THE STATUS OF THE FERMILAB MAIN INJECTOR PROJECT

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The Fermilab Main Injector is a new 150 GeV synchrotron now in the fourth year of a scheduled seven year funding profile. An R&D program has been completed, and both civil construction and the production of technical components are well underway. The Main Injector Project is part of a larger upgrade program at the Fermi National Accelerator Laboratory called Fermilab III which is designed to ensure a Collider luminosity in excess of $5x10^{31}$ $cm^{-2}sec^{-1}$ while simultaneously providing a 2 microAmp resonantly extracted 120 GeV beam. The 120 GeV beam will provide unique capabilities in the realm of rare neutral K decays and long baseline neutrino oscillation experiments. The expected performance characteristics of the Main Injector will be discussed, and the status of the construction and the schedule for completion will be reviewed.

I. OVERVIEW

Fermilab III, a program to produce at least a factor of 30 increase in the Tevatron Collider luminosity as compared with a 1988-89 baseline of $1.6x10^{30}$ $cm^{-2}sec^{-1}$ has included several projects at Fermilab of which the Main Injector is designed to produce the final factor of five increase in luminosity. The other projects: new low-Beta focusing systems at both colliding experiments, 22 electrostatic separators to eliminate collisions other than at the experiments, improvements to the antiproton source, and the Linac Upgrade Project have already produced initial luminosities in excess of $2x10^{31}$ $cm^{-2}sec^{-1}$, leading to the hope of achieving a luminosity above $1x10^{32}$ $cm^{-2}sec^{-1}$ with the Main Injector. The present Fermilab accelerator complex is a cascade of four accelerators (400 MeV Linac, 8 GeV Booster, 150 GeV Main Ring, Tevatron) The Main Ring and Tevatron share a single tunnel enclosure. The Main Injector will functionally replace the Main Ring in a separate tunnel enclosure. An ancillary benefit is to remove the 150 GeV accelerator from the vicinity of the Collider experiments where the operation of the Main Ring introduces an undesirable background which can only be avoided by a combination of shielding and gating. The gating reduces the D-Zero experiment live time significantly.

The Main Injector is an accelerator with the two fold symmetry of a sheared oval, the exact shape being dictated by siting considerations. The circumference is 3319 meters, seven times the Booster, or 28/53 of that of the present Main Ring. The lattice is based upon a 90^o FODO cell, with zero dispersion straight sections created with short dipoles. The transverse admittance is 40π mm.mrad and the longitudinal admittance is 0.5 eV-sec. β_{max} is 58 meters representing stronger focusing than the Main Ring.

In addition to the 3319 meter Main Injector accelerator, there are five beam lines to provide for: injection from the Booster at 8 GeV, two lines for proton and antiproton transfers from the Main Injector to the Tevatron at 150 GeV, and two lines at 120 GeV for extraction of protons for antiproton production and to the existing fixed target switchyard.

New technical components including 344 dipoles and 12 dipole power supplies, 80 long quadrupoles, 108 sextupoles, 208 dipole correctors, and 18 rf power amplifiers are included in the project. "Recycled" technical components to be relocated from the existing Main Ring include 18 rf cavities, 128 quadrupoles and 6 power supplies, 102 correction magnets, 589 beam line magnets, and assorted power supplies, controls, and instrumentation. A second 345 kVolt substation will be built on the Fermilab site with some back feed capability between the existing substation and the new one.

Transfers to the Tevatron for fixed target physics acceleration cycles, or for Collider operation, are made at 150 GeV. Twelve Booster batches are presently required to fill the Main Ring. The Main Injector will be filled with six Booster batches, requiring two Main Injector acceleration cycles to 150 GeV to fill the Tevatron for fixed target physics at Tevatron energies. Antiproton production at 120 GeV, on the other hand, only requires a single Booster batch. The Main Injector has been designed with a faster cycle time than the Main Ring to increase the rate of antiproton production. If loaded with six Booster batches, one batch is sufficient for antiproton production while simultaneously permitting the direct extraction at 120 GeV of the other five Booster batches for a dedicated fixed target research program at 120 GeV.

