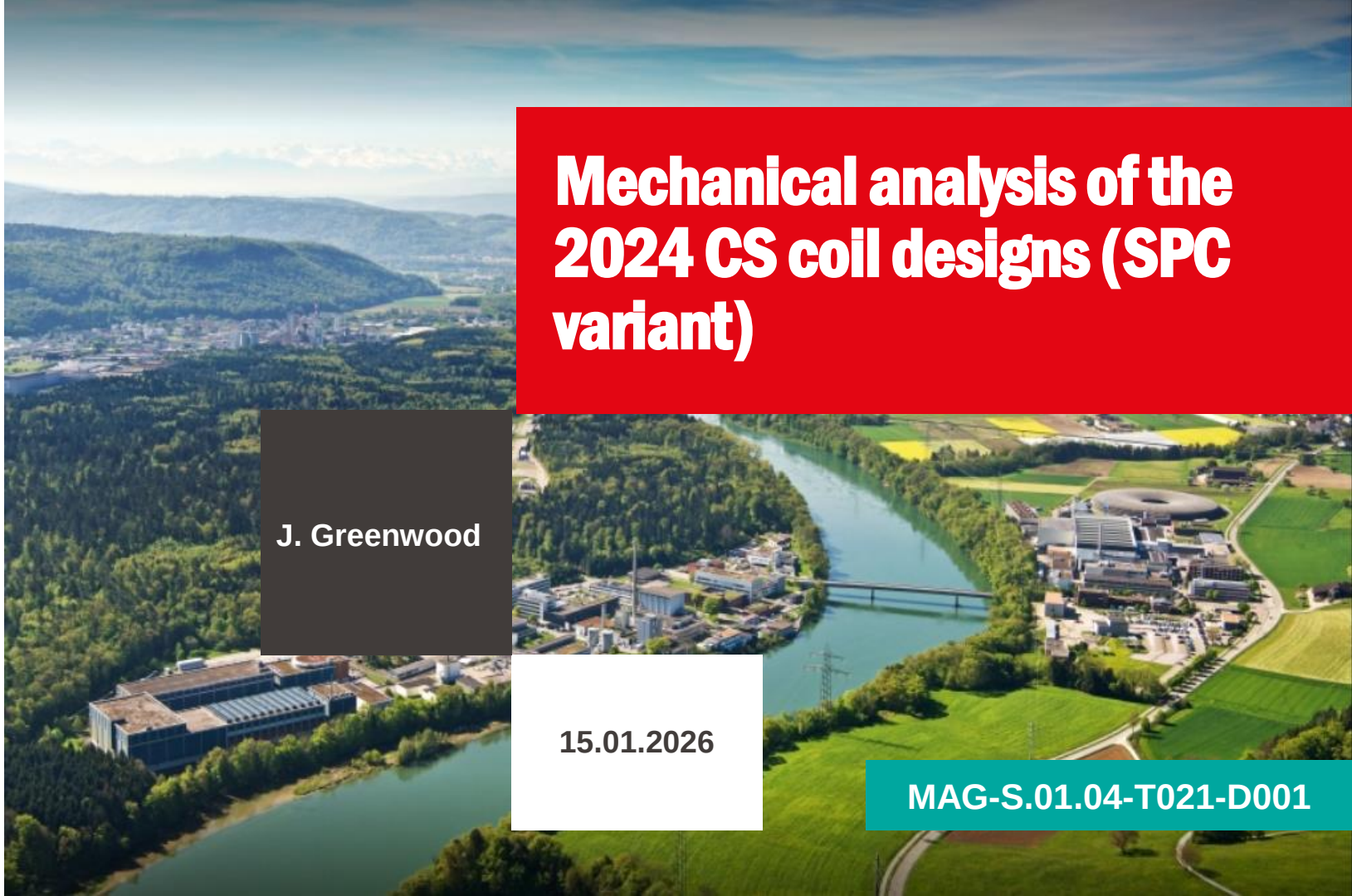
Mechanical analysis of the 2024 CS coil designs (SPC variant)



J. Greenwood

15.01.2026

MAG-S.01.04-T021-D001

SWISS PLASMA CENTER

Outline

Mechanical analyses to support SPC's CS design for LAR-DEMO:

- Crack growth studies
- 2D winding pack analysis
- 2D precompression structure analysis

