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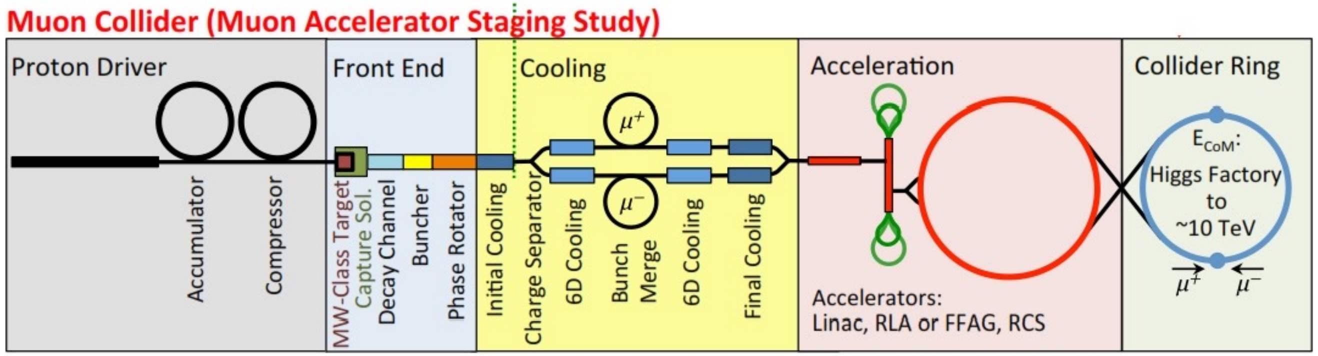
International
MUON Collider
Collaboration

Conceptual design of a ReBCO non-insulated 40+ T solenoid for the Muon Collider

B. Bordini, C. Accettura, A. Bertarelli,
L. Bottura, A. Dudarev, A. Kolehmainen,
T. Mulder, A. Verweij, M. Wozniak

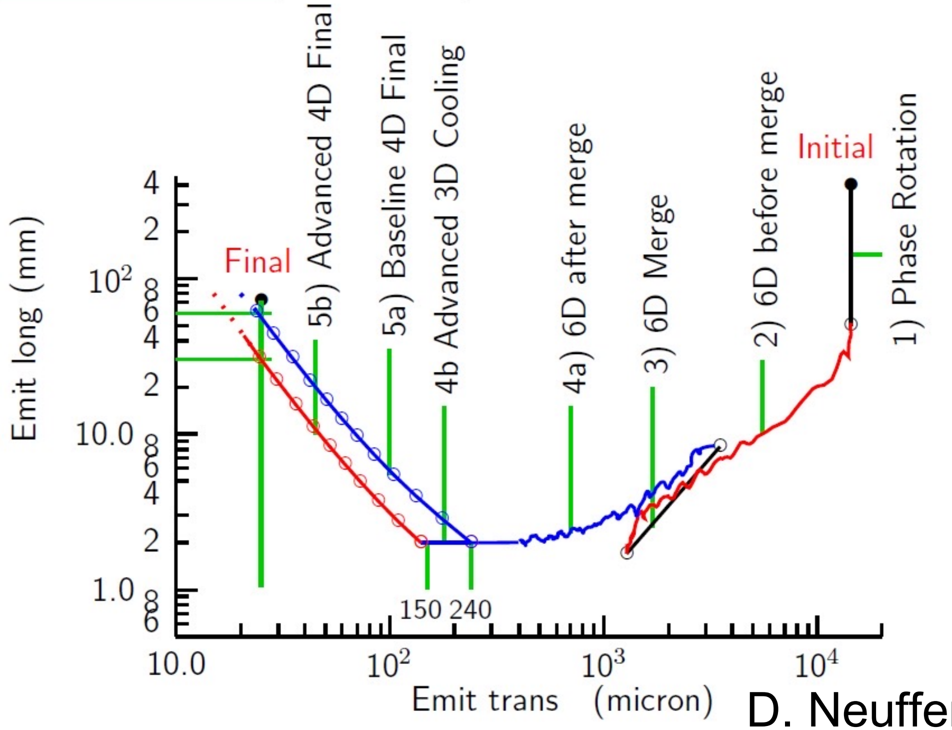
16th European Conference on Applied Superconductivity

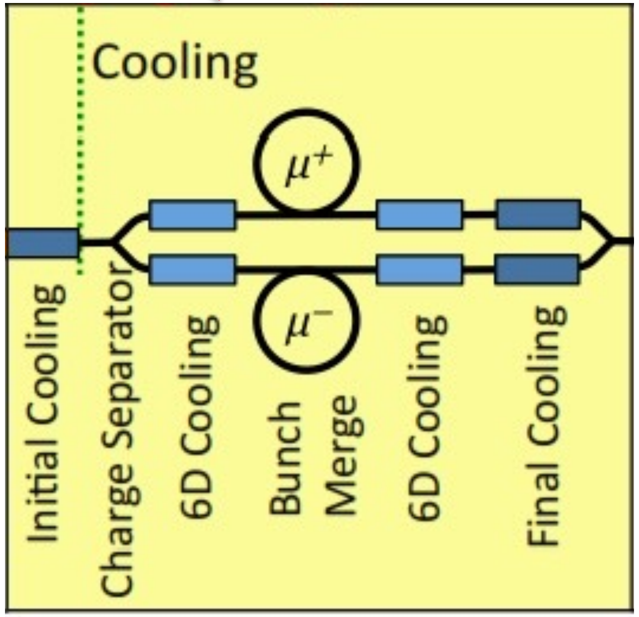
The Cooling System



- The **final cooling solenoid** is part of the **cooling system**

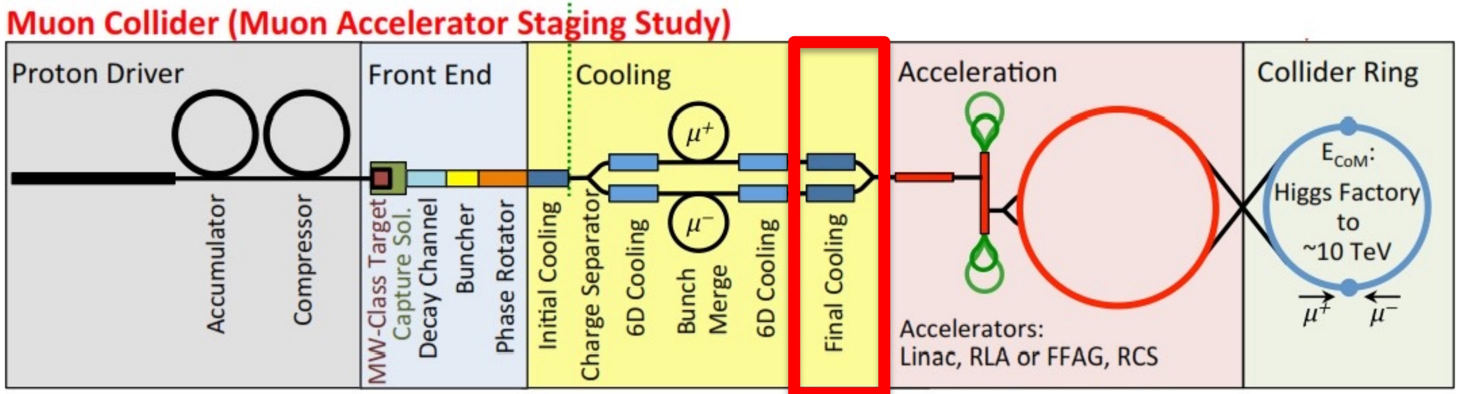
- The cooling system is designed to **reduce** the **transversal emittance** while **preserving** the **longitudinal emittance**



