DE LA RECHERCHE À L'INDUSTRIE

ITER SIDE CORRECTION COIL QUENCH MODEL AND ANALYSIS

Sylvie NICOLLET[1], Denis BESSETTE[2], Daniel CIAZYNSKI[1], Jean-Luc DUCHATEAU[1], Florent GAUTHIER[3], Benoit LACROIX[1]

[1]CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France

[2]ITER Organization, Route de Vinon sur Verdon, 13115 Saint Paul Lez Durance, France

[3]Soditech Ingenierie, 4 bis allée des Gabians, ZI La Frayère, 06150 Cannes, France

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ITER COILS

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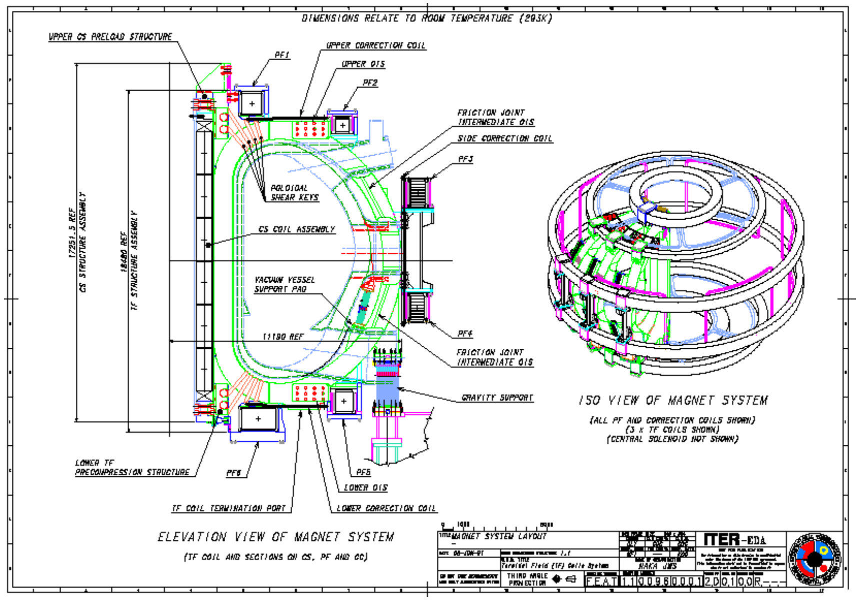
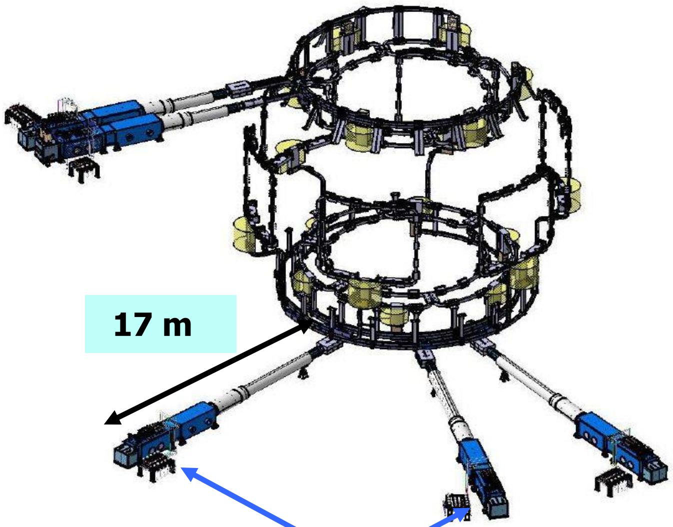
Propagation, development an behaviour during a quench.

The primary quench detection system is based on resistive voltage. In addition, a secondary quench detection is required & could rely on thermo-hydraulic nature signals.

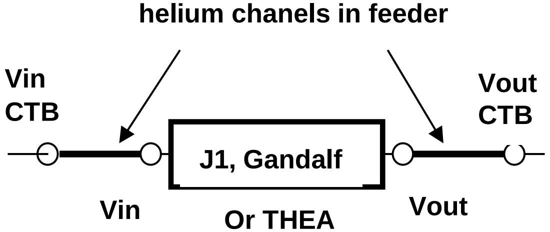
Objective : see the feasibility and necessity of secondary quench detection





CTB, Cold Termination Box, Location of sensors for secondary detection

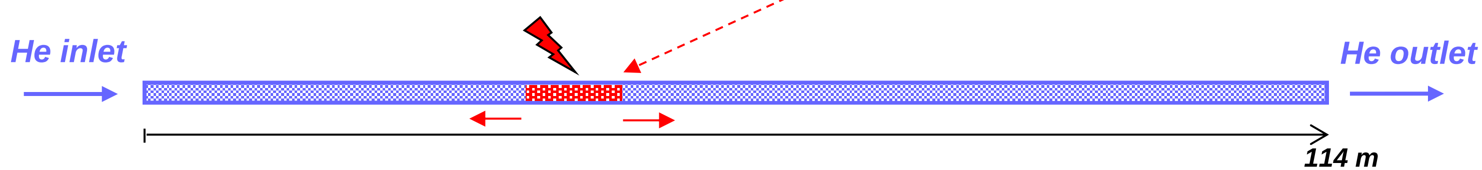
An important point : study of a secondary quench detection in case of undetected quench by primary (voltage) detection in the TF system



What is a quench ?

- Irreversible transition from superconducting state to normal resistive state
  - **Large energy dissipation** due to Joule heating
  - If not quickly detected, **possible permanent damage** of the magnet

Starting from a localized perturbation, the normal (quenched) zone propagates and generates a large resistive power

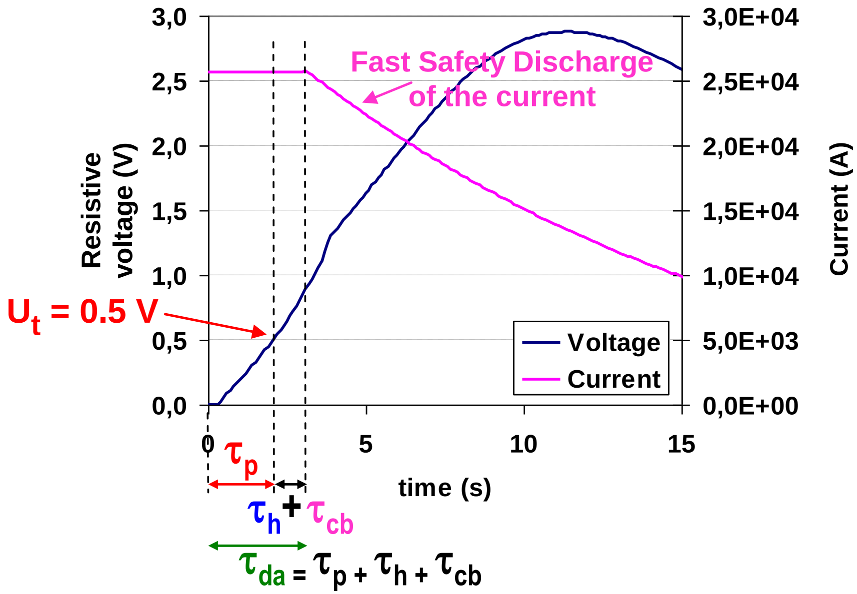


Courtesy of IRFU/SACM CEA Saclay

- **2 methods for quench detection:**
  - **Electrical signature (resistive voltage) → fastest method, so primary detection**
  - **Thermo-hydraulic signature (He mass flow, pressure) → secondary detection**
- **Voltage compensation (from coil to coil) to discriminate resistive voltage from magnetic disturbances**

Principle of primary quench detection

Features of primary detection



4 phases for a protection sequence:

1. **Propagation → τ_p (U_t)**
2. **Filtering phase → *holding time* τ_h**
3. **Current breakers opening → τ_{cb}**
4. **Fast Safety Discharge of the current (τ_{FSD})** for dumping magnetic energy (1.06 GJ for 18 TF coils) into an external resistor

Primary detection parameterization = setting the values (U_t, τ_h)

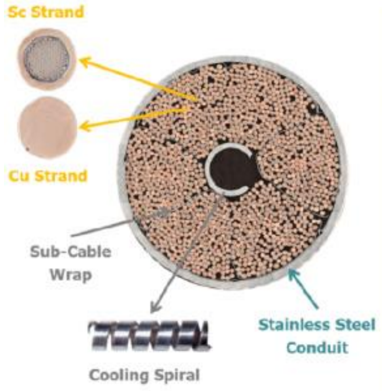
- ✓ **Hot spot criterion (maximal acceptable Tcond) → detection and action time τ_{da}**
- ✓ **Choice of the voltage threshold U_t → $\tau_p(U_t)$**
- ✓ **$\tau_h = \tau_{da} - \tau_p(U_t) - \tau_{cb}$**

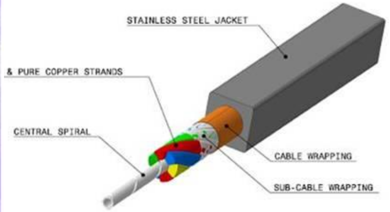
- **A high propagation velocity is favourable for quench detection**
- **$\tau_p(U_t)$ → requires a reliable simulation of quench propagation**

THERMOHYDRAULIC CALCULATION CODES : SUPERMAGNET : THEA & FLOWER

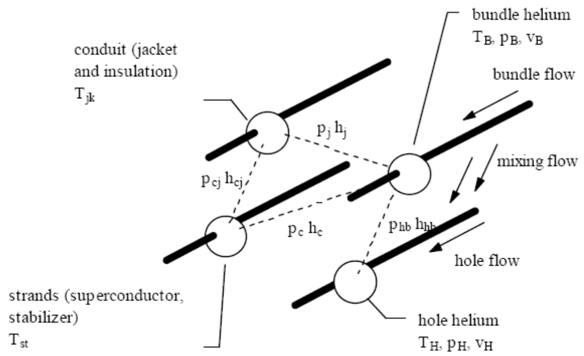
The CryoSoft suite SUPERMAGNET is the manager application that launches two or more of the codes, schedules communication & terminates execution as appropriate → analysis of specific issues in superconducting magnet systems.

THEA (Thermal, Hydraulic and Electric Analysis of Superconducting Cables) [1], FLOWER (Hydraulic Network Simulation) [2], POWER (Electric Network Simulation of Magnetic Systems) and HEATER





Gandalf & THEA Parameters



GANDALF or THEA Code [1] is the numerical implementation of a 1-D model for the thermohydraulic simulation of Cable In Conduit Conductor:

→ Model of 4 independent components: the strands, the conduit, the bundle helium and central helium.

→ I, B (x,t) → In the case of a quench, the Joule heat generation is computed consistently with the non-linear critical current density correlation.

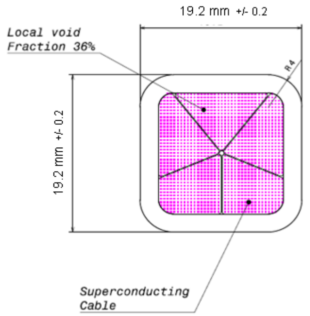
→ The solver decides quench or recovery has taken place.

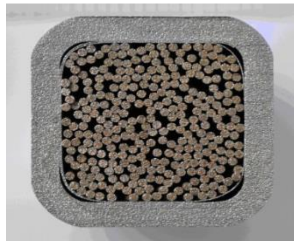
The codes communicate through a data exchange mechanism (described later) that achieves the desired physical coupling and makes it possible to describe a series of processes such as:

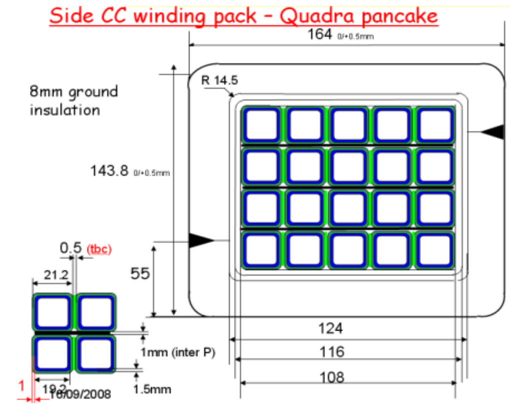
- effect of helium expulsion during thermal transients on the proximity cryogenics;
- evolution of the coil current during quench, including the effect of quench resistance;
- cooling of a coil with thermally coupled parallel channels;

[1] L. Bottura et al., A numerical model for the simulation of quench in the ITER magnets, Journal of Computational Physics 125, 26-41, Article N° 0077, 1996.
[2] L. Bottura, C. Rosso, Flower, a model for the Analysis of Hydraulic Networks and Processes, Workshop on Computation of Thermo-hydraulic Transients in Superconductors, Karlsruhe, 15-18 September, 2002.

