Conceptual Design Study of a 40^{+} T ReBCO Solenoid for the MUON Collider

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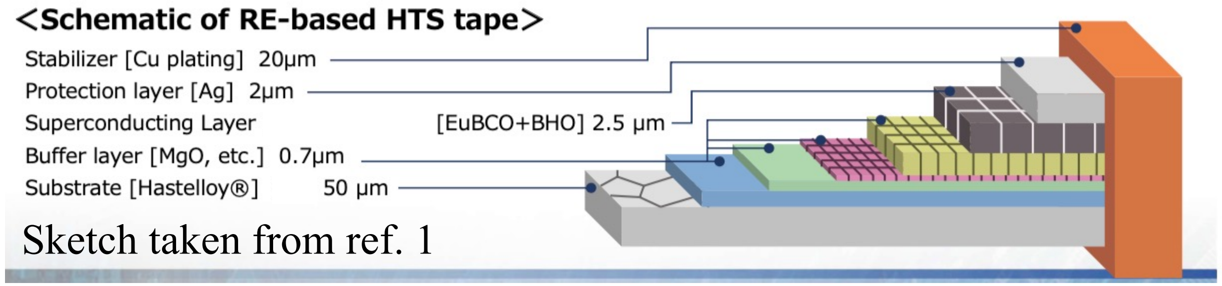
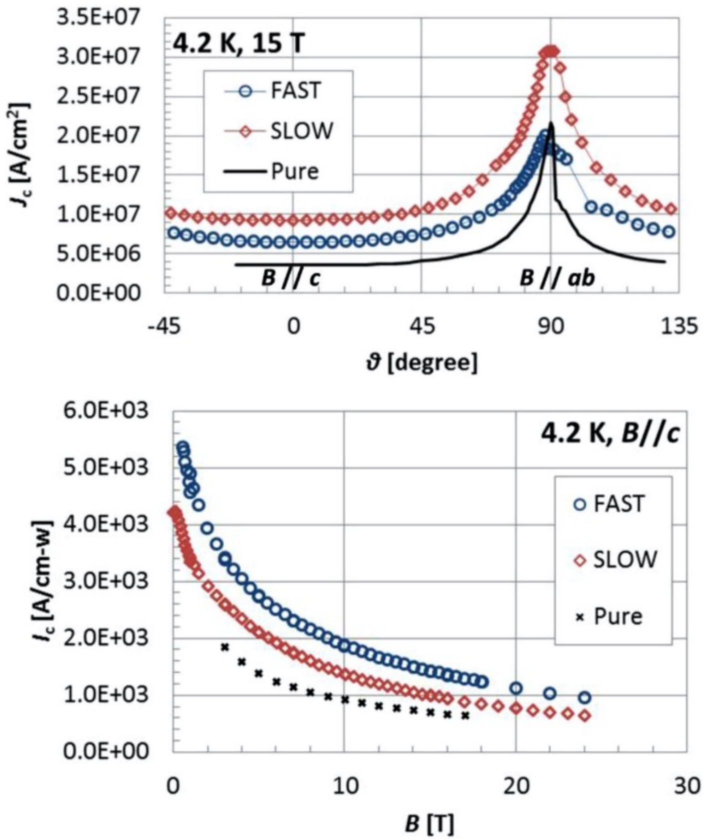
Reference Conductor for the study 1/2

- **Reference Conductor** for the following analysis is the **Fujikura FESC-SH12**[1]



Sketch taken from ref. 1

- **12 mm wide** EuBCO+BHO tape with a **Hastelloy** and **Copper thickness** respectively equal to **50 μm** and **40 μm**
- **Measured**[2] J_e **(4.2 K)**
  1. $J_e(B_{\perp}=15\ T) \sim 1.5\ kA/mm^2$
  2. $J_e(B_{/\!/}=15\ T) \sim 4.5\ kA/mm^2$
- **Estimated** I_c **(4.2 K)**
  1. $I_c(B_{\perp}=50\ T) \sim 300\ A$,
  2. $I_c(B_{/\!/}=50\ T) > 1000\ A$



