HTS Metal-Insulated technology development at CEA towards HFM 20 T dipole magnets

CEA-CERN HFM collaboration agreement on HTS MI dipoles developments WP2.11

Thibault Lécrevisse (CEA) on behalf of HFM HTS team

Amalia Ballarino (CERN)

Overview

1. **Program introduction**
   - Program philosophy
   - HTS development plan
   - Two-years project planning
2. **Numerical modelling**
   - Introduction : some MI Racetrack possibilities
   - Tools overview
   - PEEC-R model and examples
   - Salome / CASTEM FEM model
   - Mechanical structure conception
3. **Experimental developments**
   - Developments and Characterization to be done
   - Radial thermal conductivity characterization
   - Electrical connection developments
   - First small MI pancake coil with copper rings
   - Effect of thermal cycles on HTS and joints
   - Racetrack winding development
4. **Perspectives**
   - Models validation
   - Concept validation

1. Program introduction

1. HTS high field dipole development Philosophy

Eucard block magnet

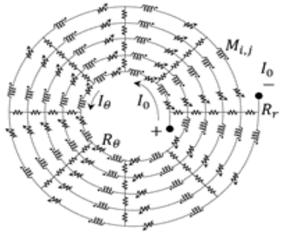
Damaged at 4.2 K, SF and about 50% of margins

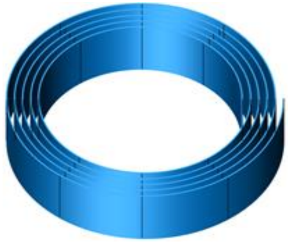
UHF insert NOUGAT

Quench protection helped by **M**etal as **I**nsulation (**MI**) winding

Quenched at 32.5 T without thermal damage

NI-MI Partial Element Equivalent Circuit model (PEEC)



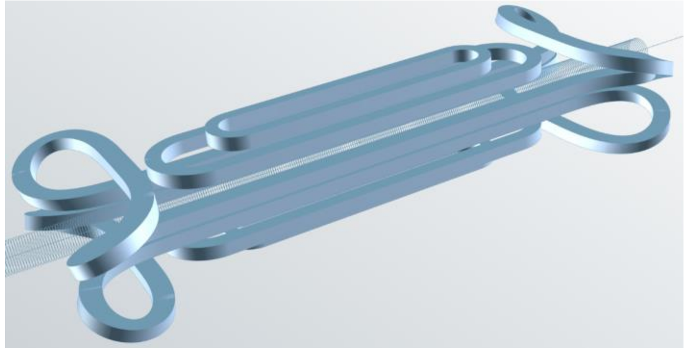


MI technology for dipole ?

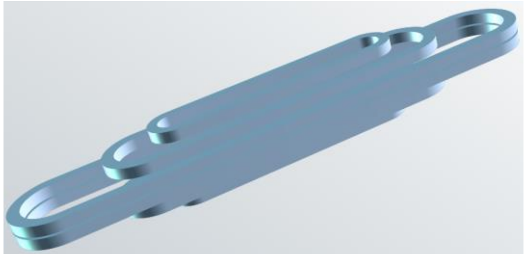
- Develop racetrack models
- Develop racetrack MI winding
- Study specific technological aspects (Joints, assembly…)
- Step by step validation :
  - Mockups for models
  - Racetrack coils for learning
- Test coils up to the limits

1. HTS high field dipole development plan

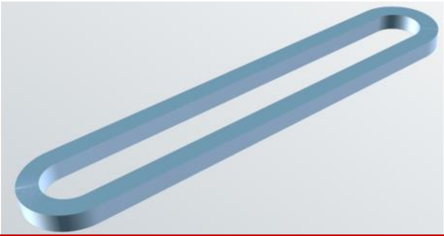
Phase 3 :
MI
16 T+ dipole magnet

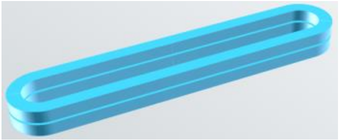


Phase 2 :
MI 16 T+ dipole field
« EuCARD1 V2 »



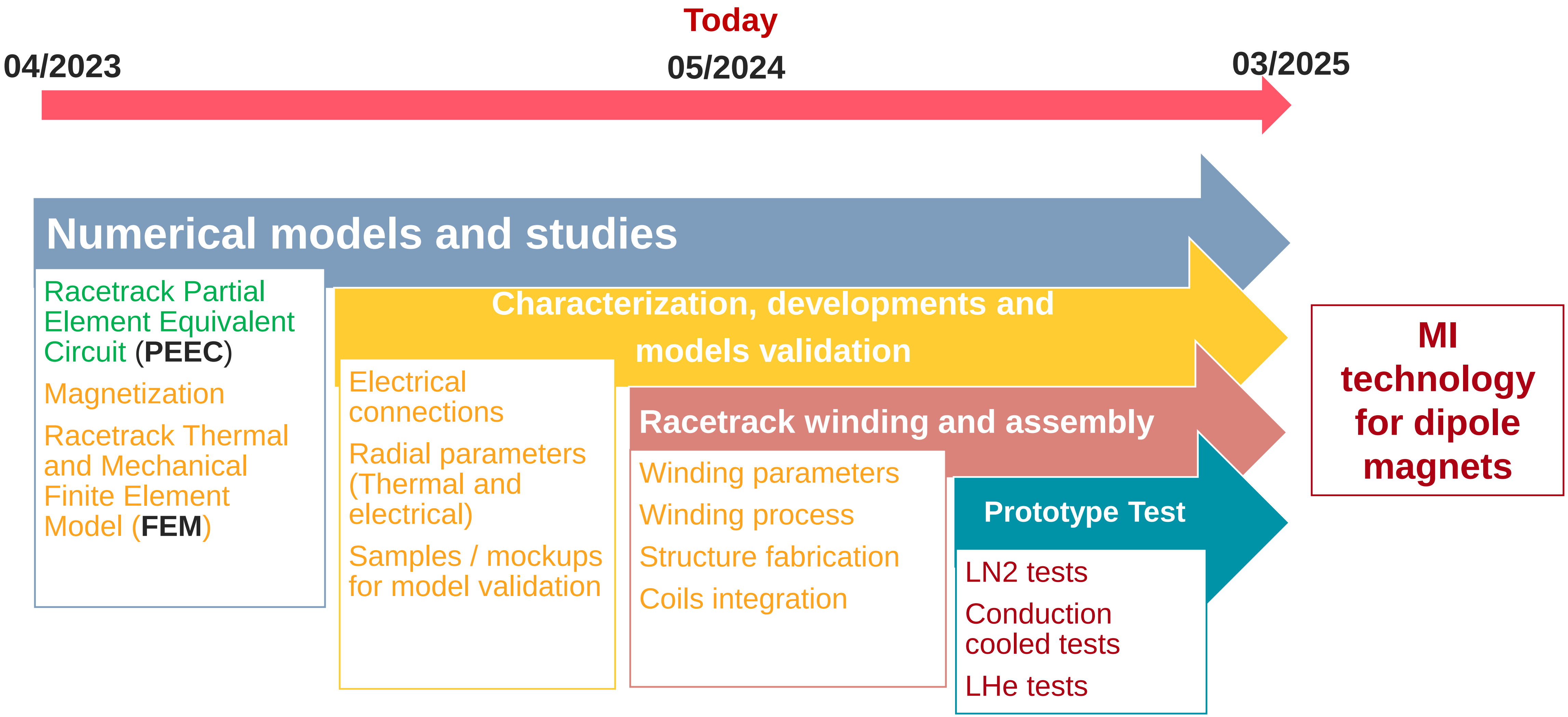
Phase 1 **2023-2025**:
Racetrack MI





CERN-CEA
HFM WP2.11 (KE5647)

1. Planning


Today
04/2023
05/2024
03/2025
Numerical models and studies
Racetrack Partial Element Equivalent Circuit (PEEC)
Magnetization
Racetrack Thermal and Mechanical Finite Element Model (FEM)
Characterization, developments and models validation
Electrical connections
Radial parameters (Thermal and electrical)
Samples / mockups for model validation
Racetrack winding and assembly
Winding parameters
Winding process
Structure fabrication
Coils integration
Prototype Test
LN2 tests
Conduction cooled tests
LHe tests
MI technology for dipole magnets

2. Numerical modelling

2.1. Introduction : some MI Racetrack possibilities
2.2. Tools overview
2.3. PEEC-R model and examples
2.4. Salome / CASTEM FEM model
2.5. Mechanical structure conception

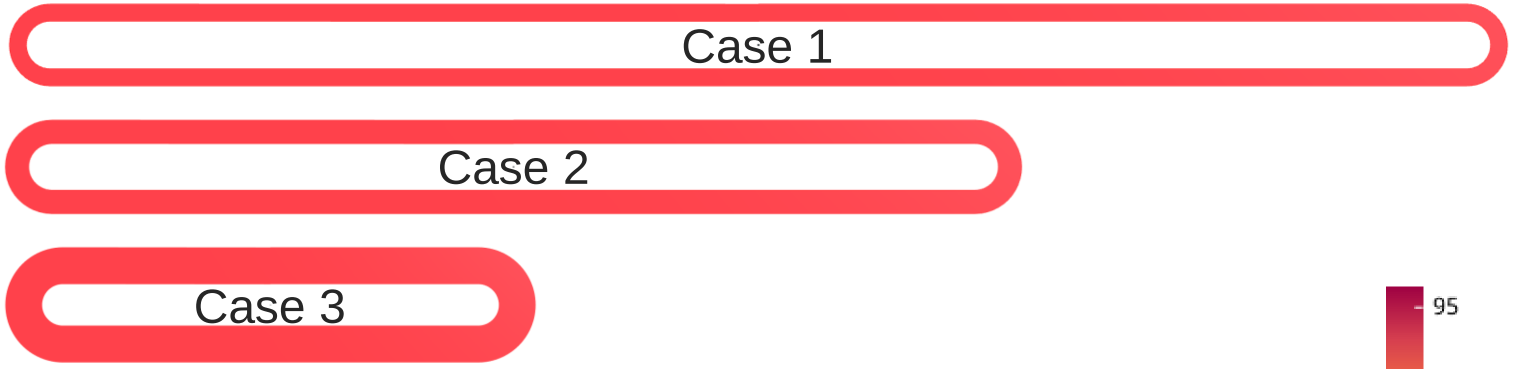
2.1. Introduction : some MI Racetrack possibilities

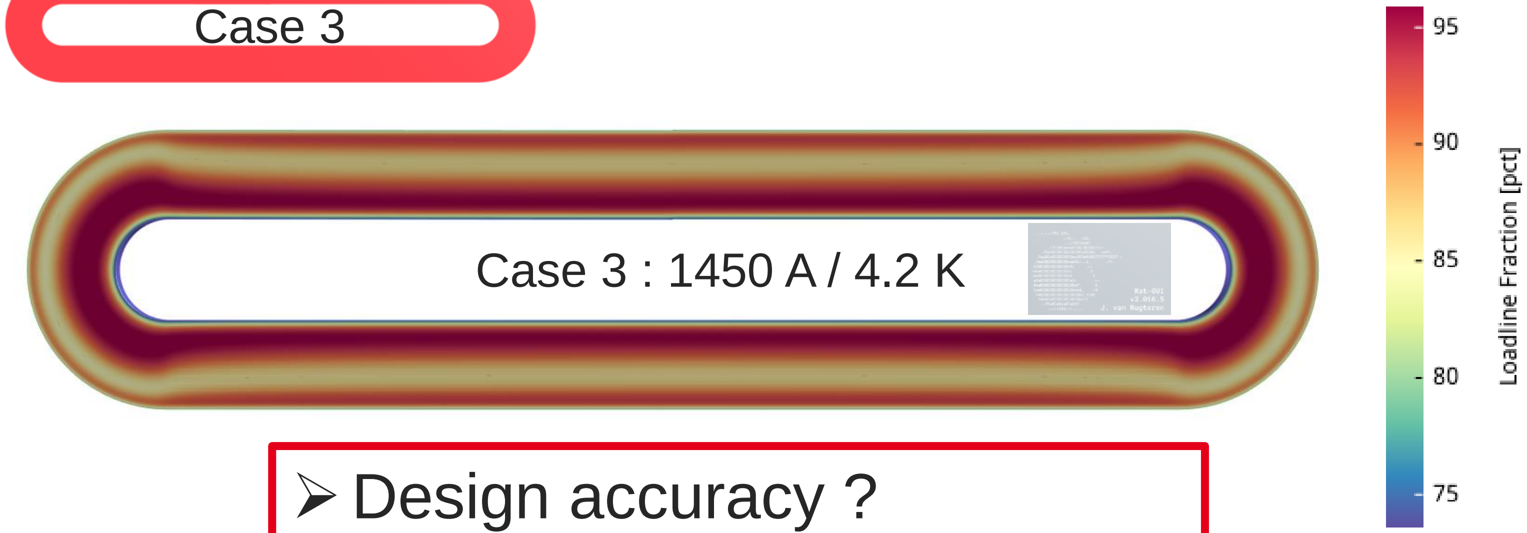
Parameter		Unit	Value
REBCO Tape (SST)	Thickness	µm	72
	Width	mm	4
	I_c, 77 K, SF	A	> 210
	I_c, 4.2 K, 20 T //c	A	> 460
	Unit Length	m	100-200
Durnomag®	Thickness	µm	30
	Width	mm	4
Racetrack	Straight part length	mm	300 - 900
	Width	mm	30
	Unit length	m	60-100-200

2.1. Introduction : some MI Racetrack possibilities

Parameter	Unit	Case 1	Case 2	Case 3
Width	mm	30	30	30
S. Part length	mm	900	600	300
# turns	-	103	148	257
Inductance	mH	10.2	13.6	20.7
B at center	mT/A	2.07	2.72	3.99
B peak	mT/A	6.99	8.24	10.32
$I_{max,\ 4.2\ K}$	A	1575	1545	1510
$B_{center,max}$ 4.2 K	T	3.26	4.20	6.02
J_e, max 4.2 K	A/mm²	3860	3785	3700

Protection ?