When built and operated as a 400 GeV accelerator in the early 1970's the Main Ring had a transverse admittance much higher than the approximately 12π mm.mrad measured today at 8 GeV injection from the Booster. The reduction in admittance is the result of many changes made to the Main Ring since its inception. The most significant of these changes are the introduction of the vertical overpasses at the CDF and D-Zero colliding detectors, a source of vertical dispersion which the original planar machine did not have, and the introduction of more extraction and injection points, especially for antiproton production and Tevatron injection, which has further reduced the aperture of the Main Ring. The reduced admittance of the Main Ring at the 8 GeV transfer from the Booster is the greatest single limitation on luminosity increases left in the acceleration cycle. The Main Injector has been designed to have a minimum of a 40π mm.mrad admittance at 8 GeV. This has been achieved by the design of large aperture magnets and with great care to place injection and extraction devices at advantageous places in the lattice. These considerations, coupled with the requirement

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for a 1.5 second cycle time to 120 GeV for antiproton production, or a 1.8 second cycle time for neutrino production, have implied the necessity of designing new conventional copper and iron magnets with a good field quality over a large aperture with a cost effective high ramp rate. Power supplies and rf capabilities matching these requirements have also been developed. The design and prototype production of the dipole magnets, the dipole power supplies, and rf power amplifiers were the subject of the completed R&D Program.

II. DESIGN; R&D PROGRAM; FUNDING

The actual construction of the Main Injector was proceeded by two pieces of the project program, both of which were also necessary in the process of obtaining funding and approval to begin construction. The first was the completion of a design report, which evolved into the Title I design report and later into the Main Injector Technical Design Handbook. The design report was an iterative process that specified the accelerator lattice, the beam transfer lines, injection and extraction techniques, and the necessary equipment: magnets, power supplies, rf, vacuum, instrumentation, controls, utilities, etc. Using the design report, it was then possible for both civil and technical designers to begin detailed designs in each area. Also, the lattice could be checked by tracking programs and then the actual measured values of magnetic fields, with harmonics, could be inserted into the tracking programs used during the initial designs, and the whole process iterated.

On the basis of the design report, it was possible to count the necessary new technical components, as well as to identify those items which could be reused from the Main Ring, such as the main quadrupoles. A complete cost estimate leading to the definition of the project financial baseline was thus generated.

In the course of the design studies, three areas were identified which were the focus of a large R&D effort. These were the main guide field dipole magnets, the dipole power supplies, and an improved rf power amplifier. The R&D program began in FY90 and was completed in early FY95. The first major emphasis was placed upon the demonstration that a reliable large aperture conventional dipole magnet with rapid excitation could be designed and then mass produced at a reasonable cost. The second project was the design, construction, and operation of the necessary 9500 Amp power supply for the dipole guide field, and finally the development of a solid state rf power amplifier using commercially available technology, and a demonstration that it was reliable using the existing Main Ring.

The dipole R&D program consisted of the following activities. First, two dipoles were constructed and completed during FY91. These dipoles were used to first study the body field in the magnet and to assure that the field was adequate at both injection and at 120 GeV and 150 GeV extraction energies. Next, the details of the 'end pack' design were worked out by a combination of design calculations and physical construction, both carried out in iteration. Finally, after consultation with business and procurement personnel from the Department of Energy, a business strategy for the procurement of the dipoles in production quantities was defined, and ten more R&D dipoles were constructed using commercial vendors for all tasks that were not to be done at Fermilab. Additional quadrupoles and sextupoles are also required, and were designed at this time.

A first prototype dipole power supply was constructed and operated with R&D magnets as a test load at site E4R, originally constructed for the 4 cm SSC magnet test string. The prototype design suggested several modifications, and a second dipole power supply was also constructed under the R&D program. Both oil filled and dry type 13.8 kVolt transformers are undergoing evaluation as part of the ongoing testing of the R&D dipole power supply.

