DE LA RECHERCHE À L'INDUSTRIE

Experimental analysis of quench behavior in a Cable-In-Conduit-Conductor cooled by stagnant superfluid helium

Unai DURAÑONA ----- DRF/IRFU/DACM/LCSE

MADMAX – Context

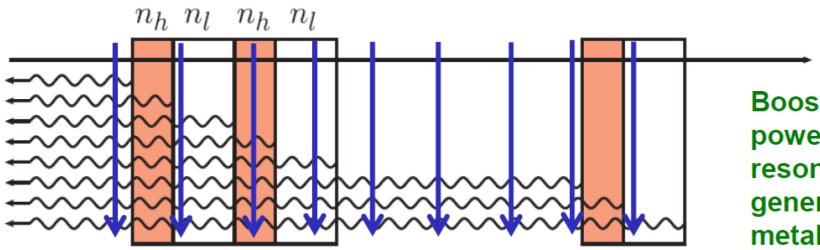
- **International partnership MPI – CEA – Noell**

- **Research of Axion Particle**
  - Axion can solve strong CP problem
  - Candidate for Dark Matter

- **Axion-Photon conversion at surfaces**

Many surfaces → resonator→ "photon boost"

J. Jaeckel and J. Redondo, Phys. Rev. D 88 (2013) *115002 [arXiv:1308.1103]*



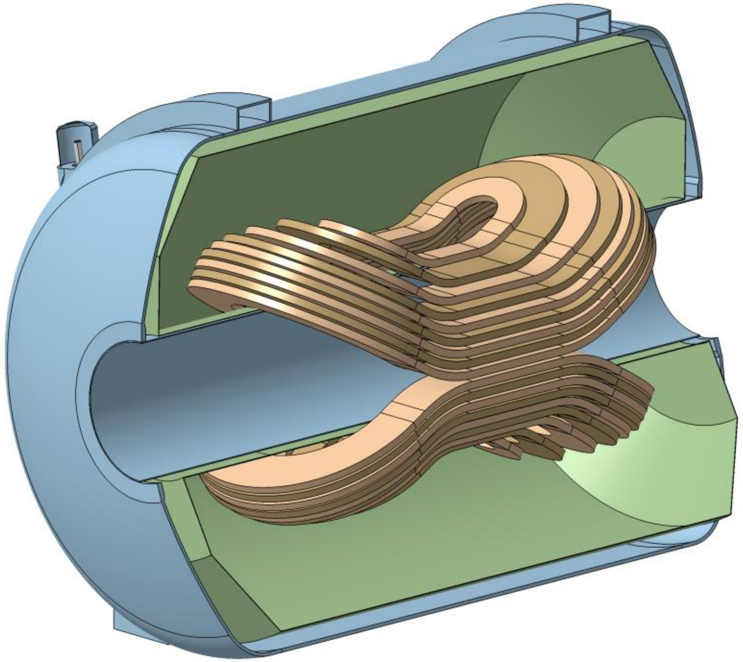
Boost factor:
power generated in resonator/power generated on single metallic (ε_r=∞) surface

$$(P/A)_{\text{resonant cavity}} \sim 2 \cdot 10^{-27}\ \text{W/m}^2 \cdot (B_{\parallel}/10\text{T})^2 \cdot c_\gamma^{\,2} \cdot f(\varepsilon_{m1}, \varepsilon_{m2}) \cdot \beta$$

β : Boost factor, depends on:
frequency (axion mass), ε of materials, number of surfaces, displacement between surfaces, etc.

MADMAX – Magnet and key issues

- **18 CICC coils**
  - 10 km of conductor
  - 500 MJ
- **Cooled at 1.8K with superfluid helium**
- **9 T in a 1.35 m diameter bore**



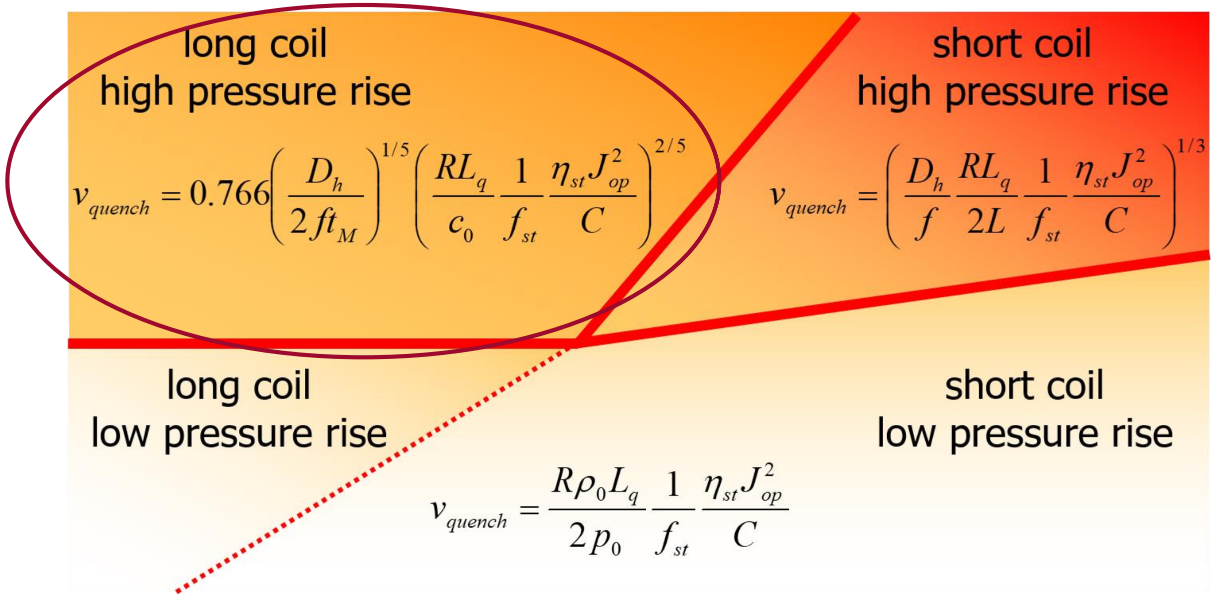
MADMAX

- **Quench protection = key issue**
  - Risks to burn the magnet
  - Quench propagation speed key parameter
  - Two approaches to estimate it : analytical and numerical calculations

MADMAX – Quench protection: analytical approach

- **Analytical correlations:**

~3 cm/s

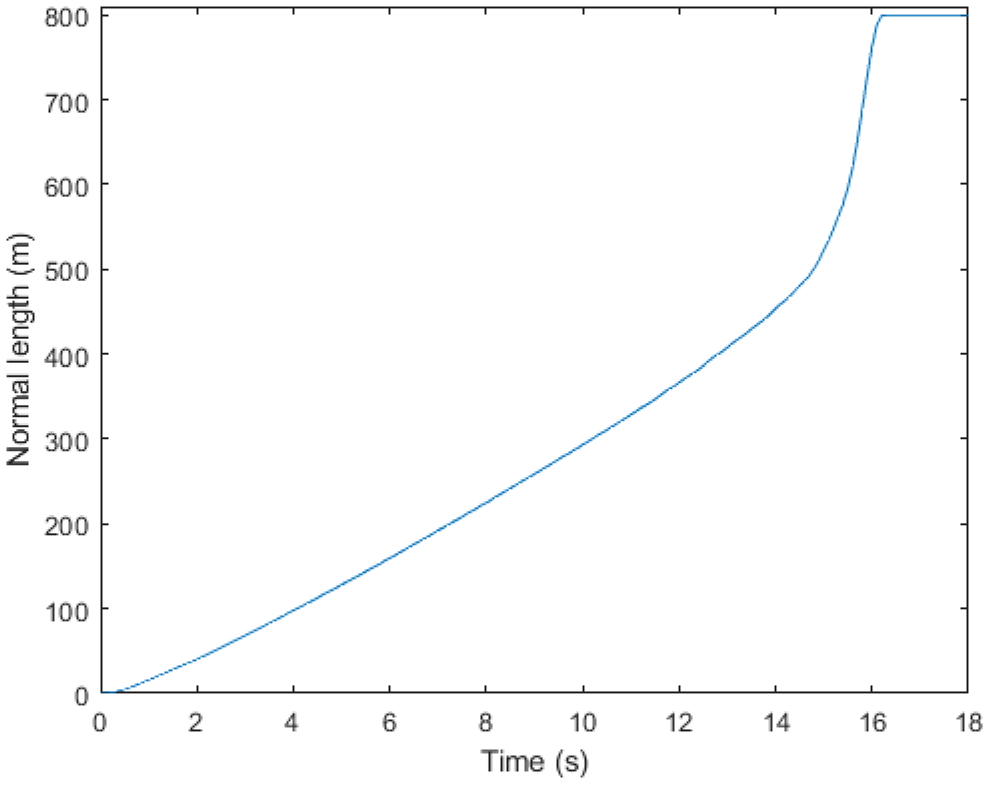


- **In this configuration, ~78 s needed to detect the quench**

  - ❑ Magnet totally burnt
  - ❑ **Change completely the conductor's and quench protection design**

