The Fermilab Upgrade -- The Main Injector

May 9, 1989

Fermi National Accelerator Laboratory
Batavia, Illinois

**Operated by Universities Research Association, Inc.
Under Contract with the United States Department of Energy**

CONTENTS

PART I: OVERVIEW

PART II: MAIN INJECTOR DESIGN

1 SUMMARY

This report is based upon an earlier document: The Fermilab Upgrade -- An Overview, which was issued in January 1989. The upgrade is designed to maintain and extend the potential for High Energy Physics under the constraints imposed by the US program to build the SSC and in the context of the world's inventory, existing and soon to exist, of particle accelerator facilities. Fundamental to this proposal is the assumption that first rate physics with major discovery potential is an essential ingredient in the pre-SSC era. It is likely that the Upgrade program will also develop unique and important niches in collider and fixed-target physics in the period beyond the SSC operation.

The Upgrade proceeds in three phases. The first phase is already underway and is designed to increase the luminosity of the proton-antiproton collider to $\sim 1 \times 10^{31} cm^{-2} sec^{-1}$ at 1 TeV x 1 TeV. It will also double the fixed-target intensity to $\sim 3 \times 10^{13}$ ppp. Here it will provide a modest increase in energy to 900 GeV.

In the second phase the present Main Ring is replaced with a new Main Injector in a separate subsurface enclosure. Initial (peak) luminosity in collider physics is then expected to increase to $\sim 5 \times 10^{31} cm^{-2} sec^{-1}$. The Main Injector would be capable of delivering $\sim 6 \times 10^{13}$ protons to the Tevatron. This machine will have a high repetition rate and, in addition to its use as a $\bar{p}$ producer and source of test and calibration beams for fixed-target users during collider operation, its high repetition rate will provide a unique source of 120 GeV protons for high energy physics. It is proposed to initiate the R&D phase in FY90, the construction in FY91, with completion scheduled for 1994.

In the last phase we have considered the possibility of a second superconducting synchrotron to be installed in the collider tunnel. Collider physics would be carried out at an energy of 1.8 TeV per beam and at a luminosity of ~ $10^{32}cm^{-2}sec^{-1}$. The enhanced physics potential resulting from this phase arises from the energy increase rather than from the relatively modest luminosity increase. Fixed-target physics will be carried out at an energy of 1.5 TeV, the lower energy being necessitated by cryogenic considerations. At this stage the Laboratory is concentrating very largely on the issues related to Phase I and II. However, some of the physics virtues of Phase III are included herein.

In the body of the report a lengthy section is devoted to the physics motivation associated with this upgrade. Following that section, we review Phase I and present the Main Injector in considerable detail.

A resume of the virtues of the Main Injector is now listed:

1. The old Main Ring with its aperture and other limitations is replaced by a ring optimized in design to provide for pbar production and Tevatron injection.

2. The Main Injector results in an increase in collider luminosity of a factor of five and an increase in Fixed-Target intensity of a factor of two.

3. Main Ring backgrounds and hinderances to CDF and DØ are eliminated.

4. One additional IR becomes available for a new detector initiative e.g. a Bottom Collider, and with some effort, it can be made equivalent to BØ and DØ.

5. The Main Injector at 120 GeV and 10^{13} pps is a unique and interesting physics machine by itself.

6. Beams for testing e.g. SSC detectors and fixed-target debugging are available all year round. This will reduce the fixed-target running time requirements by an average of 2 months per run.

7. Room is left in the original tunnel for possible addition of a (Phase III) new TEVATRON ring.

8. Very time consuming tuning of the beam through all the Main Ring aperature restrictions and overpasses should result in more efficient and reliable operation.

9. No increase is incurred in operating costs.

10. The Fermilab Accelerator Division now has the people, the enthusiasm and the superb track record to build a successful Main Injector. This is the fulcrum of the US High Energy Program and must proceed expeditiously if we are to have an exciting and forefront HEP program in the next decade.

1.1 Context, Constraints, and Conclusions

The Fermilab Upgrade plan has profited from wide discussions in the HEP community and in particular with URA, DOE, HEPAP, and the Fermilab Users Group. It has been assumed, with considerable enthusiasm, that the SSC will indeed proceed on schedule and begin to publish physics results by 1999. This is a prudent assumption for the community to accept. If LHC becomes a European project, there is no way, as presently described by Carlo Rubbia, it can substantially beat SSC. LEPI should become operational by 9:00 a.m. on July 14, 1989 and LEPII about 2-3 years later. HERA, at $\sqrt{s}$ = 330 GeV will begin to commission in 1990. UNK is harder to estimate but the best guess is that the 3 x 3 TeV collider phase will come late in the 1990's. Recall that neither UNK nor LHC have begun the 8-10 year task of constructing a high luminosity 4π detector. All this is to assert that the Tevatron at $\sqrt{s} \geq 2$ TeV will be the highest energy, fully commissioned and instrumented accelerator for at least the next decade. This makes it eminently logical that Fermilab and the US community exploit this feature and this inevitably implies the Upgrade program. *To sharpen this, there is already reasonably solid evidence from early CDF results that new physics will very likely require runs with at least 100 pb^{-1} of integrated luminosity.*

In planning the Upgrade, other factors entered the decision making. These had to do with the fact of SSC, its timing and its impact on funding and on people, the latter coming in two flavors, accelerator and user types. Thus, for example, the construction of a new general purpose 4π detector that could survive at $\sim 10^{32} cm^{-2} sec^{-1}$ was ruled out.

A detailed study of user demographics indicates that the Upgrade program is compatible with a decrease in Fermilab user population by 300-400 from the peak of 1300. With proportional flow from other HEP activities and a large foreign contingent, SSC should have no trouble with its user population. The problem of accelerator physicists is somewhat harder but there exists a vast population of non-HEP accelerator experts. (Witness the accelerator conferences where HEP people constitute only 20% of the attendees.)

The Upgrade plan also considers life beyond the SSC. There will be niches that will provide complementary physics just as the AGS is now providing with rare K decays. Although it is too early to predict, the Main Injector is seen as a unique instrument for difficult experiments involving very intense and fairly energetic kaons and neutrino beams. Also the collider, when not pushing on high energy, can provide three or more interaction regions for a variety of very specialized kinds of physics, e.g., B physics if SSC backgrounds prove to be terrible, structure functions at $x \sim 10^{-4}$, detailed studies of jet architectures etc. The future of the "standard" fixed-target program in the SSC era will depend on the success of UNK's 3 TeV machine.

A crucial element in the Upgrade is the fact that CDF (and soon DO) is confronting formidable problems in high rate, low cross-section hadron physics. With the Upgrade they will be confronting subtle signatures at the level of 10^{-11} to 10^{-12} of the total cross-section. *There is no way of simulating this experience.* The Upgrade, in addition to the impressive physics potential, is guaranteed to provide unique experience in this crucial area. Prospects for successful exploitation of the Upgrade by these detectors seem excellent. There is no sign that CDF is running into detector limitations. Extremely clean dijets have been recorded at a rate of about 100 events per pb^{-1} above the mass of 300 GeV/c^2. Thus, the Upgrade will yield tens of thousands of hard collision events on the constituent level at energies well beyond LEPII and HERA.

Progress in the understanding of physics, progress in detector technology with the detector upgrades, progress in accelerator technology as increasingly denser bunches are handled, and progress in the training of physicists are all essential ingredients in a successful exploitation of the SSC. As everyone knows, the stakes are much bigger in Texas!

In summary, a proposal is presented here that, admittedly, will put some stress on the community in the SSC construction era but which is in fact responsible, affordable with *absolutely unique* capabilities for learning new physics and essential technologies. This plan is believed to be correct primarily because it offers the best physics potential within the constraints imposed.

2 INTRODUCTION

2.1 Brief Description

For at least the next decade, the Tevatron will remain the focus of the US High Energy Physics Program. The Tevatron is not without competition in its ability to advance the frontiers of elementary particle physics. Even today the Sp$\bar{p}$S is a serious competitor because of its experience over the past seven years and the high luminosity of ACOL in spite of its lower energy. For the Tevatron to be able to maintain its status as the pre-eminent high energy facility it must be improved to fully exploit its potential during this time span. This report describes an upgrade program which can provide opportunities at the forefront of physics in both fixed-target and colliding beams physics activities at Fermilab in the pre-SSC era. The lessons of history are also clear in that, with the Upgrade, it is likely that areas of physics will exist for which the Tevatron may be more appropriate than the SSC, given the importance of the highest energy, especially in the early years of SSC physics.

Collider physics, when done with a slowly evolving general purpose 4π detector at a fixed energy, demands something like a doubling of the integrated luminosity with each run in order to maintain the discovery potential for new physics at each stage. The Tevatron I project set $10^{30}cm^{-2}sec^{-1}$ as the design luminosity, and that has been achieved and exceeded. The new program calls for increasing the luminosity from run to run until a peak of $5 \times 10^{31}cm^{-2}sec^{-1}$ is achieved and integrated luminosities per run in excess of 200 pb^{-1} are feasible. Indeed, data from the 1988/89 CDF run, tentative as they are, indicate that runs greater than 100 pb^{-1} will be essential for new physics. Fixed-target experiments will also benefit from the increases in both proton energy and intensity.

The Upgrade proceeds through phases, the first of which is already underway. In this initial phase, improvements to the antiproton source, the installation of separators in the Tevatron, new interaction region optics for the two major detectors, and the increase in the linac energy to 400 MeV will bring the luminosity to the $10^{31} cm^{-2} sec^{-1}$ level for the fourth collider run in 1992. Cryogenic system modifications should permit operation of the Tevatron at 1 TeV for collider physics and 900 GeV for fixed-target physics. The projected total cost of this phase in then year dollars (1989-1991) is $48.3 million of which the linac upgrade is a major component.

The second phase consists of a significant construction project: the replacement of the Main Ring with a Main Injector in a separate subsurface enclosure. Collider runs subsequent to its commissioning are expected to enjoy another step of about a factor of 5 in luminosity, and there are a variety of other benefits as well, including an increase of the fixed-target intensity to above pre-Tevatron levels, the removal of a major background source from the colliding beam interaction regions, and provision of a new and unique source of extremely intense beams of 120 GeV protons.

2.2 Criteria and Technical Constraints

The aim of the next few paragraphs is to show how the luminosity and energy goals above turn into parameter choices, and especially, to highlight the importance of antiproton stack size, antiproton stacking rate, and separated beams.

The luminosity of head-on collisions may be written

$$L = \frac{3}{2} \gamma f_o \frac{B N_p N_{\bar{p}}}{\epsilon_N \beta^*}$$

where B is the number of bunches in each beam, the N's are the number of particles in each bunch for the two particle species, f_0 is the revolution frequency of the synchrotron, β^* is the amplitude function in both transverse degrees of freedom at the interaction point, γ is the Lorentz factor, and ϵ_N is the normalized emittance. The factor of 3/2 is associated with the specific definition of emittance -- i.e., the phase space areas containing 95% of a gaussian beam -- but it is not particularly relevant because the emphasis will be on scaling augments.

The original antiproton collider design report specified a luminosity of $10^{30}cm^{-2}sec^{-1}$ through the collision of three proton bunches with three antiproton bunches, each containing 6×10^{10} particles with a normalized emittance of 24π mm mrad at an interaction point where $\beta^* = 1$ m. Shorn of powers of ten and other constraints, the luminosity expression for the design has the pattern.

$$L \propto \frac{BN_pN_{\bar{p}}}{\epsilon_N\beta^*} = \frac{3 \times 6 \times 6}{24 \times 1}$$

A combination of circumstances -- particularly an antiproton production cross section lower than that assumed in the design and the restricted transverse admittance of the Main Ring -- resulted in the use of the pattern

$$\frac{6 \times 7 \times 2}{24 \times 1/2}$$

to obtain the design luminosity. As this is written, the typical initial luminosity of a store is $1.5 \times 10^{30}cm^{-2}sec^{-1}$, with the pattern

$$\frac{6 \times 7 \times 3}{24 \times 1/2}$$

It is from this situation that the Upgrade begins.

The denominator of the luminosity expression offers relatively little flexibility for major gains. If the amplitude function at the interaction point is reduced significantly below 0.5 m, the bunch length correction diminishes the potential benefits of low β^*. Though the new interaction region optics permit $\beta^* = 1/4$ m, no value lower than 0.5 m will be used in the following discussion. A potential change in frequency of the acceleration system is held in reserve as a means of escaping this limitation.

The other factor in the denominator is the emittance. Quite aside from the difficulty of producing and maintaining beams of arbitrarily small emittances with reasonable intensity, there is a limitation due to the beam-beam effect, and that couples the emittance with one of the bunch intensities in the numerator. The proton bunch intensity is at least as large as the antiproton bunch intensity throughout the Upgrade, and so the former intensity will be used. The betatron oscillation tune spread experienced by the antiprotons is approximately

$$\Delta\nu = H \cdot \frac{3N_p r_o}{2\epsilon_N}$$

$$= 0.0075H \frac{N_p x\ 10^{-10}}{\epsilon_N x\ 10^6/\pi}$$

where H is the number of passages through oncoming bunches per turn and r_o is the classical radius of the proton. The necessity of avoiding low-order resonances limits the tune spread to a value of about 0.02. At present, the collider operation is tune spread limited, with $\Delta\nu \approx 0.025$. The emittance of the protons is intentionally increased by almost a factor of two before injection of the antiprotons to keep the tune spread within bounds. By separating the proton and antiproton orbits except at the collision points, H can be reduced from 12 to 2, the lower limit corresponding to the number of major detectors that will be in operation for the next collider run. The present separator scheme allows for 44 bunches of each particle type. Nearly a factor of 2 in luminosity can then be gained as it will no longer be necessary to dilute the particle emittances. But to reach the goal of $5 \times 10^{31} cm^{-2} sec^{-1}$ at 1 TeV x 1 TeV another factor of 20 must be found.

The remaining factors in the luminosity expression, $BN_{\bar{p}}$, represent the total number of antiprotons in the collider. In order to capitalize further on the avenue to higher luminosity provided by separated beams, it is necessary to improve both the antiproton stack size and the stacking rate. The stack size must, of course, be larger than the number of antiprotons required to fill the collider. The overall transfer efficiency from accumulator stack to low-β collisions is now about 70% to 80%, and so 18×10^{10} antiprotons undergoing collision implies the extraction of about 25×10^{10} from the accumulator. This in turn requires a stack size of about 60×10^{10} antiprotons. Though the number of extracted antiprotons will go up by an order of magnitude, it is anticipated that the required stack need only be about 25% larger than the number extracted, as a result of increasing the number of bunches.

The storage time is likely to remain roughly constant. In today's operation, the luminosity lifetime is sufficient to permit stores in excess of a day, but the actual average store duration is just under 14 hours. Most stores are terminated unintentionally due to a variety of fault conditions. While the sources of these fault conditions are being gradually eliminated, the new equipment associated with the Upgrade will inevitably bring new causes for store termination. Therefore, it is planned to improve the stacking rate by nearly an order of magnitude throughout the Upgrade.

The progression in luminosity, stack size, and stacking rate is summarized in Table 1. To reach these design luminosities, only 22 bunches are needed. consistent with the projected capabilities of the antiproton source during the Upgrade. Should the source be able to produce larger stacks, it is conceivable that the luminosity could go up by as much as another factor of two.

Phase	L	$\frac{BN_p N_{\bar{p}}}{\epsilon_N \beta^*}$	ΔStack	p/sec	$\bar{p}/p$	Rate($\bar{p}$/hr)	ΔStack Rate
Now	1.5×10^{30}	$\frac{6\times7\times3}{24\times1/2}$	25×10^{10}	0.65×10^{12}	7×10^{-6}	1.7×10^{10}	15
Ia	7×10^{30}	$\frac{6\times7\times7}{17\times1/2}$	60×10^{10}	0.85×10^{12}	10×10^{-6}	3.1×10^{10}	19
Ib	1×10^{31}	$\frac{22\times10\times3}{17\times1/2}$	98×10^{10}	1.4×10^{12}	14×10^{-6}	7.0×10^{10}	14
II	5×10^{31}	$\frac{22\times33\times6}{24\times1/2}$	14×10^{11}	2.8×10^{12}	14×10^{-6}	14×10^{10}	10
III	8×10^{31}	$\frac{22\times33\times6}{24\times1/2}$	14×10^{11}	2.8×10^{12}	14×10^{-6}	14×10^{10}	10

Table 1:

Progress in initial luminosity, stack size, and stacking rate throughout the Upgrade. The initial phase is divided into two parts; Ia is everything except the 400 MeV linac and the antiproton target sweeping system, and Ib includes the linac. The luminosity pattern is the same as that used in the text.

3 PHYSICS MOTIVATION

There are at least 19 basic parameters of the Standard Model. The Collider and Fixed Target Upgrade program addresses issues as fundamental as these parameters:

1. Gauge Couplings: Precision measurements of the electroweak coupling α_W (or equivalently $\sin^2\theta_W$) come both from the Collider program through measurements of the properties of the $W^{\pm}$ and Z^{0} and from the neutrino program.

   The 'running' of α_s is proposed to be well-measured for the first time via a future muon scattering experiment.

2. Masses: If not already found with the present Tevatron, the top quark mass should be determined, or at least tightly constrained, with the Upgrade. Fourth generation (or other) quarks and leptons are also objects of search in the Collider program. The Main Injector provides a powerful tool for searching for neutrino masses and mixings.

3. Mixings: Two of the four independent KM parameters need determination. The unitarity of the KM matrix should be tested. Both the Fixed Target and Collider programs directly address these questions.

4. Higgs Sector: While the standard Higgs particle may prove out of reach, variants (axions, charged Higgs', technicolor, ...) need not be. Considerable discovery potential exists for these variants.

In addition, there exists in the program considerable sensitivity to phenomena beyond the Standard Model, not only in the Collider mode but also in the Fixed Target program (e.g. experiments on rare K decays using beams from the Main Injector).

Clearly this program addresses extremely basic issues. In what follows the physics potential of the Upgrade program is presented in more detail.

The Phase I (a and b) Upgrade will increase the luminosity for $\bar{p}p$ collisions to a peak luminosity of $\mathcal{L} = 10^{31}cm^{-2}sec^{-1}$ and raise the energy of collisions to $\sqrt{s}$ = 2.0 TeV. This will provide a substantial increase from the present average peak luminosity of approximately $\mathcal{L} = 1.5 \times 10^{30}cm^{-2}sec^{-1}$ along with a modest increase in energy from the present 1.8 TeV. Phase Ia includes all of the improvements that have been underway since 1987, to make it possible to provide CDF and D0 with simultaneous high luminosity interaction regions. The commissioning of the D0 detector will be concurrent with the completion of Phase Ia. Phase Ib corresponds to an upgrade of the existing 200 MeV linac to a 400 MeV linac. The improvement will increase both the rate at which antiprotons are accumulated and the quality of the proton beams.

Phase II involves the construction of a Main Injector in a separate tunnel. This will improve the luminosity for $\bar{p}p$ collisions by another factor of 5 and remove a major source of background from the colliding beam interaction regions. It will be possible to transport 120 GeV protons from the Main Injector to all targets in the fixed-target experimental areas during Collider operation of the Tevatron. The primary and secondary beams can be used to check out the large multiparticle spectrometers prior to the changeover of the Tevatron to fixed-target operation. This will significantly reduce the two months of Tevatron time now being used for detector startup thereby making better use of the Tevatron fixed-target beam time. It will also increase the proton intensities for fixed target running by at least a factor of three. This will be particularly important for the fixed target heavy quark physics program. The very high intensity source of protons from the Main Injector will create unique opportunities for neutral kaon physics and neutrino physics. These fixed target physics opportunities are a natural extension of work in progress at Fermilab and will be discussed below in subsequent sections. It will make test and calibration beams available for SSC detector development and Tevatron collider detector calibration throughout most of the year. Finally, but not the least of the benefits, it permits the possibility of creating a third interaction region for high luminosity collider physics. Such a region would open the way for the Bottom Collider Detector (BCD) proposal, now in the process of being formulated.

In Phase III we have been considering a New Tevatron which would be installed in the present tunnel. This new ring will increase the energy for $\bar{p}p$ collisions to $\sqrt{s}$= 3.6 TeV. Furthermore, the peak luminosity will increase to $\mathcal{L} = 8 \times 10^{31}cm^{-2}sec^{-1}$.

The Upgrade will enrich both the collider and fixed target programs at Fermilab. However, since the major thrust of the Upgrade program is to improve the physics potential for the Collider program a detailed exposition of the physics benefits is given here. In order to present such a quantitative discussion of the physics motivation a number of parameters and assumptions need definition.

The experience of the past three years of operating the Tevatron for collider physics and fixed target physics indicates that a standard collider run will have a duration of ten months. Eight of these months will be scheduled for high luminosity collider physics at BO (CDF) and DO. The other two months will be used for special runs, the times when low luminosity experiments at EO and CO will be scheduled, and accelerator studies. The record shows that 4×10^5 seconds (~110 hours) of stored beam can be achieved reliably during a week. The average luminosity during a store is typically 45% of the initial luminosity. Hence, a standard run will be equivalent to ~ 6×10^6 seconds at peak luminosity. Another factor must be included to take into account the detector efficiency. Presently, the Tevatron Collider operates at a center of mass energy ($\sqrt{s}$) of 1.8 TeV and an initial luminosity which averages $\mathcal{L} = 1.5 \times 10^{30} cm^{-2} sec^{-1}$. To date, an integrated luminosity of 9 pb^{-1} has been delivered to CDF and 4.5 pb^{-1} has been recorded on tape. A suitable goal for this run is a total integrated luminosity of 5 pb^{-1} on tape.

In future runs, the detector efficiency is expected to reach 80% routinely. An extrapolation of the performance to date indicates that with the completion of Phase II of the Upgrade a standard run at center of mass energy of 2 TeV and peak luminosity of $5 \times 10^{31} cm^{-2} sec^{-1}$ will yield 200 pb^{-1}.

To study the physics potential of this proposed Upgrade it is useful to consider its various phases:

1. Phase II - The Upgrade after the completion of the Main Injector. Although the energy for $\bar{p}p$ collisions will remain at $\sqrt{s}$ = 2.0 TeV, the Main Injector will increase the peak luminosity by a factor of 5, from $\mathcal{L} = 1.0 \times 10^{31} cm^{-2} sec^{-1}$ at the end of Phase I to $\mathcal{L} = 5 \times 10^{31} cm^{-2} sec^{-1}$. Thus a standard run would yield an integrated luminosity of 200 pb^{-1}.

