Design of a 16 T bending dipole for the Future Circular Collider (FCC)

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Abstract

After LHC will be turned off, a new accelerator machine will be needed in order to explore unknown areas of high-energy particle physics. Because of this, the project FCC (Future Circular Collider) has started at CERN, in Geneva. The aim of this project is to produce collision between 50 TeV proton beams (100 TeV in the center-of-mass reference system), which will run in a 100 km circular collider.
One of the main activities needed in order to reach this task is the design of a superconducting bending dipole, able to produce a 16 T magnetic field in the bore. This field is necessary to obtain the required energy, keeping the machine size below what established.
Here, the conceptual design of a Nb$_3$Sn superconducting dipole is presented. The coil layout follows a cosine-theta configuration. It is proved that it is possible to produce 16 T in the bore using this superconducting material, in this configuration, with a good field quality, and with coils of a reasonable size. Moreover, it is possible to maintain the huge electromagnetic forces under control designing a suitable mechanical structure, and it is possible to protect the magnet from the transition to the normal-conducting state.

ELECTROMAGNETIC DESIGN

Here, the electromagnetic design of the magnet is shown. The field is produced basically by the current, and the field quality is due to the windings arrangement, while iron has basically just mechanical support functions. The layout is a double aperture (LHC-style)

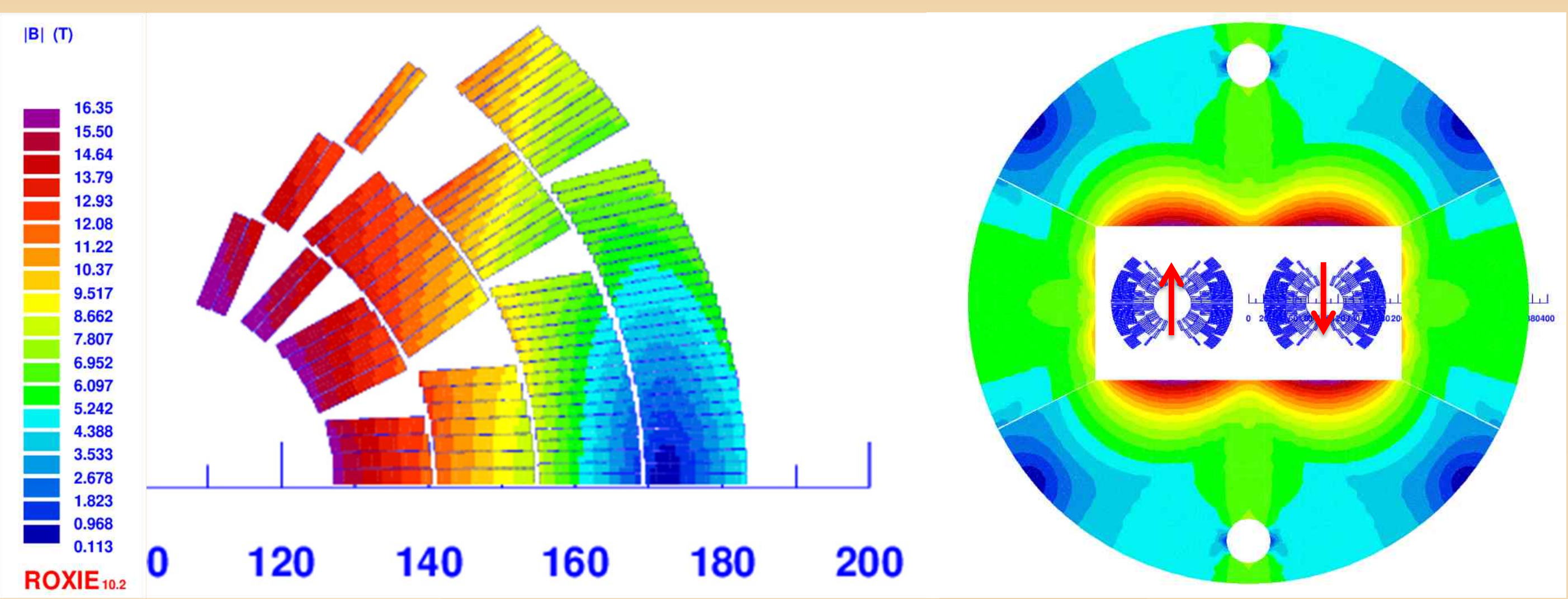


Figure 1: Cross section of the magnet

TABLE 1 Magnet parameters

Material	Nb$_3$Sn
Current	11060 A
Number of windings	200/aperture
Coil width	55 mm
Yoke diameter	750 mm
Beam-beam distance	204 mm
Type of conductors	2
Conductor size	13.5x2.192 mm^2 (HF) 13.95x1.504 mm^2 (LF)
Copper/Not-copper	0.9 (HF) / 2.2 (LF)

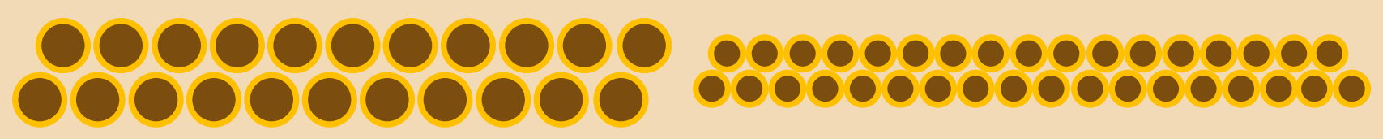


Figure 2: Type of conductors. Two conductors are used, with a different number of cables, with different size. Moreover, each cable has a different amount of superconductor.

NORMAL RELATIVE MULTIPOLES @ 16 T:

b 1: 10000	b 2: -27.6	**b 3: -0.41**
b 4: -0.69	**b 5: 0.99**	b 6: -0.01
b 7: 1.72	b 8: -0.00	b 9: 1.4
b10: 0.00	b11: 1.03	b12: 0.00
b13: -0.18	b14: 0.00	b15: 0.01