ITER SCC COIL AND CONDUCTOR







CICC Characteristics	CC Conductor
Geometrical characteristics	
Jacket type/ outer dimensions (mm)	Square steel 316L 19.2 x 19.2
Cable type/ outer dimensions (mm)	14.8 x 14.8
Stainless Steel Jacket cross section (mm²)	138.5
Cable wrap	0.08 mm thick, 40% overlap
Electrical characteristics	
Total Insulation section (mm²)	Not modelled
Type of strand	NbTi
Nominal Peak Field (T) Maximum Operating Current (kA)	5 / 10
RRR / cos teta	100 / 0.97
Cabling pattern	3 x 4 x 5 x 5
Number of SC strands	300
SC Strands diameter (mm)	0.73
SC Strands Cu :non-Cu ratio	2.3
Non copper untwisted [twisted] section (mm²)	37.6 [38.8]
Total non copper area in strands (mm^2)	51.7
Extra Cu cross section (mm²)	34.9
Total copper untwisted [twisted] section (mm²)	86.6 [89.2]
Voltage threshold for discharge (V)	0.2
Detection and action time Tda (s)	1.5
Temperature margin at peak temperature (K)	1.5
Equivalent discharge time constant(s) hot spot	18*
Hydraulic characteristics	
Coolant Inlet temperature / maximum Operating Temperature (K)	4.5 / 5.4
Cooling channel length (m)	133.9 for Side CC
Total conductor wetted perimeter (twisted strands) (m)	754.82
Wetted perimeter Helium Jacket (mm)	58.4
Helium section in Bundle region (mm²)	76.67
Bundle region hydraulic diameter (mm)	0.4063
Void fraction (%)	35.4

(*) note the use of warm aluminum busbars as discharge resistors

$$\frac{\Delta P}{L} = f_{EU} \cdot \frac{P_w . \dot{m}^2}{8.\rho_{He} A_{He}^3}$$

$$f_b = \frac{1}{V_f^{0.742}} \left(0.0231 + \frac{19.5}{\mathrm{Re}^{0.7953}}\right)$$

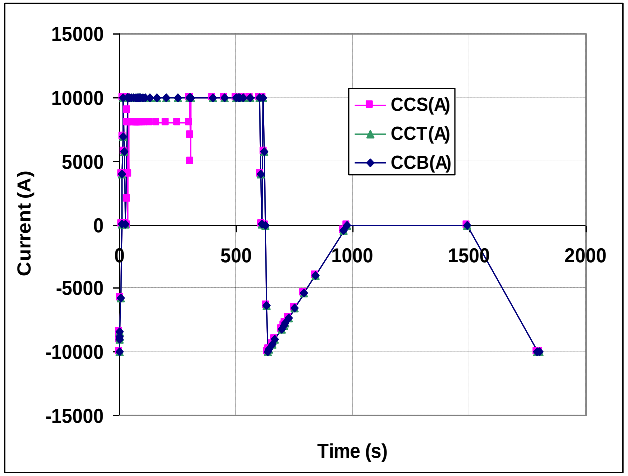
Convective heat exchange coefficient is equal to Colburn , with the following formula and without any limitation at zero mass flow rate:

$$h_{conv,b} = \lambda_{He} (0.023 * \mathrm{Re}^{0.8}) * \mathrm{Pr}^{1/3} / Dh$$

ITER SCC CONDUCTOR : FIELD, CURRENT & QUENCH DETECTION

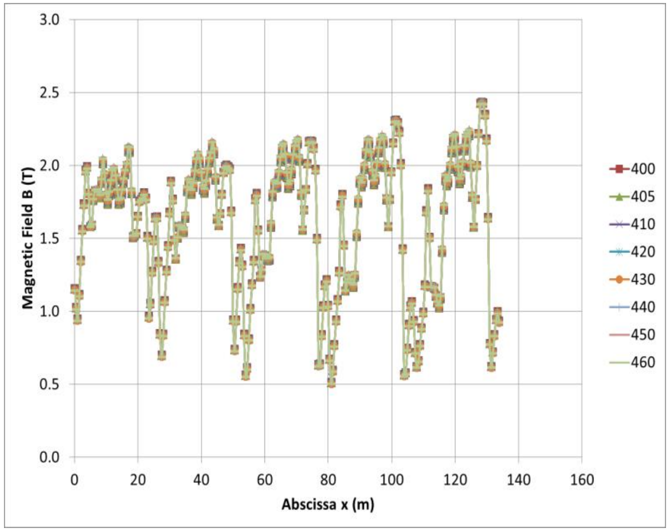
Jc parameterization has been established from NbTi strand Ic experimental data, following the method recommended at the SWG meeting. PF and CC conductors, Jc law Fitting Formula by L. Bottura :

$$Jc = \frac{C_0}{B}.(1-t^n)^{\gamma}.b^{\alpha}.(1-b)^{\beta} \qquad t = \frac{T}{T_{c0}} \qquad b = \frac{B}{B_{c2}} \qquad B_{C2}(T) = B_{C20}(1-t^n)$$



The electrical field E(I,B,T) is computed locally from the power law considering the peak value of magnetic field.

PF2-5 and CC conductors cabled from CN NbTi strand cu:noncu ratio 2.3: B_{c20} = 13.72 T, T_{c0} = 8.79 K, C_0 = 113200 10^6 AT/m², α = 1.00, β = 0.98, γ = 1.96, n = 1.70

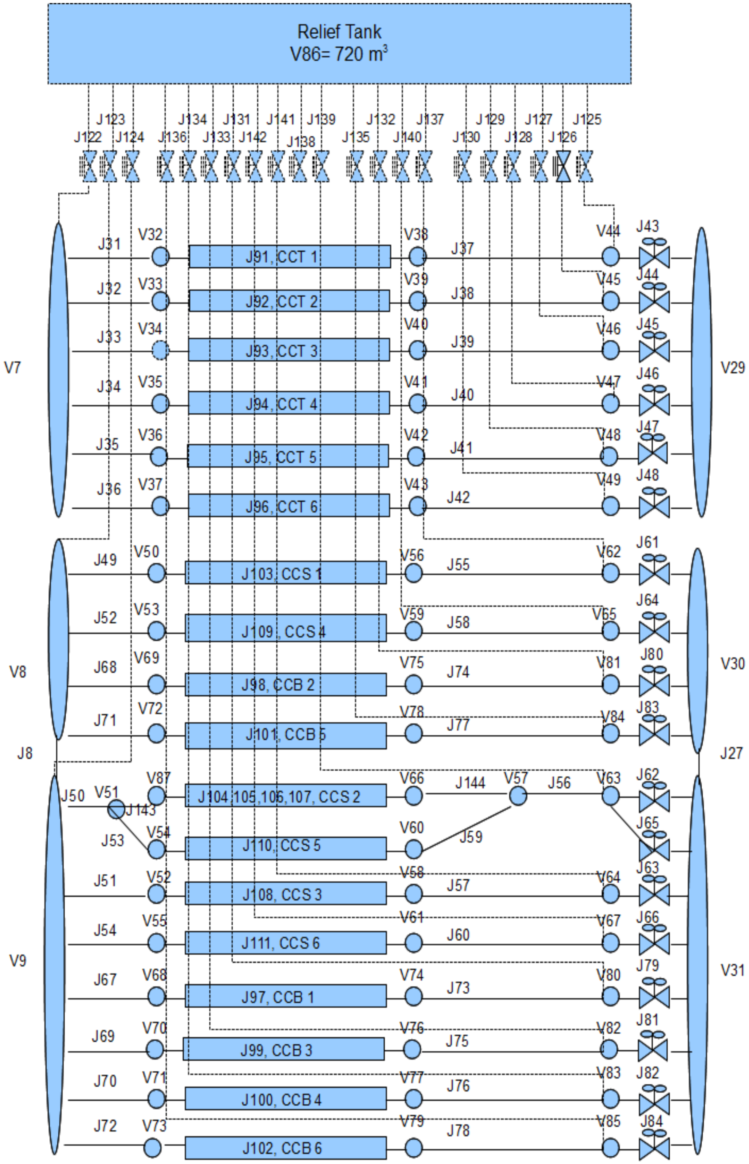


Bav data along the SCC conductors are provided; in SCC pancake #1 is the closest to the plasma. The pancake showing the highest field values should be retained, i.e. pancake #1 in SCC with the minimum temperature margin.

The quench is initialized from 400.5 s to 401.5 s with a MQE = 89 W/m on Pancakes 1, 2 and 4 and MQE = 95 W/m on Pancake 3

- → **Range of resistive voltage threshold Vr = 0.2 V**
- → **Current decay will be initiated only after an action time Ta = Th + Tk + Tcb= 1.5 s**
- → Th = 0.5 s holding time (confirmation of quench detection)
- → Tk = 0.5 s "killing time" of plasma
- → Tcb= 0.5 s maximum current breaker opening time

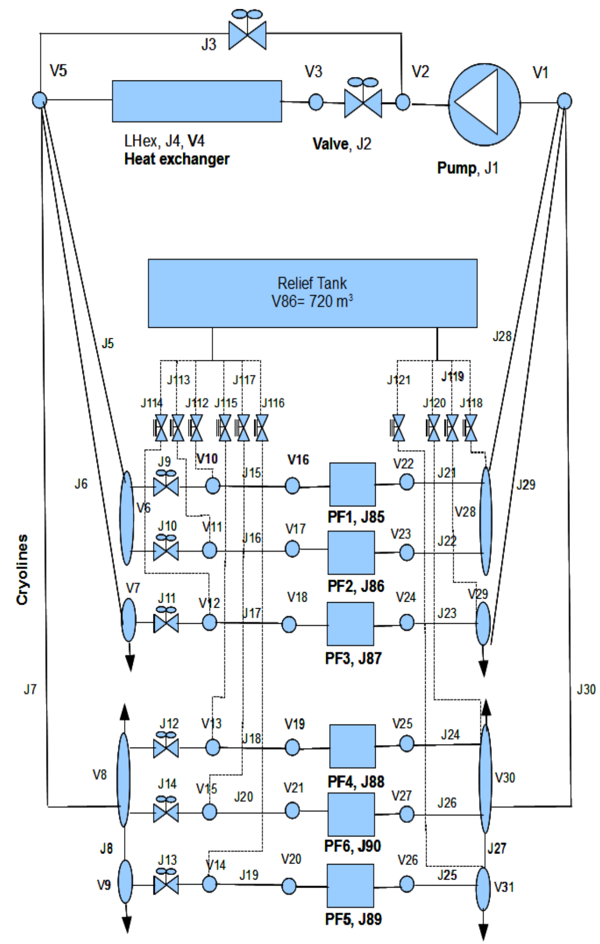
ITER SCC QUENCH: FLOWER MODEL



FLOWER Model **initial conditions** :

T=5 K, P=0.55 MPa, m_{pump}=1.8kg/s,

m_{SCC2} = 1.4g/s per pancakes, DP $_{reflief\text{-}valves}$ = 2.0 MPa



ITER SCC2 QUENCH FLOWER MODEL

CC CICC: nominal mass flow rate = 1.4 g/s at T = 4.4 K and Pin= 0.46 MPa for each pancake.

SCC2 Coil Quench in Flower scheme:

→ **4 Pancakes modelized by THEA**

→ **All the other coils (CC and PF)** modelized by Flower Junctions, in parallel with equivalent friction factor ft (to conserve DP) & Additional tubes shortest CICC, same DP

→ Relief valves extremities (2.0 MPa).

$$\Delta P = f_t . \frac{\rho . v_t^2}{2} . \frac{L}{Dh_t} = f_t . \frac{m_t^2}{2.\rho . S_t^2} . \frac{L}{Dh_t}$$

$$\Delta P = (\Delta P_b + \Delta P_h)/2 = \frac{1}{2} . \left(f_b . \frac{m_b^2}{2.\rho . S_b^2} . \frac{L}{Dh_b} + f_h . \frac{m_h^2}{2.\rho . S_h^2} . \frac{L}{Dh_h} \right)$$

$$f_t = \frac{1}{2} . \left(f_b . \frac{m_b^2}{2.\rho . S_b^2} . \frac{L}{Dh_b} + f_h . \frac{m_h^2}{2.\rho . S_h^2} . \frac{L}{Dh_h} \right) . \frac{2.\rho . S_t^2}{m_t^2} . \frac{Dh_t}{L}$$