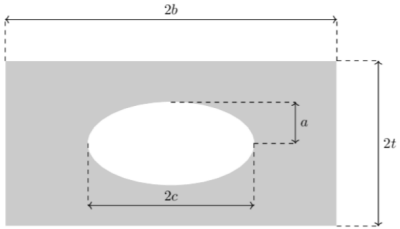
FCGR Studies

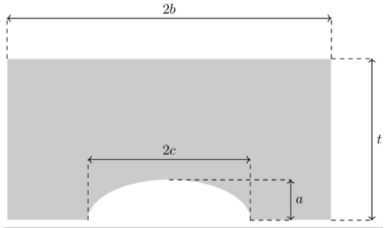
Cracks are iteratively grown in plates according to the Paris Law

The same safety factors and assumptions were used. **No relaxation**

- 71 mm wide plates
- Residual stress 240 MPa
- Initial defect size: 2 mm^2 (surface), 5 mm^2 (embedded)
- 2 load cycles per plasma cycle
- 2x number of cycles (safety factor)
- 2x initial area (safety factor)

...



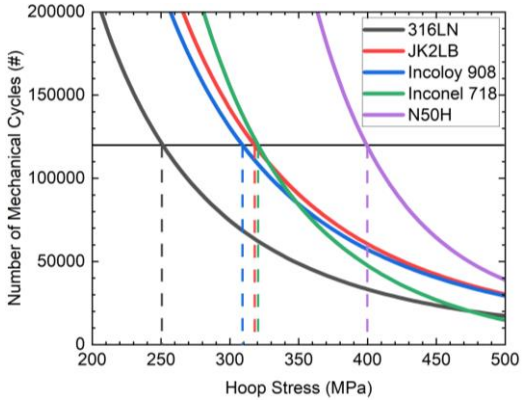


Material	C (m/cycle)	m	K_{IC} (MPam$^{1/2}$)
316LN	6.5×10^{-13}	3.5	200
Incoloy 908	2.84×10^{-13}	3.58	200
Incoloy 718	8.26×10^{-15}	4.55	75
JK2LB	1.75×10^{-13}	3.7	200
N50H (≤37.1 MPam$^{0.5}$)	3.826×10^{-16}	7.355	250
N50H (>37.1 MPam$^{0.5}$)	4.416×10^{-8}	2.434	

