AC losses in JT-60SA TF magnet during commissioning: experimental analysis and modeling

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ABSTRACT

• JT-60SA tokamak Integrated commissioning started in April 2020, superconducting magnets tests from January to March 2021
• Toroidal Field (TF) magnet successfully achieved 25.7 kA nominal current
• TF current tests create AC losses in TF winding pack (WP) and casing
• Losses estimated from enthalpy balances using TF He inlet/outlet sensors
• Theoretical calculation of hysteresis and coupling losses in the WP and eddy currents losses in the casing
• Comparison between experimental and theoretical energy values

AC LOSSES MODELING

• Hysteresis losses computed as in [1] (Traps field map [2], B. Turck analytical formulae [3], def=18 µm [4] and Jc(B,T) measured in [5]).
• Coupling losses computed with \( P = \pi R_B^2 \mu_0 \) (TF discharge time constant > 10 s >> \( \tau \)). We assume \( \pi R_B^2 \mu_0 = 1/(aB + b) \) and \( b = \) deduced from \( \pi \tau (5.65 T) = 279 \) ms (Sultan [5]) and \( \tau = (0.5 T) = 604 \) ms (CEA [6]). To account for field orientation, we use \( P = \pi R_B^2 (aB^2 + \) x)
• Eddy currents losses in TF casing are computed through solving of RL circuits equations with data from [8]

\[
\begin{align*}
R_{c,\text{cass}} + L_{c,\text{cass}} \frac{dI_{c,\text{cass}}}{dt} + M_{c,\text{cass}} \frac{dI_{c,\text{cass}}}{dt} = -M_{c,\text{cass}} \frac{dI_{c,\text{cass}}}{dt} \\
R_{y,y} + L_{y,y} \frac{dI_{y,y}}{dt} + M_{y,y} \frac{dI_{y,y}}{dt} = -M_{y,y} \frac{dI_{y,y}}{dt}
\end{align*}
\]

\[ E_c[I] = \int P_{cass} \text{d}t = \int R_{c,\text{cass}} I_{c,\text{cass}}^2 \text{d}t \]

Inner leg (IL) of casing is shorter and thinner than its outer leg (OL) → 43% of total power is generated in IL and 57% in OL → average power per unit volume is 1.55 times higher in IL than in OL.

SYNTHESIS AND COMPARISON EXPERIMENT VS MODELING

• Theoretical transient heat loads computed with AC losses modeling and joints Joule losses estimate from \( R_{\text{TF joints}} \).
About 90% of the load is due to eddy currents losses in TF casings
• Comparison between total experimental and theoretical transient heat load show a fair agreement in the 5-15% range even with a conservative estimate of the joints contribution
• WP absorbs about 50 % of the load while 90 % of it is generated in casing → casing heats WP
• Lorentz forces increase this effect

EXPERIMENTAL DATA ANALYSIS

• Enthalpy balances of Helium flow in TF WP and casing during fast discharge tests allow AC losses determination (transient heat loads)
Simplified scheme of Helium mass-flow, temperature and pressure sensors is shown on the right.

\[
\begin{align*}
\Delta H_{\text{WP}}[\text{W}] &= \dot{m}_{\text{WP}} h(T_{\text{out,WP}}, P_{\text{out,WP}}) - h(T_{\text{in,WP}}, P_{\text{in,WP}}) \\
\Delta H_{\text{Cas}}[\text{W}] &= \dot{m}_{\text{Cas}} h(T_{\text{out,Cas}}, P_{\text{out,Cas}}) - h(T_{\text{in,Cas}}, P_{\text{in,Cas}})
\end{align*}
\]

<table>
<thead>
<tr>
<th>( I_{FD} ) [kA]</th>
<th>( \tau_{FD} ) [s]</th>
<th>Transient heat loads [kJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP</td>
<td>Cas</td>
<td>WP</td>
</tr>
<tr>
<td>10</td>
<td>14.9</td>
<td>1114</td>
</tr>
<tr>
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<td>2471</td>
</tr>
<tr>
<td>18</td>
<td>12.6</td>
<td>3859</td>
</tr>
</tbody>
</table>

Results for different fast discharge (FD) currents \( I_{FD} \).

TF fast discharge time constants \( \tau_{FD} \) are decreasing with increasing \( I_{FD} \) because \( \tau_{FD} = L_{\text{TF}}/R_a \) and the higher \( I_{FD} \) the higher the energy dissipated in the dump resistance \( R_d \), so the higher its effective temperature and resistance.

• Joints Joule losses participate in transient heat loads during TF current tests so their total resistance \( R_{\text{TF joints}} \) needs to be determined
At the end of the plateau at nominal current, from an enthalpy balance we determine \( R_{\text{TF joints}} = 573 \) nΩ. This value is conservative since the stationary regime is not completely reached (see plot above).

CONCLUSION

• AC losses modeling in fair agreement with JT-60SA experimental results
• Major contribution of casing eddy currents and large redistribution to WP
• Consistency of observation with AC losses study in CTF [1]

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