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Progress in the Design of a Hybrid HTS-Nb_3Sn-NbTi Central Solenoid for the EU DEMO

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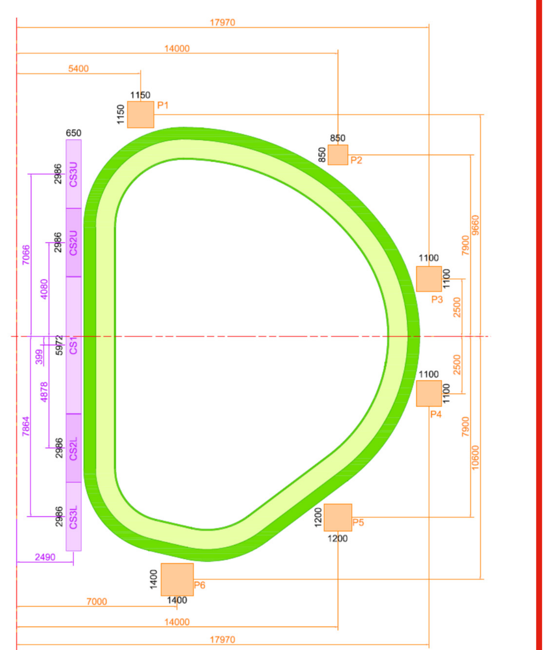
Abstract

- **Benefits** of a **hybrid Central Solenoid (CS)** in a pulsed tokamak:
  - **Reduce** the **outer radius** (i.e., reduced overall size and cost), or
  - **Increase** the **magnetic flux** (which can extend the plasma burn time and efficiency).
- **A hybrid CS** is proposed for the EU DEMO based on **10 layer-wound sub-coils** using **HTS, Nb_3Sn, and Nb-Ti** conductors.
- The design makes use of **superconductor** and **steel grading**.
- **Mechanical fatigue** is the **main design driver** of the EU DEMO CS.
- Alternatives to reduce the sensitivity of the proposed design to fatigue are under investigation.

Requirements and assumptions

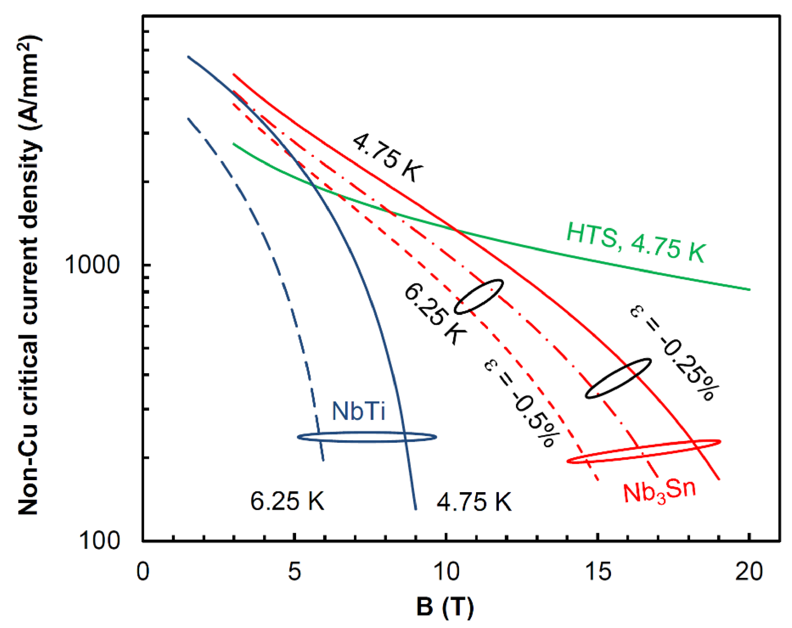
- Geometrical and operational requirements are based on the output provided by the reactor systems code PROCESS [1].
- The present reference for magnet design is the Baseline 2018 [2].

