Round Coil Superferric Magnet for the High Luminosity LHC upgrade

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25th International Conference on Magnet Technology

ID Poster: **Thu-Af-Po4.01 [06]**

Abstract

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 based on the previous proposal of I. F. Malyshev and V. Kashikhin. This type of magnets is suitable to 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. A preliminary electromagnetic design of such magnet in sextupole configuration was presented, using MgB2 superconducting tape for the coil. In this paper we present the advances in study for the construction of the 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 mechanics and the quench protection, considering a new type of MgB2 superconducting cable for the coils. At the end of 2017 the magnet will be assembled in the LASA laboratories and then tested in 2018.

Electromagnetic Design

The presented work is developed in the framework of the HiLumi-LHC program, which aims to the upgrade of the integrated luminosity of the accelerator from 300fb^{-1} to over 3000fb^{-1}, inside the collaboration between CERN research program and the LASA Laboratories (INFN, Milan). The construction of this superconductive magnet aims to create the first demonstrative prototype of a single round coil magnet (RCSM) using HTC superconductors like MgB$_2$ wires to produces an arbitrary multipolar order of magnetic field. This novel type of magnet is suitable to arbitrary multipolar orders of magnetic field created in order to cancel the principal undesired harmonics of the main superconductive magnets used in the circular accelerator (Dipoles and Quadrupoles). In fact, the magnetic field of these magnets, in the transversal plane perpendicular to their axe of rotational symmetry, can be decomposed, through Fourier Transform, to obtain all the harmonics. To cancel the dipole's and quadrupoles' undesired harmonic with $n = 3$ (order of rotational symmetry is equal to the 2n order of the harmonics) we use a sextupole superconductive magnet with a new type of MgB_2 wire, Figure (1), 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**. The electromagnetic 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 equipotential surfaces, according to Maxwell Equations (eq. 3). Considering the saturation of the iron yoke we recreate the load line of the coil through electromagnetic simulations made with OPERA 3D program and set the working point at (1.55 T, 155.28 A) at 60% of margin from the critical surface (Fig. 3).

