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THE FERMILAB $p\bar{p}$ PROJECT; A COMPARISON WITH $p\bar{p}$ at CERN*

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ABSTRACT

Fermilab's $p\bar{p}$ project is described, with emphasis on the $\bar{p}$ source. A detailed comparison is made with the design goals and accomplishments of the CERN $p\bar{p}$ project.

I. Introduction

This is a particularly good time to review the plans for p̄p physics at Fermilab. The superconducting 1000 GeV Tevatron is well on its way with commissioning and fixed target physics expected to start early next year. As well, a design report has just been completed for the p̄ source which is soundly based on CERN inventions and recent experience. A large p̄p detector, the Colliding Detector Facility, has been designed and construction of its underground experimental area is expected to start this summer.

Since the newest aspect of Fermilab's p̄p plans is the p̄ source design, I shall emphasize p̄ accumulation in this report. First I will describe the steps of p̄ accumulation and then the steps leading to p̄p collisions in the Tevatron. Next we can look at detailed comparisons between the design parameters of the CERN[1,2] and Fermilab[3,4] schemes. This will also provide an opportunity to list the already formidable CERN achievements.

As an introduction I can mention the major differences between the Fermilab p̄ source and collider compared to the CERN scheme. Most important is the increased energy of the Tevatron, 1000 GeV vs. 270 GeV at the SPS.

For p̄ production there are two major differences. The first is that at Fermilab, Main Ring protons will be used at 125 GeV to produce 8 GeV p̄'s, while 26 GeV protons from the PS produce 3.5 GeV/c p̄'s at CERN. SPS collisions and p̄ production by the PS can be more or less independent. At Fermilab, where the Main Ring and Tevatron are in the same tunnel, p̄ production and p̄p collisions may necessarily be sequential so that a higher p̄ accumulation rate is necessary. The second difference is that there are two separate rings used at Fermilab to capture and store p's. The CERN antiproton accumulator (AA) is one ring with a large momentum aperture. The outer part of the AA is used for momentum precooling by stochastic techniques. At Fermilab, effective precooling is obtained by rf bunch rotation in the extra ring.

II. Fermilab p̄ Source

Figure 1 shows the relative orientations of the 5 rings used for p̄ physics at Fermilab. The Debuncher and Accumulator rings operate at a fixed energy of 8 GeV which is the normal injection energy of protons from the Booster into the Main Ring. The Tevatron is 66 cm below the Main Ring.

The Main Ring cycles between 8 GeV and 125 GeV every 2 seconds during p̄ accumulation. Transfers of protons and antiprotons from the Main Ring to the Tevatron are at 150 GeV. Normally, after sufficient antiprotons have been accumulated and cooled, three bunches of p̄'s from the Accumulator and three bunches of protons are injected into the Tevatron at 150 GeV in 6 successive

Fig. 1. General Plan of the Fermilab Antiproton Source. Two new 8 GeV rings, the Debuncher and Accumulator, are to be built before 1985. The 1000 GeV superconducting Tevatron occupies the Main Ring tunnel and is 66 cm below the 400 GeV Main Ring Accelerator. For $\bar{p}p$ colliding beams the Main Ring not only provides protons for $\bar{p}$ production but also serves as injector for the Tevatron.

