Present challenges for future accelerator magnets

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Outline:

- *Why superconductors?*
    - *The Large Hadron Collider*
    - *Niobium-titanium (Nb-Ti)*
- *Why Nb-Ti is not enough?*
    - *High Luminosity LHC (HL-LHC) and Future Circular Collider (FCC)*
    - *Niobium-tin (Nb_3Sn)*
- *Challenges of Nb_3Sn magnets*
- *Path toward solutions*

Why Superconductors?

Superconductors are better than normal materials

In a perfect superconductor: R = 0 Ω

No power consumption except for refrigeration

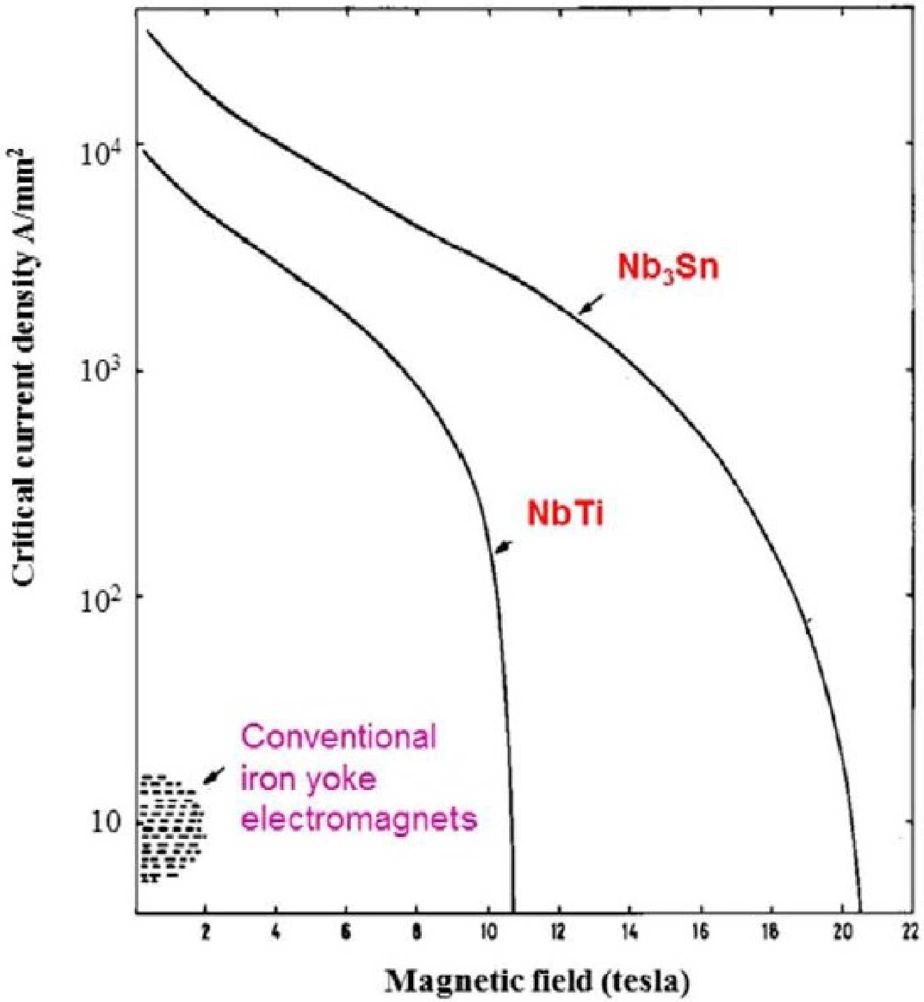
→ *lower power costs*

High current density

→ *compact windings / less volume*
→ *high magnetic fields*
→ *high energy*
→ *high gradient*
→ *high luminosity*

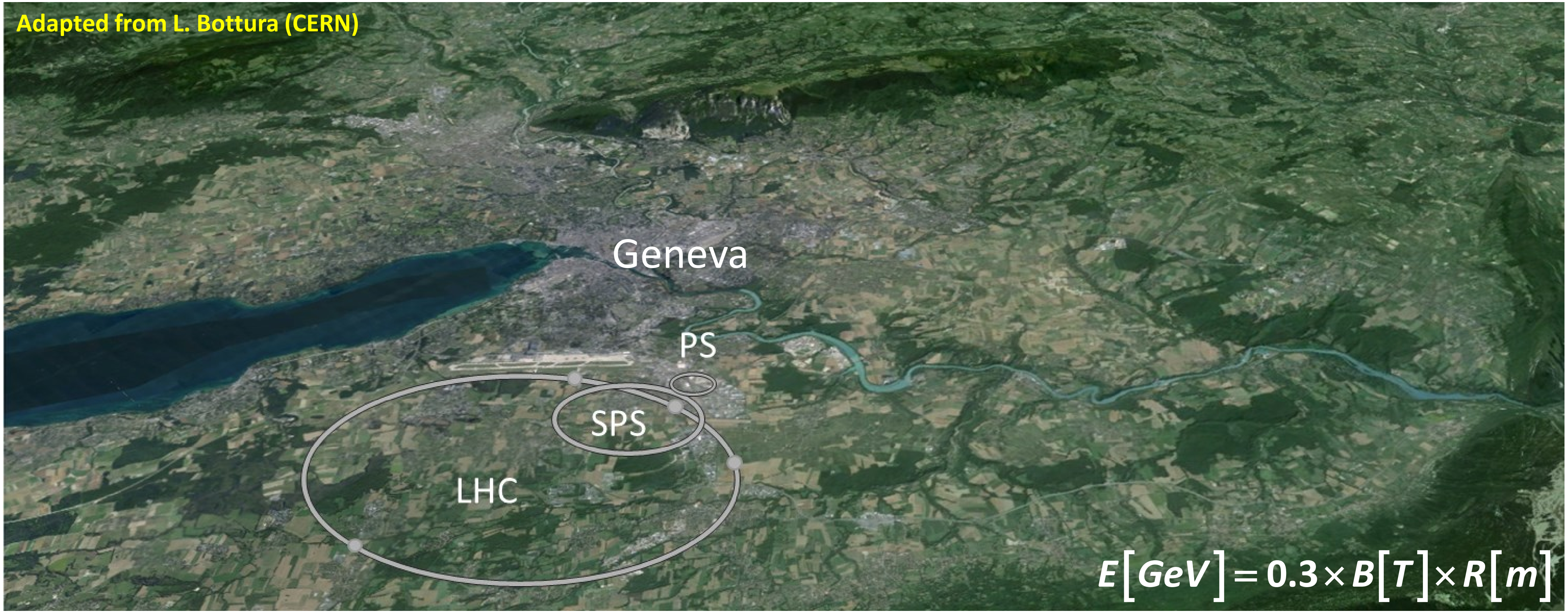
But superconductors suffer losses when the magnetic field change

Critical current density lines at 4.2 K



Wilson, M. N. *Superconducting Magnets. (Clarendon Press, 1983)*

The Large Hadron Collider



LHC

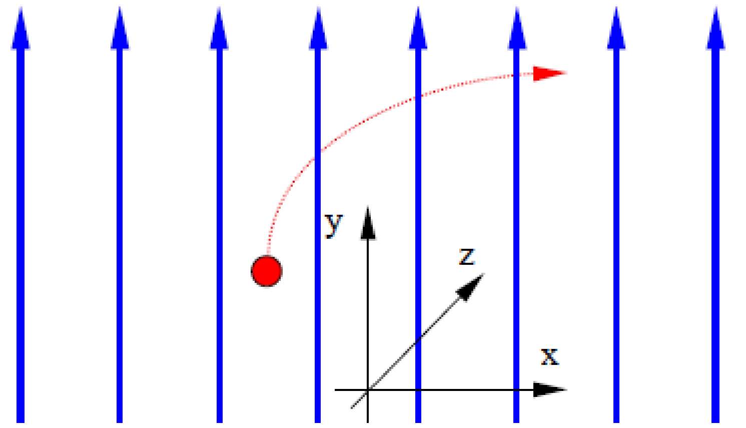
27 km, 8.33 T
14 TeV (c.o.m.)
1300 tons NbTi

