BEAM BASED ALIGNMENT OF COMBINED FUNCTION MAGNETS IN THE UPGRADED HERA INTERACTION REGIONS

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Abstract

In order to maximize the achievable luminosity of HERA the final focusing triplets of the lepton beam are installed close to the interaction point (IP). The dipole component of the magnets produces the necessary separation angle between the lepton and the proton beam. The synchrotron radiation generated in the magnets has to be passed through the detector beam pipe with extremely small losses for background reasons. Shape and power of the synchrotron radiation fan depend critically on the precise alignment of those magnets. We present measurements aimed at the determination of the beam vs. magnet offsets, as well as the identification of magnet position errors. We discuss systematic and random errors and difficulties that arise from the non-zero design offsets of the magnets. In order to increase the reliability and the speed of the measurements, automated procedures were developed and incorporated into the HERA control system.

1 INTRODUCTION AND MOTIVATION

HERA is an electron–proton collider with beam energies of 27.5 GeV and 920 GeV respectively. Recently the interaction regions (IRs) of the machine were rebuilt with the goal to increase the luminosity about threefold by decreasing the beam spots at the interaction point. The basic idea of the HERA upgrade project consists in positioning the final quadrupoles to focus the colliding proton and electron (or positron) beams closer to the IP. In order to allow for an early separation of the beams we use combined function quadrupoles to focus the beam, and to deflect the leptons at the same time by the necessary separation angle of about 8 mrad. The two innermost magnets are super-conducting, installed inside the experimental detectors. On the left side, from where the electrons come, the magnet is 3.2 m long. There are two normal conducting magnets on the left side, each with an iron length of 1.88 m. On the right side the super-conducting magnet has only a dipole component and the focusing is done with 3 normal conducting magnets of the same type as on the left side. All of these magnets contribute to the separation angle and the beam passes them off-center. The interaction region is shown in Fig. 1 with the above discussed triplet structures covering the region between -10 m and $+10$ m. A critical aspect of the new interaction region is the production of strong synchrotron radiation (SR) in the close vicinity of the detector. This radiation must pass the detector with very small losses in order to keep the background at acceptable levels. On the other hand the radiation generated in the triplet quadrupoles tends to exhibit relatively large opening angles since the beam tails radiate over proportional in a quadrupole field. Beam positions and angles have to be adjusted precisely in the triplet quadrupoles in order to pass the radiation fan safely through the beam pipe to the final absorber at 25 m distance to the IP. Beam–based alignment (BBA) methods are directly sensitive to the magnetic field the beam experiences in the quadrupoles and are therefore best suited to diagnose the beam orbit with respect to the magnetic centers of the quadrupoles across the IR.

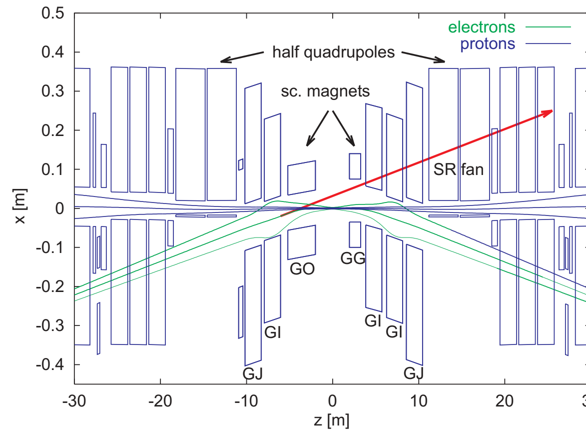

Figure 1: Top view of the new interaction region. The electron beam with $20\,\sigma$ envelope and the proton beam with $12\,\sigma$ are indicated as well as the synchrotron radiation fan and the magnets.

