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

JOULE ENERGY ESTIMATION WITH SUPERMAGNET AND STREAM

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1) Introduction

2) Normal length estimation from voltage measurement

3) Numerical and analytical quench models

4) JT-60SA TFC02 acceptance quench test in Cold Test Facility analysis

5) JT-60SA TFC quench in Tokamak environment: predictive calculation

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

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.

Copper matrix

0,8 mm

22 mm

26 mm

≈8 m

NbTi filaments

Strand

CICC (Cable-In-Conduit-Conductor) cooled by supercritical helium forced-flow

WP (Winding Pack)

TFC (Toroidal Field Coil)

He inlet

He outlet

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

18 TF coils and 2 spare coils were tested for:

- Acceptance tests before delivery
- Quench phenomenon investigations

Helium temperatures at Winding Pack inlet and outlet

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

\[ V_{b,DP}(t) = L_{DP} \frac{dl(t)}{dt} + M_{dp} \frac{dlp(t)}{dt} + R_{DP}(t) I(t), \]

Inductive voltage due to the mutual inductance between coil and passive structures were estimated negligible \( (M_{DP} \frac{dlp(t)}{dt} \approx 0 \text{ V}) \) using an analytical method.

Application to TFC02 acceptance quench test

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

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

[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:
  \[ R_p(t) = \frac{R_{DP}(t)}{2} = \frac{V_{DP,\text{resistive}}(t)}{2 I(t)} \]

- Maximal conductor temperature calculation: \( T_{\text{cond,max}}(t) \)
  
  Initial condition: \( T_{\text{cond,max}}(t = 0) = T_{cs} \)

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

- Linear temperature profile assumption:
  
  Boundary condition: \( T_{\text{cond}}(t, x = 0) = T_{\text{cond,max}}(t) \)

  \[ \frac{dT_{\text{cond}}(t, x)}{dx} = \frac{T_{cs} - T_{\text{cond,max}}(t)}{L_q(t)} \]

- Predicted and measured resistances comparison

- CICC normal length evolution at each time step

\[ [2] \text{Y. Huang, ‘Study and modelling of the thermohydraulic phenomena taking place during the quench of a superconducting magnet cooled with supercritical helium’, p. 179, 2019} \]
3.1) TF COIL AND CRYODISTRIBUTION SUPERMAGNET MODEL

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

FLOWER modelisation of the cryodistribution
(pump, heat exchanger, quench relief tank, valves and heater)

\[ q_{\text{PowerLoss,CTF}} = \frac{f_{EU} \lambda_f R e P_r^{1/3}}{8 D_R} \]

\[ q_{\text{InterturnCoupling}} = \frac{\Delta T_{(\text{turn1-turn2})}}{R_{th}} \]

Quench primary detection: voltage threshold \( U_{\text{detec}} = 0.1 \text{ V} \)
Current discharge \( (I(t) = I_0 e^{-t/\tau}) \) triggers after quench detection and action time \( (\tau_{da} = 0.1 \text{ s}) \)

\[ \rightarrow \text{Developed numerical SuperMagnet model of JT-60SA TF coil and its cryodistribution} \]

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:

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

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

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

$$\frac{\Delta p}{p_0} = \frac{r \rho_0 \alpha_0 j_0^2 L_{q,ini}}{2 p_0 v_q(t_m)} > 1$$

$$v_q(t) = \frac{dL_q(t)}{dt} = 0.766 \left( \frac{2 D_h}{f} \right) \left( \frac{r L_{q,ini} \alpha_0 j_0^2}{c_0} \right) \frac{1}{t^\frac{5}{3}}$$

$$L^2 > \frac{24 D_h c_0^2 t_m}{f v_q(t_m)}$$

$$\alpha_0 = \min_{T=[T_{cr}:300]} \left( \frac{A_{Cu} \eta_{Cu}(T)}{A_{cond} \rho_{cond} C_{cond}(T) + A_{jacket} \rho_{jacket} C_{jacket}(T)} \right)$$

4.1) TFC02 ACCEPTANCE TEST: QUENCH PROPAGATION

- 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 (\( v_q \approx 50 \text{ m/s} \)) by a quench propagating through electrical inter-pancake joints

- Magnetic field and current sharing temperature profiles

- Normal length propagation (SM, STREAM, Exp)

- Quench propagation test, double-pancake resistance (Exp)
4.2) TFC02 ACCEPTANCE TEST: ELECTRICAL RESULTS

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

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

- **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.