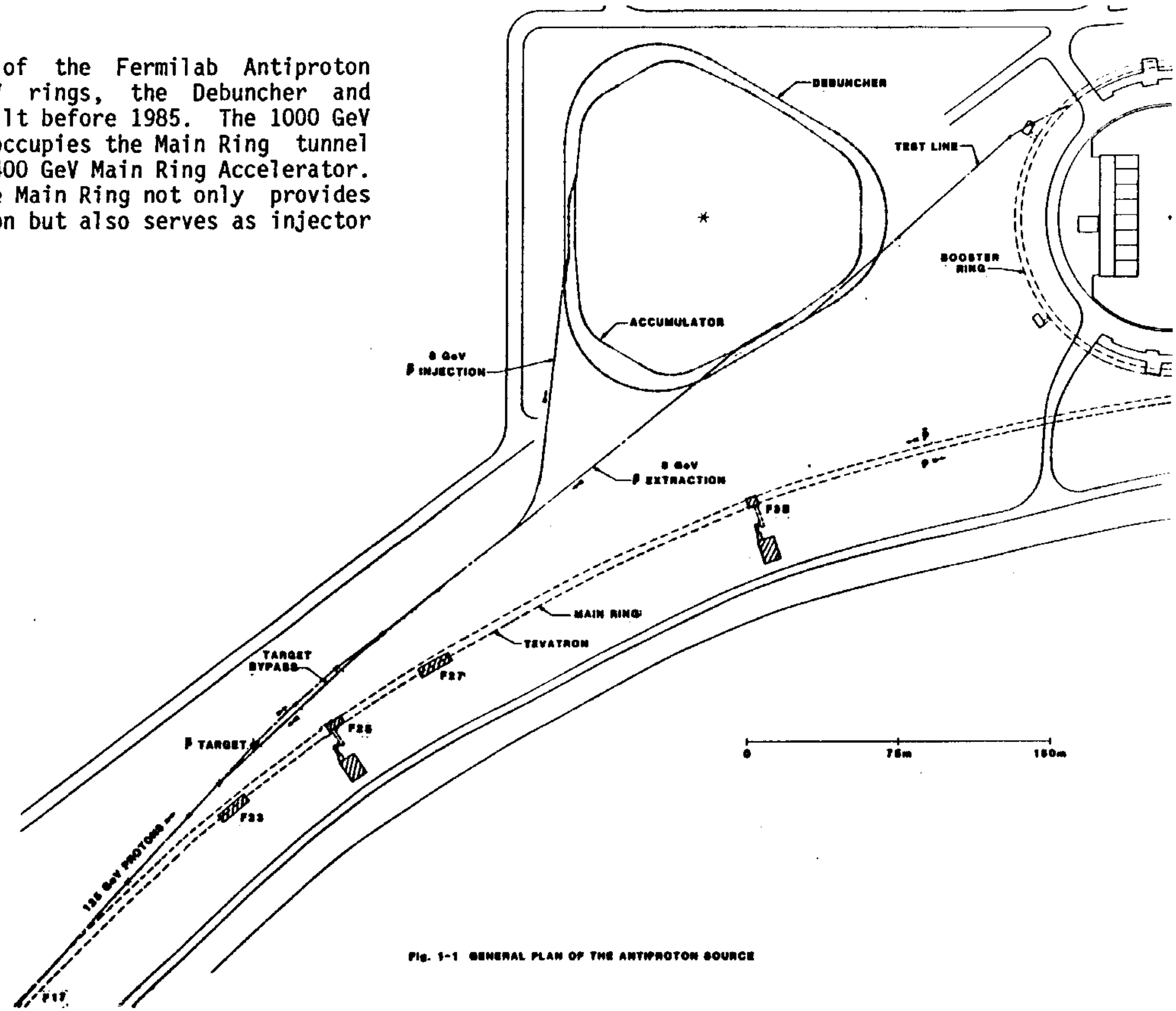

Fig. 1-1 GENERAL PLAN OF THE ANTIPROTON SOURCE

Main Ring cycles. Then all 6 bunches are accelerated to 1000 GeV and the low β insertions are adiabatically energized starting a store which should last more than ten hours.

The actual process of $\bar{p}$ accumulation is based on a 2 second repetition cycle of the Main Ring. First, one Booster circumference of 3E12 protons is accelerated to 125 GeV. RF gymnastics are performed to make each rf bunch very short in time. Second, these 80 rf bunches are extracted onto the production target where 80 equally short bunches of $\bar{p}$'s are produced. A focusing system starting with a lithium lens is used to inject these $\bar{p}$'s into the Debuncher ring.

The third step is then to trade the short time structure and large momentum bite of the $\bar{p}$ bunches of the injected beam for longer time and smaller momentum by performing rf bunch rotation. That is, the bunches are injected into large rf buckets in the Debuncher ring where they rotate one quarter of a synchrotron oscillation period. This is shown schematically in Figure 2 (by the way, this is the inverse of the operation done in the first step to produce short proton bunches). The rf bunch rotation takes only 12 ms and so almost 2 seconds remain before the next batch of antiprotons is injected into the Debuncher ring. These 2 seconds of "free time" are used to reduce the transverse beam sizes by stochastic betatron cooling.

