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Mechanical Design of the Nb_3Sn $cos\theta$ Short Model Dipole for the Future Circular Collider

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ABSTRACT

The future of the particle accelerators points to a new CERN’s circular collider with an order of magnitude increase in the center-of-mass energy compared to the Large Hadron Collider (LHC). To achieve this goal a 100 km tunnel and a new generation of double aperture magnets capable of generating a ***16 T*** magnetic field in a 50 mm bore will be required. To manage this challenging task a roadmap was planned in the development of accelerator-grade Nb_3Sn magnets under a CERN-INFN agreement. The first of these steps will be the construction of a short, single aperture $\boldsymbol{cos\theta}$ dipole, with a target magnetic field of ***12 T*** and an ultimate field of ***14 T*** called ***Falcon Dipole*** (Future Accelerator post-LHC $Cos\theta$ Optimized Nb_3Sn). This contribution presents 2D and 3D finite element analysis able to describe all the constructive steps that meet the requirements imposed by the project to ensure the correct operation of this magnet. To cope with the intense magnetic forces that are generated in the magnet during operation, a novel mechanical structure has been adopted, the so-called ***“bladder & key”*** (B&K), that has never been used in $cos\theta$ dipoles and needs to be validated.

INTRODUCTION

In order to explore unknown regions of the high energy physics, CERN will need a new generation of particle accelerators that will improve the performance of the LHC bringing up the center-of-mass energy from 14 TeV up to ***100 TeV***, along a ***100 km*** ring, with ***16 T*** bending dipoles. The worldwide project led by CERN goes under the name of Future Circular Collider (FCC). The $cos\theta$ option for the main dipole has been designed by the Italian Institute for Nuclear Physics (INFN). Considering the extreme fields that these dipoles will have to produce it is needed a state-of-the-art ***Nb_3Sn*** cable with its high critical field, but on the other hand it shows a pretty brittle behavior after the heat treatment that generates the superconducting intermetallic compound.

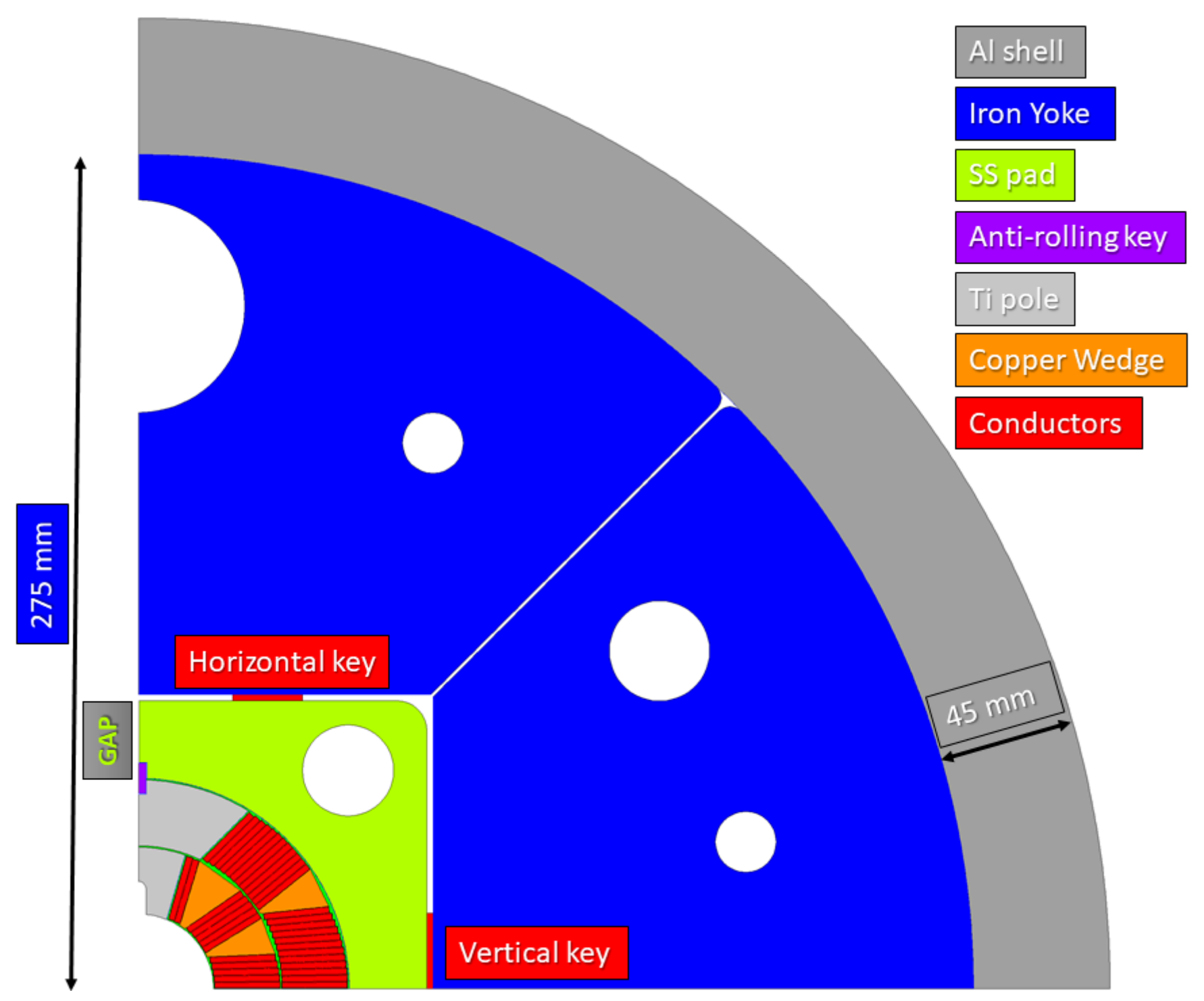
Due to the mechanical issues, it is fundamental to develop a strong R&D strategy, in order to achieve the needed knowledge to manage the production of such innovative magnets. These R&D activities will include the implementation of a cutting edge concept for the mechanical structure surrounding a $\boldsymbol{cos\theta}$ dipole, i.e. the ***B&K*** technology, nowadays used only for quadrupoles or R&D block-type magnets. The $cos\theta$ configuration has been elected as the baseline design in the Conceptual Design Report of the FCC project. It has been signed an agreement between CERN and INFN which gave rise to an intermediate project called ***Falcon Dipole***. The aim of the FalconD is to design and develop a single aperture $cos\theta$ 1.5 m long model with a target magnetic field of ***12 T*** in the bore and an ultimate field of ***14 T***.

