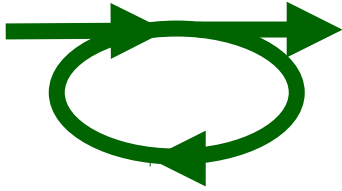


MAIN INJECTOR



MI-BPM-Version-1.0

FNAL Div./Group or Supplier

FNAL MI Department

Date: 26 February 2003

Functional Specification

MAIN INJECTOR BPM SYSTEM UPGRADE + NUMI BEAMLINER BPM REQUIREMENTS

Abstract

This document establishes the functional requirements for the Main Injector Beam Position Monitor system upgrade. The current MI BPM system utilizes 4 detectors per betatron wavelength in both horizontal and vertical planes. At present the MI has 208 BPM for the 3320-meter ring. The associated beam lines have an additional 106 (MI8 line has 64, A1 line has 16, P1 line has 15 and P2 line has 11) BPM. + NuMI Beam line has a total of 26 BPM.

NOTE: THIS DOCUMENT IS NOT THE LAST WORD ON THE MAIN INJECTOR BPM REQUIREMENTS. THE DOCUMENT MAY/WILL EVOLVE AS PER DISCUSSION AND UNDERSTANDING BETWEEN THE MI/RR GROUP AND THE INSTRUMENTATION GROUP.

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1. INTRODUCTION

The Fermilab Main Injector is a synchrocyclotron which accelerates protons from 8.9GeV to 120GeV for, anti-proton production, for low intensity slow resonant proton extraction (slow spill) for test beam to experimental areas, for high intensity slow spill for dedicated kaon experiments, and for high intensity fast single turn extraction for dedicated neutrino experiments (NuMI/MINOS). It accelerates protons from the Booster from 8.9GeV to 150 GeV, and anti-protons from the Accumulator from 8.9 GeV to 150 GeV, for Tevatron injection.

The Main Injector is seven times in circumference (3319.42 meter) of the Booster (474.2m) from which it accepts the protons, and is slightly larger than half the circumference of the Tevatron (2000π meter) to which it transfers both the protons and the anti-protons. The harmonic numbers of the Booster, MI and the Tevatron are 84, 588 (84×7), and 1113 (84×13.25) respectively.

Only six Booster cycles are utilized to fill the MI, allowing rest of the space for the abort gap. Two MI cycles fill the Tevatron.

The Main Injector operation includes protons and anti-protons which circulate in opposite directions in the ring. Protons and anti-protons do not circulate simultaneously in the Main Injector.

The MI operates or will operate in several different modes as discussed below. The number of batches, the number of bunches in a batch, the bunch intensity in the ring and the beamlines varies according to the physics need. The acceleration cycle time varies depending primarily on the techniques used for injection (number of batches and bunches) and extraction.

1. **Loading Tevatron for Fixed Target Mode: Cycle Time 2.0 Sec. – 53MHz** – Six batches of Booster beam are injected into the MI at 8.9GeV. Each Booster batch can contain upto 84 bunches, filling up to 504 MI buckets out of 588. The beam intensity can vary between $0.5E10$ to $12E10$ proton per bunch, to yield a maximum MI ring intensity of $\sim 6E13$ protons. The beam is then accelerated to 150 GeV and transferred to the Tevatron. Two MI cycles fill the Tevatron with twelve intense proton bunches for a maximum Tevatron ring intensity of $\sim 12E13$.
2. **Anti-proton Production Mode: Cycle Time 1.5 Sec. – 53MHz** – A single Booster batch usually with $\sim 5E12$ protons, is injected into the MI at 8.9 GeV. The protons are accelerated to 120 GeV and extracted in a single turn through the P1 beamline for delivery to the anti-proton production target. In future, it is possible that two Booster batches may be injected one after the another in the Main Injector, merged together using slip stacking or some other scheme and higher intensity proton batch may be sent for anti-proton production. In such a scenario the cycle time will be longer than 1.5 sec.
3. **Collider Mode (36 X 36): Cycle Time 4.0 Sec. – 53MHz & 2.5MHz** – This acceleration cycle is used to fill the Tevatron with either 36 bunches of protons or anti-protons. For proton, a group of Booster bunches, usually from 5 to 9 (typically 7), of varying intensity are injected into the MI, accelerated to 150 GeV, coalesced into a single bunch ($\sim 30E10$ ppb) and transferred to the Tevatron through the P1 beam line. Thirty-six MI cycles fill the Tevatron with 36 proton bunches. For anti-proton injection to the Tevatron, 4 groups of upto 12 anti-proton bunches are extracted from the Accumulator and injected into the MI.

These are accelerated to 150GeV, coalesced into 4 bunches (presently $\sim 4E10$ ppb, in future $\sim 11E10$ ppb) and transferred to the Tevatron. Nine MI cycles fill the Tevatron with 36 anti-proton bunches. In future, it is possible to have 12 bunches of beam in the MI at a time, and three MI cycle will be required to fill the Tevatron.

