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Conceptual Design Improvement of a Toroidal Field Coil for EU DEMO using High Temperature Superconductors

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***Abstract*— In the frame of the pre-conceptual design of the next generation fusion power plant (EU DEMO), the PROCESS systems code is used for nearly twenty years in which the main reactor components (e.g. plasma, blanket, magnets) are integrated in a unique computational algorithm and simulated by means of rather simplified mathematical models (e.g. steady state and zero dimensional models).**

In this work the boundaries given by PROCESS code for the toroidal field coil (TFC) of EU DEMO are used as a starting point for the design of a TFC winding pack, using High Temperature Superconductor (HTS) material *RE*BCO as alternative to Nb_3Sn. As the DEMO system code parameters are under continuous adjustment the PROCESS outcome of the July 2012 version is used. This defines the cable space area, the winding pack current density and the total current in one TFC to generate the required magnetic field on the plasma axis. Based on this and as an extension of the work published in [1] and [2], the electromagnetic, structural mechanics, cooling, and thermo-hydraulic properties of an HTS-TFC are presented and parameters like operation current, magnetic field and Lorentz forces, operation temperature, structural requirements, cooling, and quench performance are calculated. It is demonstrated that HTS material can be used for the TFC of EU DEMO. At present the design is made at an operation temperature T_{op} = 4.5 K allowing adaptation to higher temperatures if the material properties shall improve in future.

***Index Terms*— EU DEMO, Fusion, High Temperature Superconductor, *RE*BCO, Toroidal field coil.**

I. INTRODUCTION

IN the frame of the EUROfusion Power Plant Physics & Technology Work Programme a conceptual design for a Demonstration Fusion Power Reactor (DEMO) to follow ITER by 2050 is under development. The whole programme is embedded in the so-called roadmap aiming at realizing Fusion Electricity to the European grid by 2050 [3]. Within the pre-conceptual design of DEMO, the PROCESS systems code developed since more than 20 years is used in which the main reactor components (e.g. plasma, blanket, magnets) are integrated in a unique computational algorithm and simulated by means of rather simplified mathematical models (e.g. steady state and zero dimensional models) [4]. According to the actual planning, EU DEMO has 1.8 times larger plasma volume compared to ITER [5],[6],[7]. Therefore, the size of the superconducting magnet system is significantly larger with higher magnetic fields at the plasma axis and at the conductor. While the challenges for larger superconducting magnets are escalating, there has been new breakthrough in materials. Example of such novel material is the so-called second generation (2G) HTS also known as rare-earth-barium-copper-oxide (*RE*BCO) tapes. This material has superior capabilities in terms of current density (J_c) and mechanical stability at higher critical magnetic fields (B_c), in comparison to existing low temperature superconductors (LTS). These HTS tapes are commercially available (see for example [8]).

The present paper investigates if this actual available HTS material can be used to design a TFC operated at 4.5 K for EU DEMO with the available space given by the PROCESS code. The key parameters discussed in this paper are the shape of the TFC, conductor current, number of turns, peak magnetic field in the TFC, toroidal magnetic field at the plasma axis, dump time constant and hotspot temperature.

II. DEFINITION OF TFC WINDING PACK USING HTS

As part of the work under the European Fusion Consortium (EUROfusion), the input parameters for the design of the HTS TFC were taken from PROCESS System Code output dated of July 2012 [5] using the pulse DEMO model. In the following we refer as “pulsed DEMO”. Some of its main parameters are given in Table I [9].

TABLE I
INPUT PARAMETERS FOR TFC OF PULSED DEMO (JULY 2012)

	Quantity
Number of TFC	16
Total current in one TFC	19.11 MA
Stored energy of one TFC	9.05 GJ
Peak magnetic field	13.06 T
Peak toroidal field at plasma	6.79 T
Total available winding pack area	1.10 m^2
Overall steel cross section, inboard	1.34 m^2

III. DEFINITION OF HTS CONDUCTOR

The HTS conductor used in the conceptual design is made of copper stabilized *RE*BCO tapes arranged in “superstrands” of 6 – 9 mm in diameter and combined in a Rutherford cable. The number of superstrands was selected such to achieve a critical current of approx. 80 kA at 13.5 T and 4.5 K. The cable is embedded in a stainless steel jacket of 6.5 mm

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thickness and finally insulated by 1.5 mm Glass-Kapton-Glass. The resulting void in the conductor is used for cooling with 4.5 K forced-flow helium. The resultant parameters are summarized in Table II. Details about the conductor concept can be found in [10].

