EPFL

DEMO CS: Mitigation of fatigue Alternative mech designs (MAG-3.1-T017)

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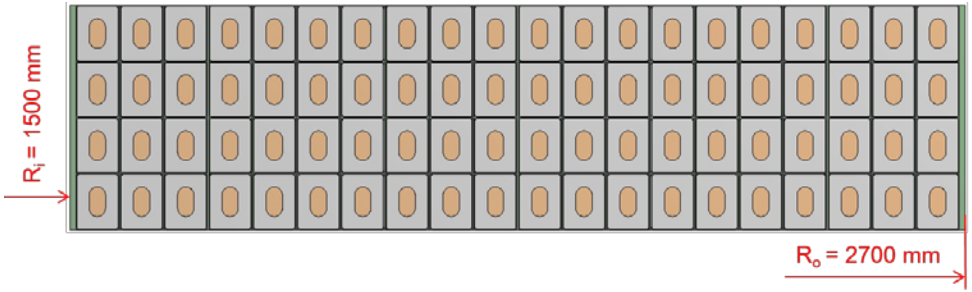
Outline

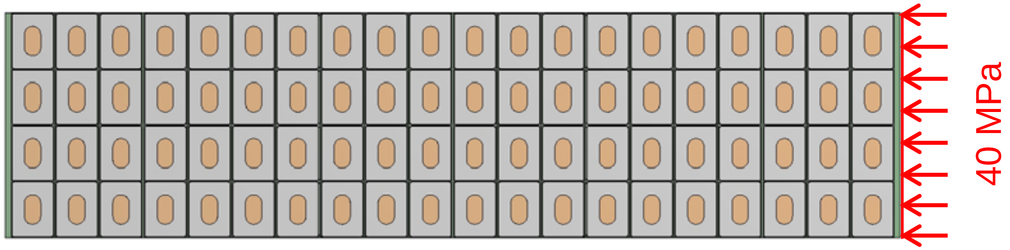
- **Radial pre-compression**
- Non-leak tight jacket
- Conclusions

Radial pre-compression in solenoids

- The use of radial pre-compression in solenoids is well known to reduce the amplitude of hoop stress during operation
- One possible alternative is to use the centering force of the TF coils to provide this radial pre-compression (known as "bucking")
  - **Standalone design**



  - **Bucked design** (TF centering force can provide a bucking pressure of 40 MPa)



Bucked solenoid design

- Use of the **TF centering force** in the DEMO CS:
  - **Reduces** the **hoop stress** in the conduits
  - Ultimately can lead to an **increase of 20% in the generated CS flux** compared to a standard standalone solenoid.
- However, bucking implies having a **uniform current density** over the whole length of the **solenoid** (limited plasma shaping capability).

Design	Total current [MAt]	Conductor current [kA]	R_i [m]	R_o [m]	σ_{hoop} [MPa]	Fatigue life [# cycles]	B_{peak} [T]	Mag flux [Wb]	
								Only CS	CS + PF
Standalone	72.235	46.305	1.5	2.7	288.9	84.2×10^3	15.72	**207.4**	221.6
Bucked	86.632	55.533	1.5	2.7	289.3	82.5×10^3	18.05	**248.7**	265.8

Use of high strength reinforcement

- Zylon/epoxy are very high strength composites used as reinforcement in high field (up to 100 T) pulsed solenoids:
  - These solenoids operate at room temperature and above
  - Typically, the Zylon fibers are pre-tensioned to 700 MPa during coil winding (it increases the filling factor of Zylon in the epoxy matrix and limits the hoop stress in the solenoid when powered)
- For our purpose, the main limitation of Zylon is the **negative thermal expansion coefficient (α)**
  - Other high strength composites (e.g. carbon fiber comp) have also a negative α

Mechanical properties of zylon/epoxy pre-stressed at 700 MPa (77.5% filling factor)

