
(b) Computed density evolution.

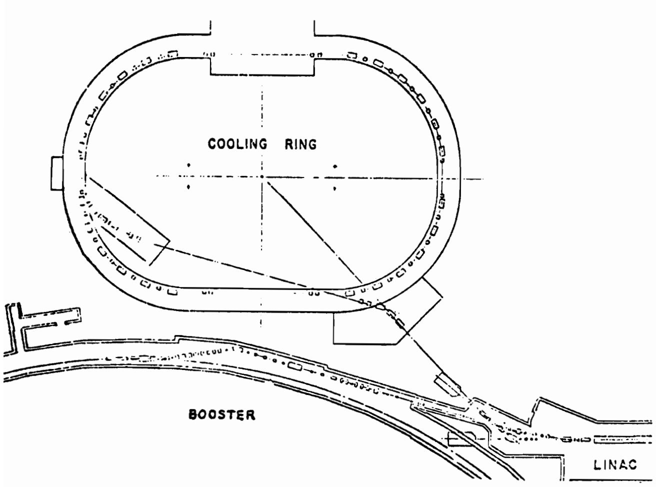

Fig. 12. 200 MeV Storage Ring Layout.

4) Targets. It is perhaps possible to gain a factor of 2 to 4 in target efficiency by passing a current through the target producing a magnetic field sufficient to contain the antiprotons produced.[12] This forces the antiprotons to exit the end of the target and avoids the depth of focus problem. However, there are two problems:

(1) the target explodes due to the current (>10KA) and

(2) the incident protons diverge.

More research and development is needed to ascertain the improvements that may be made.

Fermilab $\bar{p}p$ Collection System Present Status

Initiation of a $\bar{p}p$ colliding beam program at Fermilab was stimulated by submission of proposal 492 [13] in May, 1976, by D. Cline, P. McIntyre, F. Mills and C. Rubbia. In May, 1977, Fermilab started construction of a 200-MeV storage ring (see figure 12) to study electron cooling and accumulation [6] of protons. In 1978, a collaboration between Argonne National Laboratory, Fermilab, Lawrence Berkeley Laboratory, Institute of Nuclear Physics at Novosibirsk and the University of Wisconsin was formed to conduct R & D on collection of antiprotons for use in a $\bar{p}p$ colliding beam facility. On November 11, 1978, a meeting was held at Fermilab to set the goals for colliding beams. The goals are to construct a 1 TeV antiproton colliding beam facility giving a luminosity of greater than 10^{30} cm^{-2} sec^{-1}. In July, 1979, a first draft of a conceptual design report [12] was issued.

The 200 MeV storage ring (see figure 13) first circulated beam in September, 1978.

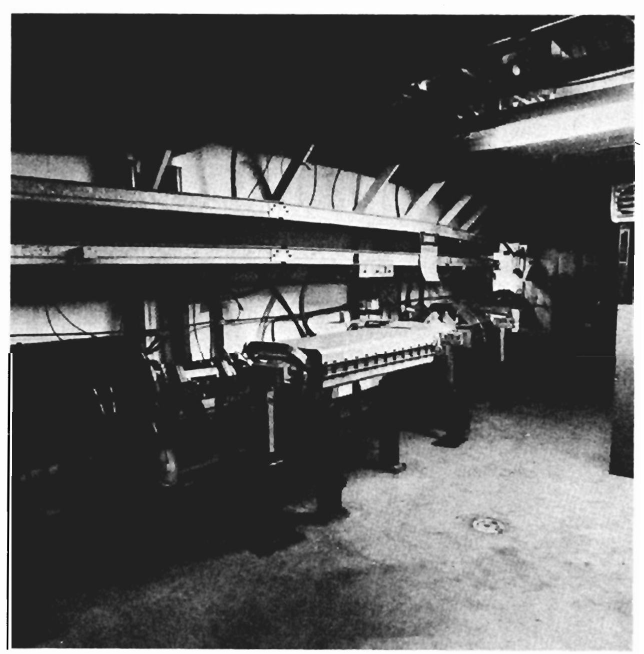

Fig. 13. Fermilab 200 MeV Storage Ring.