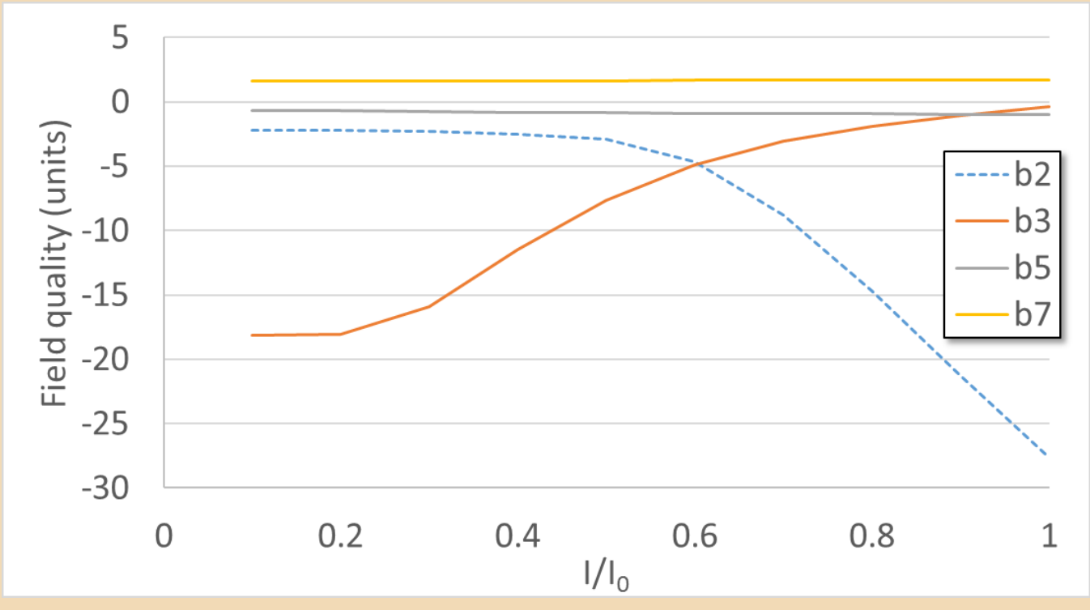
