Short Model Coils project:

Magneto-mechanical optimization and realization of a subscale Nb$_3$Sn high-field dipole magnet

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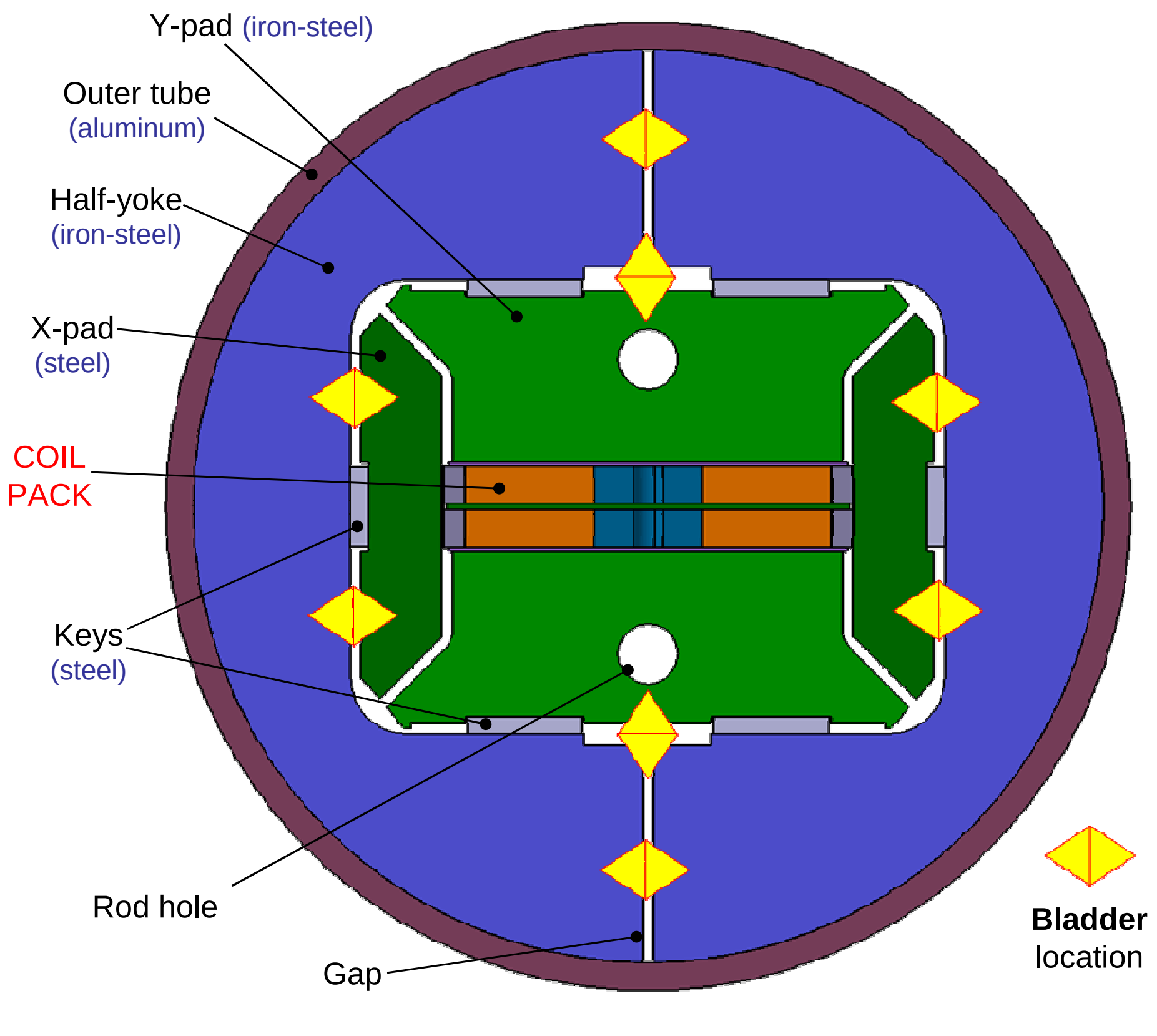
The goal of the "SMC" program is to design, manufacture and test 13 T Nb$_3$Sn subscale accelerator coils in dipole configuration. An adapted support structure is used to perform training studies while investigating the pre-stress influence on coil behaviour and quench triggering. Such a system should help define the mechanical stress limit on different coil pack configurations with innovative insulations. The initial magnetic optimization phase has led to validate the coil pack properties and the corresponding field. The mechanical design phase has led to an efficient support structure managing the coil stresses while providing a variable preload.

