

Assembly and Test of the HL-LHC Twin Aperture Orbit Corrector Based on Canted Cos-Theta Design

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Abstract. In the frame of the high-luminosity upgrade project (HL-LHC) at CERN, a double aperture, independently powered, family of beam orbit corrector magnets will be installed close to the two main LHC experiments ATLAS and CMS. These 2.6 T magnets, built using a canted cos-theta design. This paper describes the development of the prototype, full size 2-m-long magnets. We first focus on design and assembly techniques: from coil winding using a CNC machined aluminium former to impregnation, layer-jump, quench protection, and yoke assembly. We then present the power test results at 1.9 K: training, field quality and protection.

1. Introduction

The Large Hadron Collider (LHC) has been the largest and most powerful particle accelerator in the world since it became operational in 2009. In order to improve the chances of observing rare particle events and to increase the statistics of the measurements of particle properties, an upgrade of the machine is planned for the horizon of 2023-25 [1]. The goal of the HL-LHC is to achieve an integrated luminosity of 250 fb^{-1} per year in the two general-purpose experiments (ATLAS and CMS), which is about an order of magnitude larger than the yearly integrated luminosity of the LHC. To achieve this, the magnets on both sides of the main experiments ATLAS and CMS will be replaced with larger aperture magnets [2]. Among the about 100 new magnets to be installed, the recombination dipole D2 will have two 105-mm-wide apertures separated by 188 mm and an integrated force of 35 T.m [3]. This dipole requires horizontal and vertical correctors on both apertures with a 5 T.m integrated force. The design of these orbit correctors must fit with tight field quality requirements, with multipoles lower than or equal to 10 units in any powering configuration. Since the apertures are large, little iron remains for magnetically separating the two apertures: previous studies [4] shown that 2.65 T is the maximal field that can be reached satisfying the field quality targets, thus giving a 2.2-m-long magnet. A second requirement is a radiation resistance of 20 MGy. We initially considered a sector coil with Rutherford cable, as described in [5],[6]. In 2016, we decided that in this range of field the canted cos theta (CCT) design had the advantage of a simpler, less expensive design. The project started with the design optimization, then manufacture of two short, 0.5 m long model coils that were mounted into a single yoke. Both short coils achieved ultimate current in very few quenches. Field quality was inside the specification. The full 2.2 m long twin aperture prototype was then launched. (CERN High-Luminosity name MCBRD). This prototype magnet would be suitable for insertion into LHC. During manufacture many improvements, simplifications were proposed for the series set of magnets, these are discussed in [7],[8]. In summer 2018 a contract was signed with Chinese teams. CERN will provide the build-to-print design and special yoke steel, the Chinese collaboration at the Institute of High Energy Physics (IHEP), part of the Chinese Academy of Sciences (CAS) will build, 4K test and deliver the 8 magnets plus 4 spares series set of magnets to CERN.



2. Building the 2.2 m prototype

2.1. The LHC MCBRD (CCT) component assembly

The minimal number of components needed to build CCT type magnets are shown in Figure 1. The only components not visible in the figure are the return-end end-plate, the small copper tubes used when making the superconducting joints, and a layer of polyimide sheet insulation under the cable and voltage tap cover, see item 18 in figure 1. The two apertures are identical. They are mounted in the yoke so that the blue aperture has a vertical magnetic field and the red aperture has a horizontal magnetic field. The yoke locks the apertures in place fixing the angular and transvers position of the two apertures. In figure 1, we can see the lead end of the aperture, outer support tube (2), with a flange. This flange is a modification to the prototype magnet design. The flange is trapped between the last yoke lamination and the lead-end, end-plate (16). This provides the axial fixed point to the magnet assembly. Any relative thermal contraction between the yoke and the aluminium coil apertures is relative to this fixed point. We expect the aperture to contract ~ 9 mm and the yoke ~ 4 mm. hence the cold centre of the magnet will move ~ 5 mm towards the joint end. Both apertures are powered independently. The powering leads are routed from the two aperture coils to joint box through G10 channels. The wires in the channel are a tight fit and are covered with two insulation sheets then a metal, radiation hard cover plate closes the box.