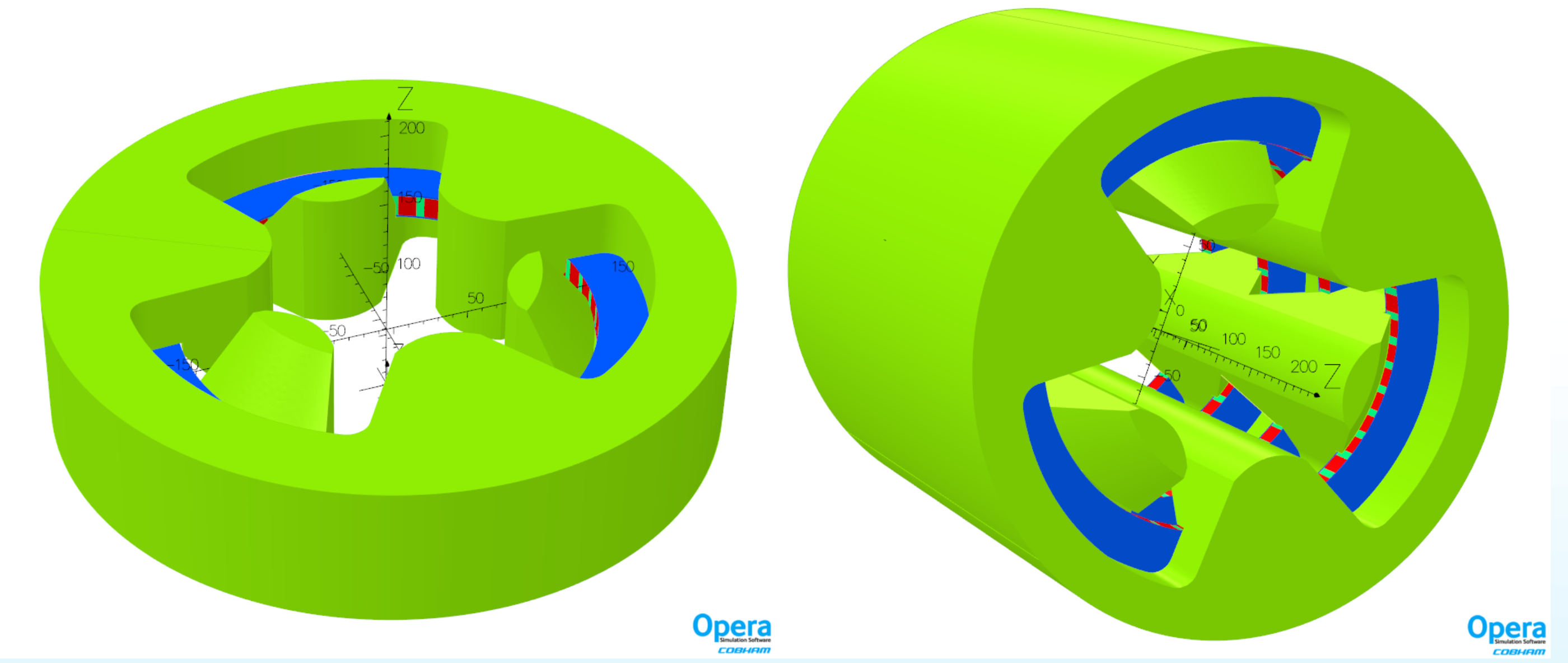

Fig. 1. Semi-Module and 2 Modules configurations of the RCSM magnet (OPERA simulation). The coils are the red and blue part in the image.

$$B = \sum_{i=1}^{\infty} r^{n-1} C_n e^{i(n-1)\vartheta}$$

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

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

Eq 1. Decomposition of the magnetic field in its harmonics in the transversal plane (X,Y).

$$a_n = \frac{A_n R^{n-1}{}_{ref}}{A_m R^{m-1}{}_{ref}} \qquad a_n{}^* = \frac{\int_{-\infty}^{+\infty} A_n R^{n-1}{}_{ref}}{\int_{-\infty}^{+\infty} A_m R^{m-1}{}_{ref}}$$

Eq 2. Field Harmonics and their integral values normalized to those of the main field harmonic of the 3rd order.

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

eq. 3. Equation for the Equipotential Surface for the shape of the poles.

Diameter (mm)	Nº filaments	Filament size (µm)	MgB$_2$	Nb	Ni	Monel	Cu
1 ± 0.01	37	55	11.50%	14.50%	14%	46%	14%

Tab. 1. Composition of the superconductive MgB$_2$ wire

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. Values of undesired harmonics in the 2-Module Configuration

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	R_{dir} 42 Z_{dir} 24.8 Φ_{dir} 109	8.81
Iron Yoke	270	6.96

Tab 3. Mechanical properties of the wire and the coil used in the simulation. We report here the Young Modulus and the Thermal Expansion Coefficient used for the Opera simulations