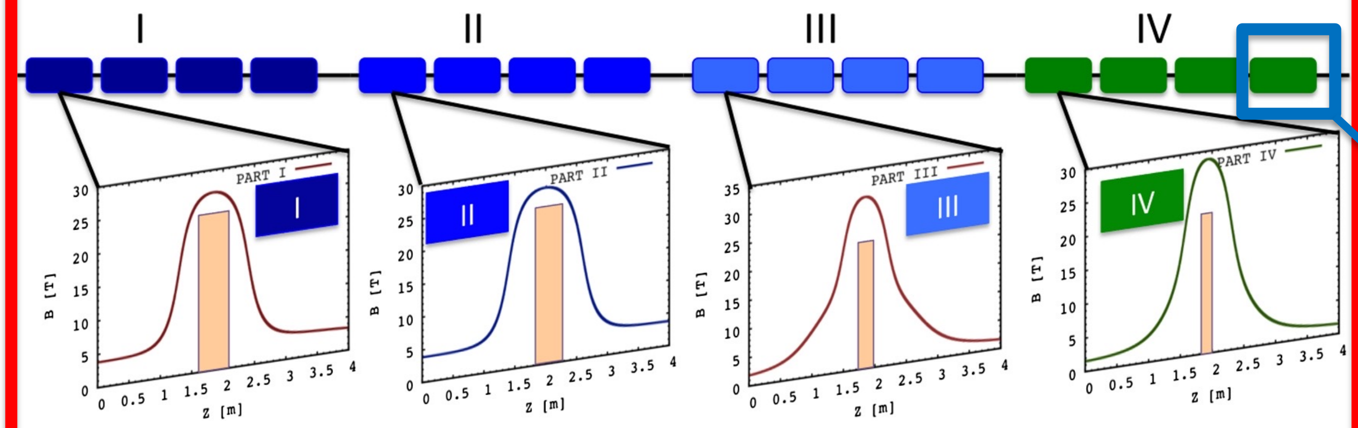


D. Neuffer et al 2017 JINST 12 T07003

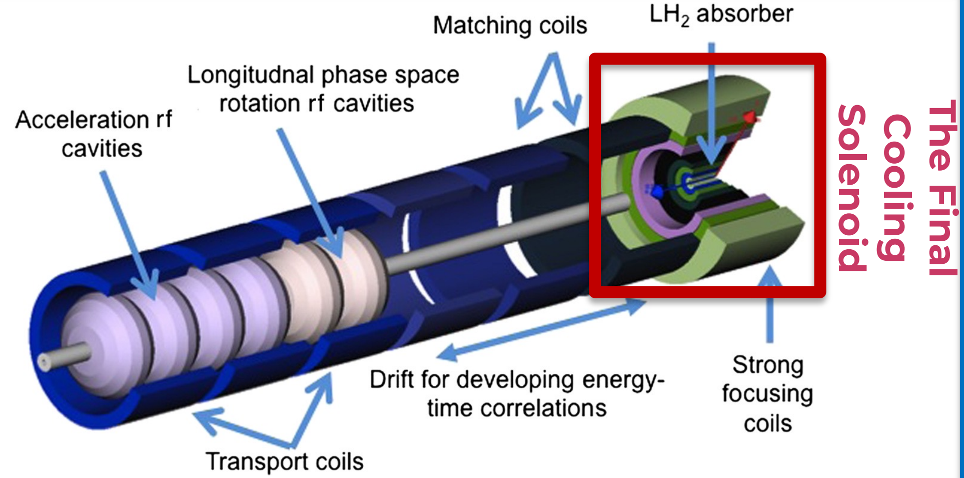
The Final Cooling Solenoid



- The final cooling solenoids are part of the the **final cooling channel**, which is constituted by several **cooling cells**
  - **16** were proposed by the MAP study
  - **14** are presently considered by IMCC



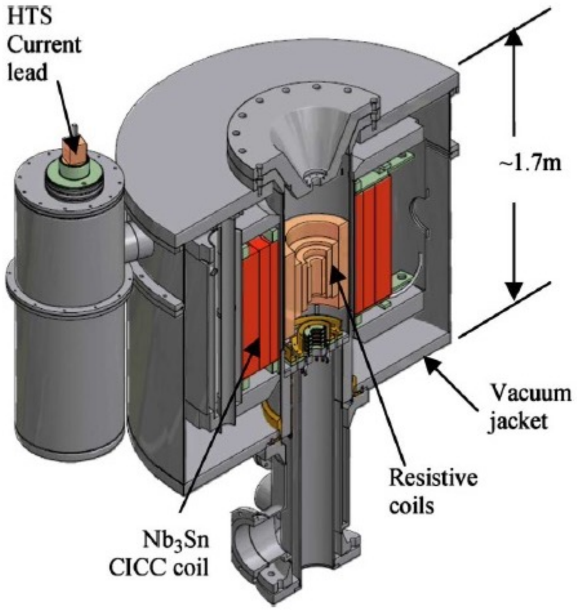
A layout schematic of **16 cells** of the **final cooling channel** defined by the MAP study (Sayed et al. Phys. Rev. ST Accel. Beams **18**, 091001). The coloured boxes in the top represent the **cooling cells.** The bottom figures show a sample of the on-axis field of the strong focusing solenoid; the shaded areas show the corresponding absorbers lengths.



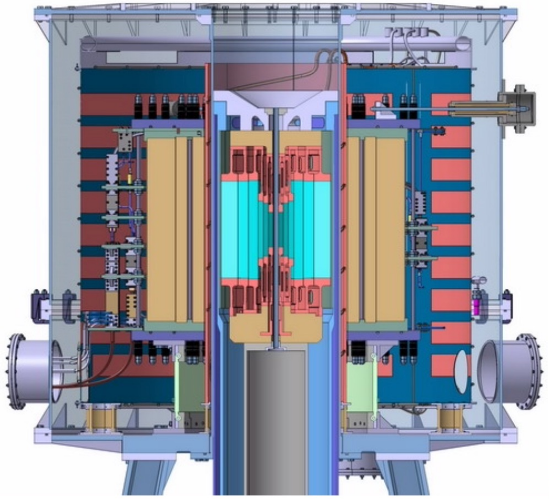
Schematic of the elements of one ionization **cooling cell**, Sayed et al. Phys. Rev. ST Accel. Beams **18**, 091001

Main Specs & State of the art

- **Main specs** used for the CERN conceptual design
  - **B ≥ 40 T**, aperture $\phi \geq$ **50 mm**,
  - field **homogeneity 1 %** over **0.5 m**
  - **Energizing** time **6 hrs** and **persistency 0.1 Units/s**
- Presently, in the world, only **two solenoids** can produce **B ≥ 40 T** in a free bore with a diameter no much smaller than **50 mm**
  - One at the National High Field Magnet Laboratory (**NHFML**) in the **US** and the other at the **Chinese** Field Magnet Laboratory (**CHFML**)
  - These two solenoids are both **Hybrid Magnets**: 33.5/29 T from **resistive insert**, 11.5/11 T by superconducting outsert
  - their **large power consumption** is **unacceptable** for accelerator magnets



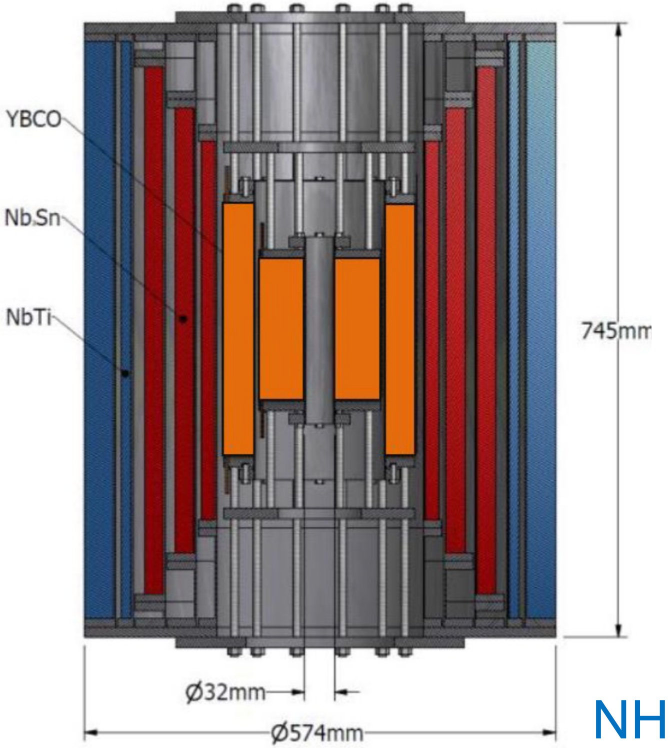
Cross section of 45 T, 32 mm **NHFML** user facility solenoid 30 MW power comsumption