Figure 14 is a picture of the storage ring, Booster, reverse beam line/$\bar{p}$ target area and Main Ring. (See figure 16 for schematic drawing.)

Fig. 14. Picture of Fermilab storage ring, Booster, reverse beam line/$\bar{p}$ target area and Main Ring.

Figure 15 is a picture of the 110kV, 5-m long, 26-amp electron-beam system.

Fig. 15. Fermilab electron beam system.

The reverse line will serve to inject 8 GeV protons or antiprotons into the Main Ring. The $\bar{p}$ target area will be used to target 80 GeV protons and produce $\sim$ 4 GeV antiprotons for the collection system. The goals for 1980 are:

1) electron cool 200-MeV protons. The cooling time expected is 300 milliseconds.

2) rf stack, cool and accumulate 200 MeV protons.

3) transverse and momentum stochastic cooling experiments in the cooling ring.

4) production and yield measurements of 4-GeV antiprotons.

5) rf bunching experiments in the Main Ring. Firstly, it is necessary to redistribute the protons of the full main ring into 1/13 (booster circumference) of the ring so that a single extraction can be used to fill the booster with antiprotons, and secondly, to coalesce 5 Main Ring rf bunches into 1 to achieve 10^{11} protons per bunch.

During 1981, tests of antiproton collection will be made. Eighty GeV protons will be extracted from the Main Ring onto the $\bar{p}$ target where 4-GeV antiprotons will be collected and injected into the booster, decelerated to 200 MeV and injected into the cooling ring for cooling and accumulation.

Fermilab $\bar{p}$p Facility-Conceptual Design

The conceptual design[12] includes the addition of a 4-GeV precooler ring for momentum stochastic cooling. (See figure 16) The sequence envisioned for producing $\bar{p}$p collisions is:

1) Accelerate protons in the Main Ring to 80 GeV, coalesce the protons into 1/13 the circumference and extract onto the $\bar{p}$ target;

2) Collect 4.5 GeV antiprotons ($\pm$ 2% $\Delta p/p$) in the precooler, momentum stochastic cool for 2 seconds, (compress by a factor of 5), decelerate to 2.5 GeV and momentum cool for another 2 seconds, decelerate again to 1 GeV and momentum cool and finally decelerate to 200 MeV and inject into the electron cooling ring for cooling and accumulation.

3) Repeat steps 1 and 2 four thousand times (5 hours) to collect 10^{11} antiprotons in the electron cooling ring.

4) Bunch the antiprotons in the electron cooling ring into 12 bunches, extract 1 bunch at a time into the Booster, accelerate to 8 GeV and inject in the reverse direction into the Main Ring, accelerate to 150 GeV and inject into the Doubler. Load the other 11 bunches into the Doubler.

5) Load the Main Ring in the normal direction with protons and accelerate to 150 GeV, rebunch the beam to obtain 10^{11} protons per bunch, eliminate all but 12 bunches properly spaced in the Main Ring and inject into the Doubler.

6) Accelerate both $\bar{p}$ and p in the Doubler to 1 TeV and turn on the low β^* (1.5 meters) section. The expected luminosity is greater than 10^{30} cm^{-2} sec^{-1}.

Figure 17 depicts the straight sections in the Main Ring/Doubler. Straight section B will be dedicated to colliding beams. Construction of the area

