BEAM BASED MACHINE MODELLING FOR ORBIT CONTROL AND FEEDBACK AT DELTA

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Abstract

The 1.5 GeV electron storage ring Delta uses quadrupole magnets with integrated sextupoles and steerers to obtain a compact lattice. However, saturation and hysteresis effects result in nonlinear interactions between the magnet components. Therefore, optic models have so far failed to reproduce the observed optics with the required precision. We thus used beam based methods to obtain a heuristic machine model. Beam based calibration has been used to measure offsets between the signal centers of the beam position monitors and the magnetic centers of their close-by quadrupoles. Measured response matrices are used as basis for orbit feedback and local orbit bumps. These steps have significantly improved machine stability and reliability.

1 SURVEY

1.1 Beam Position Monitors at DELTA

The electron storage ring DELTA uses capacitive beam position monitors (BPMs) with four pick-up electrodes to monitor the beam position in both transverse planes across the ring. There is a total of 43 BPMs, 40 of which are mounted close to an adjacent quadrupole yoke. 50% of those BPMs have bulged tapers to fit tightly between the hyperbolic pole shoes of their adjacent quadrupole, thus retaining a relative position to the mechanical center of the magnet within $\pm 70\,\mu$m. The remaining BPMs are allowed for relative movement of up to ± 1 mm ("floating BPMs") [1].

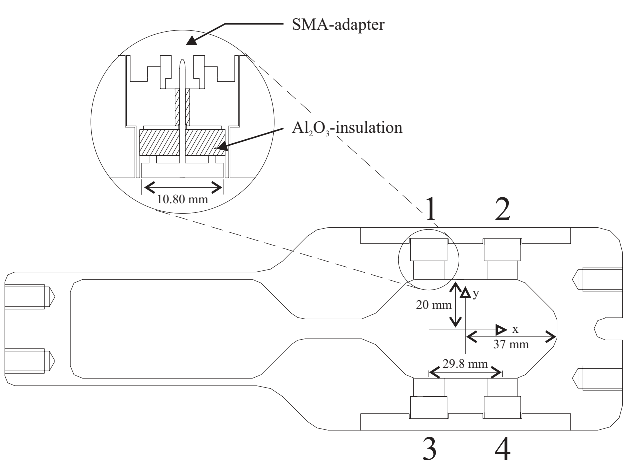

Figure 1: Transverse section through a capacitive pick-up BPM at DELTA.

Induced electromagnetic signals at the buttons of each BPM are dispensed by a multiplexer into a single 500 MHz amplifier of a high quality factor. The single amplitudes are then evaluated by means of subtraction and normalization to obtain a signal proportional to the beam offset. A 10 Hz low-pass filter reduces sampling noise while retaining a reasonable bandwidth for slow orbit feedback. A 12-bit ADC allows to resolve a relative orbit difference of about 5 μm. For a more detailed description see [2].

1.2 Diagnosis

A four quadrant power supply may be hooked up to each of the 76 DELTA quadrupoles for diagnostic purpose. This is accomplished by the use of two cascades consisting of successive layers of relais, each cascade responding to 6 digital input-lines [1]. This setup allows to vary the excitation current for each quadrupole within ± 3 A.

2 BEAM BASED CALIBRATION

2.1 Theory

Assuming a linear machine, it is possible to calibrate a BPM with respect to the magnetic center of a nearby quadrupole, by plotting the response of the closed orbit caused by variation in strength of its adjacent quadrupole versus the measured orbit offset within this BPM. With the closed orbit passing off-center through a quadrupole by an offset u, a variation of the quadrupole strength by Δk causes an orbit kick of

$$\theta = \Delta k l_{\text{eff}} \left[1 + \frac{(k+\Delta k) l_{\text{eff}} \beta_0 \sin\Psi}{2\cos\Psi - \Delta k l_{\text{eff}} \beta_0 \sin\Psi - 2} \right] u.$$

