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Round Coil Superferric Magnet for the HiLuminosity LHC upgrade

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Abstract

The LASA Lab. (INFN, Milan) is developing a new type of superferric magnets suitable to arbitrary multipole order which we refer to as Round Coil Superferric Magnets (RCSM). It is developed for the High-Luminosity LHC program and in particular for the upgrade of the multipolar magnetic correctors of the proton beamlines. This type of magnets is suitable for strain-sensitive superconductors, because it only uses a single round coil, which has a large bending radius, to create the magnetic field. The round yoke with arbitrary multipoles is able to create the desired harmonic component for the magnet. The electromagnetic design of such magnet in sextupole configuration allow the use of a MgB_2 superconducting wire for the coil [1]. In this work we present the studies for the construction of the first prototype. We analyze the electromagnetic properties of the coil and of the round multipole iron yoke, focusing on the optimization of the principal multipole harmonic desired. We also study the mechanic and the protection from the quench. In the next months the magnet will be assembled in the LASA laboratories.

Electromagnetic Design

The principal types of superconducting magnets used in circular accelerators are Dipoles, used to bend the beamline, and Quadrupoles, used to focuse the bunches along the axis to maintain fixed their trasversal size. The magnetic field of these magnets are described in the equation (1). All of these magnet, however, present other components, called harmonics, that arise from the non ideality of the magnet itself even if there is symmetry of the poles. Describing the magnetic field as function of the radius r and the angle ϑ we can obtain all the harmonics of the field. To cancel dipole's and quadrupoles's indesired harmonics with $n = 3$ (order of the magnet is equal to the 2n order of the harmonics) we use a sextupole superconductive magnet with a new type of MgB_2 wire, Figure (3), developed for CERN. **The 6 poles are excited by a solenoidal coil only, to create a sextupolar field, without using the "classical" configuration with one coil for each pole, see Figure (7)**. The coil and the iron yoke's design focuses on the improvement of the main magnetic field's harmonic and on the suppression of other multipolar orders. Shape of the poles follows the equipotential surfaces according to Maxwell Equations to create a perfect sextupolar field inside the bore, eq. (2). Considering the effect of the iron magnetic saturation we need to set the operational point of the coil selecting the current that flows in the MgB_2 wire and the magnetic field peak inside the coil. We recreate the load line of the coil through electromagnetic simulations made with OPERA 3D program. Operational point of the coil has to be lower than the critical surface of the Superconductor Material, Figure (1), which describes the transition of the superconductor to the normal resistive state. The selected point of work is at (1.55 T, 155.28 A) at 60% of margin from the critical surface.

Dipole

$$\begin{cases} B_x = 0 \\ B_y = B_0 \end{cases}$$

Quadrupole

$$\begin{cases} B_x = Gy = Gr\sin\vartheta \\ B_y = Gx = Gr\cos\vartheta \end{cases}$$

Sextupole

$$\begin{cases} B_x = B_3\, r^2 \sin 2\vartheta \\ B_y = B_3\, r^2 \cos 2\vartheta \end{cases}$$

eq. 1. Dipole, Quadrupole and Sextupole Magnetic Field.

$$\begin{cases} B_x = \sum_{i=1}^{\infty} r^{n-1}[A_n \cos(n-1)\vartheta + B_n \sin(n-1)\vartheta] \\ B_y = \sum_{i=1}^{\infty} r^{n-1}[B_n \cos(n-1)\vartheta - A_n \sin(n-1)\vartheta] \end{cases}$$

$$x = \frac{R_{bore}\cdot\cos(\vartheta)}{\sqrt[n]{\cos(n\vartheta)}}\ ,\ y = \frac{R_{bore}\cdot\sin(\vartheta)}{\sqrt[n]{\cos(n\vartheta)}}$$

eq. 2. Equation for the Equipotential Surface for the shape of the poles.