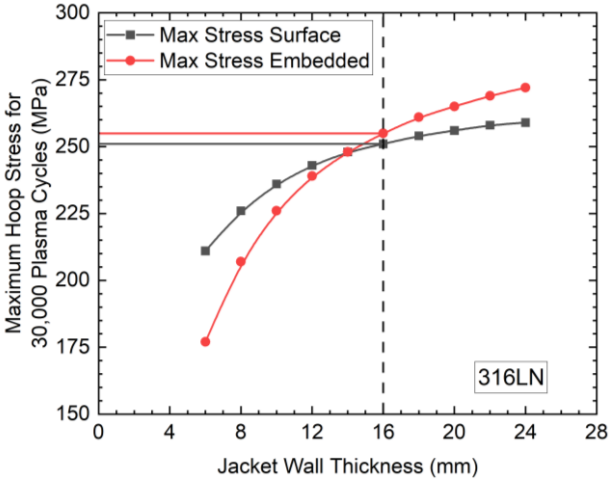
W: 71 mm

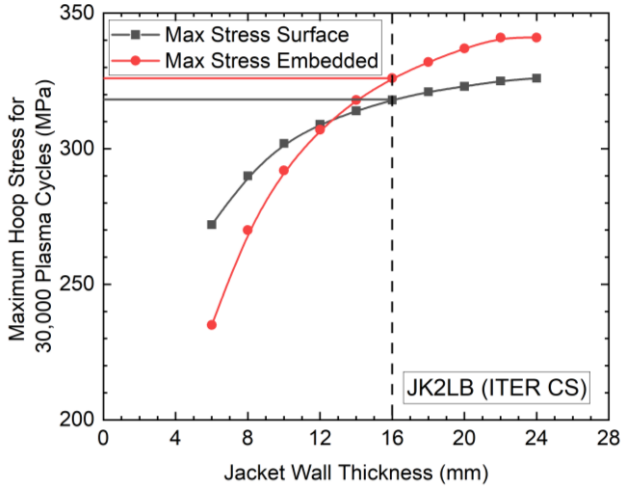
T: 16 mm

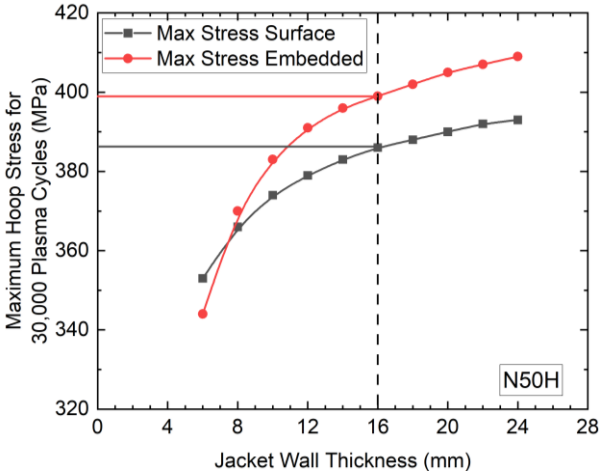
Surface Crack (Initial size 2mm^2)



Maximum Hoop Stresses for 30,000 Plasma Cycles







FCGR Results & Observations

For T=16 mm, surface cracks generally lead to failure first

There is little lifetime to be gained by thickening the jacket wall beyond ~16 mm

316LN, JK2LB, and N50H were considered for SPC's CS

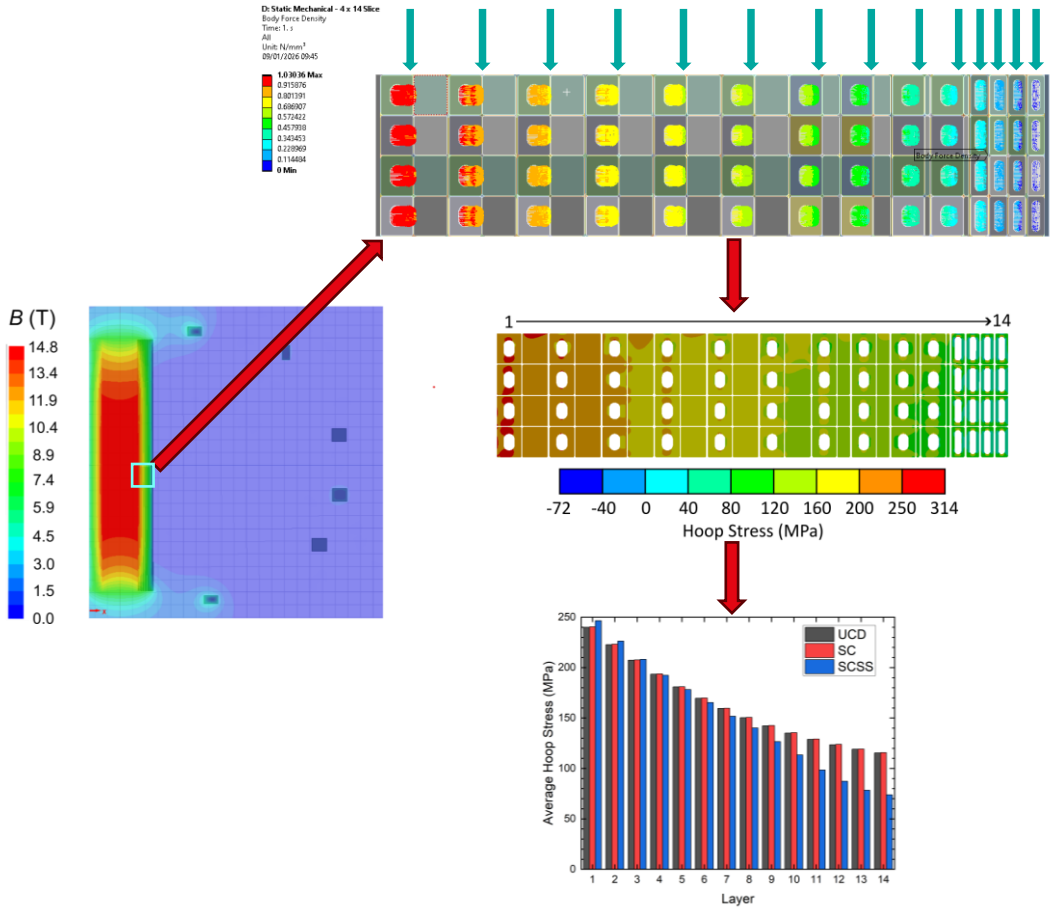
Material	Maximum Hoop Stress for 30,000 Plasma Cycles
316LN	250 MPa
JK2LB/Inconel/ Incoloy	~300 MPa
N50H	380 MPa

2D Winding Pack Analysis

2D Winding Pack Analysis

Axisymmetric simulation; axial and radial forces are included.