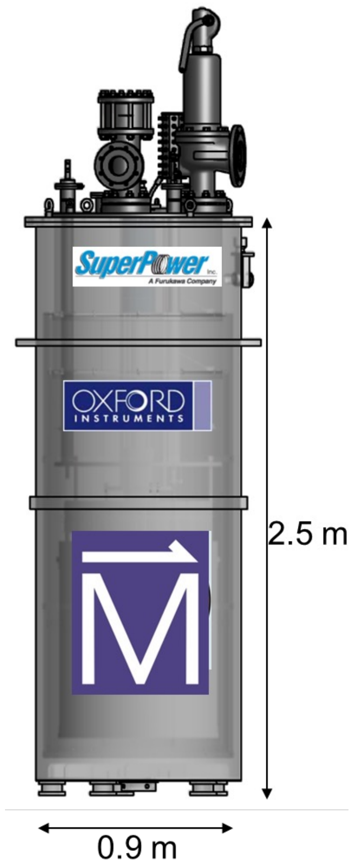


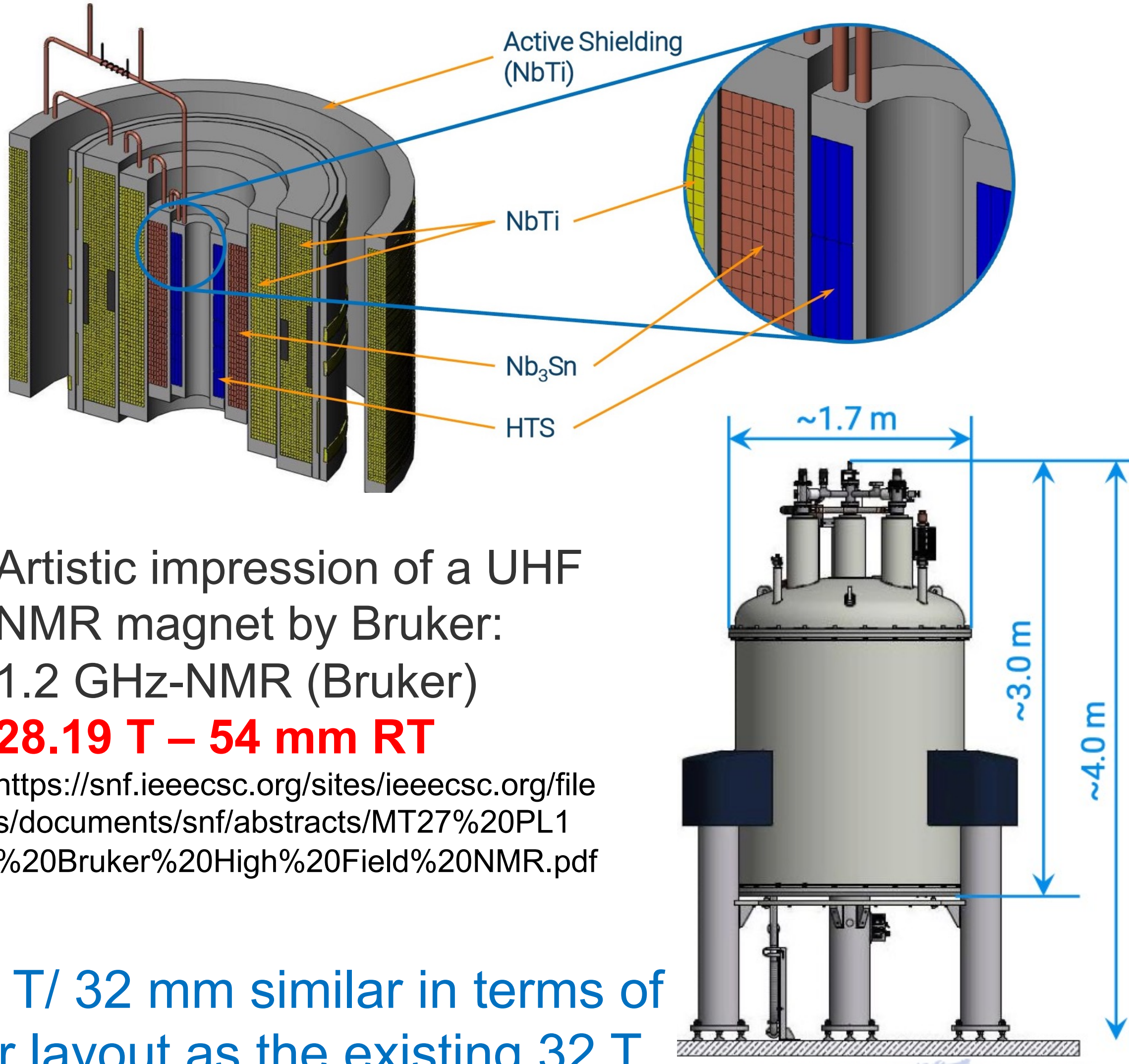
Cross section of 40*/37 T, 32/50 mm **CHMFL** user facility solenoid 20 MW power comsumption

State of the Art Ultra High Field Full Superconducting Solenoids

Cross section of **32 T** (15 T LTS, 17 T two ReBCO double pancake coils), **32 mm** user facility solenoid
https://nationalmaglab.org/user-facilities/dc-field/magnets-instruments/





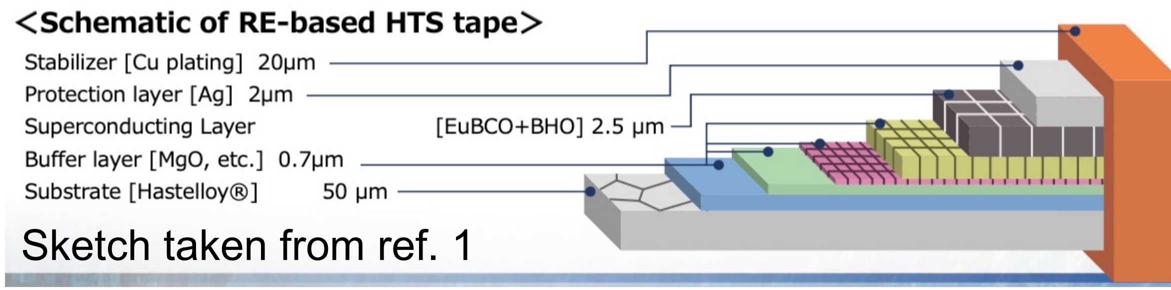


Artistic impression of a UHF NMR magnet by Bruker: 1.2 GHz-NMR (Bruker)
28.19 T – 54 mm RT
https://snf.ieeecsc.org/sites/ieeecsc.org/files/documents/snf/abstracts/MT27%20PL1%20Bruker%20High%20Field%20NMR.pdf

NHMFL is now developing a 40 T/ 32 mm similar in terms of dimensions and superconductor layout as the existing 32 T

Electro-mechanical Properties of the ReBCO tape

- For a **12 mm wide tape**, we can assume critical current I_c values of this level
  - Measured[2] at 4.2 K: I_c ($B_\perp$=15 T) ~ 1.8 kA;
    I_c ($B_{/\!/}$ =15 T) ~ 5.4 kA
  - Estimated at **4.2 K**: I_c ($B_\perp$=50 T) ~ 300 A;
    I_c ($B_{/\!/}$ =50 T) > 1000 A