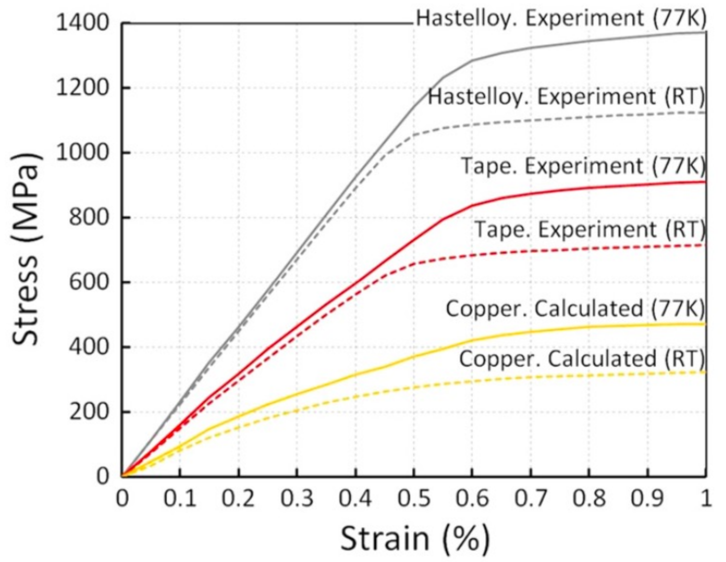
Plots taken from ref. 2

[1] https://www.fujikura.co.jp/eng/products/newbusiness/superconductors/01/superconductor.pdf
[2] Shinji Fujita, Satoshi Awaji et al. IEEE TAS, VOL. 29, NO. 5, AUGUST 2019

Reference Conductor for the study 2/2

- Mechanical **stresses** producing **irreversible** critical current I_c **reduction**
  - **Tensile longitudinal** stress **> 600 MPa**[1] (this number can be substantially increased by reducing the copper thickness, Hastelloy deforms plastically at tensile stresses above 1000 MPa[2])
  - **Compressive** stress in **thickness direction > 400 MPa**[1]
  - **Compressive** stress in **width direction > 100 MPa**[1]
  - **Tensile** stress in **thickness direction: 10-100 MPa**[3]
  - **Shear** stress > **19 MPa**[3]
  - **Cleavage/Peel** stress[3] (tensile at tape extremities)<**1 MPa**[3]

K Ilin *et al*



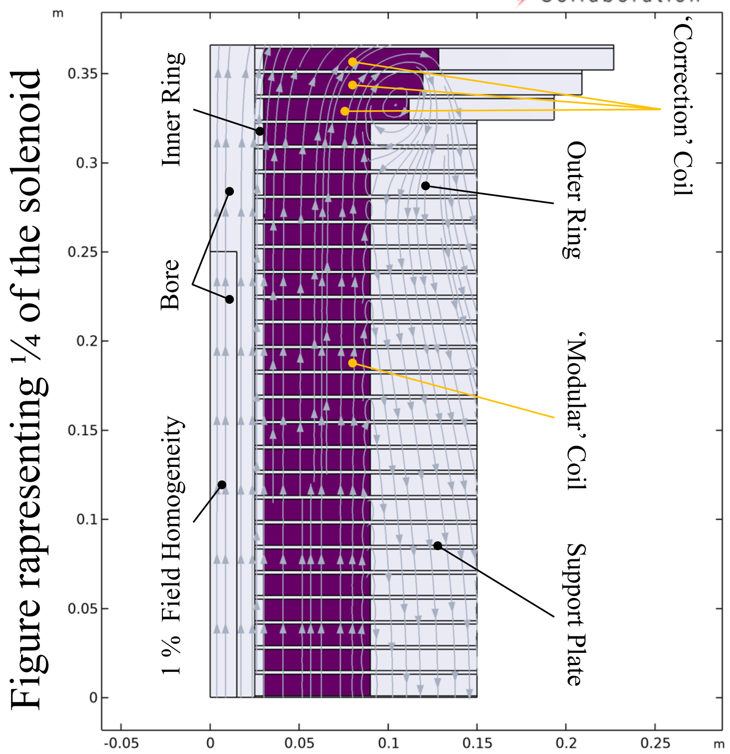
Picture taken from ref. 3

[1] https://www.fujikura.co.jp/eng/products/newbusiness/superconductors/01/superconductor.pdf
[2] K Ilin *et al* 2015 *Supercond. Sci. Technol.* **28** 055006
[3] Hideaki Maeda and Yoshinori Yanagisawa IEEE TAS, VOL. 24, NO. 3, JUNE 2014

