CHAPTER 1

INTRODUCTION AND OVERVIEW

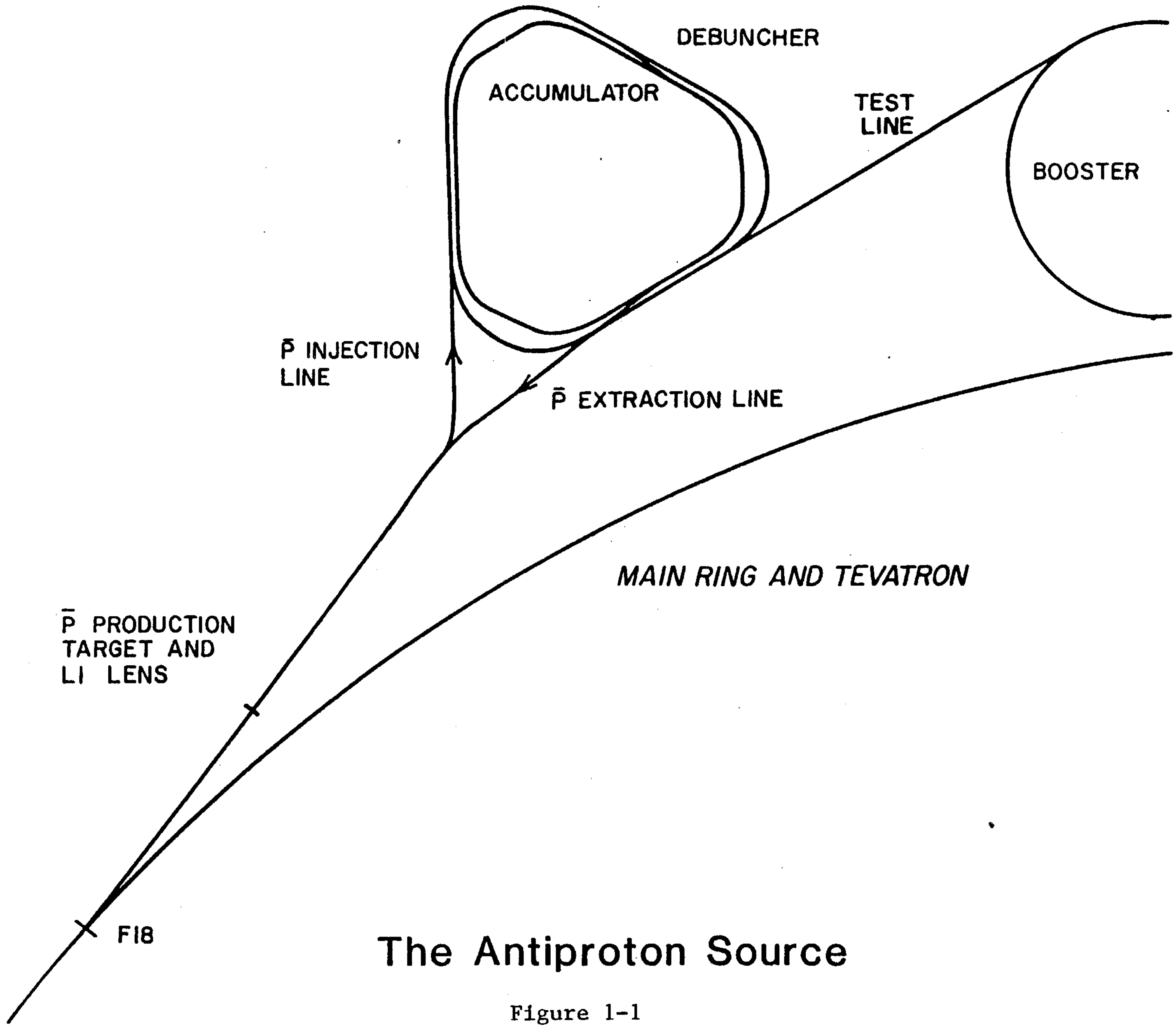
This report describes the design of the Tevatron I Project, which will enable Fermilab to produce proton-antiproton collisions in the Tevatron accelerator. Center-of-mass energies near 2 TeV, by far the highest available anywhere in the world for high-energy physics research until at least the decade of the 1990's, will provide enormous opportunities for exciting new physics.

After the energy, the most important parameter determining the utility of a colliding-beam facility is the luminosity, or interaction rate per unit cross section. The first goal of the Tevatron I project is to achieve a peak luminosity of $10^{30}cm^{-2}sec^{-1}$ for proton-antiproton collisions at the maximum energy in the Tevatron.

