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IMPACT OF PERSISTENT CURRENTS ON ACCELERATOR PERFORMANCE

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Persistent currents are superconducting eddy currents circulating inside the filaments of a s.c. magnet cable. They are induced by external field changes and due to their contribution to the multipole components of the magnets they have a strong influence on the accelerator. Based on the experience at the proton ring of the HERA collider, the impact of persistent currents on the performance of a large superconducting accelerator is discussed. Measurements of the magnet quality and the stability and reproducibility of the machine are presented at static operation and during beam acceleration. The correction system which is used to keep the impact of p.c. within the required tolerances is presented.

1 INTRODUCTION

Superconducting magnets have played an essential role in the design and construction of the big hadron accelerators such as the TEVATRON p-$\bar{p}$ collider at Fermilab and the proton-lepton collider HERA at DESY. Even more important is the impact of this magnet technology for the new machines such as RHIC and LHC that are in the design and construction phase at present.

Unfortunately superconducting magnets are — as conventional magnets too — not perfect. They suffer from imperfections and non-reproducibilities and the emphasis of this paper is to take a closer look at the influence of superconducting eddy currents on the performance of the machine and on the beam parameters. These so-called persistent currents are induced by changes of the external magnetic field and circulate inside the superconducting filaments of a magnet cable.

2 MULTIPOLE CONTRIBUTIONS OF PERSISTENT CURRENTS

The persistent currents inside the filaments of a superconductor severely affect — at least at low magnetic fields — the field quality of the magnet: They contribute to the multipole components of the magnetic field. With r denoting the radial, and θ the azimuthal direction, the azimuthal field component B_θ of a magnet can be expanded in a series of normal and skew components b_n and a_n:

$$B_\theta(r,\theta) = B_{\text{main}} * \sum_{n=1}^{\infty} \left(\frac{r}{r_0}\right)^{n-1} * \{b_n * \cos(n\theta) + a_n * \sin(n\theta)\} \quad (1)$$

where r_0 denotes the reference radius (25 mm for the HERA magnets). It corresponds to about $\frac{2}{3}$ of the inner coil radius and approximates the free-bore radius of the beam-pipe. B_{main} is the "main field" of the magnet, e.g. the dipole field in a main bending magnet and in the case of a quadrupole lens $B_{\text{main}} = r_0 * g$ with g being the gradient.

In Figure 1 such a multipole composition is presented for the main bending and focusing magnets of the HERA proton ring.[1] The measurements were obtained using a system of rotating coils[2] at a transport current through the magnets of $I_0 = 5000$ A which corresponds to an energy of 800 GeV. On the left hand side of the figure the multipole components of the dipole magnet are presented. The right hand side shows those of the main quadrupole lenses. The data are split with respect to the two production lines (i.e. German/Italian in the case of the bending magnets and German/French for the quadrupole lenses).

The normal as well as the skew multipole coefficients b_n and a_n of the HERA main magnets are in the order of 10^{-4}. The contribution of persistent current field errors can be neglected at high fields of about 5 Tesla where the measurements shown in Figure 1 have been taken. For low fields however i.e. close to the injection energy of HERA the field quality of the superconducting magnets is seriously affected by persistent currents. Strong multipoles up to high orders allowed by the coil geometry are created, i.e. in the case of a dipole magnet $n = 1, 3, 5, \ldots$ and for a quadrupole $n = 2, 6, 10, \ldots$.

For transport currents between 100 and 1000 A corresponding to magnetic fields in the bending magnets of $B = 0.09$ T to $B = 0.9$ T, the persistent-current contribution to the dipole field in the bending magnet and to the

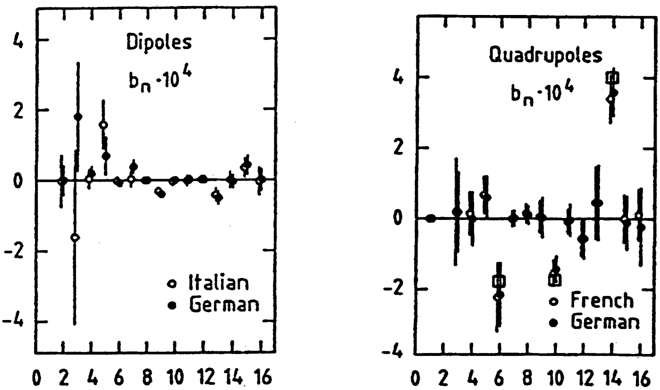

FIGURE 1 Normal multipole coefficients b_n up to order 16 of the HERA main dipole and quadrupole magnets measured at a magnetic field of about 5 Tesla. The average values are plotted with error bars indicating the rms spread of the magnet sample.

quadrupole component in the main quadrupole lenses of HERA are shown in Figure 2. The star in the plot refers to the injection field of $B_{\text{inj}} = 0.2267$ Tesla.[1] Each dot represents a measurement of the persistent-current contribution for the given transport current through the coil.