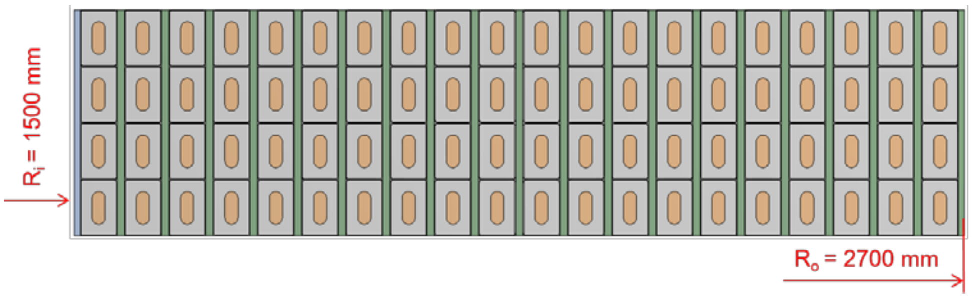
Temp	Tensile tests (along fibre)			Transverse comp tests			Thermal exp. coeff (K^{-1})
	UTS (GPa)	E_3 (GPa)	ν_{31}	UTCS (MPa)	E_1 (GPa)	ν_{12}	
RT	3.3	205	0.35	60-150	3	0.6	-6×10^{-6}
77 K	4.3	222	0.35	-	-	-	

[1] Y. K. Huang *et al, Composites: Part B*, 33 (2002) 109-115

Use of high strength reinforcement: Zylon

- The layout of the proposed winding pack is similar compared to uniform current density designs proposed by SPC:
  - The interlayer insulation changes:
    - Thickness is increased from 2 to 10 mm (at the expense of reducing the thickness of the conductors).
    - It is assumed to be made of Zylon/epoxy (77.5% filling factor) pre-tensioned to 700 MPa at room temperature (properties shown in previous slide).

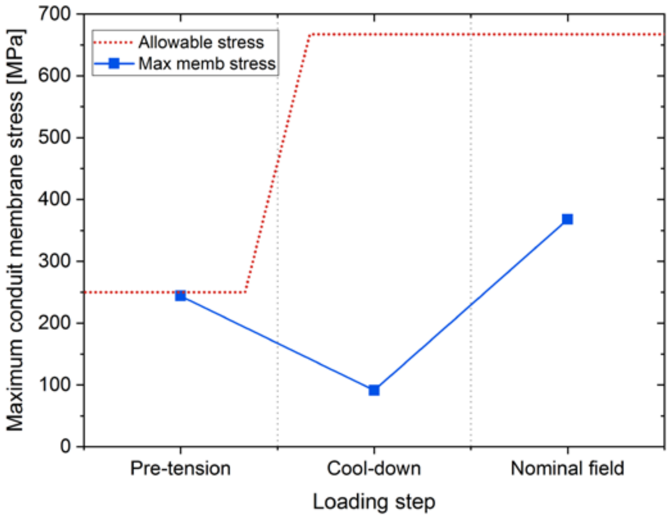
- Zylon/epoxy is assigned to the parts shaded in green below:



Use of high strength reinforcement: Zylon

- Due to the different thermal coefficients, the zylon/epoxy has to be heavily pre-tensioned at room temperature.
- The **limit** is **not set by the static limits of Zylon,** but the **stress** transferred to the stainless steel **conduits**

- The **actual gain of magnetic flux** is limited to **7.2%** compared to a standard standalone solenoid.



	Magnetic flux [Wb]	
	Only CS	CS + PF
Standalone (standard)	207.4	221.6
Bucked design	248.7 **(+19.9 %)**	265.8
Standalone + Zylon	222.4 **(+7.2 %)**	237.7

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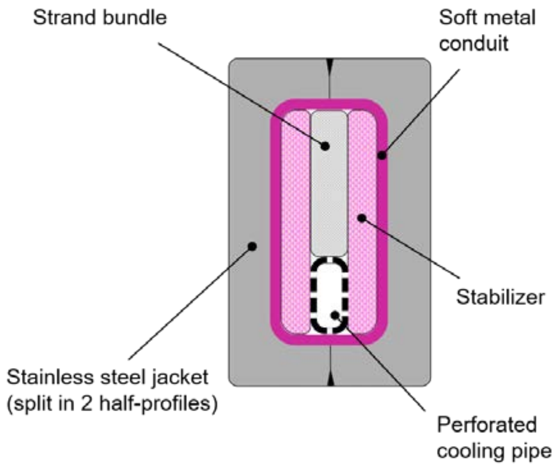
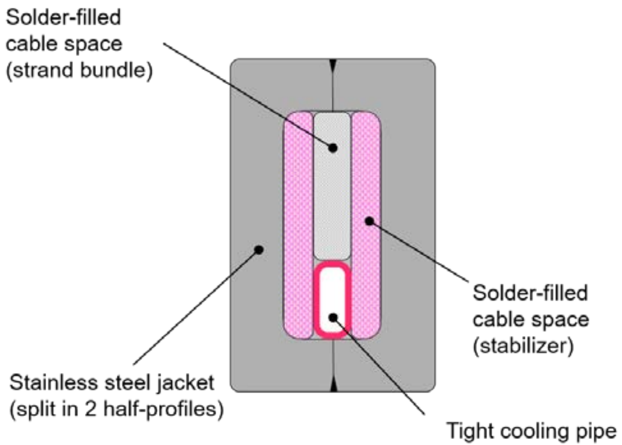
Use of non-leak tight jackets