►Accelerators are key tools for particle physics. To reach the very high magnetic fields required to produce the high energies of collision, superconducting materials are used. Future LHC upgrades requiring higher fields in larger apertures will demand the use of a superconductor with greater performance than NbTi. The use of Nb$_3$Sn is one possibility, allowing peak fields in the conductor up to 24 T. However, this material remains very sensitive to mechanical constraints. Its upper stress limit is estimated around 150 MPa, but is not precisely known.

►The goal of the SMC project is to create a 13 T subscale Nb$_3$Sn coil and its testing device. To that aim, SMC will utilize the experience of Berkeley's SD01 coil which is pre-stressed by a shell-based structure using bladders and keys.



OVERVIEW OF THE SMC STRUCTURE

►Part of the pre-stress is applied during cool-down by the aluminum shell and of the axial rods

►The remainder is applied by water-inflated stainless steel bladders replaced by steel keys when target pre-stress level achieved

►This architecture should enable us to reach very high and well-controlled pre-stresses in the three directions

We will focus on the axial (X) and longitudinal (Z) stresses: Y-bladders play a positioning role

HIGHLIGHTS

COIL

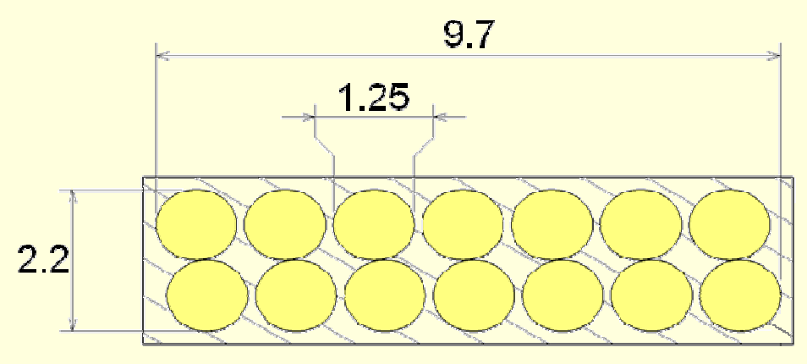
Type: Superconducting Dipole
Shape: 2 Double-pancake racetracks
Dimensions: 420 x 190 x 42 mm

PERFORMANCES

Peak Field: 13 T on conductor
Target current: 14 kA
Working Temperature: 4.2 K
Forces: 2 MN.m^{-1} on straight section (X)
Stored Energy: 200 kJ

CONDUCTOR CABLE

Material: Nb$_3$Sn (IT)
J_c: initial 1700 A.mm^{-2} target 2500 A.mm^{-2}
Cable length: 75 m
Estimated stress limit: 150 Mpa
Insulation: Epoxy + matrix or Ceramic
Dimensions:



MAGNETIC OPTIMIZATION

►Magnetic optimization has been cross-check between:
3 laboratories (CEA, CERN and RAL)
3 codes (CAST3M, ANSYS, Vector Fields)