The LHC has a total of ~1230 dipoles and ~475 quadrupoles

The Large Hadron Collider

Dipole

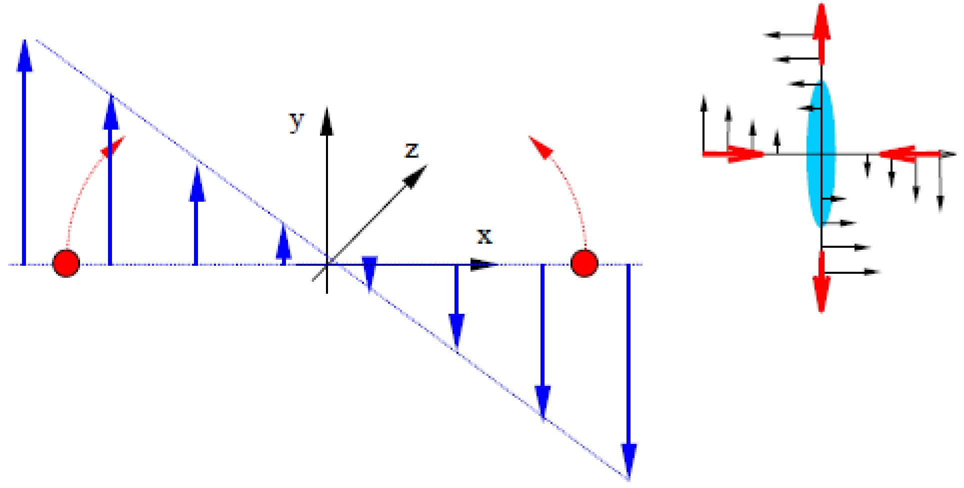
Bending the beam



Uniform field

Quadrupole

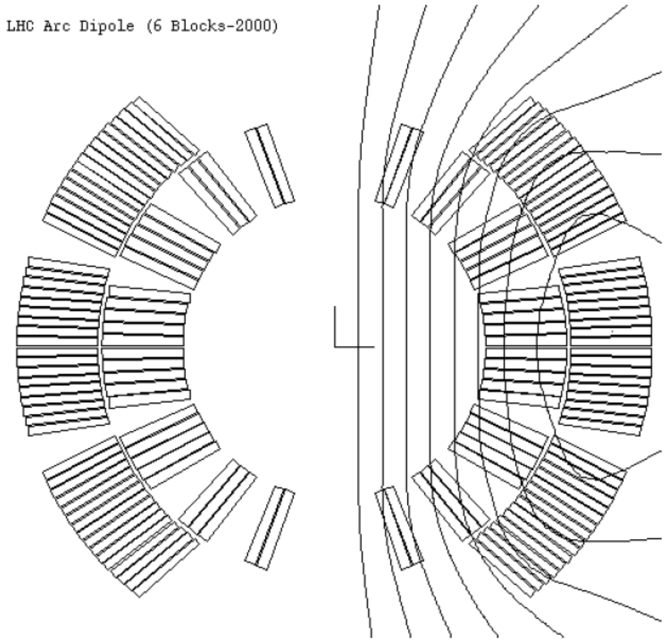
Focusing the beam

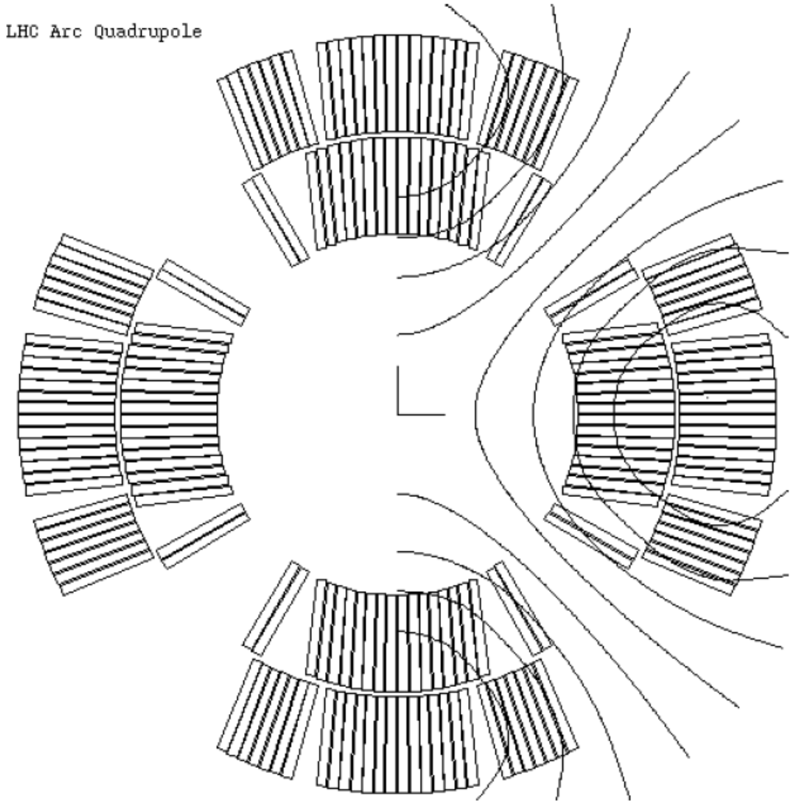


Gradient field

Senatore C. *Superconductivity and its applications* https://senatore.unige.ch/lectures/

The Large Hadron Collider



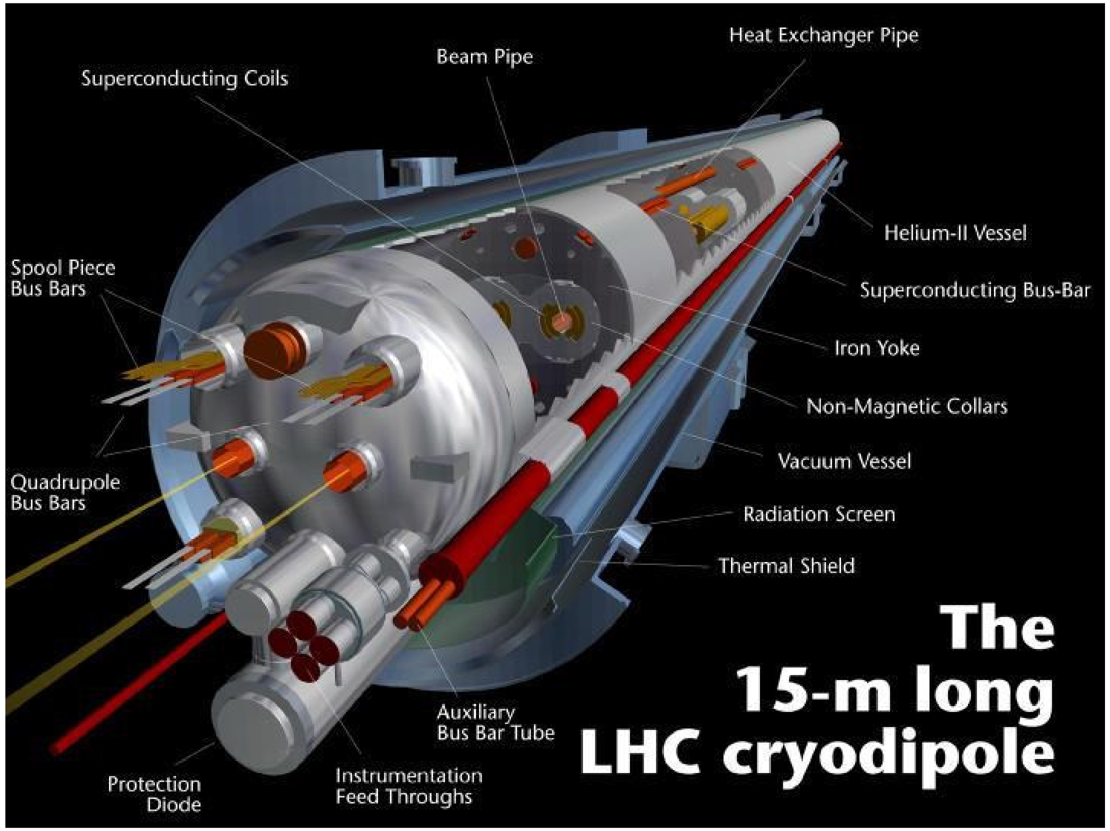


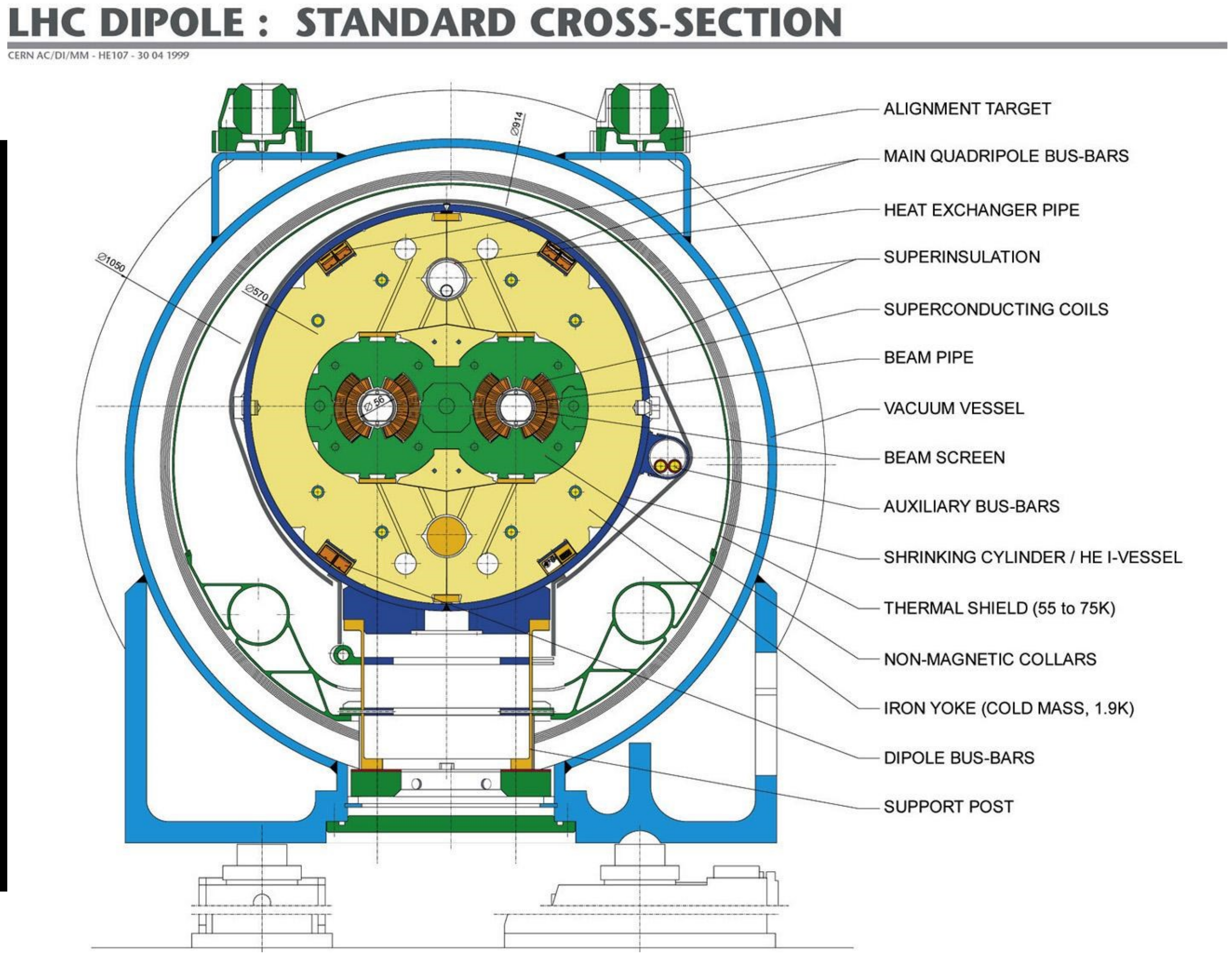
LHC dipole cross section

LHC quadrupole cross section

Senatore C. *Superconductivity and its applications* [*https://senatore.unige.ch/lectures/*](https://senatore.unige.ch/lectures/)

The Large Hadron Collider





1230 dipoles → 7000 km of this cable → 36 wires twisted together → ~260,000 km of wire

