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THE ENERGY SAVER TEST AND COMMISSIONING HISTORY

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Introduction

Beam was first injected into the completed Energy Doubler[1] Superconducting Accelerator on June 2, 1983. Accelerated beam was first achieved on July 3, 1983, and resonant extracted beam first sent to the Beam Switchyard area on August 2, 1983. These events were the culmination of ten and a half years of R & D, tests, construction, and installation of the new accelerator system in the Main Ring tunnel. The final goal of a 800 to 1000 GeV proton beam at $\sim 2 \times 10^{13}$ppp for fixed target physics[2,3] and $\bar{p}$-p storage and collision[4] at $10^{30}\text{cm}^{-2}\text{sec}^{-1}$ must await further tuneup and the construction of the $\bar{p}$ source (TeV I).

In this paper a brief history of tests, fabrication, and installation will be given. The events and problems encountered during commissioning are recounted. Early measurements of beam properties are discussed. Some of the operational reliability problems are outlined.

What Is Different in This Accelerator?

The Superconducting Magnet design and measurements have been discussed in detail elsewhere[5-9] and will not be covered here.

The use of superconducting magnets in a large accelerator brings with it the necessity for major new engineering systems and their control. Together the magnitude of the overall amount of equipment, system complexity, and fragility of these new utility-like systems not only dwarfs the corresponding components of the conventional accelerator, but also influences their design. It is imperative that the conventional components work effectively so that during early stages of commissioning, when overall reliability is not high, progress can be made toward obtaining an accelerated beam.

The superconducting magnets require a large cryogenic system to supply both liquid helium at 4.8 deg K and liquid nitrogen. The cryogenic system for the Energy Doubler provides 24KW of cooling at 4.8 deg. The operation of this system is discussed elsewhere in this Conference.[10]

The Energy Saver magnets require an "active" quench protection system[11] so that the magnet conductor is not damaged by overheating when a magnet goes normal and "quenches". The active protection system continuously monitors voltage across the magnet cells (about 250 points) and detects any resistive component greater than one half volt at a 60Hz rate. Upon quench detection, three things happen: a) Stainless steel strips in the magnets adjacent to the coil are heated by discharging capacitors into them thus causing uniform energy absorption in the quenched cell and reducing overheating at isolated spots. b) The main bus current is diverted around the quenched cell through a bypass circuit external to the cryogenic system. c) The main power supplies are bypassed and dump resistors are enabled so as to extract the total ring stored energy (350MJ at 1000 TeV) with a 12 sec decay time constant. The quench protection system is a ring-wide system with 24μ processors (one in each service building) which are in constant communication with one anaother. Each is constantly checking voltage reading from its part of the magnet string. Any missed communication or noise can potentially turn off the magnet power system and/or quench the magnet accidentally.

The vacuum system[12] for the superconducting magnets is much more complicated than for a standard accelerator. The system consists of an outer vacuum jacket with four isolated inner volumes each of which must be leak tight to the insulating vacuum. These volumes are: a) the bore tube high vacuum region in which the beam runs; b) the single phase helium space; c) the two-phase helium space; d) the nitrogen shield space. Not only must one provide pumps and instrumentation for the two separate vacuum systems, but during installation, leak checking must be performed on the four separate internal volumes where the flange joints are not externally available for classical leak check procedures. One potential advantage is that the beam vacuum bore tube is at low temperature and provides very low pressure. Past discussions have raised the question of possible beam-vacuum instability problems.[12]

Because of worry about the feasibility of the operation of the cryogenic system, the quench protection system, and the vacuum system, special efforts were made early on in order to develop workable engineering plans both for implementing the systems and successful installation procedures. Very substantial efforts were required from the electrical engineering and controls groups in order to meet the demands of the "utility systems" on a timescale which allowed for test debugging and refinement of techniques before the scheduled start of beam operation.

Superconducting magnets are sensitive to beam loss and have magnetic field characteristics different from iron magnets. Within the conventional accelerator systems, particular attention has been given to the correction and adjustment coil system and to the beam position and loss monitor system.

The beam position and loss monitor systems[13] were planned with the view that one wanted to obtain the most information possible from a single shot of injected beam. If the magnets quenched from the beam being mis-steered, corrective action could be taken during the quench recovery time (typically, 10 minutes to 2 hours) and the beam could get further on the next pulse. Special attention was also given to being able to run at very low intensity (10^{10}p) so as to reduce the magnet quench probability. Specific attributes with the system are:

a) One turn position and intensity information.

b) Closed orbit and loss measurements at many energies (times).

c) The ability to abort the beam (single turn, fast extract) on adjustable position or loss thresholds.

d) Circular buffer memory to record data prior to an abort trigger.

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*Operated by the Universities Research Association, Inc., under contract with the U.S. Dept. of Energy.

e) Turn-by-turn position information for up to 1024 turns at two positions in the ring.

The one-turn position information, coupled with the one-turn abort system, and beam loss information proved to be very effective in locating obstacles in the aperture and in obtaining correct injection conditions including guide field setting. The one-turn and closed-orbit information can be relayed to a program that determines dipole correction coil adjustments. As it turned out, the closed orbit did not change appreciably with excitation making the problem of accelerating to higher and higher energies less arduous than expected. The ability to abort the beam on loss has been of substantial use in trying to go to higher intensities, especially during extraction time. The turn-by-turn position information has been of great value not only at injection time for minimizing coherent betatron oscillation mismatch, but also for minimizing injection guide field mismatch and for doing tune measurements at any excitation in conjunction with a "pinger" to induce coherent betatron oscillations.

The correction coil system[14] is composed of corrections and adjustments for steering, tune and chromaticity control, and resonant extraction control. The system allows for programming control of all circuits from injection to full excitation. It is desirable to be able to center the beam accurately with dipole corrections at any excitation thus making full use of the available aperture. This is particularly true at extraction time when the resonant beam is making large excursions. The system allows for any unexpected shift or rotation of the main magnets with excitation, quench, or upon a warm-up/cool-down cycle, without recourse to magnet realignment which is somewhat risky to the vacuum integrity. Though the initial magnet survey alignment[15] and stability of the superconducting magnets so far seems good, the advantages of the full excitation corrections in terms of operational convenience seems well worth the expense in this machine and in any future large accelerator where strength of superconducting correction is not a problem.