2D MECHANICAL ANALYSIS

The mechanical structure of the Falcon Dipole has to be designed in such a way to withstand the huge Lorentz forces which arise once the magnet is energized. These forces may be responsible of movements of the cables that could generate heating, due to friction, eventually leading to a quench.
To give the proper pre-load to the winding the ***B&K*** technique it has been chosen for the ***Falcon Dipole***. This technique supply the pre-stress to the coils in two steps: one at room temperature through the insertion of ***SS interference keys***, using water-pressurized bladders, that transfer to the coils about half of the needed pre-stress. The other one is at 1.9 K and it exploits the higher thermal contraction coefficient of the ***external Al alloy shell*** that shrinks more than the inner components of the magnet, reaching gradually the intended pre-load. The goals of the optimization of the mechanical design are: keeping the winding and the Ti pole in ***compression*** during the energization and ensuring that all the materials involved stay within their ***stress limit*** during each step of the analysis. While the horizontal key interference is set to 0.1 mm, the vertical one increases with the magnitude of the magnetic field, following the increase of the Lorentz forces. It has been set to 0.35 mm for the 12 T case and 0.6 mm for the 14 T one.

Main characteristics of the dipole magnet at the fields of 12 T and 14 T

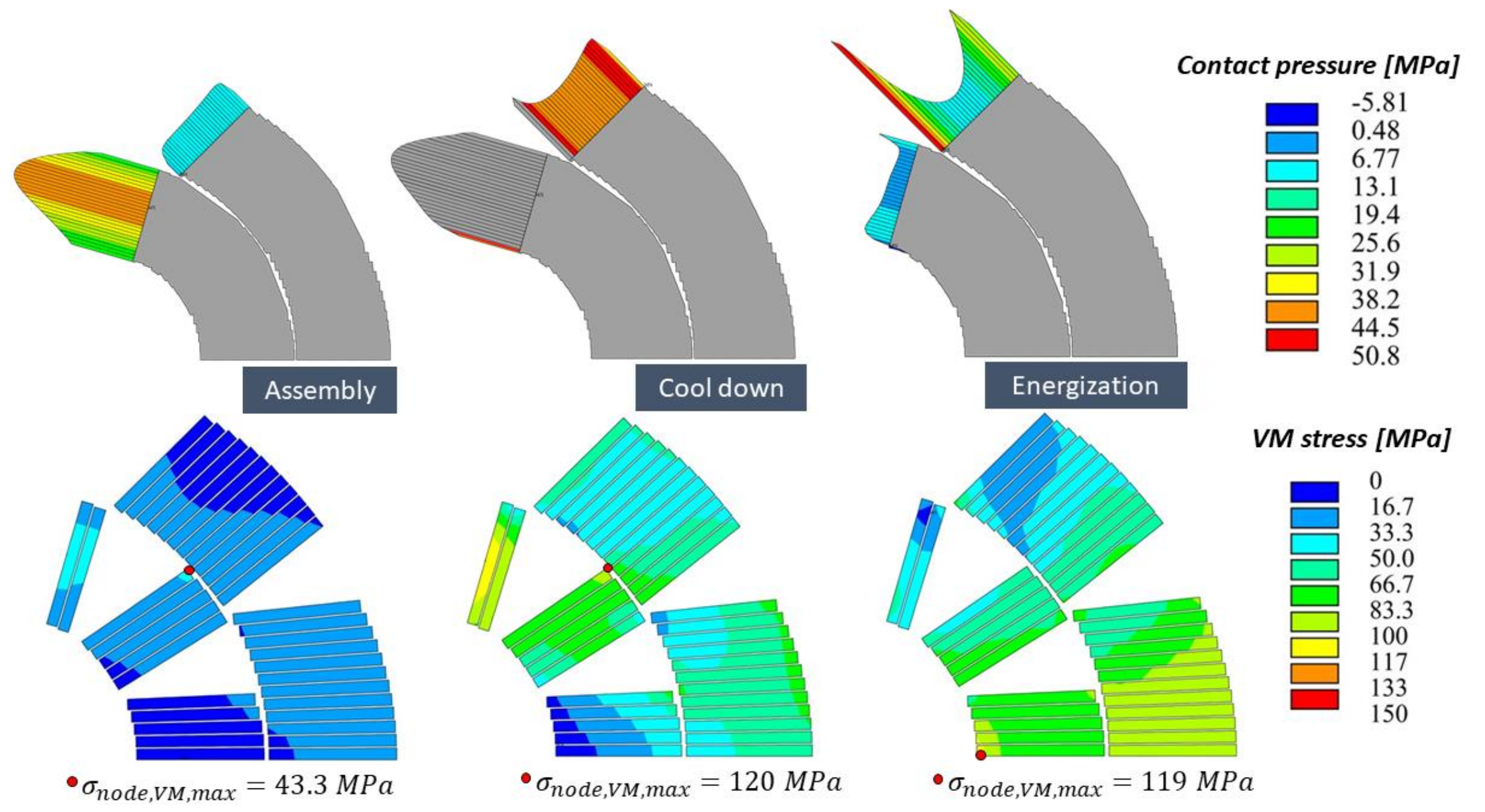
Characteristics	Unit	Value @ 12 T	Value @ 14 T
Bore diameter	mm	50	50
Iron yoke radius	mm	275	275
Operating temperature	K	1.9	1.9
Margin on loadline	%	23.64	10.51
Peak field	T	12.53	14.63
Operating current	A	20991	24906
Stored energy	MJ/m	0.543	0.741
Inductance	mH/m	2.235	2.188



