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Evolutions of EU DEMO reactor Magnet System design along the recent years and lessons learned for the future

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Abstract. The DEMO reactor is expected to be the first application of fusion for electricity generation in the near future. In the DEMO power plant the management of magnet system is of central importance as being driver on many crucial aspects such as nominal power plant performance (toroidal field scales fusion power), overall investment budget (about 1/3 of the total construction cost), production efficiency (full power total availability heavily impacted by magnet off-normal events). Therefore a careful approach is requested for this kind of component to ensure a safe design compatible with a power plant production conditions, keeping a control on the factors prone to degrade the economic model (cost, risk). The derivation of those considerations into practical activities results in a constant attempt to lead in parallel extensive design activities and the mastering of upstream knowledge in magnet behavior. In this purpose design activities on DEMO magnet system were continuously conducted in Europe, particularly evolving since 2012 in structured environments, always backed on the association of several laboratories. Since then, the actors underwent preparatory design phase and then the pre-conceptual design activity (CDA) phase, that led to evolutions of design in many aspects, from design features bottom lien themselves to evolution of associated tools and methods up to global strategic considerations.

1. Introduction

The International Thermonuclear Experimental Reactor (ITER) tokamak being well advanced in its contruction phase the next step is now drawing an increasing attention in Europe (EU). In this framework and following the European Horizon 2020 roadmap [1] a pre-conceptual design activity is conducted on the DEMOnstration (DEMO) reactor, as the first generation of fusion power plant to be implemented after ITER tokamak operation. DEMO is actually in pre-conceptual design phase and an intense activity is ongoing in EU. In order to lead those activities the EUROfusion Consortium took over the former framework (EFDA) since 2014, establishing a project structure in which a project team dedicated to Magnet System was established, with members from 19 European laboratories. It drove the carrying out of a broad range of activities, from the dimensioning of reactor coils to longer term R&D. In this paper we will focus on the critical core of the activity, i.e. the DEMO reactor dimensioning, which in its strong majority involves low temperature superconductors (LTS) technology.

2. Pre-conceptual design activity context & organisation

The pre-conceptual design activity (PCDA) phase is expected to prepare the next step, i.e. the conceptual design activity (CDA) phase, by robustly establishing design baselines of the main DEMO tokamak components, associated with consolidated assessments on economic, risk or manufacturing considerations. The magnet system is a major component which, among other functions, drives the whole tokamak performances, therefore should be considered as critical in terms of technical assessment. The organisation of PCDA relies on a central team that manages the evolution of top-level system definitions such as machine operation point, plasma parameters and space reservation for main components. Since 2012 the tokamak underwent important evolutions to which magnet system had to accommodate. At the same time magnet design had also to advance into the definition of the more appropriate concept to adapt to DEMO configuration specificities. Furthermore, the EU magnet project team, called Work Package Magnet, or WPMAG, was structured to make collaborate the 19 EU laboratories using for the best the competences synergies while having them involved in a project structure, considering its deliverable-oriented and collaborative transverse aspects.

3. TF Magnet Design

The TF magnet was addressed in first priority given the importance it bears for ensuring the plasma performances in DEMO operation. The first attempts to address TF design were started out of EUROfusion structure (former 2012 EFDA program) with a DEMO 2012 first configuration [2] which main parameters, issued from PROCESS code are shown in Table 1. At this time the first TF design concepts proposed used either react & wind (RW) route [3] or wind & react (WR) route [3]. The concepts were at this time differentiated from ITER approach, being layer-wound and omitting the use of radial plates. Then, from 2014 on, i.e. in the EUROfusion context, a third option was proposed [4], closer to ITER technological approach as considering pancakes winding. All details will be provided in following sections. On the ground of WPMAG methodology context a design evaluation process was considered, through which all those design had to undergo in order to be validated. This process bears basically three main steps (see figure 1) with:

- first, a design concept proposal stage; the design initial version is established using simple tools, therefore including some approximations / margins. The proposal is meant to be consistent with central configuration.
- second, a design evaluation stage; the design is evaluated against classical acceptance criteria regarding thermo-hydraulic performances and resilience to mechanical loads. At this stage detailed analyses can be conducted
- third, an optimization / system feedback stage; according to the second stage results the initial design can be refined / optimized to obey acceptance criteria. Also, feedbacks are transmitted at system level to manage the consistency between central configuration and the new magnet optimization (e.g. clash management between components).