TABLE II
CONDUCTOR PARAMETERS

Parameter	Value	Unit
Total superconductor area from HTS	1.82	mm^2
Total silver area from HTS	5.48	mm^2
Total Hastelloy area from HTS	91.3	mm^2
Total copper area	554.9	mm^2
Current density in copper	90	A/mm^2
Stainless steel jacket area	1056.2	mm^2
Total area for helium cooling	272.2	mm^2
Void fraction	28	%

IV. RESULTS OF ELECTROMAGNETIC ANALYSIS

The July 2012 DEMO design has 15% smaller winding pack area than that of the DEMO April design, which was used in [1]. As a consequence, the pancake winding pack proposed for EU DEMO as reported in [1] does not match the updated boundary conditions. The necessary modifications to adopt the winding pack changes led to 14 inner pancakes and 2 outer pancakes on each side with 384 turns in total as reported in [2]. A conductor current of 50 kA was chosen leading to a magnetic field at the plasma center of B = 6.853 T and a peak magnetic field in the mid plane of the inner leg of 13.27 T. The conductor layout used in [2] resulted in an operating to critical current ratio of 0.7 and to a current sharing temperature T_{cs} of 16.4 K with a temperature margin (T_{cs}-T_{op}) of 11.9 K. This conductor and winding pack design is used for the following analysis.

V. RESULTS OF 2-DIM STRUCTURAL ANALYSIS

In the 2-D structural analysis presented in [2], it was assumed that the cable space inside the jacket has the Young's modulus of copper weighted with the cable volume within the cable space. In addition the winding pack was rigidly connected to the coil casing (bonded model) and plane-strain elements were used. Details can be found in [2]. But as the cable is made by a compound of REBCO, Hastelloy, copper, solder etc. which is hard to simulate it was decided to use conservative value of zero Young's modulus for the cable space. In reality, when such huge Lorentz forces act on the winding pack, the winding pack including ground insulation will detach from the casing in the inboard leg towards the center of the machine. Finally plane-stress elements were used as they should give a more realistic approximation of the 2-dim mechanical behavior of the TFC in vertical direction. The simulation was repeated by keeping all other parameters and boundary conditions fixed.

The simulation with ideal elastic properties (model 2A) led to exaggerate Von Mises stresses up to 2800 MPa in the jacket. Figure 1 shows the Von Mises stress in both the casing and the winding pack. Thus the simulation was repeated with ideal elastic-plastic properties of stainless steel in the region of the highest stresses (model 2B). With this approach the resultant Von Mises stresses were found to be ≈1000 MPa. Figure 1 shows in addition the enlarged view of the highly stressed jacket region. In Table III the main results of the two structural analysis models are compared.

From these results it is expected that local plastic deformation will occur to relax peak stresses in the jacket.. Future investigations with a detailed cable layout are necessary to identify critical stresses.

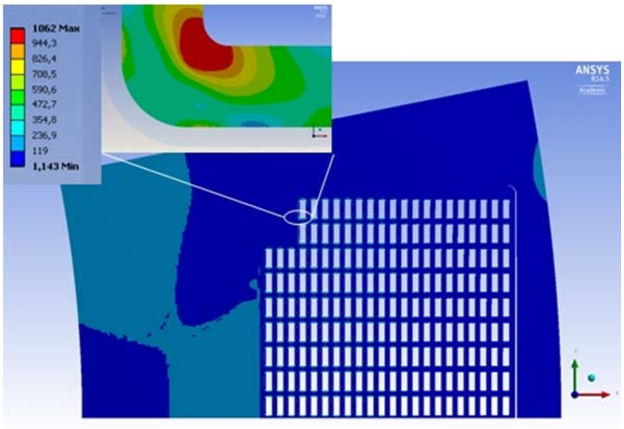

Fig. 1. Von Mises stress in both the casing and the winding pack for the ideal elastic model. The zoomed picture shows the maximum stress in the jacket area calculated with the ideal elastic-plastic model.