The control system here again plays an essential role in the success of these sophisticated correction and detection systems.[16,17] Extensive use of micro-processors to provide local control curve generation and data storage has been a fundamental feature of these systems.

Magnet String History

The importance of the test efforts carried out during the Energy Saver R & D and Contruction Phase cannot be emphasized enough. These test efforts included: 1) vertical dewar tests of short magnets and cable in order to measure quench propagation, to conquer coil motion, training and quench current restrictions of the basic coil package; 2) both room temperature and cold magnetic measurements to obtain and maintain the necessary field quality and reproducibility during prototyping and construction; 3) the establishment of the B12 test area (an above-ground magnet string test area located near station B12 of the Main Ring tunnel); and finally, 4) tunnel system testing in A Sector.

The B12 test area was where installation and vacuum problems were first addressed, then cryogenic operation, then quench propagation in the magnet string environment. Also, quench protection, power supply, vacuum, refrigeration and control systems prototyping was done here. Tunnel tests were done on individual magnets, on strings of prototype magnets and on the A Sector R & D final system. This progression from single component tests to the final large integrated systems tests over the period of about nine years undoubtedly has been of paramount significance in the rapid turn on and commissioning of the accelerator.

Table I lists some of the milestones associated mostly with the B12 and tunnel tests. It does not go into any of the development of magnet coils or magnetic measurements. Talk on the idea of a superconducting magnet system started as early as September of 1970, but no serious discussions began until the Fall of 1972 after the Main Ring accelerator had begun operation at 200 GeV for fixed target experiments. Real organized and committed R & D effort on the Energy Doubler began in the first part of 1973.[18] By 1975, two tests had been carried out where prototype magnets had been installed in the tunnel and beam transported through them. Not only were these installations basic milestones in the construction of cryogenic systems, but also they gave valuable data on the sensitivity of superconducting magnets to beam loss.

Early in 1976, the B12 test area was started with one 10-foot magnet. Tests continued until late Spring of 1981 when the start of final installation in the tunnel took priority. The B12 area was reconfigured a number of times. It progressed to two 10-foot magnets, then two 22-foot magnets, then a four dipole string which could not ramp above 2000A because of an inadequate relief valve system. The next configurations had two half cells of magnets, then four (one quad and four bends per half cell). The bends were still of the longer 22-foot variety. The final configuration had four half cells of the final ring quality magnets and also final correction coil spools. A number of the configurations were changed when the tests terminated with the magnets blowing up.

Tunnel tests on magnet strings were carried out in two steps prior to the final ring installation shutdown. At the end of 1978, five half cells of magnets were successfully installed, made leak tight, and cooled down. A 100 GeV beam was extracted from the main ring and transported through these magnets for 500 feet. Even though these magnets could not be ramped to appreciable excitation because of lack of quench protection heaters, this was another important step in system development as well as a further test in transporting beam through magnets. One learned about how to survey the magnets (there were no correction coils), learned about quenches from injection errors, and to some extent, field stability after quench, and also tested the position detector system.

The most significant and final test program, "The 3/4 A-Sector Test" was carried out in the first half of 1982.[11,19] It represented a full system test of 1/8 of the final ring components and controls. It tested to full potential all of the cryogenic systems and pressure piping, the power supply system and quench protection system. Extensive tests were performed to determine the possibility of voltage-to-ground breakdown of the electrical system during quench. The successful carrying out of this test was the final step in development of an overall system which would be reliable enough for operation when beam commissioning started about one year later.

Magnet Installation

The dipole production and installation time schedule is illustrated in Figure 1. It stretched over a four-year time period, beginning in the Summer of 1979, when the decision to shorten the bend magnets from 22-feet to 21-feet was made in order to allow dedicated space for correction coils (instead of building them in the quadrupole magnet). The construction authorization for the project was given at this time and new shorter coils were soon available. Availability of complete magnets lagged because of a failure problem found in the anchor system which tied the coil assembly to the outside of the cryostat. The learning curve is apparent both in the magnet production and in magnetic measurements. Coil production dropped off in 1982 because of problems in obtaining conductor. The gap between the curve of "measurement complete" and "available for installation" reflects not only the delay for paperwork between the time of measurement and the time at which the data became available, but also the need for a buffer from which to sort and select magnets to compensate for the variations in sextupole moment. It also reflects the fact that a number of magnets required rework in order to bring them up to the quality of the acceptance specification.

Initial installation proceeded during a shutdown in the Summer of 1981, for a month at the end of 1981, and then the final installation started in June of 1982 with the last magnet going in the ring on March 18, 1983. Leak checking was first carried out on strings of four dipole magnets, then quadrupoles and spoolpieces were installed for final leak check. Generally, special components were not quite ready when first needed but did not hold up leak check appreciably because of the option of moving and working in other sections of the tunnel.

Near the end of installation, the time delay between when magnets were first moved into A-Sector and when the string was finally cryogenically cold was six months.

Manpower for tunnel magnet installation, survey, flange hookup and vacuum leak check took at peak about 54 people total. The total time period, counting work done in 1981, was about 15 months. The manpower distribution was: 10 for installation, 2 to 4 for survey, and 40 for magnet flange interface connection and leak check. (An interface is the joint between two magnets or magnet and correction coil spool. Work involves bus splice connection, making up four small flange connections and the one large external flange.) By far the largest effort went into this interface and leak check work. It is estimated that it took 50 manhours per interface with a total of 1200 required.

Handling damage during installation continued to be a problem throughout installation and many repairs were required in places in the tunnel. Vacuum leaks in components ran about 3% for the dipoles to about 13% for the spools and special components, even though all components were leak checked prior to installation. The low leak failure of dipoles indicates the superior quality control of the large quantity devices.

