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THE TEVATRON AS AN SSC PROTOTYPE: EXPERIENCE VERSUS PREDICTIONS*

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SUMMARY

Early machine experiments on the TeVatron which are relevant to the SSC are discussed. Despite the preliminary nature of the data, there have been some interesting observations which may influence the design of the SSC. In particular, comparisons of measured betatron tunes, chromaticities, and resonance line widths with those predicted from computer simulations using magnetic field measurements have been made; the predictablity for low order phenomena seems acceptable. Coasting beam studies indicate long lifetimes and lack of strong resonance driving terms. Low energy studies of beam behavior indicate that a dynamic range of a factor of 15 from injection to operation energy should be possible.

INTRODUCTION

Status of the Tevatron

In the following discussion, Tevatron is used in the generic sense. Doubler, ED/S, Saver, Tev I, Tev II, and Collider are considered operating modes of the Tevatron.

Fixed Target

The primary purpose of the Tevatron for the present and the next two years is to provide beams for fixed target physics. As a consequence, virtually all machine studies have been directed toward the goals relevant to extraction and high intensity fixed target physics. The present situation is that low intensity beams have been accelerated to 700 GeV and extraction to experimental areas has been accomplished up to 512 GeV. The present operating mode is at 400 GeV, about 10**13 ppp, 15 s flat-top, with a 39 s cycle. /ref 1/

Some data from the commissioning of the fixed target program are particularly relevant to the SSC, even if the SSC is not used for fixed target physics. These data are mostly to answer the question "How predictable is/was the Tevatron ?"

What will be presented here are comparisons of Magnet Test Facility (MTF) data /ref 2/ on individual magnet measurements with the corresponding data extracted from measurements of circulating beam behavior. This includes the <a1>, <b1>, and <b2> magnetic multipole moments and the width of the 1/2-integer stop-band.

Collider

In 1983 there were three sessions of coasting beam studies. These were directed towards the development of storage techniques and to get a first look at the Tevatron as a collider. Indeed, the techniques were quickly implemented and the initial coasting beam studies at 400 GeV were very encouraging. The transverse stability of the coasting beam seems to be very good with long lifetimes even on potentially strong resonances. Longitudinal dilution seems to occur rapidly, however, indicating noise problems in the low level rf system.

Machine Studies

In 1983 there were two machine study sessions devoted to the dynamic range of superconducting magnets. These studies are particularly relevant for HERA, which will have an injection energy of 40 GeV and a top energy of 820 GeV, more than a factor of 20 higher. As well, the magnets and lattice are similar to the Tevatron design.

For the SSC to operate between 1 and 20 TeV implies that the Tevatron should certainly have a reasonably good field aperture from 50 GeV to 1 TeV. Details of SSC magnet construction such as bore diameter and filament size as well as lattice design make the measurements described here more or less relevant.

For these studies the beam was injected into the Tevatron at the normal 150 GeV Main Ring energy and then decelerated. This technique has several advantages over trying to inject directly at 50 GeV. First, it isn't necessary to change anything in the Main Ring itself or to the MR to Tevatron transfer system. Second, by starting from a known set of operating conditions the beam can be decelerated in a more controlled fashion in small steps, if necessary. The major disadvantage of the deceleration technique is that it is necessary to understand the hysteresis of the Tevatron magnets.

MAGNETIC MULTIPOLES

The multipole moments of the dipole magnets are defined by:

$$B_y + iB_x = B_o \sum_{n=0}^{\infty} (b_n + ia_n)(x + iy)^n ,$$

where the pole number is given by 2(n+1).

The average of the MTF measurements of the 774 dipoles subsequently installed in the ring are used in the following discussion. And, although detailed measurements on each magnet are available up through 30-pole, only the very lowest terms have been investigated. This is mostly due to lack of time. However, it might be noted that the only zero harmonic correction element strings which have been powered (and needed) are the 2 quadrupole, the 2 sextupole, the skew quad, and the 2 octupole circuits. Thus it will be more difficult to investigate the higher terms of the multipole expansion.

the average quadrupole, <b1>

One of the the first surprises in the commissioning of the machine was that the horizontal and vertical tunes were measured to be 19.6 and 19.2, respectively, instead of the predicted 19.4 in each plane. This is now understood as an error in the physical curvature of the magnets themselves.