The fourth step is to transfer the bunch-rotated and transversely cooled $\bar{p}$'s from the Debuncher to the Accumulator. Six stochastic cooling systems are then used to merge the freshly injected $\bar{p}$'s into the stack of accumulated $\bar{p}$'s. This process of stochastic stacking is the most complex of all the steps and, in fact, is the limiting factor in determining the rate that $\bar{p}$'s can be accumulated. Figure 3 shows the $\bar{p}$ density distribution in the accumulator as a function of energy. The contours show the evolution of the stack shape after accumulation begins. Four of the six cooling systems are for transverse dimensions. These four are used to counteract transverse blow-up caused by the longitudinal cooling as well as do the final transverse emittance reduction.

The four steps are repeated every 2 seconds for 4 hours or until the density of $\bar{p}$'s in the stack core is sufficient to achieve the desired luminosity in the Tevatron. A small rf system is used to extract a bunch of these $\bar{p}$'s from the stack core. The bunch is then transferred to the Main Ring, accelerated to 150 GeV and transferred to the Tevatron. (Since the bunch is too large to pass through transition in the Main Ring, it must be separated when transferred to the Main Ring into several bunches which are later recombined at 150 GeV). When the Tevatron has been filled with 3 bunches of $\bar{p}$'s and 3 bunches of protons the field is ramped to 1000 GeV.