Average and peak stresses are extracted for each layer.



Key Coil Design Parameters – 316 LN Design

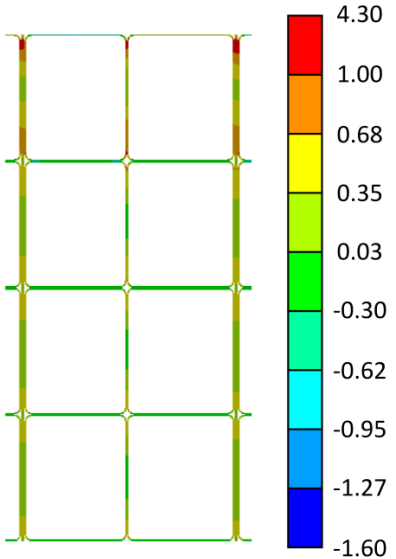
Parameter	UCD	SC graded	SC + steel graded
Total current (MAt)	76.27	76.27	76.27
Conductor current (kA)	60.53	60.53	60.53
WP R_i (m)	1.415	1.417	1.399
WP R_o (m)	2.62	2.62	2.62
SC material in sub-coils (RE-123/Nb_3Sn/Nb-Ti)	14/0/0	4/8/2	4/8/2
Peak B field (T)	14.86	14.86	14.83
CS flux during premagnetisation (Wb)	**192.0**	**192.4 (+0.2%)**	**215.0 (+12%)**