After assembly, the dipoles were bent to have 8 mr of curvature. Subsequent relaxation effectively changes the coordinate systems defined by the MTF relative to what the beam actually sees. And, as it turns out, a change of 1 mm in the sagitta will cause an effective change of 1.E-4/inch of <b1> due to a "feed-down" from the <b2> term.

Fig. 1 shows the average quadrupole <b1> as measured by MTF compared to the values needed to predict the beam behavior. The points on the curves correspond to where the measurements were actually made.

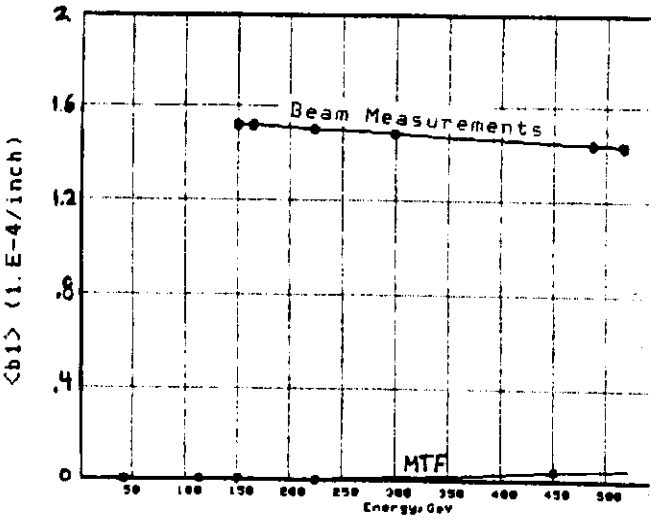

Figure 1. Average quadrupole <b1> vs. Energy. The units are 1.E-4/inch and GeV, respectively. The upper curve is from beam measurements of betatron tunes, the lower curve from MTF data.

the average sextupole, <b2>

Fig. 2 compares <b2> from the MTF measurements with the values needed to predict the chromaticity behavior of the beam at several energies. For reference, a change of 1.E-4/inch**2 of <b2> roughly corresponds to 20 units of natural chromaticity, dQ/(dp/p). In order to derive a consistent set of data it was necessary to assume an offset of about 0.5 amps in the two sextupole correction element strings. This could be due to persistent currents in the correction elements themselves or a simple read-back error.

the average skew quadrupole, <a1>

Fig. 3 shows the current in the skew quad correction element circuit needed to reduce the horizontal-vertical betatron coupling as a function of beam energy. The amplitude is several times larger than predicted by the MTF values for <a1>. This could be due to some rotated quadrupoles in the ring. Nevertheless, there are two rather interesting features worth noting.

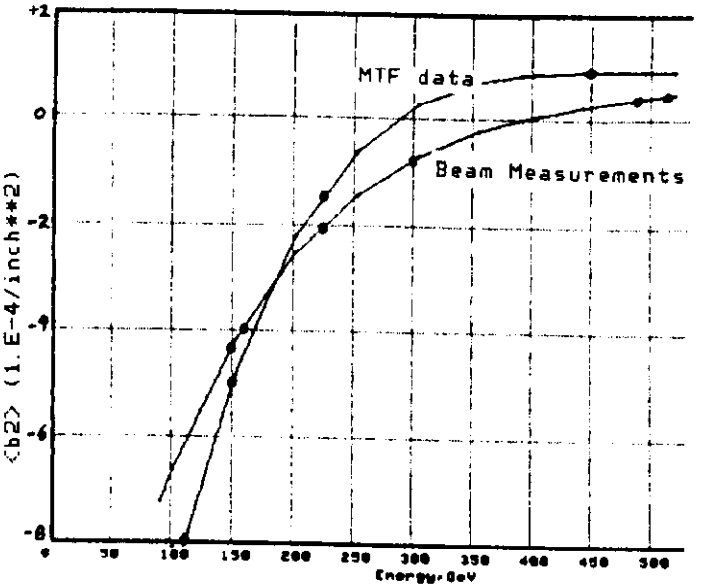

Figure 2. Average sextupole <b2> vs. Energy. The upper curve at high energy is from beam measurements of chromaticities; the lower curve from MTF data.

