Progress in the Design of a Hybrid HTS-Nb_3Sn-NbTi Central Solenoid for the EU DEMO

Xabier Sarasola, Rainer Wesche, Ilia Ivashov, Kamil Sedlak, Davide Uglietti, and Pierluigi Bruzzone

***Abstract*— State-of-the-art high field solenoids make use of hybrid designs exploiting the superior high field performance of High Temperature Superconductors (HTS) in the innermost region. The benefits of a hybrid Central Solenoid in a pulsed tokamak like the EU DEMO can be two-fold: either to reduce its outer radius (which would result in a reduced overall size and cost of the tokamak), or to increase the generated magnetic flux (which could extend the plasma burn time and possibly increase the power plant efficiency). In the framework of the pre-conceptual design studies for DEMO coordinated by EUROfusion, a hybrid Central Solenoid is proposed based on ten layer-wound sub-coils using HTS, Nb_3Sn, and Nb-Ti conductors respectively for the high, medium, and low field sections. The design exploits the flexibility of layer winding by grading both the superconductor and the stainless steel cross sections in each sub-coil, which has the potential for space and cost savings. Mechanical analyses have identified fatigue as the main design driver for the EU DEMO Central Solenoid. Possible alternatives to reduce the sensitivity of the proposed design to fatigue are currently under investigation.**

***Index Terms*— High-temperature superconductors, Niobium-tin, Solenoids, Superconducting magnets.**

I. Introduction

THE pre-conceptual design activities of the European (EU) DEMO are coordinated by EUROfusion and focus primarily on the design of a pulsed tokamak device [1]. The pulsed nature of the reactor operation imposes fundamental constraints in the design of the Central Solenoid (CS), which induces most of the toroidal current required for plasma confinement by ramping the magnetic flux.

The present study uses a simple model to estimate the impact of fatigue due to cyclic loading in the EU DEMO CS coil, and explores the benefits of a layer-wound coil design. Layer winding allows a more cost effective design of the solenoid since the superconductor cross-section and the stainless steel fraction can be graded within the winding pack. Other studies address the design of a EU DEMO CS coil based on pancake winding without the possibility of grading [2], [3].

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II. Design Requirements and Assumptions

A. Geometrical and Operational Requirements

The geometrical and operational requirements for the design of the magnets in the EU DEMO are based on the output provided by the reactor systems code PROCESS [4]. The present reference for magnet design is the Baseline 2018 [5], which assumes a free-standing CS coil located in the bore formed by 16 wedged Toroidal Field (TF) coils. The space allocated for the CS coil is 17.92 m high and 5.63 m in diameter. The solenoid is divided in 5 electrically independent modules to allow plasma shaping control. The CS modules are stacked upon each other and compressed vertically by a pre-compression structure to avoid separation between modules. A radial space of 115 mm is preliminary allocated for the pre-compression structure, allowing a maximum outer radius of 2.7 m for the solenoid winding pack (WP).

The coil equilibrium currents are provided at three instants during the CS magnetic flux swing [6]: Pre-magnetization (Pre-mag), Start-Of-Flattop (SOF), and End-Of-Flattop (EOF). The largest magnetic field and mechanical stresses in the solenoid occur during Pre-mag. At EOF the currents in the central module (CS1) are fully reversed, and the tensile hoop stress in CS1 is comparable to that experienced during Pre-mag. Thus, since the EU DEMO is designed to operate 20,000 plasma cycles [7], the CS coil design has to ensure survival during 40,000 mechanical cycles.

The studies described in this manuscript focus on the design of the CS1 WP, which is the most mechanically demanded.

B. Winding Pack Layout

Fig. 1 (a) shows a radial slice of the CS1 coil with four rows of conductors illustrating the layout of a uniform current density WP. The coil is layer-wound in 10 double-layer sub-coils using Cable-in-Conduit Conductors (CICCs), allowing the possibility of grading, Fig. 1 (b). The proposed CICCs use rectangular steel conduits as structural material. The WP insulation scheme follows the recommendations of EUROfusion [8]: 1 mm around each conductor turn, 2 mm of additional insulation between layers, and 8 mm of ground insulation around each module.

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C. Superconductor and Cable Assumptions

The considered non-Cu critical current densities are the same used in previous studies [9]. Particularly, the scaling laws for Nb_3Sn and Nb-Ti are those described in [8]. The operating temperature (T_{op}) is 4.75 K and the temperature margin (ΔT_m) for Nb_3Sn and Nb-Ti is 1.5 K. HTS tapes operate at 80% of the critical current.

