JT-60SA TOROIDAL FIELD COIL QUENCH MODEL AND ANALYSIS:

JOULE ENERGY ESTIMATION WITH SUPERMAGNET AND STREAM

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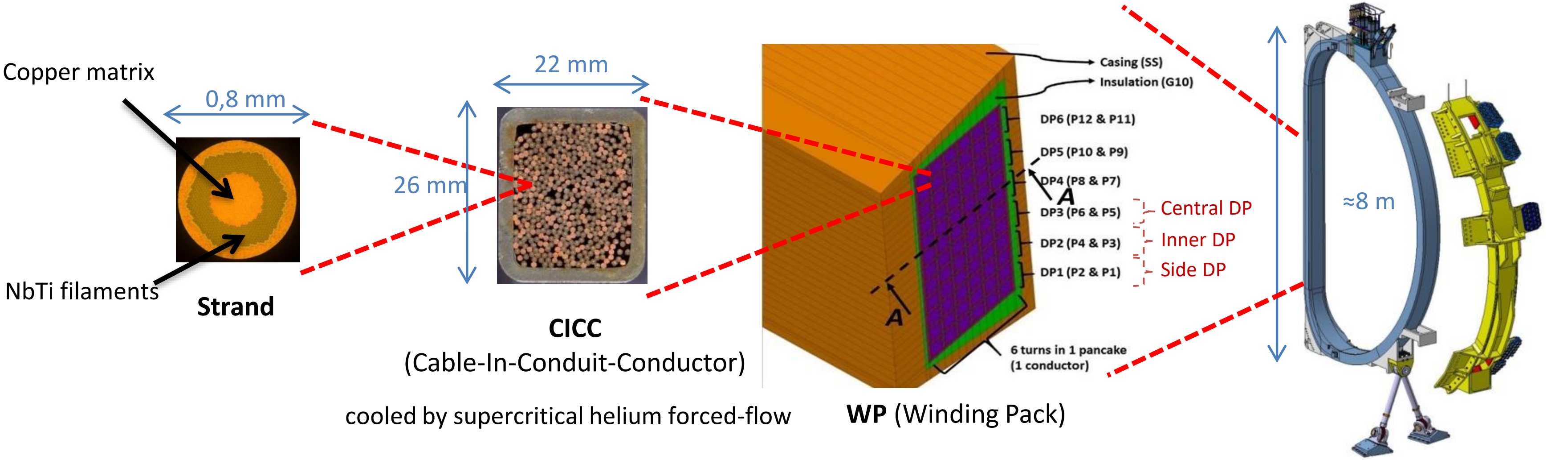
Chats 2021 Applied Superconductivity

CONTENT

1.1) JT-60SA TF COIL AND QUENCH IN CICC



cooled by supercritical helium forced-flow

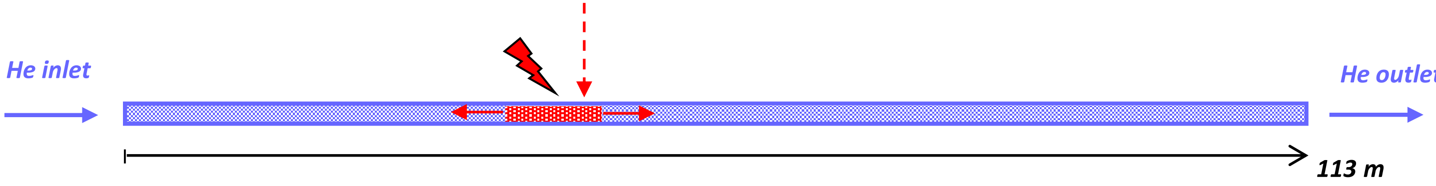
WP (Winding Pack)

TFC (Toroidal Field Coil)

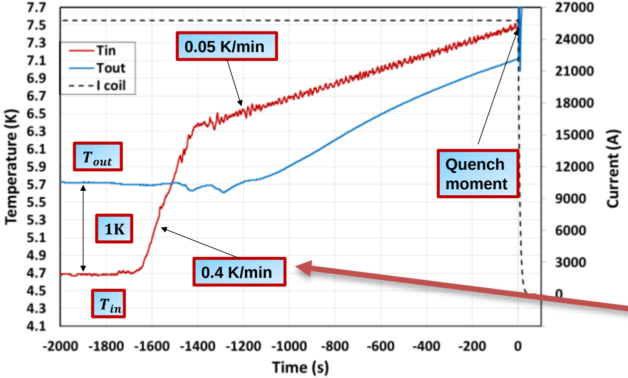
Quench: Irreversible transition from superconducting state to normal resistive state.

➢ If not quickly detected, it may lead to **possible permanent damage** of the magnet.

➢ Starting from a local perturbation, the normal (quenched) zone propagates and generates a large resistive power by Joule effect.



1.2) JT-60SA TFC QUENCH TESTS IN COLD TEST FACILITY (SACLAY, 2016-2018)



Helium temperatures at Winding Pack inlet and outlet

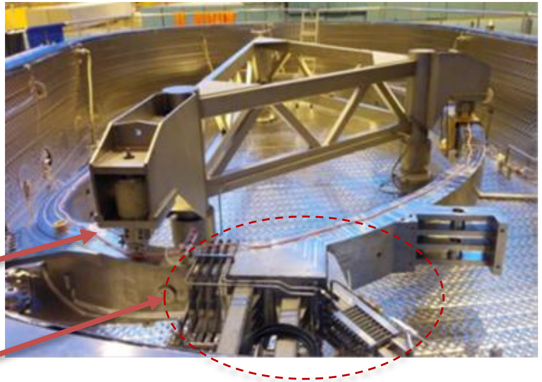
18 TF coils and 2 spare coils were tested for:

- **Acceptance tests before delivery**
- **Quench phenomenon investigations**

Inlet quench initiation by increasing the injected helium temperature

Pick-up coil

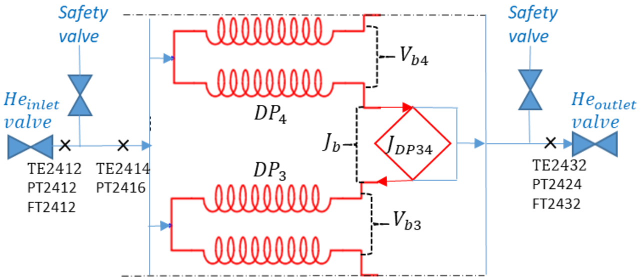
Joints and helium inlets box



JT-60SA TFC in Cold Test Facility

2.1) RESISTIVE VOLTAGE ESTIMATION FROM VOLTAGE MEASUREMENTS

Cold Test Facility **instrumentation** allows to study the **quench propagation** and the resulting **helium expulsed mass flow** from the coil.