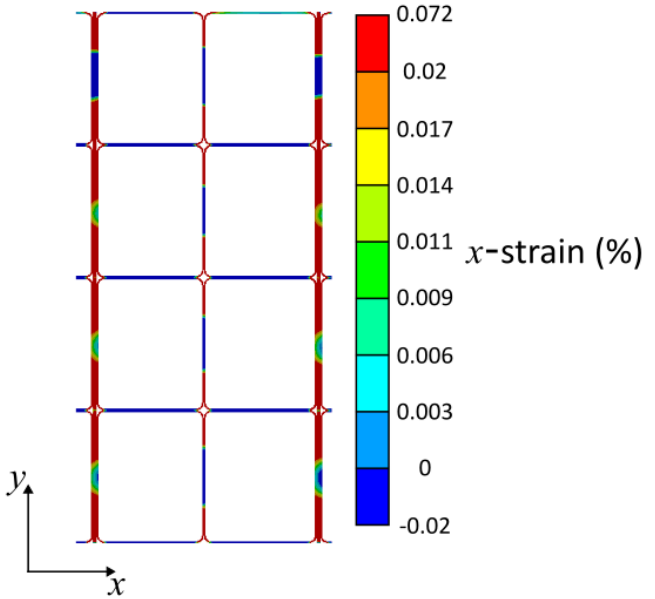
Insulation Stresses & Strains

A preliminary assessment of the insulation stress/strain state was made

The insulation was assumed to be bonded → no stress relief allowed

Stress/strain limits were exceeded at some conduit and strip corners

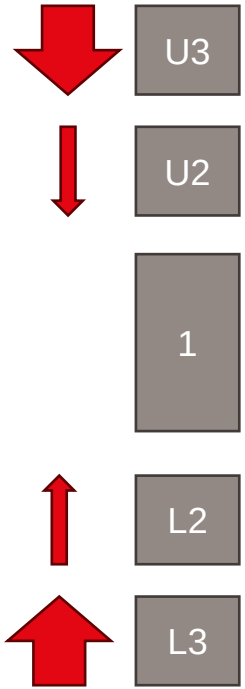




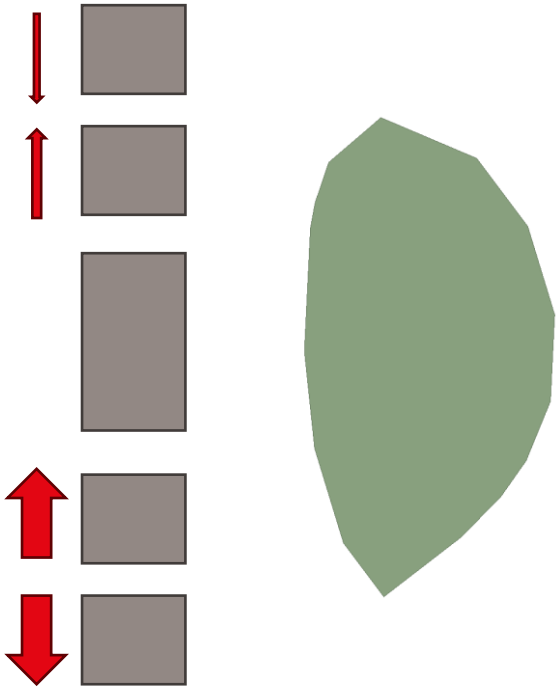
Precompression Structure

Module Force Directions in Different Scenarios

Premagnetisation



Start of Flat Top

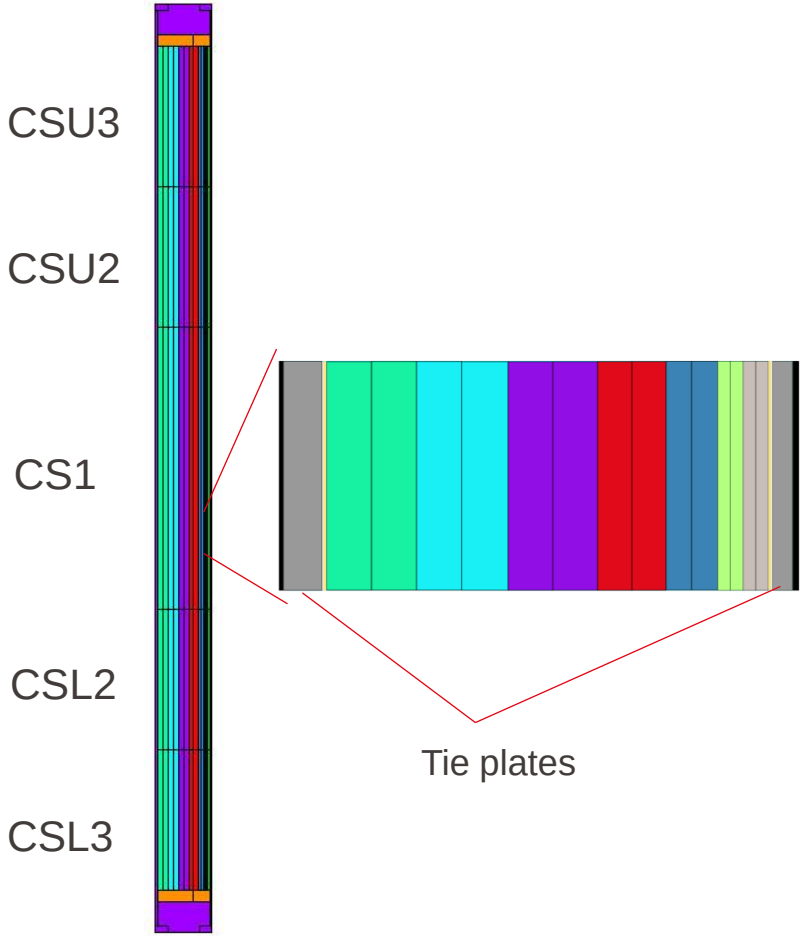


Precompression Structure

Forces calculated for SPC's CS with 316LN jackets **(215 Wb)**

	Premag.	SOF	EOF
$F_{z,\ CSU3}$ (MN)	-651.95	-2.55	-155.76
$F_{z,\ CSU2}$ (MN)	-124.71	25.87	-460.68
$F_{z,\ CS1}$ (MN)	-5.55	-5.63	-140.92
$F_{z,\ CSL2}$ (MN)	78.96	130.07	337.85
$F_{z,\ CSL3}$ (MN)	786.10	-156.07	465.75

Material	Radial thickness (mm)	
	Inner tie plates	Outer tie plates
Nitronic 50	148	92
316 LN	210	110