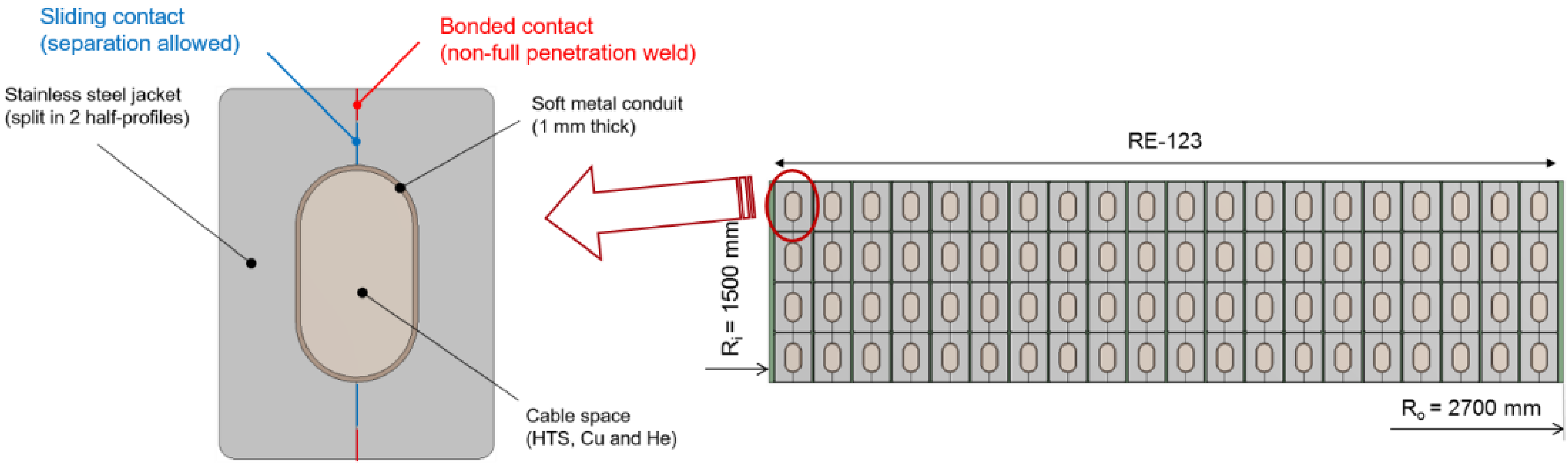
- In standard CICCs, the jacket provides:
  - **Structural support** for the operating loads
  - **Helium containment** function (which imposes stringent constraints in the mechanical design, since no local crack can be tolerated through the jacket wall thickness).
- Therefore, **decoupling the two main functions of a CICC jacket** can be very attractive.
- **If the presence of a local crack is acceptable** from the structural point of view, the **required** jacket **cross section** might be **closer to** the **static** load case.
- Two alternatives are considered:





Proposed winding pack layout

- The general WP layout is similar to previous design iterations:
  - Baseline 2018, uniform current density HTS design
- CuNi and Ti are considered for the inner soft metal conduit.
- Contact between steel U-profiles:
  - Bonded contact models the welds (typically, non-full penetration welds),
  - Standard sliding contact (separation allowed) is used elsewhere



Potential benefits of a double-wall CICC

- Static and fatigue criteria of the conduits are checked
- The **magnetic flux can be increased up to 26%**

