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STUDIES OF DECAY AND SNAPBACK EFFECTS ON LHC DIPOLE MAGNETS

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Abstract

LHC model magnets have dynamic field imperfections of various nature. Two effects of particular importance are field component decay during injection and "snapback" during the first few seconds of acceleration, which happens over typically 15 to 20 mT. The dynamic behaviour of the model magnets was measured as a function of several parameters in the operation cycle and powering history. We demonstrate how the systematic variation of only one single operation cycle parameter can affect the behaviour of the sextupole component.

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ABSTRACT: LHC model magnets have dynamic field imperfections of various nature. Two effects of particular importance are field component decay during injection and "snapback" during the first few seconds of acceleration, which happens over typically 15 to 20 mT. The dynamic behaviour of the model magnets was measured as a function of several parameters in the operation cycle and powering history. We demonstrate how the systematic variation of only one single operation cycle parameter can affect the behaviour of the sextupole component.

1. INTRODUCTION

The field in a plane perpendicular to a magnet's axis can be expanded in a Fourier series, where b_n and a_n are the normal and skew multipole coefficients, which are expressed in relative "units". B_1 is the main field and R_{ref} the reference radius of 17 mm:

$$\mathbf{B}(x,y) = B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1} . \qquad (1)$$

Field errors in superconducting dipole magnets have several origins. Geometric field errors result from the deviation of the real current distribution in the cables from the ideal current distribution of the desired magnetic field. At high fields a further deviation is caused by the saturation of the iron yoke. Both contributions are reproducible, can be predicted accurately and may be inferred from warm measurements. Additional effects are caused by the diamagnetic properties of the superconducting filaments in the cable, which are due to persistent currents. This contribution can be important at the low injection field level. During ramps, eddy currents are induced in the Rutherford cable and contribute to its diamagnetic behaviour. Persistent and eddy current effects are reproducible, but require measurements in the superconducting state. Finally, the LHC will have to deal with a new class of effects (Bottura 1997). During long periods of constant current excitation, especially during injection, all field components show a decay behaviour. As soon as, after the end of injection, the current is ramped up again, the field components rapidly recover from the decay and follow the course of the original hysteresis curve (*snapback*). In the LHC magnets the typical sextupole change during snapback is in the range of 10^{-4} (1 unit). On the other hand, a sextupole change of 1 unit causes a chromaticity change of about 50 units, one order of magnitude larger than the required tolerance. The sextupole changes during snapback therefore need to be corrected accurately. Note that in contrast to older machines, corrections not only have to be applied to the sextupole, but also to the decapole component. This effect was noticed for the first time as a time dependent chromaticity variation during injection tests at the Tevatron, followed by a fast chromaticity change during the initial acceleration phase at the end of particle injection.

Initially flux creep was thought to be the source of the change, due to the logarithmic decay behaviour. Measurements were performed at HERA on all magnets, which showed deviations from the logarithmic decay. Brück (1989) reported a large variation in the decay rate from magnet to magnet, which could be grouped into two families, corresponding to the manufacturer. As the initial current cycle showed a strong influence on the decay behaviour and as it is not possible to heat up all HERA magnets before each run, investigations focused on finding a current cycle, which reduces the decay behaviour. A 30 minute long pre-injection porch at low current turned out to be quite effective. For further compensation look-up tables and magnetic measurements from two reference magnets were used. At the SSC Devred (1991) identified two different components of the field component decay. The first and logarithmic one is caused by flux creep, lasts for about 300 s, is not affected by the excitation history and can be stopped by decreasing the magnet temperature. The second component, however, exhibits a long lasting decay, cannot be stopped, depends on the powering history and only appears when the magnet is precycled to a high current. A source of the second decay component can be found in a “current imbalance“ in the Rutherford cable, where different strands take different fractions of the transport current. During a ramp supercurrents are induced in the magnet heads, where the cable is exposed to a variation in the field sweep rate (Verweij 1995). During stable current conditions the amplitude decays due to currents diffusing into the straight section of the magnet, which changes the magnetisation in the filaments. A ramp after injection immediately “switches on” the original magnetisation (Wolf 1997).