	Premag	SOF	EOF
ICS3U [MAt]	29.11	13.63	-5.94
ICS2U [MAt]	29.11	-1.42	-29.11
ICS1 [MAt]	58.23	-9.6	-58.23
ICS2L [MAt]	29.11	-7.17	-29.11
ICS3L [MAt]	28.13	25.14	-12.44
IPF1 [MAt]	16.53	14.19	2.32
IPF2 [MAt]	3.86	-5.22	-5.89
IPF3 [MAt]	-8.47	-5.12	-6.08
IPF4 [MAt]	12.03	-3.98	-3.64
IPF5 [MAt]	-9.91	-7.76	-8.98
IPF6 [MAt]	24.03	15.46	10.25
Iplasma [MA]	-	17.86	17.86



- The EU DEMO is designed to operate 20,000 plasma cycles, thus the CS design has to ensure survival during **40,000 mechanical cycles**.
- The studies described focus on the design of the CS1 winding pack (most mechanically demanded).

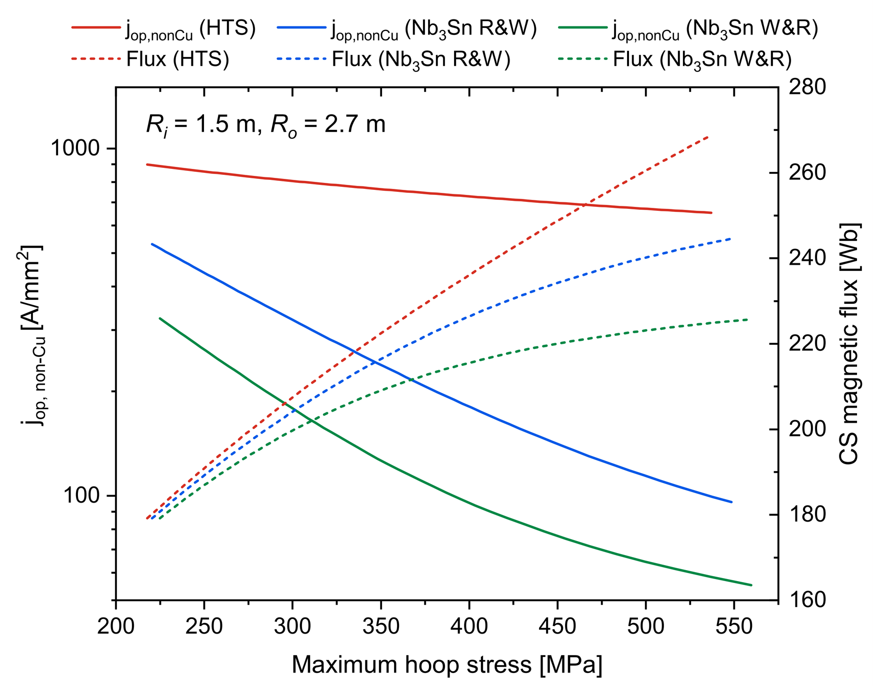
- **Superconducting properties:**
  - Nb_3Sn and Nb-Ti:
    - Scaling laws from [3]
    - T_{op} = 4.75 K
    - ΔT_m = 1.5 K
  - HTS tapes:
    - $J_{op} = 0.8 \times J_c$
    - T_{op} = 4.75 K



- **Mechanical properties:**
  - Static assessment: properties defined for design of DEMO WPs [4]
  - Fatigue properties at 4 K taken from the ITER Material Database [5]

Methodology

- Magnetic field, flux and hoop stress can be computed in a **uniform current density CS**.
- For a given solenoid R_i, R_o, and allowable hoop, the intersections of required and achievable $J_{opnon\text{-}Cu}$ provide maximum possible flux.

