Design Studies, Magnetic and Structural calculations for a DEMO hybrid CS proposal

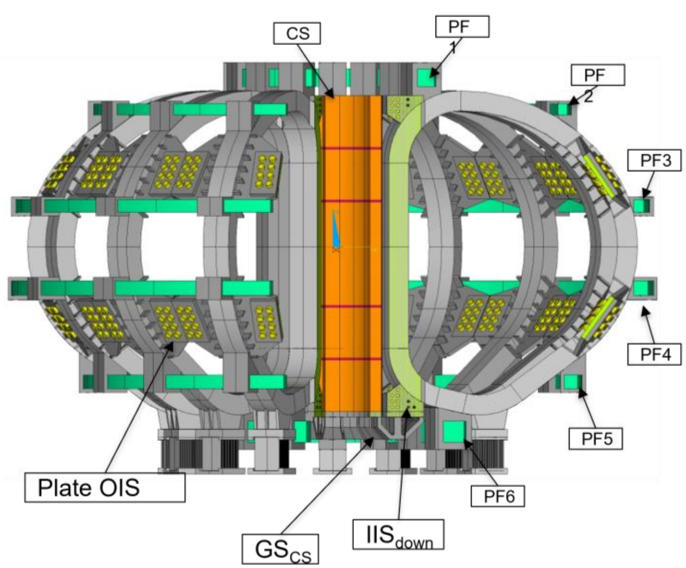
L. Giannini, L. Muzzi, A. Di Zenobio, G. Romanelli, L. Zoboli, G. De Marzi, S. Turtù, G. Celentano and A. della Corte

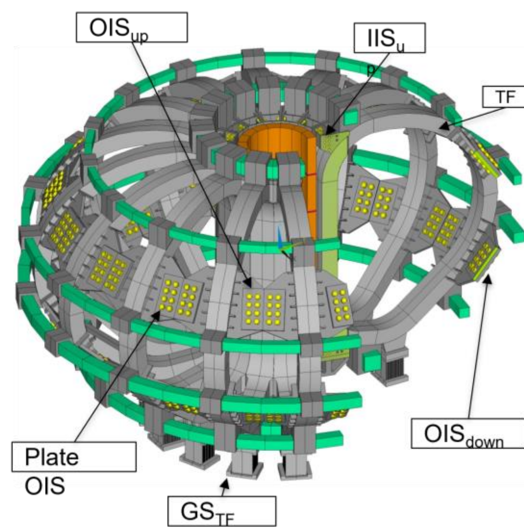
ENEA, Superconductivity Laboratory, C.R. Frascati, Italy

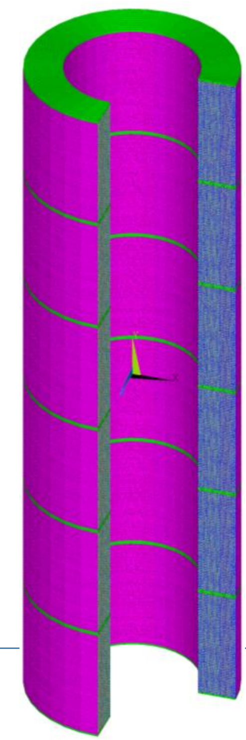
Corresponding author: lorenzo.giannini@enea.it

Introduction

- The ENEA design proposal is based on a **layer wound graded design**, comprising for each CS module a HTS, a LTS High Field, a LTS Medium Field and a LTS Low Field sub-module
- Among the different CICC design options being considered, a new possibility is proposed identified with the acronym RRIS (**Round-in-Round-In-Square**): a circular insulated jacket is inserted in an external rectangular 316LN structure and protected with a ceramic insulation layer
- The proposed solution aims to obtain a cable capable of withstanding the intense electromagnetic loads generated during the DEMO plasma scenarios, preserving the CICC turn insulation integrity
- This work presents the updated solution generated via the ENEA Design Explorer algorithm







6 modules

4 Grades

CS Design Explorer Algorithm

Independent parameters:

- $n°_{Layers}(HTS, HF, MF, LF) = [2, 6]$
- $n°_{Turns}(HTS, HF, MF, LF) = [40, 70]$
- $I_{op} = [40, 100]\ kA$

Fixed parameters for the stack:

- $Re_{CS} = 2.7\ m$
- $h_{module} = 2.9\ m$
- $h_{spacers} = 0.1\ m$
- $N_{modules} = 6$
- Ground Insulation $= 5 - 10\ mm$

Fixed parameters for the LTS cable:

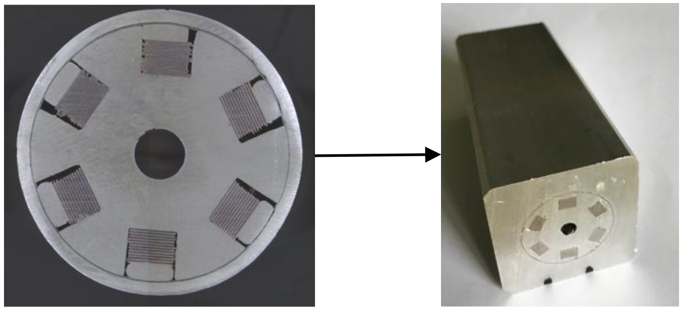
- $d_{Nb_3Sn\ wire} = 0.82/1\ mm$
- $\cos(\theta)_{Nb_3Sn\ wire} = 0.97$
- $r_{cooling\ channel} = 5\ mm$
- n_{strand} for the triplets = {1500 1440 1350 1296 1200 1152 1080 972 960 900 864 810 768 720 675 648 540 486 360 324 300 216 180 162 144}
- Cu: nonCu = 1, Ref. strand $J_c(6.5K; 12T; -0.6\%) \sim 320 \frac{A}{mm^2}$

Fixed parameters for the HTS cable:

- ENEA design with a 4 or 6 slotted core for the REBCO tapes
- From the ENEA sample the current density for the Al stabilizer (core) is $J_{Al} = 50 \frac{A}{mm^2}$ at 18 T
- The superconducting critical current density is set as a function of the peak field at 4.2 K from tipical commercial tape data