Cold Test facility instrumentation scheme

The fast current discharge decreases magnetic field which induce **inductive voltage** inside coil and passive structures.

$$V_{b,DP}(t) = \underbrace{L_{DP}\frac{dI(t)}{dt} + M_{DP}\frac{dI_p(t)}{dt}}_{V_{DP,inductive}} + \underbrace{R_{DP}(t)\, I(t)}_{V_{DP,resistive}}$$

Inductive voltage due to the mutual inductance between coil and passive structures were estimated negligeables ($M_{DP}\frac{dI_p(t)}{dt} \cong 0$ V) using an analytical method.

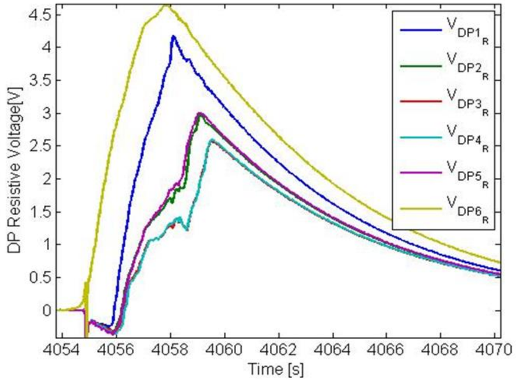
Resistive and inductive voltage determination

Pure Current Fast Discharge (PCFD) test (without quench $R_{Dp}(t)$ =0 Ω) was used in order to estimate inductive voltage induced in TFC02 double-pancakes.

$$\gamma_{DP}(t) = \left(\frac{V_{b,DP}(t)}{V_{pickup}(t)}\right)_{PCFD} = \left(\frac{V_{DP,inductive}(t)}{V_{pickup}(t)}\right)_{quench}$$

Application to TFC02 acceptance quench test

($I_0 = 25.7$ kA, $B_{max} = 3.05$ T, $\dot{m}_{He} = 24$ g/s, $\tau_{da} = 0.1$ s, $\tau = 8$ s)



TFC02 acceptance quench test, double-pancake resistive voltages (Exp)

[1] A.Louzguiti et al., 'Modeling of AC losses and simulation of their impact on JT-60SA TF magnets during commissioning', ASC Conference, 2020

Heuristic quench propagation model for normal length estimation

- Experimental pancake resistance assumption:

$$R_P(t) = \frac{\boldsymbol{R_{DP}(t)}}{\mathbf{2}} = \frac{V_{DP,resistive}(t)}{2\,I(t)}$$

- **Maximal conductor temperature** calculation: $T_{cond,max}(t)$

  Initial condition: $T_{cond,max}(t=0) = T_{cs}$

  0-D energy conservation relations applied to helium, conductor and jacket

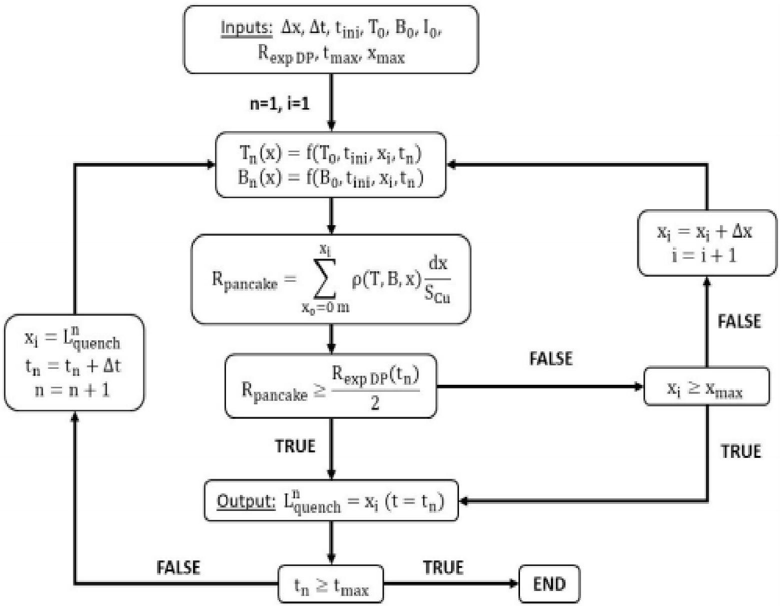
- **Linear temperature profile** assumption:

  Boundary condition: $T_{cond}(t, x=0) = T_{cond,max}(t)$

$$\frac{dT_{cond}(t,x)}{dx} = \frac{\left(T_{cs} - T_{cond,max}(t)\right)}{L_q(t)}$$

- Predicted and measured **resistances comparison**

- **CICC normal length evolution at each time step**



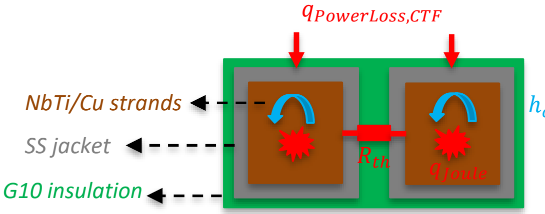
Schematic of the heuristic quench propagation model

[2] Y. Huang, 'Study and modelling of the thermohydraulic phenomena taking place during the quench of a superconducting magnet cooled with supercritical helium', p. 179, 2019

SuperMagnet code (L. Bottura ,CERN, fortran):
Coupling THEA (1-D CICC electrical and thermohydraulical model) and FLOWER (hydraulical model)

THEA modelisation of 12 CICC with helium, strands and jacket components

Magnetic field profile (TRAPS) and friction factor correlation (OTHELLO facility) for each pancake



$$h_{conv} = \frac{f_{EU}\, \lambda_f\, R_e\, P_r^{\frac{1}{3}}}{8\, D_h}$$

$$q_{InterturnCoupling} = \frac{\Delta T_{\{turn1-turn2\}}}{R_{th}}$$

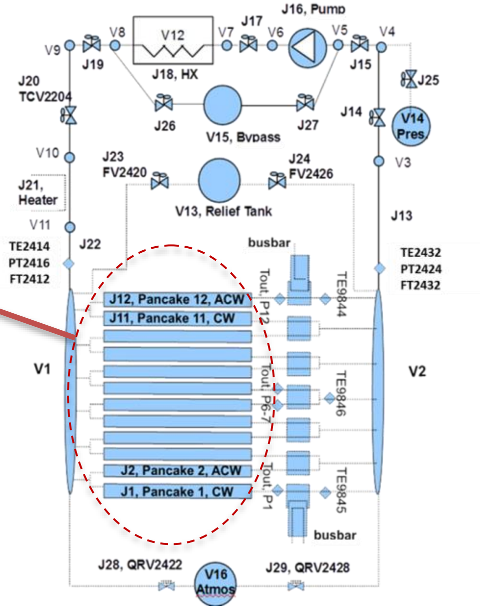
Quench primary detection: voltage threshold U_{detec}= 0.1 V

Current discharge ($I(t) = I_0 e^{-t/\tau}$) triggers after **quench detection and action time** (τ_{da}= 0.1 s)

→ Developed numerical SuperMagnet model of JT-60SA TF coil and its cryodistribution

FLOWER modelisation of the cryodistribution

(pump, heat exchanger, quench relief tank, valves and heater)



Schematic of TFC and cryodistribution SuperMagnet model

[3] S. Nicollet and al., 'Parametric Analyses of JT-60SA TF Coils in the Cold Test Facility With SuperMagnet Code', IEEE Trans. Appl. Supercond., vol. 28, no. 3, p. 4205205, Apr. 2018.