2. EXPERIMENTS

A series of short models was manufactured at CERN within the frame of the R&D program for LHC dipoles. The magnets were assembled from four superconducting coils in a support stucture of laminated collars. The assembly was completed by an iron yoke and enclosed into a shrinking cylinder of stainless steel. The magnets considered in our experiments are the 1m long single aperture models MBSMS1 to MBSMS23. MBSMS1 to MBSMS13 are made from 5 blocks of cable per quadrant and Al-alloy collars. The following models MBSMS15 to MBSMS23 feature the new optimized 6 block design. Four of them (MBSMS15 to MBSMS18) have Al-alloy collars. The other five (MBSMS19 to MBSMS23), however, contain collars from austenitic steel and represent the closest match to the baseline design of the LHC main bending dipoles. Several of the magnets have been reworked in different “versions”, changing the collaring and yoking conditions. The measurements of decay and snapback were performed in a vertical test set-up. The magnets were cooled with superfluid helium at a temperature of 1.8 K. During our experiments rotating coils were used to measure the components of the magnetic field. They were mounted on a glass-fibre shaft and rotated inside the bore of the magnet. All coils were read-out simultaneously by a chain of VME integrators. Thus, the magnetic flux signal was measured as a function of the rotation angle. The major problem in the understanding of dynamic effects in the magnets is related to a strongly non linear dependence on the excitation history. Thus, we modified single parameters of a standardized operation cycle step by step and performed snapback measurements on the model magnets.

2.1 Variation of Operation Cycles

The current cycles used during our experiments are shown in Fig.1. An initial quench erases all persistent currents, the following pre-cycle moves the operating point away from the vergin curve onto a reproducible hysteresis curve. The pre-injection porch reduces the decay and snapback during injection and acceleration. Three parameters were found to be of special importance: The pre-cycle flat-top current, the flat-top duration and the pre-injection duration. Different pre-injection currents, however, did not significantly affect the snapback (Schneider 1998).

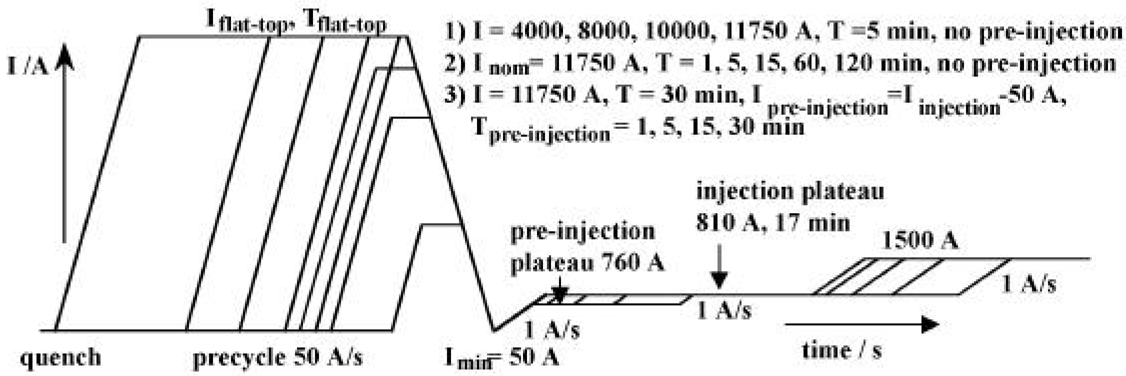

Fig. 1: Variation of flat-top current, flat-top duration and pre-injection duration

2.2 Variation of Pre-Cycle Flat-Top Current and Duration

During the pre-cycle experiments no pre-injection porch was used. For flat-top currents between 0 and 4000 A no significant influence on the snapback amplitude was found. Above 4000 A, however, we observed an almost linear increase of the snapback amplitude with the pre-cycle current (Fig.2). Many of the 6 block magnets (MBSMS15 to MBSMS23) showed a higher snapback amplitude and a stronger dependence on the flat-top current than the 5 block ones (MBSMS1 to MBSMS13). Also the influence of the pre-cycle flat-top duration on the snapback amplitude is different for the 5 and 6 block design (Fig.3). The 5 block magnets show an "exponential" increase and a saturation for an increasing flat-top duration. A time constant of less than 1 hour can be found by fitting the data to an exponential model. The snapback amplitude of most 6 block magnets, however, increases to a maximum at a flat-top duration of about 10 to 20 minutes, decreases significantly above this threshold, and possibly saturates for higher flat-top durations. MBSMS9 shows an anomalous behaviour.

