TEVATRON USED AS $\bar{P}P$ COLLIDER

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Assuming that electron cooling performs more or less as expected, we describe here how it will be used to obtain $\bar{p}p$ colliding beams in the Tevatron and give the expected performance.

I. Choreography

The present cooling ring is 2/7 the size of the Booster. For $\bar{p}p$, we shall assume that the ring is stretched to the same circumference as the Booster, as shown in Fig. 1. We start with standard acceleration of protons to 8 GeV in the Booster and injection into the Main Ring. Normally we fill the Main Ring to 2.5×10^{13} protons by 13 pulses from the Booster. For this operation, we can inject perhaps only 12 pulses to leave gaps for the rise time of the kickers. Then we accelerate the beam in the Main Ring to 80 GeV, the highest energy at which we can extract from a medium straight section. We extract one Booster batch at a time in synchronism with the Booster cycle (see Fig. 2). The 80-GeV protons strike a $\bar{p}$-production target and produce 5.18 GeV $\bar{p}$'s. The choice of energy is based on the following: the bunch spacing of the 80-GeV protons is 1/1113 of the Main-Ring circumference or 1/84 of the Booster circumference, but because of the energy (velocity) difference, the spacing of the $\bar{p}$'s from the target is necessarily smaller. To use the same Booster rf system for decelerating the $\bar{p}$'s, their bunch spacing must be 1/85 of the Booster circumference or their velocity 84/85 that of the 80-GeV protons. This gives a $\bar{p}$ energy of 5.18 GeV, which is, fortunately, a convenient and reasonable value.

Each Booster batch of $\bar{p}$'s is decelerated to 200 MeV and transferred to the cooling ring, where they are electron-cooled and stacked within a Booster cycle time. It takes 12 Booster pulses to empty the Main Ring of 80-GeV protons. The Main Ring is then returned to its 8-GeV injection field and the cycle starts over again in approximately 3 sec. The cooling and stacking of $\bar{p}$'s can go on for hours.

At the end, we fill the Tevatron with one Main-Ring pulse of 100-GeV (normal beam transfer energy from Main Ring to Tevatron) protons. The $\bar{p}$'s stored in the cooling ring are then bunched (by a small constant-frequency rf system in the cooling ring), accelerated in the Booster (with field reversed) and the Main Ring (counterclockwise), and transferred to the Tevatron (counterclockwise) at 100 GeV to join the already stored protons. The counter-circulating p and $\bar{p}$ beams are then both accelerated to 1000 GeV, and the low-β^* insertion energized for high luminosity colliding beams.

We will now discuss each of the processes involved quantitatively and in detail.

II. Antiproton Production

The cross section for forward production of 5.18 GeV $\bar{p}$'s with 80-GeV p's on H_2 target derived from Fermilab and ISR data, is about 50 mb/sr/($\Delta p/p$). The Booster acceptance at 200 MeV (40 π mm-mrad horizontal, 20 π mm-mrad vertical) translated to 5.18 GeV is 4π, 2π (the momentum ratio is just about 10). We have designed a beam transport using only quadrupole lenses which gives a β of 2.5 cm at the target. This gives an acceptance solid angle of

$$\pi\times\frac{\sqrt{4\times 2}}{0.025}\times 10^{-6} = 3.5\times 10^{-4}\ \text{sr}.$$

Together with an acceptance momentum bite of $\Delta p/p = 3\times 10^{-3}$, this gives

$$\text{Cross section for accepted } \bar{p} = 5\times 10^{-5}\ \text{mb}.$$

With a targeting efficiency of 1/3 (5-cm long W target) and a total cross section of 40 mb we get

$$\frac{N_{\bar{p}}}{N_p} = \frac{1}{3}\,\frac{5\times 10^{-5}}{40} = 4\times 10^{-7}.$$

In one hour, at 1 pulse/3 sec and 2.5×10^{13} p/pulse we get

$$N_{\bar{p}} = 10^{10}/\text{hr}.$$

III. Luminosity

For head-on collisions of two round Gaussian beams with standard deviations (rms beam widths) σ_p and $\sigma_{\bar{p}}$ the luminosity is given by

$$L = 3f\,\frac{n_p n_{\bar{p}}}{\epsilon_p+\epsilon_{\bar{p}}}\,\frac{N}{\beta^*},$$

where

$$\left\{\begin{array}{rl} f & = \text{revolution frequency} \\ n_p,\ n_{\bar{p}} & = \text{number of each particle per bunch} \\ N & = \text{number of bunches} \\ \beta^* & = \beta \text{ at collision point} \\ \epsilon_p,\ \epsilon_{\bar{p}} & = \text{emittance of each beam} \\ & \left(\epsilon \equiv \dfrac{6\pi\sigma^2}{\beta}\right). \end{array}\right.$$