Tab. 1. Wire composition

Diameter (mm)	N° filaments	Filament size (μm)	MgB_2	Nb	Ni	Monel	Cu
1 ± 0.01	37	55	11.50%	14.50%	14%	46%	14%

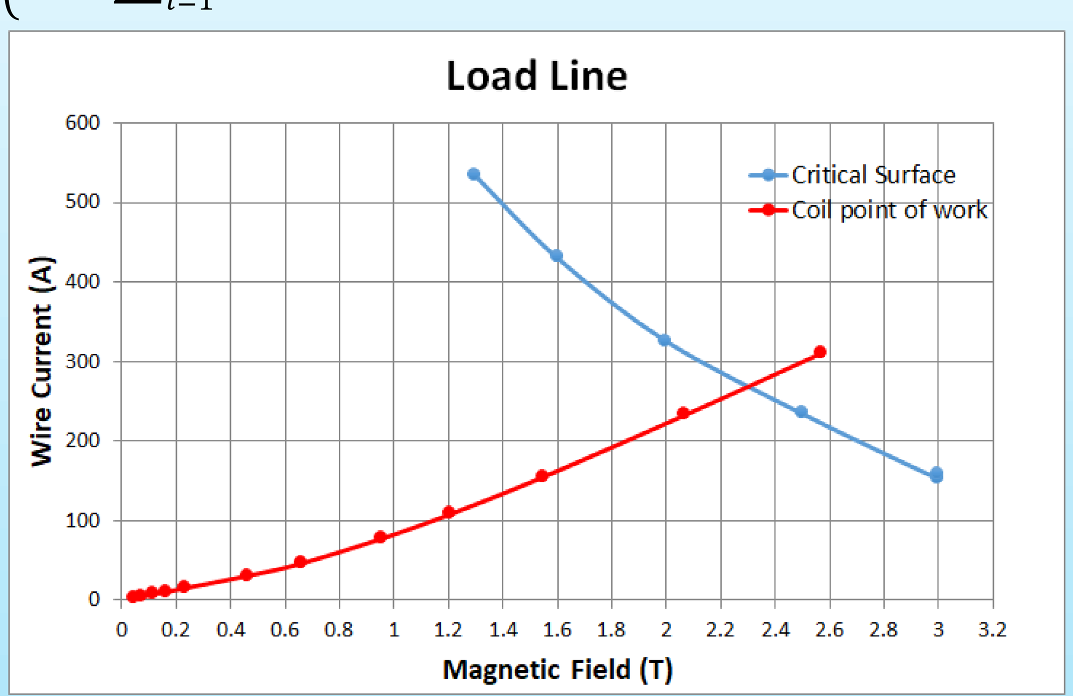

Fig. 1. Load line of the Coil to set the operational point for the magnet

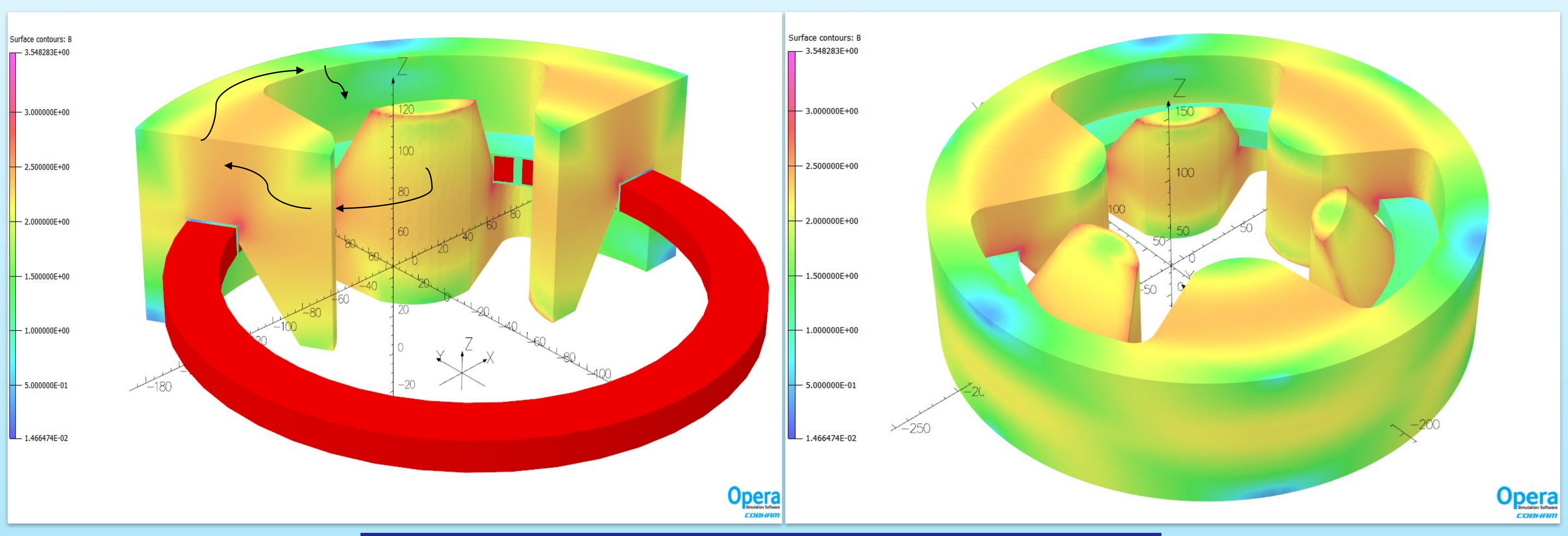

Fig. 2. Simulation of the Magnetic Field with OPERA 3D. We can analyse 1/3 of the problem for symmetry.

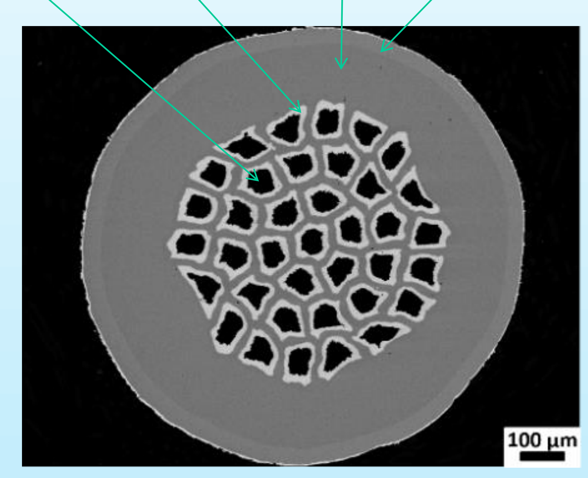

Fig. 3. Section of the MgB_2 wire made from Columbus Superconductors Industry containing 37 filaments surrounded by Nb shield, Monel and Copper Matrix

Field Quality and Quench Analysis

The magnet has to provide 0.063 Tm integrated Field along Z axis at operational current and calculated at R =50 mm. The magnet shown in the Figure (2) rapresents one semimodule. The coil is 32 mm wide and 15.6 mm high with $R_{int} = 133\ mm$ and contains 336 MgB_2 wires that provide 50 kAturn totally. The Iron Yoke has a diameter of $\emptyset = 390.6\ mm$ and is 96 mm high. To provide the requested magnetic field integral we have to stack four semimodules and connect them in series creating a unique magnet of 384 mm high. From preliminary analysis of the magnetic field quality, the main higher order harmonic that arise from the asymmetry of the magnet is of the 6° order. The field Harmonics (normalized respect to the main sextupolar harmonic and evaluated as units of 10^{-4}) are reported in the Table (2) and Figure (4). Main component of the field reaches 0.070 Tm as required by CERN technical specifics for the magnet while all of the others higher orders harmonics are less or equal to 790 units. To ensure the protection of the magnet from damage during transition to the normal resistive state (in which there could be large parts of the magnet that become resistive and generate huge amount of heating damaging the coil) we studied the rise of temperature with Quench Simulations using the QLASA program (developed at LASA laboratories). We report in Figure (5) the Temperature rise and Current decay during the transition. The magnet during quench reaches a maximum temperature of 139.5 K which can be considerated a safe value.