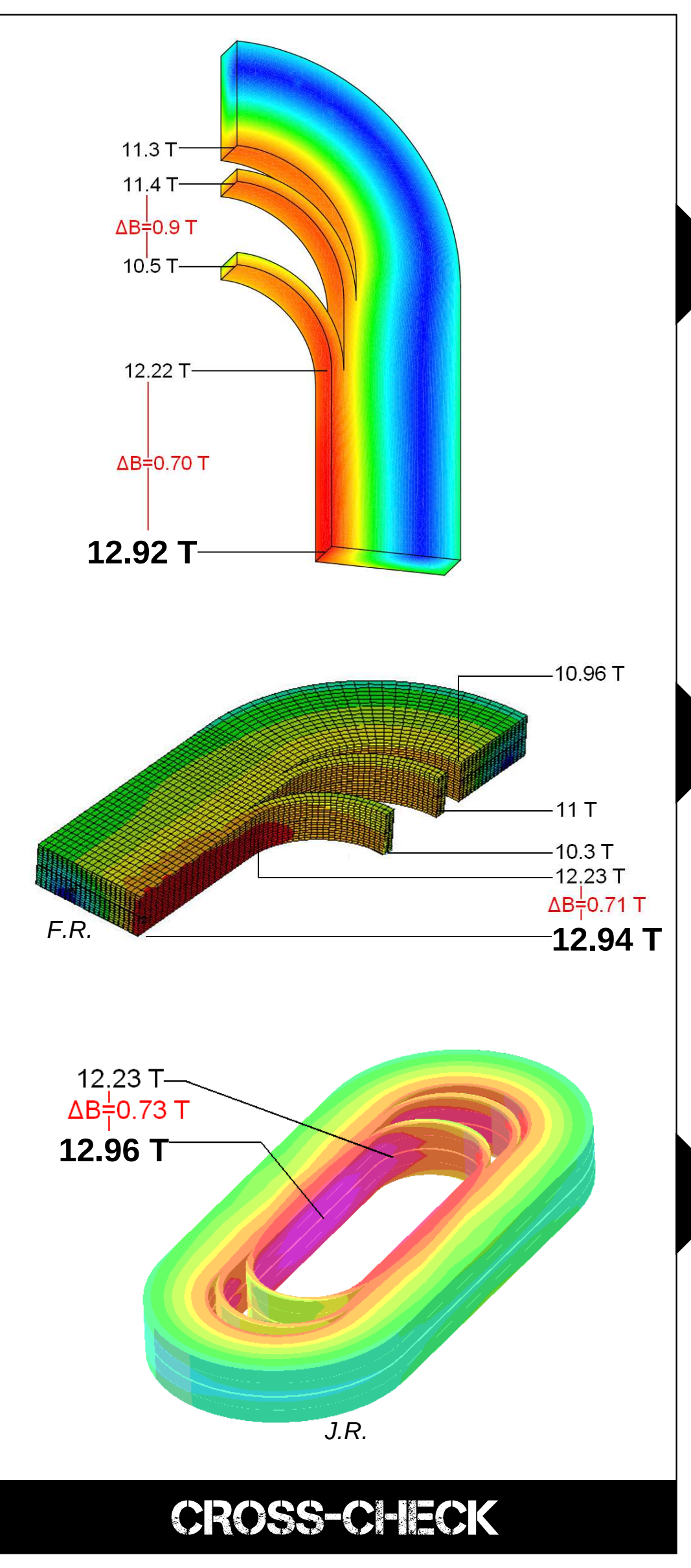
►First computations have been performed in 3D without iron to get the baseline coil features. Non-linear effects (iron saturation and short sample conductor behavior) have been added then. **The cross-check has showed an excellent agreement between all codes and formulas.**

►To reach our specifications, the difficult point has been to move the peak magnetic field to the center of the straight section. This has been made possible by **end spacers** (two on each end) and by **iron surrounding parts**.