With

$$\left\{\begin{array}{rl} n_{\bar{p}} & = 10^{10}\ \text{(1 hour collection)} \\ n_p & = 2\times 10^{10}\ \text{(present normal operation)} \\ N & = 1 \\ \beta^* & = 2.5\ \text{m (see below)} \\ \epsilon_p & = 0.02\ \pi\ \text{mm-mrad (at 1000 GeV)} \\ & \left(\epsilon_{\bar{p}} << \epsilon_p\right) \\ f & = 48\ \text{kHz}. \end{array}\right.$$

We get

$$L = 1.8\times 10^{28}\,\text{cm}^{-2}\text{sec}^{-1}.$$

To get a luminosity of $10^{30}\text{cm}^{-2}\text{sec}^{-1}$ we can collect $\bar{p}$ for 3 hours or increase the target efficiency, or both, to get $n_{\bar{p}} = 3\times 10^{10}$. A scheme will be described later to collapse 8 (say) proton bunches into 1 bunch with $n_p = 1.6 \times 10^{11}$ protons. We can further reduce β^* to 1 m in both planes. Altogether this gives a factor of $3 \times 8 \times 2.5 = 60$ and a luminosity of

$$L = 1.08 \times 10^{30} \mathrm{cm}^{-2} \mathrm{sec}^{-1}.$$

The discussions below will show that this luminosity can be obtained with a relatively high degree of confidence.

IV. Beam-Beam Tune Shift

The tune shift suffered by a $\overline{p}$ going through the high-density core of a Gaussian p bunch is given by

$$\Delta\nu_{\overline{p}} = \frac{3}{2} \frac{r_0}{\gamma} \frac{n_p}{\epsilon_p},$$

where $r_0 = 1.53 \times 10^{-18}$ m is the classical proton radius. With $n_p = 2 \times 10^{10}$ and $\epsilon_p = 0.02\ \pi$ mm-mrad at 1000 GeV ($\gamma = 1067$) we get

$$\Delta\nu_{\overline{p}} = 0.0007.$$

Increasing n_p 8-fold we will have $\Delta\nu_{\overline{p}} = 0.0056$ which, although greater than the commonly accepted safe limit of 0.005, may nevertheless be tolerable for reasonably long beam lifetimes.

With a total of 3×10^{10} $\overline{p}$'s, we can divide them into 3 bunches with 10^{10} in each bunch. Thus we can still have the proton tune shift

$$\Delta\nu_p = \frac{3}{2} \frac{r_0}{\gamma} \frac{n_{\overline{p}}}{\epsilon_{\overline{p}}}$$

within safe limits while maintaining $\epsilon_{\overline{p}} << \epsilon_p$.

We have been considering only the tune shift caused by one beam bunch. There is some evidence that the tune shifts due to distant bunches do not add constructively and that it is only the tune shift per bunch which measures the damaging effects of the nonlinear field of one beam on particles in the other beam. In any case, we will show below that it is possible to keep the p and the $\overline{p}$ orbits separated everywhere except near the collision region, so that each particle sees indeed only one bunch of the other beam.

V. Low-β Insertion

The low-β insertion for the Tevatron is described in detail by D. E. Johnson in Fermilab TM-737, "Main Ring/Doubler Low-Beta Insertions," June 1977. We will mention here only that

(1) It is an antisymmetric insertion with 4 independently adjustable anti-pairs of quadrupoles. For antisymmetric insertion we always have $\beta^*_H = \beta^*_V$.

(2) The β^* value can be continuously adjusted from the normal 70 m down to less than 2.5 m. The β^* is tuned to a low value only after both the p and the $\overline{p}$ beams have been accelerated to 1000 GeV.

(3) When β^* is tuned to a small value, the dispersion η^* at the collision point is also reduced to some small value, typically less than 1 m. Hence the contribution to horizontal beam size from momentum spread is negligible.

VI. Orbit-Separating Bump Electrodes

With a normal tune of $\nu = 19.4$, we can separate the p and $\overline{p}$ orbits over most of the ring circumference by using electrostatic dipoles to bump them into 19 oscillations in opposite directions. The p and $\overline{p}$ orbits coincide over only the 0.4 tune advance, hence allowing head-on collisions.

