Quench Tests Analyses of the First JT-60SA Toroidal Field Coils

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Context (JT-60SA)

Fusion energy:

**Fusion reactions:**

*Deuterium + Tritium*

\[ \text{He}4 (3.56\text{MeV}) + \text{neutron} (14.03\text{MeV}) \]

*Deuterium + Deuterium*

\[ \text{He}3 (0.82\text{MeV}) + \text{neutron} (2.45\text{MeV}) \]

(plasma state: high temperature \(\sim 10^8\) K)

**Fusion approaches:**

*Magnetic confinement*

- tokamak (donut shaped chamber)
- spherical tokamak
- stellarator, etc

**Inertial confinement** (lasers’ high energy)

- direct drive
- indirect drive, etc
Context (JT-60SA)

International fusion project prospects\(^{(1)}\):

*First step:* scientifically feasible (1970s ~ 2000)
e.g. TFTR, JET, JT-60U

*Second step:* technically feasible
e.g. ITER\(^{(2)}\), 2005~2025 construction;

*Third step:* commercially feasible
e.g. DEMO, design & concept.

(1) «Fusion – The energy of the universe», Garry McCracken & Peter Stott
(2) International Thermonuclear Experimental Reactor
Context (JT-60SA)

**Fusion experiment: JT-60SA**

**Background:** JT-60U (copper coils)

**Participants:**
- Europe (18 Toroidal Field coils: fabrication and tests)
- Japan (existing infrastructure JT-60U + other components)

**Role:** Support to the operation of ITER
- Addressing key physics issues for ITER & DEMO

**My topic:**
- **Quench test** analyses of the first JT-60SA Toroidal Field (TF) Coils

**Quench:** electrical conductor’s sudden transition from superconducting state to normal resistive state
**Instrumentation**

**Configuration of TF coils:**
- 4.5 x 7.5 m;
- ~ 16 t;
- 12 pancakes stacked;
- 113 m long / pancake
Instrumentation

**Cold Test Facility (CEA Saclay):** cryostat, valve box, helium refrigerator, power supply, rapid acquisition system, etc

<table>
<thead>
<tr>
<th>N° TF coil</th>
<th>Manufacturer</th>
<th>Test date</th>
<th>N° DP quench</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>France</td>
<td>19/02/2016</td>
<td>DP6</td>
</tr>
<tr>
<td>10 (bis)</td>
<td>France</td>
<td>25/02/2016</td>
<td>DP1</td>
</tr>
<tr>
<td>11</td>
<td>France</td>
<td>11/04/2016</td>
<td>DP6</td>
</tr>
<tr>
<td>12</td>
<td>France</td>
<td>11/07/2016</td>
<td>DP1</td>
</tr>
<tr>
<td>13</td>
<td>France</td>
<td>04/10/2016</td>
<td>DP4</td>
</tr>
<tr>
<td>14</td>
<td>France</td>
<td>03/11/2016</td>
<td>DP3</td>
</tr>
<tr>
<td>15</td>
<td>France</td>
<td>09/02/2017</td>
<td>DP2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>N° TF coil</th>
<th>Manufacturer</th>
<th>Test date</th>
<th>N° DP quench</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Italy</td>
<td>07/06/2016</td>
<td>DP5</td>
</tr>
<tr>
<td>03</td>
<td>Italy</td>
<td>31/08/2016</td>
<td>DP6</td>
</tr>
<tr>
<td>04</td>
<td>Italy</td>
<td>28/11/2016</td>
<td>DP6</td>
</tr>
<tr>
<td>05</td>
<td>Italy</td>
<td>12/01/2017</td>
<td>DP6</td>
</tr>
<tr>
<td>06</td>
<td>Italy</td>
<td>13/03/2017</td>
<td>DP3</td>
</tr>
</tbody>
</table>
Instrumentation

Operating conditions **CTF:**
- Tinlet 4.7 K => 7.5 K
- Pressure ~10 bar
- Nominal current 25.7 kA
- Peak field ~ 3 T
## Data