LTS cable

HTS cable



Design Explorer LTS cable

- $B_{LF} = \frac{n^{\circ}_{Turns} n^{\circ}_{Layers} i_{op} \mu_0}{h_{module} N_{modules}}$
- $B_{MF} = \frac{n^{\circ}_{Turns} n^{\circ}_{Layers} i_{op} \mu_0}{h_{module} N_{modules}} + B_{LF}$
- $B_{HF} = \frac{n^{\circ}_{Turns} n^{\circ}_{Layers} i_{op} \mu_0}{h_{module} N_{modules}} + B_{LF} + B_{MF}$

$$Ic_{sc} = f(B) \rightarrow N_{sc} = \frac{I_{op}}{I_{sc}} \rightarrow S_{Cu} = \frac{1}{2}\frac{(N_{sc}\pi\, d_{fili}^2)}{2}$$

$$\text{If } J_{Cu} = \frac{I_{op}}{S_{Cu}} < 140\,\frac{A}{mm^2} \rightarrow N_{cu} = \frac{4}{(\pi\, d_{fili}^2)^{0.5}}\left(\frac{I_{op}}{J_{Cu}} - S_{Cu}\right)$$

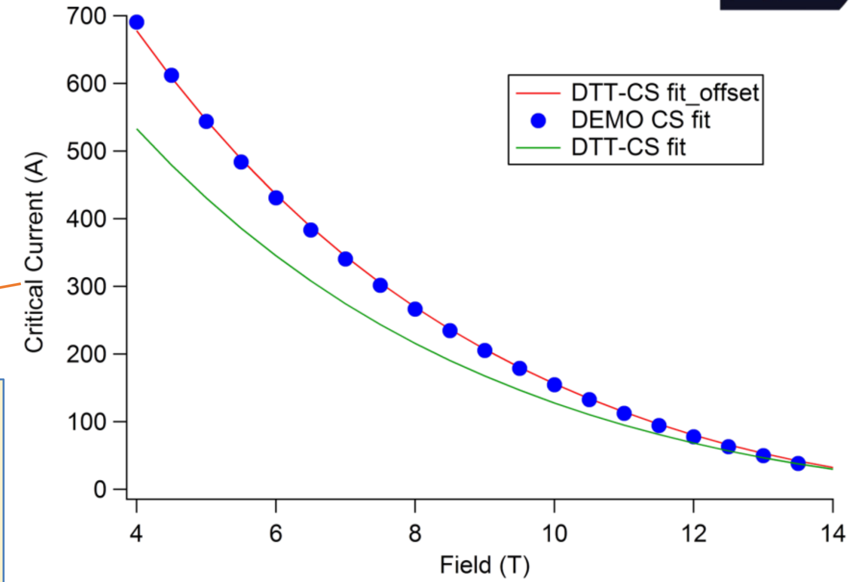
$$\rightarrow N_{tot} = N_{Cu} + N_{sc}$$

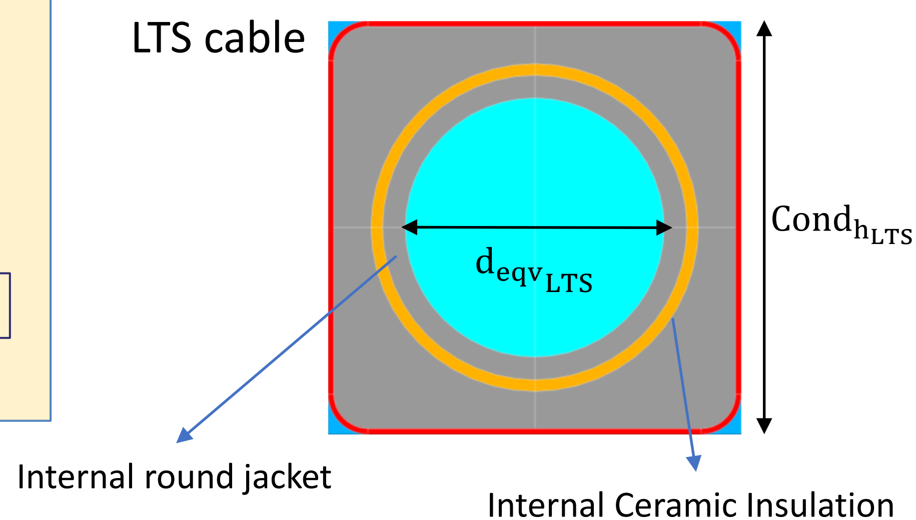
$$A_{cable_{LTS}} = \pi\left(\frac{N_{tot} d_{fili}^2}{4\cos(\theta)\, VF} + r_{cc}^2\right)$$

$$d_{h_{LTS}} = \left(\frac{4\, A_{cable_{LTS}}}{\pi}\right)^{0.5}$$

$$Cond_{h_{LTS}} = \frac{h_{module}}{n^{\circ}_{Turns}}$$

From LF to HF submodule





Design Explorer HTS cable

$$B_{HTS} = \frac{n^{\circ}_{Turns} n^{\circ}_{Layers} i_{op} \mu_0}{h_{module} N_{modules}} + B_{LF} + B_{MF} + B_{HF}$$

$$A_{HTS} = \frac{I_{op}}{J_{Al}} + \pi r_{cc}^2 + \frac{I_{op}}{J_{REBCO}}$$

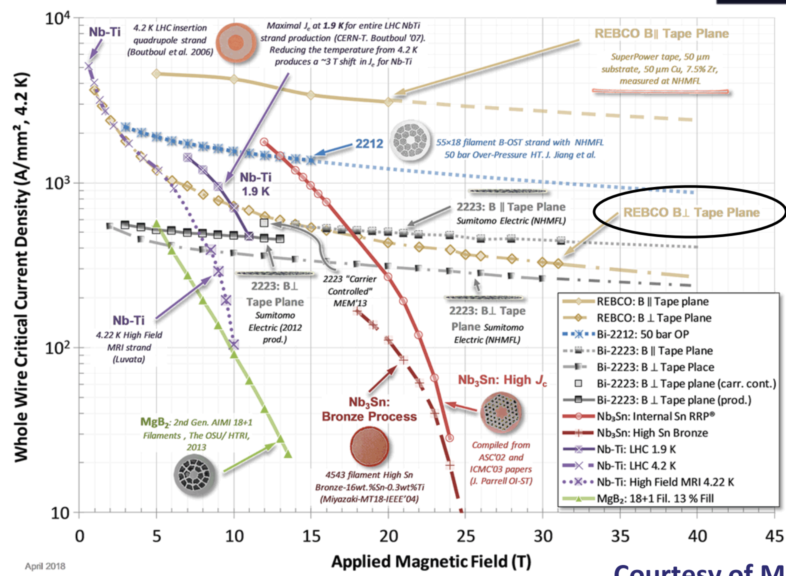
$$d_{eqv_{HTS}} = \left(\frac{4\,A_{HTS}}{\pi}\right)^{0.5}$$

