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Maximization of the magnetic flux generated by a DEMO CS coil using HTS conductors

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The present work is performed within the framework of the EUROfusion DEMO project. Previously, it was demonstrated that for a maintained magnetic flux the use of HTS conductors at highest magnetic field in a layer-wound CS coil would allow the reduction of its outer radius by around 0.5 m as compared to the DEMO reference design using only Nb_3Sn conductors. Alternatively, the superior high field performance of HTS conductors can be used to maximize the magnetic flux of a CS coil with a given outer diameter, which could significantly prolong the duration of plasma burn phase and thus the overall power plant efficiency. In the present study, the maximization of the magnetic flux, generated by a layer-wound CS coil of fixed outer radius, is considered. HTS conductors are envisaged to be used at highest field, while Nb_3Sn and NbTi are foreseen to be used in intermediate and low field layers, respectively. The inner radius of the CS coil is optimized with respect to the generation of a maximum flux taking into consideration the superconductor properties, the hoop stress and the axial stress. In order to provide reasonable starting values for the finite element analysis, first a simplified model with layer-dependent current densities, however, without stainless steel grading will be considered. In the final outline design of the CS coil a superconductor and stainless steel grading will be implemented.

Keywords: Central solenoid, European DEMO, high temperature superconductor, stainless steel grading.

1. Introduction

The present study aims to maximize the magnetic flux, generated by a CS coil of a fixed outer radius, by means of the use of high-temperature superconductors (HTS) in the highest field layers. The design of European DEMO [1, 2] allocates an outer radius of 3.2 m for the CS coil without the pre-compression structure. As in previous studies [3, 4] with the target to minimize the outer diameter of the CS coil for a maintained magnetic flux of 307 Wb, generated exclusively by the CS coil, layer winding is considered, which allows the use of Nb_3Sn and NbTi in layers at intermediate and low field, respectively. In order to maximize the flux the inner radius and the total current of the CS coil have been varied leading to different values of the peak magnetic field and the hoop stress.

2. Procedure and assumptions

The CS coil of European DEMO is composed of the five modules CSU3, CSU2, CS1, CSL2 and CSL3. The vertical positions of the CS modules and the six PF coils, used in the present study, can be found in [5, 6]. The most demanding plasma scenario leading to the highest peak magnetic field and the largest mechanical stress is the pre-magnetization. The PF coils contribute less than 0.6 T to the peak magnetic field at the inner radius in the central plane of the CS coil. For simplicity, the ratio of the currents in the CS modules is kept as in the reference design [4]. It is expected that a higher magnetic flux of the CS coil would require an adaptation of the flux generated by the PF coils. A change of the PF coils currents would modify their contribution to the peak field. Because of their absolutely small contribution to the peak magnetic field a variation of the PF currents has only a minor impact on the CS coil design.

As a starting point, CS modules with a uniform current density are studied. The maximum hoop stress is estimated analytically as in a previous study [5]. The fraction of stainless steel in the winding cross-section is selected in such a way that the maximum hoop stress in the stainless steel is limited to 475 MPa. A current density of 120 A/mm^2 has been selected for the copper stabilizer. In the winding cross-section, 10% of the area is allocated for the insulation. Hence, the cable space is $A_{cable} = A_{CS1} \times (1 - f_{steel} - f_{ins})$, where A_{CS1} is the cross-section of the module CS1, f_{steel} the fraction of steel and f_{ins} the fraction of insulation in the winding pack (WP). The cross-section available for the superconductor is $A_{non\text{-}Cu} = A_{cable} \times (1 - f_{void}) - A_{Cu}$, where the void fraction f_{void} = 30% and A_{Cu} is the copper cross-section.

2.1 Superconductor properties

The non-Cu critical current densities J_c, used in the present study, are presented in Fig. 1. The nominal operation temperature of the CS coil is 4.75 K. The J_c values of NbTi and Nb_3Sn are based on the scaling relations presented in [7]. The performance of the HTS tapes is slightly better than that used in previous studies [3]. The operation current of the HTS tapes has been limited to 80% of the critical current.

