QUADRUPOLE SHUNT BPM SYSTEM AND ITS POSSIBLE APPLICATION TO BEAM BASED ALIGNMENT

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This beam position measurement system uses a method to measure the beam-position with high precision in a storage-ring with respect to the quadrupole magnets magnetic centra. The absolute position of the pickup elements does not affect the beam position measurements so a calibration of the pick-up elements absolute position can be done in situ. This paper describes the QSBPM-system, and shows results from a working system at the MAX I storage ring. A short discussion on the possible application to beam based alignment is included. Algorithms for beam based alignment can be found elsewhere in these proceedings [7].

1. Introduction.

The main beam position determining element in a storage ring is the quadrupole magnets which are usually very accurately aligned. We have in them very good reference points for beam position measurements. To be able to control the position of the beam inside the machine the beam position has to be measured with an accuracy greater than the stability demand on the beam. With a stability demand of less than 0.10 this is not a trivial problem in the third generation storage rings with very small beam dimensions. The users set very high demands on the beam stability of synchrotron radiation produced by undulators and wigglers because of very long beamlines and high resolution spectroscopy, refs. 1,2.

Most existing systems today use the pickup elements position as the reference against which the beam position is measured. The quadrupole magnets in a machine determines where the position of the ideal closed orbit should be. With the QSBPM system, problems related to the BPM heads calibration, alignment, their positional and electrical drifts have been eliminated. This greatly relaxes the design constraints on the rigidity of the support structures for the pickup heads and gives as many measuring points as there are quadrupoles in the machine. The QSBPM system can also be used to perform an in situ calibration of the pickup systems absolute zero position. The QSBPM system uses very little additional hardware which makes it very easy to retrofit to an existing machine. It is also easy to measure the b-functions in all quadrupoles in the machine from the control room using the same equipment.

2. Detectors, ‘pickups’.

Any kind of position pickups can be used. Any well functioning BPM-system is usable if it has at least a few working pickup heads in suitable positions around the ring. One good way to detect a beam position change in a small low energy storage ring like MAX I is by looking at the visible synchrotron radiation produced in the storage ring dipole magnets. In this small ring it is easy to with high accuracy measure the electron beam position at a fixed point in a dipole hend-