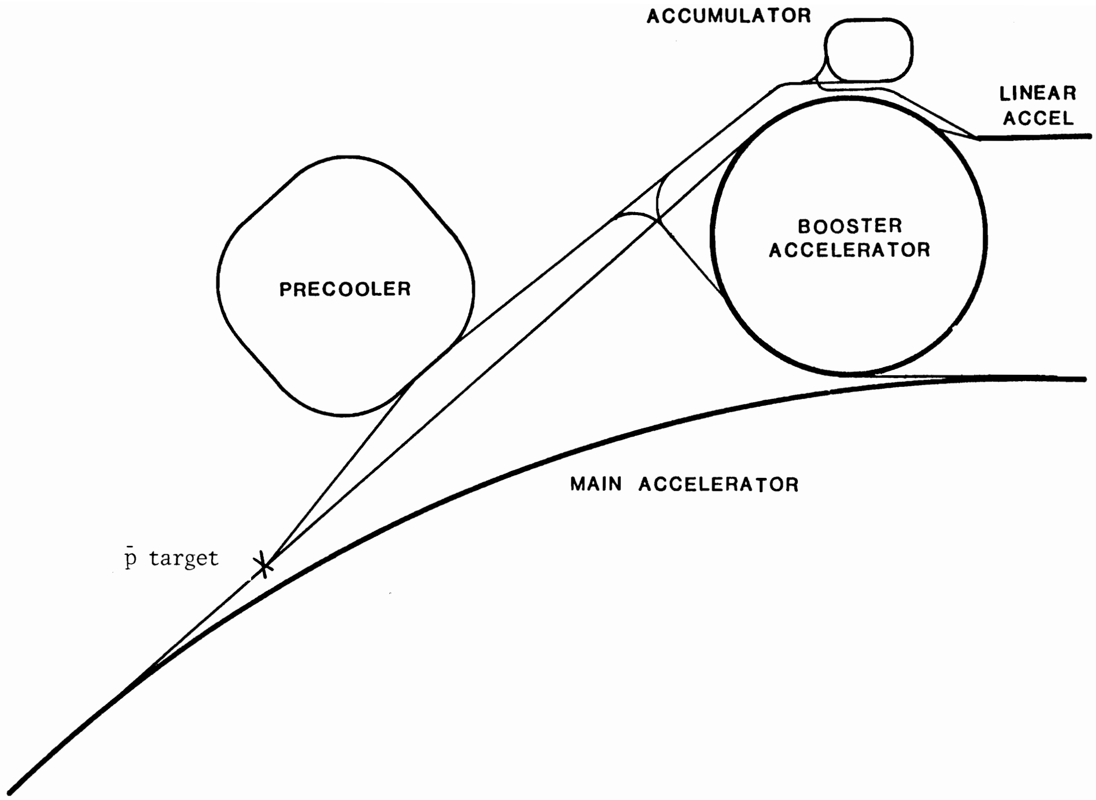

Fig. 16. Schematic drawing of Fermilab p̄ collection system.

will be done in 1981. The experimental facility will have an assembly area on each side of the ring to permit interchange of detectors in a short period of time (∿ day). A second area is possible at straight section D and will be developed later.

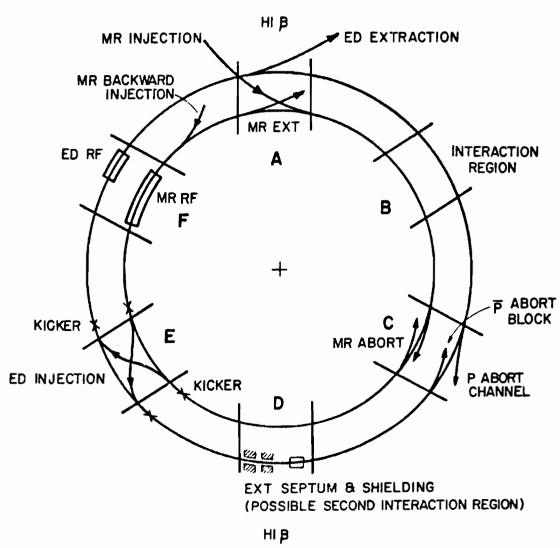

Fig. 17. Use of the six long straight sections in the colliding-beams mode.

CERN p̄p Facility

The CERN scheme for p̄p collisions[14] is shown in figure 18. The sequence for achieving 270 GeV p̄ and 270 GeV p is as follows:

1) Accelerate protons in the PS to 26 GeV and coalesce them into 1/4 of the ring, extract and target to produce 3.5 GeV/c antiprotons (large transverse and longitudinal phase space).

2) Collect the antiprotons in the AA injection orbit and momentum stochastic cool by a factor of 9 in 2.2 seconds, then rf stack for accumulation. Continue to stochastically cool the accumulated beam in all 3 planes.

3) Repeat steps 1 and 2 every 2.6 seconds for 24 hours.

