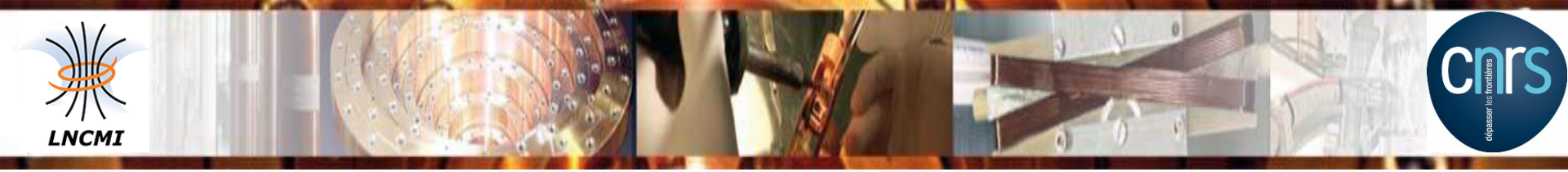


Cold Spray materials for high field magnets at the LNCMI

Olivier Jay[1]
François Debray[1], Florence Lecouturier[1],
Christophe Trophime[1], Christophe Verdy[2], André Sulpice[3]

[1] Laboratoire National des Champs Magnétiques Intenses
Univ. Grenoble Alpes, INSA Toulouse, Univ. Toulouse Paul Sabatier, EMFL, CNRS, FRANCE

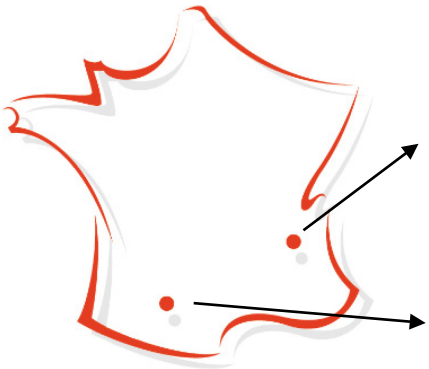
[2] Laboratoire Interdisciplinaire Carnot de Bourgogne
Univ. Bourgogne Franche-Comté (ICB - UTBM), CNRS, FRANCE

[3] Institut Néel
Univ. Grenoble Alpes, CNRS, FRANCE

MT 26 International Conference on Magnet Technology
Vancouver, Canada | 2019

❑ LNCMI ≡ French national laboratory for high magnetic fields

- Large scale research facility in France.
- Enabling researchers to perform experiments in the highest possible magnetic fields.



Grenoble site
Steady magnetic field
37 T

Toulouse site
Pulsed magnetic field
98.8 T – 209 T

Non-destructive – Semi-destructive
(MegaGauss)

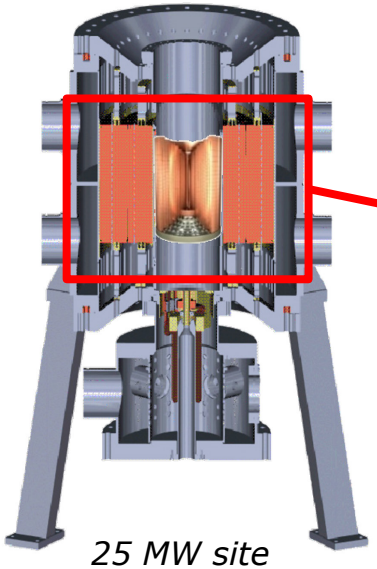
Copper alloy electromagnets are used to produce magnetic field.

➔ For both type of magnetic field production:
materials are a key point for sustainability and development.