The assumed current density of the copper stabilizer is 120 A/mm^2, and the void fraction within the cable space is 30% to allow the circulation of supercritical helium.

D. Mechanical Properties

The static mechanical assessment described in Section III uses the mechanical properties defined for the design of the DEMO WPs [10]. Whereas, the crack growth model uses the fatigue Paris constants at 4 K specified in Table I, [11], [12].

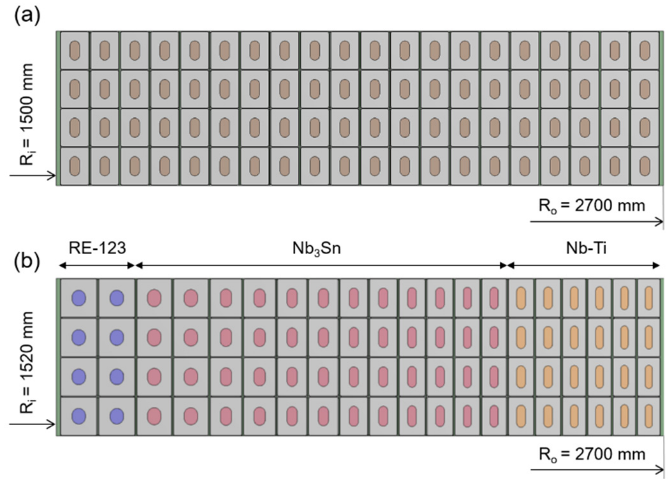

Fig. 1. Radial slice showing four rows of conductors of the CS1 winding pack. (a) Uniform current density design. (b) Superconductor and Stainless Steel (SC+SS) graded design.

TABLE I
ASSUMED PARIS CONSTANTS FOR FATIGUE AT 4 K (R=0.1)

	SS 316LN	JK2LB	Incoloy 908	Inconel 718
C (m/cycle)	65×10^{-14}	1.75×10^{-13}	28.4×10^{-14}	8.26×10^{-15}
m (-)	3.5	3.7	3.58	4.55
Reference	[11]	[12]	[11]	[11]

III. METHODOLOGY

A. Uniform Current Density Solenoid: Parametric Analyses

In a finite uniform current density solenoid, the generated magnetic field and flux, as well as the hoop stress experienced in the mid-plane, can be computed analytically [9], [13], [14]. This allows the implementation of simple parametric studies in which the total current in the solenoid is varied until the maximum achievable flux is obtained for a given superconductor material and coil geometry. This approach is used in previous studies to maximize the generated flux for a fixed solenoid outer radius (R_o = 3.2 m), [9], and minimize the outer radius for a target flux (φ = 307 Wb), [13], [14].

In the EU DEMO solenoid, the radial Lorentz forces are dominant and are reacted within the CS WP by the tensile hoop load held by the conduits. The conduits also experience vertical compressive stress varying with time, but the hoop stress (σ_h) drives mechanical fatigue and crack growth.

The parametric analysis presented in Fig. 2 shows the flux generated at pre-magnetization by an HTS uniform current density CS coil with an outer radius R_o = 2.7 m. The generated flux has a relatively flat maximum peaking at an inner radius $R_i \approx$ 1.5 m for the range of hoop stress in the conduit explored. During these parametric studies the total current in the CS1 module is varied until the maximum achievable flux is obtained for each combination of R_i and σ_h. The current in the other CS modules is defined maintaining the ratio of currents between each CS module and CS1 defined in the EU DEMO baseline 2018 [6].

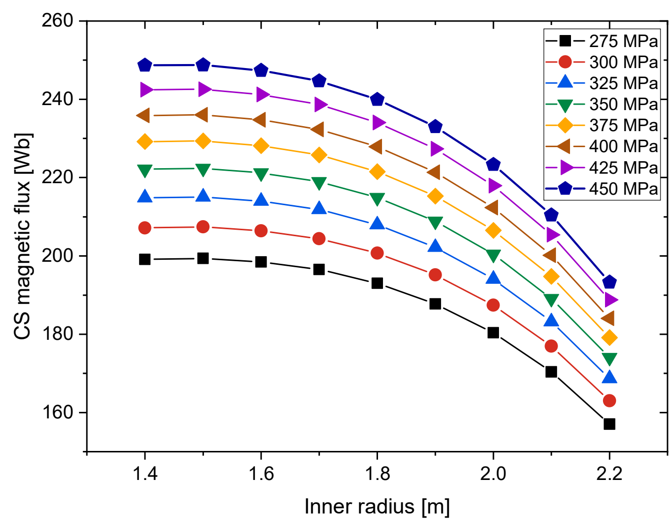

Fig. 2. Flux generated at pre-magnetization by an HTS uniform current density CS coil with an outer radius R_o = 2.7 m. The inner radius of the solenoid and the maximum hoop stress in the conduits are varied parametrically.

