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A Levitated-Pole Superconducting Dipole for Use in the Beam Separators of LHC

Peter McIntyre and Akhdiyor Sattarov

Abstract—**A design is presented for a superconducting levitated-pole dipole for applications requiring operation in high heat load and/or radiation damage to the superconducting coil. The application that motivated the design is the first dipole D1 that coalesces and separates the proton beams in the insertion region for the Large Hadron Collider (LHC). The superconducting coils are supported on cold-iron pole pieces that are 'levitated' within a warm-iron flux return by balancing the force between coils against the image force across an insulating gap in the steel flux return. It is possible in this design to provide a 9 Tesla dipole field with no heat intercept in the mid-plane, so that the heat and radiation from secondary particles do no harm.**

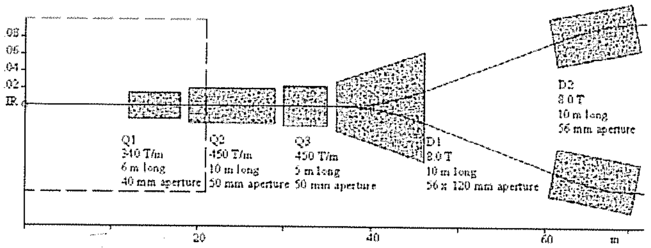
Index Terms—**superconducting dipole, heat transfer, radiation damage**

I. INTRODUCTION

EACH high-luminosity intersection region (IR) in the Large Hadron Collider LHC poses three significant challenges for the match of the physics mission of the collider with the optical train of the arcs: focal optics, crossing and separation of the two beams, and management of heat and radiation from secondary particles that are produced in proton-proton interactions and then lost into the cold mass of the magnets. The focal optics is optimized by placing the quadrupole triplet as close as possible to the interaction point (IP). This minimizes β_{max} and also minimizes the sensitivity to chromaticity and to alignment errors and error multipoles in the IR magnets. Preliminary discussions with both experimental teams indicate that the first quad could be placed at a distance s~12 m from the IP.

The beams must be crossed at small angle and then separated, and the separation dipole must be placed as close to the IP as possible to minimize the number N_s of subsidiary bunch-bunch crossings that make long-range beam-beam interactions.

The proton-proton interactions at the IP produce an intense flux of particles in the forward directions. Many of those particles strike the first quad Q_1 and the separation dipole D_1. Indeed the most energetic particles travel down the beam tube and are swept into the side walls of D1 by its dipole field The resulting heat load is estimated at ~3 kW for the design luminosity [1]. Designs have been suggested for dipoles with no superconductor in the midplane [2], but the best solution for such an extreme radiation and heat environment would be to remove all cryogenic structures from the midplane.



Fig~~ure~~ 1. Placement of optical elements in an IR optimized for high-luminosity at LHC.

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Table 1. Main parameters of the elements in the optimized IR.

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magnet	structure	field/ gradient	Length (m)	aperture (mm)
Q_1	Ironless, round cable	340 T/m	6.5	40
Q_2	Block-coil, iron return, Rutherford cable	450 T/m	10	50
Q_3			5	50
D_1	Levitated-pole dipole	9 T	10	56 x 120

We are investigating an optimization of IR design [3] in which the optical elements are located as close as possible to the IP, as shown in Fig~~ure~~ 1. The above criteria have led us to X particular choices for the technology of each of the magnetic elements, as summarized in **Error! Reference source not found.** ? The purpose of this paper is to present the design for a levitated-pole dipole that could provide the required performance for D1. A companion paper [4] describes a structured-coil quadrupole for Q1.