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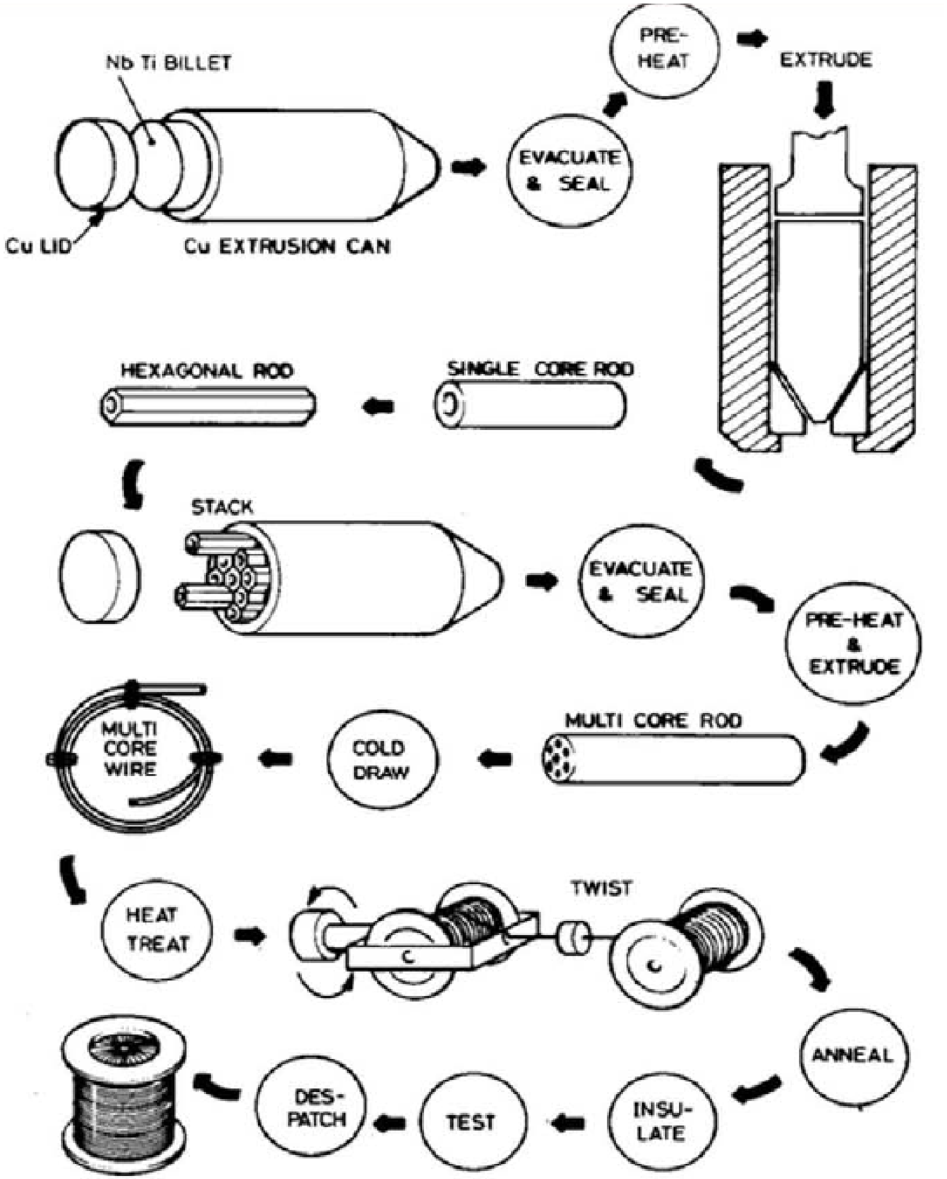
Nb-Ti

Niobium–titanium is an alloy with the quality of being rather INSENSITIVE to mechanical deformation

The production is based on hot extrusion of Nb-Ti and Copper billet

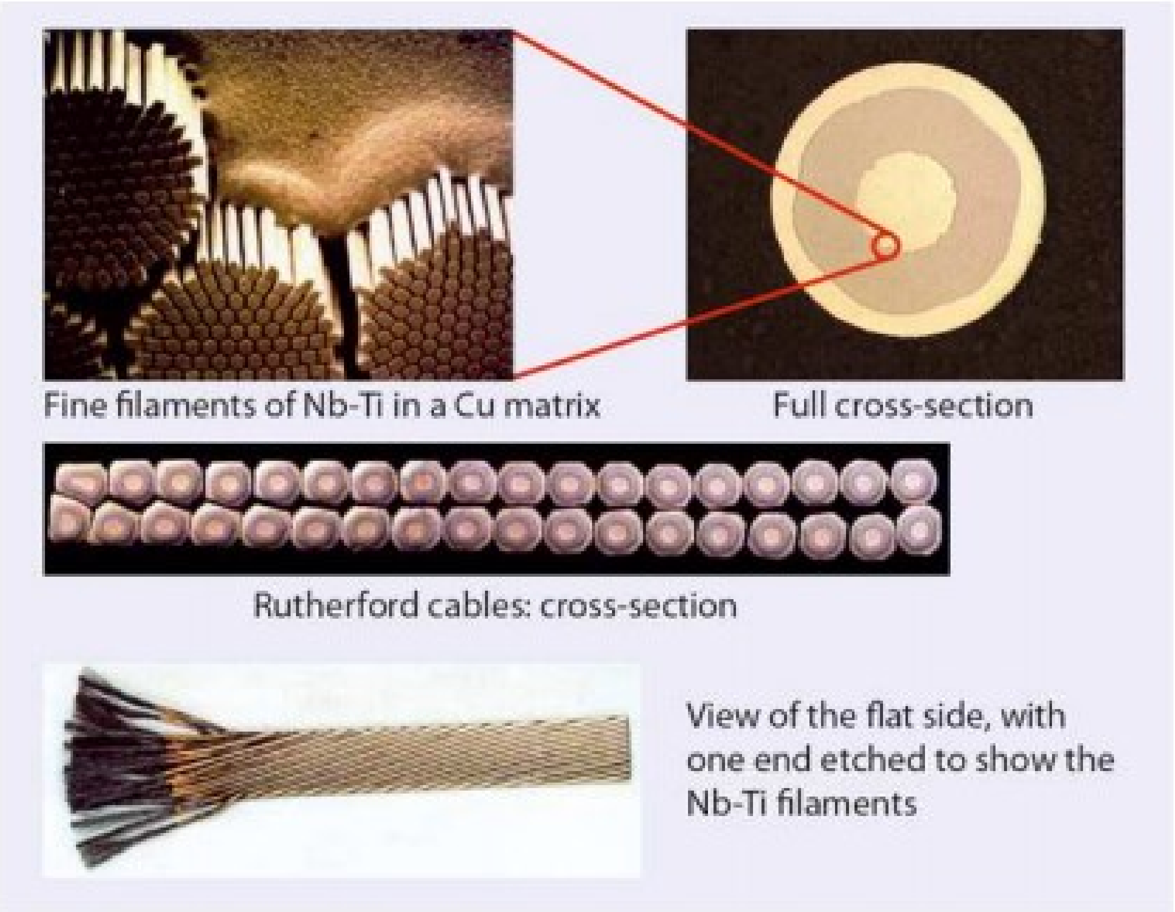
A sequence of cold drawing and intermediate heat treatment is used to produce small filaments necessary for thermal and electric stability

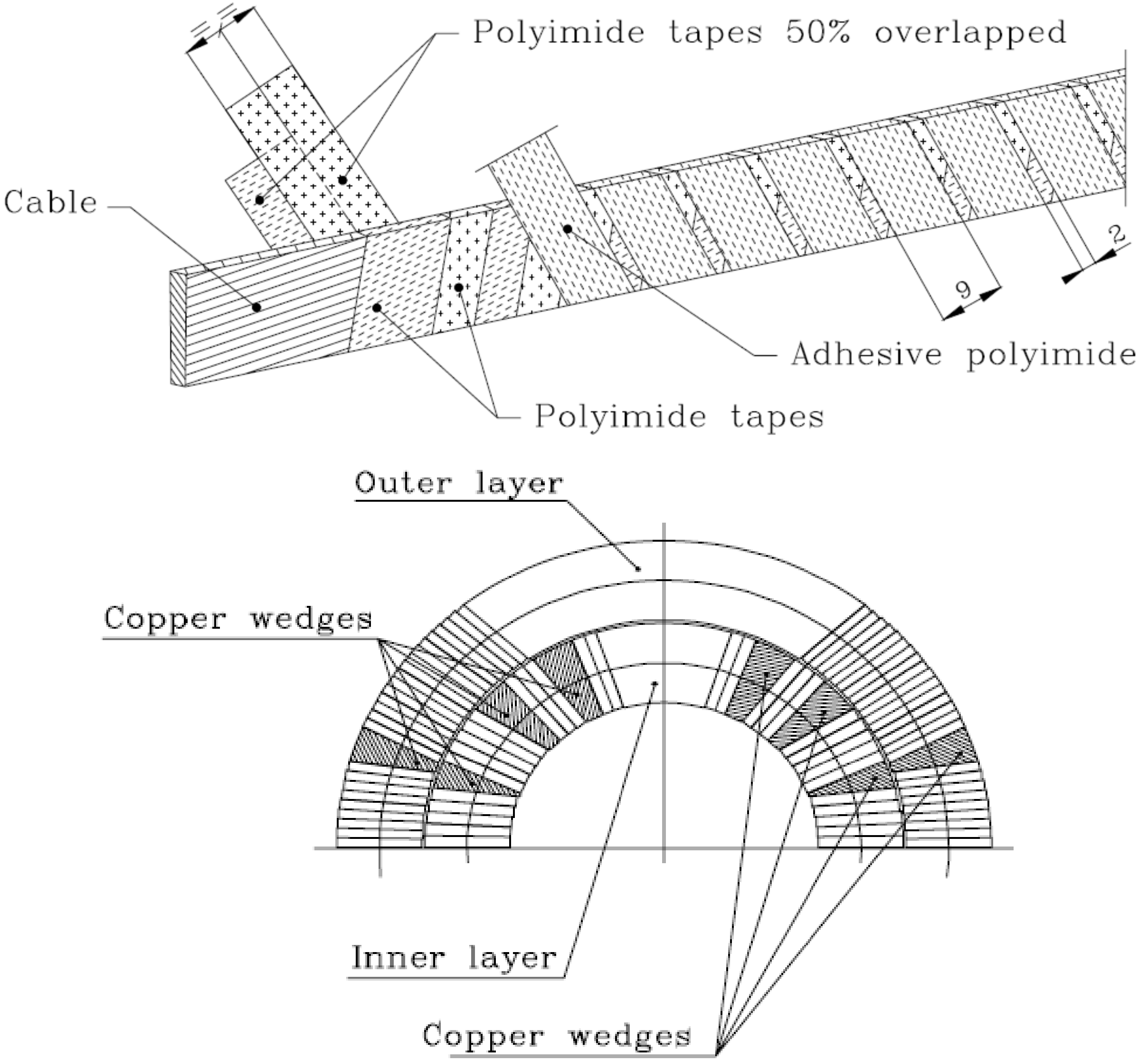
At the end of the production the wire is twisted to minimize coupling losses



Wilson, M. N. *Superconducting Magnets. (Clarendon Press, 1983)*

Nb-Ti magnet assembly





LHC Design Report (The LHC Main Ring vol 1) CERN-2004-003.