If the orbit is bumped by an angle θ at β_E, the amplitude of the oscillation at β_{max} is

$$A = \sqrt{\beta_E \beta_{max}}\,\theta = \sqrt{\beta_E \beta_{max}}\,\frac{eE\ell/c}{p},$$

where E and ℓ are the field and the length of the bump electrode, for

$$\begin{cases} \beta_E = \beta_{max} = 100 \text{ m} \\ pc = 1000 \text{ GeV} \\ E\ell = 50 \text{ kV/cm} \times 6 \text{ m} = 30 \text{ MV}. \end{cases}$$

We get

$$A = 3 \text{ mm}.$$

That is, the p and $\overline{p}$ orbits are separated by ±3 mm at the peak, which is adequate.

VII. Scheme to Collapse 8 Proton Bunches Into 1

We start by injecting 8 consecutive bunches of 2×10^{10} p/bunch into the Main Ring and accelerating them to 100 GeV. The Main Ring is then flat-topped. The longitudinal emittance of the beam has been measured to be about 0.1 eV-sec/bunch. (Some recent measurements give much higher values. The cause of this recent emittance growth is not yet known.) The total emittance of 8 bunches is, then, 0.8 eV sec = 0.24 (GeV/c) m.

We first debunch the 8 beam bunches adiabatically (see Fig. 3). After debunching the dimensions of the total occupied phase area (using physical coordinates Δz and Δp) are

$$\begin{cases} \Delta z_0 = 8\,\dfrac{2\pi R}{1113} = 45.2 \text{ m} \\ \Delta p_0 = \dfrac{0.24}{45.2} \text{ GeV/c} = 0.00531 \text{ GeV/c}. \end{cases}$$

At the end of debunching, the 1113-harmonic cavities are all turned off and we abruptly turn on a set of rf cavities operating at a harmonic number much lower than 1113/8. We shall take 70. By rotating the phase area 1/4 of a phase oscillation in the central (linear) part of the stationary h = 70 bucket, we want to change the dime sions to

$$\begin{cases} \Delta z = \dfrac{70}{1113}\,\Delta z_0 = 2.84 \text{ m} \\ \Delta p = \dfrac{1113}{70}\,\Delta p_0 = 0.0845 \text{ GeV/c}. \end{cases}$$

The dynamics of the rotation gives

$$\begin{cases} \Delta z = K^{-1} \Delta p_0 \\ \Delta p = K\,\Delta z_0 \end{cases} \text{where } K \equiv \frac{mc}{R}\left(\frac{h}{2\pi}\,\frac{eV}{mc^2}\,\frac{\gamma}{\Lambda}\right)^{\frac{1}{2}}.$$

With h = 70, γ = 107.6, $\Lambda = 1/\gamma_t^2 - 1/\gamma^2 = 0.00276$, to get K = 0.00187 (GeV/c)/m we need

$$V(h = 70) = 8.58 \text{ kV}.$$

The interesting parameters of the h = 70, V = 8.58 kV buckets are

Bucket height = 0.107 GeV/c
Bucket area = 6.11 (GeV/c) m
Phase oscillation wave number = $\nu_s = 5.11\times 10^{-5}$
(0.10 sec for $\frac{1}{4}$ oscillation).

The rotated bunches having Δz = 2.84 m, Δp = 0.0845 GeV/c and containing 1.6×10^{11} protons are then transferred to the Tevatron and captured into the matched stationary buckets of the Tevatron with h = 1113 and V(h = 1113) = 1113/70×8.58 kV = 136.5 kV. These buckets have the same height (Δp) as the h = 70 buckets, but are only 70/1113 times as wide (Δz) hence 70/1113 times the area.

Although the calculation given here is rather simplistic, the beam should behave pretty much as described. The only worries are instabilities. Immediately after debunching, the momentum spread is $\Delta p_0/p = 5.31\times 10^{-5}$, which may be too small to keep the beam stable against longitudinal instabilities. Various head-tail type of instabilities can also occur to the intense beam bunch of 1.6×10^{11} protons. All these should be examined in detail.

VIII. Incoherent Detuning of the Proton Bunches

At 100 GeV, the tune shift will be imagine dominated and given by

$$\delta\nu = \frac{r_0 R^2}{\nu\gamma}\,\frac{G}{g^2}\,\lambda,$$

where

λ = linear density = $(1.6\times 10^{11})/2.84$ m = 5.6×10^{10} m^{-1}
g = half aperture = 1.5 in. = 0.038 m
G = geometrical factor = $\pi^2/12$ (worst value corresponding to round beam in rectangular beam pipe).

This gives

$$\delta\nu = 0.023 \quad \text{(at the worst)}$$

which is entirely tolerable.