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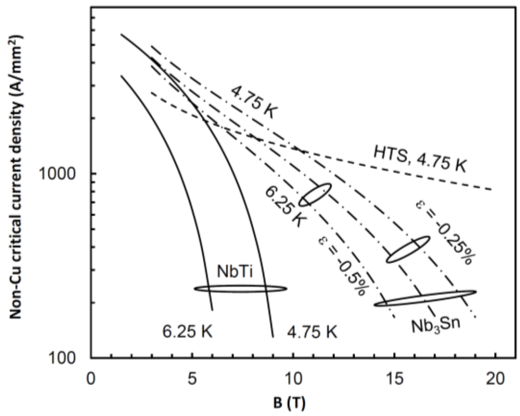

Fig. 1. J_c of HTS, Nb_3Sn and NbTi versus field at 4.75 K. For NbTi and Nb_3Sn, the J_c values at 6.25 K are also shown. The J_c values of Nb_3Sn depend on the operational strain. The J_c of Nb_3Sn at 4.75 K and -0.5% strain is nearly identical to J_c(6.25 K, ε = -0.25%).

For NbTi and Nb_3Sn a temperature margin of 1.5 K has been selected. In case of Nb_3Sn, an operational strain of -0.5% has been assumed for wind & react (W&R), while a value of -0.25% has been used for react and wind (R&W).

2.2 General procedure

In the study of the CS modules with uniform current density, the magnetic field and the hoop stress at the inner radius in the central plane of the CS1 module is calculated as a function of the total current in the CS1 module. Integration of the magnetic field contribution of all five CS modules over the cross-section up to the outer radius of the coil provides the flux generated only by the CS coil. For each value of the current, the calculated non-Cu cross-section is used to determine the non-Cu operation current density ($J_{op}^{non\text{-}Cu}$) needed to reach the magnetic flux in question. This required current density

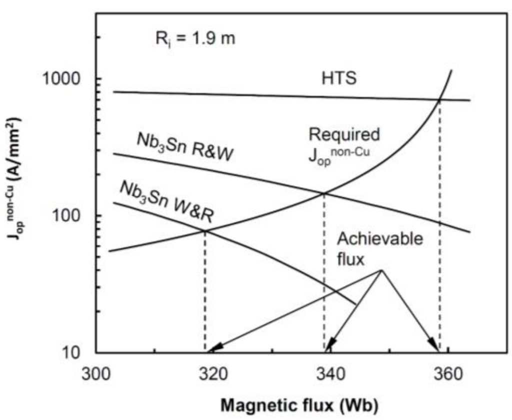

Fig. 2. Required non-Cu current density versus generated magnetic flux and $J_{op}^{non\text{-}Cu}$ achievable in HTS, R&W and W&R Nb_3Sn. The intersections provide the achievable magnetic flux.

HTS, R&W and W&R Nb_3Sn. The intersections of the lines of required and achievable $J_{op}^{non\text{-}Cu}$ provide the maximum possible magnetic flux as illustrated in Fig. 2

2.3 Finite Element Model

A 2D coupled magnetic and structural Finite Element (FE) analysis is used to evaluate in more detail the magnetic and mechanical stress fields in the DEMO CS1 WP. The magnetic FE model includes the geometry of the five CS and the six PF coils (assumed to be axi-symmetric) and computes the magnetic field distribution and forces in the conductors during pre-magnetization. The mechanical model imports the Lorentz forces and vertical loads acting in a slice of two radial rows of conductors above and below the solenoid mid-plane. The assumed mechanical properties of the WP components are those specified in [8]. Both magnetic and mechanical FE models are solved in ANSYS [9].

The FE analysis is initially used to evaluate the design that generates the maximum magnetic flux in a uniform current density coil (Section 2.2). Based on magnetic field distribution, a superconductor graded design is proposed using HTS conductors in the three highest field sub-coils, Nb_3Sn in the intermediate field region, and NbTi in the two outermost sub-coils. A stainless steel graded design is proposed as a result of an iterative process, in which the steel fraction is adjusted across the WP in order to have the required amount of steel in each sub-coil [4], while the radial stress remains compressive across the WP.

3. Results

3.1 Uniform current density

Fig. 3 shows the maximum magnetic flux achievable for the use of HTS, R&W and W&R Nb_3Sn versus the inner radius (R_i) without ground insulation. In general, the maximum possible magnetic flux depends on R_i of the CS coil. The variation of the magnetic field within the bore is relatively small, whereas the field in the WP decreases nearly linearly from the peak value (B_{peak}) at the inner radius to a value close to zero at the outer radius. Thus, a reduction of the inner radius reduces the flux in the bore, while it increases the flux in the WP. At constant peak field the loss of flux in the bore is generally larger than the gain of flux in the WP. An increase of the flux in a CS coil of reduced inner radius requires therefore a higher B_{peak} leading to a larger hoop stress, which needs to be compensated by a larger fraction of stainless steel in the WP to limit the hoop stress in the steel to 475 MPa. Because of higher peak fields $J_{op}^{non\text{-}Cu}$ decreases with decreasing inner radius. At a certain inner radius the additional space available in a thicker WP is no longer able to surpass the effects of an increased f_{steel} and a reduced $J_{op}^{non\text{-}Cu}$, and hence after reaching a maximum the generated flux decreases again.