Here, β_0 is the amplitude of the local beta function and $\Psi = 2\pi Q$ represents the total phase advance along the entire ring for the plane under consideration. This kick will result in an orbit distortion at the location of BPM i of

$$\Delta u_i = \theta \sqrt{\beta_0 \beta_i} \frac{\cos(\pi Q - |\psi_0 - \psi_i|)}{2 \sin \pi Q}, \qquad (1)$$

with $\psi_0 - \psi_i$ being the phase advance between quadrupole and BPM. Note that the response is linear in θ, which in turn is linear in u so that

$$\sum_i \Delta u_i^2 \sim \theta^2 \sim u^2.$$

By taking a series of measurements using a constant Δk, it is thus possible to determine the orbit offset $\bar{u}$, which minimizes the effect upon the closed orbit by variation of the close-by quadrupole. One simply evaluates the location of the minimum of the measured parabola. Fig. 2 shows a typical example for such a series of measurements.

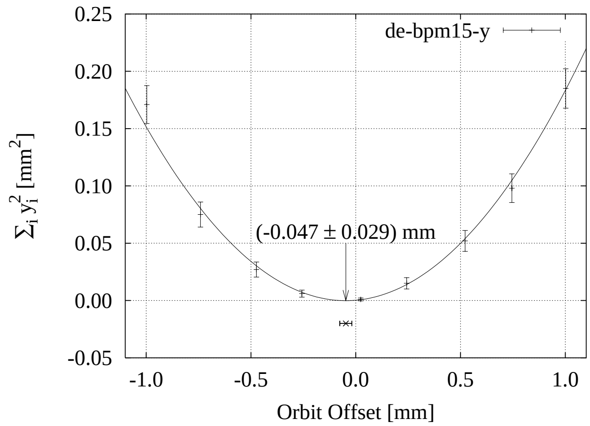

Figure 2: Typical series resulting in a vertical offset for BPM 15 of about $\bar{u} = -50\,\mu$m.

Due to an improved software interface for the corrector magnets, the use of a fast hook-up supply for diagnostic purpose and optimized software, the overall time consumption for a calibration of all 40 calibratable monitors has been reduced from a former 4 hours [1] to about 1 hour in total. With a well adjusted machine, beam loss during a complete series of measurements is negligable.

2.2 Accuracy

The statistical error of $\bar{u}$ may be reduced to any extent by the number of measurements taken. The major issue leading to a reduced accuracy is an unknown angle of incidence of the electron beam. Since the longitudinal position of the BPM and its adjacent quadrupole differ by half the length of the quadrupole yoke –i.e. 0.1 m for DELTA– this incidence generates an additional orbit offset between the two of them. Typical closed orbit angles value about ± 0.5 mrad. However, by using a local orbit bump or a single orbit corrector to sweep across the desired offset span, an additional slope of up to ± 2 mrad may result due to a linear dependency between the orbit offset and its slope. We label the real BPM offset $\bar{u}_0$, and the slope induced offset by $(\kappa + \gamma u)$. Employing the variances given above, $\kappa \approx \pm 50\,\mu$m and $\gamma \approx \pm 0.1$. Hence, the measured parabola as a function of the orbit offset u at the BPM transforms from $\alpha[u - \bar{u}_0]^2$ for a BPM centered within its quadrupole to $\alpha(1-\gamma)^2 \left[u - \frac{\bar{u}_0+\kappa}{1-\gamma}\right]^2 \equiv \alpha'[u - \bar{u}]$. To finally express a worst case estimate for the accuracy of measurement $\delta\bar{u}$, we solve

$$\left|\bar{u}_0 - \bar{u}\right|_{\bar{u}_0 = \delta\bar{u}} = \delta\bar{u}$$

for $\delta\bar{u}$ and obtain $\delta\bar{u} = |\kappa/(1-2|\gamma|)| \approx 65\,\mu$m for DELTA.

2.3 Results

Successive measurements have been taken over the last 20 months and allow to compare their results. After each measurement, monitor calibrations have been adjusted by the computed offsets, so that an immediate follow-up measurement should in principle yield zero offset for the corrected monitors. Fig. 3 shows the results of three series of measurements, two of which have been performed as an immediate follow-up.