3.2) ANALYTICAL STREAM MODEL

STREAM: Superconductor Thermohydraulical and Resistive Electrical Analytical Model (S. Nicollet, IRFM, Matlab):

Thermohydraulical governing equations:

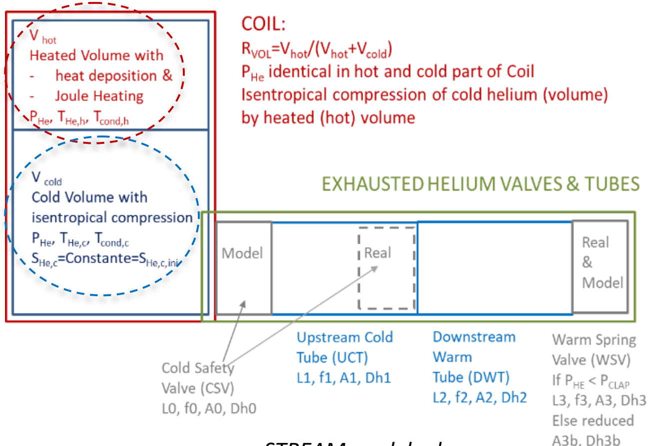
0-D adiabatic cold volume submitted to **isentropic compression**:

$$\frac{dW(t)}{dt} = -p(t)\frac{dV_{cold}(t)}{dt} = p(t)\frac{dV_{hot}(t)}{dt}$$

0-D **energy conservation relations** applied to conductor, helium and jacket:

$$\frac{dT_{cond}(t)}{dt} = \frac{\frac{\eta_{Cu}(t)\, L_q(t)}{A_{Cu}} I(t)^2 - h_{conv}\, P_{w,cond}\, L\,\left(T_{cond}(t) - T_{He}(t)\right)}{L\,\left(A_{Cu}\,\rho_{Cu}\,C_{Cu}(t) + A_{NbTi}\,\rho_{NbTi}\,C_{NbTi}(t)\right)}$$

Second law of thermodynamics, **energy** and **mass conservative relations** describe the **1-D expulsed helium flow** from the coil when reaching a **pressure drop threshold.**

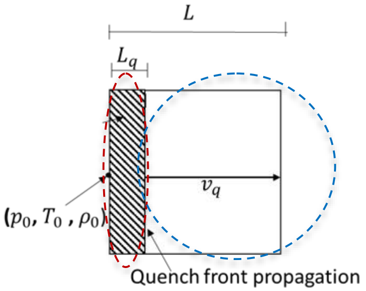


STREAM model scheme

A. Shajii analytical quench propagation model: Long coil - High pressure rise Regime

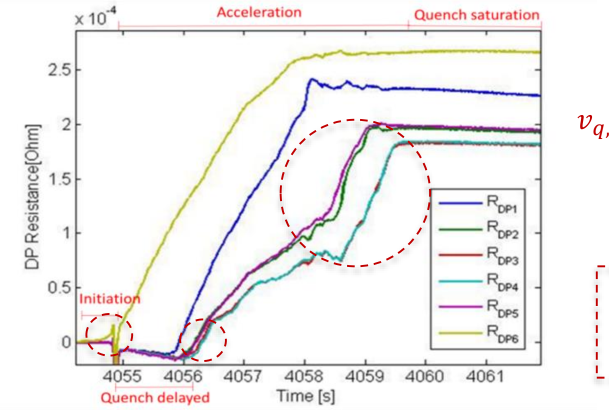
$$\frac{\Delta p}{p_0} = \frac{r\,\rho_0 \alpha_0 J_0^2\, L_{q,ini}}{2\,p_0\,v_q(t_m)} > 1 \qquad v_q(t) = \frac{dL_q(t)}{dt} = 0.766\left(\frac{2\,D_h}{f}\right)^{\frac{1}{5}}\left(\frac{r\,L_{q,ini}\,\alpha_0 J_0^2}{c_0}\right)^{\frac{2}{5}}\frac{1}{t^{\frac{1}{5}}}$$

$$L^2 > \frac{24\,D_h\,c_0^2\,t_m}{f\,v_q(t_m)} \qquad \alpha_0 = \min_{T=[T_{cr}:300]}\left(\frac{A_{cu}\eta_{Cu}(T)}{A_{cond}\,\rho_{cond}\,C_{cond}(T) + A_{jacket}\,\rho_{jacket}\,C_{jacket}(T)}\right)$$



[4] A. Shajii, J. P. Freidberg, and E. A. Chaniotakis, 'Universal scaling laws for quench and thermal hydraulic quenchback in CICC coils', IEEE Transactions on Applied Superconductivity, vol. 5, no. 2, pp. 477–482, Jun. 1995

4.1) TFC02 ACCEPTANCE TEST: QUENCH PROPAGATION



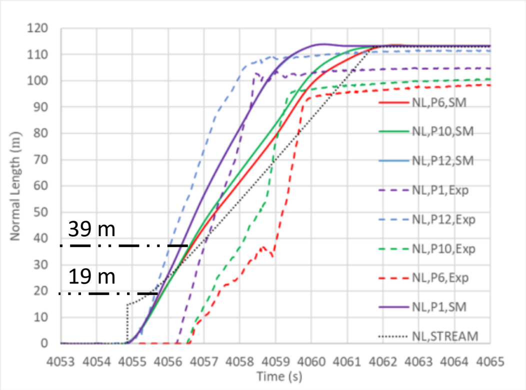
TFC02 acceptance quench test, double-pancake resistance (Exp)

