Instrumentation Requirements for the Fermilab Main Injector

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Abstract

The Fermilab Main Injector will be used as an injector of 150 GeV/c protons and antiprotons for the existing Tevatron. Additionally, it will provide 120 GeV/c protons for antiproton production, year around 120 GeV/c low intensity slow resonant proton extraction (slow spill) for test beams to all experimental areas, 120 GeV/c high intensity slow spill for dedicated kaon experiments, and 120 GeV/c high intensity fast resonant proton extraction for dedicated neutrino experiments. Much of the instrumentation is scheduled to be recycled from the existing Main Ring while some is to be newly built. A brief description of the Main Injector parameters will be presented along with instrumentation requirements for the accelerator and its associated beamlines.

Introduction

This report discusses the beam diagnostic equipment that will be required for commissioning and operation of the Fermilab Main Injector (FMI) ring and beamlines. There are a few basic beam properties that require monitoring (and control). These include beam position, intensity, and loss information, transverse profiles, and longitudinal profiles. From the measurement of these beam properties, with or without an external stimuli (i.e. shaking or displacing the beam transversely or longitudinally), the beam qualities such as (but not limited to) transverse and longitudinal emittances, momentum distribution, transverse transfer functions, momentum dispersion, betatron tune, chromaticity, transverse coupling, coupling between transverse and longitudinal motion, beam intensity and emittance lifetimes, resonance widths and other nonlinear phenomena, may be determined. It is implicitly assumed that if a beam property may be measured that some mechanism is present to modify or control that property. This loop of measurement and control may be either manual (human intervention) or automatic (feedback). For the most part, this report will discuss which beam properties are to be monitored and the FMI accelerator parameters that influence the choices for the diagnostic equipment. The specific instrumentation required for guide field control, resonant extraction, beam dampers, or RF control will not be included here. Prior to discussing equipment details and quantities, a brief description of the FMI accelerator, its beamlines, and its envisioned operational scenarios is given.

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Accelerator Description

The Fermilab Main Injector is being constructed to replace the existing Main Ring.[1,2] The FMI project involves the construction of a 150 GeV/c accelerator and the associated beamlines required to integrate the accelerator into the existing Fermilab accelerator complex. Figure 1 shows a schematic view of the FMI and its integration into the existing accelerator complex. The FMI is seven times the circumference of the existing Booster and slightly larger than half the circumference of the Tevatron. The harmonic numbers of the Booster, FMI, and Tevatron are 84, 588 (7X84), and 1113 (13.25X84). To allow for an abort gap, six Booster cycles are utilized to fill the FMI and two FMI cycles to fill the Tevatron.

