Experiences of the QSBPM System on MAX II

Peter Röjsel

MAX-lab, Lund University, Lund, Sweden

Abstract. The MAX II is a third-generation synchrotron radiation source. The first beamline is in operation and several others are in the commissioning phase. The storage ring is equipped with a Quadrupole Shunt BPM (QSBPM) system for *in situ* calibration of the button-pickup BPM system. The calibration system uses switchable shunts on the combined-function quadrupole-sextupole magnets to find their magnetic centers. The BPM system has a time constant of several seconds, so a switched system is the only possibility. Each BPM pickup head and its corresponding electronics have been calibrated with the QSBPM system. The system has been in operation for about two years and operational experience, together with the technique itself, is discussed. The quadrupole shunts that are a part of the QSBPM system are, together with a spectrum analyzer and a tracking generator, also used to measure the beta functions individually in all main quadrupoles of the machine.

INTRODUCTION

The BPM system of MAX II is a multiplexed button pickup system of a type similar to that used at many third generation synchrotron radiation sources. The light source has a high brightness and small beam dimensions, which sets very high requirements on the stability of the beam and consequently on the BPM system. The QSBPM system makes it possible to do an *in situ* calibration of the BPM system's zero position reading using the main quadrupole magnets as the position reference.

Error sources in a BPM system

A number of sources generate errors in the BPM readings. Apart from the obvious mechanical positioning errors of the BPM pickups, we have a number of electrical "positioning" errors. The main error source in the MAX II BPM system is the unequal attenuation of the rf signals in the signal path of the BPM system, where the four rf signals from the buttons in one BPM head travel through different cables, connectors, filters and different inputs of the rf-multiplexer at the input of the BPM electronics. From the multiplexer's common point onwards, the BPM-button signals travel through and are processed by common circuits, multiplexed in time.

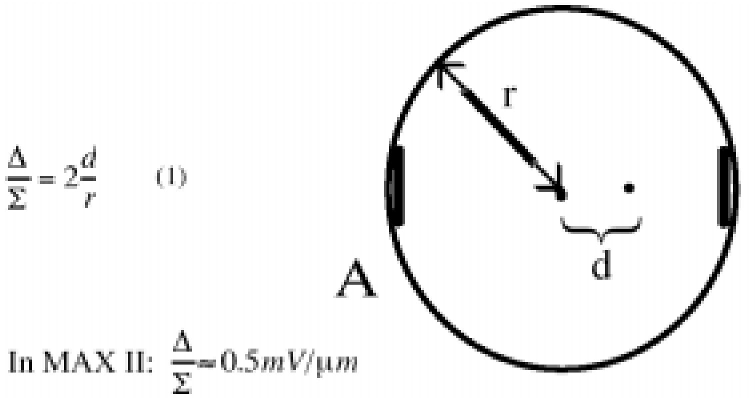

FIGURE 1. Signal in a BPM head.

Normal tolerances of attenuation imbalance in the electronic rf components can result in significant amounts of position error. Here is an example: A difference in attenuation between the channels A and B, connected to a BPM head of ±0.3 dB results in an error in the absolute beam position reading from that BPM head of ±0.5 mm. How can this be?

Let us, in our example in Figure 1, take d=0 and the voltage output from our BPM electronics to be 15 V for button A, a perfect signal, and the signal from button B to be (15–0.0005)V, as a less-perfect signal. The difference between A and B in dB is then: 0.5µm = 0.0003 dB and 1mm = 0.58 dB. The input multiplexer of the MAX II BPM system has a guaranteed maximum unbalance of 0.3 dB between the four input channels. This amounts to approximately 0.5 mm in offset!

An SMA connector exhibits a change in through attenuation in the range of 0.006 dB when being unplugged and then reconnected (and tightened using an SMA torque wrench), which corresponds to 10 µm offset. It should be noted that SMA connectors are among the type of connectors exhibiting the best data for this kind of application.

We clearly have a need to calibrate the BPM systems position offset *in situ* since even the unplugging and reconnection of high-quality connectors will affect the offset.

QSBPM PRINCIPLE

The basic idea of the QSBPM is quite old. It is based on the principle that, when modulating the strength of a single quadrupole magnet in a circular machine holding a stored beam, the closed orbit will move if the beam is not centered in the modulated quadrupole magnet. The modulation can be made in a variety of ways. In MAX II we use individually switchable shunts on each quadrupole magnet in the machine since our BPM system has a time constant of several seconds and a faster modulation would not be registered by the BPM system. The QSBPM system measures the BPM pickups offset with respect to the quadrupole magnets' magnetic centers in the machine by shunting off some current from the quadrupole nearest to the BPM head where the position offset is to be measured. The QSBPM system requires a BPM system with rather high resolution to read the beam position changes. We shall see later that some tricks can be used to increase the amount of data available, which, via averaging, increases the precision.

