OPTIMIZATION OF ELECTRON SPIN POLARIZATION BY APPLICATION OF A BEAM-BASED ALIGNMENT TECHNIQUE IN THE HERA ELECTRON RING

M. Böge and R. Brinkmann*

Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, D-22603 Hamburg

Abstract

The maximum degree of electron spin polarization in a real storage ring is mainly limited by the tilt of the equilibrium polarization direction $\vec{n}_0$ with respect to the direction of the main bending fields. The tilt is mainly caused by random vertical closed orbit kicks introduced by nonzero vertical offsets inside the quadrupoles. A tilt correction algorithm is presented which makes use of the known correlations between transverse offsets of quadrupoles and adjacent beam position monitors. These offsets can be determined by the application of a beam-based alignment technique.

An automatic alignment procedure has been successfully applied to the vertically focussing quadrupoles in the arcs of HERA which should give the main contribution to the $\vec{n}_0$ axis tilt. The results of measurements made in spring 1995 are presented followed by a discussion on the possible influences on the degree of spin polarization.

*Now at CERN, CH-1211 Geneva, Switzerland

OPTIMIZATION OF ELECTRON SPIN POLARIZATION BY APPLICATION OF A BEAM-BASED ALIGNMENT TECHNIQUE IN THE HERA ELECTRON RING

M. Böge and R. Brinkmann*
Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, D-22603 Hamburg

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 [3].

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.

The equation for the resulting difference orbit is

$$\Delta y''(s) - (k(s) - \Delta k(s))\Delta y(s) = \Delta k(s) y_Q(s). \tag{1}$$

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

*Now at CERN, CH-1211 Geneva, Switzerland

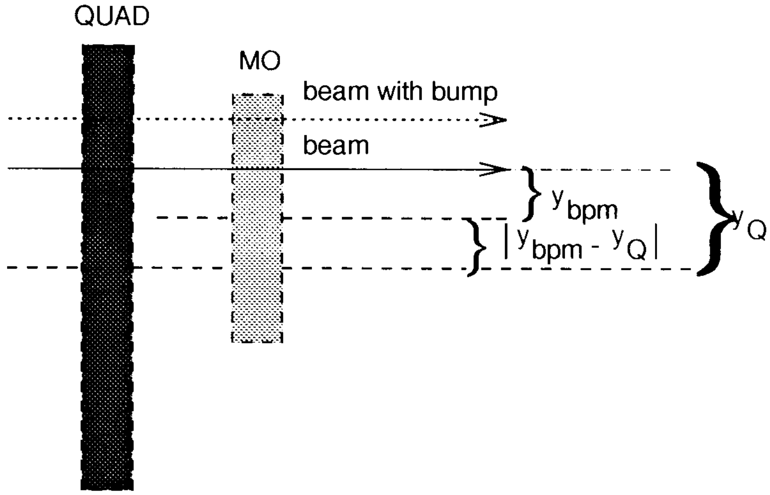

Figure 1: *Illustration of the beam-based alignment technique applied to the vertically focusing quadrupoles (QUAD) with adjacent monitors (MO)*

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 principle of the method is illustrated in figure 1. 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 Δkl = 0.03 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 has been first tested in November 1992 [4] 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 [5]. Within the limits of the 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.

During the winter shutdown 1993/94 switches were installed that allow the strength of individual quadrupoles in the arcs to be varied although being powered in series with many other quadrupoles [6]. During the machine shifts in November 1994 an automatic alignment procedure for the vertically focussing arc quadrupoles was successfully tested, including the control of the switches, the change of the quad strengths, difference orbit measurements and the variation of local orbit bumps [7]. It was shown that the alignment of these arc quads can in principle be done in less than 24 hours without human intervention. This was confirmed in 1995 where the alignment was done for 148 arc quadrupoles within three machine shifts of eight hours.