2 BBA FOR IR MAGNETS

In conventional beam–based alignment procedures, the relative alignment of a quadrupole to a nearby beam position monitor is determined by finding a beam position in the quadrupole at which the closed orbit does not change when the quadrupole field is varied. The final focus magnets of the interaction regions of circular colliders often have some specialized properties that make it difficult to perform conventional BBA procedures. At the HERA interaction points, for example, these properties are: (a) The quadrupoles are quite strong and long. Therefore a thin lens approximation is quite imprecise. (b) The effects of angular magnet offsets become significant. (c) The possibilities to steer the beam are limited as long as the alignment is not within specifications. (d) The beam orbit has design offsets and design angles with respect to the axis of the low-beta quadrupoles. (e) Often quadrupoles do not have a beam position monitor in their vicinity. Therefore a BBA procedure was derived which determines the relative offset of the closed orbit from a quadrupole center without requiring large orbit changes or monitors next to the quadrupole [1]. By taking into account the alignment angle, the sensitivity to optical errors was reduced by one to two orders of magnitude. In reference [1] the BBA measurements of all IR quadrupoles are used to determine the global position of the magnets and the sensitivity to errors of this BBA method is evaluated and its applicability to HERA is shown.

Usually, BBA methods evaluate the difference orbit that is excited by a change in the strength of a quadrupole. But quadrupole errors around the machine might lead to a misinterpretation of the quadrupole offsets to be evaluated and we therefore create a closed bump by changing the strength of the test quadrupole and by appropriately exciting two corrector coils.

The transport matrix G^+ of a dipole with superimposed quadrupole with a focusing strength that is changed by Δk can to first order be described by a matrix $\underline{\delta}$ applied at the center between two half quadrupoles g,

$$G^+ = G + g\underline{\delta}g + O(\Delta k^2)\ , \quad \underline{\delta} = \Delta kl \begin{pmatrix} 0 & \frac{1}{k}\sigma^- \\ -\sigma^+ & 0 \end{pmatrix} \tag{1}$$

with $\sigma^+ = \frac{l\sqrt{k}+\sin l\sqrt{k}}{2l\sqrt{k}}$ and $\sigma^- = \frac{l\sqrt{k}-\sin l\sqrt{k}}{2l\sqrt{k}}$. A positive k refers to a focusing quadrupole strength.

When there is no dipole component superimposed to the quadrupole, a deviation of Δx between the beam and the quadrupole center therefore creates a kick of strength $\theta = -\Delta kl\sigma^+\Delta x$ and an angle $\Delta x'$ leads to a orbit displacement at the center of the quadrupole of $\Delta = \frac{\Delta kl}{k}\sigma^-\Delta x'$. For an additional dipole component with curvature κ it turns out [1] that the effective quadrupole center in the alignment procedure is shifted so that Δx is given by $x-z-f$ with the closed orbit x, the position of the center of the quadrupole z and the shift $f = \frac{\kappa}{k}\left(\frac{1}{\sigma^+}\frac{\sin(\frac{l}{2}\sqrt{k})}{\frac{l}{2}\sqrt{k}} - 1\right)$. When the orbit oscillation which is excited by the kick θ and the displacement Δ at the center of the quadrupole is closed by two corrector coils with angles θ_1 and θ_2, then one can compute Δx and $\Delta x'$. With the Twiss parameters at the corrector coils and at the center of the quadrupole, where the betatron phase is chosen to be 0, one obtains

$$\vec{x} - \vec{z} = \frac{\kappa}{k}\begin{pmatrix} f \\ 0 \end{pmatrix} + A^{-1}\vec{\theta}\,, \quad A^{-1} = \frac{1}{\Delta kl} \times$$
$$\begin{pmatrix} \sqrt{\frac{\beta_1}{\beta}}\frac{\cos\phi_1+\alpha\sin\phi_1}{\sigma^+} & \sqrt{\frac{\beta_2}{\beta}}\frac{\cos\phi_2+\alpha\sin\phi_2}{\sigma^+} \\ \sqrt{\beta_1\beta}k\frac{\sin\phi_1}{\sigma^-} & \sqrt{\beta_2\beta}k\frac{\sin\phi_2}{\sigma^-} \end{pmatrix} \tag{2}$$

Beam optics distortions between the compensating kicks and the test quadrupole lead to misinterpretation of the difference orbit and to a corresponding error of the evaluation. It turns out that this error can already be rather large for Δx but it is unacceptably large for the alignment angle $\Delta x'$.