$v_{q,P1,SM} = v_{q,P12,SM} = 22.5$ m/s

$v_{q,P12,Exp} = 25.6$ m/s

$v_{q,Average,SM} = 17.4$ m/s

$v_{q,STREAM} = 16.1$ m/s

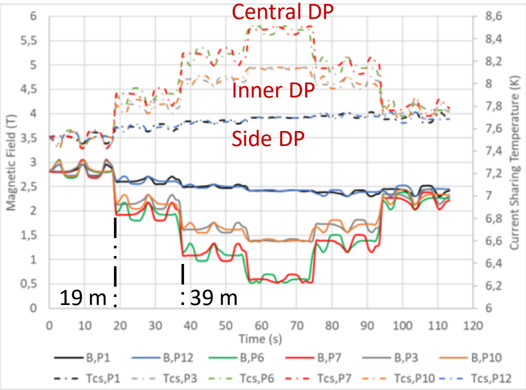


TFC02 acceptance quench test, normal length propagation (SM , STREAM, Exp)

- Quench initiation at inlet of side double-pancake 6 caused by the **thermal loss from thick casing to Winding Pack**
- Helium reverse flow effect: **warm helium injection** (expulsed mass flow from side pancake) → **simultaneous quench initiation** in inner and central double-pancakes
- Quench propagation mitigated by V-shape **magnetic field distribution:**

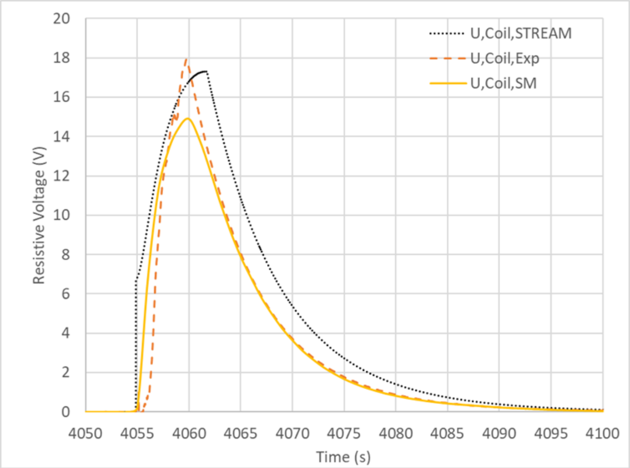
$$v_{q,P6,SM} = 16.2 \text{ m/s} < v_{q,P10,SM} = 17.4 \text{ m/s} < v_{q,P12,SM}$$

- Re-acceleration phenomenon: Second quench initiation in inner and central double-pancakes (v_q ≅50 m/s) by a quench propagating through **electrical inter-pancake joints**

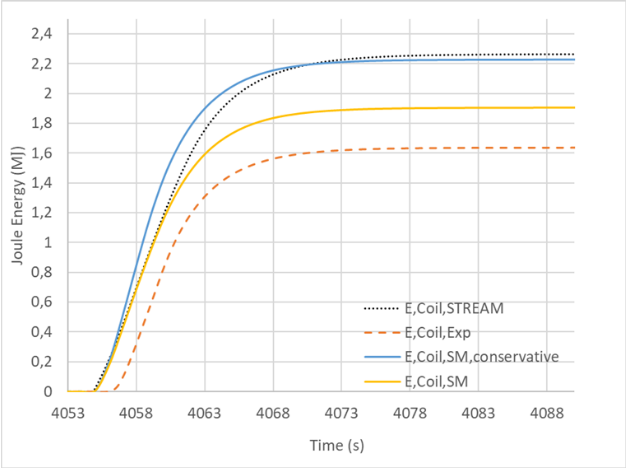


TFC02 acceptance quench test, Magnetic field and current sharing temperature profiles

4.2) TFC02 ACCEPTANCE TEST : ELECTRICAL RESULTS



TFC02 acceptance quench test, coil resistive voltage (SM, STREAM, Exp)



TFC02 acceptance quench test, coil Joule energy dissipation (SM, STREAM, Exp)

$$U_{Coil,max,SM} = 14.9\text{ V} < U_{Coil,max,STREAM} = 17.3\text{ V} < U_{coil,max,Exp} = 17.8\text{ V}$$

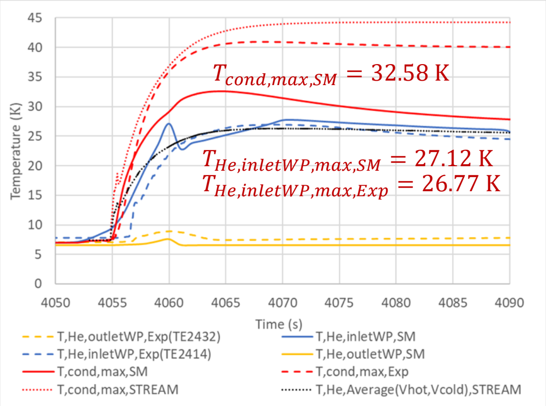
$$E_{coil,Exp} = 1.64\text{ MJ} < E_{coil,SM} = \mathbf{1.90\ MJ} < E_{Coil,STREAM} = 2.21\text{ MJ}$$

$$E_{Coil,SM} = \sum_{i=1}^{i=N_{tot}} E_{Pi} = \sum_{i=1}^{i=N_{tot}} \int_0^{t_{end}} \int_0^{L_q(t)} R_{Pi}(x,t)\, I(t)^2\, dx\, dt$$

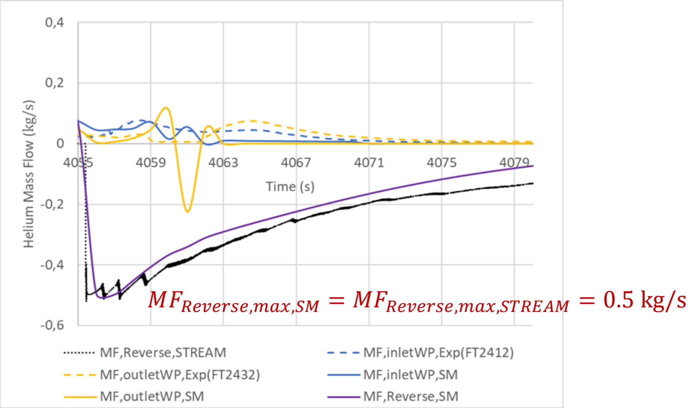
$$E_{coil,SM,conservative} = N_{tot}\, E_{Pi,max} = 2.20\text{ MJ}$$

- **Good agreement** between experimental, analytical and numerical results.
- **STREAM is conservative**, indeed the model extrapolates results from one CICC to the twelve composing the coil.