2. Phase III - As an example of further development, we have examined a New Tevatron at its maximum energy $\sqrt{s}$ = 3.6 TeV. With a peak luminosity $\mathcal{L} = \sim 10^{32} cm^{-2} sec^{-1}$ a standard run would yield an integrated luminosity of 400 pb^{-1}. For many reactions this extra energy is equivalent to a <u>much</u> higher (3 to 10x) luminosity at 2.0 TeV. This can be read from the graphs or Table IV below.

The physics potential of the Tevatron Collider program can be divided into three broad classes: Standard Model Physics, Minimal Extensions, and New Directions. Each of these classes will be discussed in turn. After a summary of the Collider physics motivations, there is a brief discussion of the benefit to the fixed target program of the higher energy of the New Tevatron. New physics opportunities associated with the Main Injector are discussed in the final section.

3.1 Standard Model Physics

At the Tevatron the physics of the standard model can be studied in great detail. Perhaps the most exciting opportunity at present is the discovery and subsequent study of the top quark in $\bar{p}p$ collisions. The lower bound on the top mass is 41 GeV/c^2 which comes from the analysis of UA1 data.[1] There are no reliable theoretical predictions for the top mass. However within the Standard model with three generations there is an upper bound on the possible top mass which is determined by the deviation of the ρ parameter from unity.[2] The present experimental constraints on the ρ parameter imply that top is no heaver than 180 GeV/c^2. At Tevatron energies and above the dominant mechanism for producing top (or any heavy quark) is gluon fusion. The cross section for heavy quark production via gluon fusion is shown in Figure 1 for the present Tevatron energy and the various Upgrade phases.

---

1. G. Altarelli et. al., Nucl. Phys. B308, 724 (1988).
2. P. Langacker, W. M. Marciano, and A. Sirlin, Phy. Rev. D36, 2191 (1987). Also see U. Amaldi et. al, Phy. Rev. D36, 1385 (1987).

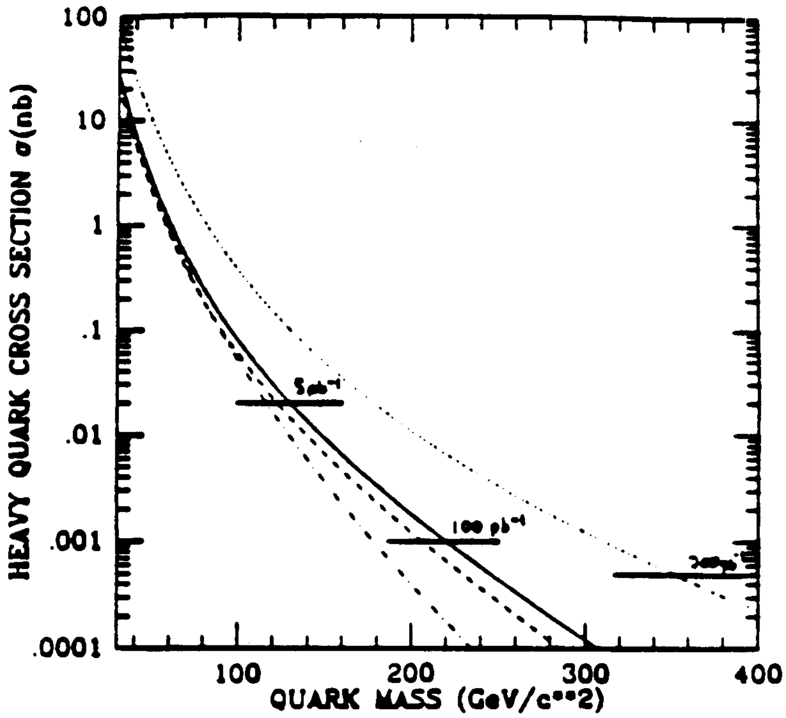


Figure 1

Total cross section, σ(nanobarns), for pair production of heavy quarks (by gluon fusion) in pp collisions at $\sqrt{s}$= 1.8 TeV (dashed curve), 2.0 TeV (solid curve), and 3.6 TeV (dotted curve): and in pp collisions at $\sqrt{s}$ = 2.0 TeV (dash-dotted curve). The EHLQ parton distribution functions (with Λ = 290 MeV) were used. The cross sections required to produce 100 heavy quark pairs in a standard run of integrated luminosity of 5 pb^{-1}, 100 pb^{-1}, and 200 pb^{-1} are indicated by horizontal solid lines. The cross section required with an integrated luminosity of 1000 pb^{-1} is .1 pb.

The detection of a top signature may require as few as 100 produced pairs, while a clear proof of top accompanied with a mass measurement may require as many as 1000 produced pairs. Therefore with 5 pb^{-1} CDF can see evidence for top for masses up to about 90 GeV/c^2. The upgraded CDF with better muon coverage will have an improved efficiency and capability for top search. The Main Injector will extend the range for discovery to 260 GeV/c^2 and presumably for measurement if the mass is less than ~ 170 GeV. Since this is safely above the theoretical upper bound on the top mass, the discovery of top within the Standard Model will be assured with the Upgrade. In the more fortunate circumstance that top will be discovered at a much lower mass, perhaps even in the present collider run, the Main Injector will allow the collection of 50K tops. This provides the potential for studying rare decay modes including channels which could indicate new physics e.g. fourth generation.

The collider will also produce sufficient events to allow detailed studies of the electroweak bosons ($W^{\pm}$ and Z^{0}) and the bottom quark. Table 2 shows the number of produced events for various known particles at the present Tevatron with integrated luminosity of 5 pb^{-1} as well as standard runs for Phase II and III of the Upgrade.

Table 2: Event Rates for Standard Particles

Particle(Mass)	Events in Standard Run		
	Now	Phase II	Phase III
$b(4.75GeV/c^2)$	2.5×10^8	1.1×10^{10}	5×10^{10}
$W^{\pm}(81GeV/c^2)$	6×10^4	2.6×10^6	1×10^7
$Z^0(92GeV/c^2)$	2.0×10^4	8.8×10^5	3×10^6
$W^{\pm}\gamma(E_T^{\gamma} > 10GeV/c^2)$	75	3300	15,000
$W^+ W^-$	32	1500	6400
$W^{\pm} Z^0$	8	350	1500
$Z^0 Z^0$	4	180	600

The study of bottom meson decays, mixing, and CP violation will provide critical information about the quark mixing matrix (i.e. the KM matrix) in the three generation standard model. It is very likely that most of the information about B_u and B_d mesons obtained in the next 5 years will come from LEP and CESR and a smaller but significant contribution from the Fermilab fixed-target program. In particular, with a planned upgrade CESR will be capable of producing 10^7 B mesons per year by 1995. Some exploration of the physics of B_s mesons and b quark baryons will likely occur at Fermilab. We should however be aware that, in principle, the fixed-target program with exquisite detector technology could do much better.

There are still large uncertainties in the total hadronic rate of bottom quark production. Recently, the full calculation through order

α_s^3 has been completed.[3] The results are shown in Figure 2. The range of theoretical uncertainty is indicated by the upper (dotted) and lower (dashed) curves. Although the variations are large, the dependence of the total cross section with $\sqrt{s}$ is quite accurately linear in the energy range above $\sqrt{s}$ = 500 GeV and hence the ratios of cross sections for the present Tevatron and the Upgrade options should be quite reliable. These ratios are 1.0 to 1.1 to 2.0 for the Tevatron, Upgrade Phase II, Upgrade Phase III, respectively. The rate of bottom quark production shown in Table 2 is the nominal result of the order α_s^3 calculations. However, as seen from Figure 2 and Table 2, even taking these uncertainties into account the cross section of b quark production would be at least 20 μb in phase II and could be 150 μb.

In contrast the e^+e^- cross section for $\bar{B}B$ production at the upsilon (4S) is about 1 nb, 10^5 times smaller than the estimated 50 μb cross section for $\bar{B}B$ production in $\bar{p}p$ collisions at the Tevatron. Even with the proposed luminosity upgrade of the CESR collider, the Main Injector will be capable of producing a thousand times more events. In addition the Tevatron provides a Lorentz boost to the B's which gives promise of reconstructing the secondary vertex of the B meson. If the detection problem for B's produced in a hadron collider can be solved as it was solved for charm in fixed-target hadron experiments then the future of b physics could be very bright for the Tevatron. The study of CP violation in the neutral B system would greatly extend the understanding gained from the the K system, leading to a precise determination of all the KM matrix elements. Furthermore, the study of not one or two but many CP-violating decay modes in the B system, would over constrain these parameters.

---

3. P. Nason, S. Dawson, and R. K. Ellis, Nucl. Phys. B303, 607 (1988).

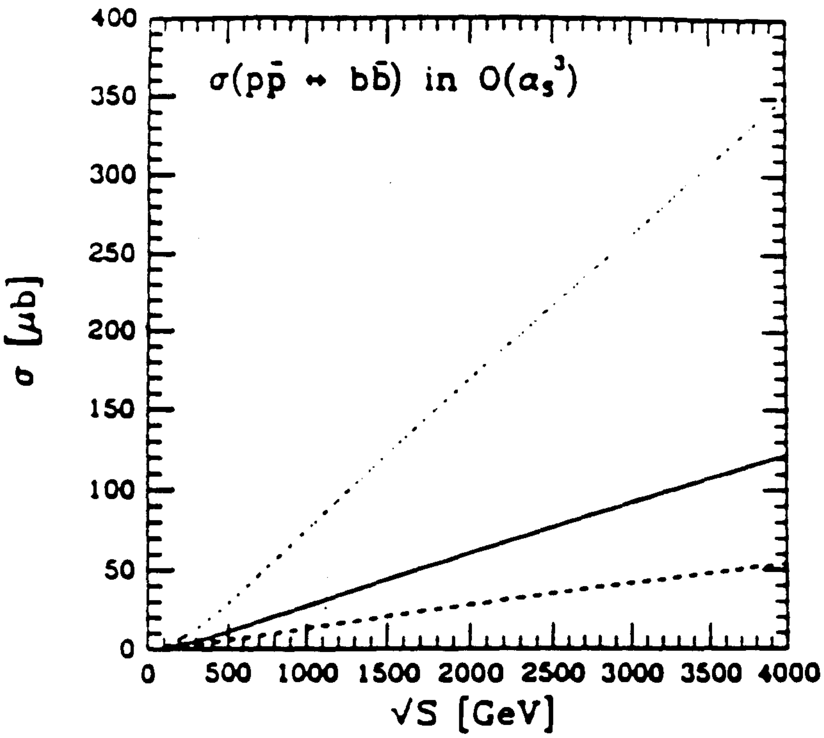


Figure 2

Total cross section, σ(nanobarns), in order α_s^3 for the production of the bottom quark via gluon fusion in $p\bar{p}$ as a function of center of mass energy $\sqrt{s}$ (GeV). The theoretical uncertainties are illustrated by three choices of the three parameters of the calculation: The bottom quark mass, m; the QCD scale, Λ; and the scale of the process, μ. The middle (solid curve) uses the nominal values of these parameters: $m = 4.75$ GeV, $\Lambda = 170$ MeV, and $\mu = m$. The largest cross section (dotted curve) uses extreme values: $m = 4.5$ GeV, $\Lambda = 250$ MeV, and $\mu = m/2$. The smallest cross section (dashed curve) uses the opposite extreme values: $m = 5.0$ GeV, $\Lambda = 100$ MeV, and $\mu = 2$ m. The DFLM parton distribution functions were used.

The determination of the CP-violating asymmetry of B-decay branching ratios, $A = [\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})]/[\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})]$ directly measures elements of the KM matrix. Such asymmetries are expected to be in the range 0.05-0.30 for some favorable modes. However, it is anticipated that decay modes with large asymmetries have small branching ratios. When the final state f is a CP eigenstate the theoretical interpretation of A is particularly clean. However a very large sample of produced B's is required to make a measurement of this asymmetry. Also, when the final-state $f = \bar{f}$, the identification of the parent B as a particle or an antiparticle must come from a tag based on the reconstruction of the other B in the event.[4]

In order to realize the full potential of the B system, a sample of several thousand B-$\bar{B}$ events in the modes of interest (branching ratios $\sim 10^{-5}$) must be fully analyzed, including full reconstruction of one B meson and sufficient reconstruction to identify the particle-antiparticle nature of the other. It is generally accepted that hadron colliders at high energy are the ultimate B factories. This is because of the very large B cross sections, about a millibarn, and the very favorable ratio of the B cross section to the total cross section (about 1%, like charm photoproduction).

The kinematics of B production at the collider are very similar to those at the SSC. Therefore, the technical challenges in mounting an experiment in the collider are similar to the challenges in the low-luminosity (beauty) region at the SSC. Since the challenge is so great, many physicists believe that an intense effort to build such a detector should begin immediately. Some components could be built after a few years' R&D, others will require many years. But the goal of a major physics measurement prior to the SSC greatly sharpens the focus of the needed detector development.

---

4. For a discussion of CP violating decays in the B system, see: F. Gilman, B Physics, Proceedings of the Workshop on High Sensitivity Beauty Physics at Fermilab (Nov. 11 - 14, 1987), p. 1 and the references therein.

The most critical detector element is the (probably) solid-state vertex detector, with about a million channels and a 4π geometry to reconstruct tracks and vertices in 3-D. The experience at the Tevatron collider, will lead the way to the ''best'' approach for the SSC.

A detector concept for the Tevatron collider has been recently proposed. This is based around a large dipole magnet, with field transverse to the beam to maintain good momentum measurement for all charged tracks of $P_T < 5$ GeV/c. In addition to the silicon vertex detector, there will be a straw-tube tracking system, Ring-imaging Cerenkov counters for π-K-p separation, transition-radiation detectors and an electromagnetic calorimeter for electron identification and triggering, and a large farm of on-line numeric processors.

An R&D program has been initiated to address the many technical issues involved in building such a detector. An interim goal might be to place a portion of the vertex detector and tracking system in one of the low luminosity intersections at Fermilab during the 1991 collider run, in order to demonstrate that secondary vertices can be detected in a hadron-collider environment. Useful signals include $K_s^0 \rightarrow \pi^+ \pi^-$, and $D^0 \rightarrow K^- \pi^+$.

The measurement of CP violation in the B system may be a distant goal but this drive allows many interesting features of the B system to be studied along the way: the details of $b\bar{b}$ production in hadron collisions, mixing, rare decay modes, etc. The combined prospects of new physics and an intermediate step toward high luminosity running at the SSC render the b physics potential of the Tevatron upgrade an important element of a healthy high energy physics program in the 1990's.

The high $W^{\pm}$ rates in hadron collisions makes the Main Injector very competitive with LEPII for studying the physics of $W^{\pm}$.[5] One example of what might be done with the high rates at the Upgrade has recently been studied by the DO collaboration.[6] The high statistics available in $W^{\pm}$ and Z^{0} production permit the determination of the $W^{\pm}$ mass to a statistical precision comparable to that obtainable at LEPII. Using the value of the Z^{0} mass obtained by LEPI or SLC a determination of the $W^{\pm}$ mass to a precision of $\pm$ 100 MeV/c^2 free of absolute energy calibration error may be achievable.[7] In the Standard Model with three generations, the mass of the $W^{\pm}$ depends strongly on the top quark mass and more weakly on the Higgs boson mass as shown in Figure 3. A precision measurement of the $W^{\pm}$ mass with an accurate measurement of the top quark mass enables one to test the consistency of the three generation Standard Model. Such a consistency check could be one of the first indicators of either a fourth generation or physics beyond the Standard Model(eg. Supersymmetry or Technicolor).

From Table 2, it is clear that detailed study of electroweak pairs will not be easy even with the Tevatron upgrade. The signal to background rate for $W^{\pm}$ plus two jets (with pair mass near M(W)) is not encouraging and the rate for totally leptonic channels is very small. However, there will be enough events (particularly in the W^+W^- channel) to look for any gross disagreement with the Standard Model prediction. For example, if the $W^{\pm}$ and Z^{0} were composite, resonances might occur in electroweak pair production at high energy or the $W^{\pm}$ might have an anomalous magnetic moment. One can search for strong resonances or any other large deviation of the cross section in any of these channels at subprocess energies well above the highest LEPII energy.

---

5. 'Physics at LEP at Very High Energies', G. Barbiellini et. al., in 'Physics at LEP Vol. 2', edited by J. Ellis and R. Peccei, CERN Preprint 86-02, p.1 (1986).
6. 'Theoretical Implications of the $W^{\pm}$ - Z^{0} Mass Difference and the Capabilities of the D0 Detector in Measuring It', R.Raja, Fermilab preprint CONF-88/198 (1988).
7. Ibid.

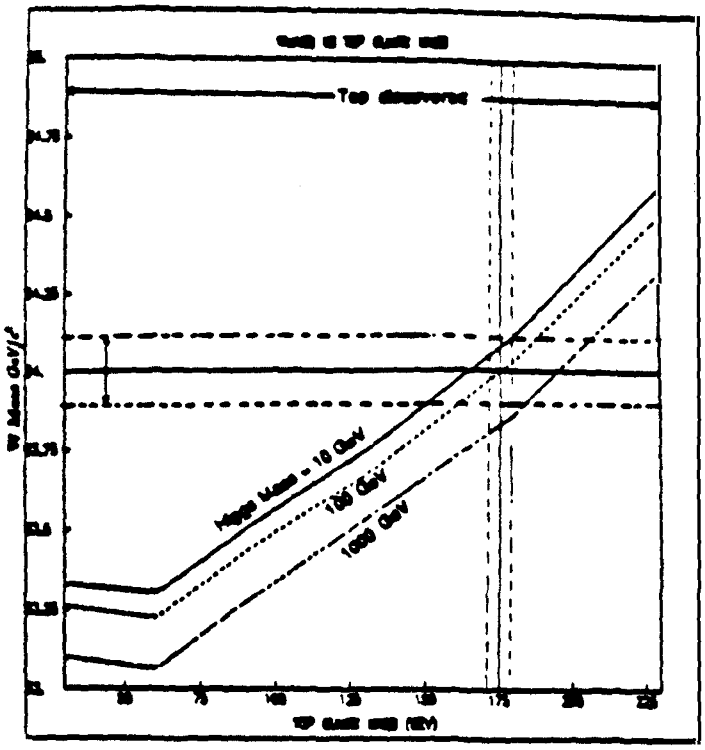


Figure 3

Dependence of the W mass on the top mass for fixed Z^0 mass (Assumed here to be 94 GeV/c^2). The solid curve assumes the Higgs mass of 10 GeV/c^2; the dashed curve assumes the Higgs mass of 100 GeV/c^2; *and the dash-dotted curve assumes the Higgs mass of 1000 GeV/c^2. The 1σ bands are shown for a top mass of 175 ± 5 and a W mass of 84.0 ± .1 are illustrated. (From Ref. 6)*

3.2 Minimal Extensions

The Tevatron energies are high enough to be sensitive to new physics at the electroweak scale. The simplest extension is the possibility of a fourth generation of quarks and leptons. If discovery requires 100 produced pairs a fourth generation quark could be discovered for masses up to about 100 GeV/c^2 in the present run of the Tevatron. With the Main Injector discussed above, the discovery limit for new quarks will be extended to 250 GeV/c^2. This range of masses is particularly important within the standard model. Figure 3 shows the bounds on new quarks implied by the standard model. If it is assumed that there is no new physics (beyond a fourth generation) all the way to the GUT scale ($\gtrsim 10^{15}$ GeV) then a more stringent unitarity upper bound can be obtained for quark masses.[8] As shown in Figure 4 the upgraded collider will be sensitive to any quark masses within the whole region allowed by these theoretical bounds.

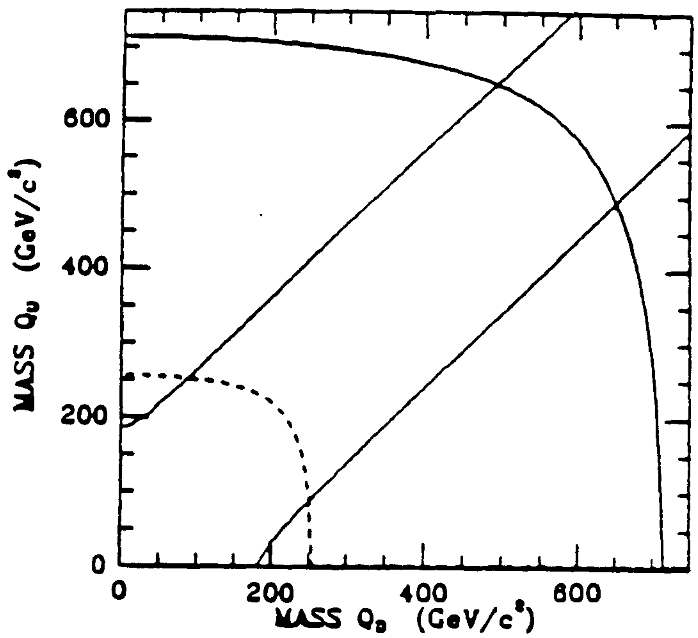


Figure 4

Theoretical bounds on the quark masses of a postulated fourth generation. The pair of diagonal lines give the upper bound on the magnitude of the Q_U - Q_D mass difference arising from bounds on the rho parameter. The solid curve gives the upper bound on the masses consistent with perturbative unitarity. Finally the dashed curve gives the bound arising from the assumption that perturbative unitarity will hold at all scales below the GUT scale. (See Ref 8 for more details).

8. C. Hill, Phy. Rev. D24, 691 (1981), and references therein.

New $W^{\pm}$ and Z^{o} gauge bosons are required in almost any model which extends the standard model by unification. In models which restore a Left-Right symmetry at high energies additional charged weakly interacting gauge bosons are required ($W^{\pm}$)[9] and in many unified models, including the presently popular E_6 model motivated by superstrings, neutral gauge bosons are required (i.e. Z'^{o}).[10] The strongest present limits on new $W'^{\pm}$ and Z'^{o} come from deep-inelastic neutrino scattering experiments and require that the mass of any new boson with couplings similar to the couplings for the standard $W^{\pm}$ and Z^{o} to be greater than 300 GeV/c^2. The cross section for a Z'^{o} at the Tevatron and for the various Upgrade phases and pp Option is shown in Figure 5. In its present run at the Tevatron, CDF will be able to discover a new W'^{o} or Z'^{o} with masses up to 400 GeV/c^2. With the Main Injector masses up to 850 GeV/c^2 can be discovered. This represents a very significant window on new physics.

Furthermore, if a W'^{o} or Z'^{o} was discovered at the present run at the Tevatron, the Main Injector will allow detailed study of its properties. For a mass at the discovery limit of the present run (400 GeV/c^2), 6200 events will be produced in a standard run at the Upgrade.

