REPRODUCIBILITY AND PREDICTABILITY OF PERSISTENT CURRENT EFFECTS IN THE HERA PROTON STORAGE RING

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Abstract

The contribution of persistent current effects to the sextupole component of the HERA dipoles is determined, based on measurements in the reference magnets. It is used to calculate the overall chromaticity of the machine and compared to the actual settings of the sextupole correction coils and measurements on beam. The fill-to-fill predictability of the persistent current effects in HERA is presented and the question is discussed whether corrections can be applied in an adequate way before beam transfer to avoid beam losses during injection.

1 INTRODUCTION

The field quality of the magnets used in large storage rings is of major concern as it has a strong influence on the beam dynamics and the routine operation of the accelerator. Mainly in the case of superconducting rings (e.g. TEVATRON, HERA, RHIC, LHC) the field quality is strongly affected by long-lasting eddy currents, and correction procedures have to be applied at the flat bottom operation and during beam acceleration to avoid particle losses. A theoretical model of these so-called persistent currents (p.c.) and the impact of the generated multipoles on the performance of superconducting storage rings has been presented in great detail in different papers (see [1], [2], [3]).
In the case of the HERA proton storage ring the beam energy, the tune and most of all the chromaticity of the machine is influenced by persistent currents. Therefore reference magnets powered in series with the magnets in the ring are used to measure the multipole contributions, and procedures have been established to compensate the effects.
These reference magnets are equipped with Hall- and NMR-probes to measure the dipole field, and rotating coils for the sextupole component (Fig. 1)

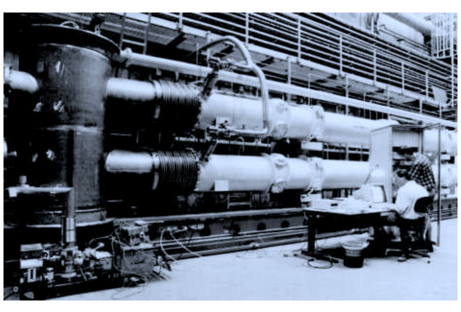

Figure 1: The HERA reference magnets used for the p.c. compensation.

After the magnet cycle which is performed to prepare the machine for the next injection, the NMR measurements are used to set-up the correct magnetic field needed for the beam injection. Its values combined with the integral fields of all horizontal correction dipoles leads in general to dipole field values which differ only by about 0.1 permille from the ideal value.
In the case of the chromaticity the situation is more severe. The contribution of the induced persistent current sextupoles due to the b_3 component of the dipole magnet of $b_3 \approx 3.2 * 10^{-3}$ surpasses the natural chromaticity by about a factor of 5 (see Table 1 and [4]).

b_3 refers to the usual expansion of the azimuthal component of the magnetic field

$$B_\theta(r,\theta) \;=\; B_{\text{main}} \cdot \sum_n (\frac{r}{r_0})^{n-1} \cdot (b_n \cdot \cos(n\theta) + a_n \cdot \sin(n\theta)),$$

with r_0 denoting the reference radius, b_n and a_n the normal and skew multipole coefficients and B_{main} the main field (i.e. the dipole field in this case).

	natural	b3 (dipoles)
ξ_x	-44	-275
ξ_y	-47	+245

Table 1: Chromaticity of HERA-p at injection energy

2 THE HERA PERSISTENT CURRENT SEXTUPOLE CORRECTION SCHEME

In Fig. 2 the measured sextupole component of the persistent currents is plotted during a normal magnet cycle. A strong hysteresis of the b_3 component as a function of the ramp direction shows up, and depending on the ramp direction of the main dipole field even the sign of the effect is reversed. In the lower part of the figure the situation at injection energy is shown on a larger scale: During the time needed for beam injection the b_3 component is varying due to the decay of the corresponding persistent currents which are re-induced on the first steps of the next ramp.