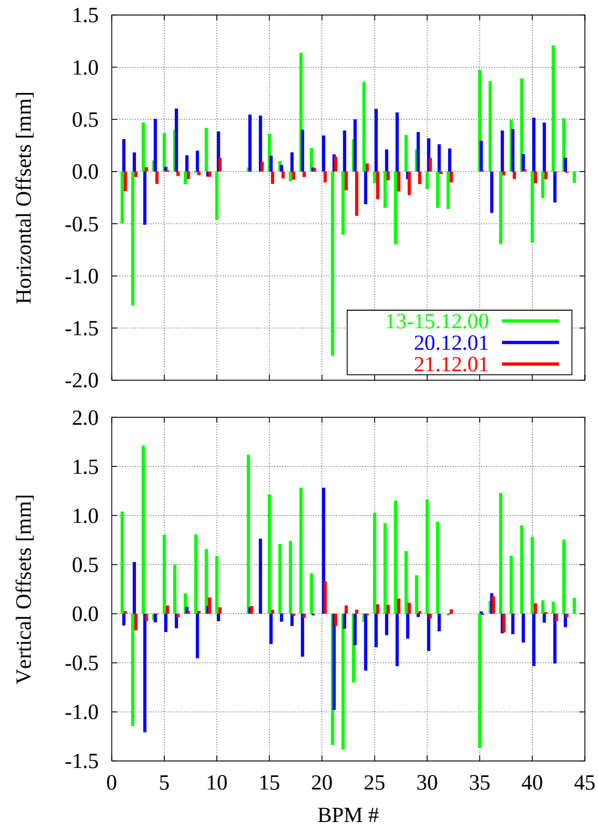

Figure 3: Calibration offset of three series of measurements.

First thing to notice are the rather big offsets measured for the first series taken in 12/00. The second series –taken a year later in 12/01– already shows significant smaller offsets, whereas the third measurement basically verifies an asymptotic improvement of monitor offsets. Indeed, this is what is to be expected, since an iterative refinement of monitor calibrations and orbit correction (see next section) should yield an optimized closed orbit, where nonlinearities and static orbit slopes (i.e. κ in the discussion above) will be minimized. Yet, this last measurement exhibits corrections beyond the measurement error of typically well below $100\,\mu$m, especially in the horizontal plane between BPM 20 and BPM 30. This is accorded to a local improvement of the horizontal orbit within this range, since a former abided DC injection bump has been taken back. When comparing offsets for floating and fixed BPMs, no significant difference becomes obvious. This suggests, that the floating BPMs may already be forced tight into the quadrupole aperture by chamber tensions. Hence they virtually lose their ability of free movement and behave like their fixed counterparts.

3 BEAM RESPONSE MATRIX

The quality of closed orbit feedback and local orbit bumps highly depend on the accuracy of the underlying machine model. In particular, the beam response matrix, i.e. the closed orbit changes in response of beam steering, must be as precise as possible. As Fig. 4 exemplifies, the response as calculated by the MAD (Methodical Accelerator Design) software [3] does not match measurements well enough. Thus, we decided to perform orbit correction based on measured beam responses only.

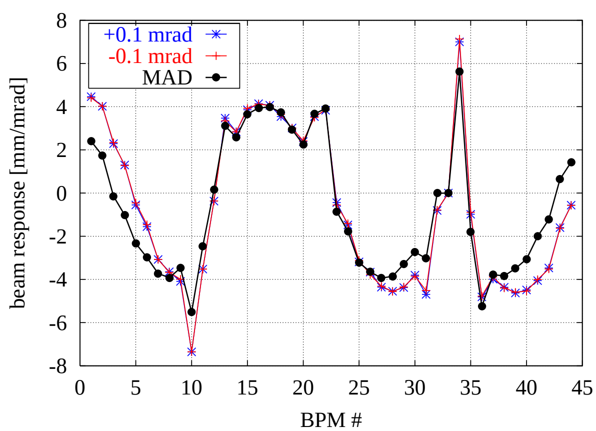

Figure 4: Beam response of a vertical steering magnet in comparison with its theoretical prediction (MAD).

