High Field Dipoles for accelerators

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PhD student

Background

- 2009: Graduated from “Ecole Normale Supérieure”
  → French famous school for higher education and research.

- 2009: Master degree in Electrical Engineering, University of Paris-Sud

- PhD thesis at CEA Saclay
  → Center for Atomic Energy, great research institution
  → Paris area
  → My department, IRFU, involved in many CERN projects

- 2012, September: PhD defense

- Teaching charge at university, during the PhD

Outline

I. Some issues in high field magnets
   1. High field magnets for LHC
   2. Innovative insulations

II. Theoretical work : Magnetic Design
   1. 2D cross-section design
   2. 3D coil-ends design

III. Experimental work : Ceramic Insulation Developments
   1. Critical current measurements
   2. Improvement outlooks

IV. Conclusion
   1. Contribution to high field magnet
   2. Interests in LARP

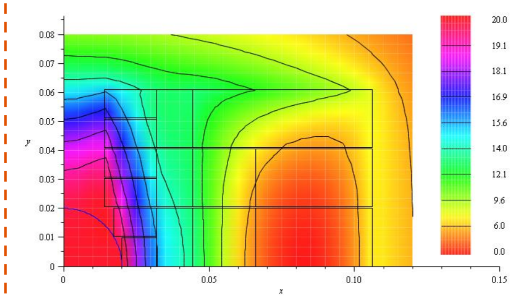
I. Some issues in high field magnets

I. Some issues in high field magnets

1. High field magnets for LHC

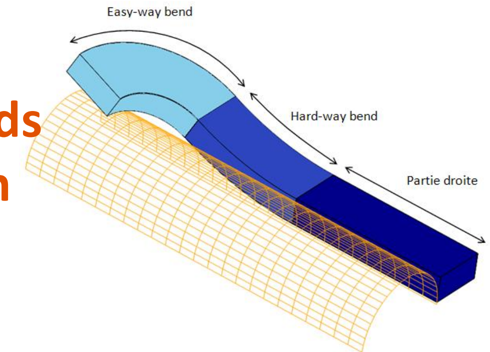
- LHC upgrades → Increase energy: HE-LHC
  → Increase luminosity: HiLumi
- Increase the bending field: NbTi limited, use Nb3Sn
- Beam stability → Good field homogeneity
- Avoid magnet quenching → Operational margins
- Nb3Sn very sensitive to stress → Manage forces

⇒ **Cross- section designs**



- Connect the straight parts → end-parts
- Respect the bending limits of the cable
- Keep field homogeneity and margin

⇒ **Coil-ends design**



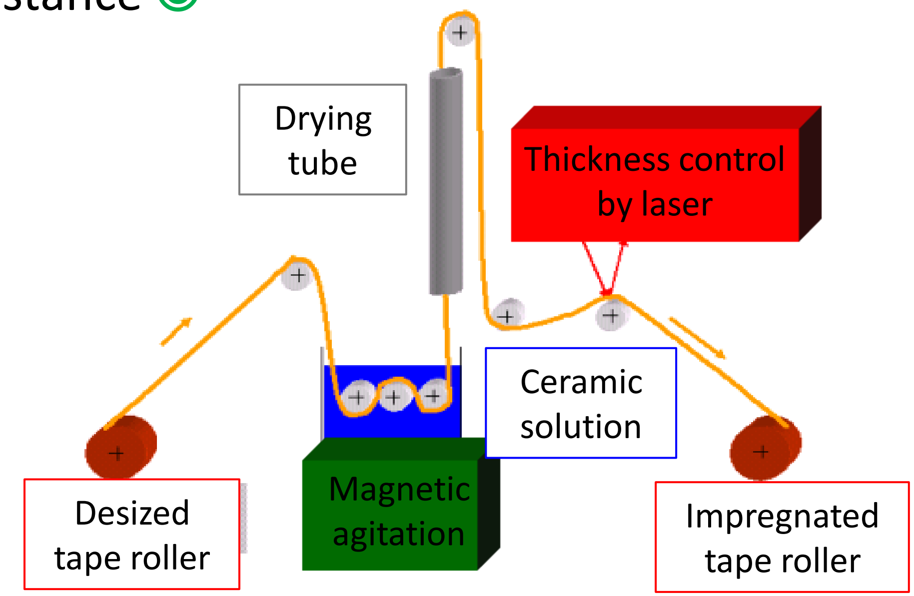
2. Innovative insulations

- Ceramic insulation developed at CEA [2 patents, 2001 & 2003]
  - Porous material → excellent heat evacuation ☺ [S. Pietrowicz, B. Baudouy, ICMC 2011]
  - Ceramic → withstands the 650 °C heat treatment ☺
    - → good resistance to irradiation ☺
    - → good electrical resistance ☺
  - Wind, Impregnate & React
    - → less risks ☺
  - Tests on small solenoids OK

- Issues:

Is the mechanical strength sufficient ? ☹

What is the electrical behavior of insulated cables ?