II. THE LEVITATED-POLE DIPOLE

We propose a somewhat different design in which the cold-iron poles of the dipole are supported within a warm-iron flux return across a gap, as shown in Fig~~ure~~ 2. The coil geometry and the separation gap can be designed such that the total Lor-

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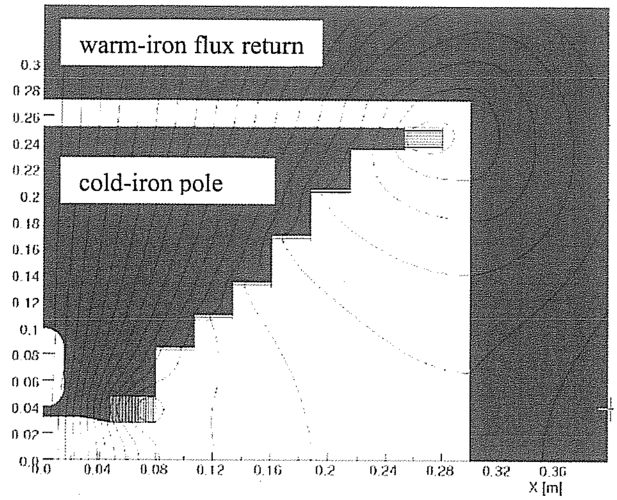

Fig~~ure~~ 2. Levitated-pole dipole: 9 Tesla, 56 mm aperture.

entz force on the assembly of the cold-iron pole piece and the coils is *zero* – we call this a levitated-pole dipole. The concept was first utilized by T. Kawaguchi *et al.* [5] in the design of the sector magnets for a ring cyclotron. In this approach the radiation and heat from particles is deposited in room-temperature steel.

The magnetic field strength is limited by the requirement that the steel be unsaturated at the gap between pole tip and flux return. The design shown in Fig~~ure~~ 2 corresponds to a central field of 9.0 Tesla. The pole is tapered at a ~45° angle to reduce the field in the pole steel from ~9 T at the pole tip to ~1.5 T at the gap.

?X The design shown has been optimized for field quality; $b_3 \sim 10^{-4}\mathrm{cm}^{-2}$ over the dynamic range require for LHC operation. Only the winding assembly just above the beam tube needs to be made using Nb_3Sn superconductor. All of the windings along the staircase of the pole are be made of NbTi.

Because the magnetic forces on the cold pole assembly cancel, it can be supported using low-heat-load tension supports, so the overall cryogenic load should be modest.

X Fig~~ure~~ 3 shows the calculated forces on the superconducting coil and on the cold iron, as a function of field strength. Positive force corresponds to repulsion between the two pole tips. The maximum repulsive force occurs at a field of ~6.5 T, and has a total of ~200 kN/m. The force actually reverses at low field (<3 T), but the forces are quite modest there.

III. ASSEMBLY AND SUPPORT

X Fig~~ure~~ 4 shows a conceptual design for the assembly and support of the levitated dipole. The two poles are tied to one another by (6 cm)^2 stainless steel struts, located on each side of the poles, connecting to the outermost facet of each pole. Placing these struts every 75 cm along the length of the dipole should suffice to rigidly connect the two poles and support them under the forces of Fig~~ure~~ 3 with maximum deflection of < 0.5 mm. Since such deflection during ramp of the magnet is slow and distributed over a 75 cm period, it should pose little risk of quenching the coil. The gravitational load and stabilization of the unstable equilibrium in the horizontal direction are supported by tension supports extending through the warm-iron flux return. The width of the dipole field region must increase along the length of the D1 as the beams separate; the pole width can be tapered as necessary.