3.1. TF design loop process since 2014

3.1.1. DEMO configuration evolutions

Further to the initial configuration, the central DEMO configuration operation point was modified in 2012 [5] with respect to previous one (see table 1) and further underwent local dimensions changes in 2014 (mainly in vertical ports zone), resulting in a smaller space allocated to TF. In 2015, a considerable change was implemented deriving from a comprehensive scan of machine aspect ratio [6] where merits of the different configurations were evaluated. As main changes the aspect ratio was decreased from 4 to 3.1 and the number of TF coils increased from 16 to 18.

Feature	**Apr 2012**	**July 2012**	**Apr 2015**
Major radius (m)	9	9	8.76
Aspect ratio	4	4	*3.1*
Elongation κ_{95}	1.66	*1.56*	*1.59*
Triangularity δ_{95}	0.33	0.33	0.33
Toroidal field on axis (T)	7.1	*6.79*	*5.41*
Plasma current (MA)	16.03	*14*	*19.54*
Number of TF coils	16	16	*18*
Total current in TF magnet system (MA)	317.8	*305.8*	*236.8*
Stored energy / TF coil (GJ)	11.56	*9.07*	*6.06*

Table 1 : Evolution of DEMO configuration main features. Modifed parameters with respect to previous configuration are shown in italics.

3.1.2. TF WP evolutions

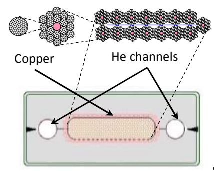
Regarding TF system winding packs (WP), three concepts using Nb_3Sn material were issued in the project team, covering a rather large technological surface, with a broad range of positioning from ITER technology. Two of the three concepts were an update of the one derived from past conceptual studies [3] while the third one emerged since 2014. All concepts used Nb_3Sn (even if not exclusively) since maximum field on conductors B_{MAX} was systematically around 12-13T.

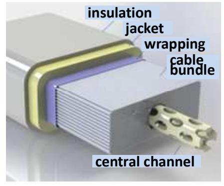
One concept (WP#1), the more distant to ITER technical choices, proposed by SPC promotes a TF conductor with high aspect ratio rectangular section, a R&W manufacturing route, and a graded layer winding approach. Another concept (WP#2), proposed by ENEA is closer to the ITER technology as TF conductor is W&R manufacturing route. However TF conductor is also with high aspect ratio rectangular section, and a graded layer winding approach is retained. And finally the latest concept (WP#3) proposed by CEA is the closest to ITER technology, having a unit aspect ratio, a W&R manufacturing route and a pancake winding approach. However those TF WP concepts still commonly bear a gap with ITER technologies as radial plates are absent and replaced by a pilling-up of square/rectangular conductors, having in this case the jacket role for containing the mechanical effort instead of the radial plates. Some of the different concepts underwent evolutions since they first emergence, changes typically being derived from either the above-mentioned DEMO configuration changes, or from the above-mentioned feedbacks issued from TF design loops. The different TF WPs evolutions are depicted in figure 1 below.

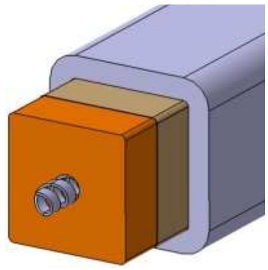
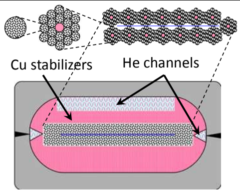
WP#1 evolved mainly in conductor concept as the dual indirect cooling channels of the initial proposal [3] were relocated inside the jacket, in direct contact with cable, the optimization deriving from thermo-hydraulic and mechanical considerations issued from the first design loop. An optimization in winding was also considered, namely aligning the jacket radial walls of all layers to avoid local overload under mechanical efforts.

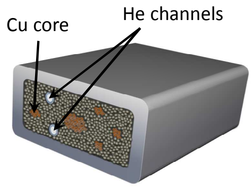
WP#2 evolved also in conductor concept with respect to the initial one [3], the change being mainly issued from an R&D feedback, forcing to adopt a geometry prone to maintain the integrity of the cooling channel, relocated in petal centers [7]. As per the winding itself, no major evolution was implemented, apart from the rearrangement of sharing between Nb_3Sn and NbTi layers.

WP#3 did not evolved in concept and remained along a constant approach in the second updated version [9].