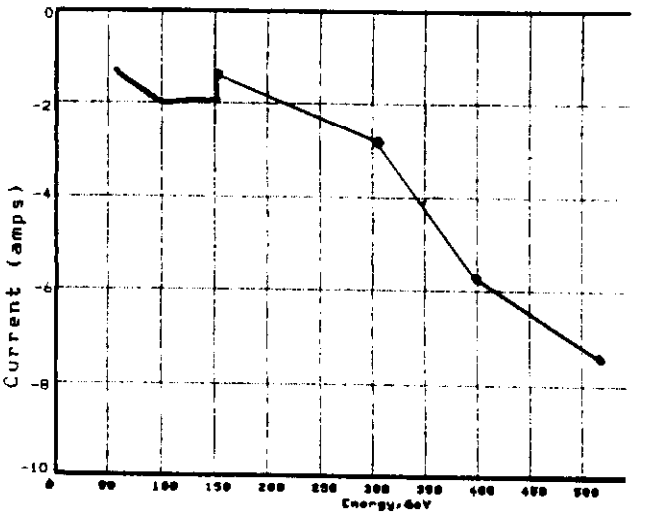

Figure 3. Skew quad excitation vs. Energy. The values below 150 Gev are from the deacceleration studies reported later.

The first is the non-linearity of the current vs energy of the skew quad correction. This might be due to something rotating with excitation or perhaps some systematic closed orbit distortion coupled with feed-down from a higher multipole moment. In any event, the phenomena are reproduceable and small enough to be easily corrected with the available circuit (15 amps out of 50 amps maximum).

The second is an observation made during deceleration studies that there is a rather large hysteresis effect. This is seen for the values less than 150 GeV. This observation probably argues for the feed-down explanation of the discrepancy between measured and

predicted <a1>.

betatron resonance driving terms

In the course of setting up the 1/2 integer extraction for fixed target operation the width of the horizontal 1/2 integer stopband was measured to be 0.007. Subsequently, using the MTF data and the positions of the dipoles in the ring, tracking studies /ref 3/ have predicted the horizontal line width to be 0.006. The vertical width, as yet unmeasured, is predicted to be 0.003.

STORAGE STUDIES

The goal of the 3 storage sessions was to develop the techniques for studying the beam in this mode. Once the various beam aborts peculiar to fixed target operation had been disabled and the extraction devices turned off, there was no difficulty in storing the beam at 400 GeV. In fact, the major difficulty was to observe beam loss.

The beam intensity and loss monitoring systems of the Tevatron were designed primarily for the initial commissioning of the machine for fixed target physics. Losses for low intensity beams with lifetimes of tens of hours need more sensitive detectors. Some results were seen using a pair of 1 square meter scintillation counter hodoscopes in the B0 interaction pit next to the beam pipe. During the longest store (3h 47m, ended out of boredom), the counting rates were low for the hodoscopes themselves (<30 kHz) and for coincidences between 2 hodoscopes separated by 10 m along the beam line (<10 kHz). That the experimental environment is so quiet even with the single beam intensity near the design value (3E11) is very encouraging.

transverse stability

Two experiments to look at the transverse stability of the beam were 1) to artificially blow up the beam by using the tune measuring pinger (a pulsed dipole which kicks the beam for one turn to excite coherent betatron oscillations) and 2) to sit near a cluster of fifth order resonances. A flying wire scanner was used to monitor the beam width.

Fig. 4 shows the beam intensity during the course of these experiments during one store. Also shown is the time when the pinger was used to dilute and enlarge the transverse emittance; the pinger was fired every minute during the indicated time. The FWHM of the horizontal beam profile as measured by the flying wire scanner is shown as points on the same figure. Note the suppressed zero of the ordinate scale.

