TeV BPM Upgrade Requirements

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There are two deficiencies in the current Tevatron BPM system that need to be addressed in the specifications of a new BPM system. First, the precision of the BPMs is too poor to get a reasonable verification of the Tevatron lattice. Second, the system cannot measure antiproton positions.

I. Scope

The scope of the BPM project will be the processing hardware and software of the 232 BPMs currently installed in the Tevatron. The actual pickups will not be modified or displaced unless required by the current maintenance plan. The scope will include any extra cabling or tunnel hardware necessary to observe antiproton positions. It will also include the ability to interface with the current Tevatron beam loss monitor system. The specifications refer to the final BPM data released by the front-end system.

II. Key Specifications (Protons):

Absolute Position Accuracy: 1.0 mm
Relative Position Accuracy: 5%
Long Term Position Stability: 0.02 mm
Best Orbit Position Resolution: 0.02mm
Position Linearity: 1.5%
Intensity Stability: 2%
Specification Range: ±15mm

Total number of BPM channels required: 232 x 2

The **absolute position accuracy** of the BPMs creates a limit to the sum of the position offset and the relative error at full range. This specification dictates how well we know the position of the beam relative to the center of the quadrupole for all beam conditions, position, and time.

The **relative position accuracy** describes the limit of the position error variation as a function of relative beam displacement. This specification does not include offset errors, but it does include scale errors, non-linearities, and random errors. It takes precedence over the absolute position accuracy specification.

Position linearity describes how much the relative position error can deviate from a linear function. It is similar to the relative position accuracy, but scale errors do not affect it.

Orbit position resolution refers to the smallest change in beam position that the BPM system can reliably observe. This specification will not be affected by offset errors, but it will be affected by scale errors, non-linearities, and random errors. The specification lists the best resolution of the system, because this specification will vary with operating conditions. More details are listed below.

Long term position stability refers to the BPM system's ability to give the same position value for the same beam position and intensity over multiple stores or even a one week shutdown. The BPM position value should not change by more than this amount over a week.

Intensity stability refers to the allowed drift in the measured beam intensity signal for a particular beam intensity.

Specification range refers to the amount of BPM aperture, relative to center, in which the listed specifications remain valid. Beyond these points, the performance is not specified.

III. Front End Processing and Triggering:

There are three modes of front end processing that determine the processing specifications, **flash mode**, **turn-by-turn mode,** and **closed orbit mode**. The front end design must allow the two modes to run simultaneously and independently. When flash data is retrieved, closed orbit acquisition must continue undeterred. Each mode should have at least 1000 data points of internal storage and include both position and intensity data.

The **flash mode** is used to take a fast sample of positions relative to a clock event, state, or manual command. The bandwidth of the flash mode should be on the order of a single revolution period, so that it can be used to diagnose problems of a fast nature. These would include injection misteering and kicker misfires. This mode should also be capable of sampling positions at a rate of at least once per turn.

In order for the flash mode to successfully diagnose sudden changes in beam orbit or to capture first turn injection closed-orbit information, all of the data from the BPMs must be tightly synchronized. The time specification for the synchronization of the data samples must be better than a single turn. This time stamp should be accessible by the application program so that the program can organize and sequence the different BPM readings properly.

There are three different ways that the flash mode could be triggered to take data. One way is just a straight TCLK event. Another way would be a multicaste Tevatron state change, or a state change that arms the system to wait for a TCLK event. A third way to trigger the system would be to manually request data from an application page. The front end must be capable of sending data to the application program at a 1Hz rate.

The **turn-by-turn mode** is a superset of the flash mode. Its primary purpose is to measure the amplitude and relative phase of betatron oscillations at each BPM around the accelerator. From this, information about the lattice is deduced. The sampling rate of the turn-by-turn mode must be fast enough to prevent aliasing of necessary betatron information. Once per turn is the minimum sample rate. Also, the memory must be deep enough to provide enough resolution bandwidth, so that other frequency components do not corrupt the phase information from the betatron frequency.

The turn-by-turn mode places the tightest requirements for the accuracy of the data time stamp. Random errors in the time stamp act as phase noise modulation on the beam spectrum. If the modulation amplitude is large enough, signals from other components of the beam spectrum could spill into the resolution bandwidth of the betatron frequency detection. This will also corrupt the phase information from the betatron frequency.

The **closed orbit mode** is a lower bandwidth but more precise mode. Closed orbit data will be requested at a maximum rate of 1Hz, so the processing bandwidth can be much lower. This mode will entail more averaging than the flash mode and will offer more precise position measurements. It will have all the same trigger options that the flash mode has, and it will probably have its values consistently datalogged at some low frequency rate (~1Hz).