Sketch taken from ref. 1

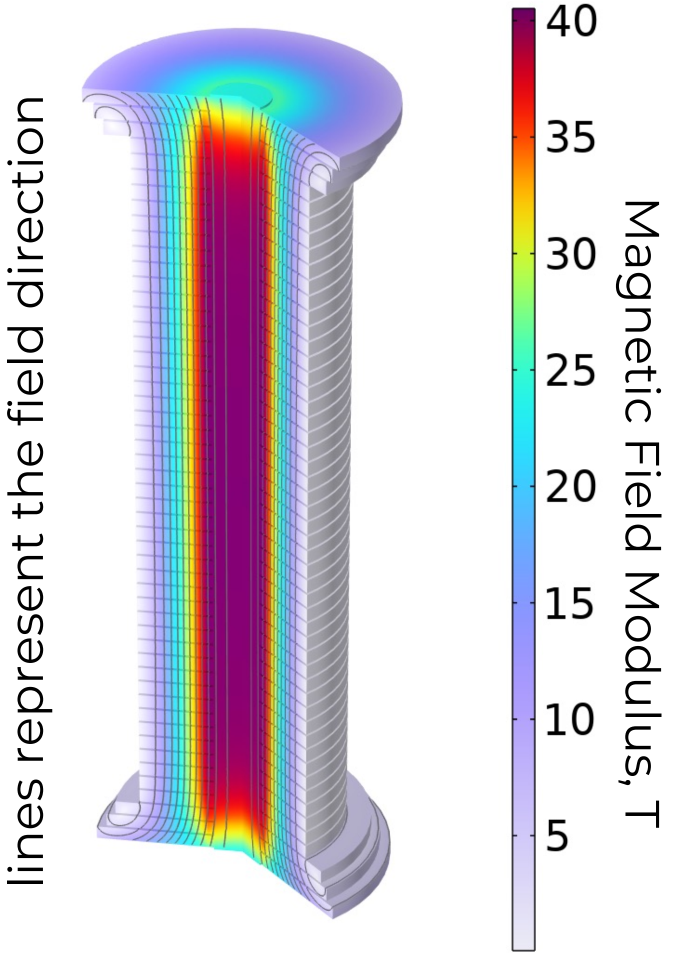
[1]https://www.fujikura.co.jp/eng/products/newbusiness/superconductors/01/superconductor.pdf
[2] Shinji Fujita, Satoshi Awaji et al. IEEE TAS, VOL. 29, NO. 5, AUGUST 2019
[3] Hideaki Maeda and Yoshinori Yanagisawa IEEE TAS, VOL. 24, NO. 3, JUNE 2014

- **Mechanical stresses** producing **irreversible I_c reduction**
  - **Tensile longitudinal strain > 0.4 %**[1] (600-800 MPa depending on the Hastelloy fraction)
  - **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]**

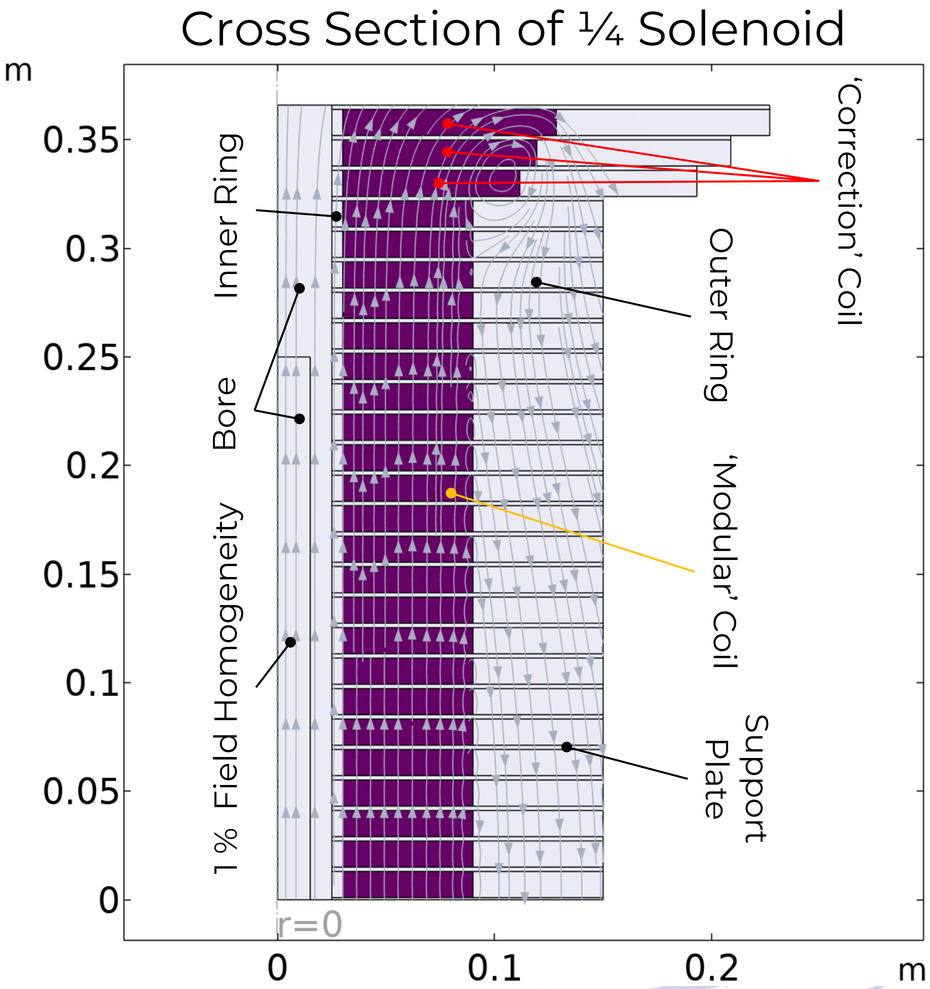
Picture taken from ref. 3

40⁺ T Conceptual design
Reference Layout

- **46** identical **‘modular’** and **6 ‘correction’** pancakes



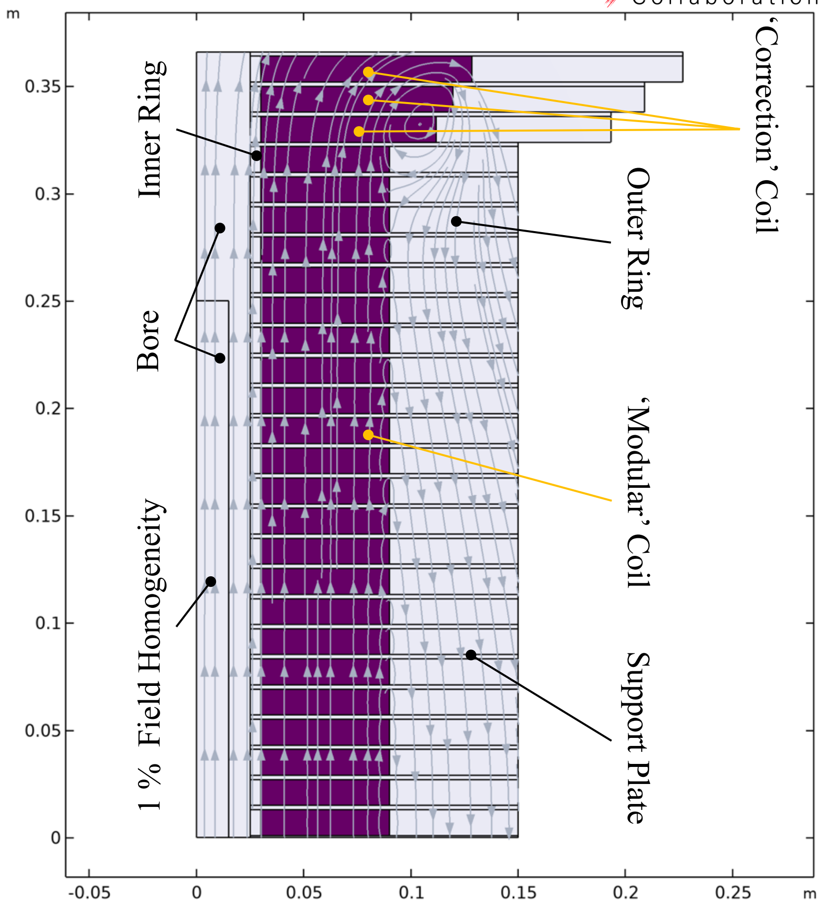
- **‘modular’** pancake:
  - Bore **aperture 50 mm**
  - Inner ring thickness 5 mm
  - Coil **winding thickness 6 cm**
    - R_o = 9 cm !!! ; R_i = 3 cm
  - Tape Width 12 mm
  - Outer ring thickness *X* times (>1) coil winding thickness
    - If *X*=1 (3) → R_o = 15 (27) cm
  - Support Plate thickness 2 mm
  - **J_e = 632 A mm^{-2} → 40 T**