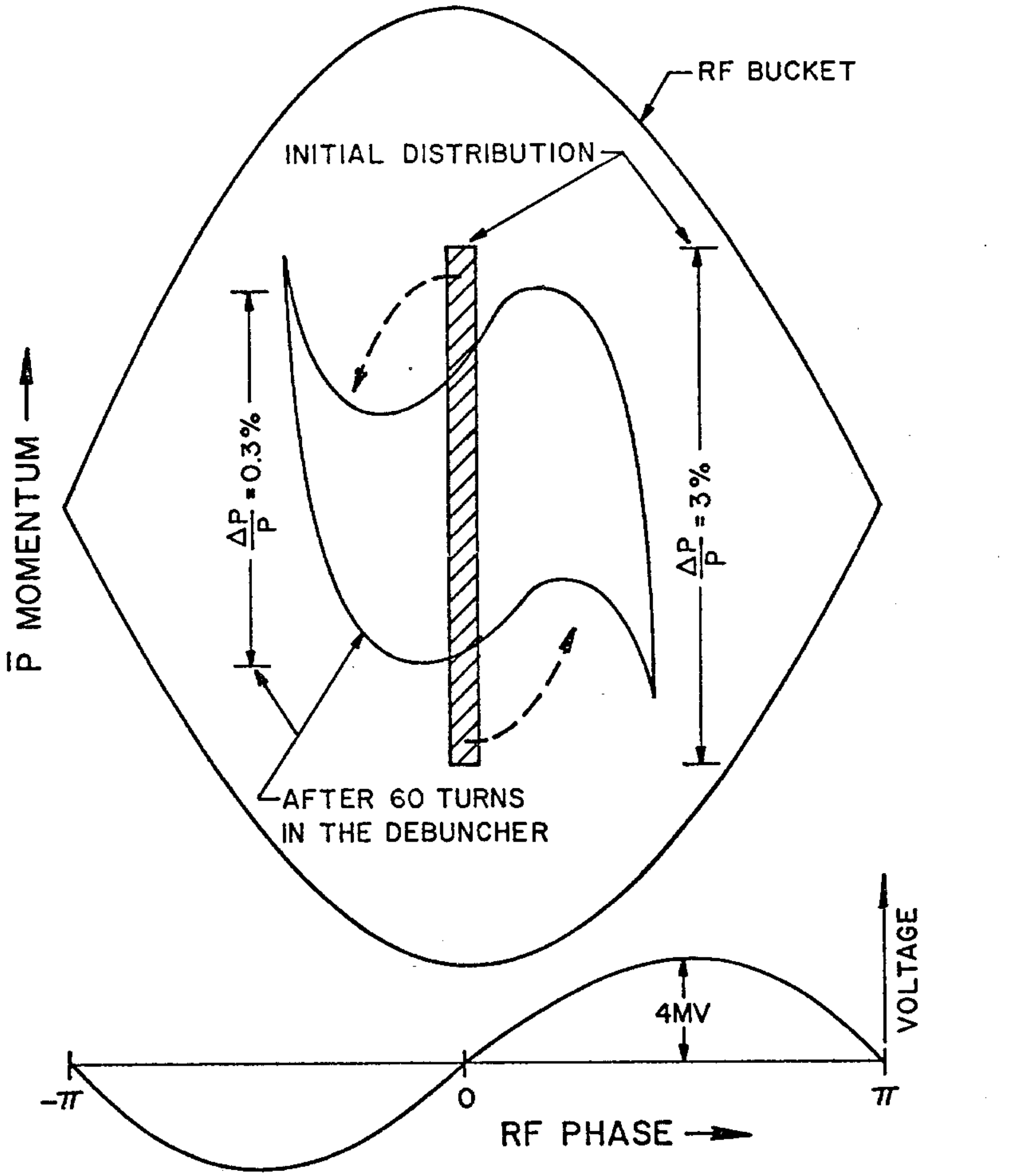

Fig. 2. RF Bunch Rotation in the Debuncher Ring. The short $\bar{p}$ bunches are injected into the Debuncher where a 4 MV rf system rotates the phase space area to get effective momentum cooling. On successive revolutions a higher (lower) momentum particle arrives at the rf cavity later (earlier) than the synchronous particle and sees a negative (positive) voltage. Typical particle trajectories are shown as dashed lines on the figure. After 60 revolutions the particles, on average, have moved 1/4 of the way around the phase-momentum plot. The final distribution is the propeller-shaped figure; the vertical scale has been magnified to show that, even with distortions due to the non-linear rf waveform and complex machine lattice, the momentum width is reduced more than a factor of 10 in less than 100μs. Another 12 ms is required to adiabatically turn off the rf.

The important parameters of the $\bar{p}$ accumulation process are listed in the table below. The transverse emittances are indicated, for example, by $(20\pi)^2$; this means 20π mm-mr horizontally and 20π mm-mr vertically.

Step	Description	Parameter
1	Proton acceleration rf bunch rotation	3×10^{12}p, 125 GeV .5 ns $\rightarrow$ .17 ns
2	p^- production transport to Debuncher	1×10^8 $\bar{p}$, .17 ns, 8 GeV $(20\pi)^2$, $\Delta p/p$=3%
3	rf bunch rotation transverse stochastic cooling	$\Delta p/p$=3% $\rightarrow$ 0.2% $(20\pi)^2 \rightarrow (7\pi)^2$
4	stochastic stacking more transverse cooling	4.3×10^{11} $\bar{p}$'s in 4 hrs. $(7\pi)^2 \rightarrow (2\pi)^2$
5	Collisions in Tevatron	$3(6\times10^{10})\bar{p}\times3(6\times10^{10})p$ $\rightarrow\mathcal{L}=10^{30}$ cm^{-2} s^{-1}