### Instrumentation of CTF

#### Cryogenic system

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE2414</td>
<td>WP inlet temperature</td>
</tr>
<tr>
<td>TE2432</td>
<td>WP outlet temperature</td>
</tr>
<tr>
<td>TE9844</td>
<td>DP6 outlet temperature</td>
</tr>
<tr>
<td>TE9845</td>
<td>DP1 outlet temperature</td>
</tr>
<tr>
<td>TE9846</td>
<td>Joint DP3-4 outlet temperature</td>
</tr>
<tr>
<td>PT2416</td>
<td>WP inlet pressure</td>
</tr>
<tr>
<td>PT2424</td>
<td>WP outlet pressure</td>
</tr>
<tr>
<td>P_Capa_C</td>
<td>Helium container pressure</td>
</tr>
</tbody>
</table>

#### Electrical system

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vb1</td>
<td>DP1 voltage</td>
</tr>
<tr>
<td>Vb2</td>
<td>DP2 voltage</td>
</tr>
<tr>
<td>Vb3</td>
<td>DP3 voltage</td>
</tr>
<tr>
<td>Vb4</td>
<td>DP4 voltage</td>
</tr>
<tr>
<td>Vb5</td>
<td>DP5 voltage</td>
</tr>
<tr>
<td>Vb6</td>
<td>DP6 voltage</td>
</tr>
<tr>
<td>U_Jb1-2</td>
<td>Joint DP1-2 voltage</td>
</tr>
<tr>
<td>U_Jb2-3</td>
<td>Joint DP2-3 voltage</td>
</tr>
<tr>
<td>U_Jb3-4</td>
<td>Joint DP3-4 voltage</td>
</tr>
<tr>
<td>U_Jb4-5</td>
<td>Joint DP4-5 voltage</td>
</tr>
<tr>
<td>U_Jb5-6</td>
<td>Joint DP5-6 voltage</td>
</tr>
<tr>
<td>U_SL1</td>
<td>Feeders DP1-valve box voltage</td>
</tr>
<tr>
<td>U_SL2</td>
<td>Feeders DP6-valve box voltage</td>
</tr>
<tr>
<td>Vpick</td>
<td>Pick-up coil voltage</td>
</tr>
</tbody>
</table>

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**Temperature measurements of TFC11**

**Voltage measurements of TFC11**
Data exploitation

Transit resistance for double-pancakes: method by **pick-up coil compensation**
Faraday’s law of induction => **eddy currents** induced by changing magnetic field
  => create another magnetic field to oppose the original one

**Calculation of transit resistance** $R_{DP}$ **with the pick-up coil compensation**:

$$U_{DP\, mes} = U_{DP\, inductive} + I_{mes} \times R_{DP}$$

With

$$U_{DP\, inductive} = L_{total} \times \frac{dl}{dt} \propto U_{pick\, up} (v)$$

Notes: with the test Fast Discharge (Coil 10), the ratio $\gamma$ can be determined

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**Voltage measurements of TFC11**

- **$U_{pick\, up}$**
- **$L_{total} \times \frac{dl}{dt} + I_{mes} \times R_{DP}$**
Data exploitation

Transit resistance for double-pancakes: method by *pick-up coil compensation*

Faraday’s law of induction \( \Rightarrow \) *eddy currents* induced by changing magnetic field

\( \Rightarrow \) create another magnetic field to oppose the original one

Faraday's law of induction:

\[
\text{Faraday's law of induction} = \nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t}
\]

Top view of coil

*Pick-up coil*

\[ U_{\text{pick up}} \]

*Eddy current*

\[ I_{\text{eddy}} \]
Quench dynamics (TFC11)

Transit resistances of TFC11

4 quench dynamic phases:
- Quench **initiation** phase

Source: TFC11 quench test, 11 avril 2016
First phase: quench initiation phase

Quench dynamics (TFC11)
Quench dynamics (TFC11)

**First phase**: quench initiation phase

\[ R_{DP} = \rho_{Cu}(RRR, T, B) \times \frac{l_{tr}}{S_{Cu}} \]

