# MAIN RING BEAM EXPERIMENTS FOR THE $\bar{p}p$ COLLIDER

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A brief description of the Tevatron I proton-antiproton Collider project appeared in these pages last month. Production, collection, and subsequent acceleration of anti-protons (and their proton counterparts) to 1 TeV will require operation of the Main Ring and the Tevatron in modes that are quite different from those used in the familiar fixed-target operation. Although these unusual operation modes appear to be straightforward in principle, there will almost certainly be unforeseen practical difficulties associated with their execution. Because of this, an effort has been underway for several years to demonstrate the feasibility of these operations in a series of accelerator experiments.[1]

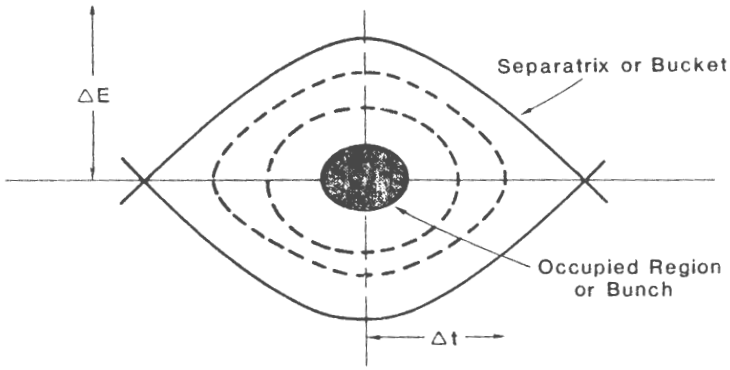
About 11 8-hour shifts of dedicated accelerator time were devoted to these studies during the most recent accelerator operation period, which was extended for a few days following the termination of HEP on June 14 to accommodate a short intensive period of study requiring some accelerator changes not consistent with interlaced HEP. During the extended operating period, use of the Main Ring was shared between our Tevatron I group and the Energy Saver group, who were studying extraction from the Main Ring for injection into the Energy Saver.

The primary experimentors were James Griffin, James MacLachlan, and Keith Meisner. Others, including Z. B. Qian, C. Ankenbrandt, S. Pruss, C. Moore, M. Rebuehr, R. Vargo, and J. Ziober, gave significant assistance. In addition, many members of the Accelerator Operations Group led by Robert Mau and William Merz provided much-needed assistance.

The Tevatron I operating scenario will require the Main Ring to accelerate only one intense Booster 'batch' (about 82 bunches) on each accelerating cycle instead of the usual 13 batches. This means that only a small segment of the ring (1/13.25) will contain bunches of protons during acceleration. A further requirement is that each of the 82 bunches of protons, when extracted from the Main Ring at 125 GeV and delivered to the antiproton production target, must have the shortest possible time length. This will result in a train of antiproton bunches with very large momentum spread, each with the same very short time structure, preferably 1 nanosecond or less. The empty space between bunches will be about 17.5 nanoseconds so that in a later operation (debunching) the antiproton distributions can be rotated in momentum and time so that the empty space is filled with particles and the momentum spread reduced accordingly.

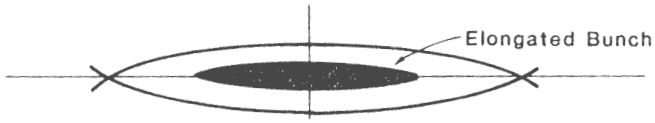
Protons within bunches in the Main Ring are confined to a region in time that is established by restoring forces resulting

Figure 1



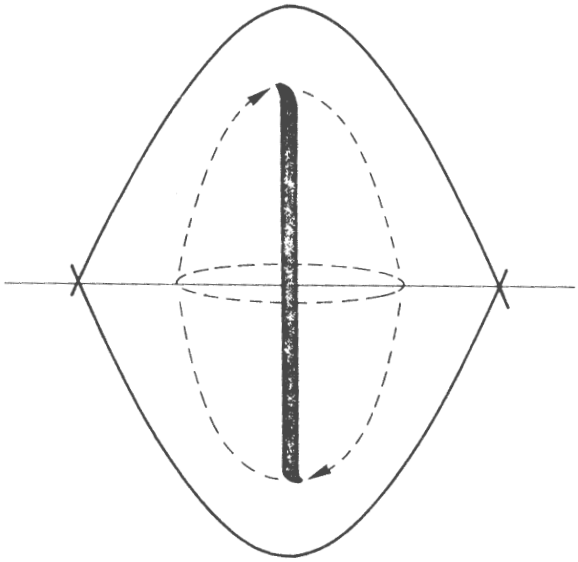

a.