Main Specs & Principles guiding the design study

- Main **Specs**: 1) **bore field > 40 T;** 2) **aperture 50 mm;**
  3) magnetic field **homogeneity 1 % over 0.5 m**

- **Principles** guiding this conceptual design **study** (based on a **stationary analysis** - dynamic studies to be performed at a later time)

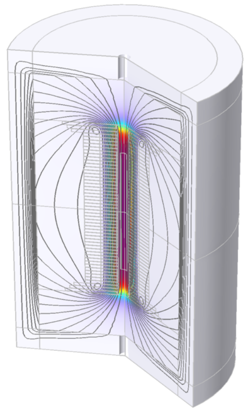


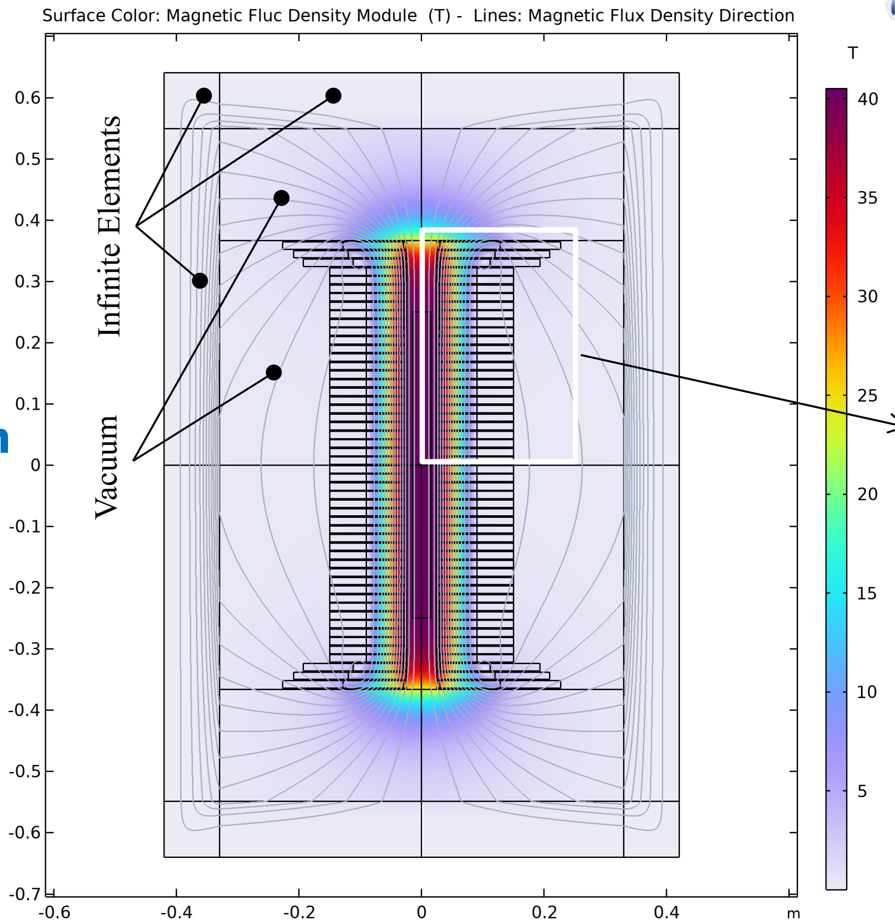
  - **non-insulated coils** (protection, mechanical robustness)
  - **avoid tensile radial stresses** (minimize the risk of critical current degradation)
  - **modular single layer pancakes** (design as simple and flexible as possible)
  - use as **wide** as possible **tapes** (12 mm, to **limit** the number of **pancakes**)
  - **intercept axial** Lorentz **forces** between pancakes via support plates (minimize the pancakes mechanical interactions)
  - In the 'modular' coils, maintain, as much as possible, the magnetic **field** lines **parallel** to the **tapes (minimize axial** Lorentz **forces** and **maximize** the conductor **critical current)**
    1. **current per tape < 1000 A** < estimated I_c(4.2 K, $B_{//}$ =50 T)
  - **Radially support** each **coil** via an **outer ring** that could eventually apply a **precompression** on the coil (**limit** the **hoop stress** and to **avoid tensile radial stresses)**

