Early Operating Experience with the New TEVATRON Low-β Insertion

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Abstract

New low-β insertions will be used in the TEVATRON Collider at both the B0 and D0 interaction regions. To reduce the beam-beam tune shift, electrostatic separators will be installed to separate the beams horizontally and vertically at all but the two interaction points. We have installed an insertion at the B0 straight section and enough separators to create collisions at B0 only. We will describe the initial beam tests using these devices. The procedures for tuning of the insertion and separators will be described. We will also discuss the procedure to change the lattice from injection lattice to the 50 cm β^* lattice used in high energy physics.

Introduction

During the 1988-1989 TEVATRON Collider run the luminosity was limited by the 0.024 beam-beam tune shift that the TEVATRON could accommodate. This corresponded to 0.002/head-on crossing at 12 locations [1]. In addition, the low-β insertion at B0 was not matched in either betatron or momentum space to the rest of the lattice, resulting in β and dispersion waves around the ring. In future collider runs we plan to reduce the beam-beam tuneshift by separating the p and $\overline{p}$ beams both horizontally and vertically using electrostatic separators [2]. In order to install a low-β insertion for a second high energy physics detector, the insertion was redesigned to be matched with the rest of the lattice [3]. One of these insertions has been completed and installed in the B0 interaction region. We have commissioned this system to the point of accelerating protons to 900 GeV/c, squeezing to 50 cm β^* with the separated orbit, and then programming the separators to produce the orbit that would allow the beams to collide at B0 only. We will describe the results of these commissioning studies.

Properties of the Lattice

The most important change in the TEVATRON lattice is the presence of the low-β insertion at B0. The original 50 cm low-β insertion was matched properly to the injection lattice where β^* was roughly 70 meters, but became badly mismatched with β_{max}'s of 1300 m at low-β. In addition, a dispersion wave of several meters around the ring was introduced. In the new low-β system, injection occurs with β^* of 1.7 meters, and the lattice is properly matched down to a β^* of 50 cm, with β_{max} of about 800 m. The insertion consists of 18 cold-iron quadrupoles arranged as a triplet and 6 "trims" on each side of the interaction region. The triplet is directly adjacent to the interaction region and the trims extend several cells into the arcs. The magnet locations can be surveyed to an accuracy of 0.02". A horizontal and a vertical dipole corrector have been added just outside of the triplet on each side of the interaction region. These correctors can correct up to a 0.02" placement error in the triplet. If the beams do not pass through the center of the triplet to within 0.02", the correctors will not be able to correct completely the quadrupole steering, and the closed orbit will deteriorate. Such a problem can only be fixed by re-aligning the magnet which is misaligned.

Electrostatic separators have been installed in 4 of the straight sections around the TEVATRON. During injection, accelerations, and the squeeze one separator in each plane will be turned on to produce spiral orbits without head-on collisions between p's and $\overline{p}$'s. After the squeeze, the separator power supplies are programmed to bring the beams into collisions at B0 only. This is done by programming three separators in each plane to make a 3-bump which excludes only B0. If the TEVATRON closed orbit with the separators turned off passes through the center of all magnets, the effect of the helix will be to introduce differential tune and coupling shifts for the p's and $\overline{p}$'s. These differential shifts can be corrected with sextupole circuits placed around the TEVATRON, and we have installed 28 sextupole circuits to make these corrections. We have also developed an interactive orbit and lattice program which calculates the lattice dynamically based upon the measured currents in each of the elements. We expect to be able to smooth the orbit to ± 0.5 mm with this program [4].

Low-β Insertion Studies

All initial experiments were done with the electrostatic separators turned off. Since the insertion is matched to the lattice, and since injection occurs at the E0 straight section, injection into the new lattice should be straightforward. Complications can arise if the magnets have not been aligned properly or if they have been wired incorrectly. These problems would appear as difficulties establishing a good first turn trajectory or in storing beam. What we observed was that the trajectory was smooth from E0 to B0, but that a large oscillation was induced at B0. We were able to eliminate this oscillation by using a single dipole just upstream of the insertion. The smooth injection orbit is shown in Fig. 1.

Once circulating beam was established we accelerated to 900 GeV flattop and concentrated on smoothing the orbit and adjusting the quadrupole and sextupole circuits to establish acceptable tunes, coupling, and chromaticity on the ramp using the control software [4, 5]. Acceleration to 900 GeV has been over 90% efficient.

Neither injection nor acceleration make any fundamental changes to the lattice. However, high energy physics experiments are done with the 50 cm β^* lattice. Changing the lattice from the injection lattice to

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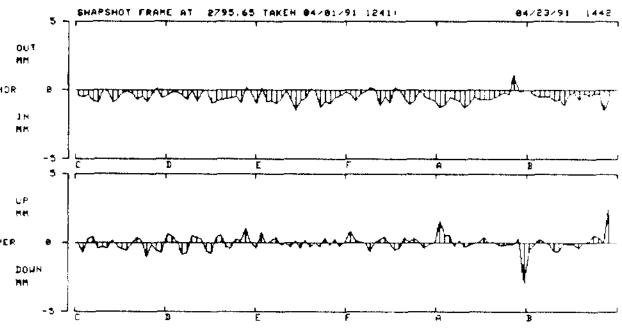

Figure 1: Smooth TEVATRON injection orbit.