The luminosity depends on the intensity and phase space density of the interacting beams. The design luminosity of $10^{30}cm^{-2}sec^{-1}$ can be achieved with as few as 1.8×10^{11} protons and 1.8×10^{11} antiprotons of appropriate phase space density. The number and phase-space density of antiprotons produced by bombarding a dense target with one pulse of protons from the Main Ring are too small by orders of magnitude to achieve the design luminosity. Thus it is necessary to collect many pulses of antiprotons in an accumulator ring and to increase their phase-space density, i. e. to cool them, by roughly six orders of magnitude. To minimize user frustration and maximize the average luminosity, the accumulation time should be as short as possible, at least short compared to the luminosity lifetime, which is expected to be larger than twenty hours. The second goal of the project is to accumulate and cool the required number of antiprotons in five hours or less, starting with no antiprotons in the Accumulator.

The design presented here to meet these goals is based on the method of stochastic cooling developed by van der Meer, Thorndahl, and coworkers.[1] This method generates a non-uniform phase-space density distribution of the accumulated antiprotons, with only the high-density core useful for colliding beams. Thus the source has been designed to accumulate a total of 4.3×10^{11} antiprotons in 4 hours, of which typically 1.8×10^{11} antiprotons from the high-density core will be injected into the Tevatron. Subsequent accumulation cycles starting with the antiprotons left from the previous cycle will require considerably shorter times to achieve the necessary core density.

The amount of cooling to be done depends on the phase-space density at production. The higher the initial density, the easier it is to achieve the final density. The yield of antiprotons per incident proton is proportional to the product of the spatial solid angle and the momentum spread accepted by the beam-transport system, and the initial phase-space density can therefore be increased only by decreasing the spot size and



The Antiproton Source

Figure 1-1

time spread of the antiprotons. The initial protons that produce the antiprotons determine these parameters and it is therefore useful to reduce the proton spot size and time spread.

The proton rms spot size will be reduced to 0.38 mm by the use of standard quadrupole lenses. Further reduction would provide little gain because the apparent spot size is ultimately dominated by the large antiproton beam divergence and the finite length of the target.[2] The first collection lens must match the large angular divergence of the antiproton beam at the target into the small angular admittance that is characteristic of a beam-transport system or a storage ring. This is achieved by using a lithium lens of the type developed by the Institute of Nuclear Physics at Novosibirsk.[3]

The time spread can be minimized by rf manipulation of the proton beam in the Main Ring just prior to extraction. The narrow time spread and large energy spread of the resulting antiproton bunches can be transformed into bunches with a much lower energy spread by rf phase rotation in a separate ring called the Debuncher. The rf phase-rotation system[4] makes it possible to start with a large momentum spread from the target, thereby increasing the antiproton flux. The reduced energy spread also greatly simplifies the design of the magnets and cooling systems of the Accumulator ring.

The design thus uses two fixed energy rings, the Debuncher and the Accumulator, located south of the Booster as shown in Fig. 1-1. The Accumulator has the same circumference as the Booster; the Debuncher is slightly larger. Both rings operate at a kinetic energy of 8 GeV, the Booster energy. The sequence of operations leading to colliding beams involves seven steps:

1. <u>Proton Acceleration for Antiproton Production</u>. Every two seconds, one Booster batch containing 2×10^{12} protons in 82 rf bunches is accelerated in the Main Ring to 120 GeV and held at that energy while the rf manipulation described in the next step is carried out.

2. <u>Preparation of Protons for Targeting</u>. The proton bunches at the beginning of the 120-GeV Main Ring flattop are matched to buckets produced by 1 MV per turn. When the rf is turned off for about 160 turns, the bunches shear so that the particles of extreme momentum spread reach a point that lies on a phase-space contour of $\Delta E = \pm 185$ MeV for 4 MV per turn of rf.[5] At this time the rf is turned back on at the 4 MV per turn level so that the sheared distribution is rotated slightly more than one quarter of a synchrotron oscillation to become a narrow distribution with energy spread $\Delta E = \pm 185$ MeV and a width of approximately 0.7 nsec. This train of short bunches is extracted from the Main Ring at F17 as soon as the rotation has produced the minimum bunch width.

3. Antiproton Production and Transport. The short proton bunches strike a tungsten target, producing a train of 82 equally short antiproton bunches. The peak energy deposition in the target is the same as that used successfully at CERN. 7×10^7 8.9-GeV/c antiprotons are collected by the lithium lens and transported to the Debuncher. The momentum spread of the beam is 3% and the transverse beam emittances are 20π mm-mrad in each plane.

4. Bunch Rotation in the Debuncher. The antiprotons are injected into 53-MHz rf buckets in the Debuncher. The rf voltage is large enough that the antiproton bunches rotate just as the proton bunches rotated in the previous step. After a quarter of a synchrotron oscillation, the narrow time structure and large momentum spread have been transformed into a small momentum spread and a broad time structure. The rf voltage is then rapidly lowered to match the bucket to the rotated bunch, and finally adiabatically lowered to reduce the momentum spread to 0.2%.