*A. Shajii, J. Freidberg, J. Appl. Phys., **76** (5), 477-482, 1994.*

- **Numerical calculation made with THEA**
  - 2 propagation phases
    - Linear phase ~ 17 m/s
    - Acceleration phase ~ 50 m/s
  - Acceleration due to a Thermal Hydraulic Quench Back (THQB)
- **Quench detection in ~ 0.2 s < 1 s → safe configuration**



Evolution of normal zone

MADMAX – Experimental R&D to study quench propagation

Analytical approach	*Numerical approach*

Use of superfluid helium

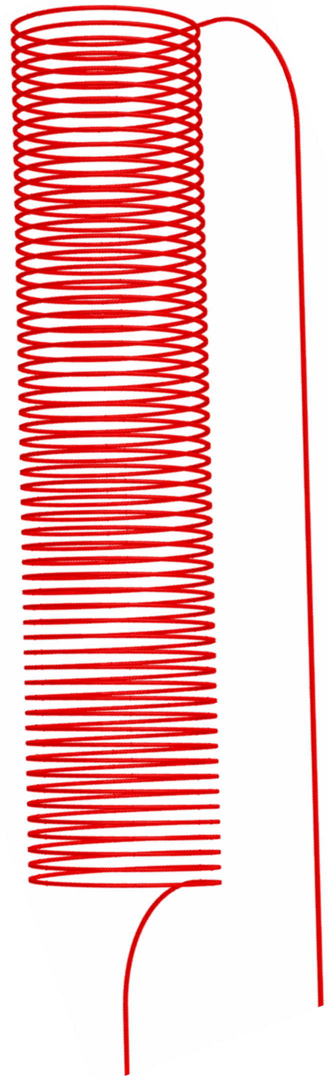
No THQB predicted: correlations reliable ?	Impact of He II on THQB with THEA ?
High risk to damage the coil	Low state of the art

Design, manufacture and test of a mock-up coil MACQU for quench propagation studies

MACQU: prototype for quench studies

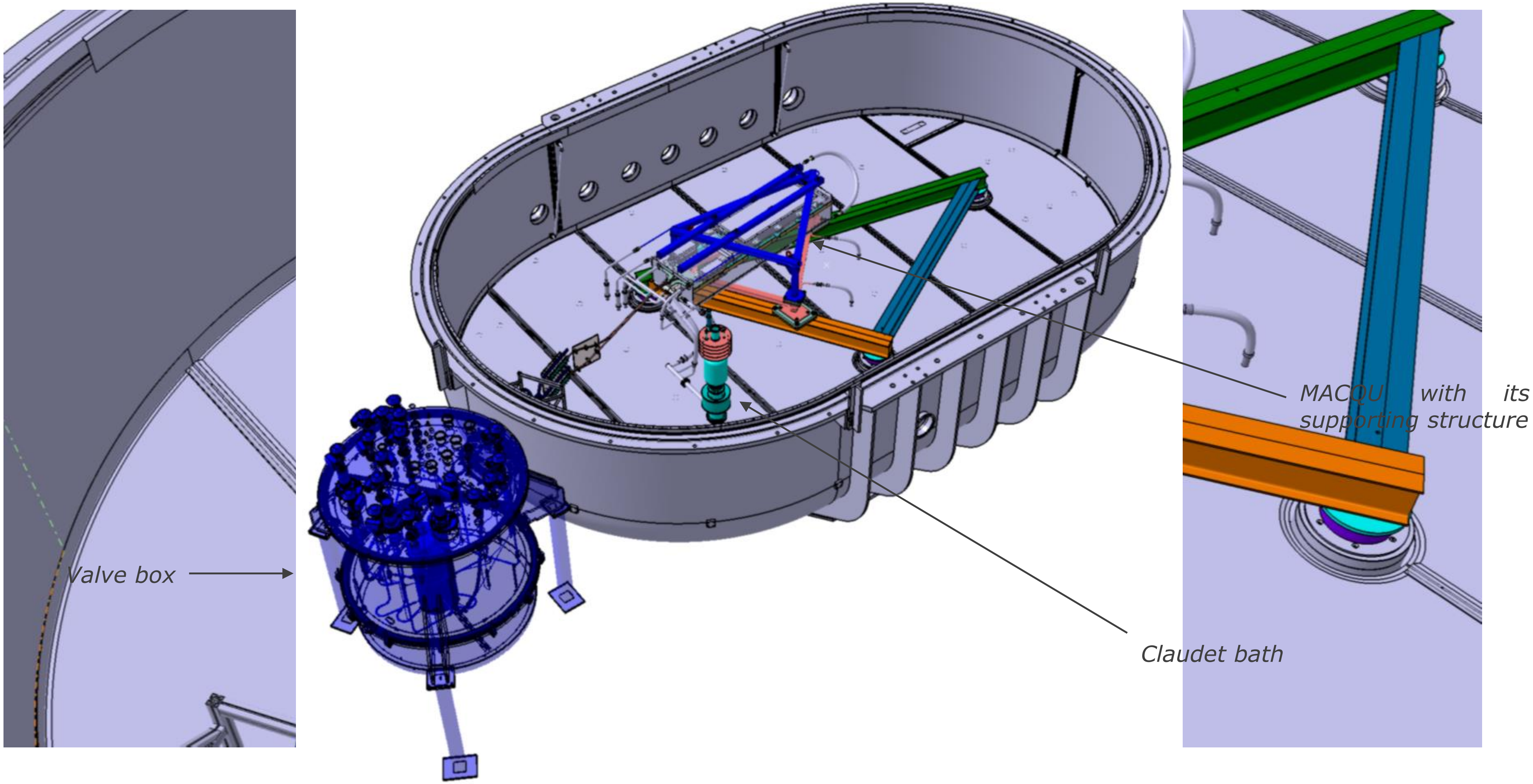
- **Designed during 2020 and received at CEA on March 2021**
- **MADMAX-like magnet to have similar quench behavior:**
  - Cable-In-Conduit-Conductor
  - Copper profile
  - Cooled with stagnant He II inside the conduit (1.8 K)
  - No direct cooling with a bath around
- **Tested in already existing cryostat : JT60-SA cryostat**

	MACQU
Length (m)	50
Turns	58
Height (m)	1.3
Current (A)	20 000
Bpeak (T)	2.663
Energy (J)	37 673
Inductance (mH)	0.161