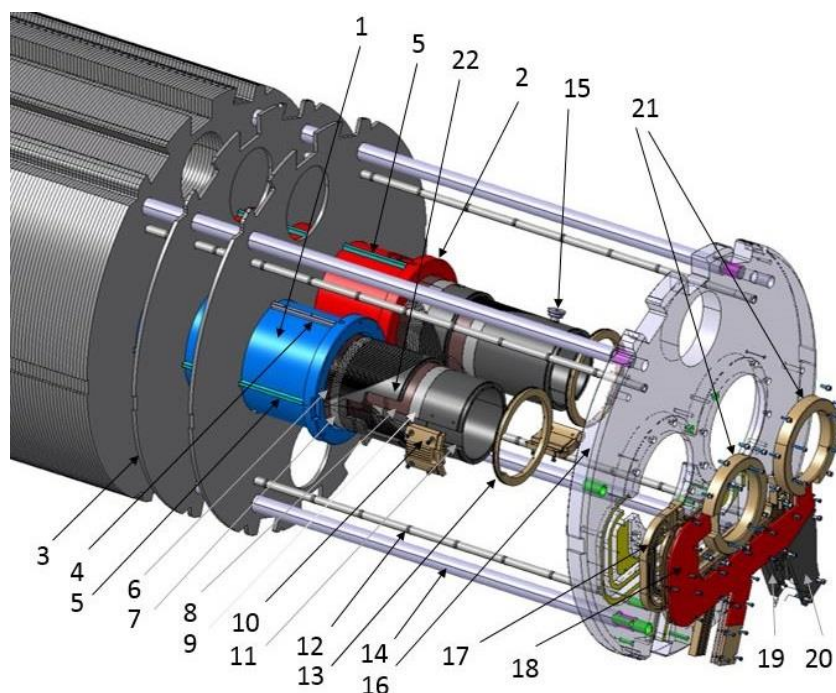


Figure 1. MCBRD Magnet Components. (1) vertical field aperture outer support tube (blue aperture), (2) horizontal field aperture outer support tube (red aperture), (3) yoke lamination, (4) hybrid yoking key half magnetic on pole, (5) yoking key non-magnetic on mid-plane, (6) polyimide insulation two sheets 0.125 mm thick, (7) glass cloth 0.1 mm thick, (8) polyimide insulation two sheets 0.125 mm thick, (9) glass cloth 0.1 mm thick, (10) GRP joint box, (11) inner layer CCT coil former hard anodized Aluminium, (12) spring pins that lock yoke lams, (13) GRP coil end ground insulation labyrinth ring, (14) M20 tie rod diameter 24 mm, (15) inner to outer coil former precision lock pin one at both ends, (16) lead-end end plate, (17) GRP insulation guide and mechanical support for power leads and instrumentation, (18) Aluminium lead cover plate, (19) GRP magnet to bus bar joint box, (20) Aluminium bus bar joint box cover, (21) GRP beam pip bump guide ring. (Glass-Reinforced-Plastic, GRP G10).

2.2. *Parameter list for MCBRD CERN prototype***Table 1.** MCBRD-P1 (CCT) CERN 2.2 m prototype.

Parameter	Unit	Value
Clear aperture warm / cold	mm	105.35 / 105.0
CCT skew angle optimized	degrees	30
CCT layers		2
Number of wires in the channel	Width / High	2 / 5 (total 10)
CCT coil former channel pitch warm	mm	5.222
Channel size width/depth after anodization	mm	2.06 / 5.20
Former thickness under the channel warm	mm	1.79
Number of channel turns in each layer		365
Outer support tube/collar thickness	mm	13.75
Coil formers & outer collar material		AL6082-T6
Coil former surface finish		Hard-Anodized
Anodization layer thickness / surface build-up	μm	40 / 20
Coil impregnation resin at 3 Bar		CTD101K
Aperture assembly max. coil former stress	MPa	40
Aperture assembly max. deflection	μm	50
Magnetic length	m	1.93
Nominal field	T	2.59
Nominal integrated field	Tm	5.0
Beam Separation cold	mm	94.0
Yoke diameter	mm	614
Magnet Mass	kg	4006
Number of lamination in the 2.2 m magnet		364
Yoke packing factor		98.6%
Nominal current	A	394
Ultimate current	A	435
Short sample current at 1.9 K CERN / WST wire	A	767 / 868
Short sample current at 4.2 K CERN / WST wire	A	570 / 658
Load line fraction at 1.9 K CERN / WST wire		55 % / 45.4%
Current sharing temp. - 6% I_c , T_{cs} CERN / WST	K	5.9 / 6.5
Nominal Strand diameter CERN / WST	mm	0.825 / 0.830
Insulated strand diameter	mm	0.988 / 1.026
Cu to superconductor ratio CERN / WST wire		1.95 : 1 / 1.3:1
Nominal differential inductance per aperture	mH	820
Nominal stored energy per aperture	kJ	72.7
Wire length in one aperture 2 layers	km	~ 4.4
Extraction voltage: Dump resistor / Varistor	Volts	562 / 450

The parameter list in Table 1, contains a combination of calculated and measured values. This is the set of parameters for the CERN prototype and series magnet production in China. With the exception of the Nb-Ti Chinese superconducting wire, which has little effect on magnet protection as values discussed later.