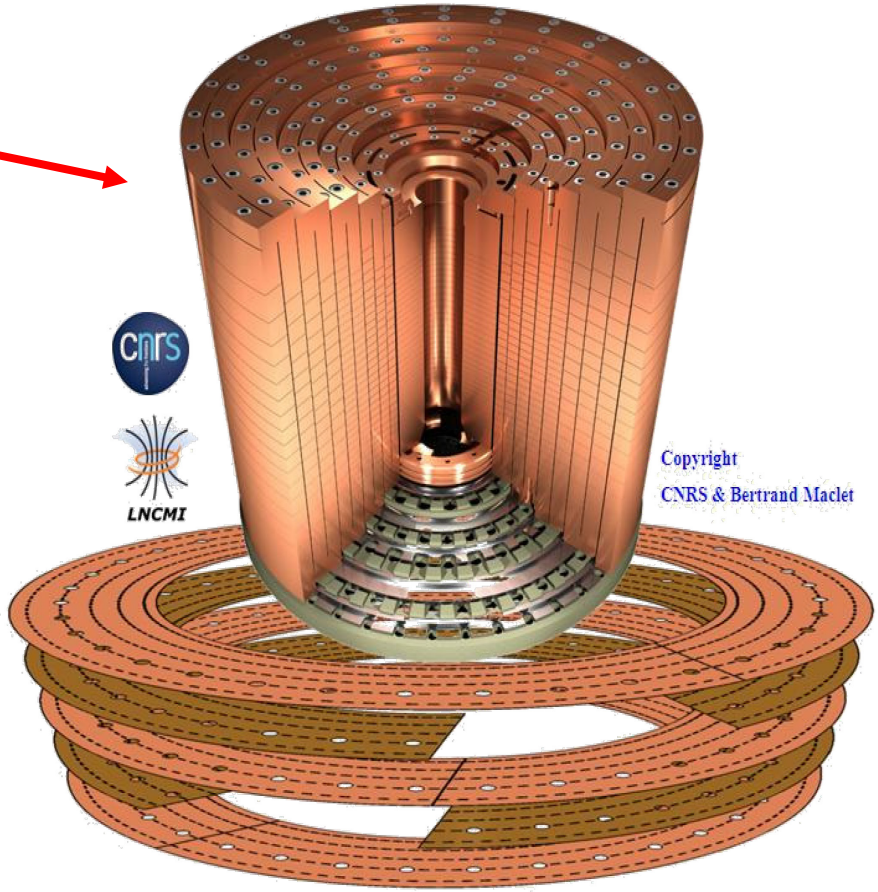
→ Materials for steady magnetic field: *this presentation*

→ Materials for pulsed magnetic field: next presentation by Simon TARDIEU

❑ Two technologies for the high field magnets at the LNCMI Grenoble



25 MW site



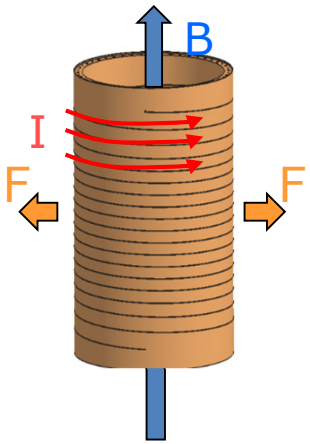
Polyhelix technology
→ up to 27 T

Bitter technology
→ up to 11 T
background field

Polyhelix technology♦:
- allows optimization of the current distribution
- possibility to tailor B to fit the user needs

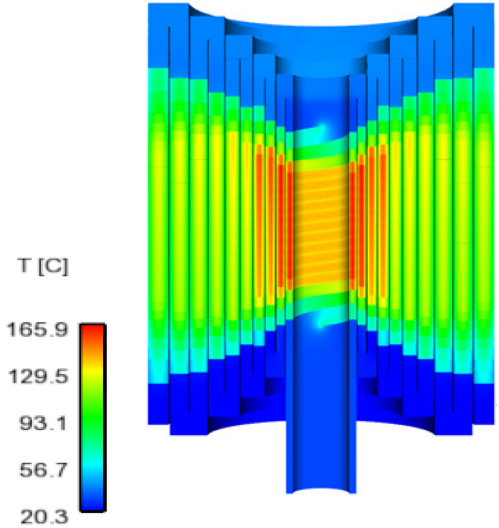
♦*Generation of the highest continuous magnetic fields; Schneider-Muntau et al.; IEEE Transactions on applied superconductivity; vol. 14; No 2; 2004*

❑ Challenge: 30 000 A per cm² under ~ 30 Teslas



- Laplace forces ∝ square of magnetic field
  $F \propto B * I \propto B^2$
- Thermal constrains ∝ square of magnetic field
  $P \propto R * I^2 \propto B^2$

