HIGH-VOLTAGE COILS OPTIMIZATION FOR THE LHC BEAM DUMP DILUTOR KICKER MAGNETS

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Abstract

Two sets of 6 fast-pulsed vertical and two sets of 4 fast-pulsed horizontal dilutor kicker magnets form part of the so-called LHC beam dumping system, which removes the counter-rotating beams safely from the collider onto an absorber block. Each vertical and horizontal diluter magnet is powered by a pulse generator via a low-impedance transmission line resulting in maximum damped sinusoidal voltage of 16 kV and a maximum damped sinusoidal current pulse of 30 kA. The fast-pulsed dilutor kickers magnets, MKBV and MKBH, consist of a steel yoke with excitation coils, which are immersed in the accelerator vacuum. As part of a consolidation program, high-voltage insulated coil spares will be manufactured. The coils are composed of conductor bars of quasi-rectangular cross-section, junction pieces, and conductor contact pieces. The coils are completely insulated for the 16 kV and 10 kV peak voltages. The surface of the insulation is coated with a resistive layer and connected to earth. The connector contact terminals are moulded sockets, surrounded by stress rings. This paper describes the design of the MKBV and MKBH kicker magnets, focusing on the fabrication processes and validation tests for both types of coils.

INTRODUCTION

During a HL-LHC beam dump, energies up to 700 MJ per beam at 7 TeV must be absorbed in the dump block. To perform a safe beam dump the dilution kicker magnets sweep the beam, in a spiral pattern (see Fig. 1), reducing the peak energy density and avoiding damage to the dump block [1].

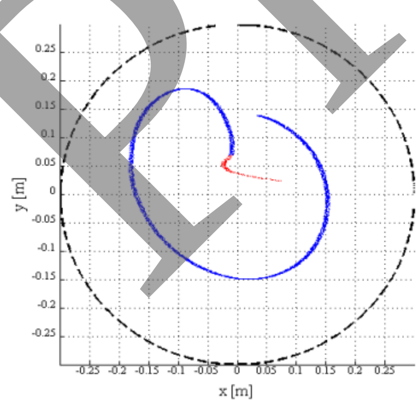

Figure 1: Diluted beam sweep on the dump block. Blue: nominal particles, red: particles in filled abort gap.

To perform the sweep the MKBV magnets are first energised with a damped sinusoidal voltage of 13,2 kV peak, producing a damped sinusoidal current pulse with a maximum amplitude of 24 kA and a period of 87 µs. Fifteen microseconds later, the MKBH magnets are energised with a similar sinusoidal voltage of 24,5 kV, resulting in a damped sinusoidal current pulse with a maximum amplitude of 25,3 kA with a period of 73 µs [2].

All the dilution magnets are located outside the circulating beam line and installed in vacuum tanks, typically at a pressure of ~10^{-8} mbar. Dilution kicker magnets parameters are show in Table 1.

Table 1: Dilution Kicker Magnets Parameters

	MKBV	MKBH
Number of magnets per system	6	4
Number of magnets per tank	2	2
Maximum Deflection angle per system [mrad]	0.277	0.278
Kick strength per magnet [T.m]	1.077	1.624
Operating Voltage (peak) [kV]	13.2	24.5
Operating Current (peak) [kA]	24.0	25.3
Coil turns per magnet	2	1
Magnet horizontal beam aperture [mm]	70	63
Magnet vertical beam aperture [mm]	43.5	36
Magnetic effective length [mm]	1267	1936
Mechanical yoke length [mm]	1196	1899
Vacuum length (flange to flange) [mm]	4076	4582

MKBV KICKER MAGNET COIL

The MKBV is a window-frame magnet that consists of a steel yoke with a two-turn excitation winding. The yoke is composed of tape-wound cores made from 50 µm thick Si-steel, into which a gap is cut, as shown in Fig. 2.