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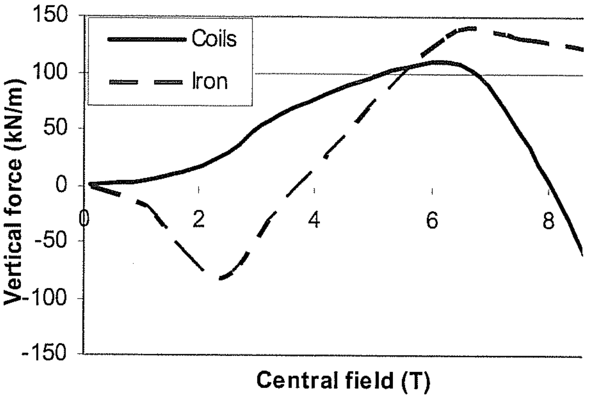
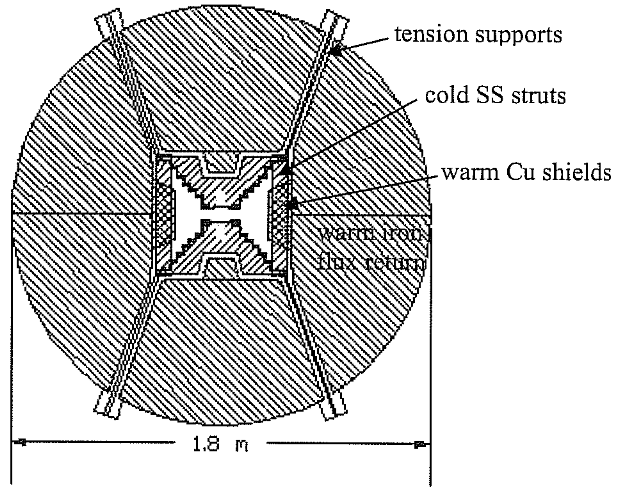


Fig~~ure~~ 3. Forces on coil and cold iron as a function of field.



Fig~~ure~~ 4. Assembly of levitated-pole dipole showing support of pole structure within flux return.

Lastly the cold struts connecting the two poles are at cryogenic temperature and span the midplane, so they would intercept some of the secondary particles swept to the sides. Non-magnetic absorbers can be attached to the warm-iron flux return as shown, filling much of the gaps between struts and shadowing the cold struts from receiving heat load.

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Steering the field quality in the production of the main quadrupoles of the Large Hadron Collider

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Abstract—**The main issues concerning the field quality in the main quadrupoles of the Large Hadron Collider are presented. We show the trend plots for the field gradient and multipoles at room temperature covering more than 2/3 of the production. We describe the correction of the coil layout to improve b_6 at injection field level. A non-negligible fraction of the quadrupoles has been manufactured with collars featuring a magnetic permeability somewhat higher than the specified limits. We show plots for this anomaly. Field quality correlations to measurements in operational conditions are discussed. The dependence of field quality on cable manufacturer is analysed**

Index Terms—**LHC, Quadrupole, Magnets, Large scale superconductivity, Field Quality.**

I. INTRODUCTION

THE Large Hadron Collider (LHC) consists of more than 8000 superconducting magnets. The main magnets are 1232 dipoles (MB) and 392 quadrupoles (MQ) used for the lattice or in the dispersion suppressor regions. The remaining magnets are used for correction or in the regions close to the interaction points for dispersion suppression, matching and low beta focusing [1].

The series production of the MQ magnets started in 2003 and will end in summer 2006. The production of magnets takes place in Accel Instruments, Germany. Technology transfer and follow-up is done by CEA-Saclay, France [2].

Each quadrupole is composed by two coil apertures, magnetically and mechanically decoupled, arranged in one yoke assembly. For more details on the design see [3]. The assembly of a magnet at the manufacturer premises takes several weeks and a few months are needed from the first assembly step (coil winding) to the final acceptance tests in operating conditions (1.9 K) at CERN. Repair of faulty magnets is both expensive and time consuming as magnets rejected at CERN must be sent back to factory for the cold mass disassembly. Therefore, electrical tests and several types of measurements are foreseen all along the production according to the quality assurance plan. The magnetic field measurements are an essential test: measurements at room temperature are used to predict the magnetic field in operational conditions and can also be used for finding assembly defects. All magnets are measured at room temperature at a current of 12.5 A (about 0.1% of the operating current). Measurements of the magnetic field at 1.9 K are foreseen on a sample of 10% of the magnets to evaluate the offsets in warm-to-cold correlations. In this paper we give the status of the field quality based on measurements at room temperature of ¾ of the production, and on the warm cold correlations established on 5% of the production.