A new solid state rf power amplifier using commercial components was constructed and has been operated without failure throughout the most recent Collider run in the Main Ring.

It is not possible to conclude a discussion of the design of the Main Injector without reference to the project funding profile, since this also has a significant iterative impact on the details of the planning for project construction. It was originally conceived that an aggressive funding profile should be assumed since, among other advantages, a rapid funding profile can be easily demonstrated to minimize overall project costs. It was assumed at first that an approximately flat four year profile was both sensible and achievable. In fact, the actual appropriations and the funding profile that has been incorporated in the last three fiscal year's appropriation is not aggressive at all. The project is now shown as a seven year project with a total, then year cost, estimated at $229.6M on the plant line with a total project cost of $259.3M. Now in the fourth year of plant line appropriations, the total appropriated to date (FY92 through FY95) is $94.65M. The actual appropriations have been: FY92 $11.65M, FY93 $15M, FY94 $25M, FY95 $43M, and budgeted amounts for future years are FY96 $52M, FY97 $52M, FY98 $30.60M, with commissioning extending into FY99. It should be noted that in order to start both the technical and civil construction it has been necessary to make extensive use of both phased funding and bids with options to extend, and to divide work which could easily be accommodated into larger contractual obligations into relatively small pieces. This has had an impact on the civil design and on the methodology of technical component construction.

As of April 1, 1995, the cost estimate included $101.1M for technical components, $88.7M for civil construction, $8.2M for project management, $1.4M for G&A, and the remainder ($30.2M) unassigned contingency.

III. CIVIL CONSTRUCTION

The first conceptual civil design for the Main Injector was made by the Fermilab civil engineering group prior to FY91. It was then decided that the detailed Title I design package, the individual Title II bid packages, and a substantial part of the Title III effort would be done by an outside A&E firm in support of the Main Injector Project Office and a small group from Fermilab. Thus in early 1991 an A&E selection board was constituted and as a result Fluor Daniel, a national A&E firm with a substantial Chicago office, was selected as the Main Injector A&E firm. An important early assist to this endeavor was a State of Illinois Challenge grant totaling $2.2M which permitted Fluor Daniel to prepare some advanced Title I designs prior to the formal release of federal funding. The Illinois Challenge grant was also used to help prepare the Environmental Assessment. Details of the approval stages prior to the unrestricted release of funding for construction have been reported previously. [1,2] Fluor Daniel carried out the Title I and Title II design effort on the basis of a negotiated fixed price contract.

The basic civil requirements of the Main Injector are: 1) a Ring Enclosure for the accelerator consisting of 1181 precast units in an inverted "U" shape and cast-in-place tunnel segments at 'non-standard' locations, 2) Tunnel connections for transport of 8 GeV Protons from the Booster to the Main Injector (211 more precast units), and for transfer of 150 GeV Protons and Antiprotons from the Main Injector to the Tevatron, 3) Connections to existing enclosures at the Booster and at MR/Tev F0, 4) Service buildings at appropriate locations around the Main Injector, on the 8 GeV transfer Line, and as necessary for connection to the Tevatron, 5) Site Utilities - water, electrical, new 345 kVolt service, etc., and 6) various other installations.

By the standards of many large civil projects, the Main Injector is not a particularly large construction project. It is possible to consider such a project as either one or a very few construction contracts. The funding profile discussed above, however, led management and the A&E firm to adopt a very different approach. The civil work has been divided into approximately 24 packages for construction and/or procurement. It need hardly be observed that this rather fine subdivision of the work does create a significantly larger number of bid drawings and specifications sets, and even then there is a considerable connection to an assumed obligations profile which, if altered, causes some disruption of assumptions designed and drawn into the many individual bid packages. This all translates into increased EDIA (Engineering, design, inspection, administration) costs as compared with the minimum conceptually possible.