4. **Slow Spill Mode: Cycle Time 2-3 Sec. – 53MHz** – Six Booster batches will be injected into the MI, accelerated to 120 GeV and resonantly extracted during a 1msec to 1sec flat-top. With a ring intensity of up to $1E12$ proton per pulse this mode could be used to deliver low intensity test beam to the experimental areas during the collider operation. In future, with a ring intensity of $\sim 3-6E13$ ppp, this mode can be used for dedicated Kaon physics.
5. **Fast Spill Mode: Cycle Time 1.9 Sec. – 53MHz** – Six Booster batches will be injected into the MI, accelerated to 120 GeV and fast extracted during a $11\mu s$ period. With a MI ring intensity of up to $6E13$ ppp this mode will be used to deliver high intensity fast spill for production of neutrino beam for NuMI/MINOS experiment.

Six different beamlines transport beam to and from the MI. They are:

1. **MI8 Line: 53MHz beam only** - Transports 8.9 GeV protons from Booster to MI.
2. **P1 Line: 2.5MHz & 53MHz beam** - Transports 8.9 GeV anti-protons from Accumulator to the MI, transports 150 GeV protons from MI to Tevatron, transports 120 GeV protons for anti-proton production, and transports 120 GeV slow spill to P2 beamline
3. **A1 Line: 53MHz beam only** - Transports 150 GeV anti-protons from the MI to the Tevatron. It can also be used for reverse proton from Tevatron to MI.
4. **P2 Line: 2.5MHz & 53MHz beam** - Transports 120 GeV beam for anti-proton production from P1 to existing AP1 beamline, and transports 120 GeV slow spill from P1 to P3 beamline.
5. **P3 Line: 53MHz** - Transports 120 GeV slow spill to Switchyard and the fixed target area.
6. **NuMI Line: 53MHz** – Will transport 120 GeV protons for NuMI/MINOS neutrino production.

The main injector will accelerate protons and anti-protons with varying intensity and cycle times. This requires the BPM instrumentation to switch between single bunch to multi-bunch, to multi-batch measurement with very different beam intensity from cycle to cycle.

The Main Injector has four BPM detectors per betatron wavelength in both the horizontal and the vertical planes. There are a total of 208 BPMs for the 3320 meter ring. Out of these, 203 are MI style ring BPM, and are located in the downstream end of every MI quadrupole. The other 5 are wide aperture BPM, and are adjacent to the Lambertson magnets. The wide aperture BPMs are located at Q101, Q402, Q522, Q608 and Q620 locations.

The associated beamlines have an additional 106 (MI8 beam line has 64, the A1 beam line has 16, the P1 beam line has 15, and the P2 beam line has 11) BPM. The P3 beam line BPM will not be discussed in this document and the NuMI line BPM's will be discussed in a separate section.

The ring BPM is formed from four transmission line strips, or strip-lines, located on the perimeter of the beam pipe. It is elliptical in shape with long face 4.625"(11.7cm) and short face 1.9"(4.8cm) in aperture. It has a characteristic impedance of 50Ω which is determined by the strip and the beam pipe dimensions. The RF module input impedance is matched to 50Ω within a 5 MHz bandwidth centered at 53MHz. The outputs are combined in pairs externally to form either a horizontal or a vertical detector. Each strip-line is shorted at one end and connected to a ceramic feed-through at the other end, which makes these BPMs non-directional. At present any BPM measures either the horizontal or the vertical position per cycle at each quads. It can be easily switched to the orthogonal mode.

The large aperture BPMs with 6" long plates and a 4.625" aperture, are located adjacent to the Lambertson magnets and require large aperture detectors mounted external to the quadrupole.

This document specifies the required functionality and performance of the Beam Position Monitoring system for the MI Ring, MI8, A1, P1, P2 and NuMI beam transport lines to support machine commissioning, operation, and diagnostics.

NOTE: This section has been generously taken from "Fermilab Main Injector – Technical Design Handbook", and from MI-Note-76,(1992) "Instrumentation Requirements for the Fermilab Main Injector", by D. E. Johnson, and modified with the latest information.

2. BEAMS IN THE MAIN INJECTOR AND TIME STRUCTURES

At any particular instance of time there will be only one kind of beam in the MI. It will be either proton or anti-proton. Proton and anti-proton do not circulate simultaneously in the MI. The beam energy will vary between 8.9 GeV to 150 GeV. The time structure of the beam will be:

1. 53 MHz - Protons or anti-protons. Up to 84 bunches in successive 84, 53MHz buckets (19ns apart). The full width per bunch varies between 1ns to 19ns. Bunch length range from a gaussian sigma of 0.3ns to 5ns. 0.3ns is expected near the transition, and 5.0ns is for a single coalesced bunch. The range includes a single coalesced bunch, short batch (between 5-13 bunches), long batch (~84 bunches), and multi-batch (6 batches) operation.
2. 2.5 MHz - Protons or anti-protons. 1 to 4 bunches in successive 1 to 4, 2.5MHz RF buckets (396 ns spacing). Bunch lengths range from a gaussian sigma of 25ns to 50ns.

3. DYNAMIC RANGE AND MEASUREMENT PRECISION

The BPM system is required to measure the position and the intensity of the proton beam and the anti-proton beam. The "dynamic range" for different possible beams

scenarios in the MI and the precision associated with the measurement is given below in two tables.