<table>
<tr><th>WP#1 conductor</th><th>WP#2 conductor</th><th>WP#3 conductor</th></tr>
<tr><td>

2013</td><td>

2013</td><td rowspan="2"></td></tr>
<tr><td>

2015</td><td>

2015</td></tr>
</table>

Figure 1 : Evolution of DEMO TF conductor concepts proposed in WPMAG. On the leftside WP#1, in the middle WP#2 and on the rightside WP#3.

3.1.3. TF WP evaluation loop

3.1.3.1. Thermohydraulics

The first evaluation loop was applied to thermohydraulics performances in order to check the design compliance with acceptance criteria. Those criteria were agreed within the WPMAG team in order to establish a standard & code-like approach for the methodology of magnet design. All elements are edited [10][11][12] and regularly updated since then.

Detailed analyses were conducted on both normal and off-normal scenarios (burn and quench regimes, respectively). The loads (magnetic field map, nuclear heat map, and heat transfer from casing to WP) were updated and applied to the different configurations. An initial analysis was carried out with an analytical tool to spot large deviations. Then more detailed analyses were carried out applying numerical codes (THEA, 4C) that first underwent a successful cross- benchmark in a basic configuration.

As an example on TF WP#3 2015 configuration featuring 8 double pancakes, burn analyses were performed on both clock-wise central and lateral conductors, the central one being the most critical regarding the magnetic field, while the lateral one receives more heat load from casing. The 2 hour burn scenario was simulated with the THEA code on the square-shaped conductor, carrying a nominal current of 111.6 kA. The corresponding effective magnetic field map was considered [4], while the nuclear heat load map was taken the same as in previous year studies [13]. The thermal fluxes transferred from the structures to the conductors were computed by a Finite Element Cast3M model [14], considering either case cooling or not. The minimum temperature margin was found on the CW central pancake, ΔT_{ma} = 1.52 K or 1.35 K with or without case cooling respectively. The sensitivity to thermal coupling with central channel or bundle friction factor correlation was also investigated showing a considerable effect on bundle mass flow rate (about +40 %), which would allow considering reducing overall mass flow and pressure drop for the benefit of circulation power.

Quench studies focused on several scenarios, either very penalizing as commonly agreed by involved RUs in 2014 [12] (notably quench initiated at middle of hydraulic length), or more realistic (quench initiated in first turn, cryogenic malfunction inducing He inlet T increase by 2K/min). Considering a voltage threshold U_t = 0.5 V and a delay time τ_{delay} = 2 s (filtering time + current breakers opening) for quench detection features, WP#3 TF design was found compatible with the 150 K hot spot criterion on jacket temperature for the studied scenario.

Further to this overall analysis showing that across its evolutions, TF WP#3 designs were sound, a similar approach was applied to the other WP options, i.e. the TF WP#1 [15] and the TF WP#2 evaluated under normal and off-normal configurations [16][17]. Those studies, similar in methodology gave also in majority positive results regarding the soundness of design proposed, at the expense of some optimizations in the superconducting volume adjustment. The latter condition is not critical since it can be considered as not critical since both WP#1 and WP#2 radial thickness were proposed with a margin versus the total radial space allocated to TF.

Besides, an analytical tool was developed [18], enabling to rapidly spot deviations in temperature margin. This tool was confronted to thermo-hydraulic detailed studies and showed a good consistency.

3.1.3.2. Mechanics

In a first attempt (2014 version) the three TF WPs were analysed [19] on a common structures geometry, WP being the only differences. Since both PF scenarii and structure concepts were not mature enough, the study was confined to the load scenario including cool-down and in-plane forces. The analysis approach is based on a first step with a global model using smeared WP properties (see figure 2) followed by a detailed stress map reconstruction through consideration of ad-hoc critical paths on the mesh. As a result the 3 TF WPs were found at various degrees above the acceptance stress criteria, therefore advocating for an intermediate stage of design optimisation. This step namely induced some of the TF conductor changes evoked in previous section.

In a second attempt, after the 2015 DEMO configuration change, an extensive FEA was conducted [20] on the most conservative TF configuration, i.e. the one with WP#3 (having the lower stainless steel proportion for a given radial built). It should be noted that prior to this second loop a macroscopic tool was developed by FzJ [20] to enable an accurate pre-dimensioning at WP#3 design stage, reinforcing the reliability of the proposed WP design. An illustration of the FEA results is shown in figure 2.