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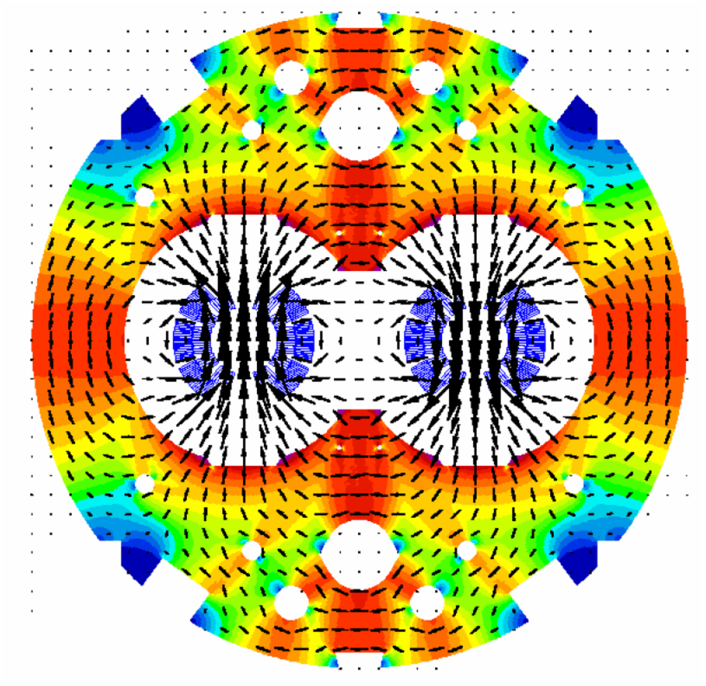
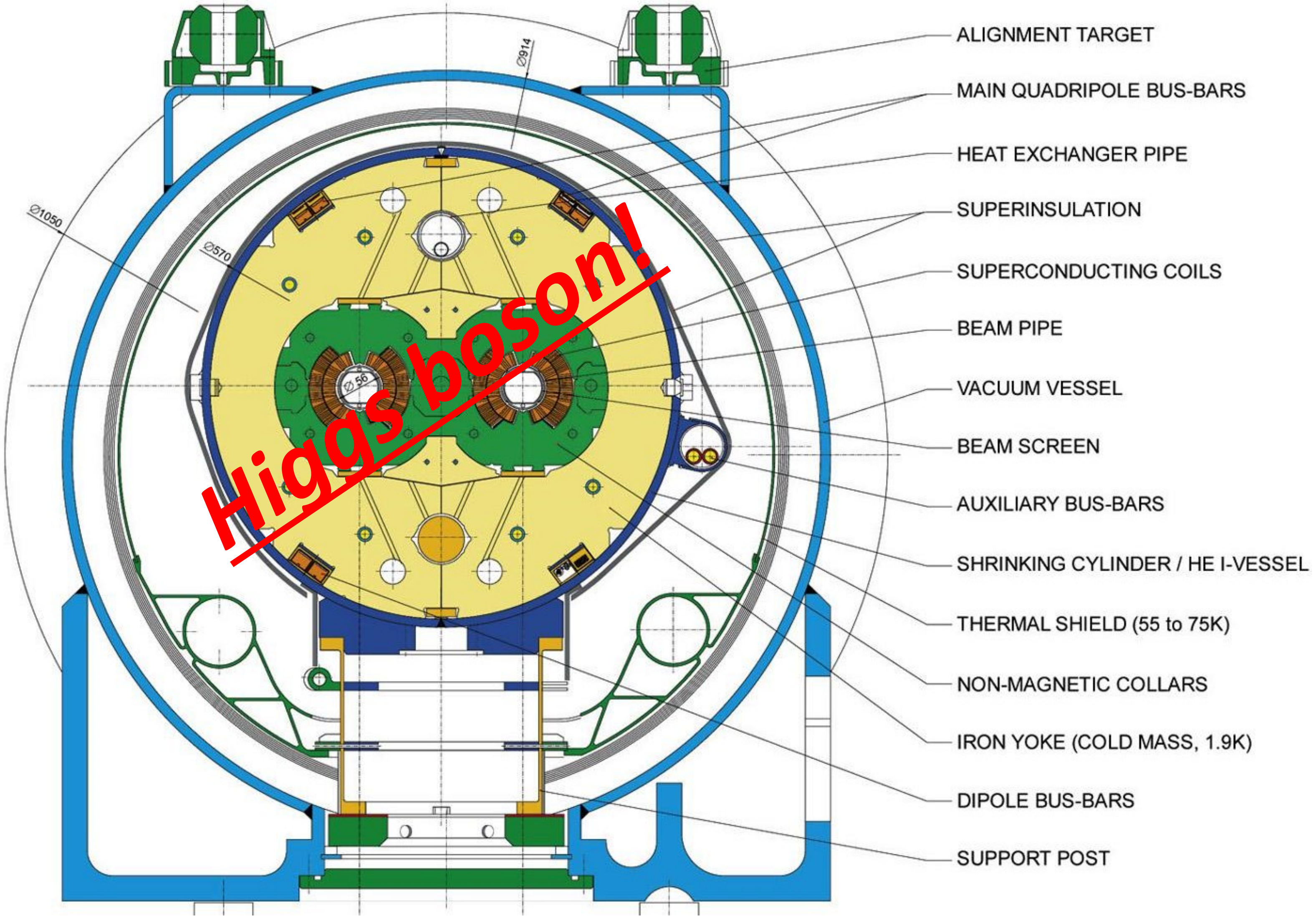
Nb-Ti dipole magnet

Dipole magnetic flux



The assembly steps after the winding phase are not showed (impregnation, curing, quench protection, collaring, etc.)



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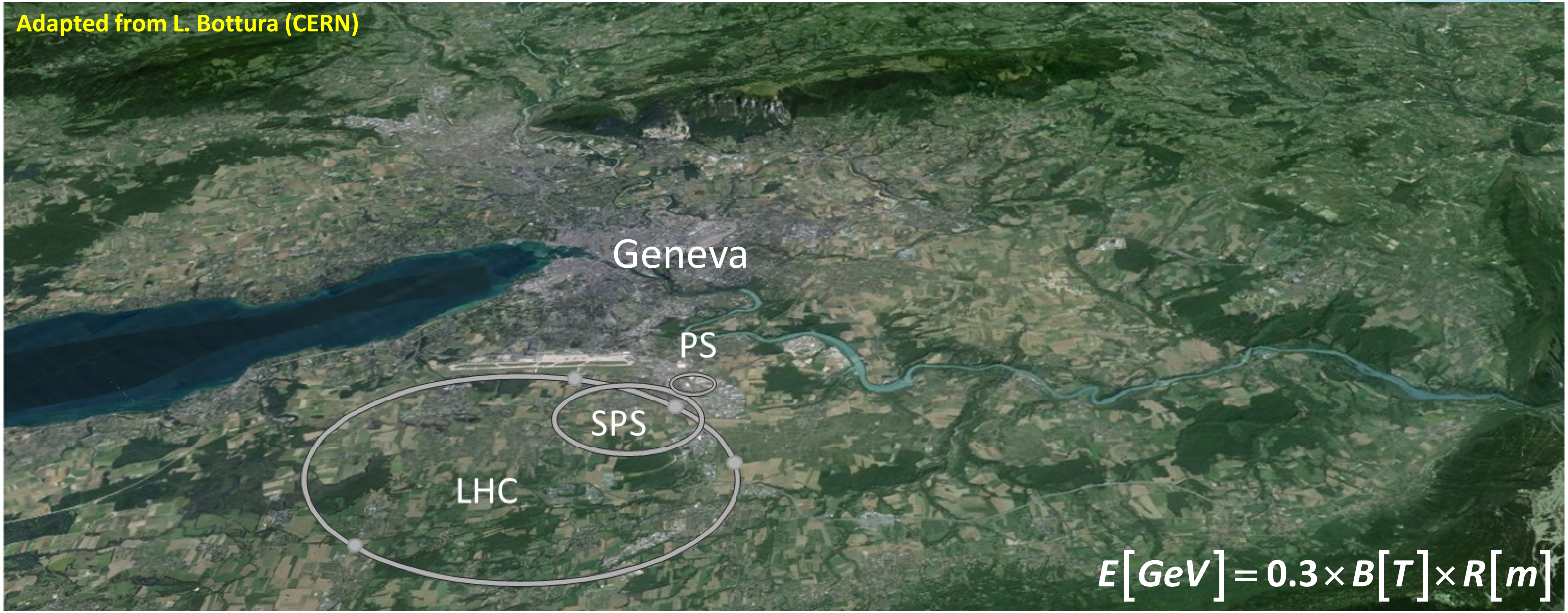
  - ***Niobium-tin (Nb_3Sn)***

- ***Challenges of Nb_3Sn magnets***

- ***Path toward solutions***

High Luminosity LHC

High Luminosity LHC Project



$$E[GeV] = 0.3 \times B[T] \times R[m]$$

HL-LHC project aims to crank up the performance of the LHC

The objective is to increase the integrated luminosity by a factor of 10 beyond LHC

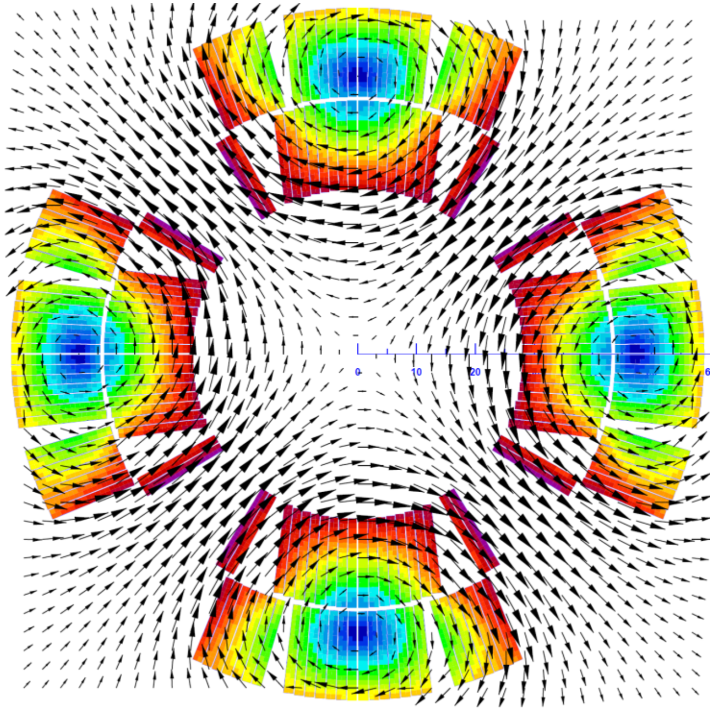
HL-LHC

Luminosity is a key component to boost an accelerator's potential for new discoveries. Luminosity (L) is the ratio of the number of events detected (dN) in a certain period of time (dt) to the cross-section (σ)

$$L = \frac{1}{\sigma}\frac{dN}{dt}$$

To achieve the designated luminosity the beam will be more intense and more concentrated than at present in the LHC

