Fermilab/AD/MIBPM
Beams-doc-2732–v4

Main Injector BPM Project Closeout Report

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(For the MI BPM Upgrade Project)

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1. Scope and background

The Main Injector Beam Position Monitor (MIBPM) project concluded in October, 2006. This document provides a general overview of the performance of the project as well as the lessons learned during the project execution. The goal is to use these experiences to improve the execution of similar projects in the future.

This document covers the design, fabrication including integration, installation, and commissioning phases of the MIBPM system upgrade. In the context of this document, system verification and validation activities for the project are generally defined as follows:

The net outcome of the validation process is the assurance from the experts and users of the system that the integrated, installed and commissioned system with hardware and software/firmware and documents:

- Meets or exceeds expectations of users
- Solves the right problems
- Is adequate for the MIBPM system operations team who can conduct routine operations and maintenance

Detailed documents referred here are available on-line:

1. All documents are accessible through Beams-docDb database for Accelerator Division. Document numbers refer to the Beams-doc numbers
2. Large files related to "as built" (http://projects.fnal.gov/MIBPM/wbs/VnV/Asbuilt/) documents including

archived software and firmware file and test data (http://projects.fnal.gov/MIBPM/wbs/VnV/Test_Data/) are archived on the project web site on Fermilab's AFS space..

3. Electronic system configuration files are available at: http://projects.fnal.gov/MIBPM/wbs/VnV/Hardware/
4. MIBPM project related information is available at http://projects.fnal.gov/MIBPM/wbs/index.html

2. Checklist for the closeout review

The following checklist was used to verify that the project is complete. No incomplete issues exist.

Requirements validation

Verify that the system fulfills requirements specified in the MIBPM requirements document (beams-doc-1786-v6, October 24, 2005).

The Main Injector BPM upgrade was completed in October, 2006. Many but not all of the requirements have been achieved and documented. Some have been achieved but not documented. In other cases, there are good reasons to believe that the system meets the requirement. In some cases the requirements were not met because of small signals compared to noise at certain BPM locations. This is likely to be improved by replacements of cables in those locations. The "noisy" BPMs depend on the MI state and the list of noisy BPMS for each state is documented in beams-doc-2838.

A. Measurements required (taken from P.10-15 of the requirements document, beams-doc-1785-v6). The required measurement capability is listed here:

Measurement Modes

- **Wide bandwidth**: one measurement per MI turn.
- **Narrow bandwidth**: measurements averaged over about 100 turns.

Measurement Types

- **Flash Frame**: A single turn orbit measurement, performed in wide bandwidth mode, associated with injection or extraction of beam.
- **Turn-by-turn**: A measurement of the orbit on every turn (588 53 MHz RF buckets) for a specified number of turns, performed in wide bandwidth mode.
- **Averaged orbit**: An average of a specified number of turn-by-turn measurements.
- **Display Frame**: A narrow bandwidth measurement triggered by the display frame TCLK ($7B). This measurement occurs once per cycle.
- **Profile frame**: A narrow bandwidth measurement triggered by the profile frame TCLK ($7A). This measurement can occur up to 128 times per cycle.
- **Fast time plot (FTP)**: a narrow bandwidth measurement taken at least at 500 Hz. FTP measurements for all channels in parallel must be supported.

All of the above are part of the functioning Main Injector BPM upgrade as of October, 2006.

B. Key Specifications (53 MHz bunch structure) (taken from Table 7 of the requirements document, beams-doc-1786-v6):

Measurement Range: +-25mm, +-30mm (large aperture BPM)	
Absolute Position Accuracy: 1.0 mm + 5% of actual beam position	*Likely*[1]
Long Term Position Stability: < 0.2 mm	*YES*[2]
Best Orbit Position Resolution: < 0.05mm ,0.1mm (TBT)	*YES*[2]
Position Linearity: < 1.5% over +-15mm	*Likely*[1]
Relative Position Accuracy: < 5%	*Likely*[1]
Intensity Accuracy: < 10%, 20% (large aperture)	*Likely*[1]

C. Key Specifications (2.5 MHz bunch structure, pbar nominal intensity taken from Table 8 of the requirements document, beams-doc-1786-v6):