❑ 14 helix configuration: simulation 37.9 T at the center / 12.5 MW:



- T from 70 to 170 °C
  → Need of electrical conductivity > 85 % IACS
  (to keep T_{magnet} < 170°C)

- σ up to 440 MPa
  → Need of high strength materials > 500 MPa
  (Hoop Stress)

❑ Requirements:

Copper alloy tubes with a suitable balance between conductivity and yield strength

- Specific series of products with large dimensions →
  - $Ø_{in}$ from 36 mm to 340 mm
  - thickness from 16 mm to 40 mm
  - height from 250 mm to 400 mm

- **Since 1990:** Forged CuCrZr (*Schmelzmetall*, casting under controlled atmosphere)

$Re_{0,2}$ → ~ 400 MPa
ε → ~ 18 %
σ → ~ 50 $MS.m^{-1}$

Optimization of: - alloy composition
- work hardening
↳ possibility to increase $Re_{0,2}$ but ↘ σ

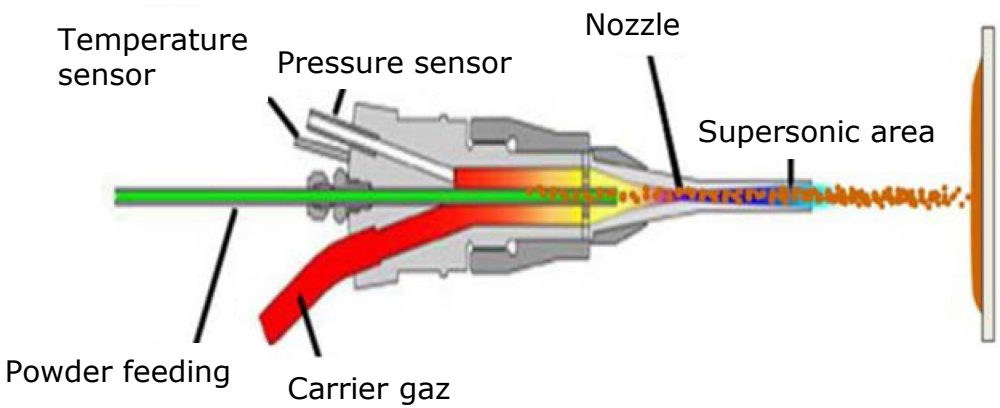
➔ For field higher than 35 teslas materials with higher properties were needed.

- **Since 2011:** collaborative development of cold spray products

LNCMI icb Laboratoire Interdisciplinaire Carnot de Bourgogne utbm université de technologie Belfort-Montbéliard

❑ Cold spray process:

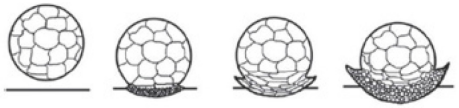
Process realizing deposition on substrates using a high velocity jet (300 – 1200 m.s^{-1}) of fine particles (1 – 50 µm) accelerated by a supersonic gas.