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

\[
E_{\text{Coil,SM}} = \sum_{i=1}^{i=N_{\text{tot}}} E_{Pi} = \sum_{i=1}^{i=N_{\text{tot}}} \int_{0}^{t_{\text{end}}} \int_{0}^{L_{q}(t)} R_{Pi}(x, t) I(t)^2 \, dx \, dt
\]

\[
E_{\text{Coil,SM, conservative}} = N_{\text{tot}} \, E_{Pi, \text{max}} = 2.20 \, \text{MJ}
\]
4.3) TFC02 ACCEPTANCE TEST : THERMOHYDRAULICAL RESULTS

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

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

**Hydraulic 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 hydraulic 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.
5.2) JT-60SA TFC IN TOKAMAK: QUENCH PROPAGATION VELOCITIES & RESISTANCES

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

\[ v_{q,P6,SM} = v_{q,P10,SM} = v_{q,P12,SM} = 15.7 \text{ m/s} \quad 0 \text{ m} < \text{NL} < 29 \text{ m} \]
\[ v_{q,P6,SM} = v_{q,P10,SM} = 12.3 \text{ m/s} < v_{q,P12,SM} \quad 29 \text{ m} < \text{NL} < 48 \text{ m} \]
\[ v_{q,P6,SM} = 9.4 \text{ m/s} < v_{q,P10,SM} = 10.9 \text{ m/s} < v_{q,P12,SM} \quad 48 \text{ m} < \text{NL} < 113 \text{ m} \]

The analytical quench propagation velocity \( v_{q,STREAM} = 14.7 \text{ m/s} \) allows to predict a coil resistance dynamic matching the SuperMagnet calculation.
5.3) JT-60SA TFC IN TOKAMAK: CALCULATED JOULE ENERGY & TEMPERATURE

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

Quench maximal conductor temperature criteria:

\[ T_{\text{cond, max, numeric}} = 60.29 \text{ K} < 150 \text{ K} \] (criteria for non-adiabatic conductor exchanging heat with helium and jacket)

Quench criticality:

\[ v_{q,P1,SM} = 19.5 \text{ m/s} \Rightarrow E_{P1,SM} = 0.585 \text{ MJ} \Rightarrow T_{\text{cond,P1(inlet),SM}} = 60.29 \text{ K} \]
6) **CONCLUSION**

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

**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 robustness and capacity to simulate the quench phenomenon against experimental data.

**Quench phenomena analysis:**
Further investigations and numerical simulations will be carried 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**.
Thank you for your attention


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

\[
\begin{align*}
\frac{dT_{\text{cond}}(t)}{dt} &= \frac{\eta_{\text{Cu}}(t) L_q(t)}{A_{\text{Cu}}} \left( I(t)^2 - h_{\text{conv}} P_{w,\text{cond}} L (T_{\text{cond}}(t) - T_{\text{He}}(t)) \right) \\
\frac{dT_{\text{He}}(t)}{dt} &= \frac{h_{\text{conv}} P_{w,\text{cond}} (T_{\text{cond}}(t) - T_{\text{He}}(t)) - h_{\text{conv}} P_{w,\text{jacket}} (T_{\text{He}}(t) - T_{\text{jacket}}(t))}{A_{\text{He}} \rho_{\text{He}}(t) C_{v,\text{He}}(t)} \\
\frac{dT_{\text{jacket}}(t)}{dt} &= \frac{h_{\text{conv}} P_{w,\text{jacket}} (T_{\text{He}}(t) - T_{\text{jacket}}(t))}{A_{\text{jacket}} \rho_{\text{jacket}} C_{\text{jacket}}(t)}
\end{align*}
\]
STREAM: second law of thermodynamics, energy and mass conservative relations describe the 1-D expelled helium flow from the coil

\[
\begin{align*}
\frac{dH}{2} + \frac{dc^2}{2} &= \delta Q_e \\
Tds &= \delta Q_e + \delta Q_f \\
D &= \rho \ c \ A = Cst
\end{align*}
\]

\[
\frac{d\rho}{\rho} + \frac{dc}{c} + \frac{dA}{A} = 0
\]
ANNEX 3

JT-60SA TF COIls FULLY ASSEMBLED
SINCE 18/06/2018
ANNEX 4

JT-60SA CRYOGENIC SYSTEM (CEA/F4E)

- Cryogenic Hall
- Compressor Building
- Six He gas storage vessels
- LN$_2$ tank
ANNEX 5

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