BPMS FROM DESIGN TO REAL MEASUREMENT

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Abstract

Beam Position Monitors (BPM) are an essential tool for the operation of an accelerator. Therefore BPM systems should be included from the beginning in the design of a new machine. This contribution describes the development of a new BPM system up to its operation with a focus on the mechanical design process. It includes the collection of the requirements and boundary conditions which defines the type of BPM system. The mechanical design process is described where simulations are used to predict the signals. These results are input parameters for the design and optimization of the electronics. Several contributions are considered which can modify the BPM signal like feedthroughs, heating due to wake losses, supports, cables etc. The steps from the design, the prototyping and series production including laboratory and test accelerator measurements up to the commissioning are described.

INTRODUCTION

The beam position needs to be controlled during the operation of an accelerator. Therefore when designing a new accelerator the BPMs should be included early in the design. First the type of BPM system has to be decided. Different type of BPMs are available with different properties, see [1, 2]; BPMs can be divided into capacitive and resonating pickups. Capacitive BPMs use opposing antennae to detect the beam offset relative to the beam tube; this BPM type includes button, stripline and shoe-box. A BPM based on a resonance (cavity BPM) can use only one antenna to detect the beam offset in one plane (beside a reference cavity); opposing antennas can be combined to increase the sensitivity. The BPM performance (resolution, accuracy, linear or non-linear responds, x-y coupling, sensitivity, complexity) differs between each type. Based on the requirements of the accelerator the choice of a BPM type should be done in an early stage of the accelerator design.

This contribution describes the process of the development of a BPM system from the design until the commissioning in an accelerator; the focus lies on the mechanical BPM design where the number exceeds the in-house production capability. The paper is divided into the requirements, wherein the BPM performance values are listed. The description of the BPM designing process follows with important aspects including prototype production with extensive tests of the performance. The selection of companies is described since for large quantities the production may have to be outsourced; together with the necessary quality tests. The last chapter contains the commissioning of the system.

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REQUIREMENTS

At the beginning of the development of a BPM system the requirements have to be fixed to be able to select a type of BPM system. The requirements are the basic parameters which need to be fulfilled by the system. Changes in the requirements during the development or later requires additional effort with increased costs and time and therefore should be avoided. The BPM requirements are [1]:

- Resolution: is the ability to determine small displacement variation (relative position); this is influenced by the type of BPM, electronics and ADC granularity.
- Accuracy: is the ability to detect the position relative to a mechanical fix-point (absolute position); this is influenced by mechanical tolerances, alignment accuracy, cable differences, support vibration, thermal effects.
- Dynamic range: is the ability to detect the beam position within a beam current (charge) and offset range.
- Detection threshold: minimum beam current (charge) to be detect with still adequate resolution.
- Availability of components, mean time between failure of components, time duration of commissioning, single or multi-bunch detection, fast signal for machine protection, project budget duration of the development.

The values listed above make it possible to decide the type of BPM. Based on the type the following boundary conditions have to be determined to start the design process:

- shape and size of the beam tube
- number of items
- item space of each BPM
- environment temperature (for the case that the BPM is installed in a cryogenic chamber)
- area for BPM support: larger space needed for remotely movers for position calibration; vibrations
- vacuum aspects like pressure and particle reduced area
- distance between BPM and front-end electronics (attenuation of signal amplitude due to cable, phase differences between cables)
- area for electronics (within the accelerator room: shielding); temperature stability in the rack
- sub-components: trigger (internal from the signal itself or external from the machine), synchronization
- (low) maintenance effort

For the development of the BPM system the following values have to be agreed upon between the BPM mechanical body and the electronics to accomplish the requirements:

- sensitivity: amplitude with respect to the position
- bandwidth: frequency range available for measurement including deviations due to production
- signal to noise: ratio between wanted and unwanted background amplitude

With the definition of the type of BPM the main components of the system can be fixed and a rough estimate can be made to obtain that the requirement will be fulfilled with the chosen system. Note also that contributions like ground jitter, cables and beam parameters influence the BPM performance. In addition the total monetary costs and time effort should not exceed the requirement. Quite often the machine parameters are not fixed in all details. Therefore some extended safety margins in the design are most helpful.

