6.6 TEVATRON COLLIDER IMPROVEMENTS

Increased numbers of antiprotons will probably be the most difficult requisite for collider improvement, especially for the first years of operation. The basic parameters of the pbar source such as yield, cooling efficiency, and transfer efficiencies will be improved with time. Other improvements which involve departures from the original Tev I design such as higher frequency stochastic cooling hardware and different schemes for targeting the MR beam will also be important.

Along with the pbar source developments, there is a list of improvements to the older accelerators in the chain. These include a γ_t-jump scheme in the Booster as well as rf system improvements in the Main Ring.

More ambitious projects to improve many aspects of the Tevatron's performance are also under investigation. An addition to the present 200 MeV Linac to increase its energy is one such possibility. This would allow injection of H^- ions into the Booster at higher energy where space charge tune shifts are reduced. The beam brightness would be improved, leading to higher luminosities for colliding beam operation and higher intensities for fixed target physics. Another means to achieve the same goal is to add a rapid cycling synchrotron between the Linac and Booster. A rather detailed design for this Prebooster has been developed[1]. A Postbooster ring and a replacement for the present Main Ring are also being discussed.

Within the Tevatron itself, the three major improvements which are being pursued most actively are the addition of electrostatic separators, improvements to the low β insertion designs, and increasing the machine energy. These topics and operational implications of various implementation schemes are discussed below.

ELECTROSTATIC SEPARATORS AND MULTIBUNCH OPERATION

the beam-beam tune shift

Each time an antiproton passes through a bunch of protons it is subjected to a focusing force with a strength which depends on its radial displacement from the center of the bunch. This increased focusing increases the betatron tune of the antiproton depending on the intensity and emittance of the proton beam. Remarkably, this tune shift is independent of the lattice parameters and can be written:

$$\Delta\nu_{bb} = \frac{3\,N\,r_p}{2\,\epsilon_n}$$

where r_p is the classical radius of the proton, and ϵ_n is the 95% normalized transverse emittance in the plane of interest. Traditionally, N is the number of protons per bunch and $\Delta\nu_{bb}$ is the tune shift per crossing. The total tune shift is this value times the number of beam crossings per revolution, n_c.

Actually, the tune shift in the above expression is for the particle with the minimum betatron amplitude. A particle with large betatron amplitude sees a small focusing force in passing through the outer edge of the counter-rotating bunch and experiences a smaller tune shift. The beam-beam tune shift then is a measure of the spread of the betatron tunes of the beam. The practical problem is to find a spot on the working diagram where the tunes of all particles are between the significant resonance lines.

During Tevatron study periods, long coasting beam lifetimes have been obtained in the region of $\nu_x = 19.42$, $\nu_y = 19.41$, where tune shifts of $\pm$ .01 seem to cause no problem. Larger deviations cause losses on fifth and seventh order resonances. For the purposes of the following discussion a maximum $n_c \Delta\nu_{bb}$ of 0.02 is assumed. This is based on the observation that single beam lifetimes are not affected over this range if the operating point is chosen appropriately. Unfortunately, this is not the whole story as the beam-beam interaction itself can drive higher order resonances.

<u>the need for many bunches</u>

The following table shows the total beam-beam tune shift for various operating conditions. The 6 columns are for different bunch intensities, where the proton and antiproton intensities are assumed equal. The lowest value of 0.3E11 corresponds to one half the Tev I design. The highest, 1.8E11, is approximately the maximum value achieved for proton bunches at the SPS. The next row shows the number of interactions per crossing for that bunch intensity.

The various parameters for different numbers of bunches are displayed. The 3X3 case, for three bunches of protons interacting with three bunches of pbars, is shown next. The luminosity at any given interaction point, which depends on the number of bunches and the intensity of each bunch is given in units of 10^{30} $cm^{-2}s^{-1}$. In all of these calculations the transverse emittance is assumed constant and equal to the Tev I design parameters. The β^* of the interaction point is also assumed to be the Tev I design value of about 1 m in each plane.

<u>need for electrostatic separators</u>

For the 3X3 case there are 6 beam crossings and one can in principle increase the bunch intensity to twice the Tev I design value before the tune shift limit of .02 is reached at a luminosity of 4E30 $cm^{-2}s^{-1}$. Electrostatic separators can be used to separate the beams at 3 out of the 6 crossing points to reduce the total beam-beam tune shift. With the separators, the single bunch intensity could be increased to 2.4E11 (4 times the Tev I design) before the beam-beam tune shift limit were reached at a very hypothetical luminosity of 1.6E31 $cm^{-2}s^{-1}$.