3.1 Measurement

The beam response is defined as $\vec{r}_j = \partial\vec{u}/\partial\theta_j$, where $\vec{u}$ is the vector of orbit distortion at the BPMs (in x or z plane) caused by a kick angle of θ by steerer magnet j. The $\vec{r}_j$ can be combined to a matrix $\mathbf{R}_{ij} = \partial u_i/\partial\theta_j$. The theoretical beam response matrix is calculated in analogy to equation (1) as

$$\mathbf{R}_{ij} = \sqrt{\beta_j\beta_i}\frac{\cos(\pi Q - |\psi_j - \psi_i|)}{2\sin\pi Q}.$$

To measure $\mathbf{R}$, a set of kicks $\Delta\theta_{j,k}$ is successively applied to all steerers while the orbit distortions $\Delta\vec{u}_k$ are measured. The averaged $\mathbf{R}_{ij} = \langle(\Delta u_i/\Delta\theta_j)_k\rangle$ is a good approximation to the response matrix. The measurement is done by an automated software program and takes less then 10 minutes for both planes.

3.2 Local Bumps

To calculate a closed orbit bump, a combination of three steerer kicks must be found that have minimal effect on the orbit outside the bump region while producing a given distortion Δu within. Let $\vec{a}, \vec{b}, \vec{c}$ be the orbit responses $\vec{r}_a, \vec{r}_b, \vec{r}_c$ respectively but with the values $\mathbf{R}_{ij}$ within the bump region removed. Then the bump is closed when $(\theta_a\vec{a} + \theta_b\vec{b} + \theta_c\vec{c})^2$ reaches its minimum while $\theta_a\mathbf{R}_{ia} + \theta_b\mathbf{R}_{ib} + \theta_c\mathbf{R}_{ic} = \Delta u$ at BPM i within the bump. This can be achieved by

$$\begin{aligned}
\theta_b &= \theta_a \frac{(\vec{a}\cdot\vec{b})\vec{c}^2 - (\vec{a}\cdot\vec{c})(\vec{b}\cdot\vec{c})}{(\vec{b}\cdot\vec{c})^2 - \vec{b}^2\vec{c}^2} \equiv \theta_a\, F_b \\
\theta_c &= \theta_a \frac{(\vec{a}\cdot\vec{c})\vec{b}^2 - (\vec{a}\cdot\vec{b})(\vec{b}\cdot\vec{c})}{(\vec{b}\cdot\vec{c})^2 - \vec{b}^2\vec{c}^2} \equiv \theta_a\, F_c \\
\theta_a &= \frac{\Delta u}{\mathbf{R}_{ia} + F_b\,\mathbf{R}_{ib} + F_c\,\mathbf{R}_{ic}}
\end{aligned}$$

A bump with four steerers can be calculated in a similar way [4].

3.3 Global Orbit Feedback

The best corrector method can be implemented by minimizing the residual error $\varepsilon_j = |\vec{r}_j\,\theta_j - \vec{u}|$ with respect to a steerer kick θ_j. This leads to a kick of $\theta_j = \vec{r}_j \cdot \vec{u}/\vec{r}\cdot\vec{r}$. The best corrector is the steerer j whose ε_j is the least. One can show that this is the one with the largest effectivity $E_j \equiv (\vec{r}_j\cdot\vec{u})^2/\vec{r}\cdot\vec{r}$.

We often use the alternative method of the most efficient corrector. That is the steerer whose response vector is most similar to the orbit to be corrected, i.e. $(\vec{r}_j \cdot \vec{u})^2$ is the largest. The kick θ_j is calculated the same way as for the most effective corrector, but tends to have smaller values. This gives a slightly less optimal correction but has the advantage that the limits of the steerer kicks are not reached so soon.

The absolute closed orbit has been reduced to below $\pm 100\,\mu$m in each plane, with short-time drifts of less than $\pm 50\,\mu$m over several hours.

4 SUMMARY AND OUTLOOK

Successive progress of monitor calibrations and beam based orbit feedback have added to a significantly improved closed orbit at DELTA. Lifetime and beam stability have been increased. More calibrations are to be taken to verify a successive improvement in monitor offsets and to study heat induced monitor movements as a function of DELTA beam current.

5 REFERENCES

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