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ATTAINMENT OF 500-GEV BEAM IN THE FERMI LAB SYNCHROTRON

The Fermilab Staff
(Presented by: F. Turkot)

Fermi National Accelerator Laboratory*
Batavia, IL 60510

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Summary CONF-770313-114

A successful experiment to accelerate a proton beam to 500 GeV in the Fermilab synchrotron is described.

1. Introduction

In the early morning hours of May 14, of last year the accelerator status display of Fig. 1. appeared on all of the TV monitors at Fermilab; it heralded the achievement of one of the basic design goals¹ of the Fermilab accelerator, viz., acceleration of a proton beam to 500 GeV. Acceleration to the 400-GeV level was first achieved in December of 1972, and has been the standard operating energy since the installation of the 100 MVA pulsed-power transformer in July, 1975.

Fig. 1. Monitor display of ramp and beam.

The main ring magnet system for the Fermilab synchrotron was designed to have adequate aperture to accelerate and efficiently extract beam up to 400 GeV.¹ At this energy the field in the bending magnets is 17.9 kG and at the pole tip of the quadrupoles is 10.0 kG ($QH=QV=19.4$). Individual magnets are routinely tested to fields equivalent to 500 GeV; as seen in Fig. 2, saturation of the iron results in a 20% decrease in field per unit current at this excitation and a substantial change in field distribution is observed.² The B1 bending magnets (3.81 cm vertical gap) saturate more than the B2 (5.08 cm gap), yielding an ~1% smaller bending power at 500 GeV; since they occur in roughly equal numbers and are in series on a common current bus, a closed orbit distortion will result. The most important departure from linearity of the fields is the sextupole moment in the bending magnets; its calculated effect on QH for an orbit 15 mm on the inside is shown by the dashed line in Fig. 2. A linear lattice would have a shift of $\Delta QH=+0.11$. An earlier analysis of the field distortions³ indicated that there should be sufficient aperture to accelerate to 500 GeV and execute single-turn extraction, but that slow extraction might be difficult.

The system⁴ which powers the main ring magnets is voltage limited to an equivalent beam energy of ~425 GeV. It was recognized in 1973 that one could raise the power supply capability to ~500 GeV by the addition of a series capacitor bank (referred to as the Captree⁵) in the 13.8 kV ac power feeders between the main transfor-

Fig. 2. Magnetic saturation effects.

mer (100 MVA) and the sixty-one individual dc power supply transformers (3 MVA). This capacitor bank compensates the reactive current due to the leakage inductance of the transformers, resulting in a 37% higher voltage capability at the output of the dc power supplies. The Captree⁵ became operational in April 1976 and shortly thereafter it was decided to attempt 500 GeV.

2. Anticipated Problems

The magnet current at 500 GeV (~6700 A) exceeds the peak ratings of several of the components in the dc power supplies, making unclear at the outset precisely what level would be possible. Immediately preceding ramping the magnets to excitations greater than 400 GeV, a "no fire" run of all sixty-one dc power supplies was carried out; this is important to prevent damaging power supplies. The full bus current is carried by three SCR's in parallel; if one of the three is inoperative (a "no-fire"), the other two will be overloaded and a catastrophic failure ensues. A second precaution was a full-ring inspection of the bus and magnet system with power on at 450 GeV; no foreboding effects due to the higher mechanical and thermal stresses were uncovered.

The early portion of the accelerator ramp (i.e. energy vs. time) for higher energy is identical (see Fig. 3) to the standard 400-GeV ramp, the anticipated problems in establishing beams are then: (1) different remanent fields at injection, (2) closed orbit distortions above 400 GeV, and (3) betatron tune regulations for the portion of the ramp above 400 GeV. Precision tune regulation is accomplished by regulating the currents in the D and F quadrupole busses normalized to the current in the bend bus. The desired quad currents for a desired tune are obtained by interpolation from an empirical table of tune vs. quad currents. The table is obtained by simultaneous measurement of tune and bus currents with real beam. The linear interpolation formulae are derived from the machine lattice and magnetic measurements of the quads in the unsaturated region. The tune regulation is therefore a bootstrap procedure. The main ring had been operating at a tune of ($QH=19.4$, $QV=20.4$) for five months prior to this endeavor.

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Fig. 3. Magnet current ramp and beam.

3. The 500-GeV Odyssey

The realization of 500-GeV beam was the culmination of an intensive three-day effort starting on May 11, 1976. Since it was unclear just where the ultimate limitation might occur, it was decided to raise the magnet ramp and beam energy in three steps, first to 450 GeV, then 480 GeV, and finally 500 GeV.

Approximately 20 minutes after the 450 GeV magnet ramp was established, a low intensity beam (1.5×10^{12} ppp) was accelerated close to flattop after only minor injection tuning. To reach 450 GeV, empirical tune bumps starting at ~400 GeV were required, of values $\Delta Q_H = -.04$, $\Delta Q_V = +.13$. Beam loss above 400 GeV was caused by QH approaching 19.5; this resulted from the fact that the tune table had been linearly extrapolated from 400 to 450 GeV, the higher starting value of QV causes greater saturation in the D quads relative to the F quads, allowing QH to rise. Fast single-turn extraction to the beam dump was quickly accomplished. Encouraged by the ease of achieving 450 GeV, the 480-GeV ramp was activated; after four hours of effort - much of the time occupied with magnet power supply problems - a comparable beam was accelerated to 480 GeV (now only a 100-ms flattop) and fast extracted. As with 450 GeV, opposite sign tune bumps were required ($\Delta Q_H = -.27$, $\Delta Q_V = +.17$) to keep QH away from 19.5. A series of tune measurements were then made from 400-480 GeV in order to construct an improved tune table. At the end of this first day's effort a brief attempt was made to establish a 500-GeV ramp, it was terminated by a frightening ferroresonance trip of the Captree system before reaching 500-GeV currents in the magnets.