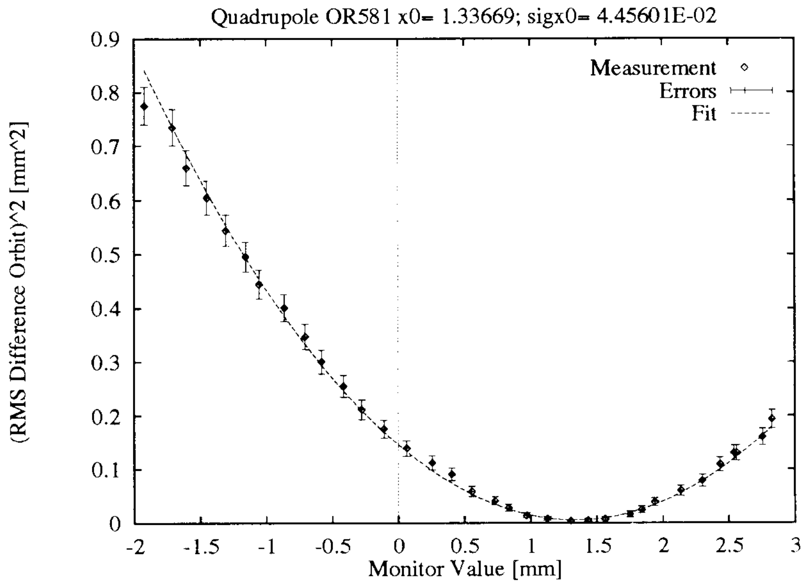

Figure 2: *Square of the rms value of the vertical difference orbit which is defined by the closed orbit before and after a change of the quadrupole strength by 20%, versus the nominal monitor value* y_{bpm} *for 33 different local orbit bump amplitudes. The minimum of the resulting parabola defines the position of the quadrupole axis with respect to* y_{bpm} *which is calculated to be 1.34 mm. The bars on the individual data points represent the error of the rms difference orbit measurement which assumed to be 0.02 mm. This leads to an error of 0.046 mm for the offset measurement.*

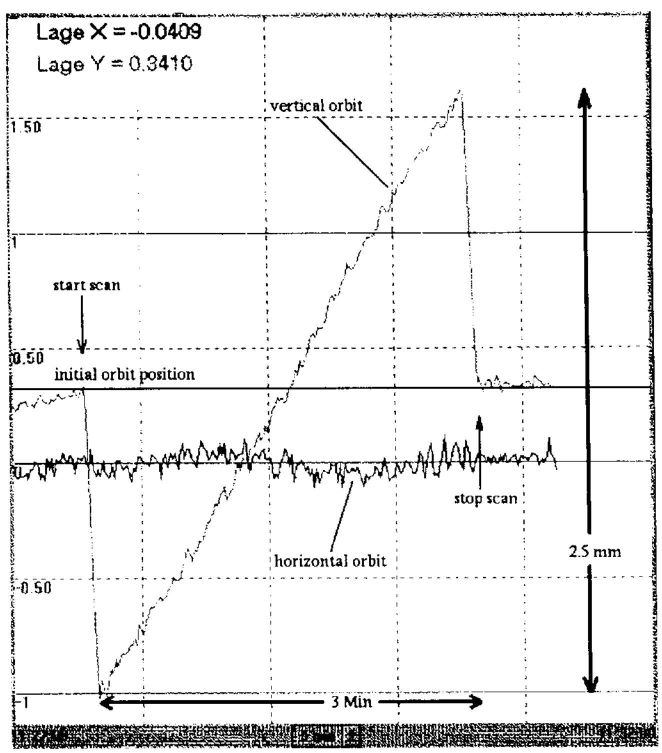

Figure 3: *Change of the vertical beam position as seen by the monitor next to measured quadrupole during the local orbit bump scan. The scan (which in this case consists of 20 different orbit amplitudes over a range of 2.5 mm) takes about 3 minutes. After the measurement the initial orbit position is restored.*

