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Main Injector BPM Review Committee Report of the meeting on March 4, 2003

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Introduction

P. Bhat and M. Church formed a committee to review the specifications for a new Main Injector Beam Position Monitor (BPM) system. The committee consisted of M. Martens (Chair), D. Morris, S. Pruss, V. Lebedev, M. Syphers, K. Gollwitzer, and C. Moore, all from the Fermilab Beams Division. The committee met on March 4th, 2003 where P. Bhat presented the charge to the committee and B. Choudhary presented the MI BPM specifications. Following this there was a round table discussion with the committee members, presenters, and interested audience members. This report summarizes the conclusions and recommendations of the committee.

The charge given to the committee was:

- Is the proposed set of BPM measurement capabilities complete? Are they adequate to ensure the effective operation of the Main Injector (and associated beamlines) through Run II?
- Are the BPM requirements over-specified?
- Prioritize the proposed measurement capabilities. In your view, which ones are most important, and which are least important?

Presentation on the MI BPM Requirements:

B. Choudhary presented a talk on the proposed requirements for the Main Injector BPM system. The talk[1] is documented in "Requirements for the Main Injector & Associated Transfer Lines BPMs Including the NuMI Beam Lines," B. Choudhary, Beams-doc-472, and the MI BPM requirements are further documented in the note[2] "Main Injector BPM System Upgrade & NuMI Beamline BPM Requirements." B. Choudhary, Beams–doc-471.

Round Table Discussion and Questions from the Committee:

Following the presentation a round table discussion took place with opportunities for members of the audience and the committee to ask questions and make suggestions. Based on the presentation, the round table discussion, and further communications after the meeting the committee drafted a set of recommendations that we present in this note.

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[1] ***The talk is available on the web at http://beamdocs.fnal.gov/cgi-bin/public/DocDB/ShowDocument?docid=472***
[2] ***The document is available on the web at http://beamdocs.fnal.gov/cgi-bin/public/DocDB/ShowDocument?docid=471***

Committee Report

First, the committee would like to thank Brajesh Choudhary for a well thought out and thorough presentation of the proposed specifications for the MI BPM system. The documentation was complete and covered not only the specifications required for designing the BPM electronics, but also documented the operational aspects of the BPM system and the manner in which data should be collected. This level of detail is needed in the process of specifying, designing, and building a new BPM system.

The committee fully supports the need for an upgrade of the Main Injector BPM system. However, we have some recommendations and comments that we hope will be useful. In this section of the report we report our findings and divide these into three main categories: General Conclusions; Comments on BPM Accuracy Specifications; and a list of Miscellaneous Comments.

General Conclusions:

The committee fully supports the proposed upgrade of the MI BPM system. The upgrade of the MI and associated transfer line BPM systems are needed due to the multitude of beam conditions (intensity and structure) and the 20+ year-old electronics currently in use. The Main Injector and the associated beamlines are (and will be) required to perform many tasks including collider operations with protons and antiprotons, pbar stacking, beam delivery to NuMI, fast & slow spill for 120 GeV beam to switchyard, and beam transfers to/from the Recycler, Booster, Pbar Source, and Tevatron. Having a reliable, operational, and accurate system will be important to the success of MI operations.

Our biggest concern with the proposed MI upgrade is the specifications for the BPM accuracy and repeatability. Most notably we recommend a more detailed description of the BPM accuracy requirements and suggest that the requirements, as stated, may be more stringent than is necessary. This is an important topic that generated much discussion and is therefore addressed separately in the next section of this report.

The committee was not asked to make recommendations on the schedule, cost, or resources needed to complete this project. This aspect of the decision process will require input from the Beams Division management after consultation with the engineers and management of the Instrumentation Department. Despite being absent from our charge, it is difficult for us to ignore this aspect when considering recommendations for BPM specifications, especially when the MI has asked for a completed system by the end of FY 2003. It is noted that there are still other BPM systems (Tevatron, Debuncher and transfer lines P3, AP1, AP2, AP3, and D2A) using the old systems and have the same reliability issues as stated in the documentation. We recommend that the groups responsible for the other BPM systems determine if any of these systems should be included. (In particular we know that the Tevatron BPM system may be upgraded and recommend that a set of specifications for these upgrades be developed.) However, it is important that the Main Injector BPM upgrade project is not delayed by other groups.

In a related topic, we note that attempts have been made to include the BPM upgrades for the NuMI beamlines into the specifications for the MI BPMs. This is useful and should be pursued. We note, though, that the NuMI experiment may be on a different timeline than the MI and delays in the MI BPM upgrade should not hinder progress on the NuMI experiment. Given limited resources, it may be necessary to focus on the NuMI BPMs separately and earlier than the MI BPMs.