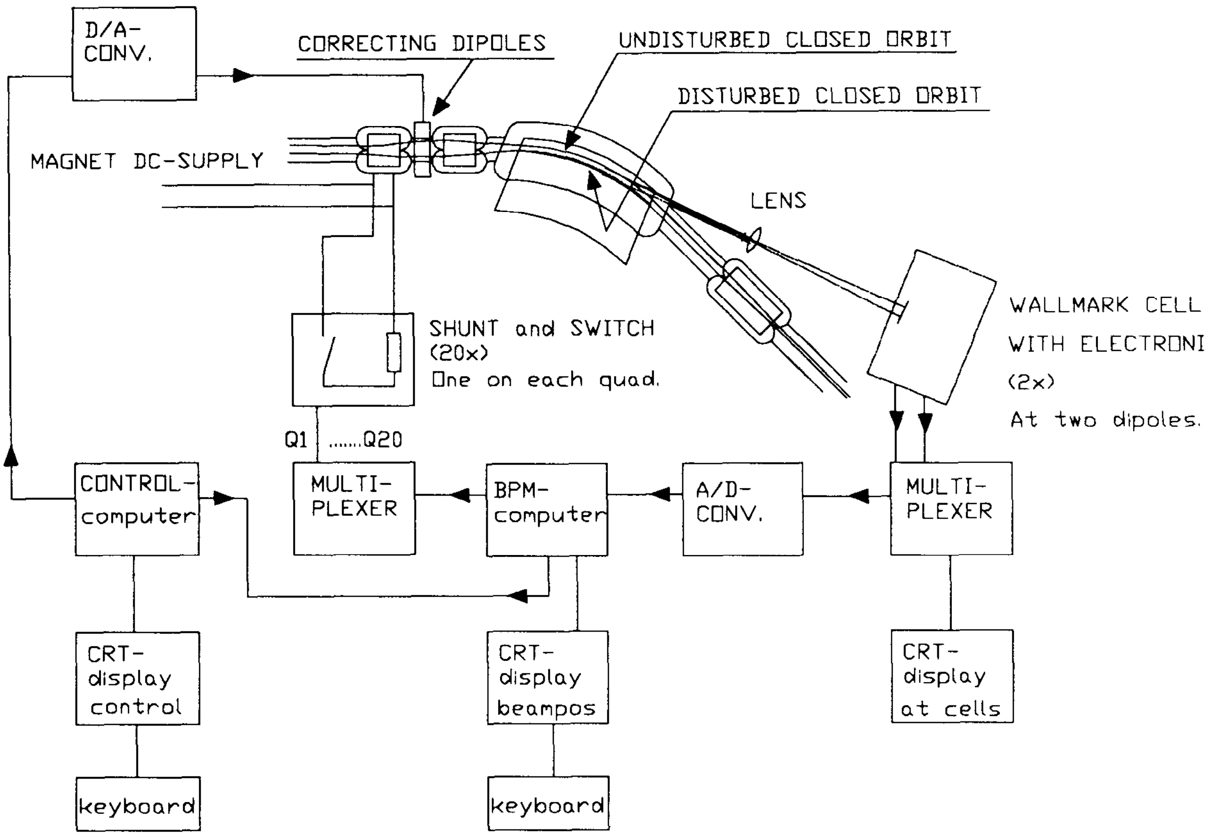

Fig. 1. Block schematic of the measuring system.

ing magnet. The synchrotron light is via a single lens focused onto the position detector. The detector can be placed at some unused dipole beam port. A typical setup is shown in Fig. 1.

The detectors in the MAX I storage ring are Wallmark plate detectors for visible light. These plates can determine a lightspots centre of gravity position with an accuracy of 0.001 mm or better on the surface of the detector element. The detectors used here are described in ref. 3.

3. How to measure the beam position with respect to a quadrupole magnets magnetic centre.

If the beams centre of gravity is offset from the centre of a quadrupole the whole beam will be bent in the quadrupole. To determine this offset we change the strength of the quadrupole magnet slightly. The beam will then be bent a little differently and a new closed orbit is created in the machine. Two BPM pickups separated 90° in betatron phase space provides information to calculate the beam position in the changed quadrupole.

To calculate the beams offset position from the magnetic centre in that particular quadrupole magnet. we need to know the betatron functions of the machine, the field gradient in the quadrupole magnet, the position of the detectors and the position of the changed quadrupole magnet in the ring.

The simplest and fastest method to translate the beam position movement on a detector to a beam position in the quadrupole at runtime is to multiply each detector signal by a coefficient. A table of coefficients can be calculated beforehand with some kind of accelerator design program.

3.1. Coefficients.

To calculate the table of coefficients from the lattice data we use an analytical formula: eq. 1a, which can be derived from eq. 1, that is found in ref. 4.

$$y = \left(\frac{\sqrt{\beta(s)\,\beta_k}}{2\sin\pi Q} \frac{\delta(B\,l)}{B_\rho} \right) \cos Q\varphi(s) \qquad \text{(eq. 1.)}$$

The coefficients C_{xj} and C_{yj} are defined as:

$$\frac{1}{C_j} = \left(\frac{\sqrt{\beta_{detector}\,\beta_{quad}}}{2\sin\pi Q} K_{quad}\, k_{shunt}\, L_{quad} \right) \cos(2\pi \left| \nu_{detector} - \nu_{quad} \right| - \pi Q) \qquad \text{(eq. 1a.)}$$

Where:

β is the beta function at the detector and the changed quadupole respectively,

K_{quad} is the strength of the undisturbed quadrupole in m ($K_{quad} = B0/rB\rho$),

k_{shunt} is the size of the disturbance applied to the quadrupole,

L_{quad} is the length of the quadrupole,

Q is the betatron tune of the machine,

and $|\nu_{detector} - \nu_{quad}|$ is the advance in betatron phase from the detector to the changed quadrupole.

We can see from eq. la that a bigger change in the quadrupole strength (a bigger k_{shunt}) will result in a larger beam position change when a shunt is activated, and a smaller C_j. The value of k_{shunt} also influences the lattice of the machine changing the β function and the tune. As an example, here are some of the parameters for the MAX I storage ring: k_{shunt} is about 0.04 which means that the quadrupole strength is reduced about 4% which is enough to make an accurate measurement and still not disturb the machine too much. This coefficient has to be determined for each lattice this measuring method is to be used on. In the MAX I ring the tune changes by about 1 %. Horizontally from 3.16 to 3.14 and vertically from 1.31 to 1.32 when one shunt is activated. The beta function at the shunted quad changes less than 10 %, from 5.83m to 6.33m horizontally and from 3.5m to 3.6m vertically. This is in a horizontally focusing quad.