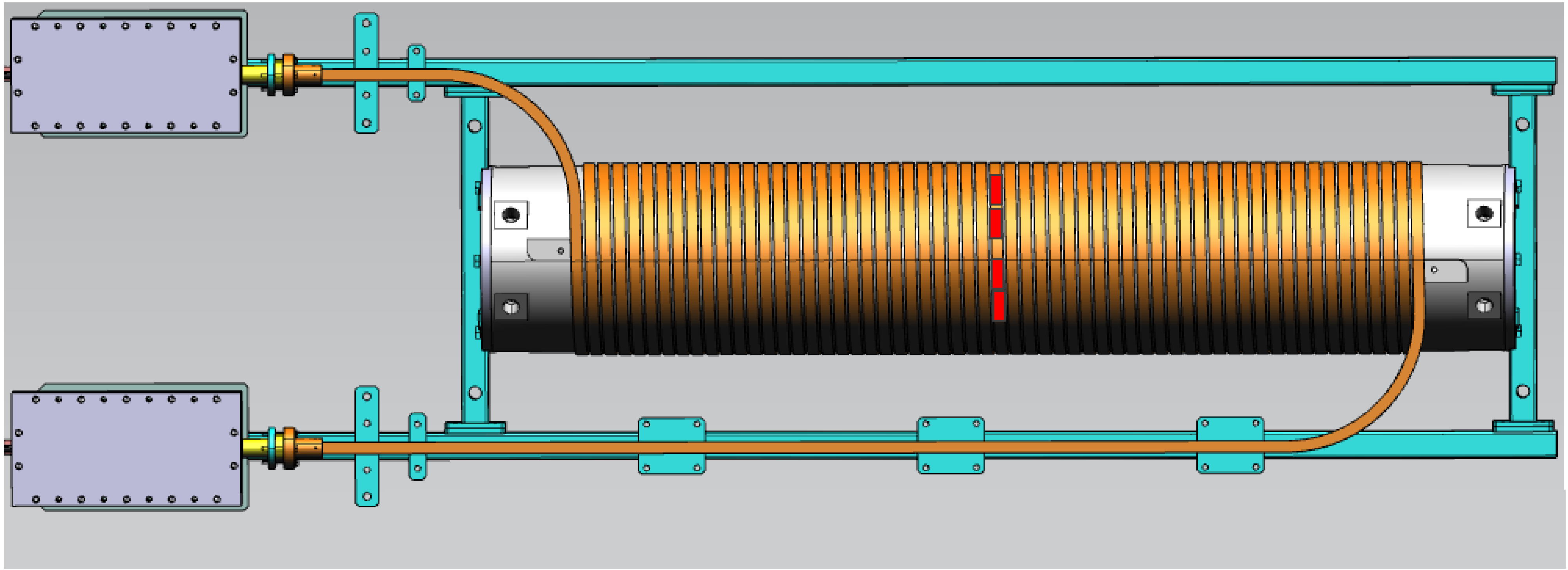
MACQU solenoid

JT60-SA – Test facility



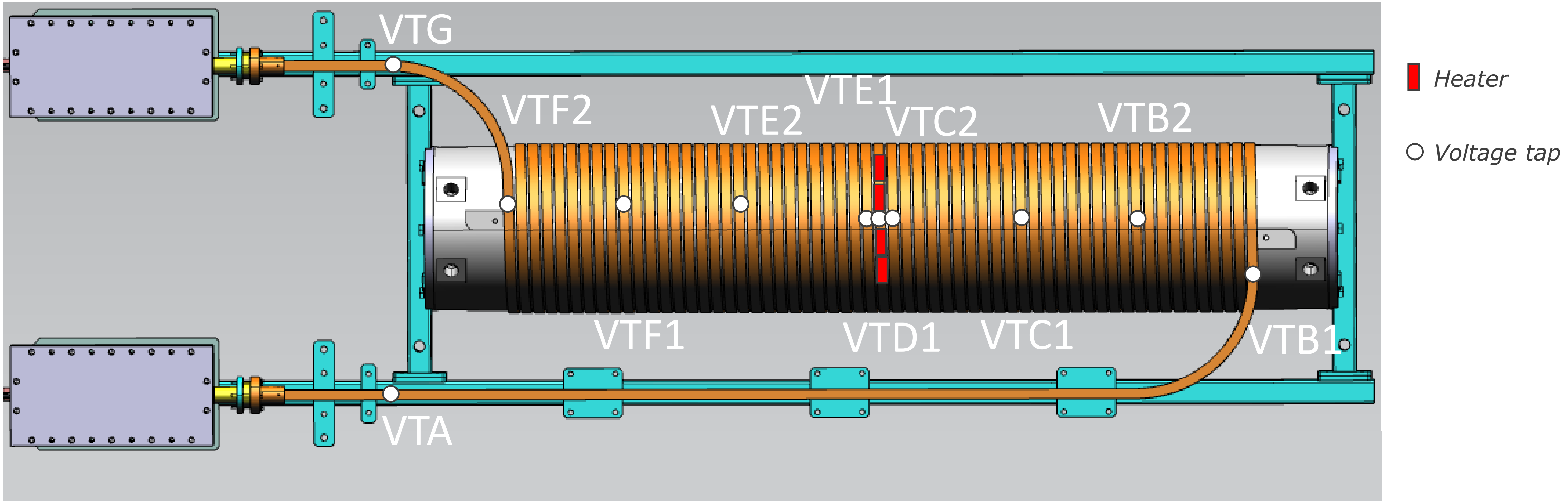
- **How to initiate the quench ?**
  - With flexible heaters (All Polyimide Thermofoil HAP6945, 390 W/m)
  - Glued directly on bare copper with conducting glue below insulation for efficient heat deposition
- **4 heaters available, placed at the middle**
  - Study the symmetry (or not) of the quench
  - Longest available length for quench study without border effects

