Coupling loss in prototype CFETR CS conductors with different cable patterns, measurement and modeling

Anvar. V.A\textsuperscript{1,2}, T. Bagni\textsuperscript{1}, K.A. Yagotintsev\textsuperscript{1}, J. Qin\textsuperscript{3}, Y. Wu\textsuperscript{3}, A. Devred\textsuperscript{4}, M.S.A. Hossain\textsuperscript{2}, C. Zhou\textsuperscript{1}, A. Nijhuis\textsuperscript{1}

\textsuperscript{1} University of Twente, Faculty of Science & Technology, 7522 NB Enschede, The Netherlands
\textsuperscript{2} University of Wollongong, Wollongong, Australia
\textsuperscript{3} Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China
\textsuperscript{4} ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St. Paul Lez Durance Cedex, France

August 27 – September 1, 2017
Outline

• Introduction
• Experiments
• JackPot – Modeling
• Results
• Conclusion
**Introduction**

- CFETR stands for “China Fusion Engineering Test Reactor”
- CS – Central solenoid
  - 6 Coils made of Nb$_3$Sn strands, 0.82 mm diam.
  - Design requirement CFETR CS model coil: 12 T peak field

<table>
<thead>
<tr>
<th></th>
<th>New ASIPP cable design - Triplet modification</th>
<th>New Twente Cable Design</th>
<th>ASIPP CSMC cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample state</td>
<td>Virgin (2)</td>
<td>Virgin</td>
<td>Virgin (2)</td>
</tr>
<tr>
<td></td>
<td>Press – Initial state (1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cable pattern</td>
<td></td>
<td>(2Sc + 1Cu) x 3 x 4 x 4 x 6</td>
<td></td>
</tr>
<tr>
<td>Twist length (mm)</td>
<td>(40/10)x49x89x160x450</td>
<td>50x58x66x76x450</td>
<td>20x50x80x150x450</td>
</tr>
<tr>
<td>Void fraction</td>
<td>32</td>
<td>28</td>
<td>33.4</td>
</tr>
<tr>
<td>Outer diam. (mm)</td>
<td>32.6</td>
<td>31.6</td>
<td>32.6</td>
</tr>
</tbody>
</table>
Introduction

Cable patterns

New triplet ASIPP cable design - triplet modification only in first stage by shorter twist pitch for copper strand

Regular ITER CS cable design for CICC cables with same twist pitch for all strands in same stage
Experiment - Ac loss Measurement

Sample preparation

- Cryostat
- Calorimeter outlet to massflow meter
- Calorimeter (sample is mounted inside)
- Helium gas outlet
- Connection for vacuum pump
- Liquid He bath
- Sample, PU and CC
- Sample chamber
- Superconducting dipole magnet
- Heater
- Cryostat
- Pick up coil (PU)
- Individual Strands
- Central hole for Liquid helium flow
- er Jacket
- Compensation coil (CC)
- Connections from PU, CC and Heater
- He gas outlet to Massflow meter
- Sample at 4.2 K
14 Nb$_3$Sn strands are selected at random from different petals

- After heat treatment (brittle)
- Four-point measurement using current of 20 – 30 A.
JackPot - ACDC CICC cable model

- Inter-strand contact resistance distribution from contact area
- Strand’s mutual inductances
- Coupling with self & background field
- Strand properties scaling law $I_c(B, T, e)$ & n-value

Cable / joint model describing all (>1000) strand trajectories in CICC; including cable compaction steps.

Cable cross section from JackPot simulation
Results

AC loss - Experiment

- New triplet - Virgin 1
- New triplet - Virgin 2
- New triplet - Initial state
- Twente Virgin
- CSMC Virgin CB
- CSMC Virgin CD

ASIPP CS conductors

Ba 0.15 T Bdc 350 T
$R_c$ Results

Resistance measurement - Experiment

Intra-petal $R_c$ expected range. Inter-petal $R_c$ very low (unintended low petal wrap coverage, 40%)

Large spread in $R_c$ of direct neighboring petals due to direct interstrand contacts (locally no petal wrap coverage)

$R_c$ distribution measured for New Triplet design somewhat unexpected, confirmation needed.

Intra-petal $\rightarrow$ within a petal
Inter-petal $\rightarrow$ between petals

Twente Cable

CSMC cable design

New Triplet ASIPP cable
Results JackPot

Coupling loss Experiment and Modelling

AC coupling loss calculated by JackPot based on realistic $R_c$ distributions founded on large experimental data base.
Results JackPot

Interstrand Resistances: Experiment and Coupling loss Modelling

$R_c$ measurements and JackPot model in good agreement for Twente & CSMC

$R_c$ measurements - New Triplet design: data confirmation needed on values and distribution (petal wrap coverage petals 40 instead of 70%).
## Results Comparison

<table>
<thead>
<tr>
<th></th>
<th>New triplet ASIPP Cable Design</th>
<th>Twente cable Design</th>
<th>CSMC ASIPP cable Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupling loss time constant $n\tau$ [ms]</td>
<td>3900</td>
<td>1110</td>
<td>770</td>
</tr>
<tr>
<td>Inter-strand Resistance [$n\Omega \text{ m}$]</td>
<td>10</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Inter-petal Resistance [$n\Omega \text{ m}$]</td>
<td>13 – 16</td>
<td>20 – 30</td>
<td>80 – 150</td>
</tr>
<tr>
<td>Petal wrap Coverage (%)</td>
<td>70 (40)</td>
<td>70 (40)</td>
<td>70</td>
</tr>
<tr>
<td>Void fraction (%)</td>
<td>32</td>
<td>28 (22)</td>
<td>33.4</td>
</tr>
</tbody>
</table>
Comparison of experiments - SULTAN and TWENTE

Good agreement Sultan - Twente

Time constant ($n\tau$) represents the coupling loss

CICC is multiple time constant system

For single $n\tau$ concept, as mostly used, determined $n\tau$ value depends strongly on considered frequency range

Approach used here: initial slope $Q_{cpl}(f)$ curve (higher $n\tau$).
Conclusion

• New triplet ASIPP design, but also Twente design shows higher coupling loss than CSMC layouts.
• Void fraction doesn’t play much role in inter-strand resistances.
• Petal wrap coverage is one of the dominant factors determining intra-petal resistances, hence coupling loss
• No definitive conclusion about better geometry for CS cable at this stage. Multiple parameters varied unintended for different cable pattern variations; void fraction and petal wrap coverage.
• More work needed.
Thank you!