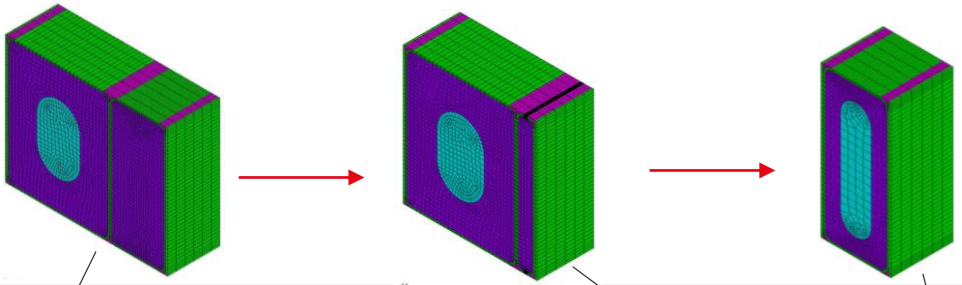


Smeared Properties

Unit cell:

- 1 conductor
- Co-wound strip (if present)
- Insulation

All components are bonded



Property	Sub-coil number						
	SC01	SC02	SC03	SC04	SC05	SC06	SC07
E_x (GPa)	100.26	100.19	99.78	85.62	72.11	28.30	27.49
E_y (GPa)	127.09	127.19	128.08	118.31	104.68	81.86	83.56
E_z (GPa)	171.79	171.87	172.37	163.20	151.6	112.13	113.24
G_{xy} (GPa)	31.36	31.40	31.49	27.19	22.68	6.27	6.29
G_{yz} (GPa)	49.32	49.50	49.74	46.59	42.57	33.05	33.64
G_{xz} (GPa)	40.41	40.32	40.28	34.80	29.69	14.87	14.59
ν_{xy}	0.227	0.227	0.225	0.218	0.221	0.140	0.140
ν_{yz}	0.1215	0.215	0.216	0.210	0.200	0.210	0.212
ν_{xz}	0.175	0.175	0.174	0.159	0.146	0.0789	0.0761
α_x (1/K)	1.10×10^{-5}	1.10×10^{-5}	1.10×10^{-5}	1.12×10^{-5}	1.15×10^{-5}	1.20×10^{-5}	1.20×10^{-5}
α_y (1/K)	1.06×10^{-5}	1.06×10^{-5}	1.06×10^{-5}	1.06×10^{-5}	1.05×10^{-5}	1.04×10^{-5}	1.04×10^{-5}
α_z (1/K)	1.01×10^{-5}	1.01×10^{-5}	1.01×10^{-5}	1.01×10^{-5}	1.00×10^{-5}	9.95×10^{-6}	9.94×10^{-6}

Results and Observations

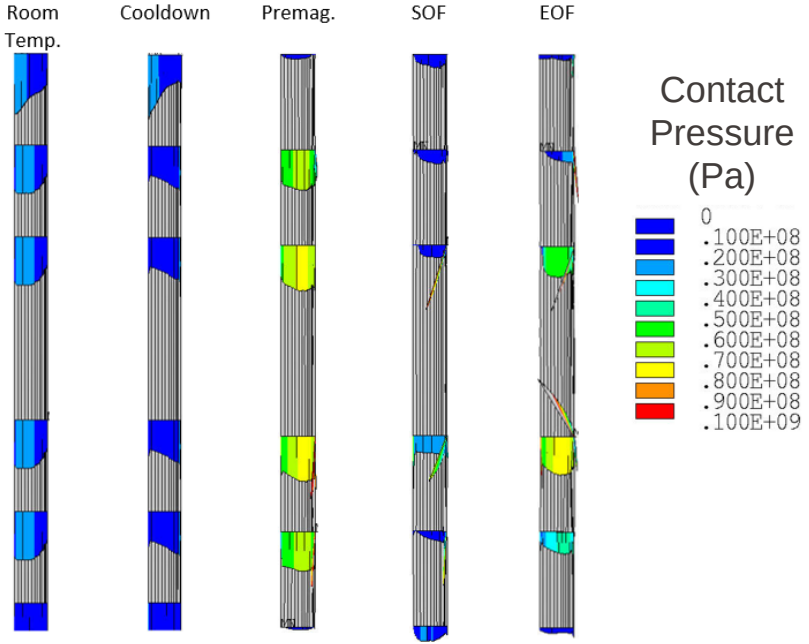
ITER criteria:

- ≥25% of module boundaries remain in contact ✓
- Contact forces are ≥ 15 MN ✓

Tie plates do not exceed membrane stress limits at room temperature

Both 316LN and N50 tie plates are viable

Fatigue lifetimes of plates have not yet been considered in detail



	Radial thickness (mm)	
	Inner tie plates	Outer tie plates
Nitronic 50	148	92
316 LN	210	110