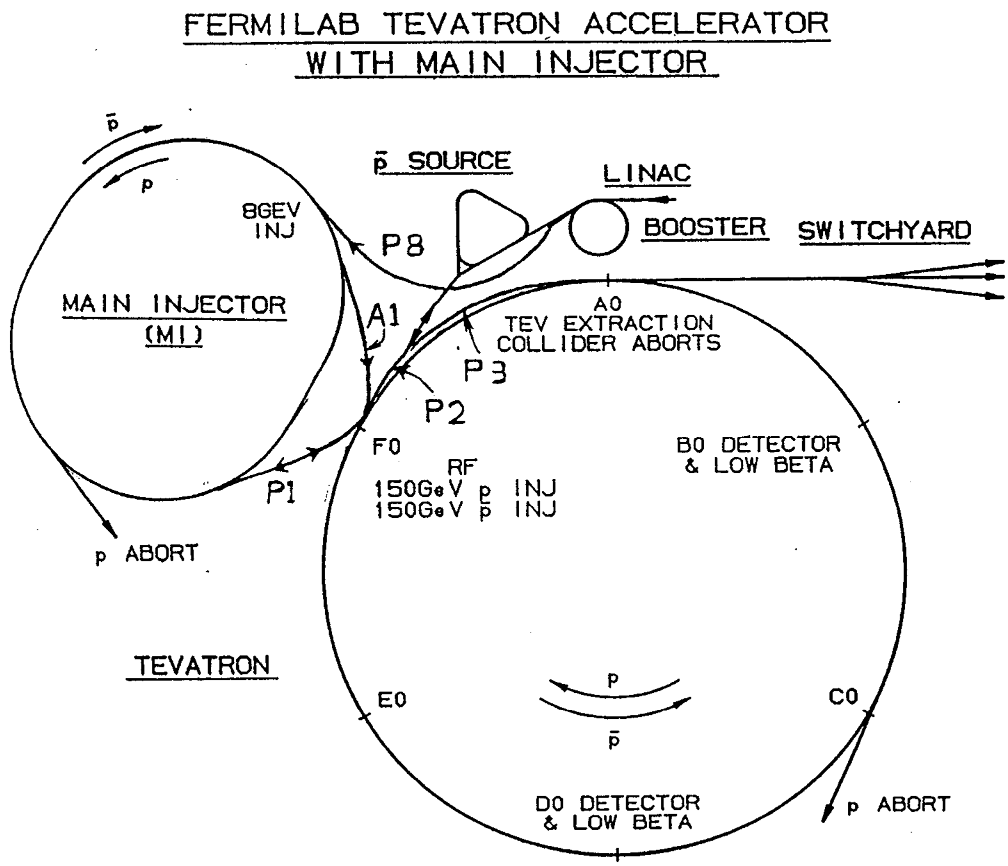

Figure 1: Schematic View of the Main Injector Connections to the Booster, Antiproton Source, Tevatron, and Switchyard

Five transport lines are required to integrate the FMI into the existing accelerator complex. The ultimate instrumentation requirements for each beamline will be determined by its functionality. The required beamlines are:

- P8 beamline: Transports 8.9 GeV/c protons from the Booster to the FMI.
- P1 beamline: Transports 150 GeV/c protons from FMI to Tevatron; transports 120 GeV/c protons for antiproton production; transports 120 GeV/c slow spill

to beamline P2; transports 8.9 GeV/c antiprotons from the Antiproton Source to the FMI.

- A1 beamline: Transports 150 GeV/c antiprotons from the FMI to the Tevatron.

- P2 beamline: Transports 120 GeV/c beam for antiproton production from P1 to existing AP beamline; transports 120 GeV/c slow spill from P1 to beamline P3.

- P3 beamline: Transports only 120 GeV/c slow spill to Switchyard and the fixed target area.

Several modes of operation (acceleration cycles) for the FMI have been identified.[3] The number of bunches and bunch intensity in the ring and beamlines vary depending on the particular acceleration cycle of the FMI. These are enumerated below.

- Fixed Target mode (2.4 sec. cycle time): Six batches of Booster beam are injected into the FMI at 8.9 GeV/c, filling 498 buckets out of 588. Each Booster batch contains 83 bunches with a maximum expected bunch intensity of 6 to 8E10 per bunch to yield a ring intensity of 3 to 4E13 protons. The beam is then accelerated to 150 GeV/c and transferred to the Tevatron. The FMI will cycle twice to fill the Tevatron with twelve intense proton bunches for a ring intensity of 6 to 8E13.

- Antiproton Production mode (1.5 sec. cycle time): A single Booster batch, containing 5 to 7E12 protons, is injected into the FMI at 8.9 GeV/c. The protons are accelerated to 120 GeV/c and extracted in a single turn for delivery to the antiproton production target.

- Collider mode (36X36)[1] (4.0 sec. cycle time): This acceleration cycle is used to fill the Tevatron with either 36 proton or antiproton bunches. Twelve groups of (up to) 13 Booster bunches are injected into the FMI separated by 21 RF cycles. These are accelerated to 150 GeV/c, coalesced into 12 bunches (3.3E11), and transferred into the Tevatron. The FMI cycles three times to fill the Tevatron with 36 proton bunches. Four groups of (up to) 13 antiproton bunches are extracted from the Antiproton Source and injected into the FMI. These are accelerated to 150 GeV/c, coalesced into 4 bunches (3.7E10), and transferred into the Tevatron. The FMI cycles nine times to fill the Tevatron with 36 antiproton bunches.