4.3) TFC02 ACCEPTANCE TEST : THERMOHYDRAULICAL RESULTS

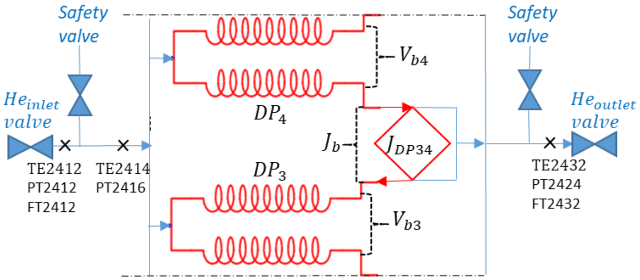


TFC02 acceptance quench test, helium and conductor temperatures (SM, STREAM, Exp)



TFC02 acceptance quench test, helium mass flows (SM, STREAM, Exp)

- Normal zone induces **local helium depletion** and **high forced convection** expulsing **helium mass flows** in two opposite directions (reverse and accelerate mass flows)
- Quench detection time (t=4055 s): **Helium inlet and outlet valves are closed** (quasy isochoric system)
- 5 s period (t=4060 s) **: Quench safety valves opening** (releasing the warmed helium from the coil into the quench tank)
- The **maximal conductor temperature** calculated numerically reach **32.58 K** in the side pancake 12 (first pancake reaching the quench saturation phase)

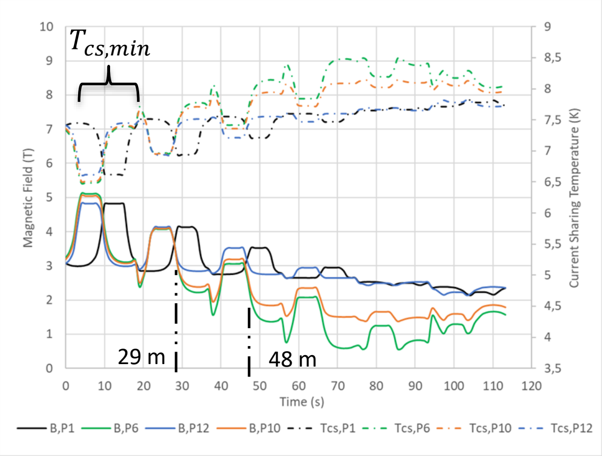


Cold Test facility instrumentation scheme

5.1) JT-60SA TFC IN TOKAMAK CONFIGURATION

Study in collaboration with A. Louzguiti in the framework of WPSA

Name	Tokamak	CTF	Unit
TF Coil			
TF stored magnetic energy	58	20.5	MJ
Maximum magnetic field	5.65	3.05	T
Minimal Current Sharing Temperature	6.47	7.45	K
Current discharge time constant	14	8	s
Helium Coolant			
WP Helium inlet temperature	4.5	4.7	K
WP Helium inlet pressure	0.53	1.038	MPa
WP Nominal mass flow rate	48	24	g/s



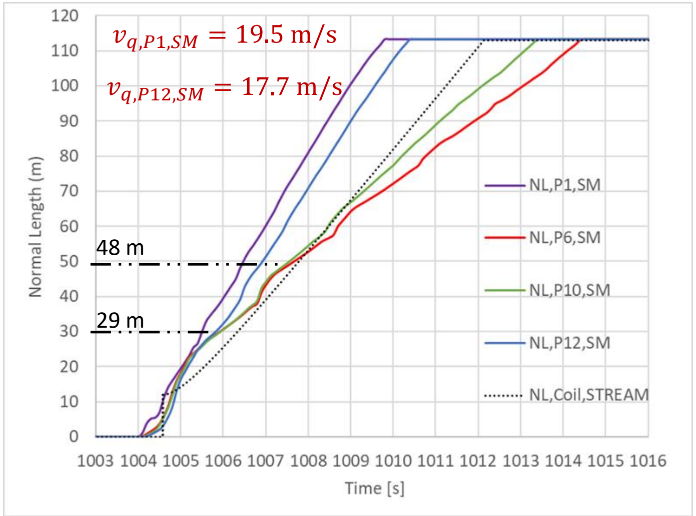
JT-60SA TFC in Tokamak configuration, Magnetic field and current sharing temperature profiles

Hydraulical coil protection:

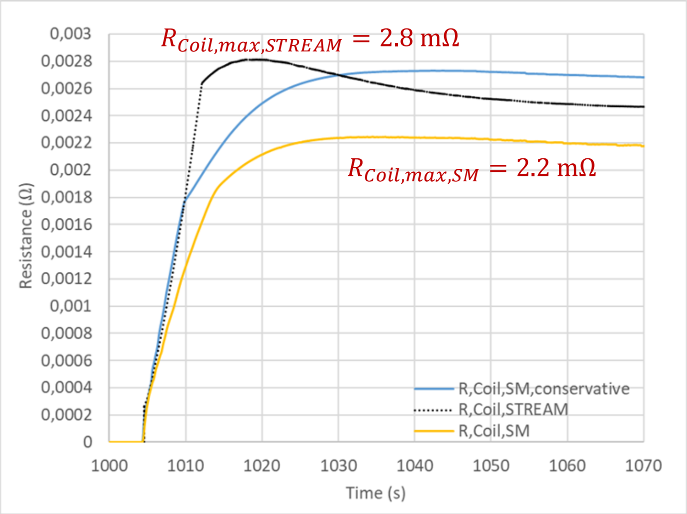
The quench incident during Tokamak operation is simulated **without isolating the coil from cryogenic plant** at the quench detection time. For this configuration **quench relief valves with pressure threshold of 20 bars** are the only hydraulical protection for the coil.

Quench initiation:

The resistive transition is induced by **Minimum Quench Energy** deposition of **30 W/m** during **5 s** over **each pancake first turn,** precisely at absissa **5<x<19 m**. The quench **begins at the helium inlet of the central pancake 6** where the minimal current sharing temperature belongs.



JT-60SA TFC in Tokamak configuration, calculated normal zone propagation (SM, STREAM)



JT-60SA TFC in Tokamak configuration, calculated coil resistance (SM, STREAM)

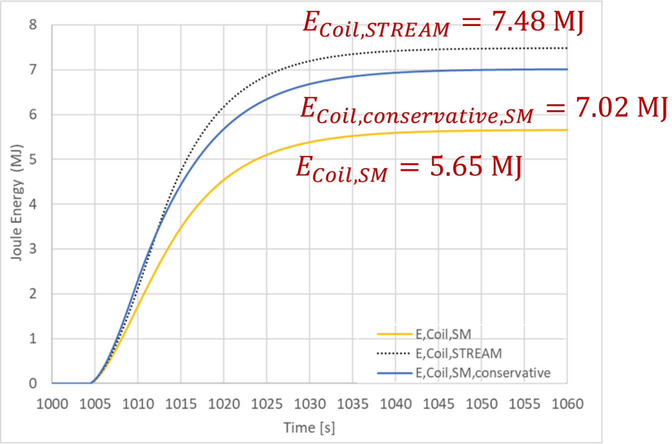
Magnetic field distributions induce significant **thermal margin** and **quench propagation velocity differences** between **central, inner and side double-pancakes:**