*(Before fast discharge: RRR, T, B are constants)*

\[ v_l = \frac{l_{tr}}{\Delta t_{ini}} = 3.5 \text{ m/s} \]
First phase: quench initiation phase

**R_D_P initiation phase**

- **T\textsuperscript{Casing} = 15 K**
- **T\textsuperscript{Winding} = 7.5 K**
- 6 turns in 1 pancake (1 conductor)

- **Casing (SS)**
- **Insulation (G10)**

**R_D_P (mOhm)**

**Time (s)**
Quench dynamics (TFC11)

4 quench dynamic phases:
- Quench initiation phase
- Quench acceleration phase

Transit resistances of TFC11

Source: TFC11 quench test, 11 avril 2016
Quench dynamics (TFC11)

**Second phase:** quench acceleration phase

**Graph:**
- **R_Dp acceleration phase**
  - R1 (mOhm) in blue
  - R6 (mOhm) in orange

**Axes:**
- **R_Dp (mOhm)** on the y-axis
- **Time (s)** on the x-axis
Quench dynamics (TFC11)

Second phase: quench acceleration phase

\[ v_{l6} = \frac{L_{tot} - l_{tr}}{\Delta t_{accel}} = 32.2 \text{ m/s} \]

\[ v_{l1} = \frac{L_{tot} - l_{tr}}{\Delta t_{accel}} = 45.6 \text{ m/s} \]
Quench dynamics (TFC11)

Second phase: quench acceleration phase

R_DP acceleration phase

- Eddy current (Stainless Steel)
- Casing (SS)
- Insulation (G10)
- DP6 (P12 & P11)
- DP5 (P10 & P9)
- DP4 (P8 & P7)
- DP3 (P6 & P5)
- DP2 (P4 & P3)
- DP1 (P2 & P1)

6 turns in 1 pancake (1 conductor)
Quench dynamics (TFC11)

- Quench initiation phase
- Quench acceleration phase
- Simultaneous transition phase for latter quenched pancakes

Source: TFC11 quench test, 11 avril 2016
Quench dynamics (TFC11)

**Third phase**: simultaneous transition phase for latter quenched pancakes

![Graph showing R_DP simultaneous transition phase](image)
Quench dynamics (TFC11)

**Third phase:** simultaneous transition phase for latter quenched pancakes

**Reverse flow effect**

0~2s: \( \dot{m}_{\text{reverse flow}} = 50 \text{ g/s} \sim 75 \text{ g/s} \)

\( t_{\text{quench num}} = 6830 \text{s} \)

\( t_{\text{quench exp}} = 0 \text{s} \)

0~2s: \( v_{\text{reverse flow}} = -10 \sim -15 \text{ m/s} \)
Quench dynamics (TFC11)

4 quench dynamic phases:
- Quench initiation phase
- Quench acceleration phase
- Simultaneous transition phase for latter quenched pancakes
- Quench saturation phase

Source: TFC11 quench test, 11 avril 2016
Quench dynamics (TFC11)

**Last phase:** quench saturation phase

![Graph showing R_DP saturation phase](image)
Quench dynamics (TFC11)

Last phase: quench saturation phase

Global decrease of $R_{DP}$: $\sim 0.02\text{mΩ}$ during 6.0 s

$R_{DP}$ saturation phase

Current discharge from 16 kA to 7 kA during 6.0 s

$\Rightarrow$ Decrease of Magnetic field $B$
Conclusions

- **Successful quench tests for 12 JT-60SA TF coils (update today)**
- **A quasi-complete database and a correct way for data exploitation**
- **Experimental analyses for all possible quench dynamics**
- **Already some verifications with modeling results**

**Prospects for next step** (Quasi-3D computation codes for modeling quench behavior):
- **THEA** (Thermal Hydraulic and Electric Analysis of superconducting cables) for 1D thermo-hydraulic modelling along the CIC (Cable-In-Conduit) conductor
- **Cast3M** for 2D transverse thermal diffusion in a limited number of coil cross-sections
Thank you for your attention!