Three characteristics of the data shown in Figure 2 are important:

- The persistent current contributions are large compared to the normal multipole imperfections of the magnetic field plotted in Figure 1. At 40 GeV injection energy of the HERA p-ring the transport current amounts to 244 A which is close to the value where the persistent current field error reaches its biggest contribution (see Figure 2). The magnetic field at injection in HERA ($B_0 = 0.2267$ T) has to be reproduced to a level of $\frac{\Delta B}{B} \approx 0.1$ Gauss to guarantee a good energy matching between the preaccelerator PETRA and the HERA machine for efficient transfer of the proton bunch trains. As can be deduced from the plot, the persistent-current effect surpasses this required accuracy by more than a factor of 100; resulting in a field contribution of approximately $\Delta B_{\text{pc}} \approx 11$ Gauss, far too much to be neglected.
- The persistent-current contribution in both the dipole field and the quadrupole field of Figure 2 shows a strong dependence on the main field

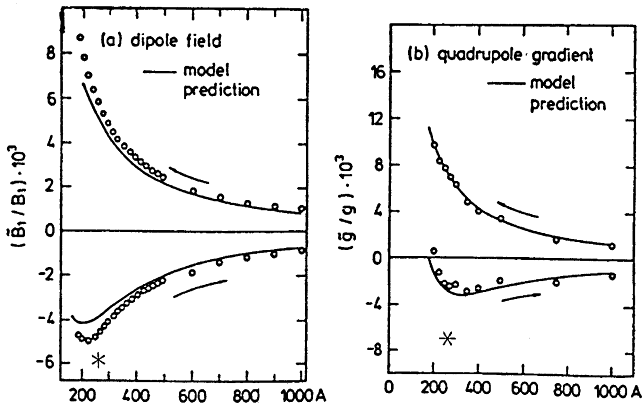

FIGURE 2 Contribution of the persistent-current fields to the main dipole field and to the quadrupole gradient as a function of the transport current. The injection energy of 40 GeV is marked by a star.

of the corresponding magnets. For the ramp-up direction of the magnet a negative persistent-current component is detected, for the down ramp a positive one leading to a hysteresis in the response of the magnetic field for changes of the transport current. (The ramp direction during the measurement is indicated in the plots by arrows.) At higher fields the effect diminishes and can be neglected completely in HERA at the flat top energy of 820 GeV.

- In the two plots of Figure 2 model calculations have been included[3] assuming that the induced persistent currents circulate inside the filaments at a constant current density.[4] They are in excellent agreement with the measurements on the hysteresis, the diminishing effect at higher fields, and also the absolute strength of the p.c. contributions. In addition to the dipole field distortion due to persistent currents, the sextupole contribution in the main bending magnets is of great importance for the machine performance. As in the case of the p.c. dipole and quadrupole components, the typical hysteresis is observed again (see Figure 5). The influence of this distortion on the chromaticity $\xi = \Delta Q / \frac{\Delta p}{p}$ of the machine is remarkable: The natural chromaticities of the HERA proton ring at injection energy amount to $\xi_x = -44$ and $\xi_z = -47$ in the horizontal and vertical direction.

The b_3 component due to the influence of the persistent-current fields is, according to Figure 5, about $b_3 \approx 32 * 10^{-4}$ at the injection current of 244 A. The resulting distortion of the chromaticity ξ_{pc} surpasses the natural one by roughly a factor of 5:

For completeness it should be mentioned that even the decapole component in the dipole magnet is affected by p.c. effects as well as the 12-pole and 20-pole coefficient of the main quadrupole lenses.[5]

The persistent-current effects discussed above have a considerable influence on the parameters of the accelerator: The size of the p.c. contributions to the energy and chromaticity are large compared to the nominal values of the machine. Therefore two questions are of paramount importance for the operation of the accelerator: *Are the persistent-current effects stable? — Are they reproducible?*

Unfortunately the answer is a twofold "No". The influence of p.c. on the machine performance depends on the history of the magnets, i.e. on the detailed excitation curve the magnets have been passed through, the effects decaying as a function of time. During the construction phase of HERA this behaviour was studied in detail. At the current of $I = 250$ A which is close to the actual injection current used today the persistent-current effects were observed as a function of time. As an example the dipole field contribution in a HERA bending magnet is shown in Figure 3.