Due to these effects a prediction of the sextupole contributions and the p.c. chromaticities is more difficult than in the case of the beam energy. During normal beam operation therefore the chromaticity of HERA is corrected at injection using a low-intensity pilot bunch train. By shifting the rf-frequency of the machine the chromaticity is measured and corrected to values of about $+1 \ldots + 3$ in both planes. Afterwards these values are kept constant automatically: The rotating coils situated in the reference

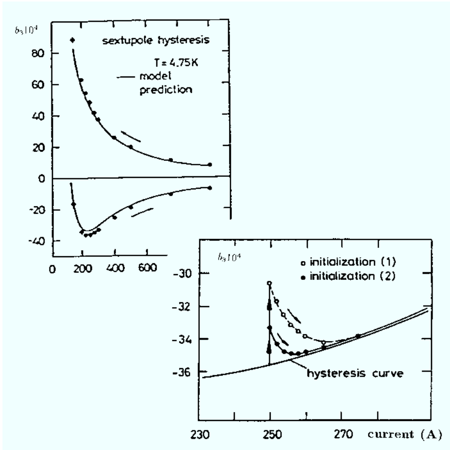

Figure 2: Persistent current contribution to the sextupole component b_3 of the main bending magnet in HERA. At the HERA injection field, corresponding to $I = 244A$ in the plot, the decay of the p.c. effect is shown in the lower part of the figure.

magnets detect any change of the b_3 component, and corrections are applied accordingly to the sextupole magnets in the ring. During the time needed for injection of the 180 proton bunches and during the first part of the ramp up to an energy of 150 GeV this scheme works very well.

However the correction procedure described above is time consuming and particle losses due to the shifting of the rf frequency cannot be excluded.

The aim of these studies was to investigate the predictability of the overall chromaticity of HERA at injection energy. As the natural chromaticity ξ_{nat} can be calculated accurately the major concern here was to calculate the absolute value of the p.c. contribution to ξ_{total}, based on the b_3 component measured in the reference magnets. The values obtained were compared to those resulting from the actual settings of the sextupole correction magnets and the measured values on beam.

The model used in the calculations is shown in Fig. 3.

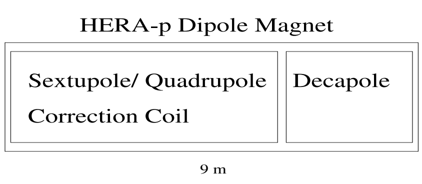

Figure 3: Schematic view of a superconducting HERA dipole magnet with its multipole correction coils.

The superconducting HERA dipoles are equipped with quadrupole and sextupole windings of about 5.9 m length. These correction coils are not centered longitudinally in the main magnet but, having a length of about 5.9 m, are located on the first part of the 9 m long dipole magnet. In the second part of the dipole magnet an additional decapole correction coil is installed.

In contrast to this the p.c. b_3 component is acting on the whole length of the dipole. As the $\beta-$ function and the dispersion of the beam optics are changing in the magnet this effect has to be considered in the calculations. The corresponding beam optics in the periodic FODO structure of the HERA ring is shown in Fig. 4.

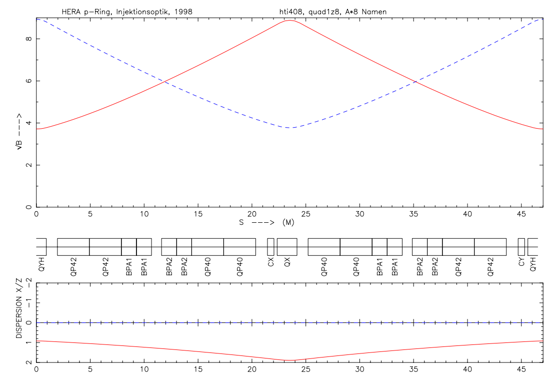

Figure 4: Beam optics in the FODO section of HERA-p

3 PREDICTABILITY OF PERSISTENT CURRENT SEXTUPOLE EFFECTS

During one month of HERA luminosity operation the settings of the sextupole correction magnets, that were applied for the required chromaticity of $\xi \approx +1 \ldots + 3$ during injection, had been stored. With the MAD program [5] the corresponding magnet strengths were used to calculate the effect on the beam. At the same time the readout of the rotating coil was used to deliver the p.c. sextupole as measured in the reference magnets. The resulting b_3 component was applied as multipole strength in MAD acting on the 9 m long dipole magnets. The data are summarized in Fig. 5 to Fig. 8.

Fig. 5 shows the chromaticity resulting from the b_3 component of the reference magnets for normal, i.e. routine running conditions. As indicated in Table 1 the persistent current effect leads to a chromaticity of about $\xi = -272$ in the horizontal plane. The values plotted vary within a band of ± 2, but in general they show a smooth behaviour. It can be seen in the plot that some data points have been omitted: Sextupole component values measured after a quench of the machine or switching off the magnets for access and maintenance are not included.