	PF1 & 6	PF5	PF2,3&4	PF3	PF2	PF1	PF4	PF6	PF5
Number of Pancakes Nz				16	12	16	16	18	16
Number of turn Nr				12	10	16	11	26	14
Hydraulic length (m)				**447.0**	**258.5**	**200.0**	**408.5**	**359.0**	**368.5**
Helium section in bundle region AHEB (mm²)	347.2	297.2	297.4	9515.7	7136.8	8332.3	9515.7	12498.4	9511.4
Bundle void fraction	34.61	34.34	34.35						
Hydraulic diameter of bundle region DHB (mm)	0.3787	0.3930	0.4008						
PHTC (mm)	3667.0	3025.0	2967.9	94971.2	71228.4	88008.7	94971.2	132013.1	96798.4
PHTJ= PHTCJ (mm)	59.2	55.4	55.4	1774.4	1330.8	1421.3	1774.4	2131.9	1774.4
PHTHB (mm) wetted perimeter between h/b	37.7	37.7	37.7	1206.4	904.8	904.8	1206.4	1357.2	1206.4
Central hole section AHEH (mm²)	113.1	113.1	113.1	3619.1	2714.3	2714.3	3619.1	4071.5	3619.1
alpha = mb / (mb + mh)	**0.261**	**0.241**	**0.245**						
Total helium Area AHE (mm²)	**460.3**	**410.3**	**410.5**	**13135**	**9851**	**11047**	**13135**	**16570**	**13131**
Total wetted perimeter (mm)	3764	3118	3061	97952.0	73464.0	90336.0	97952.0	135504.0	99776.0
Global Hydraulic diameter Dht (mm)	**0.4891**	**0.5264**	**0.5364**	**0.5364**	**0.5364**	**0.4891**	**0.5364**	**0.4891**	**0.5264**
Linear pressure drop (Pa/m)	**133**	**140**	**138**						
Pressure drop along the pancake (MPa)				**0.06169**	**0.03567**	**0.0266**	**0.05637**	**0.04775**	**0.05159**
Total length considered (m)				450	450	450	450	450	450
ST additional length (m)				3.0	191.5	250.0	41.5	91.0	81.50
ST cross section A (m²)				4.96E-04	5.80E-04	7.13E-04	7.21E-04	7.45E-04	7.35E-04
ST Hydraulic diameter DhST (m)				0.02513	0.02717	0.03012	0.03029	0.03079	0.03059
DP ST (MPa)				0.001027	0.027300	0.036149	0.005843	0.014568	0.010954
DP total (MPa)				**0.062713**	**0.062973**	**0.062749**	**0.062216**	**0.062315**	**0.062544**

	CC Side	CC Top/Bottom	ex:	CCT1-CCB6	SCC1-6 or SCC2
Number of Pancakes	4	8		8.00	4
Hydraulic length (m)	**140**	**65**		65.40	140
Helium section in bundle region AHEB (mm²)	76.67	76.67		613.36	306.68
Wetted perimeter U = PHTC (mm)	754.82	754.82		6038.56	3019
Hydraulic diameter DH (mm)	0.4063	0.4063		**0.4063**	**0.4063**
Bundle void fraction	0.3500	0.3500			
Linear pressure drop (Pa/m)	**420**	**420**		420.00	420.0
Pressure drop along the pancake (MPa)	**0.05880**	**0.02747**		0.02747	0.05880
Total length considered (m)	450	450		450.00	450.0
Additional length (m)	310	385		**384.60**	**310**
Hydraulic diameter for additional length DhST (m)	0.01200	0.01014		0.01014	0.01200
DP ST (MPa)	0.00381	0.03542		0.03542	0.00381
DP total (MPa)	**0.06261**	**0.06288**		0.06288	0.062613

ITER SCC2 QUENCH : 5 CASES STUDIED

Quench behavior of the SCC2 is quite similar compared to CS Pancake one [3], TF Pancake one [4] and [5], PF Pancake one [6] or BCC Pancake one [7].

The quench is initialized from 400.5 s to 401.5 s with a MQE = 89 W/m on Pancakes 1, 2 and 4 and MQE = 95 W/m on Pancake 3.

5 cases have been studied:

→ ***Case 1: Quench on the first turn of Pancake # 1, without Fast Discharge (FD)***

→ ***Case 2: Quench on the first turn of Pancake # 1, with Fast Discharge (FD)***

→ ***Case 3: Quench on the first turn of all Pancakes, without Fast Discharge (FD)***

→ ***Case 4: Quench on the first turn of all Pancakes, with Fast Discharge (FD)***

→ ***Case 5: Quench on the middle turn of Pancake # 1, without Fast Discharge (FD)***

→ **Range of resistive voltage threshold Vr = 0.2 V**

→ **Current decay will be initiated only after an action time Ta = Th + Tk + Tcb= 1.5 s**

[3] S. Nicollet et al., Quench of Central Solenoid: Thermo-Hydraulic detection and main impact on cryogenic system, ICEC 23rd, July 2010.

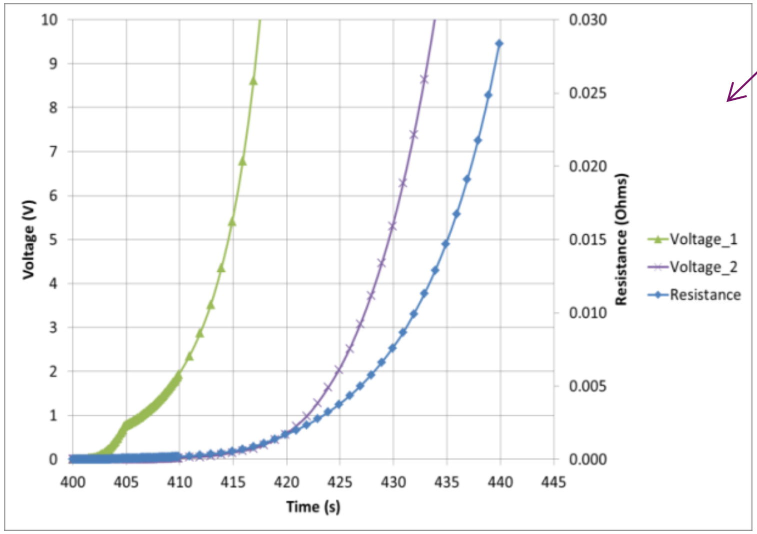
[4] S. Nicollet et al., Thermal-Hydraulic Behaviour of the ITER TF System during a Quench Development, SOFT, Porto, 2010.

[5] S. Nicollet et al., Thermal Behaviour and Quench of the ITER TF System during a Fast Discharge and Possibility of a Secondary Quench Detection, MT22, 2011.

[6] S. Nicollet et al. Quench of ITER Poloidal Field Coils: Influence of some initiation parameters on thermo-hydraulic detection signals and main impact on cryogenic system, CHATS 2011.

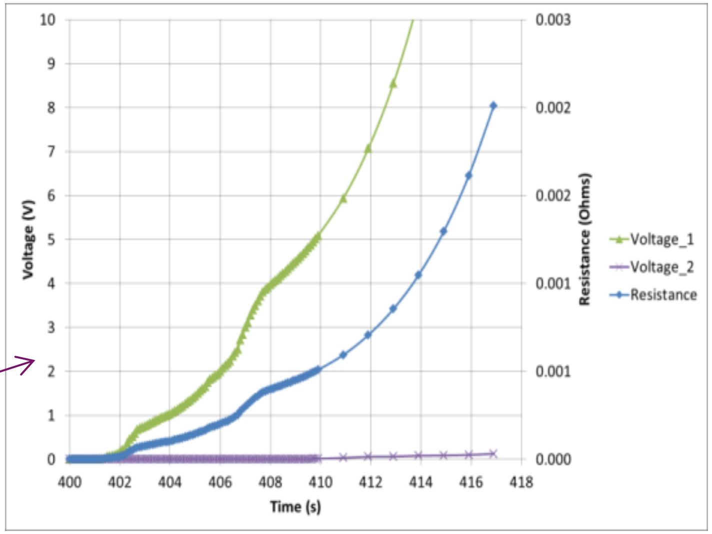
[7] S. Nicollet et al., Secondary Thermohydraulic Quench Detection for the ITER Correction Coils, ASC 2012.

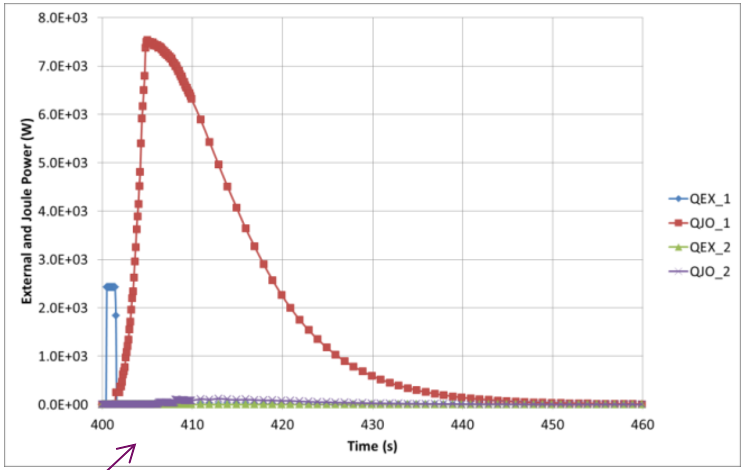
ITER SCC2 QUENCH : VOLTAGE AND JOULE ENERGY



Case 1: Evolution in time of Voltage and Resistance, quench first turn Pancake 1 without FD

Case 5: Evolution in time of Voltage and Resistance, quench middle turn Pancake 1, without FD





Case 2: Evolution in time of External and Joule heating in W, quench first turn Pancake 1, With FD

Case 1 or 3: quench on first turn

→Voltage reaches 0.2 V at time 403.3 s.

Case 5: quench at middle turn pancake #1

→ voltage reaches 0.2 V at time 402.1 s

Case 1 or 3: quench without FD

→Joule energy reaches 2.5 MJ (t=440 s one pancake) and 1.4 MJ for each pancake (t=435 s 4 Pancakes).

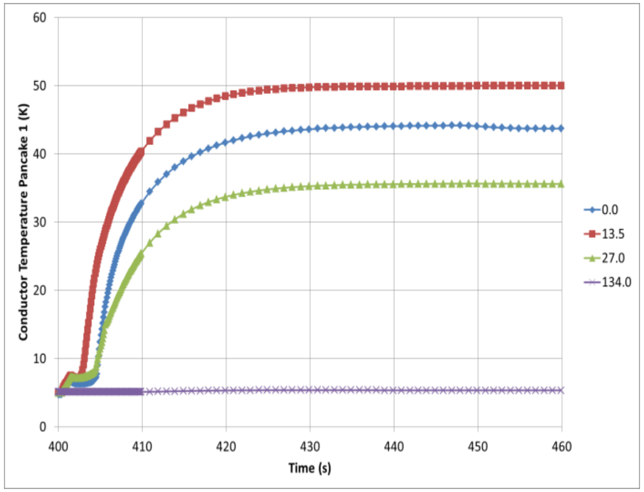
Case 2 or 4: With FD

→ maximum value =7.5 kJ (t=405 s for both cases)

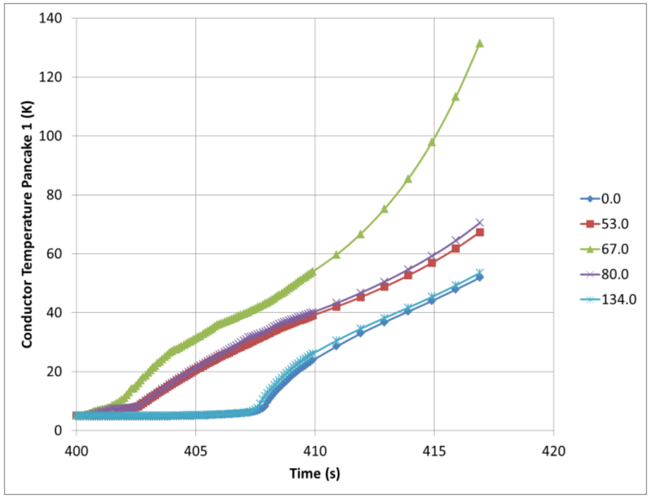
SCC2 QUENCH : CONDUCTOR TEMPERATURE (TCO) & NORMAL LENGTH (NL)

→ With FD, **TCO** at middle of heated zone **reaches a plateau = 50 K**
→ compared with **the hot spot criteria of 150 K (with helium and Jacket).**
→ Without FD, maximal TCO= 750 K (t=440 s and near 450 K at time 435 s, 1 CICC or 4 CICC quenched).
→ Without FD, Quench initialized at the **middle** TCO max=130 K at time 417 s.

