# Beam-Based Alignment and Polarization Optimization in the HERA Electron Ring

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*Abstract*

In a real electron storage ring the maximum achievable degree of electron spin polarization is mainly limited by the deviation of the equilibrium polarization direction ($\vec{n}_0$-axis) from the direction of the main bending fields. This $\vec{n}_0$-axis tilt is caused by random vertical closed orbit kicks. The paper describes a method for minimizing the average $\vec{n}_0$-axis tilt by a correction algorithm which makes use of known correlations between transverse offsets of quadrupoles and adjacent beam position monitors.

## 1 INTRODUCTION

One important prerequisite for obtaining high spin polarization in an electron storage ring is a well corrected vertical closed orbit in order to avoid depolarization due to a tilted $\vec{n}_0$-axis. Furthermore, the closed orbit kicks generate spurious vertical dispersion which also gives rise to depolarizing effects. In principle, provided that a sufficient number of correction coils and efficient closed orbit optimization algorithms are available, the nominal closed orbit as measured by the beam position monitors (BPM's) can be made very small (a few tenths of a mm (rms) in a real machine). However, due to mechanical and electronical imperfections even for a nominal orbit which reads zero in all monitors, there will remain random offsets of the beam in the quadrupoles because the monitor and the quadrupole axis do not coincide. Therefore, a tilt of the spin $\vec{n}_0$-axis remains even for an apparently, perfectly corrected machine and empirical polarization optimization procedures have to be applied (e.g. the harmonic bumps scheme [1][2]). We present a method to improve the alignment of the monitor axis with respect to the magnetic axis of the quadrupoles. That enables us to optimize polarization in a more systematic way and, if combined with empirical procedures, can eventually lead to a higher degree of polarization as well as a faster setup of the machine for optimum performance regarding polarization.

## 2 BEAM-BASED ALIGNMENT PROCEDURE

Our method is based on the well known fact that if the strength of a single quadrupole in the ring is changed, the resulting difference in the closed orbit $\Delta y(s)$ is proportional to the original offset $y_Q$ of the beam in this quadrupole.

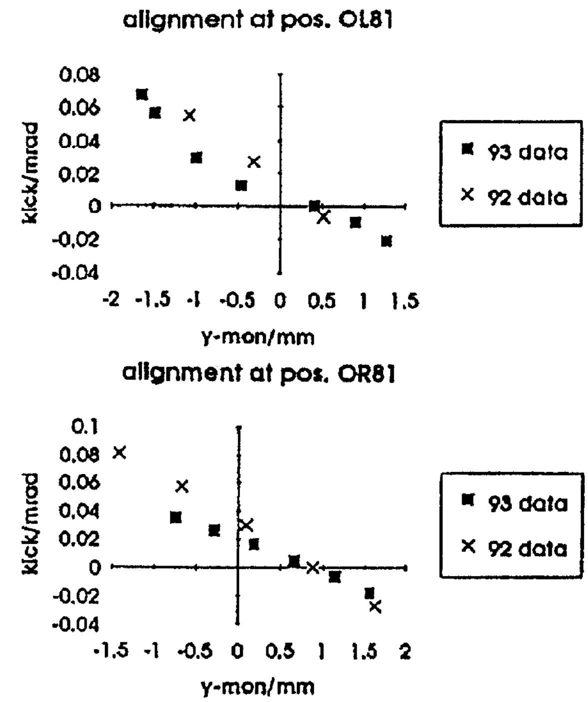


Figure 1: *Results of the beam-based alignment test measurements for quadrupoles and monitors at position OL81 and OR81 in the straight section East of HERA-e. Shown are the kicks obtained from the difference orbit for various values of the nominal orbit in the monitor. The offset of the monitor with respect to the quadrupole is given by the x-axis intercept of a straight line fitted to the data*

The equation for the resulting difference orbit is

$$\Delta y''(s) - (k(s) - \Delta k(s))\Delta y(s) = \Delta k(s) y_Q(s). \qquad (1)$$

The difference orbit is thus given by the closed orbit formula for a single kick, but calculated with the perturbed optics including $\Delta k(s)$. From the measured difference orbit the kick and thus $y_Q$ can be easily determined and compared to the nominal orbit $y_{bpm}$ in the monitor adjacent to the quadrupole, yielding the offset between monitor and quadrupole axis. The precision of the method is very much improved by taking difference orbit data for several local beam positions $y_Q$ varied with an orbit bump. The error of the nominal position $y_{bpm}$ for which the beam goes through the centre of the quadrupole is then given by the resolution of the BPM system. In the HERA electron ring

(HERA-e), a difference orbit with an amplitude of 0.1 mm can be clearly resolved. This results in a resolution for the local kick of about 0.005 mrad. Since a change of a quadrupole strength of $\Delta kl = 0.03\,\mathrm{m}^{-1}$ is possible without losing the beam, a minimum beam offset of $y_{Q,min} = 0.15$ mm can be easily detected. Taking several data points by varying the local bump, the quadrupole-to-monitor alignment can be done with a precision of about 0.05 mm.