$0\ \mathrm{m} < NL < 29\ \mathrm{m}$: $v_{q,P6,SM} = v_{q,P10,SM} = v_{q,P12,SM} = 15.7\ \mathrm{m/s}$

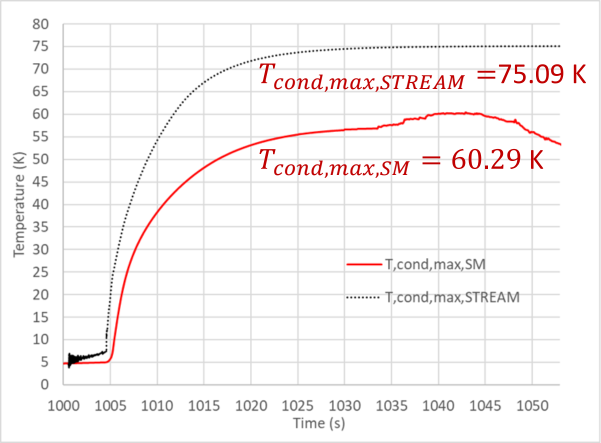
$29\ \mathrm{m} < NL < 48\ \mathrm{m}$: $v_{q,P6,SM} = v_{q,P10,SM} = 12.3\ \mathrm{m/s} < v_{q,P12,SM}$

$48\ \mathrm{m} < NL < 113\ \mathrm{m}$: $v_{q,P6,SM} = 9.4\ \mathrm{m/s} < v_{q,P10,SM} = 10.9\ \mathrm{m/s} < v_{q,P12,SM}$

The **analytical** quench propagation velocity ($v_{q,STREAM} = 14.7\ \mathrm{m/s}$) allows to predict a **coil resistance** dynamic **matching** the **SuperMagnet** calculation.



JT-60SA TFC in Tokamak configuration, calculated coil Joule energy dissipation (SM,STREAM)



JT-60SA TFC in Tokamak configuation, calculated maximal conductor temperature (SM, STREAM)

Heat loads on JT-60SA cryogenic plant:

+ 7 MJ Conservative Joule energy dissipated during the **quench of one TFC** (12 % of the TF stored magnetic energy)

+ 11 MJ Joule energy dissipated in the **18 TFC thick casings by Eddy currents** induced during the Fast Current Discharge

[5] M. Wanner, "JT -60SA Plant Integration Document (PID)," V4.2

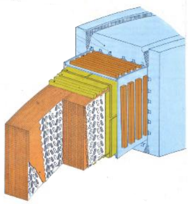
Quench maximal conductor temperature criteria:

$T_{cond, maximal, numeric}$ = **60.29 K< 150 K** (criteria for non-adiabatic conductor exchanging heat with helium and jacket)

Quench criticality: $v_{q,P1,SM} = 19.5$ m/s → $E_{P1,SM} = 0.585$ MJ → $\boldsymbol{T_{cond,P1(inlet),SM} = 60.29}$ **K**

Quench model development:

STREAM were upgraded from superfluid helium bath to **Cable-In-Conduit-Conductor** cooling process.



WEST TFC cooled by superfluid helium bath

Cable-In-Conduit-Conductor cooled by supercritical helium forced-flow

Models validation:

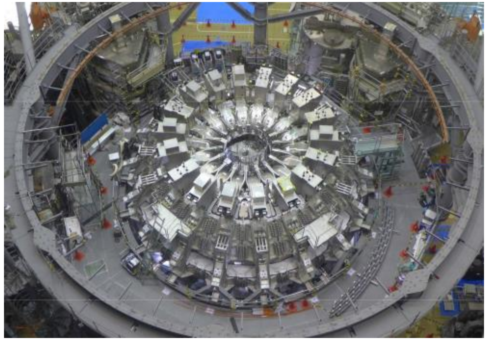
Large scale models of the **JT-60SA TFC** and its **cryodistribution** simulated the **TFC02 quench acceptance test in Cold Test Facility** using the numerical code **SuperMagnet** as well as the analytical **STREAM** model.

They proved their robuthness and capacity to simulate the quench phenomenon against experimental data.

Quench phenomena analysis:

Further investigations and numerical simulations will be carry out in order to simulate the **reverse mass flow effect** and **re-acceleration phenomenon**.

Partial quench of the TFC02 occurred during CTF tests at **reduced current** and analysis are in progress.



Preparation of JT-60SA operation:

Help for **commissioning** and **operation** by estimating **heat loads on JT-60SA cryogenic plant (18 MJ)** in case of eventual **toroidal field coil quench incident**.

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Thank you for your attention

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[2] S. Nicollet *et al.*, ‘Parametric Analyses of JT-60SA TF Coils in the Cold Test Facility With SuperMagnet Code’, *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, p. 4205205, Apr. 2018.

[3] Y. Huang, ‘Study and modelling of the thermohydraulic phenomena taking place during the quench of a superconducting magnet cooled with supercritical helium’, p. 179.

[4] A. Shajii, J. P. Freidberg, and E. A. Chaniotakis, ‘Universal scaling laws for quench and thermal hydraulic quenchback in CICC coils’, *IEEE Transactions on Applied Superconductivity*, vol. 5, no. 2, pp. 477–482, Jun. 1995.

[5] M. Wanner, “JT -60SA Plant Integration Document (PID),” V4.2.

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[8] M. Bagnasco, D. Bessette, L. Bottura, C. Marinucci, and C. Rosso, ‘Progress in the Integrated Simulation of Thermal-Hydraulic Operation of the ITER Magnet System’, 2010.

[9] L. Bottura, C. Rosso, and M. Breschi, ‘A general model for thermal, hydraulic and electric analysis of superconducting cables’, *Cryogenics*, vol. 40, pp. 617–626, Aug. 2000.

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[12] L. Bottura, ‘A practical fit for the critical surface of NbTi’, *IEEE Trans. Appl. Supercond.*, vol. 10, no. 1, pp. 1054–1057, Mar. 2000.

[13] L. Zani, P. Barabaschi, E. D. Pietro, and M. Verrecchia, ‘Extended Quality Control Process Applied on TF Strand and TF Conductor Production for JT-60SA Project’, *IEEE Transactions on Applied Superconductivity*, vol. 25, no. 3, pp. 1–5, Jun. 2015.

[14] S. Nicollet, D. Ciazynski, J. L. Duchateau, B. Lacroix, and B. Renard, ‘Chapter 136 - Evaluation of the ITER Cable In Conduit Conductor heat transfer’, in *Proceedings of the Twentieth International Cryogenic Engineering Conference (ICEC20)*, L. Zhang, L. Lin, and G. Chen, Eds. Oxford: Elsevier Science, 2005, pp. 589–592.

[15] L. Bottura and C. Rosso, ‘Flower, a model for the analysis of hydraulic networks and processes’, *Cryogenics*, vol. 43, no. 3, pp. 215–223, Mar. 2003.

