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Performance analysis of a graded winding pack design for the EU DEMO TF coil in normal and off-normal conditions

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A B S T R A C T

The superconducting magnet system plays an important role in the framework of the design of the EU DEMO tokamak. In recent years, ENEA developed a prototype of cable-in-conduit conductor (CICC) with two low-impedance central channels to be used in the DEMO Toroidal Field (TF) coils with a graded winding pack (WP). In this paper, a model of a TF coil based on the thermal-hydraulic code 4C has been developed, including the WP, the steel casing with dedicated cooling channels (CCCs) and the two independent cryogenic circuits cooling the WP and the casing, respectively. The first part of the work analyzes the performance of the WP during a series of standard plasma pulses in normal operating conditions. In the second part different off-normal operating conditions during the plasma pulses are studied, namely the collapse of one or both central channel(s) in the most critical CICCs and the plugging of some CCCs at the most critical locations in the magnet.

1. Introduction

In the frame of the EU DEMO design activities [1], a big effort is being devoted in the Work Package Magnets (WPMAG) to the preliminary design of the Toroidal Field (TF) coils, resulting in the proposal of three different conductors and corresponding winding packs (WPs) by different European institutions [2,3]. These proposals are periodically updated and optimized taking into account the feedback from mechanical and thermal-hydraulic (TH) analyses, as well as, of course, the updates in the input from the EUROfusion Project Management Unit.

The TH code 4C [4] was already used to develop the first model of an entire EU DEMO TF coil, including structures and a simple cooling circuit [5], and applied, with the addition of quench lines in the model, to the quench analysis of the magnet [6]. In this paper, the previous model is updated to the new WP and conductor designs proposed by ENEA after the 2015 DEMO design review that increased the number of TF coil from 16 to 18 [7]. The model is then used first to assess the coil DC performance, considering, as a major difference with past works analyzing steady state burns [5,8,9], the standard pulsed operation currently foreseen for DEMO: several cycles are simulated, up to a periodic behavior of the coil. The value (and location) of the minimum temperature margin ($\Delta T_{\mathrm{marg}}^{\mathrm{min}}$) in the WP is computed and compared with the minimum acceptable value of 1.5 K [2]. The study is then repeated in off-normal conditions, i.e. considering the choking of the flow in the pressure relief channels of the most critical conductor or in some casing cooling channels (CCCs).

2. Conductor and WP

The most recent WP proposal by ENEA (the so-called WP2016#2) is an upgrade of the 2015 design [10] and consists of a double-layer (DL) wound WP, see Fig. 1a, that allows the grading of the SC cross section in the different DLs, depending on the magnetic field, thus optimizing the use of SC. The WP consists of six DLs where the jacket thickness of each conductor increases with the distance from the plasma to withstand the higher mechanical stresses [11]. The originally circular cable-in-conduit conductors (CICCs) are compacted and squeezed to a rectangular shape, see Fig. 1b, with two low-impedance cooling channels (“holes”) [10] delimited by spirals.

Each DL is constituted by a single conductor; the supercritical He at the nominal conditions of 4.5 K and 0.6 MPa is supplied to

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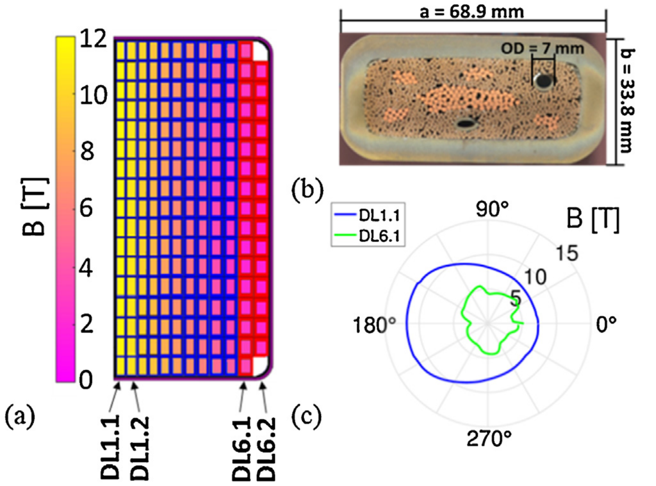

Fig. 1. (a) ENEA 2016 design of the TF WP with six DLs including Nb_3Sn (blue) and NbTi (red) conductors. The 2D magnetic field amplitude map on the inboard equatorial cross section is reported (the plasma is on the left). (b) Cross section of the ENEA conductor concept on which 2016 WP design is based. (c) Polar distribution of the magnetic field amplitude in the central turn of DL1.1 (blue) and in the last turn of DL6.1 (green), at nominal operating current; the inboard equatorial plane is at 180°. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the two layers of the same DL through a single inlet (a hole in the jacket). The inlet mass flow splits between the two layers, so that the He flows in counter-current in adjacent layers. In each layer, the He distributes among the three parallel cooling channels (i.e. the two holes and the bundle) according to their hydraulic impedance. The main geometrical parameters of the conductors are reported in Table 1.

