SPC CS coil design and analyses (2.1-T025, 2.3-T007)

X. Sarasola &
R. Wesche

February 12th, 2020

SWISS
PLASMA
CENTER

Outline

- **Requirements and assumptions**
- Methodology
- Uniform current density vs graded designs
- Conclusions

Requirements and assumptions

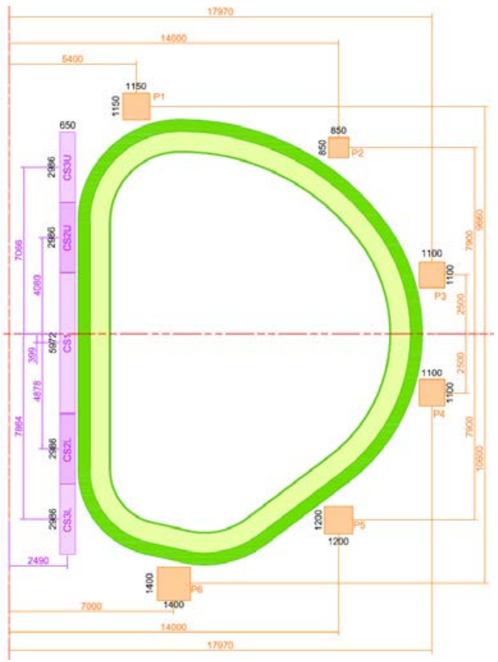
- Update the CS coil design to the baseline 2018:
  - The **generated magnetic flux is maximized** for the outer radius (R_o) and height (h) given in [1].
  - A radial space of **115 mm** is preliminary allocated for the **pre-compression** structure, allowing a maximum $\boldsymbol{R_o}$ **= 2.7 m for the solenoid winding pack**.
  - **Fatigue is the main design driver** for the DEMO CS:
    - The EU DEMO is designed to operate **20,000 plasma cycles** [2].
    - Therefore, the CS coil design has to ensure survival of **40,000 mech cycles**.

- The studies focus on the design of the **CS1 winding pack**:
  - Layer-wound.
  - 10 double-layer sub-coils.
  - RE-123, Nb_3Sn, and Nb-Ti are used respectively for the high, medium, and low field layers of the solenoid.

[1] R. Ambrosino, "Equilibria EOF/SOF 2018 PhysMag." https://idm.euro-fusion.org/?uid=2NV5BB.
[2] C. Bachmann, "DEMO Plant Load Specification," 21-Sep-2017. https://idm.euro-fusion.org/?uid=2MY7H3.

Requirements and assumptions

- Note on baseline 2018:
  - The **peak B field** is observed in **module CSL2** (not CS1!) during pre-mag.
  - It does **not include 100 mm insulation spacing between** the CS **modules**.
  - If 100 mm spacing is included between modules:
    - ΔB is a bit larger (but small, in any case, ΔB = +0.063 T compared to CS1)
    - The current density also becomes slightly larger in CSL2
- The design studies focus on the **CS1 WP.**
- No gap is considered between modules.



Baseline 2018		CSU3	CSU2	CS1	CSL2	CSL3
Max B (T)	No mod gap	12.177	12.288	12.324	12.329	12.099
	With mod gap	12.195	12.443	12.428	12.491	12.011