"DYNAMIC RANGE" FOR DIFFERENT BEAM SCENARIOS IN THE MI"

1.	Protons or anti-protons to/from the RR, and the anti-protons from the Accumulator (2.5MHz)	0.5E10/bunch (2.0E10 total) to 7.5E10/bunch (30E10 total). $\sigma(t) = 25\text{ns to } 50\text{ns.}$
2.	Protons from the Booster (53MHz) (19ns spacing)	From 1 to 84 bunches. Minimum Intensity = 0.5E10/bunch. Maximum Intensity = 12E10/bunch. Number of batches = 1 to 6.
3.	Protons to the Tevatron (5-9 bunches, typically 7) (53 MHz, 19ns spacing)	Up to 30 Booster bunches for tune up. Each bunch with intensity between 1-12E10. For Collider running – up to 6E10/bunch or 30E10 after coalescing. (27E10 – TeV Run IIB Document).
4.	Anti-protons to(from) the Tevatron. (53 MHz bunch in 2.5MHz spacing)	36 single bunches, 4 bunches each in 9 separate batch (4X9), each bunch with intensity of $\leq 15\text{E}10$ (5E10). (10E10 – TeV Run IIB Document).
5.	Fixed Target Running (including NuMI/MINOS) (53MHz, 19ns spacing)	0.5E10 to 12E10 per bunch for 50-504 bunches.

The BPM system should be capable of measuring the beam position with 6 batches in the MI.

MEASUREMENT PRECISION OVER THE FULL DYNAMIC RANGE

This is a 3σ (sigma) requirement on the precision over the full dynamic range. It implies that 99.73% of the measurements should be within these limits.

Position Accuracy – $0.40\text{mm} \pm 5\%$ of the actual position.

Difference between two measurements on pulses with stable beam. It covers long term stability and resolution.

Calibration Precision – $0.20\text{mm} \pm 1.25\%$ of the actual position.

4. MEASUREMENTS

The following three measurements – FLASH, CLOSED ORBIT, and TURN-BY-TURN (TBT), are needed to understand the beam behaviour in the MI. The data from these measurements will be written in separate buffers for every MI reset.

4.1 FLASH MEASUREMENT

A FLASH mode measurement is the single turn measurement of the beam position at each BPM location in the ring (or in a transfer line). Flash measurements are particularly important for observing the first turn of the injected beam or the last turn before extraction.

At present, a MI reset initiates a FLASH measurement. FLASH data is transient, over-written by the next FLASH data for any MI reset. The system in general is self-triggered (beam intensity threshold). It does not have a beam-synch clock based trigger for all the measurements. But for FLASH, it has been made to work with beam synch clock based trigger.

In the proposed system, we expect the system to be triggered using a MI beam synch clock event. A FLASH measurement shall be initiated and triggered by a MI Beam Synch Clock event. Data will be collected at a delay from the turn marker specified by the set-up configuration. FLASH data shall be transient, over-written by the next FLASH data, for the same MI reset.

4.2 CLOSED ORBIT MEASUREMENT

A CLOSED ORBIT mode measurement is the measurement of the machine's closed orbit position at each BPM. It shall be obtained by averaging a programmable number (1 to 256) of FLASH mode measurements at each BPM location in the ring. At present, the closed orbit measurement averages between 8 to 64 turns.

At present, a MI reset initiates a CLOSED ORBIT measurement. CLOSED ORBIT data is transient, over-written by the next CLOSED ORBIT data for any MI reset.

In the proposed system, we expect the self-triggered nature of the system to be preserved. We also expect the new system to be triggered using a MI beam synch clock event. A CLOSED ORBIT measurement shall be initiated and triggered by a MI beam synch clock event. Data will be collected at a delay from the turn marker specified by the set-up configuration. Closed orbit data shall be transient, over-written by the next orbit data, but for the same MI reset.

4.3 TURN-BY-TURN (TBT) MEASUREMENT

A Turn-By-Turn mode measurement is the measurement of beam position at each BPM location on the same turn for 1 to 2,048 successive turns. It should be possible to read any subset of turns.

At present, the system has two buffers each with a length to accommodate data for 8,192 consecutive turns. Thus, one can write data for 16,384 consecutive turns for the TBT measurement. A FLASH measurement may be implemented as a special case of a TBT measurement.

At present, a MI reset initiates a TBT measurement. TBT data is transient, over-written by the next TBT data for any MI reset.

In the proposed system, we expect the self-triggered nature of the system to be preserved. We also expect the new system to be triggered using a MI beam Synch Clock event. A TBT measurement shall be initiated and triggered by a MI Beam Synch Clock event. Data will be collected at a delay from the turn marker specified by the set-up configuration. The TBT data shall be transient, over-written by the next TBT data, but for the same MI reset.

5. MEASUREMENTS REQUIRED FOR EACH BEAM STRUCTURE

5.1 2.5 MHZ BEAM MEASUREMENTS

Capability to obtain FLASH, TURN-BY-TURN, and CLOSED ORBIT type measurements for 2.5MHz beam is required.

FLASH, TURN-BY-TURN, and CLOSED ORBIT type measurements are required for individual bunches of the 2.5MHz beam; one bunch at a time, not all four bunches simultaneously. It will be possible to make measurements with different bunches in four different measurements. There shall also be a mode that provides an average position for the four-bunches. The accuracy requirement applies only to the measurement of the entire four-bunch distribution.