[16] S. Nicollet et al., ‘A Superconductors Thermohydraulical and Resistive Electrical Analytical Model (STREAM) applied to WEST TF Coil Quench Analysis’, Conference, 2021.

Energy conservation relations applied to helium, conductor and jacket in STREAM and Heuristic quench models

$$\left\{\begin{aligned}
\frac{dT_{cond}(t)}{dt} &= \frac{\frac{\eta_{Cu}(t)\, L_q(t)}{A_{Cu}}\, I(t)^2 - h_{conv}\, P_{w,cond}\, L\, (T_{cond}(t) - T_{He}(t))}{L\,\left(A_{Cu}\,\rho_{Cu}\,C_{Cu}(t) + A_{NbTi}\,\rho_{NbTi}\,C_{NbTi}(t)\right)} \\
\frac{dT_{He}(t)}{dt} &= \frac{h_{conv}\, P_{w,cond}\left(T_{cond}(t) - T_{He}(t)\right) - h_{conv}\, P_{w,jacket}\left(T_{He}(t) - T_{jacket}(t)\right)}{A_{He}\,\rho_{He}(t)\, Cv_{He}(t)} \\
\frac{dT_{jacket}(t)}{dt} &= \frac{h_{conv}\, P_{w,jacket}\left(T_{He}(t) - T_{jacket}(t)\right)}{A_{jacket}\,\rho_{jacket}\, C_{jacket}(t)}
\end{aligned}\right.$$

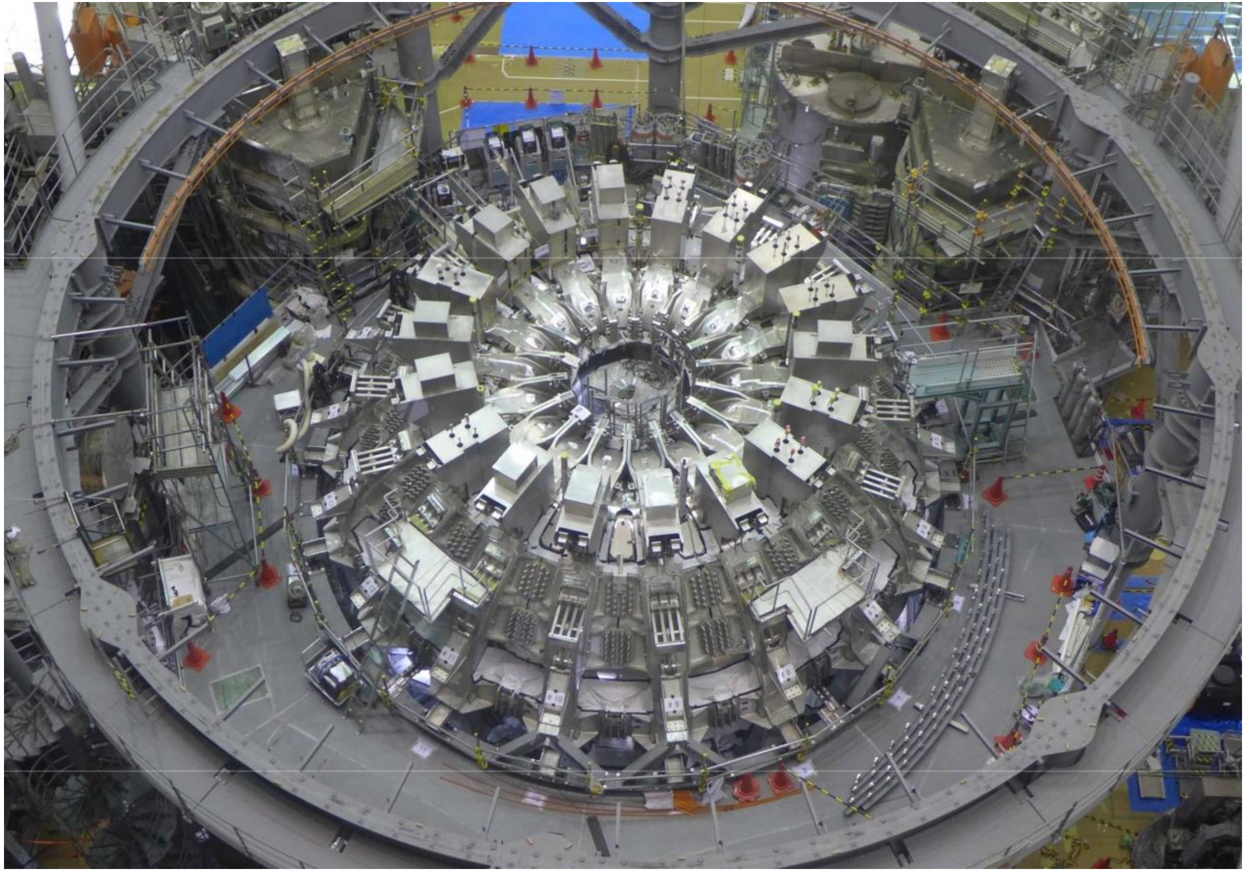
STREAM: second law of thermodynamics, energy and mass conservative relations describe the 1-D expulsed helium flow from the coil

