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Central Solenoid Winding Pack Design

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The present study aims to reduce the outer radius of the central solenoid (CS) with respect to its nominal size specified by EUROfusion for a maintained CS magnetic flux. A reduced outer CS radius would allow the reduction of the overall size and cost of the DEMO magnet system. The proposed outline design of the winding pack for the CS1 module is based on layer winding. To achieve the same magnetic flux in a CS coil of significantly reduced outer radius the peak magnetic field at the CS conductors needs to be substantially increased. The use of high-temperature superconductors is therefore envisaged in the highest field sections of the CS coil. It is planned to use react & wind Nb_3Sn conductors for intermediate field sections and NbTi at the lowest fields. In order to make a most economic use of the superconductors the proposed winding pack design considers a superconductor grading.

Keywords: central solenoid, DEMO, high-temperature superconductor, superconductor grading, winding pack

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1. Introduction

The present CS design study is based on the PROCESS data [1] for the 2015 DEMO reference, still valid in 2016, the CAD model of the full tokamak [2] and the reference flat-top equilibria [3]. In a previous study [4], the inner and outer radii of the CS coil were varied for a constant magnetic flux generated by the CS coil. In these calculations, the overall current density was kept constant in all layers of each CS module, while different superconductors were considered for the high-, medium-, and low-field sections. The results [4] indicate that the use of high-temperature superconductors (HTS) would provide the possibility to increase the peak magnetic field and to generate the same magnetic flux with a CS coil of reduced outer diameter as compared to the PROCESS data [1].

2. Reference design

The CS coil is composed of five modules, namely CSU3, CSU2, CS1, CSL2 and CSL3 [2]. The inner and outer radii of all CS modules are 2.49 and 3.31 m, respectively. The peak magnetic field of the CS coil includes a contribution generated by the six PF coils and the plasma current, and depends on the considered plasma scenario. In the present work, the equilibrium currents I_{CSU3} = I_{CSU2} = I_{CSL2} = 28.07 MA, I_{CS1} = 57.14 MA, I_{CSL3} = 20.14 MA, I_{PF1} =12.38 MA, I_{PF2} = 4.63 MA, I_{PF3} = -3.41 MA, I_{PF4} = 4.34 MA, I_{PF5} = -3.20 MA, I_{PF6} = 19.20 MA, I_{plasma} = 0 for pre-magnetization [3] are used as a reference leading to a peak magnetic field of 12.36 T in the conductor and a magnetic flux of 307 Vs, generated only by the 5 CS modules, in the central plane of the CS coil. In further considerations, the inner and outer radii of the CS coil have been varied. A maintained magnetic flux of 307 Vs requires an adjustment of the currents in the CS modules. The ratio of the currents in the different CS modules is kept at the values I_{CS1}:I_{CSU3}:I_{CSL3} = 57.14:28.07:20.18 and I_{CSU3} = I_{CSU2} = I_{CSL2}. The field contribution of the PF coils has been calculated with the above quoted equilibrium currents.

3. Superconductor properties

The superconducting properties of Nb_3Sn and NbTi are based on the scaling relations and parameters provided in [5]. In case of Nb_3Sn, the scaling parameters of the JASTEC bronze strand used in the ITER CSJA6 sample and for the CS insert test in 2015 in Naka have been selected. For the react & wind (R&W) Nb_3Sn conductors, a strain of -0.25% has been retained. The scaling relation for $REBa_2Cu_3O_{7-x}$ (RE-123, RE = rare earth element) HTS is based on the test of the SPC cable. The non-copper critical current density obeys the scaling relation [6]

$$J_c = A\frac{B_0(T)^{\beta}}{B}\left(\frac{B}{B_0(T)}\right)^{p}\left(1-\frac{B}{B_0(T)}\right)^{q} \tag{1}$$

with

$$B_0 = B_0(0)\left(1-\frac{T}{T_0}\right)^{\alpha} \tag{2}$$

where B is the magnetic field and the values of the fitting parameters are A = 15.2 MA m^{-2} T$^{1-\beta}$, α = 3.48, β = 1.61, p = 0.54, q = 2.82, $B_0(0)$ = 170.78 T. The fitting parameters have no physical meaning. Especially B_0 and T_0 should not be considered as the irreversibility field and temperature. The value of A is based on RE-123 tapes with a non-copper thickness of 55 μm.