5.2 53 MHZ BEAM MEASUREMENTS

Capability to obtain FLASH, TURN-BY-TURN, and CLOSED ORBIT type measurements of this beam are required.

FLASH, TURN-BY-TURN, and CLOSED ORBIT type measurements are not required for individual bunches of the 53MHz beam; however, sufficient signal bandwidth and sample time adjustment shall be provided to observe position changes on the time scale of twenty-one of the eighty-four bunches. There shall also be a mode that provides one "centre-of-mass" position for the entire eighty-four-bunch time distribution. The accuracy requirement shall apply only to the measurement of entire eighty-four-bunch distribution.

5.3 BEAM INTENSITY

Every BPM shall provide a measure of the magnitude of the common mode signal ("sum signal") called "beam intensity". BPM-to-BPM scaling capability shall be incorporated so that relative location-to-location beam intensities can be determined to a precision of $\pm 5\%$ on a FLASH, CLOSED ORBIT, and TBT measurements. It will allow:

1. To diagnose the position of the beam loss.
2. Can also be used as a useful cross-check on the validity of the other measurements, and
3. Can be used to diagnose the non-functioning BPMs.

6. DATA BUFFERS

At present there are five separate data buffers. They are:

1. FLASH Frame Buffer
2. SNAPSHOT Buffer
3. PROFILE Buffer
4. DISPLAY Buffer, and
5. Turn-by-Turn (TBT) Buffer

Every time a MI reset occurs the data buffers gets over written. The data buffers will be described below in detail. **We do not require any major change in the data buffer structure, but we do require that there should exist such a set of data buffers for each MI reset.** At present the MI has 8 clock-events or resets as shown in the table below. We propose to have data buffers for at least 10 MI clock-events as shown in the table. Two extra MI clock-events are proposed for future MI needs, not foreseen today.

MI CLOCK EVENT DESCRIPTION

MI CLOCK EVENT NUMBER	DESCRIPTION
20	Antiproton Deceleration
21	Switchyard
23	NuMI
29	Antiproton Stacking
2A	Collider Antiproton
2B	Collider Proton
2D	8 GeV Beam. RR/Pbar tune-up.
2E	STUDIES
SPARE (2)	For FUTURE

6.1 FLASH FRAME BUFFER

It contains a single turn position and intensity measurement of the beam at all the BPMs. This is needed to look at:

1. First turn after the injection,
2. Last turn before the extraction, and
3. Any turn for possible perturbation.

The measurement requires a unique timing, which is orchestrated through a beam synch clock. Clock and data information is put in a dedicated FLASH buffer. The data in the buffer is replaced with new data each time a new injection or extraction event is issued.

At present 14 FLASH frame buffers, and 13 FLASH trigger exists as shown in table below. In the proposed system, we do require at least 10 FLASH buffers.

For FLASH measurement, a sample of beam must be measured at each BPM location as it moves through the ring. There exists beam synch clock event for different purposes including for injection and extraction kickers. A delay set by a CAMAC card (T-clock event) waits for a specified number of turns before triggering the BPM. After the delay is complete, a FLASH trigger fans out simultaneously to all the service buildings. Local delays (internal to the BPM processor) are implemented at the service buildings to ensure that the trigger arrives precisely when the sample of beam is passing through the BPM.

FLASH TRIGGER DESCRIPTION

Name of the FLASH TRIGGER	Number
Booster → Main Injector	BEX
Main Injector → Debuncher	\$79
Main Injector → TeV Fixed target	\$78
Main Injector → Tev (Proton)	\$7C
Tev → Main Injector (Proton)	\$D8
Main Injector → TeV (Anti-proton)	\$7B
TeV → Main Injector (Anti-Proton)	\$D6
Main Injector → Accumulator at 8GeV	\$7E
Accumulator → Main Injector	\$7A
Main Injector → Recycler (Proton)	\$A2
Recycler → Main Injector (Proton)	\$A3
Main Injector → Recycler (Anti-proton)	\$A0
Recycler → Main Injector (Anti-proton)	\$A7

6.2 SNAPSHOT BUFFER (CLOSED ORBIT)

At any instance in time this buffer contains the most recent 512 sets of averaged position data in 512-snapshot data frames. The buffer is a circular buffer, and entry 0(zero) is the most recent entry. The SNAPSHOT frames do not need to be timed quite as stringently as FLASH. At present, the BPM signals are averaged over several turns (typically between 8 and 64 measurements), before being put into a frame. The data for the next frame is usually taken after several milliseconds. **We recommend that the BPM signals be an average of a programmable number between 1 to 256 turns.**

The primary purpose of this buffer is for abort analysis as the buffer stops being written at the end of each abort. The buffer also freezes at the end of a beam cycle saving the last set of data.

This buffer may prove useful in case of possible NuMI accidents.

6.3 PROFILE BUFFER (CLOSED ORBIT)

The profile buffer contains up to 128 snapshot data frames taken from the snapshot buffer, and are spaced at intervals chosen by the user. The buffer refreshes once every cycle. These 128 frames are written when the 'profile clock event' is decoded by the BPM. When the first profile clock event occurs, the BPM processor retrieves the most recently written snapshot data from the snapshot buffer (both position and intensity) and copies it to the profile buffer the pointer points to. Pointer begins to increment at this stage.