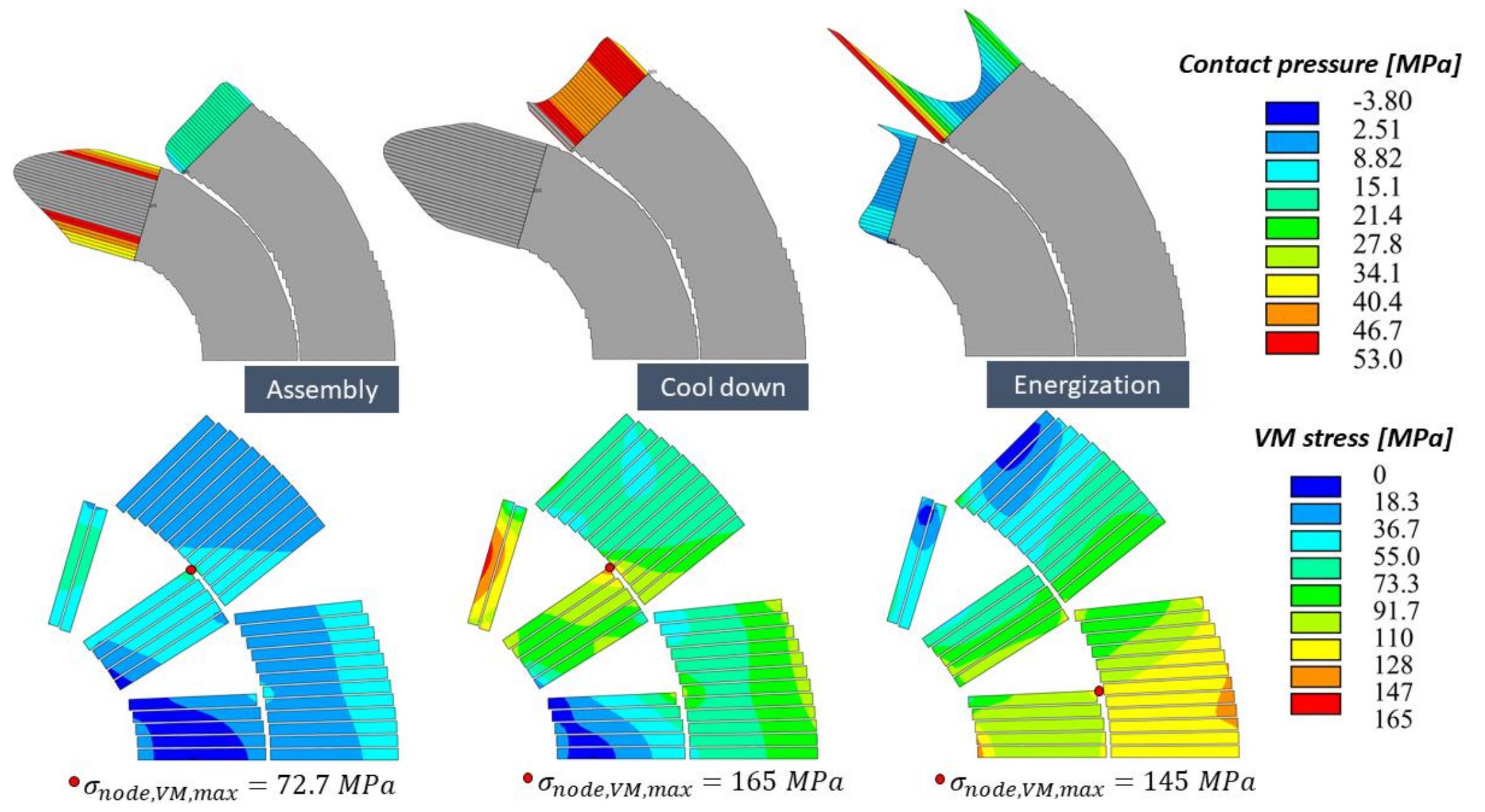
Layout of the mechanical structure

Mechanical properties of the materials at 293 K and (at 1.9 K)

Material	Stress limit [MPa]	E [GPa]	ν	$\alpha \cdot 10^{-3}$
Conductors	150 (150)	25 (25)	0.30	3.80
Copper wedges	270 (>300)	100 (110)	0.30	3.37
SS pad	350 (1050)	191 (210)	0.28	2.80
Al7075 shell	480 (690)	72 (79)	0.30	4.20
Iron yoke	230 (720)	204 (225)	0.28	2.00
Ti6Al4V pole	800 (1650)	115 (127)	0.30	1.70
Fiberglass	150 (150)	25 (27.5)	0.20	2.50



Contact pressure and Von Mises stress distribution [MPa]: after assembly, cool down and energization at 12 T