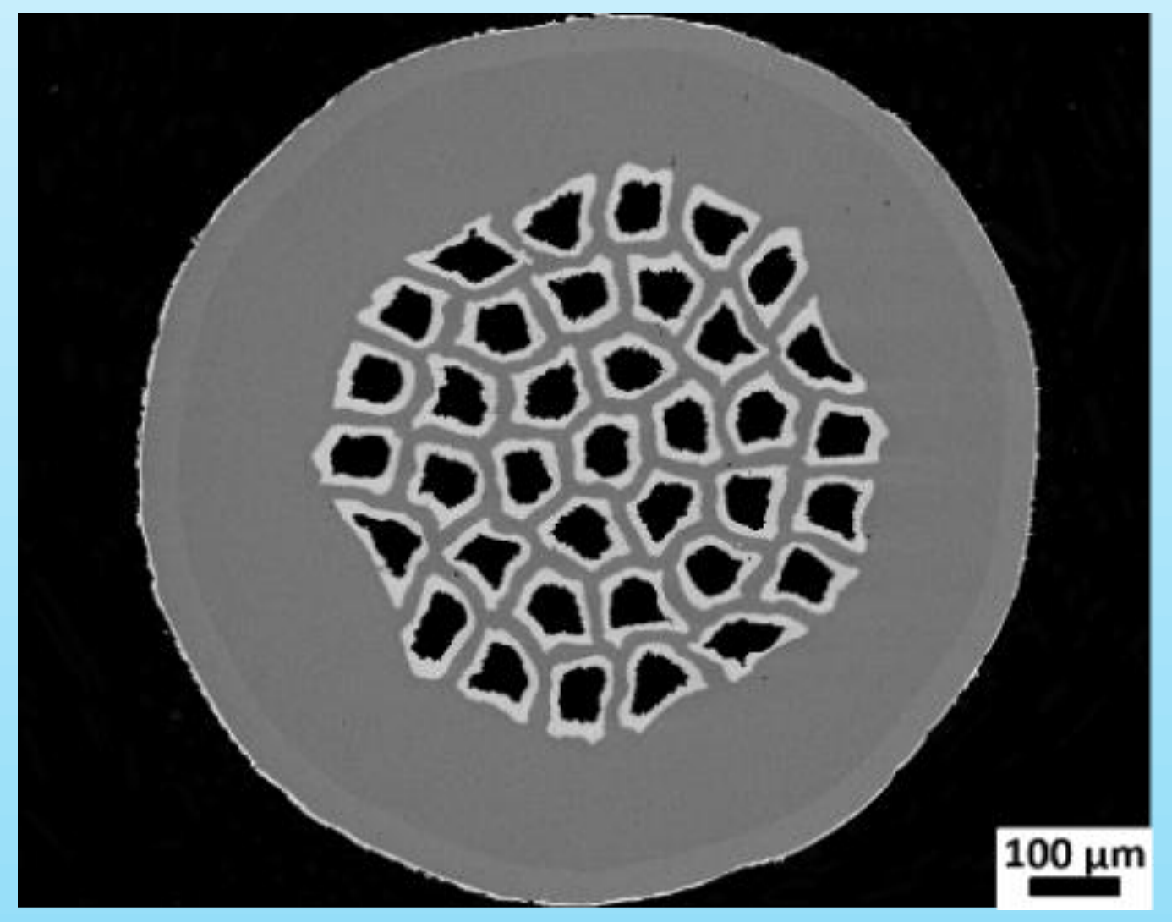

Fig. 2. Section of the superconductive MgB$_2$ used for the coil of the RSCM

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 (1) at left represents one semi module while at right we reported the 2 modules configuration (4 Coils). 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 semi modules and connect them in series creating a unique magnet of 384 mm high. Main higher order harmonics that arise from the asymmetry of the magnet is of the 6th and 9th orders, as we can see from Fig. 3 but the magnet shows all the multiples of the 3rd order of harmonics due to the asymmetry in the xy plane. Classical sextupole (symmetrical in the xy plane) show only harmonics of the 9th, 15th, 21st orders and so on. 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 67.64 Tmm as required by CERN technical specifics in the 2 modules configuration. All of the others higher orders integrated harmonics are less or equal to 152 units. To ensure the protection of the magnet from damage during the quench of the superconductive material, we studied the rise of temperature with Quench Simulations using the QLASA program (developed at LASA laboratories), Fig. (5). The magnet during quench reaches a maximum temperature of 139 K in the semi-module configuration and 178 in the 2 modules one, temperatures that can be considered safe values.

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 and to create a support of the mold for the coil to keep in the position each MgB_2 wire. Material properties [2] have been used assuming anisotropic behavior for the Coil and Isotropic one for the Duratron Insulation, Table (3). For 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 (7) – (8), that arise during the load of the magnet. Radial deformation, equal to 0.345 mm, towards the center of the magnet during thermal contraction are allowed by the 3 mm gap between the coil and the poles of the yoke. A small gap of 90 µm between the external side of the coil and the yoke can be compensated by action of 6 conical springs, preloaded with 600 N, to keep the coil in contact with the iron yoke, avoiding release of stored energy that can create the quench. The preload is used also to compensate the electromagnetic forces generated during the load of the magnet. Maximum pressure created by the Lorentz Forces is equal to 5.6 MPa and results to be under the critical level of 6 MPa, which is the amount of stress at which the epoxy resin used in the coil starts to crack.