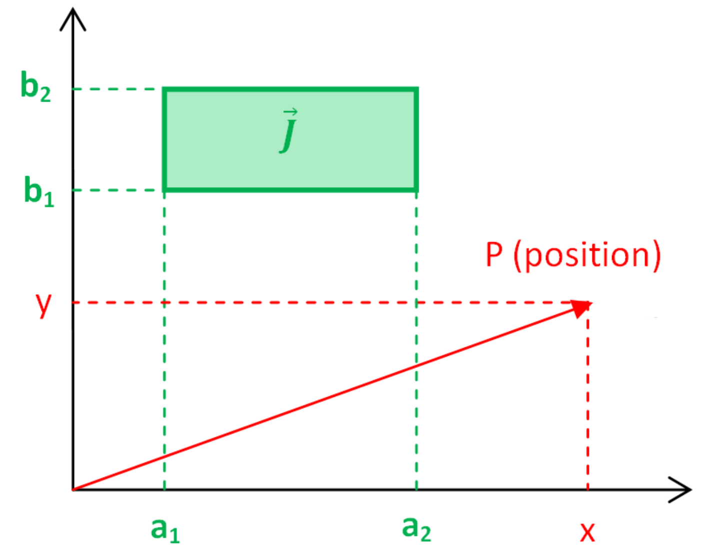


Impregnation process

II. Theoretical work : Magnetic Design

1. 2D cross-section design

- 2D model for the computation of field, harmonics and forces
  - → Analytic formulas for infinite rectangular blocks [G. Aubert, forthcoming book]
  - → Suitable for block design, Rutherford cables, ribbons



- Method to optimize cross-sections [E. Rochepault et al., IEEE 2011]
  - → 4 degrees of freedom/block
  - → Minimization of volume, forces…
  - → Easy to implement, fast, precise ☺
  - → No need for Fourier decomposition ☺
  - → No analytical form for saturated iron ☹

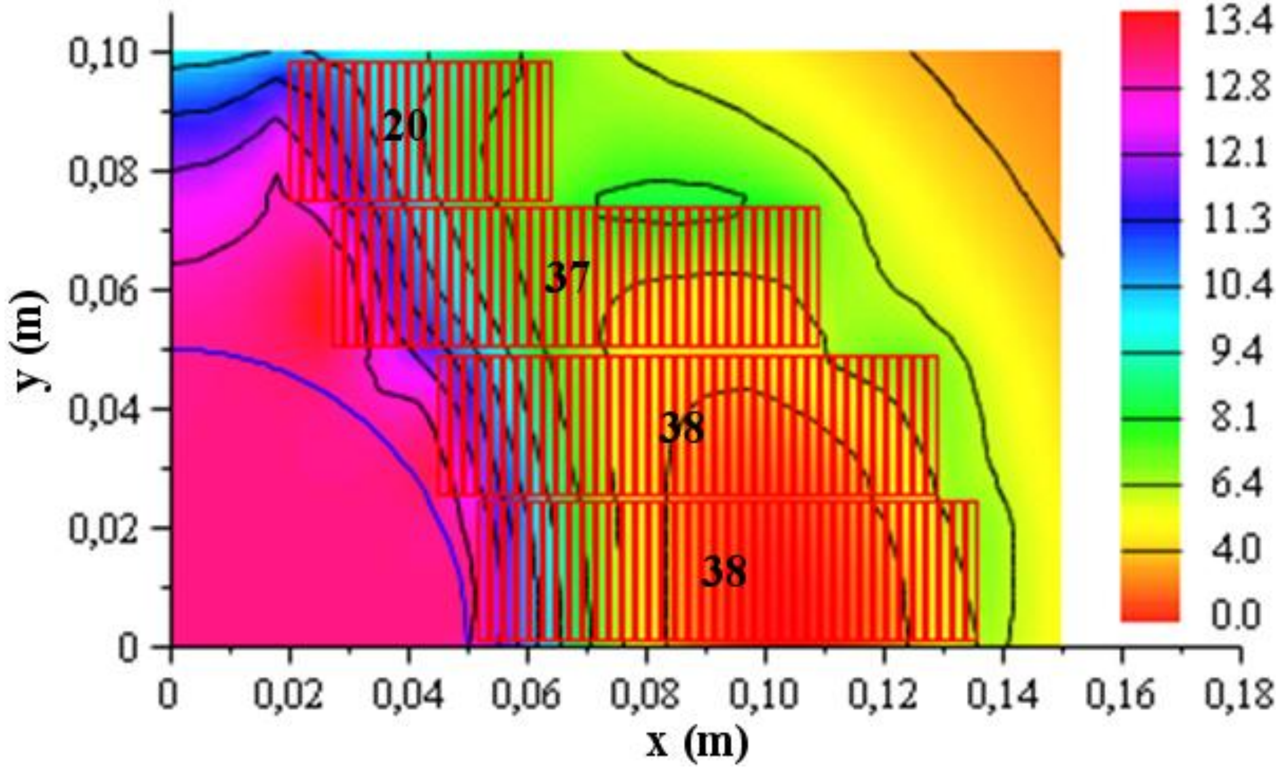
1. 2D cross-section design

FRESCA2 specifications: [HFM Magnet Design Working Group]

