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DESIGN AND TEST OF A MODEL OF
SUPERCONDUCTING CORRECTION WINDING
AROUND A GROOVED VACUUM CHAMBER

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Design and Test of a Model Superconducting Correction Winding around a Grooved Vacuum Chamber

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Abstract— In the framework of the studies undertaken for the Large Hadron Collider at CERN, it had been envisaged to install distributed correction windings around the vacuum chamber inside the 50 mm bores of the 10 m long twin-aperture dipoles. At a distance of 10 mm from the centre, the field inhomogeneity of the main dipoles may lead to systematic relative errors of up to 5×10^{-4} due to the sextupolar component and 1×10^{-4} due to higher multipoles. These errors depend on the operational conditions and need to be dynamically compensated.

A design adapted to the LHC accelerator where thousands of correctors are needed has been investigated. It is based on the principle of minimizing the number of operations during manufacture in such a way that no manual operation is needed to adjust the accurate positioning of the coils.

A 0.3 m long maquette and a 0.8 m long model of sextupolar correction winding have been manufactured at CERN to check the validity of the method. They both gave satisfactory results; the critical current of the short sample superconducting wire was reached after a few training quenches.

I. INTRODUCTION

The multipole field components are defined by:

$$By + iBx = B_0 \sum_{i=1}^{\infty} (b_n + ia_n) \left(\frac{x + iy}{R_{ref}} \right)^{n-1} \quad (1)$$

where:

- B_0 is the dipole induction in the vertical (y) direction,
- b_n and a_n are the normal and skew multipolar coefficients,
- R_{ref} is a reference radius ($R_{ref} = 1$ cm).

Although sextupole magnets powered in two families are foreseen in the LHC lattice [1] for chromaticity correction, additional sextupolar windings placed in the bores of each main dipole are the most natural way to cancel systematic errors.

At injection (450 GeV, $B_0 = 0.58$ T), for superconducting wires made of $10 \mu\text{m}$ NbTi filaments in the LHC dipole coils, the sextupolar component error due to persistent currents is evaluated to be

$$b_3 = 7.4 \times 10^{-4} \pm 0.35 \times 10^{-4}.$$

In the mean time adequate superconductors with $5 \mu\text{m}$ NbTi filaments have been produced by European industry. The errors caused by persistent currents will be halved.

At high energy (8 TeV, $B_0 = 10$ T), the sextupolar errors are: 0.4×10^{-4} for persistent current with $10 \mu\text{m}$ filaments, 1.4×10^{-4} for iron saturation, 1.2×10^{-4} for coil deformation under electromagnetic forces, that is a total systematic error:

$$b_3 = 3.0 \times 10^{-4}.$$

The corresponding sextupolar integral, referred to the maximum induction B_0 of 10 T and to an equivalent length ℓ_{eq} of 9.54 m, is:

$$\int S ds = 2B_0 \ell_{eq} b_3 / R_{ref}^2 = 575 \text{ T/m}.$$

A sextupolar compensation may be obtained by six current sheets with alternate polarities regularly spaced around a circular vacuum chamber, and covering an angle 2φ of the circumference. The normalized coefficient of the compensation is:

$$C_n = \frac{6\mu_0}{\pi} \frac{R_{ref}^{n-1}}{B_0} \frac{J (r_2^{2-n} - r_1^{2-n})}{n(2-n)} \sin n\varphi \quad (2)$$

with: $n = 3, 9, 15, 21, \dots$

- the inner radius of the coil at 1.8 K $r_1 = 20.15$ mm,
- the outer radius of the coil at 1.8 K $r_2 = 20.45$ mm,
- J is the average current density in the winding:

$$J = NI_n \times \frac{180}{\pi (r_1 + r_2) (r_1 - r_2) \varphi},$$

where N is the number of turns over the angle 2φ ; I_n is the nominal current in the correction coil. To cancel the first harmonic ($n = 9$), the chosen angle is: $\varphi = 20^\circ$

To reduce the size of the coils, a wire with a small diameter would be best, but it would lead to a high number of turns which would increase the manufacturing time and price. A compromise was made for a 0.3 mm diameter bare conductor, which is easy to wind, not too fragile and can be manufactured to tight tolerances.