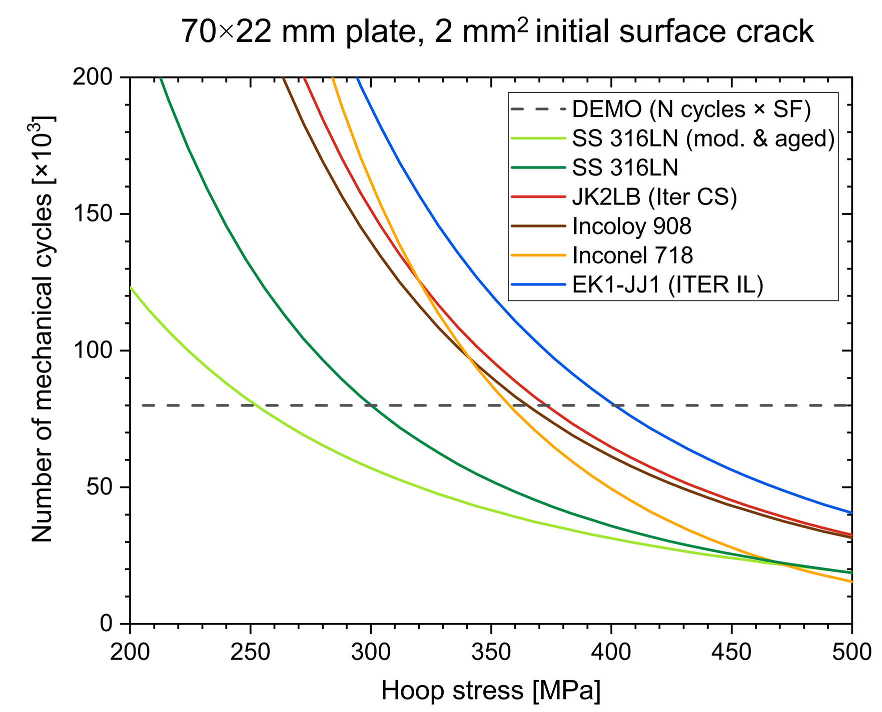


Fatigue Crack Growth Model

- Paris Law:

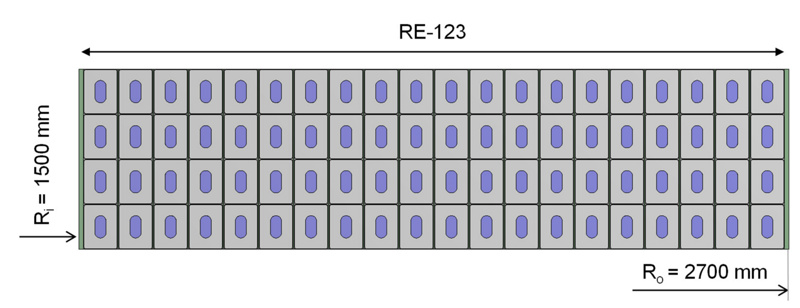
$$\frac{da}{dN} = C(\Delta K)^m$$

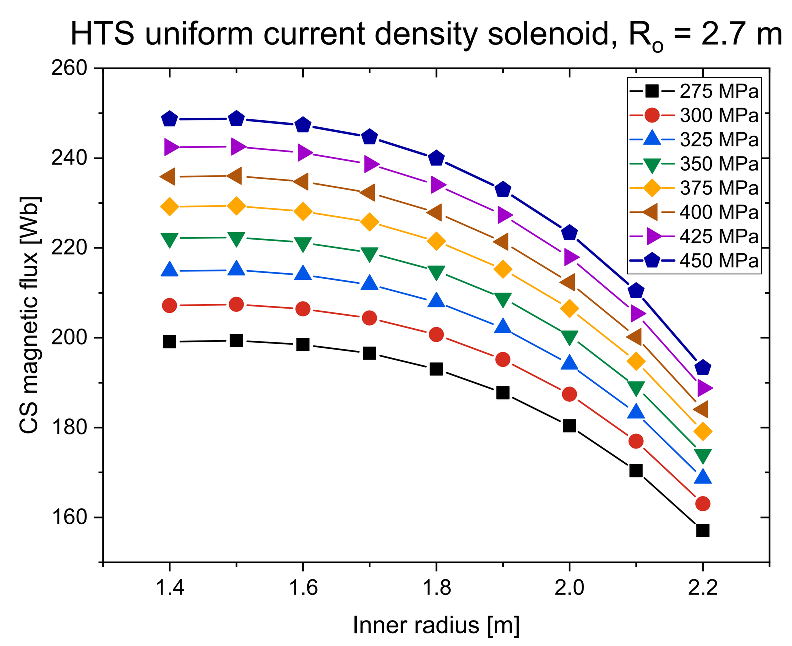
- Assumptions:
  - Initial defect size:
    - 2 mm² (surface)
    - 5 mm² (embedded)
  - Stress intensity factor:
    - Elliptical cracks
    - $\sigma_{residual}$ = 240 MPa
  - Safety factors [5]:
    - 2× in number of cycles
    - 2× in defect area
    - 1.5× in fracture toughness