- Nb3Sn
- 100 mm aperture
- 13 T bore field

Conductor section minimization:

- 13 % margin
- harmonics < 1 unit
- stress < 100 Mpa



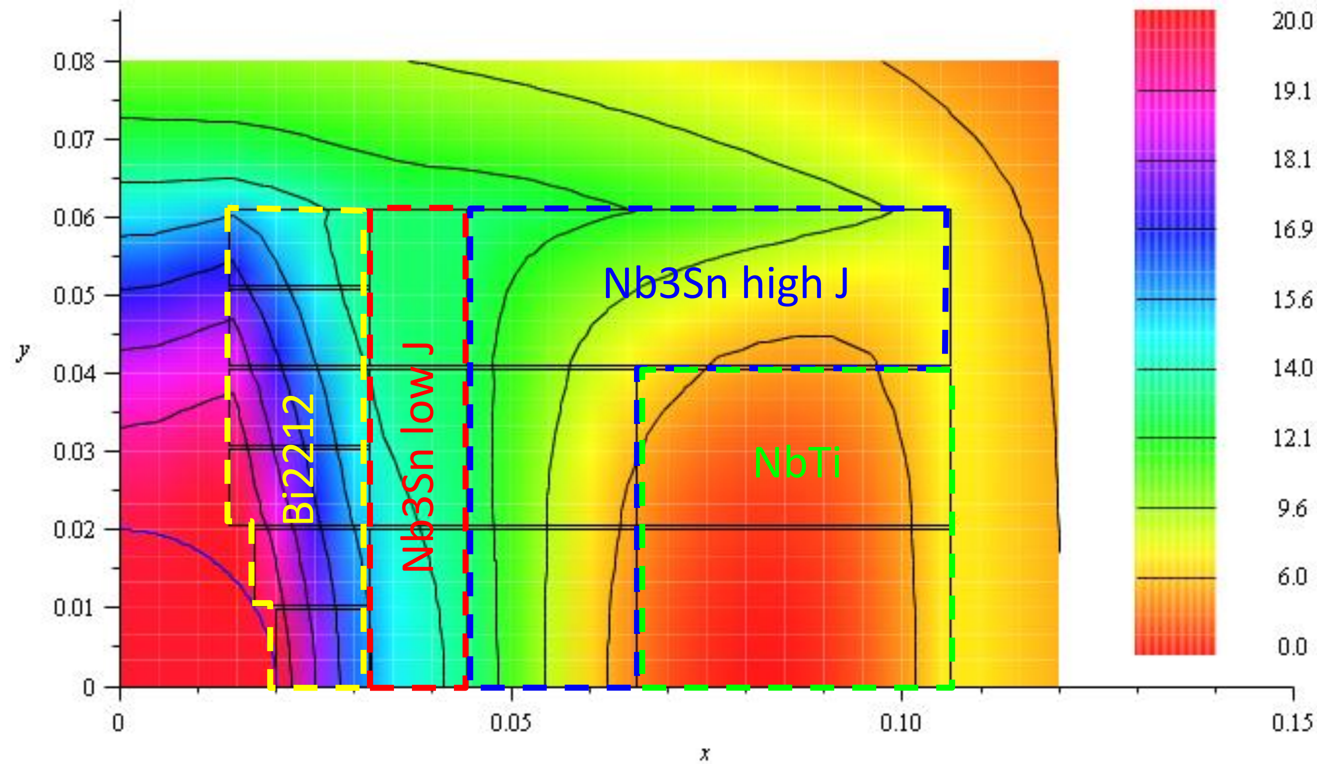
1. 2D cross-section design

HE-LHC specifications: [Rossi, Todesco]

