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High current superconductors for DEMO

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HIGHLIGHTS

- ► Definition of requirement for TF coil based on the input of system code.
- ► A TF coil and conductor design for the European DEMO project.
- ► Use of React&Wind method opposite to Wind&React with related advantages.
- ► Hybridization of winding pack, Nb/Nb_3Sn, by graded layer winding.

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ABSTRACT

In the assumption that DEMO will be an inductively driven tokamak, the number of load cycles will be in the range of several hundred thousands. The requirements for a new generation of Nb_3Sn based high current conductors for DEMO are drafted starting from the output of system code PROCESS. The key objectives include the stability of the DC performance over the lifetime of the machine and the effective use of the Nb_3Sn strand properties, for cost and reliability reasons. A preliminary layout of the winding pack and conductors for the toroidal field magnets is presented. To suppress the mechanism of reversible and irreversible degradation, i.e. to preserve in the cabled conductor the high critical current density of the strand, the thermal strain must be insignificant and no space for micro-bending under transverse load must be left in the strand bundle. The "react-and-wind" method is preferred here, with a graded, layer wound magnet, containing both Nb_3Sn and NbTi layers. The implications of the conductor choice on the coil design and technology are highlighted. A roadmap is sketched for the development of a full size prototype conductor sample and demonstration of the key technologies.

1. Introduction

Force flow, high current conductors based on Nb_3Sn technology are considered the only viable choice for a DEMO tokamak with peak field in the range of 10–18 T. For lower field NbTi may be an alternative. For higher field hybrid magnets with HTS superconductors may be considered.

The Nb_3Sn cable-in-conduit conductors for the ITER magnets are prone to substantial irreversible degradation upon cyclic load and thermal cycles [1,2]. For an inductively driven tokamak with number of cycles in the range of several hundred thousands, it is inacceptable to face the risk and the cost of dramatic performance loss in the superconducting magnets.

The keywords for the design of conductor and coil for DEMO are reliability, i.e. stable and predictable performance over the lifetime of the device, and cost effectiveness, i.e. full exploitation of the characteristics of the superconductor. In the present pre-design effort, the top requirement comes from the system code PROCESS [3] and is complemented by engineering and technology choices, leading to a preliminary layout of TF conductor and coil.

2. Identification of requirement

2.1. The input from the system code

In agreement with the EFDA DEMO team, the output of the PROCESS run dated 16th April 2012 is assumed as initial requirement. In the system code, many technology choices are assumed to be like in ITER, e.g. the Nb_3Sn superconductor for high field magnets, the case of the TF coils forming a vault to support the centering forces, the fully bonded winding pack, the cooling by forced flow supercritical helium, etc. The key parameters for the TF coil system are summarized in Table 1, in comparison with ITER [4]. DEMO is much bigger than ITER: an impression of the relative size can be taken from Fig. 1.

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Table 1
Parameters from system code for TF DEMO vs. ITER.

	DEMO	ITER
Number of TF coils	16	18
Peak field (T)	13.45	11.8
Current in one TF coil (MA)	19.8	9.11
Stored energy in one TF coil (GJ)	11.56	2.28
Av. circumference of TF coil (m)	44.2	34.1
Minimum bending radius (m)	3.09	1.95
Radial build, inboard (m)	1.59	0.91
Overall steel cross section, inboard (m^2)	1.65	0.56

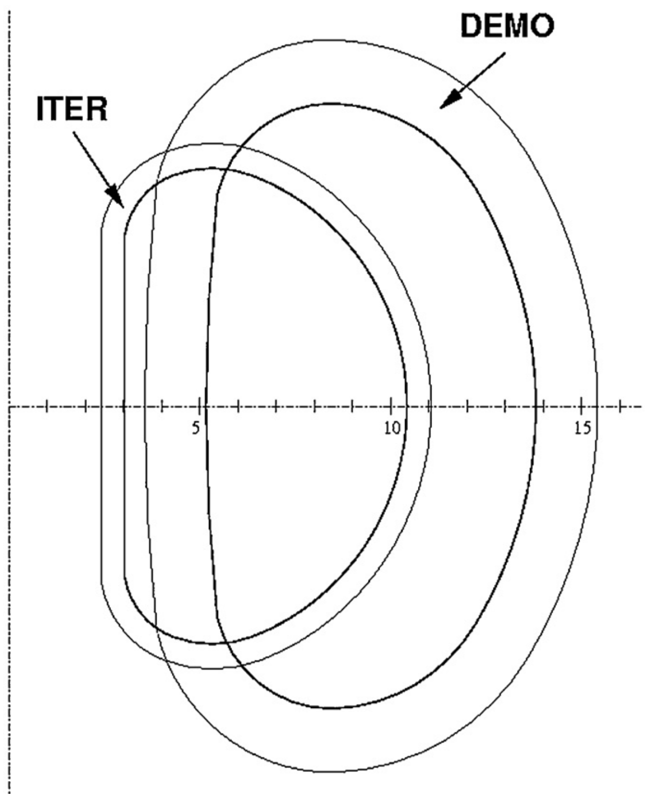

Fig. 1. Elevation view of the TF coils of DEMO and ITER.