- Design accuracy ?
- Mechanics ?
- Cooling ?
- Protection ? MI parameters ?
- Fabrication ?

2.2. Tools overview

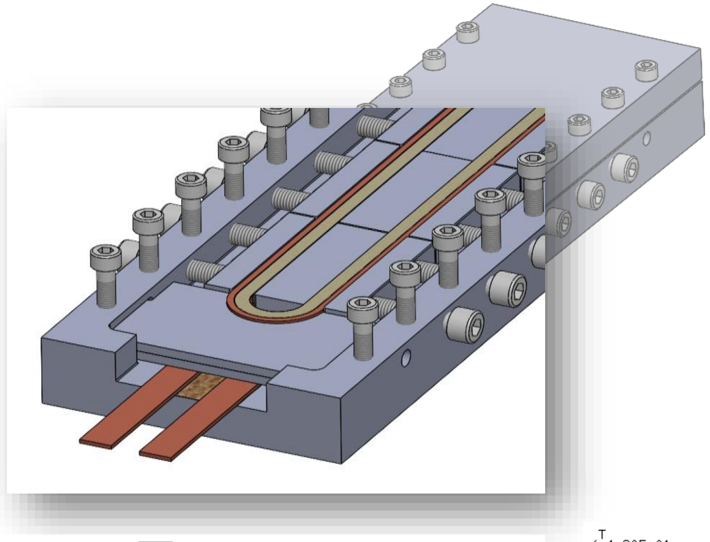
A. Blondelle P. Fazilleau C. Genot

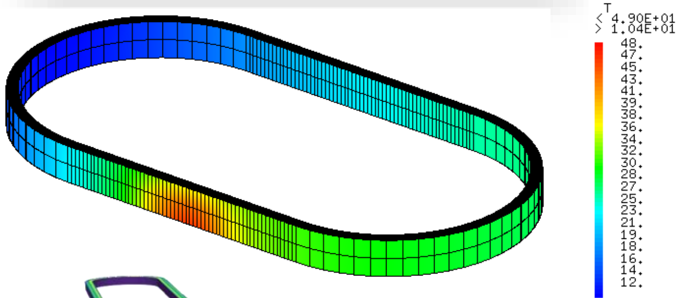
Initial parametric study

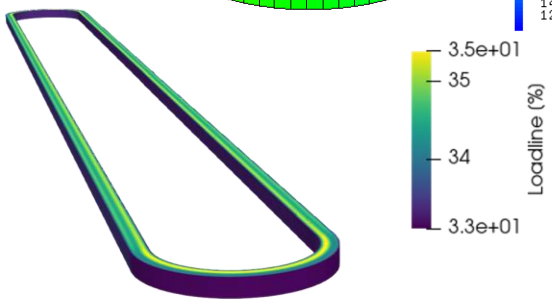
PEEC → SALOME (python) → CAST3M

A. Caunes E. Benoist A. Blondelle G. Lenoir L. Scola G. Minier F. Nunio

- Mechanical
  - Forces
  - Stresses
- Thermal
  - Conduction cooling dimensioning
  - Thermal stability
- Magnetic
  - Static field
  - Loadline
  - Temperature margin

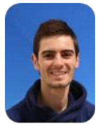




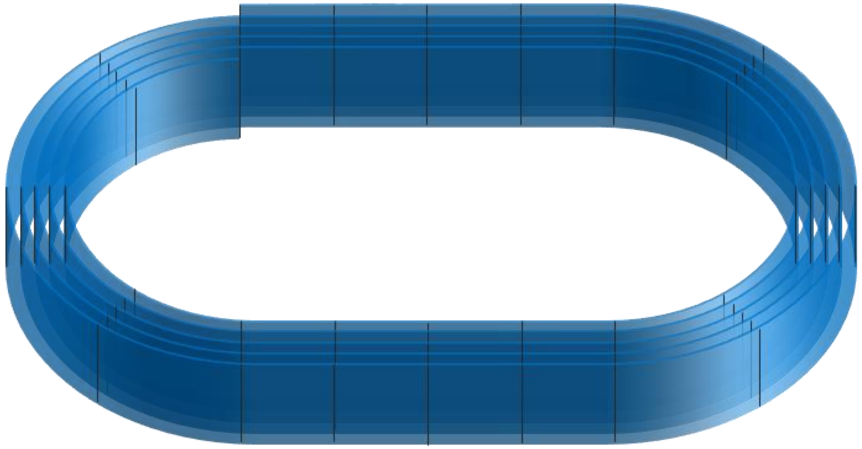


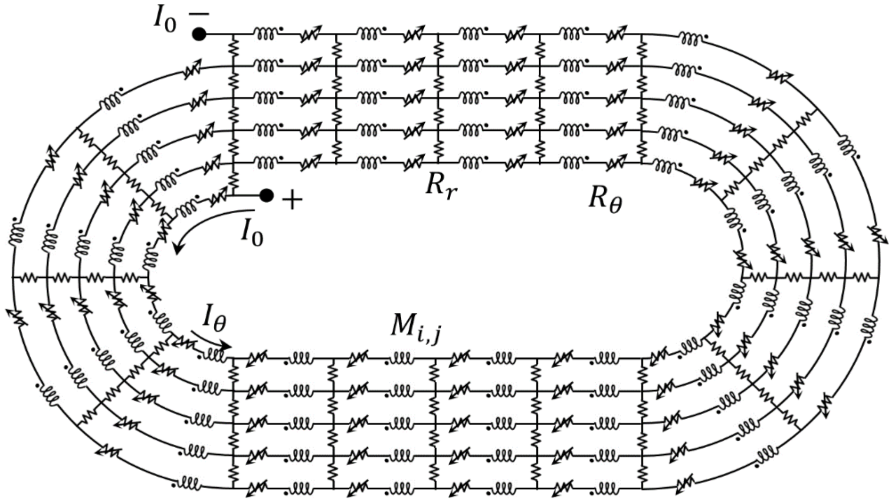
2.3. PEEC-R model and examples


A. Blondelle

P. Fazilleau

C. Genot

PEEC-R : Partial Element Equivalent Circuit - Racetracks





Equivalent Circuit solver

Fleiter's fit for critical current

Geometric description
↓
Pre-calculation *(magnetic field, current profile, …)*
↓
Electrical and thermal system solver
↓
Save & display

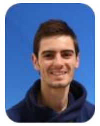
3D Electromagnetic

2D finite difference for thermal equations

No magnetization for now

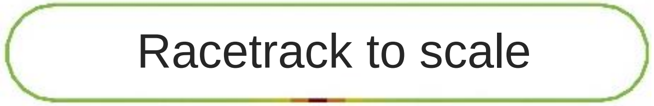
2.3. PEEC-R model and examples

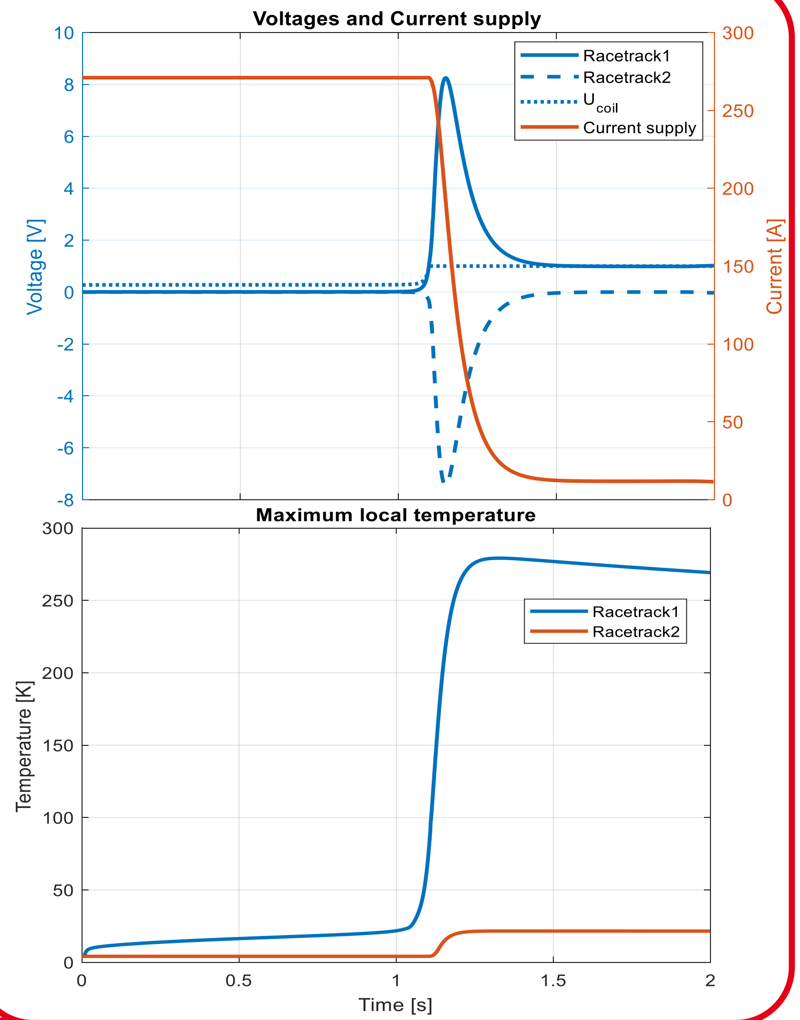

A. Blondelle

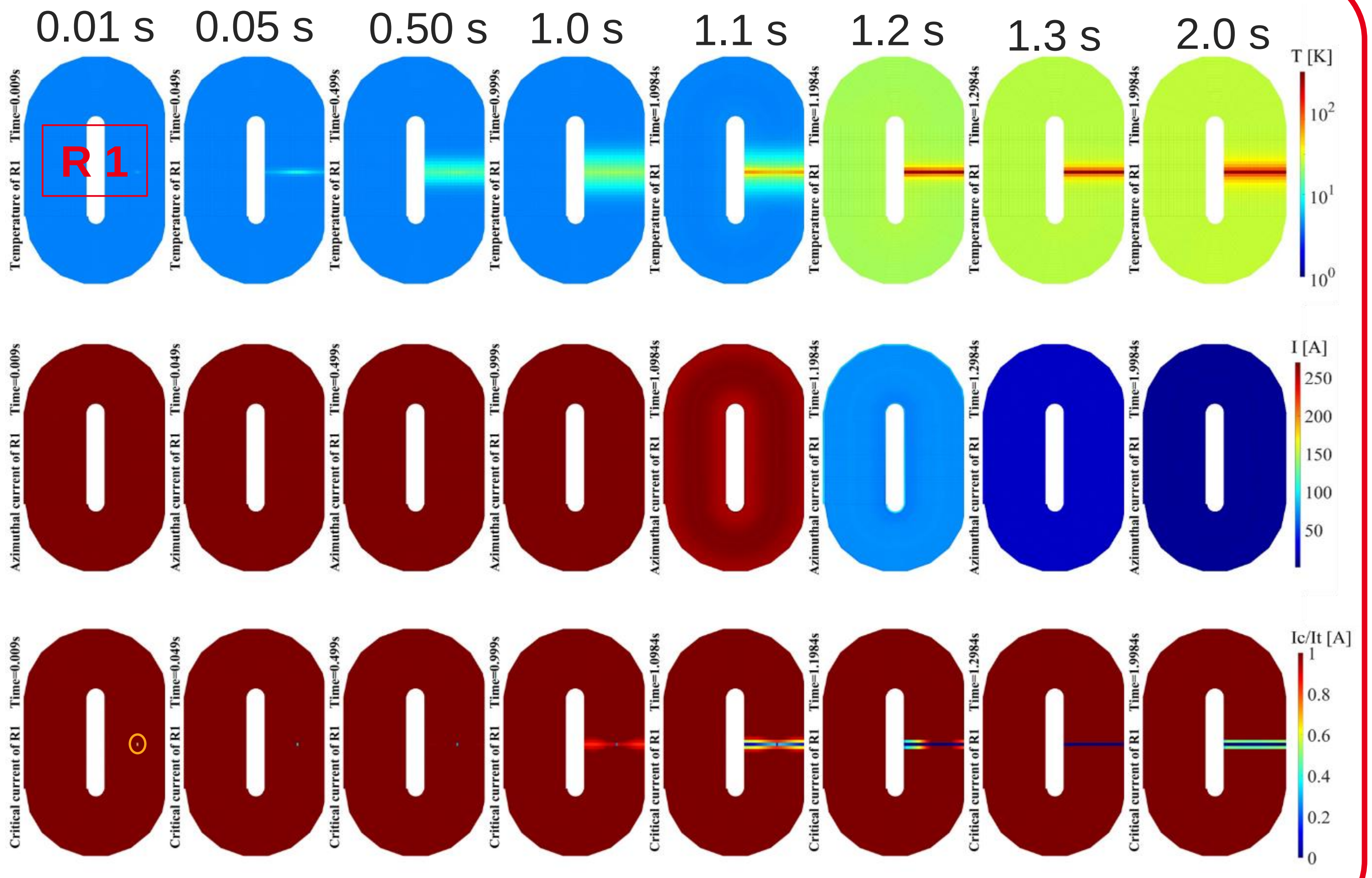
P. Fazilleau

C. Genot

Example : 2 Racetracks with local degradation at 5 ms

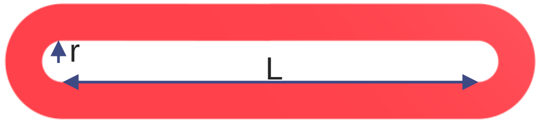
R= 50 mm ; L = 600 mm ; 4 mm wide tape ; I=271 A ; 39 Turns ; 300 mΩ.cm² ; $U_{lim,PS}$= 1 V