The profile buffer is used to measure/understand the "closed orbit" of the machine and also as an input for the "orbit correction" program. It can also be used to understand the history of the acceleration cycle. Profile buffer is not used for aborts.

6.4 DISPLAY BUFFER

The display frame buffer is a single snapshot data frame buffer written after the BPM decodes a 'write display frame'. When this event occurs the most recently written snapshot frame from the snapshot buffer (position and intensity) is copied to the display frame buffer.

A display frame buffer can be selected once every machine cycle and displayed for every pulse. It refreshes once every cycle.

6.5 TURN-BY-TURN (TBT) BUFFER

In the MI, a TBT buffer exists for every single BPM. At present, the TBT buffer for each BPM contains the data for up to 8,192 consecutive terms. There are two such buffers, so that data for 16,384 consecutive turns could be written. The TBT data mode is the highest priority and pre-empts all other data acquisition mode.

The present length of the data buffer is a historical legacy from the days of Main Ring. It is definitely not a necessity but in the Main Ring days, there were several occasions when the beam would fall out while being accelerated at slightly varying times. One of the speculations for a cause was a sparking turn-by-turn fault in a quadrupole, which would cause a tune shift. The turn-by-turn data (with 16,384 long buffer) was a good way to look for that. It is not the only way and it may not justify the cost of such a large buffer (16,384), if the cost is significant. If the cost is small, it could be very useful, and if the software supports looking at the data easily.

For the upgraded system, we require that the TBT data buffer must be at least 2,048 deep. This is required to measure the tune with a precision of 10^{-3} .

7. NUMI BPMS

1. The NuMI beam line will have a total of 26 BPMS. There are:
 - A. One large aperture BPM with 6" long plates, and 4.625" aperture at Q608 near Lambertson.
 - B. 21-split pipe BPM called the transport BPM. The outer and inner diameter of the split pipe is respectively 4" (10.1cm) and 3.875" (9.8cm – aperture).

- C. 4-split pipe BPM called the target BPM. The outer and inner diameter of the split pipe is respectively 2.125" (5.4cm) and 2" (5.1 cm – aperture).
2. The position accuracy and the calibration requirements for the transport and target BPM differ (as shown in the table below).
 3. Every BPM needs to measure the beam position individually for each batch of the proton beam.
 4. For at least one house (for the 4 target BPM), the BPM system should be capable of making multiple measurements within at-least one batch of the proton beam on every pulse.
 5. NuMI/MINOS proposes to use HELIAX cable for signal transmission, to avoid cable dispersion. With only 26 BPMs, cost is not a major factor.

7.1 NUMI BPM SPECIFICATIONS (3 σ REQUIREMENTS)

This is a 3 σ (3 sigma) requirement on the measurement precision for individual batches of protons over the full dynamic range. It implies that 99.73% of the measurements should be within these limits as defined in the table below.

	Transport BPM (particle/bunch)	Target BPM (particle/bunch)
Position Accuracy	0.50mm@1.0E10 1.00mm@0.5E10 (Over ± 20 mm)	0.25mm@1.0E10 0.50mm@0.5E10 (Over ± 6 mm)
Calibration Accuracy	0.20mm@1.0E10 0.25mm@0.5E10 (Over ± 20 mm)	0.10mm@1.0E10 0.15mm@0.5E10 (Over ± 6 mm)
Intensity Precision	$\pm 5\%$ for Position Measurement $\pm 2\%$ for Calibration	$\pm 5\%$ for Position Measurement $\pm 2\%$ for Calibration

7.2 NUMI BPM PRECISION

The precision for "transport BPM" comes from the beam control requirements based on previous usage of "Auto tune" beam control, as to be used for the NuMI beam line. For example, the corresponding numbers for some experiments were:

1. Switchyard system - activates tuning for 0.4 mm deviation from nominal (0.2 mm for septa line-up); then, correct to < 0.2mm (0.1 mm) accuracy.
2. KTeV (With a very large targeting optics magnification) - activate for 1.0 mm deviation along the transport (0.05 mm deviation at target).

In each case the required precisions were determined initially from detailed calculations of error functions using transport matrices, and finally verified in the beam operation.

The precision for "target BPM" comes from MINOS target width of 6.4mm and the upstream baffle beam hole diameter of 11mm.

8. NUMBER OF BPMS TO BE MODIFIED (NOT INCLUDING NUMI)

The MI ring has a total of 208 non-directional BPM. Out of these, 203 are MI ring BPM and 5 are large aperture BPM. Electronics and readout needs to be modified for each one of these BPM.

The associated beam lines have 106 BPM (MI8 line – 64, A1 line – 16, P1 line 15, and P2 line 11). The electronics and readout also needs to be modified for these BPM. For the beam line BPM all single pass (FLASH) mode specification requirement for MI ring BPM must be met.