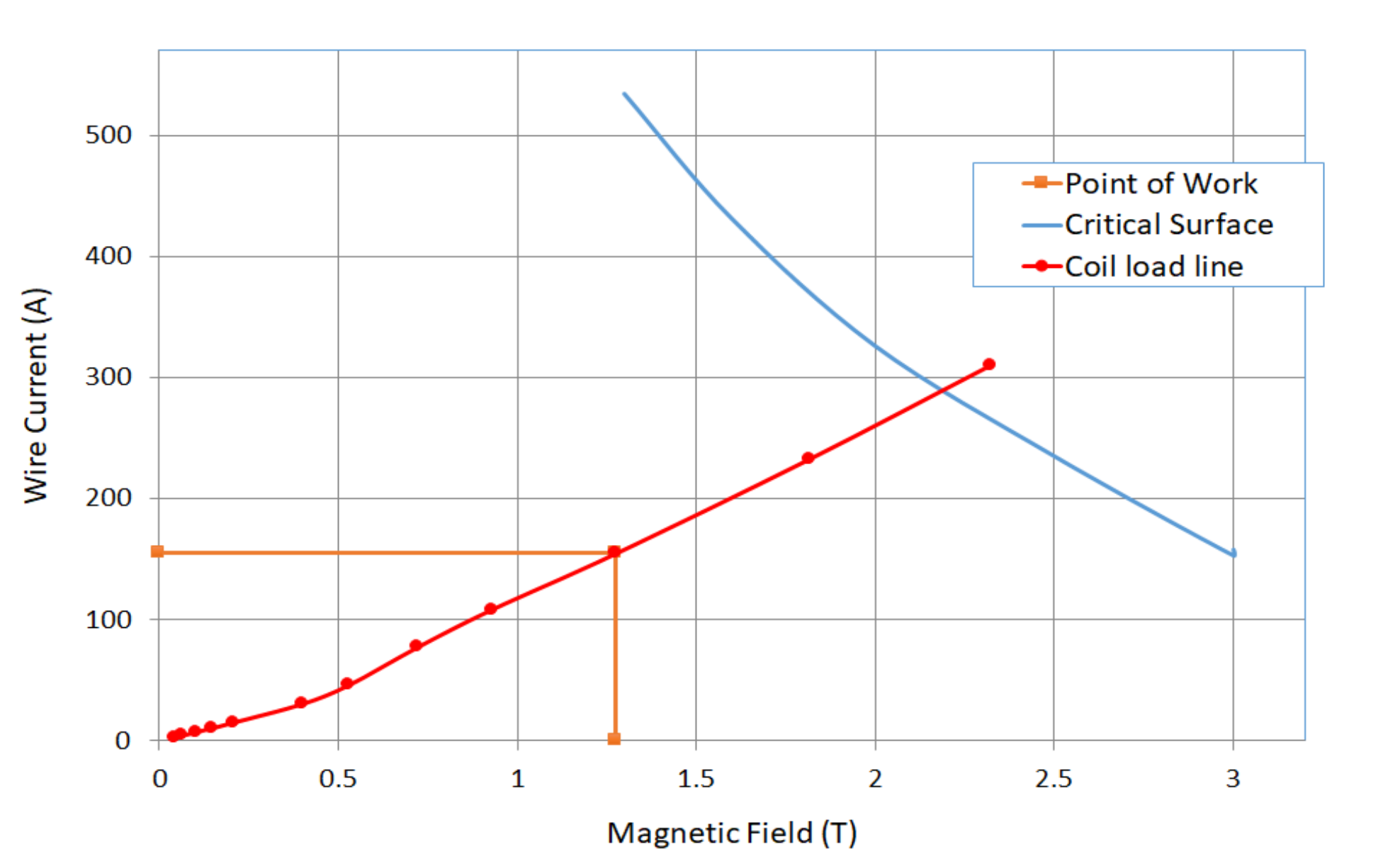

Fig. 3. Load line of the magnet and working point

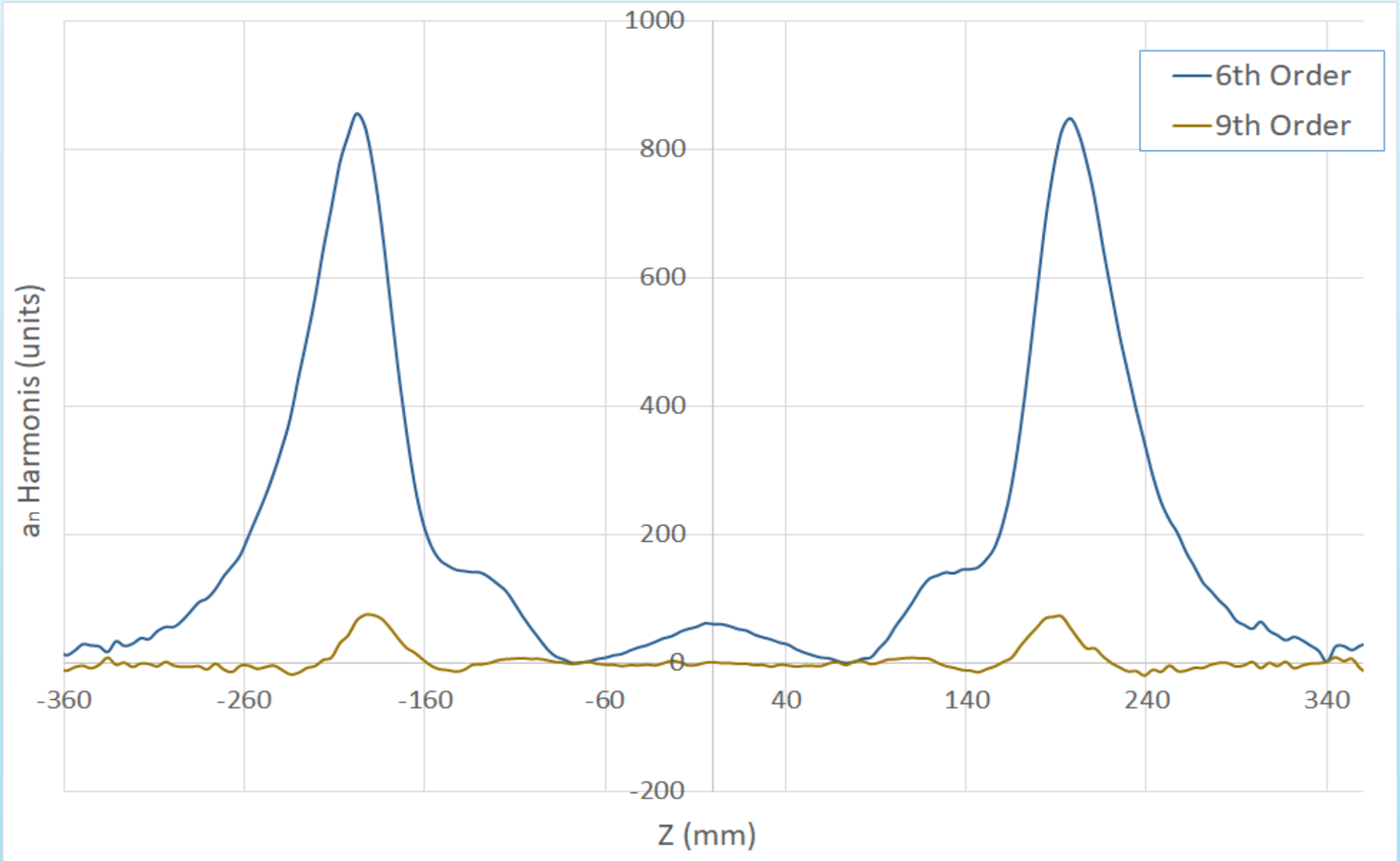

