cea

DE LA RECHERCHE À L'INDUSTRIE

Irfu - CEA Saclay
Institut de recherche sur les lois fondamentales de l'Univers

FUSION FOR ENERGY

JT-60SA Test Facility

Complementary study on Superconducting Toroidal Field Coils of JT-60SA

CHATS on Applied Superconductivity (Cadarache, FRANCE) - 20-24 September 2021

Souha KASSAB – R. VALLCORBA – J-P. LOTTIN – W. ABDEL MAKSOUD

September 21th 2021

Europe & Japan collaboration for developing a thermo-nuclear fusion reactor upgraded with 18 superconducting Toroïdal Field Coils (TFC)

Supercritical Helium
$(T_c = 5.20K, P_c = 2{,}27\ bar)$

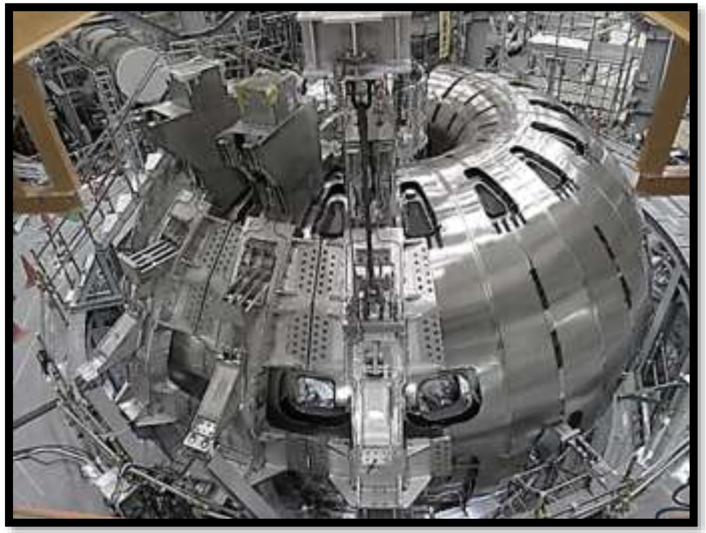


Fig.1. View of the JT-60SA tokamak machine

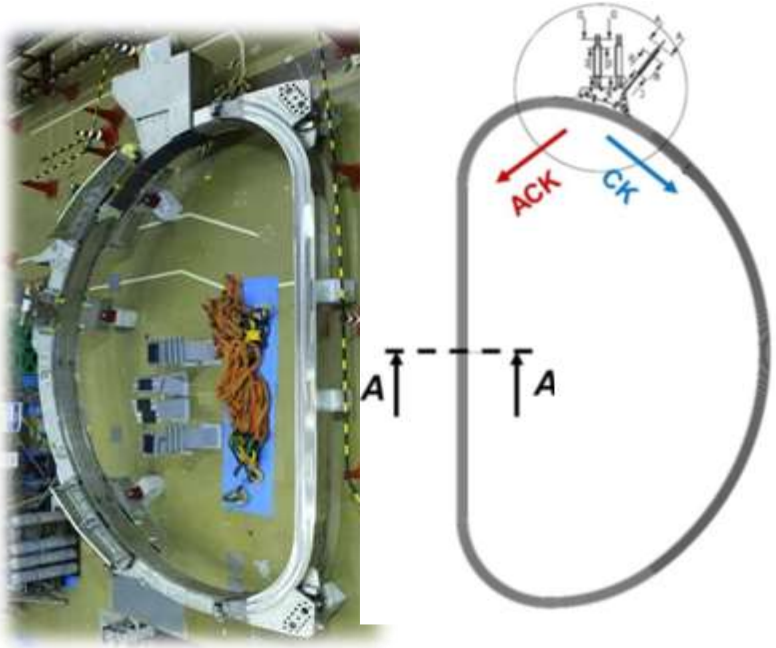


Fig.2. Upper view of one TFC

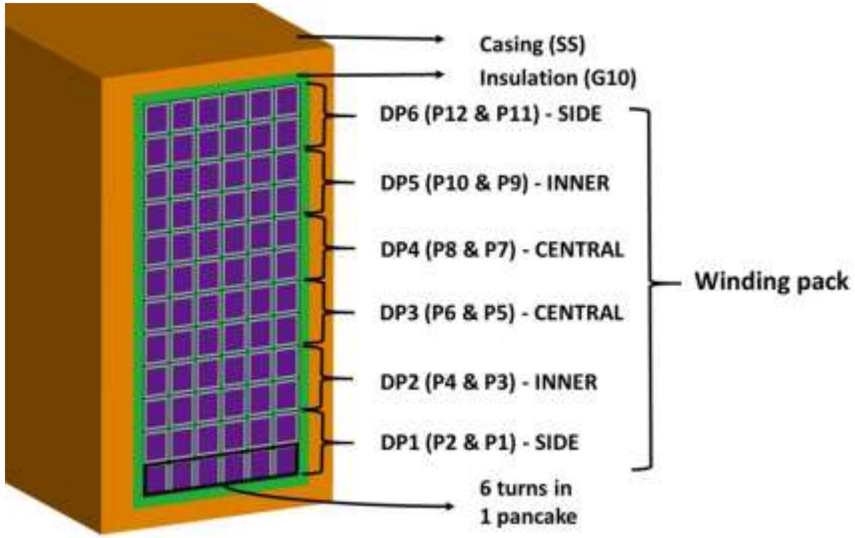
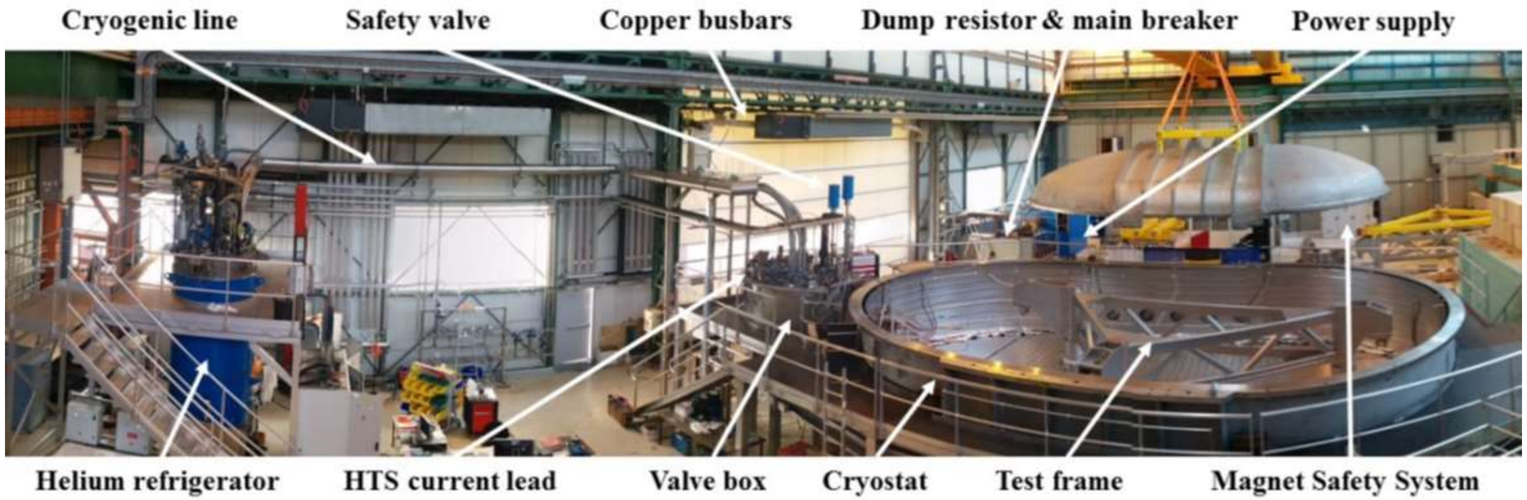


Fig.3. A-A view
(Courtesy of Huang Y. et al, "Quench tests analysis of the first JT-60SA Toroidal Field coils", 2017 Fusion Eng. Des. 124 147-152

Cold Test Facility Activity



Fg.4. Panorama photo of the Cold Test Facility and cryostat

CEA Saclay

Previous Study: experimental tests (+ numerical modelling)
Number of tested coils: All 18 TF coils, in a single coil configuration
Test configuration: Nominal (electrical and cryogenic) operating conditions: ($I_{nom} = 25.7\ kA, T_{He} = 5\ K$)

+

1 Quench protocole

Main focus: Quench dynamics in CICCS cooled with supercritical Helium flow ($T_c = 5.20K, P_c = 2{,}27\ bar$)