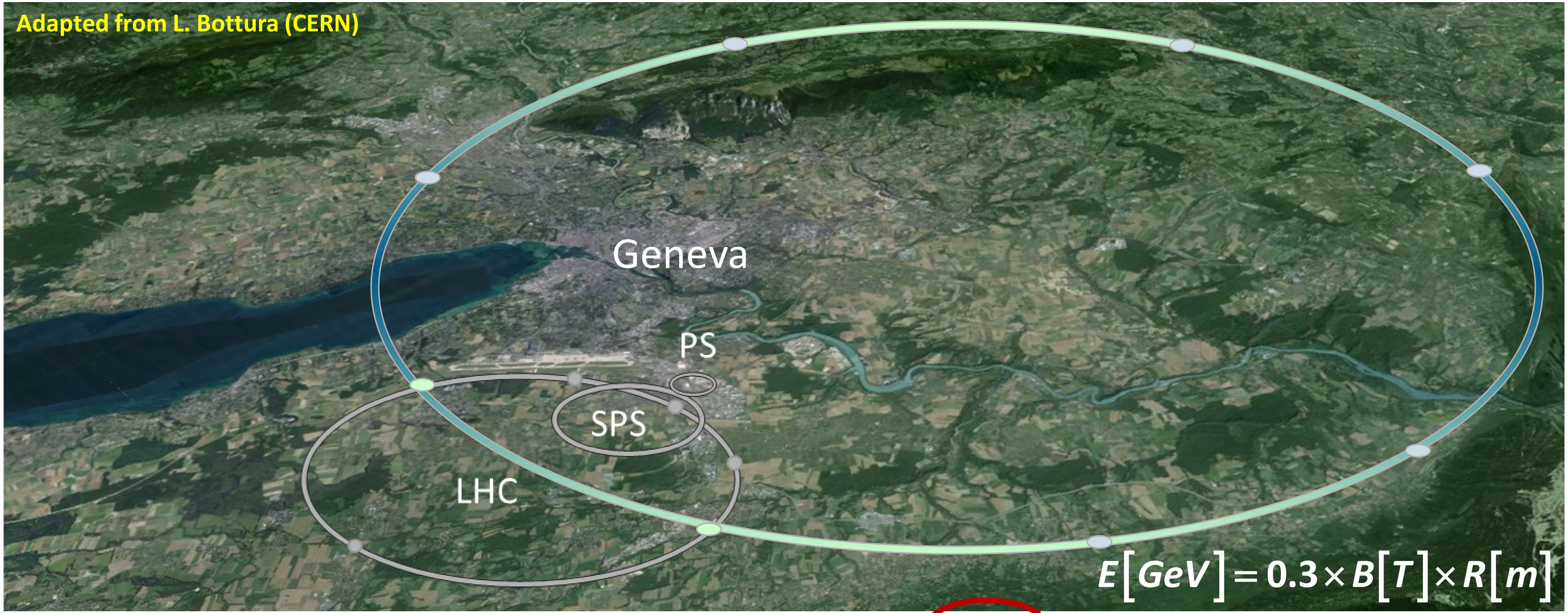
New, more powerful quadrupole magnets, generating a 12-tesla magnetic field (compared to 8 T for those currently in the LHC), will be installed either side of the ATLAS and CMS experiments



Twelve of these magnets, made of Nb_3Sn will be installed close to each detector

The Nb_3Sn magnets will prove the feasibility for this technology and open the path toward FCC

The Future Circular Collider



LHC	27 km, 8.33 T 14 TeV (c.o.m.) 1300 tons NbTi	FCC-hh	100 km, 16 T 100 TeV (c.o.m.) ~9000 tons Nb_3Sn

Nb_3Sn

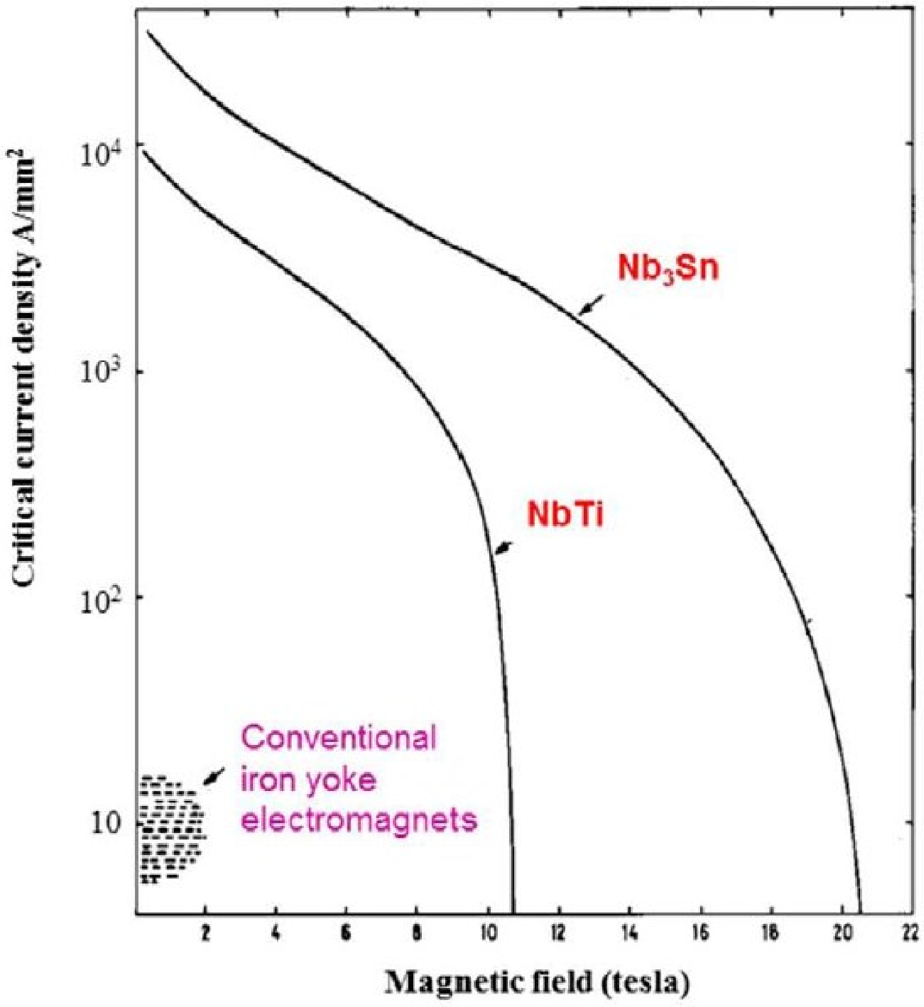
Nb_3Sn has a much higher critical current, field and temperature than Nb-Ti

Nb_3Sn is the preferred material for the windings of the coils with magnetic field above 10 T

But Nb_3Sn has a reduced mechanical strain tolerance:

- It is a brittle compound prone to fractures
- Critical current density (I_c) strongly depends on mechanical strain applied to the conductor

Critical current density lines at 4.2 K



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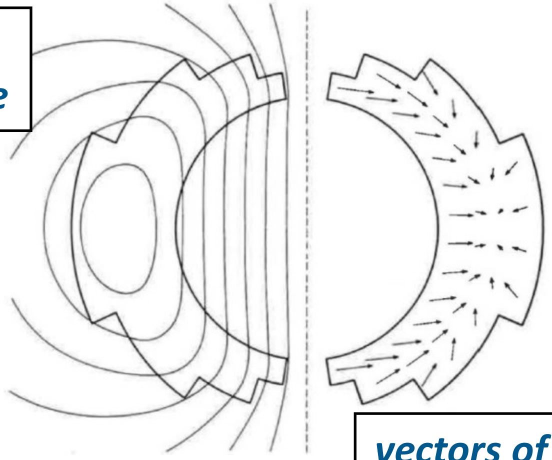
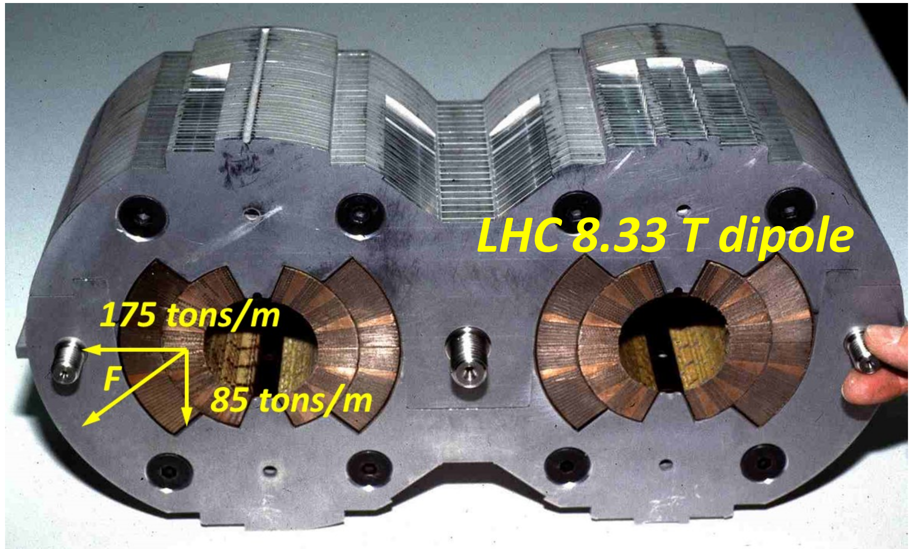
High fields come with large electro-mechanical forces

magnetic lines of force



vectors of electromagnetic force per unit volume



Nb_3Sn Rutherford cable for HL-LHC, 40 strands

The peak stresses act on transverse direction

- The magnet performance will be determined by the ability of Nb_3Sn wires to withstand the mechanical loads
- We need to set a safe stress limit for Nb_3Sn superconducting coils
- We need strategies to improve the strain tolerances

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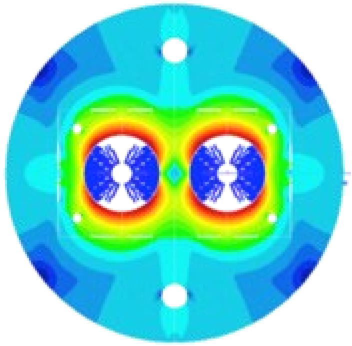
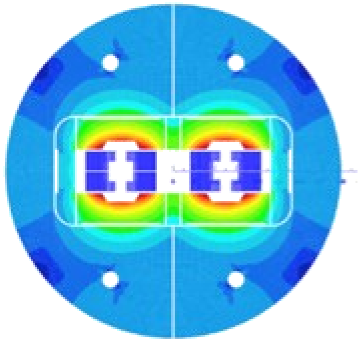
Design options for the 16 T FCC dipoles

h2020 EuroCirCol WP5, started in 2015

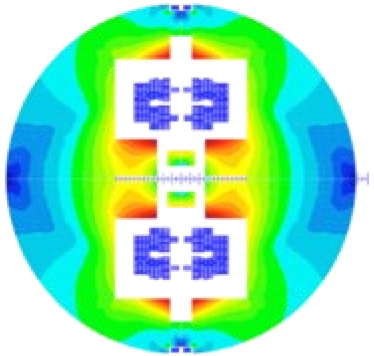
WP leader: Davide TOMMASINI, CERN



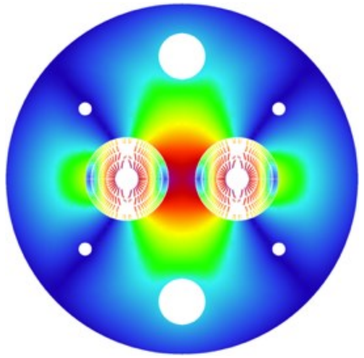
Cosine Theta Coil



Block Coil



Common Coil



Canted Cosine Theta (CCT)