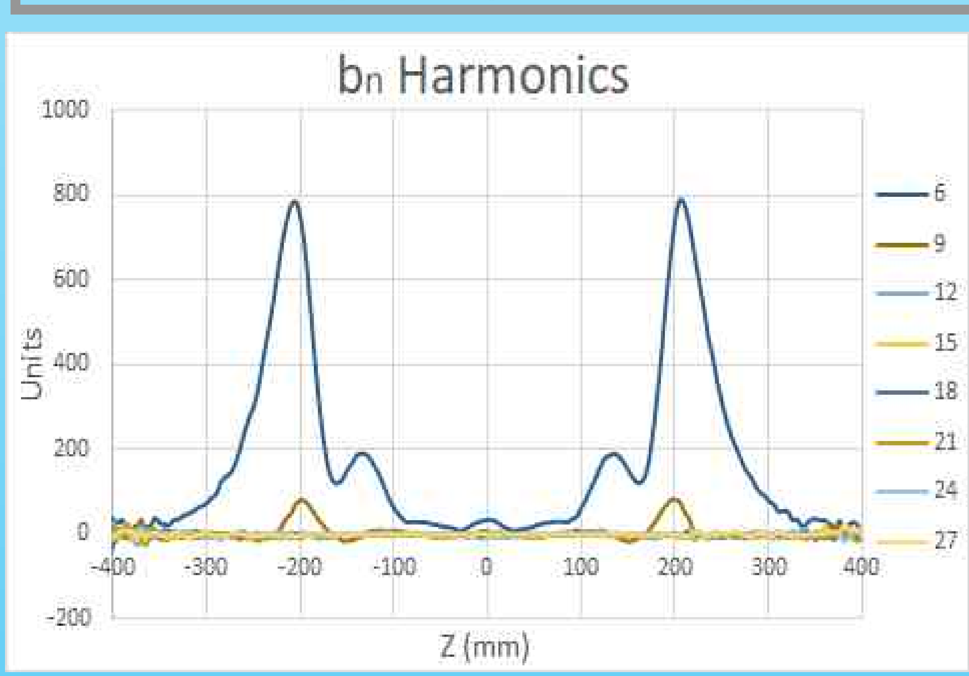

Fig. 4. Harmonics component of the sextupole magnet Module. Main components are of the 6th order and 9th order.

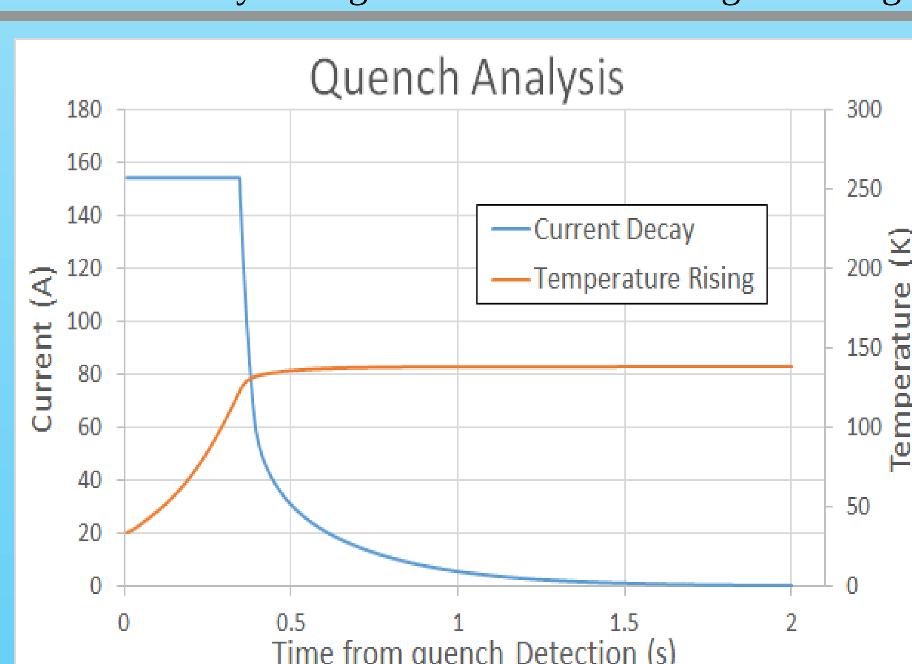

Fig. 5. Quench Analysis: the simulation describe the rising of temperature of the coil during the fast discharge of the current inside the magnet.