HAP6945 heater

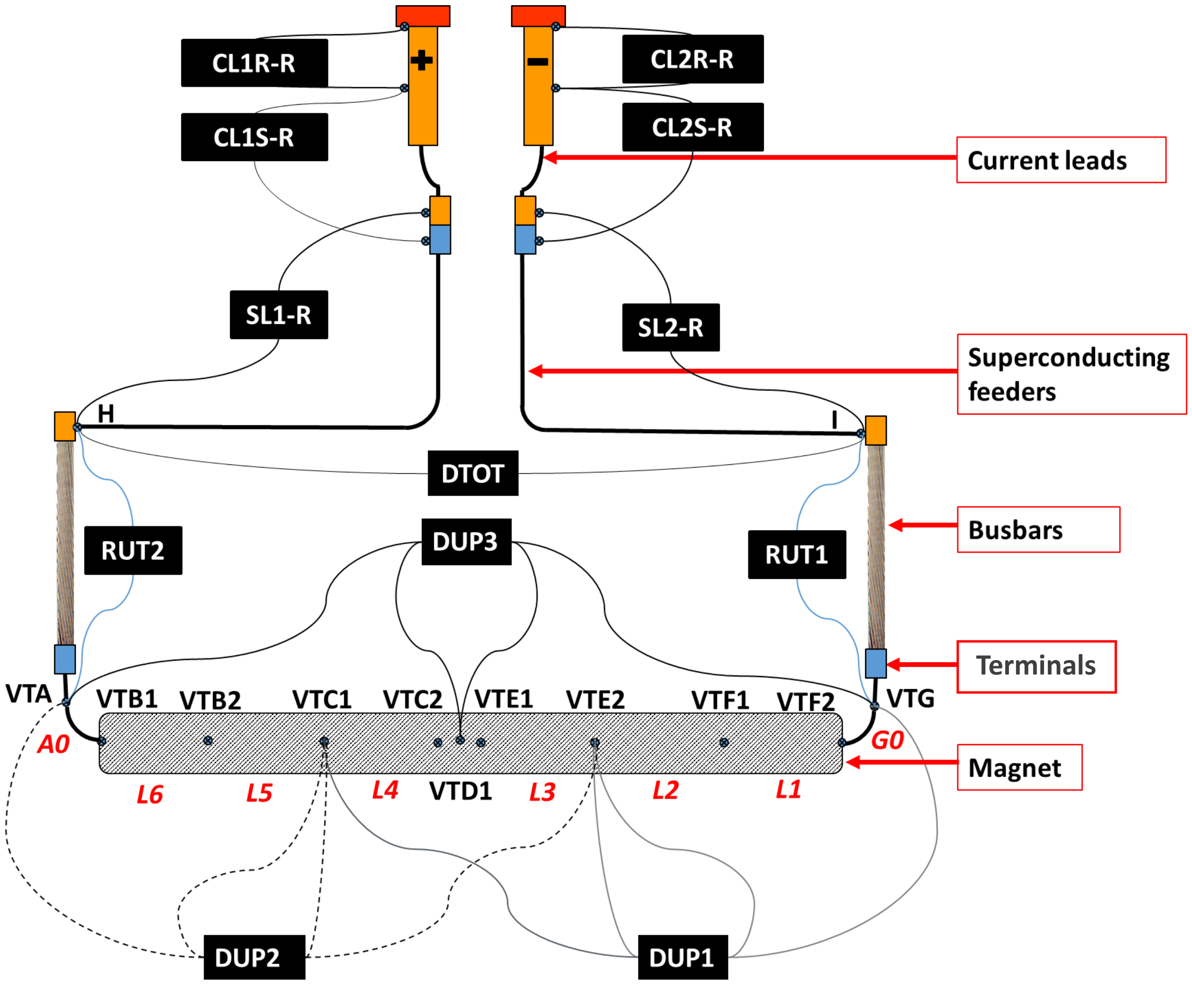


MACQU – Instrumentation: voltage taps

- **How to detect the quench, protect the coil and follow the quench propagation ?**
  - 11 Voltage Taps on MACQU
  - 6 outside (not represented here) for busbars
- **MACQU divided in 6 equal parts**
- **Center of MACQU (where quench initiated) refined for higher precision**



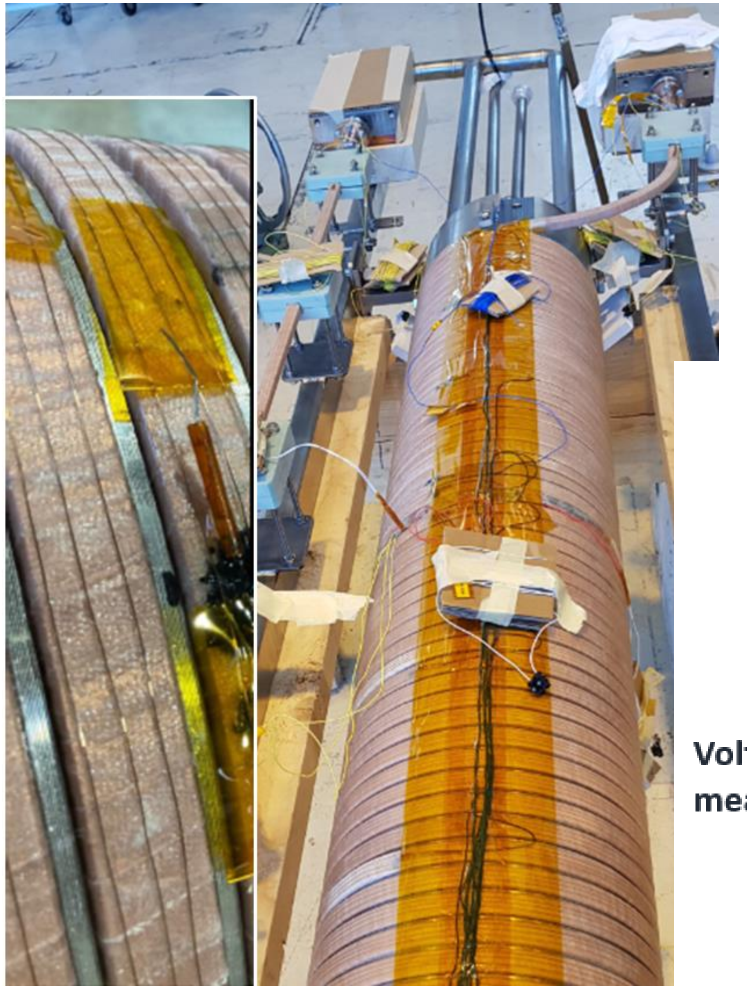
MACQU – Protection scheme



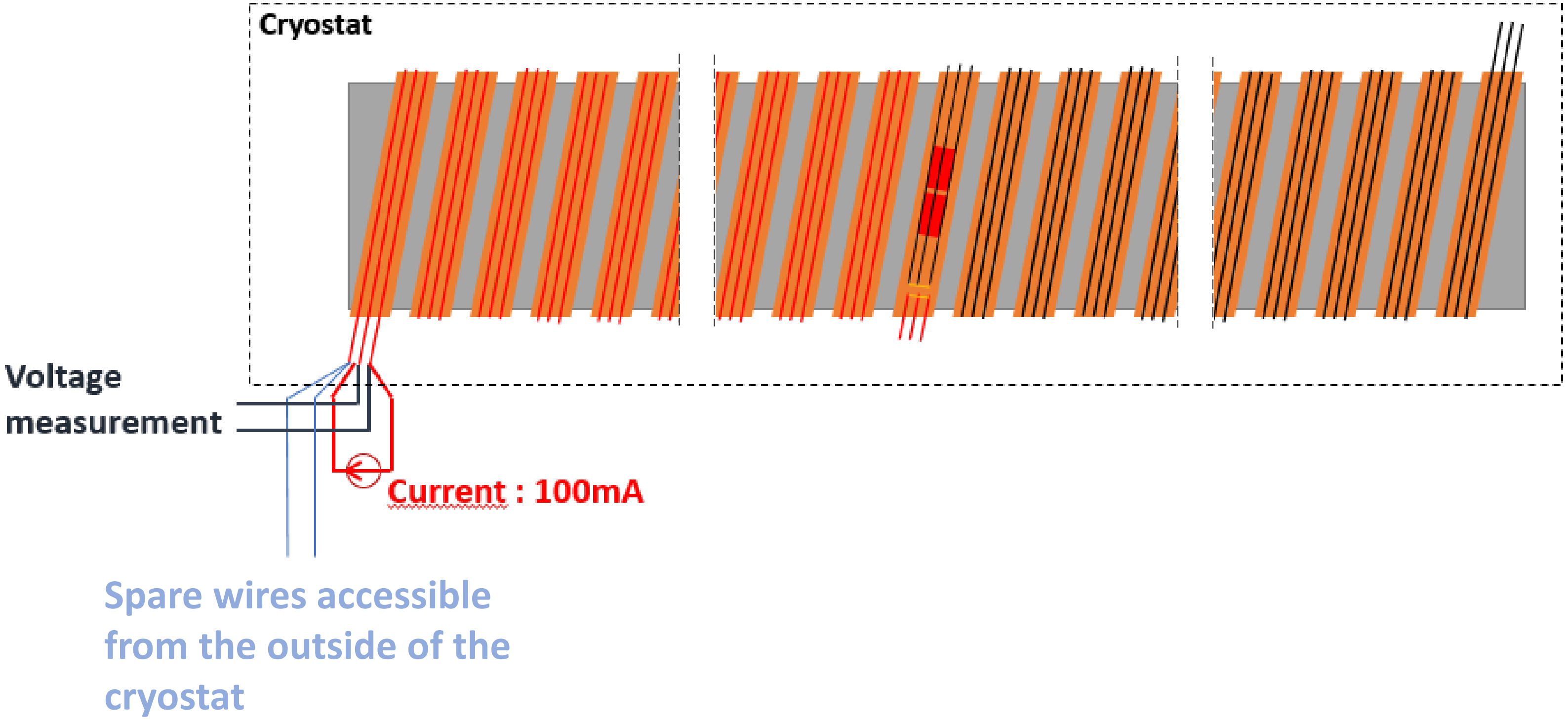
	Range (+/- V)	Threshold V (mV)	Threshold T (ms)
DUP1	10	100	100 to 4000
DUP2	10	100	100 to 4000
DUP3	10	100	100 to 4000
DTOT	1	100	100 to 7000
RUT	0.1	5	10
CLR	1	120	100
CLS	0.04	5	100
SL	0.1	10	100