The committee was asked to review the specifications from an accelerator physics point of view, and not specifically asked to comment on the engineering issues. We recognize that the final specification will evolve from an iterative process between the requestors of the BPM system and the engineers designing the system. As said, we are not qualified to make definitive statements on the engineering aspects of the BPM design, but in anticipation of engineering limitations we make some suggestions for changes. In other words there are some specifications that – if deemed too difficult or costly to implement – could be changed without objection from the committee. These are primarily related to the accuracy and calibrations specifications and are addressed in the next section of this report.

Comments on BPM Accuracy Specifications

As presented, the measurement accuracy for the MI BPMs was stated as follows:

> "This is a 3σ requirement, or 99.73% of the measurements should be within these limits.
>
> Position accuracy --- 0.40 mm +/- 5% of the actual position. Difference between two measurements on pulses with stable beam. It covers long term stability and resolution.
>
> Calibration precision of 0.2 mm+/- 1.25%"

This level of accuracy was requested over the full dynamic range of beam intensity (which is a factor of 24 in intensity[3]) and all types of beam (including 53

[3] This dynamic range of intensity will translate to a dynamic range of over ~1000 in the voltage at the pickups when both the range in per bunch intensity and the range of number of bunches is considered.

MHz bunch operations, 2.5 MHz bunch operations, coalesced beam, and batched beam) and for both protons and antiprotons.

This is an adequate level of accuracy for most operations, but we suggest that a single specification for the accuracy may by too stringent over the full dynamic range. If this level of accuracy over the full dynamic range can be designed and built then it should be used. However, if it is considered too costly or too difficult then it may be necessary to relax the accuracy specifications. The committee considers this an acceptable strategy.

For instance, we propose something like the following:

For establishing circulating beam:

For this purpose it is only necessary to measure the absolute position of the beam to within several millimeters. It will not be a problem if the BPM position has a consistent offset of ~1 millimeter from the "true" position of the beam. Errors in magnet survey are likely to contribute this amount in any case. As long as this offset is stable and repeatable this does not present a problem.

For maintaining stable operations:

For this purpose it is important that the BPM give a measurement that is repeatable from measurement to measurement, and over long periods of time (as in many months.) This allows errors in the closed orbit to be corrected. The accuracy quoted in the presentation (0.40 mm +/- 5%) is adequate for this purpose, but should be stated for a specified set of beam conditions and operation mode.

As stated, the position accuracy specification is for all types of MI operations including coalesced and uncoalesced beam, protons and antiprotons, 53 MHz and 2.5 MHz beam. This implies that the BPM system should give the same position measurement independent of the beam structure. If possible, the BPM system should meet this requirement since it simplifies Main Injector operations and makes interpretation of orbit data easier.

However, achieving this goal may add complexity to the BPM system making it more difficult to design. If this is the case, then the committee suggests a higher priority be given to repeatability from measurement-to-measurement, or day-to-day, with the same type of beam than to the repeatability of the same orbit measurement with different beam structures. We do not have a specific recommendation on the level of error that is acceptable in position measurements between, say, coalesced and uncoalesced beam. We leave this decision up to the Main Injector Department. Our only recommendation is that the BPM specification should state the amount of orbit position variation that is acceptable when measuring the same orbit with different types of beam. We also recognize that this specification will likely evolve as the BPM design matures and the trade-offs between complexity, cost, schedule, and accuracy are better understood.

For performing lattice function measurements:

For this purpose we recommend a tighter accuracy specification. Particularly, a specification of the linearity of the BPM reading over a position range of ±5 mm is needed. (This is the typical size of orbit oscillation introduced when measuring the lattice using one-bumps.) As stated, the specification does not adequately specify the linearity. To determine errors in the lattice functions of 10% (in $\Delta\beta/\beta$ for instance) the linearity requirement should be 1% (instead of the 5% requested.) While this is a tighter specification than originally requested, this level of accuracy is not required over the entire dynamic range, and for all types of beam. Lattice measurements can be made with more narrowly defined bunch intensities and can be done specifically with uncoalesced beam. In Appendix A, committee member V. Lebedev gives an individual response to this issue based on his experience with lattice measurements in the Tevatron.

We anticipate the specification for a calibration system with accuracy of 0.2 mm ± 1.25 % will not be considered feasible by the engineers designing the system. Even if the engineering realities do make a calibration system of this accuracy unfeasible, we still recommend that a calibration system be designed "as well as reasonably possible" since it will be a valuable BPM diagnostic.

Miscellaneous Comments

In our efforts to be thorough we include in this section a list of comments and questions.

- Audience member comments at the round table discussion suggest that the dynamic range of beam intensity (a factor of 24) and different beam structure will translate into a dynamic range of greater than 1000 on the voltage at the BPM pickups. While the committee is not qualified to determine the difficulty maintaining BPM accuracy over such a large dynamic range, we do anticipate that this may be a problem. We note that a more relaxed specification of the overall BPM accuracy (as noted above) may be needed. Should this be the case, the committee thinks it would be acceptable, from an accelerator point of view, to have difference levels of BPM precision for different types and intensities of beam.