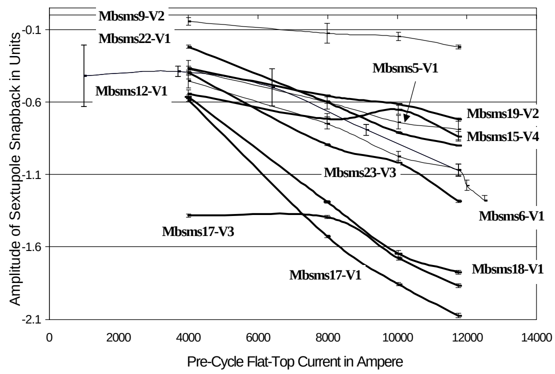

Fig. 2: Flat-top current influence

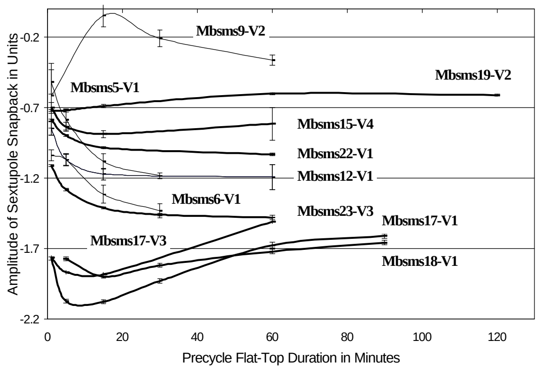

Fig. 3: Flat-top duration influence

2.3 Pre-Injection Duration

A pre-injection porch at a current 25 to 75 A lower than the injection plateau can be used to significantly reduce the snapback value (Fig. 4). For the 5-block model dipole MBSMS6-V1 a reduction of 50 % was found after 30 minutes of pre-injection duration. The 6-block magnets rather show a saturation behaviour. MBSMS19-V2, however, only showed a very small dependence on the pre-injection porch duration.

2.4 Statistics

In a statistical analysis of the snapback behaviour the whole population of our 1-meter long model magnets was investigated. The average snapback amplitudes for allowed harmonics are distributed systematically either with negative or positive sign, alternating in sign from one harmonic order to the other. The snapback values of non-allowed harmonics, however, are randomly distributed on the negative or positive side. Their average values are embedded into error bars around zero (Schneider 1998).

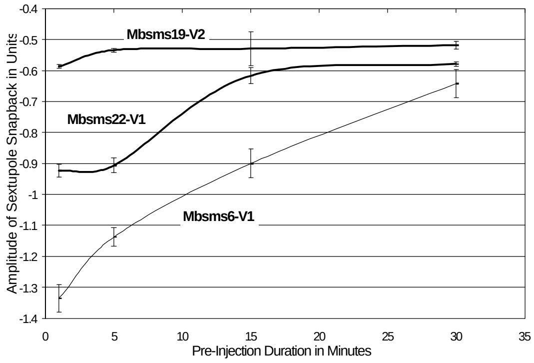

Fig. 4: Influence of pre-injection duration

3. CONCLUSION

For all magnets we found a strong dependence of the snapback amplitude on the powering history. Especially the maximum current and the duration of previous cycles have an important influence. A pre-injection porch, however, can be used in order to reduce these dynamic effects. The snapback amplitude depends on the detailed features of each magnet. Magnets of two different geometric designs were used in the experiments. They were wound from the same kind of cable, but especially the interstrand resistances varied through the years with different coatings or due to different collaring and yoking conditions. The differences in the measured snapback amplitudes are quite large in spite of the apparent similarity of the magnets. In practice this implies that all magnets should be measured before they are installed into the LHC.

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