Thus with $N = 32$ and $I_n = 12$ A:

$$C_3 = 4\sqrt{3} \times 10^{-12} J \left(\frac{1}{r_1} - \frac{1}{r_2} \right) = 4.56 \times 10^{-4}. \quad (3)$$

The corresponding sextupolar component is:

$S = 2 B_0 C_3 / R_{ref}^2 = 91.2 \text{ T/m}^2$, and the theoretical first harmonic produced becomes:

$$C_{15} = -\frac{4\sqrt{3}}{65} \times 10^{-36} J \left(\frac{1}{r_1^{13}} - \frac{1}{r_2^{13}} \right) = -1.9 \times 10^{-8}. \quad (4)$$

At a distance $R = 1.5$ cm, the induction created by the trim coil represents approximately 1.5‰ of the injection induction. The tolerances in the manufacture of the correction coils must lead to errors lower than a few 10^{-5} of the induction. All cumulated errors in the manufacture of the sextupolar coil should therefore be

$$\frac{\Delta C_3}{C_3} \leq 3 \times 10^{-2}.$$

According to (2), this can be achieved if the radii are uniform ± 0.05 mm and the position angles within $\pm 0.3^\circ$ over the whole length of the correction winding.

To manufacture distributed correction coils, several techniques have already been tested successfully for HERA [2] and the SSC [3]. The alternative approach for the design of the LHC correction coils is to use the vacuum chamber both as a winding jig and as an impregnation mould. The tolerances of the windings are the same as those of the grooves around the vacuum chamber. There is no additional manipulation of the coils which are positioned *in situ*, reducing the number of operations. For a production of more than 3400 items, the stainless steel vacuum chamber could be delivered up to 10 metres long, cold-drawn with external grooves of the required accuracy of ± 0.05 mm; to guarantee a low permeability and increase the ductility an austenitic stainless steel type 316 with reinforced nickel content (14 - 15%) could be used. But for the 0.3 m long maquette and the 0.8 m long model developed at CERN, the grooves have been machined accurately with a special fraise. A standard steel 316L with normal nickel content (11.53%) was chosen; at 4.2 K its good relative permeability μ_r was equal to 1.01 at 0.5 T and still lower than 1.02 at 0.1 T. A maximal value of $\mu_r = 1.025$ could be accepted without creating unacceptable harmonics.

Fig. 1: Cross-section of a sextupolar correction winding

II. SEXTUPOLAR COIL FABRICATION (Fig. 1)

The inner diameter of the stainless steel tube is 37.1 ± 0.1 mm, while the outside diameter is 40.16 mm for the 6 grooves over an azimuthal angle of 40.87° . Between the grooves the outside diameter is 41.1 mm. The width of the grooves takes into account the place needed for ground insulation so that the active part of the current layers cover 40° . The tube is degreased with chlorothen, the burrs are then removed and the surfaces to be insulated are roughened with an abrasive cloth. The ground insulation under the coil heads is a high-quality 50 µm preimpregnated fibre-glass fabric which may polymerize in several stages. It is glued after a prepolymerization cycle of 1/2 hour at 120 °C under the compression of aluminium semi-cylinders internally coated with Teflon™. To avoid winding at right angles and damaging the first turns of the coils, six rounded tips are glued at 120 °C over the previous insulation. The tips are made of 0.51 mm (before compression) preimpregnated fibre glass which is previously machined to the right size (6.8 mm wide) and polymerized at 160 °C for one hour under compression to mate the radius of the insulated tube. The grooves themselves are then insulated with the same preimpregnated fibre glass fabric as the coil heads. Under the compression at 120 °C of rails of adequate dimensions coated with Teflon™, the Teflon™ sheet presses the insulation radially against the tube, and azimuthally against the sides of the grooves.