X. Sarasola & R. Wesche

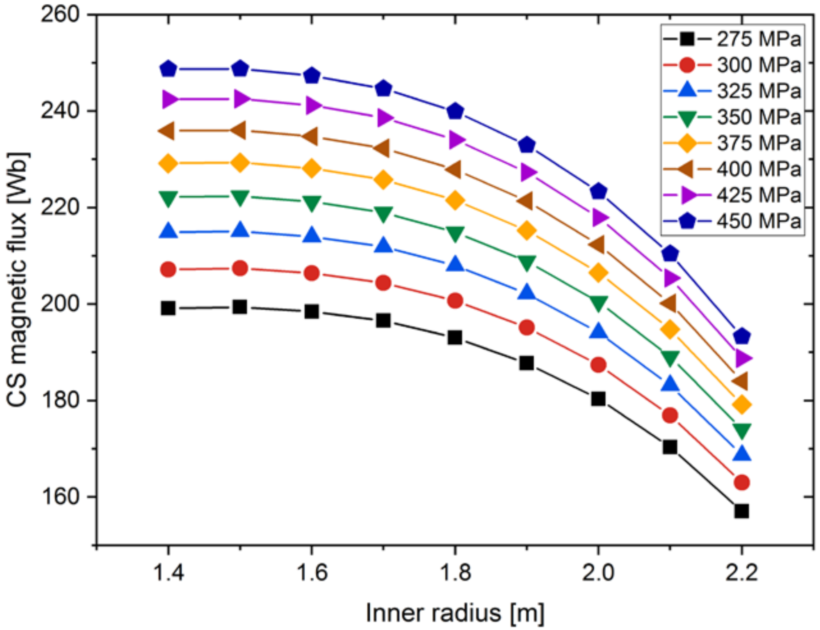
Outline

- Requirements and assumptions
- **Methodology**
- Uniform current density vs graded designs
- Conclusions

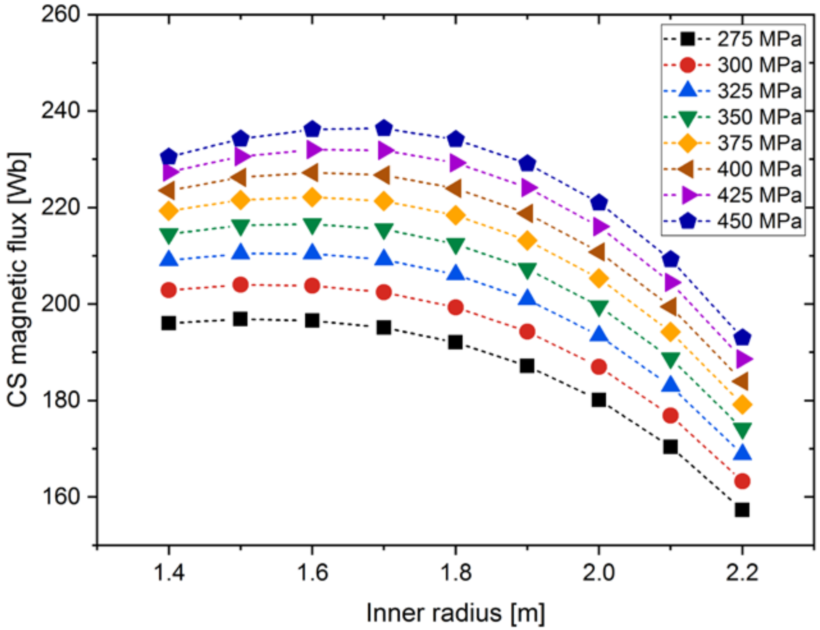
Methodology

- In a finite uniform current density solenoid, the magnetic field, flux, and hoop stress experienced in the mid-plane, can be computed analytically.
- Simple parametric studies are used to find the maximum magnetic flux for a given outer radius and hoop stress.