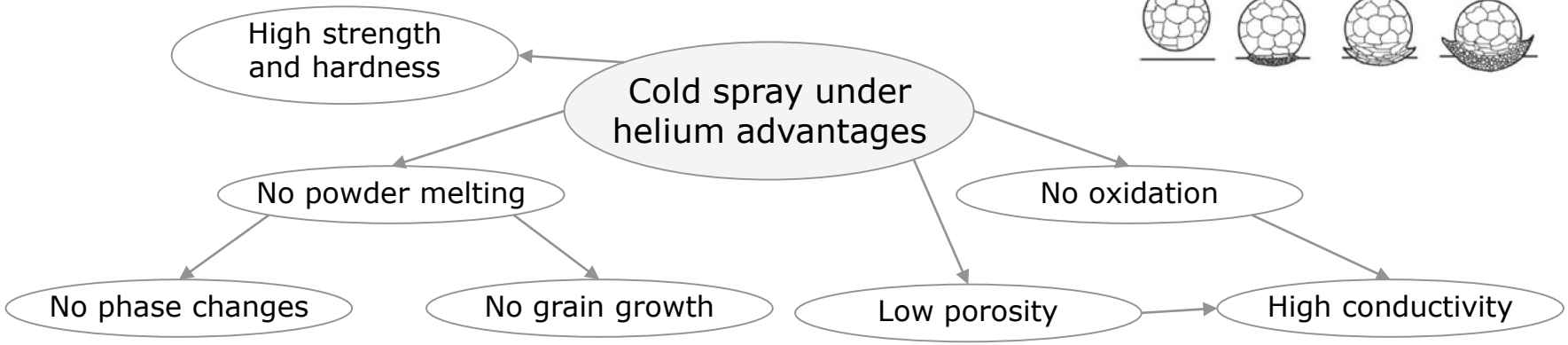


In-situ view:

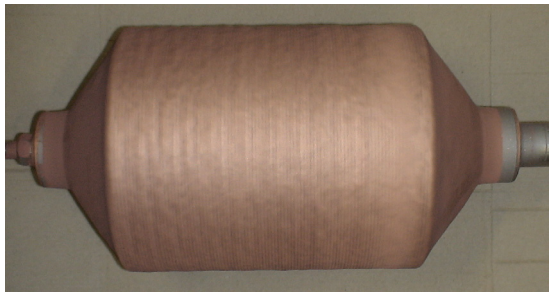
≡ layer by layer additive manufacturing

→ Conversion of kinetic energy to plastic deformation energy which leads to bonding.
→ No melting → Conservation of particles microstructure + cold working





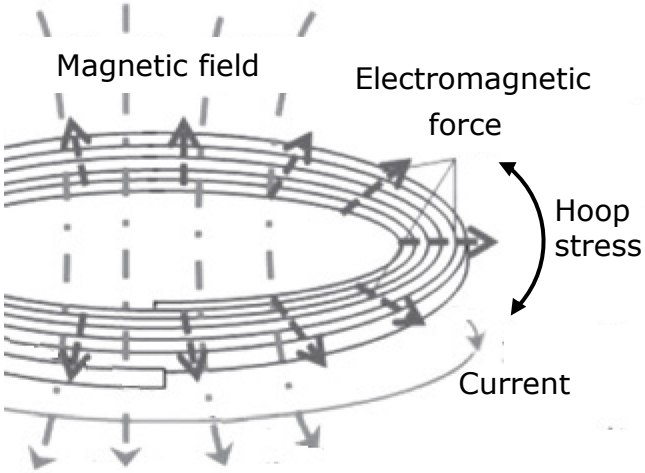
❑ Thick projection for characterizations:



Projection characteristics:

- CuAg5.35wt.%
- Oxygen content: **110 ppm**
- Porosity ≈ 1 %
- **55 mm thick** ; 192 mm height

→ Stress during operation:

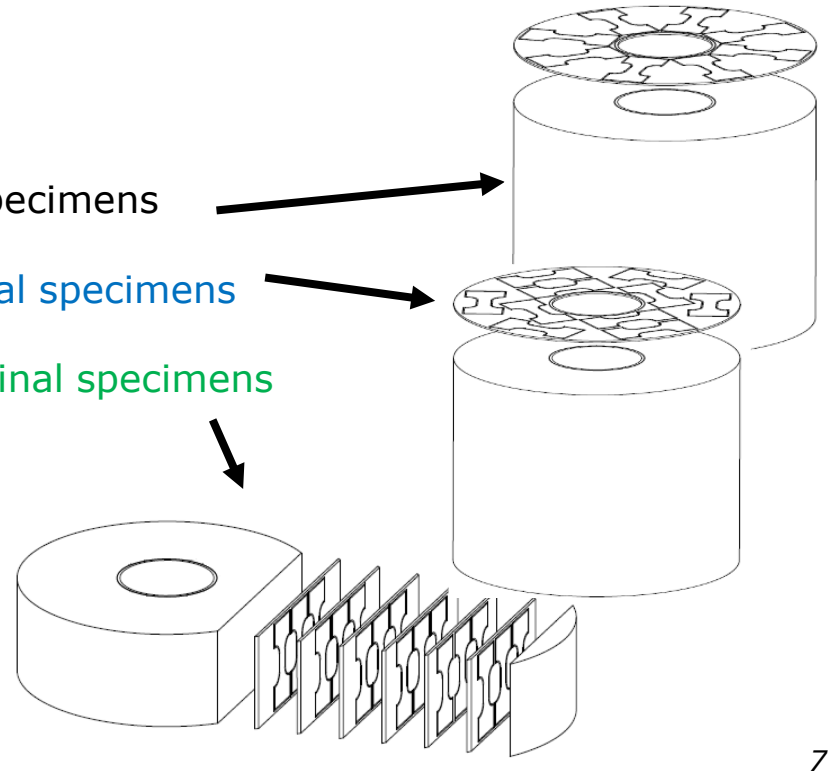


Main stress = hoop stress due to magnetic field
≡ to a tensile stress

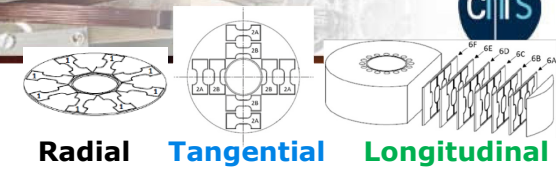
Image adapted from Carmine Senatore et al 2014 Supercond. Sci. Technol. ***27*** *103001*

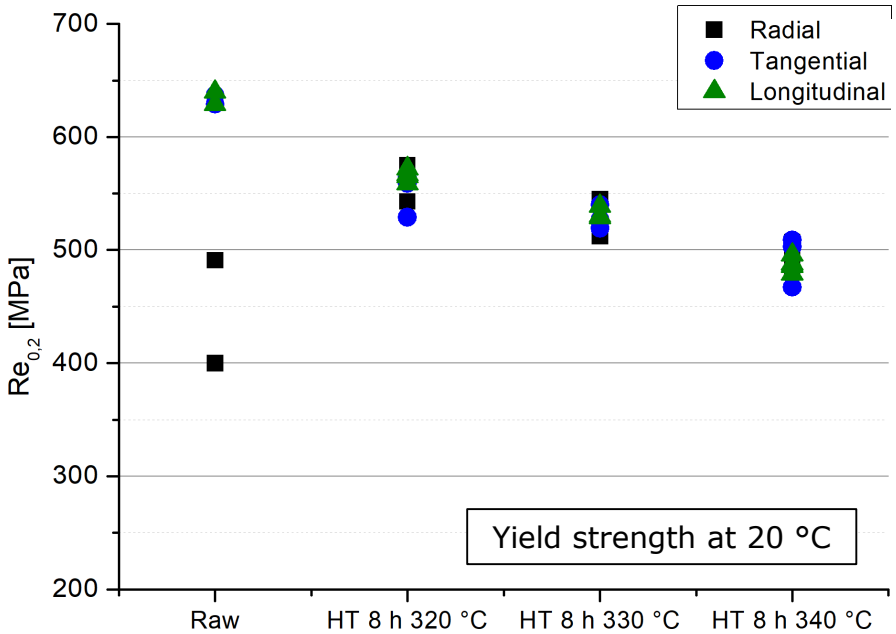
→ Mechanical testing: tensile tests

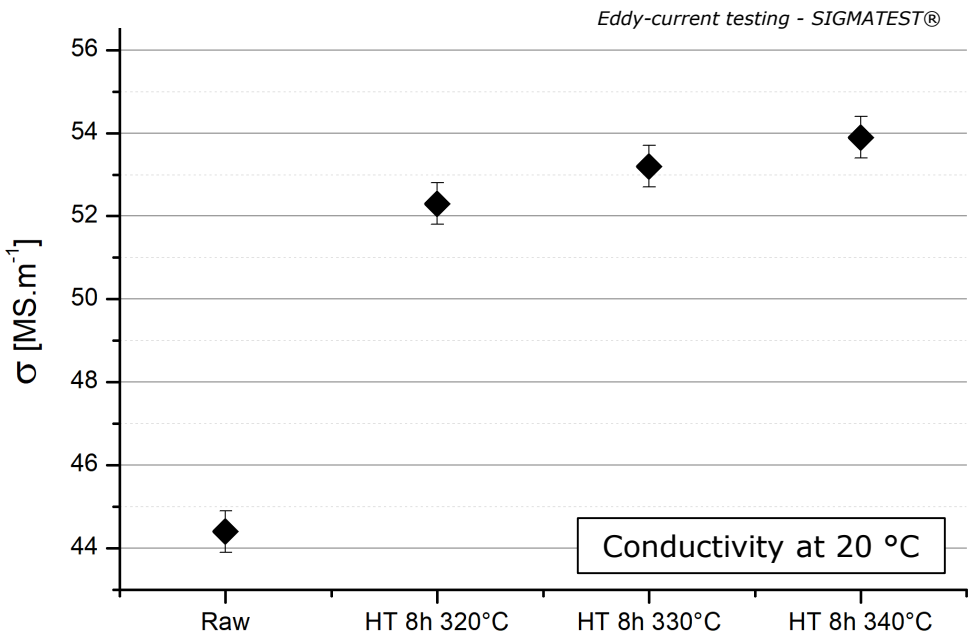
- Radial specimens
- Tangential specimens
- Longitudinal specimens



