Fermi National Accelerator Laboratory

TM-1443
0410.000

The New FNAL Booster-to-Main Ring Beam Transport System*

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March 1987

*Submitted to the Particle Accelerator Conference, Washington, D.C., March 16-19, 1987.

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

THE NEW FNAL BOOSTER-TO-MAIN RING BEAM TRANSPORT SYSTEM

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Abstract

As part of the effort to improve the emittances of the FNAL accelerators, a new beam transport system has been installed between the 8 GeV Booster and the 150 GeV Main Ring synchrotrons. The new design generates vertical dispersion which matches that dispersion produced by the Main Ring D0 vertical overpass. The biggest improvement may be the stronger focusing used throughout the new line, thus reducing the sensitivity of the transverse phase space matching of the two machines to small changes in quadrupole currents. Also included is a more passive injection system, a more flexible power supply configuration, plus improved diagnostics for measuring the Booster emittances and the phase space match to the Main Ring. The new beam transport system became operational in August of 1986. Results from the commissioning of the system are also described.

The New 8 GeV Line

During a nine month period from October, 1985 to July, 1986 the Booster, Main Ring, and Tevatron accelerators were shut down to allow for the construction of the Main Ring overpass at the Collider Detector Facility and the detector building at the D0 straight section. By the end of that period, 12 months after the redesign had been initiated, a new 8 GeV beam transport system between the Booster and Main Ring accelerators had been developed, constructed, installed and was about to be commissioned. No changes were made to the Booster extraction system. The ideal trajectory leaving the second pulsed septum magnet of the Booster extraction system remains parallel to the floor. The first horizontal bend point in the beamline remained in its old position. Two vertical bending magnets midway through the beamline bring the trajectory down to roughly the Main Ring level and the beam is then injected horizontally. An 18 ft thick cement wall was installed in the line to allow access to either the Booster accelerator enclosure or the Main Ring accelerator enclosure during the operation of the other machine.

The new focusing system contains 19 quadrupole lenses which alternate in gradient throughout the line. The beamline may be divided into three sections. The middle section, referred to as the "Cells," contains 5 quadrupoles of equal but alternating strengths and spaced equally apart. The betatron phase advance between each of these elements is 45° for both the horizontal and the vertical degrees of freedom. In front of the Cells, the Booster Match section consists of 6 quadrupoles which are used to match the amplitude and dispersion functions of the Booster to those of the Cells. After the Cells, the Main Ring Match section has 8 quadrupoles which match the amplitude and dispersion functions of the Cells to the Main Ring injection point.

Amplitude Functions

Figure 1 displays the resulting amplitude functions for both the horizontal and vertical planes. Within the Cells, the value of β_{max} is roughly 30 m. The largest value of β in the entire line is 150 m and occurs just prior to the injection point. As expected, the sensitivity of the Main Ring match to quadrupole errors is reduced by the smaller values of β. Figure 2 shows the dilution of the transverse emittance which would be generated by a quadrupole error in the new beamline compared with the same strength error in the old line, where β_{max} was roughly 600 m. Due to the requirements imposed upon them, the "matching" quadrupoles have a variety of strengths. By having independent control over each of these magnets, the matching of the amplitude functions may be adjusted.

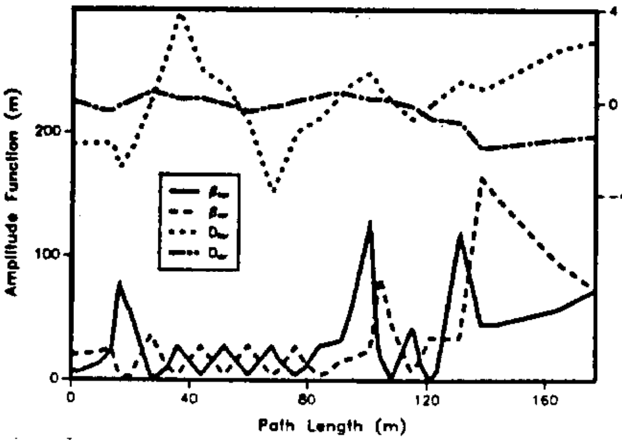

FIGURE 1 - Lattice Functions of 8 GeV Line

Dispersion Functions

To produce the required vertical dispersion at the end of the beamline (-1.4 m), the injection process into the Main Ring was switched from the vertical plane to the horizontal plane. If the beam trajectory is not lowered until just before the injection point, then the vertical bending elements would produce $\Delta D \sim +.5$ meter. Thus, the dispersion function just before these vertical bends would need to have the value -2 meters and some type of "dispersion creation" section would need to be added somewhere in the beginning of the line. By switching to horizontal injection, the beam trajectory could be lowered .5 meters to roughly the Main Ring level at any upstream point in the beamline. In par-