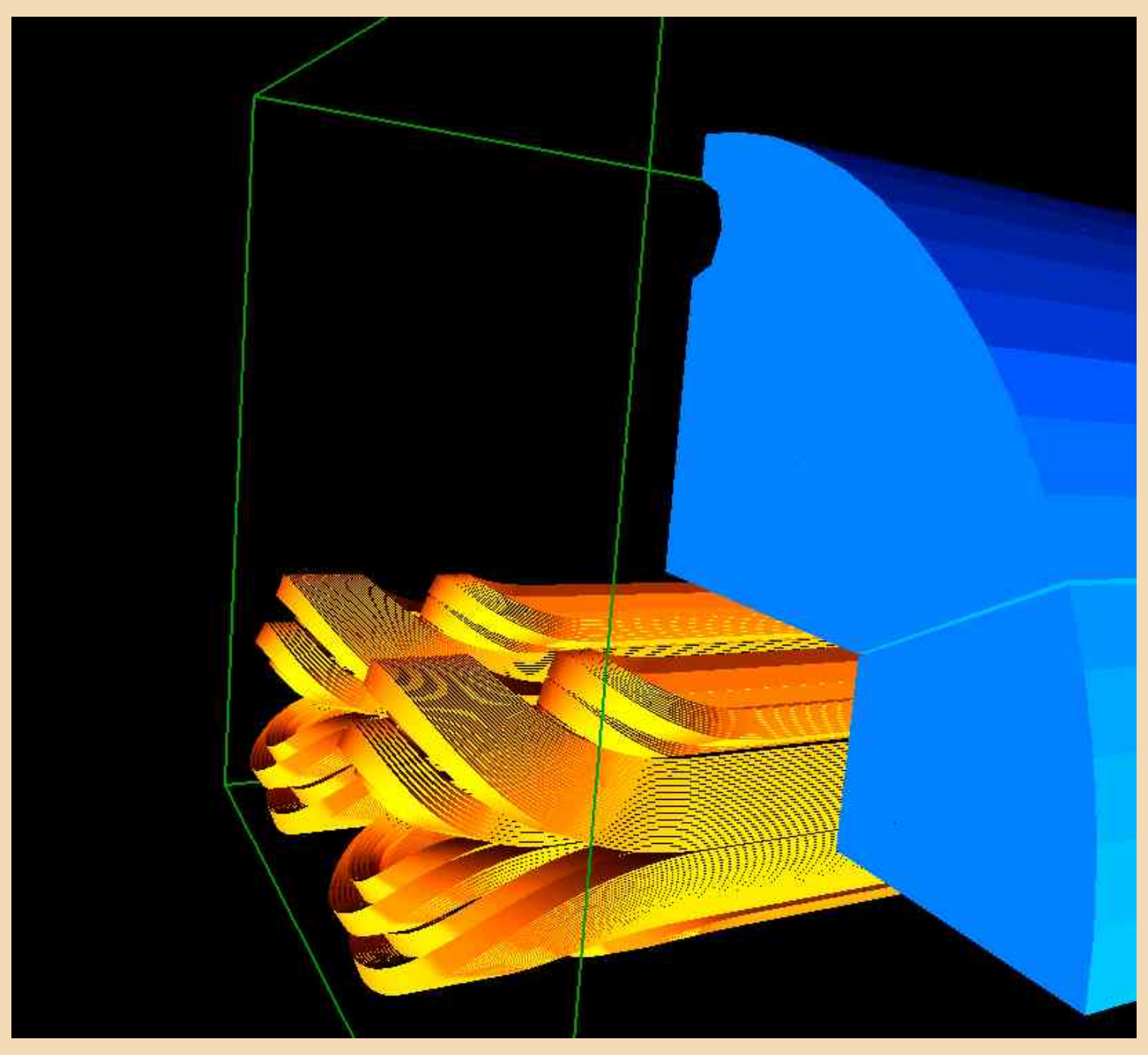