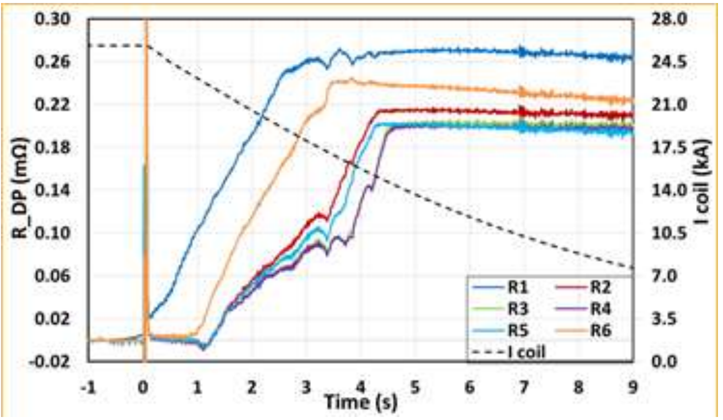


Fig.5. Example of a quench evolution for one of the tested TFC of JT-60SA

Outline

- **1. CONTEXT**
  a. JT-60SA magnet
  b. Cold Test Facility Activity
  c. Additional Tests Activity at CTF
- **2. DESCRIPTION OF QUENCH EXPERIMENTS**
  a. Experimental setup & Instrumentation
  b. Experimental quench protocol
  c. Experimental quench resistance computation: pick-up coil method
  d. Experimental study cases for numerical analysis: Observed dynamics
- **3. NUMERICAL MODELLING & ANALYSIS OF QUENCH EXPERIMENTS**
  a. Simplified 1D model
  b. Interturn
  c. Numerical analysis of the experimental quench dynamics
- **4. CONCLUSION & OUTLOOK**

Additional R&D program

F4E

Thermohydraulic tests (TFC19)

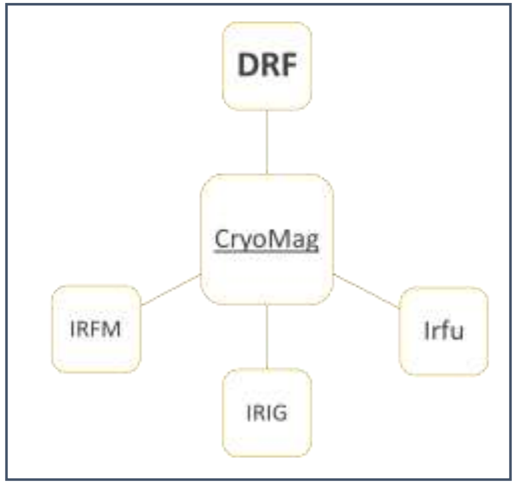
F4E

Quench tests (TFC02)

TFC spares: TFC02 & TFC19

CryoMag

Development of numerical models **(ongoing)**



ATAs Identification

Activity Name	Coil	Relevant Parameter
ATA01	TFC19	Casing Temperature Stabilisation
ATA02	TFC19	Pulsed Heat Input
ATA03	TFC19	Higher mass flow rate hydraulic test
ATA04	TFC19	Casing /Winding Pack Thermal Coupling
ATA05	TFC02	Quench under different inlet temperature dynamics
ATA06	TFC02	Lower mass flow quench tests
ATA07	TFC02	Higher mass flow quench tests
ATA08	TFC02	Sensitivity of detection time
ATA09	TFC02	Sensitivity of detection thresholds (voltage)
ATA10	TFC02	Lower Current Quench tests
ATA11	TFC02	Local Heat Input Quench

Experimental tests considered in numerical study cases

ATAs purpose

- For F4E: study of TF coils behaviour in off-nominal working conditions of the Tokamak.
- For CEA/CryoMag:

To better understand CICCs behavior
To isolate specific parameters influence
To closely observe coupled phenomena
To benchmark numerical models

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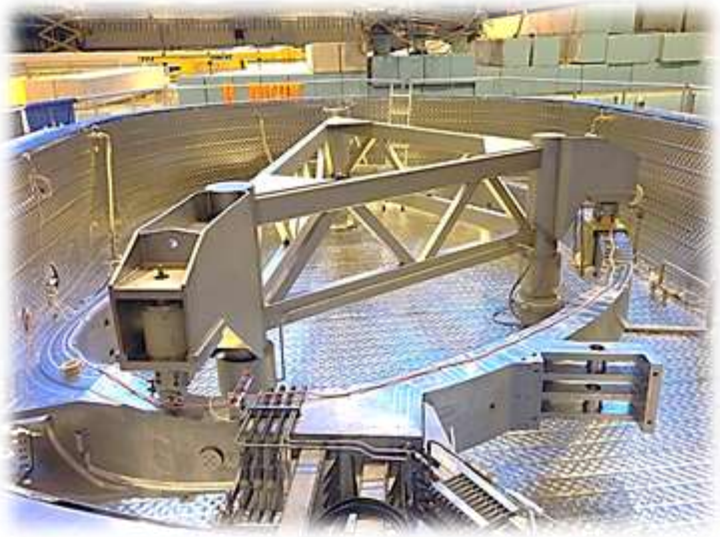
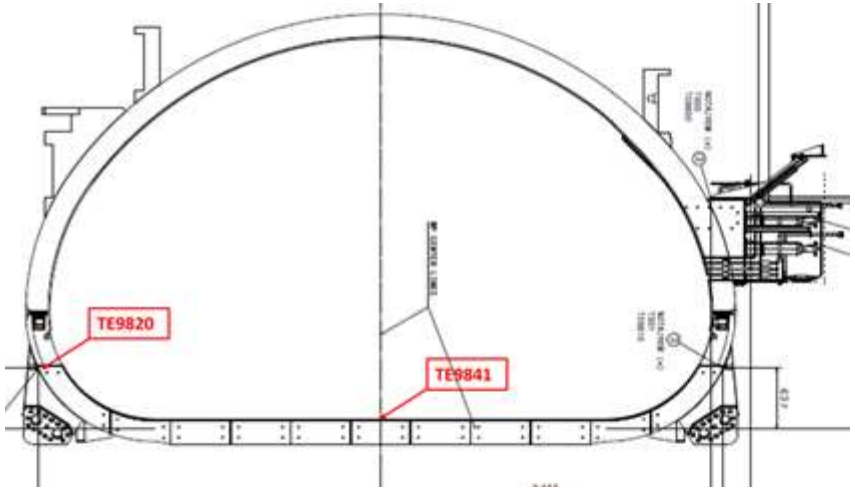
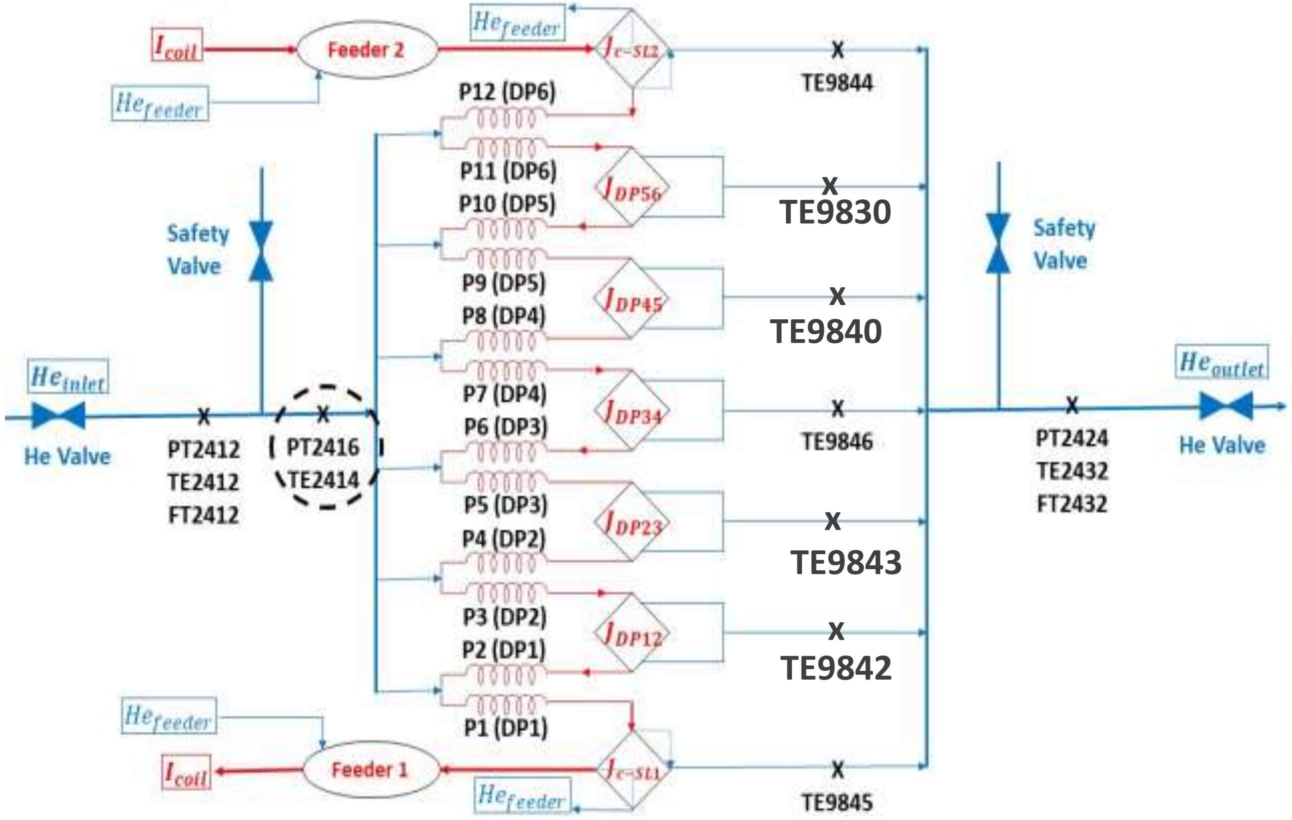
TFC inside the cryostat at CTF