The second day began with the 480-GeV ramp; accelerated beam came more easily with the help of the improved tune table. Then followed a nine-hour assault on 500 GeV. Numerous power trips from several sources were encountered, the most worrisome being those involving the Captree, which usually were accompanied by a highly visible shower of sparks (celebrating our Bicentennial Year!). At day's end it had become clear that the power supply system did not quite have sufficient voltage to reach the magical 6730 A in the bend bus, the highest reached was 6642 A; another 3% was needed in the D quad bus.

Before commencing on the third day, it was decided to take some extraordinary measures that would ensure enough voltage to make 500 GeV, that included: (1) raising the voltage tap on the 100 MVA transformer (+2.2%), (2) lowering the magnet temperature 2.8°C (+1%),

and (3) reducing QV from 20.4 down to 19.4 (+3%). With these changes, beam was first obtained with a 400-GeV ramp and injection closed orbit corrections made to adjust to the lower vertical tune. The 500-GeV ramp was then installed; during the first few cycles the beam current exceeded 6800 A, giving confidence that one at last had sufficient voltage. About one hour later, after a minor adjustment of a constant in the power supply control computer and the addition of several unphysical-looking tune bumps, 500-GeV beam became a reality. An additional two hours were required to tune-up single-turn extraction to a target in the Neutrino Lab, after which an experiment in the Internal Target Laboratory and the 15' bubble chamber proceeded to utilize the beam for data-taking. The accelerator ran for ~7 hours at 500 GeV, yielding 6 hours of useful beam time. The main parameters of the 500-GeV operation are summarized below.

Parameters of 500-GeV Operation

Beam Kinetic Energy	501.5 GeV
Beam Intensity	1×10^{12} ppp
Bend I, B	6.725 kA, 22.4 kG
F Quad I, C	6.035 kA, 298 kG/m
D Quad I, C	6.010 kA, 297 kG/m
H and V Tune	19.4, 19.4
Peak Magnet Power	325 MW
Cycle Time	18 s
Extraction Mode	Single Turn

4. Closed Orbit Measurements

Only a limited time was available to take measurements on beam behavior above 400 GeV. The most noticeable effect occurred at 480 GeV and above; the horizontal profile of the beam (as seen on the Ion Beam Scanner display) was observed to undergo a rapid shift to smaller radius together with an asymmetric broadening. The closed orbit at 400, 480, and 500 GeV, as measured during a single ramp, are exhibited in Fig. 5. The signature of any closed orbit distortion due to saturation is not obvious; it is masked by rather large momentum shifts, nearly 0.5% at 480 GeV. To compare the 400 and 500 GeV orbits, a momentum correction of 0.18% was applied to the 500 GeV orbit, the two were then subtracted and averaged over all six superperiods. The result is given by the solid curve in Fig. 5; the dashed curve is a calculated distortion⁶ assuming that the B2 dipoles are 1% stronger than the B1 dipoles. The reason for the large momentum shift now becomes clear; the horizontal position detector that supplies the feedback signal for the rf radial position control loop is marked on Figs. 4 and 5. It sits at a positive maximum of the closed orbit distortion; as the distortion grows the mean radius of the beam is decreased in order to keep its radius fixed at that detector. The behavior at 480 GeV is complicated by the fact that the rather large, empirical tune bumps ($\Delta Q = +1$) were rapidly changing at that energy, probably causing an undesirable excursion in the actual oscillation frequency.

5. Recent Intensity Records

In addition to the new energy record, substantial improvements in the maximum intensity at all stages of the Fermilab accelerator have been established in recent months. The following table summarizes these new records along with two indicators of integrated performance; the number of protons for linac and booster represents 13 cycles worth, i.e. the standard number used to fill the main ring.

Fig. 4. Closed orbits for 500 GeV acceleration.

Fig. 5. Average closed orbit distortion at 500 GeV.

Fermilab Accelerator Current Performance Records

Linac (4 μ s pulse)	300 mA (6.8×10^{13} p/MR Cycle)
Booster	3.0×10^{13} p/MR Cycle
Main Ring	2.5×10^{13} p/Cycle
Accelerated Protons/ 3 Months	6.6×10^{18}
Average Hours/Week of HEP (1976)	106 Hours.

6. Conclusion

The experiment of last May to explore the upper limits of the acceleration capability of the Fermilab Main Ring established the following facts:

a) The magnet power supply system - with Captree - can excite the magnets to the 500-GeV level at a tune of (19.4, 19.4); 60 out of the 61 dc power supplies are required to do so,

b) A low intensity ($\sim 1 \times 10^{12}$) beam can be accelerated to the full energy; same beam loss above 450 GeV is

observed, probably associated with (avoidable) variations in tune,

c) At 500 GeV the beam can be extracted with reasonable efficiency using the fast kicker for single-turn ejection,

d) The averaged closed-orbit distortion (± 10 mm) is fairly close to what is predicted from measured saturation effects in the bend magnets.

e) The accelerator ran for a nearly-continuous period of 7 hours at 500 GeV without major failures.

Acknowledgments

The present staff of the Accelerator Division enjoyed the privilege and excitement of pushing the main ring to one of its major design goals. The foundation for this achievement was laid by the original designers some ten-years ago; the realization was only possible through an accumulation of contributions by many members of the Fermilab staff in the interim.

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