The sextupole winding is composed of three subcoils. Each turn is laid manually under a traction of 0.7 daN with the help of an air motor and provisionally glued with small drops of Cyanolit 201™ near the middle of the straight part and in the coil heads. The electrical connections are tin soldered over a length of at least 3 cm at a maximum soldering temperature of 250 °C. Triplets made of three tinned superconducting wires ($\varnothing 0.3$ mm each) are used for test points and power connections. The triplets may carry the same current as the superconducting wire of the coil, but with their high copper to superconductor ratio

they are more stable from the quench point of view and less fragile. When the three subcoils are wound, they are tightly secured by a layer (without overlap) of a glass fibre which is wrapped under a force of 20 daN. These glass fibres are Straipregs products which are mechanically guaranteed by the manufacturer, the reference chosen is RC 10 800, which is the one which is guaranteed at the highest ultimate tensile strength (160 daN/mm² before curing). The roving is made of thousands of glass filaments. The filaments are 10 µm diameter continuous glass fibres which are assembled with B-stage epoxy resin in rovings 2.5 mm wide and 0.125 mm thick. Even though the thermal coefficient of glass is lower than that of stainless steel, the high pre-stress of the glass fibres at room temperature (64 daN/mm²) still guarantees a compression of the coil at cryogenic temperatures. For mechanical protection and electrical insulation, an additional insulation with 25 µm Kapton™ tape with a two-thirds overlap is provided. For the baking operation the assembly is provisionally wrapped with resin absorber tape and a polyamide shrink tape. The final polymerization of the wrapped coils is done in an oven at 160 °C for 2 hours.

The ground insulation, the interturn insulation, and the first wrapping layer are all made of glass fibres preimpregnated with compatible epoxy resins, thus avoiding the problems associated with the use of heterogeneous sheets of insulation with different thermal coefficients around the superconducting wires.

The extra resin fills in the gaps between the round wires, glues the Kapton™ insulation sheets and is eventually absorbed by the resin absorber. An aluminium alloy bandage (1.05 mm thick) is then wrapped around the Kapton™ insulation under a force of 30 daN, with a pitch equal to 3.9 mm. This Avional alloy type AlMgSi (with 0.3 to 0.8% silicon content) has a high mechanical stability; its yield stress is higher than 16 daN/mm² at 300 K and than 32 daN/mm² at 77 K. Owing to the difference between the thermal coefficient of stainless steel and that of aluminium, the compression on the coil increases favourably at cryogenic temperatures (contrary to that of the glass fibre wrapping) from 0.28 daN/mm² to 0.64 daN/mm². It corresponds to a factor of eight more than what is needed to compensate at quench current for the pressure due to the horizontal electromagnetic forces on the turns located in the horizontal plane. But the turns which are far from that plane see high shear forces; because the coils are manufactured with no lateral compression, such a factor of eight seems quite reasonable.

III. SUPERCONDUCTING WIRE

The superconducting wire of 0.3 mm diameter, includes 120 NbTi filaments of 15 µm. Smaller filaments up to a maximum of 7 µm would be necessary for series production in order to reduce multipolar errors due to their magnetization effect in the sextupolar winding which is located around the vacuum chamber, i.e. very near the particle beam. Such a wire has been obtained quickly in small quantities from Vacuumschmelze. The ratio of copper to superconductor is two to one. Its critical current is 39 A at 7 T and 4.2 K, i.e. a current density of 1650

A/mm² in the superconducting filaments. At 1.8 K and 10 T, the 32 turns of one coil will be submitted to a total force of 1250 daN/m at quench current. The distortion of the tube is calculated to be lower than 20 µm.

The bare wire is first insulated with a modified polyesterimide varnish which guarantees an electrical insulation of 2.5 kV DC for an external diameter of 0.34 mm. This insulation is mechanically reinforced with a thin glass-silk insulation leading to a diameter of 0.41 ± 0.01 mm. A final operation consists of impregnating this glass-silk insulation with a B-stage epoxy resin for a final diameter of 0.44 ± 0.01 mm. Such a resin content seems adequate for a good polymerization of the whole coil without too much extra resin. This was not the case for the maquette manufactured first, where the impregnation of the wires lead to a diameter of 0.47 mm; this reduced the number of turns to 30, and the extra resin created bubbles which had to be removed from the Kapton insulation of the assembly.