- Bi2212, Nb3Sn, NbTi
- Grading
- 40 mm aperture
- 20 T bore field

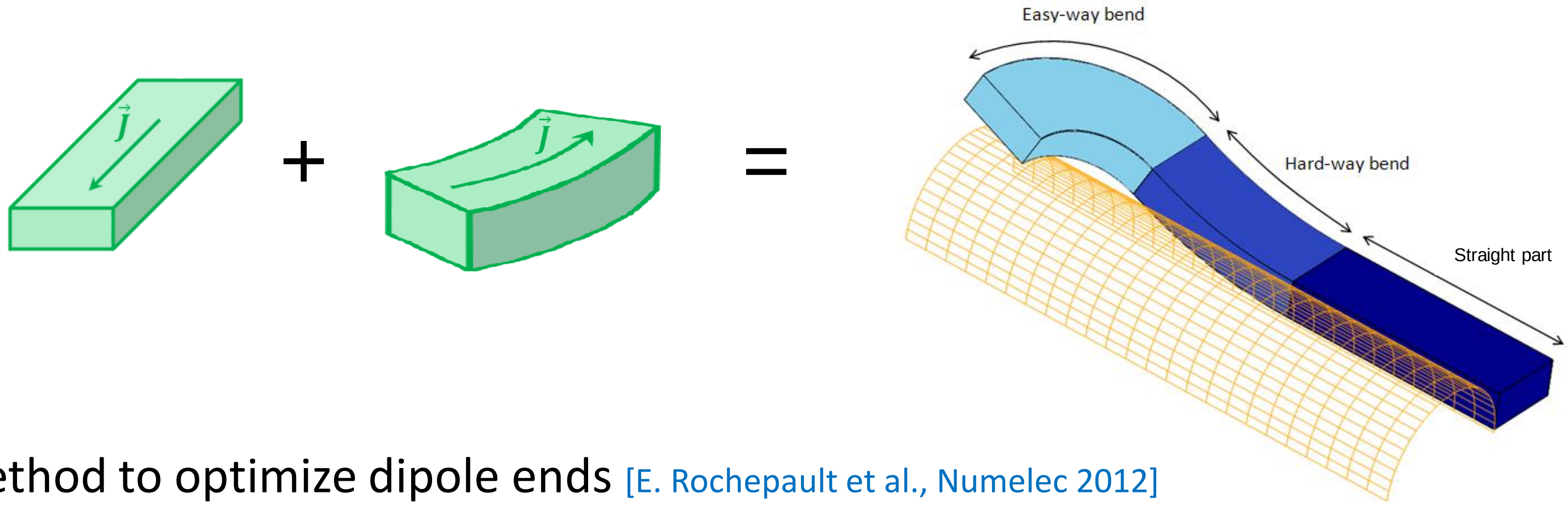
Financial cost minimization:

- 20 % margin
- aligned blocks



2. 3D coil-ends design

- 3D model for the computation of field in space
  - → Analytic formulas for blocks & arcs [G. Aubert, forthcoming book]
  - → Suitable for a block design + "pancake model"



- Method to optimize dipole ends [E. Rochepault et al., Numelec 2012]
  - → 6 degrees of freedom/block
  - → Minimization of the harmonic integrals along the tube
  - → Need for Fourier decomposition ☹

II. Theoretical work : Magnetic Design

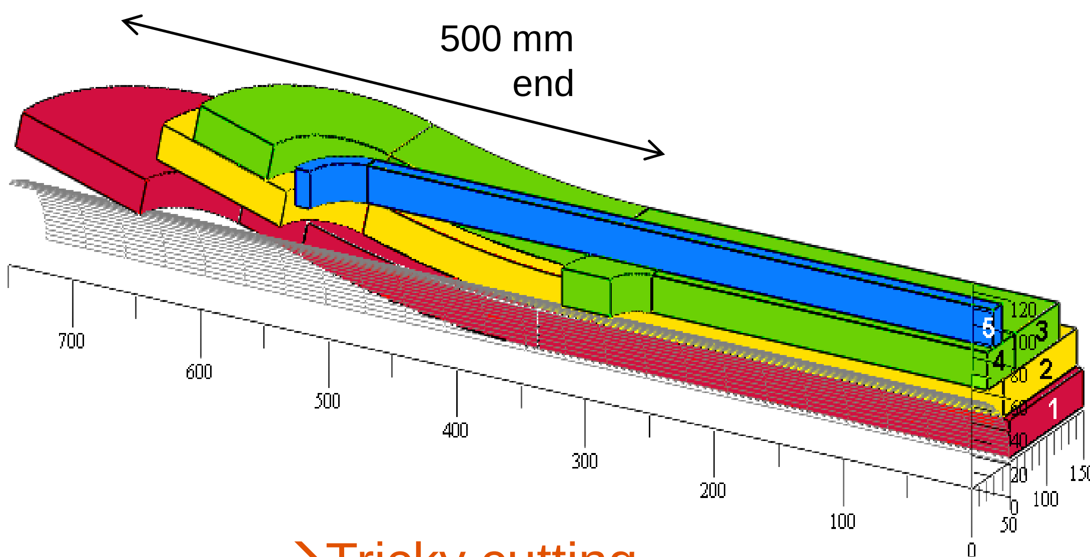
2. 3D coil-ends design

2D optimization :

- 4 layers
- 100 mm aperture
- 13 T bore field
- 13 % margin
- $B_3 = B_5 = B_7 = B_9 = B_{11} = 0$

3D optimization :