❑ Impact of heat treatment on properties:





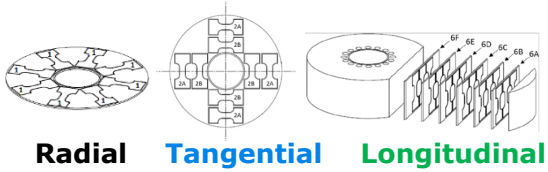


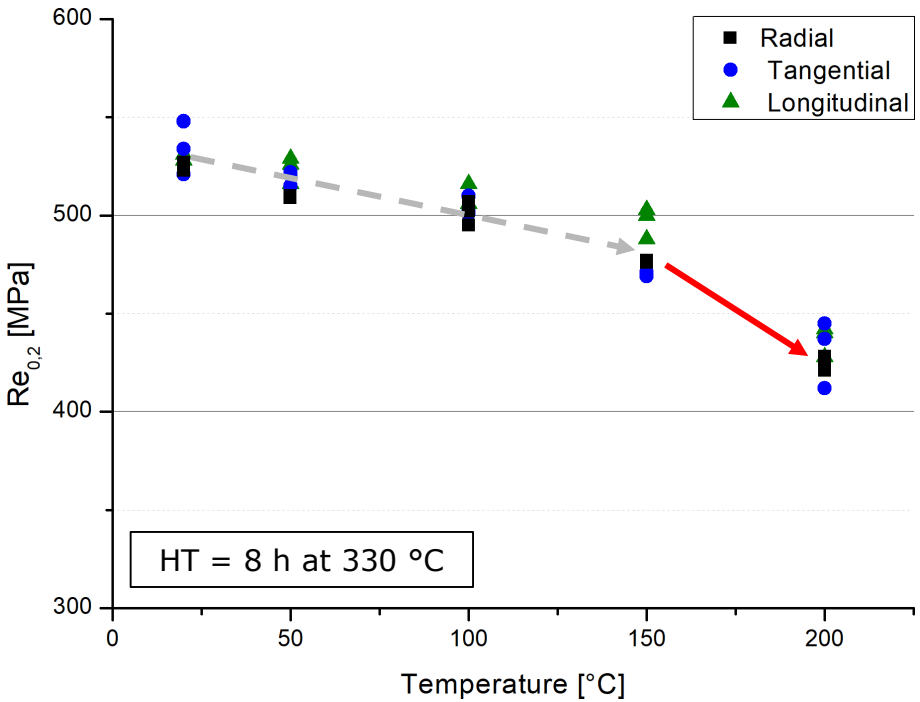
- Mechanical properties:
  - decrease of yield strength on radial direction for the raw material
    ↳ due to the cold spray process
  - isotropy for the yield strength after HT

- Electrical property:
  - highly conductive material
    σ > 90 % IACS
    > 52.2 MS.m^{-1}

➔ Possibility to tune the couple of properties (mechanical;electrical) for the application.