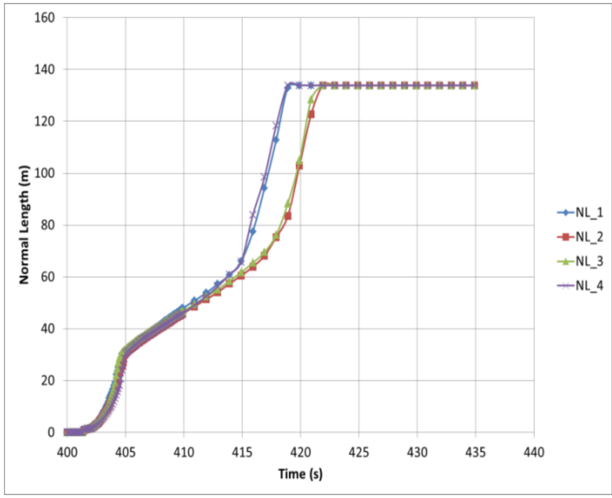
→ Without FD quench one pancake (all pancakes, first turn), **NL** reaches whole CICC (140 m), at t=420 s: **velocity =7 m/s one front.**
→ With FD, NL obtained at t=460 s is only 60 m. this is the case also for the 4 quenched Pancakes.
→ Without FD, quench middle of CICC → propagation velocity higher →whole length quenched at time 408 s: **velocity =9 m/s over each of the two front.**



Case 4: TCO, Pancake 1, quench on the inner turn of all Pancakes, with FD

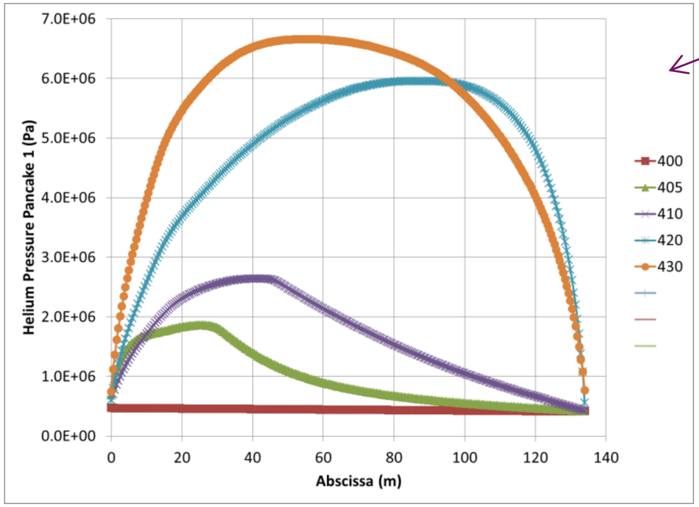


Case 5: TCO Pancake 1, quench on the middle turn of Pancake 1, without FD



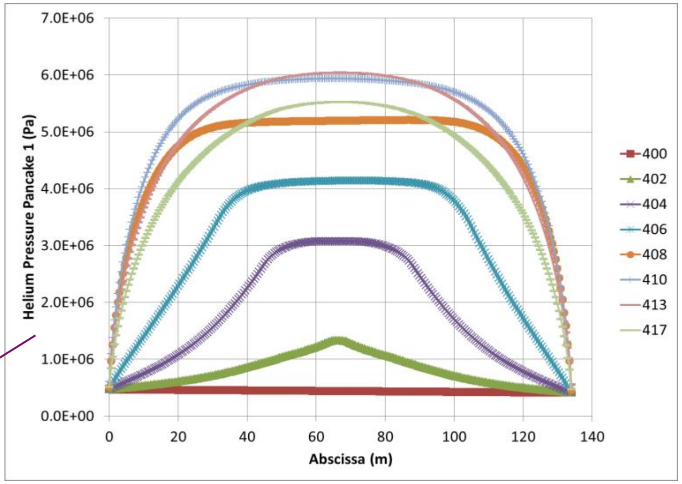
Case 3: NL, quench of inner turn of all Pancake, without FD

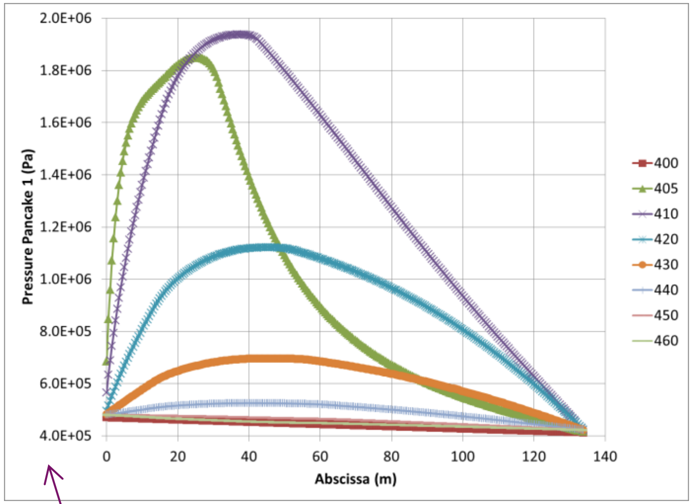
ITER SCC2 QUENCH: MAXIMAL PRESSURE (PMAX)



Case 3: Pressure, Pancake 1, quench on the inner turn of all Pancakes, without FD

Case 5: Pressure, Pancake 1, quench on the middle turn of Pancake 1, without FD





Case 4: Pressure, Pancake 1, quench on the inner turn of all Pancakes, with FD

Joule heat input during quench important

→ pressure increases significantly:

→ Case 1 or 3: first turn & Without FD, pressure reaches maximum near middle of CICC: 6.0 MPa (t=440 s, 1 pancake) & 6.5 MPa (t=435 s, 4 pancakes).

→ Case 5: Without FD, Quench at CICC middle, Pmax= 6.0 MPa but reached earlier (t=417 s for one quenched conductor → **two times faster than previously due to propagation on two front**).

→ Case 2 or 4: With FD →Pmax localized nearest from the conductor inlet and reaches 1.9 MPa (t=460 s: for both, one or 4 pancakes quenched).

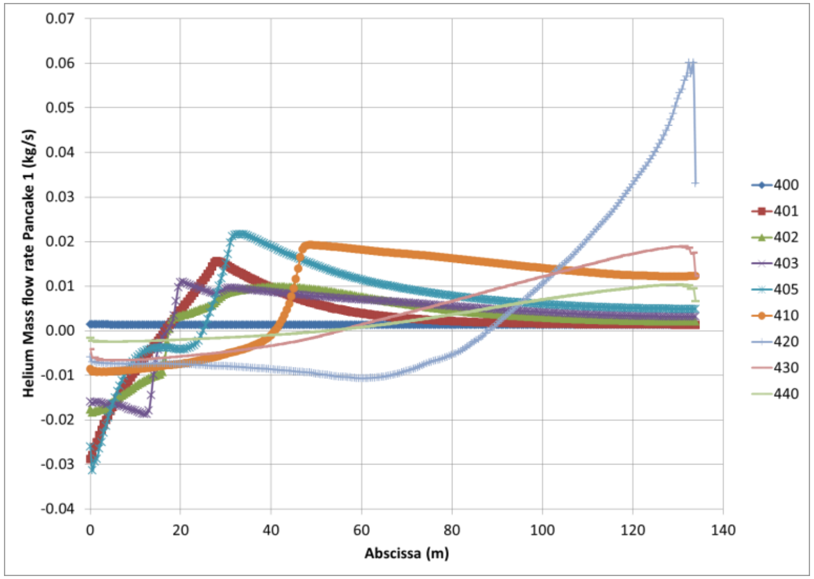
ITER SCC2 QUENCH : HELIUM MASS FLOW

Mass flow rate presents a reverse flow at the CICC inlet & an acceleration at CICC outlet:

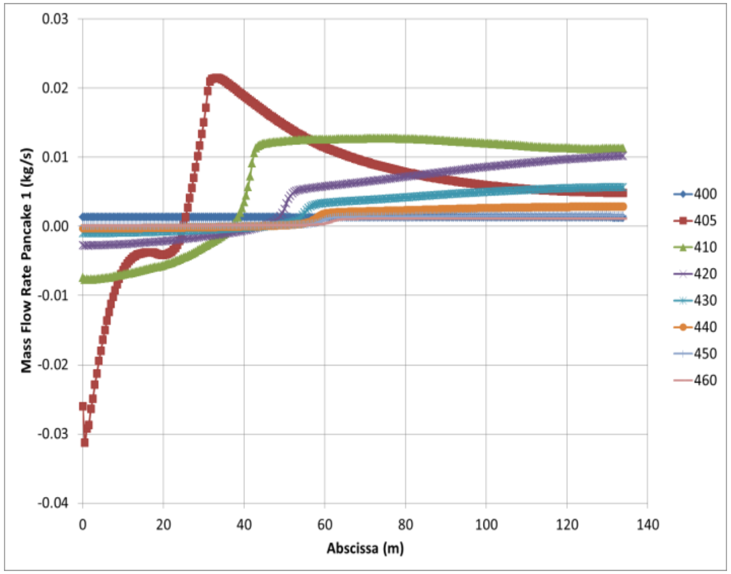
→Case 1 or 3: Without FD, quench at CICC inlet →maximal reverse flow reaches -0.03 kg/s & acceleration +0.06 kg/s. Each quenched pancake has the same behavior concerning mass flow rate.

→Case 5: Without FD, quench at CICC middle→ mass flow rate evolution symmetrical along abscissa : reverse mass flow of -0.06 kg/s & an acceleration of +0.06 kg/s.

→Case 2 or 4: With FD helium mass expulsion is less important and **happens with slowly manner :**reverse mass flow -0.03 kg/s at t=405 s and acceleration of +0.01 kg/s at t=410 s.

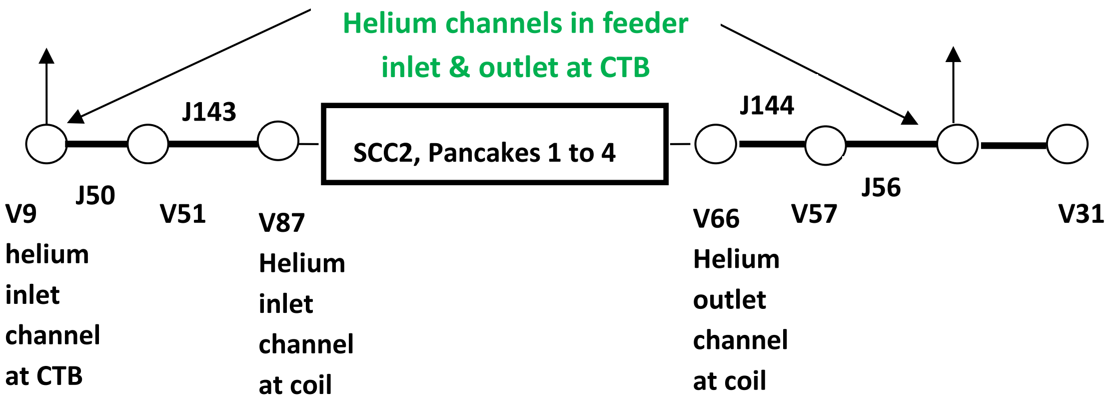


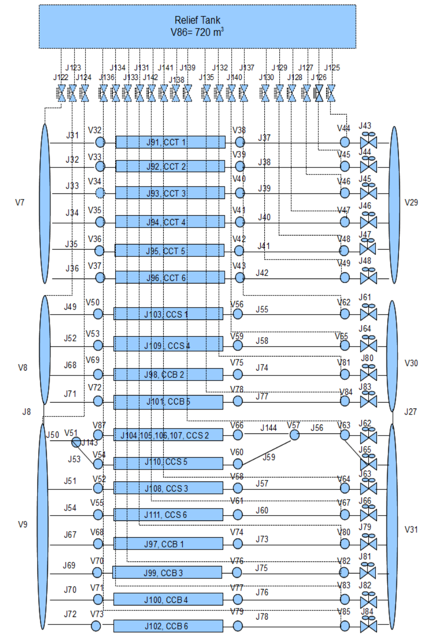
Case 1: Distribution of mass flow rate, Pancake 1, quench on the inner turn of Pancake 1 without FD



Case 2: Distribution of mass flow rate, Pancake 1, quench on the inner turn of Pancake 1 with FD

ITER SCC2 QUENCH: PROPAGATION AT THE FEEDERS





Sensors location for the secondary detection is V9 & V63

V9= inlet helium channel in feeder, in CTB or Inlet of Junction 50 at x=0

V63 =outlet helium channel in feeder at CTB or outlet of the Junction 56 at x=24 m

Relief valves connected to the extremities of the feeders

→ With our simplified model, In any case of the SCC2 Quench, there is NO opening of the Quench relief Valves, Pmax < 2.0 Mpa but an in-depth model is required to conclude

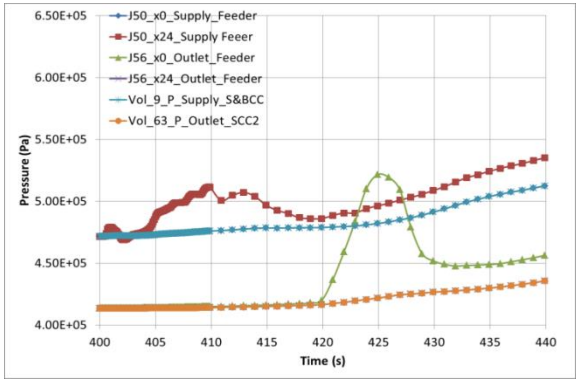
→ good agreement with studies performed on BCC, 2011 [9]

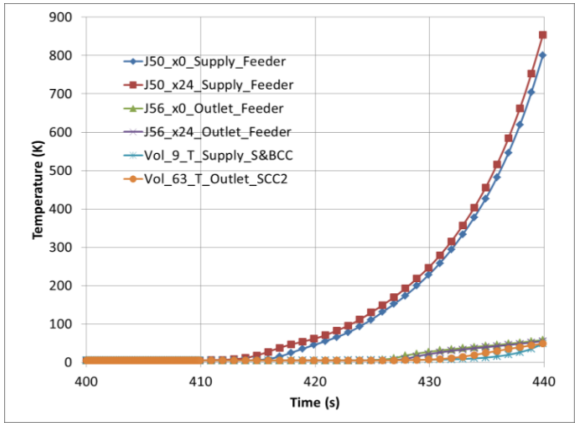
Opening of relief valves observed only in case of the quench of the eight Pancakes.