Casing instrumentation of TFC



TF coil Intrumentation at CTF for quench tests



- PT: pressure transmitter
- TE: temperature gauges
- FT: mass flow rate transmitter
- J_{DP}: interpancake joint
- J_{C-SP}: connecting joint (coil-superconducting feeder)

2.b. Experimental quench protocole in three steps

1 Coil energizing phase
(steady state)

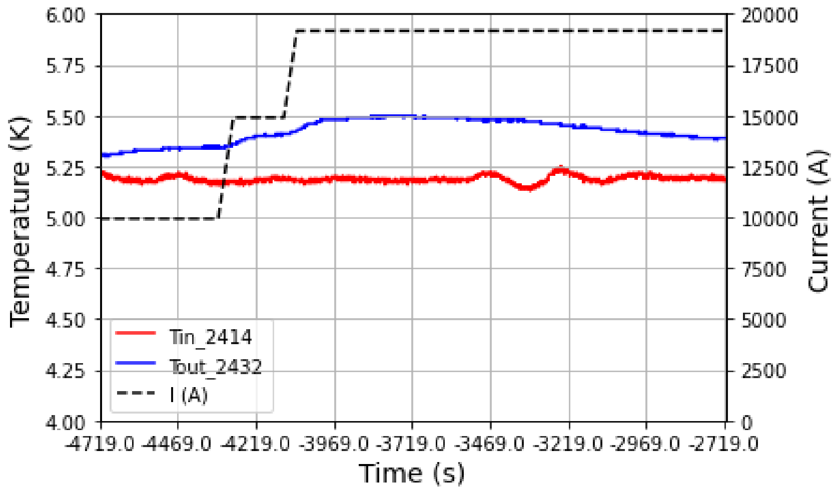


Figure 1-Temeprature and current evolution during the Helium steady-state

2 Temperature-increasing phase
(slow transient state)

Second slower slope

First rapid slope

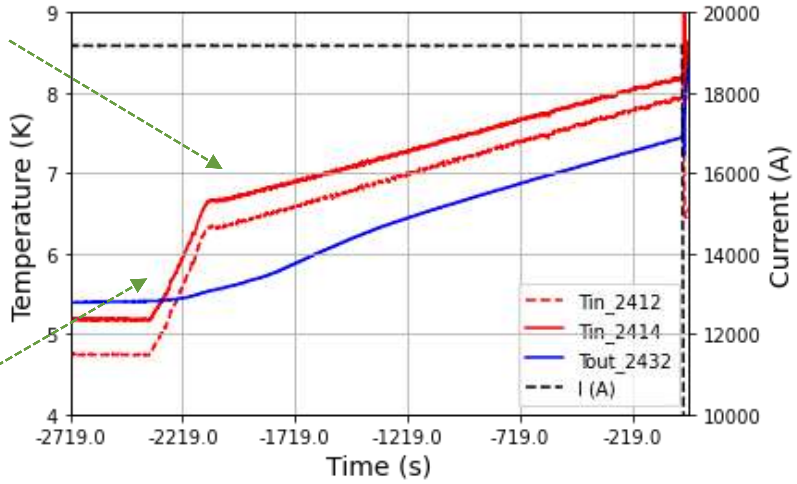
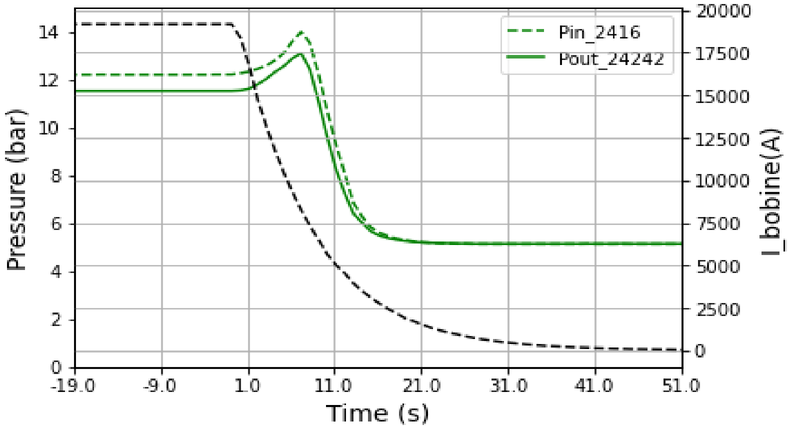


Figure 1-Temperature and current evolution during Helium slow transient state

Quench detection of 100mV during 100ms

3 Current Fast discharge
(Fast transient state)



Protocole example for lower current quench test (I=19.5 kA)

Recall: Computation of the experimental quench resistance in three steps

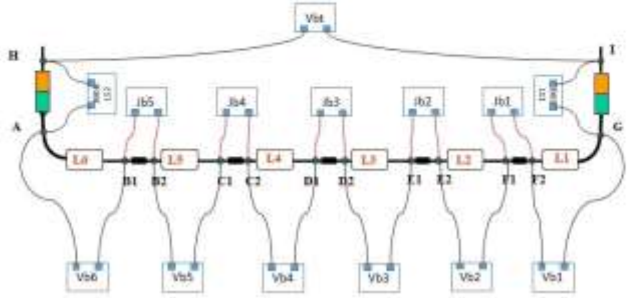
1. Electrical data acquisition:

The experimental DP’s **quench development resistance** obtained from the **voltage measurements**.
Time evolution of the voltage U_{DP} is due to a competition between the inductive voltage $U_{DP\ ind}$ and the quench resistive voltage $U_{DP\ quench}$:

$$\boldsymbol{U_{DP} = U_{DP\ ind} + U_{DP\ quench}}$$

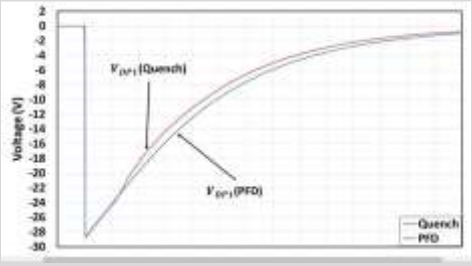
$$= \mathbf{L}\frac{dI}{dt} + IR_{DP}$$

How to deduce the quench resistive contribution from U_{DP}?



Pick-up coil

Pure Fast Discharge



2. Pure fast discharge (PFD):

no quench in this coil
The voltage corresponds to a purely inductive voltage only depending on the current variation.