IX. General Considerations of Tevatron Aperture, Vacuum, and Impedances

1. The aperture requirement for $\bar{p}p$ operation is less demanding than that for either fixed-target operation (slow resonant extraction) or pp operation (momentum stacking à la ISR).

2. With cold-bore, the vacuum in the Tevatron is expected to be better than 10^{-11} Torr. Hence there will be no problem with neutralization, gas lifetime, or pressure-bump instability. The vacuum is essentially a "sealed" system. The cold vacuum-pipe wall acts as a very fast getter pump. One only has to make sure that the starting pressure and the leaks are reduced to such an extent that the pumping capacity of the pipe wall is not exhausted in too short a time. Presumably, warming-up and flushing the ring to rejuvenate the pipe wall once every 6 months is not too bad.

3. For most (not all) instabilities, the threshold given by Landau damping is proportional to

$$\frac{ZI}{\gamma},$$

where Z = impedance of the beam environment, I = beam current, and γ = beam energy. The increase in I can be offset either by increasing γ (higher energy) or reducing Z (improving the feedback system). Although the instabilities should be individually investigated in detail, at first glance none of them appear to impose any serious problem.

We conclude that, provided electron cooling works approximately as expected, the scheme described above should yield $\bar{p}p$ colliding beams in the Tevatron with a luminosity of 10^{30}cm^{-2}sec^{-1} at 1000 GeV×1000 GeV in a relatively straightforward manner.

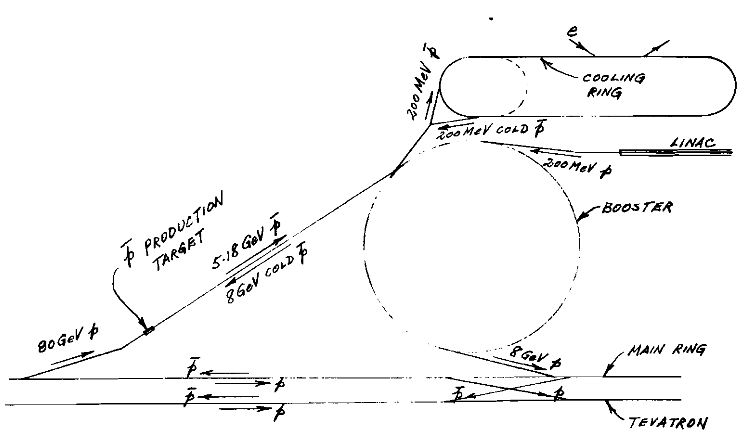

Fig. 1. The Cooling-Ring, Booster, Main-Ring, Tevatron complex showing the choreography for attaining $\bar{p}p$ colliding beams.

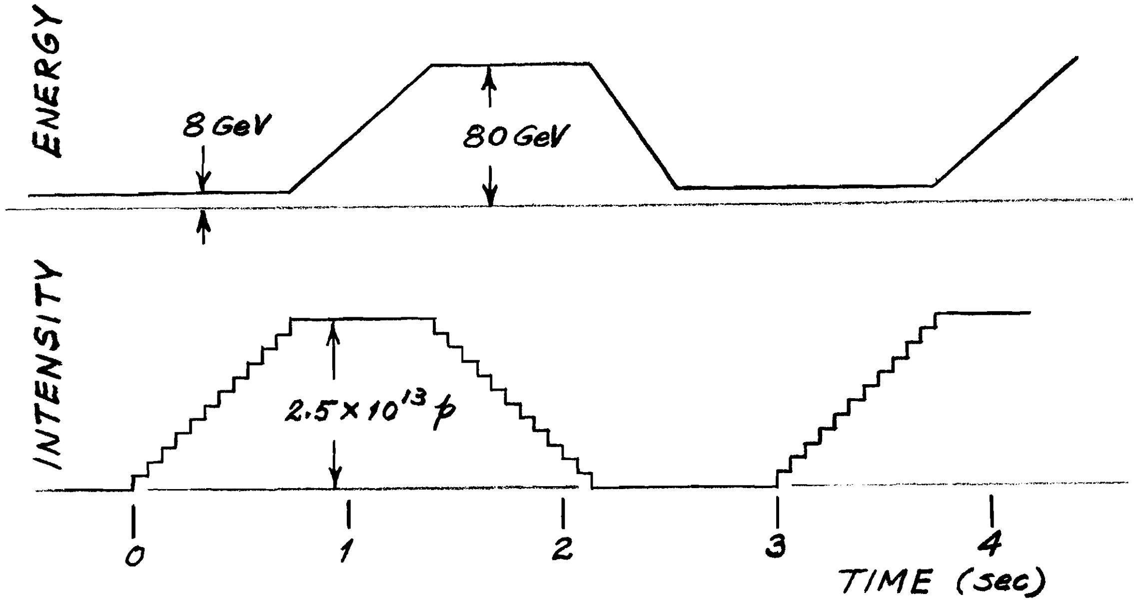

Fig. 2. The Main-Ring cycle during production-cooling-accumulation of $\overline{p}$'s.