2.3. The superconducting wires CERN & WST

The CERN prototype coils were wound with CERN Nb-Ti strand, 0.825 mm diameter from the LHC stock originally used in the LHC dipole cable [5]. The Chinese company Western Superconducting Technologies Co.,Ltd. (WST) will supply the wire to the Chinese teams. This wire was tested at CERN to measure its critical current (I_c) at 4.3 K, the magnets initial test temperature in China, and at 1.9 K the final operation temperature in the LHC. The CERN prototype magnet wire had small 6 μm filaments, and a copper to super-conductor ratio of 1.9:1 resulting in a margin to quench at nominal current of $\sim 45\%$ at 1.9 K. Both wires, CERN & Chinese WST, have the same diameter, the WST filaments are larger at 20 μm . This will change the magnets field quality at low field, considered acceptable by CERN beam dynamics. The WST wire has more superconductor due to the lower copper to super-conductor ratio of 1.3:1. This reduces the operating point in the magnet to $\sim 45.4\%$, and will give a larger temperature margin (current sharing temperature 5.9 K CERN / 6.5 K WST) to cope with beam heating. Although the operating point is lower, the change in Cu:Sc ratio makes protection more difficult. This first WST wire I_c results were for non-insulated / heated wire. We plan to re-test the wire after insulation, to see if the heating that bonds the insulation to the wire will degrade the I_c values, we saw a 5 to 7 % reduction with the CERN wire after heating to bond the insulation. The reduction in copper will affect the quench protection! This will be compensated for with the Energy Extraction system discussed later.

2.4. Wire insulation

The wire insulation needs to be tough to survive the winding process without being damaged as the ten wires are simultaneously placed into the CCT former channel. A 38 μm thick, 6 mm wide polyimide tape with a 4 μm layer of polyimide adhesive on the inside was wrapped onto the wire. The adhesive was activated with a 20 to 40 second duration of 420°C heating. We wanted a minimum of two layers of tape on the wire surface to protect against pinholes in the polyimide. Due to geometry, when the 6 mm wide tape was wrapped onto the 0.825 diameter wire, it resulted in a small area 342 μm long having 3 layers. See figures 2 and 3.

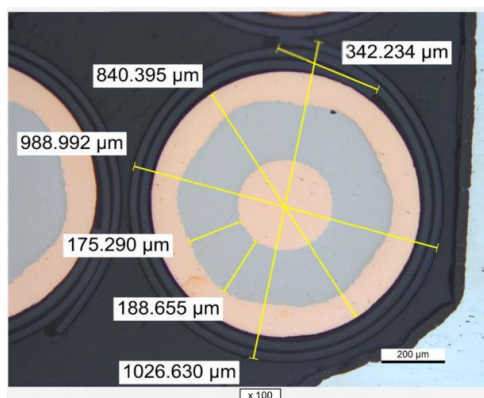


Figure 2. Test section of CERN insulated wire in channel, we see the two layers of 38 μm thick insulation tape, the 40 μm hard anodized coating on the aluminium former, and the resin impregnation enveloping each turns and bonding to the anodizing.

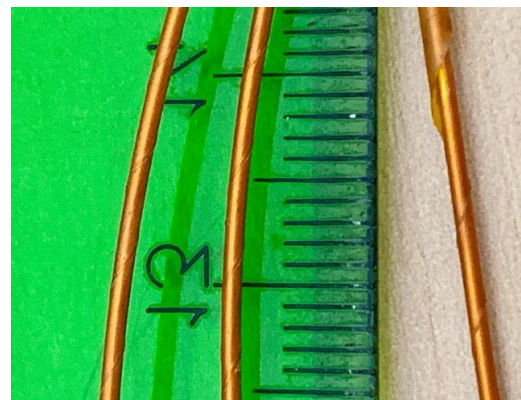


Figure 3. Image of wrapped insulation with spiralling 4 mm pitch. The tape overlaps 2.11 times with a Polyimide adhesive on the inside tap surface that when heated, bonds the tape to the wire and the other layers of tape.