II. WARM MEASUREMENT DATA

The magnetic field in a quadrupole is expressed as a power series

$$B_y(x,y)+iB_x(x,y)=10^{-4}B_2\sum_{n=1}^{\infty}(b_n+ia_n)\left(\frac{x+iy}{R}\right)^{n-1}$$

where (x,y) are the transverse coordinates, R is the reference radius (17 mm for LHC), and B_2 is the main quadrupolar component. The harmonics terms b_6, b_{10}, b_{14} ..., are generated by a coil layout that satisfies the quadrupole symmetry ("allowed" components), whereas the other harmonic terms are due to imperfections in the quadrupole symmetry ("not allowed" components). The harmonics are expressed in units of the main field (b_2=10^4 units). The main component and the high order harmonics are measured at room temperature with a rotating coil of 750 mm length along 5 consecutive positions to cover the 3.1 m long quadrupole. Position 1 and 5 cover the heads of the coils, and 2 to 4 the so called coil straight part.

Room temperature measurements are done in the quadrupole manufacturer at two different stages, namely after the collaring (superconducting coils clamped in the collars, see Fig. 1), and after the welding of the shrinking cylinder (the so called cold mass, i.e. the two collared coils inside the iron yoke and the stainless steel cylinder). In Table I we give the total number of measurements at room temperature and at 1.9 K available on 11.08.2005. We split the data between the two different coil layouts that have been used in the production: cross-section 1 is the original baseline, whereas in cross-section 2 a mid-plane shim of 0.125 mm thickness has been added to optimize the mean value of the b_6. Two octants (¼ of

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the production) have been built with cross-section 1, and the remaining ¾ will have cross-section 2.

Superconducting cable from five different manufacturers are used, labeled with letters from B to K (see Table II). Although all of them produce cables according to the same specifications, the different cable layout, the different production procedures and tooling can have some impact on the coil geometry, as it is discussed in Section VI.

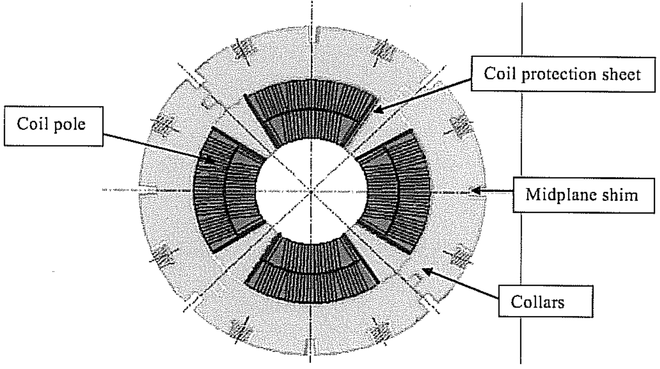

Fig. 1: The cross-section of one aperture of the LHC main quadrupole

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Table I: Number of measured apertures as function of assembly stage

Cross-section	Measurements		
	collared coil	cold mass	cold
1	204	176	24
2	427	302	10
Total	631	478	34

Table II: Number of produced apertures as a function of the cable manufacturer

Cross-section	Cable type				
	B	C	D	G	K
1	112				90
2	157	92	67	106	5
Total	269	92	67	106	95

III. FIELD QUALITY VERSUS BEAM DYNAMICS TARGETS

In Figs. 2 and 3 we give a global picture of the field quality [4]. The underlying hypotheses on warm-cold correlations are the followings: a persistent current shift of -4 units on b_6, and no shift induced by correlation on “not allowed” multipoles. Moreover, we assume that the random part is dominated by geometrical effects which are completely known with room temperature measurements. The beam screen impact on the magnetic field evaluated using a BEM-FEM code [5] is included in the analysis.

The triangles are the average of the multipoles in all measured apertures at room temperature. The solid lines are the targets given by beam dynamics requirements. All the multipole mean values (usually denoted by systematic) are within specifications. The main field gradient is not given here since its absolute value can be set using the power supply and therefore there is not a beam dynamic target.