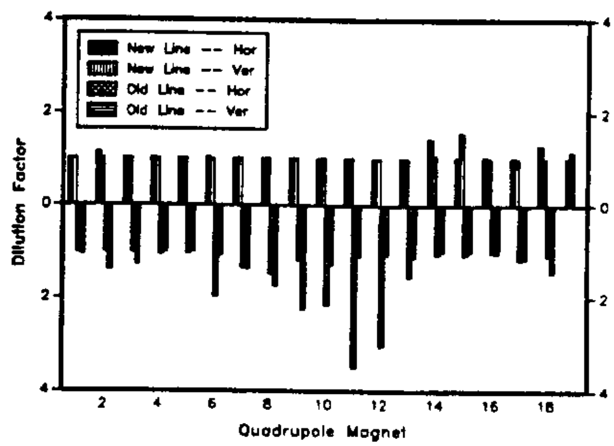

FIGURE 2 -- Transverse emittance dilution due to a single gradient error of $\Delta B'/B' = 4\%$.

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ticular, the beam is lowered at a point 180° in betatron phase upstream of the injection point, hence the positive dispersion produced by this action is translated to a negative dispersion at the end of the line. Also, since the values of the amplitude functions through the line and at the injection point are roughly 20 meters and 70 meters respectively, then the resulting value of the dispersion function is amplified by a factor of $(70/20)^{1/2} \sim 2$. The resulting dispersion functions are shown in Figure 1.

The horizontal dispersion function through the Cells was made to alternate from large to small values intentionally to provide a method for performing useful beam measurements. The Booster Match quadrupoles plus the first bend center modify D_x so that at the entrance to the Cells, $D_x = 4$ meters and $D'_x = 0$ in the middle of the sixth quadrupole. Because the phase advance between each quadrupole is 45° throughout the Cells, D_x will oscillate between 4 meters and 0 meters every other magnet while the amplitude function remains at the same value of $\beta_{max} = 27$m at every other magnet. By obtaining measurements of horizontal beam profiles at alternating β_{max} locations through the Cells, the horizontal transverse emittance may be determined as well as the momentum spread of the extracted Booster beam.

Magnets and Power Supply System

The new 8 GeV Line contains four primary horizontal bend centers and two primary vertical bend centers. A Lambertson-style magnet, which has a strong field region and a "field-free" region separated by a thin septum, is used for the final horizontal bend. The magnetic elements used for the other five bend centers are ones used in the old beamline. For the focusing elements of the new line, small aperture quadrupole magnets originally designed for use in the Tevatron I project antiproton storage rings were chosen.

In addition to the primary bending and focusing elements, seven position correction bending magnets also are provided. Five of these magnets had been used in the old beamline and the two additional correction dipoles again come from a Tevatron I project design. The maximum angles which may be produced by these magnets are less than three percent of those of the major bending elements.

Current for all elements mentioned above is produced via standard commercially available power supplies which are distributed among five already existing power supply galleries. All devices are operated DC and most elements have independent control.

Injection System

The solution to the vertical dispersion function match necessitated lowering the beam trajectory to roughly the Main Ring level 300 ft upstream of the injection point. The beam then had to be steered horizontally onto the the Main Ring horizontal closed orbit. The Lambertson-style magnet provides the 35 mrad final horizontal bend. The ideal trajectory leaving the Lambertson then has the proper horizontal position and slope yet is positioned 30 mm above the Main Ring closed orbit (which passes through the "field-free" region of the magnet). Using the last two vertical position correction magnets immediately upstream of the Lambertson, this displacement of 30 mm may be maintained while a downward slope of 0.7 mrad is produced. The beam will then arrive with zero vertical displacement at the same pulsed kicker magnets which were present in the old injection system. These pulsed magnets complete the injection process by cancelling the downward slope, placing the beam onto the proper vertical closed orbit.

Also included in the injection system are four dipole magnets which reside in the Main Ring long straight section, two on either side of the Lambertson magnet. These four magnets, powered in series, provide a local vertical displacement of the Main Ring closed orbit of 30 mm, reducing the amount of kick necessary from the kicker magnets.