---

9. J. C. Pati and A. Salam, Phy. Rev. D10, 275 (1975); R. N. Mohapatra and J. C. Pati, Phy. Rev. D11, 566 (1975); R. N. Mohapatra and G. Senjanovic, Phy. Rev. D23, 165 (1981).
10. For the properties of the additional Z^{o} in E_6 models see, for example: V. Barger and K. Whisnant, Proceedings of the Workshop: From Colliders to Supercolliders, Madison, WI, May (1987) and Int. J. Mod. Phys. A3, 879 (1988).

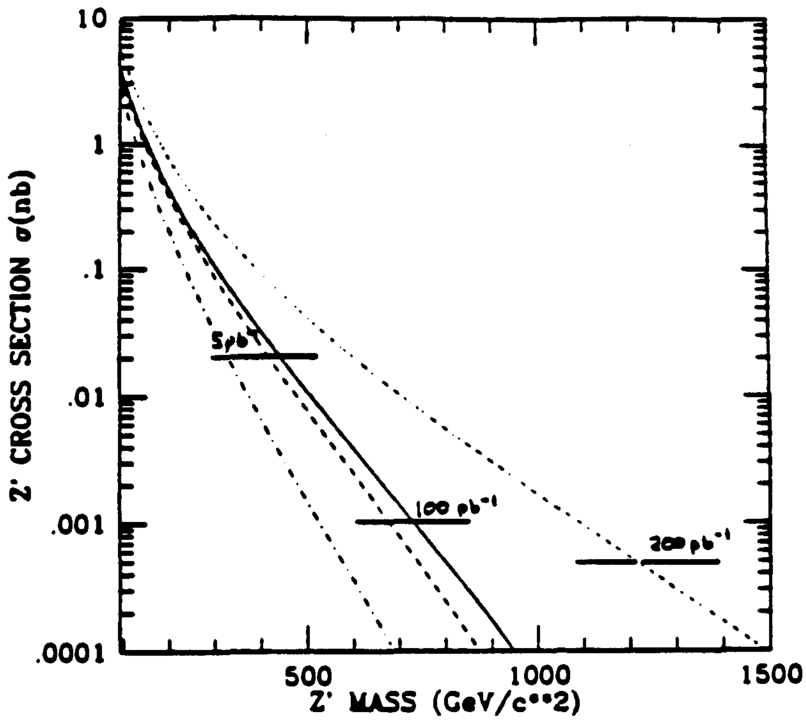


Figure 5

Total cross section, σ (nanobarns), for the production of a new neutral gauge boson, Z'^0, in pp collisions at $\sqrt{s}$ = 1.8 TeV (dashed curve), 2.0 TeV (solid curve), and 3.6 TeV (dotted curve); and in pp collisions at $\sqrt{s}$ = 2.0 TeV (dashed-dotted curve). The EHLQ parton distribution functions (with Λ = 290 MeV) were used. The couplings of the Z'^0 to quarks and leptons were assumed to be the same as the Z^0 couplings. The cross sections required to produce 100 Z'^0 events in a standard run of integrated luminosity of 5 pb^{-1}, 100 pb^{-1}, and 200 pb^{-1} are indicated by horizontal solid lines. The cross section required with an integrated luminosity of 1000 pb^{-1} is .1 pb.

3.3 New Directions

Technicolor, supersymmetry, and compositeness are three major departures from the standard model which have received considerable theoretical attention.[11] In each of these models new physics is proposed for which the Tevatron collider program can make an important contribution.

In the simplest technicolor models one expects a number of light spinless particles associated with the technicolor interaction. These particles are called technipions in analogy with the lightest particles associated with QCD, the pions. Some of these technipions will be colored (e.g. P_3 and P_8) while others are color neutral (e.g. $P^{\pm}$, P^{o}, and P'^{o}). A detailed study of the possibilities for detection of these particles at the Tevatron[12] concludes that if the production of $P^{\pm}P^{o}$ pairs through the decays of $W^{\pm}$ is kinematically allowed the detection of these color singlet technipions should be feasible at the Tevatron. For the color triplets (and octets) the rates for the expected technipion masses is marginal in the present phase but would become quite feasible with the Upgrade. Recently a variation on the standard technicolor model called Walking Technicolor [13] has attracted considerable theoretical attention because of the possibility that these models may cure the flavor changing neutral current problems of the original technicolor based models. In this new class of models one also expects new particles in the mass range, (150 - 250) GeV/c^2, which could be discovered with the Main Injector.

For supersymmetric theories the masses of the superpartners of the ordinary quarks, leptons, and gauge bosons are not presently

---

11. For a review of possible new physics and applications to the Tevatron Collider see, for example: E. Eichten, "Theoretical Expectations at Collider Energies", Fermilab - PUB - 85/178-T (1986).
12. E. Eichten, I. Hinchliffe, K. D. Lane, and C. Quigg, "Signatures For Technicolor", Physical Review, D34, 1547 (1986).
13. T. Appelquist, D. Carrier. L. C. R. Wijewardhana, and W. Zheng, Phy. Rev. Lett. 60, 1114 (1988), and references therein.

determined by theory. However, there is an expectation that the general scale of these superpartner masses should not be much above the scale of the W and Z masses, i.e. of the order of a few hundred GeV. The cross section for pair production of gluinos (the superpartners of gluons) at the present Tevatron and the various Upgrade phases is shown in Figure 6. If 100 produced pairs are required for detection, in the present run CDF should be able to detect gluinos and squarks (the superpartners of the ordinary quarks) with masses up to 140 GeV/c^2 and in a standard run with the Main Injector masses up to 200 GeV/c^2 could be detected. Alternatively, if a gluino were found in the present run at its discovery limit (140 GeV/c^2), a standard run at the Upgrade would produce 8000 gluino pairs.

Finally, the systematic study of QCD jet physics will be possible up to very high jet pair masses. In the present CDF run at the Tevatron, approximately 100 jet pair events should be observed with pair masses in excess of 500 GeV/c^2. In a standard run with the Main Injector, 100 jet pair events should be observed with a pair mass in excess of 900 GeV/c^2. This allows the possibility of testing quark compositeness up to a compositeness scale of 1.4 TeV in the present run and in a standard run with the Main Injector scales up to 2.6 TeV can be probed.

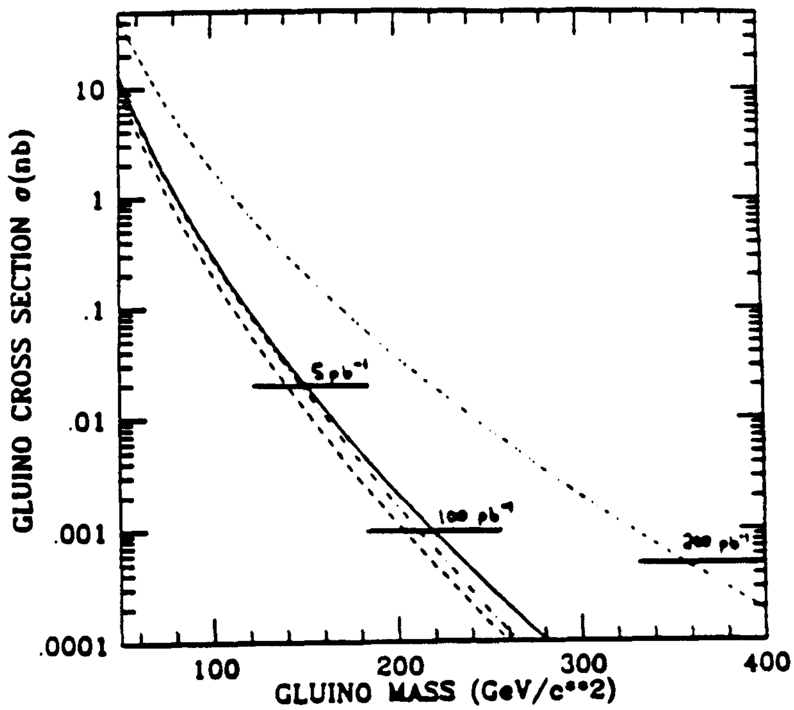


Figure 6

Total cross section, σ(nanobarns), for the production of gluino pairs in $\bar{p}p$ collisions at $\sqrt{s}$ = 1.8 TeV (dashed curve), 2.0 TeV (solid curve), and 3.6 TeV (dotted curve); and in pp collisions at $\sqrt{s}$ = 2.0 TeV (dashed-dotted curve). A rapidity cut of $|y| < 1.5$ was applied two both final gluinos. The EHLQ parton distribution functions (with Λ = 290 MeV) were used. The cross sections required to produce 100 gluino pairs in a standard run of integrated luminosity of 5 pb^{-1}, 100 pb^{-1}, and 200 pb^{-1} are indicated by horizontal solid lines. The cross section required with an integrated luminosity of 1000 pb^{-1} is .1 pb.

Table 3: Discovery Limits for New Physics

	Discovery Limit (GeV)		
	Now	Phase II	Phase III
Heavy Quark	120	260	400
Z' or W'±	400	850	1400
Gluino	140	240	450
P_3 Technipions	125	260	450
Quark Substructure	1400	2600	3500

3.4 Summmary of Collider Physics Motivations

The upgraded Tevatron collider will provide a wealth of physics opportunities within the standard model. With the Upgrade, detailed studies will be possible for the electroweak gauge bosons, jets, and heavy quarks. In particular, within the Standard Model the discovery of top is assured and if the mass is low enough that top is discovered soon then the Upgrade has the potential to be a top factory. More than 10^{10} bottom quarks will be produced in a single run at the Upgrade. This is 1000 times the rate available in e^+e^- collisions at an upgraded CESR in 1995. The Upgrade provides an appropriate environment in which to tackle the difficult problems of tagging and studying rare B decays in a hadron collider. With clever ideas and hard work the large numbers of $W^\pm$ and Z^0 electroweak bosons produced (Table 2) can be used to test the Standard Model and perhaps even get some indirect suggestion of the Higgs boson mass. These opportunities alone guarantee a successful physics program at the proposed Upgrade.

Secondly, the Upgrade will extend the discovery limits by a factor of two for: new quarks associated with a fourth generation, new electroweak gauge bosons associated with a partial unification of the gauge interactions, or gluinos and squarks associated with supersymmetry. It will also greatly extend the range in the search for new fundamental interactions such as Technicolor or quark compositeness. These results are summarized in Table 3.

Furthermore, signals of new physics which are at the discovery limit of the present run of CDF at the Tevatron collider could be studied in some detail with the Main Injector. Table 4 illustrates this by comparing the production rates for a Z'^{o} or W'^{o}, gluino, and technipion at the various Upgrade options, for the mass at the discovery limit of the present run at the Tevatron.

Finally, although a full understanding of the physics of the one TeV scale will require the SSC, the Tevatron may provide important clues to the character of this new physics. These signals are typically associated with very rare events and thus an extended effort at high luminosity will be required to discover any such signal. Clearly this phase of the Tevatron collider physics program would benefit greatly from the proposed Upgrade program.

Table 4: Factory Domain

Particle	Mass(GeV/c^2)	Events in a Standard Run		
		Now	Phase II	Phase III
Z'^{o} or W'	400	100	6.2×10^3	5×10^4
Gluino	140	100	8.0×10^3	17×10^4
P_3 Technipions	125	100	6.0×10^3	7×10^4

3.5 The Tevatron Fixed–Target Program

When the source of protons for the fixed-target program changed from the Main Ring to the Tevatron, a number of profound changes were set in motion. These changes are making heavy quark physics the major focus of the fixed-target program. It is by no means the only focus of the experimental effort. The changes that the Tevatron brought about are summarized briefly in the following.

The primary proton energy increased from 400 GeV to 800 GeV and this led to a corresponding increase in the useful energy of secondary and tertiary beams from roughly 150 GeV to 300 GeV. Certain beams such as π^- and μ^+ beams now have intense fluxes at 500 GeV. The macroscopic duty factor, the ratio of the time during which primary beam is delivered to a target to the duration of the accelerator cycle time, increased from 12% to 40%. These changes combined with advances in the performance of microvertex detectors and data acquisition systems made the detection and background free reconstruction of particles containing heavy quarks feasible. Microvertex detectors made it possible to distinguish the decay vertex of a heavy quark decay from the primary interaction vertex thereby making the assignment of charged particles to the decay vertex unambiguous. Prior to these changes, fixed-target experiments attempting to observe charmed particles detected at most a few hundred events with considerable background. Today, the most accurate measurements of charmed particle lifetimes come from E-691, a Fermilab photoproduction experiment that took data in 1985. This experiment, which observed a total of somewhat more than 10,000 fully reconstructed charm decays, also provided the world's most precise data on such diverse topics as $D^0\bar{D}^0$ mixing and excited states of charmed mesons and baryons. The ability of E-691 to separate charmed particle decays from the general background of hadrons is shown in Figure 7 which is a mass plot of 3400 fully reconstructed events with well-identified decay vertices in a single decay channel. The significance of the ''E-691 break through'' is profound for the future of hadron physics. It took about a decade to solve the problem of obtaining clear signals out of a background in which charm production is only 0.1%. Machine performance, detector technology and data processing power were the key elements. Obviously this success encourages the next stage; beauty physics.

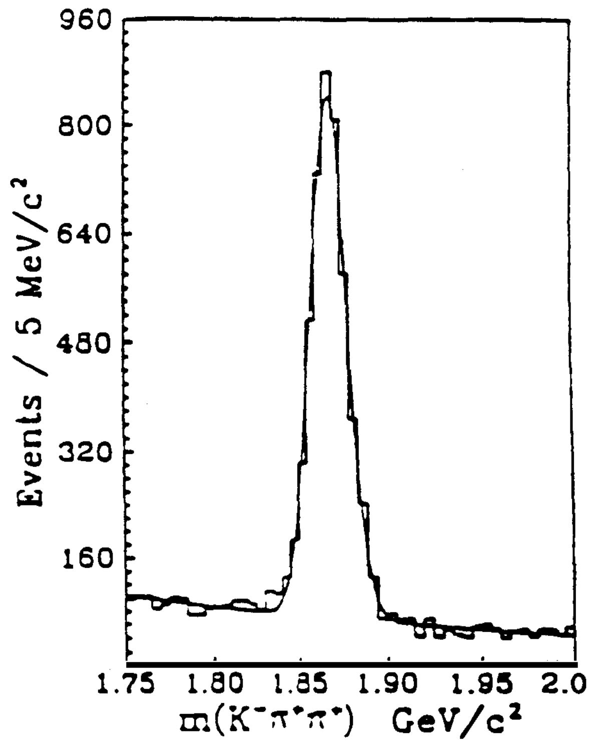


Figure 7

Mass distribution of charmed particle decays from Fermilab experiment E-691.

Since that experiment was completed in 1985, two new multiparticle spectrometers with more accurate microvertex detectors, improved particle identification, and more effective data acquisition systems have been commissioned. Two additional facilities will be upgraded with microvertex detectors in 1989. Some of these facilities will be capable of observing more than 10^6 fully reconstructed charmed particles and all are intended to obtain roughly 1,000 partially reconstructed beauty particles with well-identified decay vertices. Typically 50 beauty particles should be fully reconstructed in each experiment.

When both the 400 MeV linac and the Main Injector are operational, the number of protons per pulse could increase by a factor of four above the typical intensity achieved during the 1987-88 fixed target run. Even without improvements in detectors the heavy quark experiments should acquire three times as much data as will be obtained in the 1989-90 fixed target run. With improvements to the detectors both the fraction of b's that can be fully reconstructed and those that can be partially reconstructed should increase significantly.

The increased intensity will also allow more accurate measurements of CP violation in the $2\pi^0$ and the $\pi^+\pi^-$ decay modes of neutral kaons. Already the data from the 1987 run of E-731 should yield a measurement of ϵ' to an accuracy of 25%, if it is truly as large as 0.0035. The same data has already produced a limit on the K_L^0 branching ratio to $\pi^0 e^+ e^-$ of 10^{-9}. More accurate experiments will be possible with the Upgrade, for example it should be possible to reduce the error on ϵ' by another factor of 2 and to make a measurement of η_{+-0}, the parameter that measures the strength of CP violation in the decay of K_s^0 into $\pi^0\pi^+\pi^-$, to an accuracy of a few parts in ten thousand. During the period from now till the end of 1992, there should be two fixed target runs each of eight-month duration, exclusive of startup and shutdown. The experimental program for these runs includes the following experiments:

1. An experiment will fully reconstruct several x 10^5 charmed particles and 100 b particles, and partially reconstruct several thousand b particles from all produced by the photoproduction at an average energy of 225 GeV. These results should provide measurements of the lifetimes of the neutral and charged heavy flavor mesons and accurate measurements of the

differential photoproduction cross sections of B mesons and baryons. Rare decays of charm at the level of 10^{-6} should be identified and in so doing the limit for $D^O\overline{D}^O$ mixing should be reduced by another order of magnitude. Accurate measurements of the semileptonic branching ratios of charmed mesons should be obtained. These will in turn improve the accuracy of the $|V_{cd}|$ and $|V_{cs}|$ elements of the KM matrix.

2. Five experiments dedicated to the production of b particles in hadron beams should take data. Each of these experiments is expected to be able to separate b's from other processes by observing the b decay vertex and by this method reconstruct a few tens to a few thousand b's. Given their different emphasis on kinematics, collectively they should provide an extensive picture of hadroproduction of heavy quarks. Some of these experiments will also acquire in excess of 10^5 charmed particle decays.

3. A measurement of the phase of η_{oo} to an accuracy of 1 degree and a reduction of the lower limit on the branching ratio of $K_L^O \rightarrow \pi^O e^+ e^-$ to 10^{-11}.

4. A measurement of nuclear structure and fragmentation functions in inelastic muon scattering. The range of q^2 will be from 0.2 $(GeV/c)^2$ to 1000 $(GeV/c)^2$ and the range of X_{BJ} will be from 0.001 to 0.2.

5. A measurement of direct photon production in the collisions of 530 GeV mesons of both signs with Be nuclei and 800 GeV protons with Be nuclei will provide a comprehensive survey of direct photon production in hadron collisions. This experiment together with the planned measurements of photoproduction cross sections of heavy flavors and jets will be sensitive to the gluon distribution functions of the nucleon.

6. An experimental measurement of the asymmetry parameter of the Σ^+ decaying into $p + \gamma$ will be made by observing in excess of 10^5 events. At the same time a search will be made for the previously unseen decay $\Xi^- \rightarrow \Sigma^- + \gamma$. If the branching ratio is as large as expected a sample of several thousand radiative decays of the Ξ^- should be observed.

7. An experimental measurement of the Ω^- magnetic moment to ± 0.04 nuclear magnetons will be made, thus completing the measurement of all strange hyperon magnetic moments including the $\Sigma^0 - \Lambda^0$ transition magnetic moment to similar or better precision.

8. An experiment dedicated to the detection of charmed baryons with non-zero strangeness produced by a hyperon beam of Σ^- and Ξ^-.

These experiments are noted because follow up experiments of this type will benefit significantly from the first two stages of the Upgrade. The gradual increase in beam intensity that accompanies the first two phases of the Upgrade will increase the number of detectable b particles to the level where there are of the order of 100 events per decay mode. That gradual increase will be well matched to the detector and data acquisition development that will proceed in parallel, if the produced b's are to be detected and analysed.

While the present generation of these experiments will be completed before something like the new Tevatron can be used to produce higher energy secondary and tertiary beams with adequate intensity, the motivation to do many of these experiments more accurately will remain because of the fundamental nature of these measurements. It has been 25 years since it was established that the decay of K_L^0 did not conserve CP. Shortly thereafter it was recognized that ϵ' was an important parameter to measure. Time has only enhanced its importance.

3.6 Physics with the Main Injector

3.6.1 Kaon Physics with the Main Injector

One of the important characteristics of the new Main Injector of Phase II of the Upgrade is its high energy coupled with high intensity. It is natural to examine its potential as an intense source of high energy kaons for precision studies of CP non-conservation as well as rare decay searches with high sensitivity. Such experiments are important in that with enough sensitivity very high mass scales can be accessed. The extracted beam from the Main Injector at 120 GeV will produce a source of high energy kaons that will not be surpassed in intensity, even in the SSC era.

The attention at Fermilab in kaon physics has recently been concentrated in precision studies of the $K_L \to 2\pi^0$ decay (ϵ'/ϵ), a search for the mode $K_S \to \pi^+\pi^-\pi^0$ (η_{+-0}), and a search for the $K_L \to \pi^0e^+e^-$ decay which is very likely CP violating to lowest order. At present, the Fermilab experiments have the greatest sensitivity for these modes even though the kaon production cross section is roughly independent of energy and at BNL, where the available proton flux far exceeds that of Fermilab, there is a dedicated program pursuing rare kaon decays. The advantage for these and other modes arises primarily from the higher energy of the decay products.

How might the field of kaon decays likely evolve? Briefly, the best searches for the lepton number violating decays come from BNL experiments and these are now at the 10^{-10} level. Additionally, the interesting mode of $K^+ \to \pi^+$ + ''nothing'' seems to be best done with a stopped charged kaon beam and there BNL has the best experiment. Both of these efforts could probably be upgraded to the 10^{-11} level or perhaps better with the Booster/Stretcher combination proposed there.

At the Tevatron, the $K_L \to \pi^0e^+e^-$ sensitivity can also be pushed to nearly the 10^{-11} level. The (statistical) sensitivity to ϵ'/ϵ is now at the level of 0.0004, corresponding to over 0.5 x 10^6 detected $K_L \rightarrow 2\pi^0$ decays.

The next generation of experiment in the 2π system will likely require over 10^8 $K_L \rightarrow 2\pi^0$ decays with very little background; such a sample would permit a measurement of ϵ'/ϵ with a precision of better than 10^{-4} and this is a level where the Standard Model would certainly be definitive in its non-zero prediction. Closely coupled with the issue of a non-zero ϵ'/ϵ is the branching ratio for the $K_L \rightarrow \pi^0 e^+ e^-$ mode which is expected to be of the order of a few times 10^{-12}. So far, although this mode has been the subject of wide interest, there has been little serious consideration of the issues required to obtain this sensitivity. Although this issue cannot be addressed in detail here, it is important to point out that with an extracted beam from the Main Injector, the flux necessary to permit sensitivities to this mode in the range of 10^{-10} per hour of running is obtainable. Furthermore, the Main Injector will be the best place to perform such experiments of any presently existing or planned facility.