2.3. PEEC-R model and examples



A. Blondelle P. Fazilleau C. Genot

Geometrical study

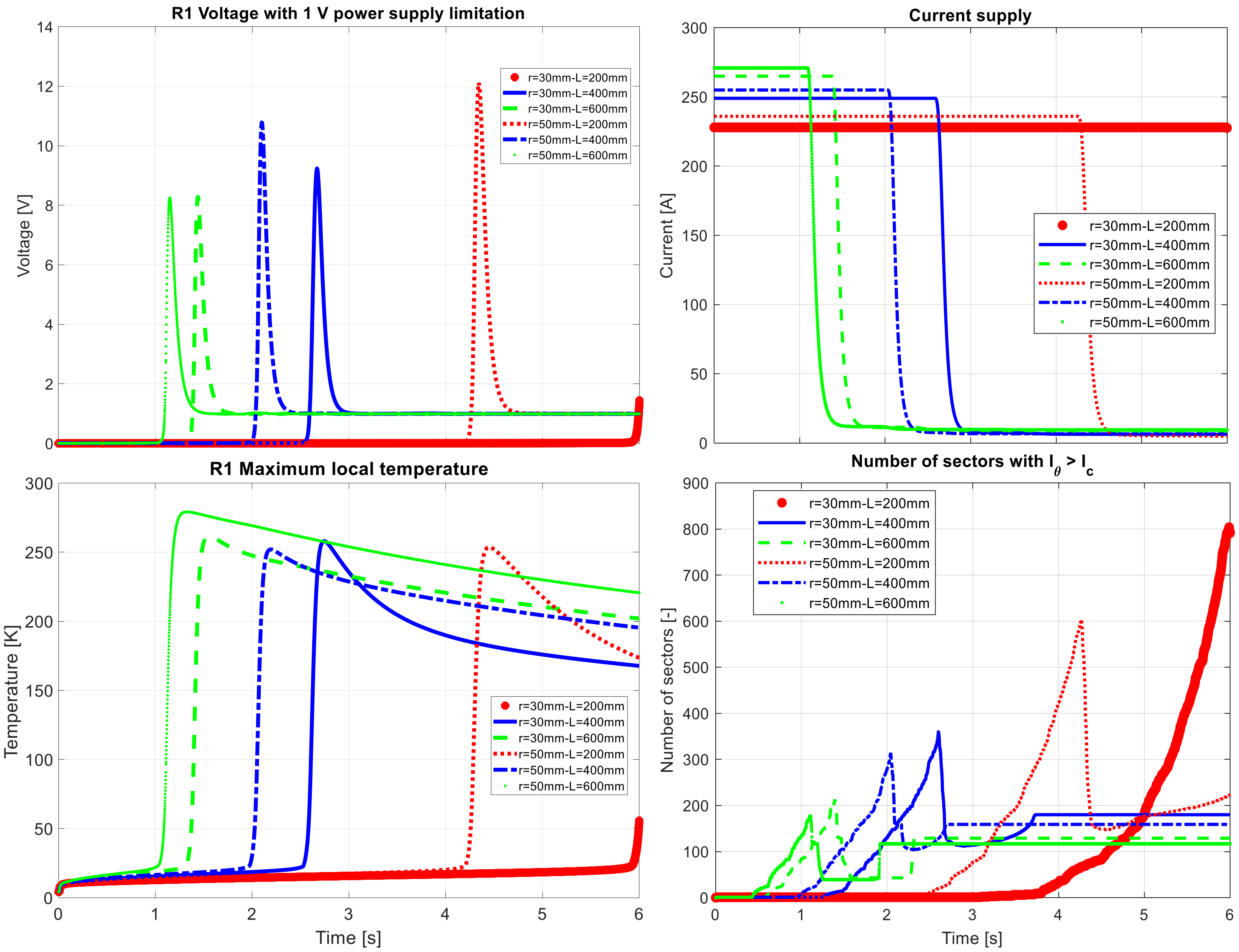
- ❑ 60 m tape
- ❑ 2 Racetracks
- ❑ 0.5 mm spacer
- ❑ Nb turns = [101;60;43;84;53;39]

- ❑ R_{ct}=300 mΩ.cm²

- ❑ 1 sector damaged at 5 ms

- ❑ Adiabatic (T_i = 4.2 K)
- ❑ 1 V PS Voltage limitation
- ❑ 85% of I_{max} [228;249;265;236;255;271]

> ➢ Thermal diffusion effect
> ➢ Results are depending on the number of turns

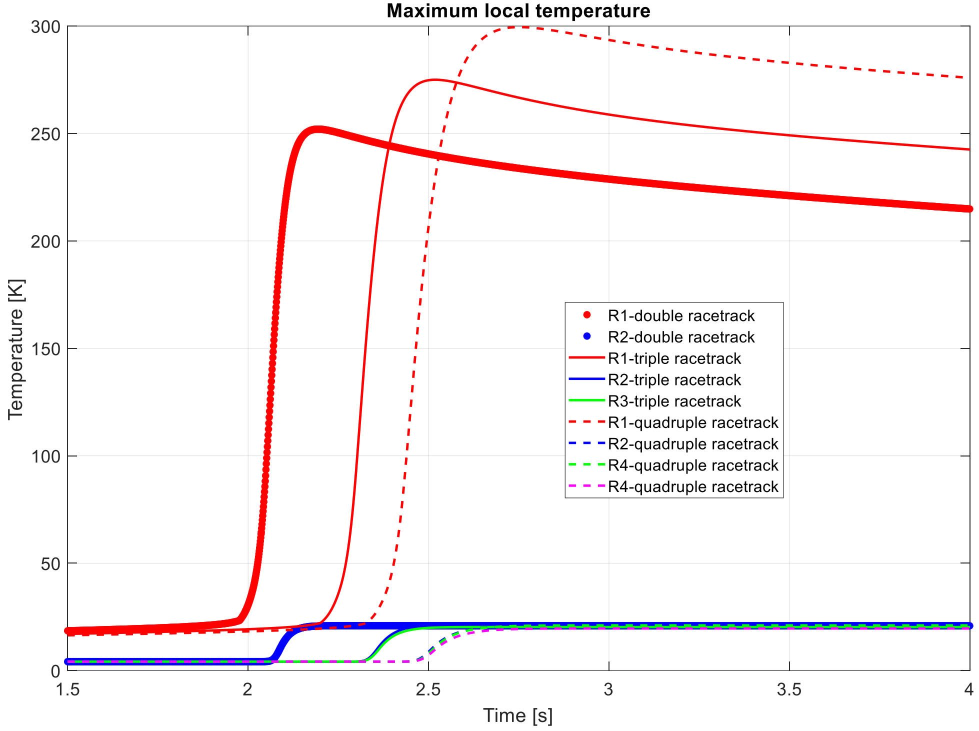


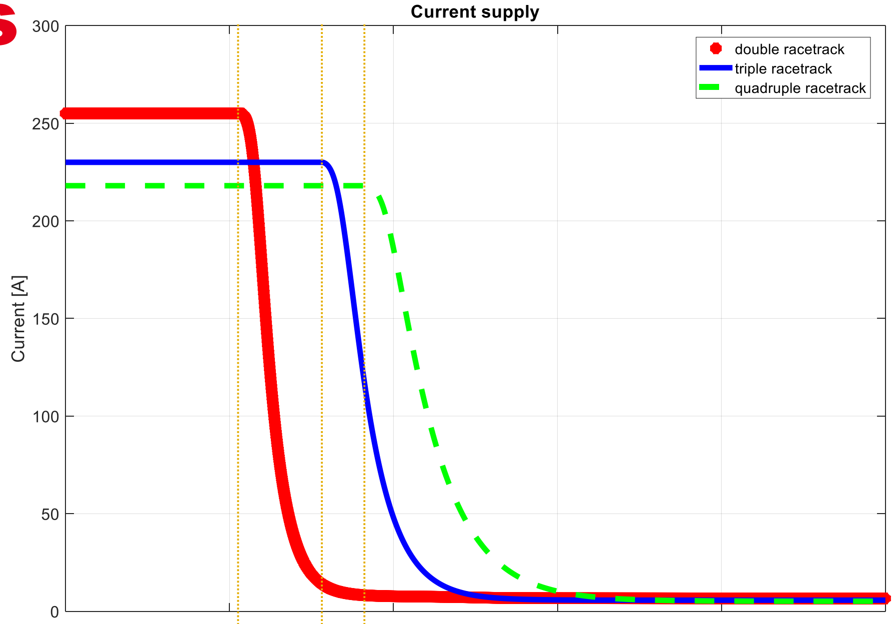
2.3. PEEC-R model and examples

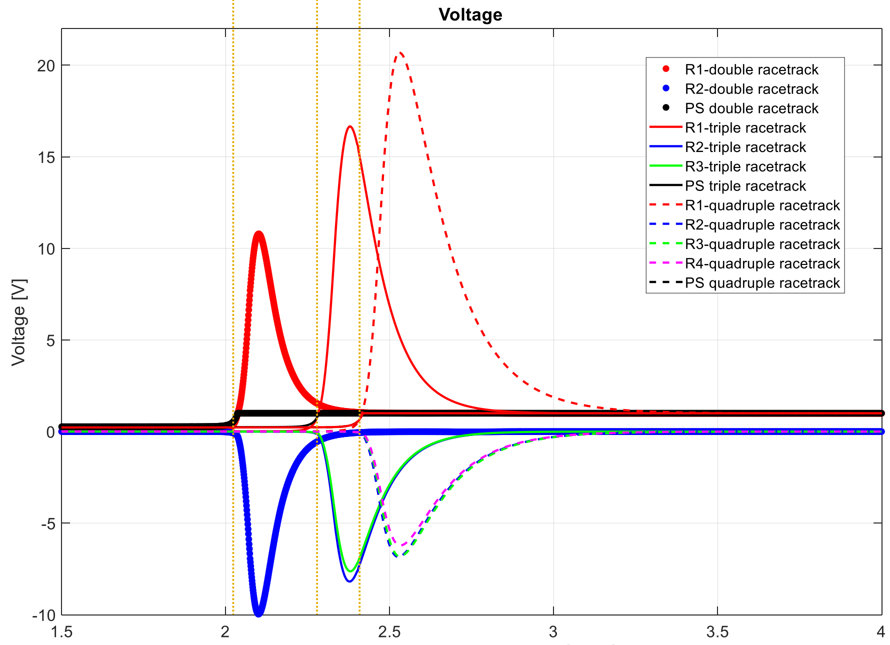
Multi-racetracks study

- 60 m tape
- Racetracks : [2;3;4]
- 0.5 mm spacer
- R= 50 mm / L = 400 mm / 53 turns
- R_{ct}=300 mΩ.cm²

- 1 sector damaged at 5 ms in R1
- Adiabatic (T_i = 4.2 K)
- 1 V PS Voltage limitation
- 85% of I_{max} [281;253;239]

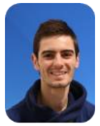




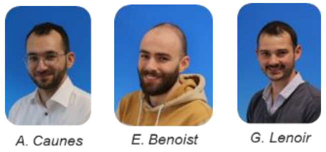


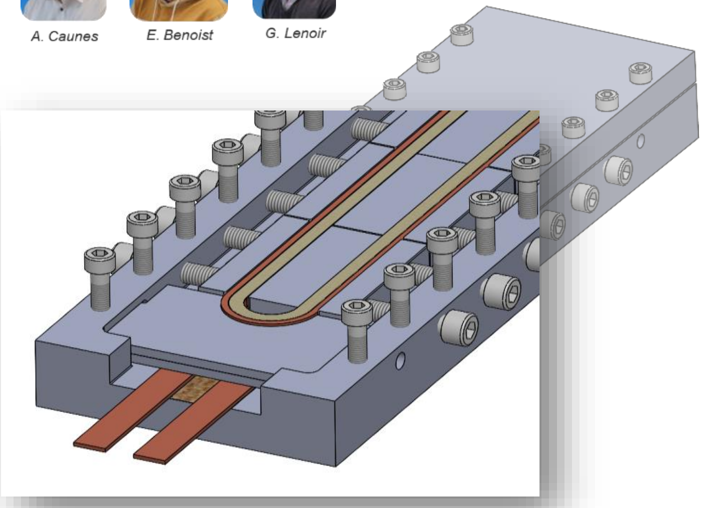

A. Blondelle


P. Fazilleau


C. Genot

2.4. Salome / CASTEM FEM model

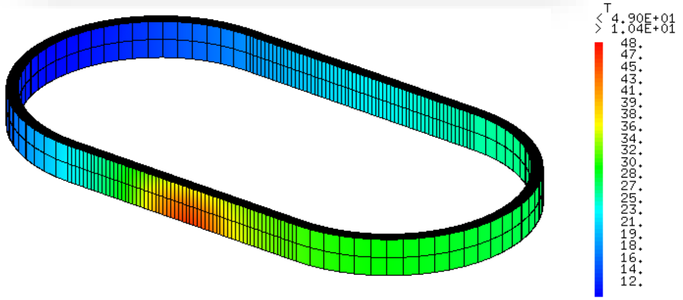


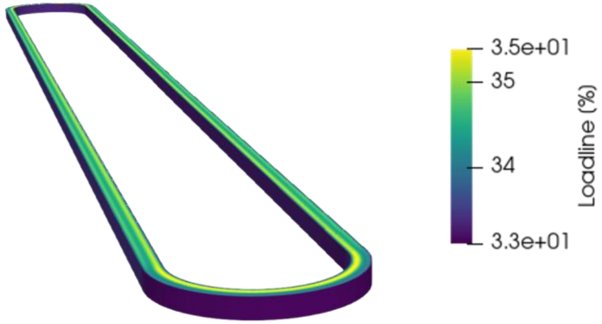


mesh | Calculations

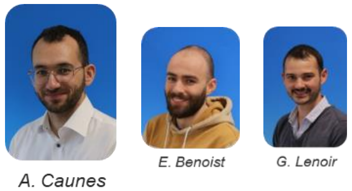
PEEC-R → SALOME (python) → CAST3M

- Mechanical
  - Forces
  - Stresses
- Thermal
  - Conduction cooling dimensioning
  - Thermal stability
- Magnetic
  - Static field
  - Loadline
  - Temperature margin