Part way through installation a very high failure rate of >25% of the lead coated, inconel vacuum C seals was experienced. This practically brought leak checking progress to a stop. New type seals, with aluminum shell around inconel springs (Helicoflex), reduced all failures to an insignificant level.

There were worries that hipot of the magnets might be a problem, but no real difficulties were encountered during installation.

Specific failures that required warmup after initial cooldown, and remaining known faults are fortunately small enough to enumerate. Two cryosections (each 1/24 of ring) required warmup because of leaks and broken ceramics on correction leads. One dipole with a turn-to-turn short was found. (Later, when the collared coil was removed from the cryostat, the short disappeared.) Two splices of the power bus at interfaces were not soldered during installation. Six beam detectors near the straight section were in the wrong orientation and five others had internally broken electrical connections out of over 200 units. Three correction magnets out of about 700 had low impedance (<30kΩ) to ground. Leaks in the insulating vacuum at eight locations required additional external pump carts to maintain sufficiently good vacuum.

Power Tests and Commissioning

Power test commissioning history is given in Table II. A total of 46 days over a four-month period were required (not counting the 3/4 A-Sector Test) to test the quench protection system and ramp the magnets to 500 GeV excitation. During this time, the one magnet with a turn-to-turn short and two bad spliced joints were discovered. This fast turnon did not allow much time for the system reliability to be hardened as was reflected in later operation during beam tests.

Beam Test and Commissioning

A chronology of the beam tests and commissioning period is given in Table III. The beam tests started April 22, 1983, with two weekends devoted to single pass beam through E and F Sectors (one-third of the ring) before the full ring was completely installed and powered. Beam was transported through the two sectors within about 15 hours after first starting to inject. The major confusion during this exercise occurred because the first four out of five horizontal detectors were reversed in polarity (very few reversals were found in the rest of the ring). The rest of the time during these weekends was spent in testing the injection kicker (not required for single pass), injecting into ramping magnets, and exercising a correction dipole tuning program and exploring the aperture.

Beam was not injected again until June 2 when the ring was complete, though limited to 100 GeV excitation because of the bad bus splices. The correction coil settings scaled from the April run were used in E and F Sectors and one turn of beam obtained within two hours of available beam time. The initial first turn beam position data is shown in Figure 2. Beam is injected at the beginning of E Sector. Only a few steering corrections (∿6) were set in Sectors A, B, C, D.

An indication of up to 13 turns was obtained before turn off two days later for warmup and repair of the bad bus splices. There was no real time intensity signal available and the indication of turns came from the position detector turn-by-turn measurement via the computer and perhaps was not the most credible of measurements.

Startup at 150 GeV injection began on June 17 with 150 GeV DC excitation. Up to 20-30 turns were obtained rather quickly but attenuation from turn-to-turn was severe. Over the next eight days, three aperture restrictions were found. The ability to look at single turn beam positions and the ability to stop the beam after a fraction of a turn or after one and a half turns, either by using the single turn extraction abort system, or by kicking the beam into straight sections using the strong dipole corrections, was of great help in finding these problems. There could be no confusion about losses from multiple turns. In the abort straight section CØ, we found that an error had been made in the design of some beam pipe and it severely limited the aperture. In the AØ extraction straight section, a wad of paper was found at a flange joint where it had been forgotten after modification to the pipe. At station E47 in one of the cryogenic regions, an obstacle was detected which appeared to cover the lower half of the beam pipe. Beam could be steered around it without difficulty. Upon subsequent warmup of the region much later, nothing was found. Once the obstructions were corrected, coasting beam was easily obtained and the RF was turned on and acceleration checked by moving the radial position with the RF system.

Once 0.8 sec of good beam to the abort time was established, ramped excitation first to 250 GeV then to 512 GeV began. Beam accelerated with only minor difficulty. Dipole correction coils are automatically scaled with energy and needed little charge with excitation.

Acceleration to 512 GeV was obtained on July 3, 1983, after about 210 hours of available system uptime and about 20 operating days from the start of full-ring operation.

After beam had been accelerated to 512 GeV, numerous measurements and adjustments at flat top were taken in order to prepare for resonant slow extraction. These measurements included: tune, tune vs. radial position ($\Delta p/p$), and horizontal/vertical coupling. Adjustments to the chromaticity and minimization of the coupling was performed. The zero harmonic octopole adjustment circuit was tested by measuring tune vs. radial position with and without it. The horizontal half-integer stop band width was measured by adjusting the tune quads through the half-integer region and finding the region of beam loss. The 39th harmonic ($\nu \cong 19.4$) adjustment quads were calibrated by using them to drive the beam to resonance.

These measurements took about three weeks (165 hours available uptime) with an interruption of one week downtime to change a clogged filter in the Central Helium Liquefier cold box. On August 2, 512 GeV beam was successfully resonantly extracted and transported to the beam dump in the beam switchyard area.

Beam Measurements and Comparison with Magnetic Measurements

The average and standard deviation of the main dipole and quadrupole multipole fields are given in Table IV. for the magnets installed in the tunnel. Correction coil circuits are listed in Table V. Computer programs[20] allow for tune or chromaticity control in one dimension (x or y) without appreciably affecting the other by simultaneous adjustment of pairs of circuits.

Some measurement results at 512 GeV are summarized here. The tune (horizontal or vertical) could be made flat to $\Delta\nu=0.01$ over $\pm 0.28\% \frac{\Delta p}{p}$. Beam could be maintained at an off momenta orbit as large as $0.35\% \frac{\Delta p}{p}$ with some loss. Under this circumstance, orbit excursions as great as 21 mm are typical at the x_p max locations. The ν_x-ν_y tune difference could not be reduced below $|\nu_x-\nu_y| \sim .01$ with the skew quad adjustment. Current required in the skew adjustment as a function of energy is given in Figure 3 and could be accounted for by an average value of the a_1 multipole moment of 1 unit ($\frac{\Delta B}{B} = 10^{-4}$ at 1 inch) in the main dipoles. This is inconsistent with Magnet Test Facility (MTF) data. The half integer horizontal stop band width (total) is $\Delta\nu_H=0.007$, about what is predicted from the b_1 multipole variation.