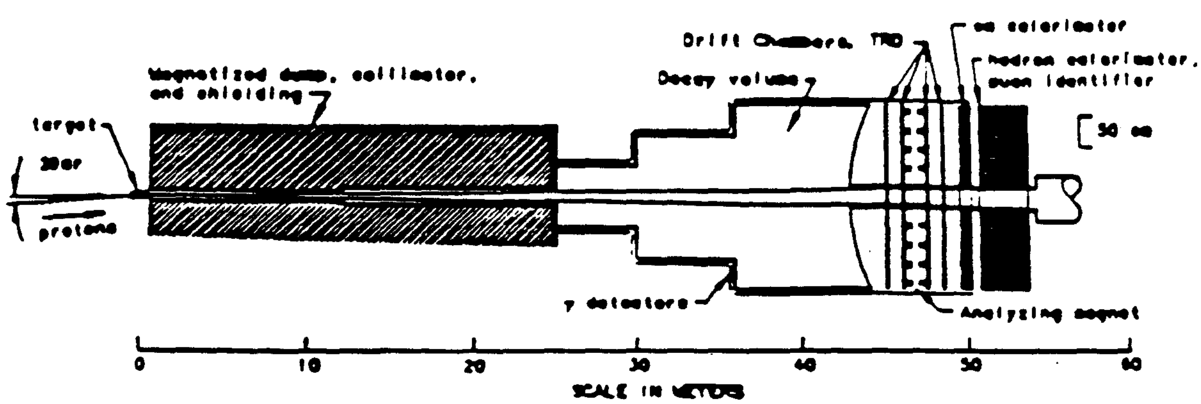


Figure 8

Model Neutral Kaon Apparatus using the Main Injector

The advantages of the Main Injector for the kaon physics discussed above can be illustrated with an example beam and high acceptance detector design (shown in Figure 8) which would be appropriate to address the arena of CP violation and rare kaon decays with very great sensitivity. The 120 GeV proton beam, with an intensity of 3.0×10^{13} at a 3.8 sec. cycle time (a variant of the high intensity Main Injector mode), strikes a Be target at about 20 mr. This is chosen in order to reduce dramatically the neutron flux in the beam relative to neutral kaons, even though in fact the neutral beam will be transported through the detector in vacuum. There follows 25 m of magnetised beam dump with collimation and shielding. The decay region is 20 m in length and the detector has a cross-sectional area of 3 m x 3 m. This model experiment concentrates on the flux greater than 15 GeV for a variety of reasons which will be given below; the solid angle of the beam is 36 μstr which results in a relatively small hole (dead region) in the detector.

The acceptance of the detector for the $\pi^0 e^+ e^-$ mode is 16% with the requirement that both photons exceed 1 GeV, and the decay rate for kaons between 15 and 50 GeV is 3.3×10^7 per sec. With a duty cycle of 50%, the sensitivity will be about 10^{-10} per hour. This should be compared to the current best sensitivity in a kaon experiment of about 10^{-10} per experiment.

The above beam design is conservative: there is a great deal more flux available were one to employ a beam of greater solid angle. In addition, it may be possible to equip the beam hole region with active detectors and this would increase the acceptance. Thus in the future, there is the potential for even more sensitive measurements although the proposed sensitivity of the relatively modest configuration is already quite an advance.

First it should be stated that there are major experimental hurdles in actually obtaining such a sensitivity. An absorber 25 m in length is sufficient to reduce the flux of target muons to well below the level of singles rates from the kaon decays themselves; they will be governed by the total decay rate in the decay volume which will be 1.3×10^8 per sec at the above intensity. It is important to note that this rate is only four times the decay rate for the high energy region of interest, namely the decay rate for decays above 10 GeV. While not every decay will be counted, the singles rates will be on the order of 10^8 per second! Clearly it will be important that any beam structure on 1 ns time scales be greatly reduced. This rate is the same as expected at the SSC with one important difference: multiplicity; kaon decays produce one or two particles, significantly less than at the SSC. The chambers will need to be very high precision and fine-grained, probably with 2 mm wire spacing. The electromagnetic calorimeter will also need to be very finely segmented, consisting of about 20,000 cells of high resolution, radiation hard material. Another important feature of the detector is its ability to detect low energy photons which miss the aperture of the calorimeter. This feature has been important in the Fermilab experiments and it directly affects the background level for the rare decays. The neutron flux will be about 1.9×10^9 per sec.

Since the kaon (and neutron) cross sections roughly scale, one could in principle do this physics at a lower energy machine. To operate at a 30 GeV machine, one would move four times closer to the target and accept decays greater than 4 GeV with a low energy threshold of 250 MeV. In practice, this is much less desirable than the configuration at the higher energy machine for the following reasons:

1. The resolution of electromagnetic calorimeters will be dominated by a term proportional to $1/\sqrt{E}$ so that the higher the energy the better the resolution and resolution is at a premium in such experiments.

2. The background of minimum ionizing particles does <u>not</u> scale with energy: a muon will simulate about 600 MeV energy deposit in an electromagnetic calorimeter so that it will be difficult to maintain the same relative threshold level as one decreases the energy. Note that for the round of $2\pi^o$ experiments of a few years ago, at the Tevatron the threshold energy was 2 GeV while at BNL energy, the threshold was 1 GeV.

3. Since the growth of hadronic showers is governed by ln(E) rather than linear in E, one can get away with a fractionally smaller beam dump region at the higher energy facility. As an important consequence, one can be situated relatively closer to the target and thus be much more sensitive to K_S decays. This opens up another realm of physics including CP violation in 3π decays and other rare K_S decays (including $\pi^o e^+ e^-$). Also, it may be necessary to observe the interference between the K_L and the K_S decays to the $\pi^o e^+ e^-$ mode to establish a CP violating effect.

4. The importance of the ability to reject events with soft photons outside of the aperture of one's electromagnetic detector in reducing background has already been mentioned. Again, the dominant problem with a low threshold will be the (non-scaling) minimum ionising background.

These advantages make the Main Injector the best place to perform such kaon rare decay experiments.

3.6.2 Medium Energy Neutrino Experiments

Neutrino experiments have been an important part of the fixed-target program since the Main Ring started operation in 1972. There is a great opportunity to do significant neutrino experiments with the Main Injector as the following examples will show.

By using a lithium lens to focus positively charged mesons, an intense neutrino beam with a small but measurable antineutrino contamination can be produced with 120 GeV protons. Figure 9 shows the expected event rate with such a beam for a 1 ton target and 2 x 10^{19} 120 GeV protons on target. The Main Injector operating at a repetition rate of 3 seconds could deliver this flux in 560 hours or just under six weeks of operation. Such an event rate would extend the limit on the mixing angle between the ν_μ and ν_τ to well below .01 radians for ν_τ masses greater than 30 eV.

A target consisting of 1 Ton of emulsions embedded within a multiparticle spectrometer would allow the identification of ν_τ interactions through the identification of the τ decay vertex. The best limit on this transition comes from E-531, a neutrino experiment done at Fermilab between 1979 and 1980 using a 100 kg emulsion target. Since the τ events would be found in the ''neutral current'' events, the background in this sample would be charmed particles produced by neutral currents. These events together with the charmed particle events produced by charged current interactions are interesting in their own right. This sample of charmed particles could be used to significantly reduce the largest uncertainty in the measurement of $\sin^2\theta_W$ obtained from the ratio of neutral current interactions to the charged current interactions in deep inelastic neutrino scattering.

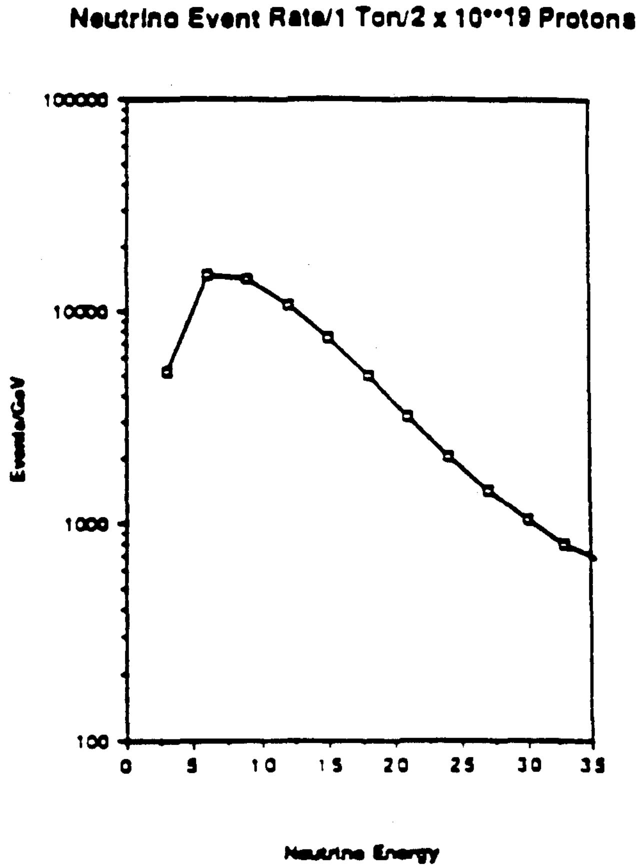


Figure 9

Charged current event rate for a 120 GeV high flux neutrino beam. Calculation assumes a 0.75 m radius detector, a 400 m decay pipe, 120 m shield, and a focussing system which is 50% efficient.

Such a beam will also make it possible to make accurate measurements of the $\nu_\mu e^-$ and $\bar{\nu}_\mu e^-$ cross sections. A detector with a 200 ton fiducial volume could detect more than a thousand $\nu_\mu e^-$ interactions for 2 x 10^{19} protons on targets. The neutrino energy range of 5 to 35 GeV is in many ways ideal for the measurement, because the electron recoil momentum is in roughly the same energy range. Electrons in this energy range are easily distinguished from charged π's and yet the neutrino energy is low enough so that coherent π^0 production on nuclei by neutrinos can be distinguished from $\nu_\mu e^-$ interactions. Such an experiment could give a very accurate measurement of $\sin^2\theta_W$ at an average q^2 of about .01 $(GeV/c)^2$. The same experiment would produce ten million charged current events and several million neutral current events. Thus, a second very accurate measurement of $\sin^2\theta_W$ could be made at an average q^2 of about 1 $(GeV/c)^2$, if it were combined with the charm production data of the emulsion experiment.

3.6.3 Medium Energy Antiproton Experiments

In addition to the kaon and neutrino experiments, the Main Injector will substantially improve the experiments which now use the Main Ring to produce secondary beams such as the search for undiscovered states of charmonium. This experiment measures the cross section for the resonance formation of charmonium states in $p\bar{p}$ collisions followed by the inclusive decay into a J/ψ. Antiprotons are produced by 120 GeV protons and stored in the Antiproton Source in the same way as is done for colliding beams. Since the Antiproton Source is dedicated to providing antiprotons to the Tevatron during collider runs this type of experiment can run only during the fixed-target running periods. The Antiproton Source Accumulator Ring, the location of the experiment, is a unique facility because of its energy and beam quality. A small detector enclosure was constructed in one of its straight sections in 1986. In 1988 a gas jet was installed in the same location and was used to observe collisions of a circulating beam with a hydrogen gas jet. The useful energy range, 2 GeV/c to 8.8 GeV/c, of the circulating antiproton beam will make it possible to search for all charmonium states between 2950 MeV/c^2 to 4000 MeV/c^2 as well as states as light as the Ξ (2240). An experiment built to search for the undiscovered states of charmonium and to measure the masses and widths of the established charmonium states will take data for the first time during the 1989-90 fixed-target run. Since the momentum spread of the beam is expected to be less than 2 MeV/c (FWHM), the widths of states as narrow as 500 KeV/c^2 (FWHM) can be measured directly.

A luminosity of $10^{31}cm^{-2}sec^{-1}$ can be achieved with 15 x 10^{10} antiprotons and under these conditions a beam lifetime of 20 hours or more is expected. While a larger number of antiprotons can be stored in the Accumulator, up to 80 x 10^{10} have been stored during collider operation, it does not appear practical to do this during fixed-target operation. The reason for such an extended fill time is that the performance of the Main Ring at injection is sensitive to the stray magnetic fields of the Tevatron, which vary continuously throughout the fixed-target cycle. As a result a broad search over the full range of charmonium masses for unexpected states cannot reach the critical level of sensitivity, because the luminosity will be limited to about $10^{31}cm^{-2}sec^{-1}$. Because the Tevatron would not interfere with the Main Injector, the Accumulator could be filled at almost $10^{11}\bar{p}$/hour. With such a fill rate luminosities of 5 x $10^{31}cm^{-2}sec^{-1}$ would be feasible and searches for the unexpected states with a sensitivity of 0.5 events/(pb^{-1}-MeV/c^2) could be carried out in a run of 2,500 hours.

3.6.4 Operating Modes for the Main Injector

It is worth noting here how such a diverse program of physics with the Main Injector might be carried out without impacting either the fixed-target program or the Collider program. During fixed-target operation the Main Injector cycle could be set at 4 seconds with a 2 second flat top. During each Main Injector cycle 6 Booster batches would be accelerated to 120 GeV. If the Antiproton Source were being filled one batch would be extracted and sent to the Antiproton Source to make $\bar{p}$'s, and the remaining 5 batches would be debunched, subsequently extracted over the next two seconds, and sent to the neutral K target in the Neutrino Area. With this cycle the $\bar{p}$ stacking rate would be 5×10^{10} hr^{-1} and the proton flux to neutrino would be reduced by 16%. When filling was not in progress, all of the intensity could go to the Neutrino Area. Since the Tevatron must be filled for fixed-target operation two Main Injector cycles of 2 second duration with 150 ms flat top would be needed. Thus a typical supercycle of 64 second duration would consist of two 2 second Main Injector cycles to fill the Tevatron, followed by fifteen 4 second Main Injector cycles for the K_L^0 experiments and the medium energy $\bar{p}p$ experiments. During slow extraction from the Tevatron, typically 23 seconds in duration, high energy proton beams, 800 GeV or 1500 GeV, would be transported to the Proton Area, Muon Area, and Meson Area simultaneously with the transport of 120 GeV protons to the Neutrino Area.

During collider operation there would be a premium on maximizing the repetition rate for $\bar{p}$ production. In this case there would be a 2 second cycle, with a 250 ms flat top. Again the Main Injector would be filled with 6 Booster batches. Again one batch would be extracted for $\bar{p}$ production at the start of the flat top and the other 5 would be extracted at the end of the flat top and sent to a neutrino beam target in the Neutrino Area. By extending the flat top on every fourth pulse and slowly extracting some of the beam, protons could be supplied to test beams in Proton, Muon, and Meson. Of course this is done at the expense of a somewhat reduced $\bar{p}$ stacking rate for colliding beams. A large variety of Tevatron supercycles such as the aforementioned are already a standard feature of operation. These examples are presented to show that it can be done easily.

In summary the use of the Main Injector will allow an emerging physics program based on 120 GeV protons to become much more effective since it will decouple acceleration and extraction of these protons from Tevatron operations without compromising the fixed-target program or the collider program.

PART II: MAIN INJECTOR DESIGN

1 INTRODUCTION

In order to meet the goals of the Fermilab research program through the 1990's a phased upgrade of the accelerator complex has been evaluated with the goal of providing a factor of about 100 increase in the luminosity in the antiproton-proton collider operation together with a threefold increase in the intensities of the fixed target beams. The upgrade proposal is formulated in three stages: the first phase is based upon an increase in the Linac energy from 200 Mev to 400 Mev; the second involves the replacement of the existing Main Ring with a new accelerator, the Main Injector; the third phase calls for a new higher energy superconducting ring in the existing Main Accelerator tunnel. The Main Injector itself provides a gain of 5 in the luminosity to 5×10^{31} cm^{-2} s^{-1} and a factor of 2 increase in the fixed target beam intensity. In this report we shall present in detail the design and operating parameters of this proposed Main Injector. In deriving these performance specifications we have assumed that the first phase of the accelerator improvements has been accomplished.

The Main Injector is a large aperture, rapid cycling, proton synchrotron designed specifically to address the fundamental limitations inherent in the present Main Ring. The role of the Main Ring has been modified significantly from the original 400 Gev fixed target operation with the advent of the colliding beams era. This has introduced a completely new set of requirements which were never envisaged in the original design. Accomodating the needs of antiproton production, bipolar injection into the Tevatron, and physical avoidance of the colliding detector experiments have inevitably resulted in reduced performance characteristics. Possible enhancements to the physics program, such as test beams for detector development, high intensity low energy proton beams for research, and possible future interaction regions, are all precluded by the present operational and physical constraints. The Main Injector addresses all of these issues in an elegant and efficient manner.

This report starts by examining the current situation with regard to the Main Ring. The design and operational parameters of the Main Injector are presented, together with their impact on the various research programs. We conclude with the proposed schedule and associated cost estimate.

2 THE MAIN RING AND ITS LIMITATIONS

2.1 Limitations

2.1.1 Transverse Aperture

The present bottleneck in the production of antiprotons and in the delivery of intense beams to the Tevatron is the Main Ring. The Main Ring is not capable of accelerating the quantity of beam which can be provided at injection by the 8 GeV Booster. This is for the simple reason that the admittance of the Main Ring (12π mm-mr, normalized, at 8 Gev) is about half the size of the Booster admittance (20π mm-mr, normalized, at 200 MeV). As a result, the Booster is run at about two thirds of its capability during normal operations. The limitation which this produces on the intensity which can be delivered by the Main Ring is illustrated in fig. 2.1-1, which shows how the emittance of the beam delivered by the Booster to the Main Ring grows with intensity. The emittance growth seen with increasing intensity above about $1.5\text{x}10^{10}$/bunch is caused by space charge forces encountered by the beam after injection into the Booster from the Linac. The Main Ring aperture restriction limits the bunch intensity of useable beams from the Booster to about $2.5\text{x}10^{10}$/bunch, where the Main Ring operates at 70% transmission efficiency. The Booster is capable of delivering up to $3.5\text{x}10^{10}$/bunch, about 40% more than this. The restricted aperture in the Main Ring is due to a combination of magnetic field quality at low excitations and perturbations to the ring which have been required for the integration of overpasses and new injection and extraction systems related to operations with antiprotons.

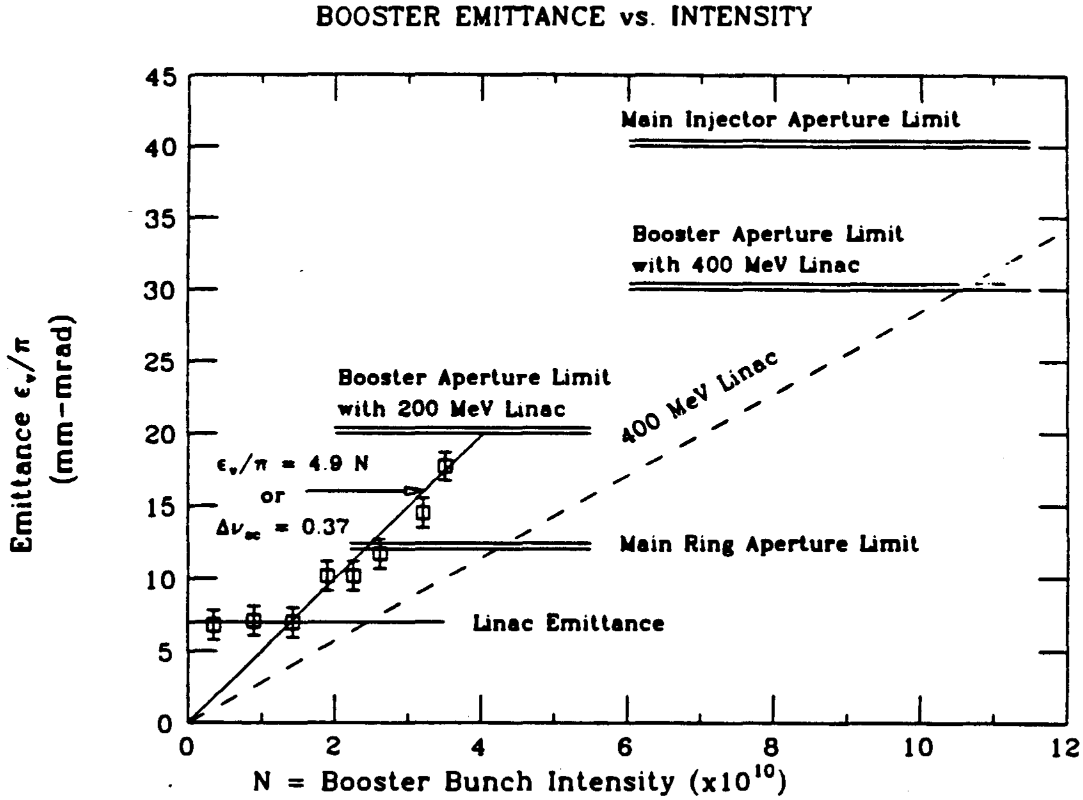


Fig. 2.1-1

The mismatch between Booster and Main Ring capabilities will become even more acute with the 400 MeV Linac upgrade. This can be seen through an examination of fig. 2.1-1. The space charge forces, which cause the observed emittance growth with intensity represented by the data and the solid line, will be reduced when the Booster injection energy is doubled with the 400 MeV Linac upgrade. After the Linac upgrade, the emittance is expected to follow the dotted line in fig 2.1-1. Although the Main Ring aperture limit will then permit it to accept about 4.5×10^{10}/bunch (an improvement of 1.75), the Booster capabilities (based solely on aperture considerations) will improve even more dramatically. Because of the adiabatic damping of the betatron oscillations at the higher injection energy, the Booster aperture limit will increase to 30π mm-mr, which should correspond to about 10^{11}/bunch. This will be a factor of 2.2 more than the Main Ring can accept.