Processing Specifications:

Bandwidth of flash mode:	~50 kHz
Bandwidth of closed orbit mode:	~100 Hz
Flash mode time stamp precision:	1 μs (3σ rms)
Closed orbit mode time stamp precision:	500 μs (3σ rms)
Resolution bandwidth of turn-by-turn mode:	<30 Hz

IV. Beam Specifications:

Coalesced Protons:
- Particles/bunch: 30e9 – 350e9
- No. bunches: 1 – 36
- Bunch Length 3σ: 4.5ns – 10ns

Coalesced Pbars
- Particles/bunch: 3e9 – 150e9
- No. bunches: 1 – 36
- Bunch Length 3σ: 4.5ns – 10ns

Uncoalesced Protons[1]:
- Particles/bunch: 3e9 – 30e9
- No. bunches: 30

[1] Currently only used for tuning and studies.

Bunch Length 3σ: 3.5ns – 10ns

Bucket Spacing: 18.9ns (53.1 MHz)

V. Beam Distribution:

Standard Store Configuration:

Each group of proton bunches has 2.5 MHz spacing (21 buckets) with abort gaps (140 buckets) between the groups. The pbar beam has the same bucket distribution as the proton beam but has a lower intensity. This is one of the most critical modes of operation for the BPMs, because we will want to tune the orbits in this mode. The resolution must be high without the pbars interfering. **(Closed Orbit Resolution: 0.02mm, Flash Mode Resolution: 0.1mm)**

Pilot Tuning Configuration:

The Tevatron will need to be tuned up immediately prior to every shot. This will involve a pilot injection to check orbits, tunes, chromaticities, etc. The current pilot is a batch of 30 uncoalesced bunches with about the same amount of integrated charge as a single coalesced bunch. The current BPM system, which is not as accurate with coalesced bunches as with uncoalesced bunches, dictates this. It is important that there be very little offset between measured pilot orbits and the final injection orbits for the shot. The pilot can be a single coalesced bunch or the current uncoalesced bunch as long as it minimizes the offset from the injection orbits. **(Closed Orbit Resolution: 0.02mm, Flash Mode Resolution: 0.1mm)**

Injection Configuration:

The proton bunches are injected one bunch at a time during the shot. The BPMs must continue to operate during this process and must meet their specifications even when the ring is only partially filled. Once all of the protons are injected, the pbars are injected four bunches at a time in the abort gaps. After three batches are injected, the pbars are cogged into the protons, and a new set of batches are injected. This process is repeated until there are 36 pbar bunches. Orbit tuning is unlikely during this configuration, but problems with kickers and gross missteering is highly likely. High resolution is not as necessary here, but accuracy must be maintained during the injection process. **(Closed Orbit Resolution: 0.05mm, Flash Mode Resolution: 0.1mm)**

Ramp Configuration:

Once the final pbars are injected and cogged, the magnets are ramped. This process requires considerable tuning of the corrector magnets during the ramp to compensate for the increasing beam energy. The resolution of the BPMs is not as important a specification due to the large orbit variations, but accuracy is still important. Also, this is the time where data throughput is most critical, because there will be a number of orbit sample points in a relatively short amount of time on the Tevatron time scale. **(Closed Orbit Resolution: 0.05mm, Flash Mode Resolution: 0.1mm)**

Pbar Only Configuration:

There will be certain study conditions that will require pbar only stores in the Tevatron. The BPMs should be able to verify pbar orbits in this condition if at a lower accuracy than the standard configurations. **(Closed Orbit Resolution: 0.1mm, Flash Mode Resolution: 0.25mm)**

Studies Configurations:

The studies configurations could involve any combination of bunches either coalesced or uncoalesced in any bucket configuration. These configurations will have a very broad possible dynamic range, and the BPMs should still register positions during these operations, although at an understandably lower accuracy. The summary for BPM resolution as a function of beam current is:

> 200e9 particles or >100e9 particles/bunch – 0.02mm
200e9 > particles > 50e9 or 100e9 > particles/bunch > 30e9 – 0.1mm
50e9 > particles > 10e9 or 30e9 > particles/bunch > 3e9 – 0.25mm

Always choose the less stringent requirement. So, if there are 36 bunches in the Tevatron with more than 200e9 total charge, but there is less than 100e9 particles per bunch, then the resolution specification is 0.1mm.

VI. User Interface Requirements:

The user interface will provide the BPM system with the proper settings for single shot and automated measurements. It will provide short term storage for data retrieved and a plotting package for examining the orbits and comparing orbits under different conditions. It will also enable system tests and calibration measurements as needed.

This interface will be single user with no protection.