4) rf unstack the p̄ in the AA ring 1/12 at a time. Each bunch of p̄ is injected into the PS, accelerated to 26 GeV and then injected into the SPS in the reverse direction.

5) Load the SPS at 26 GeV with 12 bunches of protons. Accelerate the p and p̄ to 270 GeV.

6) Contract the 12 p and 12 p̄ bunches into 6 bunches each. Turn on the low β* region to achieve a luminosity of 10^{30} cm^{-2} sec^{-1}.

Comparison of Fermilab and CERN p̄p

Table I is a comparison of the Fermilab and CERN p̄p systems. The principal differences are:

1) Incident proton energy for production of antiprotons.

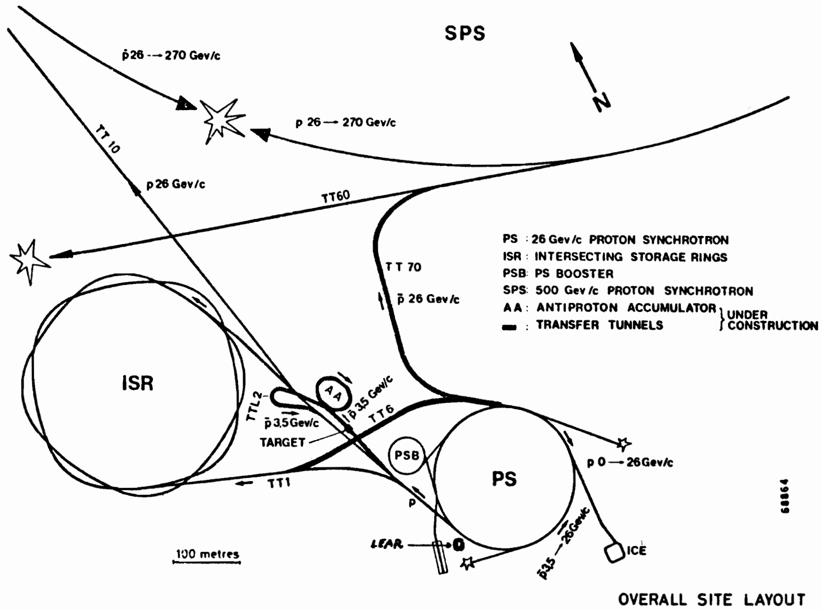

Fig. 18. Schematic drawing of CERN p̄ collection system.

2) CERN utliizes transverse stochastic cooling and thus collects a large transverse phase space.

3) Collection time at Fermilab is 5 hours; CERN is 24 hours.

4) CERN energy is 540 GeV; Fermilab 2 TeV.

Potential improvements for the Fermilab system are listed at the bottom of Table I.

TABLE I

Comparison of CERN and Fermilab p̄p Systems

	Fermilab	CERN
Production		
p energy	80	26
p̄ mom.	4.2	3.5
$\Delta p/p$	± 2%	± .75
Acceptance	$2\pi \times 4\pi$	$100\pi \times 100\pi$
$N_{\bar{p}}$/hour	2×10^{10}	2.5×10^{10}
Colliding Beams		
Energy	1000	270
$N_{\bar{p}}$	10^{11} (5 hrs)	6×10^{11}(24 hrs)
N_p	12×10^{11}	6×10^{11}
N_B	12	6
β^* (m)	1.5	1.5
Luminosity	10^{30}	10^{30}
Potential		
Acceptance	∿ 10	?
Intensity	2	-
Longer collection time	?	- ?
Innovation	?	?

References

[1] Fermilab Staff, Design Report, May, 1979. Superconducting Accelerator.

[2] J. W. Cronin, "Antiproton Production at Rest in the Center of Mass;" 1977 Summer Study, Colliding Beam Physics at Fermilab, p. 275.

[3] G. I. Budker and A. N. Skrinsky, "Electron Cooling and New Possibilities in Physics of Elementary Particles."

[4] R. R. Wilson, "Proton Cooling by Radiation," Proceedings of the Workshop on Producing High Luminosity High Energy Proton-Antiproton Collisions, LBL - 7574, p. 155, March, 1978.

[5] Fermilab Electron Cooling Experiment Design Report, August, 1978.