- Slow Spill mode (2.9 sec. cycle time): Six Booster batches are injected into the FMI. These are accelerated to 120 GeV/c and resonantly extracted during a one second flattop. With a ring intensity of 1E12 this mode is used to deliver low intensity test beams to all experimental areas during Collider operation. With a ring intensity of 3 to 4E13, this mode can be utilized for dedicated Kaon physics.

- Fast Spill mode (1.9 sec. cycle time): Six Booster batches are injected into the FMI. These are accelerated to 120 GeV/c and resonantly extracted during a one millisecond flattop. With a ring intensity of up to 3 to 4E13 this mode can be used to deliver high intensity fast spill for production of high flux neutrino beams.

To utilize the FMI's potential for delivering protons, these or acceleration cycles are designed to be combined into a set of acceleration cycles (super cycle) with minimum dwell time between individual cycles. This puts a demand on the instrumentation to be able to switch between single bunch or multibunch (up to 498 bunches) measurements on a cycle by cycle basis. Bunch intensities from a few E9 in the low intensity slow spill mode to 3E11 in a coalesced bunch for the Collider mode must be accommodated. The provisions for slow spill extends the low end of the bunch intensity range for position measurement (in beamlines) to a few E4 protons/bunch. Pertinent accelerator parameters for instrumentation considerations are listed in Table 1.

Table 1: Comparison of Main Ring and Main Injector Parameters

Machine Parameter	Main Ring	Main Injector
circumference [meters]	6283.185	3319.419
injection momentum [GeV/c]	8.9	8.9
peak momentum [GeV/c]	150	150
RF frequency [Mhz @ GeV/c]	52.8 @ 8.9	52.8 @ 8.9
	53.1 @ 150	53.1 @ 150
revolution frequency [Khz]	47.7	90
bucket length [ns]	19	19
bunch length (uncoalesced) [ns]	2-6	2-6
harmonic number	1113	588
number of bunches (Fixed Target cycle)	996	498
number of coalesced bunches (Collider cycle)	1	12
protons/bunch	2E10	6-8E10
total protons (Fixed Target)	2E13	3-4E13
transverse emittance [π-mm-mr]	12	20
transverse admittance(@ 8.9 GeV/c) [π-mm-mr]	12	40
longitudinal emittance [eV-sec]	0.06-0.4	0.4
longitudinal admittance [eV-sec]	0.4	0.5
Min/Max β [meters]	30/ 100	10.6/57
cell phase advance [degrees]	67	90
dispersion (Max in arc) [meters]	7.0	2.0
dispersion (straight section) [meters]	approx. 3	zero
Ring vacuum [torr]	5E-08	1E-08
Beamline vacuum [torr]	5E-07	5E-07

Main Injector Requirements

The requirements for the FMI diagnostics encompass the beam monitor specifications, the electronics, the micro firmware, and the applications software to integrate it into the control systems. To fully specify each diagnostic system, requirements and specifications for each of these components must be given. This discussion will focus on the beam properties to be measured and estimate the types and quantities of instrumentation required. A summary of the FMI instrumentation is given in Table 2 followed by a discussion of each category.