5. Transverse Cooling in the Debuncher. After the rf manipulations, the horizontal and vertical transverse emittances are stochastically cooled in the Debuncher from 20π mm-mrad to 7π mm-mrad during the almost two seconds before the next antiprotons are to be injected.

6. Antiproton Accumulation and Cooling. The antiprotons are extracted from the Debuncher and injected into the Accumulator. Successive batches are accumulated by rf stacking each batch at the edge of the stack. Between injection cycles, the stack is stochastically cooled using a combination of longitudinal and transverse cooling systems similar to the types developed by CERN for the AA ring.[6] A new batch of antiprotons with a density of about 7 antiprotons per eV is deposited at the stack tail every 2 sec. The fresh batch is moved by the coherent force of the stochastic-cooling system away from the injection channel and toward the center of the stack. The strength of the coherent force diminishes exponentially as the particles move away from the edge of the tail, causing the particle density to increase. Diffusion forces resulting from the Schottky noise of the antiproton stack and the thermal noise of the amplifiers cause the antiprotons to migrate from the high-density region toward the low-density region. As long as the coherent force is greater than the diffusion forces, the stack builds up in intensity until it reaches the core region where the coherent force is zero. Some antiprotons are lost during transfer and rf stacking and some diffuse away from the stack into the chamber walls. Allowing for losses, 6×10^7 antiprotons are stacked in each pulse. In 4 hours, the core will grow to a density of 1.0×10^5 antiprotons per eV. The total number of antiprotons in the core will be 4.3×10^{11}. During this time the transverse cooling systems will have reduced the horizontal and vertical emittances to 2π mm-mrad.

7. Filling the Tevatron. After accumulation is complete, antiproton bunches of the desired intensity are individually extracted from the core, transferred to the Main Ring, accelerated to 150 GeV and injected into the Tevatron. The same number of proton bunches of similar intensity are prepared in the Main Ring and injected into the Tevatron. Whether it is better to inject the protons or antiprotons first will be determined empirically. Both beams are then simultaneously accelerated to the desired energy.

Sufficient antiprotons for a luminosity of $10^{30}cm^{-2}sec^{-1}$ can be produced in 4 hours by this sequence, even with reasonable losses in production, cooling, and beam transfer. The project includes Main Ring beam overpasses at B0 and D0 to allow antiproton accumulation to proceed in parallel with colliding beams in the Tevatron. The design luminosity can be achieved without exceeding a beam-beam tune shift of 0.0018 per crossing. As the Tevatron and the Antiproton Source become more reliable, longer collection times will become practical, resulting in higher luminosity.

Beam-accumulation techniques are developing rapidly and it seems highly advisable to design an antiproton source that can accommodate future improvements. Accordingly, the third goal of this design is to incorporate flexibility for future improvements so that the Antiproton Source may ultimately achieve a luminosity of $10^{31}cm^{-2}sec^{-1}$. The potential for luminosity of the proposed source is exhibited in Table 1-I, which shows the relationship between the number of accumulated antiprotons and the luminosity.

The peak luminosity and accumulation rate are limited not by the antiproton production rate but by the cooling systems of the Accumulator Ring. Higher luminosities may be achieved through improvements in these cooling systems. The present design uses less than a half of the total number of particles collected in each accumulation cycle to reach its design luminosity of $10^{30}cm^{-2}sec^{-1}$. If future improvements can increase the final density by a factor of three, it will be possible to approach a luminosity of $10^{31}cm^{-2}sec^{-1}$. The design of the rings therefore includes provisions (aperture and straight-section space) for:

(i) Momentum precooling in the Debuncher.

(ii) Improved stochastic cooling in the Accumulator.

(iii) Improved Main Ring extraction for antiproton production.

(iv) Intermediate energy electron cooling in the Accumulator.

These features are not part of the initial design because it is difficult to foresee which improvements will be most feasible and cost-effective. The most beneficial choices will be clear only after some experience in operating the collider.

The design of each system are described in greater detail in the following sections.

TABLE 1-I LUMINOSITY PROGRESSION

$N_{\bar{p}}$ (10^{11})	N_p (10^{11})	N_B	N_T (10^{11})	L $(10^{30} cm^{-2} sec^{-1})$
0.8	0.8	1	0.8	0.65
0.6	0.6	3	1.8	1.0 (design goal)
0.8	0.8	3	2.4	2.0
1.0	1.0	3	3.0	3.0
1.0	1.0	6	6.0	6.0

$N_{\bar{p}}$ and N_p are the numbers of antiprotons and protons per bunch, N_B is the number of bunches, N_T is the total number of antiprotons, $\beta^* = 1$ m is the value of β at the center of the interaction region, and L is the luminosity.

References

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