HTS uniform current density, R_o = 2.7 m



Nb_3Sn (ε_{eff} = -0.25%) uniform current density, R_o = 2.7 m

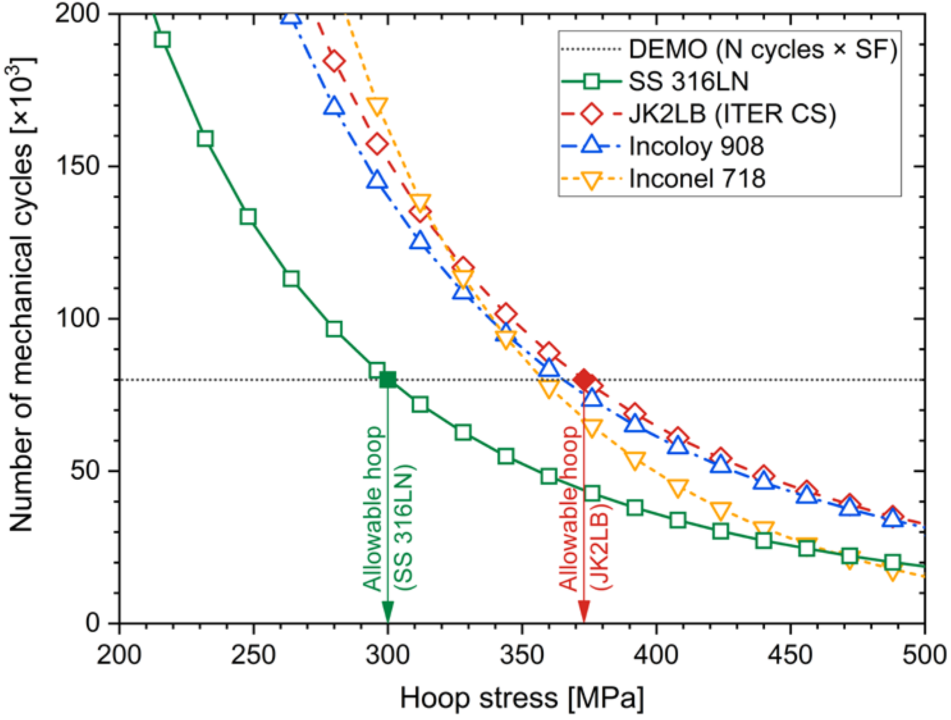


X. Sarasola & R. Wesche

Methodology: Fatigue Crack Growth Model

- Paris Law: $\frac{da}{dN} = C(\Delta K)^m$
- Assumptions:
  - Initial defect size:
    - 2 mm² (surface)
    - 5 mm² (embedded)
  - Stress intensity factor:
    - Elliptical cracks
    - $\sigma_{residual}$ = 240 MPa
  - Safety factors [3]:
    - 2× in number of cycles
    - 2× in defect area
    - 1.5× in fracture toughness

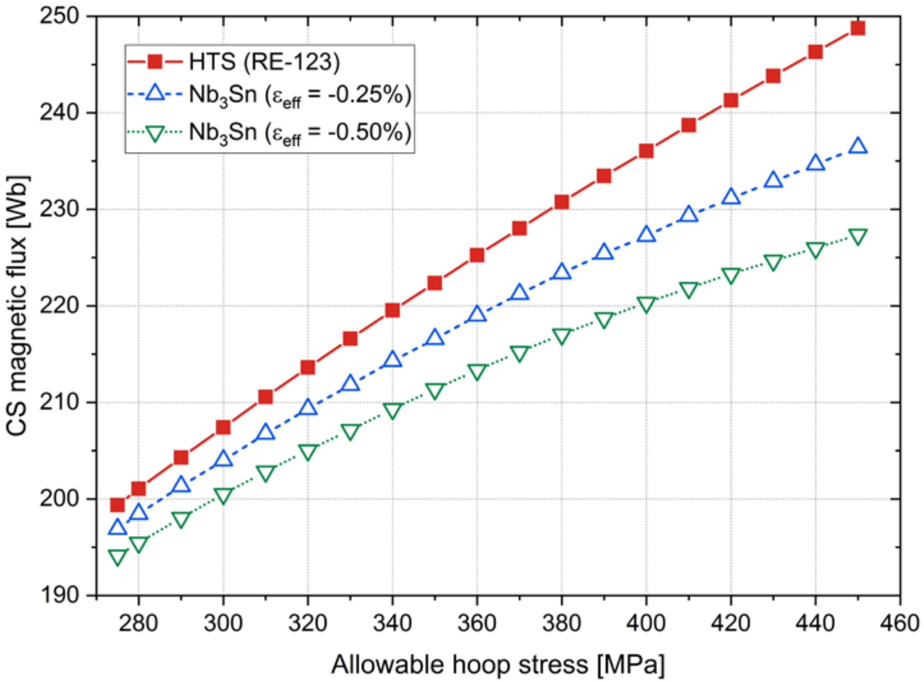
70×22 mm plate, 2 mm² initial surface crack



[3] C. Jong, "Magnet Structural Design Criteria Part 1: Main Structural Components and Welds," 2012. https://user.iter.org/?uid=2FMHHS.