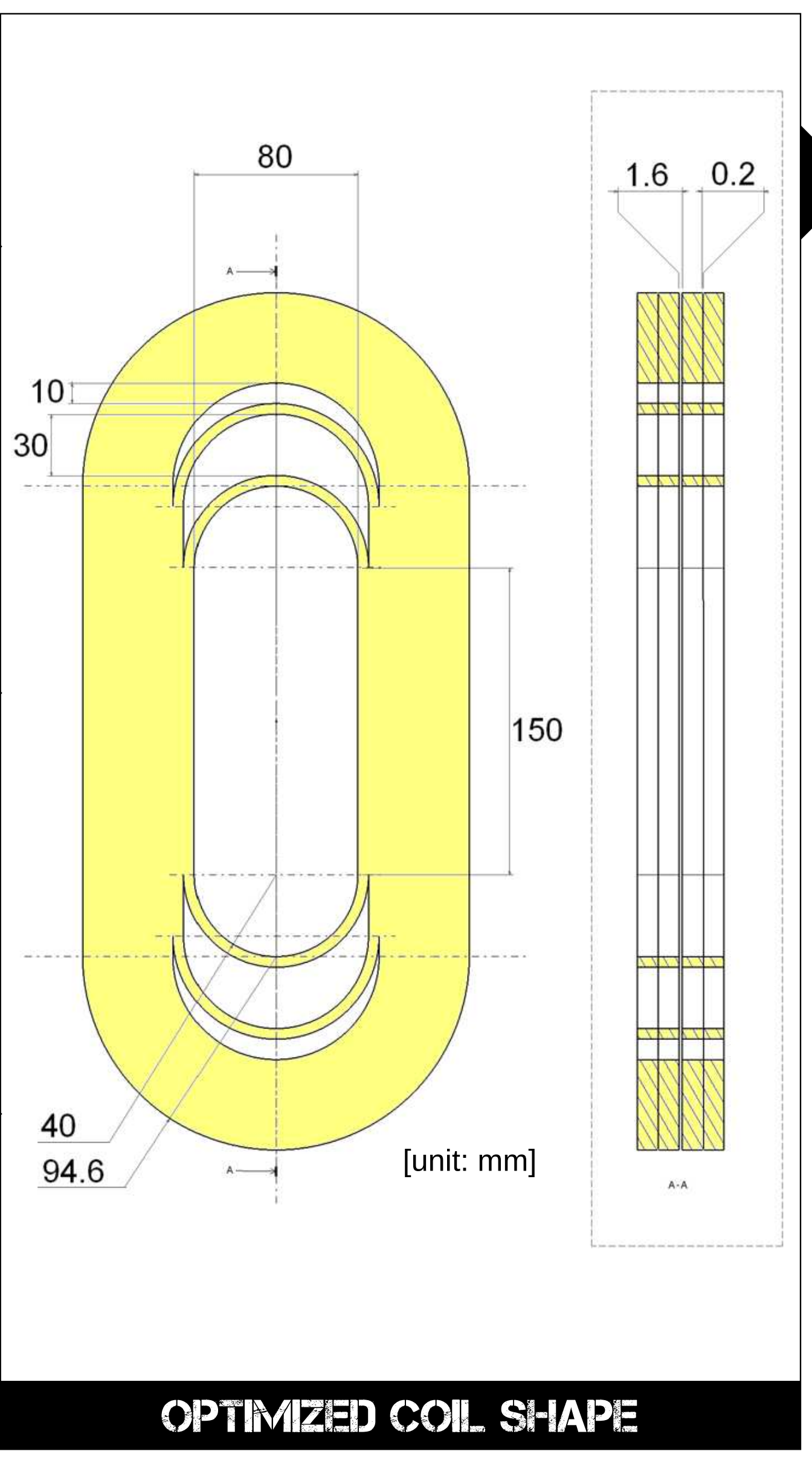
Magnetic Specifications		
Peak field	B_{max}	**~ 13 T in straight section**
B_{ss} - B_{end}	ΔB_{ss}	≥ 0.5 T
Uniform field zone length	$L_u^{1\%}$	~ 60 mm
Central field	B_0	none
Target current	I_{ss}	≤ 20 kA