TABLE III
MAIN RESULTS OF STRUCTURAL ANALYSIS AND COMPARISON TO THE RESULTS OF [2]

Parameter	Model 1 plane strain	Model 2B plain stress
Young's modulus of cable space [GPa]	30	0
Bonded/Detached model	B	D
Material behavior of stainless steel (IE=ideal elastic, IEP=ideal elastic-plastic)	IE	IEP
Max. Van Mises stress in casing [MPa]	604	474
Max. Van Mises stress in jacket [MPa]	178	1062
Max. Shear stress in turn insulation [MPa]	68	79

VI. RESULTS OF THERMO-HYDRAULICS ANALYSIS

A. *Hydraulics*

The HTS TFC winding pack for the July 2012 DEMO design consists of 14 inner pancakes and 2 outer pancakes on the either side, whose length is 858 m and 741 m respectively. The TFC conductor is cooled by forced flow supercritical helium at 4.5 K and 6 bar, as in ITER, and the helium inlet is located in the high field region.

The selection of friction factor for the hydraulic model is a prerequisite for determining the pressure drop and temperature rise in the conductor pancakes. The LTS conductors used for fusion magnets are of CICC type and use a large number of wires of small diameter in a multi-stage cable, resulting in high friction [11]. As the strands in the HTS conductor concept [10] have a much larger diameter, the friction factor of the EURATOM LCT conductor has been used [12]:

$$\text{friction factor} = \begin{cases} 47.65 * \mathrm{Re}^{-0.885} & \mathrm{Re} < 1500 \\ 1.093 * \mathrm{Re}^{-0.338} & 1500 < \mathrm{Re} < 2*10^5 \\ 0.0377 & \mathrm{Re} > 2*10^5 \end{cases} \qquad (1)$$

with f = friction factor and Re = Reynolds number.

For the simulation, a basic heat load of 0.006 W/m was assumed which counts for heat conduction through the coil casing. In addition the nuclear heat deposited in the winding pack and in the casing of the TFC has to be considered which is caused by the large neutron flux during plasma operation of DEMO. For given mass flow rates and different nuclear heat loads per unit length of conductor, the temperature and pressure profiles along the conductor was calculated by solving energy and momentum conservation equations derived by [13] and implemented in the HE-SS code [14].

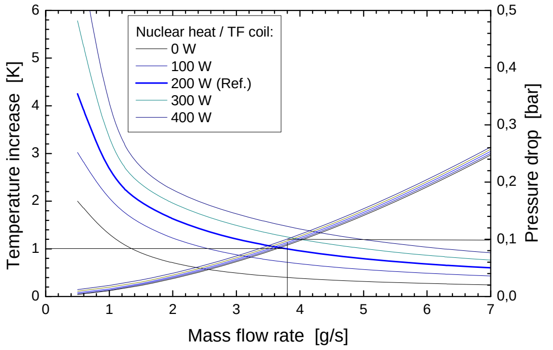

Fig. 2. Temperature increase and pressure drop of the inner pancake for different nuclear heat loads. 200 W/coil is the reference.

Figure 2 shows the temperature increase and pressure drop of the inner pancake for different nuclear heat deposition with 200 W/coil as reference [15]. It can be seen that for increasing mass flow rates the temperature increase decreases whereas the pressure drop increases, as expected. Unlike LTS conductors where the temperature margin is very low (for ITER less then 1 K), HTS conductor can be operated with a rather low mass flow rate due to its much higher current sharing temperature, leading to a much lower pumping power for the cryogenic system. A second advantage of the high temperature margin is the possibility of accepting higher heat loads than for LTS. As an example, with LTS with a temperature margin of 1 K and a heat load of 200 W/coil, a mass flow rate much higher than 4 g/s in the inner winding is necessary. Using HTS, a nuclear heat load of 400 W/coil is no problem even with a mass flow rate below 2 g/s.

B. Quench analysis

A major problem faced by any HTS magnet is quench detection due to the slow quench propagation. To analyze the complex phenomena, the CryoSoft code THEA [16][17] is used to simulate 1-D thermohydraulic analysis.