During the course of the beam blow-up by the pinger the loss rate increases as does the width of the beam. After the pinger is turned off, the losses continue until the beam width decays to its original width.

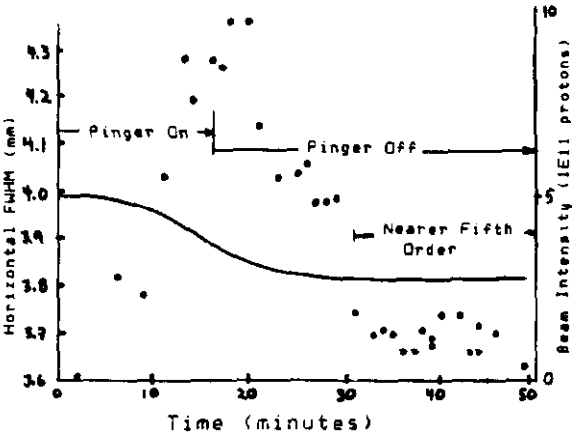

Figure 4. Beam intensity vs. time during the store to study transverse stability. The time the pinger was causing beam blow-up is indicated as is the time the tunes were moved close to the cluster of fifth order resonances.

A remarkable feature of this experiment is that it takes almost 10 minutes for the beam to come to equilibrium. That the good field aperture is so small is perhaps an indication of something else wrong, although no effort has ever been expended to optimize the correction elements for maximum good field aperture at 400 GeV. In fact, during this store the zero harmonic octupole circuit was at the same value as used for fixed target operation. This value was set to provide a large tune spread for Landau damping for stability at high intensity and should have the effect of reducing the good field aperture.

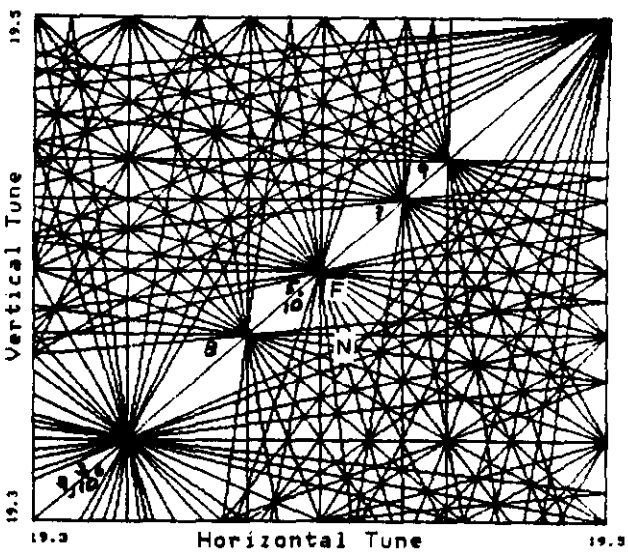

Figure 5. Working diagram for the Tevatron showing resonances up through tenth order. The normal working point and the one near the fifth order cluster are indicated.

After coming to equilibrium, the tunes were changed to bring the working point closer to the cluster of fifth order resonances shown in figure 5. For the remainder of the study period, no growth in beam size or increased loss rate was observed.

The fifth order resonances are of particular concern in the Tevatron because they can be driven by the decapole errors of the dipoles which are relatively large and were not included in the magnet shuffling criteria. /ref 4/ On the other hand, with superperiodicity of 2, there are no systematic fifth order resonances in the Tevatron.

longitudinal dilution

During the first stores an apparent beam loss was traced to the rf sensitivity of the beam intensity monitors. The loss of signal was due to the debunching of the beam as verified by signals from stripline pickups. In fact, longitudinal dilution times were under an hour and would dominate the luminosity lifetime of the Tevatron.

Some experiments and improvements already have been made to the Tevatron low level rf system. However, as shown at the SPS, to make a system with the required low noise level may take some extra effort.