DESIGN WITH SIMULATIONS

The development of the BPM system (which consists of the mechanical body and the electronics) can be done in the following ways:

1. Produce prototype BPMs based on analytic expressions with different mechanical design values and measure their performance, optimize the design values based on the measurements and produce new prototypes. When most parameters are fixed, the development of the electronics starts. This way is very time consuming because the development of body and electronics has to be done one after another with several production steps.
2. Another procedure is to predict the basic body performance with analytic expressions and simulate it afterwards. The simulated data are input values for the electronics development already in the mechanical design state. In this way the development of body and electronics can be done in parallel which saves time and might better fulfill the (typically tight) time budget.

General simulation software codes can be used for the prediction of BPM performance, e.g. CST [3], ANSYS HFSS [4], GdfidL [5], COMSOL [6], ACE3P [7] and others. A benchmarking of such simulation tools can be found in [8]. By applying the last way typical development times are listed in Table 1. The steps of development will overlap such that the overall time for the development is shorter than its sum. However, these times are comparable with the necessary time of the development of an accelerator therefore the BPM system should start as early as possible in the overall accelerator project.

Only the vacuum section including the antenna is necessary to simulate the BPM body effectively. The simulation tools are able to import mechanical designs; often unnecessary parts can be erased. Another approach is to design the vacuum section and antenna in the simulation tool and afterwards convert this to a 3D model for the mechanical design. The simulation can be used to optimize the RF design of the BPM body to match the input parameters of the front-end electronics. All mechanical values which influence the BPM performance have to be considered to get the mechanical tolerances; excessively tight tolerances increase the production costs. Therefore during the tolerance studies of the BPM body an interplay has to be done between mechanical tolerances, feasibility, electronics and system requirements. The tolerance study can be done with each mechanical value separate and calculate the sum of deviation as a worst case. A better approach is to consider all correlations which takes more time depending on the number of mechanical values but the definition of the mechanical body is more accurate.

Table 1: Time duration for the development of a BPM system in years with outsourced production

	Button	**Stripline**	**Cavity**
Development (mechanics + electronics)	1 - 2	2 - 2.5	3 - 4
Industrialization	1 - 2	2	2
Series production	1.5 - 2	2	2 - 2.5
Firmware + server	0.5	0.5	0.5
Commissioning	0.5	0.75	0.5

During the tolerance study of the design one must insure that the dissipated power in the body and on the antenna is not too high. Resonances of higher order modes and wake losses have to be simulated to get the field distribution and the power loss. A workshop summary [9] describes the procedure to calculate the dissipated power and hints are included to help prevent damage. Special care has to be taken for the antenna design. Several design considerations are available to optimize the design of the antenna feedthrough to minimize the dissipated power to avoid damages, e.g. see [10–13]. The last step of the RF design optimization is to look at nearby components like vacuum pumps and bellows. These vacuum components could influence the signal of the BPM. In case of serious distortions, counter actions have to be taken. These can be as simple as increasing the distance or as painful as redesigning the BPM and/or the nearby component.

PROTOTYPING AND MEASUREMENTS OF FEEDTHROUGHS AND BODIES

The finished RF design of the mechanical body has to be converted into a mechanical design. The feedthroughs require special care in the performance (power dissipation, see above) and signal transmission/reflection. For the case that the environmental temperature changes over a large range, e.g. when using in cryogenic chambers, test procedures of the feedthroughs for warm-cold cycles have to be made to verify the tightness under all conditions, see [14]. An additional aspect is the reliable contact between body, gasket and feedthrough. These parts have small mechanical tolerances to fulfill the accuracy and need to remain tight over a long time period. The gasket needs to be pressed but not too strongly to always be in an elastic region.