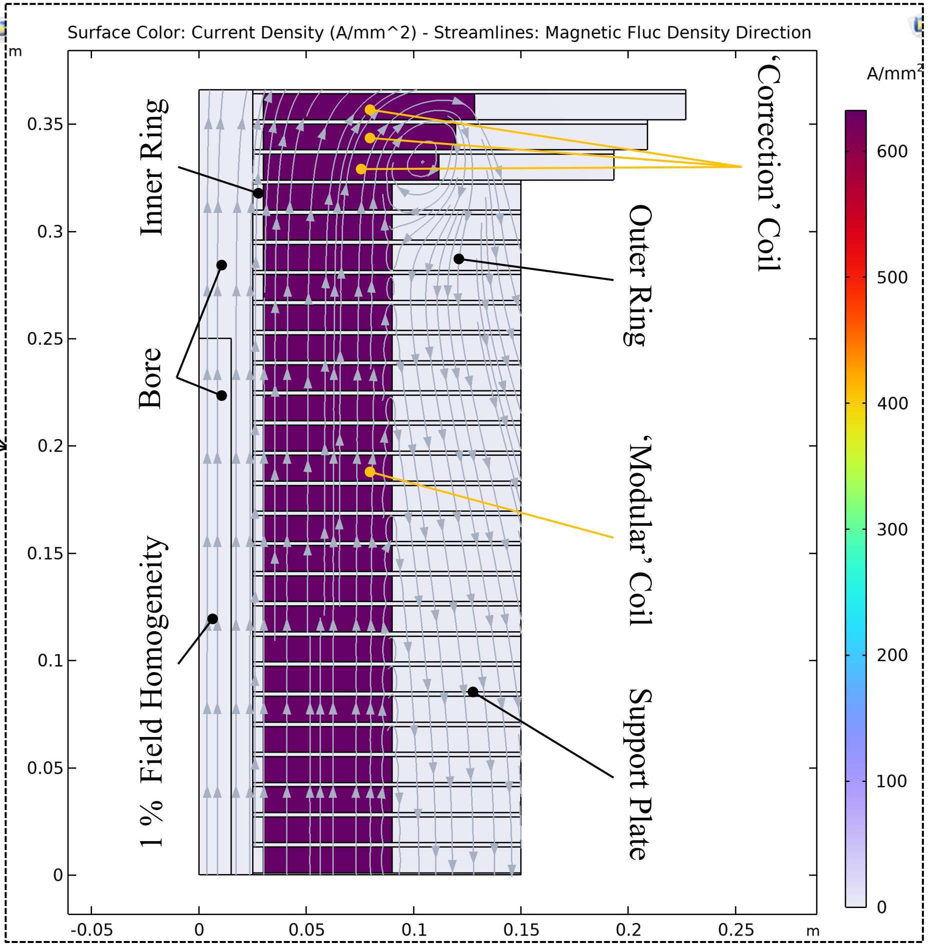
Reference Solenoid

Magnetic Field and Current Density Distribution

- **46** identical **'modular'** pancakes and **6 'correction'** pancakes
  - **Coil** of the **'modular'** pancake:
    1. **6 cm** thick
    2. **600** turns
    3. **12 mm** tape carrying **760 A**
  - **Outer** ring thickness **same** as the respective **coil**
  - **Inner** ring thickness **5 mm**
  - Support **Plate** thickness **2 mm**
  - **Bore** aperture **50 mm**



