Persistent Current Field Errors and Dynamic Aperture of HERA-P

R. Brinkmann and F. Willeke

Deutsches Elektronen-Synchrotron DESY
Notkestr. 85, 2000 Hamburg 52, Germany

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Abstract

The influence of the magnetic field errors in the superconducting HERA proton ring on the nonlinear acceptance at injection ($E = 40GeV$) is investigated by tracking calculations. We find that the relatively strong multipole components caused by persistent currents would reduce the dynamic aperture to about half the physical aperture of the machine. The computer simulations have been compared to an analytical study using perturbation theory. It is concluded that a quasi local compensation of the strongest field components in every half FODO cell is necessary to achieve sufficient acceptance for an injected $40GeV$ beam.

1 Introduction

In a superconducting proton storage ring operated at its design energy, the linearity of the magnetic fields and thus the dynamic aperture is limited by systematic and random errors resulting from fabrication tolerances. Especially at low excitation of the magnets, the field quality is additionally reduced by persistent eddy currents in the superconducting filaments. For the case of the proton ring of the HERA e-p collider presently under construction at DESY, the latter effect is particularly important because of its low injection energy ($E_{inj} = 40GeV$ as compared to $E_{max} = 820GeV$). In extensive studies on nonlinear dynamics in HERA-p [1] [2] only the dominating distortion caused by the persistent currents namely the sextupole component in the superconducting dipoles has been taken into account. However recent measurements on magnet prototypes [3] have shown that the higher multipole components (the decapole in the dipoles and the duodecapole in the quadrupoles) are larger than originally anticipated (see table 1)

In this paper we investigate the influence of these additional field distortions on the acceptance of the machine and discuss the possibility to compensate them. In the next section a brief summary of the methods applied is given. This is followed by the presentation of the results of numerical simulation of the effect of the field distortions in dipole and quadrupole magnets. Finally results are discussed and compared with perturbation theory and conclusions are drawn.

2 Tracking Procedure

The nonlinear acceptance of the proton ring has been investigated using the particle tracking code RACETRACK [4]. Usually the acceptance as obtained from numerical simulation is defined as the maximum emittance (sum of the two Courant Snyder invariants) as calculated from initial conditions of a probe particle for which the trajectory is stable over a given number of turns. However since the acceptance defined that way depends rather strongly on the initial phase, many particles with different start phases would have to be tracked to obtain a safe estimate of the acceptance. This can be improved drastically by evaluating the emittance of the particle after each turn and remembering the minimum value reached during the run which will be considered as the acceptance. We found that with this procedure, tracking of only four particles (sin- and cos-like trajectories in both planes) lead to the same results as tracking a few tens of particles with the usual acceptance definition. Thus the needed computer time could be considerably reduced. As a compromise between computer time and reliability of the results the number of tracked turns was restricted to $n_{turn} = 1000$. According to reference [2], the dynamic aperture obtained by tracking up to 10^6 turns may be up to 30% – 40% smaller than the 1000-turn dynamic aperture. The tracking runs have been performed with and without aperture limitations representing the beam pipe (we distinguish between "nonlinear acceptance" for the first case and "dynamic aperture" for the latter one). This allows to compare the dynamic and the physical aperture as well as estimating how much the physical aperture is reduced by phase space distortions ("smear"). The particle momentum is kept constant during tracking. The investigated range is $\Delta p/p$ $-0.002 \leq \Delta p/p \leq 0.002$. The closed orbit is adjusted to an r.m.s. error of $1mm$. Each run is done with four different sets of random errors. Since it turned out that the tracking results don't vary significantly if the tunes are changed, most of the systematic investigations were carried out with fixed tunes of $Q_{x/z} = 31.15/32.18$

3 Effects of Persistent Current field errors and its compensation

We first study the machine with additional 12-pole components $b_6/b_2 = 4{\cdot}10^{-3}$ at $r_0 = 25mm$ in the superconducting quadrupoles (according to recent measurements [3]).