3. The 4C model of the TF coil

The 4C model adopted here includes, as in [5], all DLs of the WP (see [12] for details), and the casing, thermally coupled to the WP across the ground insulation and cooled by dedicated CCCs. The casing is discretized in eight poloidal cuts, equally spaced on the inboard (A1-A4) and outboard (B1-B4) legs, see Fig. 2.

The He inlets are located on the equatorial plane of the outboard leg, on the lateral side of the WP, while the outlets are located on the opposite side, at the same poloidal location. The CCCs inlets are located at the bottom of the coil, as in ITER [13]. Each of the two legs has 48 CCCs connected to inlet/outlet manifolds. We consider here the once-through circulation option [5]. The preliminary design of two cryogenic circuits for the WP and for the casing cooling of [5] is adopted, see Fig. 2, supplying ~150 g/s to the CCCs circuit and ~60 g/s to the WP (with the target pressure drop of ~1 bar and inlet pressure of ~6 bar during the transient [14]).

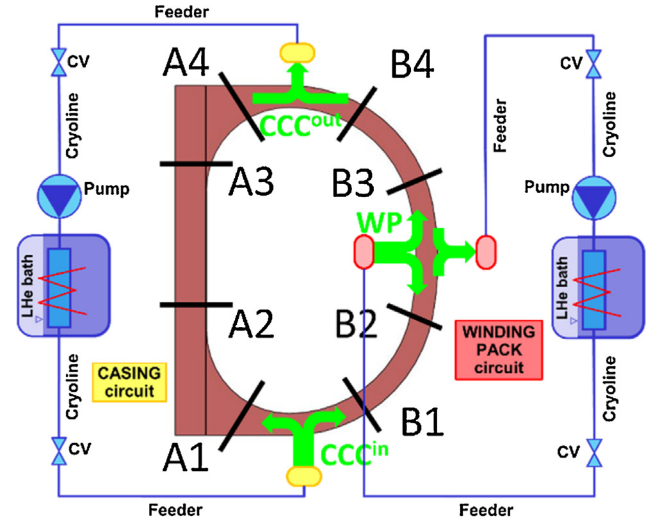

Fig. 2. Schematic representation of the 4C model of the cryogenics circuits for WP (on the right, red manifolds) and CCCs (on the left, yellow manifolds) of the DEMO TF coil. The poloidal cuts A1-4, B1-4 used for the discretization of the casing are highlighted. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

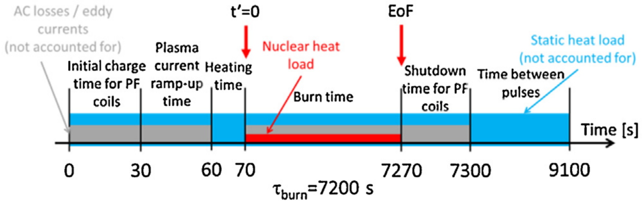

Fig. 3. Evolution of a standard DEMO plasma pulse according to [15].

The distribution of the magnetic field at End of Flat top (EoF, see below) and nominal operating current (70.8 kA) is reported in Fig. 1a and c, including all contributions from the Central Solenoid (CS), the Poloidal Field (PF) coils and the plasma. The highest field within the WP is located on the central turns of DL1.1, the innermost layer, at the inboard equatorial plane, while on the outermost DLs the maximum magnetic field is located at the coil sides due to PF contribution, see Fig. 1a and c.

4. Simulation setup

The nominal pulsed operation ("normal" operation, case α) consists in a series of standard cycles [15], see Fig. 3, including a 7200 s

Table 1
Main geometrical parameters EU DEMO TF WP2016 by ENEA. Where different, the values for the first and second layer of the same DL are separated by "/".

	Nb_3Sn					NbTi
	DL1	DL2	DL3	DL4	DL5	DL6
N. SC strands (D = 1 mm)	720	360	270	180	120	972
Strand Cu:nonCu	1	1	1	1	1	1.6
N. Cu strand (D = 1 mm)	360	720	540	630	960	0
N. Cu strand (D = 1.5 mm)	108	54	162	108	0	108
ID (OD) central channels [mm]	5 (7)	5 (7)	5 (7)	5 (7)	5 (7)	5 (7)
Bundle void fraction [%]	0.26	0.26	0.26	0.26	0.26	0.3
Jacket ext. dimensions a × b [mm]	68.9 × 33.8	68.9 × 34.9	68.9 × 38.6	68.9 × 40.8	68.9 × 46.2	68.9 × 56.6
Jacket thickness [mm]	3.9	5.3	6.8	8.4	10.0	11.7
Turn length [m]	43.92/44.16	44.40/44.64	44.90/45.17	45.44/45.72	46.02/46.34	46.68/47.06
# turns	17/17	17/17	17/17	17/17	17/17	17/15
Hydraulic length [m]	746/751	755/759	763/768	772/777	782/788	794/706