This small treble layer of tape insulation spiralled around the wire with a pitch of ~ 4 mm and provides space for the resin to fully impregnate the coil. The LHC high luminosity test criterion specifies that before seeing helium, the insulation must have a voltage test that withstands voltages 4 times the max operational quench voltage plus 1000 V in air (3.6 kV), and 2 times the maximum operational voltage plus 500 V when in helium (~ 1.8 kV). The voltage test results for this wire insulation system are high, with a brake-down voltage in air of ~ 11 kV.

2.5. Coil winding

The ten wires are wound into the channel of the hard-anodized AL6082-T6 aluminium former simultaneously. A nylon guide holds the ten wires together in the 2 wide by 5 high configuration (see Figure 4).

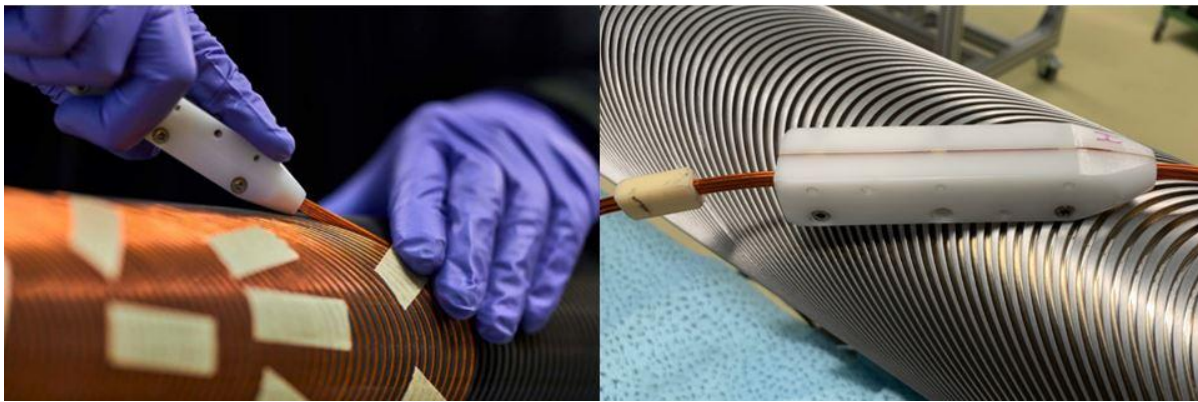


Figure 4. Left: Picture of the ten wires being placed into the former channel using the nylon hand held tool. Right: hand held nylon winding tool, on a former before it is Hard-Anodized.

The inner layer, 2.2 m coil former was mounted on a horizontal winding machine. The insulated wire is cleaned, electrically checked, and the diameter measured over its full length. Then ten spools feed the wires through a second cleaning station, to the hand held nylon guide, see Figure 5.



Figure 5. CCT 2.2m winding set up. We see the wire mounted on ten spools, the wire cleaning station where the wires run through felt pads that are loaded with cleaning fluid, and the horizontal winding machine.

The wires are manipulated by hand to fully enter the channel and then temporarily held by adhesive tape. The wires are a tight fit in the channel having a $\sim 50\mu\text{m}$ gap. With the first layer completed a set of polyimide ~ 1.5 cm wide bands of adhesive tape hold the wires in the channel during the next assembly stage. The temporary tape seen in figures 4 & 5 are then removed. A significant modification to the aperture design was made when we decided to replace the ten joints at the return end of the magnet with a layer-jump. The first layer is now wound, a glass 0.1 mm layer and two 0.125 mm thick polyimide insulation sheets are placed over the inner coil former. The outer former is slid over the inner, then the second layer coil is wound. This change in design reduced the number of superconducting joints that are in the aperture by ten. The path of the wires in the layer jump was optimised to minimise its effect on field errors. Figure 6 presents the joint box design in the lead end of the magnet. The CERN prototype used this design at both ends of the magnet to connect the inner to outer layer set of wires. Figure 7 presents the new layer jump. The outer coil former was assembled over the inner former, and the outer support tube/collar was assembled over the two coil formers using horizontal tooling. This tooling avoided the need for high ceiling cranes, and gave easy access to inspect the full surface of the coils layer jump and joint box areas. See figures 6 and 7. Jointing, vacuum then pressurized impregnation with CTD101K resin, and yoke assembly was covered in a previous paper [8].