TRANSFER LINE EXISTING BPM PROPERTIES

	TRANSFER LINE	BPM DESCRIPTION	ELECTRONICS & FRONT-END
1.	MI8	MI8 style split-pipe round BPM.	Uses an AD640 log-amp. Sample and hold, & MADC.
2.	A1	MI8 style split-pipe round BPM.	Uses an AD8307 lag-amp. Recycler front-end. [Being replaced with modified log-amps].
3.	P1	MI8 style split-pipe round BPM.	Uses an AD648 lag-amp. Recycler front-end. [Being replaced with modified log-amps].
4.	P2	MR style split box rectangular BPM	AM to PM system, and MI style multi-bus crate.

Large aperture BPM is used at Lambertson in all of these beam lines.

The existing system must be maintained until replaced by the system specified by this document. Designated representatives of the MI/RR and Instrumentation Departments shall coordinate installation, integration, and commissioning of this new system. After the new system is fully operational, remaining parts of the old system shall be maintained until the MI/RR Department decides those parts should be declared un-necessary.

9. SYSTEM CALIBRATION (ABSOLUTE BPM CALIBRATION)

A calibration system must be provided to allow the required position and intensity precision as defined earlier to be verified and maintained.

This system shall provide means to check and calibrate hardware from the BPM to the front-end electronics in the service buildings, to testing the software, and to store calibration data in a user-friendly manner.

The calibration system must be capable of delivering an equivalent charge (as discussed in the "Dynamic Range" table) to the BPM electrodes to simulate positions of -20mm, 0mm, and +20mm to be read out through the entire chain.

Accuracy of the calibration system must be adequate to assure position accuracy of $0.20\text{mm} \pm 1.25\%$ of the actual position, for the position measurement precision and $\sim 2\%$ in intensity.

10. BPM FRONT-END FUNCTIONALITY

In general the functionality of the front-end should be similar to the existing front end, **except that the new system will be a multi-user system, a multi-buffer system, and will be self-triggered (beam intensity threshold based trigger) as well as beam-synch clock based triggered.** In order to make measurements, the system will generally need to know the following information:

10.1 INPUT PARAMETERS

- a. Beam Type: Proton or Antiproton beam
- b. Measurement Type: CLOSED ORBIT, TBT, or FLASH. TBT will be the default mode.
- c. Time Structure of the Beam: 53 MHz and 2.5MHz.
- d. Number of Turns: CLOSED ORBIT average, TBT total number.
- e. Trigger Information: MIBS event & delay, house delay, & BPM delay - The house delay and the BPM delay can probably be independent of measurement type, but the MIBS event and delay will depend on the measurement type.

10.2 MEASUREMENTS

The system is expected to be prepared to make any measurement in more than a single mode at one time. The system is expected to support multiple users (more than one application program at a time) and multiple MI resets. The FLASH, Closed Orbit and the TBT modes are event triggered by MI beam-synch clock events or by intensity threshold based trigger. The system is expected to follow the sequence of trigger in data-acquisition. The trigger timing separation will be decided by the hardware and software requirements of the system.

10.3 READBACK

The system should provide read back of all settable parameters as well as detailed status information. Measurement data consists of position and intensity information for each BPM. Each buffer shall also contain the relevant measurement parameters and appropriate timestamp(s) to identify the data. It shall be possible to read only portions of the data including: position or intensity data only, one turn or a range of turns of TBT data, and measurement parameters only.

11. APPLICATION SOFTWARE

Our effort is to minimize the need of new software required by adopting the present software as much as possible. The major changes that we need are:

1. Separate data buffers for FLASH, TBT, SNAPSHOT, PROFILE, and DISPLAY mode for each individual MI reset.
2. Closed orbit measurement for programmable number of turns.
3. A simple to use test of the integrity of the system. A combination exercise of the calibration and a list of non-functioning BPM.
4. Intensity

12. SCHEDULE

We would like the new system to be fully functional by the end of FY2003. We would like first the MI ring BPM to be replaced, followed by the beam line BPM.

NuMI time frame is independent of the MI needs. If for any reason, the MI BPM modification gets delayed which we don't expect, the NuMI BPM must be ready by the end of FY2003.

13. SUMMARY

The MI BPM electronics, and the front-end readout need to be replaced to meet the scientific demands on the MI, and for the coordinated improved performance of various accelerators at the Fermilab.

The DOE review committee has asked for it.

The Physics requirements have been laid out in great detail in this document.

So, lets have the system ready by the end of FY2003, or at the earliest possible with a tested technology available in the market.

14. APPENDIX:

14.1 WHY DO WE NEED A PRECISION BPM SYSTEM?

1. To reproducibly centre the orbit in the physical aperture of the machine, thereby maximizing acceptance.
2. To verify stable orbit position from day to day, ensuring stable tuning conditions.
3. To have an accurate turn-by-turn (TBT) lattice measurement.
4. To understand geometrical and optical defects in the ring in terms of a calibrated geometrical survey.
5. To understand and interpret the results of beam experiments which are expected to produce static or transient beam orbit changes (pinging, orbit bumps, synchrotron oscillations etc.)

6. To monitor and adjust the beam position in the injection and extraction lines, and the single turn orbit between the lambertson and the kicker in the ring.
7. To independently measure orbit closure and injection oscillations.