- **Let the quench propagate as long as possible to well study quench propagation, at constant current**
- **Short threshold for quench detection**
- **High threshold for quench propagation**

MACQU – Instrumentation : SQD

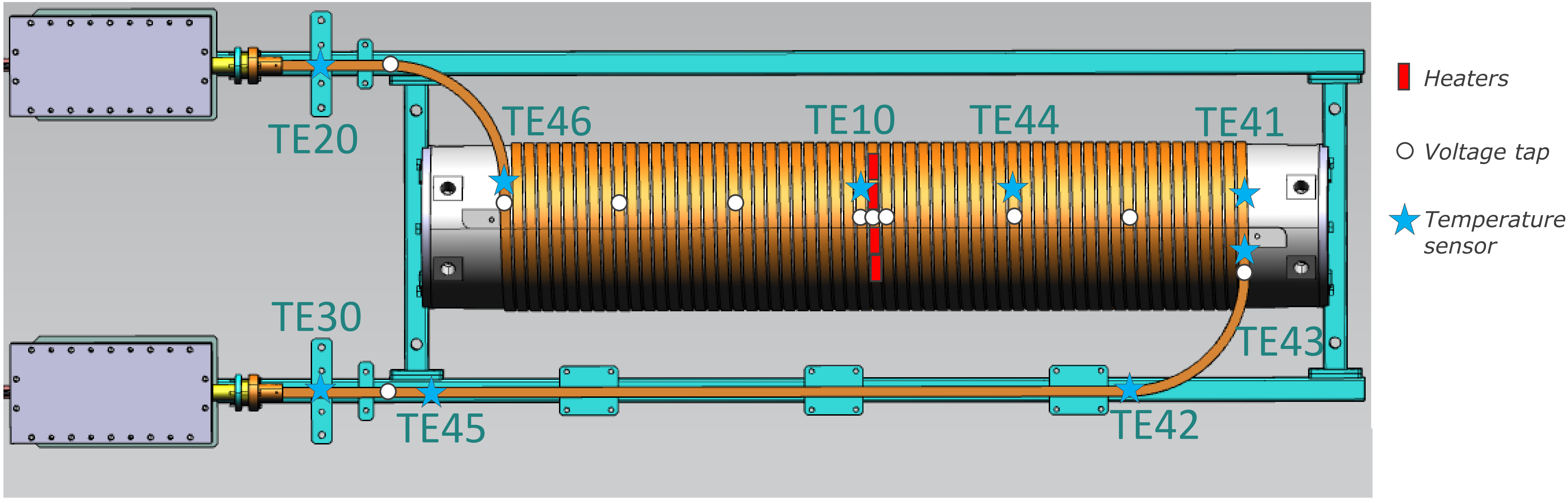


- **Superconducting Quench Detector, co-wound with the conductor**
- **Very sensitive to quench propagation**
  - 2x25m on each side of MACQU
  - RRR ~ 1.15
- **Not perfectly symmetric to follow quench propagation even at center**



MACQU – Instrumentation : temperature sensors

- **9 temperature sensors dispatched all along MACQU + 1 on thermal shield**
  - 4 on MACQU directly
  - 5 on the exits to the box
- **Double interest:**
  - Estimate experimentally the hotspot / thermal profile
  - Study the thermal behaviour of the exits that are not directly cooled-down



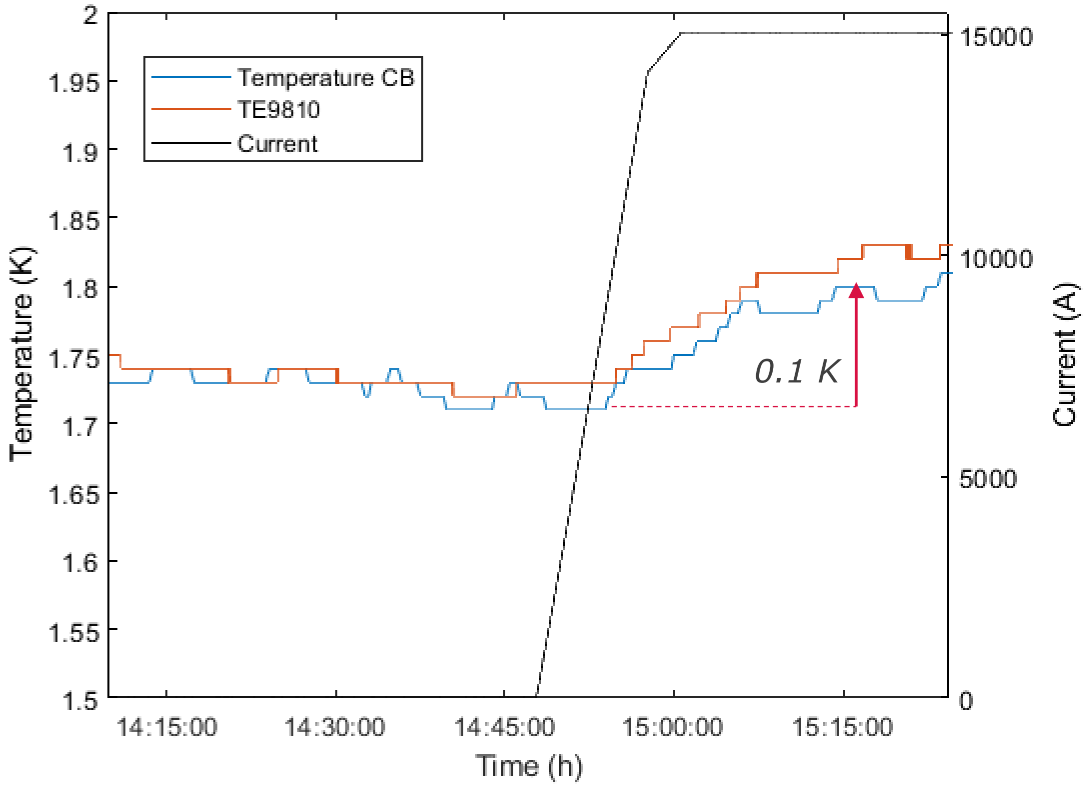
- 20 initiated quench from May to August

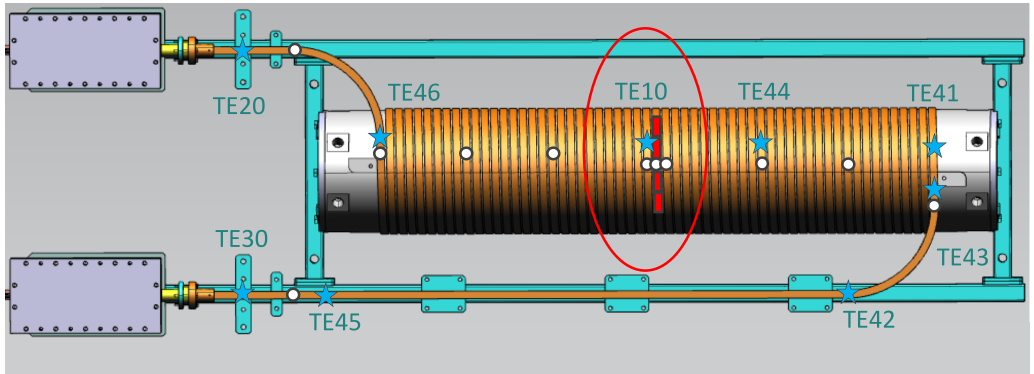
	Minimum testing value	Maximum testing value
Temperature (K)	1.75	2.01
Current (A)	10000	17000
Peak field at heaters position (T)	1.30	2.21

- Focus on one typical quench
  - Initial temperature: 1.81 K
  - Nominal current: 15 009 A
  - Peak field at heaters position: 1.95 T