Table 1.
Assumed Fluctuating Multipole Components of the HERA-p S.C. Dipole Magnets

n	2	3	4	5	6	7	8	9	10
normal b_n	0.8	4.0	0.5	1.0	0.5	0.5	0.5	0.5	0.5
skew a_n	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

normalized to b_1, in units of 10^{-4}

The acceptance is compared to the one obtained for a machine with chromaticity correcting sextupoles and fluctuating higher order multipole components in the dipoles only (see table 1). The resulting dynamic aperture for both cases is shown in fig 1. The presence of the persistent current 12-pole reduces the dynamic aperture by about a factor of three. Also in this case the acceptance is rapidly reduced with increasing r.m.s. orbit deviation (see fig 2). For an orbit rms error of only 1mm, the dynamic aperture is already significantly smaller than the linear aperture over the full range of the momentum spread. An additional introduction of aperture limitation does not change the results any more.

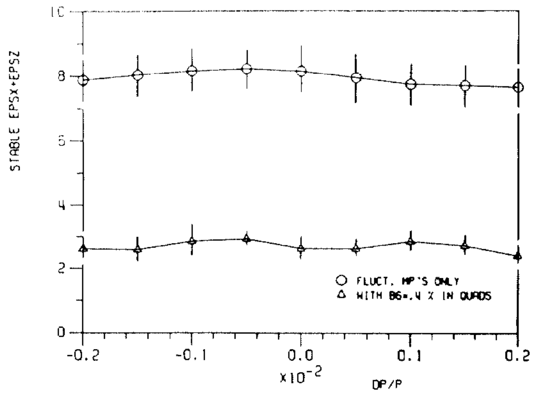

Figure 1: Dynamic aperture for a machine with fluctuating multipoles only(○) and for a machine with an additional 12-pole component in the quadrupoles (△)

We present next the influence of the persistent current decapole component in the superconducting dipole magnets. Its value at injection energy is $b_5/b_1 = -0.001$ at $r_0 = 25mm$ which is about 25% of the persistent current sextupole component. The latter one is very well compensated by $6m$ long coils in each of the $9m$ long dipole magnets. As it can be seen in fig 3, this additional multipole has only a small effect on the dynamic aperture for $\Delta p/p = 0$, but the acceptance drops rapidly with increasing momentum deviations resulting in a reduction of more than a factor of three. This is accompanied by a large nonlinear tune shift with amplitude as it can be seen from fig.4. The 1000-turn dynamic aperture is for $\Delta p/p \leq 0.001$ larger than or comparable to the linear aperture. Therefore including the aperture

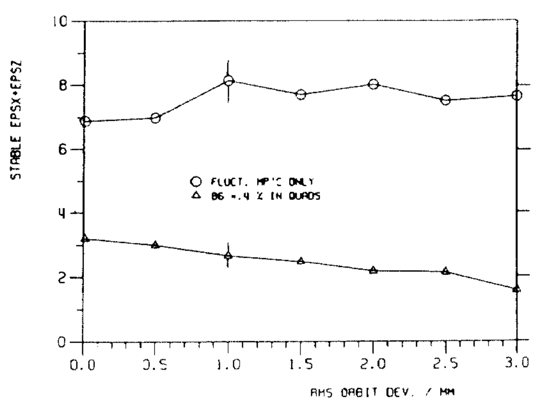

Figure 2: Dynamic aperture of the machine with a 12-pole component $b_6 = 0.4\%$ in the quadrupoles as a function of r.m.s. orbit deviation (equal in both planes)

limitation in the tracking calculations causes a further reduction of the nonlinear acceptance, except for large $\Delta p/p$ (fig 5).