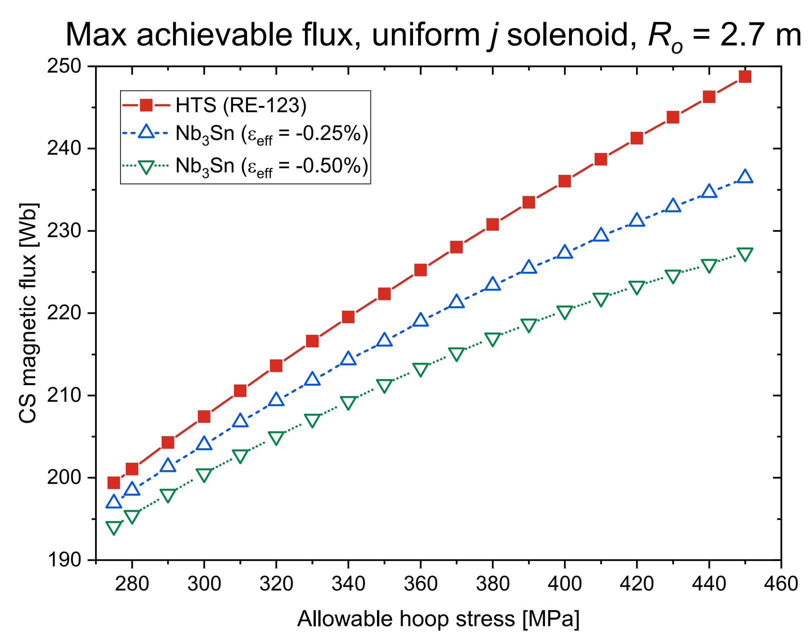


Uniform Current Density Design

- Allowable hoop defined by crack growth model.
- Higher hoop → larger B and φ
- Conduits made of SS316LN:
  - σ_{hoop} = 300 MPa
  - φ_{max} = 207.4 Wb