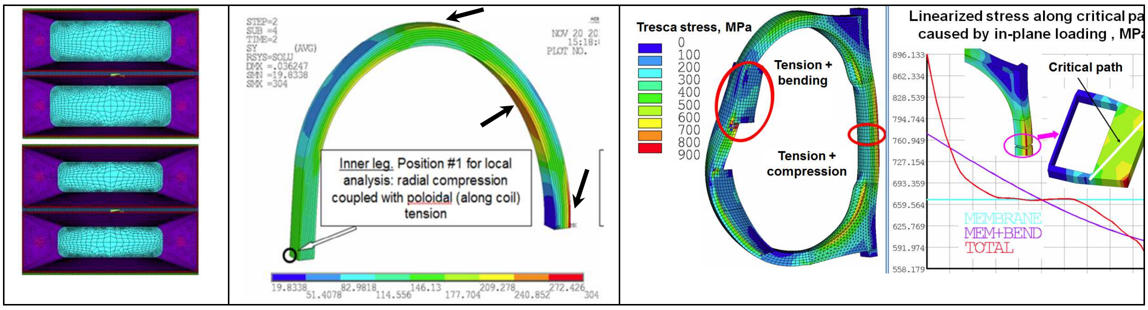


Figure 2 : (left) Smeared model used for the two innermost layers of WP#1 2014. (middle) Output of the 2014 global model for WP#2, showing where a local analysis is carried out to evaluate maximum stress (see black arrows).(right) FEA analysis for 2015 configuration for WP#3 with full load.

This broad study provided valuable conclusions:

- The most conservative WP configuration from a space utilisation perspective (WP#3, i.e. pancake approach) is found almost fully compliant with mechanical acceptance criteria under OOP loads The developed semi-analytical macroscopic tool proved useful in supporting the TF coil WP design under OOP load
- In the present configuration no pre-compression ring is necessary to avoid TF coil deformation effects

- The outer inter-coil structures (OIS) seem to play a minor role, which should be better understood and checked against the possible other PF/CS scenarios.

Another important point drawn from the present activities is the definitive utility of developing macroscopic modelling for a pre-check of concepts at design stage, in order to reinforce compliance probabilities when detailed analyses are conducted under maximum load. The efficiency of the design loop is then considerably enhanced.

Under a similar approach a considerable effort was conducted since 2014 to establish a recovery tool able to efficiently carry out 2D detailed studies through importation of data from 3D smeared models. The tool was qualified by benchmark [21] versus with the above mentioned FEA and is actually in course of application on 2015 TF WP#2 configuration.

4. CS Magnet Design

Although the CS design was addressed at later stage in project advancement it was conducted at two scales: the system scale and the WP scale. Those two approached respectively aimed on one hand at scanning all possible geometries for spotting optimized configurations (minimize the external radius) and on other hand at proposing a CS WP design consistent with agreed design criteria.

As main result for system study [22], considering a temperature of current sharing (T_{CS}) of 8 K, the reference outer radius of the CS coil would be of 3.31 m with a Wind & React (W&R) conductor, 3.21 m with React & Wind (R&W), and 3.01 m with HTS.

Regarding WP proposal [9], a pancake-wound CS design was proposed with an ad-hoc macro tool developed and allowed to establish a consistent WP design having a 40 kA-class CS conductor. Further to this a preliminary thermohydraulic study was conducted, focused on the recharge of CS magnet during dwell, with full I_{max} swing. AC losses were assessed considering n_τ = 638 ms for coupling losses [23] and estimating hysteretic losses from [24]. The minimum ΔT_{ma} was found at end of recharge equal to 1.48 K assessing a weak impact of AC losses, related to heat deposition on first turn only, as the conductor pancake-wound.

5. Developments on R&D and auxiliaries

5.1. TF R&D

The R&D on TF was launched since 2013 and allowed to establish a consolidated workline in the direction of assessing through experimental tests some of the TF conductor design features proposed. In this regard the two main achievements are:

- The manufacture and tests of RW1 sample, representing a R&W TF conductor option (see figure 3). The RW1 was conceived and assembled at SPC and electrical tests were conducted in EDIPO mid-2015 through three campaigns, leading to valuable conclusive assessments [26], namely on the equivalent effective strain of about -0.35% to apply in design activities. It also pointed some items to be further investigated, e.g. the high level of coupling losses or the importance of joints quality.
- The manufacture and tests of WR1 sample, representing a W&R TF conductor option (see figure 3). The RW1 was conceived at ENEA, assembled at SPC and electrical tests were conducted in EDIPO mid-2016 [27]. The results showed good DC performances, with an effective strain of about -0.55 %. This assesses some manufacturing procedures for conductor and confirms the J_C parametrization for the WP#2 design.