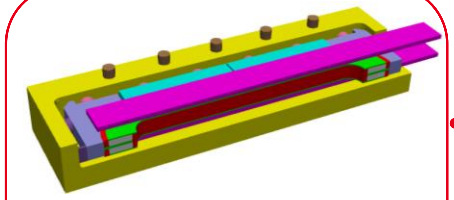


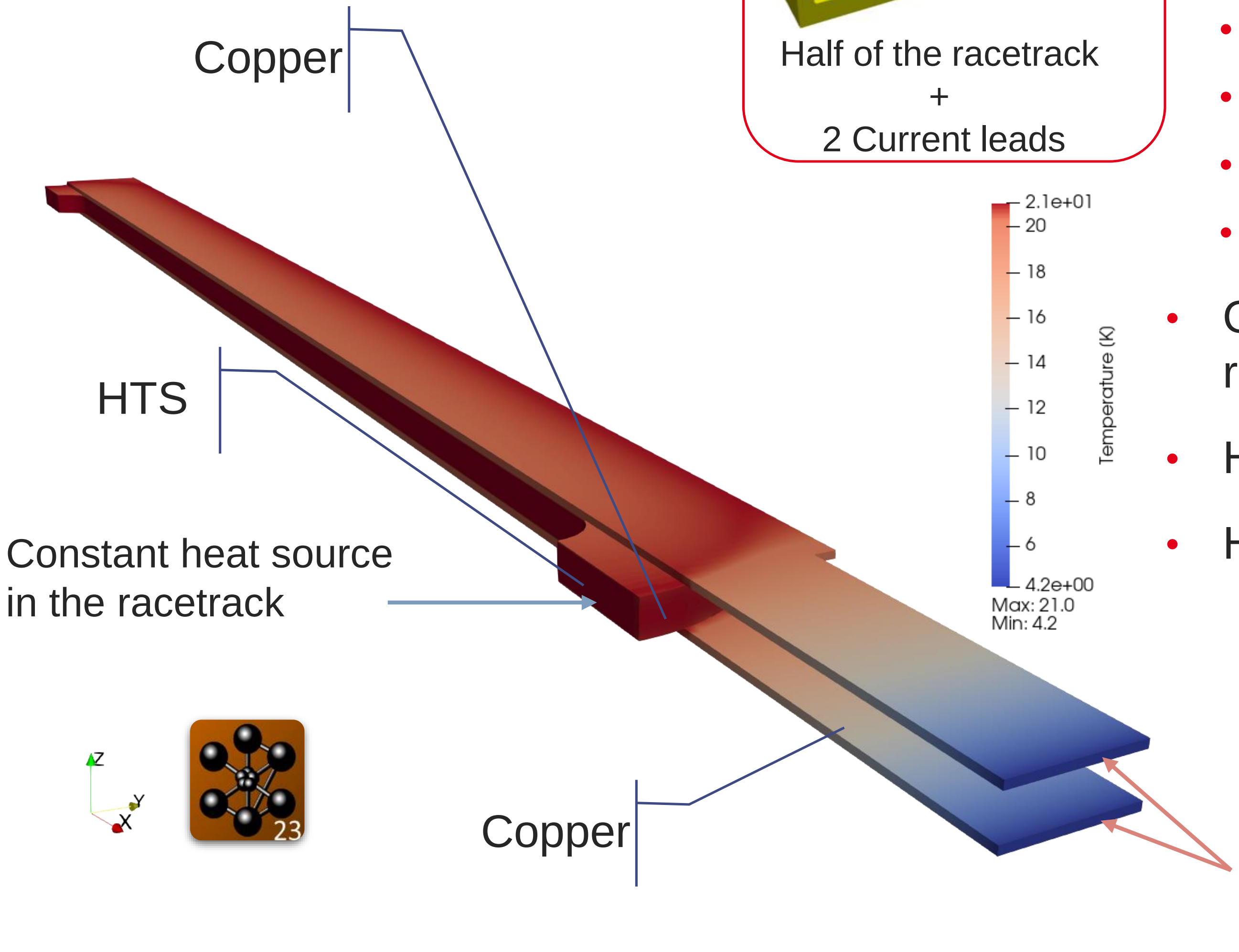


2.4. Salome / CASTEM FEM model



➢ Static thermal model (CASTEM)

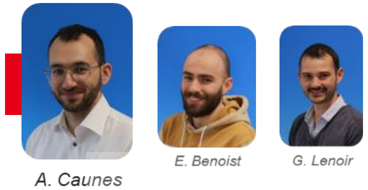




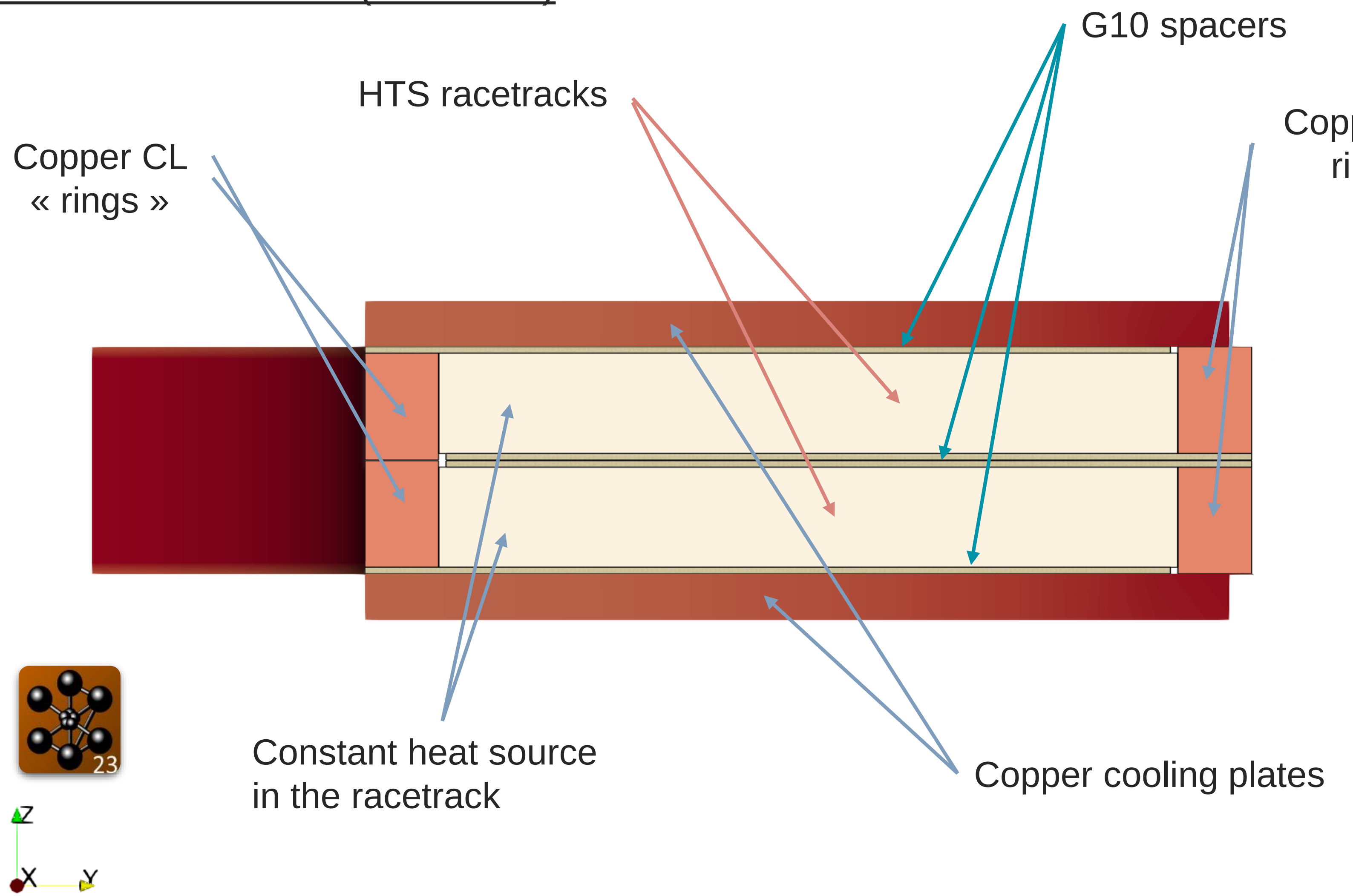
- Nonlinear materials used for:
  - HTS tapes (Stainless Steel + copper),
  - copper current leads and cooling interfaces
  - G10 insulation layers
  - Stainless steel structure
- Orthotropic thermal conductivity in the HTS racetrack
- Homogeneous thermal conductivity in the copper
- Homogeneous and constant heat source in HTS

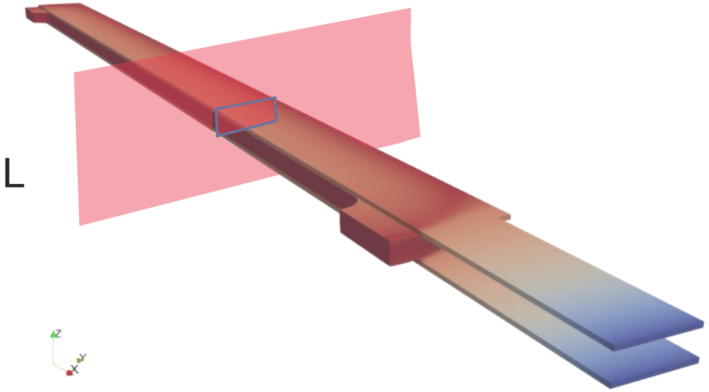
➢ Volumic losses due to
  ➢ Radial current (ramping)
  ➢ AC losses (ramping)
➢ Local losses due to
  ➢ Electrical connections (∝ I^2)

2.4. Salome / CASTEM FEM model

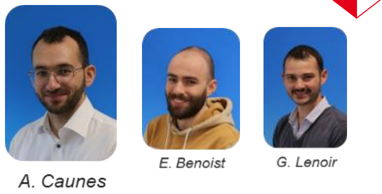


- Static thermal model (CASTEM)

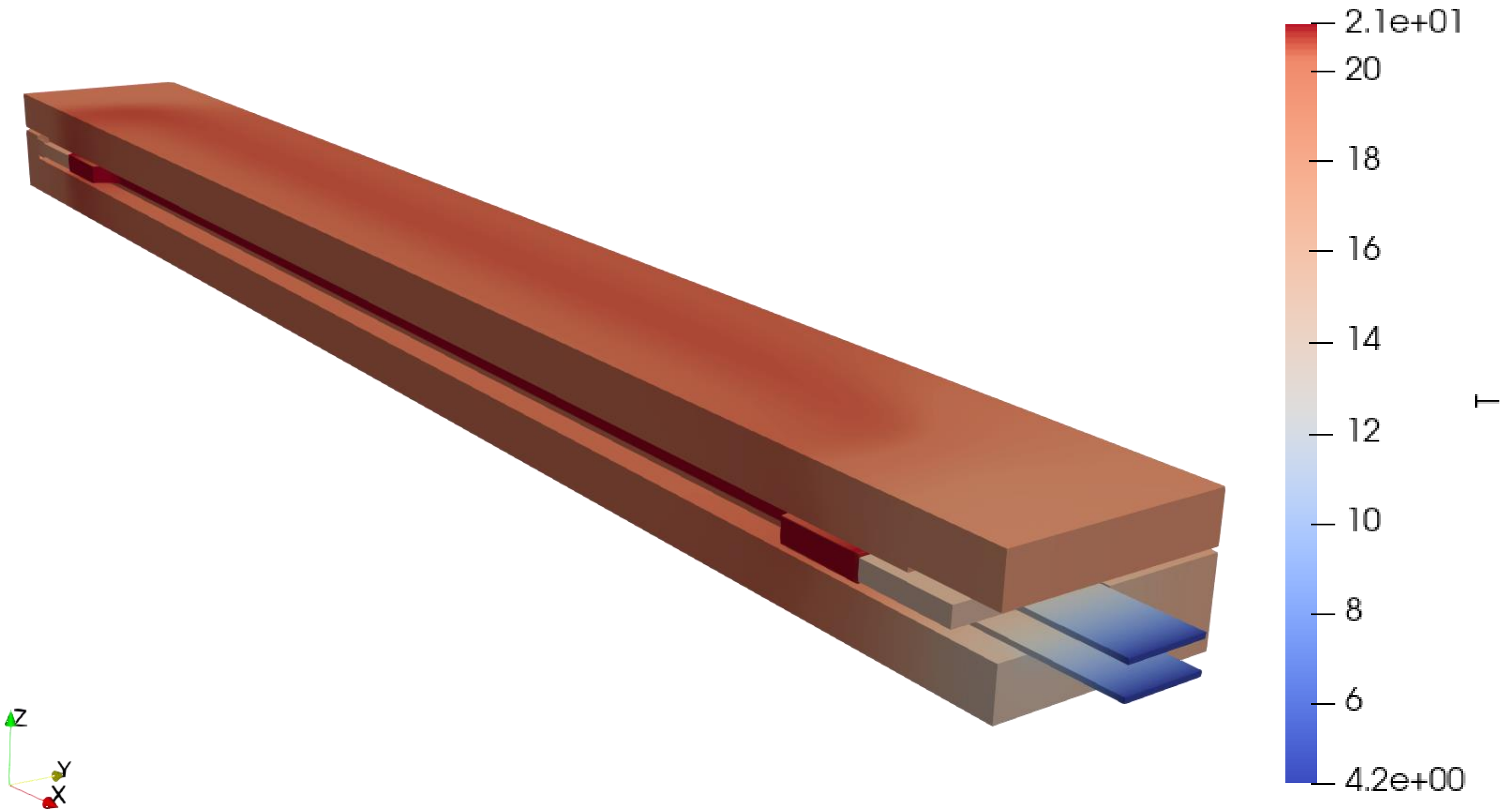




2.4. Salome / CASTEM FEM model



➢ Static thermal model with structure (CASTEM)