$$A_{wr} = \left(\left(d_{eqv_{HTS}} + t_{rj}\right)^2 - \left(d_{eqv_{HTS}}\right)^2\right)\frac{\pi}{4}$$

$$A_{cable_{HTS}} = A_{HTS} + A_{wr}$$

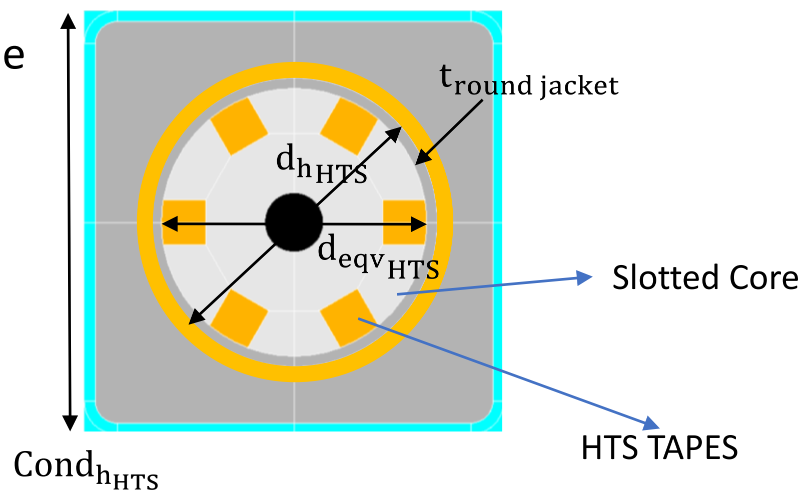
$$d_{h_{HTS}} = \left(\frac{4\,A_{cable_{HTS}}}{\pi}\right)^{0.5}$$

$$Cond_{h_{HTS}} = \frac{h_{module}}{n^{\circ}_{Turns}}$$



Courtesy of Maglab fsu

HTS cable



Design Explorer – layout definition

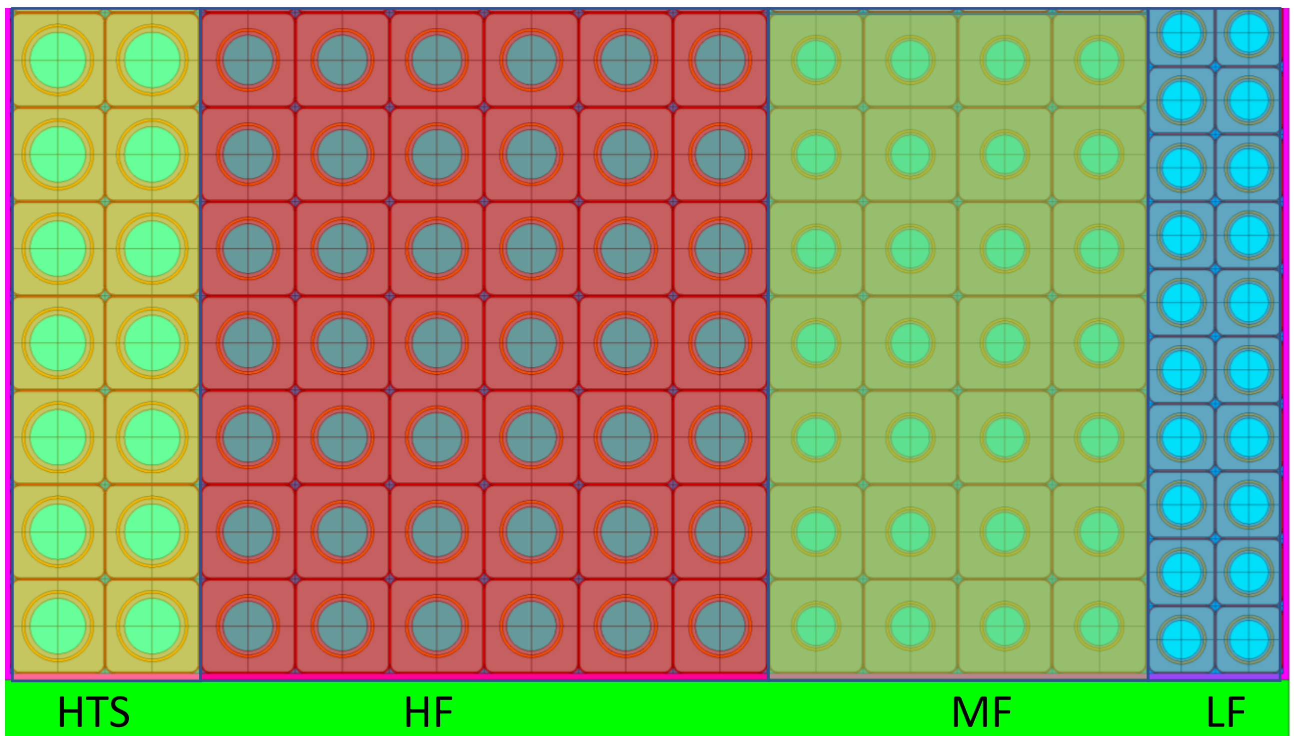
Once the cable widths of each submodule are calculated, starting from Re(CS) we have:

$$Ri_{HTS} = Ri_{HF} - (N_{layer_{HTS}} Cond_{w_{HTS}})$$

$$Ri_{HF} = Ri_{MF} - (N_{layer_{HF}} Cond_{w_{HF}})$$

$$Ri_{MF} = Ri_{LF} - (N_{layer_{MF}} Cond_{w_{MF}})$$

$$Ri_{LF} = Re_{CS} - Grnd_{ins} - (N_{layer_{LF}} Cond_{w_{LF}})$$



Hot Spot temperature analysis

The operative current and the dimension are fixed, the program checks:

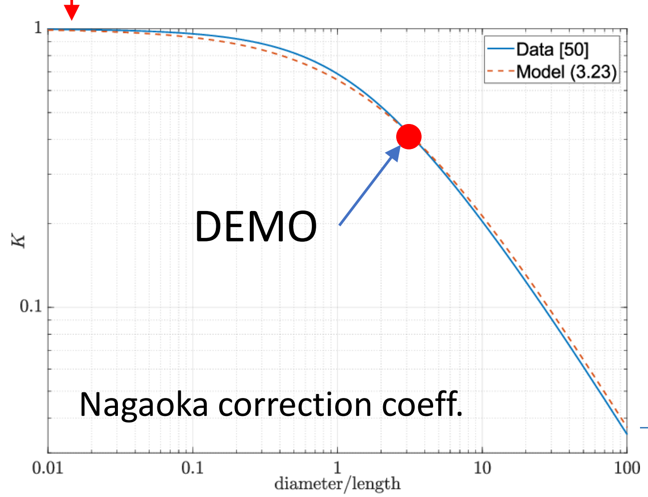
Non-segregated — Segregated

$$A_{Cu} = \frac{1}{2}\pi N_{Cu}\frac{d^2_{Cu\,wire}}{4} + \frac{1}{2}\pi N_{Nb_3Sn}\frac{d^2_{Nb_3Snwire}}{4}$$

$$\rightarrow\ J_{Cu} = \frac{i_{op}}{A_{Cu}}$$

Considering a discharge $V_{MAX} < 10\ \mathrm{kV}$

$$L = \frac{N^2\pi R_m^2\mu_0}{k\ h_{module}} \rightarrow \tau_{discharge} = \frac{L\ i_{op}}{V_{MAX}}$$



The quench initiating point, computed within a simplified adiabatic approximation: in a zero-dimensional model, the local balance between heat generation, through Joule dissipation, and heat absorption, through materials heat capacities is calculated (Wilson 1971):

$$J^2_{Cu}(t)\ \rho_{Cu}(B,T)dt = \left(\sum_i C_i(T)\ \gamma_i f_i\right) dT$$

quantities are averaged over the cross section:

C_i(T) : specific heats of the different materials in the cable
γ_i : materials densities; **f_i** materials fraction in the cross section
Above **T_{cs}**, all current flows in copper:
J_{Cu}(t): Cu current density;
ρ_{Cu}(B,T): temperature and magnetic field dependent Cu resistivity
RRR=100 → copper inside superconducting strands
RRR=300 → segregated copper strands

When only superconductor and Cu are considered, the limit for a CICC undergoing a quench, as specified by ITER design criteria is: **$T_{hotspot}$<250 K**

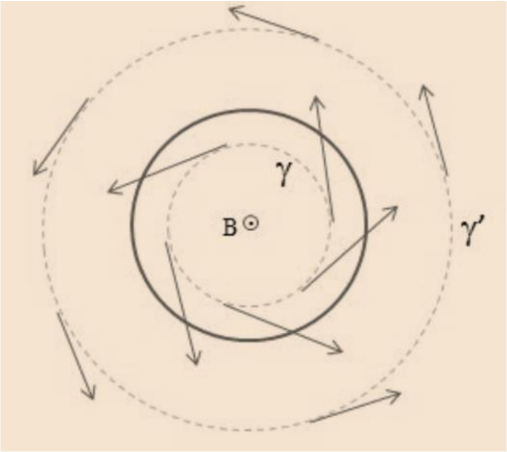
Design Parameters – Analitycal Definition

The magnetic flux can be obtained by integrating the Ampere's law from the outer to inner radius for each submodule:

$$\Phi_B = \left(R_\gamma^2 + R_{\gamma'}^2 + R_\gamma R_{\gamma'}\right) \frac{\pi B}{3}$$

Or can be obtained from the Maxwell relation with the vector potential formulation:

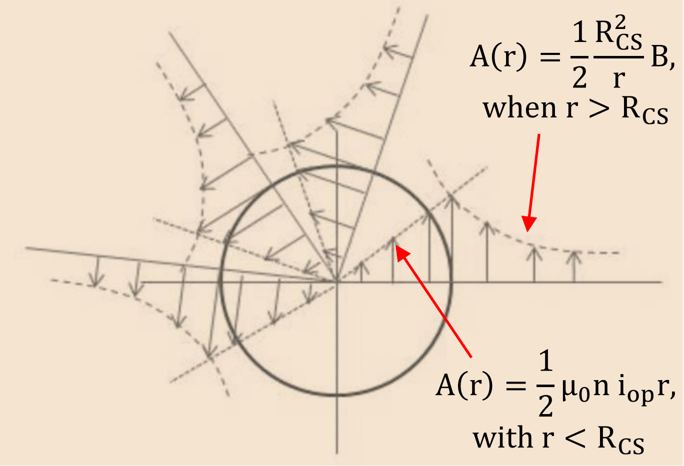
$$\Phi_B = 2\pi R_\gamma A(R_\gamma)$$



These value are compared with the outputs of the FEM simulations

To obtain the radial force exerted by each module, the Lorentz force can be interpreted as:

$$F_L = i_{op} N \int_0^{2\pi} R_\gamma \, d\theta \times B$$

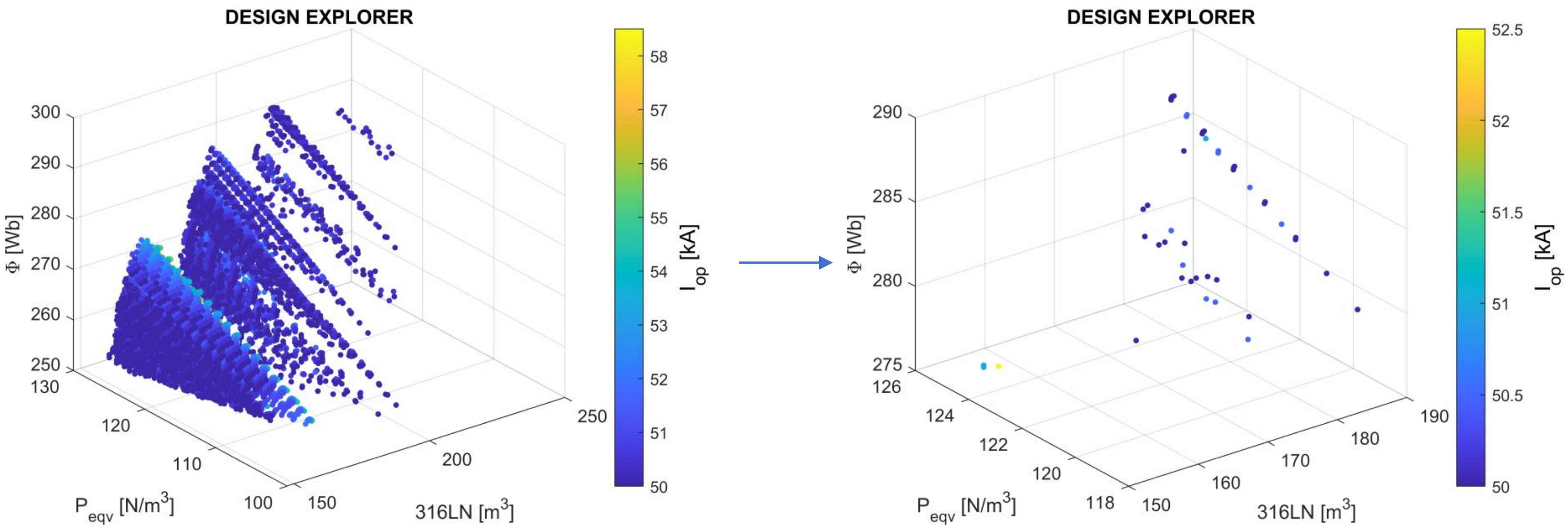


Design Parameters – Analitycal Definition

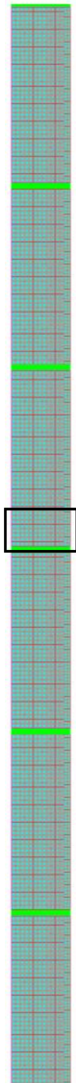
A down selection is done to obtain the optimal design in terms of average hoop stress on the CS cross-section

The design parameter combines the Lorentz force field with the steel volume allocated: $P_{eqv} = \frac{F_L}{V_{steel}}$

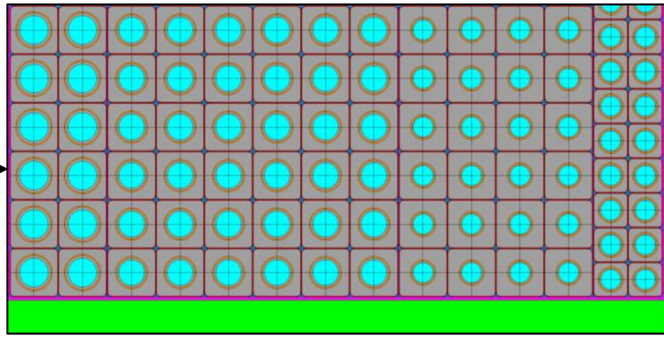
Examples of cloud of points which represent the feasible layouts. In the last iteration, the program also imposes a grading on the jacket thickness from the HTS to the LF sub-module:



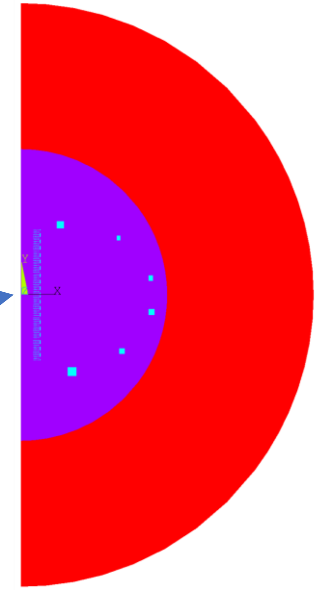
Link to the FEM calculations



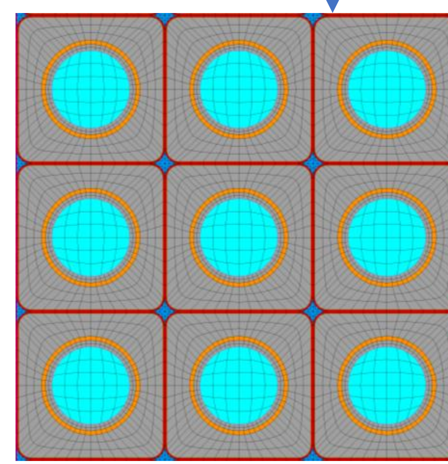
Design Selected



Electromagnetic model



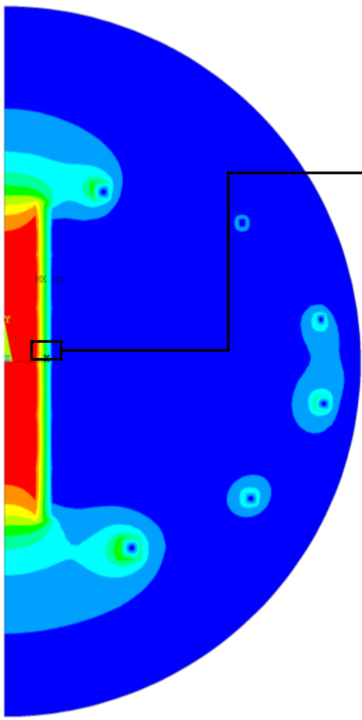
Structural model

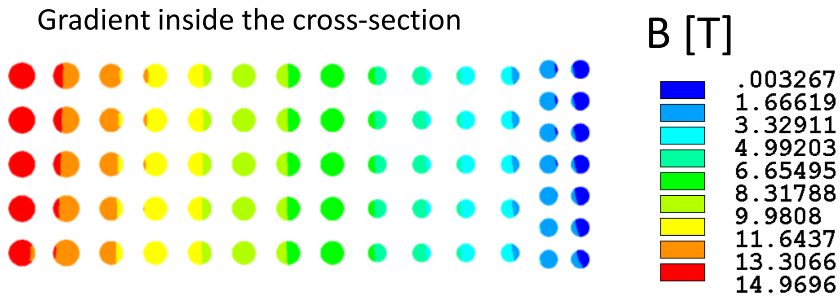


	HTS	HF	MF	LF
Operating current		59000 A		
Peak Field	14.71 T	12.73 T	6.76 T	2.78 T
Magnetic Flux	20 Wb	82 Wb	75 Wb	61 Wb
# of s.c. wires	-	972	162	144
# of Cu wires in CICC	-	51	456	465
HTS A cable	1430 mm^2	-	-	-
Jacket thickness	13.8 mm	16.0 mm	20.3 mm	10.1 mm
CICC dimensions	77.25 mm	77.25 mm	77.25 mm	51.60 mm
# of layers x turns	2 x 40	6 x 40	4 x 40	2 x 56
CS inductance		2.18 H (each module)		
T HS		105	120	93
Ri sub-module	1.72 m	1.86 m	2.3 m	2.6 m
Radial Force (avg)	521 MN	1570 MN	653 MN	203 MN