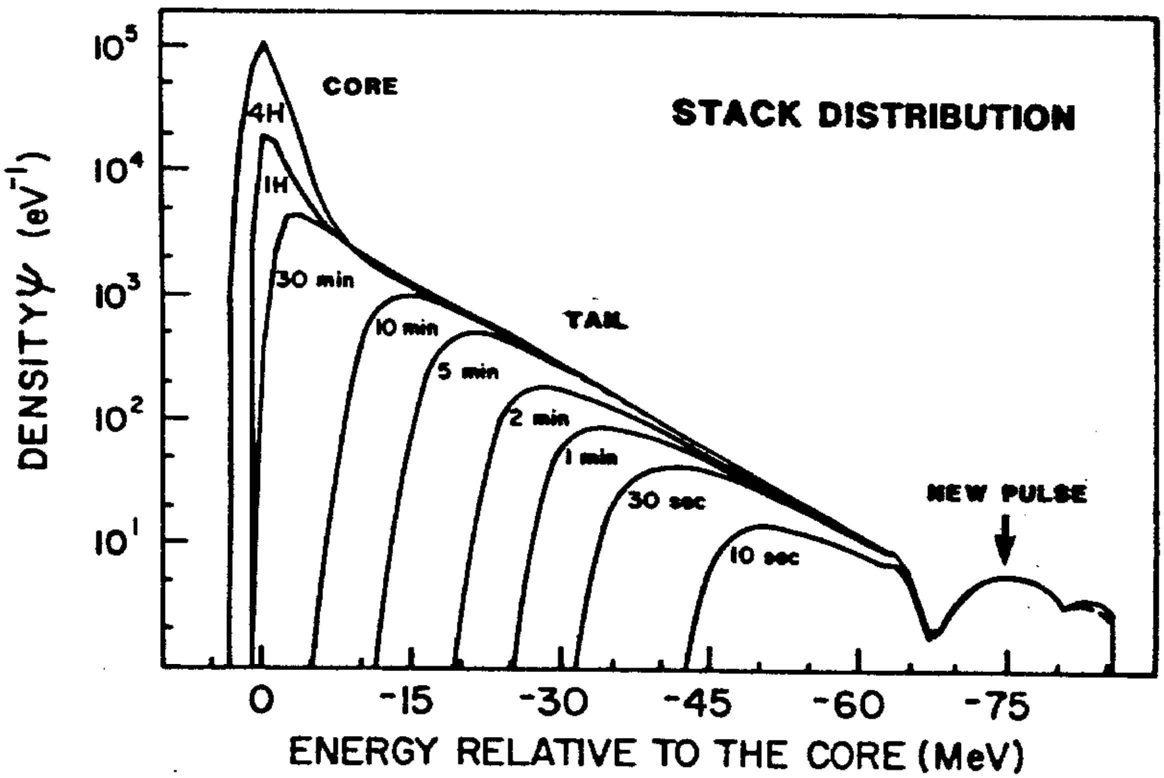

Fig. 3. The Distribution of the Stack of Antiprotons in the Accumulator. The contours show the time evolution of the particle distribution from the time accumulation starts. A new pulse of 10^8 $\bar{p}$'s is added every 2 seconds. The evolution of the distribution is described by the Fokker-Planck equation. This equation, wherein the coherent force of the stochastic feedback system battles the dissipative forces of noise generated by nearby particles, thermal noise, and intrabeam scattering, must be solved by numerical integration.

III. Comparison of Techniques and Parameters

In the following tables some of the more interesting design report parameters for CERN and Fermilab are compared. Also listed are the best values achieved at CERN at this time (~May 1982), when different than the design value.

Targeting

	Fermilab Design	CERN Design	CERN Achieved
Incident proton beam			
momentum (GeV/c)	125	26	
number/cycle (10^{13})	0.3	1	1.2
cycle time (s)	2	2.6	2.4
Target			
material	W	W	Cu
diameter (mm)	>>beam spot=.4	3	
length (mm)	50	110	
peak energy density (J/gm)	224	>185	
Focusing	Li Lens	Horn	
Secondary $\bar{p}$ beam			
momentum (GeV/c)	8.89	3.5	
number per cycle ($\times 10^7$)	10	2.5	0.8
emittance, (mm-mr)	$(20\pi)^2$	$(100\pi)^2$	$(80\pi)^2$

The CERN design figure for the number of $\bar{p}$'s per cycle was based on optimistic interpretations of experimental data and extrapolations to high density targets. More recent calculations at CERN and Fermilab (including the calculation used for the Fermilab design) indicate the CERN design value is about a factor of two too high. No calculation, however, predicts the empirically determined fact that a copper target produces more $\bar{p}$'s than tungsten in the case of the CERN AA.

Calculations also indicate that the lithium lens developed at Novosibirsk should perform better than a magnetic horn both at Fermilab and CERN. However, the operational experience is certainly less for the lithium lens and one could imagine some problems which might preclude its use. Even if a horn were used at Fermilab, enough $\bar{p}$'s would be collected to saturate the collection rate of the Accumulator.