Methodology

- Designs with higher allowable hoop stress can operate at larger j_{eng} (larger B and φ)
- The benefit of using HTS dilutes for low allowable hoop stress.
- In order to ensure fatigue lifetime (assumptions in previous slide):
  - The $\boldsymbol{\sigma_{hoop}}$ has to be limited to **300 MPa** if **SS316LN** is used for the conduits **(~375 MPa** in the case of **JK2LB**)

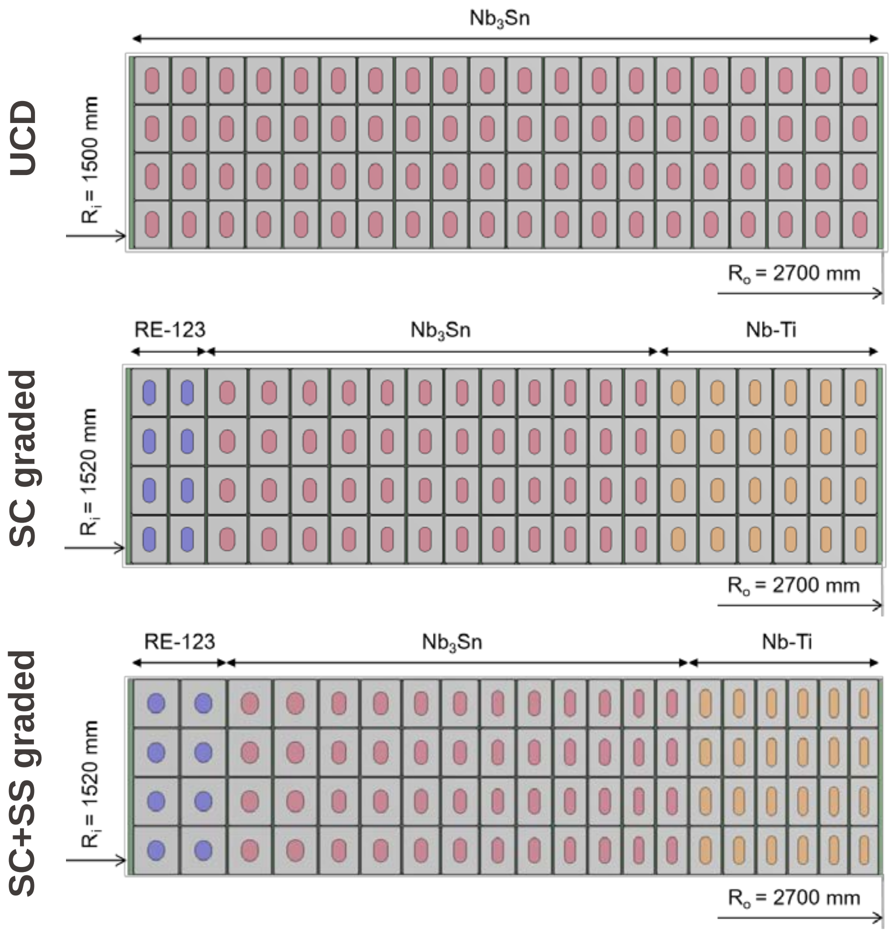


Outline

- Requirements and assumptions
- Methodology
- **Uniform current density vs graded designs**
- Conclusions

Uniform current density vs graded designs

- For an allowable σ_{hoop} = 300 MPa and R_o = 2.7 m, the maximum flux is generated for $\boldsymbol{R_i} \approx$ **1.5 m.**
- The proposed Uniform Current Density (UCD) design is analyzed in ANSYS.
- The radial distribution of the B field is used to propose a more economically sensible superconductor (SC) graded design.
- The stainless steel fraction can be adjusted across the winding pack.
  - The radial stress in the insulation shall be always compressive
  - The hoop stress is such that fatigue lifetime is guaranteed using jackets made of SS316LN.