The natural (uncorrected) tune of the machine is given in Figure 4 as a function of energy. The average of ν_x and ν_y is about what is expected from magnetic measurements, however, the tune split is about what might be caused by an average b_1 dipole multipole of 1.5 units. Here again the MTF data does not indicate this.

Figure 5 shows the chromaticity setting C that is required in order to achieve zero measured chromaticity (ξ). Ideally, the computer program which generates the curves for the correction circuits puts in compensation for the known $\langle b_2 \rangle$ of the dipoles as measured at MTF. An average value of b_2 of up to 1 unit is not accounted for. It can only be remarked that one multipole unit is equivalent to 2 gauss at 1 inch out of 20 kG at 500 GeV.

Figure 6 shows the measured orthogonal currents required in the 39th harmonic correction quad circuits in order to bring the beam to the half stop band from tunes of 19.486 and 19.468. Overlaid are circles representing calculated required currents to reach the stop band from any phase. The double circle indicated the size of the measured stop band. The origin of the circles has been shifted to best fit simultaneously the correction data and the measured stop band data which should intersect the origin of the x,y axes. Data shows good consistency and can be used to determine the relative phase of the natural stop band.

The beam spot size has been measured with a flying wire as a function of energy. Figure 7 indicates the results. Beam blow-up is evident in data above 300 GeV. The invarient emmitance ($\gamma\varepsilon$) is about 28π mm-mr. As of yet, we have little information on blow-up, however, it is not typical at low intensities.

Operational Experience and Reliability

The reliability during the beam commissioning time was very poor as can be seen just by comparing the number of days it took for any phase with the amount of available uptime. (Available uptime is defined as any time when there was not recorded downtime. It does not reflect the inefficiences of interruptions and confusion when controls do not seem to respond, for example.) Actual usable uptime seemed to the crews to be about half of what is indicated here. Whole shifts would go by with nothing productive accomplished. We have always planned on poor reliability in initial operation and the data gathering of beam information was very effective in making efficient use of beam when it was available.

Figure 8 illustrates the amount of downtime caused by various systems in the Energy Saver and caused by the conventional accelerator (Linac-Main Ring). Downtime increased substantially when ramping of the superconducting magnets was initiated and proper cooling required full Central Helium Liquefier output. Quench recovery, which was not a problem at 150 GeV DC operation, took considerably longer when quenches occurred at higher excitation. Failure of a number of devices could cause quenches which took much longer to

~~recover from than the adjustment or repair of the~~ original problem. The refrigeration system was more reliable than expected probably because of the reasonably long time (3 months) over half of the system had been in operation before beam time. The power supply quench protection system on the other hand had little operating time before beam startup.

Refrigerator Problem Summary:

1. The system will not run without the Central Helium Liquefier (CHL). More compressors will be purchased to make the dependence on CHL less critical.

2. There were power lead flow control problems and helium gas restrictions at a cryo loop turnaround point. These problems do not seem to be fundamental at 512 GeV excitation but may return at higher excitation.

3. The refrigerator system generates a permit for power supply operation. Pressure oscillations on the system drop the permit. Possibly it would be safe to operate under these conditions but it has not been tried.

4. Turning the power supply ramp on and off produces instability in the refrigeration system so the cycle time must be very long (2 minutes) when first starting.

5. The plugged filter at CHL has caused 5 day downtimes to replace. (Later the source of the plugging was found and fixed.)

Quench Recovery Summary:

1. Quench recovery normally takes 1/2 hour to one hour. We have not spent effort trying to improve this yet.

2. Sometimes after a quench, the magnet relief valves stick usually from debris coming out of the magnets. When this happens, recovery can take 3 to 5 hours and the vacuum may also go bad.

3. The fast beam abort trigger on losses seems to work well and minimize the number of beam-related quenches.

Quench Protection Summary:

1. The quench protection system has had numerous SCR failures which cause the magnet heater firing units to quench the magnets.

2. The voltage to frequency connectors, which detect resistive voltage, sometime give spurious readings which may be caused by humidity and the power lead protection system is sensitive to common mode noise. These problems are getting less and less frequent with time.

3. A persistent problem which causes significant downtime is that the control transmission loop, by which the power supplies and quench protection units communicate with one another, is sensitive to thunderstorms. During times of storm activity, the system can be inoperative for hours. New cables and link electronics are being installed to alleviate this problem.

4. The important thing is that so far we have not blown up any magnets.

Miscellaneous Other Problems:

1. The bore tube vacuum valves close on noise while the beam is in the ring.

2. These valves also leak, making it difficult to install things in the warm section of the vacuum system adjacent to cold magnets.

3. The injection kicker has had reliability problems and quenches the magnets when it does not fire at injection time. Reliability seems to be much better lately.

4. The central control computer system dies in various ways. It is improving all the time.

5. There have been problems reading and restoring the files for the dipole correction element wave forms, but this problem does not seem to be fundamental.

Miscellaneous Systems Which Have Been Very Reliable:

1. The vacuum system has been reliable though we may have problems recovering from warmup of the magnets.

2. The correction element system has behaved almost flawlessly.

3. The beam position and loss monitor systems have been invaluable.

4. The abort system kickers have given no problems.

5. The large number of service buildings microprocessors ($\sim$350) have been very reliable.

6. Finally, the RF system has come on and run without difficulty.

<u>Summary</u>

The Energy Doubler gives every indication of being a very stable, rational accelerator with no particular aperture problem and with classical optical properties. It still must get to design intensity and energy. Problems which occurred during installation and commissioning were sufficiently small as to allow enumeration here. None seem fundamental at this time. The long, careful test program was probably instrumental in making for a rather rapid turn on period.

On August 15, 1983, during this Conference, beam was accelerated to 700 GeV and on August 19, a test of the controls for beam storage was attempted. Beam was held for about 13 minutes before being aborted on command. Beam attenuation during this time was less than 3-4% even though all 12 power supplies were on and no attempt was made to select any particular tune value. The major technical goals of a superconducting accelerator have been achieved.