Principles Guiding the study 1/2

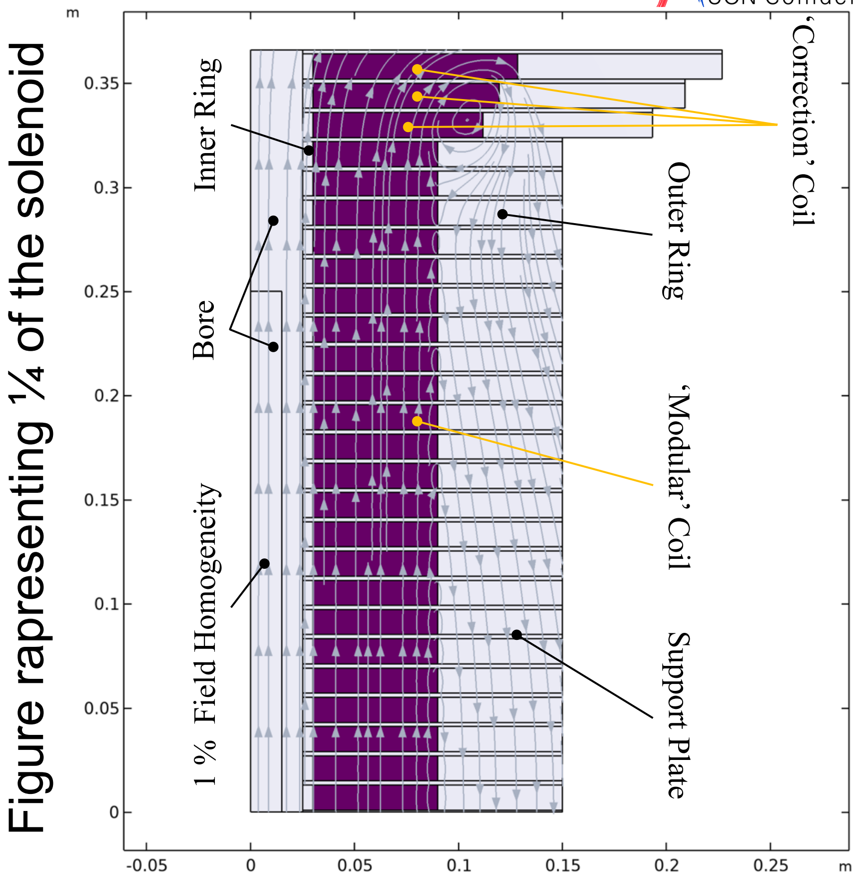
- **J_e > 500** A mm^{-2}
  - limit **costs** and **dimensions**
- **Modular Single** coil **pancakes** (not nested coils)
  - **simplify** the **design**, the magnet **system** and the **protection**
- **Non/metal insulated** coils
  - **protection**, mechanical **robustness**, high J_e
- **Avoid tensile radial stresses** and limit the **hoop strain** to values **lower** than **0.4 %**
  - **minimize** the **risk** of I_c **degradation**
- **Radially support** each pancake **via** a stiff **outer ring** that also applies a radial **precompression** on the coils
  - **limit** the **hoop strain** and **avoid tensile radial** stresses

Figure rapresenting ¼ of the solenoid



Principles Guiding the study 2/2

- Maintain the magnetic **field lines** practically **parallel** to the **tapes** in the **'modular'** coils
  - **minimize axial** Lorentz **forces** and **maximize I_c**
- **Intercept axial** Lorentz **forces** between pancakes via **support plates**
  - **minimize** the pancakes **mechanical interactions**, **avoid** the **accumulation** of axial forces
- Use as **wide** as possible **tapes**, 12 mm
  - to **limit** the number of **pancakes**

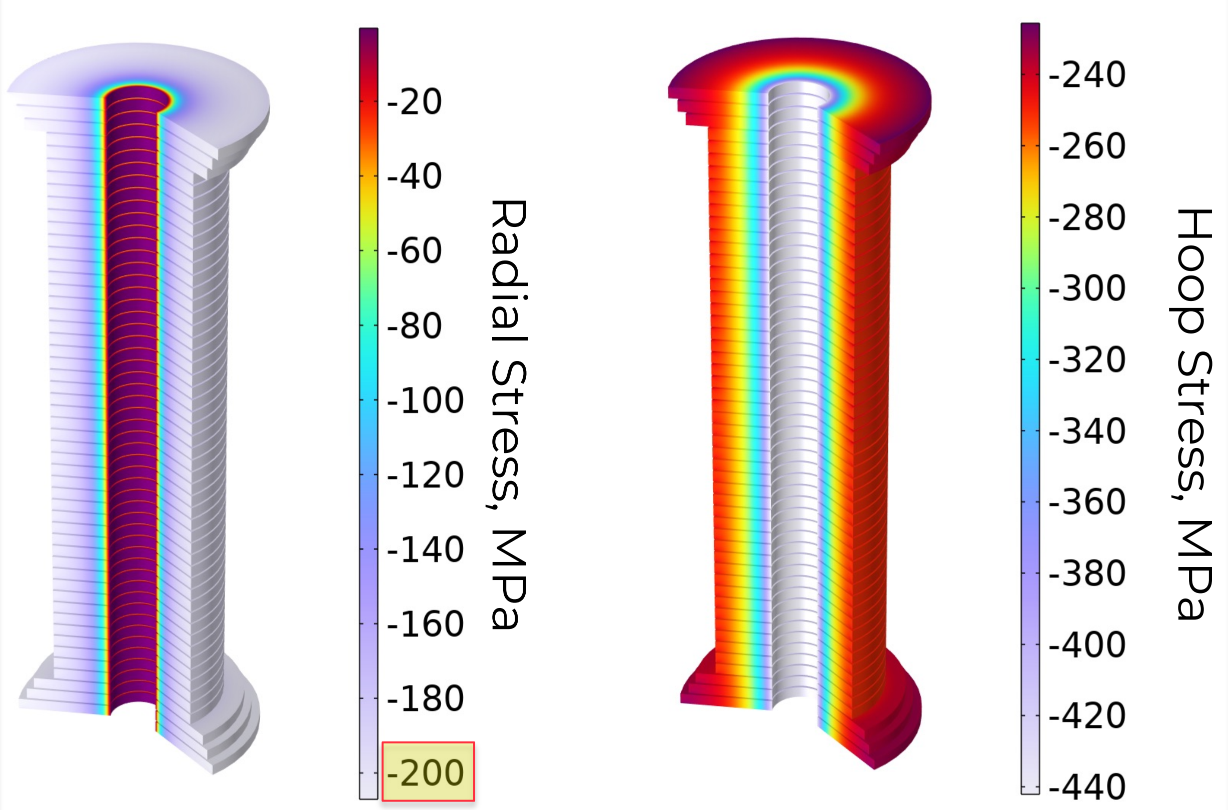


- **Robust design** for the **'correction'** coils, to **account** for the not negligible **axial forces** (significant radial fields) and the conductor **magnetization** (tape striations ?)
  - **protection**, mechanical **robustness**

