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LTS and HTS high current conductor development for DEMO

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HIGHLIGHTS

- Design and R&D for DEMO TF conductors.
- Wind&react vs. react&wind options for Nb_3Sn high grade TF conductors.
- Progress in the manufacture of short length Nb_3Sn proptotypes.
- Design and prototype manufacture for high current HTS cabled conductors.

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ABSTRACT

The large size of the magnets for DEMO calls for very large operating current in the forced flow conductor. A plain extrapolation from the superconductors in use for ITER is not adequate to fulfill the technical and cost requirements. The proposed DEMO TF magnets is a graded winding using both Nb_3Sn and NbTi conductors, with operating current of 82 kA @ 13.6 T peak field. Two Nb_3Sn prototypes are being built in 2014 reflecting the two approaches suggested by CRPP (react&wind method) and ENEA (wind&react method). The Nb_3Sn strand (overall 200 kg) has been procured at technical specification similar to ITER. Both the Nb_3Sn strand and the high RRR, Cr plated copper wire (400 kg) have been delivered. The cabling trials are carried out at TRATOS Cavi using equipment relevant for long length production. The completion of the manufacture of the two 20 m long prototypes is expected in the end of 2014 and their test is planned in 2015 at CRPP.

In the scope of a long term technology development, high current HTS conductors are built at CRPP and ENEA. A DEMO-class prototype conductor is developed and assembled at CRPP: it is a flat cable composed of 20 twisted stacks of coated conductor tape soldered into copper shells. The 10 kA conductor developed at ENEA consists of stacks of coated conductor tape inserted into a slotted and twisted Al core, with a central cooling channel. Samples have been manufactured in industrial environment and the scalability of the process to long production lengths has been proven.

1. Introduction

The European activity for the conceptual design of the DEMO fusion reactor started in 2011 under EFDA-PPPT (European Fusion Development Agreement – Power Plant Physics and Technology), who coordinates the effort of European Laboratories through individual tasks. The activity included studies and R&D for large size fusion magnets based on both low temperature (LTS) and high temperature (HTS) superconductors [1–6]. In 2014, the Eurofusion consortium replaced EFDA maintaining the same roadmap approach for DEMO, with other European labs joining the program.

The development of a high current carrying, forced flow superconductor for the toroidal field coils has been in the focus of the joined efforts of CRPP and ENEA [4]. The top-level requirements for the magnet system, e.g. major radius of the tokamak, ampere-turns, centerline geometry, stored energy, etc. are provided by the system code PROCESS [7]. The reference run of PROCESS, retained since 2012 as basis for the design, is dated July 25th 2012.

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The baseline for the magnet system of the European DEMO is LTS, same as ITER, i.e. the forced flow, low temperature superconductor technology using NbTi and Nb_3Sn superconducting materials. The key words guiding the R&D for DEMO magnets are "*reliability*" and "*cost effectiveness*". The issue of reliability includes the design robustness, the predictable performance, the easy access to technology, the straightforward quality assurance and the ability to endure mechanical and radiation loads over the reactor lifetime. The cost effectiveness must be demonstrated in the magnets of DEMO and will be crucial to motivate the interest of the utilities toward fusion as an energy source [8].

The development of high current conductors made by HTS tapes is meant as a long term technology target. The advantage of HTS over LTS conductors is the higher thermal stability and hence the tolerance to high nuclear heat load. Long lengths of technologically mature conductors have become available during the last decade. The price of HTS is decreasing, but remains much higher compared to LTS. A selection between LTS or HTS for the over-next generation of fusion magnets may be done after a phase of R&D for HTS high current conductors, including magnet technology aspects, e.g. heat removal and quench protection. The objective for the next period to verify, at full-scale, the *feasibility* and *performance* of HTS-based fusion conductors. The challenge of designing and manufacturing high current/high field conductors starting from thin tapes of coated conductors can be approached with a variety of layouts, whose pros and contras must be investigated by the assembly and test of full size, short length prototypes.

For CRPP and ENEA, only the R&D for LTS is partly supported by Eurofusion, which does not fund the effort of CRPP and ENEA on HTS high current conductors.

2. The LTS conductors

The requirements for the TF conductors are summarized in [2] since 2012, when a first layout of the TF winding pack was drafted according to the reference PROCESS run of July 2012. In 2013 and 2014, while maintaining the reference of July 2012, the CAD model maintained by EFDA-EUROFusion was updated with a reduction of the cross section for the winding pack, driven by the need of vertical ports in the tokamak for remote maintenance. The evolution of the TF coil cross section at the in-board is highlighted in Fig. 1. An updated list of the relevant requirements and operating parameters (most from [2]) is gathered in Table 1, with the corresponding ITER data for comparison.