Measurement Range: +-25mm, +-30mm (large aperture BPM)	
Absolute Position Accuracy: 1.0 mm + 10% of actual beam position	*Likely*[1]
Long Term Position Stability: < 0.5 mm	*Likely*[1]
Best Orbit Position Resolution: < 0.3mm, 0.5mm (TBT)	*YES*[3]
Relative Position Accuracy: < 10% of actual beam position	*Likely*[1]
Intensity Accuracy: < 20%, 30% (large aperture)	*Likely*[1]

D. Key Specifications (2.5 MHz bunch structure, pbar low intensity)(taken from Table 8 of the requirements document, beams-doc-1786-v6).

Measurement Range: +-25mm, +-30mm (large aperture BPM)	
Absolute Position Accuracy: 1.0 mm + 20% of actual beam position	*Likely*[1]
Long Term Position Stability:	*N/A*
Best Orbit Position Resolution: < 0.5mm	*YES*[3]
Relative Position Accuracy: < 20% of actual beam position	*Likely*[1]
Intensity Accuracy: < 30%	*Likely*[1]

The requirements listed above have either been shown to be satisfied in some very specific measurements or have not been looked at. In general, the system has the capability to make the measurements with the precision required. In many cases it will take more work to disentangle real beam motion from measurement errors and to make corrections for non-linearities or off-axis positions to provide the accuracy and precision required

From note 2157 the resolution is quoted as 3 μm (vertical, closed orbit) and 10 μm (horizontal, closed orbit). These correspond to 9 μm and 30 μm (3 sigma) – better than

[1] The system is likely able to meet the requirements of absolute position accuracy, position linearily, relative position accuracy, and intensity accuracy. This is based on test bench measurements of the pickups, simulations, design criteria and specifications and measurements of the transition boards, cables, and Echotek modules. The final "proof" of the ability to meet the requirements was not done as part of the project and requires substantial additional effort. See beams-doc-1803, 1978, 2153, 2234, 2411 for many of the details.
[2] See beams-doc-2157 for details.
[3] See beams-doc-2536 for details.

the requirement of 50 μm. The repeatability of the measurement is quoted as 3 μm, much better than the 0.2 mm required.

From note 2536 the turn-by-turn resolution (one sigma) is measured to be approximately 200 μm or 600 μm (three sigma). This is approximately equal to the requirement of 500 μm. It is likely that the actual resolution is better than this because the measured resolution contains contributions both from the true BPM resolution and from true beam motion that was not subtracted. In addition the transition board gain had not been set optimally at the time that these measurements were made

3. Overview of System Requirements and Design

Functional requirements of the MI BPM system may be described in three steps:

a) Pick up BPM signals and combine them as necessary using newly designed Combiner Boxes (Fig. 1) from the BPM instrumentation enclosures in the main injector tunnel and transmit them to the seven MIBPM system racks located at seven service buildings, namely MI10, MI20, MI30, MI40, MI50, MI60S, and MI60N.
b) Preprocess incoming signals using the Transition module (Fig. 2) of the MIBPM system before sending them to the digital receiver boards contained in the digital module. This module uses separate frequency selective gain stages to acquire 53 MHz proton signals and 2.5 MHz anti-proton signals.
c) Process signals using the Echotek digital module (Fig. 2) and the front-end software.

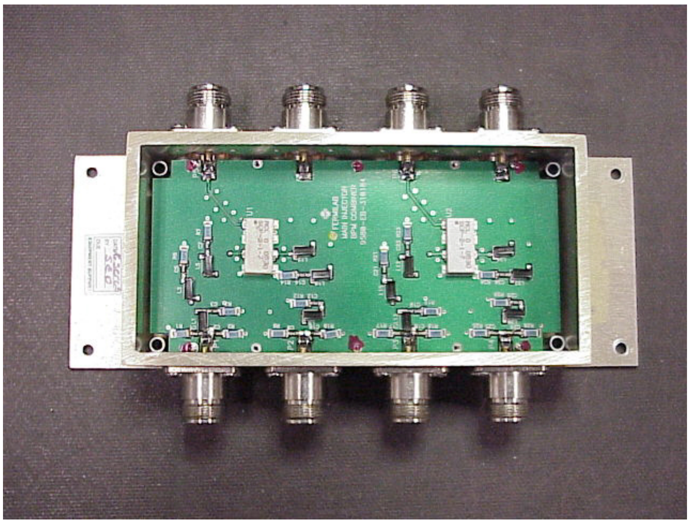

Figure 1: Combiner Module

Each of the seven MIBPM houses contains one analog and one digital module crate, both modules being rack mounted. See BEAMS-docDB#1786 for MIBPM Requirements Specification. A brief description of each of the newly designed and deployed MIBPM system components is given below:

- Combiner boxes: These combiner boxes are used to combine pickup signals arriving at the BPM instrumentation inside the main injector tunnel. These boxes were designed and fabricated in-house using commercial power combiners procured from Mini-Circuits.

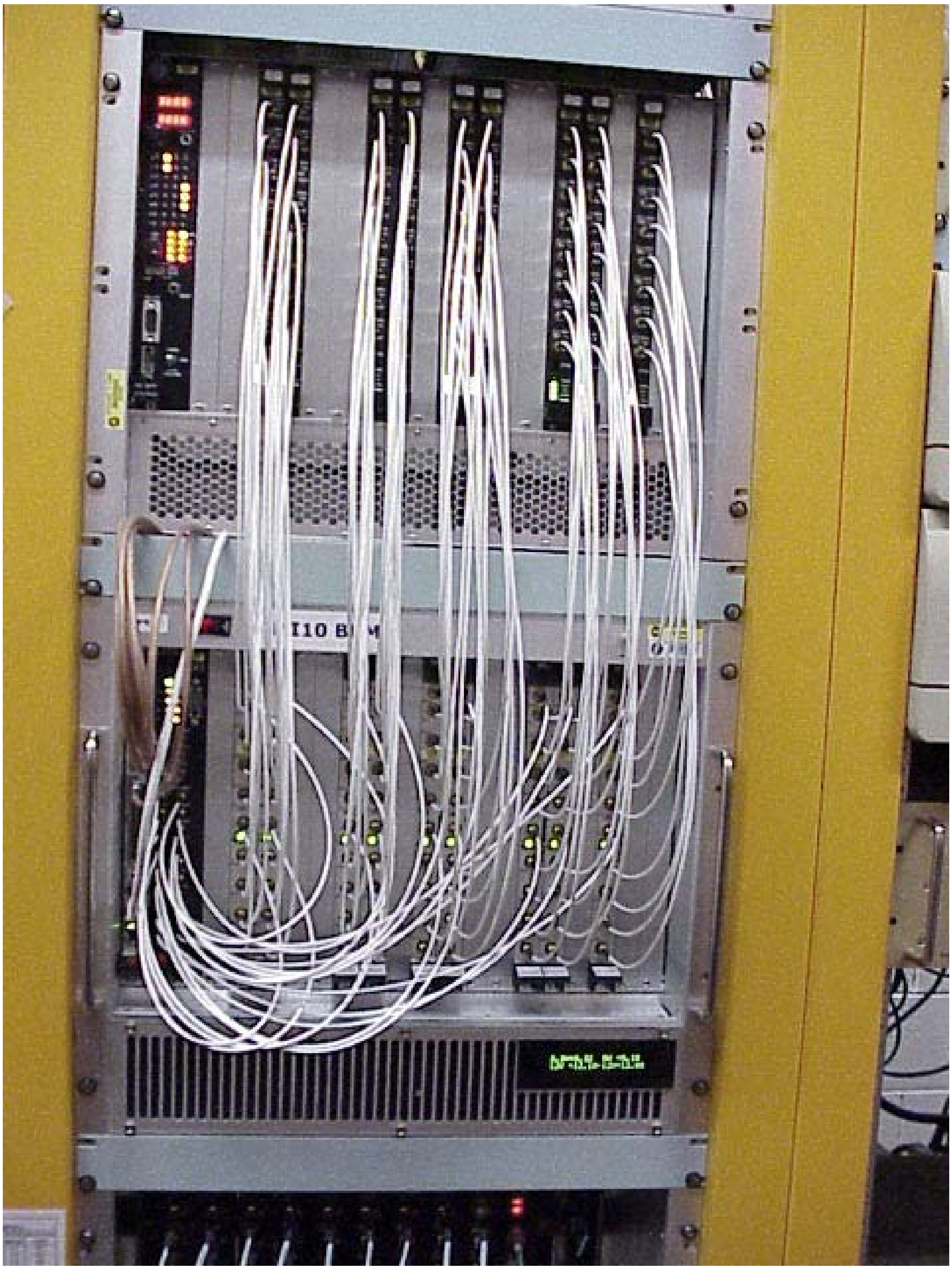

Figure 1: M10 rack with new BPM installed
Transition module crate (top), Digital crate (bottom)