MACQU – Current ramping

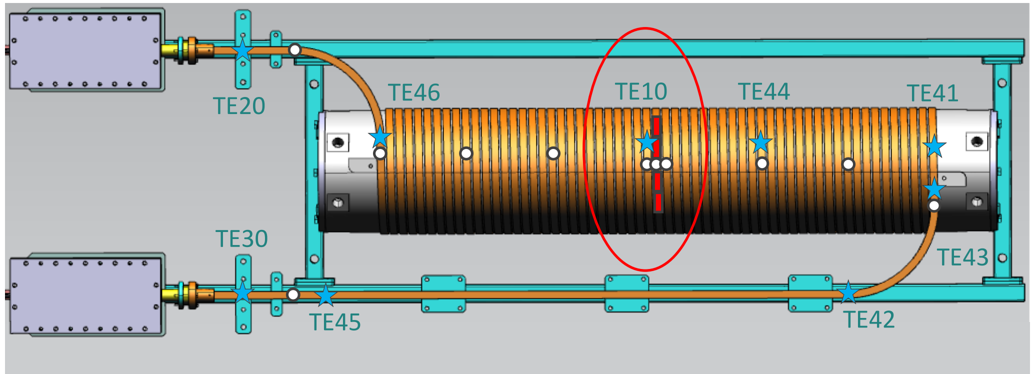
- **Current ramp up in 2 phases**
  - 20 A/s until 14 kA
  - 6 A/s higher
  - Plateau at 15 kA

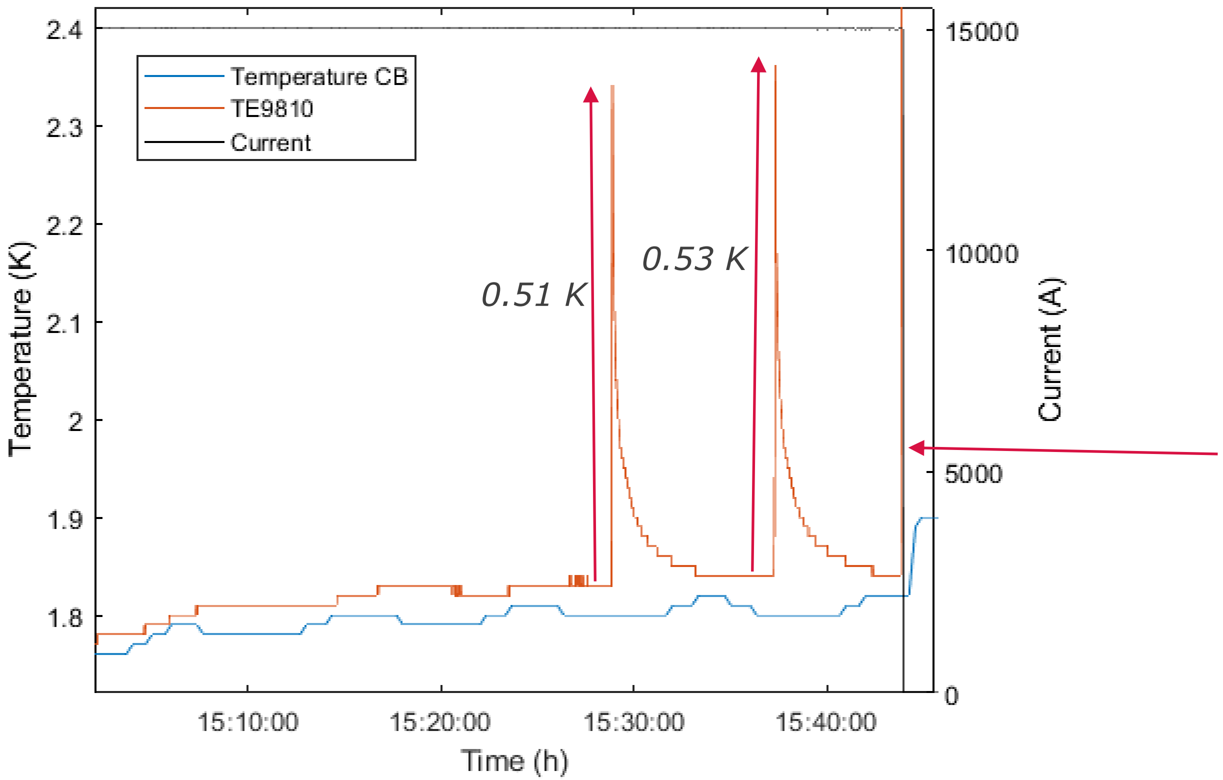




- **Helium pumping group speed fixed**
- **Joule effect losses in the terminals**
  - Temperature increase during plateau
  - Increase of the thermal gradient inside MACQU

- **MQE measurements:**
  - 4.9 W deposited
  - 2.4 s deposit
  - Time step : 0.1 s ⇔ 0.49 J



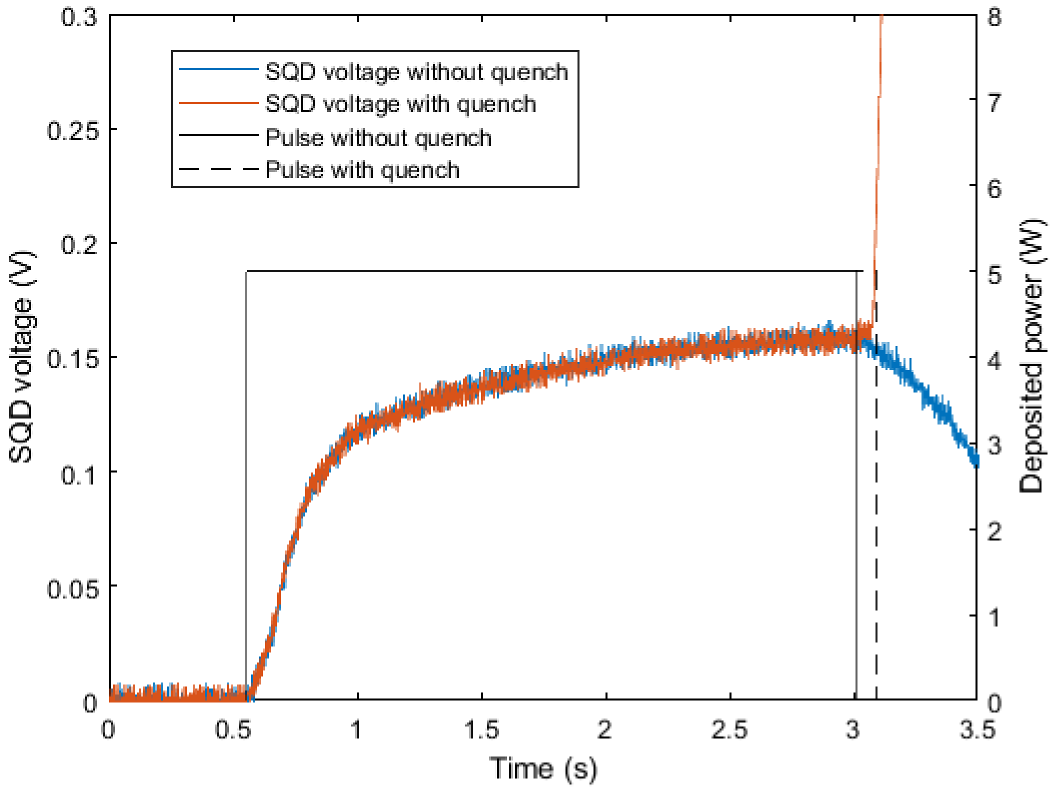


- **Time between consecutive pulse ⇔ steady state recovery time**
- **Quench started 3rd pulse (2.6 s deposit)**
  - Current decrease due to fast discharge
  - Temperature increase
- **Focus on transition**