14.2 WHY AN UPGRADE?

The MI BPM electronics and front-end should be upgraded for the following reasons:

1. Present MI BPM electronics is blind to 2.5MHz time structure. It is also unreliable for position measurement of a single coalesced 53MHz bunch, as well as for fewer than 20-30 bunches of 53MHz beam.
2. The system is quite limited. It is essentially a single user, single buffer system. The stored data gets overwritten when the next valid MI reset occurs.
3. The computer interface is a multi-bus based system with an 8-bit ADC.
4. The system has limited resolution (beyond $\pm 10\text{mm}$) because of the non-linearity of the AM to PM detection, the BPM geometry and the 8-bit ADC used in the present electronics.
5. The firmware is written in Z80 machine code, which is now obsolete. Only one person (Alan Baumbaugh) at the laboratory is familiar with the code. About ~ 15 years ago, Sharon Lackey used the then existing TeV code from Alan Baumbaugh and modified the software to work for the switchyard BPM. At that time no TBT utility existed in the TeV code. She is familiar with that part of the code and if it is really needed she can be called to help.
6. The control interface is in GASP, an obsolete protocol that is being phased out by the Controls Department. This is also one of the motivations for the switchyard BPM upgrade.
7. The system is self-triggered (beam intensity threshold). It does not have a general-purpose beam synchronised clock based trigger. For FLASH only, it has been made to work with beam synch clock.
8. The system is more than 20 years old. The system is approaching its end-of-life and one can expect increasing failure rates. Some spare parts are no longer commercially available.

14.3 SYSTEM RESOLUTION

The design system resolution is given as shown below.

Beam Position	Horizontal (μm)	Vertical (μm)
$\leq \pm 5\text{mm}$	$\sim 100\mu\text{m}$	$\sim 150\mu\text{m}$
$5\text{mm} \leq x \leq 10\text{mm}$	$\sim 150\mu\text{m}$	150-200μm
$10\text{mm} \leq x \leq 15\text{mm}$	200-300μm	200-300μm
$15\text{mm} \leq x \leq 20\text{mm}$	300-600μm	300-600μm
$\geq \pm 20\text{mm}$	1-4mm	-----

The measured resolution for beam positions $\leq \pm 5\text{mm}$ varies between 50-150 μm . The new system should preserve this resolution.

14.4 SPARE PARTS AVAILABILITY

It is possible that at some stage there will not be sufficient spare parts available to fix the old system, as it slowly degrades. Since the system is ~ 20 years old, some of the spare parts are no more manufactured. For example:

1. There are about 24 spare RF modules. This particular RF module is used both in the MI and the Tevatron. One RF module is needed for each BPM. Inside the RF module there are matched filters, limiters and resonators.
 - i. The filters are available and are not a problem at this stage.
 - ii. The vendor does not produce the limiters anymore. We lose about 2-3 limiters every year. The failed limiters cannot be fixed. There are no spares outside the spare RF modules.
 - iii. There are no spare resonators, but the FNAL engineers can make the replacement if needed.
2. The clock-chip that decodes the MI event, although don't fail regularly, could be a problem. There are hardly 100 spares available. New clock chips (~ 100) have been bought and will be tested. Although it is not a problem at this stage, it could be a problem if one wishes to add more MI clock events in the future.
3. The power supply failure rate is about 10/year or $\sim 5\%$ fails/year.

14.5 MULTI-BUS SYSTEM

This section gives a brief oral history of the multi-bus system as learnt after talking to Alan Baumbaugh, Mark Averett, Paul Kasley, and Sharon Lackey.

Carl Wegner from Research division designed the multi-bus system around 1980. It became operational either in 1981 or 1982. Thus the system is more than 20 years old. Alan Baumbaugh worked on the firmware. He also designed the first turn-by-turn card.

The person who inherited the system from Carl Wegner was transferred. The person who inherited next left the laboratory. Bob Marquard inherited it next. He retired. Mark Averett inherited it from Bob. He is in-charge of the system. Paul Kasley is his boss.

The system is not very robust. One of the in-house built cards in the system fails frequently. Some spares are left, and the system can be made to work while the spares last. There may be programmable parts in the system, which are not available anymore.

There are not many experts on the system left at the laboratory. Alan Baumbaugh has been called to consult on the system. He has helped maintain the system for last twenty years but he cannot spend 100% of his time on supporting the system. Also as the time passes the memory is getting sketchy, and it takes longer to find the problem than to fix it.

Recently Roger Tokarek called a few meetings to understand and discuss errors observed related to the TBT card. Someone who is no longer at the laboratory developed these cards. Most of the people are not very familiar with the errors observed. It is getting more difficult day by day to fix the problem.

According to Alan Baumbaugh, the system could at most last five more years with increased support. Getting really hard to maintain the system.

14.6 UPGRADE PROPOSAL (WHAT IS NEEDED)

The BPM system should have the following characteristics:

- a. The MI BPM electronics should be functional at 2.5MHz, and 53MHz time structure. It should be reliable for position measurement either with a single Booster bunch, or a single coalesced bunch (53MHz), as well with multiple bunches, and multiple batches in the MI.
- b. The system should be multi-user and multi-buffer, so that different type of data can be taken during the same MI cycle, and the data taken with a particular MI reset does not get overwritten with data taken with other MI resets. For example, during simultaneous NuMI/MINOS and collider operation, one may like to take FLASH data for anti-proton production on cycle 29, and monitor the NuMI/MINOS beam on cycle 23.
- c. Attenuation due to varying cable lengths, limits the "dynamic range" of the system and thus detection of small bunch intensities. Gain should be adjusted to account for this variation.
- d. The system should at user option, be self-triggered (beam intensity threshold), as well as triggered with beam-synchronised clock.
- e. The present (old) multi-bus based system with an 8-bit ADC computer interface should be replaced by a modern and better supported architecture (for example with a VME contained system) using for example a 12/14 bit ADC for a bit resolution of $\sim 50\mu\text{m}$.
- f. The multi-bus system should be replaced for faster data throughput.