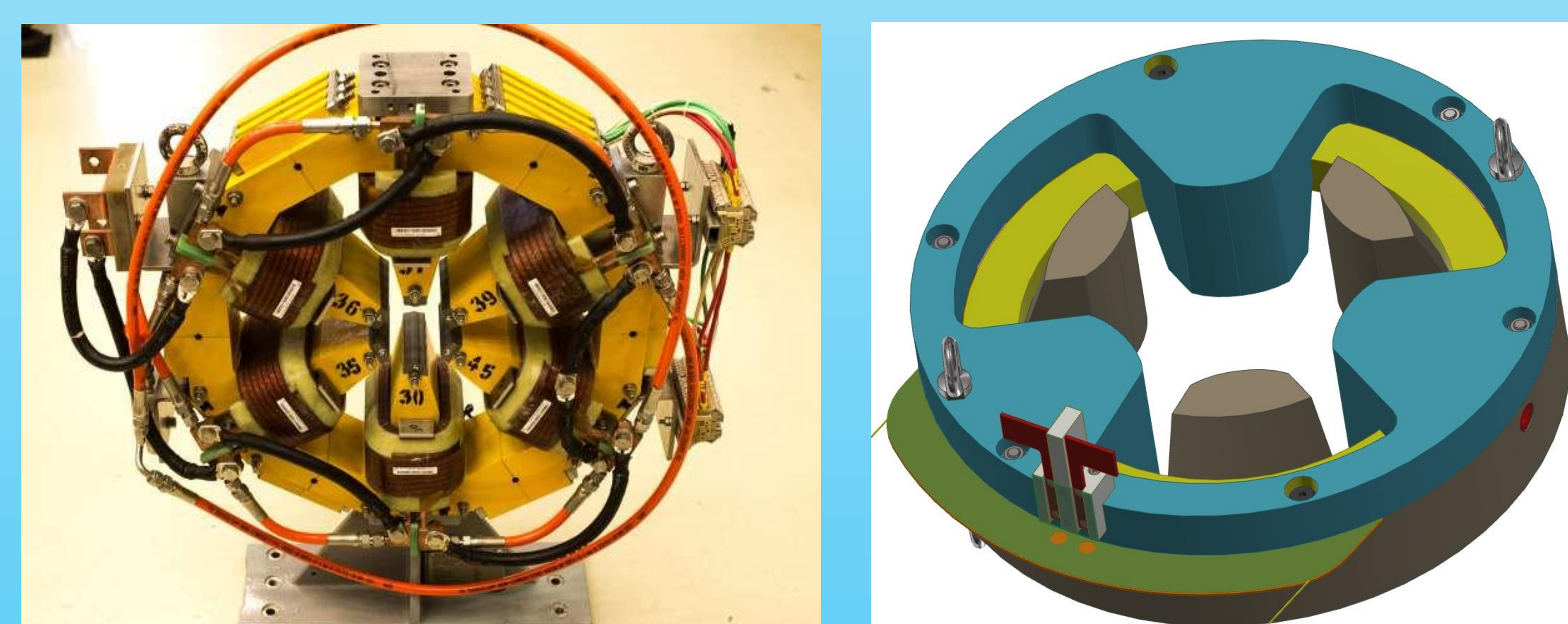

Fig. 7. Left side: we can see the classical configurations of coils for sextupole magnets. Right side: CAD Model for the whole semimodule of the magnet showing also conductors for the power supply and the solenoidal coil inside the semimodule.

Integral b3 Harmonic in Z (Tmm)	Integral $\frac{\tilde{b}_6}{L}$	Maximum $\tilde{b}_6$	Integral $\frac{\tilde{b}_9}{L}$	Maximum $\tilde{b}_9$
70.06	149.8 units	790 units	3.39 units	80.5 units

Tab. 2. Field Quality: we report the main harmonics that affect the magnet and that rise from the Z asymmetry of the poles

Mechanical Analysis

In this section we describe the mechanical analysis made with OPERA 3D program. The coil is surrounded by two slab of Duratron each of 0.15 mm of thickness in the radial direction and two 1.2 mm slab, also in duratron, in the Z axis direction to provide rigidity to the coil and to create a support of the mold for the coil to keep in the position each MgB_2 wire. We select the material properties [2] coefficient like the Young Modulus (Gpa) and the Thermal Expansion Coefficient assuming anisotropic behavior for the Coil and Isotropic one for the Duratron Insulation, Table (3). For the coil properties we calculated medium values considering Epoxy Resin as Matrix element and MgB_2 wires as fibers of the composite material. We studied the Thermal Contraction from 300 K to 4.3 K (operational temperature of the magnet) and the Lorentz Forces, Figure (6), that arise during the load of the magnet, focusing on the stresses applied on the coil to prevent the break of the epoxy resin.

