

**Observation of a Periodic Pattern in the Persistent-Current
Fields of the Superconducting HERA Magnets***

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Observation of a Periodic Pattern in the Persistent-Current Fields of the Superconducting HERA Magnets

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1. INTRODUCTION

The time dependence of persistent current multipoles in superconducting magnets [1] is still unexplained. The decay is too large to be accounted for by flux creep and it does not show the expected dependence on temperature [2]. Furthermore the decay is influenced by a preceding field sweep in the magnet, it becomes more pronounced if the magnet was previously excited to its maximum field. For a detailed study of the decay mechanism a special sensor has been developed which allows to record small sextupole components in superconducting dipole magnets. During an experimental study of the time dependence of a HERA dipole it was found that the sextupole field exhibits a sinusoidal structure along the axis of the magnet. A similar periodic structure was found for the main dipole field with the help of a nuclear magnetic resonance probe. The wavelength of the periodic pattern is compatible with the transposition pitch of the Rutherford-type cable in the magnet coils. The structure was found to exist in all HERA dipoles measured afterwards (~ 10) and also in a superconducting coil without iron yoke. With a specially developed 2 cm long pickup coil it was found that all accessible multipole components in dipole and quadrupole magnets are modulated along their axis.

2. EXPERIMENTAL TECHNIQUE

The harmonic content of accelerator magnets is normally measured with rotating pickup coils. While their sensitivity and precision is generally very good their time and spatial resolution is rather limited. For a more detailed study of the sextupole decay in dipole magnets a sensor has been developed [3], which consists of three Hall probes mounted on an equilateral triangle. The probes are temperature controlled and powered with a well stabilized alternating current of 400 Hz. By adjusting the gains of two of the Hall probes with inverting amplifiers the dipole field in the summed signal is suppressed by four orders of magnitude below 0.4 T. The remaining signal from sextupole fields is measured with the help of a lock-in amplifier. The detector is aligned with respect to gravity using a built-in sensor, so it measures the normal sextupole field B_3 . The detector has a spatial resolution of better than 5 mm and a response time of 0.3 s.

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The main dipole field in the magnets is measured with a nuclear magnetic resonance probe, which is centered on the axis of the magnet with an accuracy of better than 3 mm. This uncertainty is mainly given by a thermally insulated tube which is used in the magnet bore to allow measurements at room temperature.

To allow measurements of other multipole fields in dipole and quadrupole magnets a 2 cm long tangential pickup coil has been developed. A Fourier analysis of the voltage induced in the continuously rotating coil yields normal and skew multipole components up to 12th order.

3. EXPERIMENTAL RESULTS

3.1 Periodic Structure of the Sextupole Field

During a measurement of the time dependence at various positions along the axis of a dipole magnet we made the surprising observation that the sextupole field exhibits a periodic pattern along the axis of the magnet as shown in Fig. 1.

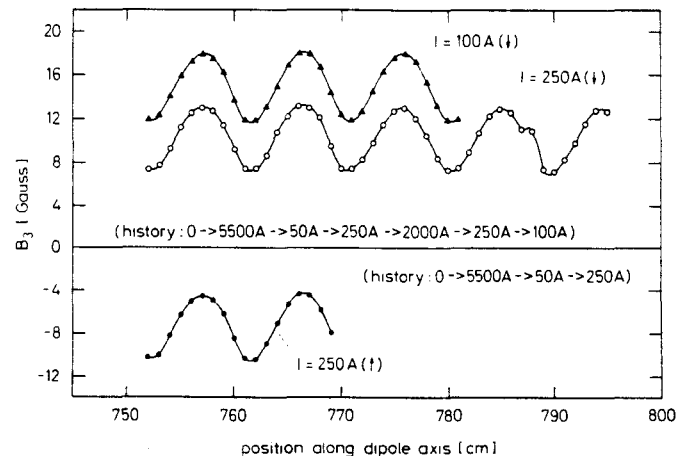


Fig. 1. Sextupole field B_3 at a reference radius of 25mm measured along the axis of an ANSALDO/ZANON dipole at a current of 250 A on the up-ramp branch.