The conception of the Energy Doubler is due to the imagination, determination, and foresight of R. R. Wilson. The success of the magnet program has its foundation in the work of Alvin Tollestrup. The environment for success has been generated under the direction of Leon Lederman who made this project the number one priority of the Laboratory.

The professionalism, desire for excellence, and commitment of the Fermilab employees to schedule and performance has brought this project to realization.

References

[1] The original name Energy Doubler seems most appropriate. Energy Saver is the project name. The final facility, which will be a combination of the Energy Saver, TeV I and TeV II Projects is called the Tevatron.

[2] J. R. Orr, "Status of the Energy Saver," IEEE Trans., NS-30, 1967 (1983).

[3] Design Report, "Superconducting Accelerator," Fermilab (1979).

[4] J. Peoples, "The Fermilab Antiproton Source," IEEE Trans., NS-30, 1970 (1983).

[5] A. V. Tollestrup, "Care and Training of Superconducting Magnets," IEEE, Vol. MAG-17, No. 1 863 (1981).

[6] A. McIntruff, et al., IEEE Trans., NS-30, 3378 (1983).

[7] R. Hanft, et al., IEEE Trans., NS-30, 3381 (1983).

[8] E. E. Schmidt, et al., IEEE Trans., NS-30, 3384 (1983).

[9] F. Turkot, et al., IEEE Trans., NS-30, 3387, (1983).

[10] C. H. Rode, 12th International Conference on High Energy Accelerators, Fermilab, August 11-16, 1983.

[11] G. Tool, et al., IEEE Trans., NS-30, 2889, (1983).

[12] C. L. Bartelson, et al., J. Vac. Sci. Technol. A1 (2), 187 (1983).

[13] R. Gerig and R. Shafer, 12th International Conference on High Energy Accelerators, Fermilab, August 11-16,1983.

[14] H. Pfeffer and R. J. Yarema, IEEE Trans., NS-30, 2870 (1983).

[15] L. Michelotti, 12th International Conference on High Energy Accelerators, Fermilab, August 11-16, 1983.

[16] D. Bogert, et al., IEEE Trans., NS-24, 2204 (1981).

[17] D. Bogert and S. Segler, Europhysics Conference - Computing in Accelerator Design and Operation, Berlin 1983.

[18] D. A. Edwards, et al., Proceedings of the International Conference on High Energy Accelerators, 184 (1974).

[19] C. H. Rode, et al., IEEE Trans., NS-30, 2892 (1983).

[20] R. Goodwin and R. Johnson, 12th International Conference on High Energy Accelerators, Fermilab, August 11-16, 1983.

TABLE I
TEST HISTORY

1973	R&D STARTED
5-75	BEAM TRANSPORTED THROUGH ONE 3-FOOT MAGNET AT B12. MAGNET HUNG ON TUNNEL CEILING.
8-75	BEAM QUENCH STUDIES ON EARLY SUPERCONDUCTING MAGNET IN AØ EXTRACTION LINE.
2-76	B12 ABOVE GROUND TEST AREA STARTED.
1976	ABOUT TEN 22-FOOT MAGNETS MADE.
1977	B12 TEST AREA - FOUR MAGNET STRING TESTS STARTED <2000A.
12-78	BEAM TRANSPORTED AØ TO A17, 22-FOOT MAGNET. (20 DIPOLES, 3 QUADS).
5-79	FINAL DESIGN REPORT - CHANGE MAGNET DESIGN LENGTH TO 21-FOOT.
6-79	B12 TEST AREA - 16 22-FOOT MAGNETS, 4 QUADS INSTALLED.
7-79	START OF CONSTRUCTION.
12-80	START INSTALLATION OF A-SECTOR.
1-81	B12 TEST AREA - 16 21-FOOT MAGNETS, 4 QUADS, INSTALLATION STARTS.
3-81	B12 TEST AREA - START TESTS ON FINAL MAGNETS.
5-81 – 12-81	INSTALLATION OF 3/4 A-SECTOR.
1-82 – 6-82	3/4 A-SECTOR TEST TO 4200 AMPS: CRYOGENICS, POWER, VOLTAGE-TO-GROUND, QUENCH PROTECTION, PRESSURE TESTS
5-81	B12 TESTS TERMINATED.
6-81	BEAM TRANSPORTED THROUGH INJECTION SYSTEM AT EØ AND 400 GEV PROGRAM TERMINATED. INSTALLATION SHUTDOWN STARTS.

TABLE II
POWER TEST 1983
(660A = 150 GEV)

	E & F SECTORS
2-22 → 3-3	500A - 1 POWER SUPPLY. QUENCH BYPASS STUDIES AND POWER LEAD QUENCHES 2 KA
3-4 → 4-15	WARM E-SECTOR TO REPAIR VACUUM LEAKS
4-15	4 POWER SUPPLY OPERATION
4-22	BEAM STUDIES
	C, D, E, & F SECTORS
5-6	1 POWER SUPPLY
5-7	660 AMPS
5-8	4 POWER SUPPLIES - CAN'T RAMP - BAD DIPOLE
5-11	LOCATED BAD DIPOLE, C29-3
	D, E, F SECTORS
5-12	660A
5-14	2 KA
	D, E, F, & A SECTORS
5-25	900A - DISCOVER BAD SPLICE
5-26	LOCATE-A22
	B, C, D, E, F & A SECTORS
5-31	220A - DISCOVER BAD SPLICE
6-1	LOCATE-B46-1
6-2	100 GEV BEAM STUDIES
6-4 TO 6-14	REPAIR A & B
6-15	RAMP TO 400 GEV (1770 AMPS)
6-16	RAMP TO 500 GEV (2220 AMPS)
	START BEAM TESTS