Figure 3: Field quality at the 16 T operating field (top), or as a function of the current (bottom). A “unit” means that the considered field component is 0.01% of the main one (dipole or b1). For example, b3 0.4 means that the sextupole harmonic in this magnet is 0.004 % of the dipole harmonic)



NORMAL 3D INTEGRAL RELATIVE MULTIPOLES
(10^{-4})

b1 = 10000.00
b2 = - 39.36
b3 = 2.59
b7 = 1.96
b9 = 1.39
Others < 1

Figure 4: design of the 3D coil ends (left) and integrated harmonics (right). At the coil ends, the field quality depends on the magnet axis. The coil ends design should mimize the integral harmics.

QUENCH PROTECTION

The transition to the normal conducting state of a magnet is called quench. This phenomenon is very dangerous, because the whole magnetic stored energy is dissipated into the resistive zone, which is usually small (few centimeters). This means that the windings could even melt. Nevertheless, quench is unavoidable, so a suitable protection system should be designed for each superconducting magnet. The protection system has to detect the quench, bypass the power supply, and spread the quench along the whole magnet (the stored energy is dissipated into a larger volume, reducing the temperature). The maximum temperature has to be lower than 350 K, while the maximum voltage to ground has to be lower than 1200 V.

TABLE 2 Quench protection results

Protection delay time	Hot spot temperature	Voltage to ground
40 ms	310 K	1100 V

MECHANICAL DESIGN

Due to the high magnetic field and current density, huge electromagnetic forces occur in the magnet (~200 MPa). These forces try to collapse the coil in the azimuthal direction, and the turns try to detach from the pole. This has to be avoided, because it induces coil movements, and as a consequence transition to the normal-conducting state. The main aim of the mechanical structure is to prevent this phenomenon. This is due providing “pre-stress” to the coils: a force distribution as similar as possible to the Lorentz forces is provided before the energization of the magnet, during the assembly and the cool-down, in order to keep the contact between windings and pole after the energization of the magnet.