4. Dimensioning of graded CS1 module

Studies of uniform current density CS coils suggest that a minimum for the outer CS coil radius can be achieved for an inner coil radius of around 1.9 m [4]. The present work considers 10 sub-coils, each composed of two layers. In the magnetic field calculations, the overall current densities in the individual sub-coils are used omitting the details of conductor trajectories in the winding pack. Furthermore, it is assumed that the same grading as in the CS1 module is also used for the four other CS modules. The peak magnetic field of each sub-coil in the central plane of the CS1 module has been used to estimate the current sharing temperature (T_{cs}) or the ratio of operation to critical current (I_{op}/I_c). For a maintained magnetic flux, a decreased outer CS coil radius leads to higher peak fields and higher overall winding current densities, and hence a larger fraction of stainless steel is required in the winding pack. The area needed for the electrical insulation depends also on the total thickness of the winding pack and the envisaged number of layers. In several iterative cycles, a solution with a self-consistent set of parameters needs to be found.

The present work considers N = 10 sub-coils, each composed of two layers, and an inner radius of 1.9 m for the innermost sub-coil. The current in each sub-coil is $I_{CS1\text{-}k} = I_{CS1}/N$, where I_{CS1} is the total current in the CS1 module and N the number of sub-coils. A copper current density J_{Cu} = 120 MA/m^2 has been selected leading to a copper cross-section of $A_{Cu\text{-}k} = I_{CS1\text{-}k}/J_{Cu}$. For HTS sub-coils, a non-Cu operation current density J_{sc_k} of 80% of $J_c(T_{op}, B_p)$ is envisaged, where T_{op} = 4.75 K and B_p is the peak magnetic field of the sub-coil in question. In case of Nb_3Sn and NbTi the operation current density is selected in such a way that T_{cs} = 6.25 K leading to a temperature margin of 1.5 K. The resulting non-Cu superconductor area in sub-coil k is $A_{sc\_k} = I_{CS1\text{-}k}/J_{sc\text{-}k}$. The cross-section $A_{cond\text{-}k}$ is the sum of the superconductor and copper areas. The non-steel cross-section (cable space) inside the steel conduit is $A_{ns\text{-}k} = A_{cond\text{-}k}/0.7$ taking into account that 30% of the cable space is allocated for voids. The fraction of steel is $f_{steel} = A_{steel\text{-}k}/A_{CS1\text{-}k}$, where

$A_{CS1\text{-}k}$ includes the area of the electrical insulation except the ground insulation. The outer radius of sub-coil k is:

$$r_{o-k} = r_{i-k} + \frac{A_{CS1-k}}{h_{CS1} - 2t_g} \qquad (3)$$

Here $r_{i\text{-}k}$ is the inner radius of sub-coil k, h_{CS1} the height of the CS1 module and t_g = 8 mm [5] is the thickness of the ground insulation. It is supposed that each of the sub-coils contributes B_p/N to the peak magnetic field and the field at the CS outer radius is zero leading to $B(r_{o\text{-}k}) = B_p(1\text{-}k/N)$ at the outer radius of sub-coil k.

The calculation of the radial and the hoop stress in a superconducting solenoid with different sub-coil overall current densities follows the procedure described in [7].

5. Outline design of CS1 winding pack

A sketch of the lower part of the CS1 winding pack (WP) is presented in Fig. 1. The WP design is based on 10 sub-coils, each composed of two layers. The total number of conductors equals 20 × 78 = 1560. Each of the 10 sub-coils carries a current of 8.36 MA leading to a conductor current of 53.6 kA. The proposed WP dimensions lead to B_p as high as 18.15 T and a flux of 307 Vs exclusively generated by the 5 CS modules.

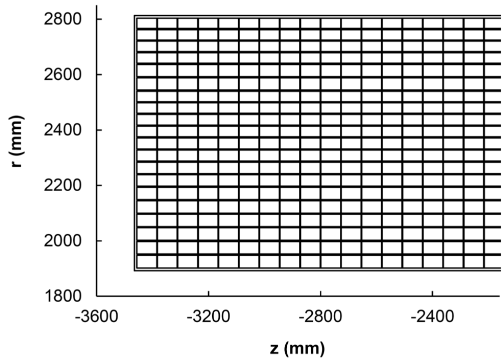

Fig. 1. Sketch of the lower part of the CS1 WP.