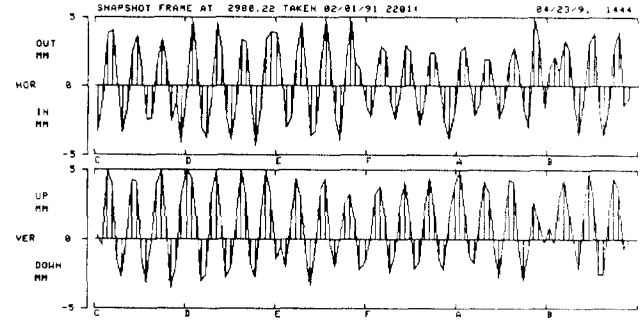

Figure 2: 150 GeV closed orbit with separators on.

the low-β lattice is done with a procedure called the "squeeze" [5]. During this process the triplet elements are almost unchanged, but the trim magnets are ramped in steps to their final values. Since these elements are in the arcs where the β functions are relatively small (maximum β's of about 100 m) the orbits and phase advances are not extremely sensitive quadrupole misalignments or misprogramming of the supplies.

The gradients for the quadrupoles were calculated and entered into the squeeze tables. We could not calculate quadrupole misalignments, variations in magnet strength, and closed orbit errors. As a result, the first few times we squeezed it was necessary to "parse" [5] the squeeze and make adjustments step by step. The only changes needed were small changes to the correction quadrupole circuits around the ring to keep the tunes at 20.58, changes to the coupling and chromaticity circuits, and a dipole bump to reduce the closed orbit oscillations to ± 2 mm. The dipole bump was put in by hand after inspecting the closed orbit and deciding where the cusp was. We are developing software to automate this using a least squares algorithm to choose a small number of correctors to adjust to get the smoothest possible orbit. Proton transmission through the squeeze has been 100% efficient.

Separator Studies

The other major part of the TEVATRON Collider Upgrade is the plan to separate the p and $\overline{p}$ beams both horizontally and vertically with electrostatic separators. For the past 21 months separators have been installed in the TEVATRON. These have been used to create 1-bumps at 150 GeV to test the feeddown compensation schemes and to do beam-beam interaction studies [6]. In the fall of 1990 additional separators were installed. With these separators we can make the 3-bumps described earlier.

The procedure for using the separators is envisioned as follows: p's are injected into the TEVATRON with the separators turned off. One set of separators in each plane is turned on with the opposite polarity from that used in physics running, creating the helical orbit with p's on the eventual $\overline{p}$ orbit. The p's are then transferred back into the Main Ring using the $\overline{p}$ injection beamlines. At this point, any needed tuning on these beamlines is done. The separators are turned off, p's are re-injected, and the separators are turned on with the normal polarity. The $\overline{p}$'s are then injected onto the helical orbit. Once $\overline{p}$'s have been injected, the TEVATRON is ramped. The separator power supplies will also be ramped to maintain adequate separation between the p and $\overline{p}$ beams [6]. At flattop the squeeze is initiated. The separators must also be programmed to maintain adequate separation despite the changing β functions and phase advances. At the end of the squeeze the separators are programmed to initiate collisions by changing from two 1-bumps in each plane to a single 3-bump in each plane. Care must be taken to ensure that the 3-bumps are properly closed or the beams will not collide head-on.

The program outlined above has been completed with p's. In Fig. 2 we show the 150 GeV closed orbit with the separators turned on with one 1-bump in each plane (no head-on collisions). Transmission of p's to low-β with the separators turned on and the initiation of collisions at low-β was carried accomplished with no loss of intensity. Figure 3 is a real-time plot of the TEVATRON beam intensity, energy, current in one of the low-β quadrupoles, and the current in the correction dipole used to correct the orbit during the squeeze. The only losses occur at the beginning of acceleration. These losses have been a characteristic of TEVATRON collider operation and are not understood. Overall, the process is 90% efficient. In Fig. 4 we show the closed orbit at low-β with the orbit separators programmed to produce collisions at B0 if $\overline{p}$'s were present. We have not yet attempted to use the feeddown sextupole circuits to correct the differential tune and coupling changes introduced by turning on the helical orbits, but we have measured some of the differential changes which we must know in order to program the feeddown sextupoles. We have not been able to determine whether the 3-bumps are properly closed and the beams will collide head-on: that will await the development of high-resolution beam position monitors at the B0 IR.