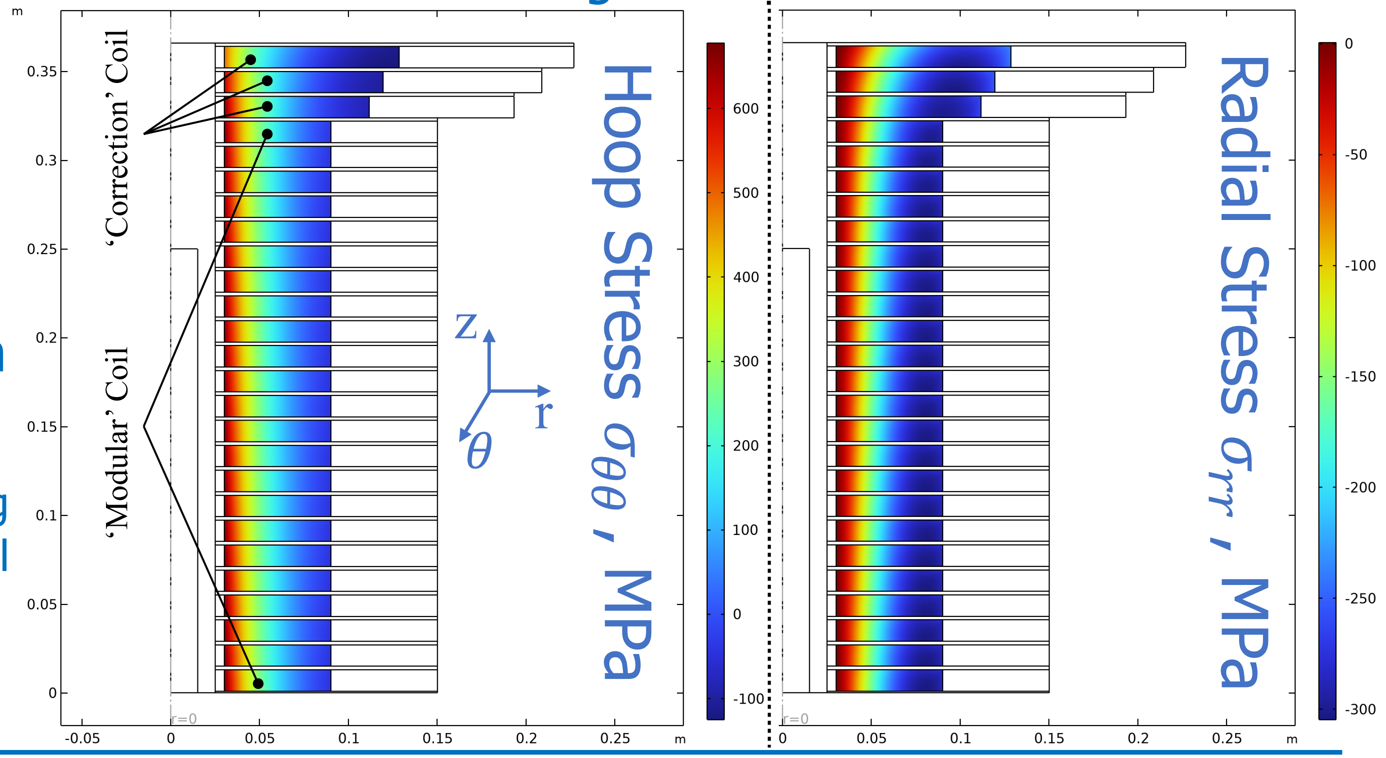




Reference Solenoid

Mechanical Stresses in the Coils

- Max **hoop** stress ($\sigma_{\theta\theta}$) **< 700 MPa** and **no tensile radial** stress ($\sigma_{rr} \leqslant 0$)
- **Outer ring** in stainless steel applying a **radial precompression** of **200 MPa** on the coil
- A **stiffer material** for the **outer ring** or a **reduction** of the **tape copper content** (now ~40%) would further **reduce** the **hoop stress** and the **risk** of having **tensile radial stress**
- **Coil young modulus: 150 GPa** (isotropic)
- **Compressive** stress in **thickness direction < 300 MPa**
- **Compressive** stress in **width** (z) **direction**
  - $-\sigma_{zz}$ **< 80 MPa** in the 6 **correction coils**
  - $-\sigma_{zz}$ **< 15 MPa** in the **modular coils** (assuming the support plate intercepting the whole axial force between two adjacent coils)
- **Shear stress** (σ_{rz}) **< 5 MPa**