DECELERATION

The only Tevatron experiment specifically directed toward the SSC has been to determine the Tevatron's maximum practical operating energy range. This parameter is particularly important for the determination of the SSC injector. And, although the final SSC design may involve quite different magnets, it should be educational and hopefully comforting to compare dynamic aperture calculations with real data, especially in the more difficult low excitation case.

The technique for studying the low energy behavior of the Tevatron has been to inject normally from the MR at 150 GeV into the Tevatron and then decelerate the beam. This procedure, as opposed to simply injecting at a lower energy, bypasses several potential problems with transfer line aperture restrictions. It also eliminates retuning the injection parameters, a time consuming process.

The major drawback to the deceleration procedure is that the large hysteresis of the superconducting magnets has to be understood. Fig. 6 shows the hysteresis behavior of the sextupole term of the dipole magnets, <b2>. The regions of interest for acceleration and deceleration are indicated. At injection at 150 GeV the upper and lower curves are separated by dQ/(dp/p) = 210. At 50 GeV the separation is 780. As far as the dynamic range of the SSC is concerned, which would only involve one side of any hysteresis curve, to decelerate is to solve a harder problem. Starting from injection on the normal upgoing hysteresis curve, the magnets move to the downgoing curve over some energy interval which must be determined empirically. And since there are differences between the <b2> as measured with the beam compared to the MTF data in the higher energy region, one must expect even larger problems for lower energies.

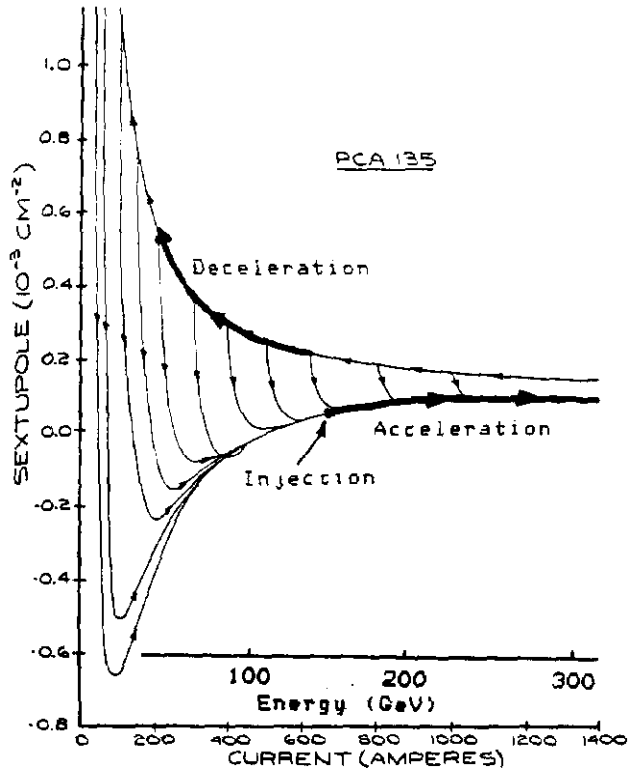

Figure 6. Hysteresis behavior of <b2> in a dipole magnet; <b2> vs. Energy. The arrows indicate indicate increasing or decreasing current.

Operating the Tevatron at energies lower than 150 GeV has interesting implications for the rf. In normal operation the rf frequency from 150 to 1000 GeV changes only about 1 kHz out of 53 Mhz. This limited operating range implied two simplifications to the rf system. The first was a limited frequency range of the low level oscillator, the second was a cavity tuning system using electric heaters and heat exchangers in the water cooling system to control the cavity temperature. For deceleration to 50 GeV the rf frequency changes about 8 kHz and requires a modification to the oscillator system. The heater circuits in conjunction with the normal rf heating keep the cavities tuned well enough for slow deceleration.

The first deceleration attempts saw the beam die as the energy diminished. This was understood as due to beam hitting the half integer stopbands because of the large chromaticity of the machine. To correct the chromaticity, however, one must measure the tunes as a function of radius. To measure the tunes correctly, the horizontal and vertical betatron oscillations must be independent. For this, the skew quad setting must be correct.