Phase space separatrix established by application of rf voltage. Dotted lines represent possible paths of charged particle motion within the separatrix, or bucket. Cross-hatched area is that actually occupied by protons. The area, in $e^{V}$-sec, is the bunch longitudinal emittance.




b.

Here the rf voltage and bucket height have been lowered slowly until the bunch extent in time is about half of the rf bucket period.



c.

The bucket height is suddenly raised to a very large value. The distribution of part b is now mismatched to the boundary and so rotates into a tall narrow strip as shown.

from the rf cavity voltage. This voltage sets a boundary (separatrix, or bucket) within which each proton moves in energy and time on an elliptical orbit. If one were to plot the location of each proton within a bunch on coordinates of energy and time (or $\Delta E$ and $\Delta t$, where each is a deviation from some mean value), one would find an elliptical area occupied by protons, as shown in Fig. 1a. The area of the populated ellipse is called the longitudinal emittance of a bunch and has dimensions of electron-volt-seconds (eV-sec). The forces imposed by the rf system are such that the density of particles near any point in the distribution must remain constant (Liouville's theorem), although the average area occupied by particles can increase if the ellipse becomes distorted or mismatched to the boundary. Such an increase is called dilution or filamentation. A reduction in the occupied area is a much more difficult matter, accomplished only by special techniques presently beyond our reach in the Main Ring. Two things are immediately apparent. Making very narrow bunches must result in an increase in the energy spread of the bunches, the extent of which may be limited by the momentum aperture of the Main Ring, and any dilution of the bunches during acceleration will adversely affect our ability to make narrow bunches.

This creates several problems. The low-level rf system, which must provide the accelerating rf cavities with a driving signal of the correct frequency and phase, takes its information primarily from the beam itself through beam-signal pickups in the beam pipe. Because the single-batch beam is present at the pickup for less than 10 percent of the time, the system requires modification in order to minimize phase drift during the periods of each turn when no beam is present at the pickups. Such a phase drift will result in dilution of the longitudinal emittance. In addition, each time the single batch passes through the rf accelerating-cavity system, it induces in the cavities a large transient voltage of the wrong phase and amplitude that, when added to the 'correct' rf voltage developed by the system, has an adverse effect on the quality of some of the bunches in the batch. The existing 'full-ring' beam-loading compensation system is not able to compensate adequately for this repeated transient beam excitation, so a further modification of the low-level system is necessary in order to provide the required compensation. Yet another modification of the system is required in order that the 18 cavities can be excited in two separate equal groups and, at a command, the phases of the rf voltages delivered to the two groups be rotated 90 degrees in opposite directions so that the net accelerating voltage, and bucket height, can be reduced to an extremely small value, then suddenly returned to its full value. This requirement is dictated by the need for a beam manipulation that produces the narrow bunches.

In order to minimize the possibility that these modifications might adversely effect the subsequent normal fixed-target operation of the accelerator, an entirely separate low-level system was assembled specifically for these experiments. In this way, the required modifications were made with fewer restrictions

and the assembled system serves as a prototype for the system that will be needed for routine antiproton production.

During 400-GeV fixed-target HEP, the longitudinal emittance of the proton bunches is purposely diluted or blown up to a uniformly large value during acceleration by introducing controlled 'phase noise' into the rf system. This is done to improve the quality and smoothness of the extraction spill by making all bunches large, because it is known that some bunches are diluted by random noise or other disturbances and this nonuniformity of bunch size creates 'superbuckets' during extraction. This procedure is, of course, precisely what we do **not** want to do during antiproton production. An early experiment during the recent series was an attempt to measure the longitudinal emittance of selected bunches at the moment of injection by measuring bunch length and calculating the emittance such a length indicates in a known bucket. The selected bunches were then subjected to intentional phase disturbances and accelerated through transition (18.5 GeV) to 25 GeV, where the emittance was carefully measured again by measuring the bunch length, then measuring the rate at which the bunch debunches when the rf is removed, giving a measure of its energy spread. The goal was to understand the importance of mismatches in initial conditions of injection and to learn how much dilution occurs when mismatched bunches are accelerated through transition. The results of the experiment were not very useful because we found that we could not accurately assess the emittance by measuring bunch length alone. Our length measurement was not sufficiently precise at 8 GeV, where the bunches are quite long. This information came from a preliminary experiment in which we made the length measurement and a few milliseconds later, still at 8 GeV, made the second measurement by removing the rf and observing the debunching rate. A useful result did emerge, however.

