IRON SHIMS OUTSIDE THE HELIUM VESSEL TO ADJUST FIELD QUALITY AT HIGH FIELDS*

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Abstract

This paper describes the development and demonstration of a novel technique of adjusting measured field quality. The technique is particularly attractive for achieving ultra-good field quality at high fields in superconducting magnets where the iron return yoke is saturated. The technique is based on placing iron shims of variable stack thicknesses, variable width and/or variable length on the outer surface of the stainless steel shell at strategic locations. Since the shims are placed outside the helium vessel, adjustments can be made without involving major operations such as opening the helium vessel. It is a simple and economical technique with a fast turn-around which is suitable for both short and long magnets. This allows one to reduce field errors well below the normal construction errors. The technique has recently been successfully applied in two magnets. This paper presents the design, measurement and adaptation of this technique which, when used in combination with the coil shims, produced near zero sextupole harmonic at the design field. The design was optimized to produce small harmonics throughout the range of operation.

INTRODUCTION

As a part of the US contribution to the Large Hadron Collider (LHC), two Interaction Region (IR) D1 dipoles (#106 and #107) were built by Brookhaven National Laboratory (BNL) for APUL (Accelerator Project for an Upgrade of the LHC). These magnets are in addition to the four D1 magnets and a spare that were earlier supplied by BNL as a part of the original US contribution to LHC [1]. Fig. 1 shows the location of one such D1 magnet in one half IR at Interaction Point 2 (IP2). D1 has a design field of 3.8 T at 5600 A, an aperture of 80 mm and a magnetic length of 9.45 meter.

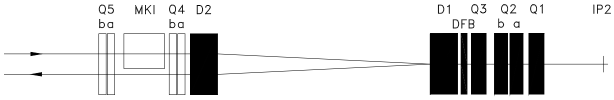

Figure 1: The location of a D1 magnet in LHC IP2.

The field quality should not have been a concern as the design has been optimized and magnets based on this design are already in use – four in the LHC [2, 3] and three hundred sixty in the Relativistic Heavy Ion Collider (RHIC) [4]. However, whereas the specifications for essentially all harmonics (see [4] for the definition of harmonics) remain the same as in the LHC D1 dipoles, the specification for the sextupole harmonic (b_3) was reduced to an absolute maximum value of 2 units at 17 mm reference radius at the design current.

This value cannot be guaranteed based on the field errors coming from normal tolerances in the parts and assembly. In addition, this new construction required new parts and new tooling which adds to the uncertainty. The new approach and technique presented here overcomes the usual limitations and assure that the tighter specification in b_3 is met. It uses iron (Fe) shims of adjustable thickness to compensate the measured b_3 at the design field. Iron shims (tuning shims) were also used in RHIC IR quadrupoles [5]. They produced magnets with field quality better than ever before. However, the tuning shims in RHIC quadrupoles were placed inside the yoke (at the iron inner radius) with influence reduced at the design field. Here they are placed outside the yoke (attached to the helium vessel) with the influence maximized at the design field.

IRON SHIMS ON THE HELIUM VESSEL

Figure 2 shows the magnetic model of the right-half of the cross-section and a picture of the magnet during construction. The left half is a mirror image of the right half. Of particular interest are the adjustable thickness Iron or Fe Shims that are placed outside the SS shell in the Shim Retainer.

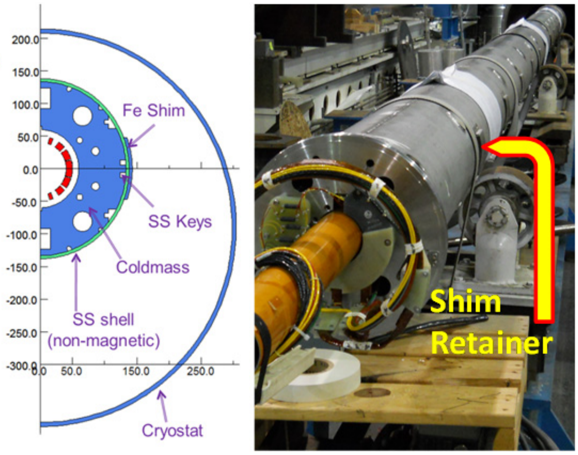

Figure 2: Magnetic model of the cross-section of the D1 magnet (left) with the Iron (Fe) Shim indicated and the actual magnet (right) during the construction (shims will be placed in the Shim Retainer).

At low field, there is no influence of Iron Shims on the field near the magnet axis. The influence of Iron Shims on field harmonics is felt only at high fields when the yoke

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iron starts saturating and the flux lines start leaking outside the stainless steel shell (see Fig. 3). The influence of Iron Shims on field harmonics will then depend on the size (thickness and/or width) of the shim. It will increase initially as the field (flux leakage) increases until the iron in the shims gets fully saturated. The behaviour is clearly seen in Fig. 4 which shows the computed change in the sextupole harmonic as a function of current when 100 mm wide shims of various thicknesses (1 mm to 6 mm) are added. Several model calculations were carried out to optimize the width and thickness combination of these shims with a goal of achieving a change of at least 3 units.