2.5. Mechanical structure conception


E. Benoist


A. Caunes


A. Blondelle


L. Scola


G. Minier

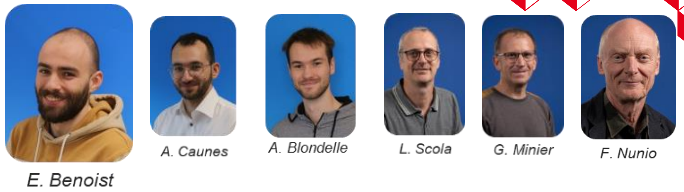

F. Nunio

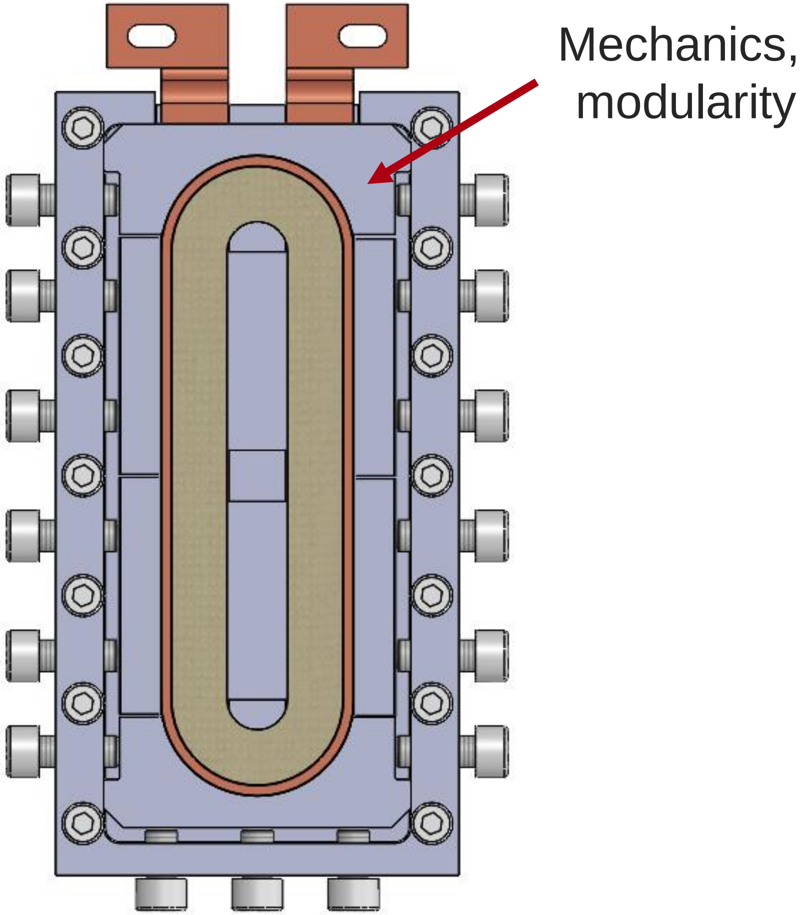
Requirements :

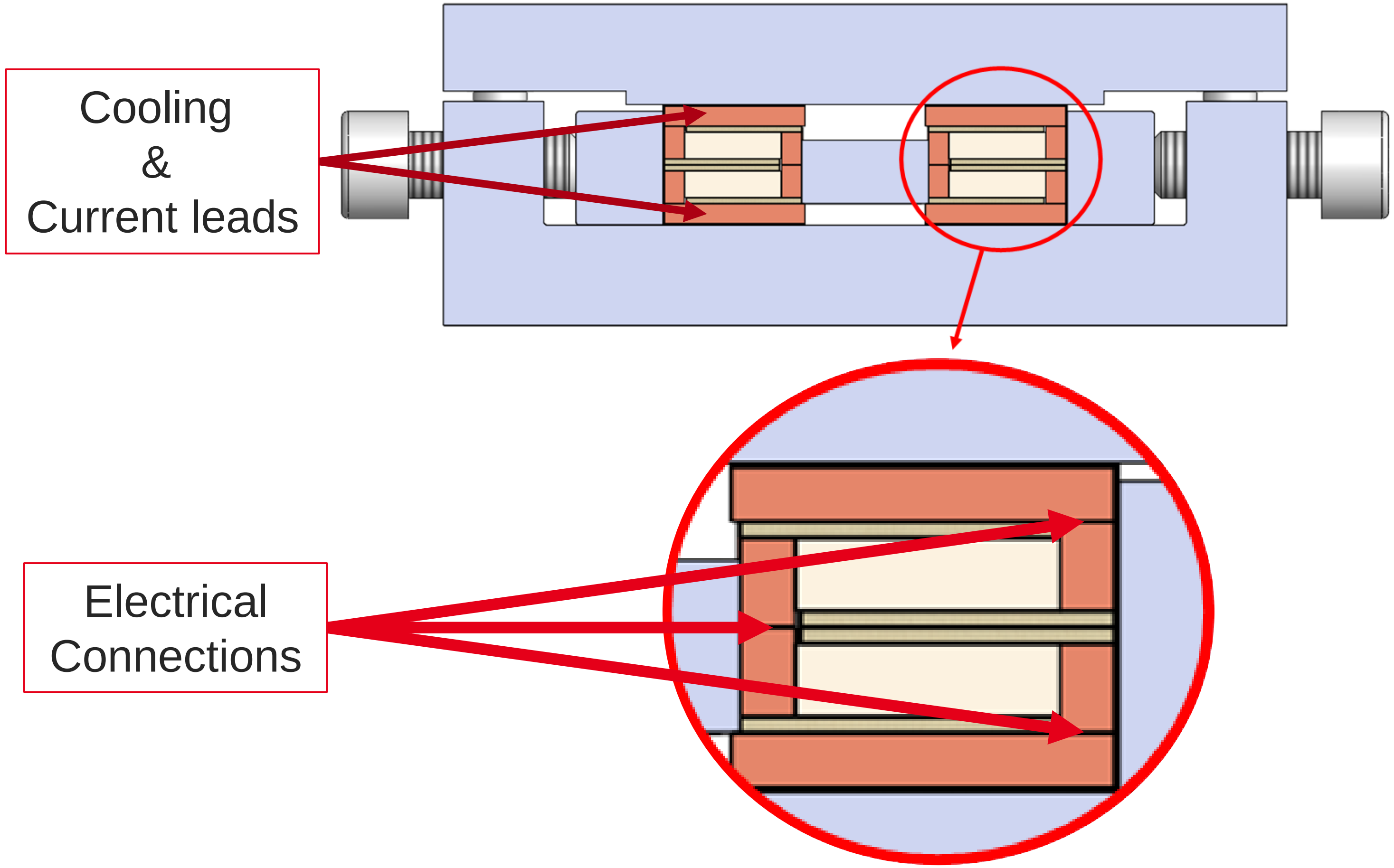
- **Mechanics** (few Tesla racetrack coil / magnet)
- **Cooling** (possibility of conduction cooling)
- **Electrical connection** (pressed copper rings and plates)
- **Instrumentation** (localized voltage taps, Cernox, Hall probes…)
- **Modularity** (number of Racetrack, size tolerances)

2.5. Mechanical structure conception

Ongoing

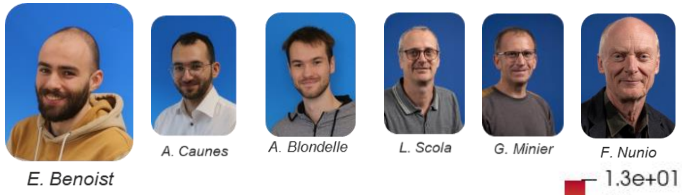




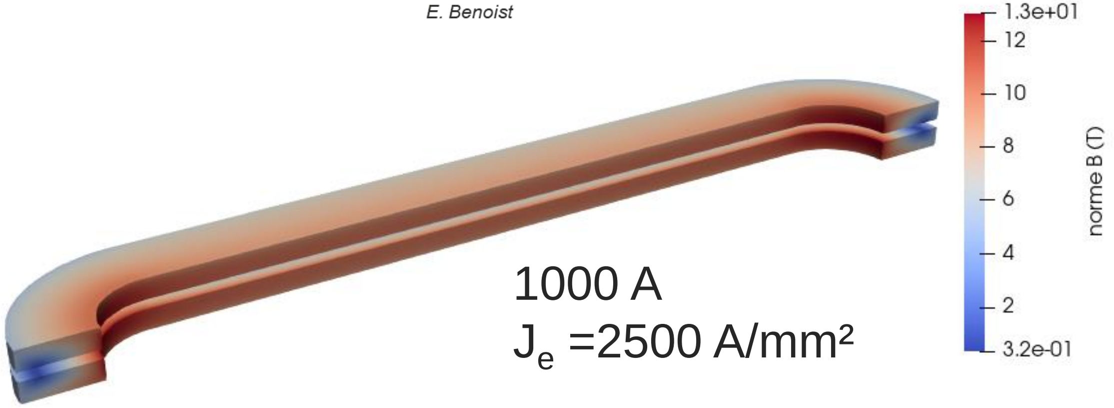


2.5. Mechanical structure conception

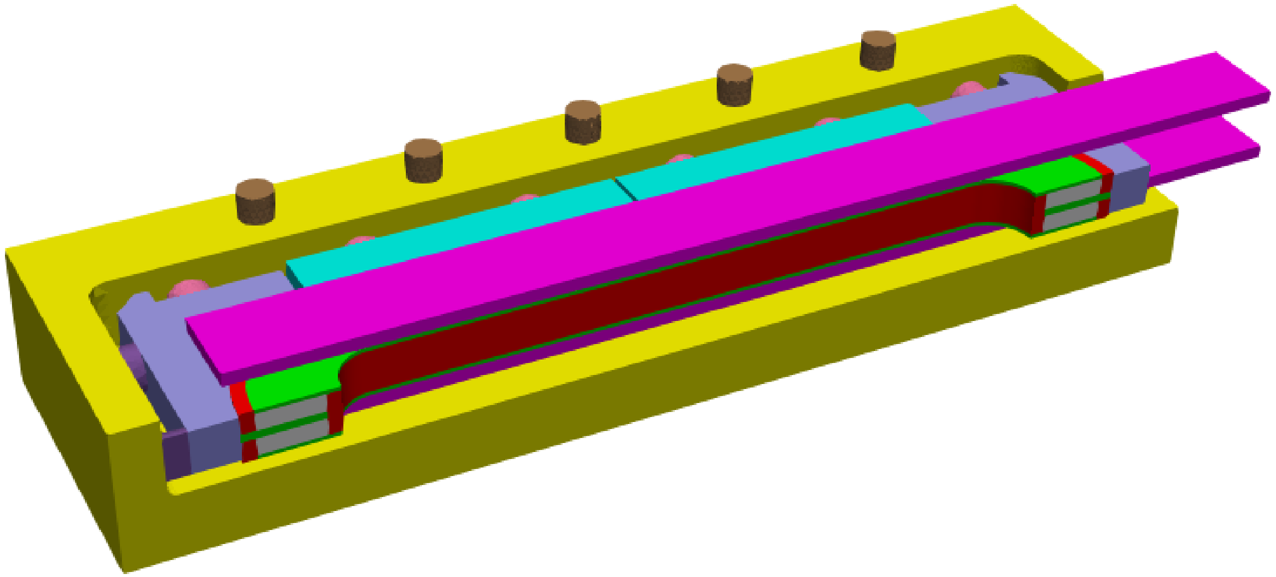
R&D Racetrack structure dimensioning



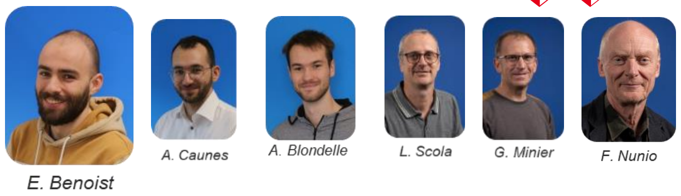
Parameter		Unit	Value
REBCO Tape	Thickness	µm	72
	Width	mm	4
	Unit Length	m	60
Durnomag® Tape	Thickness	µm	30
	Width	mm	4
Coil Geometrical parameters	Straigth part length	mm	140
	Width	mm	25
	# Turns	-	142
	# Racetrack	-	2
	Distance between R	mm	1.8