We found that the longitudinal emittance of bunches of the required intensity, $3\times10^{10}$ protons per bunch, is frequently 0.2 eV-sec at 8 GeV before acceleration is begun. This is somewhat larger than we had expected. The general impression is that much of the irregular dilution that we have been living with occurs very early in the acceleration cycle, probably at 8 GeV. In order to improve the situation, it may be necessary to improve the process of beam transfer from the Booster. In the case of single-batch acceleration such an improvement appears to be possible by changing some details in the way the Booster and Main Ring rf systems are phase-locked together at the time of transfer.

Another similar experiment done during this period has to do with the momentum spread of beam bunches at transition during normal acceleration. This is a matter of interest at present because it may relate to the design of the Overpass lattice that is to carry Main Ring beam over the B0 detector facility. In this experiment we measured bunch lengths at two energies, 14 GeV and 19.7 GeV, below and above transition, at an average intensity

of $2.6\times10^{10}$ protons per bunch (total Main Ring intensity $2.8\times10^{13}$ protons per cycle). At these energies, the bunches are short enough to get good measurements and from these measurements and other information regarding the rf voltage and the acceleration rate, we were able to get numbers for the longitudinal emittance at the two energies. The results were 0.22 eV-sec at 14 GeV and 0.28 eV-sec at 19.7 GeV, indicating a slight increase in the region of transition. Bunch lengths were also measured at transition (17.6 GeV), where they become very narrow (about 2.5 nanoseconds). From the measured bunch length and assuming the longitudinal emittance is 0.25 eV-sec at transition, we can make an estimate of the momentum spread. Such estimates are somewhat model-dependent. If the phase-space (i.e., $\Delta E$, $\Delta t$) distribution were an ellipse (which it is almost certainly not) the momentum spread would be $\Delta p/p = \pm 3.6\times10^{-3}$. Other distribution models give results as large as $\pm 4.2\times10^{-3}$.[2]

The installation of extraction equipment at E0 for Tevatron injection may have affected the momentum aperture in a way that is not consistent with our need to make very narrow bunches at 125 GeV. Consequently, after the installation and successful operation of that equipment, we made horizontal momentum-aperture measurements with single booster batches using the 'ad hoc' low-level system at 8 GeV and at 125 GeV. These measurements were done by accelerating and decelerating the beam at constant field so that the beam moves inward and outward until either 10 percent or 50 percent of the beam was lost. The result of these measurements are tabulated below.

| Energy (GeV) | Aperature, $\Delta p/p$ (90% transm.) | Aperature, $\Delta p/p$ (50% transm.) |
|---|---|---|
| 8 | $\pm 3\times10^{-3}$ | $\pm 4.8\times10^{-3}$ |
| 125 | $\pm 2.7\times10^{-3}$ | $\pm 3.2\times10^{-3}$ |

The beam bunches used as probes in these measurements have themselves a momentum spread of about $\pm 10^{-3}$ so the true single-particle momentum apertures are slightly larger than those listed. In any case the useful aperture at 125 GeV is shown to be adequate for the beam manipulations proposed.

After completion of these preliminary experiments, we set up the ad-hoc single-batch system and added components to allow good transient beam-loading compensation during injection and acceleration. We then asked the Control Room Operations Crew to tune the accelerator for maximum single-batch intensity. Within a few hours, the intensity exceeded $2\times10^{12}$ protons per cycle so we are confident that the system works adequately well, and it will be able to approach our desired antiproton production intensity of $2.5\times10^{13}$ protons per cycle. (This is equivalent to $3.25\times10^{13}$ protons per cycle for a full ring, the record intensity recently achieved.)

At this point, the way was clear for an attempt at the gymnastics necessary for generating the required narrow bunches at 125 GeV. A few additional experiments and results of older experiments all indicated that the longitudinal emittance of intense bunches at 125 GeV will be about 0.3 eV-sec. If the rf voltage is raised, the height of the bucket shown in Fig. 1a increases as the square root of the voltage. If this is done slowly with respect to the period of rotation of protons on their orbits within the bucket, (the synchrotron phase-oscillation period), then the shape of the occupied ellipse will adjust itself to the boundary shape. Since the area remains constant, increasing the height reduces the length. Raising the Main Ring rf voltage to 4 megavolts, its maximum value, at 125 GeV results in a bunch length of 2.7 nanoseconds for a 0.3 eV-sec bunch. This is not short enough for our purposes, so we must be a little more clever.