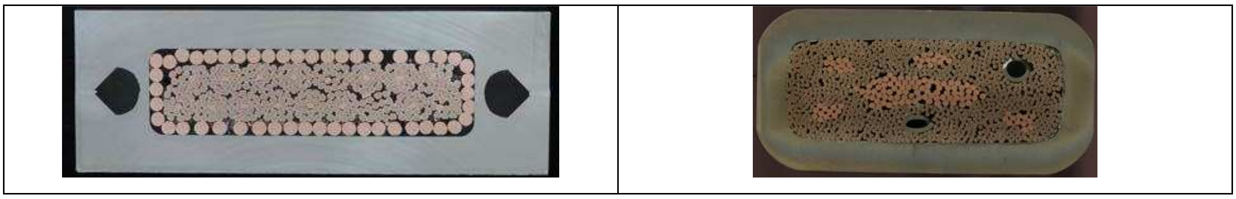


Figure 2 : Cross-sections of the two samples: RW1 (left) as prepared for jacketing tests, and WR1 sample (right). RW1 tested sample was with a single-wall jacket. The WR1 copper cores and spirals-in-petals are clearly visible

It should be noted that important small-scale experiments also accompanied the above activities, such as extensive J_C-strain characterization of the Nb_3n strands [28] that enabled to deduce the effective strain. Besides AC losses variations with mechanical cycling were conducted at Twente [29] and confirmed the importance of the coupling losses item in the TF conductor prototypes investigated. In parallel those tests were also opportunely used to support the adaptation of a modelisation code (Jackpot) [30] aiming at simulating the AC losses in a DEMO-like conductor, with the ultimate target to help in predicting / assessing the conductor at design stage. Once again here it is stressed on the importance of investing in the development of adapted tools for the representation of CICCs in order to rend the design loop more and more efficient.

And finally, in same mid-term investment approach, non-destructive examinations by tomography were conducted on a RW1-relevant sample [31], to prepare the next step with real sample observation, aiming at providing valuable information on the in-situ strands geometry, to possibly explain the variation of their performances.

5.2. Auxiliaries (Cryogenic & Quench Protection System)

Regarding Cryogenic plant, an extensive study was conducted out of the development of a modelisation tool [32]. The aim was an optimisation strategy for the cryoplant design: the minimisation of the exergy during a plasma pulse. Among the different operation regimes scanned (varying inlet and outlet temperatures and mass flow), the total cryo-distribution total exergy (i.e. related to total installed power) could be dropped by a factor of almost two.

As per QPS numerous default cases were investigated [33] with help of a newtwork representation tool. It was conducted for three TF coil network configurations, exposing their difference in behaviour and showing that the maximum voltage to ground in the default case can reach more than twice the intervention nominal voltage.

6. Lessons learned – conclusions - perspectives

In the course of EU activities for the design of DEMO magnet system since 2012, substantial progresses were achieved. Within the WPMAG project framework a broad range of investigations was conducted, leading to have the TF system pass through two full design evaluation loops, associated with confrontation with experimental R&D and the development of modelling tools. Several lessons were learned from this experience:

- The application of design evaluation loop enabled to draw lessons on design principles which led to orientate technical decisions for next design step (e.g. aligning jacket walls in layer configuration) and therefore stands as a major element of the driving force to assess the outcomes of the methodologic approach applied to design proposals.
- The confrontation to R&D outcomes is also an important point in the building of the most efficient path to magnet design consolidation, as definitely assessing or infirming some design hypotheses (e.g. cooling channel and high aspect ratio were found incompatible).

This item is also tightly linked with the validation and therefore the robustness of the modelling activity and therefore should be considered of major importance.

- The investment on development of modelling tools at either top-level (e.g. system), intermediate (e.g. mechanical macro tool) or elementary scale (e.g. TF WP design solver) demonstrated its usefulness in the aim of rending the design activity efficient by saving the passing through several design loops where detailed analyses can be forces consuming.

Capitalizing on those lessons and the associated experience, the EU DEMO magnet design activities will be continued in the next years in order to enter CDA phase with a consolidated and assessed magnet system baseline.

Acknowledgments

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