They are included in the next plot of Fig. 6. The complete ensemble of the data points now shows a much more pronounced fluctuation from run to run and jumps of the p.c. chromaticity of up to 5 units are detected.

In contrast to that Fig. 7 shows the effect of the actually applied sextupole correction magnets. For each run, the sextupole strength of the correction magnets has been calculated and ξ is plotted again as a function of the run number. It should be pointed out that now the chromaticity resulting from the real settings applied shows a fluctuation from run to run that is larger than expected from the

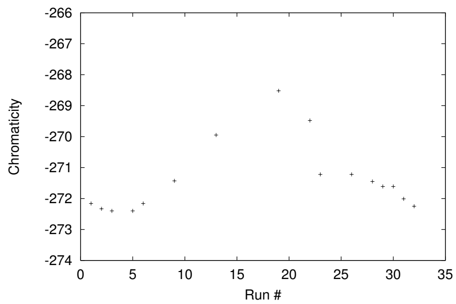

Figure 5: Chromaticity in the horizontal plane resulting from the b_3 multipole component: Only "routine conditions".

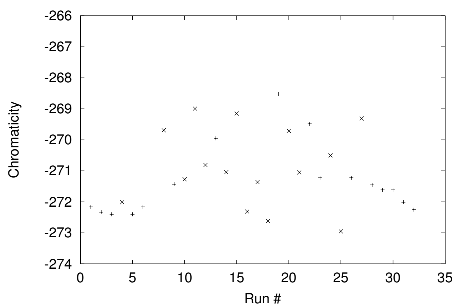

Figure 6: Chromaticity in the horizontal plane resulting from the b_3 multipole component: All runs.

reference magnet data, by up to a factor of two,. In addition there are changes from run to run measured in the real machine that did not show up in the data of the reference magnets.

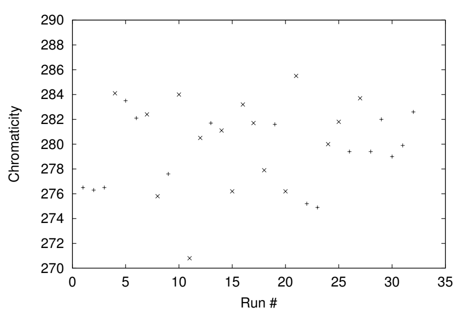

Figure 7: p.c. chromaticity calculated from the actual settings of the sextupole correction magnets.

Combining the two data sets of Fig. 6 and Fig. 7 reflects the difference between the chromaticity measured on beam, and the prediction from the reference magnet data, Fig. 8

4 SUMMARY AND CONCLUSION

The b_3 component in the HERA reference magnets has been measured for successive runs to calculate the persistent current effect on the chromaticity of the machine. In

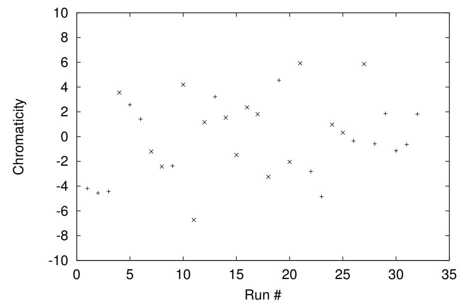

Figure 8: Difference of ξ resulting from sextupole settings and the prediction of the b_3 measurement.

addition the actual settings of the sextupole correction magnets were used for the same purpose. In an ideal case both values should coincide. However it turned out that effects exist in the machine, that lead to fluctuations of the sextupole settings, needed to achieve $\xi \approx +2$, and that are not reflected by the multipole content of the reference magnets. Especially after quenches of the magnets, interruptions of the routine running for access or maintenance etc. the p.c. chromaticity predicted by the reference magnet multipoles and the chromaticity found by the sextupole correction settings can differ by up to ± 6 and jumps of $\Delta\xi \approx 8$ have been observed from run to run.
It is concluded that additional sources of multipole components exist in the storage ring that are not measurable in the reference magnet system. A possible explanation for these additional sources of chromaticity would be the mutual influence of the nested coils. Changes in the quadrupole or sextupole correction coil can induce multipole components in the dipole main coil and vice versa. [6]. However having corrected these additional contributions on beam, the automised correction system is still able to keep the drifting chromaticity constant at flat bottom and during the acceleration.

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