Fig. 4. Undesired Harmonics arising from asymmetries of the magnet

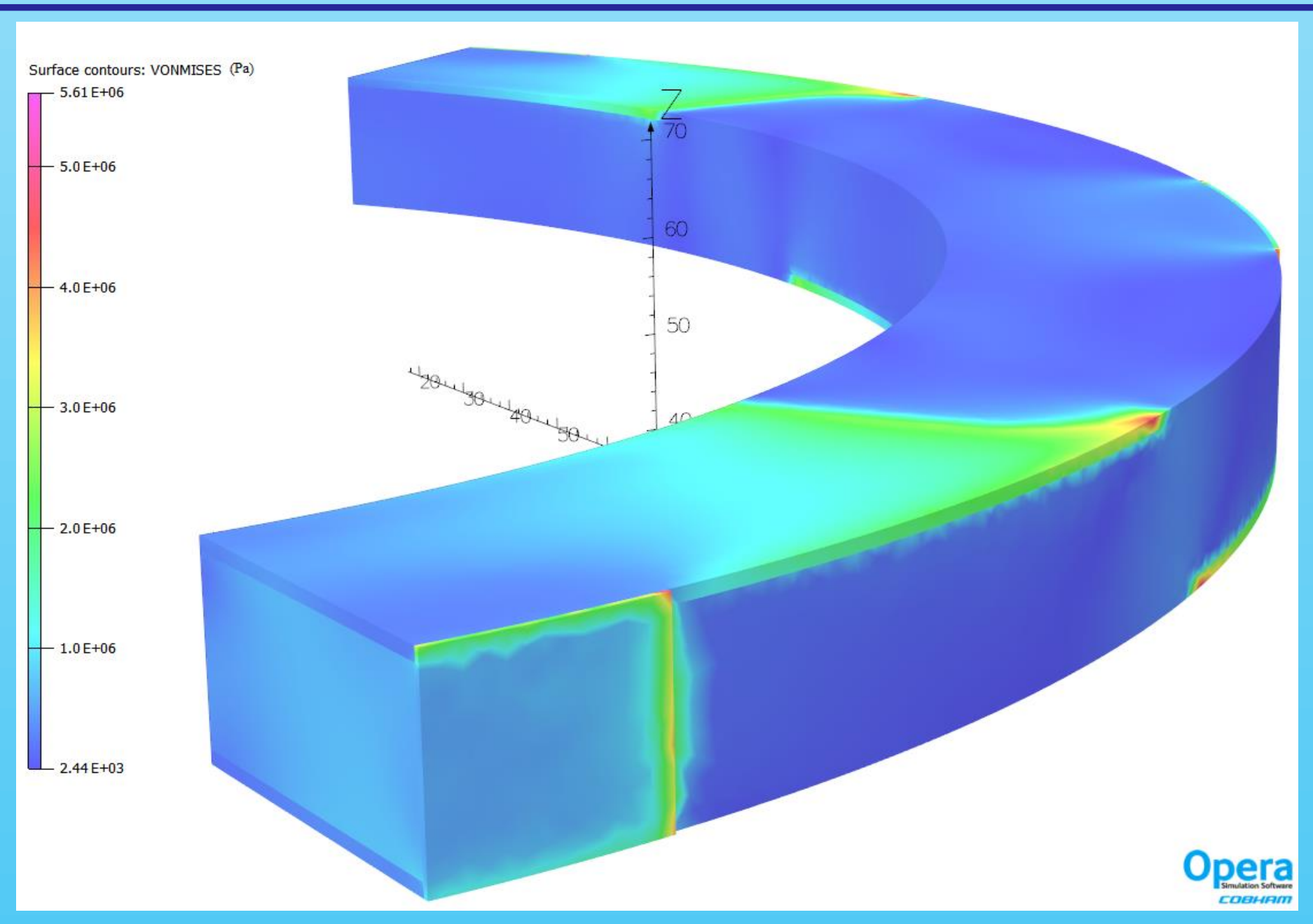

Fig. 7. Maximum Stress on the Superconductive coil