❑ Impact of temperature on yield strength:

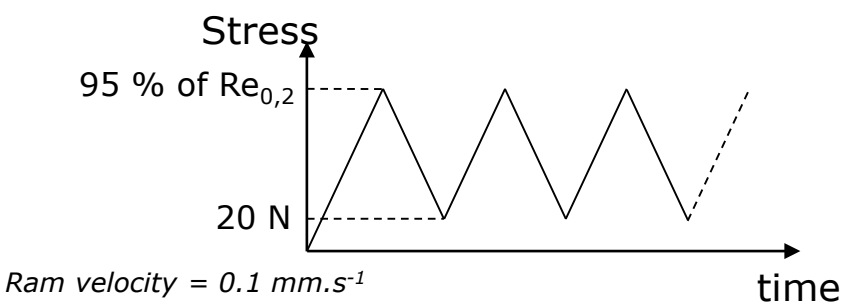




simulation ~ 38 T / 12.5 MW
→ T from 70 to 170 °C
→ σ max = 440 MPa

➔ Good thermal stability of yield strength for this application.

❑ Fatigue behavior at 20 °C:



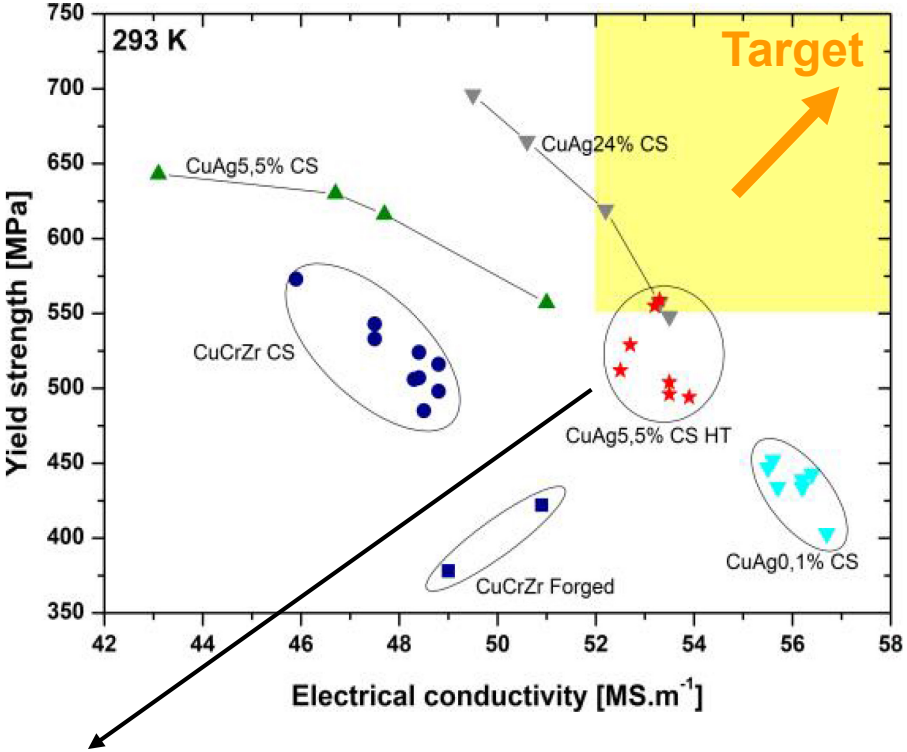
Ram velocity = 0.1 mm.s^{-1}

HT = 8 h at 330 °C

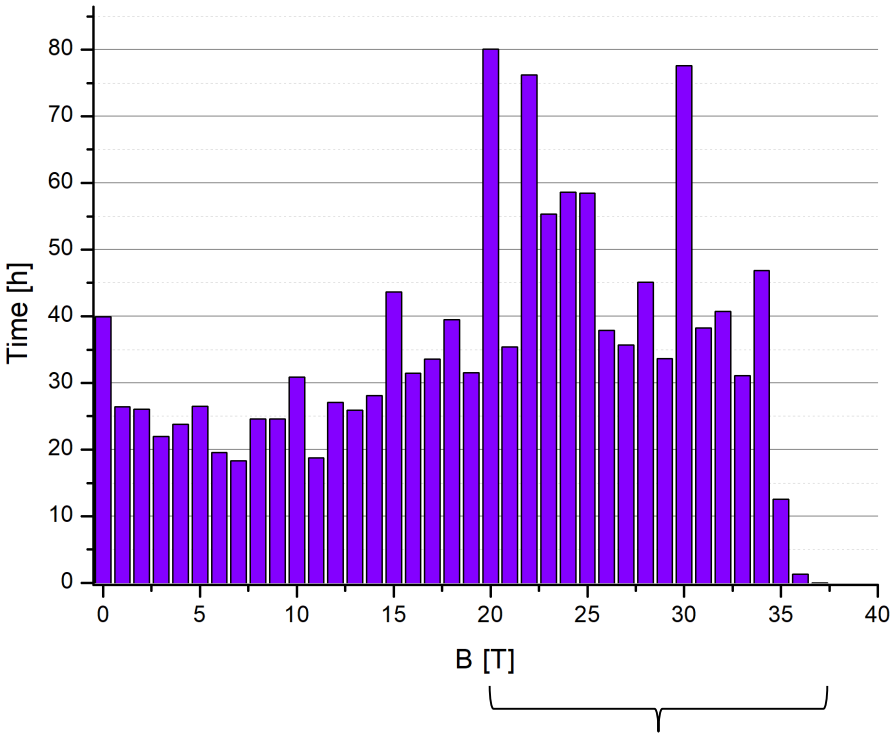
After 1 000 cycles:
Radial → no rupture ✓
Tangential → no rupture ✓
Longitudinal → no rupture ✓

➔ Fatigue behavior at higher temperature needs to be determined.