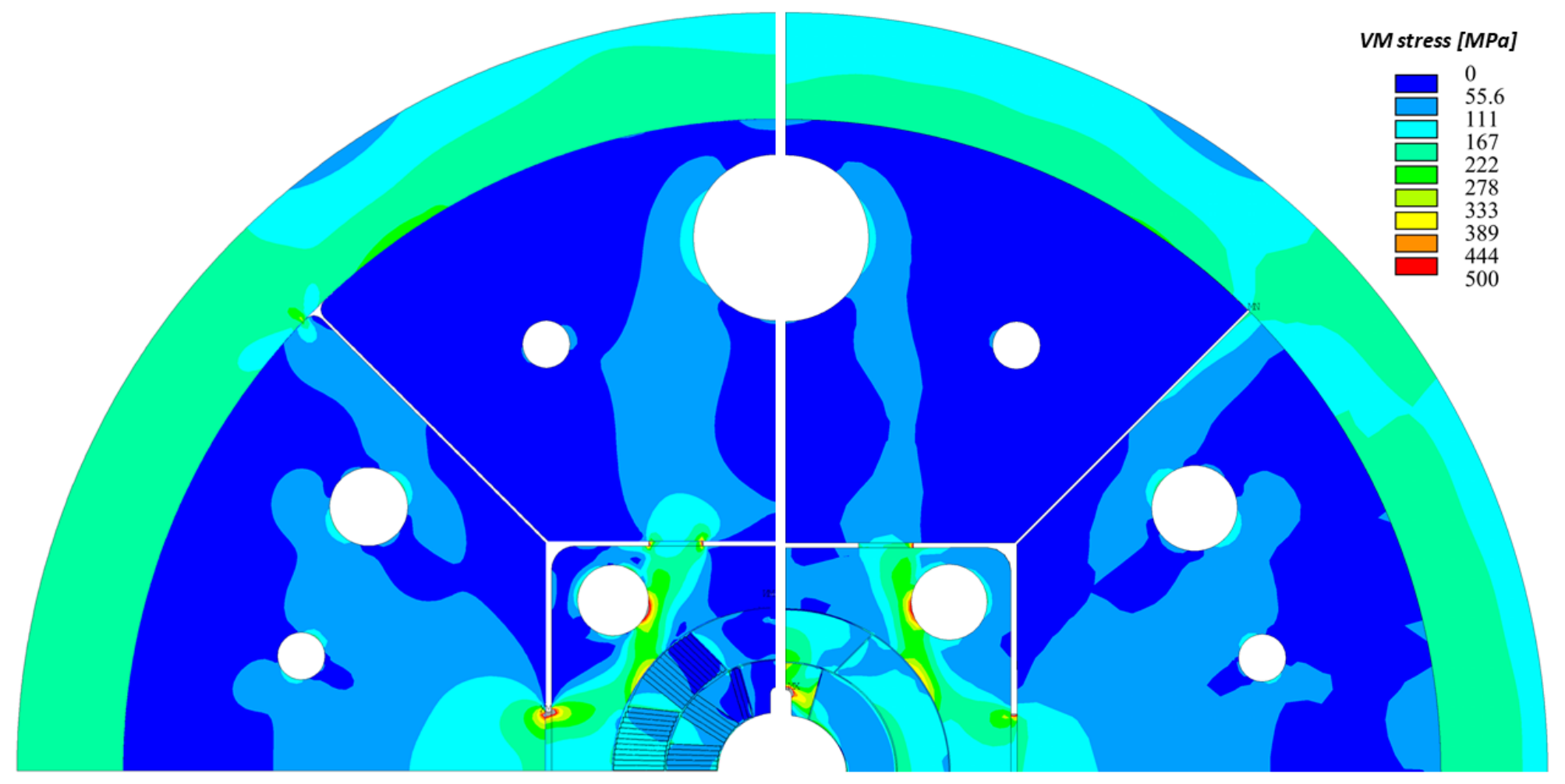


Contact pressure and Von Mises stress distribution [MPa]: after assembly, cool down and energization at 14 T