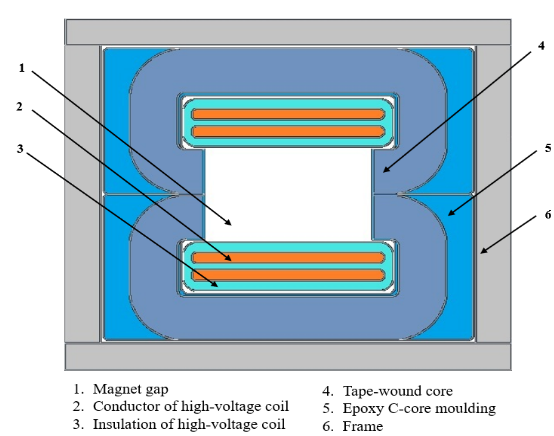

Figure 2: Cross-section of the MKBV magnet.

Three cores are moulded using a charged epoxy into a unit which form a triple pack.

During the assembly of a magnet, these triple packs are stacked up longitudinally to the required yoke length.

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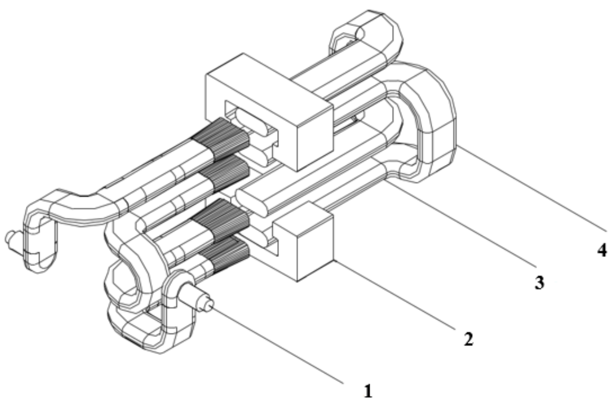
The two-turn coil comprises four copper bars of quasi-rectangular cross section, three junction pieces and two conductor contact pieces, as show in Fig. 3. The coil is completely insulated with a minimum insulation thickness of 1.5 mm. On the straight section of the coil, each pair of conductors have a further common over-insulation of 3.25 mm thickness. The full coil is coated with a semi-conductive layer (Fig. 4) .



1. Conductor contact piece
2. Tape-wound Core
3. Straight conductor
4. Junction pieces

Figure 3: MKBV High-Voltage coil schematic.

Figure 4: MKBV High-Voltage finished coil.

MKBV COIL FABRICATION PROCESS

The conductors of the high-voltage coils are manufactured from highly conductive electrolytic copper (OFE), cold-rolled to a half-hard condition, with a chemical composition of Cu ≥ 99.99 % and O_2 ≤ 5 ppm. Junction pieces are individually brazed.

The coil insulation system is threefold. First, each individual straight conductor is insulated using pre-impregnated tape and hot pressed to calibrated dimensions. Two such conductors are then assembled and further over-insulated with pre-impregnated mica tape, using the hot-pressing technique to form a conductor pair.

Both turns ends are subsequently brazed together to form the final coil geometry. Then these brazed junctions are insulated using a dry tape-wound system, followed by vacuum pressure impregnation (VPI). The two conductor contact pieces are epoxy moulded. Finally, a semi-conductive graphite coating of 500 ± 100 Ω/□ is applied.

The design voltage is 25 kV, and the inter-turn voltage is half. Test voltages of the coil before the moulding of the contact pieces are 13 kV rms between the inter-turn and 26 kV rms for the assembled coil to ground (graphite coating), 50 Hz for 5 minutes, 1.5 times the design voltage and 2.7 times the operational voltage.

The completed coil is then subjected to a final high-voltage test, between the conductors and the semi-conductive coating, at 22 kV rms, 50 Hz for 5 minutes.