At this luminosity there are three things which make the 3X3 case unacceptable. First, the number of interactions per crossing is over 11, possibly causing experimental difficulties in trigger thresholds, event reconstruction, and increased backgrounds to rare events. Second, space charge effects in the Booster and MR will probably cause emittance growth such that higher bunch intensity may not yield greater luminosity. Third, the luminosity lifetime will be greatly diminished due to intrabeam scattering; this implies a need for frequent refills and even larger numbers of antiprotons.

The 6X6 case, shown next on the table, doubles the luminosity, the number of pbars needed per fill, and the total beam-beam tune shift over the previous case. With a single set of electrostatic separators one can reach over 1.1E31 luminosity without exceeding the beam-beam tune shift limit of .02 and with about 4 interactions per crossing. With two sets of separators in each plane, allowing the beams to cross only at B0 and D0, the tune shift limit no longer applies and larger luminosities and interactions per crossing are allowed.

For 12X12 and higher, the electrostatic separators are needed for all cases considered and, with two sets of separators in each plane and only 2 crossing points, effectively remove the beam-beam tune shift from consideration. For example, for 24X24, a luminosity of 1.5E31 could be achieved with 1.4 interactions per crossing.

<u>description of separator systems</u>

To allow the proton and pbar beams to be separated at all but the two desired interaction regions, the separation should be done simultaneously in the horizontal and vertical planes. For a small number of bunches and a fixed lattice, separation in one plane can be adequate, as demonstrated at the SPS[2]. For large numbers of bunches and some freedom in the lattice parameters it becomes increasingly difficult to keep the bunches of pbars sufficiently separated from the protons where they pass each other. The option of one or two low β insertions as well as the gymnastics involved in the transition from the injection optics to the storage optics imply variable betatron phase advances between crossing points. Simultaneous separation is needed for optimum separation as well as for lattice flexibility.

By placing a vertical separator 90 degrees in phase from a horizontal separator, the closed orbits of the protons and pbars can form a double helix between the interaction regions. The separators themselves form standard "dipole bumps" between the desired interaction regions. This implies that at least 3 electrostatic separators will be needed in each plane for each of the 2 separation regions. If complete separation is desired for all possible optics configurations, a fourth separator may be needed. On the other hand, if optics transitions are made quickly enough that dilutions due to resonance crossing are small, a simpler system may be adequate.

The distance from the interaction region to the next beam crossing point is a critical consideration. This distance is 1/2 of the bunch spacing. The position of the electrostatic separators which will cause the beams to be separated at the next crossing point depends on the detailed betatron phase advances of the low β insertion. If the beams are sufficiently separated 32 m from the IR, this allows the optimum separation of all bunches except at the 2 collision points for the 96 on 96 case. A distance to separation equal to the bunch spacing (63 m) gives three head on crossings per insertion. The last table entry shows the beam-beam tune shift for this case, which is acceptable. Another possibility is to have a crossing angle through the low beta insertion which would give a partial separation at the unwanted crossings. This would allow the separators to be even farther from the interaction region, although there might be some acceptance reduction for separated beams in the regions of the insertion with large betatron amplitude.

The present plan is to incorporate the separators into the low β insertions. By putting each separator at the high β region of the insertion it is more effective and, to some extent, the need to have moveable electrodes is relaxed. Antisymmetric insertions, where the horizontal and vertical lattice functions are reversed on each side of the interaction point, are being investigated. Although the relative phase advances of the two planes in the insertion are quite different than in the machine arcs, it seems that simultaneous separation in two planes is possible over most of the machine circumference.

The betatron phase advance is the integral of $1/\beta(s)$. Thus in regions where the β function is large, the phase advance is changing slowly. Unfortunately, the strong focusing quadrupole triplets next to the low β region are necessarily high β regions. Any separator in these regions is followed by a rather long distance before the phase advance allows the angular kick of the separator to become a position change.

<u>antiproton economics</u>

At first glance, it seems that the luminosity for a given antiproton production rate is enhanced by putting the pbars in as few bunches as possible. This is really a consequence of the assumption of equal proton and pbar bunch intensities which makes the luminosity increase as the square of the bunch intensity. In fact, the intensity of the proton bunch can be independent of the pbar bunch intensity. And, given that the emittances of the two species is equal, one expects to run with the highest possible proton intensity. ~~Thus~~ as far as the antiproton usage is concerned, the same number of antiprotons yields the same luminosity whether they are put into one or several bunches.