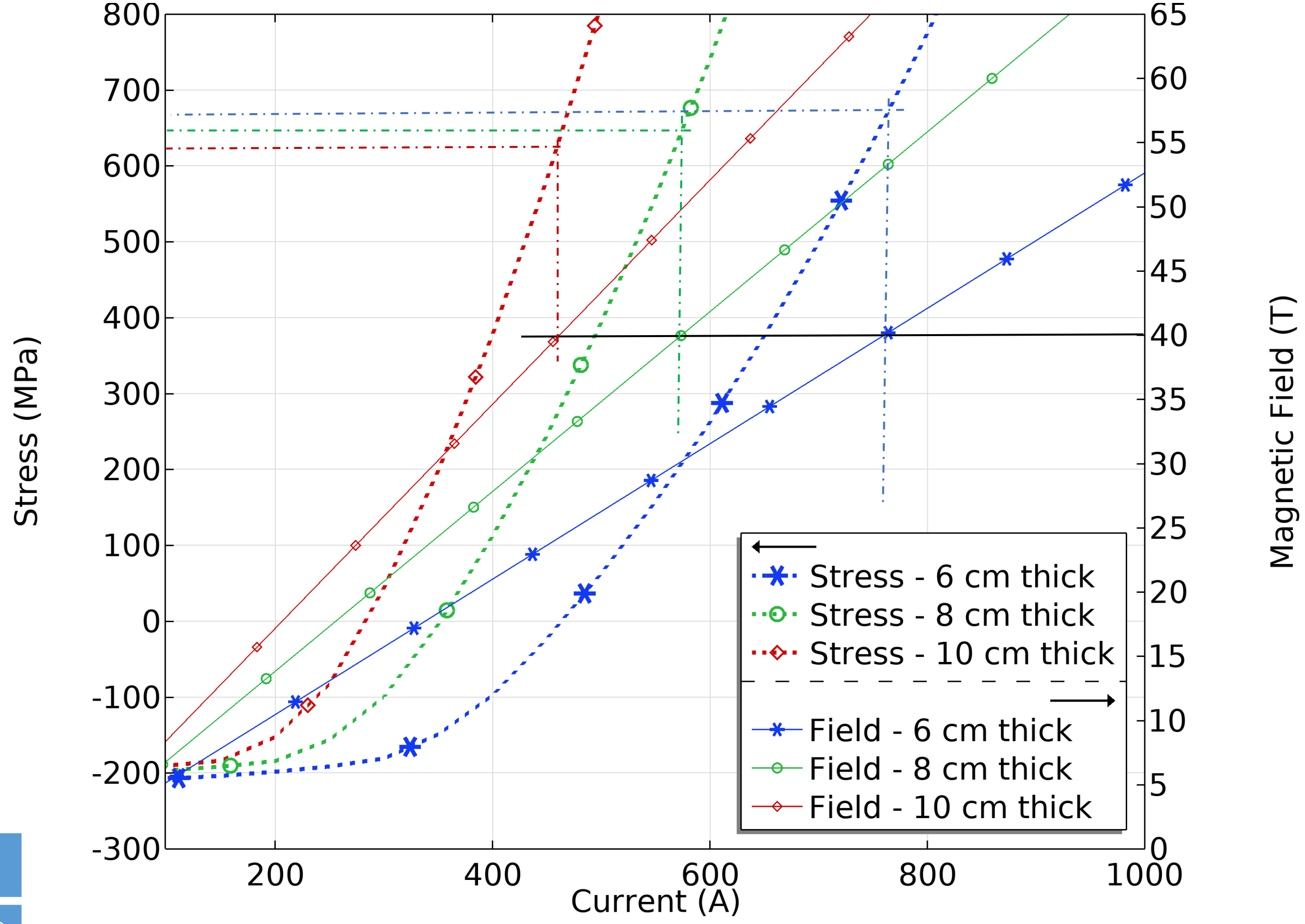


200 MPa Precompression

Hoop Stress vs Coil Thickness

- The **maximum hoop** stress in a 'modular' coil is almost **independent** on the coil **thickness** and is about **650 MPa** for a **40 T** solenoid
- At **50 T** the **hoop stress** largely **exceed** the **limit** of the conductor
- For a **single layer** pancake, **40 T** seems a reasonably **achievable target**

	Pancake thickness		