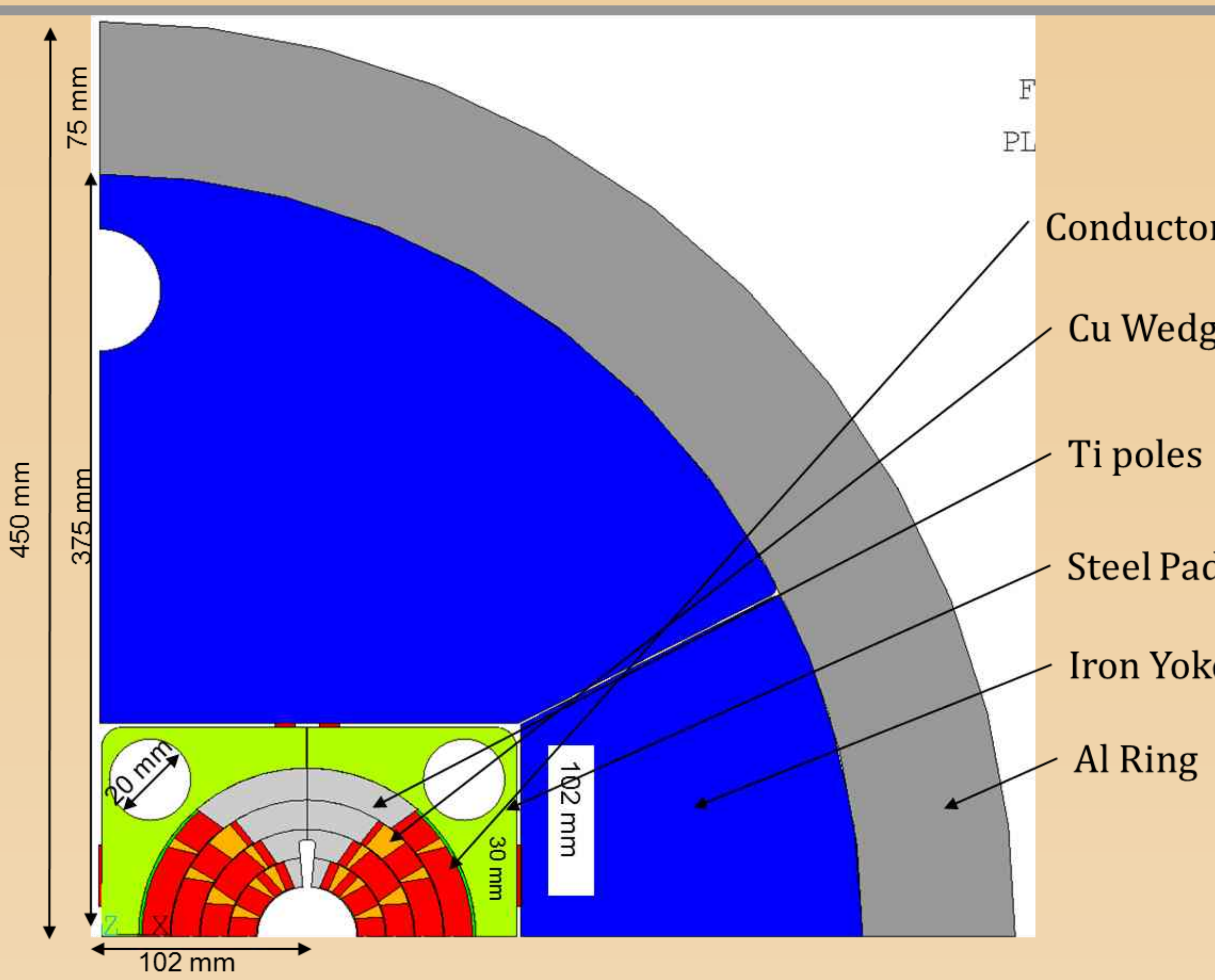


Figure 4: mechanical layout of the magnet, with all the component. The azimuthal pre-stress is provided in two phases: during the assembly, using a “bladder&key” configuration, and during the cool-down, when the aluminum ring shrinks more than the coil.