3. Computation with the pick-up coil inductive voltage

« Method « *Computation with the pick-up coil inductive voltage* » ***(Huwai Y. Method)***

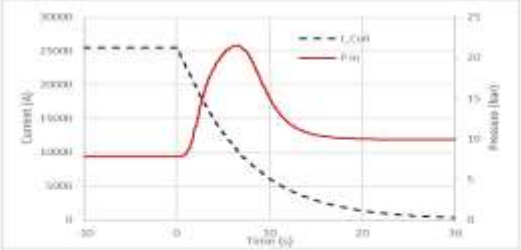
1. *During the FD, the rapid variation of the coil current produces the magnetic field variation through the pick-up coil and induces a pure inductive voltage in it.*
2. *DP inductive voltage is proportional to the one of the pick-up coil according to the relation to the seld –inductances.*

$$\gamma_i = \left(\frac{U_{DP\ i\ mes}}{U_{pickup}}\right)_{PDF} = \left(\frac{L_i\frac{dI}{dt}}{U_{pickup}}\right)_{quench}$$

$$\boldsymbol{R_{DP\ i} = \left(\frac{U_{DP\ imes} - \gamma_i U_{pickup}}{I}\right)_{quench}}$$

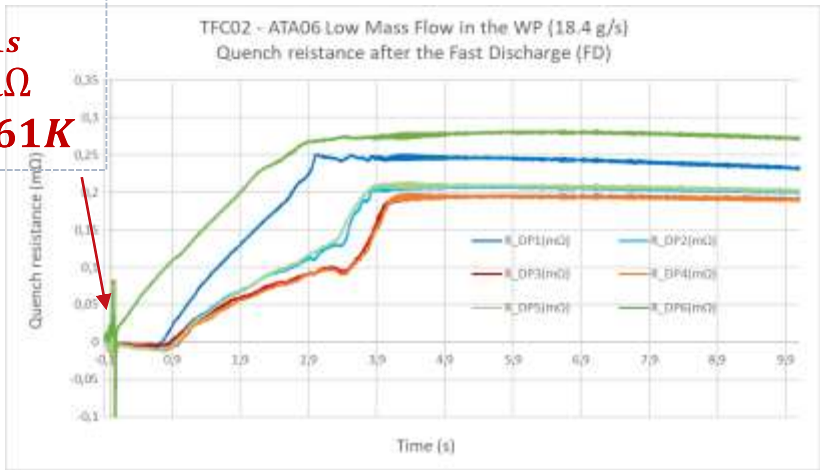
L = global inductance of the DP including the self-inductance and the mutual one

Current fast discharge during the quench



Lower Mass Flow in the WP: 18.4 g/s

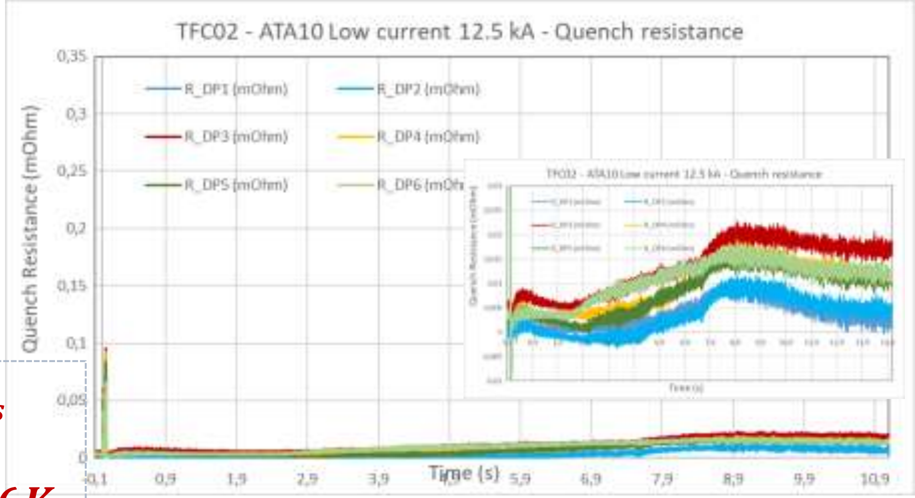
$R_{FD-0,1s} = 16\ \mu\Omega$
$T_{FD} = 7,61K$



Time delay prior to the current dump = **100 ms.**
Voltage = **100 mV**

Lower Current :

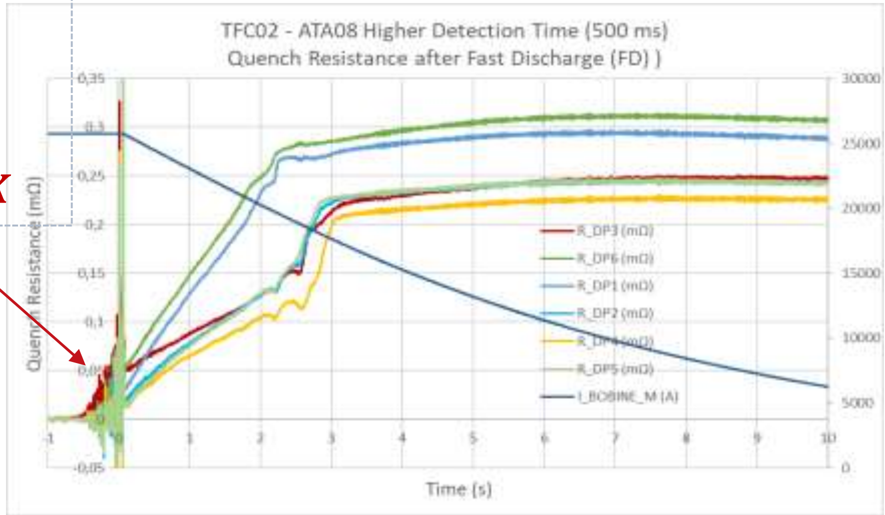
12.3 kA



$R_{FD-0,1s} = 5\ \mu\Omega$
$T_{FD} = 8.36K$

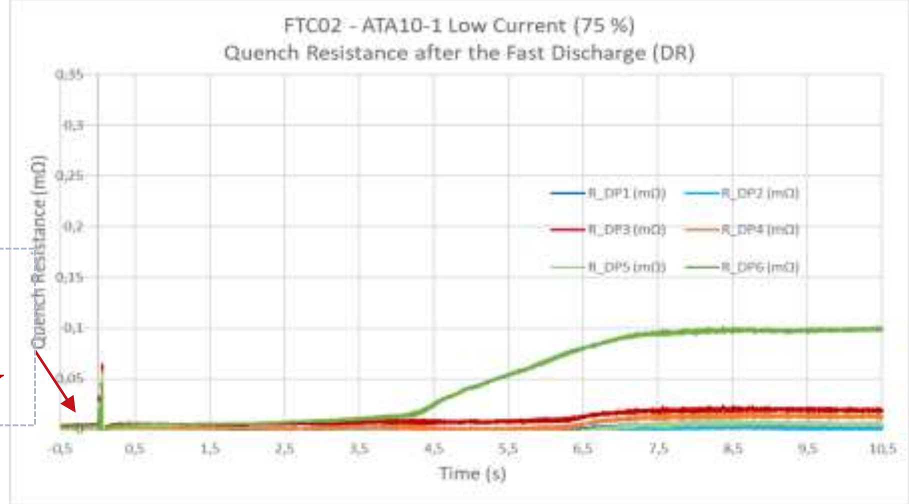
Higher Detection Time: $\tau = 500\ ms$

$R_{FD-0,1s} = 59\ \mu\Omega$
$T_{FD} = 7.51K$



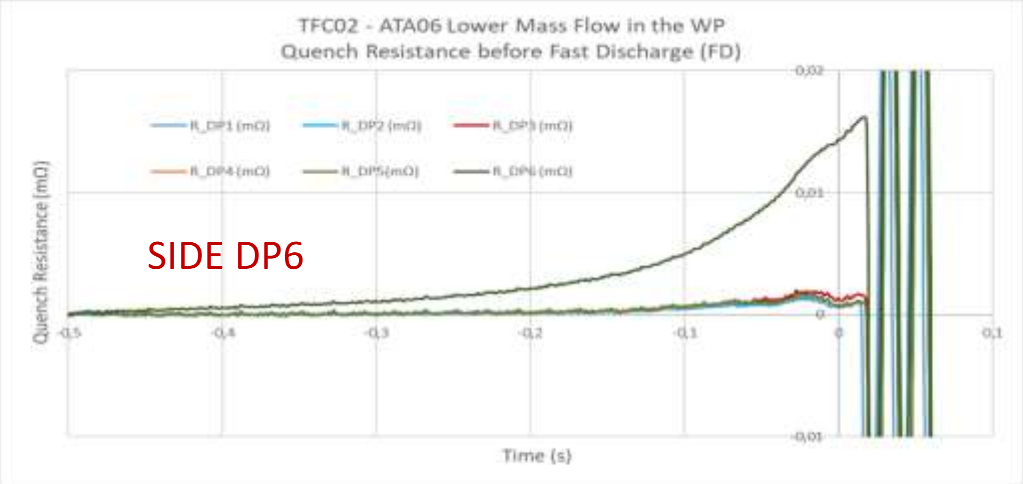
19.5 kA

$R_{FD-0,1s} = 5\ \mu\Omega$
$T_{FD} = 7.93K$

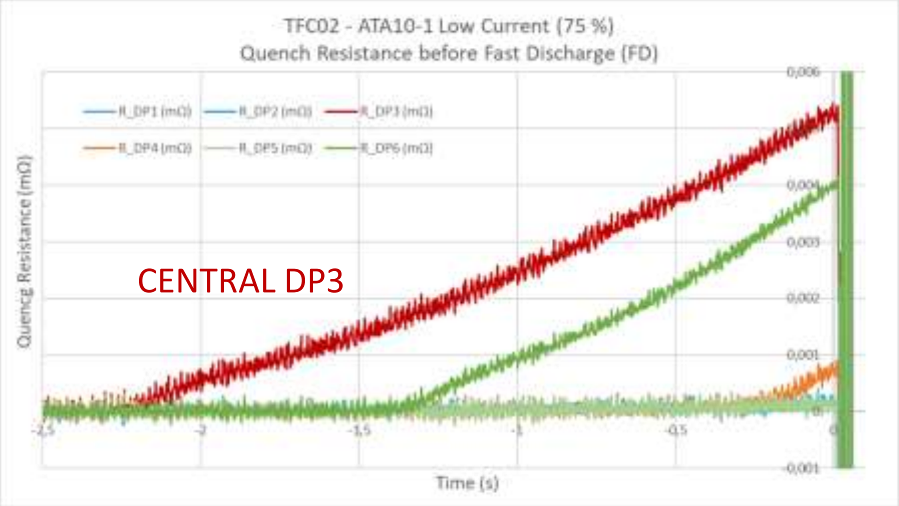


2.c. Experimental study cases for numerical analysis: DPs quench resistance evolution in DR [-0.5; +0.1]s