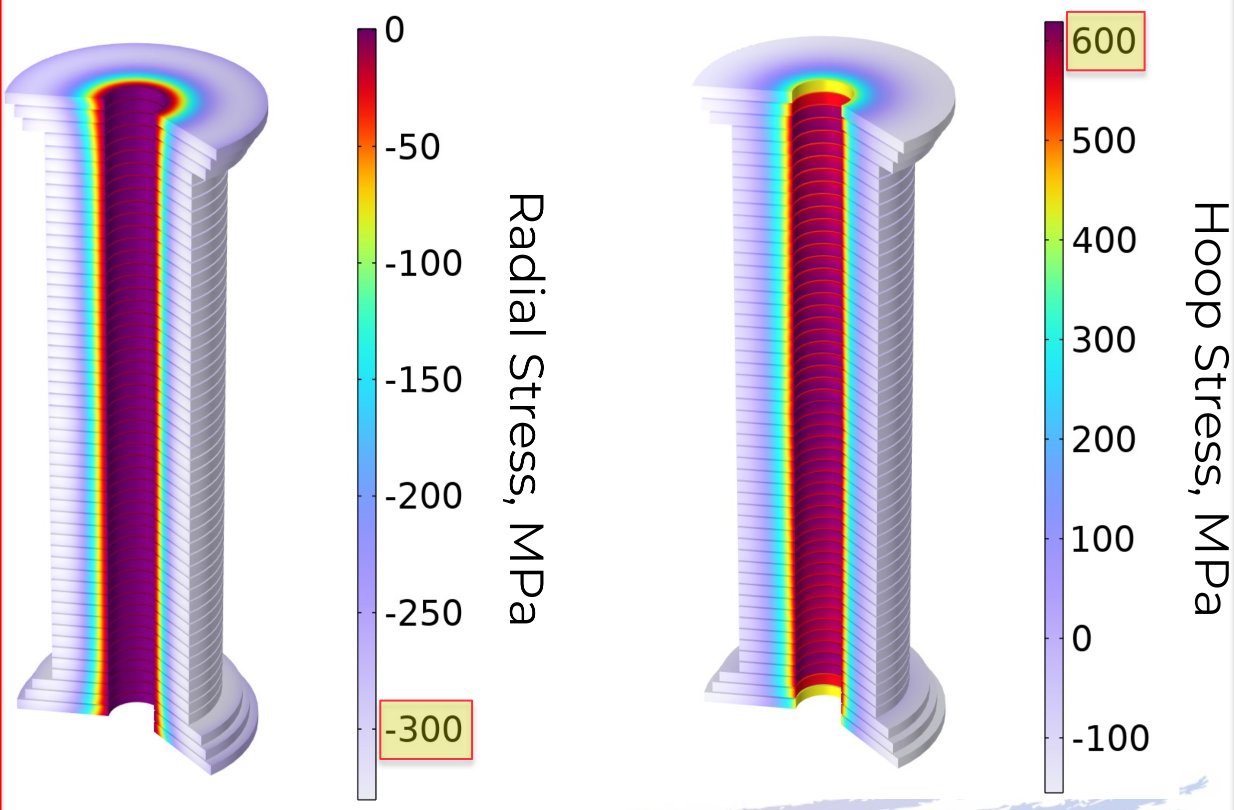
Mechanical Analysis I
main findings 1/2

- A radial **precompression** of **~ 200 MPa** is **essential** to **limit** the conductor **hoop stress** to acceptable values and to **prevent tensile radial stress**

Solenoid not Energized



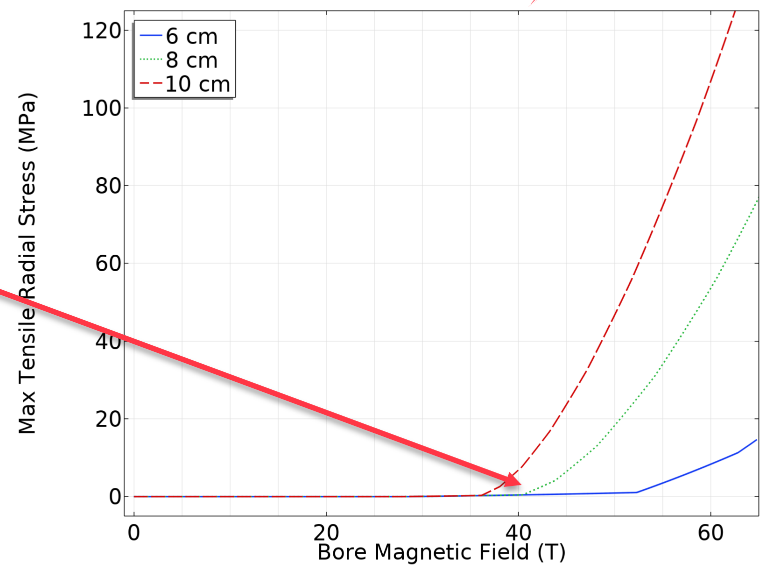
Solenoid Energized to 40 T

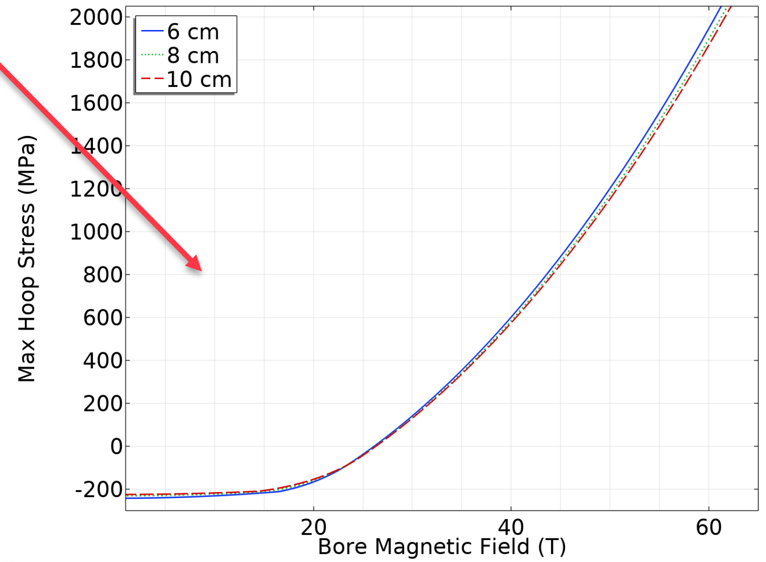


Mechanical Analysis I main findings 2/2

- In the assumption of a **200 MPa radial precompression** and an **outer ring** as **thick** as the **coil,** we concluded
  - coil **thickness** must be **smaller** than **~ 8 cm** to **avoid radial tensile stress** at field larger than **40 T**
  - The **maximum hoop stress** does **not depend much** on the **coil thickness** and for fields **larger** than **40 T**, the **maximum hoop stress** gets **too large**
    - Passing **from 40 to 50 T**, it almost **doubles**
  - At 40 T, the **shear** and **axial stresses** due to **Lorentz forces** appear low and do **not** look **critical**

- This **analysis** does **not account for**: stresses due to **magnetization** and **quench cases**
  - **to limit** the impact of the **magnetization**, **striated tapes** are considered for the **correction coils**