❑ Integration of cold spray helices in the magnets :



Magnet use with cold spray helices:
April 2017 → September 2019



High field usage up to 37 T

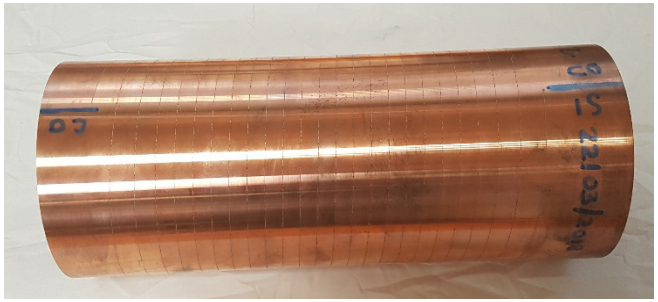
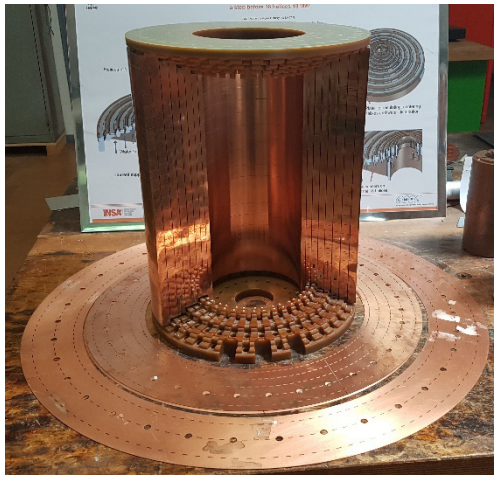
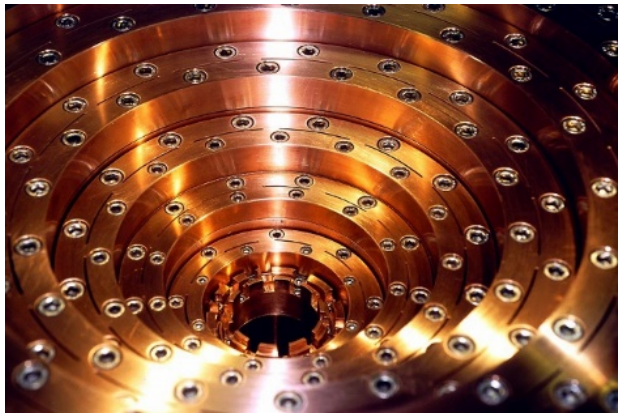
Stabilization of the production of CuAg5.5wt.% with the optimization of:

- the powder
- the cold spray deposition parameters

→ Today minimum values:

$Re_{0,2}$ = 510 MPa
σ = 52 MS.m^{-1}

→ Total hours ~ 1330 h



Thanks for your attention!