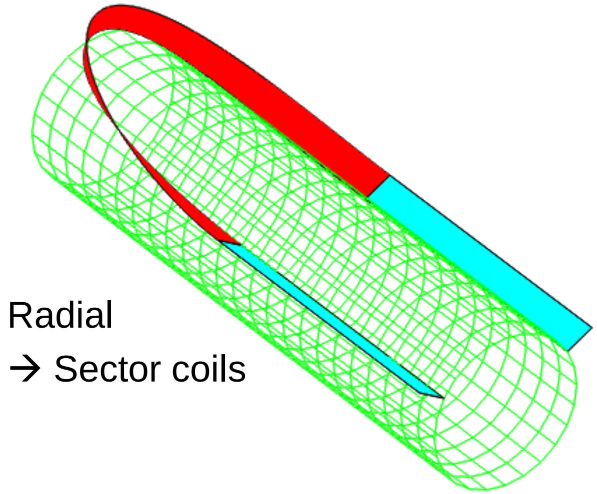
- 5 pancakes
- $\int B_3 dz = 0$
- $\int B_5 dz = 0.145$ T.m

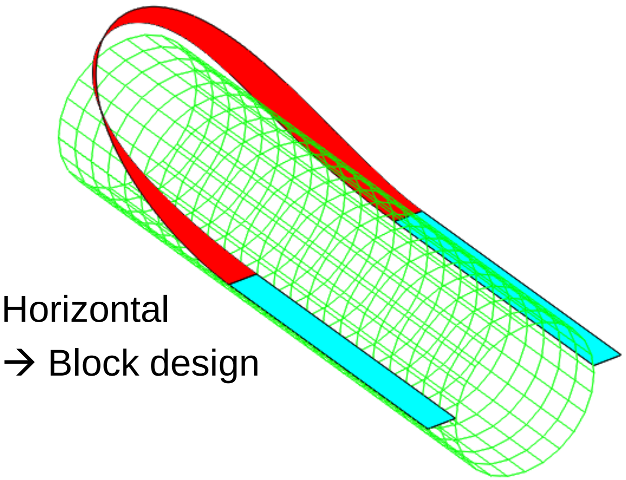


→Tricky cutting

2. 3D coil-ends design

- 3D model for the computation of harmonic integrals
  → Analytic formulas for geodesic strips [G. Aubert, forthcoming book]
  → Suitable for ribbons, approximation of Rutherford cables





- Method to optimize dipole ends
  → 1 degree of freedom/strip
  → Formulas for integrated harmonics ☺

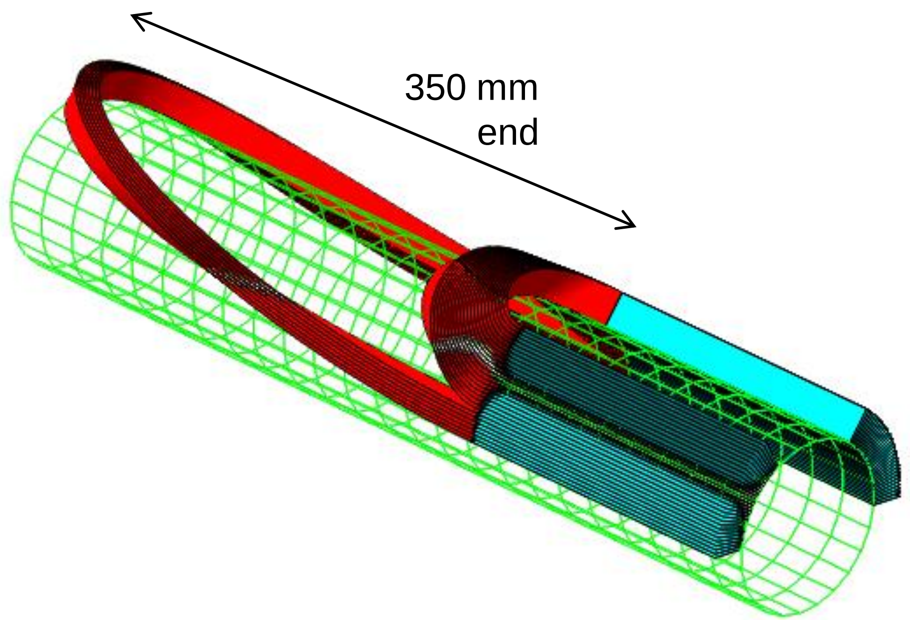
2. 3D coil-ends design

2D optimization :

- 1 angular sector
- 100 mm aperture
- 1.15 T bore field
- $B_3 = 0$

3D optimization :

- 2 parts
- minimum length
- $\int B_3 dz = 0$



III. Experimental work : Ceramic Insulation

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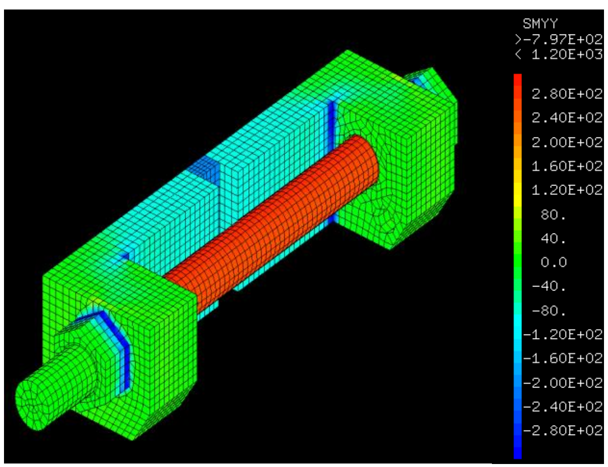
1. Critical current measurements