MAGNETIC SPECIFICATION

MODELLING



CROSS-CHECK



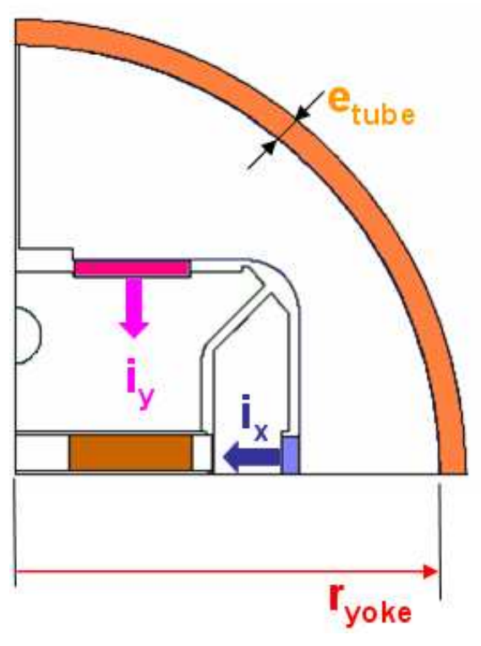
OPTIMIZED COIL SHAPE

		Magnetic Model Results				
		CAST3M	ANSYS MVP	ANSYS MSP	Vector Fields	
Peak field	B_{max}	**12.92 T**	**12.85 T**	**12.94 T**	**12.96 T**	✓
B_{ss} - B_{end}	ΔB_{ss}	0.70 T	0.71 T	0.71 T	0.73 T	✓
Uniform field zone length	$L_u^{1\%}$	~ 70 mm	~ 55 mm	~ 55 mm	~ 60 mm	✓
Central field	B_0	9.93 T	9.85 T	9.65 T	NC	✓
Target current	I_{ss}	14.01 kA	14.25 kA	13.96 kA	14.00 kA	✓