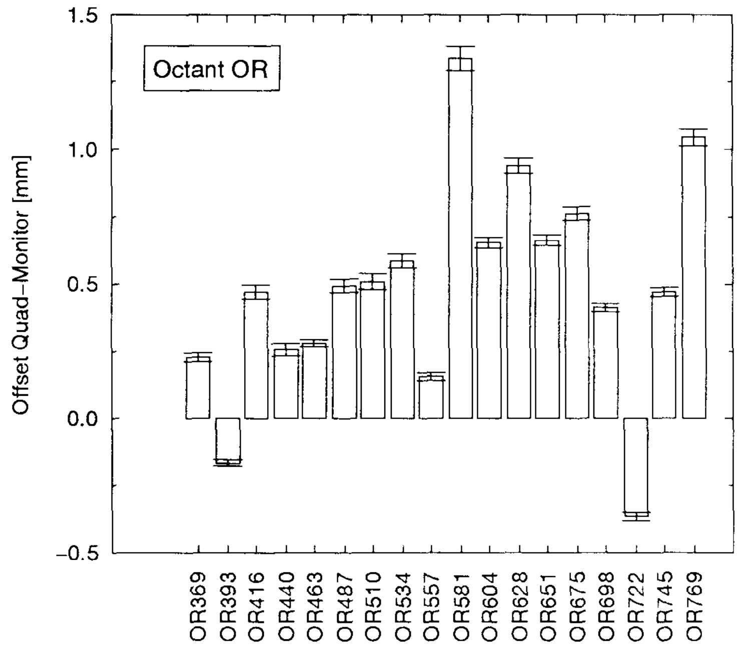

Figure 4: *Summary of the results of the 1995 measurements for the octant OR. Please note that the resulting vertical offsets are more than one order of magnitude larger than the measurement errors which are represented by the thin bars.*

As an example the alignment of the quadrupole OR581 with respect to its monitor is shown in figure 2. The plot visualizes the square of the rms value of the vertical difference orbit which is defined by the closed orbit before and after a change of the quadrupole strength by 20%, versus the nominal monitor value y_{bpm} for 33 different local orbit bump amplitudes. The minimum of the resulting parabola defines the position of the quadrupole axis with respect to y_{bpm} which is calculated to be 1.34 mm in the presented example. The error of the difference orbit measurement is approximately 0.02 mm if the orbit measurement system is operated in the 64 turns average mode [8]. The error of the offset is derived from the covariance matrix of the least square fit of a parabola to the data [9]. In this case the error is calculated to be 0.046 mm.

Figure 3 shows the change of the monitor value during a typical bump scan. Please note that the initial and final orbit positions which are marked by “start scan” and “stop scan” are identical indicating that the machine was perfectly stable during the time of the scan. This is an important prerequisite because the difference orbit measurements refer to the same initial reference orbit. Figure 4 summarizes the result for a complete octant of HERA-e. These data reflect a common feature of all data namely the nonzero mean value which is 0.49 mm in the octant OR and 0.25 mm for the average over the whole ring. The rms values are 0.4 mm and 0.36 mm respectively (see figure 5).

Summarizing one can say that the vertical quadrupole monitor offsets are more than one order of magnitude larger than the measurement error, implying that a significant reduction of the closed orbit kicks in the ring should be possible.

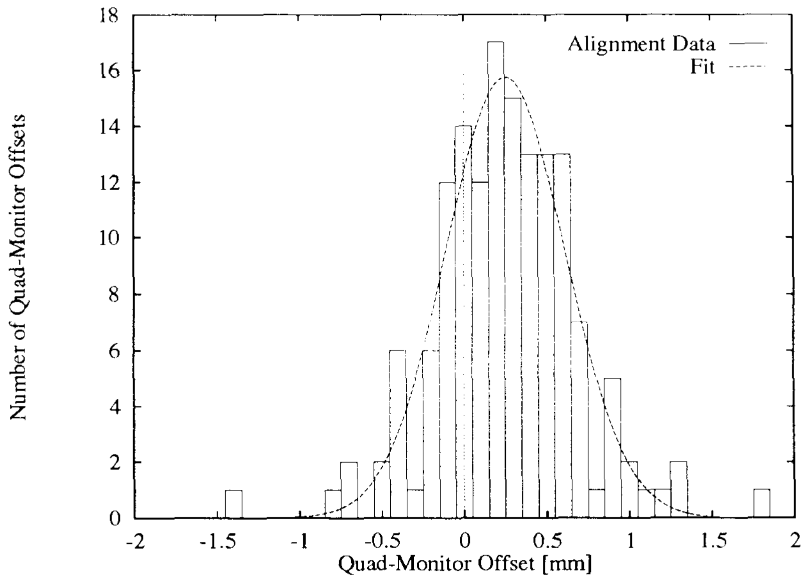

Figure 5: *Histogram of all alignment data taken in 1995. The distribution of the offsets has a nonzero mean value of 0.25 mm and an rms spread of 0.36 mm.*

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 Δy_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 Δy_{co} = 0.5 mm, then the rms kick optimization was applied, iterating several times with 20...50 correctors per step until no improvement of the rms closed orbit kick was observed anymore. We make the conservative assumption that the precision of the alignment is Δy_A = 0.1 mm and find by simulating with four different random seeds that the rms closed orbit kick of 62 ± $2\mu\mathrm{rad}$ after standard orbit correction is reduced to 31 ± $2\mu\mathrm{rad}$ 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