This alignment method was first tested in November 1992 [3] for one quadrupole circuit in HERA-e. In this case, two quadrupoles are powered in series (they are positioned symmetrically with respect to the interaction point East) so that the analysis of the difference orbit data is somewhat complicated in the sense that one has to take into account two kicks, without affecting the precision of the method, though. The measurement was repeated for the same quadrupole pair (and the adjacent monitors) one year later [4]. The results are shown in figure 1. The kick vs. BPM position data points were fitted by a straight line and the monitor-to-quadrupole offset determined by the intercept of the x-axis. Within the limits of error (0.05 mm) this offset had not changed after one year. This means that once the alignment is established, it will be stable for a long time, probably because the mechanical imperfections remain constant since the transverse positioning of the vacuum chamber in the quadrupoles is fixed. The resulting vertical offsets for the two quadrupoles are an order of magnitude larger than the measurement error, implying that a significant reduction of the closed orbit kicks in the ring should be possible, provided that the method is applied everywhere around the ring. This will in the future be possible, since during the last winter shutdown switches were installed that allow the strength of individual quadrupoles to be varied although being powered in series with many other quadrupoles [5].

## 3 POLARIZATION OPTIMIZATION PROCEDURES

In this section the methods for improving spin polarization by making use of the beam-based alignment are discussed. The first method simply minimizes the rms closed orbit kick instead of the orbit in the monitors itself. At quadrupole positions with a BPM and a vertical correction coil nearby, the local orbit kick is given by the sum of the change of $y'_{co}$ due to the orbit offset in the quadrupole and the kick of the corrector. We assume that this offset is known with an rms error $\Delta y_A$, which is the error of the beam-based alignment procedure. With a perfect optimization algorithm one expects that eventually the rms orbit kick can be reduced to $\delta y'_{rms} = \Delta y_A \times kl$, where $kl$ is the average quadrupole strength. However, in HERA-e only every second quadrupole (every vertically focusing quadrupole QD) has a BPM and a corrector nearby. The horizontally focusing quadrupoles (QF's) in-between can also be "beam-based aligned" [1], but the kick at those positions cannot be locally corrected. A global minimization of the rms orbit kick is still possible, though. We used the MICADO algorithm to test the method in a computer simulation for HERA-e without spin rotators with realistic tolerances. First the orbit was corrected with the standard MICADO algorithm down to an rms error of about $\Delta y_{co} = 0.5$ mm, then the rms kick optimization applied, iterating several times with 20...50 correctors per step until no improvement of the rms closed orbit kick was observed anymore. We assume a precision of the alignment of $\Delta y_A = 0.1$ mm. For the optics of the HERA-e ring used during 1993 operation, we find by simulating with four different random seeds that the rms closed orbit kick of $62 \pm 2\mu$rad after standard orbit correction is reduced to $31 \pm 2\mu$rad with beam-based alignment and minimization of the rms kick.

[1] In this case, the axis of the QF's with respect to the BPM's close to the QD's on either side of the QF is determined

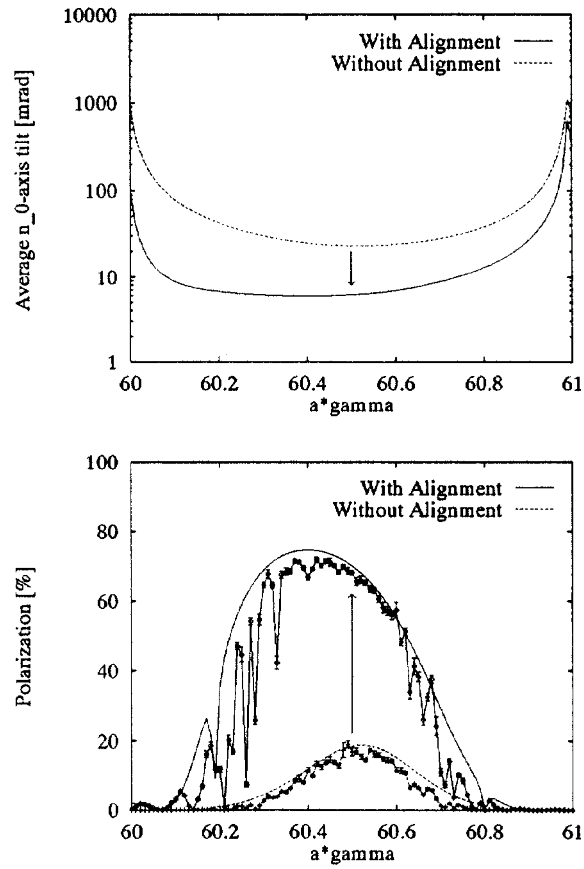


Figure 2: *Reduction of the rms value of the $\vec{n}_0$-axis tilts vs. spin tune $a\gamma$ taken at the arc quadrupole positions of HERA-e due to the application of the beam-based alignment procedure (top). This corresponds to a significant increase of polarization (bottom) which depends quadratically on the tilt variation in linear approximation. The points with errorbars represent the results of a Monte-Carlo calculation with SITROS [7]. The smooth lines represent the corresponding SITF results based on linear perturbation theory*

What is the influence on the $\vec{n}_0$-axis tilt and thus the polarization ?