	10 cm	*8 cm*	*6 cm* (Ref.)
Current (*A*) to reach 40 T	461	574	760
Current (*A*) to reach 50 T	580	720	950



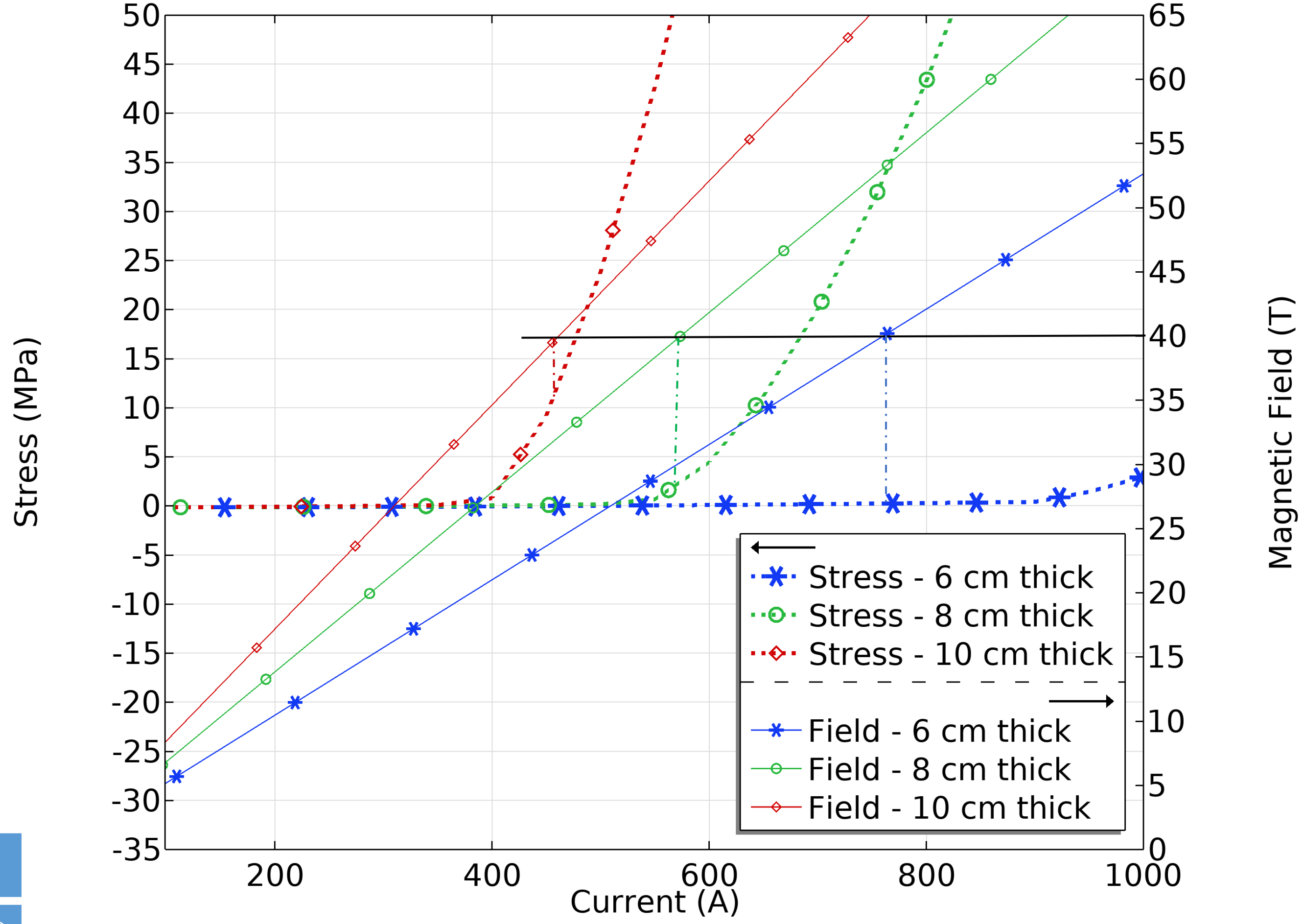
Bore **magnetic field** and **maximum hoop stress** in a 'modular' coil as a function of the tape current for **different coil thicknesses**.
The coil is constrained by a stainless-steel outer ring that has the same thickness as the coil and applies **200 MPa of radial pre-compression**