Electromagnetic calculation

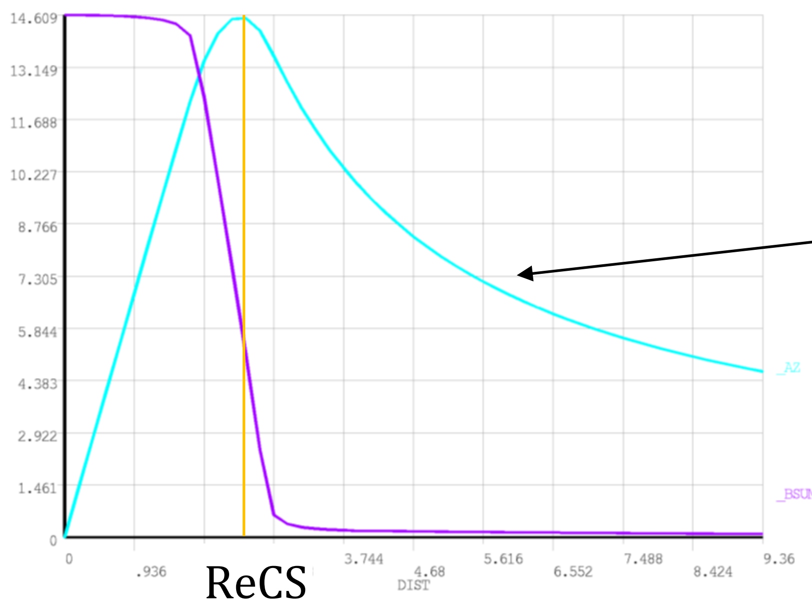
The electromagnetic model is a 2D axysimmetric based on the vector potential formulation representing the DEMO poloidal magnet system