IV. EFFECTS OF RADIATION ON THE INSULATION

For a 0.3 mm wire insulated as mentioned above and submitted to a radiation dose of 10^7 Gy, neither mechanical nor electrical degradation could be detected. But for a dose of 3×10^7 Gy the high-voltage insulation test had to be reduced from 2.5 kV to 1 kV DC.

For the 50 µm preimpregnated fibre glass fabric polymerized under a pressure of 2 MPa and submitted to a dose of 10^7 Gy, the high-voltage insulation test had to be reduced from 5 kV to 1 kV DC.

The epoxy resin used in all these products (reference 4302 from Isola) showed no significant mechanical degradation up to 10^7 Gy.

V. TESTS

The tests of the 0.8 m long model of the correction winding were undertaken in the 1 m long model magnet (8TM2) for LHC at 1.8 K [4]. After training with one polarity, a retraining with about ten quenches is observed with a reverse polarity [Fig. 2]. This phenomenon was not observed with the 0.3 m long maquette (at 4.2 K and 6 T) where a simple training in one polarity did not necessitate a retraining in the opposite polarity; a new training was necessary only after each warming-up at room temperature.

Nearly 100% of the critical current (I_c) of the short sample superconducting wire is reached for negative current, i.e. the current at which the sextupolar coils are submitted to the high ingoing electromagnetic forces. But only 95% of the quench current is obtained in reverse polarity. This would prove that the compressive forces of the aluminium alloy bandage are high enough to counteract the electromagnetic forces, but there may remain small movements due to shear stresses near the critical current of the wire.

The first quench current is 47% of I_c . Considering that the nominal current is chosen to be 33% of that critical current, the margin is still comfortable.

Fig. 2: Training and quench currents of the 0.8 m model

At 8.67 T and 1.8 K, the specific measured sextupolar component due to the trim coils is $7.62 \text{ T/m}^2/\text{A}$, which corresponds perfectly to the value given by (3). It should be noted that the sextupolar component increases from $7.37 \text{ T/m}^2/\text{A}$ without current in the dipole to $7.62 \text{ T/m}^2/\text{A}$ above 6.3 T. The lower value at low field can be explained by the fact that the sextupole winding is screened by persistent currents induced in the dipole conductor. For an intermediate induction of 2.62 T, the measured strength is $7.55 \text{ T/m}^2/\text{A}$ if the dipole is energized before the sextupolar winding, and is $7.72 \text{ T/m}^2/\text{A}$ if the correction coils are energized first. The variation in time of the sextupolar component is minimized in the latter case [5].

A quench at 9.26 T on the 1 m long dipole induced a peak voltage of 35 V on one subcoil of the sextupole winding (which quenches) whilst the tension across the full winding remained limited to below 100 mV. The sextupolar winding is shunted by a graphite resistance ($1.6 \text{ m}\Omega$ at room temperature) immersed in superfluid helium. The advantage of such a protection is that the resistance at 1.8 K is high enough not to disturb the correction winding during ramping, but in case of quench, the 12 A nominal current may go through it permanently for the expense of less than a watt in superfluid helium due to the reduction of its resistance under its own heating up. Such a protection may avoid having to switch off the power supply of a large number of multipolar correction windings in series in case of a failure of only one coil.

A quench of the correction winding induced no quench of the surrounding dipole.

VI. CONCLUSION

The feasibility of multipolar correction coils wound around a grooved stainless steel vacuum chamber is demonstrated with the 0.3 m long maquette and the 0.8 m long model, with a total thickness of 3.5 mm for the vacuum chamber, the local correction subcoils and their fixtures. In case the specified luminosity of LHC is increased from $1.4 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ to a few $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, such a precious place will be needed for the beam, and the local correction windings will be replaced by lumped multipole magnets. Even under such a hypothesis, octupole correction windings using the technique described above will be manufactured [6].

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