The tune, phase and so on are slightly changed as indicated above when one quadrupole shunt is activated. Tests at MAX I has shown that the changes are so small that it is not useful to include this second order effect in the calculations.

In the table of C_{yj} there will be some very large coefficients corresponding to points in the machine where the cosine term in eq. la becomes very small. If we use two detectors instead of one, and place them at $\pi/2$ away from each other one detector will always be near a point where the distance from the Q-pole magnet to the pickup element gives a cosine term close to ±1. In this way we can avoid the large coefficients of C_{yj}.

One table of coefficients is calculated for each detector. Signals from the detectors are weighed together to produce as accurate a measurement as possible. The weighing is proportional to the size of the coefficient $Cy_j(n)$ for each of the detectors.

The measurement scale accuracy is of course highly dependent on the correctness in size of the coefficients Cyj. If the program only is to be used for putting the beam in the magnetic centre of the machine the coefficients does not have to be absolutely correct as long as the order of magnitude and the sign is correct. No beam position shift will occur if the beam passes in the centre of the quadrupole. Zero position shift multiplied with almost any coefficient is zero. If the BPM-system is to be used to reproduce an earlier measured orbit, the important thing is to use exactly the same table of coefficients as in the earlier measurement.

3.2. β-function measurement.

As a side effect the quadrupole shunts can be used to easily measure the b-functions of the machine from the control room. Just close one shunt in the system and watch the tune shift on a network analyser connected to its pickup electrodes in the machine.

4. Hardware.

Some electronics is needed to do the measurements on the beam. The detector used in MAX I is described in ref. 3. Here follows a brief discussion on the way the quadrupole strength is changed, and of the computer hardware needed.

4.1. Quadrupole shunts.

The easiest way to change a quadrupole magnets strength a few percent is to reduce the current to the coils a few percent. This is easiest done by connecting a resistor across the coils to shunt off part of the current. A resistor is connected to the magnet windings via a semiconductor switch to secure good reproducibility. Each quadrupole magnet in a family is connected in a series chain and has a different potential with respect to each other and to ground. The control signals to the switches which has a common ground in the control computer must thus be galvanically separated from the switch elements. The switchable shunts on the quadrupole magnets are made with one powermos transistor as the switch and a resistor as the shunt element. Galvanic isolation for the transistors control signal must be provided.

4.2. Requirements on the quadrupole power supplies.

The quadrupole magnet power-supplies must be able to within some time after a quadrupole shunt is switched on or off adjust to the load change presented to them. The total impedance in the quadrupole family is slightly reduced when a shunt is activated. Although the total load on the power supply in MAX I only changes by about 0.5% the voltage across the magnet family must be reduced with 0.5% to maintain the same current as without the activated shunt.

5. Software.

The QSBPM computer program is fairly simple. The only tasks performed are control of the measuring hardware, multiplication with a table of coefficients mentioned earlier and presentation of a plot of the measured closed orbit on the computer screen. The program also has functions to measure only at specified points of the orbit and to output the plot on paper or store it on file and so on. The program can also calculate a new set of strengths for the correcting dipoles in the ring to minimise the closed orbit error. Results from automated beam position correction runs is shown later.

6. Expected sensitivity of the method and influence of errors.

The measuring sensitivity is on an ideal storage ring equal to the detector sensitivity times the coefficients calculated in eq. la. The sensitivity is as can be seen from eq. la proportional to how much of the magnet current that can be shunted away without disturbing the lattice to much. On the MAX I machine the amount of shunted current in one quadrupole is about 4.5% of the total magnet current. The average of the absolute value of the coefficients is around 38 horizontally and 15 vertically for both detectors. Now a weighted reading from both detectors is used. This means that with a detector resolution of 0.0024 mm the resolutions will be

$$\frac{38}{\sqrt{2}} * 0.0024 = 0.065 \text{ mm horizontally and}$$

$$\frac{15}{\sqrt{2}} * 0.0024 = 0.026 \text{ mm vertically.}$$

6.1. Verifying the coefficients C_{xj} and C_{yj}.

The correctness of the coefficients C_{xj} and C_{yj} can be established in a number of ways. One very simple and quick method to check the coefficients in the horizontal plane is to first measure the beam position and then change the acceleration frequency slightly, and measure again. The difference between the two orbits should show the dispersion function in the machine. The theoretical dispersion function can be calculated and plotted. If the lattice is correct (which can be established with other methods) the theoretical dispersion function will be the one plotted on the QSBPM-computer screen. A second method is to use small dipoles with well known strengths and by putting one into the machine and measuring the orbit before and after the dipole has been put in, again the difference shows if the program measures the closed orbit correctly. This second method works in both the vertical and horizontal measuring planes.