In case of a quench of only one pancake of BCC, the pressure increase remains under 2.0 MPa.

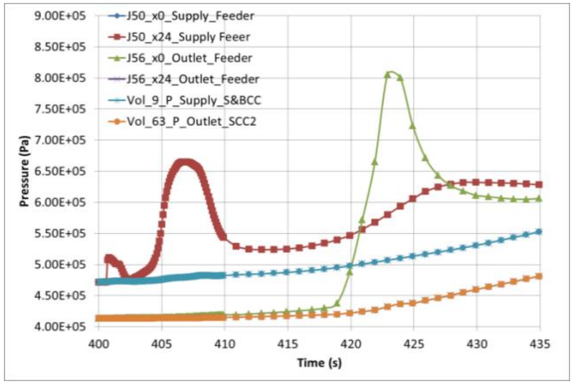
ITER SCC2 QUENCH: PRESSURE & TEMPERATURE AT FEEDERS

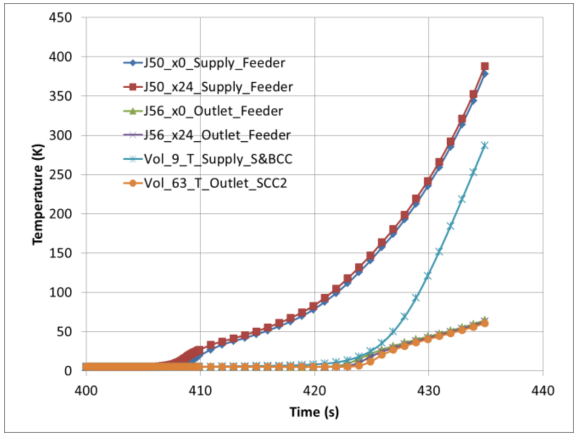
A secondary quench detection seems possible: for all quenched cases studied without fast discharge the most sensitive signals is the mass flow rate at the feeders followed by the pressure signals and then the temperature (volume 9 and 63):



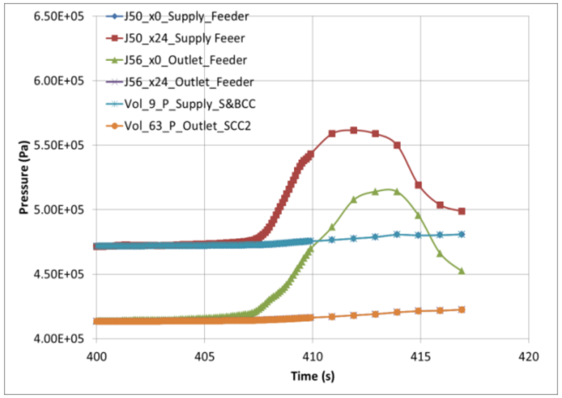


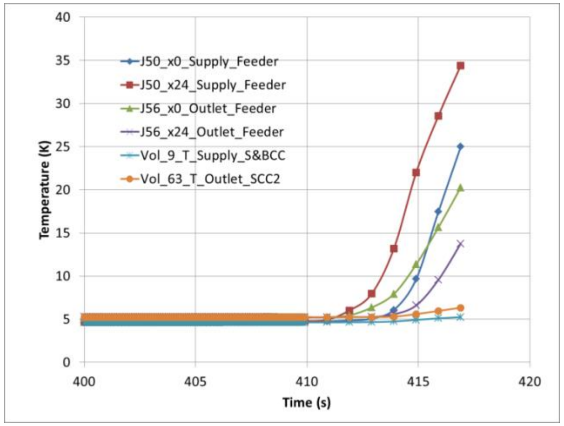
Case 1: Evolution in time of the Pressure & Temperature at feeders of SCC2





Case 3: Evolution in time of the Pressure & Temperature at feeders of SCC2





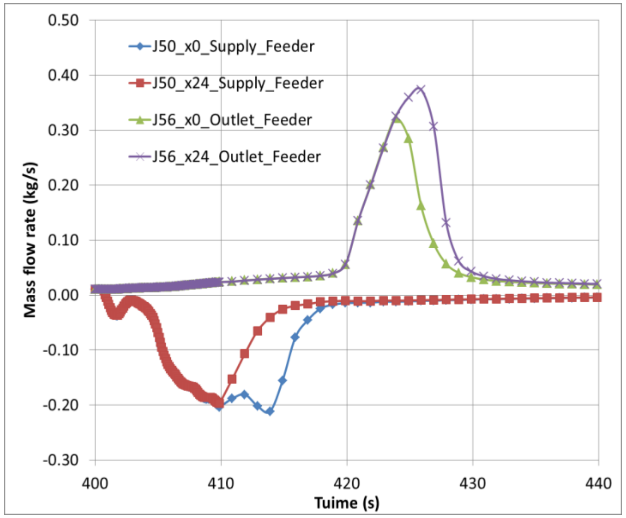
Case 5: Evolution in time of the Pressure & Temperature at feeders of SCC2,

ITER SCC2 QUENCH: HELIUM MASS FLOW AT FEEDERS

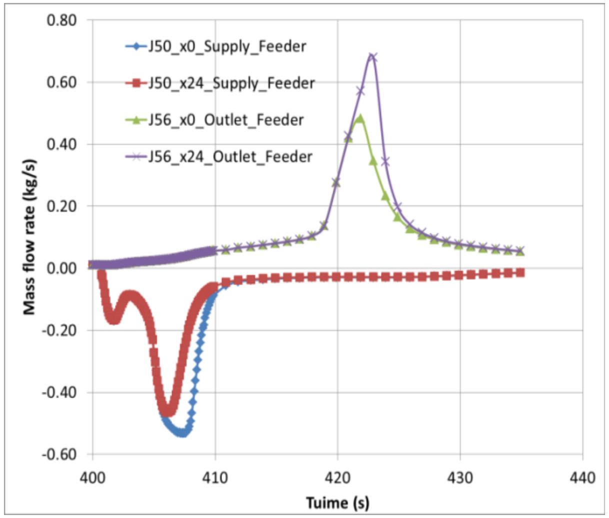
Case 1: Pressure increase is 0.05 MPa (from 4.7 to 5.2 MPa), the temperature increase is 50 K at t=440 s **reverse mass flow is obtained at 410 s with a value of -0.2 kg/s.**

Case 3: Pressure increase is higher (4 Pancakes quenched) and equal to 0.8 MPa (from 4.7 to 5.5 MPa) temperature increase is still 50 K (at time 435 s); the reverse mass flow can be easily observed and detected (-0.018 kg/s at time 402 s and -0.5 kg/s at time 407 s).

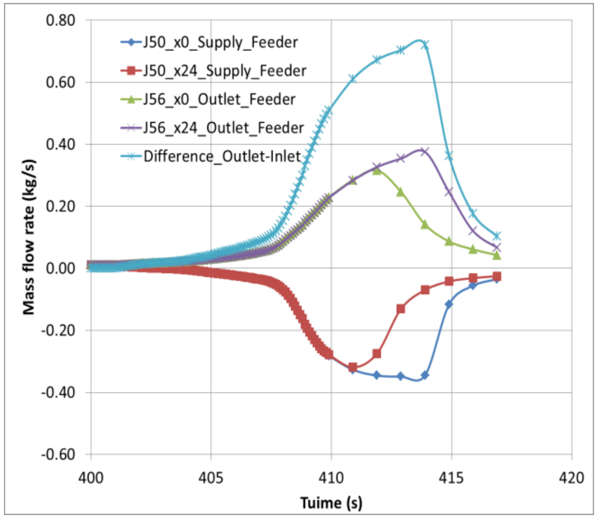
Case 5: Pressure & temperature increases are negligible; **the difference outlet – inlet mass flow rate reaches + 0.10 kg/s at t=407 s (a secondary quench detection 6 s after quench is then possible).**



Case 1: Evolution in time of the Mass flow rate at feeders of SCC2, quench of inner turn of Pancake 1, without FD



Case 3: Evolution in time of the Mass flow rate at feeders of SCC2, quench of inner turn of all pancakes, without FD



Case 5: Evolution in time of the Mass flow rate at feeders of SCC2, quench on the middle turn of Pancake 1, without FD

ITER SCC2 QUENCH: SUMMARY OF THE RESULTS

Case	1	2	3	4	5
Quench Initiation	One pancake (P1)	One pancake (P1)	All 4 pancakes	All 4 Pancakes	One Pancake (P1)
Quench Initiation	first turn	first turn	first turn	first turn	middle turn
Fast Discharge	without	with	without	with	without
External heating MQE (W/m) over 27 m and 1s	89 (P1)	89 (P1)	89 (P1,2,4) 95 (P3)	89 (P1,2,4) 95 (P3)	89 (P1)
Beginning of quench initiation (s)	400.5	400.5	400.5	400.5	400.5
Time to reach 0.2 V (s)	2.8	2.8	2.7	2.7	1.6
T delay (s)	1.5	1.5	1.5	1.5	1.5
Maximal Joule heating (W) at time (s)	2.5 MW (40s)	7.5 kW (5s)	1.35 MWx4 (35s)	7.5 kWx4 (5)s	0.2 MW (17s)
Integrated Joule heating (MJ) until time (s)	17.8 MJ (40s)	0.106 MJ (60s)	9.06x4 MJ (35s)	0.106x4 MJ (60s)	0.842 MJ (17s)
Maximal Conductor Temperature (K) at time (s)	300 (30s) 700 (40s)	50 (30s)	300 (30s)	50 (30s)	140 (17s)
Maximal Pressure (MPa) at specified time (s)	6.5 (30s)	1.9 (10s)	6.5 (30s)	1.9 (10s)	6.0 (10s)
Mass flow rate at inlet and outlet (kg/s)	-0.03 (1s) +0.06 (20s)	-0.03 (5s) +0.01 (10s)	-0.03 (1s) +0.05 (20s)	-0.03 (5s) +0.01 (10s)	-0.065 (8s) +0.055 (8s)
Maximal Normal Length (m) reached at specified time (s)	NL1 134m (20s) NL2,3,4 24m (40s)	NL1 58 m (60s) NL2,3,4 8m (60s)	NL1,2,3,4 134 m (20s)	NL1,2,3,4 58 m (60s)	NL1 134 m (8s) NL2,3,4 4.2m (17s)
Propagation Velocity (m/s)	V1 6.87 m/s V2,3,4 0.6 m/s	V1 1 m/s V2,3,4 0.13 m/s	V1,2,3,4 6.87 m/s	V1,2,3,4 1 m/s	V1 8.9 m/s / front V2,3,4 0.25 m/s
Opening of check Valves	No	No	No	No	No
Secondary detection : maximal pressure (MPa) at inlet/outlet CTB	0.512 (40s)/ 0.436 (40s)	Not used	0.55 (35s)/ 0.435 (35s)	Not used	0.48 (17s)/ 0.423 (17s)
Secondary detection: Maximal temperature (K) At inlet/outlet CTB	10 (34s)/ 10 (32s)	Not used	10 (22s)/ 10 (22s)	Not used	5 (17s)/ 6.3 (17s)
Secondary detection : Maximal mass flow (kg/s) At inlet/outlet CTB	-0.2 (10s)/ 0.017 (10s) 0.374 (26s)	Not used	-0.454 (6s)/ 0.047 (10s) 0.426 (22s)	Not used	-0.346 (14s)/ +0.2 (8s) +0.375 (14s)

CONCLUSION

- → A SuperMagnet model has been used for quench study, associated with the hypotheses concerning the conductor and 4 pancakes (THEA), and the thermal hydraulics (Flower).
- → Concerning the Side Correction Coils (SCCs) quench study, the priority has been set on the model of the SCC2.
- → 5 cases of studies have been presented: one quenched conductor on the first turn (without and with fast discharge), the all 4 pancakes conductor quenches (on the first turn, without and with fast discharge), and a last case of one conductor quenched on the middle turn of SCC2 (without fast discharge).
- → In case of fast discharge the hot spot criteria is respected (Tcond < 150 K with helium and Jacket).
- → The feasibility of a secondary thermal-hydraulic quench detection, in case of a failure of primary ΔV detection, has been explored with some signal criteria. Even in the most critical case (case 5) with a quench initialized on the middle turn of pancake 1, a secondary detection by the difference of mass flow rate (outlet – inlet) is possible near 8 s after quench initialization.
- → With our simplified Model, in any of the quench studied for the SCC, the quench relief valves do not open but an in-depth analysis is required to conclude. This is in good agreement with previous calculation performed on BCC: relief valves do open only if the 8 pancakes quench at the same time, for only one pancake of BCC quenched, the relief valve do not open neither.