The two curves in the plot correspond to two different excitation cycles the magnet had passed through. The open circles indicate a maximum current in the preceding cycle of $I_{max} = 6500$ A, whereas the dots were measured after a cycle of only $I_{max} = 2000$ A.[6] The horizontal axis is plotted on a logarithmic scale and both curves show a logarithmic reduction of the persistent-current effects — which can be explained by flux creeping in the superconducting wire.[7] The rate of the decay as deduced from the plot however is strongly dependent on the magnet history. (Latest results from theoretical investigations indicate that the decay of persistent-current fields is related to at least three effects: flux creeping of the inner filament persistent currents, decay of inter-strand eddy currents floating in loops between the different strands of a superconducting cable and redistribution of currents among cable strands.[8])

As the persistent currents are induced by a change of external field (the main-dipole field in this case) they are counteracting and thus reducing the dipole field of the accelerator magnets. The decay of the persistent currents

TABLE I Natural chromaticity compared to the persistent-current sextupole contribution b_3

	natural	b_3 *(dipoles)*
ξ_x	–44	–275
ξ_z	–47	+245

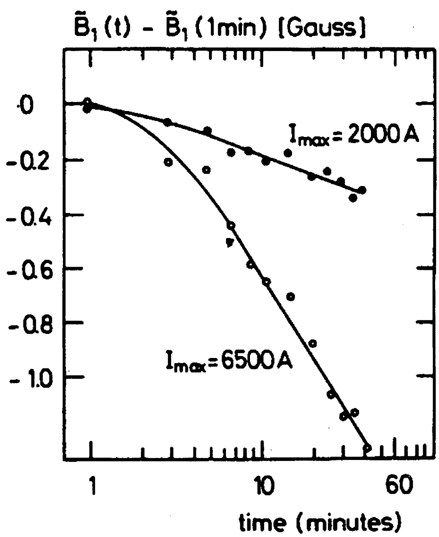

FIGURE 3 Dipole contribution of persistent currents at injection energy measured as a function of time. For two different values of the transport current in the preceding magnet cycle the value of the p.c. dipole field at the time of the measurement is compared to its value 1 minute after the end of the cycle.

shown in the last plot therefore predicts an increase of the measured magnetic dipole field during the injection phase of the accelerator, which is indeed observed. The reproducibility of HERA was investigated under routine run conditions. The correction currents needed to establish the desired values for tunes and chromaticity were measured and the corresponding offset of these parameters deduced. In Figure 4 the resulting deviations at injection energy are plotted for a number of successive HERA runs.

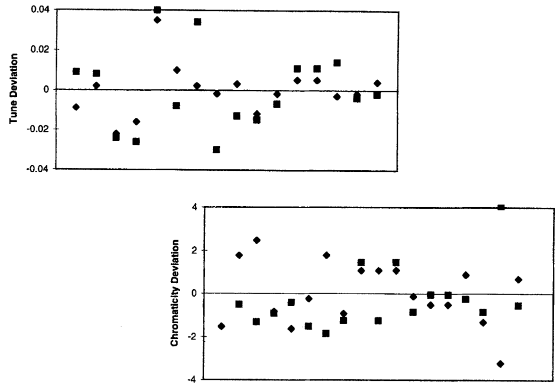

FIGURE 4 Deviation of tune and chromaticity values of HERA at injection. The horizontal and vertical values (squares and diamonds) are plotted after the standard magnet cycle.

3 PERSISTENT-CURRENT EFFECTS DURING ACCELERATION

The decay of the persistent currents in the superconducting magnets of the HERA proton accelerator play an essential role at low energies. During acceleration the situation is changing drastically again: In the first steps of the acceleration the persistent-current fields are re-induced by the changing magnetic field. After a short time (some seconds, depending on the recent history of the magnet) the persistent-current effects have reached their full strength again and we have to deal with the original hysteresis curve. The situation is shown in Figure 5. In the upper part of the figure we have plotted the hysteresis-like behaviour of the 6-pole component which appears in a similar way as the dipole and quadrupole contributions of Figure 2. During the 30 minutes injection period of HERA the 6-pole component was measured. The results are shown in the lower part of the plot where a better resolution was chosen: The measurement points show the decay of the p.c. 6-pole contribution at 40 GeV. The dots refer to a preceding magnet cycle where the usual maximum current of $I_{max} = 6000$ A was applied. The open circles describe the behaviour after cycling the magnets a second time at a lower current of $I = 2000$ A.