Table 2: Instrumentation Summary for the Main Injector

Type / Location	Ring	P8	P1	A1	P2	P3	Abort
POSITION MONITORS							
New FMI style	203						
Existing MR style		34	14	14	7	32	3
Large aperture	5	17					
Tuned detector			3		2	6	
LOSS MONITORS							
ion chamber	231	51	19	16	7	32	3
INTENSITY MONITORS							
Resistive wall	2						
Toroid		2	1	1	2	1	1
DCCT	1						
High-gain			1				
PROFILE MONITORS							
Flying Wire	4						
Wire Grid	6	4	2	2	2	3	2
Non-destructive	2	2					
DAMPERS							
Horizontal	1						
Vertical	1						
SCHOTTKY DETECTORS							
Horizontal	1						
Vertical	1						
SCRAPERS							
Horizontal	1	1					
Vertical	1	1					
PINGER							
Horizontal	1						
Vertical	1						

Beam Position Monitor System

The capability of determining the transverse position of the beam within the vacuum chamber and magnetic elements at all locations within the accelerator at all times is required. Each quad in the FMI ring (and beamlines) should have a BPM detector of the correct orientation (i.e. horizontal BPM's at focussing locations and visa versa). Calculations for the FMI ring confirm that a single BPM per cell in each plane is sufficient for the required orbit correction.[4]

Beam positions should be measured, time stamped, and stored in buffer memory for readout at a later time. The system should be capable of making measurements on any single bunch within a bunch train. The signal processing should generate real time signals for fast time plotting or use in feedback systems. For the FMI ring, the capability of acquiring global single turn positions, at any instant of time (including first and last turns), and an averaged position over some small number of turns to cancel out betatron oscillations (closed orbit) should be provided. Additionally, some set of position monitors should be capable of acquiring the beam position on a turn by turn basis. For all transfer lines, a complete set of positions for each beam pulse should be provided.

The BPM system should be able to accurately represent positions for single bunches and multiple bunch trains within the expected intensity range, as described in the Accelerator Description section.

The expected mean orbit deviations due to all errors is less than 5 mm horizontally and 4 mm vertically.[5] The closed orbit throughout the ring should be centered about zero except around the injection, extraction, and abort straight sections. A position range for the standard FMI detectors of ± 20 mm should be sufficient in both planes. Calculations of emittance dilution indicate that a .5 mm (.13 mm) offset at the injection (extraction) kicker corresponds to an emittance increase of 1 π-mm-mr.[6] The ultimate resolution of the pickup and signal processing should then be a factor of two or three better than .13 mm.

Closed orbit distortions around the injection, extraction, and abort Lambertsons are approximately 25 mm for 8.9 GeV/c. Consequently, the quad located between the extraction Lambertsons must have a large aperture BPM pickup (rather than the new FMI style) to preserve the aperture in this region. The position range should be sufficient to accurately measure these off center trajectories with the same approximate resolution as the standard ring detectors.

The beamline position detectors should have a minimum position range of ± 38 mm with a resolution of about $\pm .15$ mm. The intensity range should be similar to that of the ring. The beamlines required to transport slow spill are to be instrumented with position detectors sensitive to intensities down to a few E4 per bunch. A resolution to within $\pm .5$ mm in the range of ± 25 mm is probably sufficient for the slow spill BPMs. These detectors should be located at least up and downstream of each magnetic switch (i.e. between P1-P2, P2-P3, and between P3-Switchyard) with additional detectors throughout P3 beamline section.

Beam Loss Monitor System

The ability to determine time, location, and magnitude of beam loss in the ring and beamlines should be provided. The beam loss detector should provide information on instantaneous losses and integrated losses through out the cycle. Loss monitors should be located at each quad and at the up and downstream end of each Lambertson or c-magnet in the injection, extraction, and abort lines.

The current loss monitors utilized in the Main Ring and Tevatron are sealed glass ion chambers filled with atmospheric Argon.[7,8] This detector has a dynamic range of 10^6 and linear to 100 Rads instantaneous dose. A four decade integrating log amplifier is used to provide a large dynamic range.[7] The sensitivity and range appear to be sufficient for the intensity range of the FMI.

Beam Intensity Monitor System

Beam intensity signals may be used as a measure of transfer and acceleration efficiencies, in feedback systems for control of RF cavity beam loading, in feedback systems to control beam spill structure during resonant extraction, for bunch structure measurements, and other beam diagnostics.