The user interface will generate the following BPM system settings:

Closed Orbit/Flash Mode Select
Proton/Pbar Mode Select
Arm and Trigger Settings for Automated Measurements
Quantity of Flash Mode Data to Download

The data retrieved from each BPM will include:

BPM Azimuthal Position
Trigger Settings

Closed Orbit/Flash Mode Setting
Proton/Pbar Setting
Size of Data Array
Trigger Event for Current Data Acquisition
Arm Event for Current Data Acquisition
Array of:
- Position readings
- Intensity readings
- Time stamp for each read

The interface must have sufficient memory to store at least 1000 files that can contain at least 35 orbit readings a piece for later reference. It also must have memory to store multiple flash data acquisitions for processing. The display interface should have the following options:

Plot Closed Orbit (all BPMs)
Plot Difference Orbit (closed orbit/all BPMs)
Plot Flash Orbit (all BPMs)
Plot Flash Data (single BPM)
Plot Flash FFT (single BPM)

VII. Calibration & Maintenance:

A calibration system that maintains the specifications needs to be designed. The resolution specification only needs to be self maintained for the time specified by the long-term stability specification. Beyond that, some calibration procedure is assumed.

The system should also have enough built in maintenance procedures to realize an internal system malfunction and to diagnose the problem to the level of any replaceable component.

VIII. Justification:

There are six major functions that this BPM system must perform in order to justify an upgrade. Some of the functions are already part of the current BPM system, and some of the functions cannot be reliably performed by the current BPM system.

Tune orbits – This function requires the best resolution and accuracy of the system over a large dynamic range. Injection orbits, orbits up the ramp, and flattop orbits are tested with a pilot bunch. Reverse injection for pbar orbits are also tested. It is very important that BPM readings for the pilot bunch can be carried over to 36 bunch readings within the specifications. The readings cannot be corrupted between the beam current of the pilot bunch, and the HEP current.

Injection diagnostics – This function requires the best trigger and time stamp resolution. A flash of the first turn of injected beam is compared to a measured closed orbit or a previously saved reference orbit. Information from the injected beta wave is used to tune the beam lines. Also, any more serious injection problems, such as beam not making a complete circulation, can be resolved by monitoring individual BPM intensity data on the first turn. These diagnostics require that the BPM system trigger precisely on the first turn, or any turn specified by the user. Synchronization between BPMs is critical.

Orbit smoothing during HEP – This function requires the best resolution and long term stability. This resolution must not be corrupted by the pbars in the machine. Orbit smoothing will be performed during HEP to place the beam in its best orbit to minimize losses and maximize stability. Orbits from previous stores will be used as references, so it is important that the system not fall out of calibration from store to store.

Orbits up the ramp for shots – This function is used to verify the orbits during shots that were tested originally by the pilot bunches. Accuracy and resolution are not as essential here as with other functions. The things that make this function challenging are the number of data points required over a short time period, the changing energy and orbits over a short time period, and pbar beam.

Abort/Quench conditions – This function requires very good time stamp resolution and determines the specification for the number of stored frames. When there is a beam abort, the BPMs should stop taking data, and there should be a flash frame that shows beam conditions just before beam is kicked out of the machine. This frame (and the few frames preceding it) should reveal whether the cause of the abort was due to bad beam position. It would be able to diagnose a kicker misfire or a sudden magnet problem. Synchronization between the BPMs is critical for this diagnostic.

Lattice function measurements – This function requires very good resolution and linearity. The specified position resolution of the proton signals is a factor of 10 better than the resolution of the current BPMs. This will improve the determination of lattice parameters from a precision of 10% to a precision of 1%. Even with the improvement of resolution, we still detect about a factor 10 less precise than the magnet supplies can regulate.

IX. Schedule:

As the luminosity of the Tevatron increases, it becomes more difficult to maintain consistent performance with the current BPM system. I would like to have an upgraded system commissioned by April of 2004. This will give time for design and review before the start of a new fiscal year. The items can be ordered in FY 2004 and assembled before the April deadline.

X. Appendix:

1. Turn-by-turn Calibration:

In order to make the phase advance measurement beyond the resolution of just doing orbit bumps, the BPM processing must have a frequency resolution better than the synchrotron frequency. Otherwise synchrotron modes with different amplitude and phase advance will be smeared together, confusing the phase measurement.

Sampling the beam long enough to have a resolution bandwidth smaller than the synchrotron frequency will allow us to discern the phase advance to within an error of about 0.05°. This phase error limits the precision of the measurement and is based on the resolution of the BPMs. To have any kind of accuracy with the measurement, the delay through each BPM cable and system must be well known. The level to which the delay must be known is determined by the sampling rate of the beam. We can use the beam response itself to measure the delay if the sampling rate is high enough. The phase difference between the upper and lower betatron sidebands without delay should be asymmetric about zero degrees. The phase difference between a single sideband and its equivalent separated by a revolution harmonic should be zero. If the sample rate is only once per turn, then only one betatron line can be discerned, and knowledge of the BPM system delay is critical. If the sample rate is twice per turn, then upper and lower sidebands can be discerned, and knowledge of the system delay is not as critical. If the sample rate is three times per turn or greater, then two revolution harmonics of the lower sideband can be discerned, and the system delay need only be linear over the revolution harmonic. The following table summarizes the specifications.