TABLE III
BEAM TEST AND COMMISSIONING

AVAILABLE UP TIME (HOURS)	Event		Date
~-80	- -		4/22
	← START INJECTION AT EØ		
	FIRST 4 OUT OF 5 HORIZONTAL DETECTOR REVERSED POLARITY		
~-50	← BEAM TO END OF F-SECTOR (AØ) 150 GeV D.C.	E&F SECTOR TESTS WEEKEND 1	
	TEST INJECTION KICKER		
	- - - - - - - - - - (INSTALLATION) - - - - - - - - - - - -		4/24-4/29
	RAMP MAGNETS & TRANSPORT BEAM		
	EXPLORE APERTURE	E&F SECTOR TESTS WEEKEND 2	
	EXERCISE TUNING PROGRAM		
0	- - - - - - - - - - - (FINISH INSTALLATION & POWER TESTS) -		5/1-6/2
	← 1ST TURN		
	← POSSIBLE? 13 TURNS	100 GeV D.C.	
	- - - - - - - - - - - (FIX BAD MAGNET SPLICES) - - - - - - -		6/4-6/16
	← 20-30 TURNS		6/18
		150 GeV D.C.	
100	← CØ APERTURE RESTRICTION FOUND		6/22
	← E47 OBSTACLE TRIANGULATION		6/25
	← AØ PAPERWIPE WAD FOUND		
	← COASTING BEAM, 200 MS TO ABORT TIME		6/26
	← 1ST TURN TUNE EVALUATION & SKEW QUAD SETTING		
	RF ON - GOOD COASTING BEAM & RF RADIAL POSITION CHANGE ACCOMPLISHED		6/28
	← 800 MS BEAM TO ABORT TIME		
	- -		
200	← 250 GeV BEAM		
	← 512 GeV BEAM		7/3
		RAMPED	
	← TUNE VS ΔR & COUPLING MEASUREMENTS AT 512 GeV COMPLETE		7/15
	- - - - - - - - - - (CHANGE FILTER CHL COLD BOX) - - - - - -		7/16-7/23
300			
	← COUPLING MEASUREMENT AT LARGE ORBIT DISTORTIONS		7/24
	← ZERO HARMONIC OCT. TEST TUNE VS ΔR	RAMPED	
	← 1/2 INTEGER STOP BAD MEASUREMENT		
	← COMPLETION OF 39TH HARMONIC CIRCLE STUDY		7/31
375	← BEAM RESONANT EXTRACTED & TRANSPORTED TO SY DUMP		8/2
400			

TABLE IVA
DIPOLE MAGNET FIELD QUALITY

MULTIPOLE FIELDS (INCREASING EXCITATION)

(B_N/B_0 AT 1 IN. X 10^4)

MEASUREMENT (766 MAGNETS)

		500A	660A	1000A	2000A	3000A	4000A	DESIGN CRITERIA ≥2000A
B 1	AVG	.05	.06	.07	.09	.10	.10	±2.5
	σ	.59	.57	.57	.55	.54	.54	
A 1	AVG	-.00	-.01	-.00	.03	.09	.18	±2.5
	σ	.96	.79	.68	.62	.60	.60	
B 2	AVG	-7.87	-4.71	-1.38	.92	1.09	1.01	±6.0
	σ	4.03	3.75	3.64	3.57	3.54	3.48	
A 2	AVG	.04	.11	.19	.26	.30	.38	±2.0
	σ	1.31	1.29	1.28	1.28	1.28	1.29	
B 3	AVG	-.22	-.23	-.24	-.25	-.26	-.25	±2.0
	σ	.92	.89	.87	.86	.85	.84	
A 3	AVG	-.03	-.04	-.06	-.06	-.06	-.08	±2.0
	σ	1.70	1.67	1.65	1.65	1.65	1.66	
B 4	AVG	.16	.12	.06	-.01	-.20	-.68	±2.0
	σ	1.43	1.42	1.40	1.40	1.44	1.55	
A 4	AVG	-.03	-.04	-.04	-.04	-.05	-.08	±2.0
	σ	.59	.56	.54	.52	.51	.51	
B 6	AVG	5.26	5.48	5.75	6.04	6.27	6.63	
	σ	1.04	1.01	.99	.99	1.01	1.06	
B 8	AVG	-15.44	-15.43	-15.42	-15.42	-15.47	-15.59	
	σ	2.04	2.01	1.99	1.98	1.99	2.01	

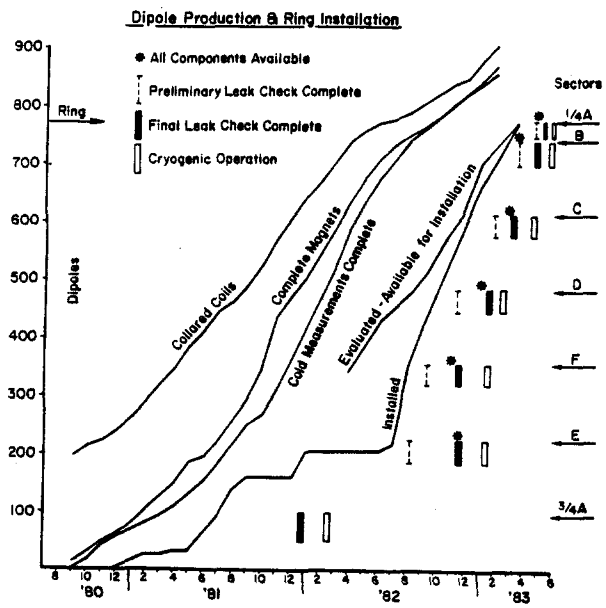


Fig. 1

TABLE IVB
66 IN. QUADRUPOLE FIELD QUALITY

MULTIPOLE FIELDS (INCREASING EXCITATION)

(B_N/B_1 AT 1 IN. X 10^4)

		500A	660A	1000A	2000A	3000A	4000A
A 1	AVG	.28	.29	.29	.31	.31	.32
	σ	.51	.52	.53	.53	.53	.54
B 2	AVG	1.91	2.00	2.08	2.20	2.24	2.29
	σ	3.79	3.81	3.84	3.86	3.87	3.90
A 2	AVG	2.97	2.96	2.96	2.97	3.05	3.07
	σ	3.75	3.75	3.76	3.76	3.74	3.78
B 3	AVG	1.21	1.24	1.27	1.26	1.27	1.28
	σ	1.03	1.00	.98	.97	.97	.97
A 3	AVG	-.35	-.37	-.39	-.40	-.41	-.40
	σ	1.94	1.92	1.94	1.96	1.96	1.97
B 4	AVG	-.40	-.37	-.35	-.31	-.28	-.29
	σ	.78	.76	.75	.74	.76	.75
A 4	AVG	-.67	-.65	-.64	-.63	-.62	-.62
	σ	.79	.77	.74	.74	.74	.74
B 5	AVG	-4.77	-3.74	-.276	-2.06	-1.92	-1.89
	σ	1.35	1.37	1.39	1.43	1.45	1.45

FIRST COMPLETE TURN!
5:42 P.M.