It is not worth trying to determine the angle alignment. But we will assume that the angle of the orbit in the magnet is approximately correct and we will therefore require our compensation to lead to the design value $-z'^0$ of the angular alignment. While the angles $\vec{\theta}$ are measured, we assume that the correct angles to close the bump would have been $\vec{\theta} - \Delta\vec{\theta}$. The errors $\Delta\vec{\theta}$ can be due to optical errors or to an error in the measurement of the corrector kicks. Since the errors $\Delta\vec{\theta}$ are not known, we introduce an estimate $\Delta\vec{\theta}^*$ of the erroneous angle such that equation (2) leads to an estimated alignment of

$$\Delta\vec{x}^* = A^{-1}[\vec{\theta} - \Delta\vec{\theta}^*] = \begin{pmatrix} \Delta x^* \\ -z'^0 \end{pmatrix}\ . \tag{3}$$

With $\vec{a}_2 = (A^{-1}_{2,1}, A^{-1}_{2,2})$ we write $\vec{a}_2 \cdot [\vec{\theta} - \Delta\vec{\theta}^*] = -z'^0$. This condition should be satisfied for a set $\Delta\vec{\theta}^*$ of angles which is as small as possible, i.e. $|\Delta\vec{\theta}^*|^2$ should be minimal. We can use Lagrange multipliers to minimize and finally find

$$\Delta x^* = \frac{\sqrt{\beta_1\beta_2}\sin\phi_{21}}{\Delta kl\sigma^+\sqrt{\beta}}\frac{\sqrt{\beta_2}\sin\phi_2\theta_1 - \sqrt{\beta_1}\sin\phi_1\theta_2}{\beta_1\sin^2\phi_1 + \beta_2\sin^2\phi_2}$$
$$-z'^0\frac{\sigma^-}{k\beta\sigma^+}\left(\alpha + \frac{\beta_1\sin\phi_1\cos\phi_1 + \beta_2\sin\phi_2\cos\phi_2}{\beta_1\sin^2\phi_1 + \beta_2\sin^2\phi_2}\right)\ .$$

When the alignment angle is not as designed, then Δx^* has a systematic error, but at least for HERA this turns out to be benign. The sensitivity to optical errors however is reduced by one to two orders of magnitude. Only together with this reduction of the sensitivity the BBA method leads to satisfactory results in HERA.

3 MEASUREMENT PROCEDURE

As explained above, the relative offset of the beam in an IR quadrupole with respect to the magnet axis can be found by changing the quadrupole strength and minimizing the thus generated difference in the orbit around the ring with two correctors (per plane) just outside of the interaction region. In HERA, we use correction coil pairs at 75 and 101 meters away from the IP in the horizontal plane and at 56 and 81 meters in the vertical. The beam offset is calculated from the change in the quadrupole gradient, the necessary current changes in the correction coils to compensate for the resulting difference orbit and the transport matrices between these three magnets.

At the beginning of the measurement, the betatron tunes are changed to a value which leaves maximum space for increasing the strength of the quadrupole. The betatron tunes in HERA can be kept constant with a slow feed-back acting on quadrupoles in the arcs around the ring, but the resulting orbit changes would interfere with the BBA measurement. A reference orbit is taken, then the quadrupole strength is increased in steps, measuring betatron tunes and orbit difference. If a specified RMS value of the difference orbit is reached, the orbit difference is corrected with the corrector pair to better than 25 μm RMS. The beam offset in the quadrupole is calculated and stored together with all relevant machine parameters.

The measurement can be iterated by increasing the quadrupole strength further, or the next magnet can be measured. The BBA measurement of all quadrupole magnets in an interaction region is fully automated using the MATLAB environment at HERA [2]. The magnets are subsequently measured, starting at the IP and moving outward to minimize optic errors between the quadrupole and the two correctors used to compensate the orbit change.

This direct measurement of orbit displacements in the magnets has been used to optimize and characterize orbits in the interaction regions. Fig. 2 and Fig. 3 show orbits before and after optimization for the interaction regions of the experiments H1 and ZEUS. The beam positions are shown on an equidistant grid with the corresponding magnet names listed on the horizontal axis.