The data was taken after a waiting period of one hour at the HERA injection field (0.23T, 250A) to eliminate most of the logarithmic time dependence. The sextupole field shows an almost perfect sinusoidal structure with a pronounced amplitude. Curve (a) is taken on the "up-ramp" branch ($\uparrow$) of

the hysteresis curve at a current of 250 A. In the horizontal plane of the magnet the sextupole field is antiparallel to the dipole field. Curves (b) and (c) are taken on the "down-ramp" branch ($\downarrow$) after going through a current cycle 250 A $\rightarrow$ 2000 A $\rightarrow$ 250 A $\rightarrow$ 100 A. The average values of (a), (b) and (c) are in agreement with the standard harmonic measurements using a 240 cm long pickup coil. The sinusoidal structure, however, has practically the same wavelength, phase and amplitude in the three measurements. This is a first indication that the oscillatory part of the sextupole field cannot be caused by magnetization currents in the NbTi filaments of the superconductor since in that case one should find different phases for 250 A ($\uparrow$) and 250 A ($\downarrow$) and different amplitudes for 250 A ($\downarrow$) and 100 A ($\downarrow$).

3.2 Influence of a Quench or Warm-up of the Magnet

Since the periodic structure remains unchanged during the current cycle above, it is tempting to attribute the phenomenon to some non-superconductor effect like a periodically magnetized material in the magnet or else to a malfunction of the detector. To rule out such explanations we have performed experiments where only the state of the superconductor is changed. After a quench the dipole current was raised to 5000 A and then lowered to 250 A. The sextupole field measured at this current (Fig. 2) shows a similar periodic structure along the magnet axis as in Fig. 1 (the amplitude is lower, see sect. 3.3).

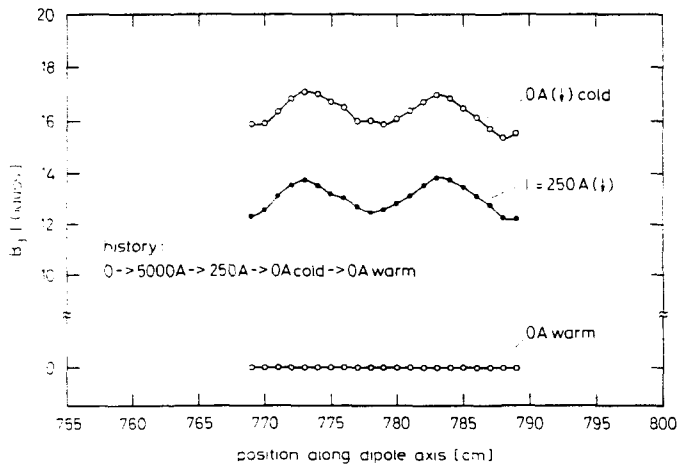


Fig. 2. Sextupole at 250 A and 0 A on the down-ramp branch. Also shown are data for $I = 0$ A with the magnet warmed up to 20 K.

When the dipole current was reduced to zero and the power supply switched off the periodic structure remained unchanged, only the average value of the sextupole field increased in proportion to the increasing critical current density. The pattern persisted without attenuation for more than 12 hours. However, warming up the magnet to 20 K extinguished any persistent currents in the superconductor and the sextupole field was measured to be zero, as expected and no periodic structure was left (Fig. 2).

From the above observation we conclude that the periodic structure is caused by superconducting currents in the cable. A very strong hint in this direction is also the observation that the wavelength of about 95 mm is in close agreement with the transposition length (95 ± 2 mm) of the Rutherford-type cable as used in the HERA magnets.