SPC designs (baseline 2018)

X. Sarasola & R. Wesche

Design		LTS-only designs		
		UCD	SC grad	SC+SS grad
Total current [MAt]		71.044		
Cond current [kA]		45.541		
R_i [mm]		1500	1540	1540
R_o [mm]		2700		
SC material subcoils [HTS/Nb_3Sn/Nb-Ti]		-/10/-	-/7/3	-/7/3
Max B [T]		15.43	15.45	15.45
Mag flux [Wb]	Only CS	204	211.6 **(+3.7%)**	215.4 **(+5.6%)**
	CS+PF	218.0	225.6 **(+3.5%)**	229.4 **(+5.2%)**
$\sigma_{memb, L01}$ [MPa]		358.6	352.3	347.9
$\sigma_{hoop, L01}$ [MPa]		289.8	292.0	291.9
Cycles until break [#]		82.4×10^3	84.0×10^3	85.4×10^3

X. Sarasola & R. Wesche

SPC designs (baseline 2018)

Design		LTS-only designs			HTS designs		
		UCD	SC grad	SC+SS grad	UCD	SC grad	SC+SS grad
Total current [MAt]		71.044			72.235		
Cond current [kA]		45.541			46.305		
R_i [mm]		1500	1540	1540	1500	1520	1520
R_o [mm]		2700			2700		
SC material subcoils [HTS/Nb_3Sn/Nb-Ti]		-/10/-	-/7/3	-/7/3	10/-/-	1/6/3	1/6/3
Max B [T]		15.43	15.45	15.45	15.72	15.71	15.76
Mag flux [Wb]	Only CS	204	211.6 **(+3.7%)**	215.4 **(+5.6%)**	207.4 **(+1.7%)**	211.6 **(+3.7%)**	218.5 **(+7.1%)**
	CS+PF	218.0	225.6 **(+3.5%)**	229.4 **(+5.2%)**	221.6 **(+1.7%)**	225.8 **(+3.6%)**	232.7 **(+6.7%)**
$\sigma_{memb,\ L01}$ [MPa]		358.6	352.3	347.9	356.0	362.1	350.0
$\sigma_{hoop,\ L01}$ [MPa]		289.8	292.0	291.9	288.9	294.5	295.4
Cycles until break [#]		82.4×10^3	84.0×10^3	85.4×10^3	84.2×10^3	80.0×10^3	83.6×10^3

Outline

- Requirements and assumptions
- Methodology
- Uniform current density vs graded designs
- **Conclusions**

Conclusions

- The **requirements** for the **CS** in the Baseline 2018 **are inconsistent**:
  - Given the space allocated for the CS coil, it is not possible to satisfy simultaneously two fundamental design requirements:
    - Required magnetic flux (Ψ = 250 Wb)
    - Fatigue lifetime (20,000 plasma cycles + Safety factors)
- At low allowable hoop stress (~300 MPa), **the use of HTS** only provides a **small gain in flux** compared to Nb_3Sn R&W.
- Use of **superconductor** and **stainless steel grading:**
  - **More cost-effective** layout.
  - **Modest increase** the generated **magnetic flux** (only a few percentage points relative to the uniform current density designs).
- Other **strategies to mitigate** the effect of **fatigue** are **under study** (see **tomorrow's presentation** on mechanical analyses).

Proposal 2020

- Further investigation of the CS coil alternative conductor design options.
- Dimensioning of the pre-compression structure based on Baseline 2018.
- Start: 01.03.2020
- End: 31.10.2020
- Resources: 0.2 ppy