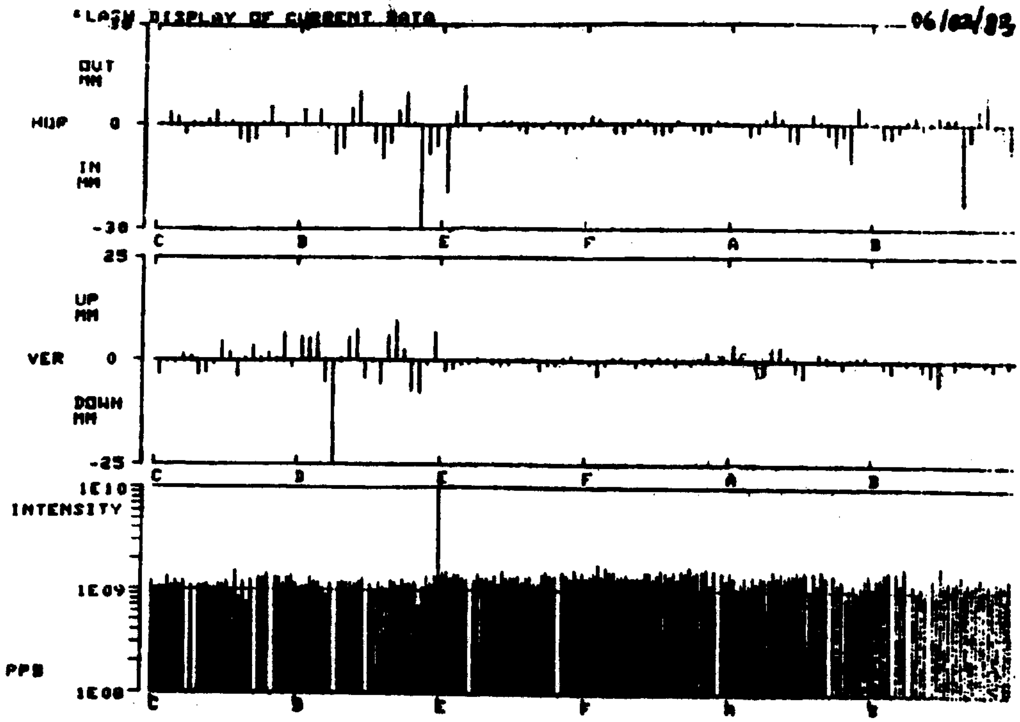


FIG. 2 BEAM POSITION AND INTENSITY DISPLAY OF THE FIRST COMPLETED TURN.

TABLE V
CORRECTION COIL CIRCUITS

	NUMBER CIRCUITS	NUMBER ELEMENTS/CIRCUIT	STRENGTH EACH ELEMENT (KG IN. @ 1 IN.)
DIPOLE	216	1	180
QUAD TUNE ADJUSTMENT	2	90	66
CHROMATICITY SEXTUPOLE	2	90	55
SKEW QUAD COUPLING ADJUST	1	48	66
39TH HARMONIC QUAD	2	4	66
39TH HARMONIC OCTUPOLE	2	16	32
0 HARMONIC OCTUPOLE	2	24 12	32

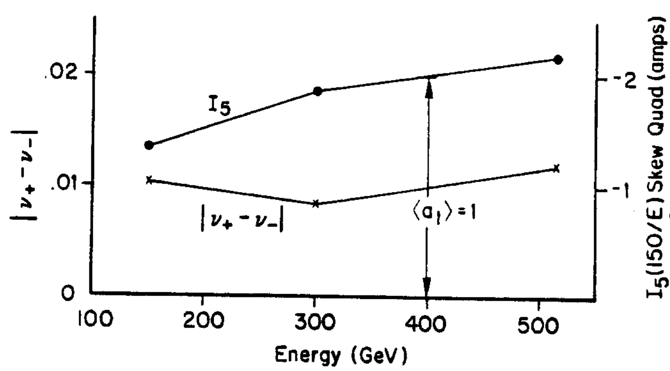


Fig. 3 Minimum horizontal-vertical tune difference and skew quad current as a function of energy.

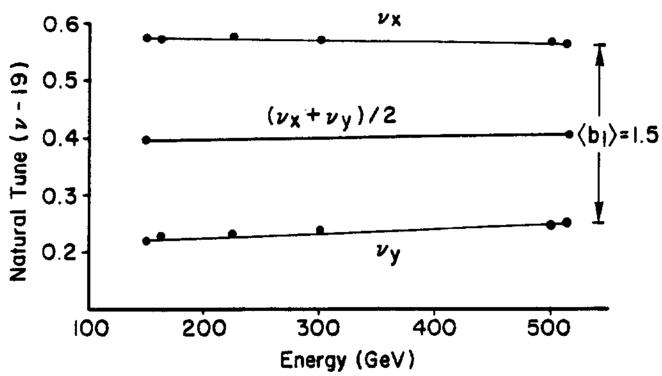


Fig. 4 The natural (uncorrected) tune of the machine as a function of energy.