MAGNETIC OPTIMIZATION RESULTS

WINDING TRIALS

MECHANICAL OPTIMIZATION

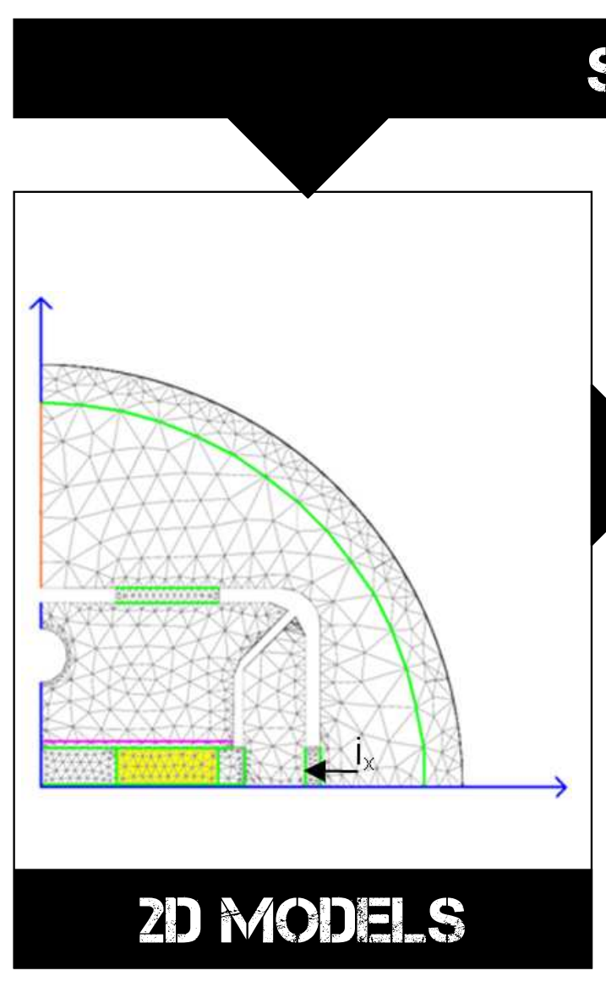


►Managing the very high forces on coil supposes very accurate mechanical models

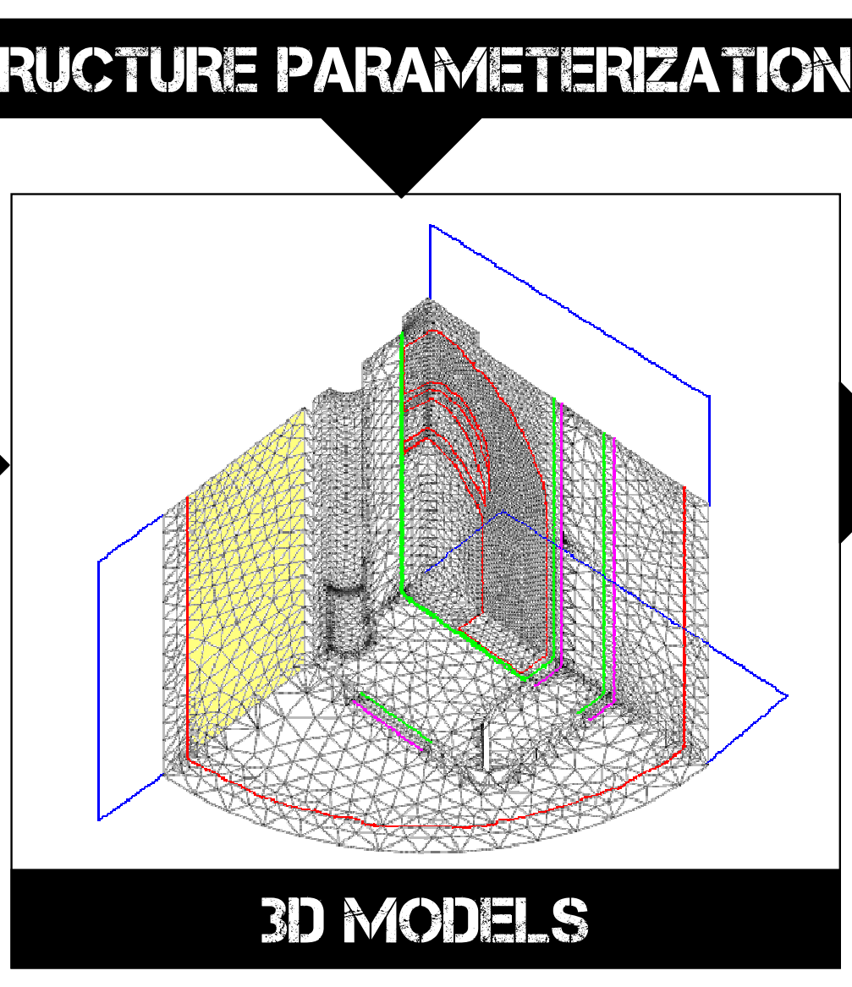
►The overall behavior of the structure can be precisely described by a few parameters:

- e_{tube} = tube thickness
- r_{yoke} = yoke radius
- i_x, i_y = bladder pre-stress
- i_z: rods + piston pre-stress (3D)