1) Material properties

Before using THEA the material properties of *RE*BCO and Hastelloy have to be identified. The critical surface of *RE*BCO is parametrized by fitting Equ. 2 [18] to the data presented in [8]. The results are shown in the figure 3 and the fit parameters are given in Table IV. Other parameters for *RE*BCO like thermal conductivity, specific heat, electrical resistance are taken from CRYOCOMP software [19] whereas the material properties of Hastelloy were taken from [20].

$$J_c(B,T) = \frac{A}{B} B_{irr}(T)^{\beta} \left(\frac{B}{B_{irr}(T)}\right)^{p} \left(1 - \frac{B}{B_{irr}(T)}\right)^{q} \qquad (2)$$

$$B_{irr}(T) = B_{irr0}\left(1 - \frac{T}{T_{c0}}\right)^{\alpha}$$

TABLE IV
FIT PARAMETERS FOR CRITICAL SURFACE OF *RE*BCO

Parameter	Value	Units
T_{c0}	90	K
B_{irr0} (Parallel to c plane)	132.5	T
A	1.82962E8	$\mathrm{Nm^{-3}T^{-\beta}}$
p	0.5875	
q	1.7	
α	1.54121	
β	1.96679	

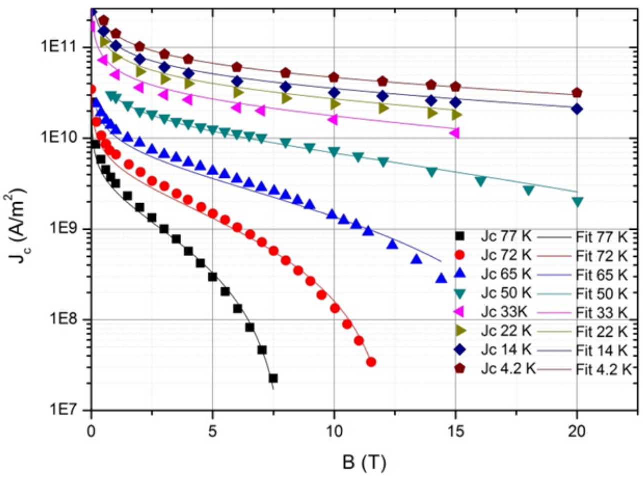

Fig. 3. Critical current density data of *RE*BCO as a function of magnetic field parallel to c-axis and fitting function

The quench behavior of the HTS cable is exemplarily studied by modelling a 39 m long conductor, corresponding to the length of the innermost turn, carrying 50 kA in a constant magnetic field of 13.55 T using a homogenized conductor model. In this model all tapes are merged together forming homogenized blocks of REBCO+copper+Hastelloy (m1) embedded in a stainless steel jacket (m2). This model takes into account the fact that the Hastelloy substrate and the REBCO layer are very close together resulting in an almost equal temperature. The supercritical helium at 4.5 K flows in the conductor and exchanges heat with (m1) and (m2). In THEA the Dittus-Boelter correlation is used for determining the heat transfer coefficient. To initiate a quench, a heat pulse of 704 J just large enough to initiate a quench was deposited in the center of the conductor over a length of one meter for 100 ms. The voltage rise of the *RE*BCO+copper+Hastelloy block is shown in figure 6. As quench detection limits the usual value of 100 mV and in addition a value of 400 mV was chosen, as this value is proposed for ITER [21]. As visible in figure 4 these values were reached after 24.24 s and 30.08 s. The voltage rise time is considerably longer than in case of LTS because of the extremely high critical temperature T_c which is 70 K even at 13.5 T and thus offers very high heat capacity. Adding 2 s for quench detection and initiation of the coil discharge results in $t_{del,1}$ = 26.24 s and $t_{del,1}$ = 32.08 s respectively. After this time an exponential current decrease is assumed with a time constant of τ_D = 30 s. 30 s was chosen to limit the discharge voltage to about 11 kV [1].

