## DEMO Central Solenoid Design Based on the Use of HTS Sections at Highest Magnetic Field

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### Introduction

The present study aims to reduce the outer diameter of the CS coil for a maintained magnetic flux. The present study is based on:

- PROCESS output for the 2015 DEMO reference [1]
- CAD model of the full tokamak [2]
- Reference flat top equilibria [3]
- 10 layer wound sub-coils
- Use of HTS in highest field sub-coils
- Use of React & Wind NbS from operational strain -0.25%
- Use of NbTi in low field sub-coils
- Superconductor & stainless steel grading

### CS1 Winding Pack Design

- Height (mm) 5710
- R/L (mm) 1892/2821
- No of sub-coils 10
- \( \tau_{\text{in}} \) (T) 17.49
- \( I_{\text{Lg}} \) (kA) 4.75
- \( I_{\text{LR}} \) (kA) 7.948
- \( I_{\text{LR}}^2 \) (kA)
- Sketch of HTS cable for sub-coil 1

### Equilibrium Currents

Equilibrium currents for PreMag, SOF and EOF (2015 reference) [3]

<table>
<thead>
<tr>
<th>Sub-coil</th>
<th>( I_{\text{LR}} ) (kA)</th>
<th>( I_{\text{LR}}^2 ) (kA)</th>
<th>( I_{\text{LR}}^2 ) (kA)</th>
<th>St**</th>
<th>( \tau_{\text{in}} ) (T)</th>
<th>( I_{\text{Lg}} ) (kA)</th>
<th>( I_{\text{LR}} ) (kA)</th>
<th>( I_{\text{LR}}^2 ) (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1900.0</td>
<td>2587.9</td>
<td>831.4</td>
<td>RE-123</td>
<td>17.49</td>
<td>102.96</td>
<td>0.799</td>
<td>10.51</td>
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<tr>
<td>2</td>
<td>2045.5</td>
<td>2453.3</td>
<td>814.4</td>
<td>RE-123</td>
<td>15.74</td>
<td>94.38</td>
<td>0.800</td>
<td>10.64</td>
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<tr>
<td>3</td>
<td>2169.3</td>
<td>2850.5</td>
<td>784.0</td>
<td>NbS5</td>
<td>14.02</td>
<td>133.22</td>
<td>0.671</td>
<td>6.25</td>
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<tr>
<td>4</td>
<td>2279.9</td>
<td>2238.0</td>
<td>727.3</td>
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<td>12.22</td>
<td>73.44</td>
<td>0.726</td>
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<tr>
<td>5</td>
<td>2371.7</td>
<td>1954.4</td>
<td>693.3</td>
<td>NbS5</td>
<td>10.45</td>
<td>50.59</td>
<td>0.765</td>
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<tr>
<td>6</td>
<td>2454.1</td>
<td>1745.8</td>
<td>672.5</td>
<td>NbS5</td>
<td>8.68</td>
<td>36.05</td>
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<tr>
<td>7</td>
<td>2530.9</td>
<td>1553.2</td>
<td>658.0</td>
<td>NbS5</td>
<td>6.92</td>
<td>26.07</td>
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<tr>
<td>8</td>
<td>2600.8</td>
<td>1796.5</td>
<td>781.3</td>
<td>NbTi</td>
<td>5.19</td>
<td>94.86</td>
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<tr>
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<td>642.5</td>
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<td>15.80</td>
<td>0.585</td>
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</table>

To maintain a flux of 320 Vs at a reduced CS outer diameter it is necessary to increase the peak magnetic field. In all calculations, \( \tau_{\text{in}} = \frac{2 \cdot \text{A}}{\pi} \cdot \text{d} \) is kept at the value for the reference design, while positions and currents of PF coils and plasma are unchanged.

### Electromagnetic Analysis

The proposed CS1 winding pack geometry is the result of an iterative process using a 2D axis-symmetric Finite Element Model (FEM) in ANSYS. Field distribution and Lorentz forces are calculated for PreMag, SOF and EOF. For the calculation of the peak magnetic field, the model includes the positions and dimensions of two rows of conductors above and below the mid-plane of the CS1 module (see below).

Overall current densities in the 10 sub-coils with and without steel grading, \( R = 2.821 \text{ m} \) (with steel grading), \( R = 2.9235 \text{ m} \) (without steel grading).

### References


### Mechanical Analysis

Local model: Stainless steel grading

4 x 20 array of conductors to evaluate the distribution of mechanical stresses in the most demanding region of the winding pack. Lorentz and vertical forces transmitted from layers and modules above and below this array of conductors are imported from the electromagnetic model. Unbalanced vertical forces are included in the analysis. Largest vertical forces at EOF, however, CS1 is mechanically most demanding during pre-magnetization.

Variation of the hoop and the vertical stress in the steel components of the conductor row just above the mid-plane of the CS1 module.

Global model: Pre-compression structure

The global FEM simulates the pre-compression at room temperature by forcing a gap between the winding pack and the tie plates, and also the cold down to 4 K. A separation force of 350 MN at 4 K [3] is assumed for dimensioning the pre-compression tie plates (max. separation force of 94 MN during SOF).

The use of the superalloy Nitronic 50 [7, 8] would lead to a minimum radial thickness of the inner and outer tie plates of 139 and 87 mm, respectively (half cover of CS winding pack perimeter). A 5 mm gap (WP-tie plates) leads to a CS outer radius of 2.913 m.

### Conclusion

- The possible design of a CS1 WP with both superconductor and stainless steel grading has been worked out.
- The use of HTS cables in the 2 highest field sub-coils allows to reach higher magnetic fields necessary to maintain the magnetic flux in a CS coil of reduced outer diameter.
- The use of react & wind NbS5 conductors in the sub-coils at intermediate field leads to a more efficient use of this superconductor.
- The presented design maintains the magnetic flux of 320 Vs in the central plane of the CS coil with an outer radius \( 500 \text{ mm} \) smaller compared to the reference design [3].
- A preliminary estimate of the space required for the pre-compression structure is provided.

### Acknowledgement

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