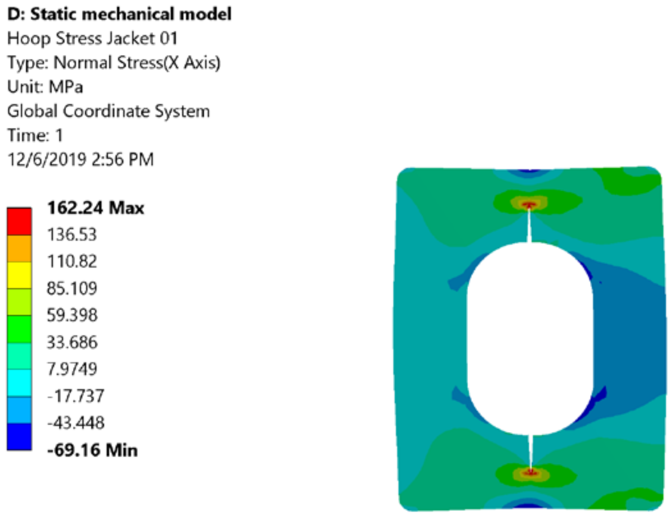
Design	Total current [MAt]	Conductor current [kA]	R_i [m]	R_o [m]	$\sigma_{hoop,steel}$ [MPa]	$\sigma_{hoop,cond}^{*}$ [MPa]	B_{peak} [T]	Mag flux [Wb]	
								Only CS	CS + PF
Reference	72.235	46.305	1.5	2.7	288.9	-	15.72	**207.4**	221.6
Double wall (CuNi + SS)	86.632	55.533	1.5	2.7	439.3	299.4	18.81	**248.7**	265.81
Double wall (Ti + SS)	90.736	58.164	1.5	2.7	489.8	307.8	19.68	**260.5**	278.4

*Cool-down not taken into account

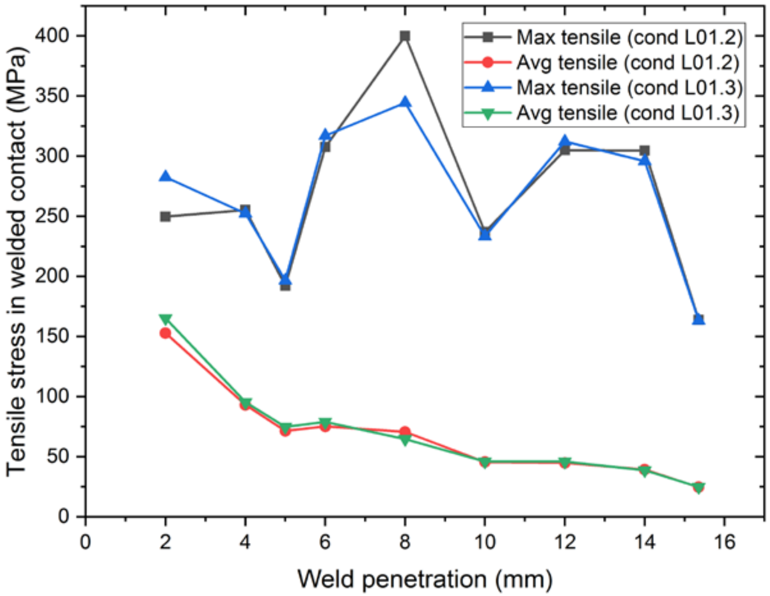
- But there are a number of issues associated to the double-wall jacket:
  - Steel conduits have to be welded (otherwise insulation fails). These welds are subjected to cyclic load and might be vulnerable to fatigue.
  - Inner conduit must hold quench pressure, welds might be also vulnerable.
  - Joints and terminations are more complicated.

Stress in the welds

- Welds are subjected to a **localized tensile stress**, which might open a crack
- The average stress obviously decreases with the penetration of the weld
- But the peak stress is mesh dependent (not reliably predicted with the FEM)
- 3D modelling is required (intermittent welds)



Tensile stress in the welded contact



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Conclusions

- In the DEMO CS reference design, the **stress in the jackets has to be limited** to **avoid** the **penetration of cracks** through the jacket wall:
  - This leads to an oversized design of the jackets, which drastically reduces the current density in the coil, and limits the ability of the CS to generate high flux.

- Two alternatives have been considered so far:

1. Use of **radial compression**:
   - Effective, but…
   - **Bucking** has **severe implications** in the design of the CS coil
   - We have **not identified** yet the ideal **reinforcement material**
2. Use of a **non-leak tight jacket**:
   - A **double-wall jacket** works on paper, but might present a number of **manufacturing issues**
   - The use of a **solder-filled cable** has also a number of issues (high AC losses, poor heat removal…) which can be studied in a SULTAN sample

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