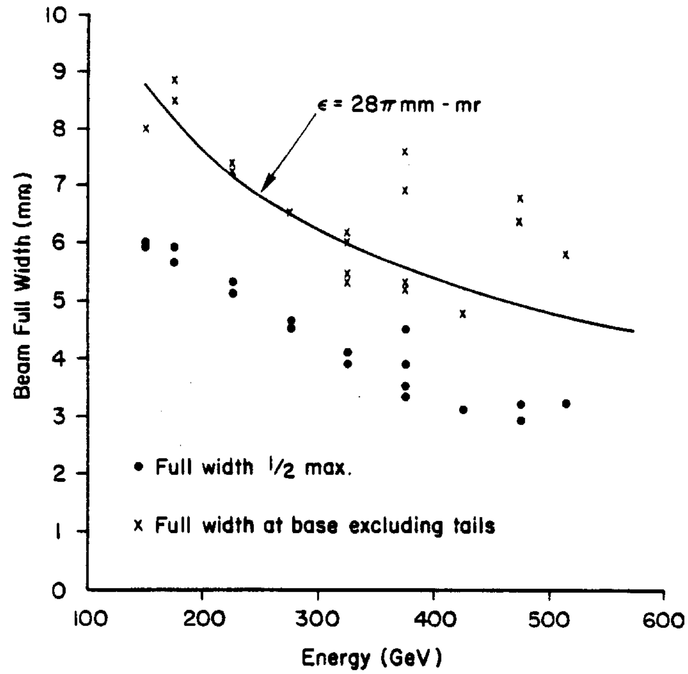


Fig. 7 Beam size as measured with a flying wire.

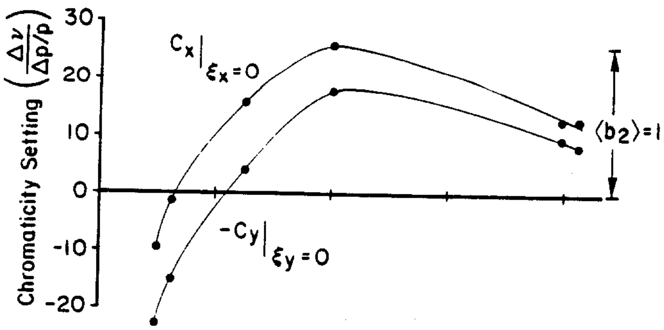
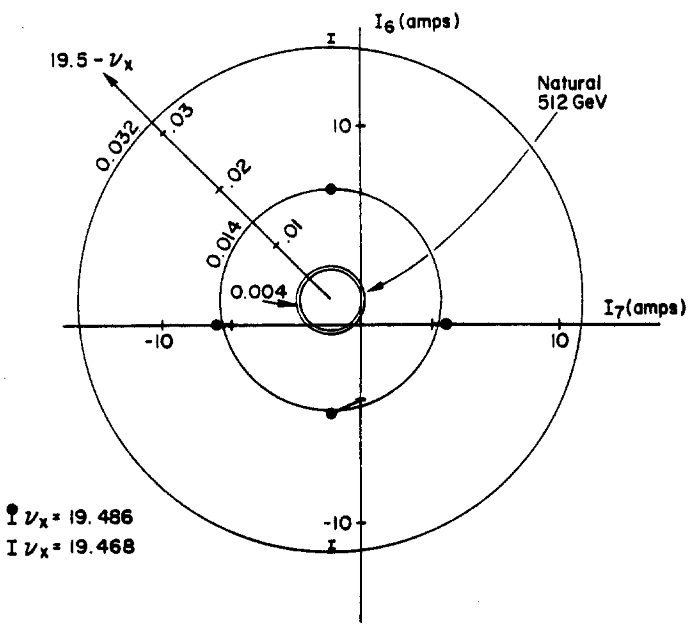


Fig. 5 The necessary chromaticity correction above that which is required by the measured sextupole fields to obtain zero measured chromaticity.



39th Harmonic Natural 1/2 Integer Stop Band (1/2 width) and Values of 39th Harmonic Correction Quad Circuits Necessary to Adjust to Stop Band

$\Delta\nu_{(1/2w)} = 1/4\pi \, q\beta N = 0.0025/\text{amp}$

Fig. 6

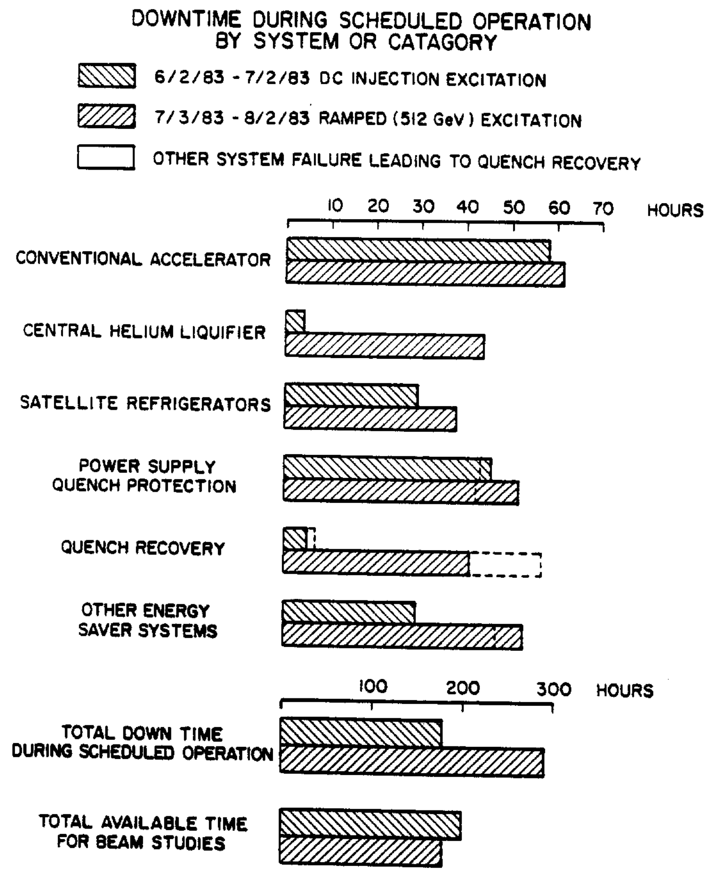


Fig. 8 Downtime during the first 2 months of commissioning.