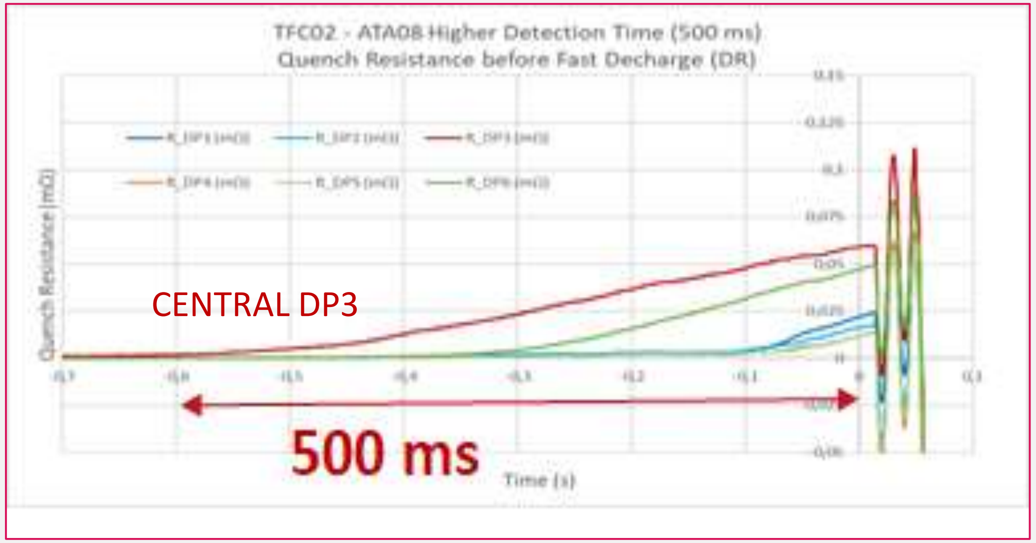
Lower Mass Flow in the WP: 18.4 g/s



Lower Current : 12.5 kA

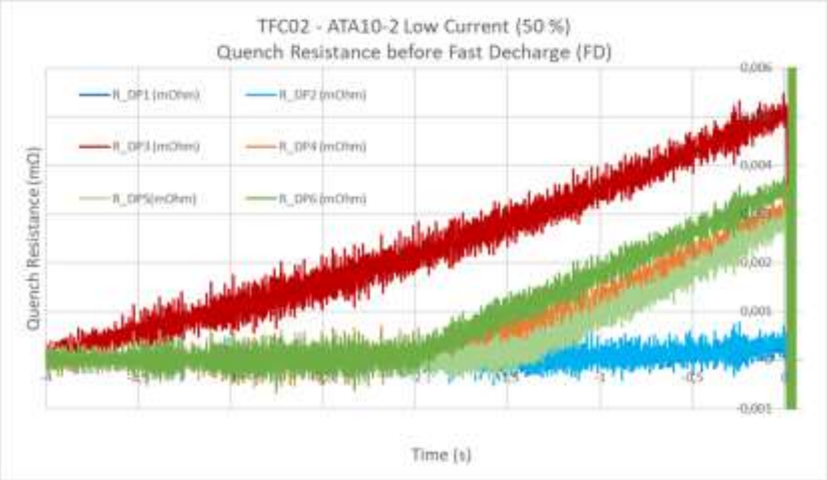


Higher Detection Time: $\tau = 500\ ms$



Lower Current: 19.5 kA

CENTRAL DP3



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  - c. Summary of the quench experimental tests
  - d. Experimental study cases for numerical analysis: Observed dynamics
- 3. NUMERICAL MODELLING & ANALYSIS OF QUENCH EXPERIMENTS
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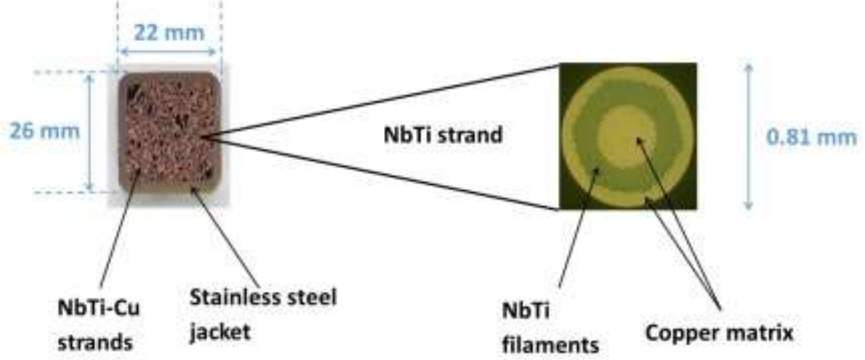
THEA (Cryosoft) is FE model for the Thermal, Hydraulic and Electrical Analysis of superconducting cables.

- **THEA computes the evolution of the temperature, coolant flow and current distribution in one cable in:**
  - steady state scenarios
  - transient (QUENCH) modes.
- **Simplified 1D steady-state model:**
  - Thermal components: strands, jacket & isolation

Matériau	Section (mm2)	Masse volumique (kg/m3)	Longueur(mm)
NbTi	56.8	6550	113.27
Cu (RRR=130)	180	8960	
Acier inoxydable	176	7900	
G10	100	1948	

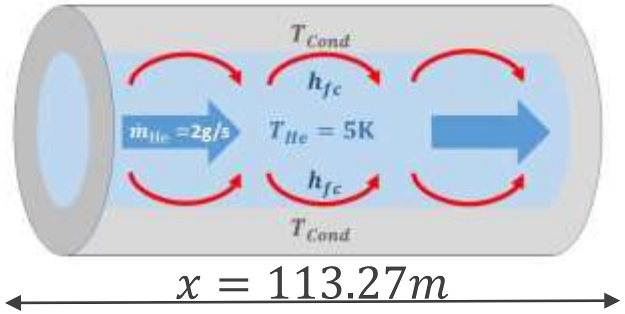
  - Hydraulic components: supercritical Helium in forced flow

Cross-section of the CICC for JT-60SA TF Coils



- **Main thermal-hydraulic parameters:**
  - $Tin = 5.14\ K$
  - $\Delta P = 550\ mbar$
- **Heat transfer coefficients**
  - Dittus-Boelter correlation: $Nu_{turbulent} = 0.023 * Re^{0.8}\ (\mathrm{Pr})^{0.4}$
- **Friction factor correlations (no central channel)**
  - Katheder correlation: $f = \alpha + \beta * Re^{-\gamma}$

*« α, β, γ **empirically fitted** at the OTHELLO test facility (CEA Cadarache, France) for all the CICCs that are used for the TF coils manufacture »*



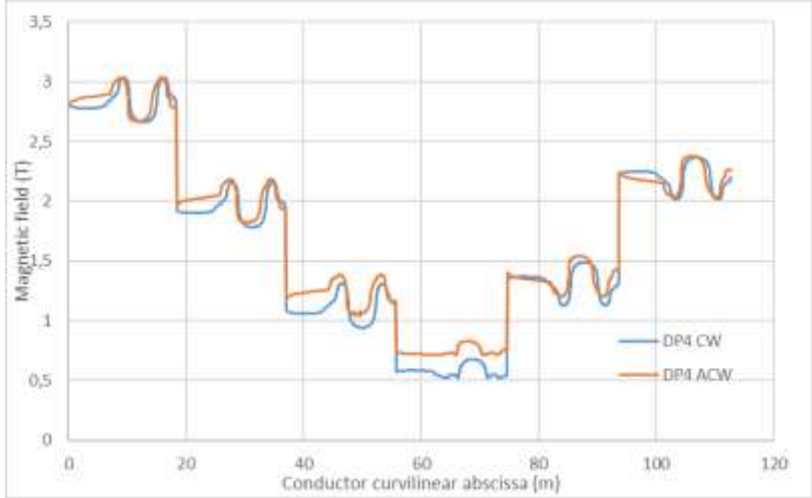
Schematic diagram of the forced helium convection in the unfolded CICC