The first step is to lower the voltage slowly down to about 20kV so that the bunch gets very long within the bucket, as shown in Fig. 1b. We want the bunch length at this point to be one half the bucket length, or about 9.4 nanoseconds. Figure 2 shows a series of bunch-length pictures with time progressing downward during this lengthening period. The bunch length at the bottom of the picture is about the required length. At this point, the rf voltage is suddenly raised to its maximum value by quickly switching the cavity excitation phases to the correct value. The elongated bunch now finds itself in a much larger bucket and the shape of the bunch is badly mismatched to the bucket shape. Protons at the extreme ends of the bunch will now travel on orbits that **are** matched to the bucket shape and they will proceed to points in the bucket that are $1/\sqrt{2}$ times the maximum bucket height (or energy). Other protons in the distribution will move similarly, so the entire distribution will rotate to a vertical configuration as shown. Because the **area** of the distribution remains constant, the waist becomes very thin at this point and we have our narrow bunches. This quarter-turn process requires about 1.3 milliseconds and the beam must be extracted precisely when the bunches pass through their narrowest state. If the beam is not extracted at that time, the rotation will, of course, continue and the bunches will become successively broad and narrow again. This rotation is not perfectly linear. Particles at the extreme ends of the distribution become distorted as time progresses. Because of this, nothing is gained by making the initial distribution larger than one-half of the bucket length. Figure 3 shows a series of bunch traces covering one-half of a rotation period. The bunches clearly behave as predicted. In the case shown the maximum voltage was 1 MV instead of the required 4 MV, so the bunches do not become as narrow as is required. In Fig. 4 we show a few traces just at the narrowest part of the evolution. The voltage has been raised to 3.6 MV and a bunch pickup with improved bandwidth was used. We see that the bunches at the narrowest point are about 1 nanosecond full width.

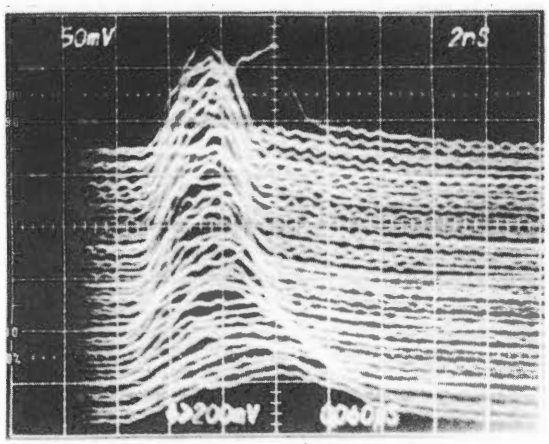



Figure 2.
Bunch broadening resulting from slow reduction in rf voltage. Time progresses downward and total debunching time is 100 msec. Final bunch length is near 9 nsec.

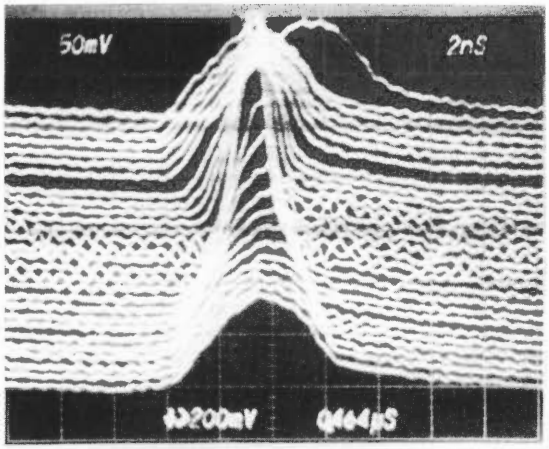



Figure 3.

Rotation of mismatched bunch following sudden increase in rf voltage to 1 MV. Time progresses downward and traces are separated by about 100 msec. The displaced top trace is a mistrigger.