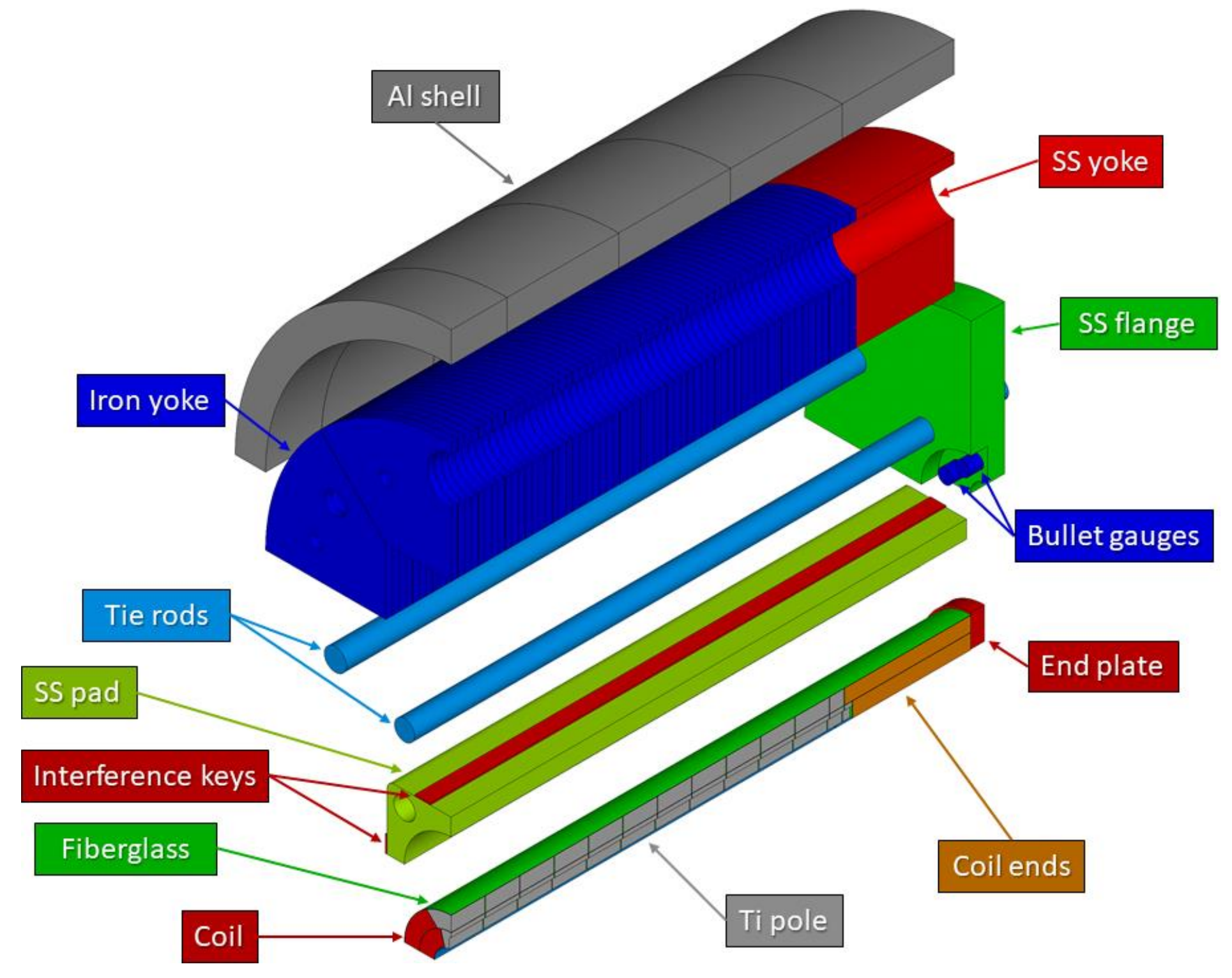
- ***12 T*** configuration: the requirements are totally fulfilled
- ***14 T*** configuration: meets the requirement imposed on the contact pressure but it slightly exceeds the 150 MPa limit of Von Mises stress in the conductors
- ***the 150 MPa limit is set for the nominal case***, which is the main target of the project, while the 14 T one is only meant to explore more stringent conditions

3D MECHANICAL ANALYSIS

The main goals of the 3D analysis are to get confirmations of the 2D analysis results and to explore the longitudinal behavior of the magnet system. Due to the intrinsic complexity of the 3D design, the finite element model necessarily contains several ***simplifications***, among which: the coil is divided into straight part and coil end and all mechanically negligible shapes are removed. The ***longitudinal pre-stress*** is provided by eight tie-rods, four of which are 30 mm thick acting on the SS pad , while the other four are 36 mm in diameter inserted in the iron yoke. Basically, the idea is that the longitudinal pre-load should ***limit the coil end movements*** between cool down and powering within a safe limit. It is required that the pre-load is large enough to ensure that the coil end is held under compression during powering. From the simulations it results that it is sufficient applying a pre-load up to ***25%*** of the longitudinal Lorentz force for the ***12 T*** configuration. On the other hand, for the ***14 T*** configuration is necessary to provide a pre-load of ***50%*** of the Lorentz force.