The WP including ground insulation is 5710 mm high. The inner and outer radii are 1892 and 2813.38 mm, respectively. Both, the conductor and the layer insulation are 1 mm thick. The radial positions of the conductors without insulation are listed in Table 1.

Table 1. Inner and outer radii of conductors without insulation.

Sub-coil	Inner layer r_i / r_o (mm)	Outer layer r_i / r_o (mm)
1	1902.00 / 1947.88	1951.88 / 1997.76
2	2001.76 / 2046.82	2050.82 / 2095.87
3	2099.87 / 2144.49	2148.49 / 2193.10
4	2197.10 / 2238.52	2242.52 / 2283.94
5	2287.94 / 2327.60	2331.60 / 2371.26
6	2375.26 / 2413.85	2417.85 / 2456.43
7	2460.43 / 2498.27	2502.27 / 2540.11
8	2544.11 / 2588.41	2592.41 / 2636.71
9	2640.71 / 2678.93	2682.93 / 2721.15
10	2725.15 / 2762.27	2766.27 / 2803.38

Fig. 2 shows the overall current densities in the 10 sub-coils. For CS1-1 and CS1-2 the use of HTS conductors is envisaged, while for CS1-3 to CS1-7 the use of R&W Nb_3Sn (-0.25% strain) is proposed. In the lowest field sub-coils CS1-8 to CS1-10, the overall winding current densities are based on the use of NbTi.

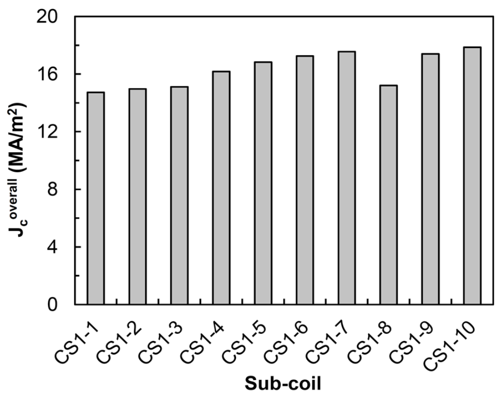

Fig. 2. Overall sub-coil winding current densities.

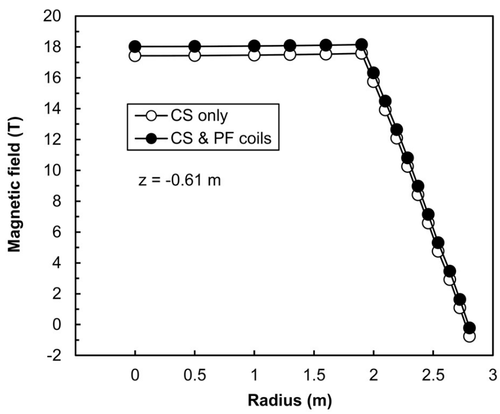

Fig. 3. Variation of the total magnetic field (solid symbols) and the field generated only by the CS coil (open symbols) in the central plane of the CS1 module.

Fig. 3 shows the numerically calculated values of the total magnetic field and the field generated only by the CS coil in the central plane of the CS1 module. The variation of the radial and the hoop stress in the central plane of the CS1 module is presented in Fig. 4. The peak value of the hoop stress is reached at the inner radius of the CS1 winding pack. From inner to outer radius, it decreases from 428.46 to 252.03 MPa. To limit the peak value of the hoop stress to 660 MPa in the steel the fraction of steel needs to be as large as 64.92%. For the time being, the fraction of stainless steel is kept at the same value in all sub-coils. The radial stress is always negative (compressive) and reaches a maximum absolute value of ≈16.6 MPa at a radius of about 2.44 m.