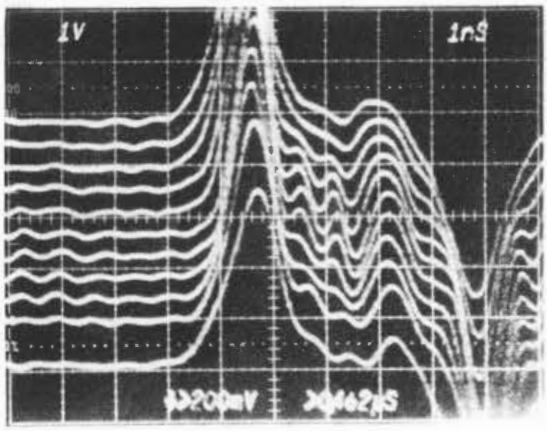



Figure 4.

Bunch length pictures near the narrowest bunch time. Traces are separated by one machine turn, 20.9 μsec. The narrowest bunch has length about 1 nsec. The beam pickup is a broadband transmission line pickup so inverted reflections from the downstream end of the pickup also appear.

The process of reducing the momentum spread of the antiprotons produced by these bunches will be the exact opposite of the narrowing process shown here. The narrow antiproton bunches will be injected into a 'Debuncher' ring where they will be centered in rf buckets of appropriate size, so that the mismatched distribution will appear just as Fig. 1c. The antiproton distributions will rotate to the low-momentum horizontal position, at which time the rf voltage and bucket height will suddenly be reduced to match the distribution as in Fig. 1b. The rf voltage will then be slowly lowered even further until the distribution is as flat as possible.

After a sufficient quantity of antiprotons has been produced, accumulated and cooled, we will accelerate quantities of about $10^{11}$ antiprotons per cycle in the Main Ring to 150 GeV for injection into the Tevatron. We expect to accelerate these particles in ensembles of about 8 adjacent bunches. This will be another task for the modified low-level rf system. During the Energy Saver extraction studies mentioned above, the number of bunches and the intensity per bunch were reduced to the minimum practicable value by mistiming various kickers. Batches of twenty adjacent bunches with a total intensity of about $4\times10^{9}$ protons were successfully accelerated with no apparent problems.[3] This is probably the lowest beam intensity ever accelerated in the Main Ring, so the accelerator has made the unique achievement of two records, the largest and the smallest beam intensities achieved, within one week. This result indicates that the system is very nearly adequate for the required antiproton acceleration.

There are still many tests to be completed, but the results of this most recent study period have gone a long way toward demonstrating that the varied accelerator operational modes required for the Tevatron I project are relatively easily accomplished and no serious barriers to achieving our goals have yet been encountered.

## References

1. J. E. Griffin, J. A. MacLachlan, and J. F. Bridges, **Review of the Fermilab Main Ring Accelerator Study Program As Directed to the $\bar{p}p$ Program**, IEEE Trans. Nucl. Sci. **NS-28**, 2040, June 1981.

2. S. Ohnuma, Private Communications, and various extant reports regarding momentum distribution at transition.

3. These operations were done by M. Harrison, J. Lackey, and others in the EO injection group.

## INFORMATION REGARDING DO PROPOSALS

Proposals for the DO $\bar{p}p$ interaction region are due on February 1, 1983 in accordance with the recommendation of the Fermilab PAC. (See Fermilab Report - June 1982). It would be very helpful to both the PAC and Fermilab if we could have a letter-of-intent by November 1, 1982 from experimenters preparing proposals. The letter should describe with reasonable completeness the objective of the experiment and the proposed apparatus. In response to discussion with the PAC we will entertain proposals which are intended for an experimental hall of volume on the order of $750m^3$. This is approximately 50% larger than originally proposed. Within limits, the detailed shape of the hall will depend on the proposal(s) finally accepted.

The detector(s) intended for DO will need to be able to be removed easily. Fermilab will attempt, if necessary, to provide limited assistance ($< \$1M$) for the construction of the detector.

The present schedule would allow the first run in FY'86 and we would hope to be able to have a complete detector assembled in DO by that time.

Presently, in addition to CDF, there are two $\bar{p}p$ experiments with Stage One approval, E-710 (total and elastic cross sections) and E-713 (particle search with a lexon detector). The PAC has suggested that these might be run in an interaction region other than DO. The PAC still has under consideration two proposals, P-714 ( a large Pb glass array) and P-719, (ep) for the DO area.

We repeat that the deadline for a useful letter of intent is November 1, 1982. We are planning a workshop to discuss the physics opportunities in DO for November 19-20, 1982. Details of the workshop will be announced shortly.

Any questions should be directed to the Program Planning Office.