- Analog preprocessing system: Each system contains one Transition Module Controller card and multiple Transition boards. These components are assembled

in a 6U cage with an external power system and custom backplane. BPM signals from the tunnel are transmitted to the transition boards using existing cables.
  - Transition module and controller module: The specification for the controller card is documented in BEAMS-docDb# 2155 and specification for the Transition module is documented in the BEAMS-docDB#1968. The Transition module is designed in-house and fabricated by Lace Technology. Other items were designed and fabricated in-house using procured, off-the shelf equipment.
  - Analog module power supply and power harness: This custom designed component provides power to the Transition modules through a VME backplane. See BEAMS-docDb#2349 for its specification and the Engineering Change Order (ECO) associated with it. This ECO affected the system installation time.

- Digital processing systems: Each system contains
  - One Timing Generator Fanout (TGF) module. See BEAMS-docDb# 2083 for details of this module. Most of the design work for the TGF module was done during the Tevatron BPM Upgrade project. However, the firmware for this module was revised significantly to address the additional complexities of the MIBPM system. Also, significant hardware design changes were implemented by taking advantage of the FPGA component. This resulted in an overall cost reduction for this module compared to a complete new design.
  - Multiple Echotek ECDR_GC814 Digital receiver boards, purchased from Mercury Computer Systems, Inc. as an option while procuring for the Tevatron BPM Upgrade project. These cards were used for the MI8 BPM upgrade project as well. These boards account for the bulk of the hardware cost for the BPM upgrade project for various accelerators. Early procurement of these cards allowed for reduced cost per board. The vendor documentation is available, but will be retained offline for proprietary reasons.

  These items are installed in a MIBPM Digital VME subrack. The specification is defined in BEAMS-docDb#2155. The digital subrack contains the MVME5500-0163 board with MPC 7455 processors and 512MB memory.

- MIBPM Cables: A large number of fabricated cables are purchased from Casco Corporation. The Cable Specification is available at BEAMS-docDb#2012.

4. Summary of Project Cost, Schedule and Complexities

The initial project cost and schedule was presented on July 25, 2005. See Beams-docDb#1905. According to this document, the scheduled project duration was one year; labor estimate was 10 FTE-Year and equipment cost estimate was $900,000. The equipment cost estimate was direct cost only.

The work on system requirements and design started on 7/1/05. Note that the start date on the Run II luminosity upgrade project WBS is 9/30/04 indicating the purchase date of the ECDR_GC814 Digital receiver boards. These boards were purchased as an option to the Tevatron BPM purchase order awarded earlier. The projected end was 8/25/06. The project officially ended as of 10/23/06 with a delay of approximately two months. This delay may be attributed to the additional work needed to implement new features of addressing and readout for MIBPM Transition Board Controller card and implementation of desired functionalities. All MIBPM equipment was installed in the houses by 8/2/06.

The project cost break down is as follows:

a. Total fully burdened equipment cost was $1,052,810. The direct material cost was $855,000. With $900,000 estimated equipment cost, the project spent 5% less than the original estimate.
b. Total fully burdened labor cost was $1,485,094. Actual project labor usage was 9.02 FTE-yrs. With the estimate of 10 FTE-yr labor, there was 9.8% project under-run.

A general profile of FTE usage for the project is given below.