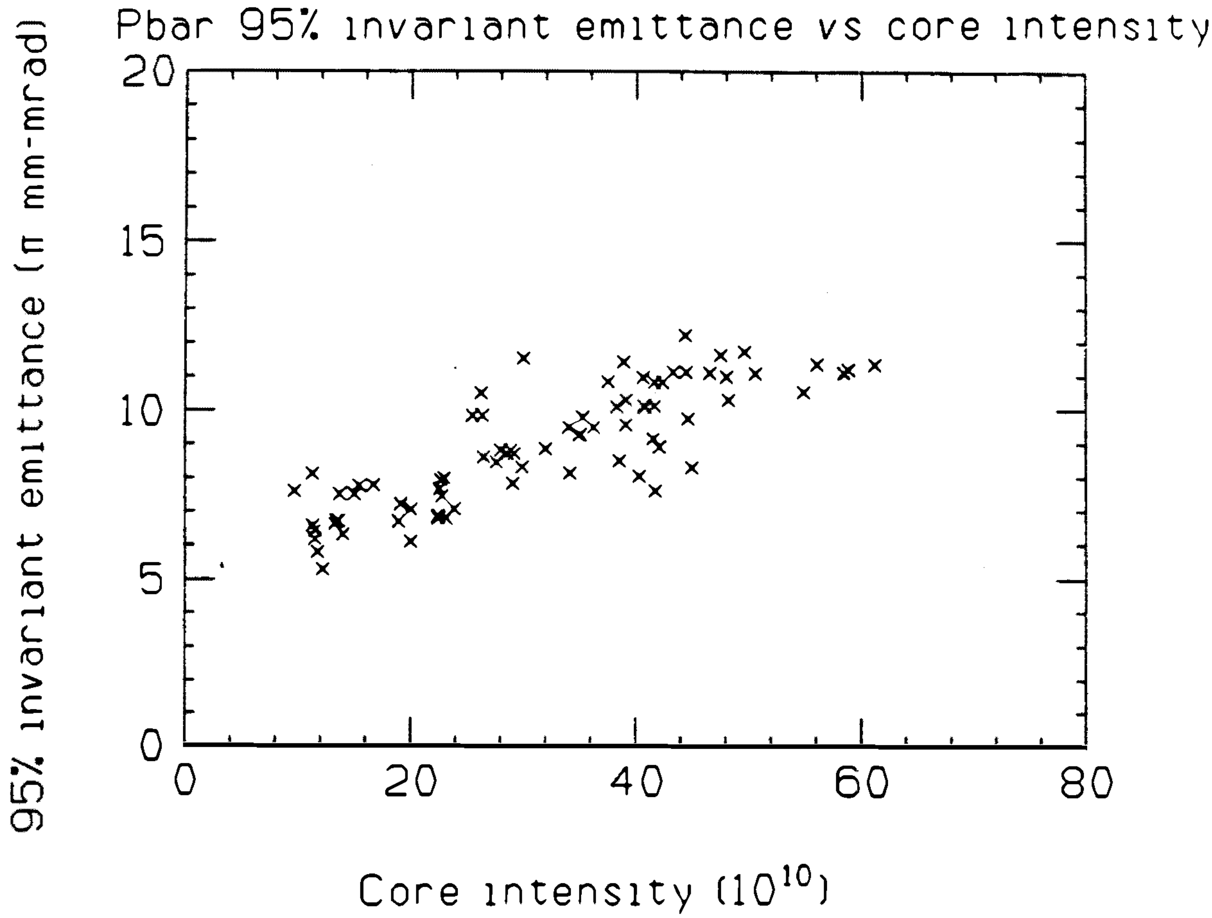


Fig. 2.1-2

The limiting aperture of the Main Ring is a problem for antiproton transmission as well as for protons. Fig. 2.1-2 shows the dependence of antiproton emittance on antiproton stack intensity. This dependence results from the balance between the core betatron stochastic cooling and various intensity-dependent heating mechanisms, such as intrabeam scattering. For core intensities exceeding 60×10^{10}, the core emittance exceeds the Main Ring aperture limit. Typical high luminosity operations to date have been with stacks in the range of $60\text{-}80 \times 10^{10}$, so that we are always completely filling the Main Ring aperture. In this regime, the antiprotons suffer significant losses of 10-20% because of inevitable injection errors, small emittance mismatches, etc. With the Phase I upgrade, which includes improved transverse cooling in the Antiproton Source, the core emittances will be reduced; but for increased luminosity, we will be operating in the core intensity range of $100\text{-}150 \times 10^{10}$. Thus, we will still be operating at or slightly beyond the limit of the Main Ring aperture for pbar injection, which will result in the same level of losses (10-20%) and the same extreme sensitivity to errors. Further increases in the stack size are also precluded.

It is thus clear that, both now and after the completion of Phase I of the upgrade, the transverse aperture limitations of the Main Ring are a severe limitation to the performance of the entire accelerator complex, both for protons and for antiprotons. This aperture restriction is removed completely by the Main Injector, which has been designed with a 40π mm-mr (normalized, at 8 GeV) acceptance (see fig 2.1-1). This feature of the Main Injector is discussed in more detail below (section 3.1).

2.1.2 Longitudinal Aperture

The situation with regard to the inadequate Main Ring transverse aperture is paralleled with regard to the longitudinal aperture. This is illustrated in fig. 2.1-3, which shows the variation in the longitudinal emittance of the Booster beam with intensity. This growth in longitudinal emittance with intensity is believed to be due to longitudinal coupled-bunch instabilities in the Booster associated with the RF cavity impedances; hence the extrapolation of the data to higher intensities is based on an exponential dependence on intensity. The dashed line corresponds to the expected dependence after the Linac upgrade; the higher injection energy will allow the removal of 1/3 of the RF cavities, which are the dominant impedance. This is expected to reduce the exponent in the growth relation by a factor of 1/3, giving the dashed line in fig. 2.1-3. Further reductions in this emittance growth may also be possible as the Booster coupled-bunch instability is brought under control by other means, but these improvements have not been assumed in this discussion.

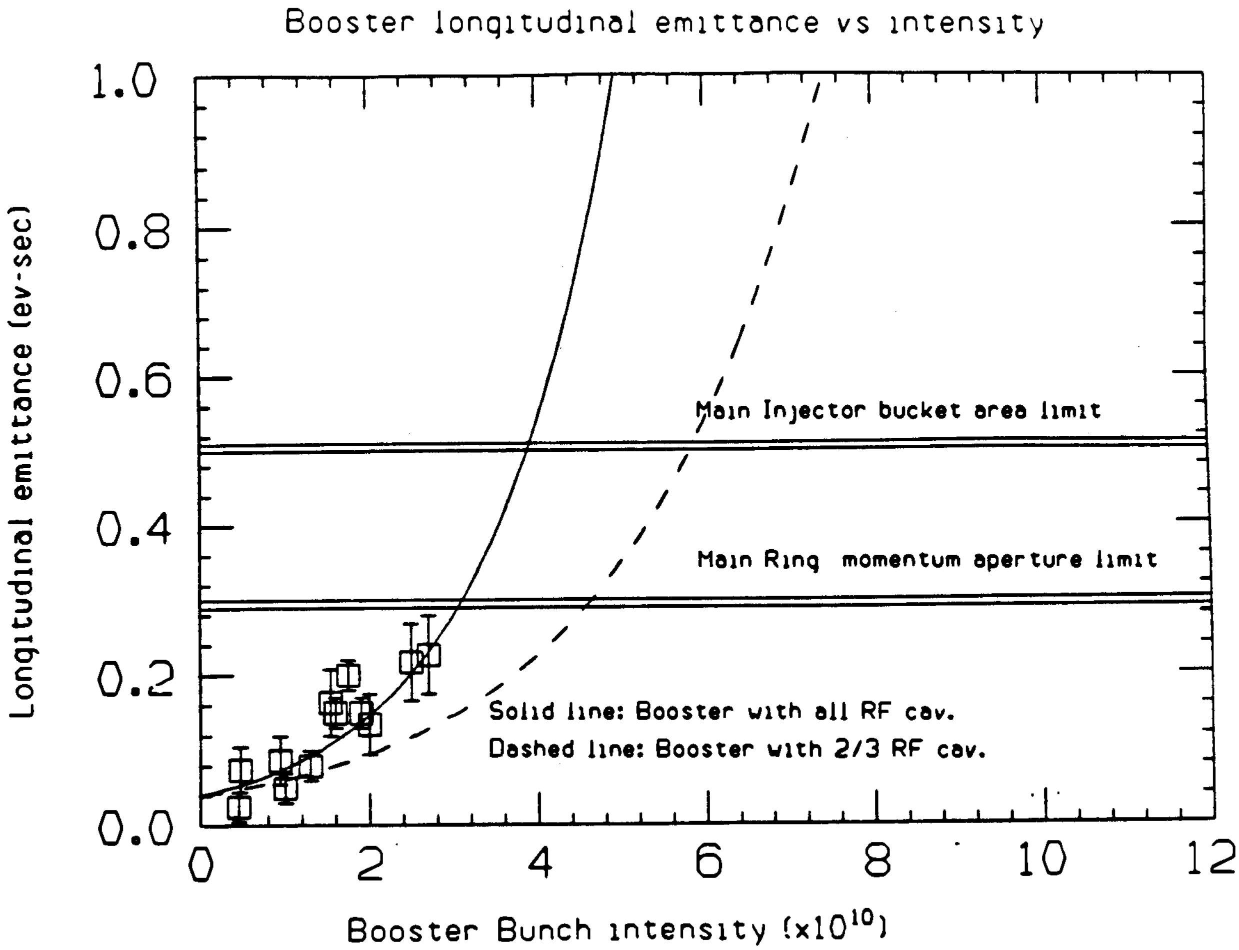


Fig. 2.1-3

As the figure shows, the usual working point for high intensity Main Ring operation is quite close to the aperture limit. The longitudinal aperture limit is not determined by the RF bucket, as in a normal machine, but rather by physical and dynamic aperture limitations at high dispersion points in the ring. This problem is exacerbated by the fact that the medium straight sections in the Main Ring lattice which are used for some of the beam transfer points are high dispersion areas and have aperture limitations from the magnetic septa and kickers. The result of this is that during the start of acceleration and at transition in the Main Ring, when the beam is perturbed in momentum from the reference orbit and the momentum spread grows, losses are frequently suffered and the machine is very sensitive to small changes in the orbit as the field starts to ramp. This problem is compounded by the vertical dispersion which the overpasses at BO and DO have introduced into the Ring.

This momentum aperture restriction is also completely removed with the Main Injector; in this machine, the actual physical momentum aperture (± 1%) gives a longitudinal emittance limit which is beyond the top edge of fig 2.1-3, and the real aperture limit is determined by the Main Injector RF bucket size, indicated in fig. 2.1-3. (The Booster RF bucket area is greater than 0.5 ev-sec.) The implications of this for Main Injector vs Main Ring performance are discussed below.

2.1.3 Losses at the Collider Detectors

The principal consequence of the necessity of operating the Main Ring close to its aperture limits, both transverse and longitudinal, is the inevitable generation of losses during injection and acceleration. These losses, whose combined effect is a typical 70% transmission efficiency through the Main Ring, are generally distributed azimuthally throughout the ring, although there is of course some localisation at the injection point and at the worst physical aperture restrictions. Although obviously a limitation for pbar production, the real problem caused by these losses is at the collider detectors, which are sensitive to loss rates of a few tens of kiloherts (one part in 10^8 of the Main Ring beam intensity). Because the losses are due to a complex combination of limited transverse dynamic aperture, limited transverse physical aperture, and limited momentum aperture in both planes, the losses are very difficult to understand and hence isolate and control. The attempt to control the losses in this difficult situation puts severe operational restrictions on the Main Ring.

The operational restrictions imply limiting the Booster intensity so that the beam emittances do not approach the aperture limits too closely; and constant vigilance in operation for $\bar{p}$ production to maintain optimised injection conditions, proper Main Ring orbit control and proper RF feedback control during acceleration.

Operational restrictions, and performance limitations, on the collider detectors themselves also result from Main Ring losses. The major problems are false triggers due to particles from the Main Ring faking a beam-beam interaction, and the actual tripping-off of chamber high voltage systems due to large chamber currents generated by particularly severe Main Ring losses. At CDF, the Main Ring passes over the Tevatron by 19 ft. Nevertheless, in order to bring these problems under control, it has been necessary to shield the CDF detector from the Main Ring beam pipe at the B0 straight section with a 2 ft thick steel cladding. With this shield in place, the detector dead time due to blanking to avoid false triggers from the Main Ring has been reduced to an acceptable level (<2-3%). There are still occasional chamber high voltage trips from infrequent Main Ring cycles with very severe losses.

The situation at D0 is of course less well understood because the detector is not yet operational. Because of the more limited nature of the D0 overpass, the Main Ring and Tevatron are separated by only 7 ft at the detector. The Main Ring beam pipe passes through the D0 hadron calorimeter and the end muon chambers. Consequently, no such shield as was necessary at CDF will be possible. Preliminary indications of the muon chamber high voltage trip problem, carried out with a test muon chamber in the collision hall this run, are that the losses can be controlled to the level that this test chamber system does not trip off during normal Main Ring operation for $\bar{p}$ production. This is encouraging, and efforts to reduce the losses at D0 even further will of course continue. However, the real situation, with the detector in place, will not be known until the end of 1990. It is possible that the problem could be so severe that the Main Ring could have to be turned off when D0 is running, with a period of Main Ring operation for $\bar{p}$ production to replenish the stack following the data collection time. This would of course severely limit the integrated luminosity which could be delivered to both CDF and D0.

2.2 Impact of these Limitations on Improvements and Upgrades to the Main Ring and Tevatron

In addition to the limitations imposed on present and future performance of the Main Ring, there are a number of improved or expanded capabilities for the Main Ring or the Tevatron which are also very difficult to carry out because of the problems noted in the previous discussion.

For example, with the advent of the separators in the Tevatron in Phase I of the upgrade, the collider abort system must be moved from CO to AO: this opens up the possibility of another major interaction region in the Tevatron at CO. However, in order to utilise it, one would have to build another overpass for the Main Ring, probably on the scale of the one at BO. The BO overpass required 10 months of machine downtime. Moreover, another overpass in the Main Ring would only add to the aperture and loss problems detailed above.

A multi-batch targeting scheme has been invented to circumvent the cycle rate limitation on the present Main Ring and thus enhance the $\bar{p}$ production rate. One of the most difficult aspects of this scheme is the multiple bunch rotations and recapture which must be done in the Main Ring. Proper control of the Main Ring RF voltage to avoid longitudinal emittance dilution during the multiple rotations was thought to be one of the most serious problems to be solved to implement this scheme. Recent operational experience has revealed that an even bigger problem is the small beam loss which occurs during the rotation process. Although this loss is small in terms of the total beam intensity in the machine, it has proven to be very serious for the collider experiments, and has prevented the use of this scheme in regular operation to date. With the Linac upgrade and the potential for higher intensity (and larger longitudinal emittance) beams in the Main Ring, these problems will only get more serious. It should be noted that, because of its rapid cycle rate, multiple bunch rotations will not be required with the Main Injector.

Another example of an increased demand for the Main Ring is the possibility of extracting 120 GeV beam at A0 for delivery to the experimental areas. This feature offers the possibility of both test beams for detector work in the experimental areas, and high-intensity, low energy production beams for experiments. With the anticipated advent of great demand for detector development test beams for SSC detectors, this possibility should be quite interesting to the high energy community. However, the realisation of these attractive possibilities is severely limited by the constraints on the present Main Ring. A study of the feasibility of slow extraction from the Main Ring at A0 is now underway, and the problems of aperture restrictions due to the devices (such as overpasses and magnetic septa) installed for colliding beam operations has been one of the first difficulties to become apparent. Another potential problem is related to the Main Ring vertical dispersion. The half-integer resonant extraction process proceeds in horizontal phase space, but it is possible that the vertical dispersion will cause a growth in vertical phase space also. It is probably true that these problems can be solved, and it will be possible to provide extracted beams from the Main Ring at A0. However, the intensity limitations on these beams during collider operation, which will depend on the extent of losses which can be tolerated by the collider detectors, may be very severe. This can only be known by experience with a real system. An efficient resonant extraction system will produce beam losses at the 1-2% level. It is thus extremely unlikely that high-intensity production beams could be delivered to the experimental areas during collider operation. At worst, even low intensity test beams may not be possible, in which case this capability of the Main Ring would only be useful during fixed target running. In this eventuality, given the competition for resources with running experiments in the fixed-target program, it is questionable whether it is worth the effort.

2.3 Prospects for Solutions to the Main Ring's Problems

Improvements to the present performance of the Main Ring are of course possible and will be pursued vigorously. An example of this is a system of ramped correctors which will be implemented during the next shutdown, and which relieve some of the problems related to orbit control during acceleration. However, it must be understood that improvements which tackle the real problems of aperture limitations and the proximity of the Main Ring to collider detectors are virtually impossible without major efforts whose scale in machine down time, if not in cost, are comparable to that associated with the Main Injector. Moreover, many of these schemes have significant flaws when examined closely.

An example of a scheme which has been considered is the removal of all the B1-style magnets in the Main Ring; the remaining B2-style magnets would be run at twice their present current, which would improve their field quality at injection, thus improving the dynamic transverse aperture limitation. However, this proposal (unlike the Main Injector) results in a significant increase in operating costs. The reliability of the Main Ring dipoles has been good since the beginning of the Tevatron era, when the machine began running at 150 Gev or less. This scheme would be equivalent to a return to 400 GeV Main Ring operation, and a consequent increase in magnet failure rate would be expected.

Other schemes have been investigated, but none have as yet been suggested which do not involve at least as much down time, and a significant fraction of the cost, of the Main Injector. The major drawback to such proposals however, is that each scheme addresses only one aspect of the operational limitations; only the Main Injector achieves the global solution that is necessary. The Main Ring will continue to be the basic limitation to improved collider performance after the Phase I upgrade is in place; and the problems of the Main Ring are simply too fundamental to be resolved without such a substantial cost and effort that a replacement of the machine itself is more efficient and cost effective.

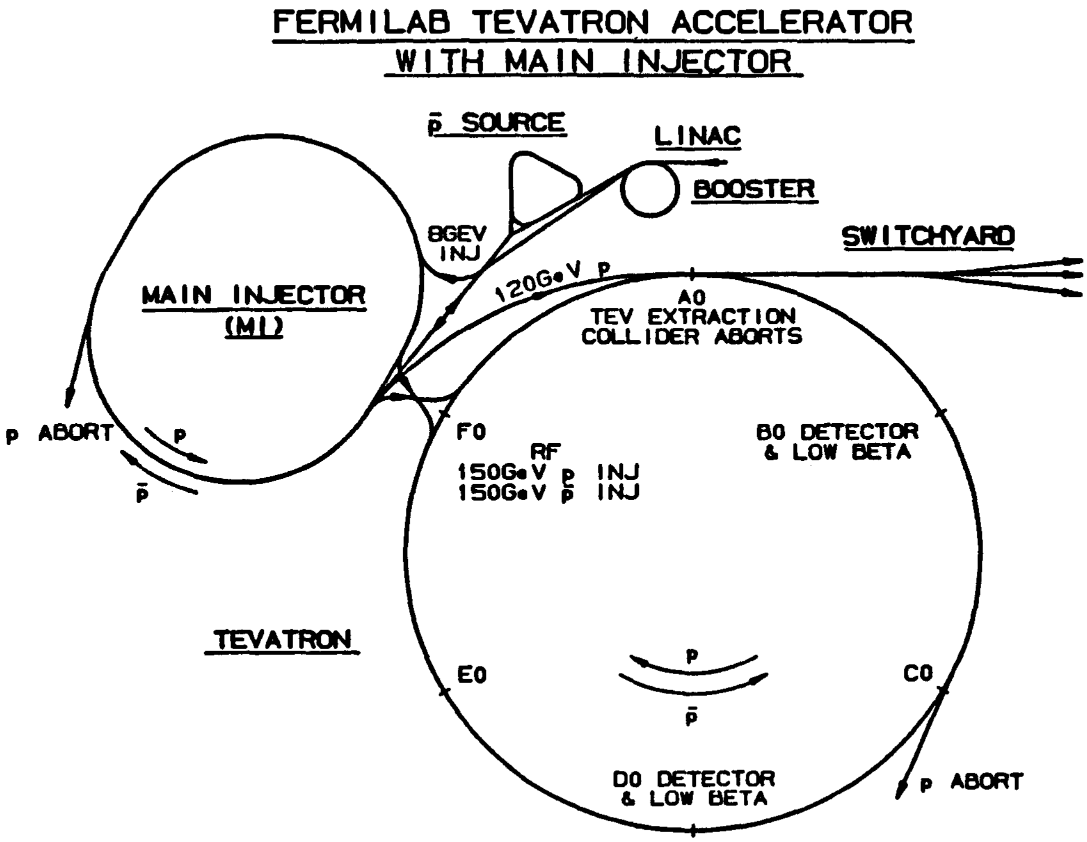
3 THE MAIN INJECTOR

3.1 Outline of Design, Operating Parameters, and Operating Scenarios

The Main Injector (MI) is to be located south of the Antiproton Source and tangent to the Tevatron ring at the F0 straight section as shown in Figure 3.1-1. The MI will perform all duties currently required of the existing Main Ring. Thus, following commissioning of the MI, Main Ring operations will cease and the background in the colliding beam detectors caused by the Main Ring will be eliminated. The performance of the MI, as measured in terms of total protons delivered to the Tevatron, is expected to exceed that of the present Main Ring operation by a factor of up to three (assuming that the linac upgrade has already taken place). The proton flux delivered by the MI to the antiproton production target could increase by as much as a factor of five above present rates from the Main Ring. In addition the MI will provide high duty factor 120 GeV beam to the experimental areas during collider operation--a capability which does not exist in the Main Ring.

The location, operating energy, and mode of construction of the Main Injector are chosen to minimise operational impact on Fermilab's ongoing High Energy Physics (HEP) program. The area in which the MI is to be situated is devoid of any underground utilities which might be disturbed during construction, while the separation between the MI and Tevatron is sufficient to allow most of the construction to be completed concurrent with Tevatron operations. The energy capability of the MI is chosen to match the antiproton production and Tevatron injection energies presently used in the Fermilab complex.

The Main Injector will be built from newly constructed dipole magnets allowing a large portion of the installation process to proceed independently of Tevatron operations. The Main Ring dipoles have a very poor record of reliability. During the period 1975 to 1982 when 400 GeV was the standard operating energy there were 141 dipoles removed either because of a failure or because there was evidence that the magnet insulation had deteriorated. However, since 1983, when the nominal operating energy was reduced to 150 GeV, only 30 dipoles have been removed for this reason. Since the Main Ring was built, Fermilab has built a large number of magnets that have been free of failures. For example none of the nearly one thousand magnets that were built for the Antiproton Source have failed although they have been in continuous use since early 1985. Of course, these magnets operate DC. Nevertheless, the dipoles for the Main Injector should be very reliable because they will have an insulation system based on the success of the past ten years of conventional magnet development at Fermilab. The use of newly designed dipoles is also desirable from the standpoint of power usage for antiproton production as is discussed below.