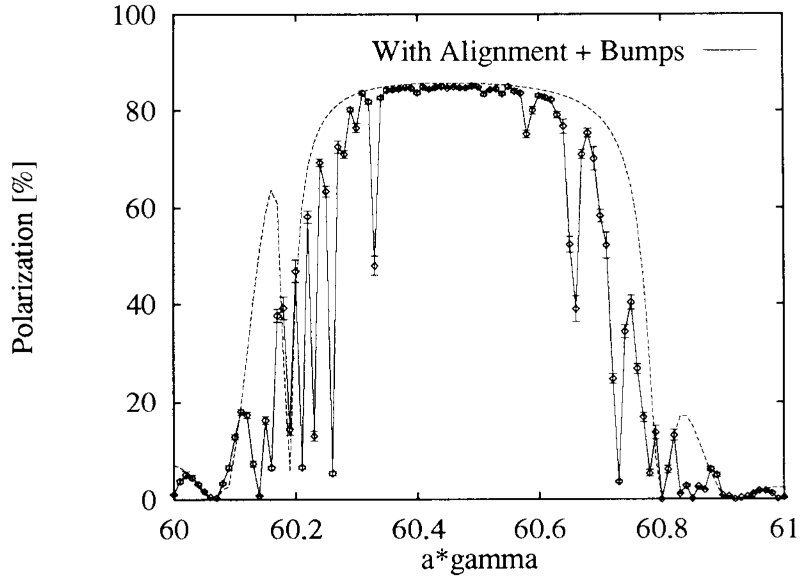

Figure 6: *Further empirical optimization of polarization using the harmonic bumps scheme [1][2] after the bearn-based alignment and the minimization of the rms closed orbit kick. The points with error bars represent the result of a Monte-Carlo calculation with SITROS [12]. The smooth line represents the corresponding SITF result 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 [10] [11]:

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

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

$$\vec{n}_0 = \vec{n}_0^d + \delta\vec{n}_0. \tag{3}$$

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]:

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

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 α is the deflection angle in the bending magnets. The constant a denotes the gyromagnetic anomaly (g $-2)/2, \gamma$ the relativistic γ-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 ± 1 mrad to 9 ± 3 mrad 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 [13]:

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

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 ± 4% to 60 ± 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 6. 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 [14].

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.

The alignment of all vertically focussing quadrupoles in the arcs of HERA-e was done within 24 hours using an automatic procedure. The measured offsets have a mean value of 0.25 mm with an rms spread of 0.36 mm indicating that all monitors are systematically shifted with respect to their adjacent quads. These data will be used during the machine development time at the end of this year to apply the proposed kick minimization algorithm.

References

[1] Barber,D.P. et al., "High Spin Polarisation at the HERA Electron Storage Ring", Nucl.Instr.Meth. A338 (1994) 166.

[2] Rossmanith,R. and Schmidt,R., "Compensation of Depolarizing Effects in Electron-Positron Storage Rings", Nucl.Instr.Meth. A236 (1985) 231.

[3] Brinkmann,R. and Böjge,M., "Beam-Based Alignment and Polarization Optimization in the HERA Electron Ring", presented at the EPAC, London, Conf. Proc. Vol. 2 (1994) 938.

[4] Brinkmann,R., in: Willeke,F. (ed.), "HERA Seminar Bad Lauterberg/Harz" (1993) 269.

[5] Gianfelice-Wendt,E. and Lomperski,M., Private communication.

[6] Bialowons,W. and Gode,W.D., Private communication.

[7] Böge,M. and Brinkmann,R., "Optimization of Spin Polarization in the HERA Electron Ring using Beam-Based Alignment Procedures", presented at the 11th International Symposium on High Energy Spin Physics, Bloomington, AIP Conf. Proc. 343 (1994) 287.

[8] Peters,F., Private communication.

[9] Press,W. H. et al.,“Numerical Recipes”, Cambridge University Press, (1992) 665.

[10] Thomas,L., Philos.Mag. 3 (1927) 1.

[11] Bargmann,V., Michel,L. and Telegdi,V.L., Phys.Rev.Lett. 2 (1959) 435.

[12] Kewisch,J. et al., Phys.Rev.Lett. 62 (1989) 419.

[13] Montague,B.W., “Polarized Beams in High Energy Storage Rings”, Phys.Rep. 113, Vol.1 (1984).

[14] Böge,M., “Analysis of Spin Depolarizing Effects in Electron Storage Rings”, Ph.D. thesis, DESY 94-087 (1994).