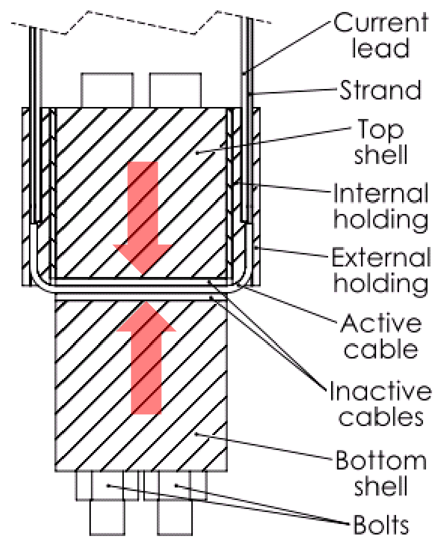
Are quenches stable when the pressure is applied ?

Does cooling has a beneficial effect on quenches ?

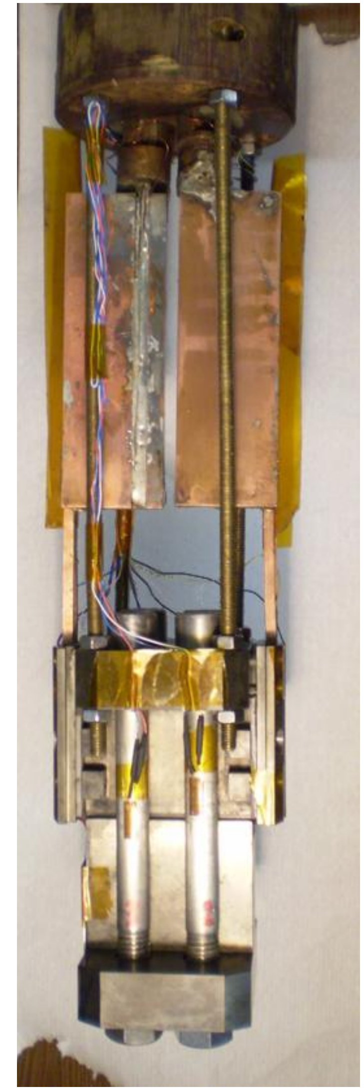
- CEA experiment: design of a new sample holder
  - → U shape, adjustable force on the cable
  - → Current measurement on a strand
  - → Background field: up to 11 T
  - → Ceramic insulation



FEM Modeling



Drawing

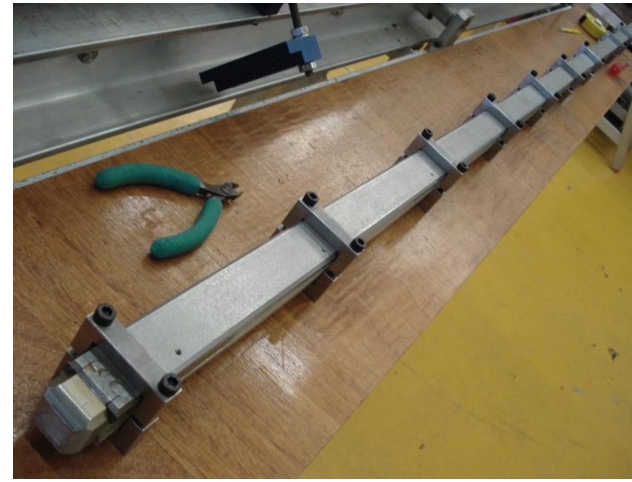


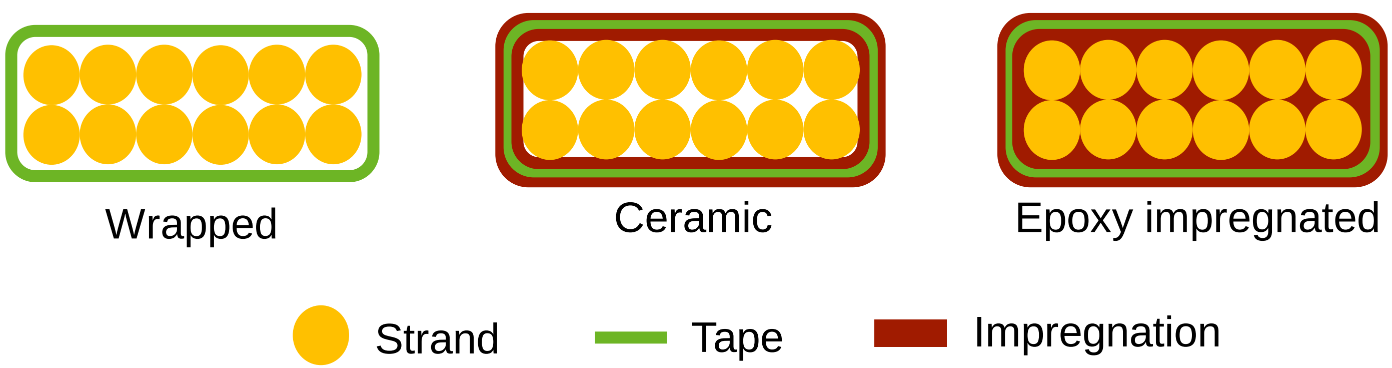
Assembly

III. Experimental work : Ceramic Insulation

1. Critical current measurements

- Collaboration with CERN: FRESCA experiment
  - → 2 cables, soldered at the bottom
  - → Adjustable pressure
  - → Quench measurement on the cable
  - → Background field: up to 9 T
  - → 3 types of insulation