Material	Young Modulus (Gpa)	Thermal Expansion Coefficient mm/(mmK) 10^{-6}
MgB_2 wire	150.2	8.83
Epoxy Resin	12	6.67
Monel	179	8.83
Duratron/G10	20	9.9
Coil	Rdir 42 Zdir 24.8 Φdir 109	8.81
Iron Yoke	270	6.96

Tab. 3. Mechanical material properties

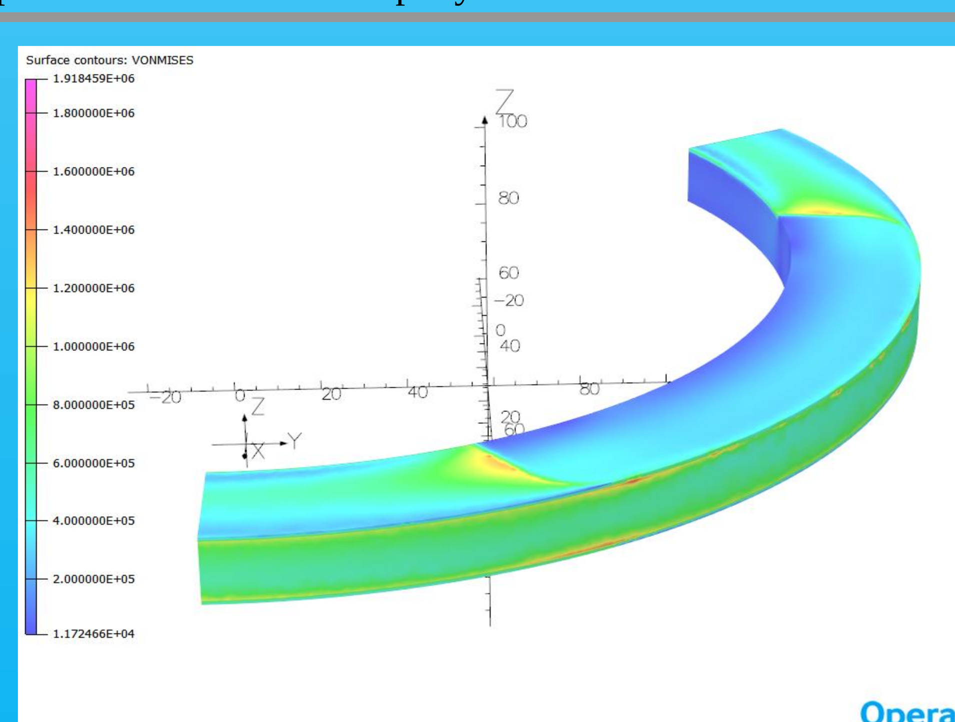

Fig. 6. Stress on the coil due to Lorentz forces

CONCLUSIONS

The electromagnetic design of the model has to be improved to reduce the higher order harmonics (6th order). The design has to be changed in particular in the shape of the iron poles and yoke which mainly contribute to the quality of the magnetic field in the bore. Quench analysis reveals that the magnet is completely protected from damage reaching the maximum temperature of 139.5 K without breaks or important deformations. The mechanical analysis has to be completed choosing the best values of the material properties to have a realistic and reliable description of the stresses applied to the coil during the cool down and the load of the magnet.

REFERENCES

[1] Giovanni Volpini, J. Rysti, M. Statera: "Electromagnetic Study of a Round Coil Superferric Magnet", *IEEE Trans. on Appl. Supercond.*, vol. 26, no. 4, June 2016, Art. No. 4103505.

[2] K Konstantopoulou et al.: "Electro-mechanical characterization of MgB2 wires for the Superconducting Link Projectat CERN", IOP Superondunctors ans Science Technology, vol. 29 (2016).