Von Mises stress distribution [MPa] in the cross section at energization in the 14 T configuration. On the left there is the 2D model and on the right the 3D one



Layout of the 3D mechanical structure

Average Young moduli, shear moduli and thermal contraction coefficients of coil’s straight part and coil ends at 293 K and (at 1.9 K)

Coil straight part	E_r [GPa]	E_θ [GPa]	E_z [GPa]	$G_{\theta z}$ [GPa]	G_{rz} [GPa]	$G_{r\theta}$ [GPa]	α_r [mm/m]	α_θ [mm/m]	α_z [mm/m]
Layer 1	53.7 (57.5)	39.7 (40.4)	53.2 (57.0)	21.4	15.4	21.2	3.49	3.59	3.49
Layer 2	34.3 (35.6)	39.8 (40.5)	34.1 (35.3)	13.4	15.5	13.4	3.64	3.59	3.57

Coil ends	E [GPa]	α [mm/m]
Layer 1	73.3 (78.2)	3.08
Layer 2	44.9 (46.6)	3.23

Average stress in each component of the cross section at assembly, cool down and energization, both at 12 T and 14 T

	12 T [MPa]		14 T [MPa]	
Assembly	2D	3D straight	2D	3D straight
σ_{avg} Al shell	37.2	35.9	58.6	56.3
σ_{avg} iron yoke	14.2	13.6	22.9	22.0
σ_{avg} SS pad	27.5	25.0	42.9	36.4
σ_{avg} Ti pole	35.9	28.2	59.6	44.4
σ_{avg} layer 1	23.6	19.2	39.5	32.2
σ_{avg} layer 2	21.0	28.7	34.9	44.1

	12 T [MPa]		14 T [MPa]	
Cool down	2D	3D straight	2D	3D straight
σ_{avg} Al shell	152.0	144.3	173.6	164.0
σ_{avg} iron yoke	41.0	40.5	48.1	47.9
σ_{avg} SS pad	100.9	106.0	112.5	112.5
σ_{avg} Ti pole	107.3	118.8	139.7	137.1
σ_{avg} layer 1	63.8	68.5	84.6	81.6
σ_{avg} layer 2	55.4	89.8	74.2	111.0

	12 T [MPa]		14 T [MPa]	
Cool down	2D	3D straight	2D	3D straight
σ_{avg} Al shell	153.5	144.5	177.4	167.0
σ_{avg} iron yoke	44.9	42.1	53.2	50.6
σ_{avg} SS pad	101.9	114.2	114.0	125.5
σ_{avg} Ti pole	48.0	145.7	53.7	172.2
σ_{avg} layer 1	66.0	76.7	82.1	91.4
σ_{avg} layer 2	68.1	107.7	88.8	132.5

- The differences between the calculation of the 2D and 3D models are ***within a range of 15 MPa*** in each simulated step, which is an acceptable agreement considering the different approximation that differentiate the two models
- To be noticed that at cool down and energization the difference between the average Von Mises stress in the Ti pole and in the second layer of the winding is pretty large. It has been verified that these discrepancies are not due to some kind of modeling error in the 3D model but they are linked to the approximation done in considering the 2D model as infinitely thin (i.e. working in ***plane stress approximation***)

CONCLUSION

The mechanical structure of FalconD has been optimized in order to ***properly work*** both at the target central magnetic field of ***12 T*** and at the ultimate bore field of ***14 T***. The mechanical structure has been designed using the ***B&K*** concept, which supply the proper pre-stress to counterbalance the azimuthal Lorentz forces after energization with excellent results at 12 T and almost acceptable results at 14 T for what concern the stress management of the straight part of the Falcon Dipole.

In order to cope with the ***longitudinal*** Lorentz forces it has been designed an effective ***pre-loading system*** consisting of eight tie-rods. From the 3D simulations turns out that supplying ***25%*** of the longitudinal Lorentz forces to the ***12 T*** configuration and ***50%*** to the ***14 T*** one is sufficient to guarantee the correct operation of the magnet. Moreover it has been possible to validate both the 2D and 3D models through a cross check of the mechanical results.