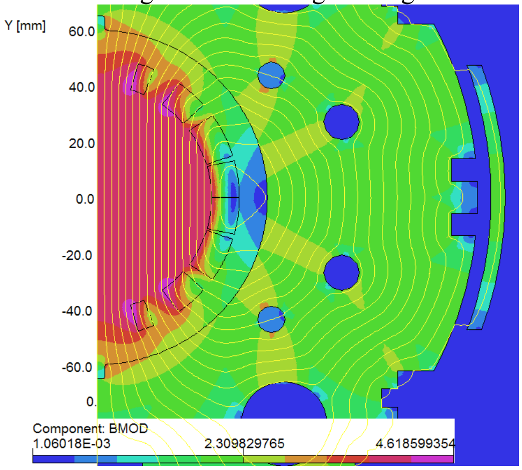

Figure 3: Field contour and field lines at 6000 A in the 2-d model of the D1 magnet (see iron shim on the right).

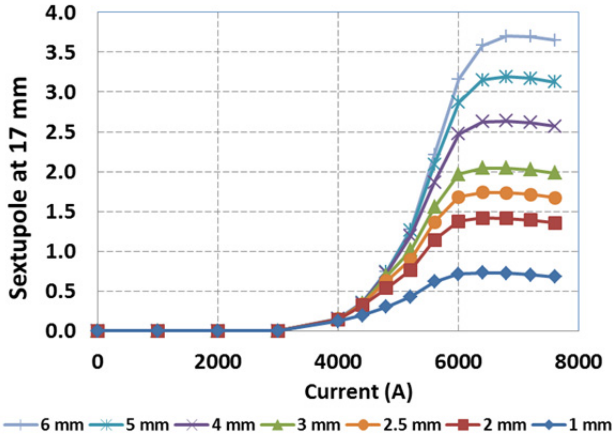

Figure 4: Computed sextupole harmonic (b_3) as a function of current added due to shims of various thicknesses.

MAGNET CONSTRUCTION

Most features of the construction of these two new magnets are similar to those used in previous construction [2]. However, these magnets use new parts and tooling. Although, the higher order harmonics are expected to be close to those measured before, the lower order terms could be significantly different. Since the specification must be met in both magnets, the correction is applied based on the measurements of each individual magnet. The width of the shim is kept fixed at 100 mm, the thickness can be in the range of 0 to 5.8 mm (step size of the increment is 0.51 mm) with the nominal thickness being 2.9 mm. These Fe shims are secured in brackets attached to the cold mass shell (see Fig 2). To change the value of the shim after the cold measurements, the coldmass would be pulled out of the cryostat, thermal blankets and heat shield removed, shim package changed and the coldmass inserted back in the cryostat. As mentioned earlier, this method avoids the much more time consuming and complicated operations such as cutting the weld of the helium vessel, etc. to change the size of the shim.

Before the final correction with the Iron Shims is applied, the following approach is used to remove the initial (geometric) errors in the sextupole and decapole harmonics (b_3 and b_5):

- Develop a flexible design that allows significant adjustability in two harmonics. The design has larger than minimum pole shims and midplane caps.
- Measure warm harmonics before the outer shell is welded.
- Use warm-cold correlations in previous magnets to estimate the b_3 and b_5 at the design field.
- If the expected harmonics are large, un-collar the coldmass, change the midplane and/or pole shims and measure harmonics again to verify the correction.

The following steps were envisioned to measure the influence of shims and determine the right size to minimize b_3 at the design field in magnets #106 and #107:

- Build coldmass #106 with (a) 1/3 length full size shim, (b) 1/3 length half (nominal) size shim and (c) 1/3 length no shim.
- Perform magnetic measurements as a function of current in coldmass #106 using a 1-meter long rotating coil in the entire length of the magnet to determine integral values of harmonics and to determine the measured change in b_3 due to the full size and half size shims.
- If b_3 at design field is outside the specifications in #106, change the thickness of Fe shim by taking the coldmass out, installing corrected shim and putting the coldmass back inside the cryostat. Perform the second set of cold measurements if the shims were changed.
- Build coldmass #107 using shims with optimized thickness, computed on the basis of warm measurements and shim calibration in #106. Do cold magnetic measurements. If b_3 is outside the specifications, change the shims and repeat the cold magnetic measurements.

MEASUREMENTS

Warm harmonic measurements were performed in both coldmasses #106 and #107 and harmonics at the design field estimated using warm-cold correlations (which have some uncertainty). The coil pole shim needed to be increased by 0.1 mm in coldmass #106 to ensure that the harmonics were in the range that could be corrected with iron shim. The same pole shims were then used in #107. Even though the harmonics measured warm were not identical, the coil pole shim was not changed as the harmonics could be corrected with the iron shims.