2.2. Other requirement

Other parameters necessary for the layout of TF coil and conductor are listed in Table 2. A long decay time constant for current dump, 23 s, is necessary to limit the electromagnetic loads on the vacuum vessel.

The number of conductor turns and the operating current must match the total current per coil, 19.8 MA. The rationale for 232 turns/coil and the operating current of 85.3 kA is driven by the need to limit the inductance and hence the peak voltage at current dump. A much higher operating current, e.g. larger than 100 kA, is avoided here to remain in a technology range similar to ITER (68 kA) for

Table 2
Other parameters for the TF coil, DEMO vs. ITER.

	DEMO	ITER
Decay time constant for current dump (s)	23	11
Number of turns in the winding pack	232	134
Operating current (kA)	85.3	68
Inductance per coil (Hy)	3.2	0.98
Peak voltage at current dump (kV)	11.78	6.05
Steel in case/steel in winding pack	79/21	50/50
Nuclear heat (1st layer of one coil) (W)	100	80

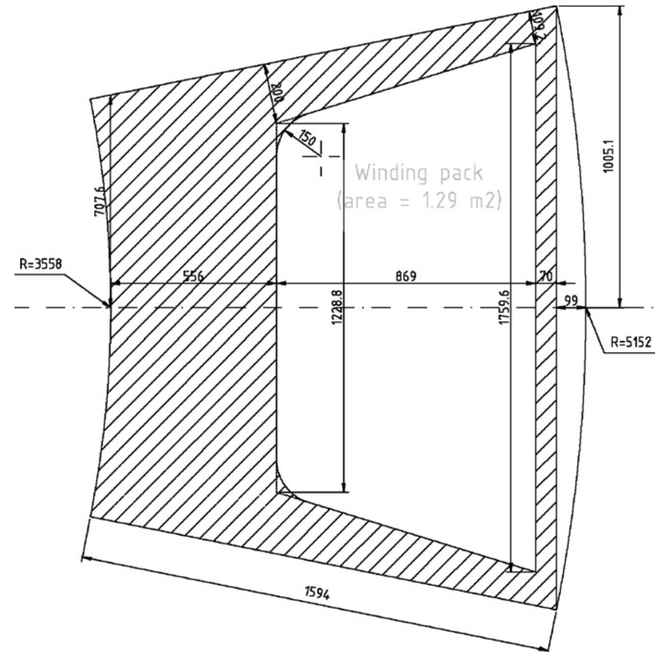

Fig. 2. Proposed cross section of the DEMO TF coil case.

power supply, busbar, current leads, electric breakers. The inductance and peak voltage follow from the stored energy and operating current.

The share of the steel cross section between coil case and winding pack (79/21) is much larger than in ITER to provide an adequate solid vault as bucking cylinder for the large centering forces (122 MN/m per coil). The inboard cross section of the TF coil according to the parameters of Tables 1 and 2 is shown in Fig. 2. The case cross section is 1.3 m^2. The tapered sides of the case and the large radius, 150 mm, at the transition between nose and sides are aimed at optimization of the distribution of the centering loads.

The cooling is assumed as in ITER, i.e. supercritical helium with 6 bar, 4.5 K at inlet and up to 1 bar pressure drop over the TF winding pack.

3. Magnet technology

The large gap between the performance of the free standing Nb_3Sn strand and the ITER cable-in-conduit conductors is due to the large thermal strain and to the irreversible degradation due to filament breakage upon transverse load [2]. To avoid the high compressive, thermal strain in the steel reinforced conductors, the reinforcing steel and the cable must be assembled after the heat treatment, i.e. the Wind&React (WR) method must be replaced by the React&Wind (RW). To improve the mechanical stability of the strand bundle, i.e. to mitigate the filament breakage ("irreversible degradation"), the cable must be very compact, with void fraction <20%, preventing local bending of individual strands upon the transverse loads in operation. A rectangular geometry, with broad side perpendicular to the main field component also helps avoiding high peak stress on the cable [4]. Relocating the pressure release channel outside the strand bundle region will also contribute to the mechanical stability of the cable. The large amount of reinforcing steel in the winding pack may need to be segregated from the conductor conduit to avoid very large and stiff conductors that may be difficult to bend on the winding table. Rather than the radial plates used in ITER [5], co-wound strips of steel are proposed for DEMO, with substantial advantage on manufacturing cost and tolerance.

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