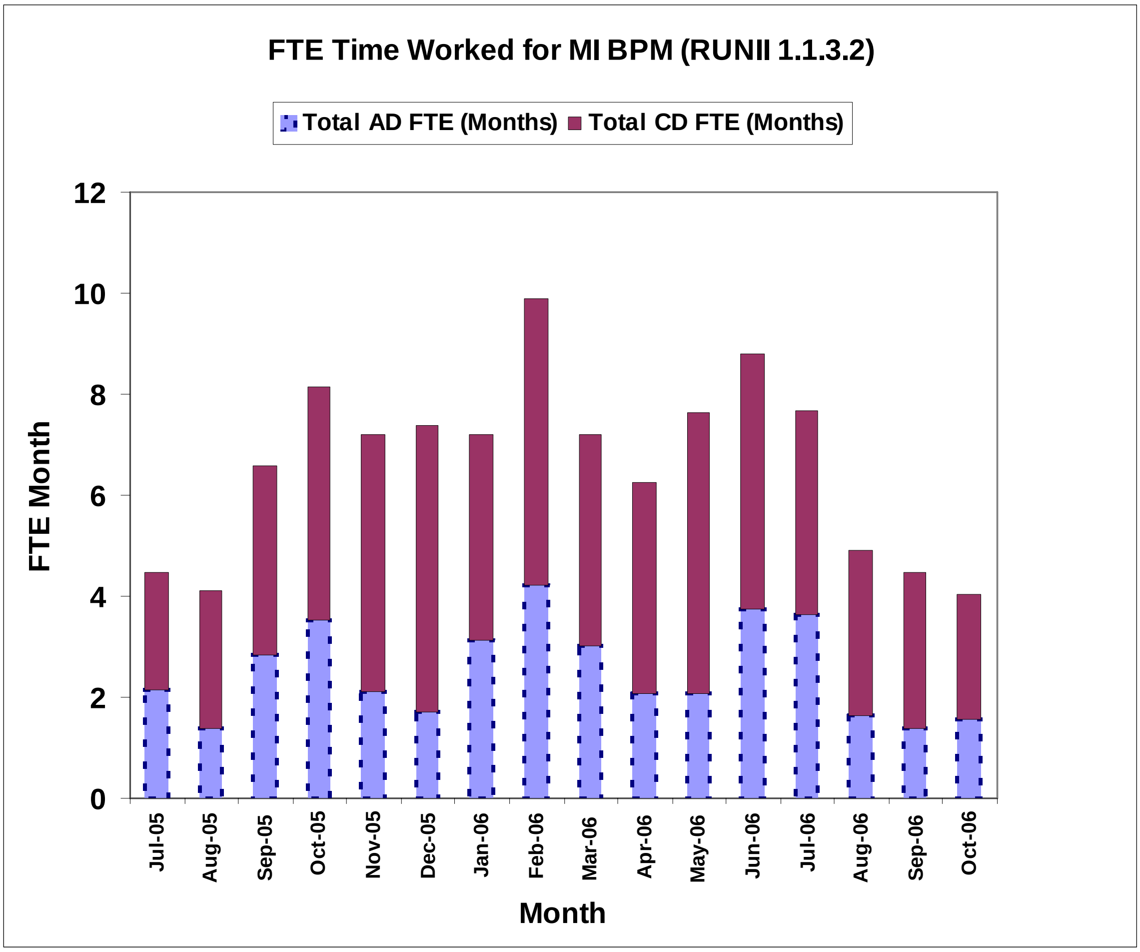

Figure 2: FTEs Used for MI BPM System Project

The following table provides the actual cost breakdown for the MIBPM system. Details of the major direct purchase costs are given in Appendix A.

Final Burdened Cost	WBS	Total
Design – OP	1.01.03.02.01	$364,101
Fabrication – EQ	1.01.03.02.02	$1,052,810
Implementation - OP	1.01.03.02.03	$519,103
Install - Comm - OP	1.01.03.02.04	$315,827
Technology/ Project	1.01.03.02.05	$286,062
Total		$2,537,905
Total – OP		$1,485,094

Table 1: Total Cost Breakdown for MI BPM System

The MIBPM project was initiated after the conclusion of the Tevatron BPM System Upgrade project. Appendix B shows a high-level view of the MIBPM WBS structure. The project team reused the significant knowledge gained from the Tevatron project. The learning curve was steep for Tevatron project because a new group of engineers, computer professional, and scientists were unfamiliar with details of accelerator instrumentation. On the other hand, the MIBPM project is significantly more complex than the Tevatron BPM project. Highlights of the complexities of the MIBPM project are described below.