A list of the bid packages (civil construction contracts) and civil procurement items is found in the following table. Projects for which the civil construction is completed are indicated "complete". Details about the scope and bidding of 'completed' projects have been previously reported. [2] Projects in progress are so indicated. Projects to be funded in this or future fiscal years are indicated by the notation of the fiscal year when the obligation is expected.

1) Wetlands Mitigation (complete)
2) Accelerator Enclosure at MI-60 (complete)
3) MI-60 Service Building (complete)
4) Site Preparation, roads, utilities (3 phases)(complete)
5) Substation Hardstand (complete)
6) Ring Enclosure Precast Units (3 phases)(in progress)
7) 8 GeV Line Precast Units (in progress)
8) Main Injector Ring Enclosure (2 phases)(in progress)
9) 8 GeV Line (3 phases)(in progress)
10) Main Injector Service Buildings (8 structures)(FY96)
11) Cable Trays in Enclosures (FY96)
12) 13.8kV Distribution (FY96)
13) 345kV transmission Line (FY96)
14) Kautz Road Substation (FY96)
15) Commonwealth Edison 345kV connection (FY95)
16) Add to MR-F0 Service Building, new F17 (FY97)
17) Cooling Ponds and Cooling System (FY96)
18) Connection of Main Injector at MR/TeV F0 (FY98)
19) Connection of 8 GeV line at Booster (FY98)
20) Landscaping, Road Paving, etc.(FY98)
21) Various Transformer Procurements (FY95)
22) Shielding Steel Procurements (in progress)
23) Survey Monuments (complete)
24) Reconstruction of E4R facility (FY95)

The ring enclosure inverted "U" precast units have been built at the rate of four units per day since early February 1994. The contractor is PBM Concrete of Rochelle, Illinois. Approximately 1140 of 1181 have been completed, and the contract should be finished approximately May 15, 1995. PBM Concrete is also building the 211 precast units for the 8 GeV line. Production will follow immediately upon completion of the ring enclosure precast units and should be completed by July 31, 1995.

The Main Injector ring enclosure was started in April 1994 by the contractor, Wil-Freds of Aurora, Illinois. Approximately 50% of this work is complete and costed. The work consists of excavation following by tunnel construction using precast units set on a cast-in-place base slab, as well as sections of cast-in-place tunnel where non-standard cross sections are required. The work also includes exit stairs and the stairs and backwalls at the locations of future service buildings. The enclosure contract should be completed in early 1996.

The 8 GeV line contract was awarded to Martam Construction of Glen Ellyn, Illinois. Work has just begun on phases 1 and 2 using FY95 funding, the third phase will be funded in FY96. Phase 2 requires an accelerator shutdown which is scheduled to begin July 24, 1995.

Shielding steel procurements subcontracted to Wil-Freds are underway. The use of 'continuous cast salvage slab' steel delivered by rail car to Fermilab has been found to be quite advantageous.

Fluor Daniel has completed the Title II packages for all of the civil construction work with the single exception of some details on the 8 GeV Connection at the Booster. To date, the actual civil construction work has been bid below the Title II estimates, and work completed, including changes to work in progress, has not exceeded the Title I baseline estimates. Civil EDIA has, however, exceeded initial estimates.

The Main Injector civil designs have included a number of capabilities for future utilizations including several possible extraction points, room for Siberian Snakes for polarized protons, and a 'keep away' region for a possible additional ring of magnets in the enclosure. A recently approved addition to the scope of the Main Injector Ring Enclosure added an extraction stub enclosure for a northwesterly extracted beam. This stub was designed at Fluor Daniel and is being added by negotiation to the enclosure contract.

IV. TECHNICAL COMPONENTS

The technical components for the Main Injector Project have been divided into ten "WBS Level 3" areas, each with a "Level 3 Manager" responsible for the cost estimate, scheduling, and overall design and production. These ten areas are: 1) Magnets, 2) Vacuum, 3) Power Supplies, 4) rf Systems, 5) Kickers and Slow Extraction, 6) Instrumentation, 7) Controls, 8) Safety Systems, 9) Utilities and Abort, and 10) Installation.