3.3 Dependence on the Maximum Current in the Initial Cycle

A number of measurements of the periodic structure in the sextupole field was done at 250 A on the up-ramp branch with different values of the maximum current in the initial cycle: Quench, 0 A $\rightarrow$ $I_{\max}$ $\rightarrow$ 50 A $\rightarrow$ 250 A. As indicated, each measurement was preceded by a quench to eliminate all persistent currents in the filaments. The amplitude of the periodic structure, plotted in Fig. 3, is seen to rise rapidly if $I_{\max}$ approaches the critical current of the conductor, which is about 6400 A at the operating temperature of 4.7 K.

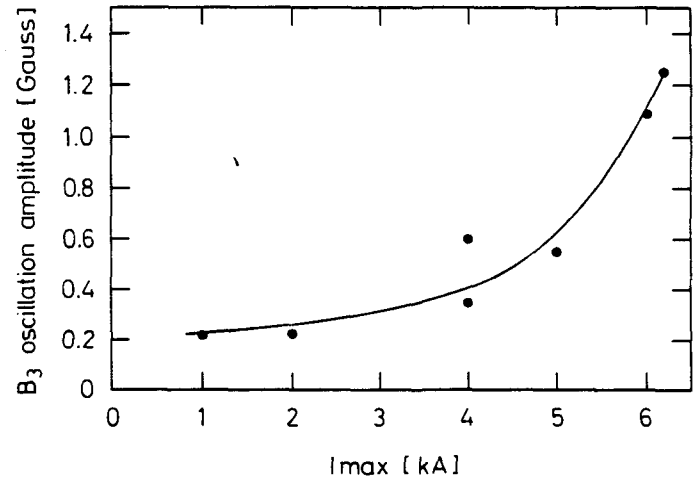


Fig. 3. Amplitude of the sextupole oscillation as a function of the maximum current in the initial cycle.

A sequence of measurements was done to study the effect of other parameters in the current cycle on the periodic structure:

- The amplitude at 250 A ($\uparrow$) increases steadily with the number of cycles between $I_{\min} = 50$ A and $I_{\max} = 5500$ A.
- Leaving the magnet with ABB superconductor for a time of 45 minutes at a high current of 5500 A led to a significant increase in the amplitude (Fig. 4).

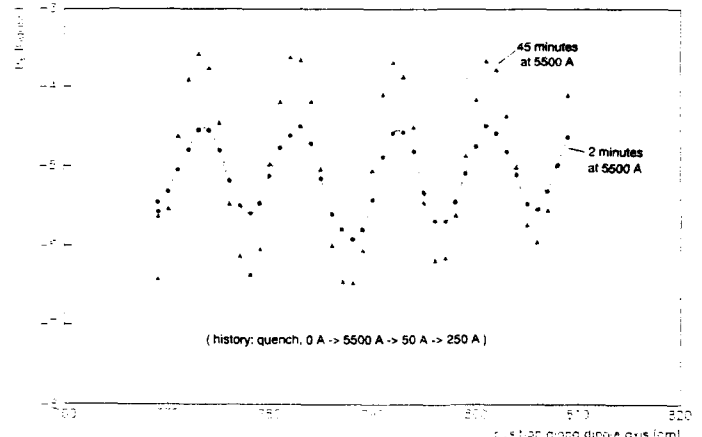


Fig. 4. Sextupole field along the axis of an ABB dipole measured after a single cycle to 5500 A with 2 minutes resp. 45 minutes waiting time at 5500 A.

- In the above cycles the current was raised with a rate of 20 A/s, but no significant change in the periodic structure was observed.

3.4 Measurements of Other Multipole Fields

In all magnets investigated so far (~10), the periodic structure was also observed in the dipole field measured with a nuclear magnetic resonance detector. The results are compared to the sextupole data for the same magnet in Fig. 5.