The MIBPM digital crate system is based on the crate developed for the Tevatron BPM. Team members for this portion of the project had also worked on the Tevatron BPM upgrade, greatly reducing training costs. However, the TGF 2 module for the MIBPM system had to be redesigned to handle a much more complex signaling scheme. The Tevatron TGF had three inputs (BSync, Tclk, and RFclk), but the MIBPM TGF2 has five different input signals (BSync, Tclk, RFclk, MDAT, and BES). The timing module was also redesigned to make better use of the FPGA reducing the final cost of the module. Apart from this complexity, the Tevatron system had to deal with only 53 MHz frequency, whereas MIBPM system addresses both 53 MHz & 2.5 MHz signal frequencies. The analog Transition module is a new design. At a later stage of the project, the Transition Controller module was improved to handle additional features for readout and addressing. New features were also added to the front-end software and on-line software. The Main Injector has many more “states” than the Tevatron, and rapidly shifts between states. Each state is rather complex, and the MI BPM upgrade was required to work in many different operating conditions.

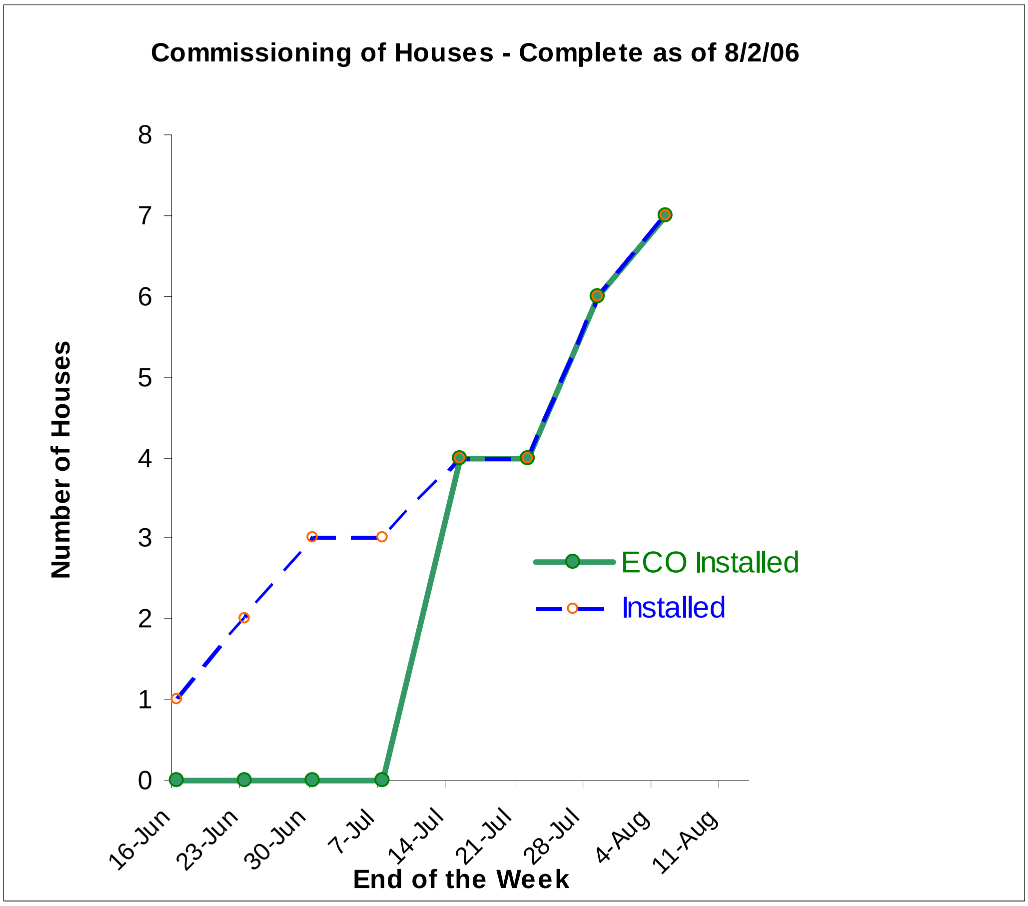

Figure 3: Installation Progress Chart
Blue line – Systems installed in service building
Green line – Final working systems available

The installation of the Combiner Boxes was completed early during the project. The progress of installation of the Transition modules was somewhat delayed by early failures of Transition modules. Once the problems were fixed the new modules were installed. Figure 4 shows the status of installation of the crates in MIBPM houses before and after the fixing of transition modules.