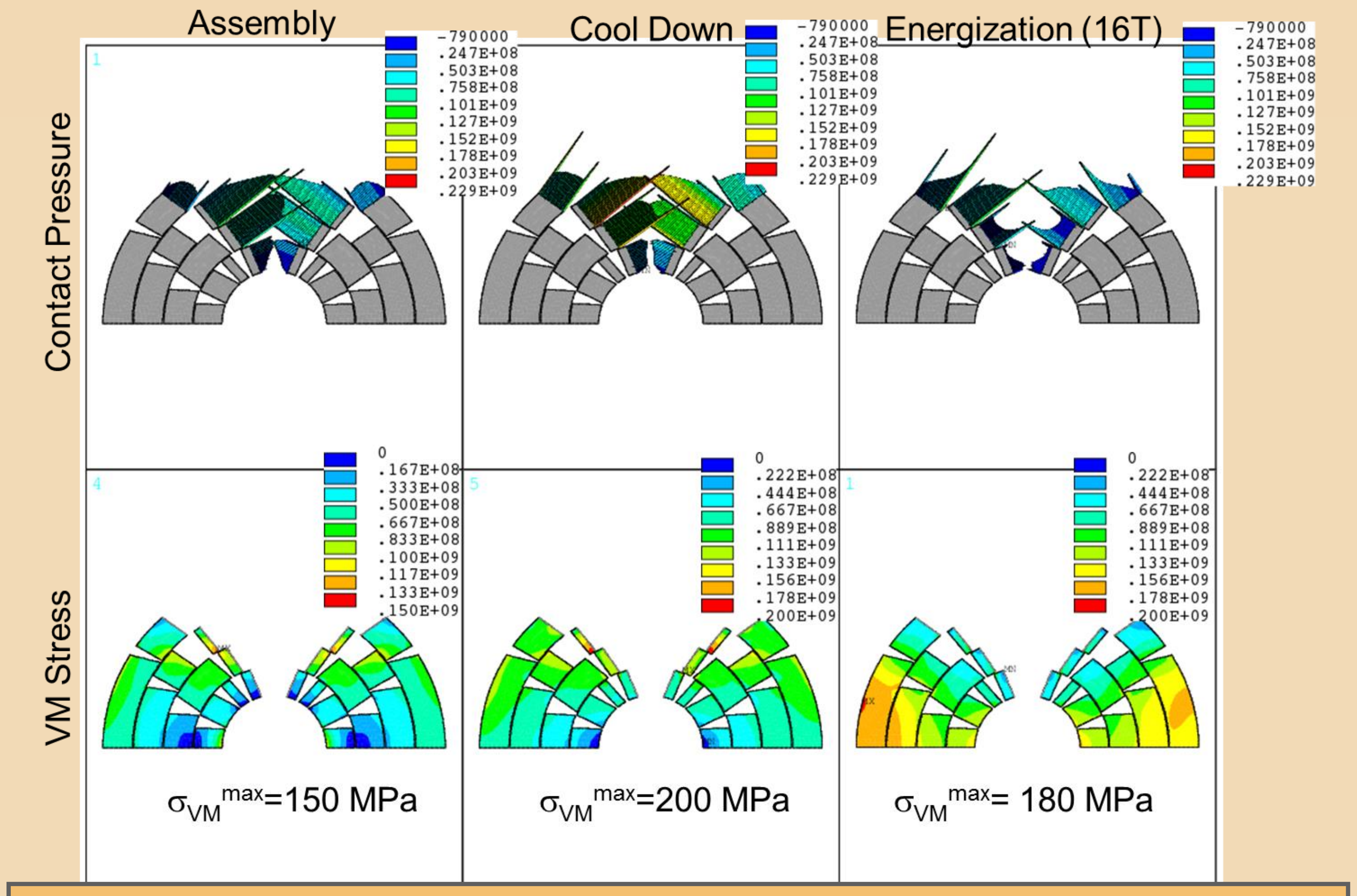


Figure 5: Contact pressure between windings and pole (top) and Von Mises stresses (Bottom) after assembly, cool down and energization. A positive contact pressure between coil and pole has to be kept, in order to avoid coil movements during the energization. The Nb$_3$Sn is a brittle material, and it should not be subjected to more than 200 MPa.

CONCLUSIONS

We have presented a 16 T bending dipole for the Future Circular Collider. The layout is a Nb$_3$Sn superconducting magnet, which follows the cosine-theta configuration. The magnetic field is basically produced by the coil, while the iron has mostly a mechanical support function; the field quality is provided basically by the windings arrangement.
The target of 16 T has been achieved, with a good field quality. The 3D coil ends have been designed, and the integrated harmonics have been optimized, in order to increase the beam quality. The mechanical structure is able to keep the mechanical forces under control: the pre-stress guarantees coil-pole contact after the magnet energization, and the brittle windings are stressed right below the material limit (200 MPa).
The magnet can safety operate at nominal current, if a suitable quench protection system is designed. This system should act in 40 ms, detecting the quench and spreading it along the whole magnet. The present technology can achieve this task.

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