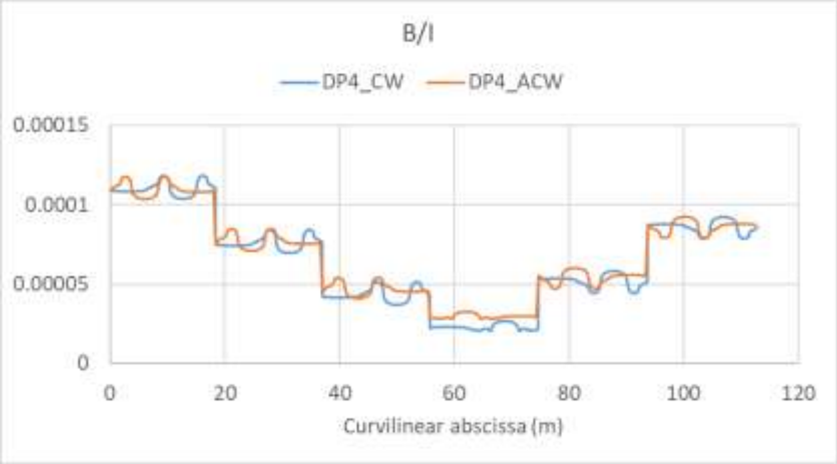
Recall: the magnetic field

Nominal current (25.7 kA)

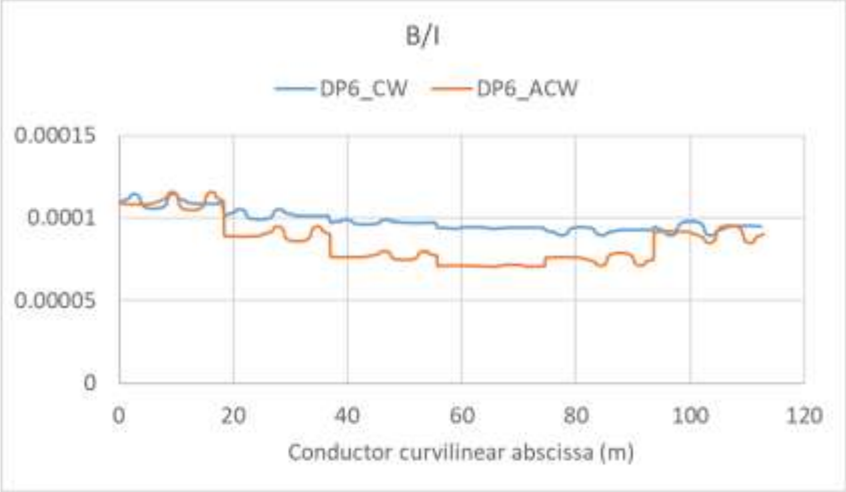
B/I ratio

CENTRAL pancake
DP4





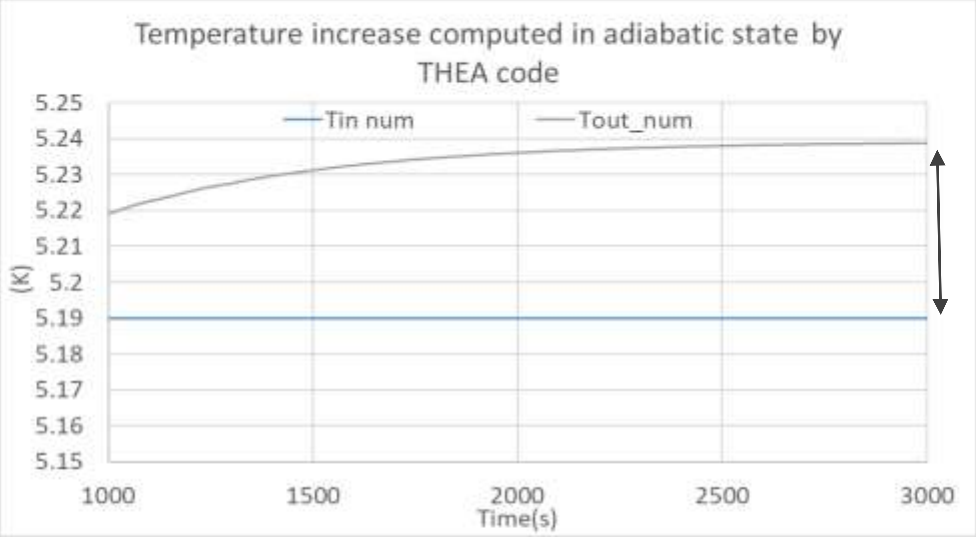
SIDE pancake
DP6



Friction factor and deposited heat before coil energizing

1. Average Heat load due to friction computed in THEA :

$$q_f = 3.53.10^{-3}\ W/m$$
$$(f(3853) = 0.1817)$$

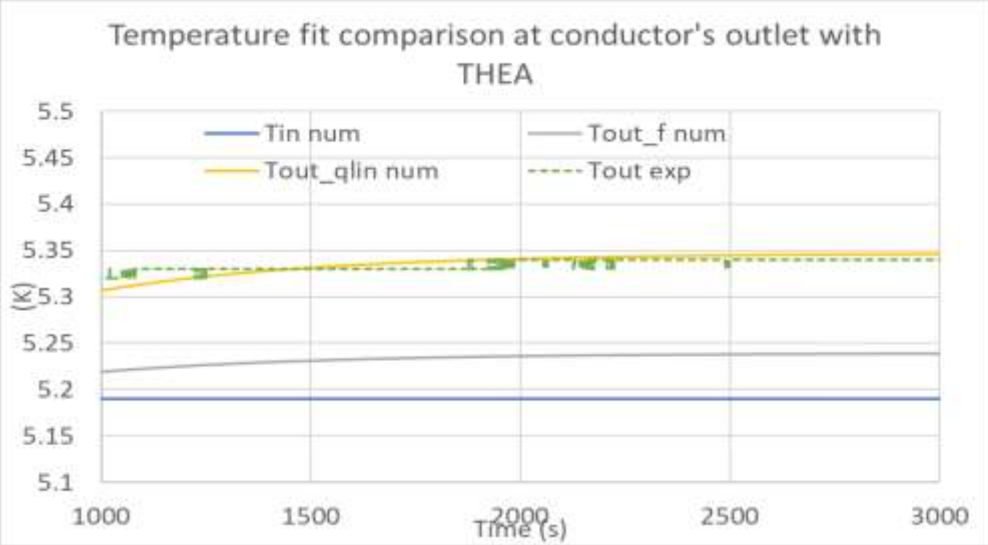


$$\Delta T_f^{num} = 0{,}05K$$

2. Average heat load deposited in the Casing:

$$q_{lin} = 0.01 W/m$$

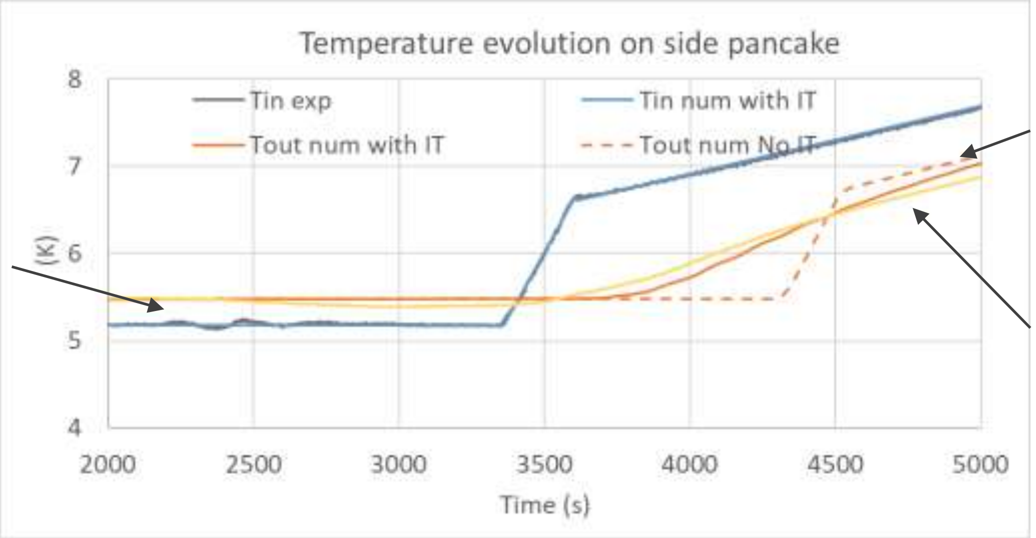
Computed from $(Q_{tot})^{exp} - q_f^{num}$