In case of the persistent current decapole a lumped compensation scheme with one $3m$ long correction coil in each half FODO cell was considered (fig 6). The strength of the corrector is adjusted to cancel the integrated decapole strength of a half cell. The tracking results for this correction scheme without and with physical aperture restriction are shown in figs. 3 and 5, respectively. The dynamic aperture is substantially improved but a small reduction for off momentum particles remains due to the the fact that the scheme is only approximately local. For the case with aperture limitations, no significant improvement of the nonlinear acceptance (except near $\Delta p/p = -0.002$) is observed. The nonlinear detuning is substantially smaller with compensations and linearity is improved in the range given by the nonlinear acceptance (see fig 4).

4 Discussion of numerical results and comparison with perturbation theory

Because of the importance of the tracking results presented in the previous section and in view of the implication the proposed compensation scheme has on the construction of the superconducting magnets, it is very desirable to gain additional understanding how the results come about.

In case of the acceptance reduction by the 12-pole in the quadrupole, it is rather obvious that the resonant harmonics of order four must be rather strong, because they build up coherently due to the 90° betatron phase advance per FODO cell. The sensitivity of the dynamic aperture to orbit deviations in this case can be explained in the following way: An orbit deviation generated by many small random kicks looks locally very much like a betatron oscillation with a coherence length large compared to a betatron wavelength [5]. Thus the decapole and skewdecapole components due to the horizontal and vertical orbit deviation in the 12-pole field have a pattern which is in phase with the betatron oscillations for several wavelengths. The nonlinear distortion resulting from these decapoles and skew decapoles then add up coherently which explains the sensitivity of the dynamic aperture to orbit deviations. The consequence

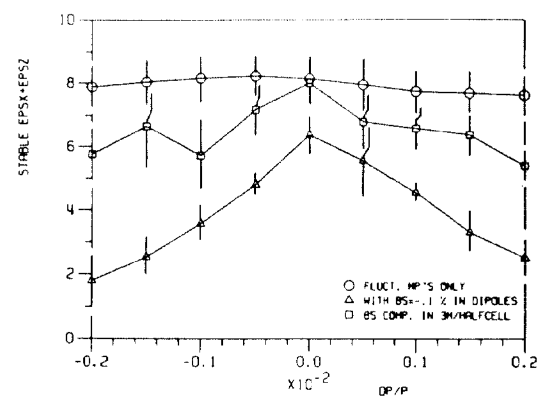

Figure 3: Dynamic aperture of the machine with fluctuating multipoles only (○) and with additional decapole $b_5 = -0.1\%$ in the dipoles without compensation (△) and with lumped correctors (□)

of the strong influence of the duodecapole in the quadrupole magnets on the beam dynamics is to provide a correction. The correction should be local, i.e. inside or at least close to each quadrupole. Correction coils placed at a few selected position in the ring would have to be extremely strong to account for the coherent effect from all the s.c. quadrupoles around the machine. This would in turn produce problems with positioning and orbit errors in the correctors, local optical distortions and higher order nonlinear effects.

The situation for the decapole components in the dipoles is not so clear. On momentum, the reduction of dynamic aperture due to this field distortion is not very drastic. This is confirmed

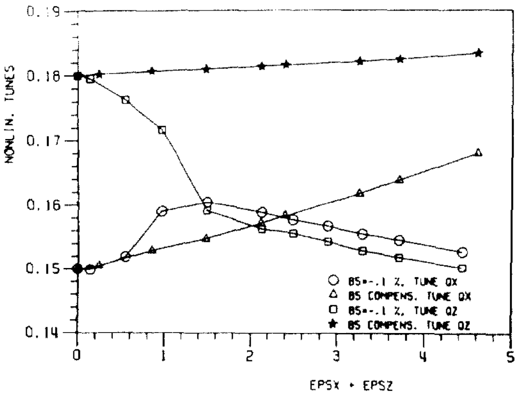

Figure 4: Tunes versus beam emittance for the machine with an uncompensated decapole $b_5 = -0.1\%$ in the dipoles without compensation (o,□)and with lumped correctors (△,*), $\Delta p/p = .002$

by the calculation of resonance driving terms and phase space distortions by perturbation theory (see [6]).