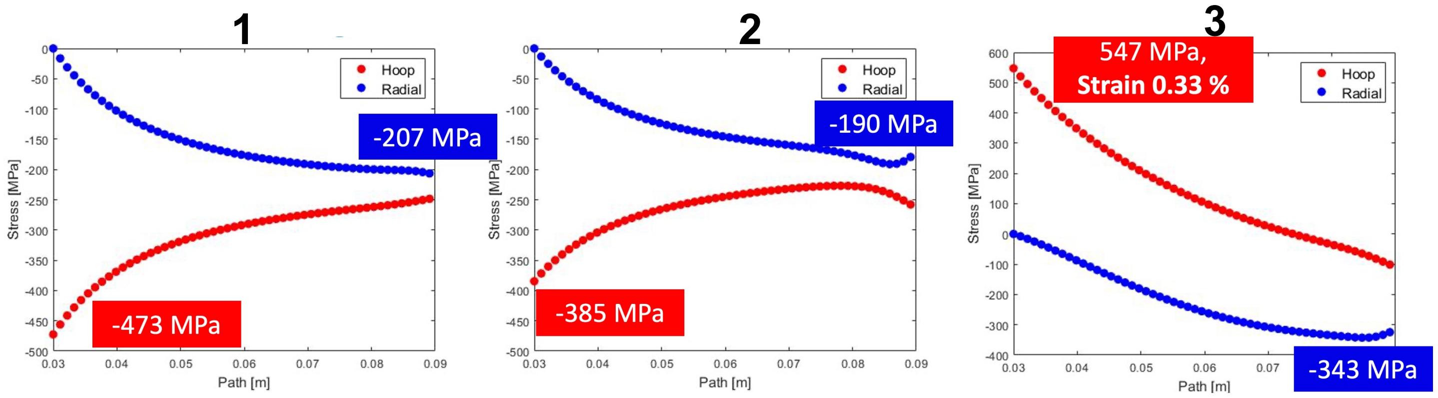


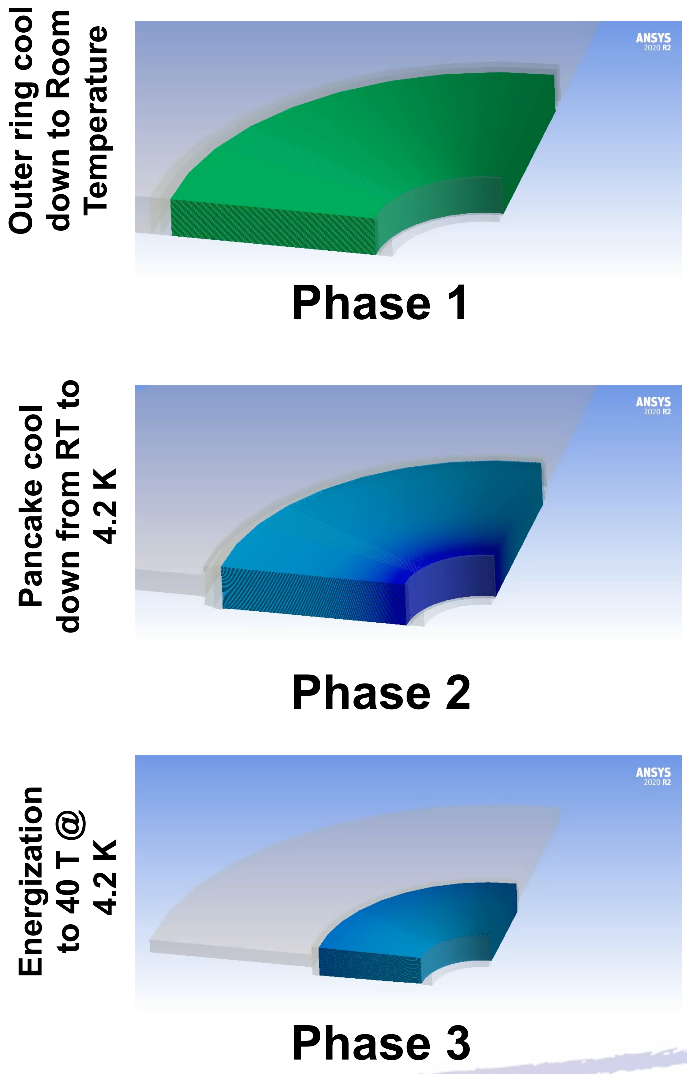


Mechanical Analysis II
Precompression

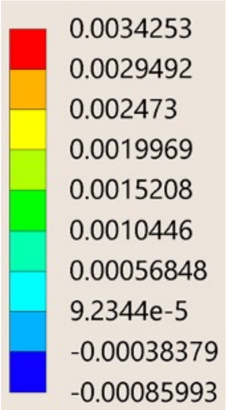
- **200 MPa** precompression **feasible** via **shrink fitting** by using an outer ring about **3 times** thicker (~18 cm) than the coil
  - Other solutions for the precompression are also studied
- Calculated **stresses** and strains are **well below** the **limits** of the superconductor

Hoop and Radial Stress profiles at the end of the 3 different phases





The colored region is the coil of a 'modular' pancake, the color represents the **hoop strain**

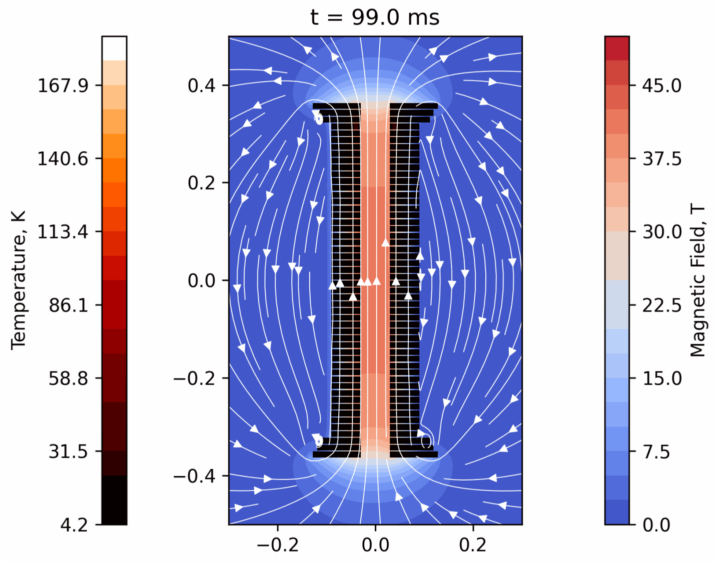


Animations and analysis courtesy of C. Accettura

Consideration about Protection

- In HTS coils, because of the very **large enthalpy margin**,
  - the **quench detection** via **voltage measurements** is very **complex**
  - the use of **quench heaters** is **not practical** for uniformly quenching the whole coil
- **Not/Metal-Insulated (N/M-I)** coils could be the solution to **protect HTS solenoids**
  - The relatively **low resistance** between turns may allow **rapid quench propagation** and less localized energy deposition
  - N/M-I coils would also allow using **QD** method based on the **fast magnetic flux variations** occurring in such coils during quenches
  - Once the quench would be detected, the whole solenoid could be **quenched** by **injecting** a **pulsed current** into the solenoid
    - The main advantage of this quench strategy is to get a quite **symmetric** and **controlled quench** where the generated **mechanical forces** would be **known** and **reproducible.**

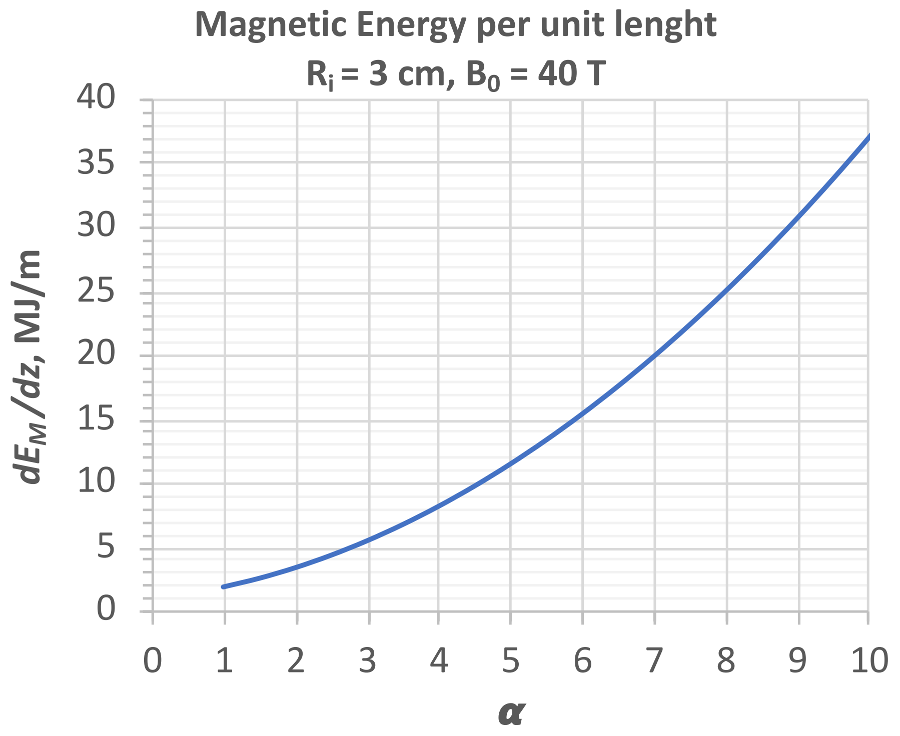
Quench at 40 T starting from the first 'modular' coil from the top: in the coil the colour represents temperature; in the remaining domain the magnetic field