An empirical procedure was quickly developed using the pinger to set the correction elements at lower and lower energies. At a particular energy the skew quad was set to minimize the vertical coherent oscillations induced by the horizontal pinger. Next, the two sextupole circuits were adjusted to give the longest possible ring time of the oscillations

induced by the pinger. That is, the tune spread was reduced and the coherence of the oscillations improved. The third step involved measuring the tunes using a Fourier transform of the oscillations and setting the correction quad circuits accordingly.

Fig. 7 shows the beam intensity and energy for some of the deceleration cycles at the end of the study session. The beam can be seen to survive with no losses down to almost 65 GeV. At that point the closed orbit needed to be corrected, but there was no time left.

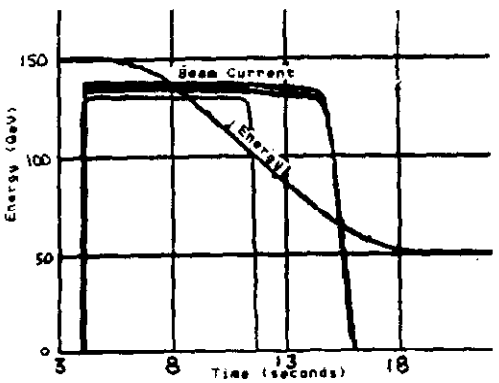

Figure 7. Beam intensity and energy vs. time.

CONCLUSIONS

With respect to the SSC, the Tevatron is unique in two respects. First, it is the only operating superconducting sychrotron. Second, each magnet in the ring has been measured to high precision and the data are available for computations and detailed comparison with beam behavior. Any SSC design calculation for single particle dynamics must surely work on the Tevatron.

The few study sessions so far have been useful to develop techniques and procedures. Some tentative conclusions relevant to the SSC are possible.

1) The Magnet Test Facility data on the dipoles can be made to agree with the beam behavior to within simple shifts of the coordinate systems for <b1> and <b2>. Something else may be the case for <a1>.

2) We have seen decay times as long as 10 minutes for particles with larger betatron amplitudes. If this effect is not due to some mundane problem with the machine, it might mean that an honest simulation of beam behavior by particle tracking may involve tens of millions of turns.

3) Although the stored beam lifetime itself is quite long the corresponding luminosity lifetime would be limited by longitudinal dilution. The development of the low level rf system and appropriate diagnostics are the critical path toward the Tevatron as a collider.

4) The dynamic range of the Tevatron for main ring sized beams (about 24 pi normalized emittance) is at least 65 GeV to at most 1000 GeV. This factor of 15 in operating/injection energy will certainly be increased with more time devoted to machine studies.

FUTURE PLANS

There is a need for methods to observe phenomena during beam storage, where the machine has performed unexpectedly well. Automated flying wires, more sensitive intensity and loss monitors, and better longitudinal detectors are needed and are being built.

Now that the fixed target experimental program is under way, the next priority for machine development will be to prepare for pbar-p collisions in 1985 and 1986. In March 1984 one of the low beta intersection regions will be ready for tests. The SSC related question of betatron resonance driving terms induced by a low beta insertion will be of first priority.

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REFERENCES

1) H. Edwards, "The Energy Saver Test and Commissioning History", Proceedings of the 12th International Conference on High-Energy Accelerators, Fermilab, Aug. 11-16, 1983, Batavia, Illinois.

2) R. Hanft, B. C. Brown, D. A. Gross, L. P. Michelotti, E. E. Schmidt, F. Turkot, "Magnetic Field Properties of Fermilab Energy Saver Dipoles", IEEE Trans. Nucl. Sci., NS-30, No. 4, (1983)2472.

3) Norman Gelfand, Proceedings of this workshop.

4) L. P. Michelotti and S. Ohnuma, "Dipole Shuffling in the Fermilab Energy Saver", IEEE Trans. Nucl. Sci., NS-30, No. 4, (1983)3381.