In Fig. 3 we plot the measured standard deviation of the multipoles versus the targets of all measured magnets (both cross-section 1 and 2). The variation of the main field gradient is about 14 units, close to the target. This value is going to increase to around 17 units since apertures with very high gradient (due to too high collar permeability) have been produced in spring 2005 and have not yet been measured as cold mass (i.e., the two apertures in the iron yoke). Indeed, there is some experimental evidence that this effect disappears at 1.9 K (see Section VII). In this case, the room temperature values would overestimate spread of the field gradient. While waiting for more data on warm-cold correlations, a dedicated installation scheme (sorting) is anyway being used for precaution. According to this scheme, quadrupoles with high field gradient are coupled at 180 degrees phase advance of betatronic motion, in order to minimizing the β-beating.

The variation of b_6 is mainly due to the mixing of cross-sections. The fact that it is 0.6 units outside specification is not considered as critical. All other standard deviations of normal multipoles are within target. The random part of the skew multipoles is also within target.

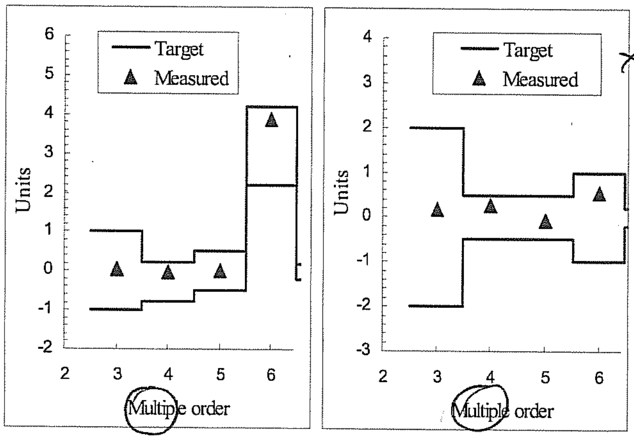

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Fig. 2: Mean of normal (left) and skew (right) multipoles measured in cold masses at room temperature versus beam dynamics targets

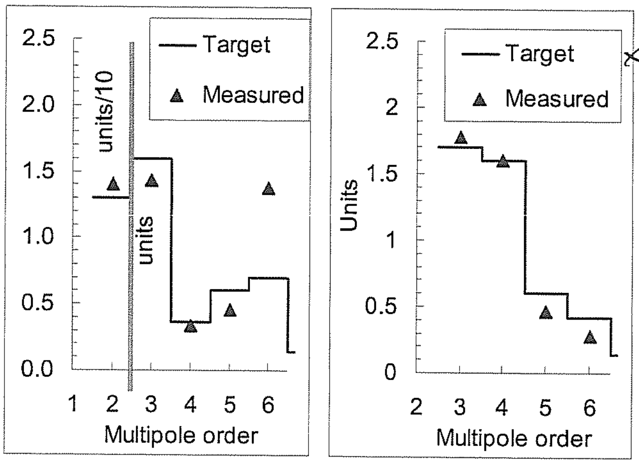

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Fig. 3: Standard deviation of normal (left) and skew (right) multipoles measured in cold masses at room temperature versus beam dynamics targets

IV. THE CORRECTION OF THE COIL LAYOUT

Magnetic measurements of the first batch of apertures have clearly shown that the systematic b_6 was a few units outside target at injection current (760 A). This fact had been already observed in the prototype phase [6]. After the beginning of the production, more beam dynamic simulations and an improved analysis of warm-cold correlation have been carried to better define the target values at room temperature. The needed correction was of -2 units of b_6. The corrective action that has been implemented was to add 125 μm in the coil mid-plane: this was calculated to give the required effect on b_6 and a negligible effect on the gradient (see Table III) [7]. The solution was successfully tested on three quadrupoles, and then implemented as a baseline. The measured effect of the cross-section change is very close to the computation from the model (See Table IV), with the exception of a lower impact on b_{10}.