MAX II combined quadrupole-sextupoles

In MAX II the main focusing quadrupole magnet also has the main sextupole component integrated (4).The sextupole component is determined by the shape of the magnet's iron yoke so the sextupole component can only be slightly adjusted with a backleg winding. To make things even more complex, the yoke is slightly saturated when the machine is ramped to its full energy of 1.5 GeV. The saturation results in the magnetic center of the magnet being moved horizontally. We compensate for this with backleg windings. When a shunt on such a magnet is activated, the saturation is reduced and the magnetic center is moved about 3 mm horizontally. This could be compensated with a backleg winding on that magnet either with an additional shunt that is made variable or by providing an individual power supply for the backleg winding. In either case, we would rely on the magnetic field maps provided by the manufacturer and a model, which would reduce the precision in the BPM offset measurements since the exact magnetic center of the magnet will not be well known. This saturation effect makes it difficult to use the MAX II magnets for QSBPM purposes at full energy. Fortunately the beam in MAX II shows a long lifetime, even at the injection energy of 500 MeV where the magnets are far from saturation and the backleg windings can be shut off completely. Now we have a well-known magnetic center for the focusing magnets. Since the energy of the machine does not affect the BPM offsets we decided to measure the BPM offsets at the injection energy of 500 MeV.

The Shunts

The shunts on the quadrupole magnets are quite simple. They consists of a power resistor, a power MOSFET as the switch, and a photovoltaic optocoupler as the galvanic isolator and drive circuit for the powerMOS switch transistor. The schematic can be seen in Figure 2. There is one shunt on each quadrupole magnet. Each shunt can be controlled individually from the accelerator's control system, which also runs the BPM program and the QSBPM calibration program. The shunts in MAX II take 2 – 3 % of the magnet current.

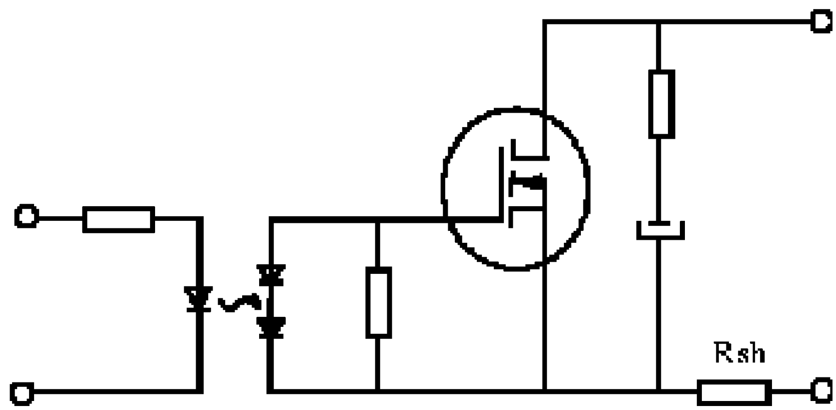

FIGURE 2. Schematic of a quadrupole shunt.

The BPM System

The BPM system must be able to measure the orbit shift induced by the quadrupole shunts. To do this with enough precision to create a BPM offset table that has the same or better precision as an ordinary BPM measurement, we have to use some tricks. One is to use data from all BPMs when determining the offset in one BPM. We can do this since only the amount of beam movement is interesting here.

The BPM system in MAX II has a time constant of a few seconds. The time for the reading to settle to its final precision is about 30 seconds. However the reading of one BPM takes almost as long as the reading of all 30 due to the parallelism used in the readout system.

Method Used to Find the BPM Offsets

We use a method that is rather easy to program so that the process can be automated, since it is rather lengthy. The example below is from MAX II but should, with adaption, be useful at most storage rings.

1. Start with beam in the machine, and a reasonably corrected, closed orbit.
2. Choose a BPM to be calibrated: e.g. Cell # 4 BPM #1 horizontal.
3. Set the nearby correction magnet to its current value –500. (The range is ±2047).
4. Measure the closed orbit and store it in a buffer.
5. Activate the shunt on the quadrupole closest to the BPM.
6. Measure the closed orbit again and subtract "buffer" from the readings.
7. Release the shunt.
8. Apply the formula given in Equation 2, below, to the shunt-induced difference position. Now, you have one point in Figure 3.
9. Increase the value of the correction magnet by +200.
10. Go to 4 if 5 points are not measured.
11. Do a least-squares fit of the five data points and find the minimum point. The correction value corresponding to the minimum point puts the beam in the middle of the shunted quadrupole.
12. Set the calculated correction value and read the BPM to be calibrated. This reading is the offset value since the beam now is in the center of the BPM.

$$f\left(I_{corr}\right) = \frac{1}{30}\sum_{i=1}^{30}\left(x_{BPMi}\right)^2 \tag{2}$$

As we can see in Figure 3 the curve minimum is below zero. A little disturbing. We found after some experiments that a fourth-order fit, which is the exact curve fit for five points actually gives a more accurate minimum although it is mathematically wrong. When this minimum is used, we get a better BPM offset reading. This is empirically confirmed, so we use it.