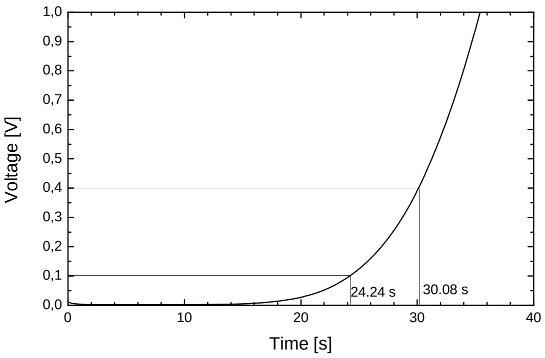

Fig. 4. Resistive voltage of HTS cable as a function of time

Figure 5 shows the temperature evolution for both t_{del} separately. For $t_{del,1}$ the maximum temperature is lower than the ITER design criteria of T_{max} = 150 K. For the longer $t_{del,2}$ which results from the unusual high quench detection voltage of 400 mV, the calculation show a quite high conductor temperature close to 230 K. These calculations show that quench detection and discharge of such a HTS-TF coil is feasible but should use a QD voltage level in the order of 100 mV or decrease the discharge time constant. The quench analysis will continue in future.

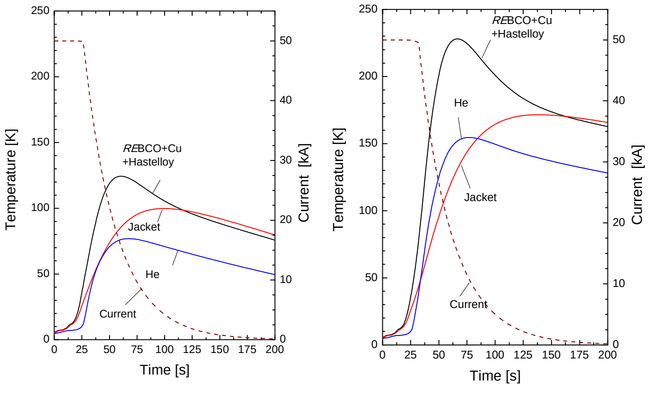

Fig. 5. Conductor, jacket and helium temperature evolution during quench of 39 m long HTS conductor for the two delay times $t_{del,1}$ (left) and $t_{del,2}$(right).

VII. CONCLUSIONS AND FUTURE WORK

With the presented results HTS conductor *RE*BCO is a potential candidate superconductor for a DEMO TF coil. An HTS winding pack principally fits in the given winding pack area and can produce the required magnetic field at the plasma axis. With the present design the peak magnetic field at the superconductor is 13.27 T. The use of HTS can increase the temperature margin to 11.9 K. All the parameters are summarized in Table. V.

As a general conclusion it is stated:

- The described generic conductor design using HTS material is feasible. The HTS material available today offers enough current density at high field to generate plenty of temperature margins well above 10 K.
- The stresses both in conductor jacket and insulation are within allowable limits but the results show some plastic deformation at the jacket using the pessimistic approach of a zero Young's modulus for the cable space. Future investigations with a known cable layout are needed.
- A first attempt of a quench analysis of the innermost turn of the inner pancake leads to a extremely slow voltage rise where 100 mV is reached after more than 24 s. Using a discharge time constant of 30 s (which corresponds to a feasible discharge voltage of ~11 kV), a maximum temperature of 124 K is obtained and the ITER hot spot criterion is fulfilled.

Recently different HTS manufacturers started to supply HTS tapes with massively increased current densities at highest field well above 10 T. These advanced pinning HTS tapes will offer even more temperature margin when operated at 4.5 K or allowing operation at higher temperatures above 4.5 K.

TABLE V
CONCEPTUAL DESIGN SUMMARY

Parameter	Value	
Peak field on conductor	13.27	T
Inductance	7.28	H
Operation current	50	kA
I_{op}/I_c	0.7	
Energy Stored in one TFC	9.09	GJ
Total number of conductors	384	
Total used winding pack area	0.95	m^2
Discharge time constant	30	s
Discharge voltage	10.83	kV
Current sharing temperature	16.4	K
Temperature margin	11.9	K
Nuclear heat deposition / coil	200	W
He mass flow rate / pancake	3.8	g/s
Temperature increase	1	K
Pressure drop	0.1	bar
T_{max} during quench (U_{QD} = 0.1 V / 0.4 V)	124 / 228	K

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