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TABLE FORMAT

Table III: Computed change in field quality [units] when adding a 125 μm midplane shim

	Gradient	b6	b10
Midplane, inner layer	-4.5	-1.9	-0.19
Midplane, outer layer	-1.4	-0.1	-0.01
Midplane total	-5.9	-2.0	-0.20

Table IV: Measured mean values in cold masses for the two cross-sections

Cross-section	Gradient	b6	b10
1	10000	5.2	-0.13
2	9993	3.1	-0.17
Difference	-7	-2.1	-0.04

V. ANOMALIES IN COLLAR PERMABILITY

Since summer 2004, significant anomalies in the field gradient and in the "allowed" multipoles have been observed: the main field was around 30 – 90 units higher than expected, and b_6 was at the same time several units lower. This was traced back to the relative magnetic permeability (μ_r) in the collars, which was out of the tolerance for the raw material before fine blanking: permeability measurements showed typical values between 1.01 and 1.02 against a $\mu_r<1.005$ as presented in the technical specifications. The measured dependence of the field gradient and of b_6 on the collar permeability has been found to be in agreement with simulations carried out with a BEM-FEM code [5], as shown in Figs. 4 and 5. After the discovery of this effect, the following actions have been taken:

- Measure the collar permeability for all apertures
- Measure the magnets with high collar permeability in operational conditions, where this effect is expected to disappear
- As a precaution, magnets with high permeability are assigned to special slots in the magnet lattice to have a local compensation

Another option is to use magnets with this possible gradient anomaly in the dispersion suppressors (32 quadrupoles), where they are compensated by individually powered quadrupole correctors (MQTL). In this case one should know the behavior in operational conditions. Indeed, measurements of a few magnets with these anomalies have shown that this effect disappear at 1.9 K. This implies the need of a special treatment of these warm measurements for the extrapolation at 1.9 K. More information can be found in Section VII. The local compensation scheme has the advantage of being effective also in the case of a vanishing anomaly at 1.9 K.

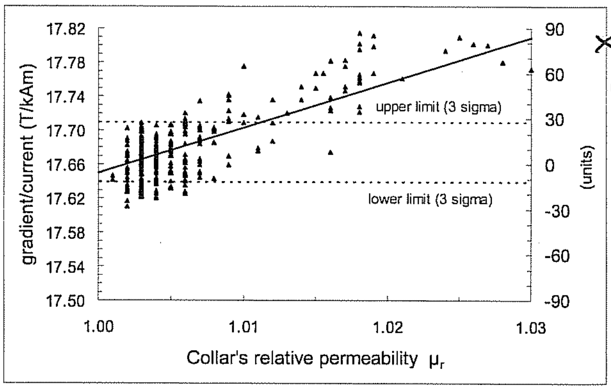

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Fig. 4: Gradient in collared coil as function of permeability: measured (markers) and model (solid line).

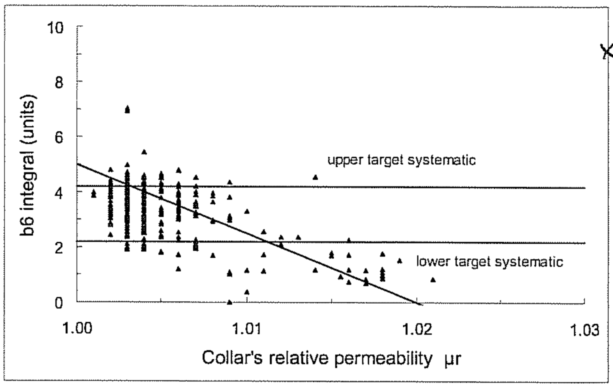

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Fig. 5: b_6 in collared coil as function of permeability: measured (markers) and model (solid line).

VI. CABLE MANUFACTURER VERSUS FIELD GRADIENT

Some variations in the main field are caused by the difference of cables: the lay-out, the production process and tooling, unique for each cable producer, can influence the field gradient of the magnet. The differences observed between the cables are presented in Table V. Data relative to magnets with high permeability collar ($\mu>1.008$) are not considered in this analysis. We process data of cross-section 1 (cable B and K) and 2 separately (cable B, C, D and G). Values of cable B (having the higher statistics, see Table II) are used as a reference for both cross-sections.