The signal reflection of a feedthrough can change the external coupling of a cavity BPM with low quality factor. Therefore the reflection of the feedthrough needs to be measured, see an example in Figure 1. When the reflection of the

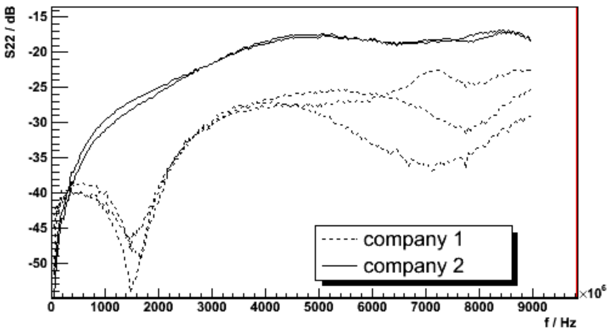

Figure 1: Measured reflection of feedthroughs from different companies. The reflection result of the feedthrough from company 1 fulfill the requirement of <-25 dB at 3.3 GHz but company 2 with cheaper feedthroughs not.

feedthrough is higher than allowed one can involve products from other proven companies or design a new feedthrough. Similar situation arises when the mechanical design of available feedthroughs does not match the RF design (e.g. button diameter). New feedthrough designs should be developed and produced with the help of experienced companies. Note that involving a new company with a new feedthrough design requires more time since the company may need to be trained to produce these items in the desired accuracy.

The next step is the construction of a prototype, often done in the in-house workshop. The goal is to measure the performance of the BPM together with the feedthrough. For the prototypes a test setup in the laboratory needs to be developed and commissioned. An aspect of the design of such a setup is to ensure its feasibility for testing a large series of BPMs (see Figure 2). The laboratory measurements could show differences with respect to the expectations. The reasons should be found and corrected in the RF and in the mechanical design, e.g. see [15]. Some differences could be caused by the limited simulation resolution or the simulation of thin layers of large structures which are difficult for these software tools.

In addition to the laboratory measurements the prototypes should be tested in an accelerator. Here final tests can be performed with electronics prototypes to verify the overall performance. A standard procedure to measure the resolution is the 3 BPM drift method, where two BPMs are used

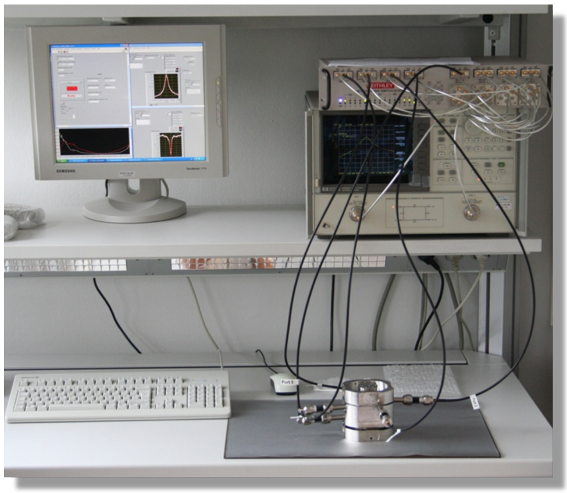

Figure 2: Test setup to measure the properties of cavity BPMs (situated on the right below) produced for the European XFEL. This setup consists of a network analyzer with computer control to measure all properties automatically with followed analysis and display of results.

to predict the position at a third BPM; the residual between predicted and measured position results in a resolution of the BPM system, see [16].

SELECTION OF COMPANIES

The production of a large number of BPMs may need to be outsourced. To fulfill the procurement rules and ensure a high quality of production the following procedure is helpful:

- Qualification: call for tender of a small number of items (pre-series).
- Test the quality of the production: identify companies who are able to produce the items with the required quality.
- Call for tender for the complete series for the qualified companies.
- Monitor the quality during all production processes (use the laboratory test setup developed during the prototyping).
- Check the finished items for precision and cleanliness, including all documentation.