Both bunch-length dependent and independent (DC component) intensity measurements are required. The measurement of the intensity distribution within the 20 nanosecond bucket should be provided. Depending on the signal processing applied, the longitudinal profile, longitudinal emittance, bunch-length, and bunch intensity should be determined. For operational modes which contain a limited number of bunches, the intensity and bunch-length should be provided on a bunch-by-bunch basis. All intensity monitors should be cross calibrated to provide transfer and acceleration efficiency data.

An integrated beam signal for the FMI ring should be provided for total ring intensities from 1E10 to 4E13. This range applies for the DC current signal (DCCT) as well as the bunch-length dependent signal (toroid and resistive wall monitor). For the cycles where single bunch intensities are required, the dynamic range should be from 1E9 to 3.3E11 (anti)protons per bunch. All beamlines should provide real time plus integrated intensity signals. The P8 beamline intensity should be measured at each end with a dynamic range of 1E10 to 4E13 protons. The dynamic range for the P1 and P2 beamlines is dependent on the cycle. For the fixed target or antiproton production, cycles it should integrate from 1E10 to 4E13 over a 10 microsecond beam pulse. For Collider cycles, the dynamic range must be from 1E9 to 3.3E11 protons per bunch. On resonant extraction cycles the intensity range is from a few E4 to a few E5 protons/bunch. The intensity monitors for the P3 beamline are only used during resonant extraction. In addition, a high-gain intensity monitor capable of measuring the low intensity 53 Mhz bunch structure present during resonant extraction is required in P1 to monitor spill structure during slow extraction. The A1 beamline monitors require an intensity range of only 1 to 4E10 for measurement of 150 GeV/c antiproton bunches for injection into the Tevatron.

Beam Profile Monitors

Instrumentation should be provided to measure the transverse profiles of the beam on a bunch-by-bunch basis in both the FMI ring and the transfer lines. On the Collider injection cycles, careful attention must be paid to preservation of transverse emittance. Therefore, the dedicated profile monitors in the P8 beamline for transverse emittance measurements should utilize nondestructive techniques. Additional wire grid type profile monitors in the transfer lines as well as the FMI ring will provide information on matching between the beamline and accelerator. These additional monitors are less critical for preserving emittance as they will generally be used as a diagnostic tuning aid rather than as a monitor during Collider injection cycles. The capability for measuring transverse profiles as a function of time in the FMI ring should be provided. Additionally, a provision for determining the transverse beam distribution of the circulating and slow spill beam just upstream of the first extraction Lambertson should be provided.

Instrumentation should be provided to measure longitudinal profiles of any set of selected bunches on a turn-by-turn basis. This requires detector and electronics capable of resolving bunch lengths of 2-15 nanosec. Depending on the triggering and signal processing, this data may be uitlized in many ways (i.e. viewed on a mountain range scope to monitor coalescing efficiency, storing longitudinal profiles for a single bunch over many turns, or integrated for bunch intensity information).

Several types of transverse profile monitors (single wire and wire grid) are used at Fermilab. These include a charge integration multiwire system used in the 8 Gev line and Main Ring , a secondary emission (SEM) multiwire system developed for the Antiproton Source[9], a segmented wire ionization chamber system (SWICS) for use in the Switchyard for slow spill[10], and a Flying wire system developed for the Tevatron[11,12] but adapted for use in the Main Ring, Booster, and the Antiproton Source. More recently a residual gas ionization monitor system is being developed as a nondestructive turn-by-turn profile monitor for Booster.[13,14]

Since the beam sizes in the FMI are roughly 60% smaller than the Main Ring, utilization of the current Main Ring flying wire system for use in the FMI is appropriate. The development of the residual gas ionization monitor in Booster should be watched closely for potential utilization in the FMI and beamlines. The requirements for the FMI beamline profile monitors (wire grids) used for matching are not significantly different than the existing monitors in use. Detailed specifications on monitor type, active area, wire spacing, resolution, etc. have not yet been tabulated for individual beamline monitors. However, from an operational point of view the standardization wire controllers with existing systems will be an important weighting factor.