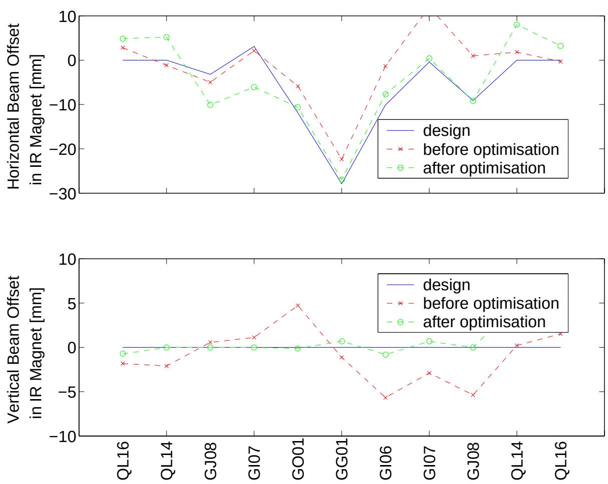

Figure 2: BBA measurements of beam positions before and after orbit optimization across the interaction region with the experiment H1.

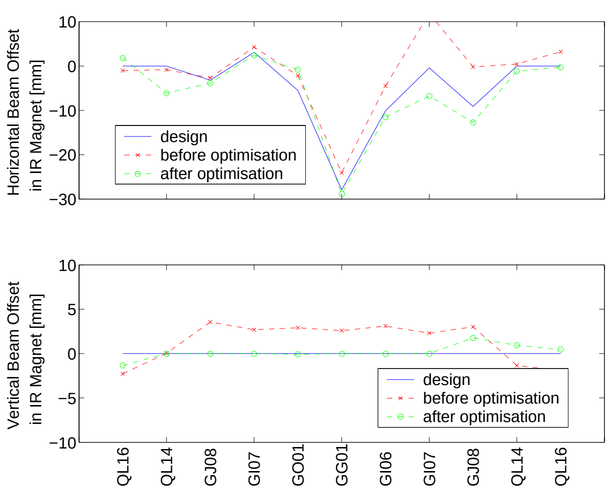

Figure 3: BBA measurements of beam positions before and after orbit optimization across the interaction region with the experiment ZEUS.

4 ABSOLUTE MAGNET POSITIONS

If the beam offset in all quadrupoles of an interaction region has been measured, the absolute position of the magnets is determined by modeling the absolute beam orbit. That requires knowledge of its initial conditions and all deflections - in bending magnets, correctors, solenoids and offset quadrupoles. The problem has $n + 2$ unknowns, n being the number of offset quadrupoles plus the 2 initial conditions for the orbit in the given plane, but we have only n independent measurements. There are different approaches to overcome that problem [3]. Presently we use the method of introducing the design positions of the magnets with a weighting factor as additional randbedingungen [1]. Fig. 4 shows reconstructed absolute vertical magnet positions in the interaction region of the experiment H1, where the common support for the left IR triplet was moved by 0.5 mm up and down at its end towards the IP. The corresponding movement of the magnets is resolved with good precision. The position of the super-conducting quadrupole GO, the last before the IP, is calculated to be 1.7 mm too low. We have since raised that magnet by that amount and find reduced corrector strengths and vertically flatter orbits (the orbits shown in Fig. 2 were taken after moving that magnet). However, especially in the horizontal plane we are not yet satisfied with the stability and precision of our approach and are looking for ways to refine it.

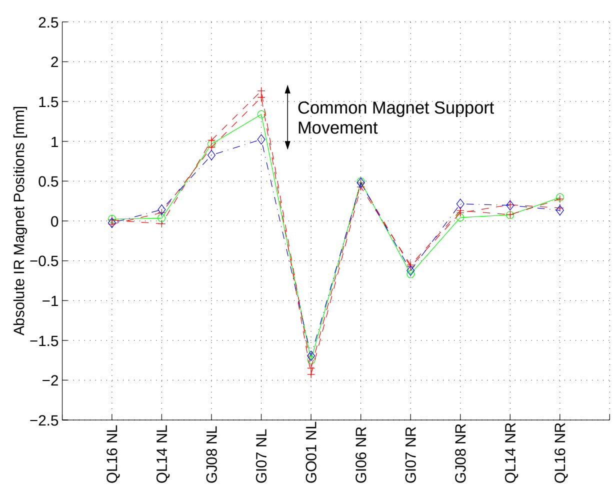

Figure 4: BBA reconstruction of absolute magnet positions for different positions of the common support for the final focus triplet.

5 REFERENCES

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[3] J. L. Warren and P. J. Channell, New method for inverting the closed orbit distortion problem, Proceedings of PAC83, 1983