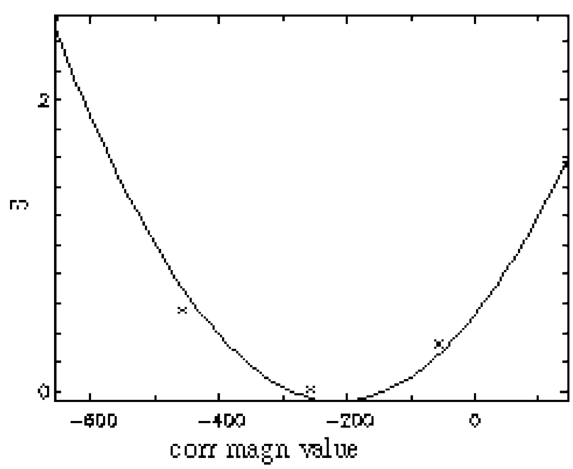

FIGURE 3. Plot of the fitted function of a real BPM calibration.

RESULTS FROM MAX II

Several BPM calibration runs using the QSBPM principle have been performed on MAX II. The results from a series of calibrations can be seen in Figures 4 and 5.

The vertical calibration runs in Figure 5 show an offset, randomly spread around the machine, with a mean value of zero. The horizontal calibration runs in Figure 4 have an offset of roughly 0.5 mm. This is an effect of the integrated sextupole component in the quadrupole magnets. If we change the backleg winding current or just use a different magnetization cycle we will change the horizontal offsets. We have thus defined a specific backleg winding current of zero and a specific magnetization cycle for the quadrupoles. This will also keep the closed-orbit reproducibility in control.

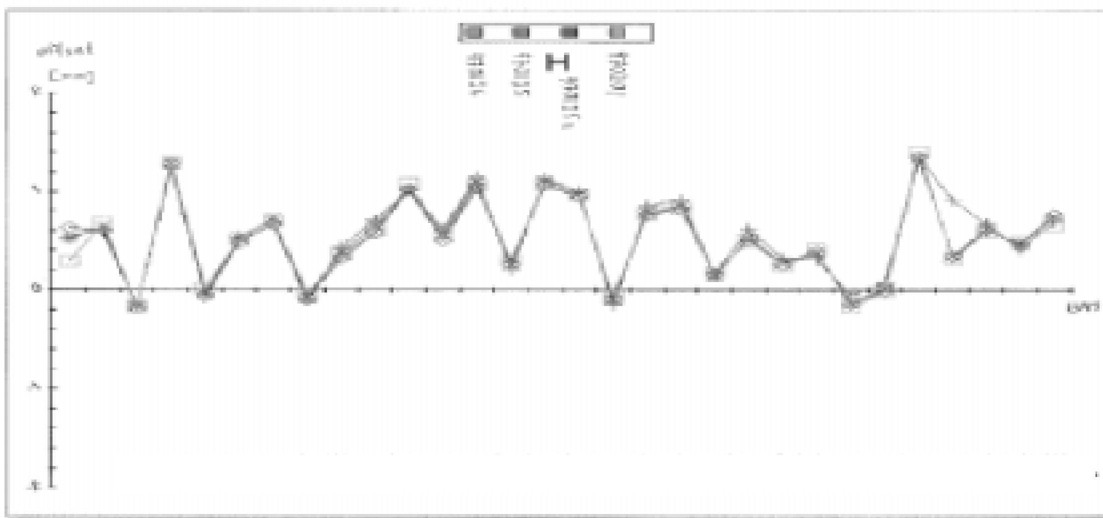

FIGURE 4. Calibration runs in horizontal, showing fairly good reproducibility.

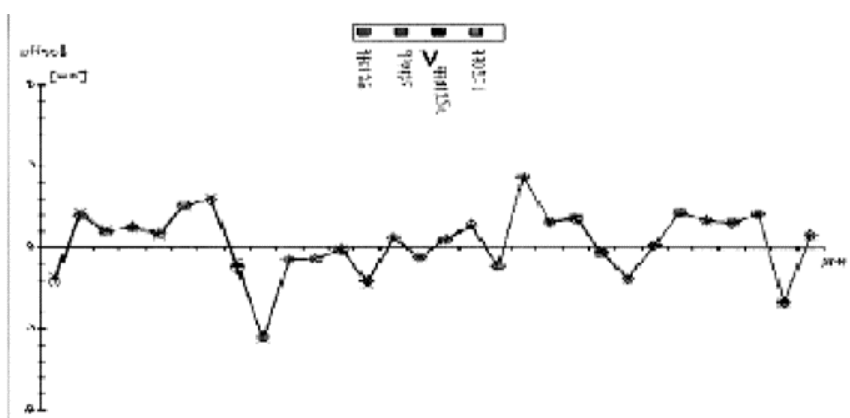

FIGURE 5. Calibration runs in vertical, showing very good reproducibility.