All designs for the 16 T dipoles share a peak stress in transverse direction in the range 150-200 MPa at operation

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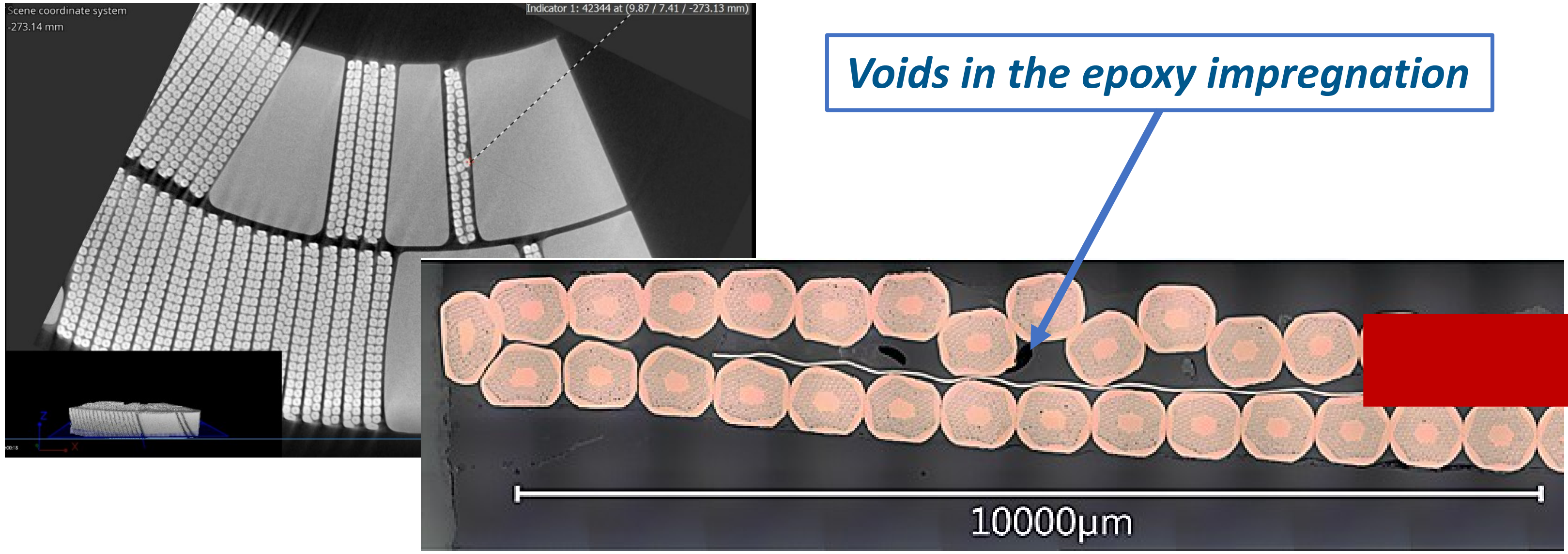
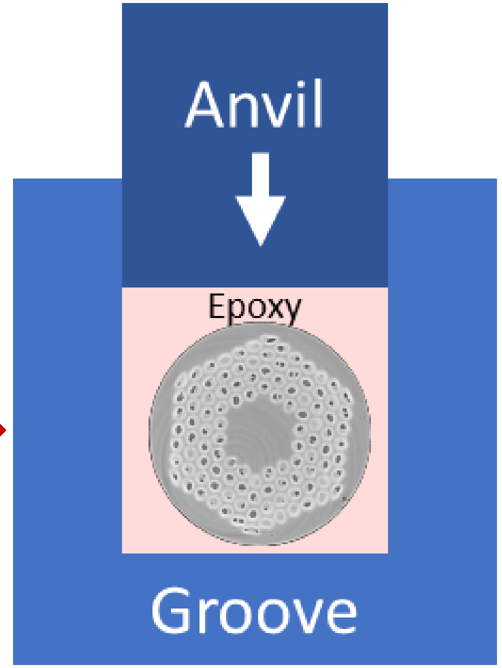
How to isolate the transverse stress?

Limited information is from coil tests on the behavior of a single wire

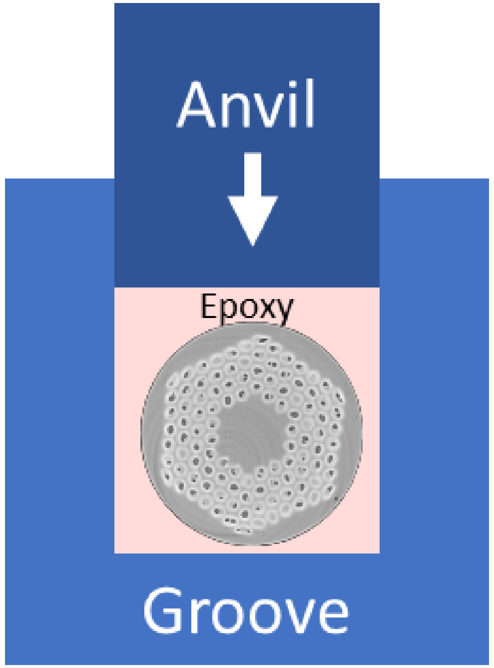
- *Difficult to isolate the role of the wire properties in the overall magnet performance*
- *Single wire tests capable to reproduce the magnet behavior are necessary*

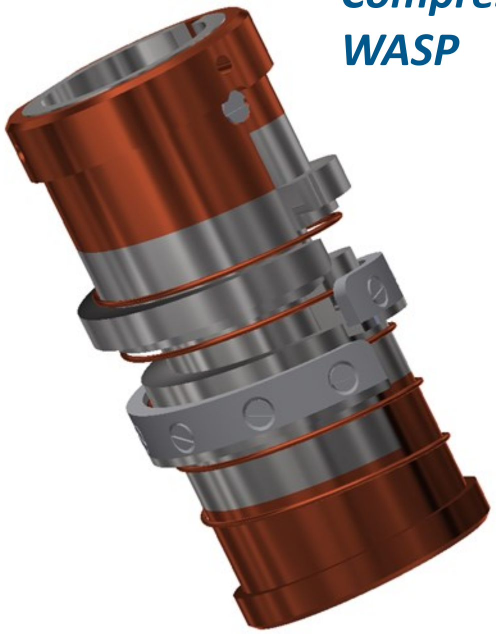


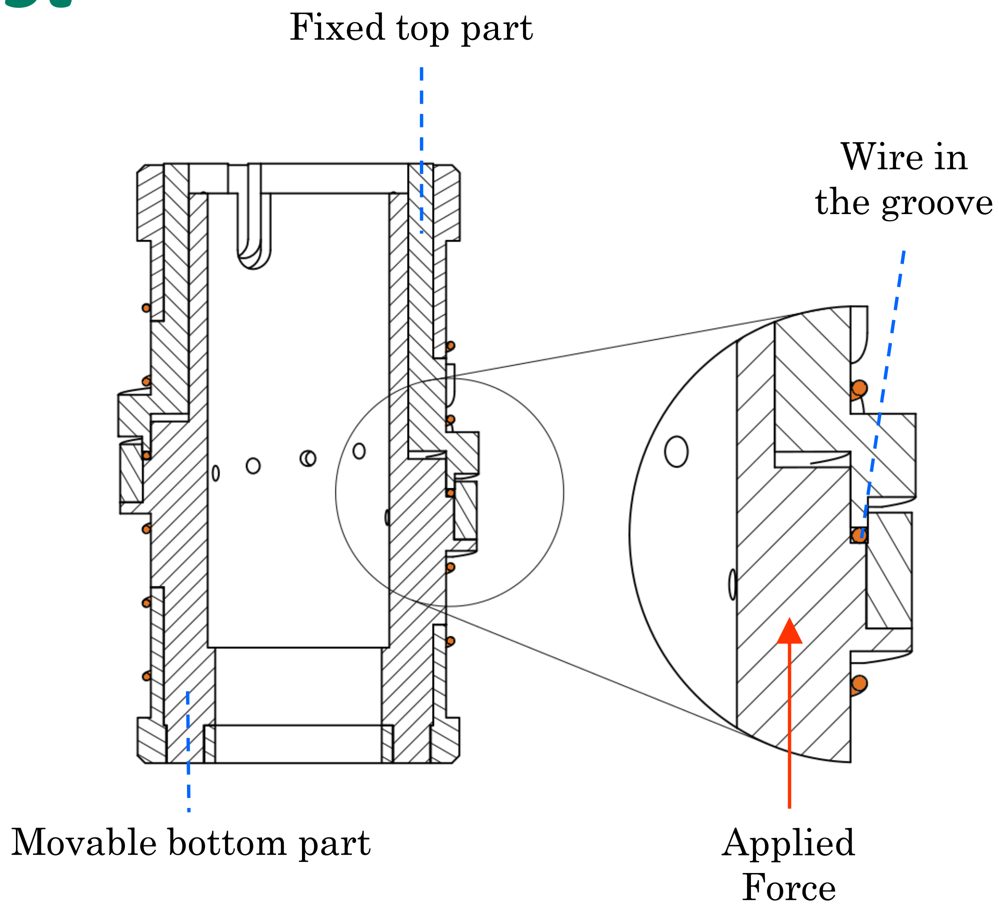


Sgobba, S. (2021) *Workshop on State-of-the-Art in High Field Accelerator Magnets*
Calzolaio, C. *Supercond. Sci. Technol* **28**, 055014, (2015)

Single wire electro-mechanical test







The wire is impregnated in a closed cavity with epoxy resin

Measurements at different magnetic fields. In general, B = 16-19 T

Calzolaio, C. *Supercond. Sci. Technol* **28**, 055014, (2015)
Gämperle L. *(2020) Phys Rev Res 013211*

