AC Loss in the DEMO TF React&Wind Conductor Prototype no. 2

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Outlook

• React & wind conductor for DEMO TF/CS
• AC loss measurement using sinusoidal AC field
• AC loss measurement using trapezoidal AC pulsed field
TF coil options of EU DEMO

WP#1
• React & Wind (low strain)
• Layer winding (grading)
• No radial plates

WP#2
• Wind & React
• Double-Layer winding (grading)
• No radial plates

WP#3
• Wind & React
• Pancake winding
• No radial plates

WP#4
• Wind & React
• Pancake winding
• Radial plates
React & Wind (RW) Conductor

- Much lower thermal strain in Nb$_3$Sn ($\varepsilon_{\text{eff}}^{\text{RW}} \approx -0.3\%$ vs. $\varepsilon_{\text{eff}}^{\text{ITER TF}} \approx -0.7\%$).

- Layer winding with grading
  - Grading in superconductor $\Rightarrow$ saves expensive Nb$_3$Sn
  - Grading in steel $\Rightarrow$ saves radial build (overall DEMO size)

- Longitudinally welded steel jacket
  - Large flexibility in the jacket shape and wall thickness
  - Jacketing done after heat treatment $\Rightarrow$ welds not exposed to high temperatures
RW 1 prototype (2015-2016):
• Based on 2013 DEMO reference
• 13.5 T, 82.4 kA.

RW 2 prototype (2017-2019):
• Based on 2015 DEMO reference
• 12.23 T, 63.3 kA.

Segregated Cu-wires

Steel strip

Cu/CuNi mixed matrix
Brass profile
“loose” cable in the conduit (0.3 mm)

Half-size mixed matrix
ENEA, Tratos; “tight fit”

Full-size mixed matrix
WST, China; cable “preloaded” (-0.4 mm)

\[ RRR_{\parallel} = 45 \]
\[ RRR_{\perp} = 19 \]

\[ RRR_{\parallel} = 400 \]
\[ RRR_{\perp} = 140 \]
• Jacketing – welding after the heat treatment.
• Cable space 0.4 mm thinner compared to the cable thickness.
"Full Profile" sample:

- Highest $T_{cs}$
- Stable DC performance
“Full Profile” sample:
• Highest AC loss (due to low $R_\perp$ of MM)
• No drop of AC after cyclic loading

“Half Profile” sample:
• Medium AC loss (moderate $R_\perp$ of MM; cut of MM profile in two halves)

“Brass” sample:
• Lowest AC loss dominated by coupling loss in the cable.
Fitted $n\tau$

$\tau$ normalized to cable + mixed matrix stabilizer area:

<table>
<thead>
<tr>
<th></th>
<th>RW2_brass</th>
<th>RW2_HP</th>
<th>RW2_FP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n\tau_{perpend}$</td>
<td>17 ms</td>
<td>98 ms</td>
<td>1060 ms</td>
</tr>
<tr>
<td>$n\tau_{parallel}$</td>
<td>3 ms</td>
<td>22 ms</td>
<td>50 ms</td>
</tr>
</tbody>
</table>
The coupling currents loss for the multistage CS and PF conductors of ITER and DEMO are largely overestimated when the $n\tau$ coupling loss constant derived from the initial slope of the loss curve is applied.

\[ Q = \frac{B_0^2 \pi \omega n \tau}{\mu_0} \]

AC Loss – Problem with Multistage CICC

\[ Q = \frac{B_0^2 \pi \omega n \tau}{\mu_0} \]

Fit based on \( n\tau \) extracted at low frequencies

**Proposed solution:**

Measure AC loss for linear dB/dt ramp (trapezoidal AC field pulse)

\[ Q = \frac{\dot{B} \Delta B n \tau_{\text{pulse}}}{\mu_0} \]

and extract effective \( n\tau_{\text{pulse}} \), which a function of the ramp-up time \( T \).

AC Loss – Trapezoidal

RW2_FP trapezoidal AC loss
B = 2T, T = 4.5 K

Full Profile

Parallel

Perpendicular

Perpendicular

0.4T, 4.5K

0.3T, 4.5K

T=0.8 s

0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13
0.14
0.15
0.16
RW2_HP trapezoidal AC loss
B = 2T, T = 4.5 K

Half Profile

Perpend. Field

ΔB = 0.4 T

ΔB = 0.3 T

Parallel Field

ΔB = 0.4 T

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Conclusions

- AC loss of the RW2 conductor:
  - For mixed matrix stabilizer dominated by eddy current loss.
    ➔ MM will be replaced by a highly compacted Rutherford cable of cladded Cu wires.
  - The coupling current loss in the cable alone is very small due to:
    - Flat cable geometry.
    - Stainless steel strip inserted between the 2 rows of the sub-bundle layers.
  - Once eddy currents in the segregated stabilizer will be reduced, the cable will be suitable also for the CS conductors.
  - Usage of effective $nτ_{pulse}$, experimentally determined from the trapezoidal field pulse, is expected to lead to more realistic and precise predictive calculation of the AC loss.
Thanks for your attention!
Steady state: a sinus sweep with variable frequency is applied as long as stable temperature gradient is established downstream of the AC field. The AC power loss is proportional to $\Delta T \cdot \frac{dm}{dt} \rightarrow \text{“Loss curve” } \rightarrow \text{ initial slope } \rightarrow n\tau_{\text{sinus}}$

Transient: a trapezoidal pulse with variable ramp time, $T$, is applied with a long flat top. The temperature increase is integrated. The AC energy loss is proportional to $\rightarrow n\tau_{\text{pulse}}(T)$