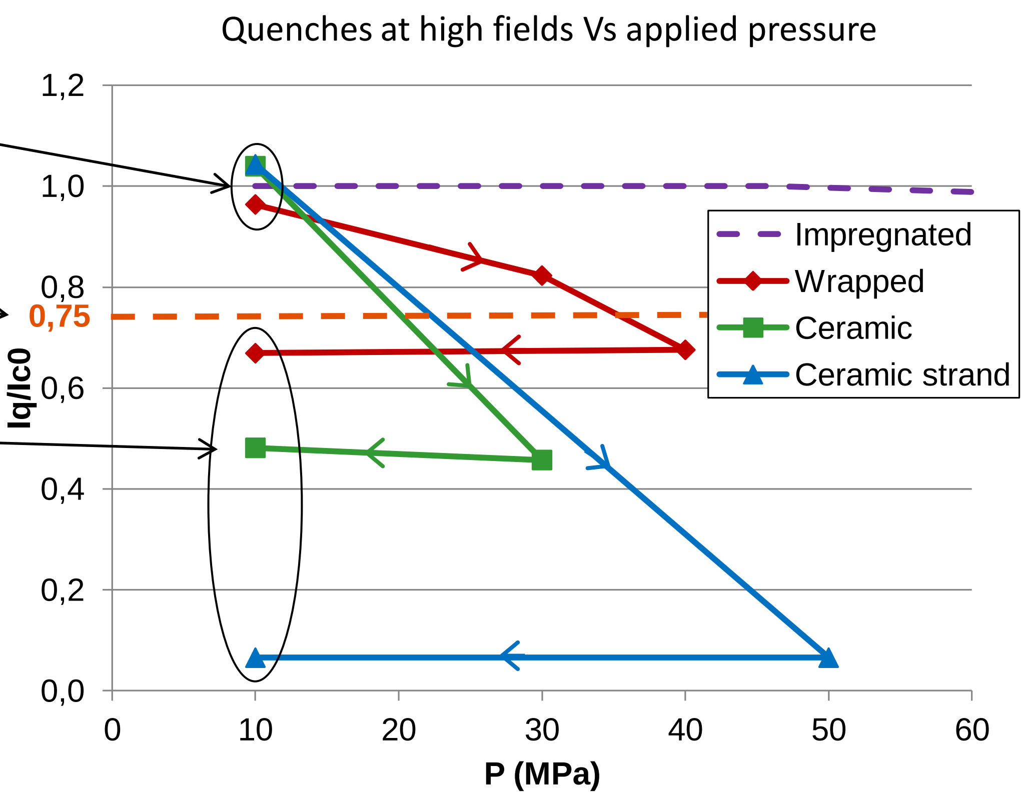


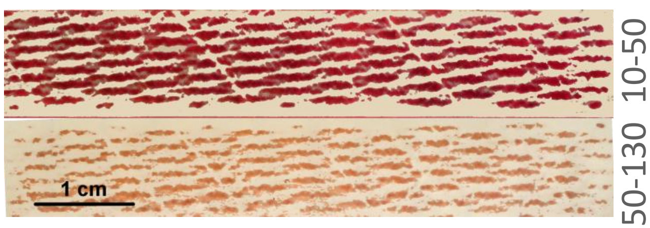
1. Critical current measurements

- No degradation
at very low pressure

- Unacceptable degradation
at low pressure

- Irreversible degradation
when pressure released





Pressure sensitive films after 40 MPa

[E. Rochepault et al., IEEE 2012], [S. Le Naour, CERN report, 2012]

→Non-impregnated cables cannot withstand even a small pressure

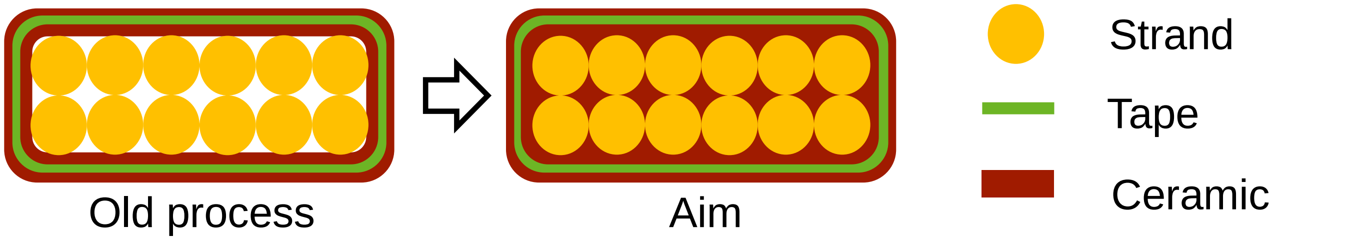
consistent with observations reported in literature

2. Improvement outlooks

Sintered ceramics can resist potentially up to 5 GPa pressures !