Diagnostics

Several improvements were made to the diagnostics system for the 8 GeV Line. A new microprocessor based system was developed for gathering and analyzing the profile monitor data. The wire planes may be inserted into the beam path from an applications program on the accelerator controls system and data from all monitors may be processed simultaneously. When in the beam path, the microprocessor automatically computes the mean and variance of the particle distribution as well as a goodness of fit compared to the normal distribution. The data may be read and the computations performed at a 15 Hz rate, which permits the analysis of beam from all Booster synchrotron cycles. The computed values are automatically updated in the accelerator controls system data base and may be plotted real time from a computer console or stored in files for future analysis.

Noninteracting beam position monitors (BPM's) are also distributed throughout the new 8 GeV Line. The BPM's are cylindrical stripline detectors similar to those used in the Tevatron accelerator.[1] The BPM's have been calibrated to provide position information via the accelerator controls system to within ±0.2 mm near the center of the detector.

The output of the position detectors is processed through standard Tevatron-style BPM electronics[2] with positions being obtainable from existing accelerator controls system software. At the injection and extraction regions, both horizontal and vertical signals from several BPM's allow precise measurements of the beam trajectories at these points.

Commissioning of the New 8 GeV Line

By the end of July, 1986 beam was being extracted from the Booster accelerator and being transported to the 8 GeV beam dump using the upstream elements of the new beamline. On August 2, 1986 beam was first transported through the entire beamline to the Main Ring synchrotron. To study the new 8 GeV Line and the injection process, the Main Ring beam abort system was set up to dispose of the beam on its first passage through the synchrotron.

Correction of Beam Trajectory

Originally, the position of the beam as seen on the beam position monitors (BPMs) was tuned manually using the correction elements discussed earlier. An automatic beamline position correction program has been developed which runs on the accelerator controls system from the Main Control Room.[3] The program calculates corrector strengths necessary to minimize beam displacements from desired positions. The program may then send these changes to the appropriate devices automatically and iterate through this procedure until the positions are within a designated tolerance.

As a result of the beam trajectory correction, the maximum position errors throughout the line are less than 3 mm for each plane. The average corrector strength is approximately 0.2 mrad and the maximum corrector strength is 0.6 mrad, far below the design maximum correction of 1.5 mrad.

The injection positions have been adjusted to within $\Delta x_{max} = 1.0$ mm of the Main Ring closed orbit for both the horizontal and vertical planes. For a 1 mm Δx_{max} and a typical beam size of $\sigma_o = 5$ mm, the amount of dilution of the transverse emittance due to position mismatch would be roughly

$$\sigma^2/\sigma_o^2 = 1 + \Delta x^2/2 = 1.02.$$

Emittance Measurements

Since the beginning of the new 8 GeV Line operation, emittance measurements have become rather routine. With the new microprocessor-based system and associated applications programs, profile data may be obtained and analysed with ease. Using the variances computed by the microprocessors, the beam sizes may be plotted in real time on a color graphics display in the Main Control room. One such plot, shown in Figure 3, allows the horizontal normalized emittance and the variance of the momentum distribution to be read.

Dispersion Measurements

On December 9, 1986 an attempt was made to measure the dispersion functions through the 8 GeV Line and determine the amount of mismatch of these functions to those of the Main Ring by recording BPM signals as the Booster RF frequency at extraction was varied. The vertical dispersion function obtained from the measurements described above is displayed in Figure 4 along with its design value. Within the accuracy of the measurement the values are in good agreement. The second half of this figure comes from BPMs within the Main Ring, showing that the vertical dispersion function is well matched to that of the machine. The beam was being aborted on the first turn and hence beam was not observed past the position labeled "CO" where the abort system is located.

Subtracting the two curves in Figure 4 and finding the maximum value of this difference yields ΔD_{max} = .5 m and, taking σ_o = 5 mm and $\sigma_p = 0.8 \times 10^{-3}$ in agreement with profile monitor data taken during the same study period, the dilution factor due to dispersion function mismatch is 1.003 in the vertical plane. Unfortunately problems encountered during the study period deemed the corresponding measurements of the horizontal dispersion function unreliable.

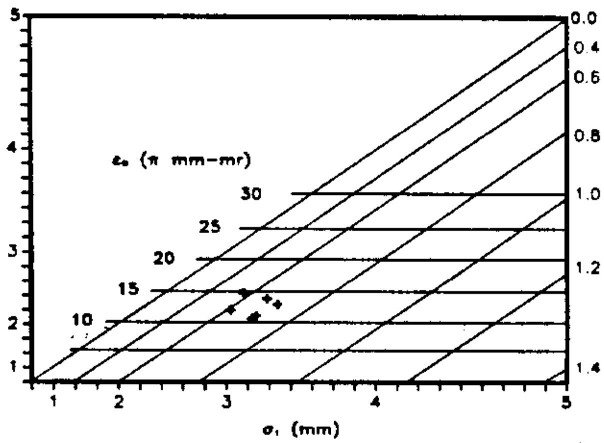

FIGURE 3 - Measurement of Booster emittance.