1000 A
J_e =2500 A/mm²



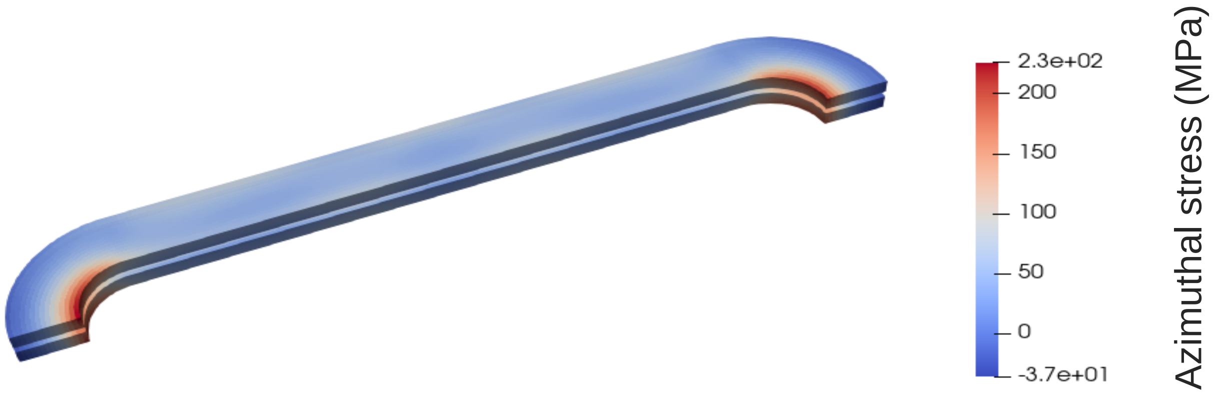
2.5. Mechanical structure conception



R&D Racetrack structure dimensioning

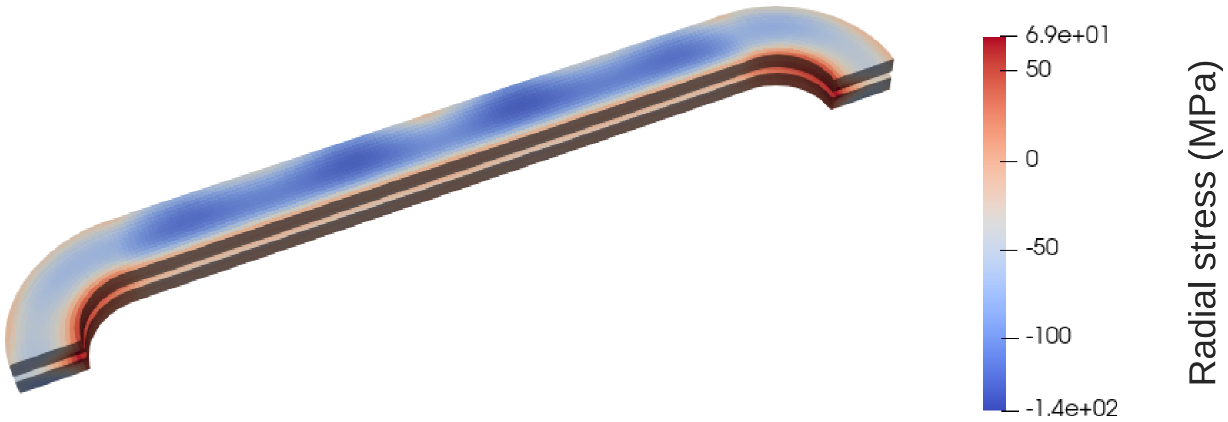
Stress on winding :

- Cooling (300 K → 4.2 K)
- Magnetic (1000 A)
- Without pre-stress



Remarks:

- Acceptable stresses
- Risk of contact loss at some locations



Need to take into account the pre-stresses to avoid local contact loss.

2.5. Mechanical structure conception

R&D Racetrack structure dimensioning

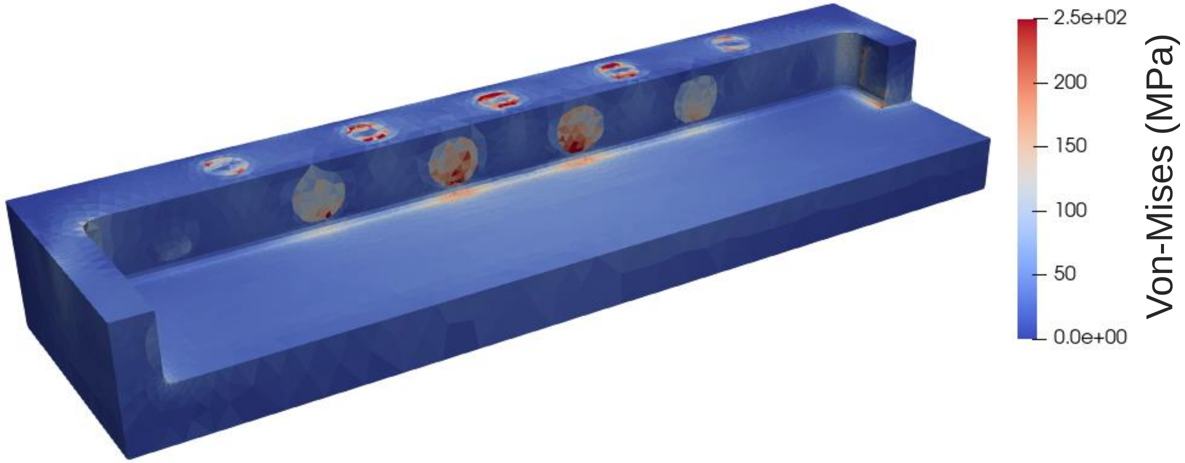
Stress on Structure :

- Cooling (300 K → 4.2 K)
- Magnetic (1000 A)
- Without pre-stress

Remarks:

- Below 250 MPa
- Some approximation on screws

Some local over-stresses or lost of contact need to be investigate but results are encouraging for the prototyping



2. Summary on numerical developments

❑ Normal Transient

- ✓ Current redistribution → PEEC-R
- ✓ Radial losses → PEEC-R
- ✓ Cooling → SALOME / CASTEM
- ○ Mechanics → SALOME / CASTEM
- × Magnetisation → investigation ongoing

❑ Fault Case (Quench)

- ✓ Current redistribution → PEEC-R
- ✓ Radial losses → PEEC-R
- ✓ Protection (voltage limitation) → PEEC-R
- × Cooling → required ?
- ○ Mechanics → SALOME / CASTEM
- × Magnetisation → required ?

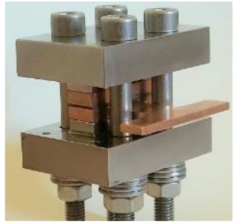
High J_e → milliseconds quench → **Cooling not required ?**
Protection → Voltage limitation → **Unbalanced forces?**
Normal transient → **Ratio AC and radial losses ?**

Models require experimental validation

3. Experimental developments

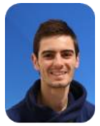
3.1. Developments and Characterization to be done

λ_{radial} R_{ct}



E. Benoist F. Gouit B. Baudouy

C. Genot's PhD



C. Genot

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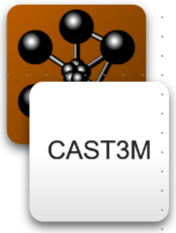
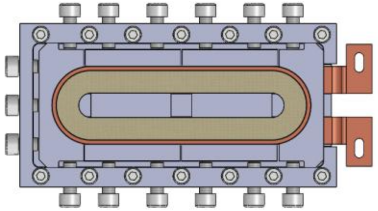
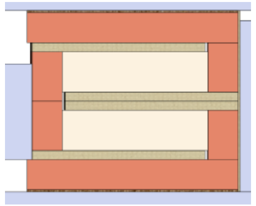
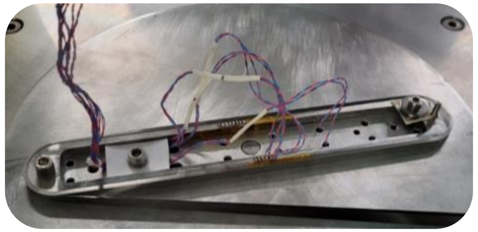




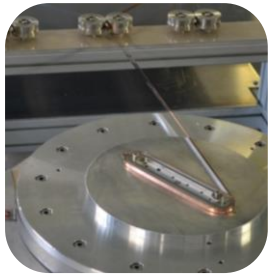


Winding related mechanics



E. Benoist

MI Racetrack winding



E. Benoist

Copper « rings » leads

Thermal cycle effect

Sc-Copper soldering

G. Lenoir A. Blondelle E. Benoist C. Genot

Almost all has already started but results in S2 2024

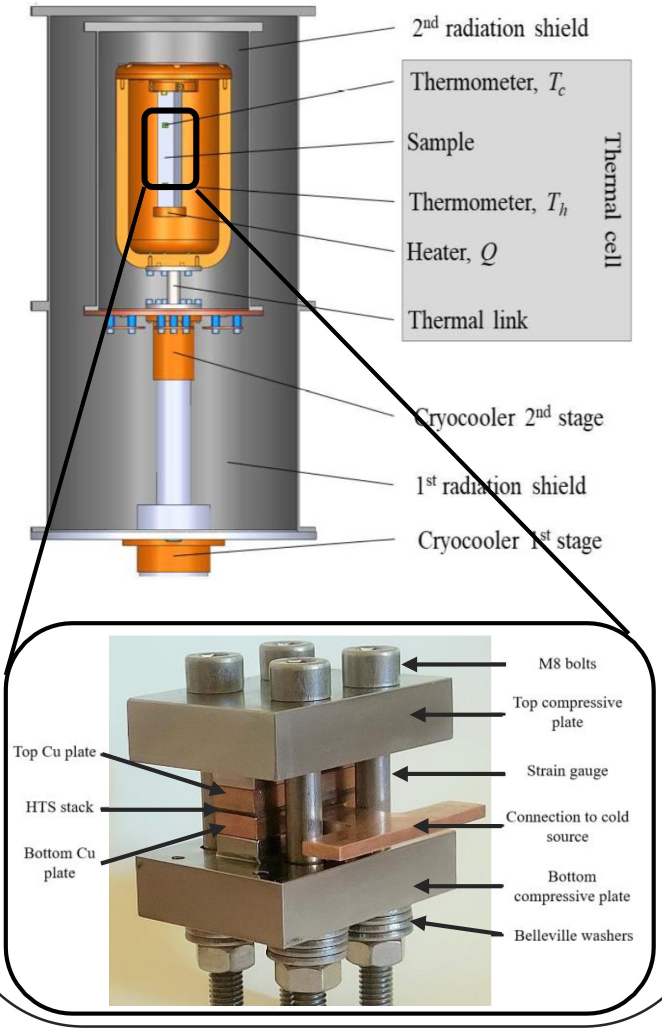
3.2. Radial thermal conductivity characterization


E. Benoist

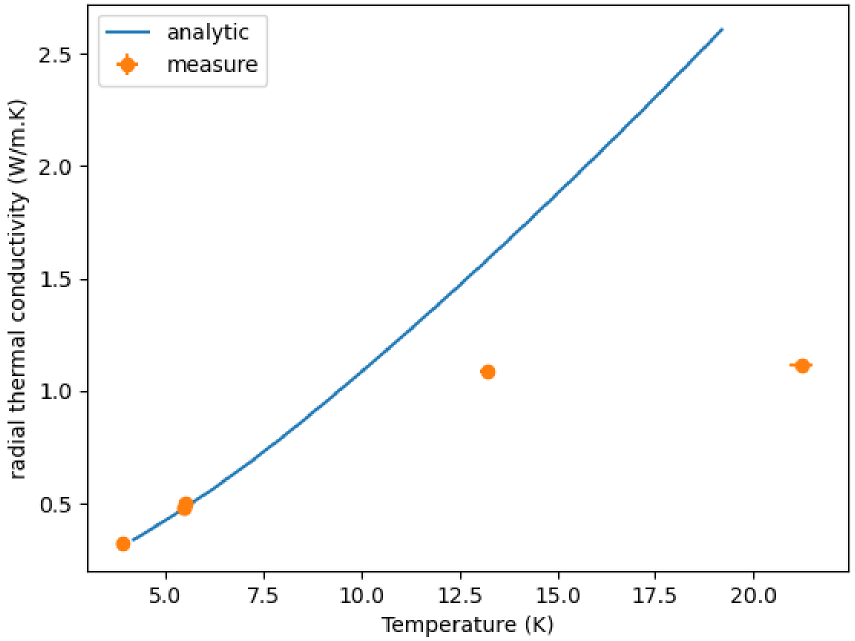

F. Gouit


B. Baudouy

Device and sample holder



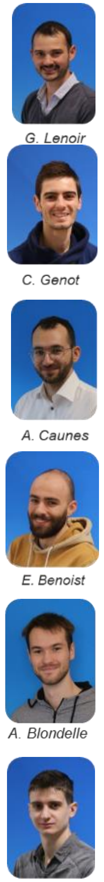
First results



Setup seems working on stack

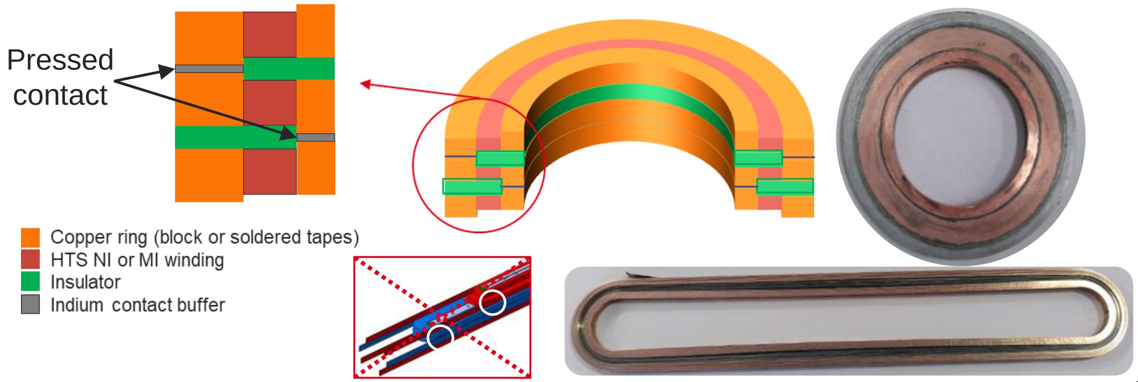
- Good agreement at low temperatures but difference above about 10 K
- **Validation on known material ongoing**
- Study on **a few MI stack** to be done