200 MPa Precompression

Radial Tensile Stress vs Coil Thickness

- The **maximum radial stress** (σ_{rr}) in a 'modular' coil of a 40⁺ T solenoid, **increases with** the coil **thickness**
- For a **40 T** solenoid, if the coil **thickness** is **8 cm** or larger, a **tensile radial stress appears** ($\sigma_{rr} > 0$) and that could cause conductor degradation
- A **6 cm thick** coil guarantees a **sufficient margin** to **prevent** the occurrence of **tensile radial stress** for a **40 T** solenoid

	Pancake thickness		
	10 cm	*8 cm*	*6 cm* (Ref.)
Current (*A*) to reach 40 T	461	574	760
Current (*A*) to reach 50 T	580	720	950



Bore **magnetic field** and **maximum tensile radial stress** in a 'modular' coil as a function of the tape current for **different coil thicknesses**. The coil is constrained by a stainless-steel outer ring that has the same thickness as the coil and applies **200 MPa of radial pre-compression**

'Modular' Coils: some numbers

	Coil thickness		
	10 cm	**8 cm**	**6 cm (Reference Solenoid)**
Max **Sustainable Current**[1] (radial tensile stress < 1 MPa)	400 *A*	550 *A*	930 *A*
I and ***J*** in the tape	400 *A* – 391 A/mm^2	550 *A* – 457 A/mm^2	760 *A* – 632 A/mm^2
Magnetic **Field** in the solenoid	34.6 *T*	38.3 *T*	40 *T*
Max **radial** compression [1]	250 *MPa*	275 *MPa*	300 *MPa*
Max tensile **hoop** stress [1]	378 *MPa*	559 *MPa*	660 *MPa*
Pancake **Inductance** *single tape conductor* [2]	1.22 *H*	0.62 *H*	0.27 *H*
Magnetic **Energy** x Pancake	98 *kJ*	93 *kJ*	77 *kJ*
Tape **length** x coil	503 *m*	352 *m*	226 *m*
Energy density in the coil [3]	170 J/cm^3	230 J/cm^3	300 J/cm^3

[1] Assuming a 200 MPa radial precompression imposed by a stainless-steel outer ring that has the same thickness as the coil
[2] The inductance would be ¼ of the reported one in the case of a double tape conductor
[3] For reference: the variation of enthalpy from 4.2 K to 195 K for the copper is about 370 J/cm^3

Conclusions

- **CERN** started to **investigate** the **possibility** of developing a **40$^+$ T solenoid** (fully based on ReBCO) for the **Muon Collider** and to **get** a **'feel'** for what the **limits** are
  - The **critical current** seems **not** to be a **limiting factor** for a 40-50 T solenoid
  - The **electro-mechanical design** will play a **decisive** role because the **stresses** on the conductor are **very large**
  - Considering the **electro-mechanical** behavior in **stationary** conditions, **40 T** appears a reasonably **achievable target** for the proposed design while **larger fields** would most likely require **double layers pancakes**, which would **increase** the design **complexity**

Much work to be done but the mission does not look impossible, and a success would be extremely beneficial for the community