6. Proposed conductor design

In the proposed conductor design, J_{Cu-k} and the area of voids have been adjusted according to geometrical needs. In Fig. 5, a sketch of the typical conductor layout is presented (L_{cond} = 71 mm, r_4 = 3 mm). The resulting inner radius of the cable space is

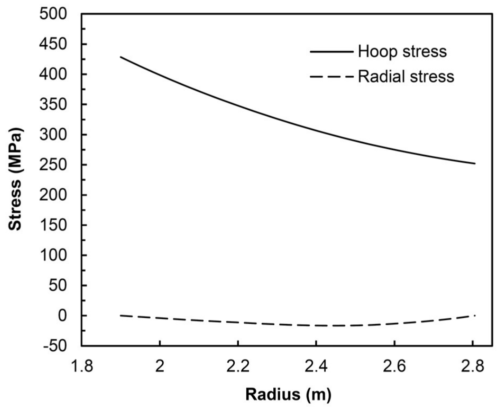

Fig. 4. Variation of hoop and radial stress in the central plane of the CS1 module.

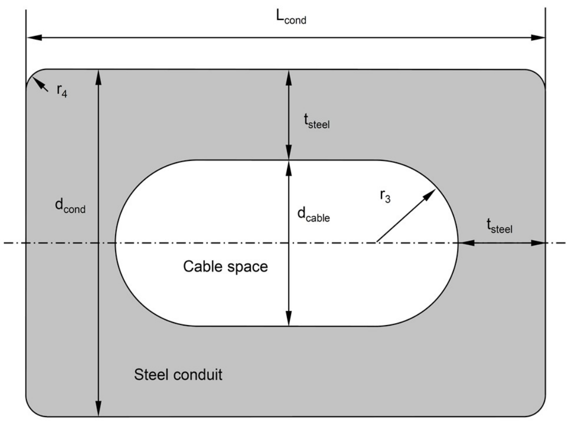

Fig. 5. Sketch of the typical conductor layout. The length L_{cond} of the conductors without insulation is 71 mm in all 20 layers, whereas the conductor thickness d_{cond} varies.

$$r_3 = -\frac{L_{cond}-d_{cond}}{\pi} + \sqrt{\left(\frac{L_{cond}-d_{cond}}{\pi}\right)^2 + \frac{L_{cond}d_{cond}-(4-\pi)r_4^2-A_{steel}}{\pi}} \quad (4)$$

Here A_{steel} is the cross-section of the stainless steel conduit. The thickness of the cable space is $d_{cable} = 2r_3$. The wall thickness of the steel conduit is $t_{steel} = d_{cond}/2-r_3$. Finally, the length of the cable space is $L_{cable} = L_{cond}-2t_{steel}$.

For the two innermost sub-coils (first 4 layers), the use of RE-123 ($REBa_2Cu_3O_{7-x}$ with RE a rare earth element) HTS is envisaged. In Fig. 6, a sketch of the HTS cable for the innermost sub-coil at the highest field is presented. Twelve strands of 7.5 mm diameter are wound around a copper core of 6.2 mm diameter. In each strand, 42 RE-123 tapes of 4 mm width and 95 µm thickness are embedded. The HTS conductor properties are listed in Table 2.

Table 2. Main characteristics of the 53.6 kA RE-123 cables for the innermost sub-coils 1 & 2.

Sub-coil	N_{str}	D_{str} (mm)	N_{tapes}	$L_{cable} \times d_{cable}$ (mm^2)	d_{core} (mm)
1	12	7.5	504	46.32 × 21.20	6.20
2	13	7.0	455	46.52 × 20.58	6.58

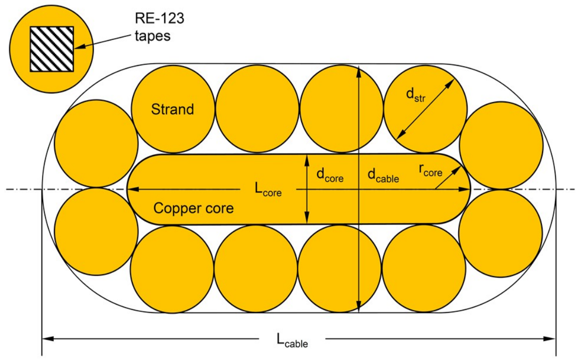

Fig. 6. Sketch of the RE-123 cable for sub-coil CS1-1.