Figure 6. Lead end. We see: the joint box, the outer support collar with flange that fixes the aperture to the yoke at the connection end, the stepped pin that accurately locates the three tubes before impregnation, and the labyrinth ground insulation end ring.

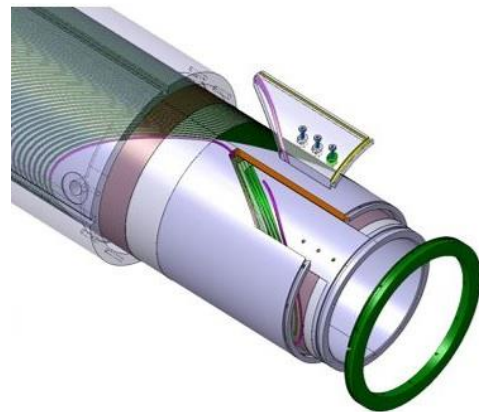


Figure 7. Revised return-end layer-jump. The cover is made from GRP bolted to the inner former, and all is covered by the outer support tube/collar. The layer jump conductor path is optimized for field quality.

2.6. Yoke stacking /assembly tooling

The yoke laminations are stacked, axially compressed with the hydraulic jacks as seen in figure 8. Elastic pins and tie rods hold the assembly together. MCBRD-P1 (the prototype) had 364 yoke laminations, with a 5.8mm nominal thickness that gave the design length and a yoke packing factor of 98.64%. The magnets full geometry was measured with a laser tracker. The laser tracker measurements placed the apertures and the relative position of the yoke, all within 50 μm of the design.



Figure 8. Left: Vertical yoke assembly tool. Right: elastic pin insertion to lock yoke laminations.

3. Prototype cold test overview

3.1. Quench performance of the two long apertures.

The magnet was tested at 1.9 K and 4.5 K during October 2018. (See figure 9). As a first step the apertures were independently powered. Aperture 1 (Red) had one low current quench at 282 A, then it went above nominal current (395 A) reaching 469 A after two quenches. Aperture 2 (blue), the second aperture to be assembled, first quenched at 275A and then took 20 quenches to achieve nominal current. Possibly due to lack of resin in the coils? However both apertures achieved 470 A. No re-training quenches after thermal cycles and no quenches at the higher test temperature of 4.5 K and 470 A, occurred.

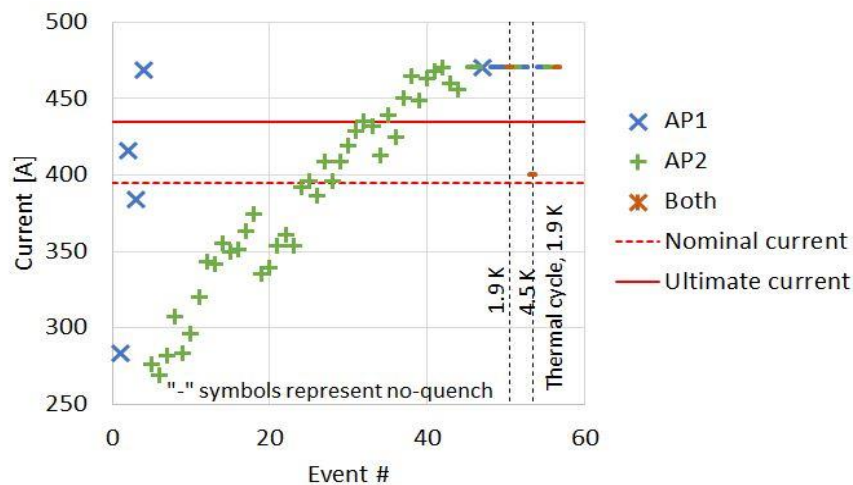


Figure 9. Quench performance of the two CERN prototype 2.2 m apertures.

3.2. Magnetic field measurements

Figure 10 presents part of the graphical magnetic field analysis performed on the two independently powered apertures. In reference [9] one can find access to the sets of presentations containing the: room temperature without iron yoke, room temperature with iron yoke, and 1.9 K full magnetic field measurements with aperture crosstalk data. The magnet is just inside the beam dynamic requirements. However, b_3 is 8 units higher than design calculations predict. Further study is planned to try and understand this discrepancy. A full set of cold test results are presented in [10]. There are small differences between the two aperture transfer functions due to the yoke saturation of the horizontal and vertical fields, at 395 A, 0.12 % to 1.23% depending on the powering configuration.