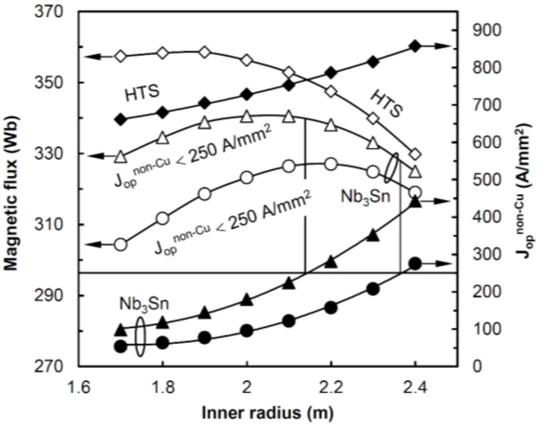

Fig. 3. Generated magnetic flux versus CS coil inner radius for σ_{hoop} = 475 MPa (open symbols). The corresponding $J_{op}^{non\text{-}Cu}$ is indicated by the filled symbols.

Fig. 3 indicates that the highest flux of slightly more than 358 Wb is reached at a total CS1 current of ≈85 MA, the use of HTS at highest field and R_i = 1.9 m. The peak magnetic field reaches 18.28 T leading to $J_{op}^{non\text{-}Cu} \approx 700$ A/mm^2.

The use of R&W Nb_3Sn would allow the generation of a flux of slightly more than 340 Wb at an inner radius of 2.1 m. The peak magnetic field would be still as high as 16.23 T leading to $J_{op}^{non\text{-}Cu} \approx 220$ A/mm^2. In case of W&R Nb_3Sn the maximum flux of 327 Wb is reached at an inner radius of 2.2 m, B_{peak} = 15.08 T and $J_{op}^{non\text{-}Cu} \approx$ 160 A/mm^2. In spite of being feasible the W&R solution would lead to an inefficient use of the expensive superconductor.

3.2 Superconductor graded design

The main geometrical parameters of the proposed superconductor (SC) graded design are listed in Table 1, along with B_{peak} and the superconductor material used in each sub-coil. The inner radius (r_i) refers to the position of the steel conduit without insulation. A_{steel} and A_{cable} are used to designate respectively the steel and cable space area in each conductor.

Table 1. Superconductor graded design: superconductor material, main geometrical parameters and peak magnetic field in each sub-coil.

Sub-coil (material)	r_i (mm)	A_{steel} (mm^2)	A_{cable} (mm^2)	B_{peak} (T)
1 (RE123)	1934.7	3603	775	18.86
2 (RE123)	2066.2	3559	766	16.99
3 (RE123)	2196.3	3517	757	15.13
4 (Nb_3Sn)	2324.9	3750	807	13.27
5 (Nb_3Sn)	2461.5	3520	758	11.41
6 (Nb_3Sn)	2590.2	3382	728	9.56
7 (Nb_3Sn)	2714.1	3292	709	7.69
8 (Nb_3Sn)	2835.0	3229	695	5.83
9 (NbTi)	2953.8	3360	723	3.97
10 (NbTi)	3077.0	3206	690	2.11

The fraction of the steel across the WP is ~76.9%, which results in a relatively flat engineering current density profile (~11.9 MA/m^2) across the coil (see Fig.4). Table 2 shows that this SC graded design making use of HTS in the high field region can generate a field of almost 19 T in the bore and 19.5% more flux compared to the 307 Wb of the reference design [6]. The flux reported in Table 3 includes only the contribution of the CS modules and is integrated in the CS1 mid-plane up to the outer radius of the solenoid.

3.3 Superconductor and stainless steel graded design

The magnetic flux can be further increased by also grading the fraction of stainless steel across the coil (SC+SS graded design). During the iterative process that results in the design presented in Table 3, the outer radius of the coil was maintained (R_{out} = 3.2 m including the ground insulation). The distribution of steel in the solenoid leads to a roughly linear profile of the current density in the coil (see Fig. 4). The large area of steel required in the two innermost sub-coils calls for the use of a co-wound steel strip, resulting in a coil layout similar to what is proposed in [4]. The field in the bore is a function of the total current in the coil (which is maintained), and thus, the additional 37.9 Wb of flux compared to the SC design is mostly a consequence of the larger bore radius.