Computation of conductor's outlet temperature

- **ATA10: lower current quench test**

Experimental Tinlet temperature in WP and THEA computed inlet temperature

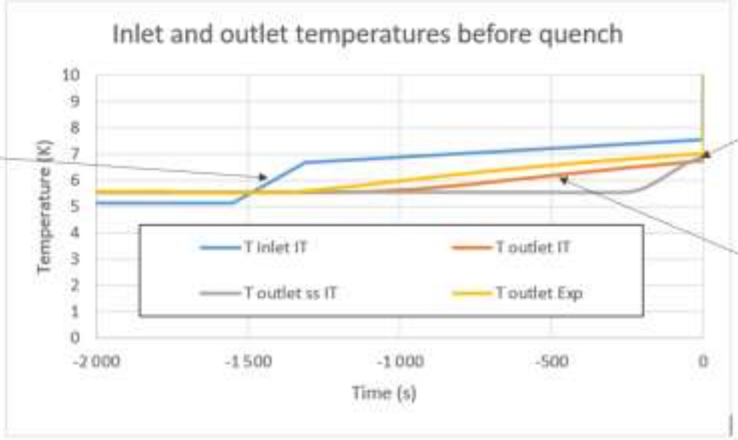


Outlet temperature using THEA model. NO interturn

Outlet temperature using THEA model with interturn and experimental outlet temperature

- **ATA06: lower mass flowrate quench test**

T inlet temperature

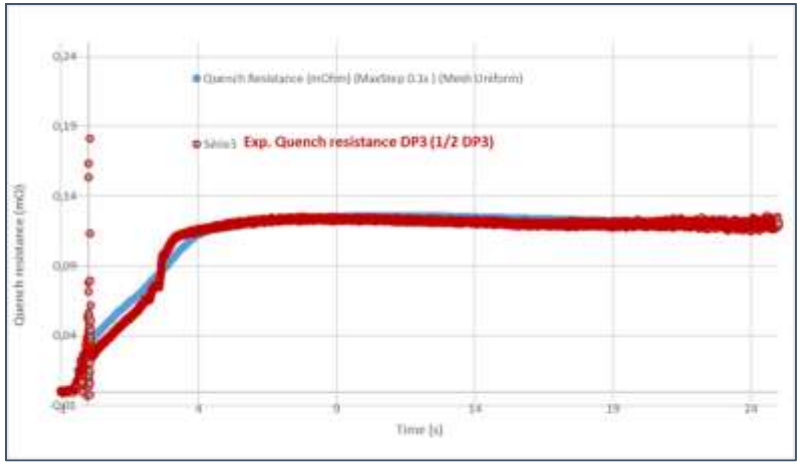


Thea calculated outlet temperature Without InterTurn Time decay due to mass flow time decay

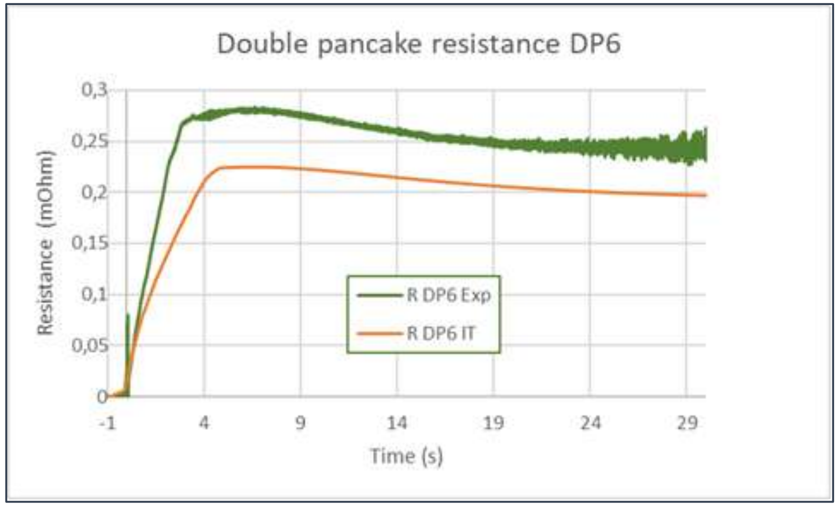
T outlet experimental temperature and Thea calculated outlet temperature with InterTurn

Quench resistance evolution computed with THEA code of a single conductor (1 pancake); variant physical parameters according to 3 different quench test case at CTF.

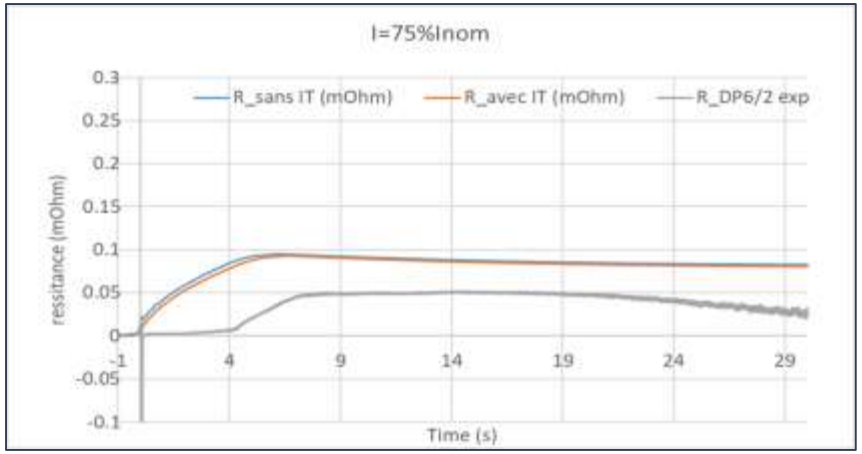
- ✓ Detection Time= 500 ms



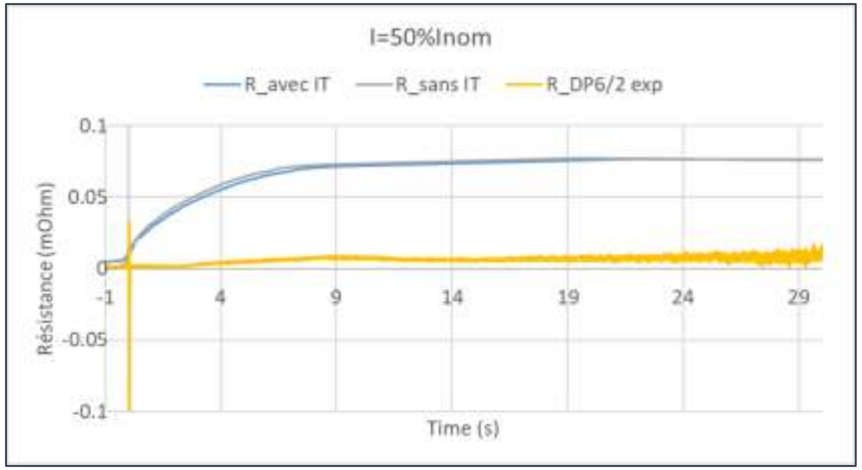
- ✓ WP flowrate = 1.5 g/s per conductor



- ✓ Electrical Current = 75% I_nom (19.5 kA)

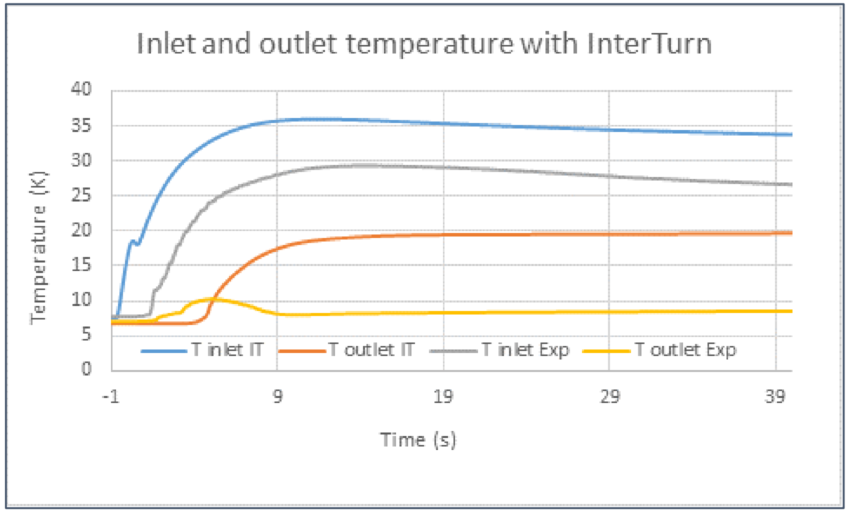


- ✓ Electrical Current = 50%I_nom (12.3 kA)