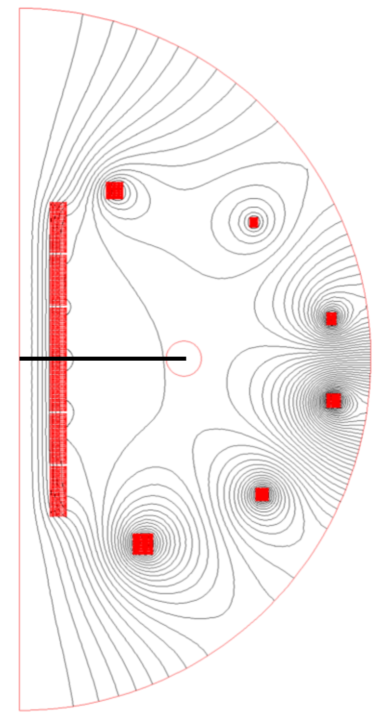




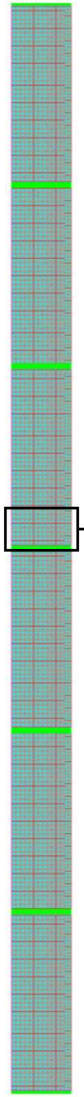
$\Phi_B(@\ \mathrm{ReCS}) = 238$ Wb

$\Phi_B(@\ \mathrm{R\ Plasma}) = 272$ Wb

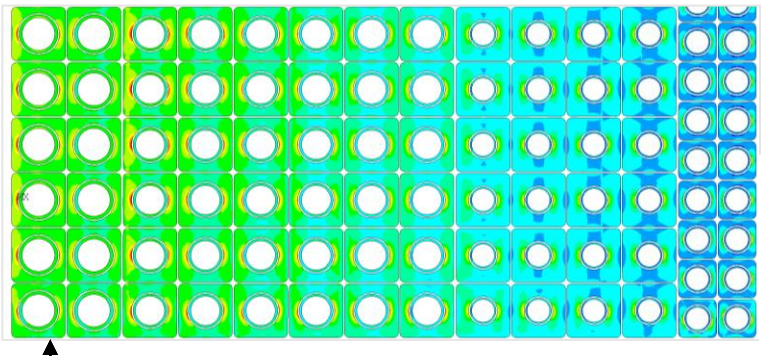




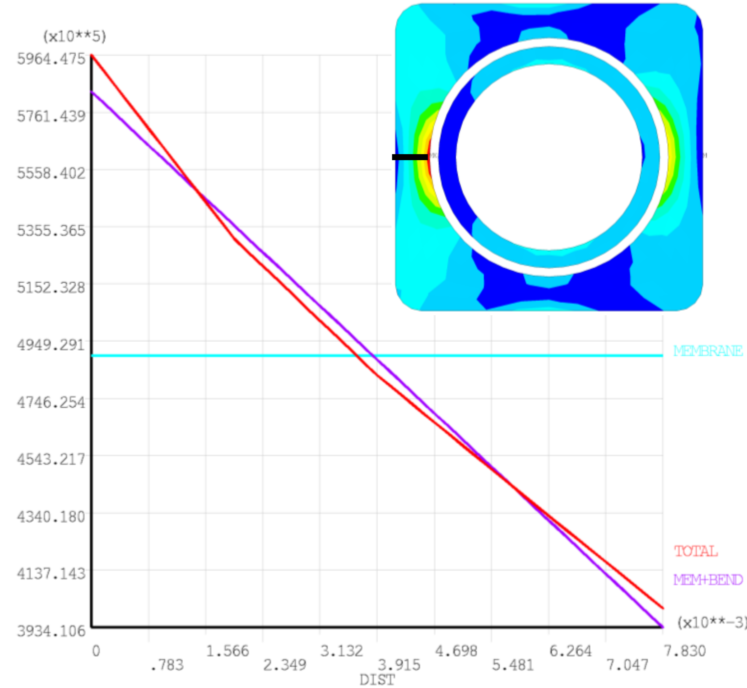
Static Assessment



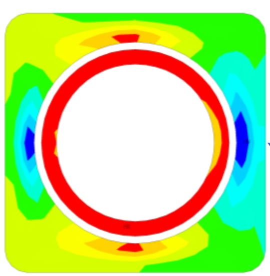
Stress Intensity

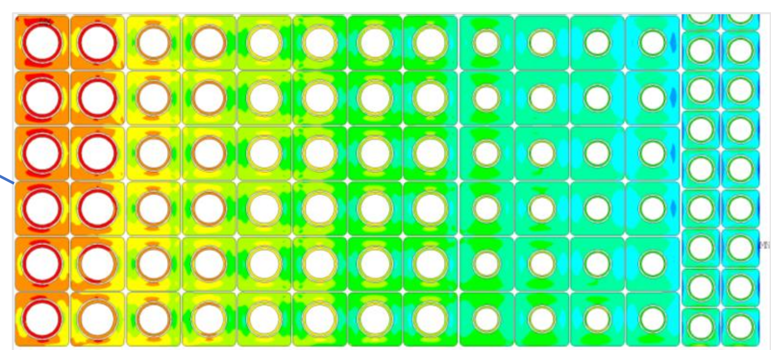


Pm = 494 MPa < 677 MPa
Pm+Pb=580 MPa < 867 MPa

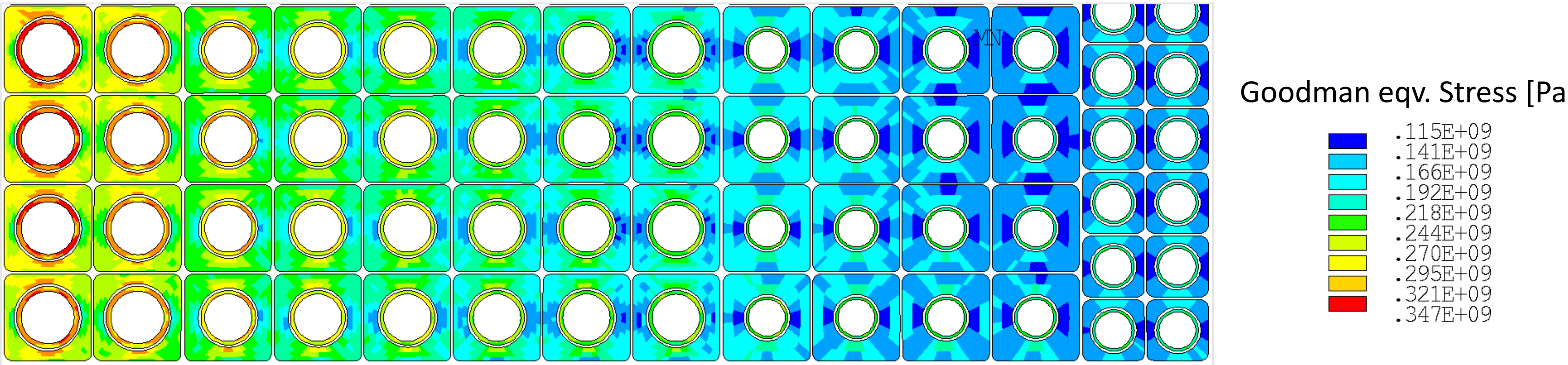


Hoop Stress



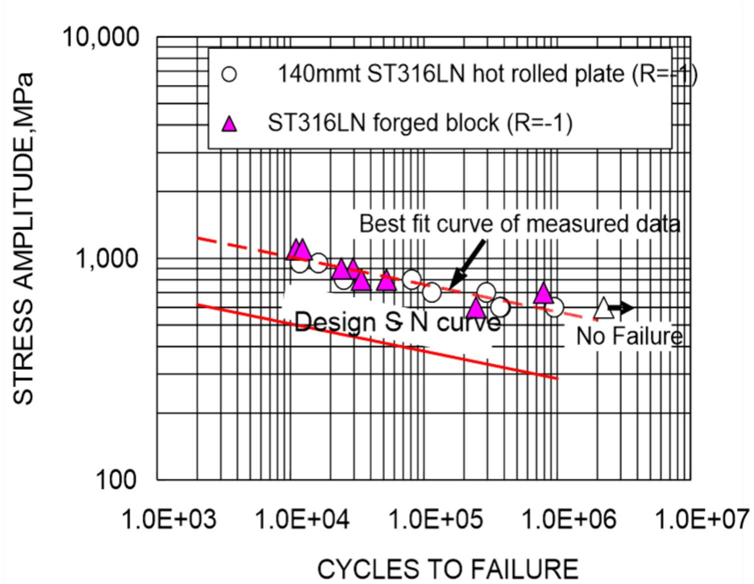


Fatigue Assessment – SN approach

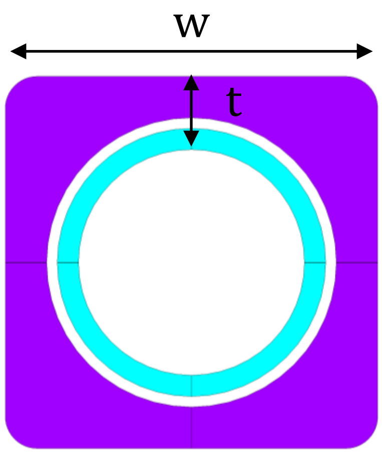


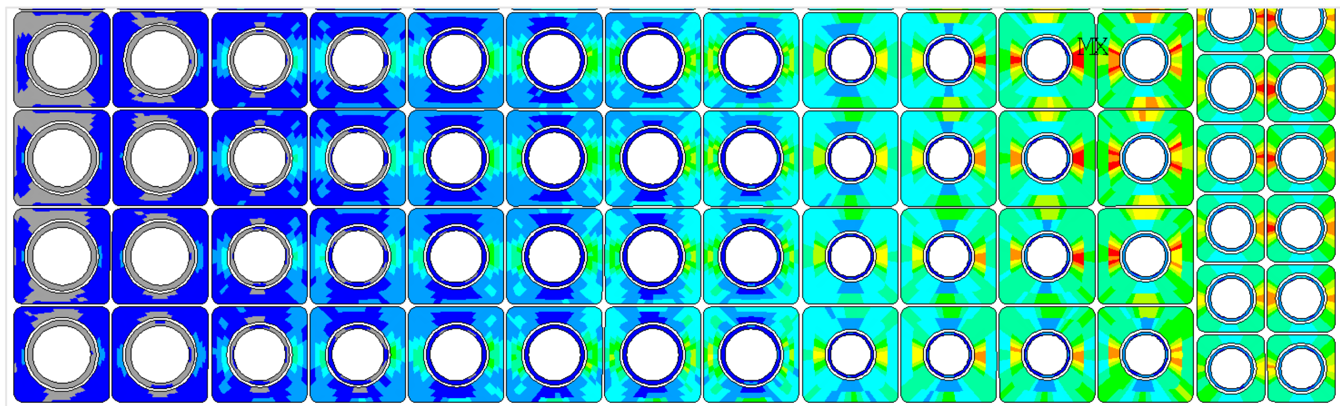
For the DEMO CS 40000 cycles are considered:

- 2*(Max Goodman stress) = **694 MPa < 850 MPa**. This limit is obtained from the 316LN S-N curve for 40 k cycles
- (Max Goodman stress) = **347 MPa < 590 MPa**, which corresponds to limit for 20*(40 k) cycles on the 316LN S-N



Fatigue Assessment – FCGR approach





Embedded elliptical defect:

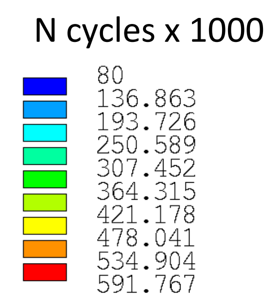
- $w = 70$ mm
- $t = 15$ mm
- $Area = 5 \times 2\ mm^2$
- $r = c/a = 3$
- $\phi = \frac{\pi}{2}$
- $R = 0$
- $m = 2.394$
- $m_{walker} = 0.382$
- $n = m\,(m_{walker} - 1)$
- $C0 = 3.86e-11 \frac{cycle}{m}$
- $Cw = \frac{C0}{(1-R)^n}$

From the relations reported in [6]: $Y = 0.91$

By integrating the Paris Law:

$$N_f = \left(\frac{1}{\left(\frac{m}{2} - 1\right) C\, S^{m} \left((pi^{0.5})Y\right)^{m}}\right)\left(\frac{1}{a_0^{\frac{m}{2}-1}} - \frac{1}{a_f^{\frac{m}{2}-1}}\right)$$

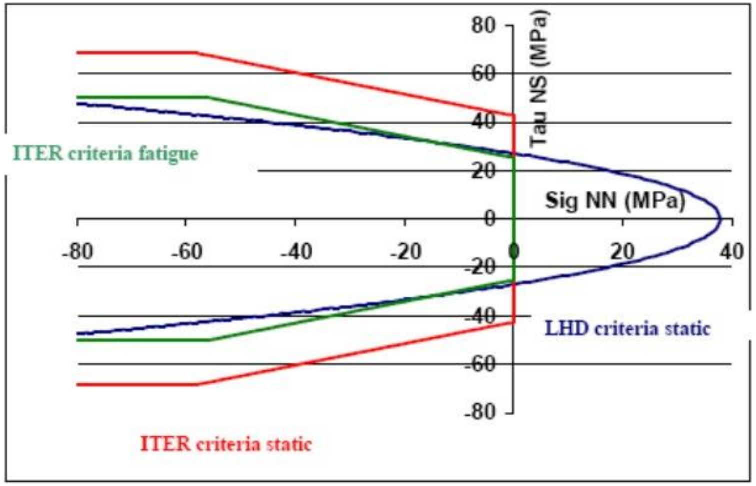
The stress level for each element is obtained from the static analysis

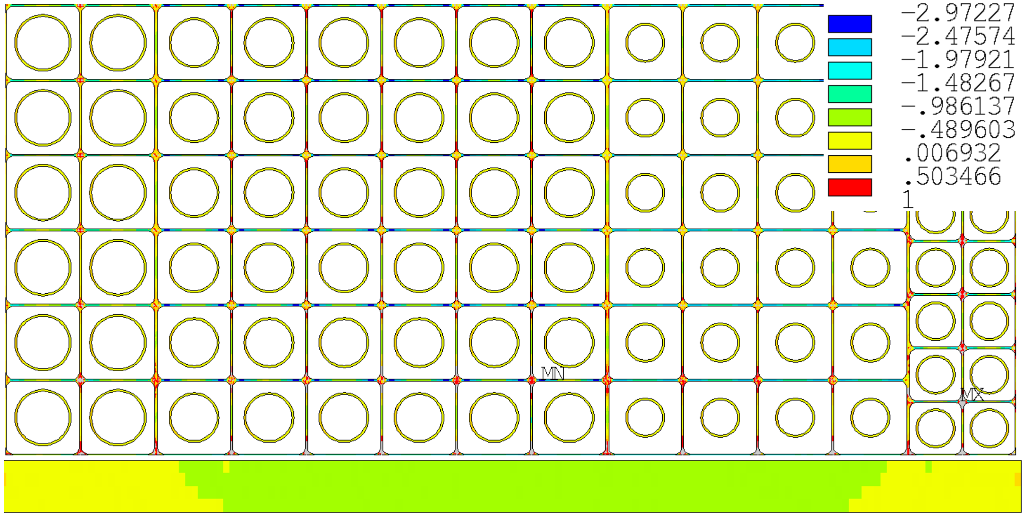


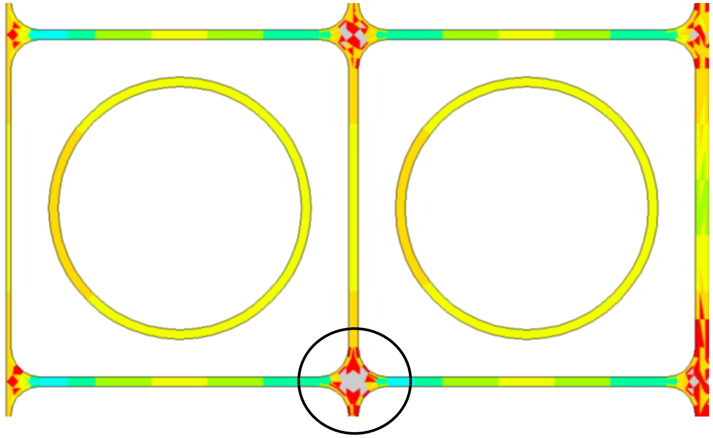
Insulation Components Assessment

The adopted criterion for the insulation components is based on the Mohr-Coulomb relation and combines the normal stress through the insulation thickness with the in-plane shear stress, to separate the regions in traction or in compression:

$$\left(\frac{\sigma}{\sigma_0}\right) + \left(\frac{\tau}{\tau_0}\right)^2 < 1$$







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