This procedure was followed for the European XFEL feedthroughs and cavity BPM mechanics (the feedthroughs for the buttons includes the button itself). The mechanical body of the button BPM was produced in-house.

SERIES PRODUCTION AND QUALITY TESTS

During the main production of the BPM series the items need to be tested consistently to ensure the quality. In case of problems the production process might need to be changed.

Therefore a particularly close contact to the company is essential.

For the accuracy of a capacitive BPM the opposing antennas have to be aligned within the required precision. The mounting of the feedthrough flange of buttons has to be done with an accuracy better than required because the depth of the button is transformed 1:1 to the accuracy. Additionally pairing of buttons with similar transmission parameters is most helpful to minimize the effects of differences of the electrical and mechanical axes. The cables for a capacitive BPM have to be tuned to match the accuracy because mismatched cables will shift the calculated offset accordingly. For the accuracy of cavity BPMs a wire can be used to obtain the difference between the electric and mechanical axes; in addition an alignment iris can be used with a laser pointer to measure the difference between the laser direction and beam, see the setup for SACLA in [17].

OPERATION AT THE ACCELERATOR

In parallel to the BPM body production, the front-end electronics have to be designed, produced, tested (maybe improved) and commissioned. In addition the system needs ADCs to digitize and send the data to the control system, if necessary FPGAs for fast position calculations. Special care has to be given to the cables: near the beam pipe use radiation hard connectors and for capacitive BPMs the differences between the cables need to be small to not influence the accuracy. Trigger and maybe synchronization signals have to be provided to select the desired signals. To increase the dynamic range beyond the linear range the position calculation can be corrected by applying correction maps from simulations and measurements, see [18]. The calibration procedure in the accelerator needs to be defined: BPMs on remote movers require more space for their supports and a higher budget, calibration with steerers results in larger uncertainties.

The base of the support needs to be defined. In particular vibrations should not influence the BPM performance. For single bunch measurement with short bunch distances (beam repetition rate exceeding 100 Hz) the ground vibrations in this frequency range are usual below 10 nm. But for frequencies lower than 100 Hz the vibrations could exceed some hundred nm. Therefore different kinds of supports have been developed to dampen the vibrations: e.g. ceramic tube filled with sand and the low level of the beam pipe for SACLA. Additional vibrations from the beam pipe and heating due to synchrotron radiation could influence the position measurement. To control the BPM position a movement monitor at PETRA III [19] and LCLS [20] has been used. Here a wire is connected to the ground floor and 4 orthogonal pickups are connected to the beam pipe. The signals of the pickups show the relative movements of the beam pipe and the BPM to the ground. Up to 4.5 μm have been measured at PETRA III [19] and 1 μm at LCLS [20].

The commissioning of the BPM system has to be done by testing the complete system with beam together with the control system. Pre-calibration based on laboratory measurements should be used. Once stable beam is available the BPMs can be fine calibrated by beam based alignment methods. The stability of the BPM readings need to be verified during machine operation, e.g. see [19, 21].

SUMMARY

The development of a BPM system requires extensive use of simulation tools to speed up the design time of the mechanical body. Tolerances and their correlations need to be simulated to start the mechanical design. The power dissipation has to be simulated and if necessary be reduced by adequate redesigns. Special attention has to be given to the feedthroughs which need to be produced with high precision and high quality before the production of the body and within the budget. A prototype production and its inspection help find differences between simulations and measurement results and help optimize the series production. The series production needs to be controlled consistently to react quickly to optimize and prevent quality degradation. Additional actions may be needed to match the accuracy requirement (cabling, mechanical alignment, support vibrations and thermal effects). The BPM system including the electronics has to be commissioned first with laboratory calibration results. The final calibration is done with beam. The overall performance of the system should be monitored during operations. Do not forget that the mean time between failure of components is limited therefore order spare parts and verify that components should be available for a longer time. Prepare a detailed documentation of the system such that it is possible to re-produce parts of the BPM system.

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