Simulation and Animation courtesy of Tim Mulder

Protection Consideration
Magnetic Energy

- Thanks to the **small dimensions** of the pancakes, the **magnetic energy** of the solenoid per meter length (dE_M/dz) is **limited**
  - Assuming $\boldsymbol{R_i = 3\ cm}$, $\boldsymbol{R_o = 9\ cm}$ (proposed design, $\alpha = 3$) and $B_0 = \boldsymbol{40\ T}$ → $\boldsymbol{5.4\ MJm^{-1}}$
  - $5.4\ MJm^{-1}$ corresponds to about an energy density in the coil of **300 J/cm³** ;
  - if **uniformly discharged only in the coil**, $5.4\ MJm^{-1}$ would **not** increase the coil temperature **above 200 K**



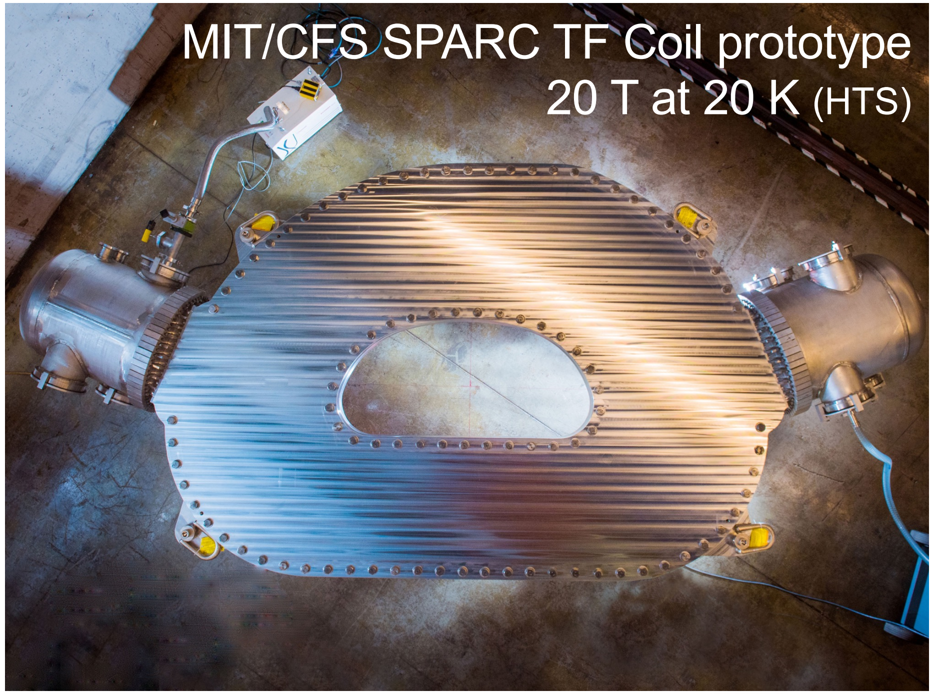
Operation

- The required **energization time**, **6 hrs**, seems **achievable** for **Not/Metal Insulated coils**

- The surface **contact resistance** can be **increased** by **reducing** the **Cu** content in the conductor, **especially** on the tape **edges**, and/or interposing a **resistive metal tape** in between the turns, or …
- **Studies** for **defining** the proper surface **contact resistance** and **how** to **achieve** it consistently, also **considering** the magnet **protection** and the required field persistency, are **on going**
  - To meet operation requirements, **other solutions**, as **correction coils** or a **power supply** with **active feed-back**, are **also considered**

Relevance to Science and Society of not/metal insulated ReBCO coils

- The **potential** of a **large coils' cost/mass/volume reduction** and of operating **at 20 K**, makes this technology extremely attractive for:
  - The **Sustainability** of medium/large particle **accelerators**
  - **Compact/Modular Fusion Reactor** based on magnetic confinement
  - **High Field Science**



Relevance to Science and Society of not/metal insulated ReBCO coils 2/2

- The development of this **technology** could also strongly **impact**
  - **Nuclear Magnetic Resonance** (see previous slides)
    - **higher fields** to improve **resolution** of the resonance spectra and the acquisition **speed**
  - **Magnetic Resonance Imaging**
    - Large bore (900 mm), high-field (11.7 T) and high-homogeneity solenoids, in persistent- or quasi-persistent mode. Nb-Ti technology is dominant but there is **strong interest for HTS**, especially for **cryo-free operation**.
  - **Wind turbine generators**
    - Compact generator essential ingredient for large turbines, the trend is now for >> 1 MW turbines

UHF MRI magnet (11.7 T, 900 mm bore, full body) developed by CEA/Alstom

Courtesy of L. Quettier

(left) The 3.6 MW EcoSwing HTS generator (blue, 4 m diameter) next to its conventional counterpart with the same power rating (red, 5.4 m diameter), prior to (right) its lift onto the turbine
https://www.utwente.nl/en/tnw/ems/research/sust/EcoSwing/

Conclusions

- The proposed **conceptual design** shows the **potential** for developing a **compact 40 T - 50 mm** final cooling **solenoid** with extremely compact dimension of the coil **R_o=9 cm**
- **Two** main **criticalities** have been **identified**:
  - The **electro-mechanical** design → **stresses** on the **conductor** are very large
  - The **electrodynamics** and **protection** of the magnet → **complex transients** to control
- The conductor **critical current** seems **not** to be a **limiting** factor while improving the conductor electro-mechanical properties would be beneficial
- **If successful**, this technology would be a **game changer** not only for **particle accelerators** but also to several other **societal applications**

Thank You For the Attention

16th European Conference on Applied Superconductivity

APPENDIX

Technologies

Technology	Pro's	Con's
Hybrid SC (LTS) + **resistive** Insulated Nested Coils	**Known technology** (TRL 9)	Large dimension and mass **Electric power** consumption
All SC, LTS + HTS Insulated Nested Coils	**Known design principles** Synergy with other fields of science application Can profit from development by others (e.g. NHMFL)	**Large dimension and mass** Developmental technology (TRL 6/7)
All SC, **HTS** Insulated Nested Coils	More compact than LTS/HTS Allows for operation at **higher temperature**	R&D at **low readiness** (TRL 4/5)
All SC, HTS **Non/Metal-insulated** Nested Coils	**Same** as **previous case** (row) **+** even **more compact,** with an **increased magnet stability** and **reduced risk** of **burning** the magnet. **Potential** of reaching even **larger fields** with **respect** to the **single coil** solution (next row). **Synergies** with **other fields of science** and **societal applications**. Can profit from development by others (e.g. NHMFL)	R&D at **low readiness** (TRL 3/4/5) **Ramping time**, **field stability** need, and **electro-mechanical** behavior during **fast transients** to be demonstrated
All SC, HTS Non/Metal-insulated **Single Coil** (No Nested)	**Same** as **previous case** (but the max. field potential) **+** even **more compact, with a lower risk** of **burning** the magnet**, simpler to protect, reduced number of** coils (one per pancake) and **joints**. Significant **cost/volume/weight reduction** for **20-40 T solenoids.**	**Same** as **previous option** (row) including TRLs + mechanical **precompression** (B>30 T) need **to be demonstrated**

- We chose the all-HTS NI/MI Single Coil (pre-compressed) option because of its very high potential (for future particle accelerator and other societal applications) and because nobody is pursuing it (as far as we know)