Sample Rate	Delay Accuracy Required	Min Front-end Bandwidth
1 per turn	3.5 ns	30 kHz
2 per turn	22 ns	50 kHz
3+ per turn	Delay must be linear to 10%	100 kHz

2. Tev Orbit Smoothing Procedure:

1) **Save the DFGs before smoothing.**
   Save the DFGs in a file ____.

2) **Inject uncoalesced beam.**
   Turn off separators

3) **Test BPMs.**
   Check the BPMs by making 1-bump orbit measurements.
   Make note of the bad BPMs.

4) **Save snapshot of orbit.**
   Collect a front porch BPM snapshot and save in a file ____.

5) **Ramp to 980 Gev flattop.**
   Ramp to flattop, but do not go to low beta.
   (This is with uncoalesced beam and separators off.)

6) **Save the ramp BPM profiles.**
Save the ramp BPM profiles in a file ____. (There will be at least 10 profiles triggered up the ramp.)
Collect a flattop snapshot BPM profile and save in a file ____.

7) **Make BPM difference file.**
Plot the just saved file of ramp profile with the reference ramp profile subtracted.
Save the ramp profile differences on the ramp in a file ____.

8) **Calculate the corrections on the ramp.**
Run orbit smoothing calculations while still at the 980 Gev flattop but before the low beta squeeze.
Smooth the horizontal and then vertical planes.

   I. For the desired position table select the reference file.
   Then mask out additional BPMs that failed the initial test.

   II. Run the smooth sequence.

   III. Plot DFG difference using CORRECTOR COMPARE.

      a) Plot DFG differences on a scale of +/- 0.02 mrad
      b) Look for DFG changes greater than +/-0.02 mrad cutoff.

      c) If any DFG change is greater than the cutoff, then mask out this DFG in the desired positions table and redo the smooth.

   IV. Send the DFG settings to hardware.

9) **Save DFG settings.**
Save the DFGs in C50 file ____.

10) **Verify the smoothing was successful (at least at flattop.**)
Take a snapshot of the flattop orbit.
Save snapshot in a file _____.
Plot this file with flattop reference orbit subtracted.
This shows how well the orbit was smoothed.

11) **Do the low beta squeeze.**
For this squeeze the DFG settings at flattop will be the newest settings, but the DFGs in the squeeze tables (the h-tables) are still the previous settings.

12) **Save the low beta squeeze BPM profiles**.
Save the low beta profile frames in files.
Frames 10-34 in T39 file _____.

13) **Make BPM difference files**.
Plot the just saved T39 files squeeze BPM profiles with the reference files 890, 891, and 892 subtracted.
Save the squeeze BPM differences orbits in T39 files.

Frames 10-34: File from above ____ - T39 file 890 = T39 file ____.

14) **Calculate correction for the low beta squeeze.**
Run orbit smoothing calculations while still at low beta, but before aborting the beam.
Smooth the horizontal and vertical planes.
Each plane requires three separate smooth calculations.

I. For both HORZ and VERT the setups should be

a) Table:	SQUEEZE
b) Slot Range:	Use slot range (3-26)
c) Plane:	HORZ or VERT
d) DFG source:	DFG
e) BPM source:	T39 file
f) BPM file:	Use file from step 13 above
g) BPM frame:	(11)
h) Desired orbit:	Desired Pos (Select file 24)
i) Selected Lattice:	AUTO
j) Algorithm:	SVD
k) Stepcut:	100

II. For the desired position table select file 24.
Then mask out additional BPMs that failed the T41 test.

III. Run the smooth sequence.

IV. Plot DFG difference using CORRECTOR COMPARE

a) Plot DFG differences on a scale of +/- 0.02 mrad.
b) Look for DFG changes greater than +/-0.02 mrad.
c) If any DFG change is greater than the cutoff, then mask out this DFG in the desired positions table and redo the smooth.

V. Send the DFG settings to hardware.

15) **Save the DFG settings.**
Save the DFGs in C50 file ___.

16) **Verify the smoothing was successful (at least at low beta.**)
Take a snapshot of the low beta orbit.
Save snapshot in T39 file ____.
Plot this file with T39 file 893 subtracted.
This shows how well the orbit was smoothed

17) **Collect orbits on proton only store**.
Get rid of beam and do another proton only store.
The store should be with uncoalesced beam and with the separators off.
Save the BPM profiles in T39 files.
Frames 0-34 in T39 file ____.

18) **Verify the smoothing was successful.**
Compare the orbits taken in step 17 to the reference orbits,
Frames 0-34 in T39 file 888.