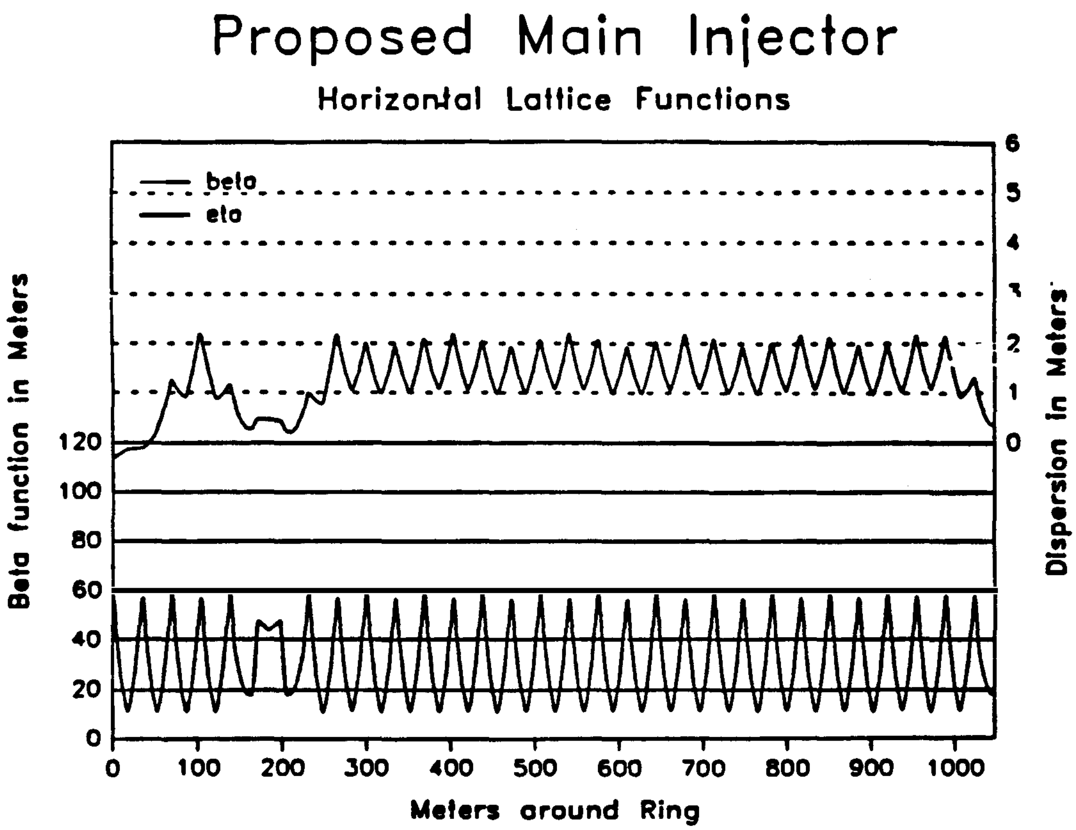


Schematic view of Main Injector connections to Booster, Antiproton Source, Tevatron, and Switchyard.

Fig. 3.1-1

The Main Injector ring and all beamline interconnections to existing facilities are shown schematically in Figure 3.1-1. (However, see below in section 3.5 for a proposed modification to the 120 GeV beamline from F0 to A0.) It is proposed to complete construction over a three and one-half year period starting on October 1, 1990. It is anticipated that the construction and operation of the new Main Injector will not require any expansion of the Fermilab permanent staff.

The Main Injector parameter list is given in Table 3.1-1. It is anticipated that the Main Injector will perform at a significantly higher level than the existing Main Ring as measured either in terms of protons delivered per cycle, protons delivered per second, transmission efficiency, or reliability. Primarily the expected improvements in performance are directly related to optics of the ring. The lattice functions of the MI are shown in Figure 3.1-2. The MI ring lies in a plane with stronger focussing per unit length than the Main Ring. This means that the maximum betas are half as big and the maximum (horizontal) dispersion a third as big as in the Main Ring, while vertical dispersion is nonexistent. As a result physical beam sizes associated with given transverse and longitudinal emittances are significantly reduced compared to the Main Ring. The elimination of dispersion in the RF regions, raising the level of the injection field, elimination of sagitta, and improved field quality in the dipoles will all have a beneficial impact on the beam dynamics.



Proposed Main Injector
Horizontal Lattice Functions
beta
eta
Beta function in Meters
Dispersion in Meters
Meters around Ring
0
20
40
60
80
100
120
1
2
3
4
5
6
0
100
200
300
400
500
600
700
800
900
1000

Fig. 3.1-2

Table 3.1-1: Main Injector Parameter List

Circumference	3319.419	meters
Injection Energy	8.9	GeV
Peak Energy	150	Gev
Minimum Cycle Time (@120 GeV)	1.5	sec
Number of Protons	3×10^{13}	
Harmonic Number (@53 MHz)	588	
Horizontal Tune	22.42	
Vertical Tune	22.43	
Transition Gamma	20.4	
Natural Chromaticity (H)	-27.5	
Natural Chromaticity (V)	-28.5	
Number of Bunches	498	
Protons/bunch	6×10^{10}	
Transverse Emittance (normalized, 95%)	20π	mm-mr
Longitudinal Emittance	.40	eV-sec
Transverse Acceptance (normalized, at 8 GeV)	40π	mm-mr
Momentum Acceptance	2.0	%
βmax (Arcs)	57	meters
βmax (Straights)	90	meters
Maximum Dispersion	2.2	meters
Number of Straight Sections	8	
Length of Standard Cell	34.3	meters
Phase Advance per Cell	90	degrees
RF Frequency (Injection)	52.8	MHz
RF Frequency (Extraction)	53.1	MHz
RF Voltage	4	MV
Number of Dipoles	300	
Dipole Length	6.1	meters
Dipole Field(@150 GeV)	17.2	kGauss
Number of Quadrupoles	202	
Quadrupole Gradient	196	kG/m
Number of Quadrupole Types	3	
Number of Quadrupole Busses	2	

The Main Injector is seven times the circumference of the Booster and slightly more than half the circumference of the existing Main Ring and Tevatron. Six Booster cycles will be required to fill the MI and two MI cycles to fill the Tevatron for fixed target operation. The MI is designed to have a transverse aperture of 40π mm-mr (normalized, at 8 GeV) (both planes). This is 30% larger than the expected Booster aperture following the 400 MeV linac upgrade, and a factor of four larger than that of the existing Main Ring. It is expected that the linac upgrade will yield a beam intensity out of the Booster of $5X10^{12}$ protons per batch with a 20π mm-mr transverse and a 0.40 eV-sec longitudinal emittance. A single Booster batch needs to be accelerated for antiproton production while six such batches are required to fill the Main Injector. The MI should be capable of accepting and accelerating these protons without significant beam loss or degradation of beam quality. Yields out of the Main Injector for a full ring could be potentially as great as $5X10^{12}$ in a single batch and $3X10^{13}$ protons in six batches ($6X10^{13}$ injected into the Tevatron). By way of contrast the existing Main Ring is capable of accelerating $1.8X10^{12}$ protons in a single batch and $1.8X10^{13}$ protons in twelve batches for delivery to the antiproton production target and the Tevatron respectively.

The power supply and magnet system are designed to allow a significant increase in the number of 120 GeV acceleration cycles which can be run each hour for antiproton production, as well as to enable a 120 GeV slow spill with a 35-50% duty factor. The cycle time at 120 GeV can be as low as 1.5 seconds for antiproton production. This is believed to represent the maximum rate at which the Antiproton Source might ultimately stack antiprotons and is to be compared to the current Main Ring capability of 2.6 seconds. The slow spill capability of the Main Injector is not presently duplicated in the existing Main Ring. The dipole magnets to be used are designed with twice the total cross section of copper and half as many turns as existing Main Ring dipoles. This is done to keep the total power dissipated in the dipoles during antiproton production at roughly the same level as in present operations while keeping the number of power supplies and service buildings low.

At least four distinct roles for the MI have been identified along with four corresponding acceleration cycles. These are shown in Table 3.1.2 along with the average power over the cycle for each case. For reference the present 120 GeV antiproton production cycle runs at 2.6 seconds and 4.3 MW; this power level will increase with the implementation of multi-batch Main Ring operation.

Table 3.1-2: Main Injector Operations Scenarios

Operational Mode	Energy (GeV)	Cycle (sec)	Flattop (sec)	Power (MW)
Antiproton Prod.	120	1.5	.05	7.1
Fixed Target Inj.	150	3.0	.05	6.2
Collider Injection	150	9.0	3.0	10.9
High Intensity Slow Spill	120	2.9	1.0	11.9
High Intensity Fast Spill	120	1.9	.05	7.5

In the antiproton production mode a single Booster batch containing $5X10^{12}$ protons is injected into the Main Injector at 8.9 GeV/c. These protons are accelerated to 120 GeV and extracted in a single turn for delivery to the antiproton production target. As discussed in 3.2.3, it is anticipated that with this flux of protons onto the target and expected improvements in the Antiproton Source the antiproton production rate will exceed $1X10^{11}$/hour.

For fixed target injection the MI is filled with 6 Booster batches each containing $5X10^{12}$ protons at 8.9 GeV/c. Since the Booster cycles at 15 Hz, 0.4 seconds are required to fill the MI. The beam is accelerated to 150 GeV and extracted in a single turn for delivery to the Tevatron. The MI is capable of cycling to 150 GeV every 3 seconds. Two MI cycles are required to fill the Tevatron at 150 GeV.

The MI operates on a 9 second, 150 GeV cycle for delivery of beam to the Tevatron for collider operations. The acceleration cycle and beam manipulations are the same for both protons and antiprotons. A 3 second flattop is required for bunch coalescing and cogging of the beams prior to injection into the Tevatron. Though the sequence of loading the Tevatron is not fully defined at this point, it is expected that the number of Main Injector cycles required to load both protons and antiprotons will not be greater than sixteen (for 22 bunch collider operation). This results in a 3 minute collider fill time.

A much higher intensity, high duty factor (34%) beam can be delivered at 120 GeV with a 2.9 second cycle time for experimental programs such as kaon decay physics. The average current delivered is about 2 μA ($3X10^{13}$ protons/2.9 sec.) and debunched beam without radiofrequency structure would be required. Running in this mode does not put any peak demands on the power supply system beyond those imposed by the antiproton production cycle, but it does expend twice the average power. This cycle can also be used to provide test beams to the experimental areas during collider running. In this mode it is likely that a much lower duty factor, accompanied by a much lower average power, would satisfy experimenters' test needs. A high intensity mode with fast resonant extraction on a short flat top for neutrino experiments will also be possible.

Combinations of the above operational modes are also possible. One such example is simultaneous operation for antiproton production and high intensity slow spill. One might load the MI with six Booster batches containing $3X10^{13}$ protons, accelerate to 120 GeV, fast extract one batch to the antiproton production target, and slow extract the remainder of the beam over a second. This would produce slightly more than half the antiproton flux and 83% of the average intensity of the first and last scenarios listed in Table 3.1-2.

3.2 IMPACT ON COLLIDER LUMINOSITY

3.2.1 Introduction

The major impact which the Main Injector will have on collider luminosity can be seen most simply from figs 2.1-1 and 2.1-3. With an increase of the available apertures, the full power of the Linac and Booster to deliver high intensity beams will be available. This has three basic consequences:

1. More protons can be delivered to the antiproton source for $\bar{p}$ production, resulting in a larger stacking rate and hence more antiprotons available for the collider.

2. More protons can be delivered to the Tevatron for collisions. These protons will be useable since the beam separation scheme to be implemented in the first phase of the upgrade will relieve limitations on large proton intensities now present due to the beam-beam interaction.

3. The larger transverse emittance $\bar{p}$ bunches produced from the high intensity stacks can be efficiently transmitted to the Tevatron.

The overall effect of these gains, as explained in detail below, will be to allow the collider luminosity to exceed $5x10^{31}/cm^2/sec$ with the Main Injector. As the following explanation develops, it will become clear that, once the Main Injector is operational, further limitations to increased luminosity are not set by Main Injector capabilities, but rather by limitations in the antiproton source (stack size limits), and by the beam-beam interaction. If these limitations could be relieved, even further substantial luminosity gains may be realized.

3.2.2 Luminosity Estimate

The sections on protons and antiprotons below describe how we can anticipate the following parameters for collider operation with the Main Injector:

Number of bunches: 22
Number of protons/bunch: 3.3×10^{11}
Proton transverse emittance: 30 π mm-mrad
Number of antiprotons/bunch: 6×10^{10}
Antiproton transverse emittance: 22 π mm-mrad.

Scaling from our present operating point, we can estimate an improvement factor as follows:

		1988-89 Collider Run	Phase I upgrade + Main Injector
B	Bunches	6	22
N_p	Protons/bunch ($\times10^{10}$)	7	33
$N_{\bar{p}}$	Antiprotons/bunch ($\times10^{10}$)	2.5	6
β^*	Low-beta (β^*, m)	0.5	0.5
ϵ_p	Proton emittance (π mm-mr)	25	30
$\epsilon_{\bar{p}}$	$\bar{p}$ emittance (π mm-mr)	18	22

	1988-89 Collider Run	Phase I upgrade + Main Injector
Relative luminosity:		
$L \propto BN_pN_{\bar{p}}/\beta^*(\epsilon_p+\epsilon_{\bar{p}})$	$\frac{6\times7\times2.5}{.5\times(25+18)} = 4.9$	$\frac{22\times33\times6}{.5\times(30+22)} = 167.5$

The overall improvement factor is thus 167.5/4.9 = 34.2; thus, the expected luminosity is 1.6×10^{30} (today) x 34.2 = $5.5\times10^{31}/\text{cm}^2/\text{sec}$. This is, in fact, a lower limit, since it assumes that the proton and $\bar{p}$ bunch lengths will be the same in the upgrade as at present. In fact, as discussed below, the $\bar{p}$ bunch lengths will be smaller because no coalescing of antiprotons will be required. Hence, the luminosity will be larger than the above estimate.

3.2.3 Antiprotons

The Main Injector will allow the number of protons per pulse which can be targeted to be increased from 3×10^{12} (corresponding to about 3.6×10^{10}/bunch from the Main Ring after the Linac upgrade) to 5×10^{12} (corresponding to about 6×10^{10}/bunch from the Main Injector). This increase is due to the increased transverse and longitudinal apertures of the Main Injector (see fig 2.1-1.,2.1-3). Moreover, because of the rapid cycle period of 1.5 sec for $\bar{p}$ production, vs. an average of 2 sec for the Main Ring in multi-batch operation, the number of protons/sec targeted for $\bar{p}$ production will increase by $(5/3)\times(2/1.5) = 2.2$; the stacking rate is expected to rise from about 7.5×10^{10}/hr to about 1.6×10^{11}/hr.

There are two issues in the antiproton source in this scenario worth mentioning:

1. Targeting 5×10^{12} protons/pulse will require a target sweeping system to preserve the target integrity. The design of this system is presently underway, and it appears quite feasible. Calculations of energy density deposition in the target with a sweeping system have been completed and have shown that the technique should work: the energy density can be kept below the point at which we now operate despite the very high proton intensities.

2. A stacking rate of 1.6×10^{11}/hr is greater than the Tev I design of 10^{11}/hr. The largest uncertainty regarding whether this flux can be handled by the cooling systems is related to the Accumulator stack-tail system. It is possible that this system will have to be rebuilt and upgraded in bandwidth. The costs associated with this are in the range of several million dollars; funds have been tentatively set aside in an AIP project to begin this work in FY1992, so that the system will

be able to cope with the expected flux by the time that the Main Injector is completed.

As is the case today, the $\bar{p}$ yield (yield=number of $\bar{p}$'s stacked into the Accumulator core per proton on the production target) will decrease as the stack intensity grows. Fig. 3.2-1 shows the expected variation of the pbar yield with stack intensity in the era of the Main Injector. The large yield at zero stack intensity (14×10^{-6}, vs about 8×10^{-6} today) is the result of improvements in the Pbar Source accomplished in Phase I of the upgrade. The predicted decrease in yield with stack intensity is due to three loss mechanisms which grow with stack intensity:

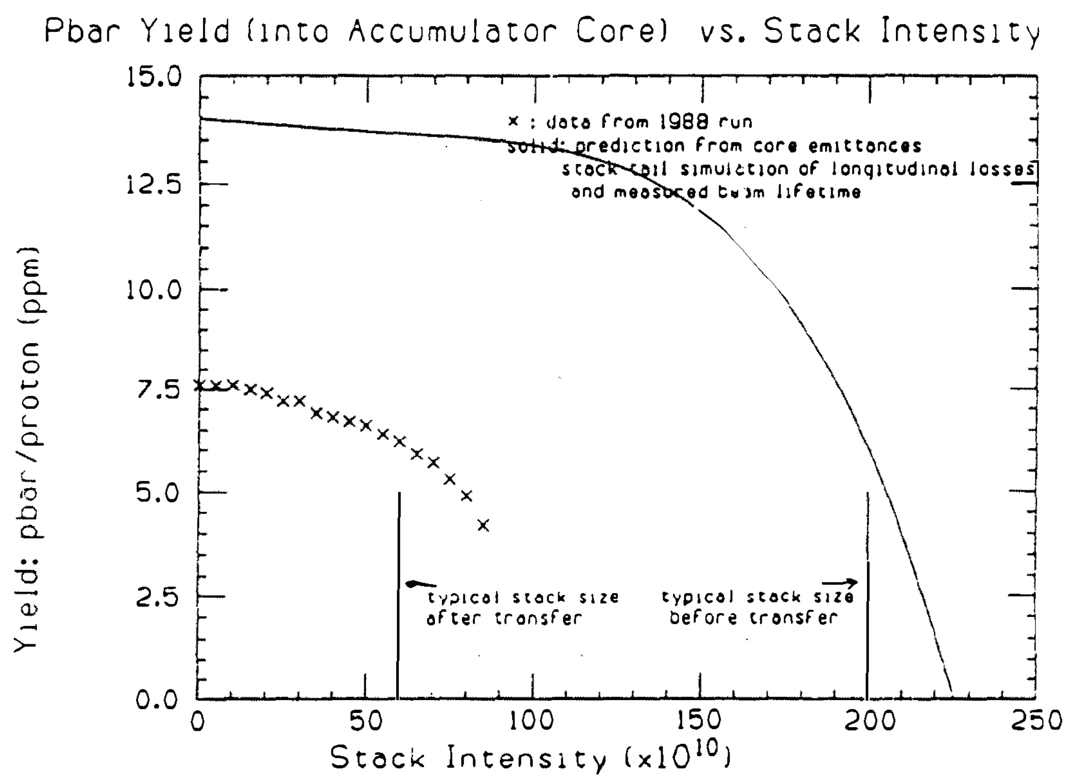


Fig. 3.2-1

1. beam loss due to interaction of the beam with the Accumulator residual gas (300 hour lifetime);

2. longitudinal beam loss from the stack tail and core due to limitations in the stochastic stacking system, which results in beam loss when the beam hits the edges of the machine momentum apertures;

3. transverse beam loss from the core, due to the growth of the transverse emittance with stack intensity (approximately linear; see fig 2.1-2) and the consequent beam loss when the beam hits the edges of the machine transverse apertures.

The stack size end point limit shown in fig. 3.2-1 (about 230×10^{10}) corresponds to the point at which the input stack flux equals the loss due to the three mechanisms described above. As indicated in the figure, typically transfers to the Tevatron would proceed from stacks of about 200×10^{10}. About 140×10^{10} would be extracted in 22 bunches of about 6.8×10^{10} each.

Figs. 3.2-2 and 3.2-3 show the expected longitudinal density and transverse emittances vs intensity of the stack. This figure is based on present experience, but scaled with an improvement factor of 2 in all planes associated with the 2x bandwidth improvement coming from the upgrade of the core systems to 4-8 GHz in Phase I. Because of the high longitudinal density, each of the 22 bunches will occupy only 0.25 ev-sec of longitudinal area. As fig. 2.1-3 shows, this is well within the longitudinal aperture of the Main Injector; hence it will not be necessary to subdivide these bunches, accelerate them to 150 Gev, and then coalesce (as is presently done). The transverse emittances, as fig. 3.2-2 shows, will be in the range of 22 π mm-mrad. This is well within the aperture of the Main Injector (see fig. 2.1-1), but of course would be impossible to transmit with the present Main Ring.

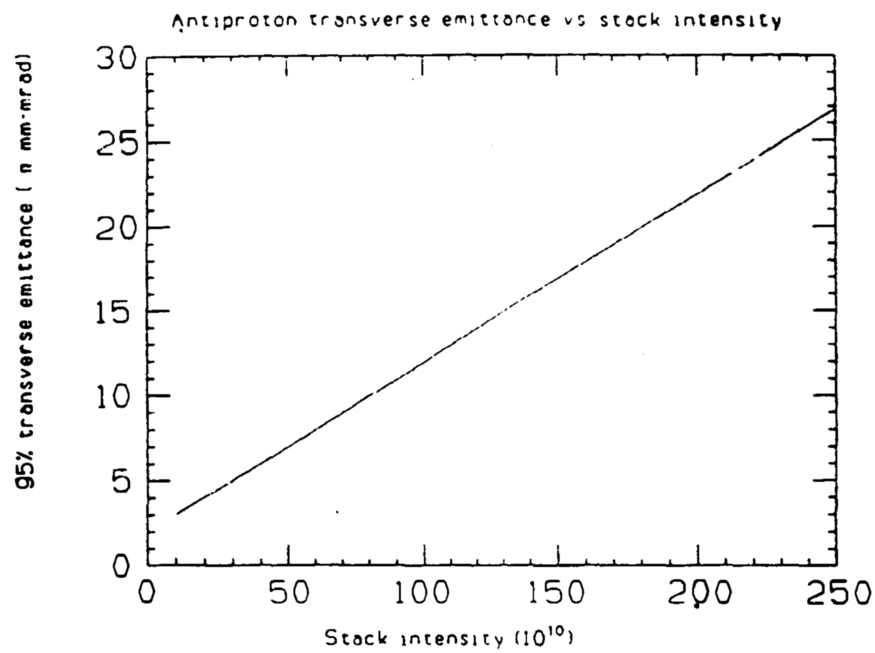


Fig. 3.2-2

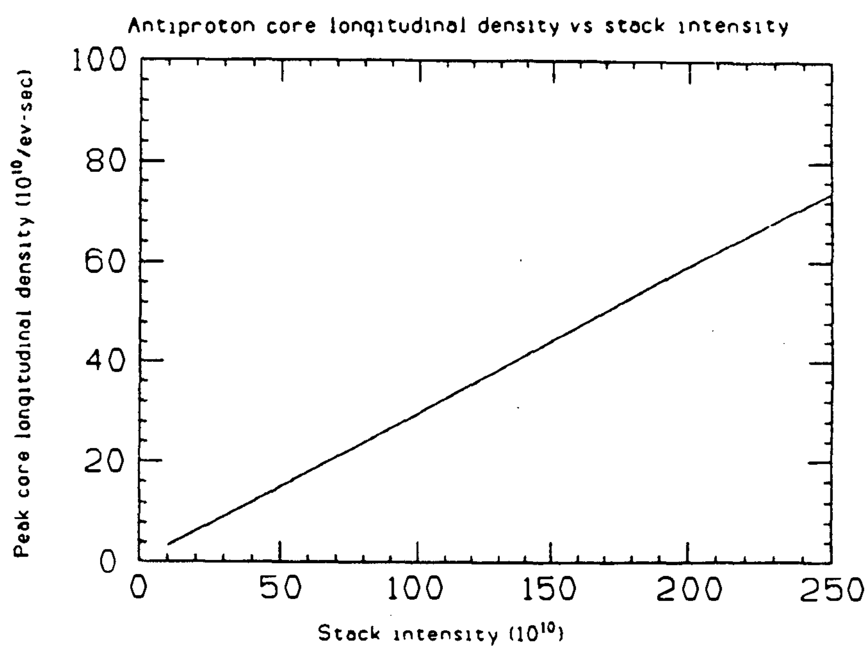


Fig. 3.2-3

Because of the lack of a need to coalesce, and the excellent expected transverse performance of the Main Injector, the transfer efficiency to the Tevatron at low beta is expected to exceed 90%. (The Tevatron transverse aperture at 150 GeV is well in excess of 30 π mm-mrad (normalised, at 150 GeV)). Thus, the $\bar{p}$ bunches at low beta will be about $6x10^{10}$ each, with about 22 π mm-mrad transverse emittance and about 0.25 ev-sec longitudinal emittance. Given the assumed stacking rate quoted above and the dependence of yield on intensity shown in fig. 3.2-1, it will require about 13 hours to replenish the source. This time is a good match to the average operational mean store duration (about 14 hours for our present run). The initial luminosity lifetime is expected to be also about this number; more on this below.