5. System Verification Checklist

System Documentation

All "as-built" MIBPM system design documents (schematics, Bill of Materials, Board Layout drawings, firmware and software are available at: http://projects.fnal.gov/mibpm/asbuilt. System crate configurations and picture files are also located here. These locations are chosen because of the very large size of these files.

- Are as-built drawings and firmware available? Yes. Hardware components built in-house are: combiner boxes; transition modules with controller cards and power harness; and digital subracks with Timing Generator modules. VME crates, Digital Receiver boards, model ECDR_GC814 were purchased. Transition modules consisting of the transition cards, controller cards, and crates with custom backplane were designed in-house. Transition cards were fabricated by Lace Technology.

- Are as-built design specifications for the hardware and software available? As-built specifications for the major hardware components and the front-end software are available. See Beams-docDb for topic area Main Injector/BPM.
- Are all as-built software and firmware installed, released, frozen, archived and accessible? All as-built software are installed and released.
  - The front-end software components specifically built for the MIBPM project is controlled by the CVS software on Accelerator Division's Nova machine. All the software is written for VxWorks 5.5.1, running on a Motorola MVME5500. As of January 2007, the installed version of the front-end software contains the following components:
    - echotek_mibpm_v1_16.tar.gz - Driver for the Echotek cards that is used in the Main Injector BPMS.
    - gbpm_v1_59.tar.gz - Generic BPM library that is used in both the Tevatron BPMs and the Main Injector BPMs.
    - mibpm_v2_101.tar.gz - Front end software for the Main Injector BPMs.
  - Due to the specific nature of the Online software, it is maintained under the control of Accelerator Division's MECCA code management system and is not archived here.
  - Are all as-built firmware, procured and developed in-house installed, released, frozen, archived, and accessible? Yes. Each MIBPM house has most up-to-date released firmware.
- Is an adequate description of the installed systems at each service building available? Yes. Installed system crate configurations information and pictures are available. However, these configurations may change during the operations phase.

Fabrication/implementation/installation

- Are adequate user documents for software and hardware available for the users to continue operations? Yes. See BEAMS-docDb#2510 MIBPM User Guide.
- Is there an adequate maintenance document available to maintain the system? Yes. See BEAMS-docDb#2083 MIBPM Electronics document and documents related to the Transition modules
- Is there a programmers' guide available to update the system in the future? Yes. See BEAMS-docDb#2083 and #2155 documents for firmware. For software, see BEAMS-docDB#2510.
- Is there a list of incomplete issues for this phase that must be addressed during the operations phase? No known issue exists to encumber the beginning of the operations phase.
- Is there a concern about the performance for the hardware? No performance issues surfaced during five months of operation.

Commissioning and decommissioning

- Is there a list of incomplete commissioning issues? No. There is no known incomplete commissioning issue. The system functioned properly for at least five months without fail.
- Is the decommissioning of the old system complete? Yes.

Operations

- Is there a high-level plan for the operations phase in place? Yes. See the MIBPM Operations MOU (Beams-docDb# 2492).
- Is there a plan for storing and distributing replacement hardware items? Yes. All MI BPM equipment is tracked by the Computing Division equipment database. Marvin Olson of AD Instrumentation Department keeps adequate amount of spares in his work area. There is a MIBPM test stand in Room TG216 (Transfer Gallery). He uses parts from this test stand for urgent replacement of hardware, replacing items as necessary from CD.

Project management

- Is there a plan for closing the project WBS and related charge codes? Yes. All project charge codes were closed formally during the month of November 2006.
- Are there new charge codes for the operations phase of the project? Yes. A new charge code was established and it is being used.
- Is there a list of lessons learned for the project execution, including scheduling and allocations? See below.
- Surety: Are there any incomplete quality, reliability and maintainability issues? No.