MACQU – Quench initiation

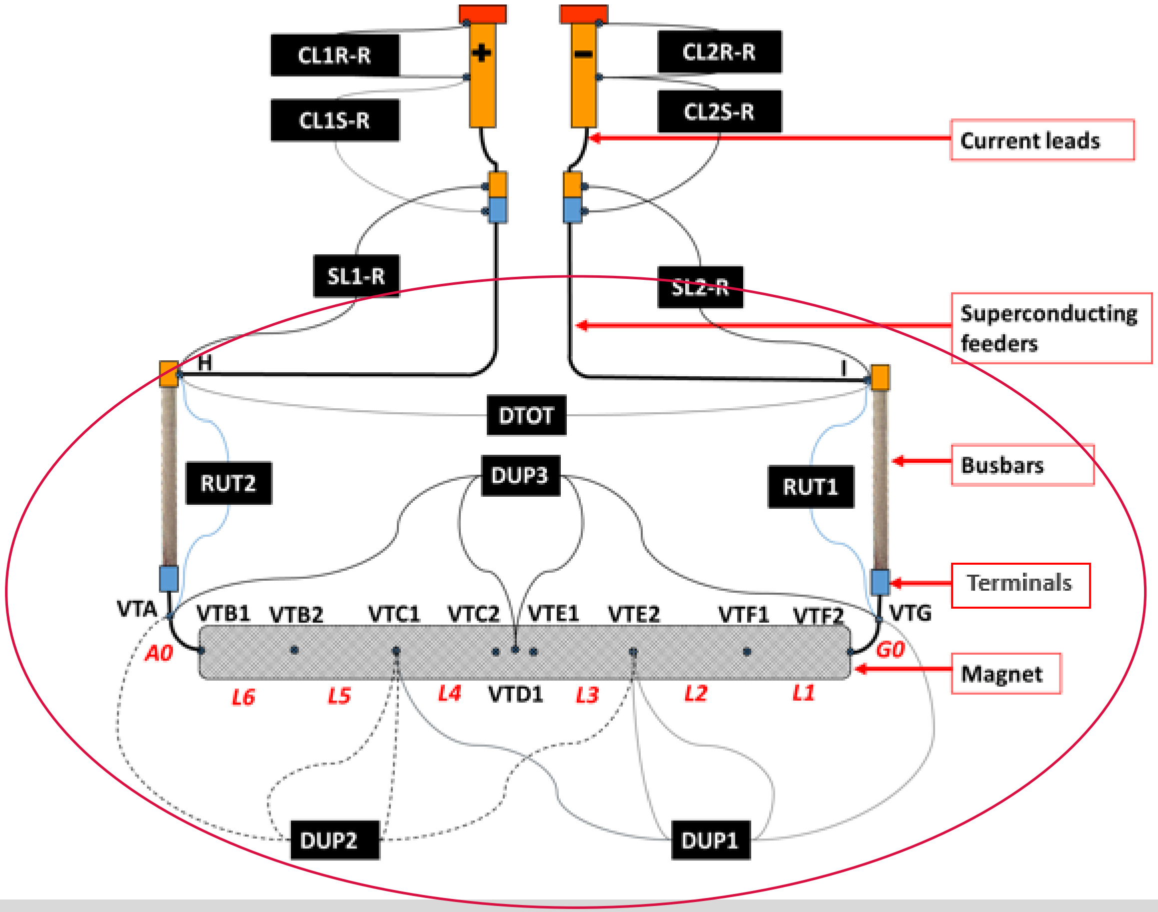
- **Comparison between 2 consecutive energy deposit**
- **Short voltage variation detected with SQDs**

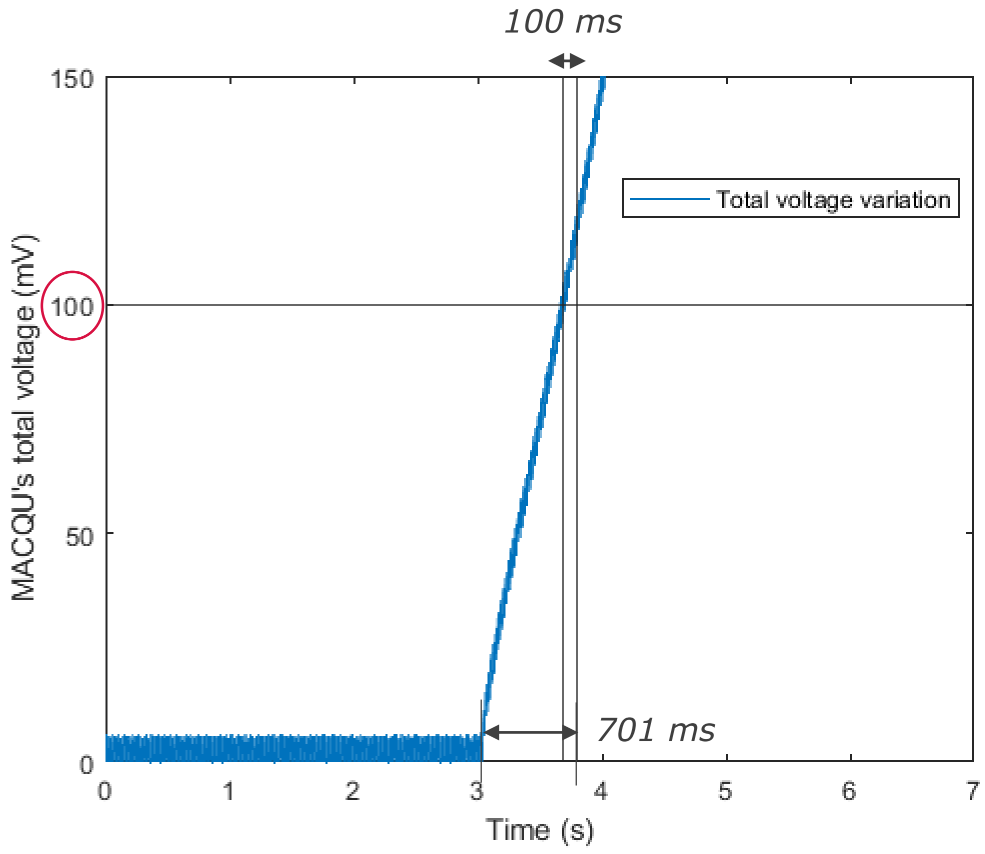
	No quench	Quench
Measured pulse duration (s)	2.46	2.54
Heaters' current (A)	0.7	
Heaters' resistance (Ω)	10	
MQE (J)	12.05	12.45



MACQU – Quench detection

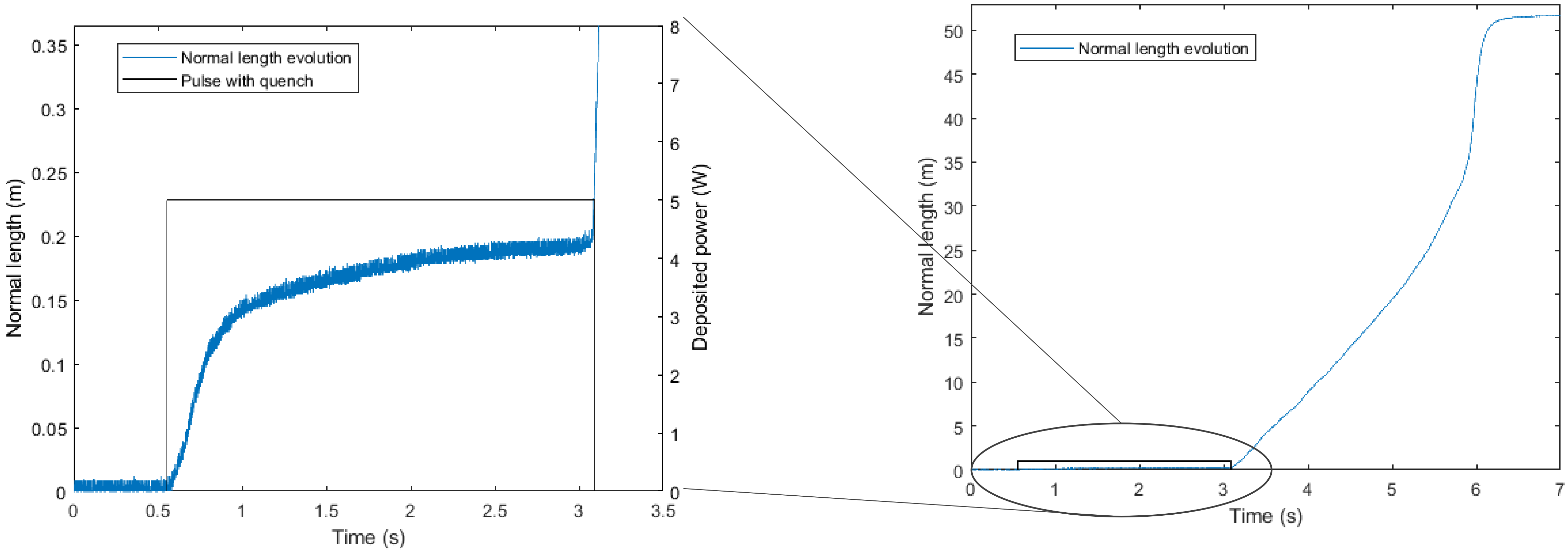
- Quench detection made on DTOT (entire magnet + busbars)
- Target : quench detected in 1s
- Threshold : 100 mV / 100 ms