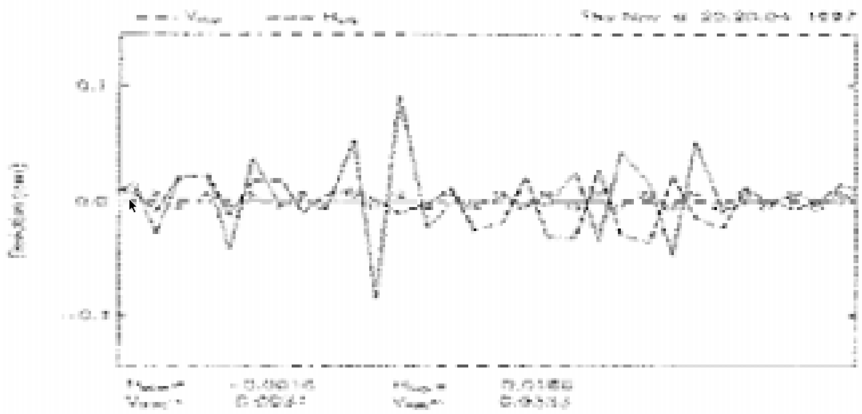

FIGURE 6. The best possible orbit correction without offset calibration.

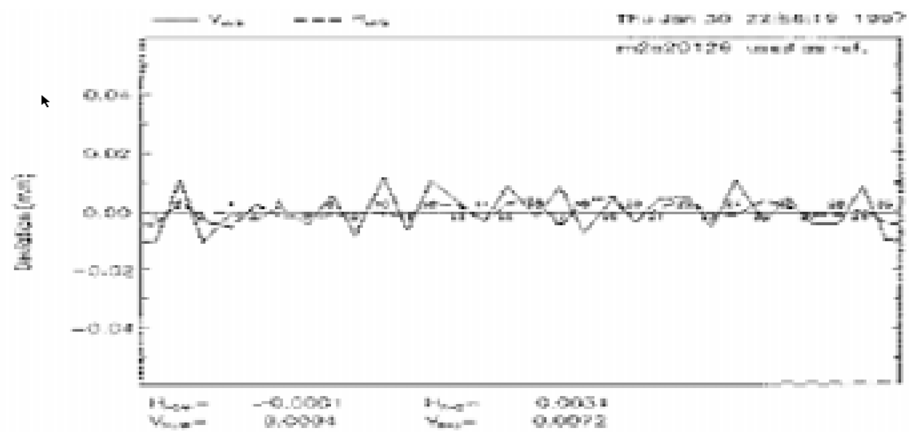

FIGURE 7. Final orbit correction after BPM calibration with the QSBPM method.

TABLE 1. BPM Offsets Measured at One QSBPM Run on MAX II

h:	BPM1	BPM2	BPM3	v:	BPM1	BPM2	BPM3
cell 1	0.559	0.627	–0.098	cell 1	–0.528	0.316	0.130
cell 2	1.387	0.011	0.611	cell 2	0.188	0.127	0.456
cell 3	0.780	–0.058	0.462	cell 3	0.516	–0.271	–1.203
cell 4	0.640	1.054	0.640	cell 4	–0.250	–0.176	–0.086
cell 5	1.128	0.271	1.186	cell 5	–0.493	0.067	–0.174
cell 6	0.993	–0.064	0.840	cell 6	0.021	0.258	–0.330
cell 7	0.890	0.186	0.617	cell 7	0.763	0.243	0.225
cell 8	0.258	0.393	–0.034	cell 8	–0.145	–0.417	–0.068
cell 9	0.121	1.401	0.446	cell 9	0.362	0.261	0.222
cell 10	0.734	0.479	0.802	cell 10	0.334	–0.716	0.074

As can be seen in Table 1, the BPM offsets are up to 1.4 mm horizontally and up to 1.2 mm vertically.

BETA FUNCTION MEASUREMENTS

The shunts can also be used to determine the local beta functions in the shunted quadrupole magnet. If we observe the tune shift induced by the activated shunt from every quadrupole magnet, we can plot the machine beta functions. This gives lattice information that can be compared to the theoretically calculated values.

CONCLUSIONS

The QSBPM system for BPM calibration has improved the quality of the delivered synchrotron radiation and shown that it can be implemented even on machines with rather “exotic” magnets such as MAX II.

QSBPM systems have been implemented in the two storage rings at MAX-lab and the technique is also used at many other labs. (2,3)

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