[6] G. I. Budker, N. S. Dikansky, et. al., Proc. of X Intern. Conf. on High Energy Acc.; Protvino, 1977, v. 1, p. 498, Serpukhov, 1977.

[7] M. Bell, J. Chaney, S. Cittolin, H. Herr, H. Koziol, F. Krienen, G. Lebee, P. Moller Petersen, G. Petrucci, H. Poth, T. Sherwood, G. Stefanini, C. Taylor, L. Tecchio, C. Rubbia, S. Van der Meer and T. Wikberg; Electron Cooling Experiment at CERN, CERN-EP/79-96, Sept. 1979

[8] C. Rubbia, "Relativistic Electron Cooling for High Luminosity Proton-Antiproton Colliding Beams at Very High Energy;" Proceedings of the Workshop on Producing High Luminosity High Energy Proton-Antiproton Collisions, LBL, p. 98.

[9] S. Van der Meer, "Stochastic Cooling Theory and Devices;" Proceedings of the Workshop on Producing High Luminosity High Energy Proton-Antiproton Collisions, LBL, p. 73.

[10] Frank J. Sacherer, "Stochastic Cooling Theory;" Proceedings of the Workshop on Producing High Luminosity High Energy Proton-Antiproton Collisions, LBL, p. 93

[11] G. Garron, H. Herr, G. Lebee, H. Koziol, F. Krienen, D. Mohl, G. Petrucci, C. Rubbia, F. Sacherer, B. Sadovlet, G. Stefanini, L. Thorndahl, S. Van der Meer and T. Wikberg, "Experiments on Stochastic Cooling in ICE (Initial Cooling Experiment)"; IEEE Trans. Nucl. Sci., NS 26, No. 3, June, 1979.

[12] Design Study Group Report, High Luminosity Proton-Antiproton Source at Fermilab; July, 1979.

[13] D. Cline, P. McIntyre, F. Mills, C. Rubbia. Fermilab Proposal No. 492, May, 1976.

[14] H. Koziol, "The CERN Antiproton Accumulator (AA); "Proceedings of the Joint CERN-KfK-Workshop on Physics with Cooled Low Energetic Antiprotons," March, 1979, p. 70.

Questions and Answers

Comment: (Erwin Gabathuler - CERN) I would just like to make a comment in addition to what Dr. Huson said. At CERN, in fact we have added an additional new project to the ideas he showed. A small 2 GeV dedicated ring for a low energy antiproton factory has been approved. It is being built in the P.S. South Hall and will provide intense low energy $\bar{p}$'s of $\sim 10^5$/sec. In this connection it is planned to use possibly the electron cooling. I would like to indicate here that Dr. Frank Krienen and colleagues have recently achieved a very good result with 50 MeV protons cooled in all dimensions. The electron cooling in fact took place so fast that the detectors couldn't really tell how fast the cooling was.

Speaker: (Fred Messing - Carnegie Mellon)

Q. What is the reason that the number of protons is limited in the Doubler to the same number as in the Main Ring?

A. We are trying to be somewhat conservative. We know that we have 2×10^{13} protons right now in the main ring and our plan is to start operation of the Doubler with single-turn injection. We certainly hope to achieve more than that with improvements after a year or two.

Speaker: (Schopper - DESY)

Q. I heard some rumors that in a recent meeting at Brookhaven new ideas came up about the beam limits in $p\bar{p}$ colliding beams. Could you comment on that?

A. I happened to not be at that meeting, so it would probably be better for someone else to comment on that. For our own situation our luminosity is not that high so we don't have those problems. Perhaps someone else (Bob Shafer - Fermilab) would like to comment on that.

Comment: (Bob Shafer - Fermilab) The tune shift limits seem to be estimated crudely in the range of $\Delta\nu = .001$ to $.005$. It is very hard to make good estimates for head on $p\bar{p}$: Electrons violate these limits primarily because of synchrotron radiation and quantum fluctuation effects, but crude estimates that E. Courant was able to make were of the order of .001 to .005 in the $p\bar{p}$ tune shift. We expect tune shifts in this range at 10^{11} per bunch.