Dampers

A transverse bunch-by-bunch beam damper system is required in each plane. These systems will be required to provide injection oscillation damping for both protons and antiprotons. They should provide sufficient damping for coherent instabilities arising at any energy. They should provide the capability of knocking out selected bunches. This feature is particularly useful during the Collider injection cycles for removing "satellite bunches" adjacent to the coalesced bunch. Another feature that should be provided is the ability to transversely heat selected bunches in either plane for tune measurements. Many of these features exist in the current implementation of the Tevatron transverse bunch-by-bunch damper system.[15] This should serve as a model for the FMI damper system.

The emittance growth due to steering errors has been investigated for both proton and antiproton injection into the FMI.[6] To limit the normalized transverse emittance dilution to 1π-mm-mr, the injection oscillations due to steering errors need to be limited to less than ± 1.5 mm in both planes. Injection steering errors amplitude should be damped much faster than the decoherence time with moderate values of chromaticity. Estimates of decoherence time due only to chromatic effects ($\xi = \pm 10$) gives a $1/e$ time of .5 msec.

To specify damper requirements for the damping of instabilities, estimates for the growth time and threshold for various instabilities must be calculated for both the Main Ring and FMI and measured in the Main Ring. Several estimates for the resistive wall instability growth rates have been calculated for the FMI and other Fermilab accelerators.[16,17] Measurements of horizontal coupled-bunch instabilities and characterization of damper gains in Main Ring have been reported.[17,18] Further impedance calculations and measurements and instability growth rate measurements are needed before conclusive parameters for a FMI damper system can be determined. However, simple scaling from Main Ring to the FMI estimates damper gains for the FMI to be a factor of two or more over the current requirements of the Main Ring.[19]

Tune Measurement System

A system for the continuous monitoring of transverse betatron tunes should be provided. This should use a nondestructive technique such as the Schottky detector systems at Fermilab.[20] The Main Injector has a 300 KHz swing in RF frequency which must be tracked by the narrow bandwidth detector and electronics. The full tune spectrum between revolution harmonics should be available for analysing tune spreads due to chromatic effects, transverse coupling, etc. In addition, a system that could lock onto and track the tunes for use in a tune control feedback system should also be provided. Such systems have been developed for the Antiproton Source and Tevatron[20,21] and should be included for the Main Injector.

Scrapers and Pingers

A set of scrapers (H and V) should be provided for the production of small emittance beams to be used in machine studies. These should be located in the P8 injection line. A second set of scrapers could be located in the FMI ring itself to be utilized in machine studies and aid in removing "satellites" around the coalesced bunches (for Collider injection).

A fast diagnostic kicker (i.e. pinger) should be provided as a secondary method of tune measurements and machine studies. Specifications for field strength, rise time and flattop length in terms of physics parameters have not yet been identified.

Summary

The current schedule for completion of the FMI project is during the spring of 1997. Prior to the completion of the FMI, the currently scheduled upgrades[1] (i.e. increasing Linac energy from 200 MeV to 400 MeV, Cold compressors to raise Tevatron energy to 1 TeV, and fast kickers to allow Colliding beams with 36 bunches of protons and pbars) will have been completed. These upgrades will require continual assessment of the current diagnostic equipment and development of new equipment for use in the Main Ring. Therefore, any planned upgrades to existing (or addition new) diagnostic hardware/software for Main Ring should be viewed for future use in the Main Injector.

A preliminary list of diagnostic equipment required for commissioning and operation of the FMI and its beamlines has been compiled. General performance specifications have been presented. The compilation of detailed performance specifications for FMI diagnostics and optimization of diagnostic equipment locations should continue.

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