Thank you
for your attention

Commissariat à l'énergie atomique et aux énergies alternatives
Centre de Cadarache | 13108 Saint Paul Lez Durance Cedex
T. +33 (0)4 42 25 62 25 | F. +33 (0)4 42 25 26 61

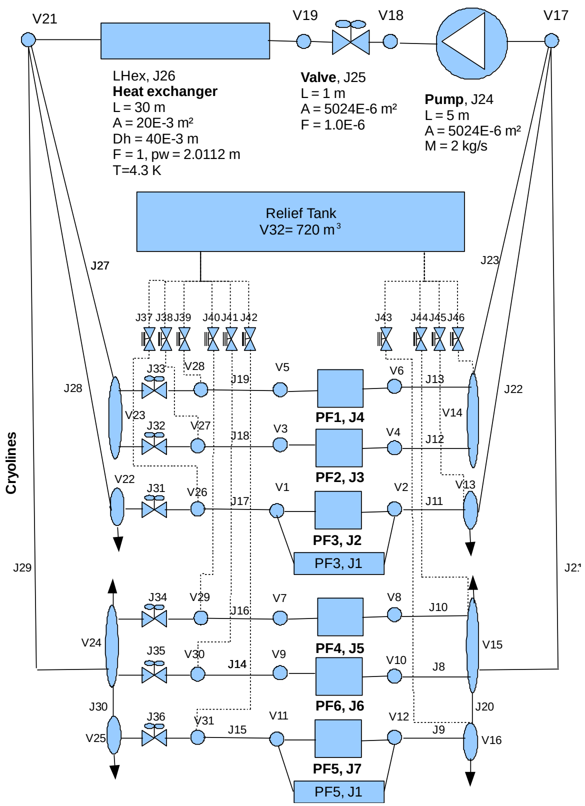
DSM
IRFM
STEP

ITER COILS QUENCH

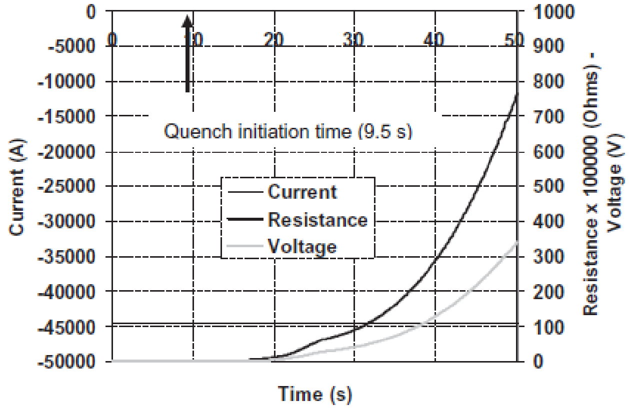
	Str	TF	CS	PF	CC	Plasma
Disruption						x
Slow Discharge			x	x	x	
Fast Energy Discharge		x	x	x	x	
Quench		x	x	x	x	
Helium Discharge	x	x		x?	x?	

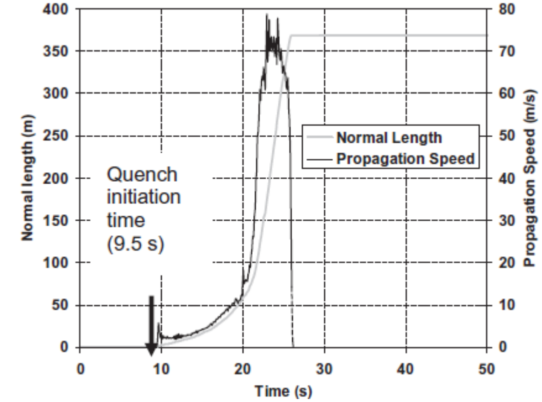
A Quench of CC will require a fast discharge of the CC system only
A Quench of PF coil will require a fast discharge of the CS and PF&CC system
A Quench of CS coil will require a fast discharge of the CS and PF&CC system
A Quench or a fast discharge of the TF system will require a fast discharge of all coils (TF, CS, PF&CC) and an He discharge of the both Structures and TF coils
It is a design requirement that the coils do not quench or undergo fast discharge after a plasma disruption (Plasma soft stop using the Fusion Power Shutdown System)

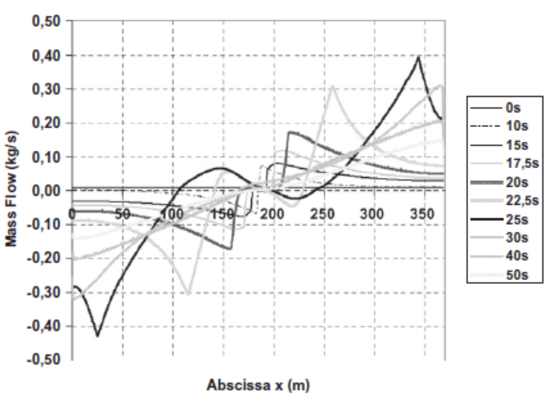
ITER PF5 QUENCH: 4TH TURN, 1 M (CHATS 2011)

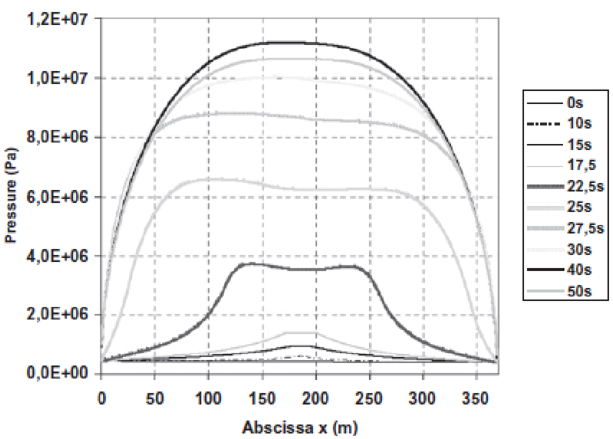


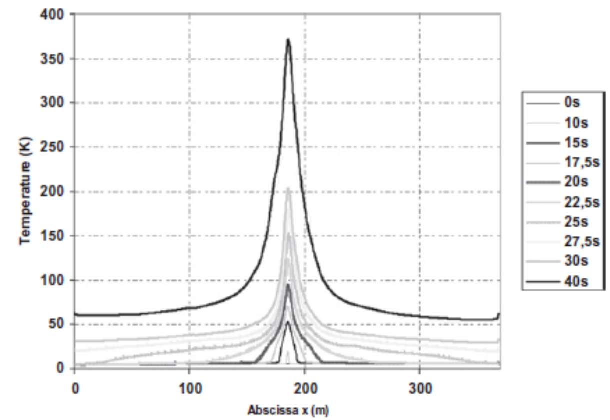
PF5 QUENCH Top Pancake : 4th turn, 1m, With MQE = 1.4 kJ with 1400 W/m (185<x<186 m) during 1 s







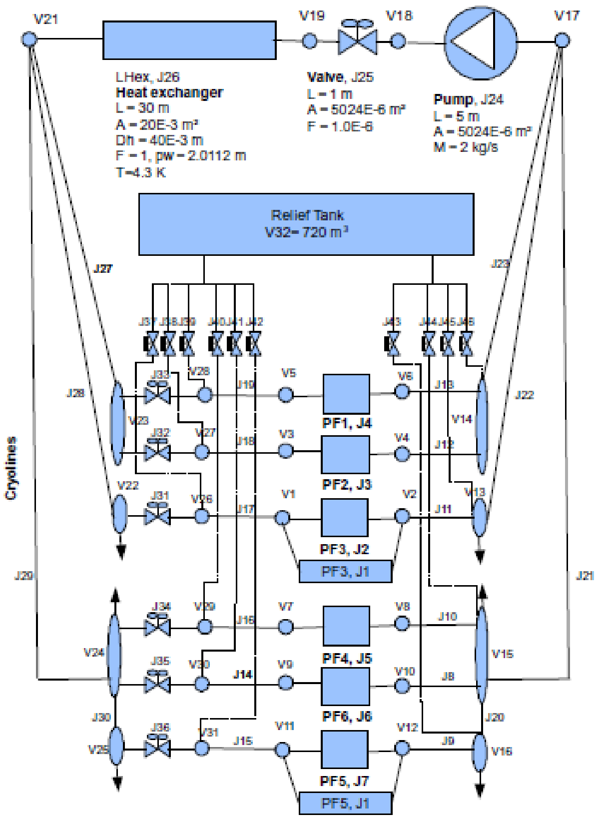


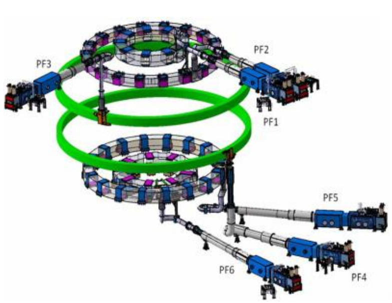


→Temperature margin =1.96 K

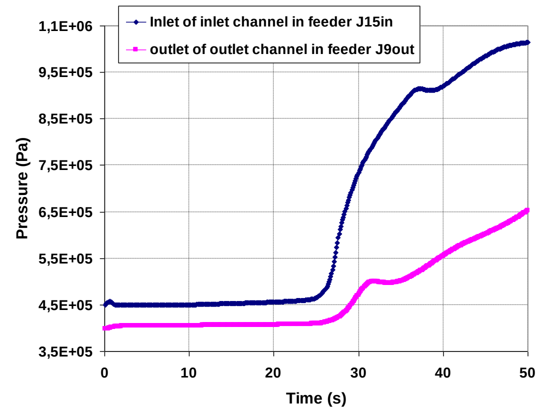
→Quench propagation very rapid 70 m/s →whole CICC (367 m) quenched in 16 s, as the current remains at very high values

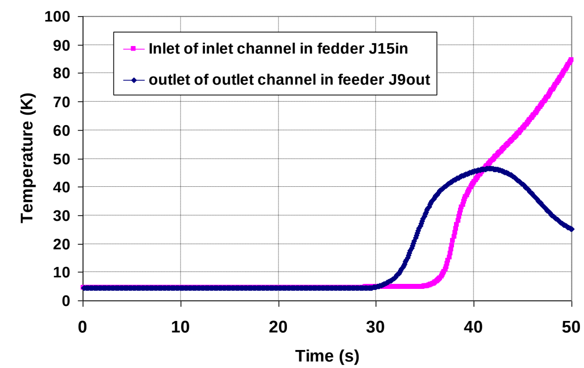
ITER PF5 QUENCH : 4TH TURN, 1 M (CHATS 2011)

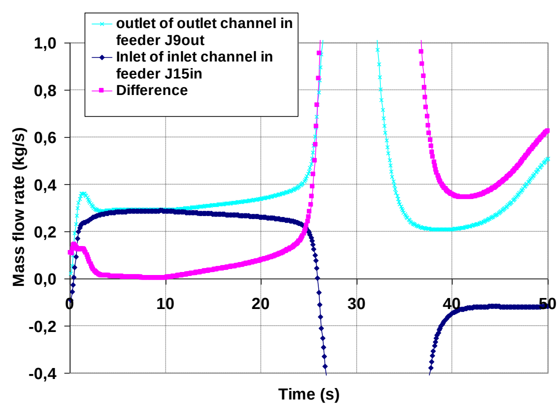


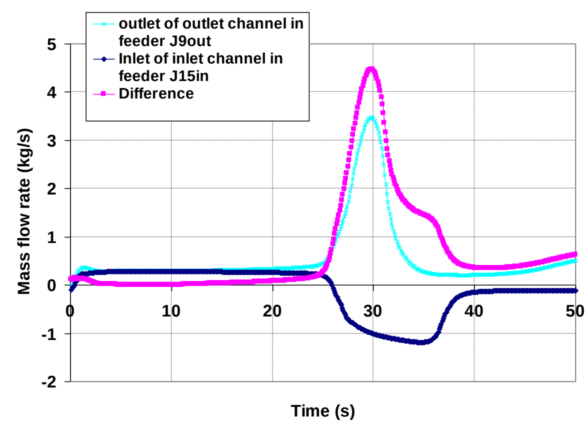


PF5 QUENCH Top Pancake: 4th turn, 1m, With MQE = 1.4 kJ with 1400 W/m (185<x<186 m) during 1 s