For a <u>filling strategy</u> one could imagine the precious pbars distributed in many bunches each with a relatively low density. The proton bunches could be more intense, blowing up relatively quickly due to intrabeam scattering. ~~Even though we are in the weak-strong case,~~ the electrostatic separators protect the pbar beam from the beam-beam interaction. After some time, the luminosity decreases due to the intrabeam scattering of the protons. At that point the proton bunches are aborted and refilled. While this involves decelerating the beams to 150 GeV, aborting and reloading the proton bunches, and then reaccelerating to storage energy, there are no fundamental difficulties. Indeed the SPS was successful[3] in operating in a storage mode with the energy cyclically ramped between 100 and 450 GeV.

For this mode of Tevatron operation, where bunches of particles can be replaced as needed, fast injection and abort kickers may have to be developed. Alternate proposals to use rf gymnastics to enable loading of large numbers of bunches into the Tevatron are also being investigated. Deceleration of beams will have to be automated with appropriate control of insertion devices, electrostatic separators, and experimental equipment.

In fact, looking at the table of antiproton economics for the cases considered in the first table, one can see that the same capability will be needed for the pbars. The present design of the accumulator is such that the maximum number of stored pbars is less than 10^{12}. Thus for large numbers of bunches in the Tevatron, the accumulator will have to be filled and emptied more than once. Of course the accumulator can be reconfigured[4] or an additional storage ring can be added, but one solution is to transfer a smaller number of pbar bunches to the Tevatron every few hours at the same time the proton bunches are refilled.

By looking at the time needed to accumulate the needed number of pbars for the various cases considered and comparing with the intrinsic beam lifetime one concludes that the operating mode suggested above is necessary. The effective luminosity is determined by the antiproton economics. The loss of luminosity due to intrabeam scattering and collision losses must be matched to the pbar production rate. Looking at the first entries in the economics table where single beam lifetime components are listed, one again sees that the necessary operating mode is with many lower intensity pbar bunches.

For any of the schemes involving large numbers of pbars the Tevatron reliability becomes increasingly important. Any unintentional beam loss in the Tevatron will be followed by a lengthy refill time which will be limited by the accumulation rate of the pbar source.

ideal numbers of bunches

The number of bunches shown in the following table was chosen to demonstrate the possibilities of multibunch operation. One consideration not yet discussed is the time between crossings, important to experimental detector readout. Whereas the optimum usage of pbars dictates large numbers of bunches, the corresponding short time between bunches imposes monetary constraints on the experimental detectors.

Many experimental triggers require information from particle detectors which takes some time to develop. In particular, calorimeters which need hundreds of nanoseconds to collect ionization information may be a critical component. If a second interaction occurs before the first is digitized and read out, some confusion is likely. To some extent, these problems can be overcome by smaller, faster calorimeter cells and more sophisticated electronics. On the other hand, if one is operating in the regime of many interactions per crossing, the problems of event overlap because of time gates that overlap bunch crossings are similar to simultaneous events within one crossing.

For most considerations the situation is better for the experiment if the event overlap takes place in separate rf buckets. For example, photons from two interactions within the same rf bucket are probably impossible to untangle. Charged particles, on the other hand, have a vertex constraint to enable the tracks to be sorted out. Another example is that fast photomultiplier-based calorimetry can be used for event triggers to replace or suppliment the slower gas calorimetry.

The Tevatron harmonic number is 1113 (divisible by 3, 7, and 53). The choice of buckets to be filled with beam is flexible, with only a few constraints. To have collisions at a fixed point, the time the filled buckets pass the point must be the same for pbars and protons. That is, the sequence of filled buckets measured in their direction of travel should be the same for each species. To optimize collisions at all 6 long straight sections, each sequence must be made of 3 identical sub-sequences. The only other constraint is that the bunch spacings are quantized in 19 ns units due to the 53 MHz rf frequency.

With large numbers of bunches one has to worry about coherent bunch to bunch instabilities. As the bunches are closer together, it is easier for them to interact via resonant cavities in the ring or just resistive wall effects. Strong instabilities have been seen with filled adjacent rf buckets. More studies may be in order.