6.2. Influence of alignment and other errors on the zero position.

The closed orbit zero position is always a well defined point in a quadrupole magnet, and so it is in the machine if the quadrupole is correctly aligned. The quadrupole magnets are thus used as the fixed references to measure the beam position from. The quadrupole magnets must in any machine be aligned with better precision than is required of the beam position so they are a most useful reference. Actually the position of the quadrupoles magnetic centre is the closed orbit zero position.

In the MAX I machine we found that when the closed orbit had been corrected as good as possible the remaining closed orbit errors came from misalignments of the quadrupoles. If in a doublet the two quadrupoles are not very closely on the same axis it will not be possible to with normal correcting magnets push the beam to the centre in both quads. To refrain from having to realign the machine we defined the most powerful of the two quads as the position reference. It can be seen in figures 4 and 5 that all quads are in the measurement, but in figure 6 where the orbit has been well corrected the measurements from the defocussing quads are not used (no bends in the curve at these points). The defocussing quads are at marks number 2,4,7,9,... in the figures.

6.3. Influence of errors on the scale.

The error in scale in the measurement when the beam is offset from the magnets centre is dependent on a number of factors. A few factors to be considered are: The tolerance of the shunt resistor, the winding resistance of the magnet, how well the tunes and the lattice are known, and so on. As a whole it can be said that these errors can be controlled to result in an error of only a few percent. The main importance lies in the fact that the errors do not change over time so that the measurements are reproducible and that zero position is well defined.

7. Automatic closed orbit correction.

The QSBPM-program is equipped with an automatic beam position correction method. Since MAX I is a rather small machine with integer tunes of 3 horizontally and 1 vertically we have chosen a method that uses a matrix describing the effect of every correction dipole in the machine on the beam position in every quadrupole magnet in the machine. The matrix is called a response matrix ref. 4. The response matrix can be either theoretically calculated or empirically measured. The empirical method includes all relevant errors in the storage ring, so the empirical method is preferred and used here. The raw data matrix is G. G is then pseudo inverted using eq. 2 to produce the matrix Δ, ref. 4.

$$\Delta = -(G^T G)^{-1} G^T Y \qquad \text{(eq. 2.)}$$

Now we have sufficient information of where the closed orbit is in the machine and how the correctors affects it. So we are now ready to centre the closed orbit in the machine.

The measured closed orbit is multiplied by the matrix A calculated in eq. 2. producing a set of correcting dipole strengths to be added to the present strengths. After applying the new correcting dipole strengths the closed orbit should theoretically be centred. In the real world a few iterations of the process where less than the full proposed change in corrector strength is applied are usually necessary.

7.1. Extracting realignment data.

In a theoretical response matrix we could put in the calculated closed orbit effects of misalignments of each quadrupole instead of the strengths of the corrector magnets. This would output a set of new position changes for the quadrupole magnets. It has however to be taken into account that a movement of a quadrupole a distance *l* will move the beam a distance *kl*. In MAX I *k* is about 5.

8. Typical results of closed orbit correction and a sample run.

Fig. 2 shows an example of a natural closed orbit in the MAX I machine before correction and with all correctors at zero strength. The marks on the horizontal axis are the quadrupole magnets. Each quadrupole magnet is a point where the beam position is measured. The dotted line shows the position in the horizontal plane and the thin solid line the position in the vertical plane. The two bars near the top of the figure are the BMS of the position errors in the horizontal and vertical planes respectively.