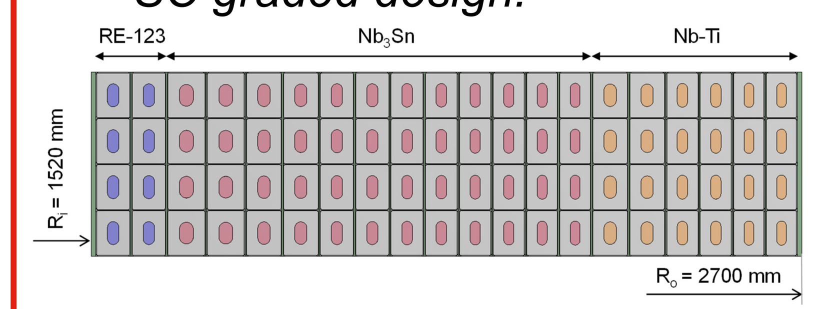




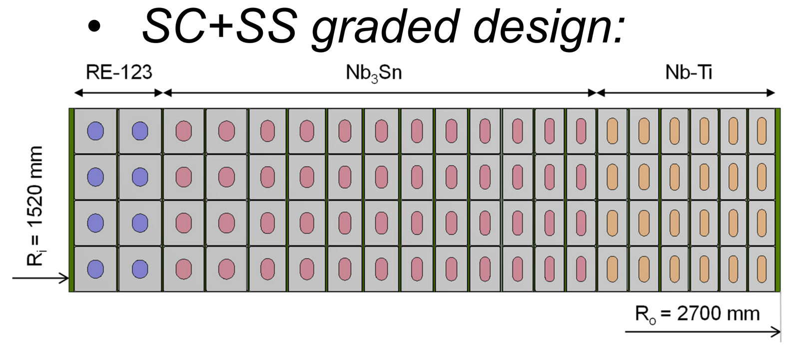


Graded Coil Designs

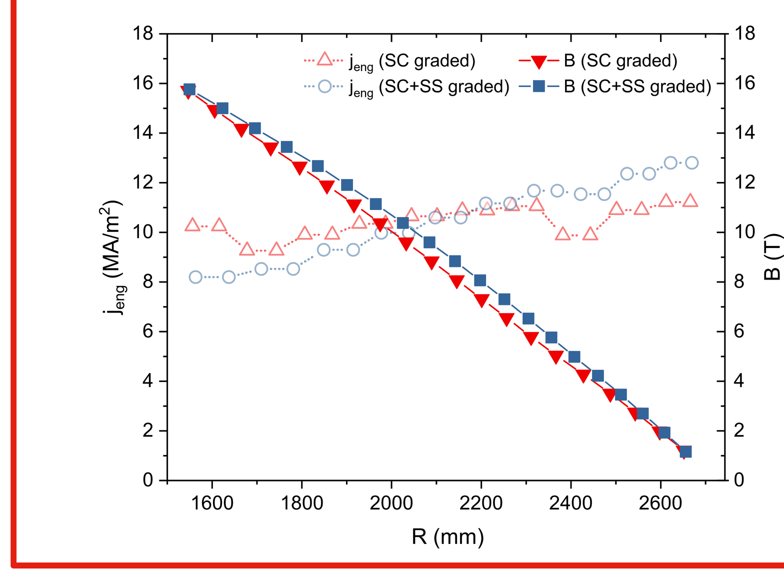
- A CS1 WP layout based on the use of HTS as superconductor and SS316LN for the conduits is used to explore the benefits of grading.
- *SC graded design:*

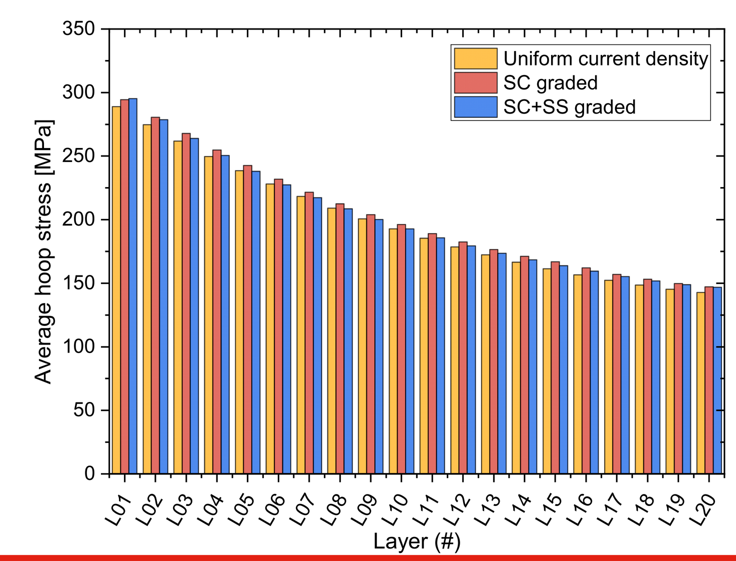


- *SC+SS graded design:*



Design	UCD	SC graded	SC+SS graded
Total current [MAt]	72.2	72.2	72.2
Cond current [kA]	46.3	46.3	46.3
R_i [mm]	1500	1520	1520
R_o [mm]	2700	2700	2700
SC material subcoils [HTS/Nb_3Sn/Nb-Ti]	10/-/-	1/6/3	1/6/3
Max B [T]	15.72	15.71	15.76
CS magnetic flux [Wb]	207.4	211.6 (+2.0%)	218.5 (+5.4%)
Membrane stress L01 [MPa]	356.0	362.1	350.0
Hoop stress L01 [MPa]	288.9	294.5	295.4
Cycles until break [#]	84.2×10^3	80.0×10^3	83.6×10^3





Conclusions

- In general, the use of HTS enhances the flux generated by the CS, but:
  - The relative gain depends on the allowable hoop stress (fatigue)
  - For **more demanding fatigue** constraints, the **effectiveness of HTS becomes smaller**
- Fatigue has profound implications in the design of a pulsed solenoid.
  - A fusion power plant based on a pulsed tokamak will experience even more demanding constraints (plasma pulses likely > 100,000)
- Grading provides a cost effective design and a modest gain in flux.

References

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[3] V. Corato *et al*., EUROfusion WPMAG-Rep (16) 16565, 2016.
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EUROfusion

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