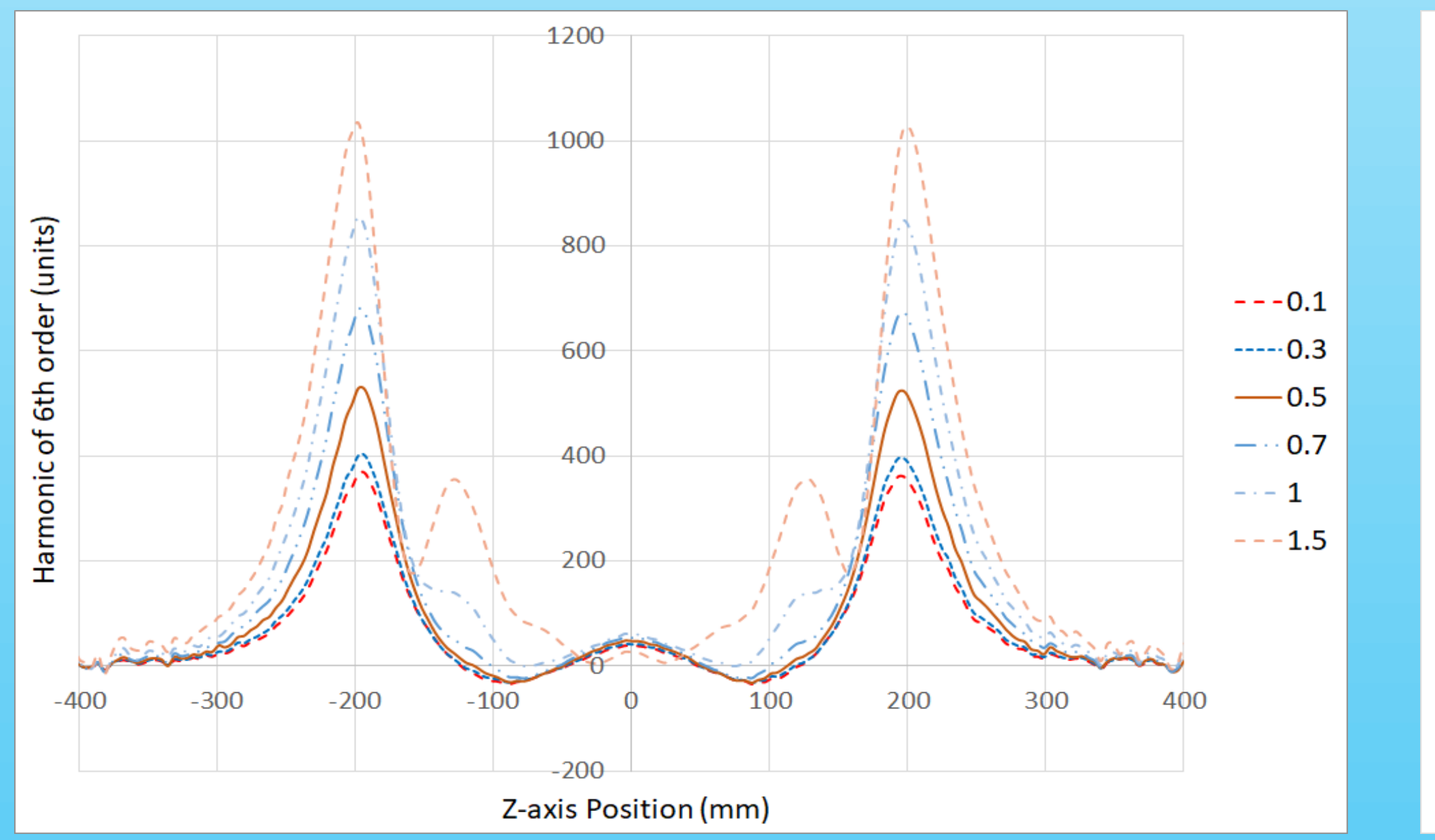

Fig. 5. Variation of the 6th order harmonic due to the iron saturation as function of the operational current