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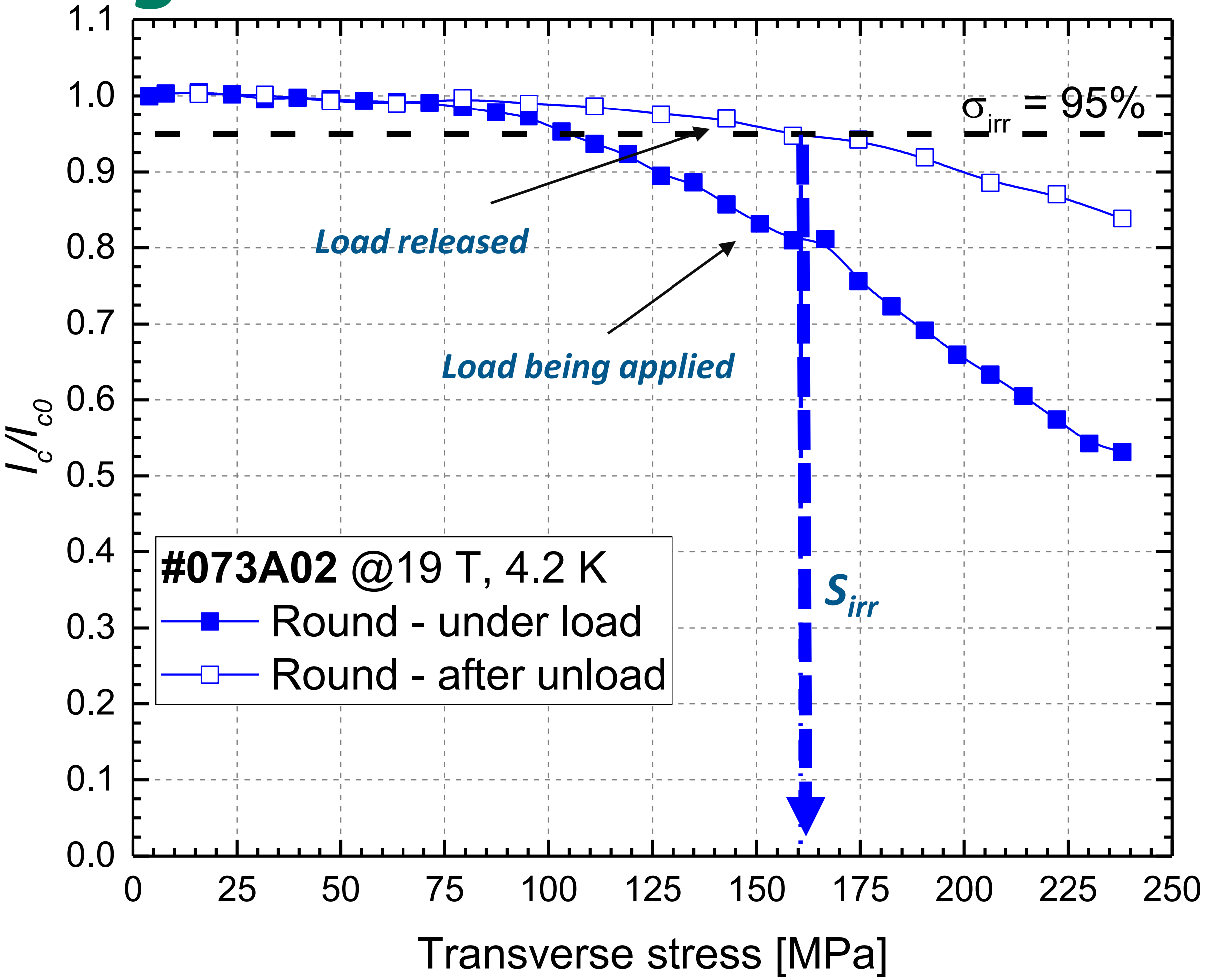
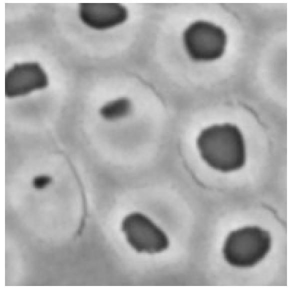
Single wire electro-mechanical test



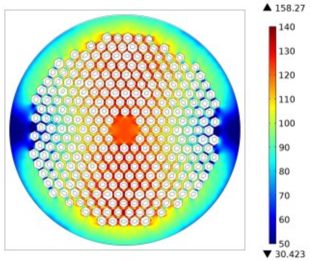
*We call the **irreversible limit** as the force level leading to a **95% recovery** of the initial I_c upon force removal*

Two mechanisms govern the irreversible degradation of the critical current under mechanical load:

- ***Formation of cracks** in the Nb_3Sn filaments*



- ***Plastic deformation** of the matrix and residual stress on the Nb_3Sn filaments*



Gämperle L. *(2020) Phys Rev Res 013211*
Troitino, J. F. et al. *Supercond. Sci. Technol* ***34****, (2021)*

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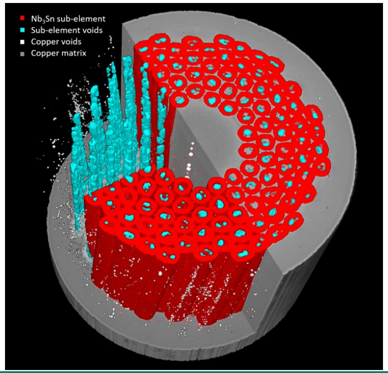
How to improve wire technology?

Mechanical FE Models based on:

- *Experimental results*
- *Real 3D wire geometry*

***Real 3D geometry**: Detecting all wire components from wire X-ray tomography*



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Electro-mechanical experiments

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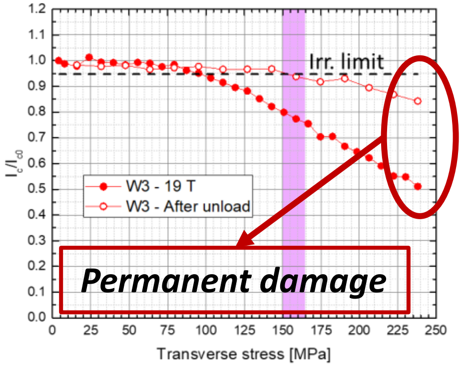

***Mechanical FEM analysis** including wire defects*

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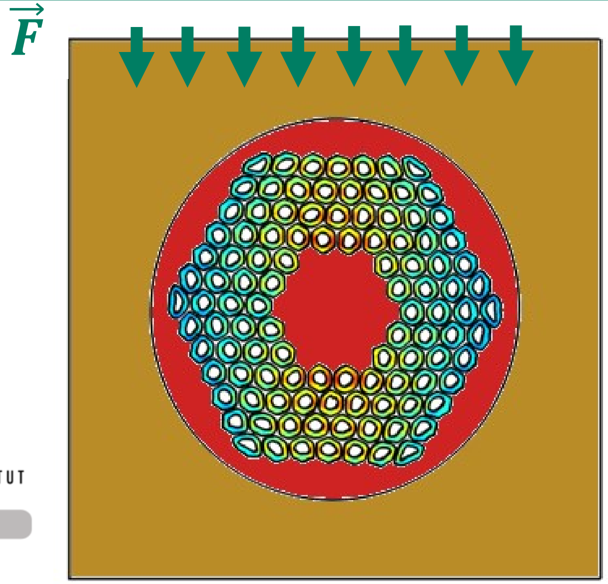

*Validation of the FEM using the wire **3D reconstruction**, after mechanical stress experiment, to compare the **cracks distribution** to the simulated peak stress distribution*

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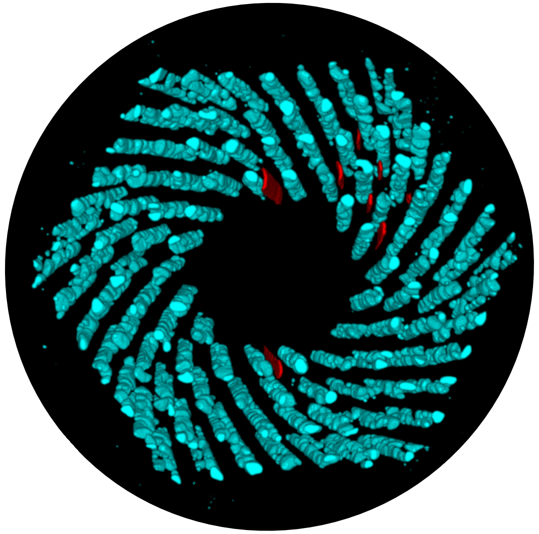
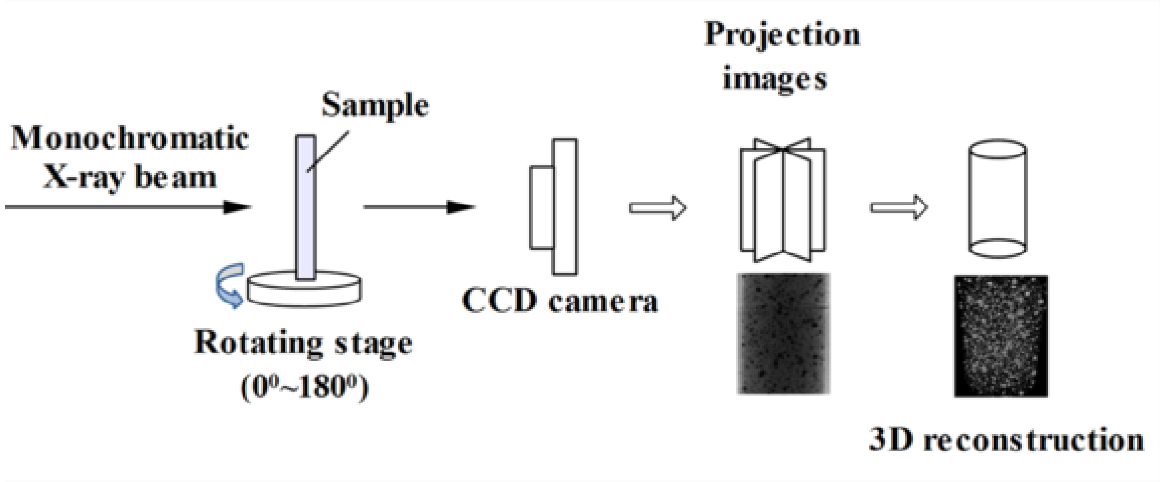


FEM goals:

- ***New insights into electromechanical properties of Nb_3Sn wires***
- ***Design new wires with higher mechanical limits***

X-Ray microtomography: ESRF - ID19

Synchrotron-based microtomography using hard X-rays (about 80 keV) is suited to study the internal features of dense materials



It allows to detect Nb_3Sn filaments, voids and cracks in a 3D volume in a non-invasive, non-destructive way