3.2.4 Protons

In addition to the substantial gains in antiproton production provided by the intense Main Injector beams, very high intensity proton bunches can also be delivered to the Tevatron for colliding beam operations. At present, the proton transverse densities in the Tevatron collider are limited by the beam-beam interaction; with the advent of the beam separators in Phase I, this limit will be relieved by a factor of up to 6 (for two IR's). This additional factor of 6 increase in proton transverse density cannot be provided by the Main Ring, even with the Linac upgrade; with the Main Injector, this is no longer true and the full potential of the Tevatron collider with separators can be realised by saturating the beam-beam limit.

As figs. 2.1-1 and 2.1-3 illustrate, with the Main Injector and the improvements to Booster and Linac associated with Phase I of the upgrade, single bunch intensities of $6x10^{10}$, with longitudinal emittances of about 0.4 ev-sec and transverse emittances of about 18 π mm-mrad, will be possible. Several of these bunches can be coalesced into a single high-intensity bunch for delivery to the Tevatron. Fig. 3.2-4 illustrates the expected coalesced proton bunch intensity which could be available in the Main Injector, vs. initial proton bunch intensity, for various numbers of bunches coalesced. The calculation is based on a coalescing efficiency computed from a numerical simulation of the coalescing process. The longitudinal emittance vs. intensity/bunch curve in fig. 2.1-3 (dotted line) has been used to correlate initial intensity/bunch with emittance. In the coalescing simulation, it has been assumed that the present Main Ring RF hardware is simply moved without change into the Main Injector; for the same cavity voltage, the bucket height is increased by 1.35 due to the smaller harmonic number in the Main Injector, resulting in a significant increase in the coalescing efficiency for intense, large emittance bunches. As fig. 3.2-4 shows, proton bunch intensities from 2 to $5x10^{11}$ are quite possible after coalescing in the Main Injector.

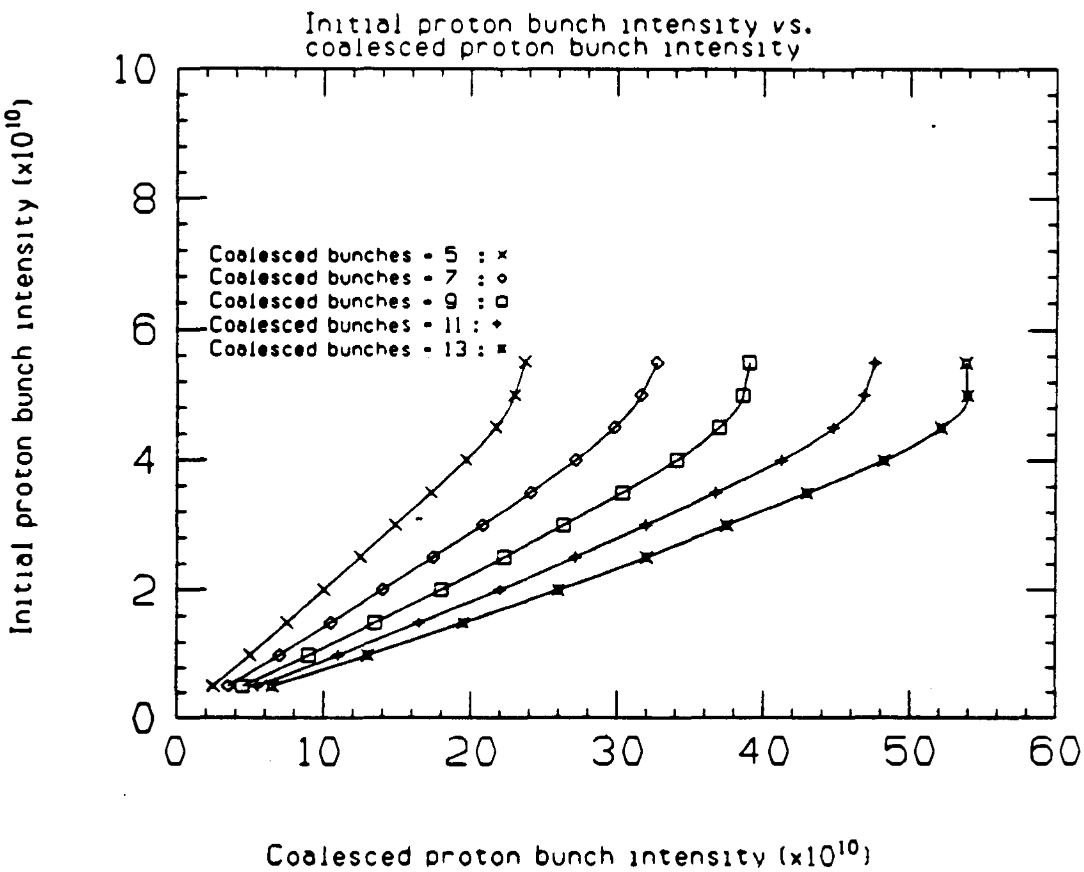


Fig. 3.2-4

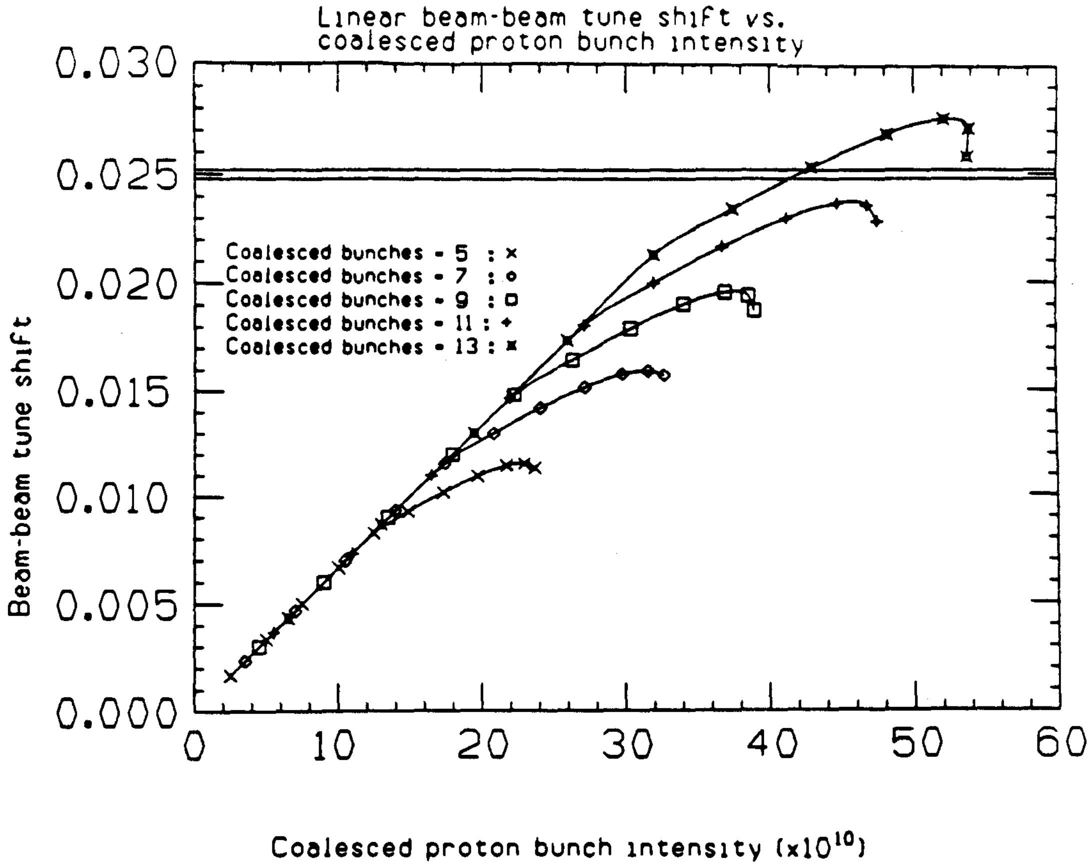


Fig. 3.2-5

These large intensity bunches in general will produce unacceptably large beam-beam effects, even with separators allowing only two crossings per turn. Fig. 3.2-5 presents the total linear beam-beam tune shift vs. coalesced proton bunch intensity. The beam-beam tune shift has been calculated from the simple formula:

$$\delta\nu = 0.00733 n_c N_p/\epsilon_p \ ,$$

where n_c = number of crossings, N_p = proton bunch intensity in units of 10^{10}, and ϵ_p = 95% proton (invariant) transverse emittance in units of π mm-mrad. The emittance has been taken from fig. 2.1-1 for the initial bunches used in the coalescing. In addition, 15 π mm-mrad of emittance growth has been deliberately added to allow shaping of the proton transverse distribution to minimise the non-linear beam-beam effects of the protons on the $\bar{p}$s. This procedure is used in the current run and has proved quite successful; the double line in Fig. 3.2-5 shows the present operational limit (about .025) for the linear beam-beam tune shift in the current run (in which $n_c = 12$), calculated by the above formula. It can be seen that with 7 bunch coalescing and the above emittance control, one can remain below 2/3 of the present operational beam-beam limit even for total bunch intensities of 3.3×10^{11}. These bunches will have transverse emittances of about 30 π mm-mrad: this is about 8 π mm-mrad more than the $\bar{p}$'s, which is similar to the situation in which we operate today. The strong beam (protons) has an emittance substantially greater than the weak beam, which puts the $\bar{p}$'s into a relatively linear region of the strong beam fields.

3.2.5 Limitations

3.2.5.1 Long-range Beam-beam Effects

A possible cause for concern is the so-called long-range beam-beam effect; this is due to the bunch interactions on the spiral orbits of the bunch separation scheme. The separators will keep the beams apart at greater than 5 σ except at B0 and D0; we have seen above how the head-on beam-beam collisions at B0 and D0 are well within the beam-beam tuneshift limits experienced in our present operation. However, there may still be some effects due to these long-range interactions. These are being studied by numerical simulations. One of the effects encountered is the distortion of the closed orbit; this distortion is different for protons and $\bar{p}$'s, and causes the beams to be displaced, and to cross at a non-zero crossing angle at the IR's. However, even for the large bunch intensities considered here, the displacement at the IR is only a small fraction of 1σ, and the crossing angle is about 25% of the ratio of the bunch transverse size to the bunch length. Consequently, the reduction in luminosity associated with these effects is only a few percent. In any case, these effects can probably be corrected with the separators.

3.2.5.2 Instabilities

The consideration of high-intensity bunches in the Main Injector and the Tevatron leads naturally to the question of instabilities. This subject has been looked at in some detail, for the specific case under consideration, viz:

1. Single bunches of 6×10^{10} protons, with 0.4 ev-sec longitudinal emittance and 17 π mm-mrad transverse emittance, injected into and accelerated in the Main Injector;

2. Several (5-13) of these bunches coalesced into a single bunch of intensity $30\text{-}40 \times 10^{10}$ at 150 GeV, with total longitudinal emittance of 3 ev-sec;

3. 22 single bunches of $30\text{-}40 \times 10^{10}$ protons each, 3 ev-sec longitudinal emittance, 22 π mm-mrad transverse emittance, injected into the Tevatron and accelerated to 1000 GeV.

The principal concerns in general seem to be with transverse instabilities; this is encouraging, since we know that the beam transverse size will have to be increased anyway because of beam-beam effects.

Regarding (1), the main issue is the slow head-tail instability at injection. With a positive machine chromaticity the dominant mode is a quadrupole oscillation; growth times of a few milliseconds are expected, which should be able to be handled by a (quadrupole) transverse damper system coupled with accurate control of the machine chromaticity.

With respect to (2), the resistive-wall coupled bunch instability appears to be a potential problem during the period of coalescing when the beam is partially debunched and the momentum spread is reduced to a minimum. Growth times of about 50 milliseconds are predicted.

However, the calculated limits here are about 3 times less restrictive for the Main Injector than for the present Main Ring. Since we presently coalesce bunches of $2x10^{10}$ in the Main Ring without transverse emittance growth during coalescing, we should be able to deal with $6x10^{10}$ in the Main Injector. A high frequency transverse damper of similar design to that in use in the Tevatron will be used if necessary.

Regarding (3), again the slow head-tail at injection seems to be the principal potential culprit, with growth times of tens of milliseconds; this again should be controllable with active damping systems.

In summary, there do not seem to be any fundamental problems with the bunch intensities and emittances discussed here, either in the Main Injector or the Tevatron. Standard active damping systems will certainly be required to control the emittances at injection in both machines in the transverse dimension. The projected bunch intensities are 3-4 times greater than those achieved in present operation, but the larger beam emittances result in bunch densities which increase by only a factor of 2. Exact calculations with regard to instability thresholds are notoriously difficult to perform; however, comparisons between the MI and the Main Ring invariably result in at least a factor of 2 better results with the MI in terms of growth rates and thresholds. None of the above calculations involved any Landau damping decoherence mechanisms (see below). Also, no consideration was given to more modern mechanical design techniques (shielded bellows, tapered transitions, etc) which will be incorporated into the MI and would be expected to result in lower impedances.

Relatively crude analytical estimates of Landau damping decoherence, based on the Keil-Schnell criterion for the amount of tune spread across the beam needed to stabilise the slow head-tail modes, indicate that a small amount of octupole-induced tune spread ($\delta\nu$ = $3x10^{-3}$) is sufficient to stabilise these higher-order modes.

These estimates are in qualitative agreement with observations in the Tevatron, where anomalous coherent Schottky signals observed with the highest achievable proton bunch intensities ($> 10^{11}$) vanish when a single antiproton bunch is injected, producing a beam-beam tune spread of about 10^{-3} across the proton bunches.

3.2.5.3 Luminosity Lifetime

With the large proton intensities proposed for collider operation with the Main Injector, the dominant component of the luminosity lifetime will be transverse and longitudinal emittance growth due to intrabeam scattering. The small $\bar{p}$ longitudinal emittance will also grow rapidly but will have less impact on the luminosity since the bunch length of the $\bar{p}$'s is a second order effect. Initial transverse emittance growth rates of 15-20 hours are expected for the protons; initial longitudinal emittance growth rates will be 5 hours for the protons and less than 1 hour for the $\bar{p}$'s. The overall luminosity lifetime will be about 10 hours initially, growing to 14 hours after 2 hours and 27 hours after 10 hours. This is a reasonable match to the time estimated to be needed to replenish the stack, and to the expected mean store durations. Note that the use of large proton emittances (30π mm-mrad) necessary to control the beam-beam interaction also benefits the luminosity lifetime.

3.2.6 Improvements

The low-β system to be installed in the Tevatron at BO and DO in phase I of the upgrade has the potential to develop $\beta^* = 25$ cm. Operation in such a lattice will require some separator electric fields to reach about 40 Kv/cm, which is quite high; nevertheless, by the era of the Main Injector we expect that experience with the separators will be substantial and achievement of such fields reliably is not unreasonable to expect. The reduction of β^* to 25 cm from 50 cm will not result in a factor of 2 gain in luminosity because of the finite bunch length of $\sigma = 45$ cm; however, a factor of 1.6 gain is anticipated, leading to an initial luminosity of > $5.5 \times 1.6 = 8.8 \times 10^{31}$. Moreover, since the length of the luminous region will be reduced, the effective use of the luminosity by the collider detectors will improve.

As discussed above, it is expected that the beam-beam interaction will provide one of the limits to luminosity under this scenario. This limit is based on our present operating experience at the current Tevatron machine tune. Other working points on the tune diagram theoretically provide a significantly larger available tune space. After the installation of the new low-β system in Phase I, the machine tune of necessity will change; moreover, it is to be expected that studies and experience in Tevatron collider operation may well reveal a better working point, allowing a larger beam-beam tune shift to be tolerated. Fig. 3.2-6 shows the relation between the luminosity and the beam-beam tune shift, as one increases the Main Injector proton intensity per bunch up to the limit set by the bucket area (limit in Fig. 2.1-3), for different numbers of coalesced bunches. The factor of 1.6 for $\beta^* = .25m$ has been included. It should be clear from this figure that the Main Injector capabilities will allow significant improvements in luminosity beyond the numbers quoted here, if the beam-beam limit can be approached. Similarly, as Fig. 3.2-1 shows, the limitations in the number of antiprotons available are set by the Accumulator stack size limit, not by any features of the Main Injector; modest improvements in the Source will immediately pay off in luminosity. It is certainly not unreasonable to think of luminosities in excess of $10^{32}/cm^2/sec$ with the Main Injector. With a 65% operational efficiency (110 store hours/week, typical of present operation), in an 8 month run at $10^{32}/cm^2/sec$, and with the luminosity lifetimes mentioned above, the Tevatron collider would deliver an integrated luminosity of about 750 pb^{-1} at each interaction region!

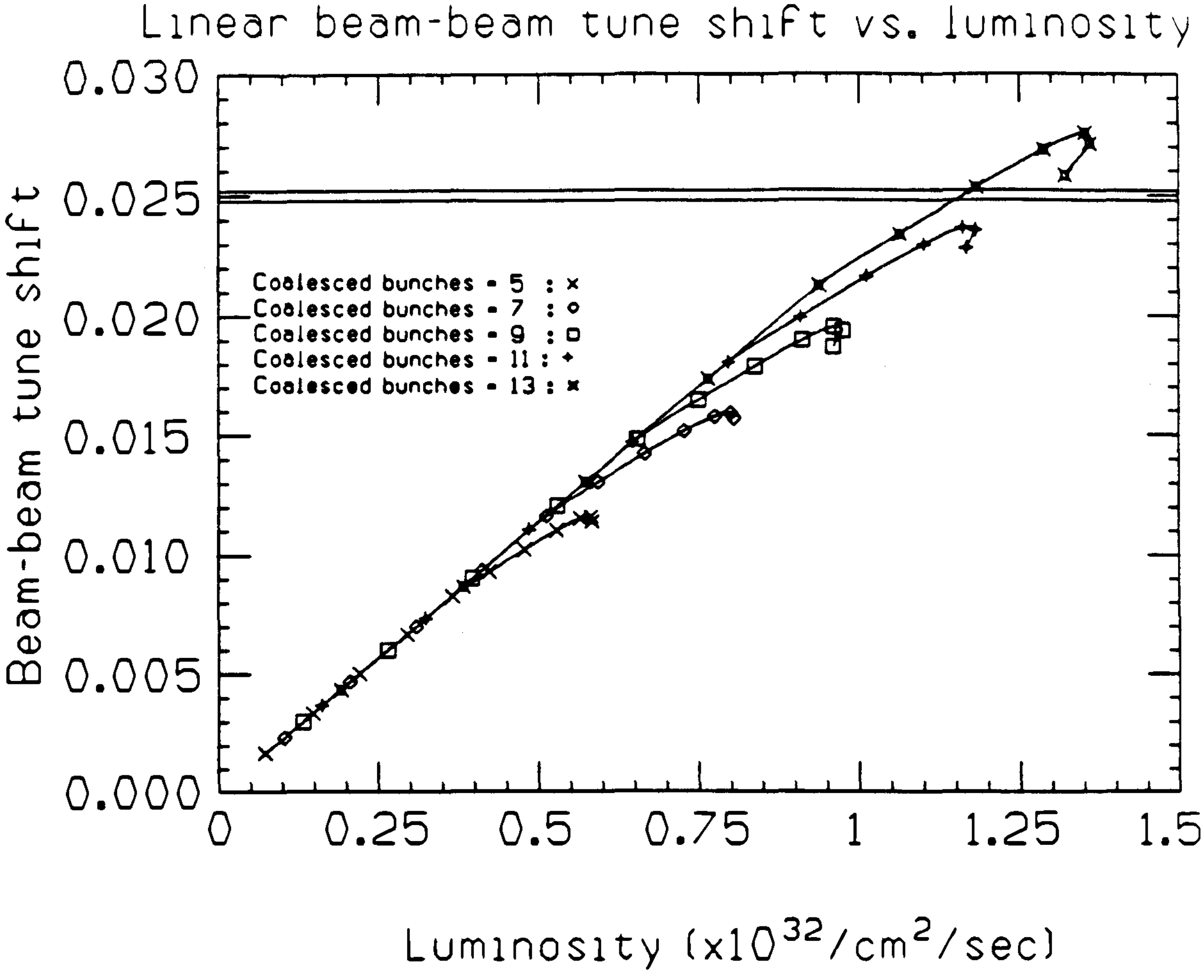


Fig. 3.2-6

3.3 Other Interaction Regions

With the removal of the Main Ring from the Tevatron tunnel, it becomes possible to realistically consider another high-luminosity interaction region for the Tevatron. This region could be either at C0 or E0. The region at C0 is made available by the removal of the abort system to A0 (which happens in Phase I of the upgrade); the region at E0 becomes available because of the removal of the beam transfer system to F0, which is necessary when the Main Injector is installed. Either one (or both) of these Tevatron straight sections then becomes, in principle, a candidate for another high-luminosity IR.