Table 1
Requirement, layout parameters and other operating condition for the TF DEMO conductor.

	DEMO	ITER
Toroidal field at major radius, *T*	6.8	5.3
Tokamak major radius, m	9.0	6.2
Number of TF coils	16	18
Peak field, *T*	13.6	11.8
Current in one TF coil, MA	19.1	9.11
Stored energy in one TF coil, GJ	9.06	2.28
Av. circumference of TF coil, m	39.8	34.1
Discharge time constant τ, s	23	14
Operating current, Ka	81.7	68
Single coil terminal voltage, kV	<10	4.8
Number of turns	234	134
Superconductor for peak field	Nb_3Sn	Nb_3Sn
Superconductor for field < 6.3 T	NbTi	Nb_3Sn
Winding Layout	Layer	Pancake
Conductor grading	Yes	No
Winding pack cross section, m^2	0.99	0.48
Winding pack current density, A/mm^2	19.3	19.0
Insertion gap winding pack/case, mm	10	10
Weight of one TF coil assembly, t	>1000	360

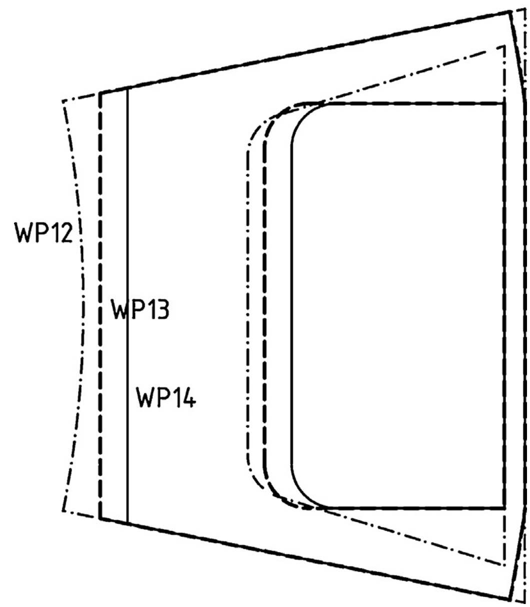

Fig. 1. Evolution of the in-board cross section of the TF coil from 2012 (trapezoidal winding pack) to 2013 and 2014 (smallest winding pack).

The selected winding layout is a graded double layer (DL) opposite to the double pancake of ITER. The choice of layer winding is mandatory to apply conductor grading, i.e. to tailor the amount and kind of superconductor to the local operating field. Each double layer has a different amount of superconductor and hence almost constant temperature margin. The six innermost double layers are based on Nb_3Sn conductors, the three outermost double layers have NbTi conductors. In terms of cost, the choice of graded, Nb_3Sn/NbTi hybrid winding allows to save about half of the superconductor cost. The graded winding also saves cross section of superconductor in favor of steel, with a higher smeared modulus of the winding pack, i.e. a more rigid structure to withstand the operating loads [9].

For design purposes the same scaling law for the critical current density of Nb_3Sn and NbTi strands are retained as in ITER [10,11].

The winding pack data listed in Table 1 are the common basis for the conductor design and R&D carried out at CRPP and ENEA. However, CRPP selected the react&wind (RW) option for conductor and coil manufacture. ENEA maintains the ITER approach of wind&react (WR) method. The thermal strain of Nb_3Sn is assumed in the design $\varepsilon_{th} = -0.3\%$ for the RW option and $\varepsilon_{th} = -0.5\%$ for the WR option. The lower thermal strain in the RW option allows additional saving in the cross section of Nb_3Sn.

2.1. The react&wind option

In the RW option, the strands are assembled to a highly compacted flat cable and heat treated before further assembling to the steel conduit and winding. To minimize the bending strain during manufacturing and winding after the heat treatment, the Nb_3Sn strands must be as close as possible to the neutral bending axis, e.g. using the flat cable geometry. The non-stabilized Nb_3Sn strands are bundled in a thin, flat cable, surrounded by the stabilizing copper. During all the manufacturing steps following the heat treatment, the bending strain must be kept within the reversibility range of the strand.

For coils with non-circular shape, as in the D-shaped toroidal field magnets of DEMO, the cable curvature during the heat treatment is optimized according to the minimum and maximum radius in the magnet. For the DEMO TF winding, the minimum

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