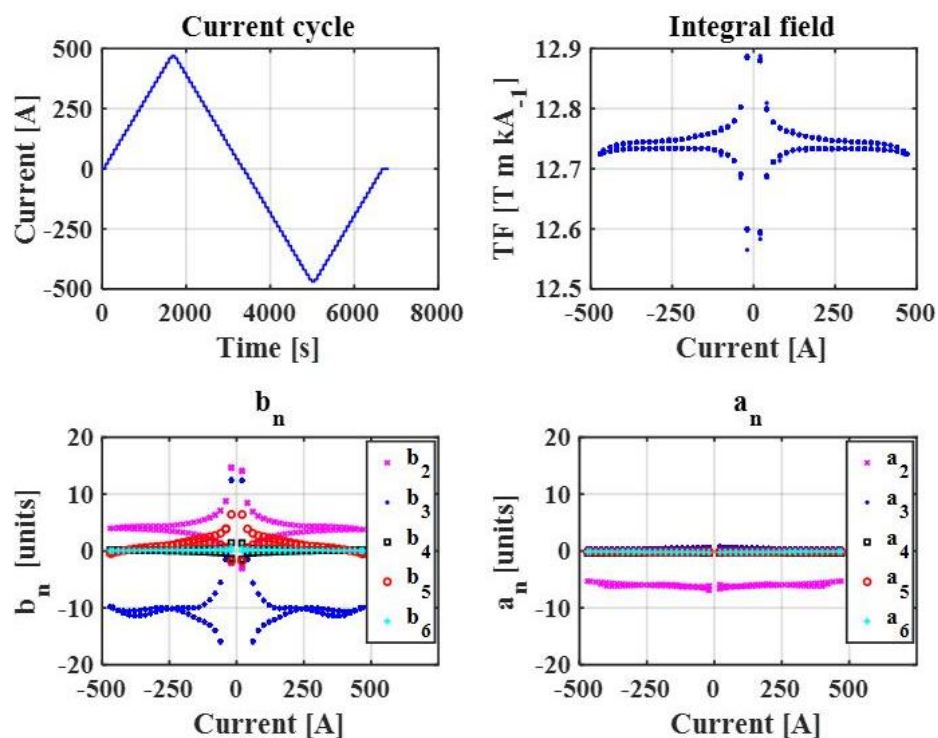


Figure 10. Top left: powering cycle beyond nominal current. Top right: average Transfer function for both apertures. Bottom left: nominal multipoles. Bottom right: skew multipoles.

3.3. Quench management via energy extraction.

To limit thermal stresses we would like to limit the magnet quench hot spot to 200 K. The bipolar 600 A CERN power converter is connected to a switch and an energy extraction dump. The power supply voltage limit is 450V to ground. Classically a stainless steel dump resistor has been used for the energy extraction component. For this set of magnets we are considering using either a 1.29 Ohm resistor or a $V=45.5 \times I^{0.37}$ Varistor. The resistor at ultimate current develops 562 V to limit the hot spot temperature to under 200 K. The second option, a constant voltage energy extraction Varistor from Mertrosil® (max voltage 439 V) to achieve just under the 200 K [11]. This option needs certifying for use in LHC and hence further testing is planned. For more detail see Oct. 29/2018 and July 31/2019 project log posting in [7][12]. Figure 11 & 12 present calculations and test results using both components.

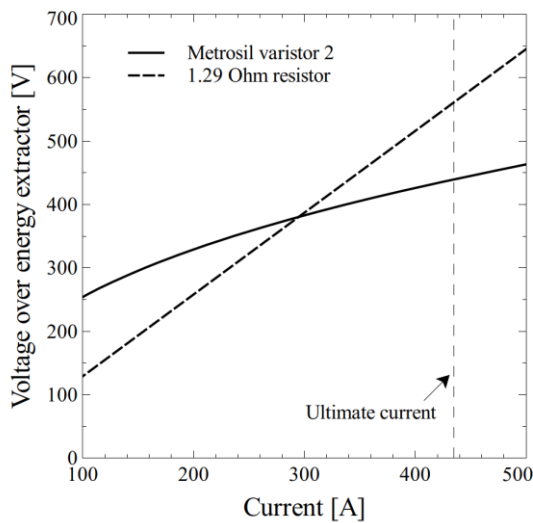


Figure 11. Comparison of energy extraction components, Classical resistor and Varistor. When set to start at 435 A, the ultimate magnet current starting point and limit the quench integrals to achieve ≥ 200 K. Resistor follows ohms law $V=IxR$. The Metrosil Varistor follows $V=45.5xI^{0.37}$.