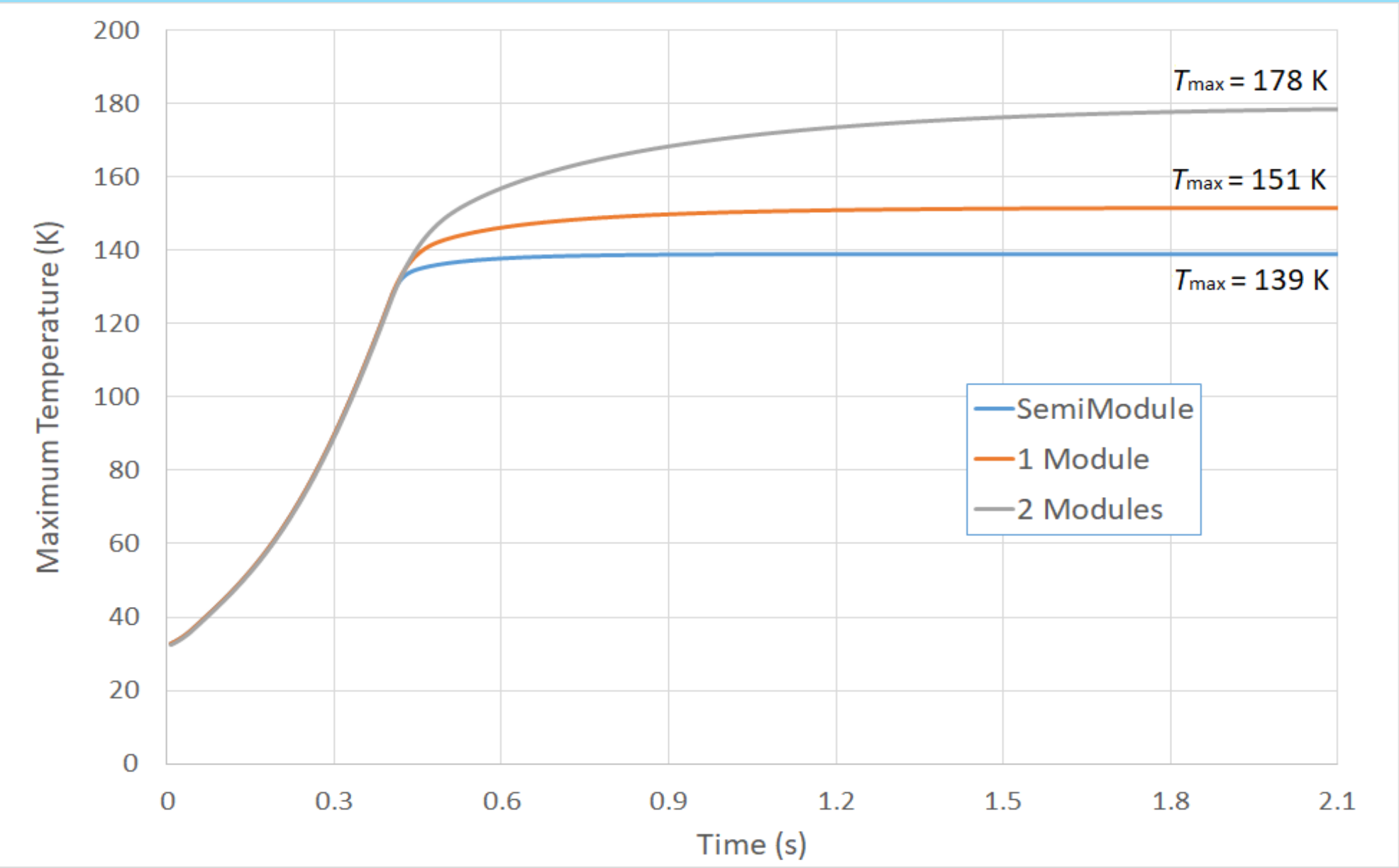

Fig. 6. Maximum temperature reached during the quench of the magnet in the different configurations