STRUCTURE PARAMETERIZATION



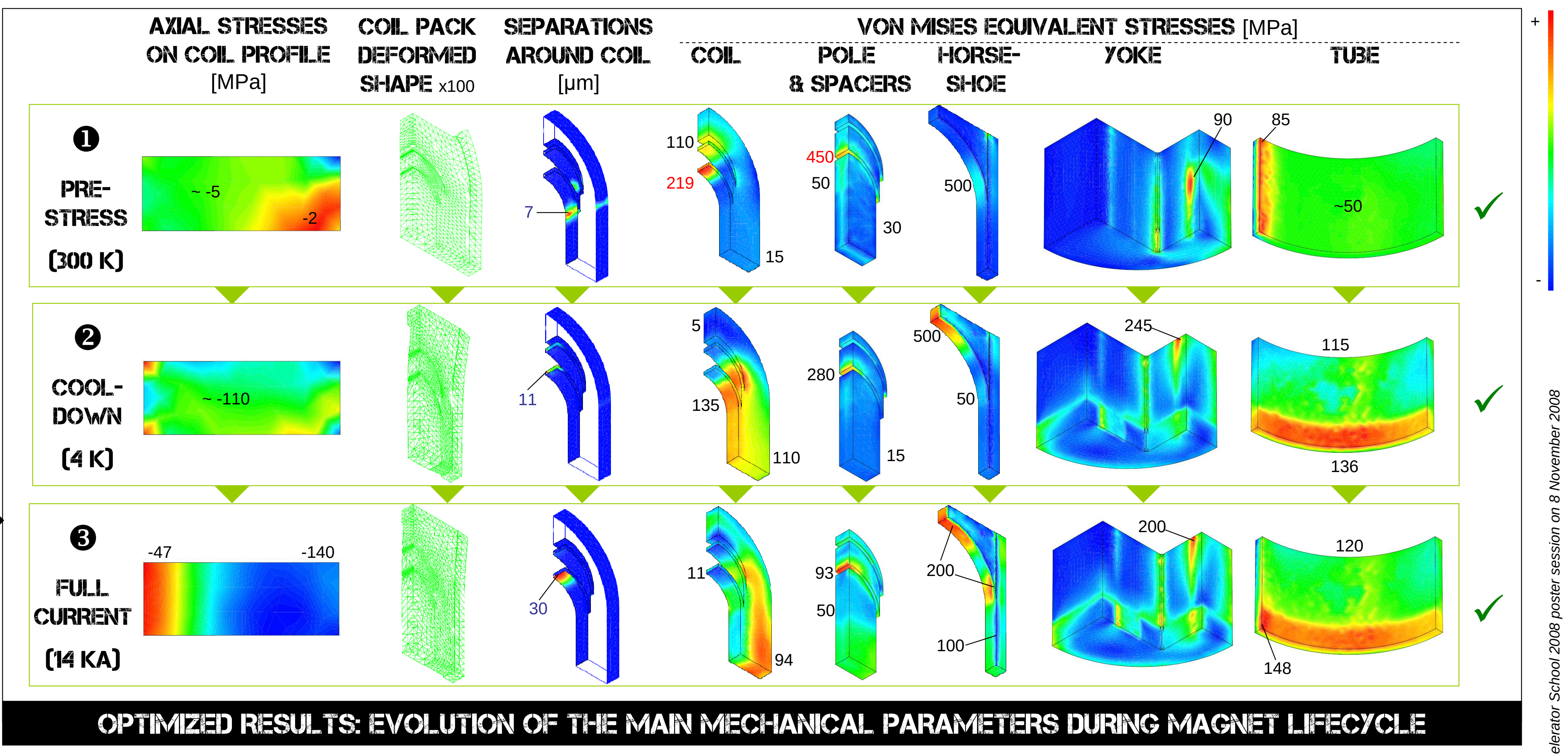
2D MODELS



3D MODELS

Parameters	
e_{tube}	20 mm
r_{yoke}	250 mm
i_x	300 µm
i_y	0 µm
i_z	500 µm

RESULTS



OPTIMIZED RESULTS: EVOLUTION OF THE MAIN MECHANICAL PARAMETERS DURING MAGNET LIFECYCLE

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REFERENCES

Tech. Note on Magnetic Design, P. Manil, F. Regis, J. Rochford *et al.*, 2008
Tech. Note on Mechanical Design, P. Manil, F. Regis *et al.*, 2009

The shared magnetic computations have enabled us to define an efficient magnet shape to reach our specifications. The mechanical design has led to a structure able to apply very high and well-controlled stresses on the coil while keeping every part of the assembly safe. This 18-months theoretical phase has been a collective success.

The SMC structure has now been built and is waiting for the last winding trials before starting the real tests.

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