Precooling

	Fermilab Design	CERN Design	CERN Achieved
Place	Debuncher Ring	Outer 1/4 of Accumulator Ring	
$\eta = p\Delta f/(f\Delta p)$	-.004	-.11	
Momentum Cooling			
Technique	RF bunch rotation	notch-filter stochastic cooling	
Initial $\Delta p/p$(%)	3 (4 possible)	1.5	
Final $\Delta p/p$(%)	0.2	0.2	$\sim$0.3
Hardware	8 rf cavities 53 MHz, 4 MV	200-500 MHz 5 KW	
Transverse Cooling			
Technique	Stochastic Betatron Cooling	None	
Emittance Reduction each plane (mm-mr)	$(20\pi)^2 \rightarrow (7\pi)^2$		

The CERN precooling step uses the Thorndahl, or notch-filter, method to cool the $\bar{p}$'s from the target while they are on the injection orbit of the Accumulator. In 2 seconds the momentum spread is reduced from 1.5% to 0.2% for 80% of the injected $\bar{p}$'s. This technique uses ferrite pickups and kickers which must have moveable shutters to allow the precooled beam to pass on to the stack region of the aperture. The shutters are heavy, fast-moving, in a region of high vacuum, and occupy one fourth of the 6% momentum aperture of the CERN AA.

So the Fermilab scheme, while it does need an extra ring for the Debuncher, does not need an expensive, high-powered precooling system with its associated moveable ferrite shutter system.

In these rings for $\bar{p}$ accumulation the relation between momentum and revolution frequency, $\eta \equiv p\Delta f/(f\Delta p) = 1/\gamma^2 - 1/\gamma_t^2$, is very important. In the case of stochastic cooling η determines the mixing parameter; in general, larger η means a larger sample randomization rate and faster cooling. For rf bunch rotation, however, the bucket area for a given rf voltage increases as $1/\sqrt{\eta}$. This contradictory requirement implies that it is difficult to use both techniques in the same ring. Nevertheless, the Fermilab Debuncher is a compromise which allows both bunch rotation and stochastic cooling.

Transverse cooling in the Fermilab Debuncher has two major advantages. First, it allows the acceptance of the Accumulator to be smaller. This saves some money on magnet aperture and also allows the stochastic cooling pickup and kicker electrodes to have smaller gaps, thus increasing coupling efficiency. The second advantage comes from the fact that the stack tail momentum cooling uses pickups in high dispersion regions to measure momentum by radial position displacement (Palmer method). Radial betatron oscillations add noise to this measurement; transverse precooling thus improves the stack tail momentum cooling in the Accumulator.

$\bar{p}$ Accumulation

	Fermilab Design	CERN Design	CERN Achieved
Ring Parameters			
Central momentum (GeV/c)	8.89	3.5	
Acceptance			
momentum (%)	2	6	
transverse (mm-mr)	$(10\pi)^2$	$(100\pi)^2$	
Average Radius	75 m	25 m	
Vacuum (Torr)	3×10^{-10}	1×10^{-10}	5×10^{-11}
Cooling Parameters			
Stack Width (%)	1	3	
$\eta = p\Delta f/(f\Delta p)$	-.02	-.08	
Initial $\bar{p}$ density (particles/eV)	7	3	
Peak $\bar{p}$ density (particles/eV)	10^5	$.65\times10^5$	$.35\times10^5$
(particles/eV-s)	$.63\times10^{11}$	1.1×10^{11}	$.60\times10^{11}$
Transverse Emittance			
Initial (mm-mr)	7π	100π	
Final (mm-mr)	2π	$1.4\pi h$, $1.0\pi h$	
Stack Tail Δp Cooling			
Bandwidth	1-2 GHz	0.25-0.5 GHz	
Installed Power	7500W	5000W	
Stack Core Δp Cooling			
Bandwidth	2-4 GHz	1-2 GHz	
Installed Power	100W	200W	
Performance Figures			
Total $\bar{p}$ in stack	$>4\times10^{11}$	10^{12}	1.9×10^{11}
Maximum Flux ($\times10^7$ $\bar{p}$/s)	3	0.83	0.25
Stacking Time to $=10^{30}$ cm^{-2} s^{-1}			
Initial fill			
Time (h)	4	33	1.9×10^{11} $\bar{p}$
Number (10^{11})	4.3	10	in $\sim$50 h
Refill			
time (h)	2	24	
Number (10^{11})	1.8	6	

The inner half of the CERN AA is identical in function to the Fermilab Accumulator. The larger maximum flux for the Fermilab design follows from the larger bandwidth of the stack tail Δp cooling system. The other component in the disparity in stacking times come from needing fewer particles at 1000 GeV than at 270 GeV to achieve a luminosity of 10^{30} cm^{-2} s^{-1}. This is because the transverse beam sizes shrink in a synchrotron as the energy increases; the enhancement factor in luminosity is proportional to the energy.