3.3. Electrical connection developments



G. Lenoir
C. Genot
A. Caunes
E. Benoist
A. Blondelle
R. Jucker

Integrated current leads



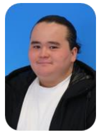
- Copper Ring : **Bulk** or **soldered tape**
- **Copper – Copper** with or w/o **Indium**
- With or w/o **graphene**
- Effect of **pressure**
- Effect of copper **roughness**
- **Mechanical cycles**
- **Thermal cycles** (77 K)
- Copper quality

➢ For now about **0.8 μΩ.cm²** with Indium
→ ~ 200 nΩ on our samples

Optimize the contact resistance and evaluate the **required contact area** for each application

3.4. First small MI pancake coils with copper rings

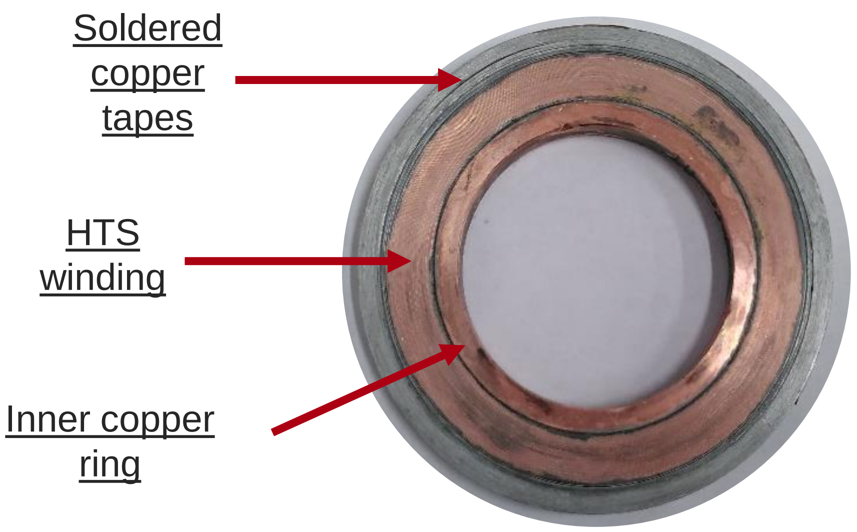
A. Caunes



M. Biron

Started : first windings done

Inner ring : 3 mm thick, OD 41 mm
Outer ring : 3 mm thick (100 µm copper tape)
HTS Winding : 50 turns



Non-insulated coils

Metal-insulated coils

Tests to be done in the next months

3.5. Effect of thermal cycles on HTS and joints


G. Lenoir


E. Benoist


A. Caunes

Why ?

Requires few thermal cycles
→ Effect on I_c and R_{joint} ?

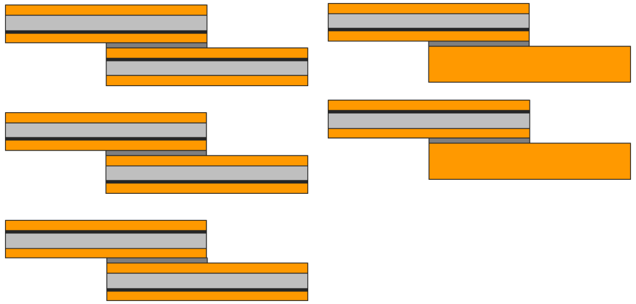
<u>Objectives</u>

- Fabrication of representative joint
- Real joint thermal cycles
- Variation in I_c and resistance
- Optimisation of joint configuration

Not Started

<u>Device</u>

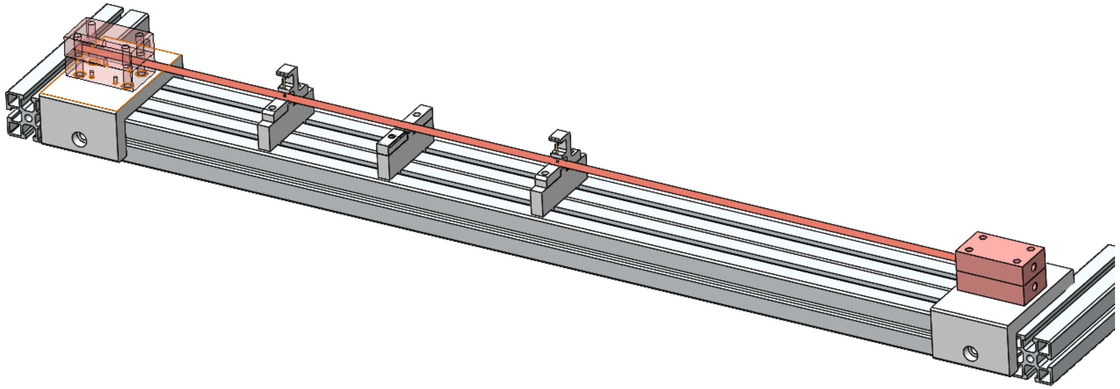
<u>Sample configurations</u>



Sc / Hast.
&
Sc / Hast

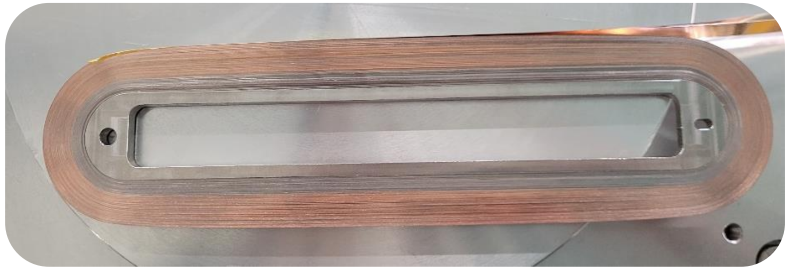
Sc / Hast.
&
Copper

<u>Modular 77 K I_c measurement setup</u>



3.6. Racetrack winding development

E. Benoist B. Maloeuvre T. Barabe T. Arbane



Example of Copper/Durnomag winding test

Example of inner racetrack copper connection

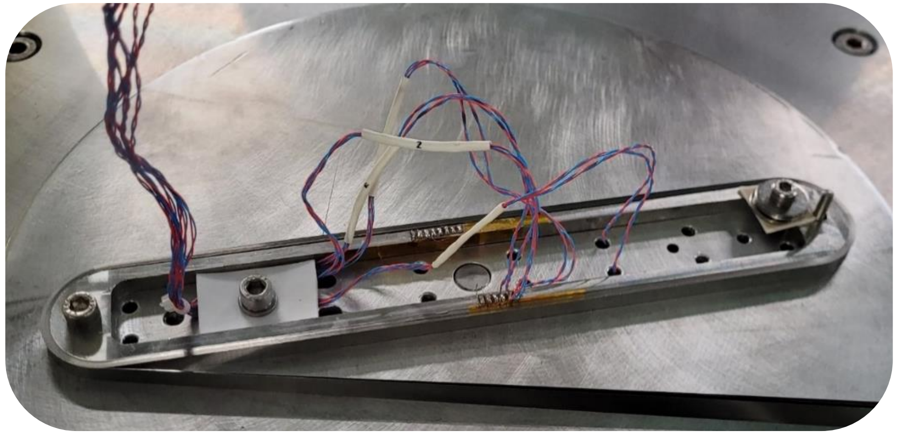
MI racetrack winding with copper “rings” developments just started

3.6. Racetrack winding development


E. Benoist B. Maloeuvre T. Barabe T. Arbane

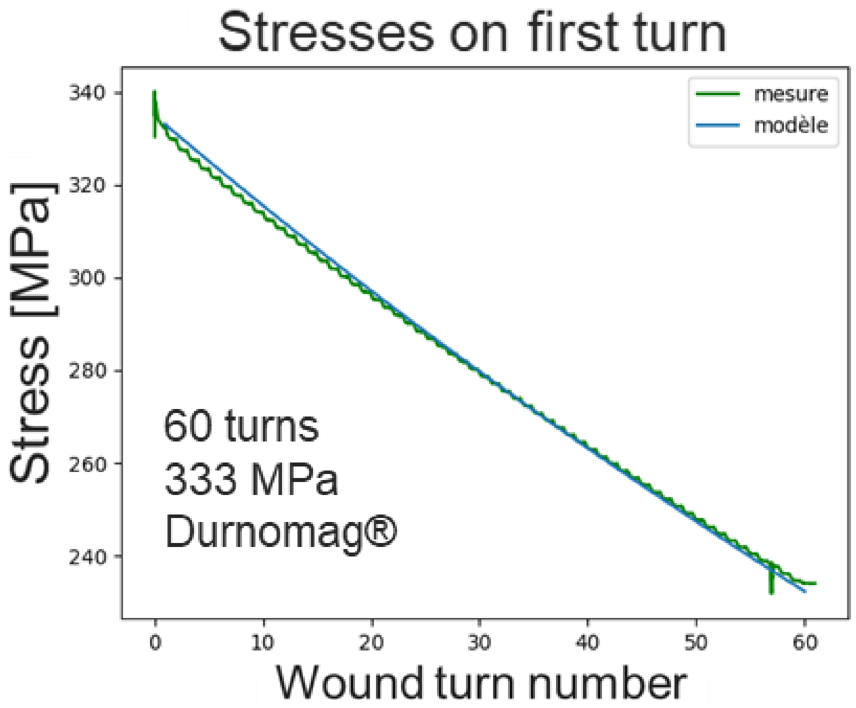
- Understand the stresses and related parameters

  - Measurements



Instrumented racetrack with strain gages

  - Analytical model



3. Summary on experimental developments

❑ Characterizarion

- MI radial conductivity
  - ✓ setup (design & fabrication)
  - ✓ First sample tested
  - o Validation on known material
  - o MI Stack study
- Joints thermal degradation
  - ✓ Setup (design & fabrication)
  - o 77 K critical current setup
  - o Thermal effect Study

❑ Technological Developments

- Integrated current leads
  - ✓ Winding on copper rings (bulk)
  - ✓ Fabrication of outer ring (soldered tape)
  - o Pressed copper rings study
  - o Fabrication of racetrack copper rings
  - o Stack of HTS pancakes
  - o Stack of HTS racetracks
- Racetrack windings
  - ✓ Tooling fabrication
  - o Fabrication process on short racetrack
  - o Tension effect study
  - o 600-900 mm racetrack winding

4. Perspectives

4.1. Models validation

4.2. Concept validation

4.1. Models validation


A. Blondelle


E. Benoist


A. Caunes

Preparation

✓ Evaluation of suitable racetrack geometries and stacking
→ 140 mm Straight part, 25 mm width, 142 turns
✓ Estimate the number of samples
→ 10 to 14 Racetracks
✓ Design of the structure for test at 77 K (GN2/LN2) and 4.2 K (LHe)
→ See next slides and previous numerical modelling
✓ Develop the device to locally reduce the critical current on a tape
→ Presented after

What tests to do ? (under discussion)

→ Volontary local degradation
→ Fast current ramp
→ Ramp with steps
→ Step at 95% of critical current
→ Suddent discharge
→ …