The decapole driven terms never exceed the effect produced by the chromaticity correcting sextupoles. Analytical estimates of the dynamic aperture based on these calculations lead to a 25% aperture reduction due to the decapole component which corresponds to what is observed in tracking (see fig 3).

Off momentum, the dynamic aperture decreases rapidly with momentum deviation (a fact observed on ealier tracking calculations for the TEVATRON which also contains strong higher order multipoles [7]). The octupole components resulting from

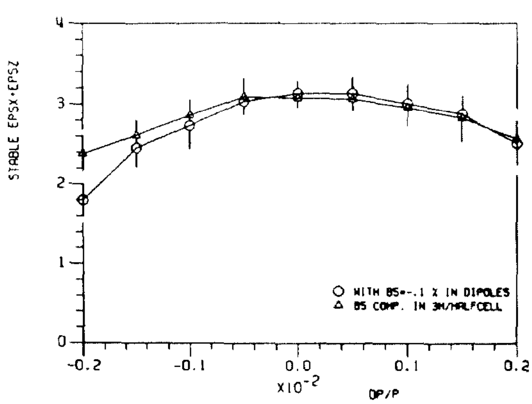

Figure 5: Nonlinear Acceptance (with physical aperture limitations) with an uncompensated (o) decapole $b_5 = -0.1\%$ in the dipoles and with lumped correctors (△)

feeddown due to the dispersion orbit in the decapole field add up coherently over the lattice just as the 12-pole components of the quadrupoles. However, calculation of the driving terms and distortion function shows, that they are not particularly strong compared with the sextupole and decapole terms. Large distortions result from the octupolar nonlinear coupling term $2Q_x - 2Q_z = 0$ which however is not expected to cause reduction of the dynamic aperture. The largest off momentum effect is the generation of octupolar detuning terms which exceed the sextupolar detuning terms by two orders of magnitude. A surprisingly strong effect is produced by the vertical dispersion which is not matched in the arcs. The nonlinear skew coupling resonance

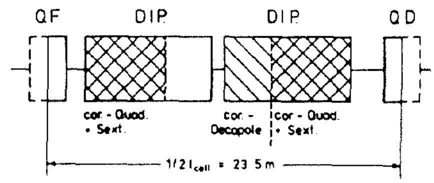

Figure 6: Half FODO cell with sextupole and decapole correction coils

$Q_x - Q_z$ generated by the feeddown due to the vertical dispersion orbit is one of the strongest resonances at a 0.2% momentum deviation. All these calculations show that there is no single effect which is responsible for the strong off momentum aperture reduction but there is a large number of potentially harmful effects. Analytical estimation of dynamic aperture based on the distortion functions result in an acceptance of $A = 0.9\pi mrmm$ at $\Delta p/p = 0.002$ which overestimates the acceptance drop by a factor of 2.

If the corrections are applied, the calculations show that the additional distortions of beam dynamics generated off/on momentum by the decapole component of the s.c.dipole are compensated by more than 75%, in most cases by an order of magnitude.

5 Conclusion

The results and discussions presented in the proceeding sections have shown that the persistent current higher order multipoles at the low injection field in the HERA s.c. dipoles have a noticeable strong influence on the beam dynamics. The acceptance of the machine can be reduced to less than 0.5 of its original value (without the additional p.c. fields). These effect can be understood semi-quantitatively by analytical methods.

In the case of the 12-pole component of the quadrupole magnet it is very advisable to install local correction coils in or near the quadrupoles.

In the case of the 10-pole component of the dipole magnet the aperture reduction is only for off momentum particles ($\Delta p/p \geq 0.0005$). The total momentum spread of the 40 GeV beam is about $\Delta p/p \geq 0.0004$. This value will however be increased by a factor of four by bunch compression and intra beam scattering. It appears therefore in this case advisable to to provide a quasi local correction in the middle of each half cell as described above (fig 6).

References

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