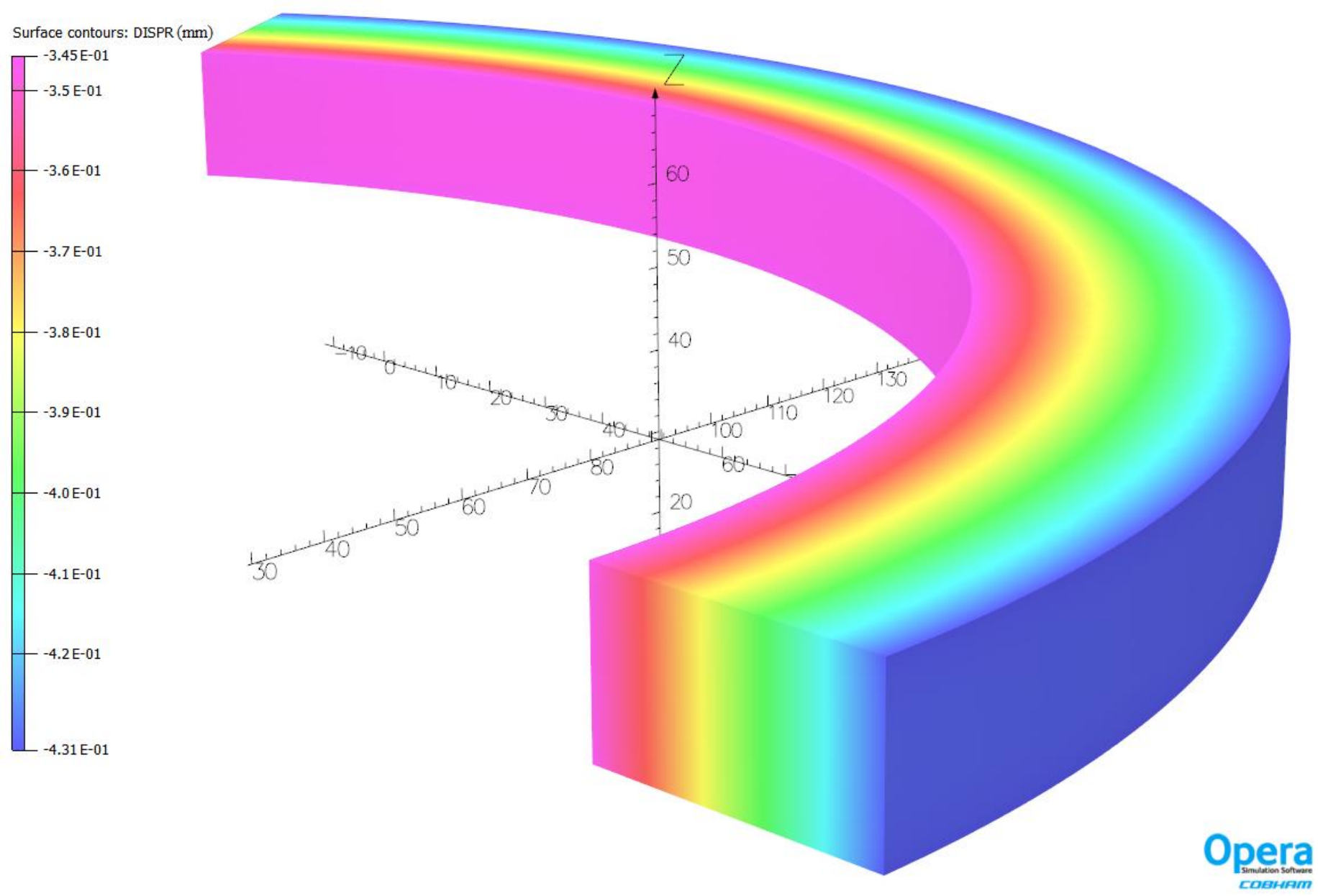

Fig. 8. Coil deformation during the cool-down

CONCLUSIONS

The electromagnetic and mechanical design of the magnet has been presented. The magnet reach the required integrated field harmonics of 62 Tmm but, compared to conventional design of superferric magnets, shows an high level of undesired harmonics, especially at the end caps of the magnet which integral is equal to 154 units. The quench protection analysis of the semi-module, module and 2 module configurations show that the stored energy can be extracted from the magnet keeping the maximum temperature under 179 K which can be considered safe for the stability. Deformations and stresses created in the magnet during the cool down and the energization of the coil at the nominal current appear to be under the critical values . The design here proposed can be used for the construction of the first demonstrative prototype. The construction of the magnet will start at the end of 2017 while the first tests will be performed at the beginning of the 2018.

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This work was supported in part by the National Institute for Nuclear Physics (INFN), Italy, by the European Organization for Nuclear Research (CERN).