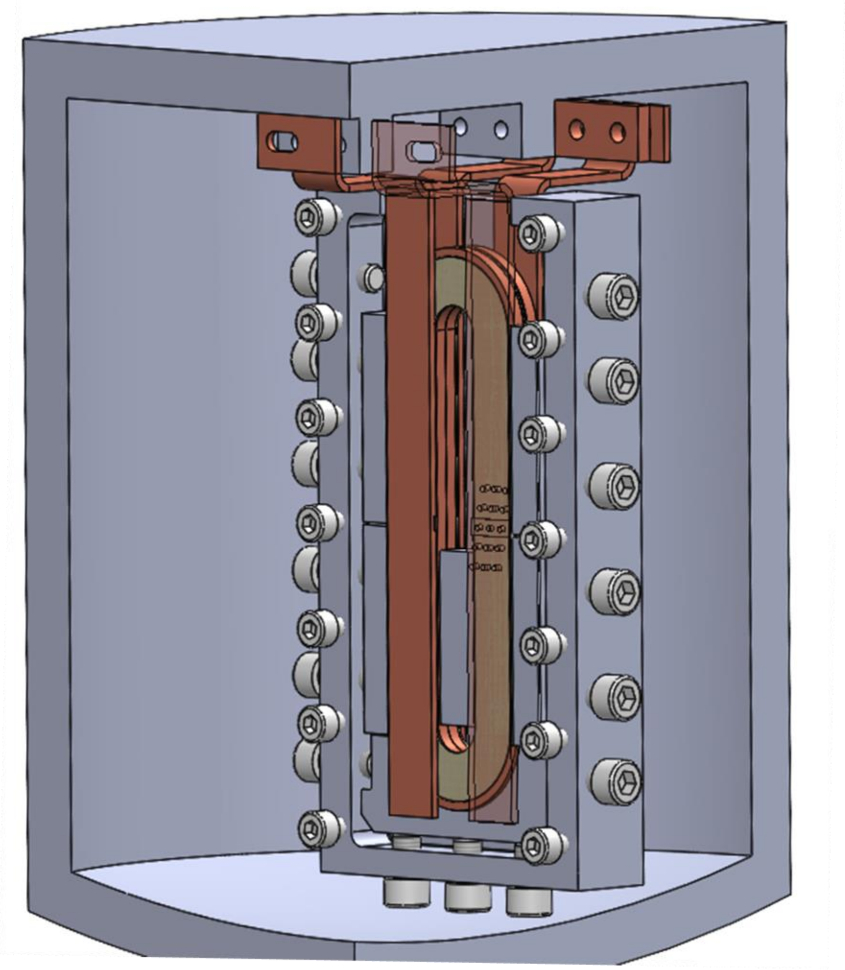
4.1. Models validation

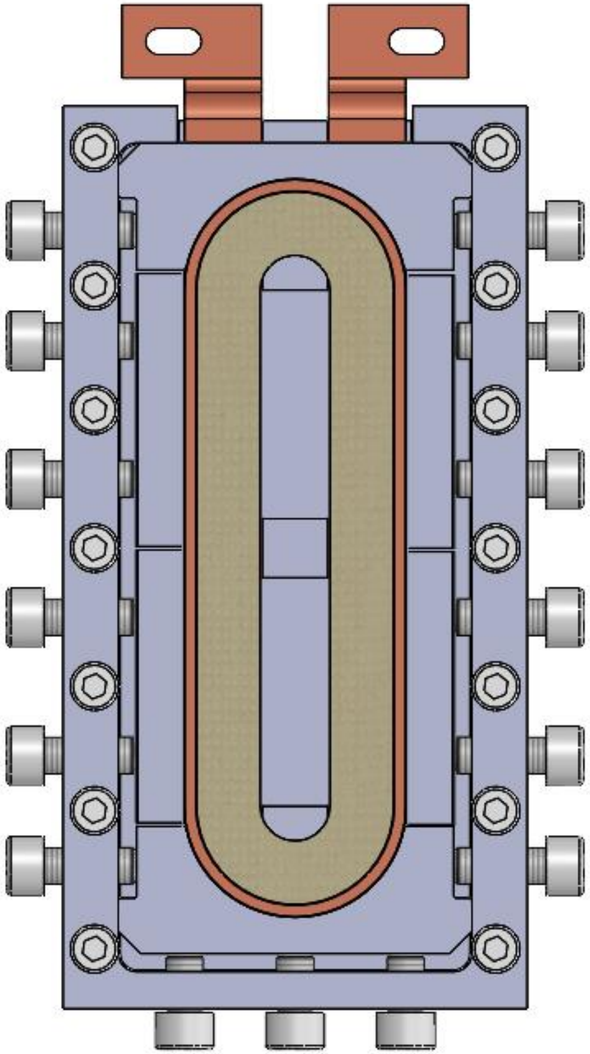

A. Blondelle


E. Benoist


A. Caunes

Structure inside a cryostat





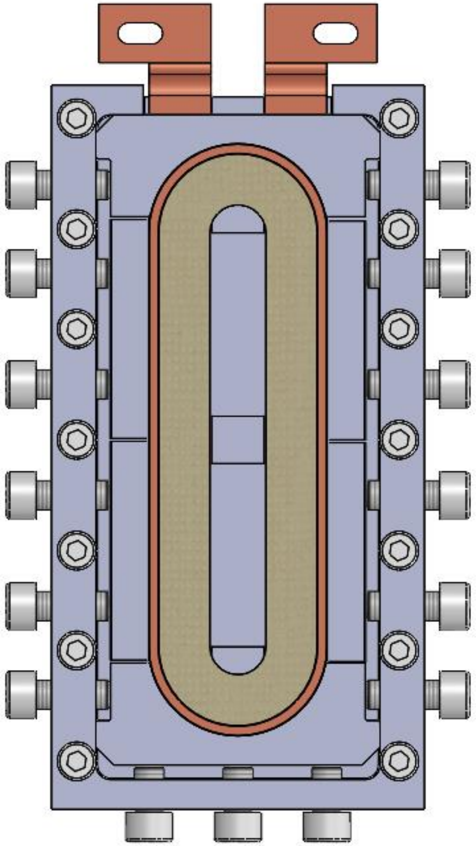
4.1. Models validation

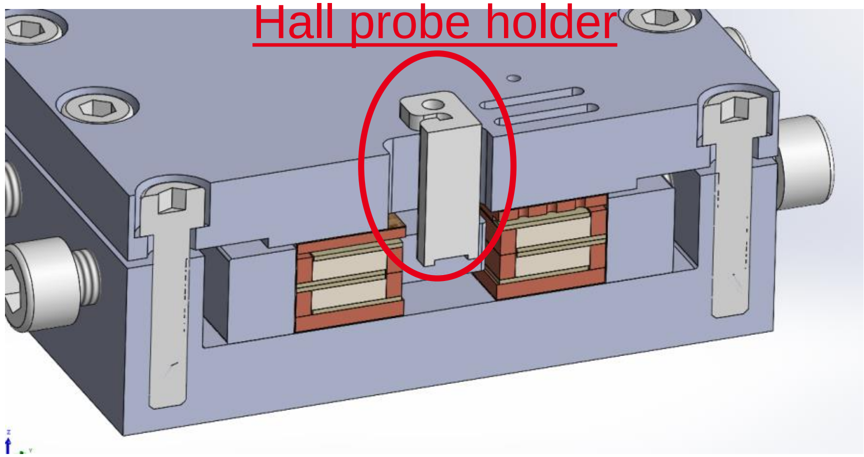

A. Blondelle

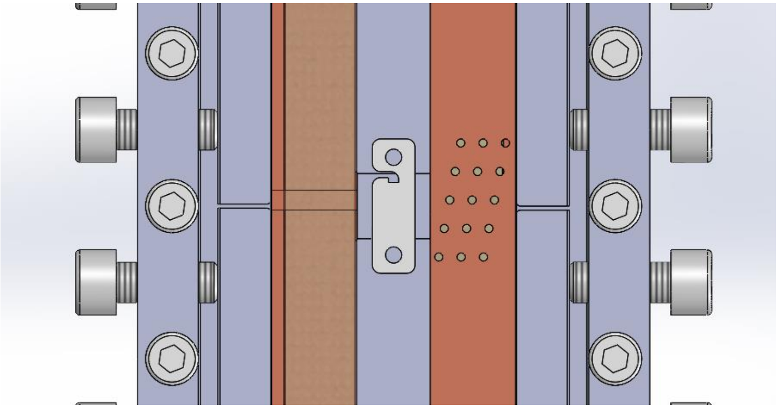

E. Benoist

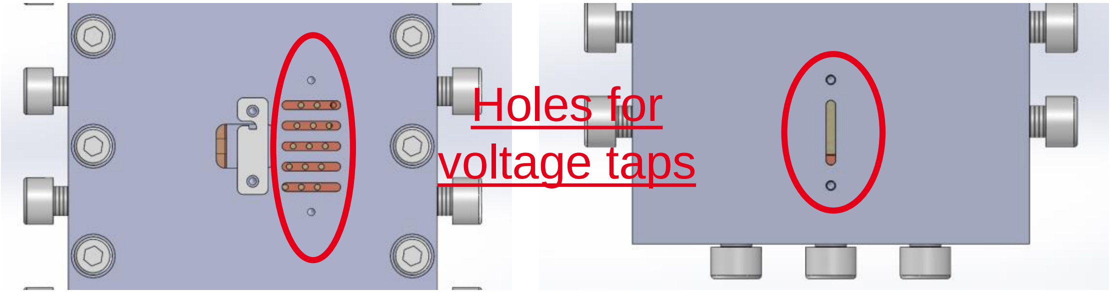

A. Caunes

Structure with instrumentation







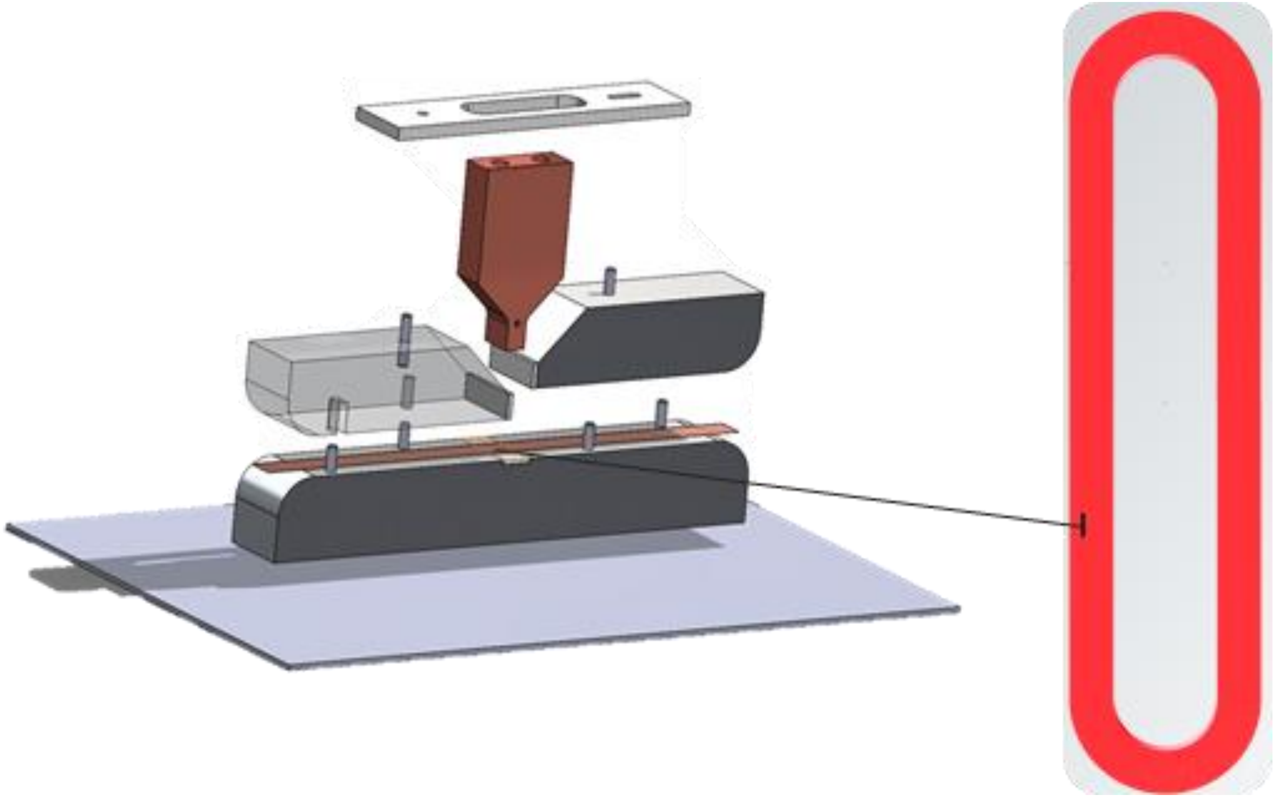


4.1. Models validation

➢ Device to locally degrade the critical current

- ❑ Degradation on 10 mm
- ❑ Evaluate the degradation with couple [T°C ; time]
- ❑ Evaluate the reproductibility

Starting May 2024



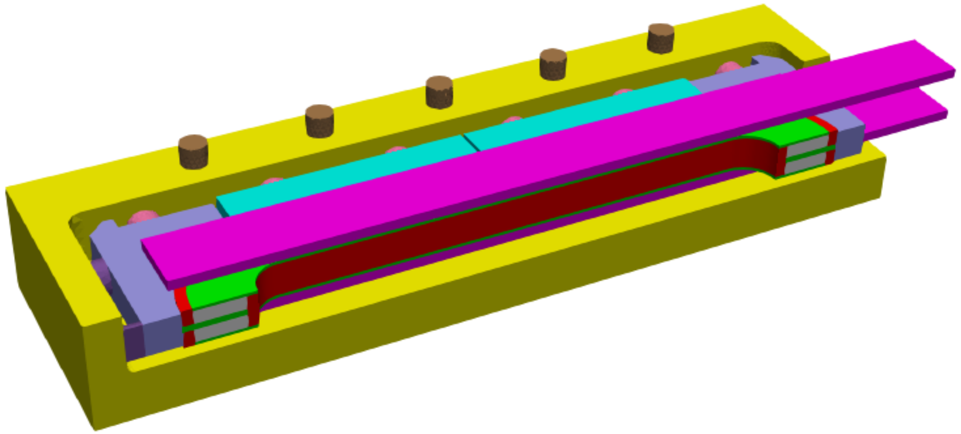
4.2. Concept validation

Parameter	Unit	Case 1	Case 2	Case 3
Width	mm	30	30	30
S. Part length	mm	900	600	300
# turns	-	103	148	257
Inductance	mH	10.2	13.6	20.7
B at center	mT/A	2.07	2.72	3.99
B peak	mT/A	6.99	8.24	10.32
$I_{max,\ 4.2\ K}$	A	1575	1545	1510
$B_{center,max}$ 4.2 K	T	3.26	4.20	6.02
J_e, max 4.2 K	A/mm²	3860	3785	3700

Protection ?

Start to evaluate the final prototype

- Consideration of I_c, 4.2 K, 20 T //c > 460 A (4 mm)
- « Long racetrack » (**600-900 mm**)
- Fabrication of Two **S**ingle **R**acetracks
- One or two HTS tape « cable »?
- Central Induction 3 – 4 T (**SR**) (5 – 6 T Double R)
- High current density (above 1500 A/mm²)
- 77 K, 20 K (?), 4.2 K (?) (conduction or liquid?)



Thank you for your attention

Questions

Many thanks to all CEA HTS team for the work done and to Amalia Ballarino for CERN Support

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