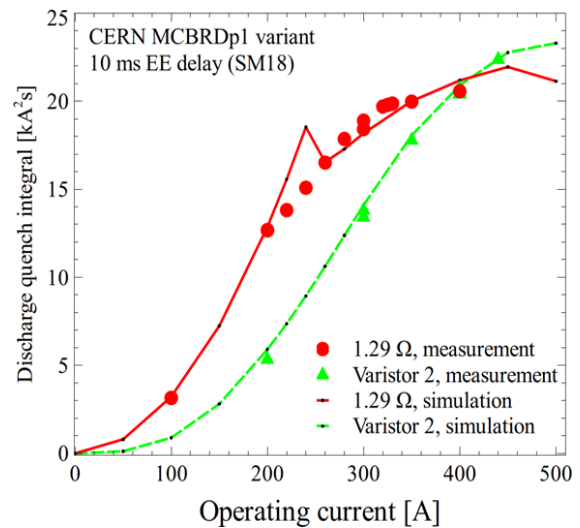


Figure 12. The protection studies indicate that the 1.29 Ohm and Varistor 2 energy extractor options both guarantee a hot-spot temperature below 200 K at all currents at and below ultimate current, with corresponding discharge quench integral limits of $24.5 \text{ kA}^2\text{s}$ for the CERN variant (shown here) and $20.5 \text{ kA}^2\text{s}$ for the Chinese variant with lower copper fraction in the conductor.

3.4. New quench detection to protect against symmetric quenches.

Symmetric quenches are when the ignition point of a quench is at a voltage tap and the quench velocity and subsequent resistive development travelling away from the voltage tap is matched in the two adjacent segments. If the quench detection is using these two segment to compare voltages when checking for quenches, it is possible that a quench can continue unseen and damage the magnet. A new system that compares multiple, unconnected sections of magnet has been developed to solve this problem (see figure 13). The comparative segments are U30%A, with U30%B, then U70%A, with U70%B. Voltage taps are soldered adjacent to joints, with identification (EE****). The DFX is the warm to cold current feed box, developed for MCBRD (CCT) and now being expanded to other systems.

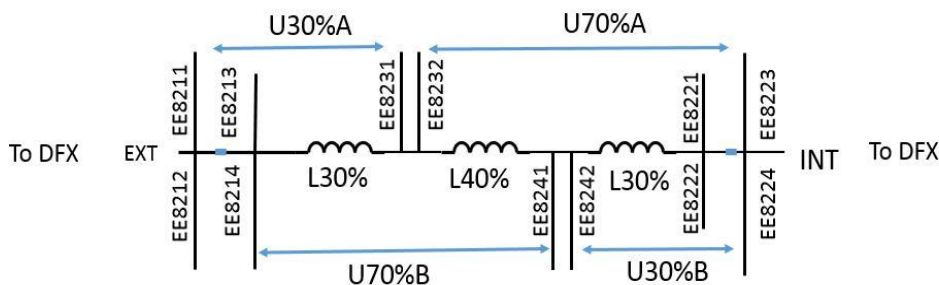


Figure 13. Symmetric quench detection circuit for one aperture.

4. Conclusion

A twin aperture full size prototype has been constructed, tested and has achieved nominal performance according to specification. This enables its possible inclusion in the upcoming high luminosity upgrade of LHC. However due to the initial unexpected long training in aperture 2, a 3rd aperture is under construction at CERN and is due autumn 2019. This new aperture incorporates many small modifications, simplifications, and cost reductions. It will be identical to the series magnet design under construction in China. The full circuit design for MCBRD is still under consideration. The field quality of the first two apertures is only just on specification, approximately 8 units from the design. This discrepancy is under investigation. The design of the MCBRD's integration into the final cold mass with the D2 separation dipole and a second MCBRD (CCT) is advanced. It has taken two years to build and test several short models then build a full accelerator ready twin aperture 4 tonne prototype. The final cost is still to be determined, indications are that it is low compared to a classical design as virtually no tooling and only few components are needed.

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