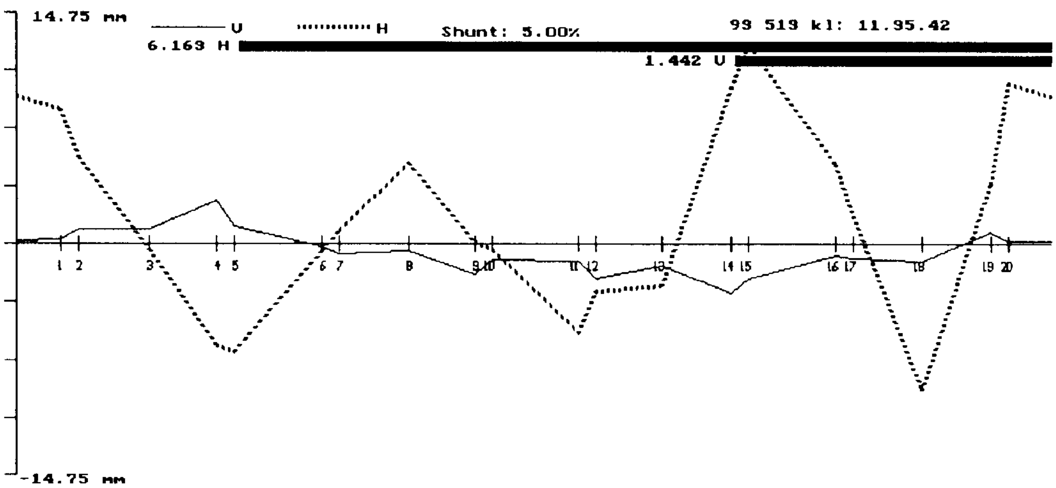

Fig. 2. Uncorrected closed orbit in MAX I. Each mark on the horizontal axis is a quadrupole magnet.

Now the resulting response matrices are multiplied with the measured beam position in the machine, producing a new set of strengths for the correcting dipoles. The inability to correct the beam position in the horizontal plane is a result of using too few correcting dipoles and of alignment errors internally in the doublet pairs. The horizontal tune is 3.16 and requires theoretically at least 10 correction dipoles, while the machine has only 8.

The requirements on the closed orbit can be somewhat relaxed after a thorough study of the requirements by the machine itself, and of what the synchrotron light users need. The points in the machine where the highest beam stability is required are in our two undulators. Both undulators are positioned in long straight sections and are thus surrounded by one horizontally focusing quadrupole on each side. The beta functions in this quadrupole which is quite strong are in the order of 6.5 meters horizontally and 3.5 meters vertically. The coefficients C_{xj} and C_{yj} are smallest in this magnet family resulting in high resolution in the beam position measurements.

The plot in Fig. 3. is almost as good an orbit as can be created in the MAX I storage ring. The difficulty in correcting the beam position is due to magnet misalignments which probably has increased over time due to settling of the floor. Fig. 4. shows a final corrected closed orbit using only the 8 most sensitive measuring points. Note that the vertical scale is expanded more than a factor of 10 relative to Fig. 2. The manual correction of some alignment errors of the quadrupoles resulted in a closed orbit deviation after automatic orbit correction that touches the sensitivity

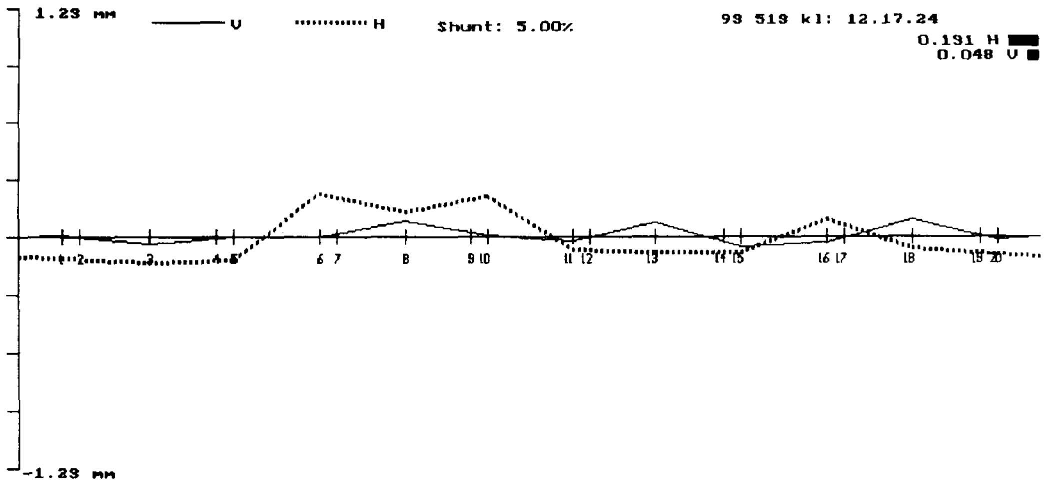

Fig. 3. The closed orbit after finished correction which is after about 3 iterations. Note the different vertical scale and do compare the RMS-bars at the top of the figure with the previous figures.

limit of the measuring system. A plot of the achieved closed orbit is found in Fig. 4. The realignment did also result in smaller strengths for the correcting dipoles giving more margin for future correction needs.