B. Fatigue Crack Growth Model

A simple crack growth model based on Linear Elastic Fracture Mechanics (LEFM) is used to estimate the allowable hoop stress in the conduits. The model follows the method described in the ITER Magnet Structural Design Criteria [15], which uses Paris law to grow a planar elliptical crack across the thickness of a 2D plate with the width and thickness of the conduit wall. The Paris law assumes the crack growth rate follows a power law:

$$da/dN = C(\Delta K)^m \quad (1)$$

where a is the size of the crack, N is the number of cycles, C and m are material constants (specified in Table I), and ΔK is the stress intensity factor. The stress intensity factor is, in turn, a function of the crack geometry (surface and embedded elliptical cracks [15] are considered), the residual stress in the conduit (from forming and butt weld operations), and the alternating tensile stress (i.e., hoop stress in the case of the CS coils).

An iterative process is used to integrate the Paris law. The crack is assumed to remain always planar (perpendicular to the hoop stress) and elliptical throughout the growth process. The initial crack size depends on the resolution of the Non-Destructive Examination (NDE) method. For this study, we assume that 2 mm^2 surface defects and 5 mm^2 embedded defects can be detected, which is in line with the limits allowed for the ITER CS jackets [16]. In the absence of accurate values, a residual stress level of 240 MPa (yield stress of stainless steel at room temperature) is assumed during the crack growth process [17], since the butt welds between conduit sections are likely to have the highest residual stress. The integration of the Paris law stops when the crack penetrates through the thickness of the considered 2D plate or the stress intensity factor exceeds the fracture toughness of the assumed material.

Finally, in order to compensate for the uncertainties associated with the modelled crack growth, the following recommended safety factors are applied: a factor of 2 in the number of cycles, a factor of 2 in the defect area, and a factor of 1.5 in the material fracture toughness [15].

Fig. 3 plots the number of mechanical cycles until failure as a function of the hoop stress in a 70×22 mm plate assuming an initial surface crack of 2 mm^2. In order to ensure the survival of a jacket of the same width and thickness during 40,000 cycles (including the safety factors specified above), the hoop stress has to be limited to 300 MPa if stainless steel 316LN (SS 316LN) is used as the jacket material or ~375 MPa if the high manganese steel JK2LB is used.

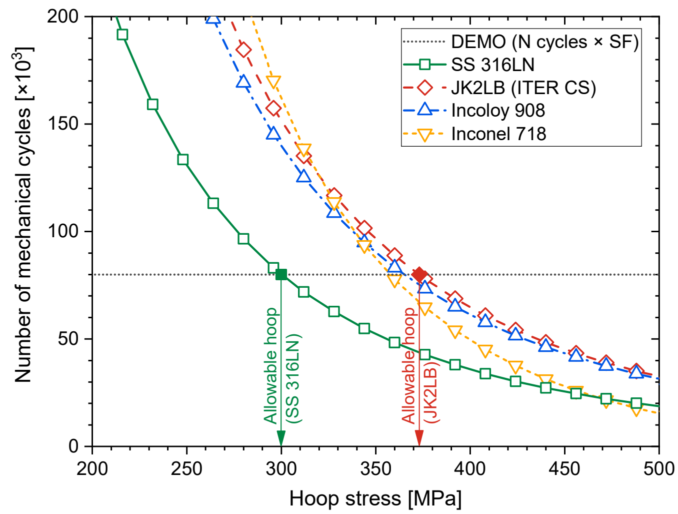

Fig. 3. Number of mechanical cycles until failure as a function of the hoop stress in a 70×22 mm plate assuming an initial surface crack of 2 mm^2.