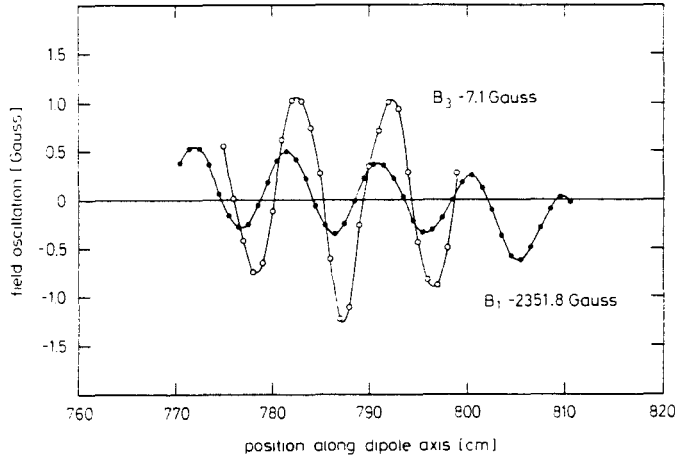


Fig. 5. Comparison of sextupole and dipole fields in magnet BR 120 (LMI superconductor). The average sextupole resp. dipole fields have been subtracted.

The same periodic structure is observed with both detectors. The slight phase shift of about 10 mm between the dipole and sextupole fields can be explained by the positioning error of the two detectors.

To check whether other multipole fields show a similar modulation along the axis of the magnet a 2 cm long pickup coil was used. The measurements shown in Fig. 6 are taken for the following current cycle: Quench, 0 A → 6000 (1 hour) A → 0 A. All measured multipole fields (normal and skew) up to the 12-pole components show a pronounced modulation along the axis of the magnet.

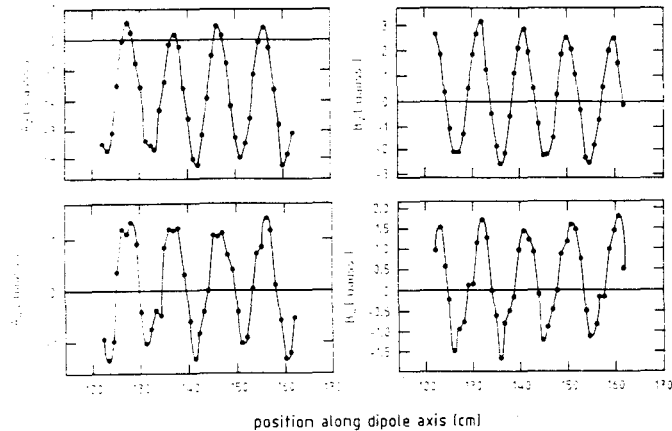


Fig. 6. Non-allowed multipole fields A_2, B_2, A_4, B_4 , on a reference radius of 25 mm at 0 A measured along the axis of a dipole magnet.

With the help of the pickup coil a similar periodic structure was found for a HERA quadrupole magnet.

4. DISCUSSION

A pronounced periodic pattern along the magnet axis has been observed for the first time in all multipole components of the HERA dipole magnets and a quadrupole magnet. The wavelength of this structure is comparable with the transposition pitch of the superconducting cable. The effect is related to superconducting currents in the cable because it vanishes when the magnet is warmed up above its critical temperature T_c . Moreover the periodic structure persists for more than 12 hours with zero transport current in the coil and no dependence on the ramp direction of the dipole field was observed. The phase of the structure is the same for up- and down-ramp of the magnet current and the amplitudes are equal for 250 A (↑), 100 A (↓) and 0 A (↓). No dependence on dB/dt was found. This excludes the possibility that induction is responsible for generating the current. The amplitudes depend strongly on the highest excitation of the magnet before performing the measurement at low field. The phase of the structure is not perfectly stable, slight shifts have been observed.

The coincidence between the wavelength and the cable pitch may be the key to an understanding of the effect. We assume that different strands in the cable take different fractions of the total transport current when the magnet is excited to field close to the critical value. If this asymmetry persists when the coil current is reduced, a periodic field modulation is expected for all multipole components from the zig-zag path of the strands in the cable. The explanation is supported by measurements at room temperature made on a model in which wires run in a zig-zag path as in the magnet coil.

ACKNOWLEDGEMENTS

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