MKBV CURRENT DENSITY DISTRIBUTION ON THE FOUR CONDUCTORS

The current density distribution is governed by the interplay between skin effect and field effect. Within each conductor pair, the two facing inner edges carry mirror currents of opposite sign. The edges facing the magnet gap convey the sum of the driving current and the returning mirror current, leading to a doubling of the effective driving current. This pattern is fully anti-symmetric between the upper and lower conductor groups, consistent with the opposing current directions required to generate the magnetic deflecting field in the MKBV magnet. Simulation results of this effect can be seen in Fig. 5.

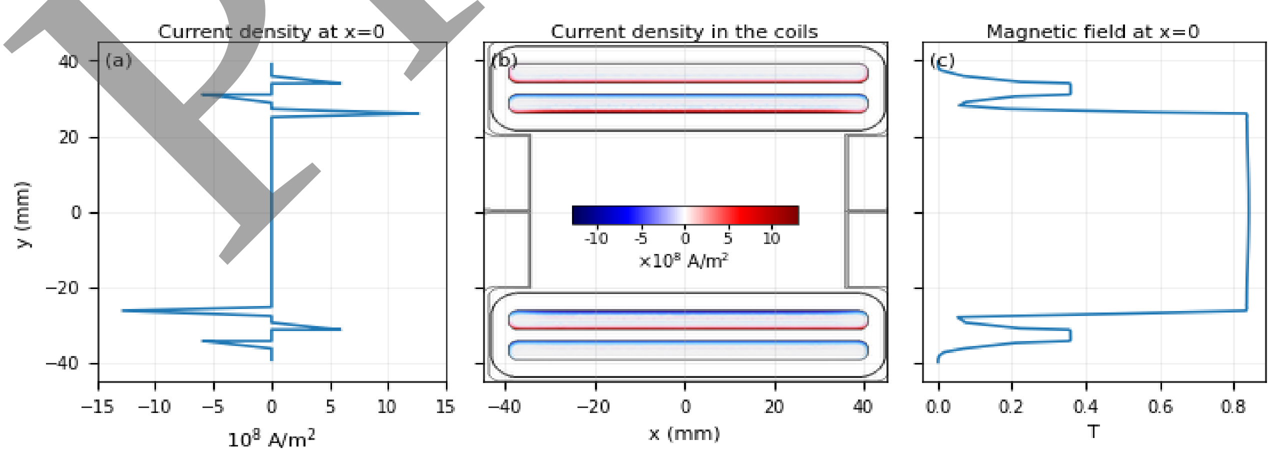


Figure 5: Current density and magnetic field distribution.

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MKBH KICKER MAGNET COIL

The MKBH is a window-frame magnet that consist of a steel yoke with a one-turn excitation winding. The yoke is composed of tape-wound cores of 50 µm thick Si-steel, into which a gap is cut. Two cores are moulded using a charged epoxy into a unit which form a twin pack (Fig. 6). During the assembly of a magnet, these twin packs are stacked up longitudinally to the required yoke length.

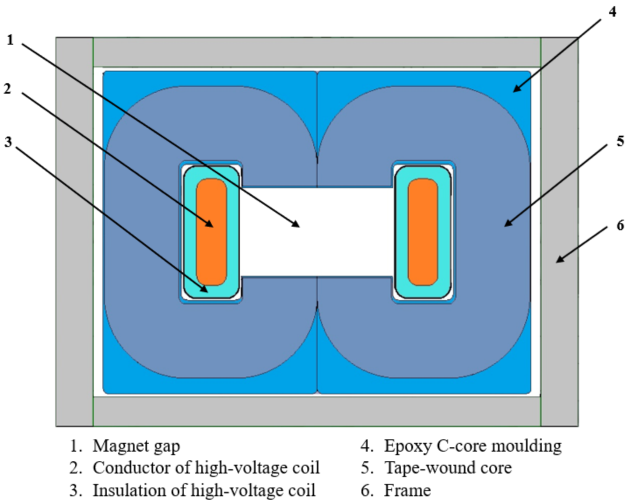

Figure 6: Cross-section of the MKBH magnet.