14.7 JUSTIFICATION FOR THE DYNAMIC RANGE

- a. $2E10$ total – anti-protons – 2.5 MHz - requires $3E10$ anti-protons, a reasonable number to use for tuning and pilot shots, given the stacking rate.
- b. $30E10$ total – anti-protons – 2.5 MHz - maximum anti-protons extracted from the Accumulator without degrading emittances.
- c. $0.5E10/\text{bunch}$ – protons – 53 MHz – for test beam and NuMI commissioning.
- d. $12E10/\text{bunch}$ – protons – 53 MHz – with ~ 80 bunches, one gets $\sim 1E13$ protons/batch. One hopes to accelerate $\sim 6E13$ protons with 6 batches in MI, for simultaneous operation of anti-proton production, collider running, NuMI and other possible physics.
- e. $30E10$ total – 53MHz – protons after coalescing for collider running.

14.8 JUSTIFICATION FOR THE MEASUREMENT PRECISION

1. The MI beam pipe is elliptical in shape with long face 117mm wide and the short face 48mm in height. A 1mm beam position error leads to a 10% loss in acceptance.
2. We use orbit difference to study the lattice. The orbit differences are limited to about 3mm to avoid beam losses, and non-linear effects. We need a 5% resolution (sigma should be 5% of 3mm, or 0.15mm) to achieve 10% precision in β measurement. That's why a 3σ -measurement precision requires 0.40mm position accuracy.

14.9 JUSTIFICATION FOR CLOSED ORBIT MEASUREMENT

Closed orbit is defined by the ring magnets and is used to close the injection. Closed orbit measurement is needed

1. To know the beam position in day to day operation
2. To maximise the main Injector aperture, and
3. To control the orbit during energy ramp

14.10 JUSTIFICATION FOR FLASH MEASUREMENT

FLASH orbit measures the deviation of the beam from the closed orbit because of

1. Injection orbit - The first turn usually has the largest oscillation if the machine is not tuned well. Comparing the injection orbit to the closed orbit provides error in injection position and angle
2. Extraction or Last Turn Orbit - To know that when the beam leaves the MI, the ring orbit remains the same and the kicker works.
3. Injection lattice and dispersion function matching, and
4. Fast perturbations of beam for any particular turn

14.11 JUSTIFICATION FOR TURN-BY-TURN (TBT) MEASUREMENT

TBT measurement simultaneously at every BPM is needed

1. To measure the lattice functions of the machine by observing the betatron oscillation caused by a ping.
2. To do higher order driving term analysis, especially to measure non-linear properties of the lattice.
3. To study beam dynamics and coherent instabilities including mode number.
4. To observe evolution of unpredictable events such as sudden beam loss or oscillations.
5. To measure the injection oscillations. A BLT also performs this function, so this will be just a crosscheck.

6. To diagnose kicker related problems on the kicked beam. This could also be understood partly with a BLT.

14.12 LATTICE MEASUREMENT USING TBT & CLOSED ORBIT

Lattice functions can be measured using either TBT or the CLOSED orbit.

1. Turn-by-Turn

- a. Measure alpha (α) and beta (β) lattice function at each BPM.
- b. Get phase advance measurement directly from the TBT data per BPM utilizing the free betatron oscillation. The errors are uncorrelated and systematic free. This is the only known model independent method to measure the phase advance.
- c. The measurement is insensitive to the accuracy of the kick magnitude.
- d. There are few kick sources.

2. CLOSED ORBIT

- a. Measure phase advance and beta (β) lattice function at each BPM
- b. Due to averaging potentially better position resolution
- c. Need a minimum of two kick sources, beta at the kickers and phase advance between them
- d. Systematic errors also include kick strengths and BPM calibration.

14.13 AVAILABLE APPLICATION PROGRAMS

At present the following application programs exists:

1. I37 – Sets the BPM control parameters.
2. I38 - Performs BPM/BLM hardware tests.
3. I39 - Displays measured positions and intensities.
4. I40 – Sets the BLM control parameters.
5. I42 - Displays turn-by-turn measurement. Measures "tune".
6. I49 – 8 GeV line orbit smoothing program.
7. I50 - Orbit smoothing program. Uses data from every BPM to calculate orbit correction and move the beam to the desired orbit position. Calculates magnet changes to smooth the closed orbit.
8. I52 – Orbit correction program. Uses position data to calculate corrections. Capable of reducing first turn oscillations and closing the orbit for the second turn.
9. I53 – BPM rms noise (diagnostic)
10. I90 – Beam line analysis.
11. I92 – TBT data analysis. Calculates α and β functions.

12.D40 – Generic BPM diagnostics used for TeV, MI, and Switchyard.

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