The development of an additional high-luminosity IR requires:

1. The installation of another low-β system, and

2. Hardware to bring the separated beams into collisions at this straight section.

We focus here on the CO region as an example of what must be done in the Tevatron to make this possibility real. The new low-β design to be implemented at BO and DO in Phase I has the feature that it leaves the lattice outside of the insertion relatively unperturbed; thus, the simple addition of another insertion at CO is possible without major modifications outside of the CO region. Fig. 3.3-1 shows the resulting lattice with three IR's, all at $\beta^* = 0.5$ m. The tunes will increase to $(Q_x, Q_y) = (21.267, 21.273)$.

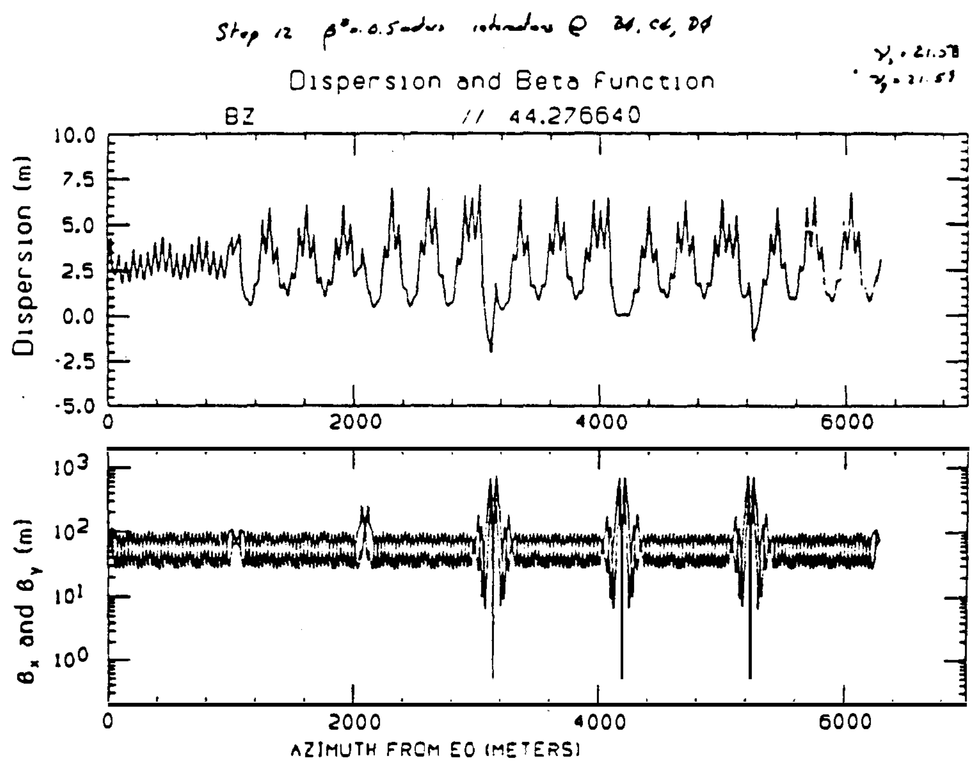


Fig. 3.3-1

The major difficulty with the insertion of another IR relates to the requirements of beam separation. The beam separation scheme between D0 and B0 remains unchanged. However, the beams must now be brought into collision at C0. To do this, it will be necessary to place electrostatic separators in the presently cold regions at the 37 and 42 locations between B0 and C0, and between C0 and D0. Fourteen additional 2.6m separators will be required. To create warm space for these devices, it will be necessary to replace existing Tevatron dipoles at these locations with new, shorter, high field (6.6 T) dipoles. The development of these dipoles is already part of our general magnet R&D program. Twenty-four new dipoles will be required. The resulting separation profile between B0 and D0 is shown in fig. 3.3-2; note that to achieve > 4σ separation everywhere, separator fields of 50 kv/cm will be needed. It is expected that, by the time another IR is required, the separator hardware development will have progressed to the point at which this will be possible.

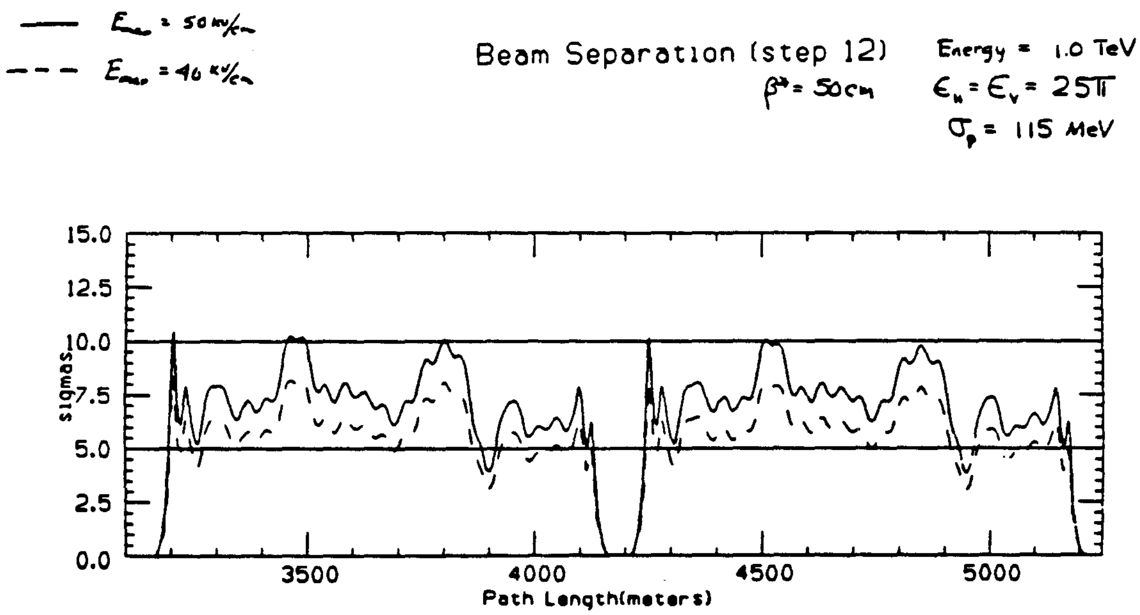


Fig. 3.3-2

Finally, it should be pointed out that, with two IR's, the Tevatron collider is expected to be pushing the beam-beam interaction limit in the scenario outlined here. Simultaneous operation of IR's at BO, CO and DO will therefore require roughly a 1/3 reduction in luminosity at BO and DO.

3.4 Impact on Fixed-target Operation

3.4.1 Tevatron Fixed Target Beams

The unique physics capabilities of the Fermilab Tevatron fixed-target program are not at present fully utilized due to limitations imposed by the Main Ring. Existing experimental detectors could make use of considerably more than the 1.8×10^{13} protons per Tevatron cycle presently available. With the Main Injector a fixed target capability of up to 6×10^{13} protons per cycle should be realizable.

In the early 1980's, the upgrading of the experimental areas to accept beam from the soon-to-be commissioned Tevatron incorporated the capability of efficient utilization of 1 TeV beams at significantly higher intensities than presently achieved. The existing Switchyard splitting stations routinely deliver beam to ten separate primary targets, each with the capacity of accepting higher flux proton beams. In short, any increase in intensity out of the Tevatron would not only be tolerated, but would be welcomed. The Main Injector would remove the present severe intensity limitation of the fixed-target program and permit more complete utilization of existing beamlines and detectors.

Instability thresholds associated with fixed target operation where the bunches are spaced at the RF frequency of 53 MHz are different than those discussed previously with respect to the collider operation. Indeed, during the 1987 fixed target run a self-stabilizing transverse oscillation was observed in the Tevatron at the highest intensities obtained during that run. Of itself transverse emittance growth is not necessarily important to fixed target operation where the extracted beam phase space is defined by the resonant extraction process and not the circulating beam. The erratic nature of this effect did cause significant problems however, since the extraction system feedback loops rely on the previous cycles to provide feed-forward information to define the initial values for the quadrupole elements. Frequently large amounts of beam were extracted at the beginning of the flattop cycle which caused the loss monitor system protecting the superconducting magnets to abort the beam; occasionally losses were so severe that quenches occurred. Raising the Tevatron intensity will require a solution to this problem. Reducing bunch densities by artificially increasing the longitudinal phase space density proved effective in raising the intensity threshold for this effect but occasionally resulted in beam losses. Allowing the beam to go unstable in a controlled fashion could also prove satisfactory. Identifying and correcting the accelerator impedance driving this effect would be the long term solution.

3.4.2 Main Injector Fixed-Target Beams

Another major positive impact of the Main Injector on the fixed-target program is the availability of year round intermediate energy fixed-target beams. The problems previously discussed of providing fixed-target beams from the Main Ring are completely eliminated. Design studies have demonstrated the feasibility of slow and fast spill resonant extraction from the Main Injector, both during collider operation and Tevatron fixed-target running.

A design linking the Main Injector extracted beam to the existing Tevatron Switchyard beam splitting system has been accomplished, which enables switching between the 900 GeV Tevatron and 120 GeV Main Injector extracted beam sources. During collider operation 120 GeV test beams can be made available simultaneously to all existing fixed-target experimental areas. The major design concern for 120 GeV beam operation with the existing Switchyard is aperture limitations of the electrostatic septa coupled with larger beam size at this energy. For efficient operation at high energy the septa have small apertures of 2 cm for the gap between cathodes and splitting wire planes. The feasibility of transporting Main Injector beams through this system with the addition of relatively minor Switchyard beam optics changes has been demonstrated in computer simulations.

The availability of Main Injector test beams should greatly enhance preparation for efficient fixed-target runs. At present the first months of each running period are dominated by the slow process of detector turn on and calibration which cannot be accomplished without beam. This significantly shortens the available physics data collection time of each running period.

Additionally the prospect of Main Injector test beams has significant impact beyond enhancement of the Fermilab fixed-target physics program. Development of the new generation of detectors required for the SSC era is dependent on ready and long term availability of test beams, preferably of this energy range. This is best and most efficiently accomplished with beams from the Main Injector to the fixed-target experimental areas.

Finally, very high luminosity extracted beam from the Main Injector makes possible the staging of a new generation of experiments, which need the energy reach not found at lower energy high flux facilities, but for which the high luminosity at 120 GeV enables physics research not presently achievable in the Tevatron fixed-target program. At least two such physics programs of fundamental import are at present being seriously considered by Fermilab user groups, utilizing the unique beam capabilities made possible with the Main Injector: the study of very rare processes and CP nonconservation in the kaon system, and a search for ν_μ/ν_τ oscillations.

To this end a design effort is well underway for a new cost efficient dedicated high intensity 120 GeV beam line through the Switchyard system, to the existing Neutrino experimental area. Using existing beam enclosures a minimum of civil construction is required for this new beam line. With the Main Injector capabilities, operation for a 120 GeV high flux fixed target program would be year round, compatible with both Tevatron collider and fixed-target operation.

3.5 Costs and Schedules

The Total Estimated Cost (TEC) for construction of the Main Injector, associated beamlines, and required modifications to existing facilities as presented to the DOE in the Conceptual Design Report and Schedule 44 dated March 6, 1989 is $129,400,000 in then-year dollars. The cost estimate is summarized in Table 3.5-1. An additional $12,000,000 will be required in direct R&D, pre-operating, and capital equipment costs to support the project. The cost estimate methodology is adapted from that used to estimate the Superconducting Super Collider (SSC). Our recent experience with the TeV I (Antiproton Source) and Main Ring overpass construction projects forms the basis for a large fraction of the cost estimate of this project. It is proposed to construct the MI over a three-and-one-half year period starting on October 1, 1990, with a disruption to HEP operations from May 15, 1993 to February 15, 1994.

The layout and cost estimate for the Main Injector Complex as given in the Conceptual Design Report are based on the assumption that space must be created within the existing Tevatron tunnel for installation of a new higher energy superconducting accelerator (Phase III of the Fermilab Upgrade). The impact of decoupling the MI construction project from any other activity related to new superconducting accelerators at Fermilab has been examined. It is found that in the absence of the simultaneous development of a new superconducting accelerator the cost required for completion of the Main Injector project can be significantly reduced. The cost reduction comes from the elimination of approximately 3500' of new beamlines from the project by leaving existing Main Ring elements intact between F0 and A0. These elements are then used for beam transport duplicating the functions of the 120 GeV beamlines (testbeam and $\bar{p}$ targeting) described in the CDR. Savings are accrued through the elimination of both civil construction and installation charges.

3.5.1 Costs

Table 3.5-2 shows the breakdown of anticipated cost savings resulting from the elimination of new 120 GeV lines. Note that only the construction and installation of these lines is eliminated from the project; the functionality is retained. Technical components savings come from not having to relocate magnets, power supplies, cable trays, water systems, etc., while civil construction savings come from the elimination of some new tunnel enclosures as well as modifications to existing enclosures (e.g. no new penetrations from AP0, no need to break into the Booster enclosure at L12). The total savings is estimated at $8,020,000 (1989 dollars). The effect of this savings on the TEC when escalated to then-year dollars is described in Table 3.5-3. The TEC is reduced from $129,400,000 to $119,600,000. The reduced level 2 cost estimate in then-year dollars is given in Table 3.5-4.

Table 3.5-1: Main Injector Cost Estimate (Dollar amounts in thousands)

WBS	Description			Total
1.	**MAIN INJECTOR CONSTRUCTION (TEC)**			129400
1.1	**Technical Components**			48840
.1	Main Injector Ring		33710	
.1	Magnets	18163		
.2	Vacuum	366		
.3	Power Supplies	3992		
.4	RF Systems	186		
.5	Aborts	71		
.6	Slow Extraction	17		
.7	Instrumentation	1040		
.8	Controls	365		
.9	Safety	329		
.10	Utilities & Install	9181		
.2	Beamlines		15126	
.1	Magnets	5318		
.2	Vacuum	294		
.3	Power Supplies	2458		
.4	Injection Systems	717		
.5	Extraction Systems	237		
.6	Instrumentation	743		
.7	Controls	446		
.8	Safety	269		
.9	Utilities & Install	4643		
1.2	**Civil Construction**			29610
.1	Site Preparation		1963	
.2	Ring Enclosure		11618	
.3	Beam Line Enclosures		3707	
.4	Ring Service Buildings		1677	
.5	MI-70 Service Building		2302	
.6	North Hatch Building		1122	
.7	Utilities & Services		1316	
.8	F0 Enclosure		2210	
.9	RF/F0 Service Building		840	
.10	Beamline Connections		1892	
.11	AP0 Target Hall Mods		20	
.12	F-17 Kicker Building		95	
.13	Landscaping & Paving		846	
1.3	**EDIA(16.9%)**			13260
1.4	**Contingency(20%)**			18340
1.5	**G&A (0.7%)**			770
1.6	**Escalation**			18590
2.	**OTHER PROJECT COSTS**			12000
2.1	**R&D**			9100
2.2	**Pre-operating**			2000
2.3	**Capital Equipment**			910
	TOTAL PROJECT COST (TPC)			141400

Table 3.5-2: Savings from Using Existing FO-AO Beam Transport
(Amounts in 1989 $K)

WBS	Description				Total
1.	**Main Injector Construction**				8020
1.1	Technical Components			1660	
.2	Beamlines		1655		
.2	Vacuum	52			
.9	Utilities and Install	1603			
1.2	Civil Construction			4020	
.3	Beamline Enclosures		1850		
.6	North Hatch Building		400		
.7	Utilities & Services		650		
.8	FO Enclosure		200		
.10	Beamline Connections		900		
.11	APO Target Hall Mods		20		
1.3	EDIA (16.9%)			960	
1.4	Contingency (20%)			1330	
1.5	G&A (0.7%)			60	

Table 3.5-3: Reduced Cost Funding Profile

(Cost in $1989 = $129,400 K - 18,590 K - 8,020 K = $102,790 K)

Year	$89	Escalation	$Then-Year
1991	27,273	1.100	30,000
1992	43,253	1.156	50,000
1993	30,662	1.223	37,500
1994	1,602	1.296	2,076
Total	**$102,790**	**1.163**	**$119,600 (TEC)**

Table 3.5-4: Level Two Reduced Cost Breakdown ($K)

	$1989	$Then-Year
1.1 Technical Components	47,180	54,900
1.2 Civil Construction	25,590	29,770
1.3 EDIA	12,300	14,310
1.4 Contingency	17,010	19,790
1.5 G&A	710	830
Total	**102,790**	**119,600**

3.5.2 Schedule

It is proposed that the Main Injector project be completed over the period October 1, 1990 through May 1, 1994. The schedule is shown in Figure 3.5-1. The period October 1, 1989 through September 30, 1990 will be devoted to R&D with preparatory engineering in support of construction beginning on October 1, 1990. The schedule results in a nine month disruption to HEP operations. This disruption will start on May 15, 1993.

A set of project milestones is given in Table 3.5-5. As can be seen the Main Injector ring and 8 GeV beamline can be largely constructed without disturbing Tevatron operations. The length of the HEP shutdown is tied to the civil construction in the area of F0. Overall downtime has been minimized by situating the Main Injector 10 meters away from F0 so that commissioning can actually begin prior to completion of construction in this area. As currently envisioned priority would be given to installing and commissioning the 120 GeV testbeam line so that operations in a fixed target mode with beams emanating from the MI would be initiated following the shutdown. The 120 GeV $\bar{p}$ production line and 150 GeV transfer lines would then be commissioned during the fixed target run, allowing for a Tevatron startup in spring 1994.

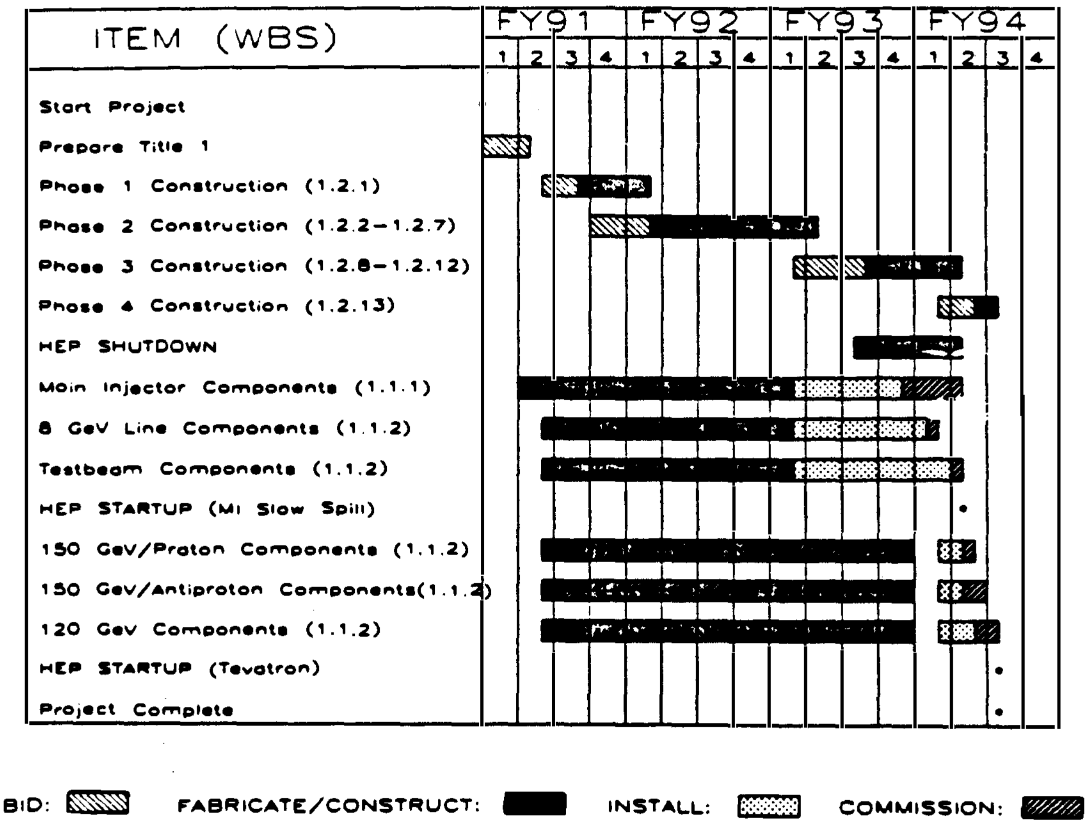

ITEM (WBS)
FY91
FY92
FY93
FY94
1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4
Start Project
Prepare Title 1
Phase 1 Construction (1.2.1)
Phase 2 Construction (1.2.2-1.2.7)
Phase 3 Construction (1.2.8-1.2.12)
Phase 4 Construction (1.2.13)
HEP SHUTDOWN
Main Injector Components (1.1.1)
8 GeV Line Components (1.1.2)
Testbeam Components (1.1.2)
HEP STARTUP (MI Slow Spill)
150 GeV/Proton Components (1.1.2)
150 GeV/Antiproton Components(1.1.2)
120 Gev Components (1.1.2)
HEP STARTUP (Tevatron)
Project Complete
BID:
FABRICATE/CONSTRUCT:
INSTALL:
COMMISSION:

Fig. 3.5-1

Table 3.5-5: Major Project Milestones

	Milestone	Date	Description
1989			
	1	October 1	Start Magnet R&D
1990			
	2	October 1	Complete First Dipole Prototype
	3		Start Project
1991			
	4	January 1	Start Magnet Production
	5	March 1	Start Civil Construction
1992			
	6	December 1	Beneficial Occupancy of Main Injector Enclosure, MI-70, and North Hatch Building. Start MI, 8 GeV, and Testbeam Installation.
1993			
	7	February 1	Beneficial Occupancy all MI Service Buildings.
	8	May 15	**Begin HEP Shutdown.** Begin Equipment Removal at F0.
	9	June 1	Start F0 Construction.
	10	September 1	Complete MI Installation. Start MI Commissioning (Power Test).
	11	September 15	Complete 8 GeV Beneficial Occupancy.
	12	November 1	Complete 8 GeV Installation. Start 8 GeV Commissioning.
	13	December 1	Beneficial Occupancy of F0 and 150 GeV Enclosures. Start 150 GeV and Tevatron F0 Installation.
1994			
	14	January 1	Start 120 GeV Testbeam Line Commissioning.
	15	February 1	Beneficial Occupancy of F0 Building.
	16	February 15	Complete Installation of Tevatron F0 Enclosure Components. Complete Commissioning of MI and 120 GeV Testbeam Line. Begin Commissioning 150 GeV, 120 GeV Lines.
	17	February 15	**HEP Startup. (MI Slow Extracted Beam).**
	18	May 1	**HEP Startup (Tevatron).**
	19	May 1	Paving and Landscaping Complete. Project Complete.