- In regards to NuMI operations, it was suggested that the MI might want to automatically abort NuMI operations on a cycle-by-cycle basis if the orbit at flattop wanders from the nominal value due to accident conditions (such as a failed dipole corrector for instance.) As specified the BPM system would not be capable of such operations. The committee has not seen sufficient justification for such a specification to be added to the BPM design. Therefore, unless specifically requested and justified, the BPM design does not need to meet the requirement. The NuMI collaboration should be made aware of this decision so that they can plan accordingly and have an opportunity to comment.

- We note that the upgraded BPMs in the P1, P2, and P3 transfer lines will not be capable of measuring the beam position during 120 GeV slow spill from the MI. We assume that a second set of resonator BPMs will be installed for this purpose, but this should be specifically stated. Also, will SY120 require tune-up with fast spill? And if so what will be the intensity and beam structure?

- We anticipate that there might be trouble building a BPM system that can report the intensity of the beam to 5% accuracy with single turn measurements. Having a BPM intensity readback is useful and should be pursued, but we do not think that it is necessary to have 5% accuracy quoted. Calibrating the intensity signals on a BPM-by-BPM basis can improve the repeatability of the intensity measurement. Even if the 5% accuracy specification cannot be met, the upgraded system should still provide an intensity measurement.

- There is a lot of software that will also need changing for the BPM upgrades and the amount of effort required to accomplish this should not be overlooked. Work towards an upgrading the BPM software has been ongoing, but it might be fruitful to take this opportunity to review the direction of the software upgrades.

- There was no discussion of how the MI BPM system would be used during slip-stacking. Potential here is 6+6 batches prior to slipping during operations. What about studies of 1+1 batches?

- Specifications state that beam energy will be 8.9 to 150 GeV. This means that the BPMs operation below 8.9 GeV is not considered and the deceleration of beam below 8.9 GeV is not considered in the scope of this project. The committee has no opinion in this matter, except to make this point explicitly clear in the specifications.

- It is not stated what the priority of the front end processing will be with multi-users, data acquisition of possible different types during the same MI cycle and servicing user applications.

- Several minor comments on the documentation: The P1 line also supports 120 GeV fast spill and 8.9 GeV reverse protons to the Pbar. The P2 line also supports 8.9 GeV reverse protons to Pbar and 8.9 GeV pbars to the MI. The P3 line also supports 120 GeV fast spill.

Appendix A

Comments by V. Lebedev on BPM Accuracy for Lattice Function Measurements.

Summarizing experience about current status of Tevatron BPMs I can say the following. RMS noise of BPM measurements is between 50-100 μm. Normally I excite beam motion of about 3 mm. That determines that relative BPM accuracy is about 1.5-3% for a single measurement. Averaging of 5 to 20 pulses further improves accuracy by another factor of 2 to 5. Usually I acquire positive and negative kicks and I control reference orbit change before and after the measurements and both of them contribute about 100 μm uncertainty. As far as I can judge differential responses of most of BPMs are also within 3% for ±3 mm beam displacements. There are a few BPMs that fall out of this picture and I can easily identify them. New system should be at least as good as the existing one and I would set a request to the linearity of electronics response to 1% within ±5 mm from BPM center.

There is a peculiarity in non-linearity of BPM plate response that we need to keep in mind. The response should be a symmetric function of coordinates and, I believe, it should satisfy to the laplace equation. That yields that BPM differential signal for vertical BPM is

$$V(x,y) = k\frac{y}{A}\left(1 + \frac{\varepsilon}{A^2}\left(y^2 - 3x^2\right) + \cdots\right).$$

As you can see signal depends on both vertical and horizontal beam displacements and correction due to horizontal displacement is larger than due to vertical one. We do not know (do not measure) the horizontal displacement in the same BPM and therefore making cubic correction for vertical displacement is not very helpful. Therefore together with electronics we need to request BPM measurements on the test stand to understand better what is actually down there. Non-linearity of electronics, if present, can be corrected in software.

Summarizing I would set the following requirements to BPM electronics for performing optics measurements, i.e. the beam has a structure and intensity assigned for optics measurements.

1. Differential response of electronics in the BPM center has to be identical for all BPMs within 1%.
2. Non-linearity of electronics response has to be measured to 1% in the entire range of beam displacements and if exceeds 1% need to be corrected in software. Non-linearity of response for all BPM cards has to be within 1% as well. (1% means that after correction the relative beam position uncertainty due to non-linearity is 1%).

There is another problem, which deserves to be mentioned. In the case of turn-by-turn measurements our signals are strongly polluted by the longitudinal beam motion and head-tail modes. We clearly saw this with old BLT electronics and we see it now for Tevatron BPMs. The request should be similar to the above:

1. Longitudinal bunch motion should not excite beam displacement above ~50 μm.
2. Head tail-modes should not change the measured bunch position from the bunch center of gravity by more than 1-2% of initial excitation. I need to mention that it is quite serious requirement.