6. Lessons learned from the project management point of view

Positive experiences gained

- The delivered system was successfully validated against the requirement. Defining requirements early in the project and refining it was useful. See details of requirements validation efforts in the project manager's report.
- The estimated cost of hardware components, after the detailed estimation, was accurate. The final cost was $855K whereas the estimate in the approved May 2005 version of the project WBS (BCA#24) was $900K. This accuracy of estimation can be attributed to the cumulative experiences of participating engineers   It should be noted that the initial fixed cost estimate in the RUN II WBS for the project was only $500K.
- The early effort of installing Combiner boxes in the Main Injector tunnel during shutdown was effective.
- The reuse of many components, in particular the Digital Receiver cards and the TGF modules, from the Tevatron BPM Upgrade project was a significant factor in relative cost savings in the labor costs.

Issues resolved and lessons learned

- The schedule for the design phase was estimated optimistically. The MIBPM system, the transition module and the controller card for it, turned out to be more complex than originally estimated.
- Although Lace Technology, a local vendor, did an excellent job of fabricating the Tevatron BPM filter cards, the fabrication of the MIBPM Transition boards had significantly high failures and quality problems. These issues are detailed in the Beams-DocDB#2312. To mitigate these problems, boards were heat cycled, fixed

and retested in–house. In the future, it may be worth while to conduct on-site qualifications of vendor before placing any critical fabrication order.

7. Future work

No new future work is planned at this time.

APPENDIX A: MI BPM Hardware Purchase Cost Breakdown

Total M&S (no Overhead)	**$854,698.15**
Total Misc. MIBPM Pos	$429,933.15
Subtract estimated MI8 BPM cost	$79,235.00
Actual MIBPM Purchases	$350,698.15
Early Echotek purchases	$504,000.00
Estimated M&S per BCA#24	$900,000.00

Items costing more than $10K (May include MI8 items)

Po Number	Item Description	Total Cost
566244	Digital VME Crate	$63,086.25
566124	MOTOROLA'S VME BOARDS (MVME5500-0163) + 512MB MEMORY	$66,330.00
566452	Lark BANDPASS FILTER	$17,250.00
566158	Acopian POWER SYSTEM, +/- 5V, 17A,	$16,687.00
568055	Lace MI BPM TRANSITION BOARD ASSEMBLY	$14,086.10
566244	Increase VME64X ENCLOSURES FROM (11) TO (16).	$13,968.75
566784	Cable parts	$13,955.00
566285	ALTERA FPGA, PART NUMBER: EP1S25B672C6	$11,250.00
566821	TECHNOBOX 2372 96-CHANNEL DIGITAL I/O WITH ALTERA FLEX 10K70 FPGA	$10,252.32

APPENDIX B: Final MI BPM Project WBS Summary

ID	WBS	Task Name	Start	Finish
138	**1.1.3.2**	**MI BPM System**	**9/30/04**	**10/23/06**
139	**1.1.3.2.1**	**MI BPM design**	**7/1/05**	**2/27/06**
140	**1.1.3.2.1.1**	**MI BPM Electronics Design**	**7/1/05**	**1/31/06**
158	1.1.3.2.1.2	MI BPM: Review (Milestone)	7/25/05	7/25/05
159	**1.1.3.2.1.3**	**MI BPM Software (Design)**	**7/1/05**	**2/27/06**
165	**1.1.3.2.2**	**MI BPM System Fabrication**	**9/30/04**	**6/27/06**
166	**1.1.3.2.2.1**	**MI BPM Procurement**	**9/30/04**	**6/27/06**
175	**1.1.3.2.3**	**MI BPM Implementation**	**7/1/05**	**7/18/06**
176	**1.1.3.2.3.1**	**MI BPM Electronics Implemen**	**7/1/05**	**7/18/06**
201	**1.1.3.2.3.2**	**MI BPM SW Implementation**	**10/25/05**	**3/29/06**
207	**1.1.3.2.4**	**MI BPM Installation/Commissionir**	**11/28/05**	**10/19/06**
224	**1.1.3.2.5**	**MI BPM Technical/Project Coordin**	**7/1/05**	**10/23/06**
231	1.1.3.2.6	MI BPM system complete	10/17/06	10/17/06