- **Quench could be detected in 701 ms !**
  - Demonstrate quench detection system safety

Quench detection validated

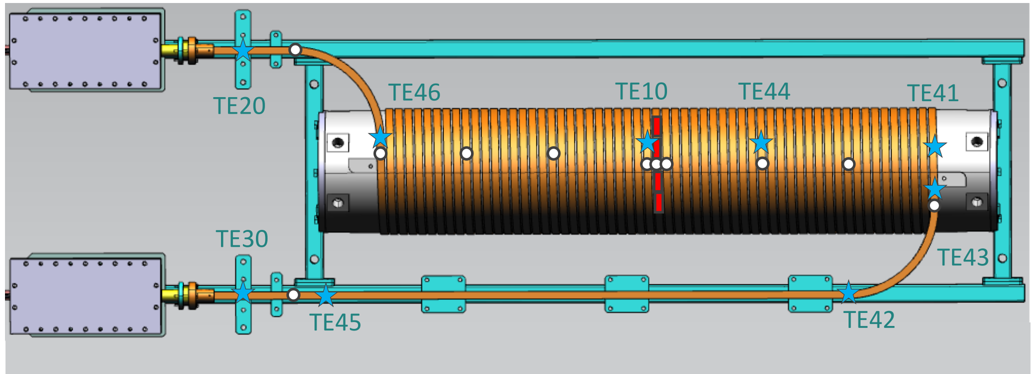


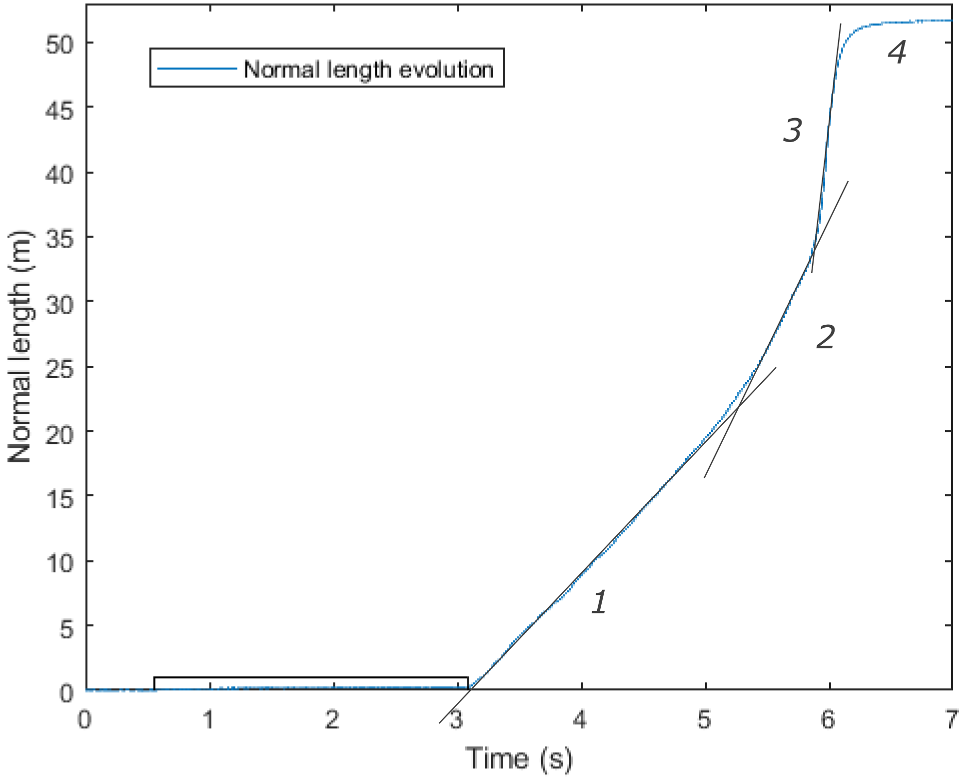
MACQU – Normal length evolution

- **Quench detection validated**
- **Different propagation phases**

- **1: beginning of the quench propagation**
  - $Vq_1 = 9.93$ m/s
- **2: beginning of quench acceleration**
  - $Vq_2 = 17.8$ m/s
- **3: clear break and strong acceleration**
  - $Vq_3 = 89.5$ m/s
- **4: strong decrease due to proximity to cold ends (< 3 m)**
  - $Vq_4 = 11.2$ m/s
- **Quench of the entire magnet in 3.5s**

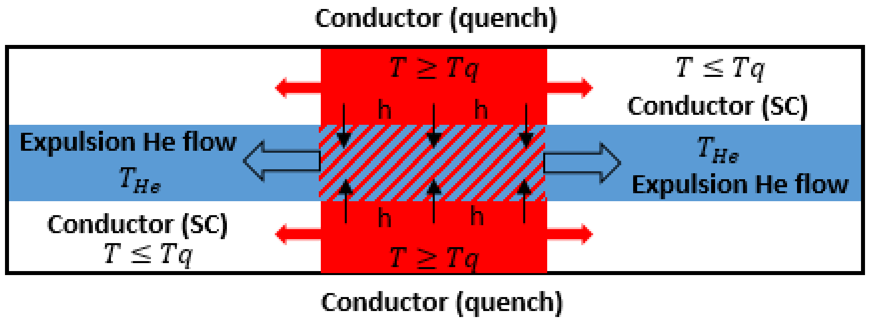
- **Acceleration due to Thermal Hydraulic Quench Back**
  - Phenomenon already seen in numerical computations
  - Factual analysis





THQB for the moment

- **Quench initiates:**
  - ❑ Heat conduction along the conductor
  - ❑ Heat exchange with Helium : temperature and pressure rise
  - ❑ Pressure differential generates Helium flow
- **Friction forces pre-warm the magnet by local energy deposit (before the quench arrival)**
- **Compression forces participate to increase the pressure inside the channel**
- **After reaching Tcs, a « new » quench starts far away from the propagation front : Thermal Hydraulic Quench Back (THQB)**



- **Strongly depends on pressure drop:**
  - Copper profile
  - Superfluid helium
- **How does it impact quench propagation ? Deep analysis on going**

Conclusion

- **Design of an experiment for quench studies**

- **Validate the conductor design for MADMAX**
  - CICC with copper profile
  - Cooled by stagnant superfluid helium at 1.8 K
  - No bath around

- **Conductor design validated**
  - Quench propagation speed ~10 m/s and detection < 1s
  - Interesting phenomenon to study : Thermal Hydraulic Quench Back (quench propagation speed reaching ~90 m/s)
  - Useful phenomenon to insure a fast quench propagation/detection ?

- **Lot of work to understand fully the phenomenon**
  - Analyse the pressure drop, heat exchange, coupled quench & helium dynamics in this particular configuration
  - Compare experimental and numerical result
  - Benchmark and develop THEA for superfluid CICC stagnant helium simulations

Questions ?

Thank you for your attention !

Unai DURAÑONA