The distribution of the membrane stress in the coil becomes closer to the allowable stress everywhere in the coil (Fig. 5) and the radial stress is always compressive except close to the conduit corners. The hoop stress in the innermost layers increases significantly compared to the SC graded design due to the larger inner radius (Table 3). Increasing the steel fraction in the innermost

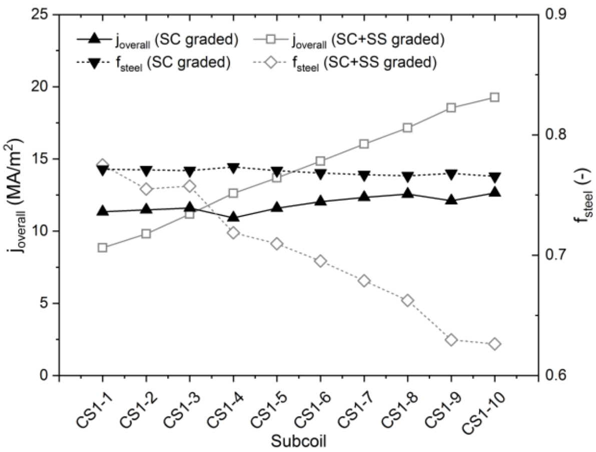

Fig. 4. Overall current density and fraction of steel (f_{steel}) across the WP for the superconductor graded (SC) and the superconductor + stainless steel (SC+SS) graded designs.

Table 2. Main parameters of the superconductor graded (SC) and the superconductor + stainless steel (SC+SS) graded designs. R_{in} and R_{out} include the ground insulation.

	SC graded	SC+SS graded	
I_{total}	85	85	MA
R_{in}	1925.7	2066.0	mm
R_{out}	3200.0	3200.0	mm
B_{peak}	18.86	18.79	T
ϕ	366.8	404.7	Wb
$\sigma_{memb\ L01}$	593.5	653.8	MPa
$\sigma_{hoop,\ L01}$	457.5	547.6	MPa

Table 3. Superconductor and stainless steel graded design: superconductor material, main geometrical parameters and peak magnetic field in each sub-coil.

Sub-coil (material)	r_i (mm)	A_{steel} (mm^2)	A_{cable} (mm^2)	B_{peak} (T)
1 (RE123)	2075.0	4773	775	18.79
2 (RE123)	2243.7	4189	766	16.95
3 (RE123)	2395.8	3692	756	15.11
4 (Nb_3Sn)	2529.3	3101	804	13.17
5 (Nb_3Sn)	2647.5	2823	755	11.30
6 (Nb_3Sn)	2756.5	2550	726	9.41
7 (Nb_3Sn)	2857.0	2307	707	7.53
8 (Nb_3Sn)	2950.1	2104	694	5.65
9 (NbTi)	3037.1	1849	715	3.76
10 (NbTi)	3117.5	1771	688	1.89

sub-coils has a negligible impact on the peak hoop stress [10] and creates radial tension in the insulation.

4. Conclusion

Two alternative designs of the DEMO CS1 module are presented showing that the use HTS in the three highest field sub-coils can enhance respectively 19.5% and 32% the flux generated by the central solenoid for a given outer radius, which can extend the duration of the plasma pulses in the European DEMO. The mechanical

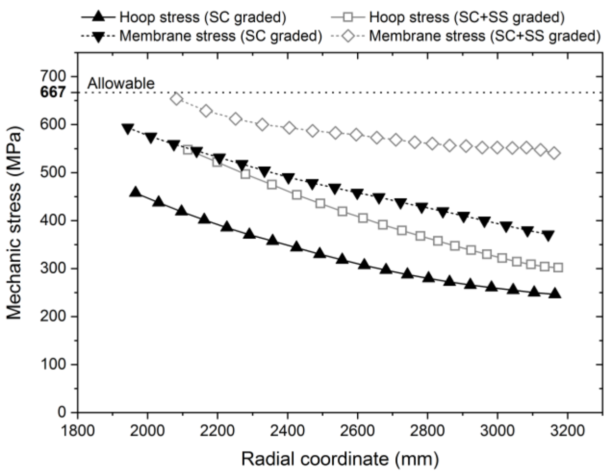

Fig. 5. Average hoop stress and membrane stress for the superconductor (SC) graded and the superconductor + stainless steel (SC+SC) graded designs.

stress in the design that makes use of stainless steel grading is close to the allowable static stress limit. Particularly, the large hoop stress observed in the stainless graded design will limit significantly its fatigue lifetime.

Acknowledgments

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