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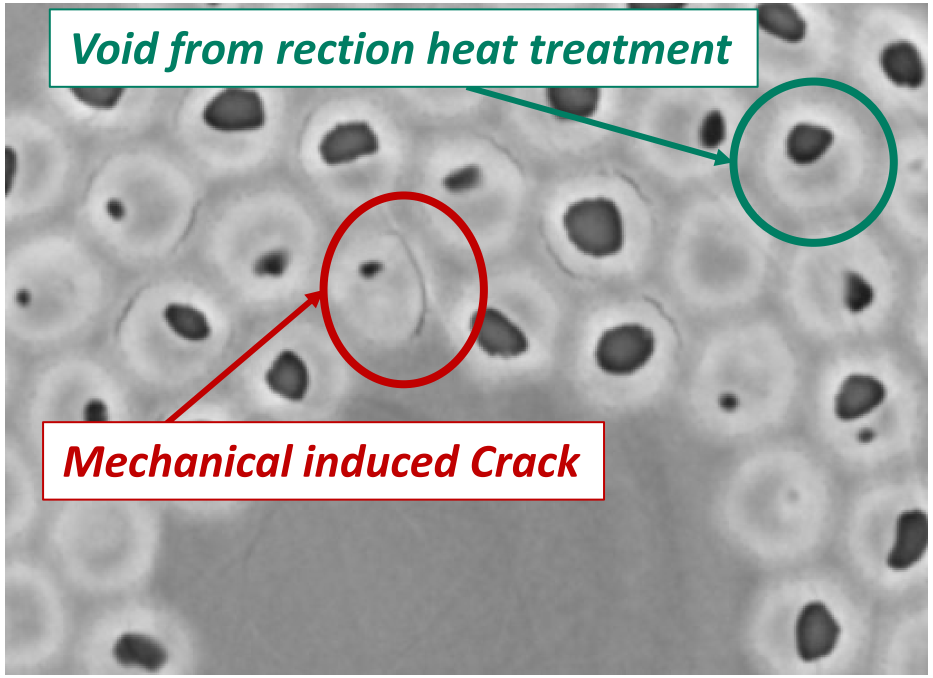
~ 0.7 μm/pixel resolution



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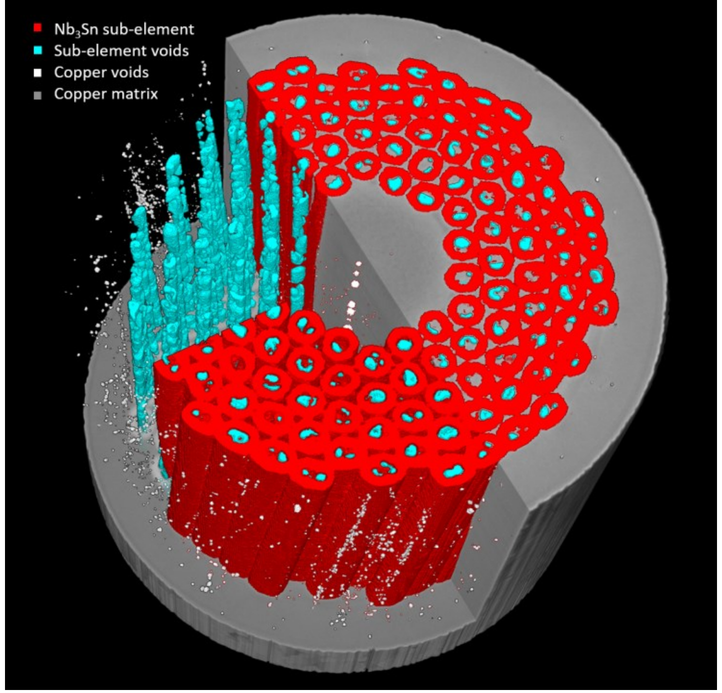
Machine Learning and Neural Network

Step 1: Unsupervised Machine Learning (UML)

Tomography Analysis Tool (TAT) was developed to isolate the different components (voids and sub-elements) in a superconducting wires. TAT exploits k-means applied to X-Ray microtomography.

TAT is not able to recognize cracks.



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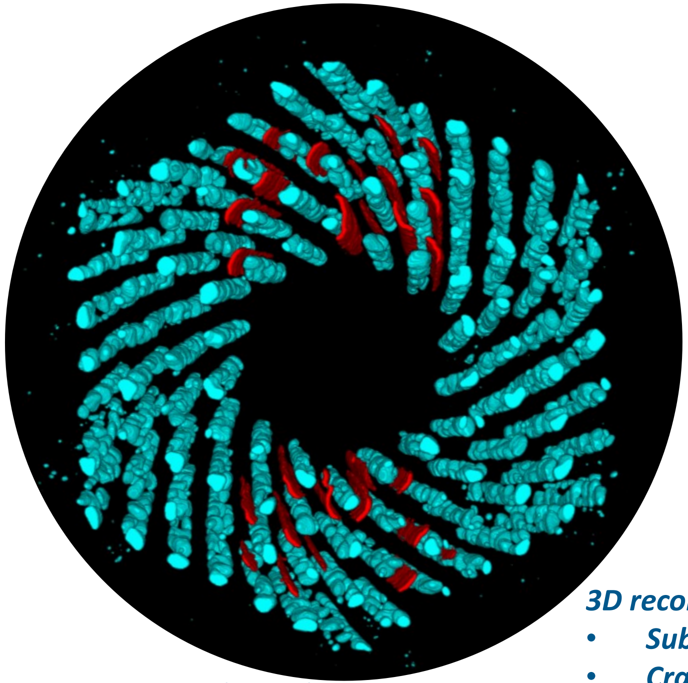
Step 2: Convolutional Neural Network (CNN)

U-Net is a CNN trained using X-Ray microtomography to detect specific features in superconducting wires (e.g., cracks and voids) based on their shape and position



3D reconstruction of the wire:
- *Sub-elements voids in cyan*
- *Cracks in red*

- *CNNs are more flexible than UML*
- *U-Net was able to successfully detect cracks and voids allowing the 3D reconstruction of these components*

Bagni, T. *et al.* (2021) *Sci. Rep* **11**, 7767
Bagni, T. *et al. IOP SciNotes* **3**, 015201 (2022)
Bagni, T. *et al. Supercond. Sci. Technol* **35**, 104003 (2022)

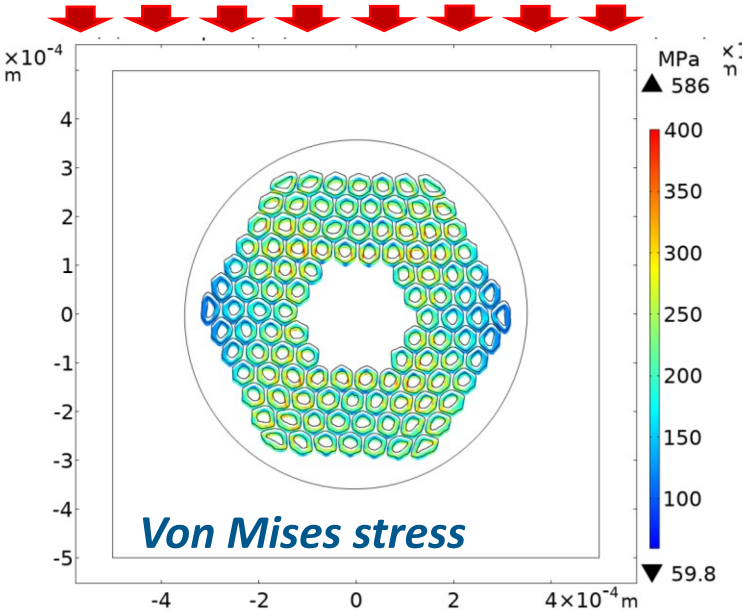
[TAT Open Source: https://tat.readthedocs.io/en/latest/index.html]

2D FE mechanical model

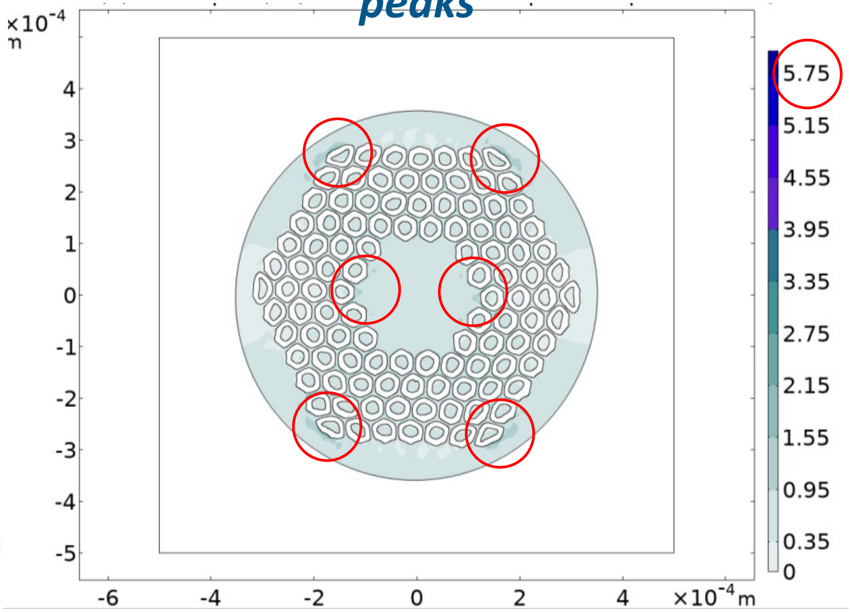
Simplified FE model to demonstrate the efficacy of the method:

- *2D geometry extracted from the SEM images of real RRP wires*
- *Bronze in the sub-elements (no voids)*

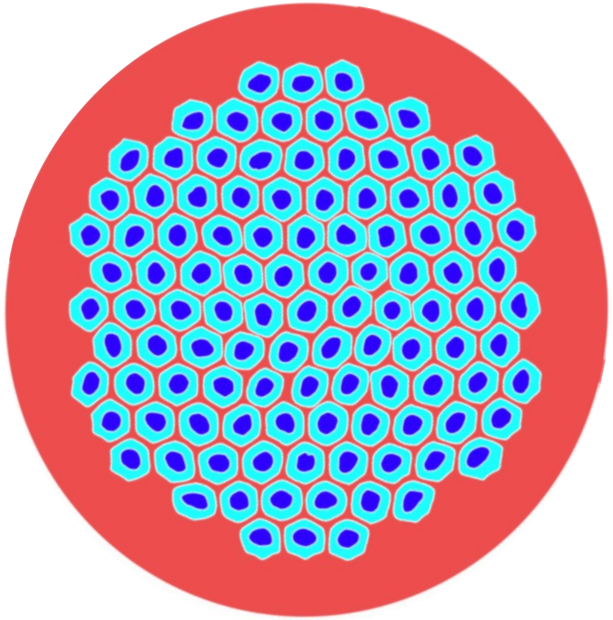
Max applied load 30kN



Copper plastic deformation peaks



NEW wire design



Wire stress irreversible limit improved by 7 %

Bagni, T. *et al. Supercond. Sci. Technol* **Paper in preparation**

Conclusion

- *Superconducting accelerator magnets are the enabling technology for present and future particle accelerators in HEP. All the present accelerator magnets have used Nb-Ti. The practical performance limit of Nb-Ti is 8–9 T*

- *The HL-LHC promises a technology breakthrough with the introduction of Nb_3Sn in the superconducting materials suitable for accelerators*

- *The development of a new generation of dipole and quadrupole magnets with nominal operation fields up to 16 T based on Nb_3Sn is a key component for the design of FCC*

- *The present research focus is on increasing the performance of Nb_3Sn wires electro-mechanical loads necessary to the exploitation of Nb_3Sn on large scale*