$$dH + \frac{dc^2}{2} = \delta Q_e$$

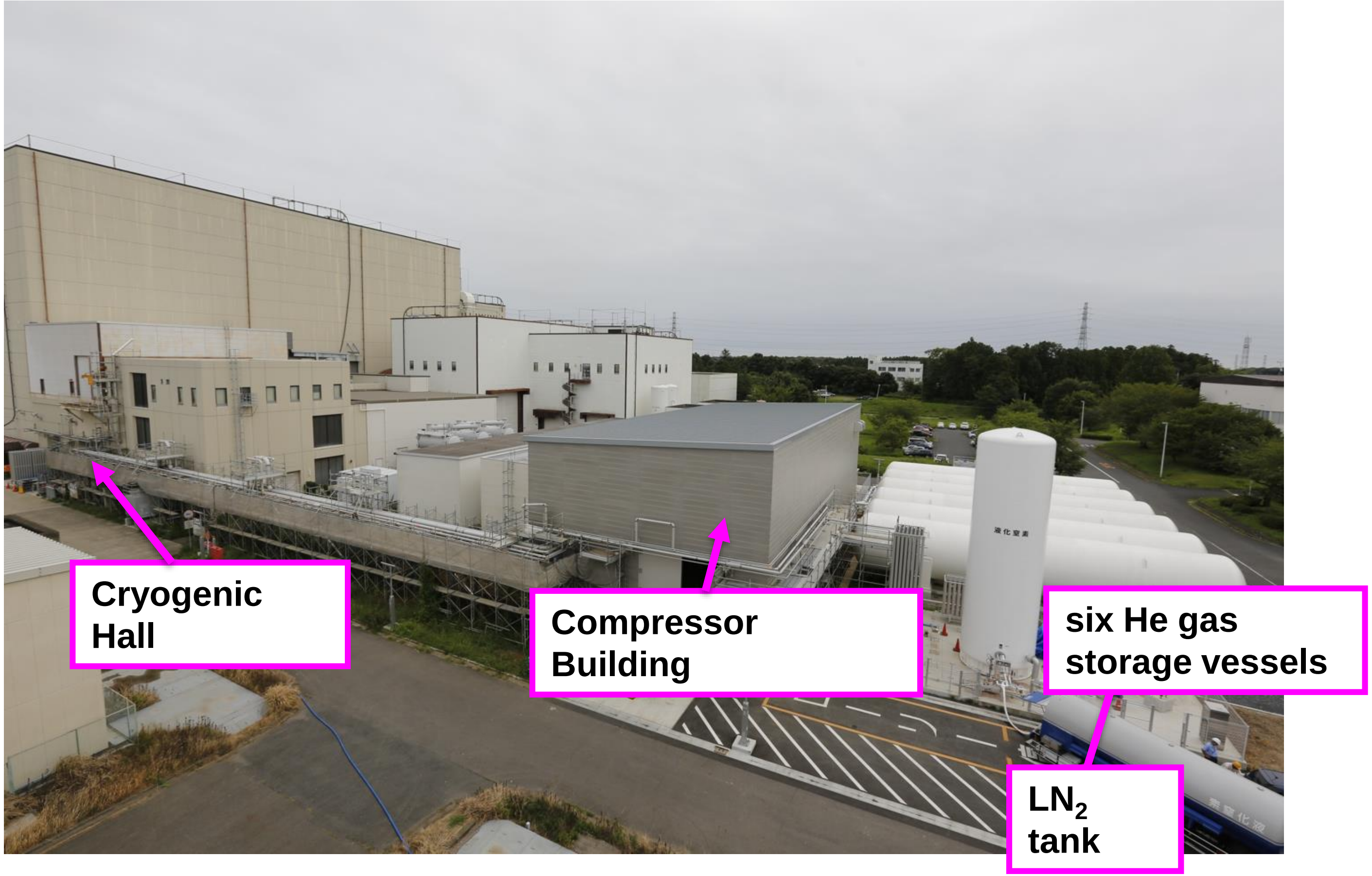
$$Tds = \delta Q_e + \delta Q_f$$

$$D = \rho\, c\, A = Cst \longrightarrow \frac{d\rho}{\rho} + \frac{dc}{c} + \frac{dA}{A} = 0$$

JT-60SA TF COILS FULLY ASSEMBLED SINCE 18/06/2018

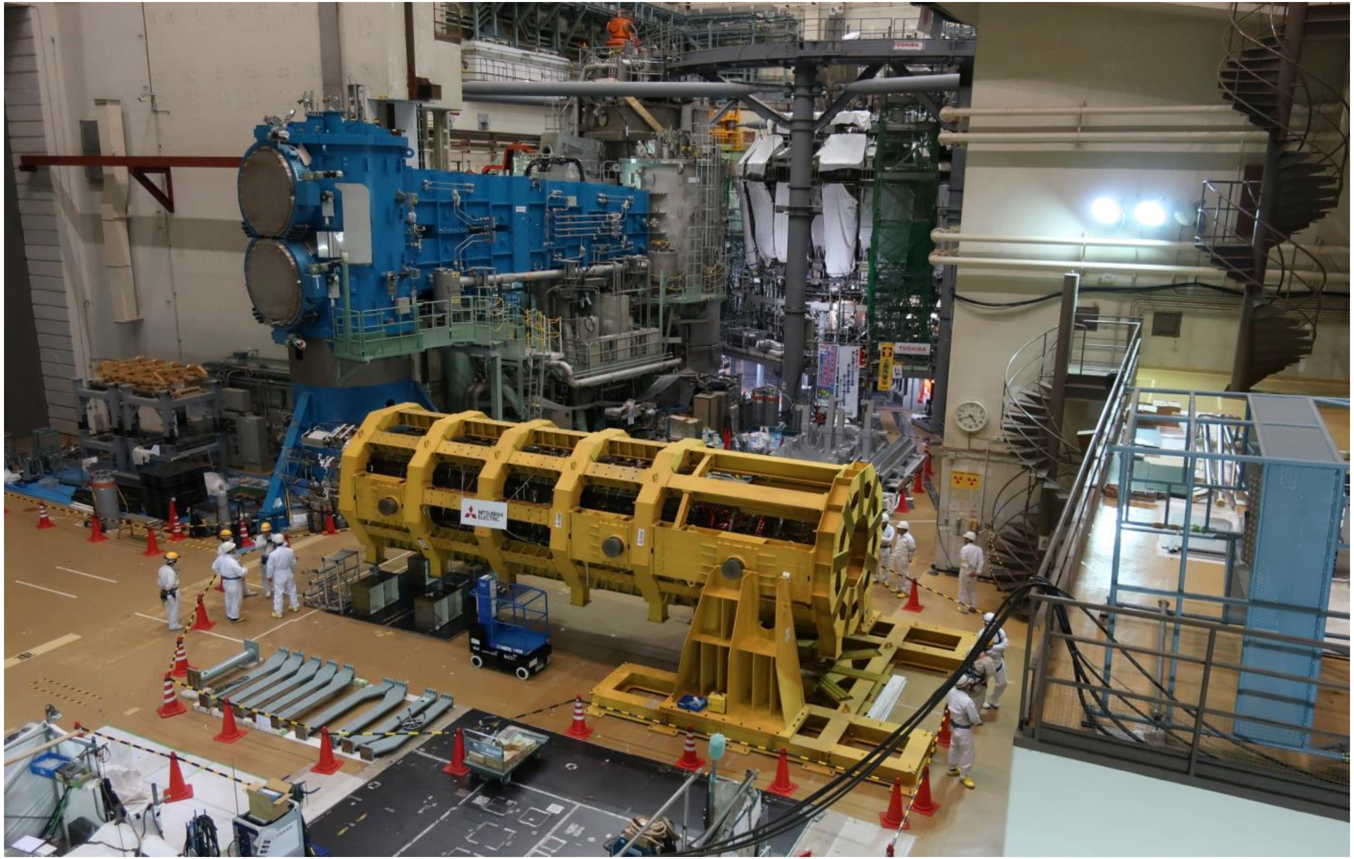


JT-60SA CRYOGENIC SYSTEM (CEA/F4E)



ANNEX 5

JT-60SA CS DELIVERED TO NAKA 16/03/2019



JT-60SA CS INSERTED