The vector $\vec{n}_0(s)$ is the periodic solution of the T-BMT equation [6]:

$$\frac{d\vec{n}_0}{ds} = \left(\vec{\Omega}_0^d + \delta\vec{\Omega}_0\right) \times \vec{n}_0 \quad (2)$$

where $s$ is the longitudinal coordinate of the usual storage ring coordinate system represented by the unit vectors $\vec{e}_x$, $\vec{e}_y$ and $\vec{e}_s$. $\vec{\Omega}_0^d$ contains the fields on the design orbit, $\delta\vec{\Omega}_0$ the additional fields on the closed orbit.

Assuming $|\delta\vec{\Omega}_0| \ll |\vec{\Omega}_0^d|$, $\vec{n}_0$ can be decomposed into two parts:

$$\vec{n}_0 = \vec{n}_0^d + \delta\vec{n}_0. \quad (3)$$

The modulus $|\delta\vec{n}_0|(s)$ describes the tilt of $\vec{n}_0$ with respect to $\vec{n}_0^d$ mainly due to the presence of a nonzero vertical closed orbit with respect to the design orbit. $|\delta\vec{n}_0|$ is given by [2]:

$$|\delta\vec{n}_0|^2 = \frac{1}{2(1-\cos 2\pi a\gamma)}\left(\left[\int_s^{s+L}\delta\Omega_{0x}\cos\phi ds\right]^2 + \left[\int_s^{s+L}\delta\Omega_{0x}\sin\phi ds\right]^2\right) \quad (4)$$

with $\delta\Omega_{0x} = (a\gamma+1)k(s)y(s)$ assuming that the vertical deflections are mainly generated by the nonzero vertical beam offsets $y_Q$ inside the quadrupoles before vertical orbit correction, and $\phi = a\gamma\alpha$, where $\alpha$ is the deflection angle in the bending magnets. The constant $a$ denotes the gyromagnetic anomaly $(g-2)/2$, $\gamma$ the relativistic $\gamma$-factor and $L$ the length of the ring. Thus the rms value of $|\delta\vec{n}_0|$ is approximately proportional to the rms closed orbit kick $\delta y'_{rms}$ which is reduced due to the application of the beam-based alignment procedure. The simulation leads to a reduction of the rms $\vec{n}_0$-axis tilt from $23 \pm 1$ mrad to $9 \pm 3$ mrad as shown in figure 2 for a certain random seed.

Owing to the fact that the depolarization rate $1/\tau_d$ depends quadratically on the $\vec{n}_0$-axis tilt variation in linear approximation, the equilibrium polarization $P$ which is given by [8]:

$$P = P_\infty \frac{1}{1+(\tau_p/\tau_d)} \quad (5)$$

with $P_\infty \approx 92\%$ and a polarization buildup time $\tau_p \approx 2600$ sec at a spin tune $a\gamma = 60.5$ corresponding to a beam energy of 26.66 GeV, increases from $18 \pm 4\%$ to $60 \pm 15\%$.

The additional application of the harmonic bumps scheme leads to a further reduction of the rms tilt and an equilibrium polarization of about 85% as shown in figure 3. This has to be compared to 75% polarization which can be achieved by the empirical optimization using the bumps without prior beam-based alignment and rms kick minimization [9].

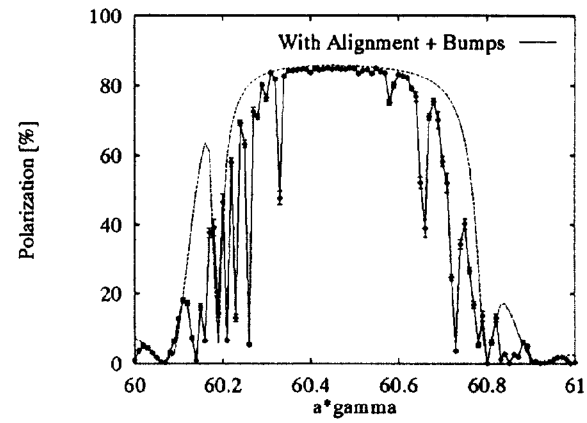


Figure 3: *Further empirical optimizition of polarization using the harmonic bumps scheme [1][2] after the beam-based alignment and the minimization of the rms closed orbit kick (see figure 2)*

The method discussed can be improved by taking into account the spin phase advance $\phi(s)$ between the quadrupoles in order to minimize $|\delta\vec{n}_0|$ given by eq. 4.

## 4 SUMMARY

This beam-based alignment procedure is a powerful tool to get high polarization in HERA-e without time consuming empirical optimization of polarization with the harmonic bumps scheme. Using both methods the simulations indicate that polarization values of about 85% are possible compared to 75% without beam-based alignment. Assuming the same relative increase in the presence of spin rotators this would lead to an increase of the effective luminosity by 30% for high energy experiments using longitudinally polarized electrons.

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