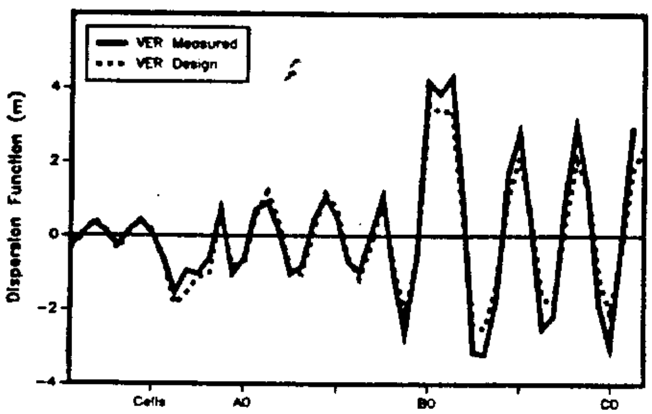

FIGURE 4 - Measurement of vertical dispersion.

Amplitude Function Measurements

By aborting the beam during its first revolution, the signals obtained from the profile monitors located within the Main Ring accelerator reflect the initial distribution of particles being delivered by the 8 GeV beamline. The emittance of this beam may be obtained by profile measurements using the monitors within the Cells region of the beamline. Hence, the amplitude functions at the locations of the Main Ring profile monitors being delivered by the beamline may be obtained and compared with design.

Eight profile monitors reside within the Main Ring at the locations of the first eight quadrupole lenses past the injection straight section. If the matrix $M(s_i/s_o)$ which transports the transverse beam trajectory (x,x') from location s_o to location s_i is known, then the value of the amplitude function at s_i will be

$$\beta_i = a_i^2\beta_o - 2a_ib_i\alpha_o + b_i^2\gamma_o$$

where a_i and b_i are the 1-1 and 1-2 elements of the matrix $M(s_i/s_o)$ and $\gamma_o = (1 + \alpha_o^2)/\beta_o$. By obtaining measurements of β_i at various profile monitor locations, an estimate of β_o and α_o at a particular reference point may be determined.

A program has been written which runs on the accelerator controls system that analyzes profile monitor data to obtain estimates for β_o and α_o.[4] The effects of momentum dispersion on the beam size are subtracted and a grid search is performed which varies the values of β_o and α_o in an attempt to find the minimum of $\Sigma(\beta_i - a_i^2\beta_o - 2a_ib_i\alpha_o + b_i^2\gamma_o)^2$, where here, β_i is the measured value of β at the ith monitor. Results of vertical profile measurements taken December 9, 1986 yield an estimated value for the vertical dilution factor of 1.02. From horizontal profile data taken the same evening, the horizontal dilution factor due to amplitude function mismatch is 1.2. It is believed that most of this horizontal emittance blow-up was caused by a problem of beam loss on the Lambertson magnet which was not recognized until after the study session was over.

Concluding Remarks

Several improvements were indeed made to the 8 GeV beam transport system. The sensitivity of the transverse emittance growth due to errors in the gradients of the quadrupole magnets was significantly reduced. The mismatch of the vertical dispersion function was resolved. A new injection scheme aided in the vertical dispersion matching process and replaced a rather questionable piece of hardware from the previous beamline. In addition, upgrades to the profile monitor system as well as an optical design more congenial to beam measurements have improved the diagnostic capabilities of the line. The quality of the magnetic elements in the line was also improved through the use of Tevatron I project quadrupole magnets and the new injection Lambertson magnet. Detailed magnetic measurements have been performed on all of these new devices.

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1. Shafer, R. E., R. C. Webber, and T. H. Nicol, "Fermilab Energy Doubler Beam Position Detector," IEEE Trans. Nucl. Sci., Vol. NS-28, No. 3, June, 1981.

2. Baumbaugh, A. E., et. al., "Beam Position Monitor System for the Fermilab Tevatron," IEEE Trans. Nucl. Sci., Vol. NS-32, No. 5, October, 1985.

3. Development of this program courtesy R. Joshel, FNAL

4. Development of this program courtesy D. E. Johnson, FNAL.