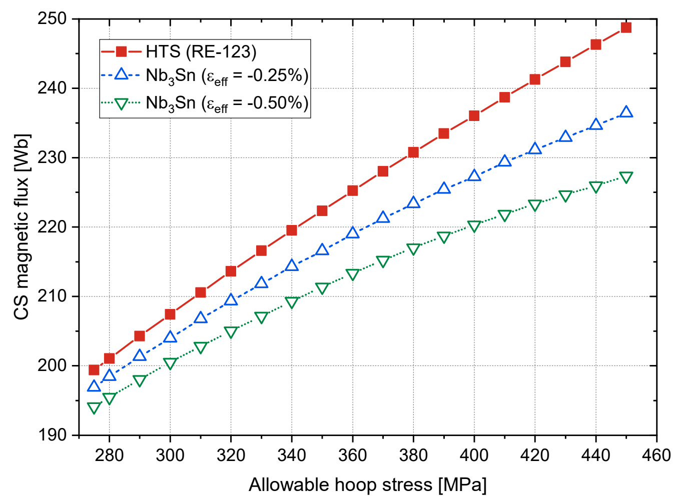

Fig. 4. Maximum achievable flux in a uniform current density solenoid of R_o = 2.7 m as a function of the allowable hoop stress in the conduits.

C. Static Assessment

The previous steps in the procedure allow to identify the uniform current density WP layout that generates the maximum flux for the allowable hoop stress estimated with the crack growth model. As a final step, a static assessment of the chosen uniform current density layout is performed using a 2D axi-symmetric Finite Element Model (FEM) in ANSYS [18], along the same lines of previous studies [9], [13].

First, the FEM computes the magnetic field and Lorentz forces in the CS and PF coils during pre-magnetization. Then, a detailed mechanical model imports the Lorentz forces and evaluates the static mechanical stress in 4 rows of conductors in the central region of the CS1 module (geometry shown in Fig. 1). The computed radial distribution of the magnetic field across the WP is used to propose a more economically sensible superconductor graded design, where the HTS is only used in the highest field layers. An iterative process is also carried out in order to improve the magnetic flux by adjusting the steel fraction in the WP sub-coils, while ensuring that static and fatigue criteria are simultaneously met.

IV. Results

A. Effect of Fatigue on the Generated Flux

The maximum achievable flux in a uniform current density solenoid of R_o = 2.7 m is shown in Fig. 4 as a function of the allowable hoop stress in the conduits. The trends of three superconductors are plotted: HTS (RE-123) and Nb_3Sn with two assumed values of effective strain: ε_{eff} = -0.25% and -0.5%. Designs with higher hoop stress can operate at larger engineering current density, which, for a given geometry, translates into larger generated magnetic field and flux. Fig. 4 also shows that the benefit of using HTS dilutes for low allowable hoop stress.

The results displayed in Fig. 4 do not include any fatigue-related assumptions. The admissible hoop stress is defined by our simple crack growth model, which in turn, determines the maximum achievable flux in the solenoid. For the conduit materials and assumptions of Fig. 3, the solenoid can generate a maximum flux of 207.4 Wb if SS 316LN is chosen for the conduits and HTS as the superconductor. The flux can increase by 10% (229.3 Wb) if a special alloy such as JK2LB is chosen for the jackets. Generating a flux beyond 240 Wb with a uniform current density solenoid will require the use of HTS and impose severe constraints in the possible materials for the conduits and/or the resolution of the NDE inspection.

B. Graded Coil Designs

A CS1 winding pack layout based on the use of HTS as superconductor and SS 316LN for the conduits is used to explore the benefits of superconductor and steel grading.

The most relevant details of a Superconductor (SC) graded design, and a Superconductor + Stainless Steel (SC+SS) graded design are compared in Table II with those of the Uniform Current Density (UCD) design that generates the maximum flux for $\sigma_h \approx 300$ MPa. The total current and R_o are the same in all three designs. R_i is slightly adjusted in the graded designs since a marginally higher hoop stress can be afforded. The graded designs use only RE-123 in the innermost double-layer sub-coil, react-and-wind Nb_3Sn (assuming $\varepsilon_{eff} = -0.25\%$) in the 6 medium-field sub-coils (between 6 and 15 T), and Nb-Ti in the 3 outermost sub-coils (below 6 T). The layout of the proposed SC+SS graded design is illustrated in Fig. 1 (b). Since the coil dimensions are the same and the magnetic field is almost identical in both graded designs, the additional flux gained in the SC+SS design is related to the modified current density profile due to the stainless steel grading within the WP [9]. Table II also reports the membrane stress and average hoop stress in the innermost layer, together with the fatigue lifetime (including safety factors). Both static and fatigue criteria are satisfied in all designs, but fatigue is the main design driver in the DEMO CS.

Table III provides the main geometrical parameters and the peak field in each sub-coil of the SC+SS graded design. The required non-Cu area is specified for each grade, showing the potential cost savings of a graded design. Further grading of the steel fraction (i.e., increasing the steel in the innermost region at the expense of reducing it in the outermost sections) results in undesirable radial tension in the coil insulation [19].