The one-turn coil is composed of two copper bars of quasi-rectangular cross section, one junction piece and two conductor contact pieces as show in Fig. 7. The coil is completely insulated with a minimum insulation thickness of 5 mm. The two conductor contact pieces are epoxy moulded. The full coil is coated with a semi-conductive layer.

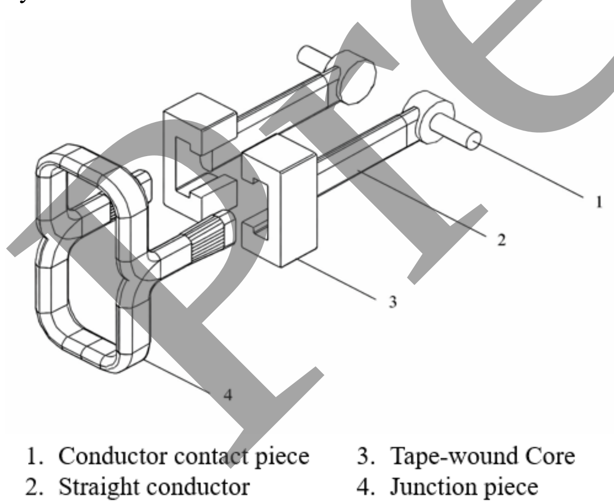

Figure 7: MKBH High-Voltage coil schematic.

MKBH COIL FABRICATION PROCESS

The conductors of the high-voltage coils are manufactured from highly conductive electrolytic copper (OFE), cold-rolled to a half-hard condition, with a chemical composition of Cu ≥ 99.99 % and O_2 ≤ 5 ppm. The junction piece is individually brazed.

The coil insulation is obtained by applying a dry tape-wound followed by vacuum pressure impregnation (VPI).

Finally, a conductive graphite coating is applied, providing a surface resistivity of 500 ± 100 Ω/□. Before the moulding of the contact pieces a high-voltage test at 26 kV rms to ground (graphite coating), 50 Hz for 5 minutes, is performed on the assembled coil, 1.5 times the operational voltage.

The completed coil is then subjected to a high-voltage test, between the conductor and the semi-conductive coating, at 22 kV rms, 50 Hz for 5 minutes.

PERFORMANCE OUTCOMES

Since its installation in 2008, five flashovers were identified in the dilution kickers with the most significant one, on July 14, 2018. There were linked to electron cloud and subject to dedicated study [3]. As result the rectangular beam pipe located inside the vacuum tank flange has been aC coated and extended towards the magnet coil and. FEM simulations have been carried out to ensure that this beam pipe will not cause increase of the electrical field in the vicinity of the coil. The root cause of these events was never linked to electrical breakdowns in the coils. Although the voltage test ratio of the coils is below the EN50209 recommendation, years of operation of the MKBH demonstrates their robustness. Nevertheless, these coils are very critical components and, in case of an electrical breakdown in solid insulation, they must be replaced, leading to a long repair duration. During the Long Shutdown 3, two sets of each coil type will be fabricated as spares.

CONCLUSION

After several years of operation, the coils have proven their robustness in demanding conditions. By combining optimised copper geometries with reliable pre-impregnated and dry-tape insulation schemes, together with hot-pressing, VPI and a controlled semi-conductive coating, the coils achieve consistent performance up to 30 kA and 25 kV. Final high-voltage qualification tests at 22 kV rms, along with inter-turn tests at 13 kV rms, confirm sufficient insulation margins.

Regarding insulation, both techniques yield excellent results. The selection of which will be applied for the fabrication of the new coils will ultimately be industry-driven, with dimensional compatibility as the only constraint.

Overall, this work validates both coil designs and fabrication process that ensures safe and reliable beam dilution for high-energy LHC operation.

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