Table V: Relative difference in normalized gradient for the various type of cable

	Cable				
	B	**C**	**D**	**G**	**K**
ΔG/i [units]	0	23	27	11	2

TABLE FORMAT

The {B,K} have similar characteristics. The {C,D} have around 25 units more in the field gradient, and cable G is in between. This non-negligible difference can be obtained in simulations by a larger cable width of 35 μm. Analysis of dimensional data relative to cable C shows that cable width is

12 μm larger than cable B [8], thus only partially accounting for this effect.

VII. WARM TO COLD CORRELATIONS

The absolute accuracy of the measurements of the integrated gradient at 1.9 K is discussed in very details in [9]. Systematic differences have been observed between the measurements performed with the automatic scanner (AS) and the single stretch wire (SSW). After an analysis of the measurement systems, the gradient measured with SSW has been judged the most accurate and an offset has been added to the measurement performed with the AS.

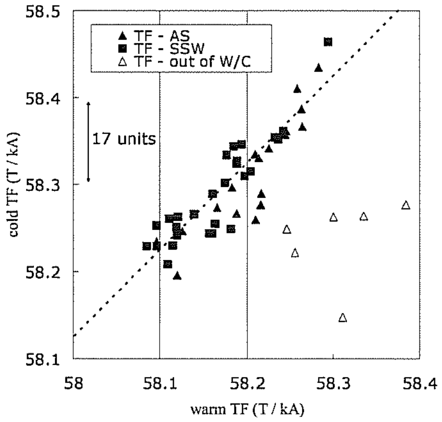

Fig. 6: Integrated gradient per unit current: room temperature measurement versus nominal field at 1.9 K.

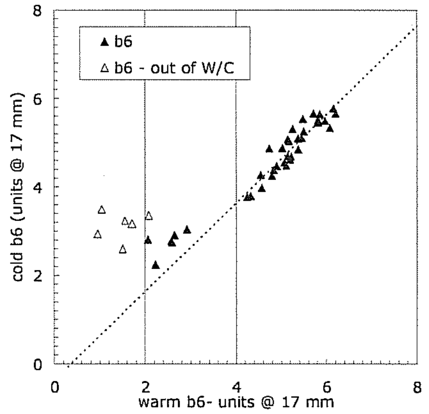

Fig. 7: Multipole b_6: room temperature measurement versus nominal field at 1.9 K.

The warm to cold correlations of the integrated gradient are presented in Fig. 6. Data relative to a few quadrupoles have an anomalous correlation where the high field gradients measured at room temperature correspond to normal or low gradients at 1.9 K (nominal energy). One of these magnets had collar permeability out of tolerance: this suggests that the higher field gradient due to this effect disappears at 1.9 K. For the other ones, no permeability measurements are available. More magnets with anomalous permeability will be measured to better establish the correlations.

Rejecting these data, the average offset between warm and cold measurements of the integrated gradient is about 22 units, and its spread is 4 units, i.e. much lower than the spread in the warm measurements (13 units).

For the first order "allowed" multipole b_6, data are clustered around two values (see Fig. 7), corresponding to the two cross-sections layout. The same magnets showing anomalies in correlation for the field gradient are not matching the correlation for b_6, having low values at room temperature (1 to 2 units) that are not found at 1.9 K (3 units). This is compatible with the hypothesis that these magnets all have high collar permeability.

CONCLUSIONS

Data relative to room temperature magnetic measurements of ¾ of the production have been presented. The systematic value of the first "allowed" multipole b_6 has been corrected through the insertion of an additional mid-plane shim. The impact on field quality is in agreement to the expectations and all mean values are within beam dynamics targets. For the random part, the main concern comes from the spread of the integrated field gradient, which is 40 to 60% above target. A consistent part of this spread has been generated by collars with a too high magnetic permeability. The problem is solved now, but a few tens of quadrupoles have been manufactured with these collars, featuring a field gradient 30 to 90 units more than average. A dedicated sorting scheme is being used as a precaution to minimize impact of these magnets on the perturbation of the optical functions in case that anomaly remains at operating field.

Even though the production is well advanced, warm to cold correlations are still in the process of being established. In particular, more measurements are needed for the magnets with anomalies in collar permeability; the first data show that this effect is likely to disappear at 1.9 K.

ACKNOWLEDGMENTS

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