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Central solenoid winding pack design for DEMO

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HIGHLIGHTS

- Reduced size of the CS coil would lead reduced of the size and the cost of DEMO.
- To maintain the magnetic flux the maximum magnetic field needs to be increased.
- Use of high-T_c superconductors would allow a 15% reduction of the outer CS radius.
- Cost effective layer-wound CS coil design with superconductor grading is proposed.
- In the highest field sections, the use of high-T_c superconductors is envisaged.

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ABSTRACT

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.

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. At start and end of flat top ($I_{plasma} = 19.6$ MA) the peak magnetic field is well below that during pre-magnetization [3]. 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 $I_{CS1}:I_{CSU3}:I_{CSL3} = 57.14:28.07:20.18$

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Table 1
Main characteristics of the CS1 module.

Parameter	Value
Number of sub-coils N/Layers per sub-coil	10/2
Copper current density J_{Cu} (MA/m^2)	120
Operation temperature T_{op} (K)	4.75
Current sharing temperature T_{cs} (K)	6.25

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]

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

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

where B is the magnetic field and the values of the fitting parameters are $A = 15.2$ MA m^{-2} T$^{1-\beta}$, $\alpha = 3.48$, $\beta = 1.61$, $p = 0.54$, $q = 2.82$, $B_0(0) = 170.78$ 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 main characteristics of the CS1 module are presented in Table 1. 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. The required copper cross-section is $A_{Cu\text{-}k} = I_{CS1\text{-}k}/J_{Cu}$, where J_{Cu} is the current density in the copper. For HTS sub-coils, a non-Cu operation current density $J_{sc\_k} = 0.8\,J_c$ is envisaged, otherwise $T_{cs} = 6.25$ K. The 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:

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

Here r_{i-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 $B(r_{o\text{-}k}) = B_p(1-k/N)$ 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].

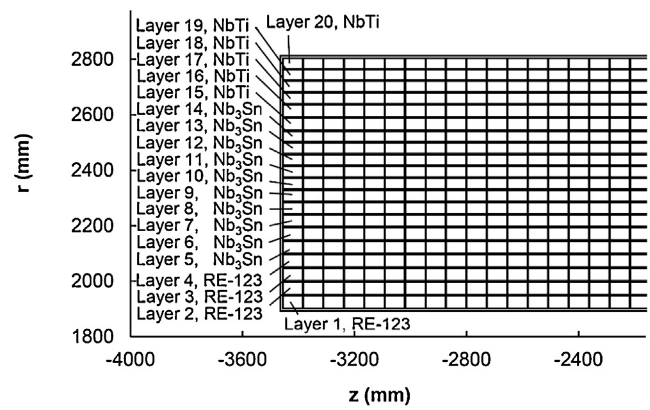

Fig. 1. Sketch of the lower part of the CS1 WP.

Table 2
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

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 ampere turns 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.

For the flux calculation, the magnetic field has been calculated at six radii inside the bore and at the inner and outer radii of each sub-coil in the winding pack.

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 2.

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.