Because of the large $\bar{p}$ accumulation rate and higher energy of the Tevatron, the design goal of 10^{30} $cm^{-2}s^{-1}$ for the Fermilab collider seems somewhat conservative. In fact, one expects to have a peak luminosity which is only limited by the beam-beam tune shift. This effect, where each beam is defocused by the counter-rotating beam, is the normal luminosity limitation in electron-positron colliders. An optimistic interpretation of the beam-beam tune shift data from the SPS collider would imply that peak luminosities greater than 6×10^{30} $cm^{-2}s^{-1}$ will be possible at Fermilab.

There is a design at Femilab of a Main Ring overpass which would raise the Main Ring some 5.5 m in the region of the BO Colliding Detector Facility. In principle, this would allow the CDF to detect $\bar{p}p$ collisions in the Tevatron even while the Main Ring is used to generate $\bar{p}$'s. It would also simplify the detector itself not to require holes and field compensations necessary for the Main Ring beam only 2/3 m above the Tevatron interaction region.

The DO straight section of the Tevatron will also be available for colliding beam experiments. This area is normally used for extraction devices when the Tevatron operates for fixed target physics. These devices can be removed for collider operation and smaller experiments can be installed. There are about five proposals for such experiments now being considered.

<u>SPS or Tevatron</u>	Fermilab Design	CERN Design	CERN Achieved
Luminosity ($cm^{-2}s^{-1}$)	10^{30}	10^{30}	5×10^{27}
Number of p($\bar{p}$) per bunch	0.6×10^{11} (0.6×10^{11})	1×10^{11} (1×10^{11})	0.7×10^{11} (0.05×10^{11})
Number of p($\bar{p}$) bunches	3 (3)	6 (6)	2 (1)
Invariant transverse p($\bar{p}$) emittance (h×V) (mm-mr)	$24\pi\times24\pi$ ($24\pi\times24\pi$)	$20\pi\times10\pi$ ($11\pi\times5\pi$)	$13\pi\times13\pi$ ($33\pi\times29\pi$)
$\beta^*_H\times\beta^*_V$ (meters)^2	1×1	4.7×1	1.5×0.75
Refill Interval (h)	>10	24	31
Vacuum (Torr)	$<10^{-10}$	5×10^{-9}	1.3×10^{-9}
Single Beam Lifetime (h)	>200	>30	200
Luminosity Lifetime (h)	>72	>30	16

IV. Status, Costs and Future Developments

If the funding for the Tevatron collider and p̄ source is sufficient (∼$100M in the next 3 years) one can anticipate p̄p collisions at Fermilab in 1985. The present Fermilab schedule calls for commissioning and fixed target physics for the Tevatron during 1983 and 1984.

With this sort of schedule in mind, we should try to put the CERN-Fermilab comparison in perspective. First, the Fermilab design is really quite solid because it represents conservative extrapolations from CERN inventions and experience. Second, as time goes on, one can expect the designs and devices of both machines to evolve.

CERN has a 5 year head start in the p̄ production business. Many improvements for the AA are being pursued. Higher PS intensity, a better horn, refrigeration of pickups and preamps, and better ferrite pickups and kickers are anticipated improvements for this year alone. Longer range projects include larger bandwidth for the stack tail cooling and rf bunch rotation using another ring of magnets. Improvements in the SPS can also be anticipated. Higher energy with improved power supplies and/or ramping the magnets during collisions as well as electrostatic deflectors to reduce the beam-beam tune-shift are two improvements being discussed.

Likewise, one of the strongest features of the Fermilab design, especially the two-ringed source, is flexibility and room for new devices. And with all the creative ability at Fermilab and CERN, we shouldn't be too surprised if a p̄p collider comparison done in 5 years were based on a luminosity goal of $10^{32}cm^{-2}s^{-1}$.

Acknowledgements

I would like to thank the CERN AA staff for their hospitality during my 16 month stay with them. In particular, Roy Billinge, Simon van der Meer (who really started this business) and Lars Thorndahl have been essential to my education. Thanks to the other members of the Fermilab p̄ source section, especially John Marriner who helped compile the comparison figures.

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