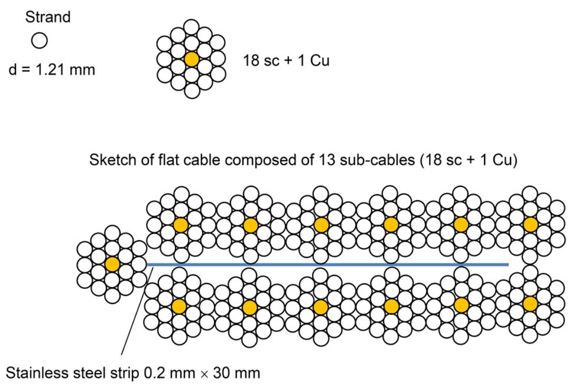

Fig. 7. Schematic layout of the Nb_3Sn cable for sub-coil 3.

In the intermediate field sub-coils 3 to 7, the use of R&W Nb_3Sn conductors is planned. For the strain in the Nb_3Sn filaments, a design value of -0.25% has been selected. In all considered Nb_3Sn strands, the Cu : non-Cu ratio equals 1. In Fig. 7, a sketch of the Nb_3Sn flat cable for sub-coil 3 is presented. Thirteen cable stages, composed of 18 superconducting strands and one copper wire, form a flat cable. The residual resistivity ratio (*RRR*) equals 100 for copper in the strands and *RRR* = 400 for the copper in the solid mixed 95% Cu and 5% Cu-Ni matrix. In order to reduce the ac loss the two layers of sub-cables are separated by a thin stainless steel strip. The assembled cable is shown in Fig. 8. The cooling channels on the left and right hand sides are beneficial for welding of the two halves of the stainless steel conduit. The peak magnetic fields reach 14.48, 12.64, 10.81, 8.97 and 7.14 T in sub-coils 3, 4, 5, 6 and 7, respectively.

The design of the lowest field sub-coils 8, 9 and 10 is based on the use of NbTi. The layout of the NbTi conductors is analogous to that of the Nb_3Sn conductors. A design value of $T_{cs} \approx 6.25$ K has been selected for all NbTi and Nb_3Sn sub-coils. In the NbTi sub-coils 8, 9 and 10, the peak magnetic fields reach 5.3, 3.47 and 1.63 T, respectively. The main properties of the Nb_3Sn and NbTi conductors are listed in Table 3.

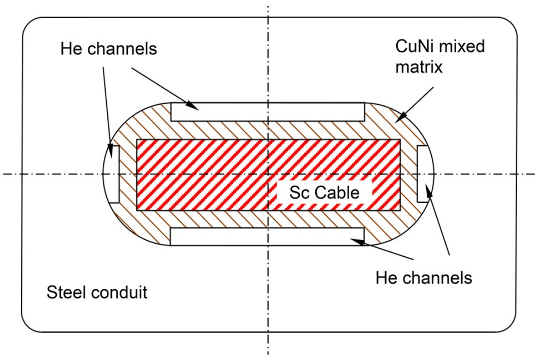

Fig. 8. Assembled Nb_3Sn conductor for sub-coil 3.

Table 3. Main properties of 53.6 kA Nb_3Sn and NbTi cables.

Sub-coil	N_{sub}	D_{str} (mm)	Cabling pattern	$L_{sc} \times d_{sc}$ (mm^2)
3	13	1.21	18 sc + 1 Cu	37.8 × 10.38
4	16	0.87	18 sc + 1 Cu	33.44 × 7.50
5	20	1.10	6 sc + 1Cu	32.4 × 5.74
6	18	0.97	6 sc + 1Cu	25.6 × 5.11
7	18	0.82	6 sc + 1Cu	21.7 × 4.31
8	14	1.06	18 sc + 1 Cu	35.6 × 9.14
9	12	1.00	6 sc + 1Cu	17.6 × 5.21
10	12	0.71	6 sc + 1Cu	12.5 × 3.75

7. Conclusions

A winding pack design for a CS1 module composed of 10 sub-coils with superconductor grading is presented. The use of HTS in the highest field sub-coils allows us to maintain the reference magnetic flux in a CS coil of reduced outer diameter by means of an increased peak magnetic field. Next, a variation of the steel fraction in different sub-coils is envisaged requiring a more detailed mechanical analysis including the vertical loads.

Acknowledgments

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