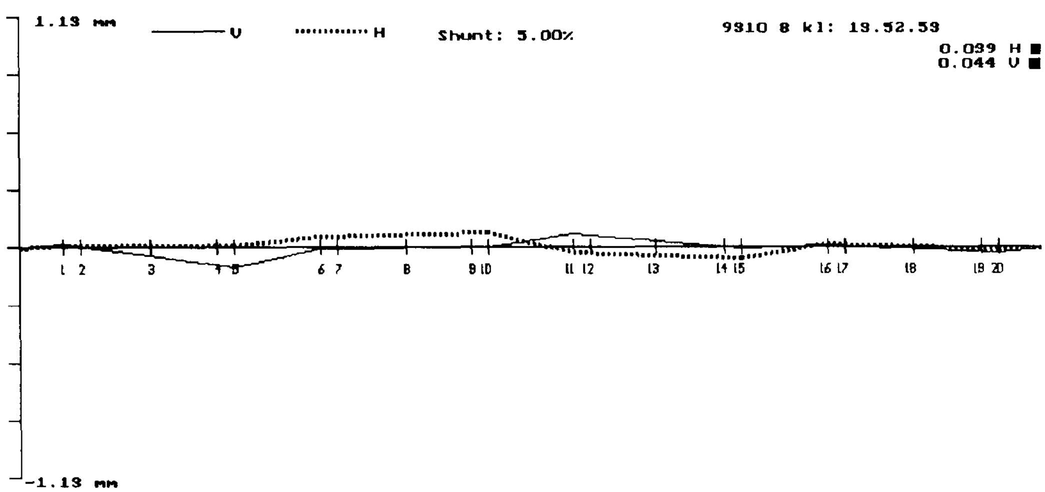

Fig. 4. The closed orbit after realignment of quadrupoles and automatic correction.

9. Using the measuring system as calibration for conventional button or stripline pickup systems.

The measurement method used in the QSBPM system disturbs the beam slightly during the measurement process, but often too much for the synchrotron light users taste. The position drift of buttons or striplines are usually a rather long term one. The shortest time scale involved is probably the time constant of the temperature in the machines vacuum chamber. By determining the difference between direct readings of the BPM electrodes and readings done by shunting quadrupoles a table of offsets can be stored in the computer and subtracted the pickup electrode measurements. This table should have the stored current as a parameter since this will he a factor that affects the reading from the pickup electrodes. This means that a set of tables with offsets for different stored currents should be stored in the computer. The calibration should for greatest accuracy and least influence of scale factor errors be done on a beam corrected to zero position.

10. Quadrupole Shunt BPM on the third generation synchrotron light source MAX II.

At MAX-lab there is another storage ring MAX II refs. 5,6, which is equipped with a similar BPM system. The machine has button pickups of conventional design, as well as Wallmark plate detectors. The electronics for the button pickups is of conventional type. However we will use the QSBPM system to continuously calibrate the conventional BPM system to eliminate all kind of long term drifts in the pickup system.

11. Conclutions.

The system described above shows a way to eliminate the problem of not knowing exactly where the perfect closed orbit is and enables calibration of an old existing BPM system as well as the possibility to find alignment errors in the machine. The described system measures the beam position with respect to the magnetic centra of the quadrupoles. We can thus relax the design constraints on the pickup heads mounting hardware and on the long term stability of the electronics involved. We has also seen that in the case of the MAX I storage ring that has no means of accurately checking the quadrupole magnets alignment mechanically, we could from the measurements with this system find some of the misalignments and correct them. The MAX II machine has a different mechanical design that aligns the magnets very accurately. However this requires that the magnetic centra of the quadrupoles are well defined with respect to the mechanical alignment surfaces on the magnets. We have also shown that the described system works very well in the MAX I machine.

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