It was decided at an early point in the project that the work would be accomplished with approximately the following priorities until funding was not an almost absolute restriction: 1) Technical R&D, 2) Technical EDIA, 3) Civil EDIA, 4) Start Civil Construction, 5) Start Dipole Magnets, and 6) Start other technical components. The result of this prioritization coupled with the actual funding appropriations outlined above has been that with the exception of the Wetlands Mitigation which was begun in late FY92, the actual civil construction began in FY93, the dipole magnet production began in FY94, and the rest of the technical components were only funded to start construction in FY95. Even with this slow start, both civil and dipole magnet obligations have been subdivided into small amounts with extensive use of 'phased funding.' In addition, the rate at which work has been scheduled has been generally determined by fiscal constraints rather than a consideration of attempting to maximize parallel endeavors.

In spite of the funding constraints, very considerable progress has been made and the rate of production of technical components being built and the accomplishment of civil construction has now reached approximately the rates projected when the project schedules were baselined, although in both instances with a several month 'start-up delay' offset. In other words, the amount of costs accrued in recent months has reached a steady state supported by the appropriations profile.

The dipole magnet R&D program was designed to flow smoothly into the production of the guide field dipoles, and when the R&D program was finished approximately at the end of the first quarter of FY94 the production of dipole magnets was initiated. Since Fermilab acts as the 'general contractor' for the dipole magnets and only performs the final assembly (about 6% value added) there was a long 'start up' period while all the queues were filled.

Now production has reached a steady state of approximately one dipole completed every two working days. There are two streams of material which meet just prior to final assembly for this to work correctly. The magnets each consist of two insulated copper coils and two steel half cores fabricated from stacked steel laminations. One stream has to provide the insulated coils at the rate of a pair every two days, and the other stream has to provide a pair of stacked half cores every two days.

The copper coils are wound at Everson Electric in Pennsylvania. The bare copper coils are shipped, via Fermilab, to Tesla Engineering in England (via rail and sea) to be insulated, and returned, (via sea and rail) to Fermilab. The steel is fabricated in the form of coils at LTV Steel, shipped to a coil 'slitter', and then shipped to a lamination stamper. The steel production is not a 'continuous process' but rather a series of supposedly reproducible runs. To avoid systematic variations as much as possible, the steel laminations are shipped to the 'stacker' (SVF in Rock Falls, Illinois) according to a 'recipe' selection which the stacker then follows. SVF is also responsible for the manufacture of 'end packs', special small stacks of laminations using non-standard laminations to produce the desired end fields. The completed half cores are then delivered to Fermilab. As of the end of April, 1995, approximately 60 production dipoles have been completed and measured, with sustained production over several months at the rate of one every two working days.

Two issues, neither damaging to the timely completion of an acceptable accelerator lattice, have arisen during the last half year of dipole production. An interruption of the delivery of the insulated coils due to transportation labor difficulties in Canada led to a suspension of production while a larger inventory was accumulated. Without some buffer in the inventory a large exposure to small upsets in the delivery transportation system could too easily again interrupt production. A review of delivery experience led to the decision to create a four week inventory to draw against for the insulated coils. Measurement of the finished magnets revealed a larger than expected, although still acceptable, variation in the higher field (only) performance of the magnets which correlated with steel from different production runs at LTV. When the source of this variation was understood, (variations in magnetic permeability in regions of the magnet far from saturation when the gap was at high field) discussions to insure that greater variations did not occur were conducted with LTV and attention to any source of steel variation is constant.[3]