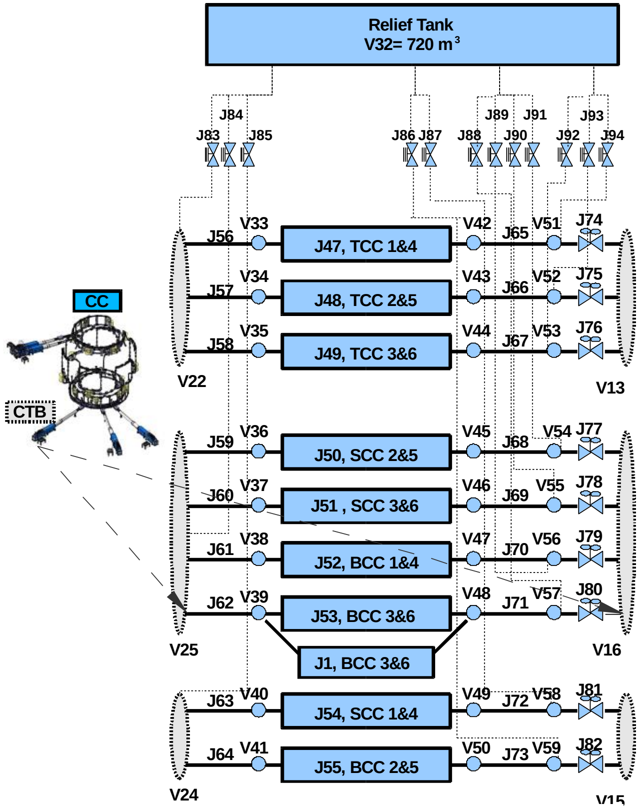


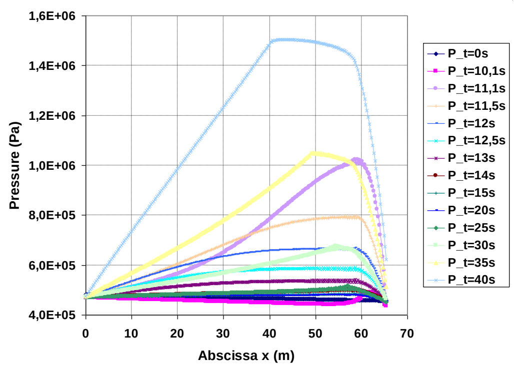




→P & T not sufficient for a secondary detection
→ Only dm could be used.

ITER BCC3 QUENCH : Top Pancake Quench Without Fast Discharge, Possibility of a Secondary Detection, ASC 2012





Quench studied at minimum DTma:

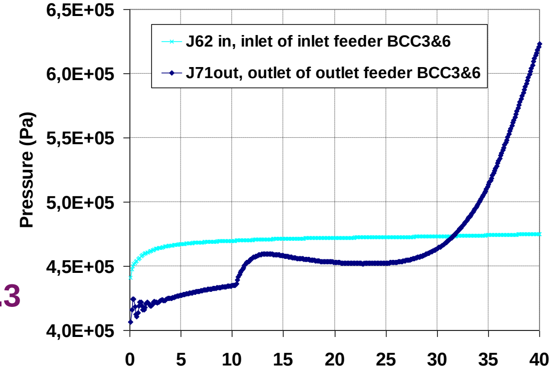
→560s < t < 600 s of the scenario (400s, 15MA), Imax = +10 kA

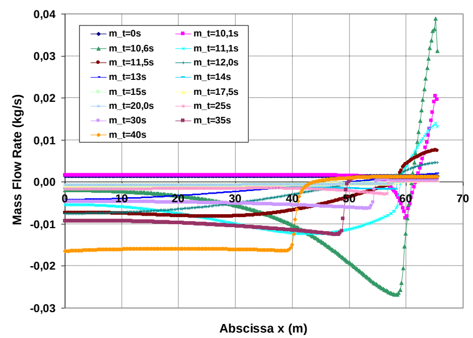
→60 < x < 65m Bmax = 3.9 T

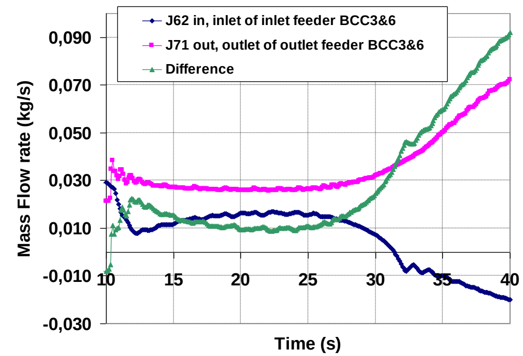
→ top pancake (8) with max. heat load

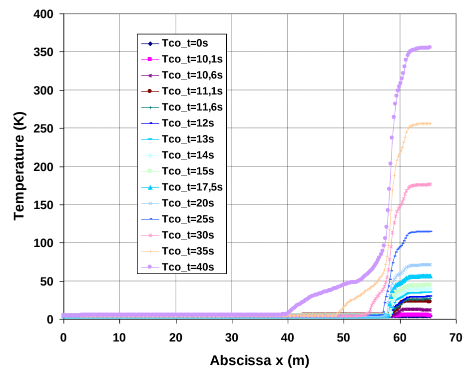
→ Tcs = 6.69 K ΔT_{ma} = 2.6 K.

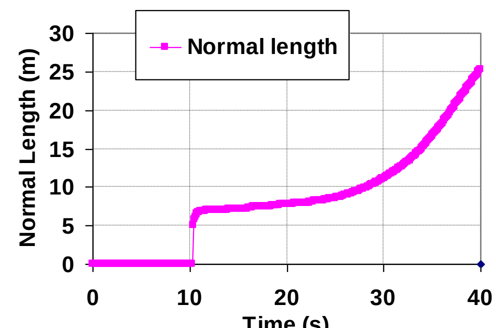
→ The heat input power is 500 W/m (total energy of 2.75 kJ) corresponding to a Minimum Quench Energy (MQE) of 4428.3 mJ/cm³ of SS



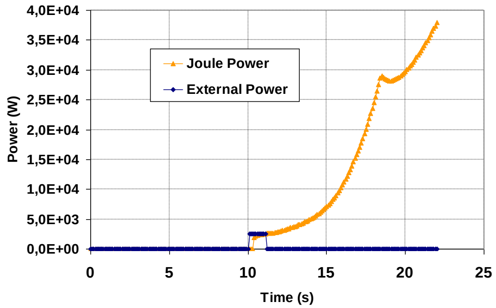


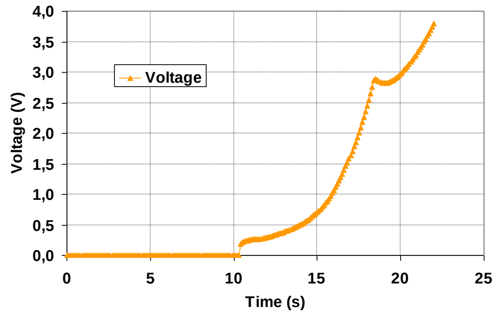


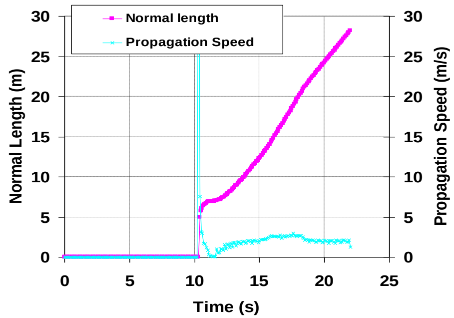


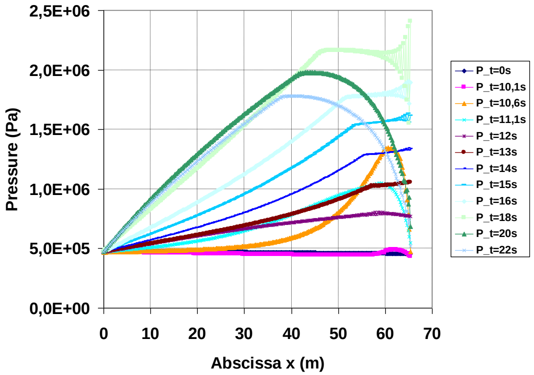


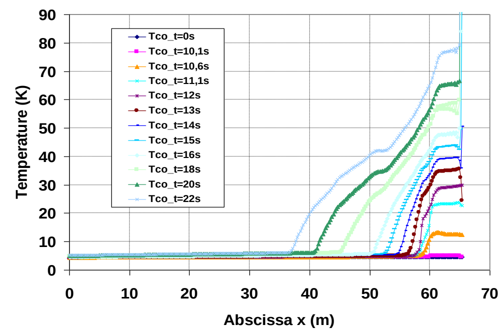
ITER BCC3 QUENCH : All Pancakes Quench Without Fast Discharge, ASC 2012

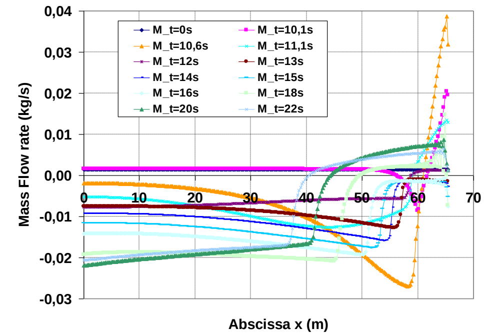


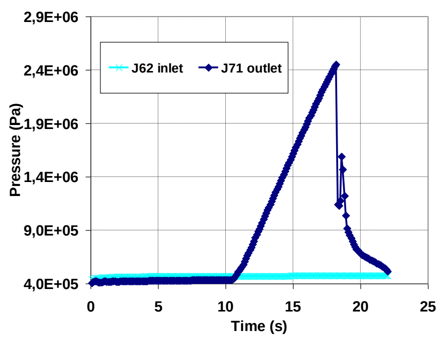


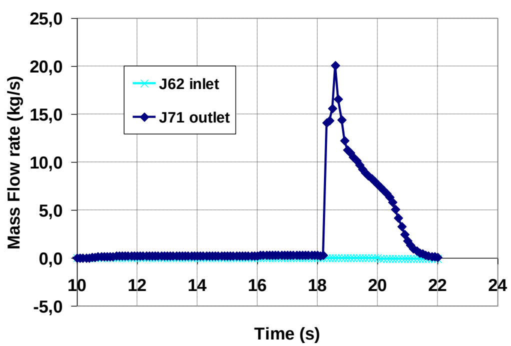


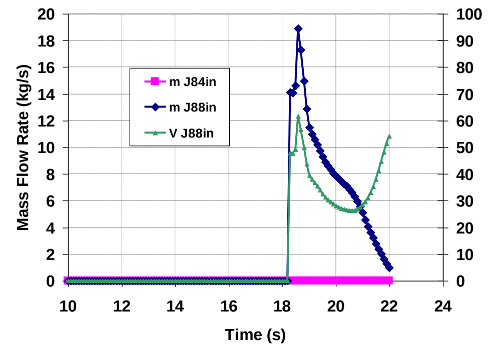






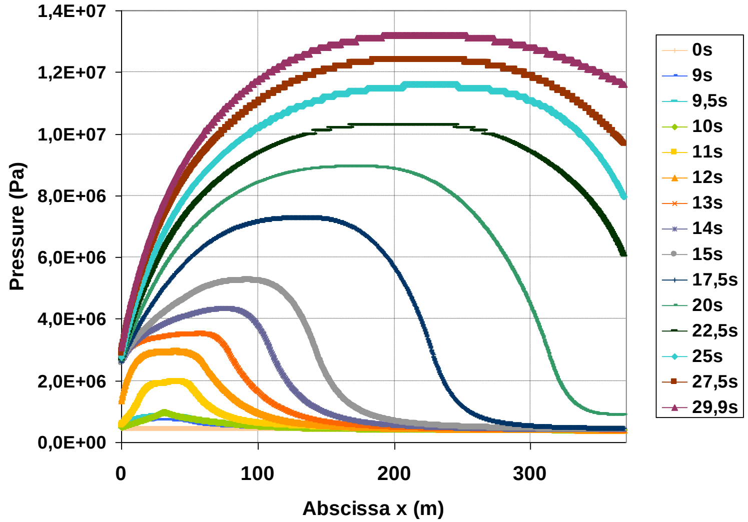






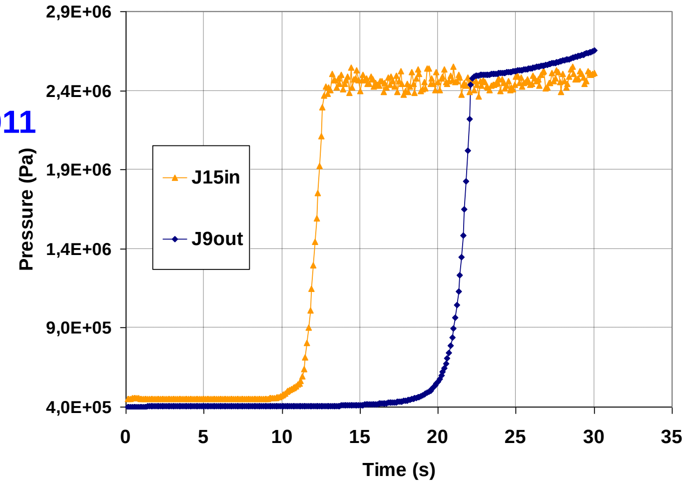
Fast Discharge: detection voltage = 0.1 V , holding time = 2 s ,electrical time constant of 14 s