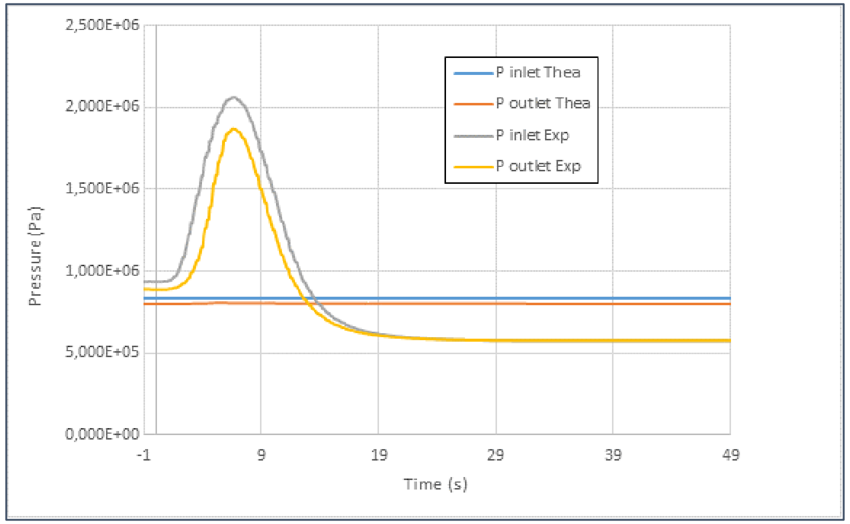


Present simulation limitations

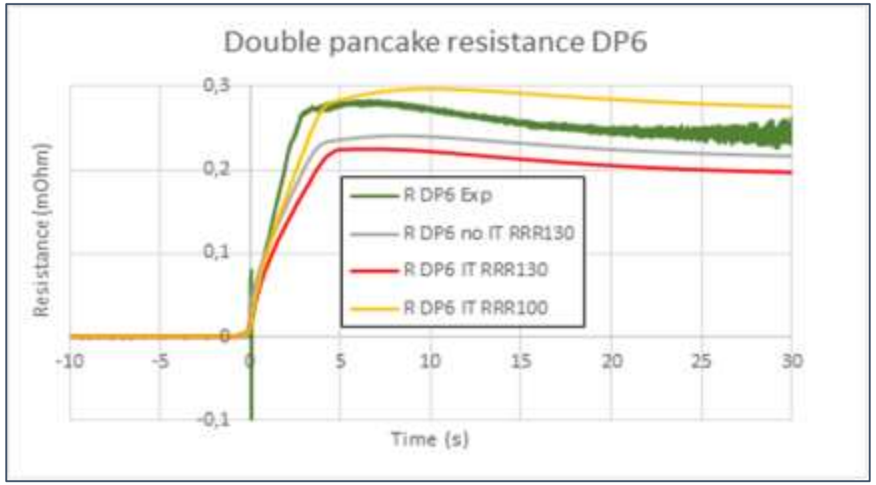
- Temperature



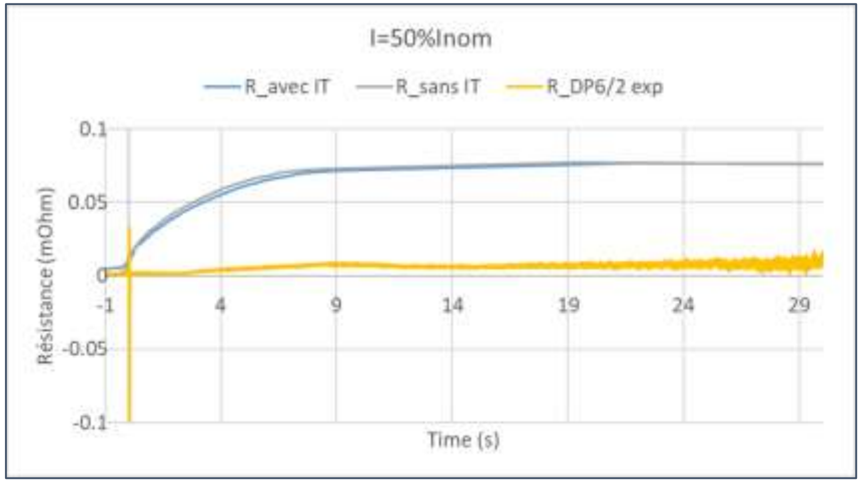
- Pressure? BC = infinite volume



- Copper characteristics?



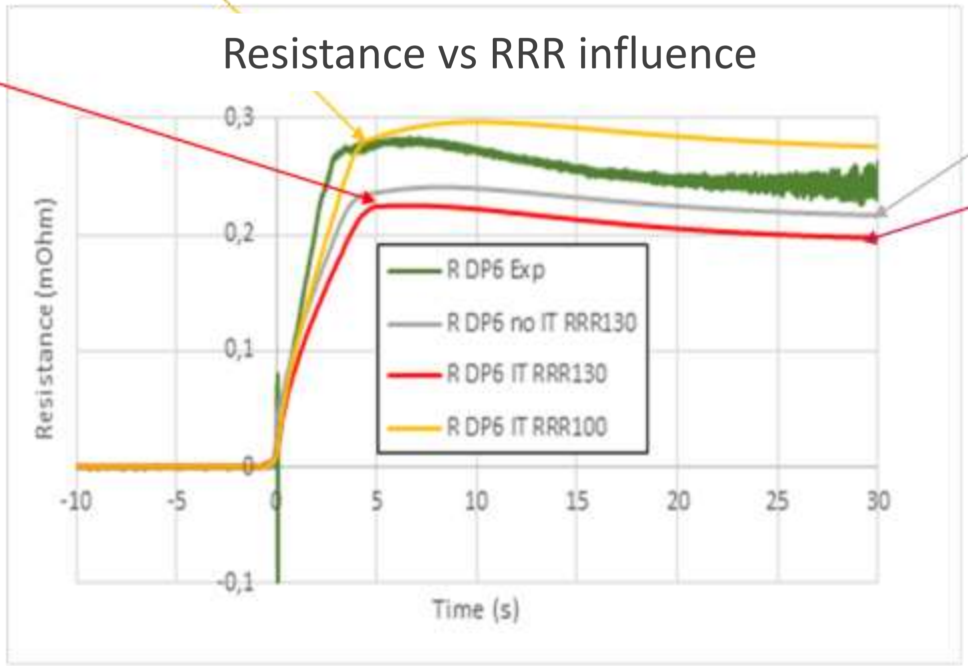
- Interpancake vs interturn influence?



Lower cooling massflow rate (1.5 g/s per conductor): interturn and RRR influence

Resistance vs RRR influence

The difference between RRR130 and RRR100 can be estimate to 32% at maximum point



Resistance vs Inter-turn influence

The influence of InterTurn can be estimate to -7% at maximum point

- An additional experimental activity was conducted in order to perform further measurements on the two TFC spares.
- A database of 6 quench tests measurements is available for developing numerical models for the CICC.
- Experimental analysis and modelling are conducted for 3 different quench scenarios:
  - $\tau = 500ms$ for quench detection (longer than the nominal $\tau = 100\ ms$)
  - Lower cooling massflow rate = 1.5 g/s instead of 2 g/s
  - Lower quench current (19.5 kA and 12.3 kA)

  THEA simplified 1D code accounting for transverse heat transfer, friction factor influence and deposited heat provides good accuracy in **steady** state case and in **slow** transient state.
- Interturn model appears occasionally less influential in case of lower quench current, whilst conductor's material properties seems more important in case of a less efficient cooling of WP.

- Questions?

MERCI POUR VOTRE ATTENTION

- [1] Y. Huang, « Study and modelling of the thermohydraulic phenomena taking place during the quench of a superconducting magnet cooled with supercritical helium. », Plasma Physics [physics.plasm-ph]. Université Paris-Saclay, Saclay, 2018.
- [2] Huang Y. et al, "Quench tests analysis of the first JT-60SA Toroidal Field coils", 2017 *Fusion Eng. Des.* 124 147-152
- [3] L. Bottura et al. , A numerical model for simulation of quench in the ITER magnets, Journal of Computational Physics 125, 26-41, N°0077
- [4] P. Decool, H. Cloez, G. Jiolat, M. Tena, L. Zani, C. Hoa, W. Abdel Maksoud, and M. Verrechia. "JT-60SA TF Coils: Experimental Check of Hydraulic Operating Conditions". IEEE Transactions on Applied Superconductivity 26, June. 2016. doi: {10.1109/TASC.2016.2520585} (see pp. 3, 16, 17, 32, 102)