The Main Injector will utilize 'recycled' quadrupoles from the Main Ring for most of the quadrupole requirements. The recycled quadrupoles will require a change of the mounting system and a change of beam tube. These quadrupoles must be left in the Main Ring until the accelerator shutdown when the enclosure connections are built at MR/Tev-F0. Eighty additional quadrupoles are required for the Main Injector Ring lattice. These quadrupoles are being fabricated at Fermilab to a larger extent than the ring dipoles. The work at Fermilab for these quadrupoles includes the steps of coil winding, coil insulation, half core stacking, and final assembly. This work also began in FY94 and is continuing. To date the complete complement of 35 254 cm (100") quadrupoles has been assembled, and work on an eventual complement of 52 295 cm (116") quadrupoles is underway with over half of the necessary coils wound and 20% of the half cores stacked. One 295 cm quadrupole is fully assembled. 113 sextupole magnets are required and are also being built at Fermilab. Ten have been completed at the rate of two per month. Essentially all of the completed magnets have been powered and measured at the Magnet Test Facility.[3,4]

Procurement of materials for Lambertson magnets and "C" magnets for the transfer lines has begun, and studies of the Lambertson end field configuration have been completed. Other quadrupoles and trim magnets are in various stages of design.

When the evaluation of the dipole power supply built under the R&D program at E4R is complete later in FY95, parts for the full complement of power supplies will be ordered. Parts are being ordered for the kicker supplies as engineering is completed.

Following the completion of the rf R&D program, approximately $1.25M of parts for the production complement of the rf power amplifiers have been ordered since January 1995. This equipment will be assembled in the MI-60 service building as it is delivered.

Design work for a beam position monitor based upon the cross section of the Main Injector beam tube is in progress, and successful prototyping has been completed.

All of the Technical Component Level 3 project areas have now been allocated funding in FY95 to complete design work and to start acquisition and construction activities to some extent. The utilities installation needed at the MI-60 building has begun, and several tasks each in excess of $100K were started in FY95 and some of the low conductivity water (LCW) piping tasks have been completed. Heat exchangers are being acquired and will be installed also. Design work for vacuum systems, controls, safety systems, and magnet installation equipment is well advanced. An installation test in an approximately 30 meter section of standard tunnel cross section in the completed MI-60 enclosure region is underway.

V. SCHEDULE

The present seven year funding profile is much slower than was originally expected or hoped. When the Main Injector was in the conceptual design stage, a four year schedule was believed to be quite realistic, and considering the original schedule for the construction of Fermilab over twenty-five years ago, such a schedule was considered demonstrated. The actual project schedule has been funding limited since the first appropriation and continues to be funding limited.

It will be necessary to turn off the Fermilab physics program for a period of approximately nine months to connect the Main Injector to the existing complex at the Booster and the Tevatron rf straight section (called MR/Tev F0) involving demolition work at both locations. To minimize the down time of Fermilab all the rest of the civil and technical construction, and the installation of new components, must be completed prior to the final civil interconnections at MR/Tev F0 and the Booster. The connection at the Booster could be accomplished at an earlier shutdown of sufficient length if the funding is available. Technical staff cannot be 'double counted' during the shutdown, so all possible prior work must be completed so staff is available to dismantle, remove, and recondition items such as the Main Ring quadrupoles being recycled into the Main Injector. According to the present funding profiles which require $52M in each of FY96 and FY97 it will be just possible to complete the pre-shutdown work in time to permit the 9 month shutdown to begin in February 1998 so that commissioning should be completed in early 1999. It is absolutely necessary that the present funding profile that has existed in the last three of the President's budget proposals to Congress be maintained if this schedule is to be met.

The Main Injector project management team is very encouraged by the progress of the project to date. Progress on all civil and technical design and construction has been rapid given the available funding, and both obligations and costing of completed work are tracking the original project baseline with a less than three month delay, almost all of which represented a slightly slow startup, some large fraction of which was delays in administrative approvals for the first expenditures. Actual contracts have been placed at favorable pricing. The project is essential for the national physics program, a point repeatedly endorsed even prior to the elimination of the SSC project. Project management is anxious to complete the job and to make this research facility available to the research community.

VI. REFERENCES

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