Other Studies and Plans

In the process of commissioning the low-β insertion and separators we have made a number of other measurements. An important early concern was that the lattice calculations might be grossly incorrect or that elements in the tunnel would be wired incorrectly. One of the earliest experiments to measure the β functions consisted of putting in a 1-bump on one side of the B0 insertion and measuring the positions at the other elements. We were able to verify that the lattice was approximately correct. Later, we systematically measured the β functions at all of the low-β trim locations by varying the single quadrupole currents and measuring the tune change with current [7].

In a system such as this, with high-gradient quadrupoles at locations with large β's, power supply noise is an important concern. If the triplet supplies have noise at the betatron frequency or its harmonics, they will contribute phase modulation and possibly transverse emittance growth. We have used the new TEVATRON Flying Wire System [8] to measure the transverse emittance growth. It is less than 0.3π mm-mr/hour in each plane. This is consistent with transverse emittance growths measured during the 1988-1989 collider run [9] and we do not believe that the quadrupole supplies are contributing to the transverse emittance

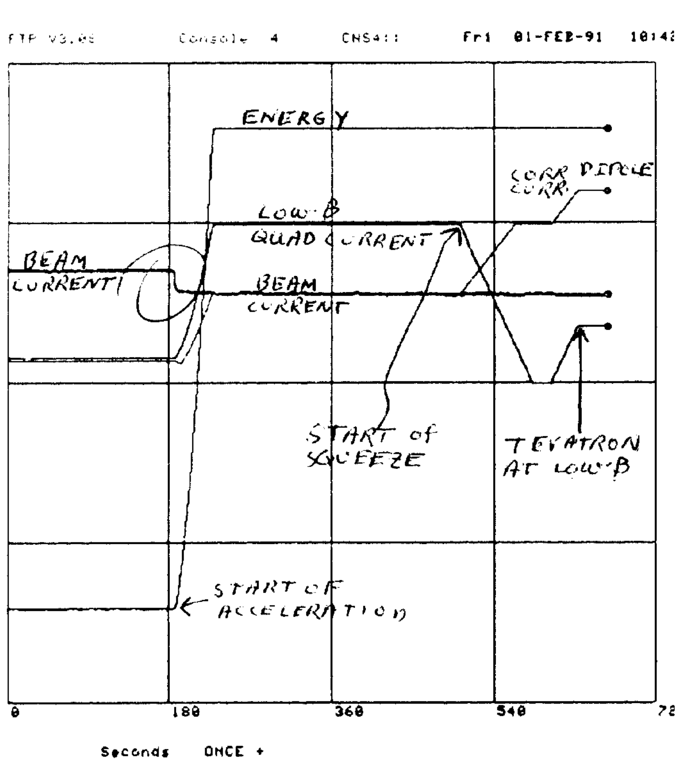

Figure 3: TEVATRON p intensity during acceleration and squeeze. This plot is taken from the TEVATRON logbook and shows the TEVATRON energy, beam current, one of the low-β quadrupole currents, and a correction dipole current.

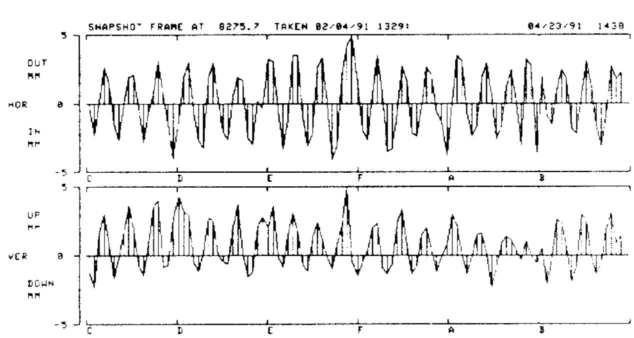

Figure 4: TEVATRON closed orbit at low-β with collisions occurring at B0.

growth.

There are also accelerator physics problems still to be faced. The Flying Wire System was made operational only at the end of the studies, and we have not been able to measure emittance growth during injection or during the squeeze. The separators have been on for tens of hours at their operational voltages and we have not observed any sparks. We need to measure the actual sparking rate and to determine if sparking will cause large emittance growth. All studies have been done with intensities of less than 5E10 $\bar{p}$'s/bunch. For the next collider run we expect to run at intensities of over 10E10 $\bar{p}$'s/bunch. We must get experience with more intense bunches. The feeddown sextupoles for the differential tune and coupling compensation have not yet been brought into operation. We have to verify that the circuits perform as expected, and then they must be integrated into the controls software.

The low-β insertions have been designed to be matched to the lattice down to β^*'s of 25 cm. If the bunch lengths are negligible, the luminosity with β^* of 25 cm will be twice that of 50 cm. We plan on squeezing to 25 cm to understand what additional problems there will be with the lattice and to determine whether that is an acceptable lattice for the TEVATRON Collider.

The next collider run will have identical insertions at B0 and D0 and additional separators to make two 3-bumps in each plane. The complexity of this system requires as complete an understanding of a single insertion with its separators as possible.

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