TABLE II
PARAMETERS OF THE UNIFORM CURRENT DENSITY (UCD), SUPERCONDUCTOR (SC), AND SUPERCONDUCTOR + STAINLESS STEEL (SC+SS) GRADED DESIGNS

Parameter	UCD	SC graded	SC+SS graded
Total current (MAt)	72.2	72.2	72.2
Conductor current (kA)	46.3	46.3	46.3
R_i (m)	1.5	1.52	1.52
R_o (m)	2.7	2.7	2.7
SC material in subcoils (RE-123/Nb_3Sn/Nb-Ti)	10/-/-	1/6/3	1/6/3
Peak B field (T)	15.72	15.71	15.76
CS magnetic flux (Wb)	207.4	211.6 (+2.0%)	218.5 (+5.4%)
Membrane stress[a] (MPa)	356.0	362.1	350.0
Hoop stress[a] (MPa)	288.9	294.5	295.4
Cycles until break (#)	84.2×10^3	80.0×10^3	83.6×10^3

[a] Membrane stress and average hoop stress are reported in layer 1 (maximum).

TABLE III
MATERIAL, GEOMETRICAL PARAMETERS AND PEAK MAGNETIC FIELD OF THE SUPERCONDUCTOR + STAINLESS STEEL GRADED DESIGN

Sub-coil (material)	r_i (mm)	$A_{non\text{-}Cu}$ (mm^2)	A_{steel} (mm^2)	B_{max} (T)
1 (RE-123)	1528.3	58.5	4548	15.76
2 (R&W Nb_3Sn)	1676.2	110.0	4262	14.19
3 (R&W Nb_3Sn)	1818.4	75.2	3874	12.67
4 (R&W Nb_3Sn)	1948.8	53.8	3573	11.13
5 (R&W Nb_3Sn)	2070.3	39.7	3329	9.60
6 (R&W Nb_3Sn)	2184.7	29.8	3127	8.06
7 (R&W Nb_3Sn)	2293.3	22.5	2960	6.52
8 (Nb-Ti)	2397.1	72.6	2935	4.98
9 (Nb-Ti)	2502.2	28.4	2739	3.45
10 (Nb-Ti)	2600.3	15.9	2632	1.92

V. ALTERNATIVE DESIGNS

Radial compression can be used to offset the hoop loads in a pulsed solenoid, and thus, mitigate the effects of fatigue.

Bucking the TF coils against the solenoid has been proposed for several machines, [20]–[22]. In the EU DEMO, the TF centering force might provide at least a radially inward pressure of 40 MPa, which partially counteracts the hoop stress in the CS, and can lead to an increase of more than 20% in generated flux compared to a free-standing design with the same fatigue constraints. However, a bucked solenoid design must be layer-wound along its whole length (no joints can be located in the interface between the TF and the CS coils), which avoids vertical coil segmentation in independent modules and restricts the CS plasma shaping capability.

Zylon/epoxy [23] and other high strength composites are used as reinforcement in normal-conducting high-field pulsed solenoids [24]–[26]. These composites can be highly pretensioned at room temperature, but they typically exhibit a negative thermal contraction coefficient. Thus, most of the radial compression provided at room temperature is released during cool-down, leading to a modest enhancement of the CS performance.

Another alternative under consideration is to assemble the cable in a double-wall CICC [27]. The inner wall contains the helium flow and can be made of soft metal, whereas a stiffer outer wall provides the mechanical function. Thus, the cross-section subjected to large alternating hoop loads is released from the fluid containment function.

VI. CONCLUSION

Mechanical fatigue has profound implications in the design of a pulsed solenoid, and has to be considered since the early design stages of the EU DEMO CS. A fusion power plant based on a pulsed tokamak will experience even more demanding fatigue constraints, since the number of plasma pulses will likely exceed 100,000 (assuming a plant cycle time in the order of 8,000 s and a power station lifetime of 40 years).

In general, the use of HTS enhances the flux generated by the central solenoid for a given coil outer radius. However, the relative gain in flux by using HTS depends strongly on the allowable hoop stress, which is determined by fatigue considerations. For more demanding fatigue constraints (e.g., higher number of operating cycles), the effectiveness of HTS to enhance the magnetic flux becomes smaller. The use of superconducting and stainless steel grading result in a more cost effective design of the CS winding pack and also provide a modest gain of magnetic flux.

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