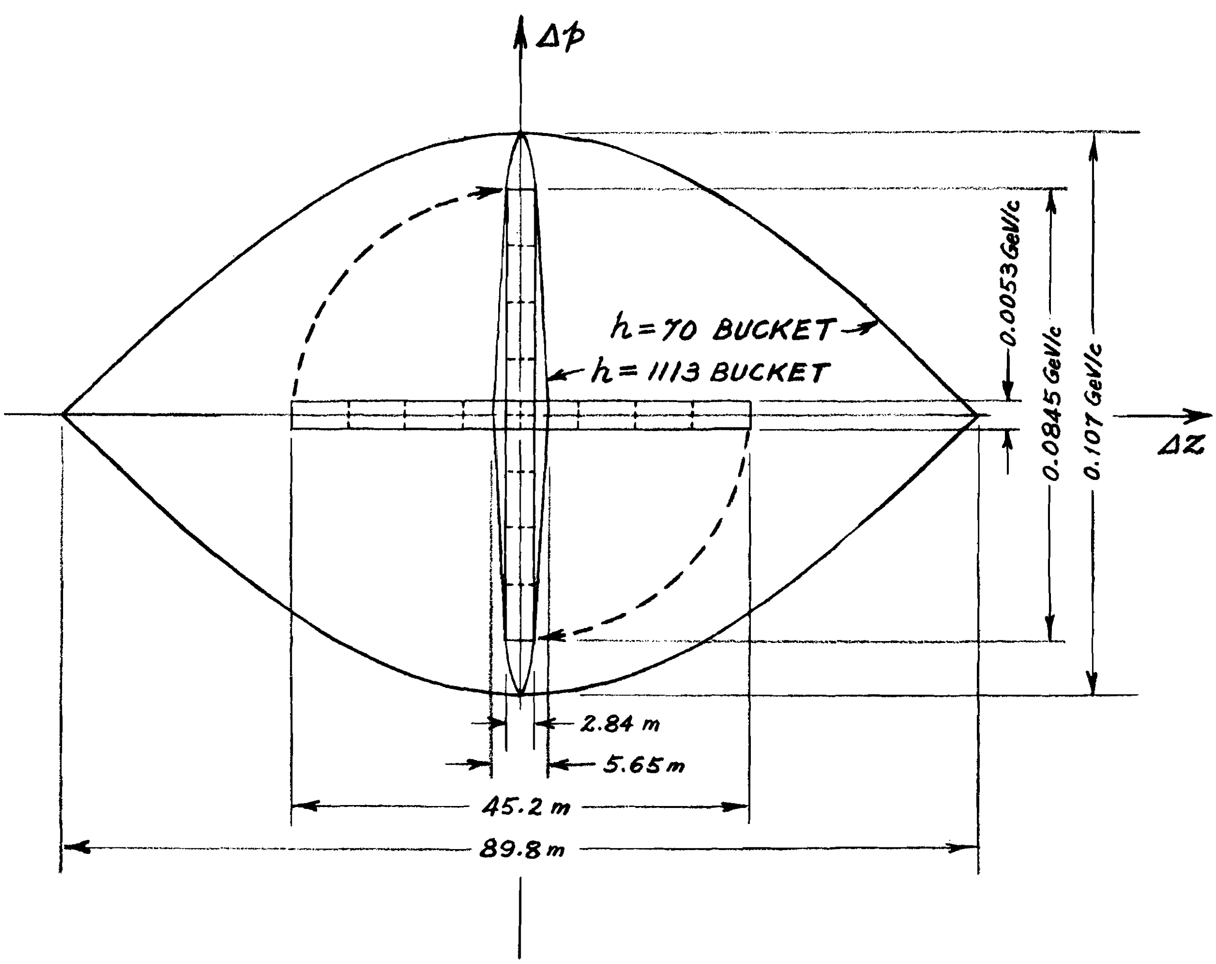

Fig. 3. Stationary rf buckets for harmonic numbers 1113 and 70 illustrating the scheme for collapsing eight proton bunches into one.