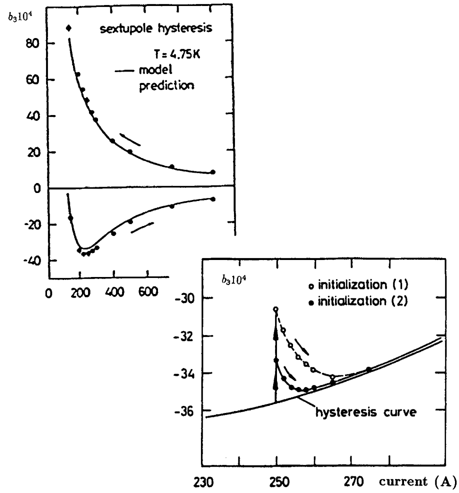

FIGURE 5 Persistent-current contributions during acceleration: The upper-left part of the figure shows the p.c. sextupole contribution as a function of the transport current. At the 244 A injection value of the transport current the decay of the p.c. b_3 component is plotted in the lower-right part of the figure where a better scale of the plot was chosen. The dots correspond to the decay after a maximum current of 2000 A, the open circles after $I_{\max} = 6500$ A in the preceding cycle. In both cases the persistent currents are re-induced to their full strength during acceleration approaching the old hysteresis curve again.

In both cases the persistent-current effects are decaying and re-approach the hysteresis curve during the first part of the acceleration process. But a strong dependence is found on the history of the magnets. After the second cycle of $I_{\max} = 2000$ A the decay turns out to be about half as strong and the re-induction of the p.c. due to the changing field on the ramp is much faster. Considering the strong influence of the p.c. 6-pole contribution on the machine a strong nonlinear deviation of the chromaticity from its ideal behaviour during the early part of the ramp is expected.

In Figure 6 the deviation of the chromaticity ξ from its nominal value (i.e. close to +1) is plotted as a function of the energy.[9] The solid line shows a measurement of the horizontal and vertical chromaticity ξ_x and ξ_z of the beam. The dotted line shows the chromaticities predicted by an online measurement the b_3-component in the HERA reference magnets. They are in excellent agreement thus forming the basis for the HERA online correction system.

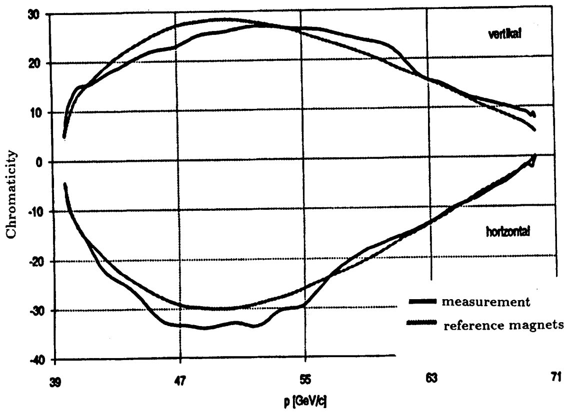

FIGURE 6 Chromaticity measurement during acceleration between 40 GeV and 70 GeV. The solid line shows the chromaticity measured during the first step of the HERA acceleration procedure. The dashed line corresponds to the chromaticity values predicted by the measured values of the changing sextupole component in the reference magnets.

4 IMPACT OF PERSISTENT CURRENTS ON ACCELERATOR PERFORMANCE

Persistent-currents affect the machine parameters most seriously at low energies, that is in general at injection and during the early stages of the acceleration process, where the influence on the beam is large. The effects can exceed the required tolerances by big factors. Moreover persistent currents are not persistent. They decay as a function of time, the rates depending on the history of the magnets and they can be reinduced during beam acceleration. As a consequence a detailed knowledge of the recent "history" of the magnets in the accelerator is required as well as the time that has passed since the last magnet cycle was performed. The p.c. multipole contributions depend strongly on the way the transport current had been changed before leading to a hysteresis-like behaviour.

Special care has to be taken if extended correction coils nested inside the main magnets are used as in HERA.[10] A mutual influence of these coils and the main magnet coil is detected which affects the multipole components of the main magnet. Changes of the transport current in the main coil may generate multipoles due to persistent currents in the correction windings and vice versa.