IMPROVED LOW β DESIGN

A low β insertion is a particularly effective method to increase luminosity. By using quadrupoles to tightly focus the beam at the crossing point, the luminosity can be increased by 2 orders of magnitude compared to the unperturbed lattice with a β^* value of 70 meters. And as stated above, the beam-beam tune shift is not affected by the β^* at the crossing point. Parameters which are affected by the particular design of the insertion, and are particularly important include the free space between quadrupoles, the maximum β values in the insertion, and the quality of the match to the regular lattice.

The free space between quadrupoles is necessary for the experiment. Large β values in the insertion and corresponding larger beam sizes lead to increased sensitivity to the magnetic multipole errors of the insertion magnets. In general, the multipoles lead to reductions in the dynamic aperture of the machine. The effective aperture of the machine is also reduced by mismatches of the insertion to the regular lattice. For example, an imperfect match can lead to a beta function distortion (sometimes called a beta beat), which reduces the machine acceptance at many places around the ring.

the optimum β^* for highest luminosity

The β value near the center of the insertion (where $\beta=\beta^*$ at $s=s_0$) varies quadratically with the distance from the center;

$$\beta = \beta^* + \frac{(s-s_0)^2}{\beta^*}$$

The longitudinal distributions of the colliding bunches must be considered to calculate the total luminosity. The Tev I design report assumes a Gaussian distribution of rms length .40 m for the proton and pbar bunches. The convolution of the bunch distributions and β distribution reduces the luminosity by a factor of 0.92 compared to constant β^* (β^*_h=.81, β^*_v=.89). The luminosity increases with decreasing β^* to the point where the β^* is the same as the length of the interaction region, $.40/\sqrt{2}$ = .28 m, although with decreasing effectiveness.

The actual β^* of the present B0 insertion is calculated to be somewhat greater than 1 m due to the fact that the insertion is only approximately matched. Another reality is that the longitudinal distributions are somewhat larger than those assumed in the Tev I design. It is not yet clear how much of the increased bunch length is due to intrinsic parameters of the accelerators and how much is due to practical considerations which will eventually be overcome. In any case, the present goal is to produce a well-matched insertion with β^* = 0.5 m. This will require the superconducting quadrupoles with higher gradients which are now under development.

Included in the new design considerations are the electrostatic separators needed to reduce beam-beam effects. Methods for making transitions from one optical configuration to another are also important.

HIGHER TEVATRON ENERGY

Along with luminosity, the beam energy is important to allow the investigation of rare processes. As an additional benefit, the adiabatic damping of transverse beam sizes with increasing energy leads to a luminosity increase proportional to the beam momentum.

The Tevatron has operated for fixed target physics and colliding beam experiments up to 800 GeV. By replacing some of the weaker magnets and upgrading some of the components it should be possible to run at 900 GeV or higher by some time next year. Further, since the possibility of quenches induced by beam losses is greater as the energy increases, one expects to be able to run at higher energy in the colliding beam mode than with the lossier resonant slow extraction of the fixed target mode.

Even higher energies will be possible if the temperature of the superconductor can be lowered. Different plans for changes in the refrigeration system are being evaluated.

NEED FOR ELECTROSTATIC SEPARATORS

Intensity/bunch ($*10^{11}$)	.3	.6	.9	1.2	1.5	1.8
# interactions/crossing (assuming 100 mb)	.28	.7	1.6	2.7	4.4	6
3X3 ($\Delta\tau$=7μs)						
Luminosity	.25	1	2.25	4	6.25	9
no separation $n_c\Delta\nu_{bb}$	.005	.01	.015	.02	.025	.03
3/6 separation $n_c\Delta\nu_{bb}$	.0025	.005	.0075	.01	.0125	.015
6X6 ($\Delta\tau$=3.5μs)						
Luminosity	.5	2	4.5	8	12.5	18
no separation $n_c\Delta\nu_{bb}$	.01	.02	.03	.04	.05	.06
7/12 separation $n_c\Delta\nu_{bb}$	.004	.008	.0125	.017	.021	.025
10/12 separation	.0017	.0033	.005	.0067	.0083	.01
12X12 ($\Delta\tau$=1.75μs)						
Luminosity	1	4	9	16	25	36
no separation $n_c\Delta\nu_{bb}$	.02	.04	.06	.08	.10	.12
15/24 separation $n_c\Delta\nu_{bb}$	.0075	.015	.0225	.03	.0375	.045
22/24 separation $n_c\Delta\nu_{bb}$	.0017	.0033	.005	.0067	.083	.01
24X24 ($\Delta\tau$=0.873μs)						
Luminosity	2	8	18	32	50	72
no separation $n_c\Delta\nu_{bb}$	.04	.08	.12	.16	.20	.24
31/48 separation $n_c\Delta\nu_{bb}$	.0142	.0283	.0425	.0567	.0708	.085
46/48 separation $n_c\Delta\nu_{bb}$	.0017	.0033	.005	.0067	.083	.01
48X48 ($\Delta\tau$=0.436μs)						
Luminosity	4	16	36	64	100	144
no separation $n_c\Delta\nu_{bb}$	.08	.16	.24	.32	.40	.48
94/96 separation $n_c\Delta\nu_{bb}$	.0017	.0033	.005	.0067	.083	.01
96X96 ($\Delta\tau$=0.218μs)						
Luminosity	8	32	72	128	200	288
no separation $n_c\Delta\nu_{bb}$	.16	.32	48	.64	.80	.96
94/96 separation $n_c\Delta\nu_{bb}$	.0017	.0033	.005	.0067	.083	.01
90/96 separation $n_c\Delta\nu_{bb}$	.0051	.0099	.015	.02	.249	.03