How to increase the mechanical strength of a ceramic insulation ?

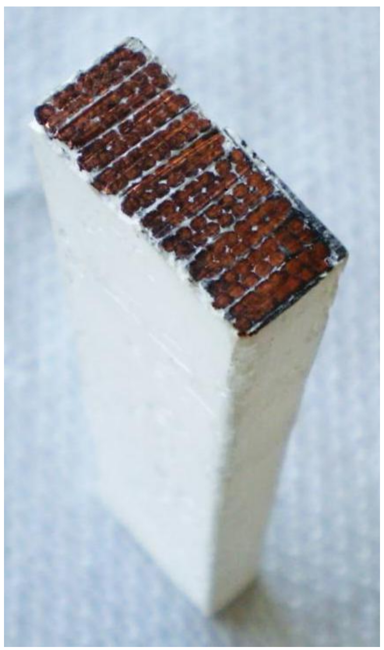
- Improve the sintering
  - → 650°C too low for ceramic sintering
  - → maybe applicable to other superconductors (Nb3Al, MgB2, HTS…) ?
- Fill the inter-strand interstices



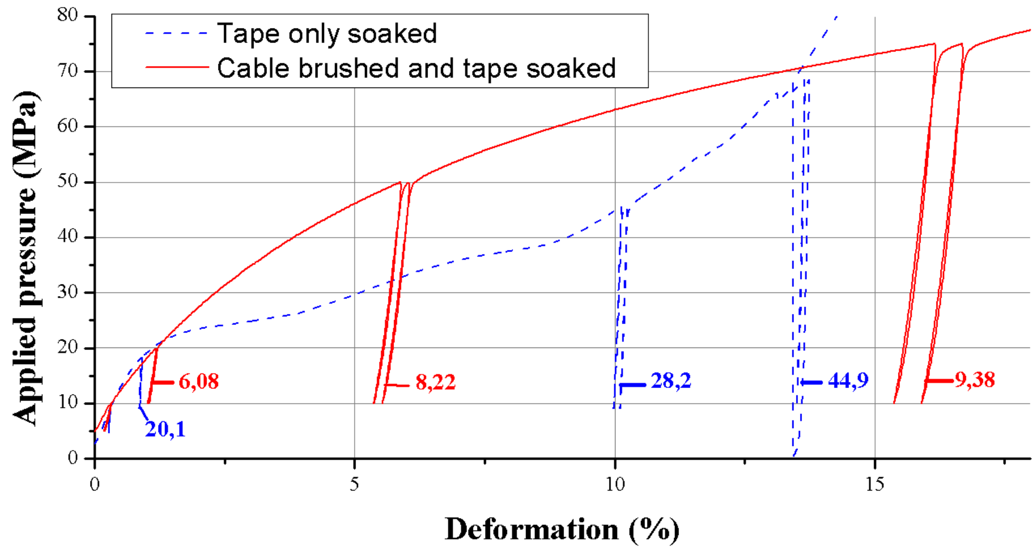
- The more mechanical strength, the less porosity
  - → heat evacuation ☹
  - → but thermal conductivity still 10-20x higher than resins !

2. Improvement outlooks

- Tests on different materials, different processes
  → Mechanical characterizations on cable stacks and mini-racetracks



Cable stack



Deformation under the press

→ Presently no ceramic insulation withstands pressures > 40 MPa

IV. Conclusion

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1. Contribution to high field magnets

- Theoretical work:
  - → Development of a 2D code and two 3D codes for magnet optimization
  - → Proposition of 2D designs for actual projects
  - → Proposition of 3D designs for Nb3Sn dipoles

- Experimental work:
  - → Design of an experiment to measure critical current of Nb3Sn cables
  - → Experimental testing of Nb3Sn cables
  - → Research on new insulation methods

IV. Conclusion

2. Interests in LARP

- Skills acquired in high field magnets design, both theoretical…
  → Mastering of field computation formulas
  → Computation of high field magnet configurations
  → Good knowledge of optimization programming

…and experimental
  → Design of an experiment
  → Preparation & testing of superconducting cables (with all the issues !)

- A good experience (and a lot of interest) in high field magnets:
  → I already worked with CERN
  → I followed an high field dipole project

- LARP is a great opportunity:
  → High field magnets projects
  → Strong CERN partnership
  → 4 laboratories of excellence with famous records in magnet technology

Thanks for your attention !

Some questions ?