PF5 Quench of ALL first turns, Without FD : Influence on BCC3 Top Pancake (1/3)

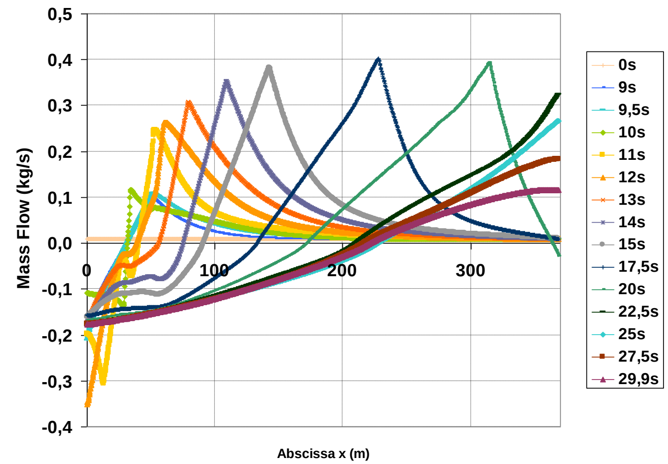


In PF

CHATS, 2011



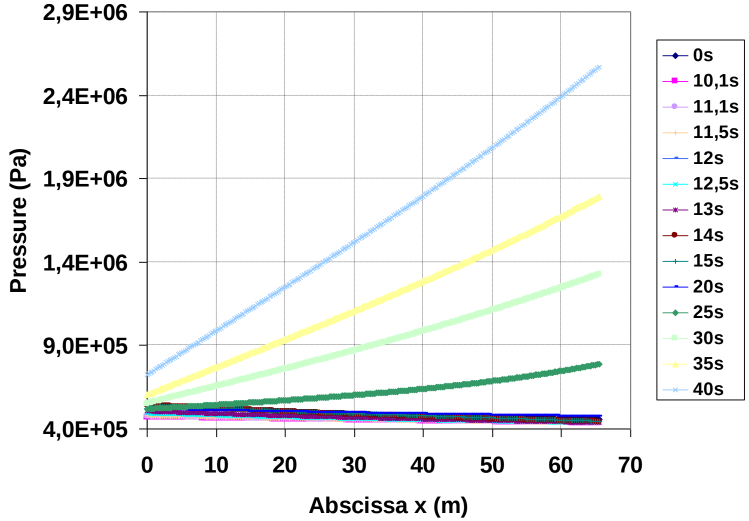
→P and T increase locally first @inlet
→opening of the inlet relief valve (3 s after quench)
→helium expulsion
→P propagates & remains maximum @ CICC middle
→hot helium near the inlet is expulsing all the "cold" helium contained in the CICC
→P increases CICC outlet → opening of the outlet relief valve (12 s after quench).

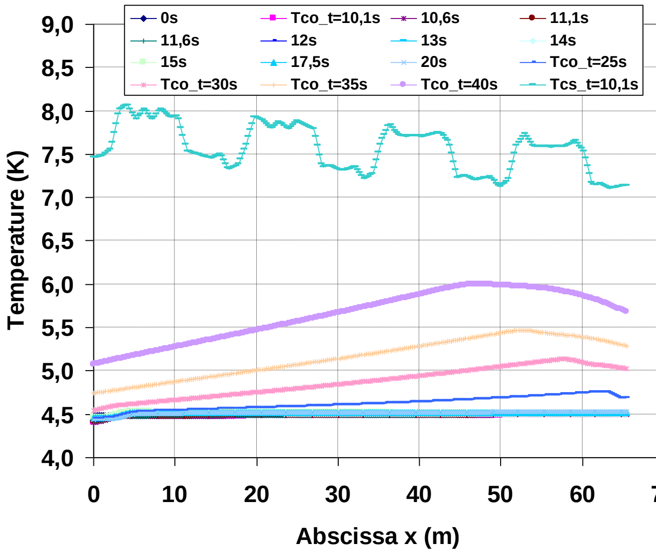


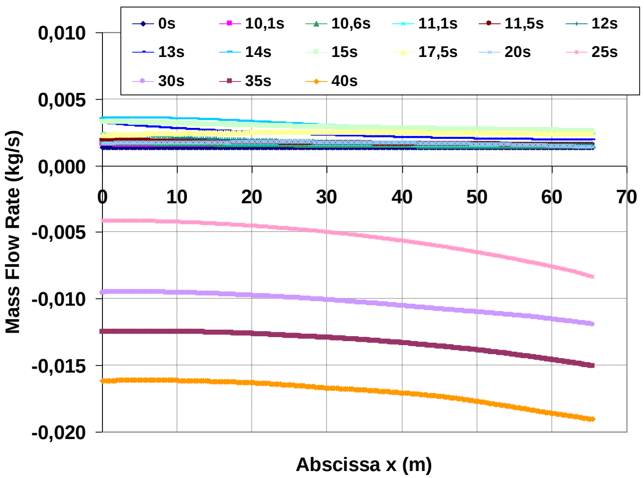
At early time : conductor pressure and temperature increase near the inlet of the conductor (quench is initiated).
Propagation: pressure wave propagates, pressurisation of cold helium→ QUENCH BACK

PF5 Quench of ALL first turns, Without FD: Influence on BCC3 Top Pancake (2/3)

- The corresponding Joule Energy deposited into Flower module equiv. whole PF5 Coil (32 pancakes),
- The Pancake 8 of BCC3 is modeled by Gandalf.





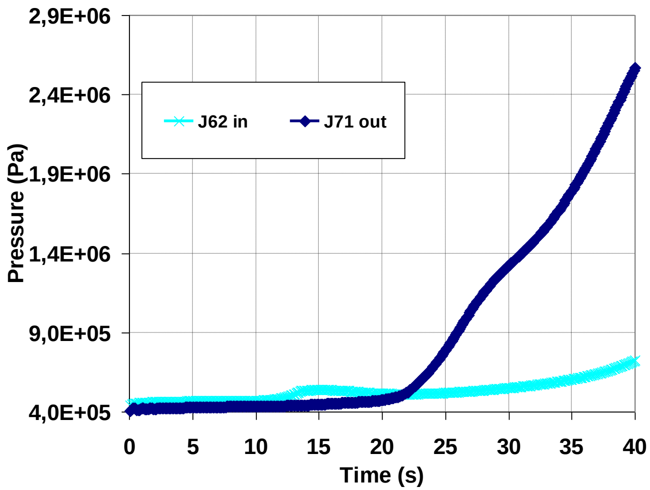


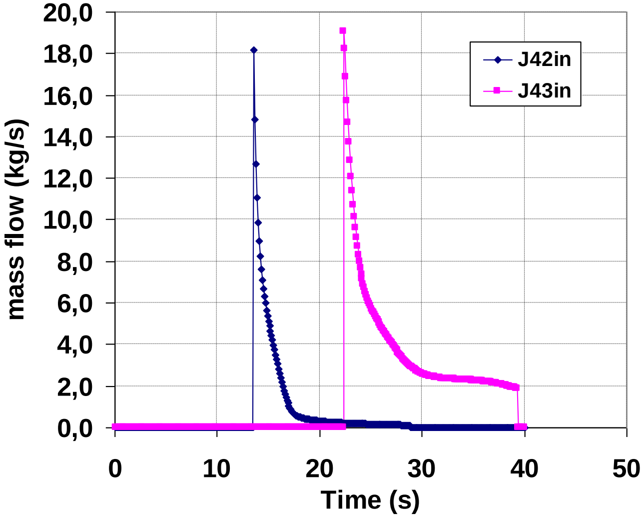
Pinlet ↑ first → much more important increase Poutlet. Maximum pressure (2.6 MPa) and mass flow (-0.02 kg/s).

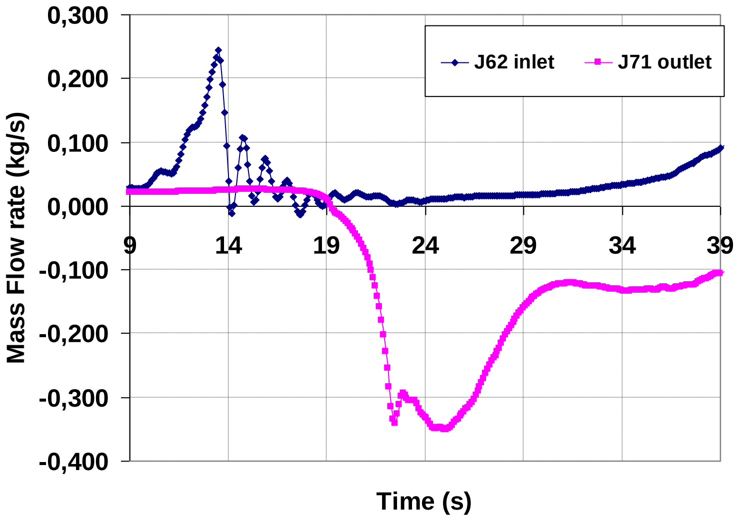
Temperature increase (up to 6 K) not high enough to cause the quench of BCC3

BUT important P increase at BCC3 feeders after PF5 quench →opening of relief valves and then an expulsion of helium followed by an induced quench of BCC3

PF5 Quench of ALL first turns, Without FD : Influence on BCC3 Top Pancake (3/3)







Phenomenon observed at CTB
for pressure (2.4 MPa) & temperature (36 K).
Important mass flows observed : first back flow from PF5 inlet, which causes the PF5 inlet relief valves to open at time=14 s (5 s after beginning of the quench) and then important acceleration at the outlet which causes the opening of outlet relief valve at time=22s.

SITE SUPPORT AGREEMENT
TECHNICAL AGREEMENT UNDER THE SITE SUPPORT AGREEMENT

SUPPORT TO STUDIES ON QUENCH BEHAVIOR AND QUENCH DETECTION FOR THE ITER MAGNET SYSTEMS
SSA16 & SSA27

ARTICLE 1 – PRESENTATION OF THE PROGRAMME

This technical specification describes the scope of work for a service contract providing consultancy and support on thermohydraulic studies related to quench detection and the quench behavior of the superconductors of the ITER magnet systems. This work is in relation with the safe operation of the ITER magnets, and owing to the high magnetic energy stored in these magnets, such studies may be linked to ITER safety analysis. These thermohydraulical studies will be performed with 2 codes, the Gandalf-Flower code and Supermagnet.

2.1. Objectives

Over the last three years, studies have been conducted by CEA with the aim of defining:
The quench behavior of the ITER magnet circuits; The quench detection systems to be used during ITER operation, both for primary and secondary units.The aim of this contract is for ITER to obtain the valuable advice and expertise from CEA experts in the domain of thermo-hydraulic quench calculations.

2.2. Scope of the Work

The task will cover the following main area: Expertise and advice to help ITER decisions in the domain of thermo-hydraulic calculations, with some analysis to be performed for specific cases.

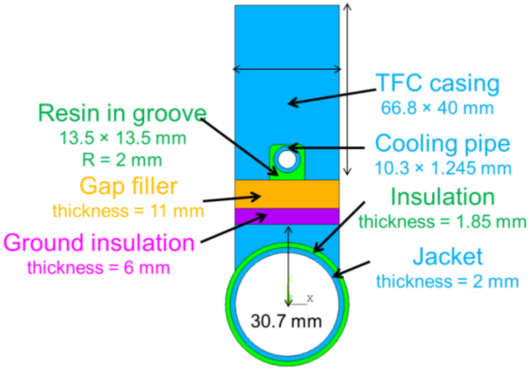
ITER SSA16 & 27: DELIVERABLES

Support Site Agreement
SUPPORT TO STUDIES ON QUENCH BEHAVIOR AND QUENCH DETECTION FOR THE ITER MAGNET SYSTEMS, CODES BENCHMARK ON EXPERIMENTS, 2013-2015

2013: Deliverables
SSA-16 : Deliverable 1.1, Janv. 2013 : TF Coil Quench
SSA27: Deliverable 1.2 : DP TF CICC

2014: Deliverables
SSA-16 : Deliverable 2.1, Janv. 2014 : DP CS CICC & 3 spirales
SSA-27 : Deliverable 2.1, Jan. 2015 : Préparation expérience HELIOS

2015: Deliverables
SSA-16 & SSA27 : TESTS HELIOS & analyses (dec. 2015)
SSA-16 : Quench Model of ITER Side Correction Coil (Juin 2015)
SSA27 : CS Insert Model (Electromagnetic + thermohydraulique)
SSA27 : Additional pressure drop on CS Conductor



HELIOS, INAC, SBT