and $\beta^* = 1$m

TABLE NOTES:

1) Equal p and pbar bunch intensities.
2) Luminosity in 10^{30} /(cm^2 s), calculated for 1 TeV Energy.
3) The total beam-beam tune shift $n_c \Delta\nu_{bb} < .02$ to avoid resonances.
4) These tables assume that the emittance is constant even though the intensity/bunch increases; larger intensity/bunch implies,
   a) the luminosity lifetime decreases due to intrabeam scattering causing emittance growth, and
   b) the initial emittance will tend to be larger because of difficulties with earlier accelerators in the chain.
5) $\Delta\tau$ is time between crossings.
6) the tables give indications of operational limits; optimization of pbar usage should also be included.
7) **Tev I design indicated by bold charaters.**

Antiproton Economics

Intensity/bunch ($*10^{11}$)	.3	.6	.9	1.2	1.5	1.8
Initial intrabeam scattering diffusion times:						
$\tau_{longitudinal}$	127	63.5	42	32	25	21
$\tau_{horizontal}$	48	24.0	16	12	10	8
Beam lifetime due to collision losses:						
τ_{coll}	250	125	104	62.5	50	41.25
3X3 ($\Delta\tau$=7μs)						
Luminosity	.25	1	2.25	4	6.25	9
pbars needed	.9	1.8	2.7	3.6	4.5	5.4
accum time	1	2	3	4	5	6
6X6 ($\Delta\tau$=3.5μs)						
Luminosity	.5	2	4.5	8	12.5	18
pbars needed	1.8	3.6	5.4	7.2	9.0	10.8
accum time	2	4	6	8	10	12
12X12 ($\Delta\tau$=1.75μs)						
Luminosity	1	4	9	16	25	36
pbars needed	3.6	7.2	10.8	14.4	18.0	21.6
accum time	4	8	12	16	20	24
24X24 ($\Delta\tau$=0.873μs)						
Luminosity	2	8	18	32	50	72
pbars needed	7.2	14.4	21.6	28.8	36.0	43.2
accum time	8	16	24	32	40	48
48X48 ($\Delta\tau$=0.436μs)						
Luminosity	4	16	36	64	100	144
pbars needed	14.4	28.8	43.2	57.6	72.0	86.4
accum time	16	32	48	64	80	96
96X96 ($\Delta\tau$=0.218μs)						
Luminosity	8	32	72	128	200	288
pbars needed	28.8	57.6	86.4	115.2	144.0	172.8
accum time	32	64	96	128	160	192

TABLE NOTES:

1) Times in hours.
2) $\tau_{horizontal}$ is the emittance growth time due to intra-beam scattering and should dominate the luminosity lifetime. i.e. $1/\tau_{lum} = 1/\tau_{horizontal} + \Sigma\ 1/\tau$, where the sum is over the proton and pbar loss rates. $\tau_{longitudinal}$ plays a role in the beam loss rates as intrabeam scattering causes particles to diffuse past the rf bucket boundaries.
3) Collision losses are for 2 IRs operating at the given luminosity with a cross-section of 0.2 Barns.
4) Accumulation times assume the accumulation rates of the Tev I design, 9E10/hour.

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