Figure 5 shows harmonics due to shims by taking the difference between the measured harmonics for (a) the full size (5.8 mm) shim and no shim and (b) the nominal size (2.9 mm) shim and no shim in magnet #106 using data obtained with the 1 meter long rotating coil.

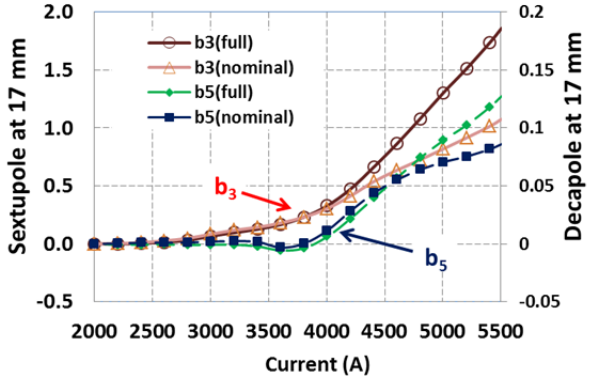

Figure 5: Harmonics due to iron shims obtained by subtracting measured harmonics with full (or nominal) shim and without shim.

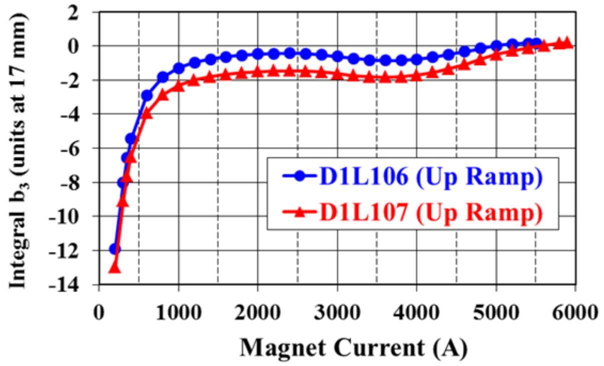

Figure 6: Measured integral harmonics as a function of current in magnets #106 and #107.

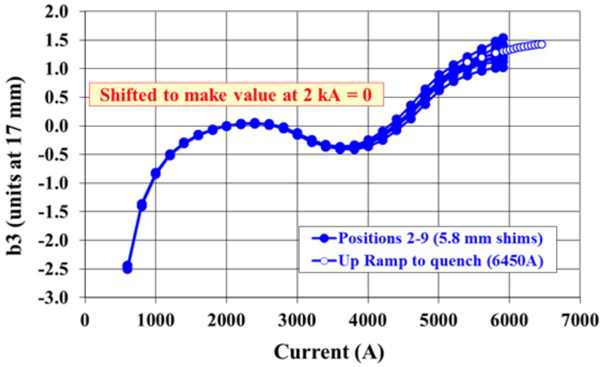

Figure 7: Measured b_3 as a function of current in eight 1 meter long sections in body of the magnet D1L107. The data are offset to make each zero at 2000 A.

Figure 6 shows the integral values of sextupole harmonic for magnets #106 (nominal average shim) and #107 (maximum shim) as a function of current during up ramp. The larger value of Fe shim was able to bring a positive shift in b_3 at the design field, as intended. The b_3 harmonic is not only within the specifications of 2 units, it is nearly zero at the design field (3.8 T at 5600 A) in both magnets. It remains small over a large range of operation.

Figure 7 shows the measured b_3 in magnet #107 as a function of current beyond the design current - to 6000 A at eight straight section positions (offset added to make each of them zero at 2000 A for easy comparison) and to 6450 A at one position. This indicates that the integral sextupole will remain small at higher fields as well.

The measured values of all integral harmonics up to 20-pole (at or near design current) are given in Table 1. All harmonics are small and deemed acceptable. Harmonics that are influenced by the design and the value of shim are odd normal harmonics such as b_3, b_5, etc.

Table 1: Measured Integral Harmonics at a Reference Radius of 17 mm in Magnet #106 and 107

	#106 @5500 A		**#107 @5600 A**	
n	a_n	b_n	a_n	b_n
2	-3.42	-0.26	-1.05	-0.20
3	-0.41	0.16	-0.14	0.04
4	-0.30	-0.06	-0.33	-0.07
5	0.05	0.27	0.09	0.24
6	-0.01	-0.01	0.00	0.00
7	-0.01	0.17	0.00	0.17
8	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00

CONCLUSION

A novel method has been developed and successfully implemented which makes field quality at the design field much better than previously possible by overcoming the limitations from construction errors. It compensates the measured harmonics without requiring opening of the helium vessel. The number of shims (two used for sextupole) can be increased to correct more harmonics.

ACKNOWLEDGMENT

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