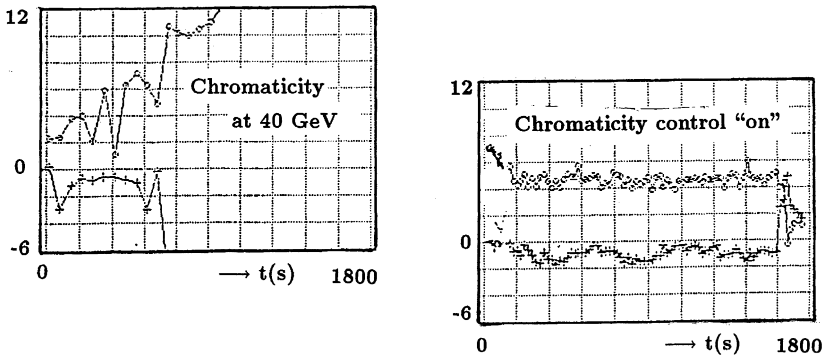

FIGURE 7 Chromaticity measurement at HERA during injection energy: Left part: Due to persistent-current decay the chromaticity is drifting in both planes in opposite directions. Right part: The changing 6-pole contribution is measured in the reference magnets and corrections can be applied to keep the chromaticity constant during injection and acceleration.

Due to these effects a well-defined procedure has been established at HERA to prepare the machine for injection. This "magnet cycle" consists of four steps:

(1) The s.c. main magnets (dipole and quadrupole magnets) are set to a field value of about 5 Tesla which is close to the maximum field.
(2) The normal-conducting magnets in the accelerator are cycled, that means set to their maximum fields, set back to zero current and then to their nominal values. At the same time the super-conducting magnets including the correction coil windings are set to their nominal injection values.
(3) The main magnets are reduced to minimum values
(4) and set to their injection values.

This procedure overwrites all existing persistent-current patterns in the main magnets and the eventual existing multipole contributions due to current changes in the correction coils. The remaining effects are the well-known hysteresis curve of the persistent-current multipoles in the main magnet field and their decay.

At HERA these parameters are measured online. The machine is equipped with two reference magnets — one for each magnet production line. They are powered in series with the main magnet chain in the accelerator tunnel and they represent the behaviour of the whole magnet ensemble. The reference magnets are equipped with NMR and Hall probes to measure the magnetic dipole field, and with rotating coils for the 6-pole contribution. A change of the injection field for example due to the decay of the persistent-current fields is detected by the NMR's and corrected by a corresponding increase of the horizontal orbit correction coils in the ring. During the acceleration procedure a stationary pick-up coil is used to measure the dipole field in the reference magnets and to lock all other elements in the machine to the ramping dipole field — however complicated the hysteresis curve might look.

The b_3-component of the dipole magnets is measured by the rotating 6-pole coils. Changes due to persistent-current decay, hysteresis or re-induction are detected and correction currents are calculated at injection and during the acceleration up to an energy of 150 GeV where persistent-current effects no longer play an essential role in the magnets. The power of this online measurement system is demonstrated in Figure 7 where the measured chromaticity of the ring is plotted at injection energy as a function of time.

References

[1] Schmüser, P. (1991). "Field Quality Issues in Superconducting Magnets", *IEEE Particle Accelerator Conference*, San Francisco, USA.

[2] Schmüser, P., Meinke, R. and Zhao, Y. (1991). "Methods of Harmonic Measurements in the Superconducting HERA Magnets and Analysis of Systematic Errors", DESY-Hera-91-13.

[3] Brueck, H., *et al.* (1989). *Z. Phys.*, **C44**, 385.

[4] Bean, C.P. (1962). *Phys. Rev. Lett.*, **8**, 250.

[5] Bruck, H., *et al.* (1990). "Persistent Current Effects in the Superconducting Hera Magnets and Correction Coils", *European Particle Accelerator Conference*, Nice, France.

[6] Brueck, H., *et al.* (1990). "Time Dependence of Persistent Current Field Distortions in the Superconducting HERA Magnets", *European Particle Accelerator Conference*, Nice, France.

[7] Kim, Y.B., Hempstead, C.F. and Strand, A.R. (1963). *Phys. Rev. Letters*, **9**, 306.

[8] Devred, A., priv. com.

[9] Meincke, O. (1992). "Measurement and Control of Q-Values and Chromaticity in the HERA Proton Ring" (in German), DESY-Hera-92-08.

[10] Pekeler, M., *et al.* (1992). "Coupled Persistent Current Effects in the Hera Dipoles and Beam Pipe Correction Coils", DESY-Hera-92-06.