Summary

FCGR studies:

Material	Maximum Hoop Stress for 30,000 Plasma Cycles (16 mm thick jacket wall)
316LN	250 MPa
JK2LB/Inconel/Incoloy	~300 MPa
N50H	380 MPa

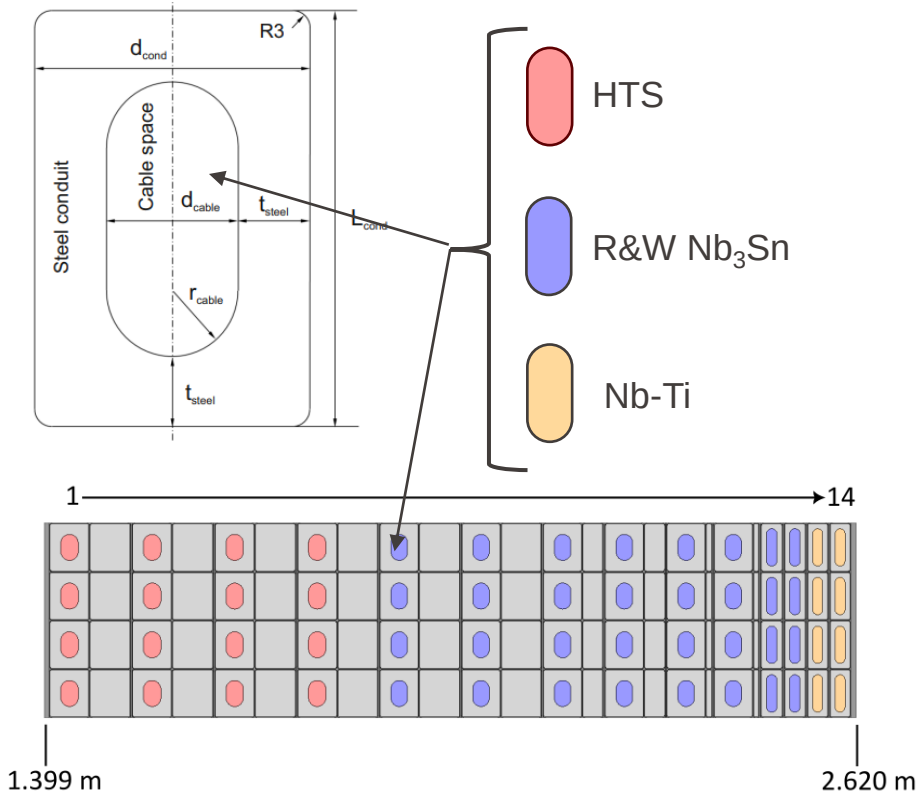
Winding pack analyses: grading the steel and including thick co-wound strips (or multiple strips) leads to a ~10% increase in flux. For 316LN (and Ro=2.62 m), the premagnetisation flux is 215 Wb. Some insulation stress/strain issues remain.

Precompression structure: viable solutions using 316LN or N50 tie plates have been found, with ≤115 mm radial space for the outer tie plates. The precompression is limited by the room temperature stress.

Conductor Dimensions - 316LN

A large amount of steel grading using thick co-wound steel strips (or multiple thin strips) is needed just to achieve **215 Wb** of flux

Layer	L_{cond} (mm)	d_{cond} (mm)	d_{cable} (mm)	t_{steel} (mm)	d_{strip} (mm)
1 & 2	71.0	58.2	26.2	16.0	60.0
3 & 4	71.0	58.0	26.0	16.0	60.0
5 & 6	71.0	56.8	24.8	16.0	60.0
7 & 8	71.0	56.8	24.8	16.0	30.0
9 & 10	71.0	56.8	24.8	16.0	8.0
11 & 12	71.0	30.8	15.8	7.5	-
13 & 14	71.0	29.7	14.8	7.5	-



Example: Surface Crack Growth

The iterative model terminates when:

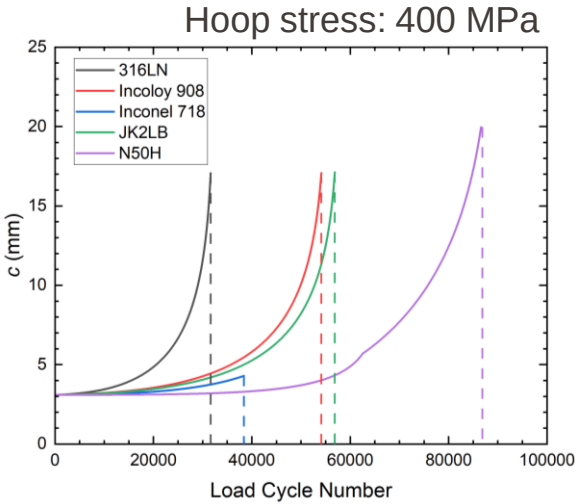
- the stress concentration factor somewhere around the crack perimeter exceeds the safe limit

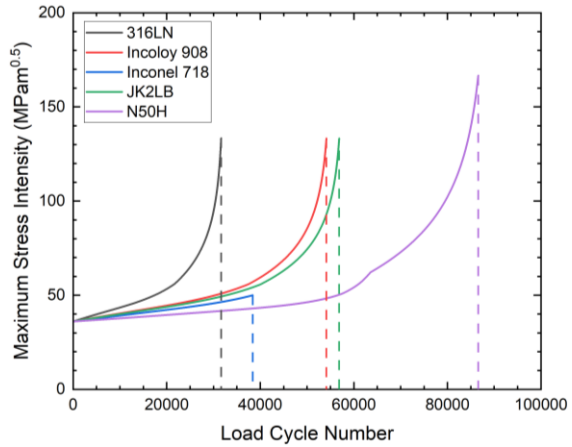
or

- the crack has grown sufficiently large

The inputs/assumptions/safety factors are the same as those used in previous SPC analyses:

- 71 mm wide plate
- Initial defect size: 2 mm^2 (surface), 5 mm^2 (embedded)
- 2 load cycles per plasma cycle
- 2x number of cycles (safety factor)
- 2x initial area (safety factor)
- …





[1] J. Lorenzo and X. Sarasola, "Fatigue Stress Assessment via crack growth analysis based on LEFM," 2021. Available: https://idm.euro-fusion.org/?uid=2PBDRG

Crack Growth in N50H Jackets

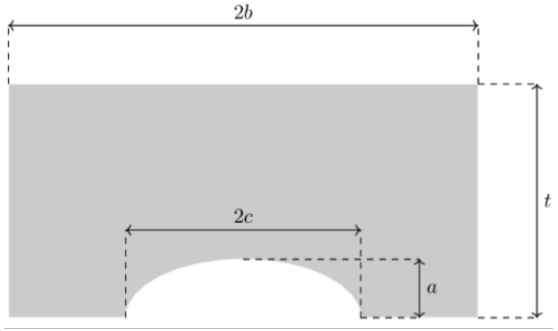
Both embedded and surface cracks are considered

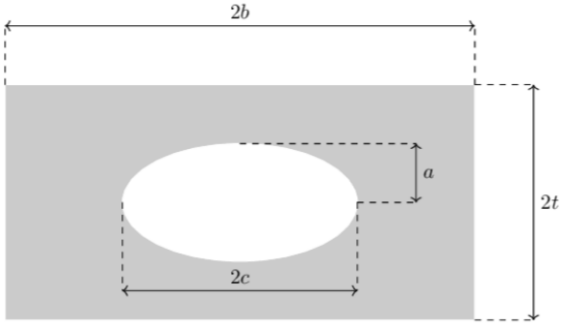
$$\frac{da}{dN} = C(\Delta K_a)^m, \frac{dc}{dN} = C(\Delta K_c)^m$$

$$K_a = K\left(\sigma_m + \sigma_r, \frac{\pi}{2}\right) - K\left(\sigma_r, \frac{\pi}{2}\right)$$

$$K_c = K(\sigma_m + \sigma_r, 0) - K(\sigma_r, 0)$$

$$K(\sigma_m, \Phi) = \left(\sigma_m + H_j \sigma_b\right)\sqrt{\pi \frac{a}{Q}} F_j(\Phi)$$





[1] ITER Structural Material Database. Art. 2 Metallic Material Database. https://user.iter.org/?uid=223BAC
[2] J. Lorenzo and X. Sarasola, "Fatigue Stress Assessment via crack growth analysis based on LEFM," 2021. Available: https://idm.euro-fusion.org/?uid=2PBDRG