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Design Tool Developed at CEA for Large Fusion Toroidal Field Magnets: Application to DEMO

A. Torre, D. Ciazynski, P. Hertout, and L. Zani

Abstract**—While the ITER machine is yet under construction, design and R&D activities regarding the next step experimental reactor DEMO are underway in Europe. Although general design tools already exist for dimensioning superconducting magnets in integrated tokamak system codes, the need to develop more specific models and codes for magnets has raised owing to the high operating constraints encountered in these huge magnetic systems, particularly the toroidal field (TF) one. This paper focuses on two key (and linked) issues related to this dimensioning: first the capability to build using realistic high current (~ 100 kA) conductors and insulation the winding pack in the TF steel casing (elsewhere dimensioned), second the accurate computation of the magnetic field on the superconductor which determines its transport current capability. The exercise was carried out within the CEA studies for the Eurofusion DEMO project in its 2014 and 2015 versions. The design of the superconducting cable is based on ITER-like conductors to take advantage of the already existing experience gained on this type of conductors through the ITER R&D and qualification programs, whereas the design criteria which are recalled have been agreed within the European fusion communit. The paper depicts the method as well as the results of the dimensioning of a proposal TF winding pack.**

Index Terms**— Fusion Reactor, TF Magnet, CICC, Niobium-tin, Winding Pack, Design.**

I. INTRODUCTION

DESIGN activities for large superconducting tokamaks rely nowadays on general multi-domain tools that make use of smeared properties, homogeneous models and strong hypotheses in order to propose operating points and design parameters that fulfill all sub-systems requirements. This approach must be followed by a refined design at the sub-system level in which issues visible only at this scale usually appear. CEA has developed over the last years a set of tools which were, for the purpose of DEMO analysis, unified in a consistent approach to perform the refined sub-scale analysis on the TF superconducting magnet system. The relation of this tool to the general system code along with the level of definition of the tokamaks requires this approach to be simple, fast, modular and precise enough to achieve three main objectives: propose a TF winding pack design which can serve as a canvas for detailed analyses, perform parametric studies to rapidly investigate alternative solutions, and give feedback on the way forward to the upscale system code.

II. INPUTS, DATA MODEL AND HYPOTHESES

A. *Data Model: Tokamak Scale Inputs*

Acting as a refining module for a larger scale design, our tool must use data inputs related to the tokamak parameters:

TABLE I – TOKAMAK SCALE INPUTS FOR TF COILS

Value name	Unit	Descritption
N_{TF}	[-]	Number of TF coils
NI_{tot}	[A.turns]	Total magnetomotive force in one coil
E_{mag}	[GJ]	Magnetic energy of the TF system
B_{max}	[T]	Maximum field on the TF conductor
$\tau_{dump\ min}$	[s]	Minimum dump time for the current as imposed by Vacuum Vessel
WPspace	[m]	Geometry of the WP space (see Fig. 1)
RBuilt	[m]	Radial built of the Tokamak
DShape	[m/°]	D-shape of the TF coil

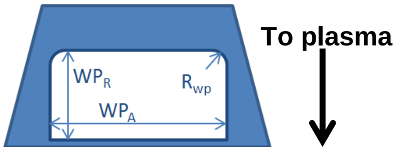

Fig. 1. Winding Pack space geometrical inputs

B. *Data Model: General Rules*

Apart from the strong requirements given by the Tokamak design, we have put down a list of rules that set the boundary conditions for our tool. They can be divided into two categories: General Rules and Limiting Values. In the former, the main choices retained for our tool are:

- The Design Tool is built so as to extrapolate many design concepts and choices from ITER. This choice was settled knowing the extensive design iterations and experimental validations done up to now in this project.
- For now, the tool is built to propose a Winding Pack (WP) wound in double-pancakes, with square in square cable-in-conduit conductors (CICC), without any radial plates.
- All material properties must be taken from established databases (ITER or EFDA databases being the most recent and consistent ones).
- The conductor should be based on an existing strand already tested inside a full-size conductor. The scaling law $J_C(B,T,\varepsilon)$ of this strand must be known, along with all other related strand parameters. For ITER conductors tested in the SULTAN facility, effective strain and n-value parameters were computed [1].

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- We assume, in a first step, a quasi linear decrease of the magnetic field from B_{max} to 0T in the radial direction across the WP cross-section (see sec. III.B).
- We base our initial hotspot estimation on an adiabatic evaluation of the maximum temperature of the cable.
- We assume that for all mechanical calculations, the D-shape of the TF coil is relevant to a Princeton-D coil [2].

C. Data Model: Limiting Values

In addition to the General Rules given above, there is a list of Limiting Values that are included in the structure of the tool. They are not driven by the design itself, but rather related to a general state of the art. In the Eurofusion DEMO framework, these values were discussed within the WPMAG activities [3].

TABLE II – LIMITING VALUES

	Criteria	Description
Inputs	$T_{in} = 4.5K$	Inlet Temperature
	$T_{op} = Tin+0.2K$	Operating temperature (incl. margin)
	$\Delta T_{margin} \geq 1.5K$	Temperature margin of the coil
	$T_{hotspot\ max} \leq 250K$	Hotspot calculation maximum temperature
	$\tau_{hold} \geq 3s$	Hold time before dump (quench detection)
	$Ins_C \geq 1mm$	Insulation thickness between WP turns
	$Ins_{PK} \geq 2mm$	Insulation thickness between pancakes
	$Ins_G \geq 8mm$	Ground insulation thickness
	RRR = 100	Copper RRR value for all strands
Outputs	$\sigma_{maxSS} \leq 667$ MPa	2/3 of the yield stress of 316LN at 4.2K
	$\Delta V_{max} \leq 10kV$	Maximum voltage to ground during dump
	$Ins_{Gap} \geq 10mm$	Insertion gap from WP to casing

It should be noted that all input values above can immediately be chosen equal to their limiting values. The ouputs are calculated by the tool and need to fulfill their inequalities.

D. Design Choices

Taking into account all the constraints described above, the tool then allows us to vary some design inputs to iteratively calculate a self-consistent WP design with optimized parameters (outputs) summarized in Table III below.

TABLE III – DESIGN CHOICES

		Name	Description	Unit
Inputs	Strand Properties	$Jc(B,T,\varepsilon)$	Strand scaling law	[A/mm^2]
		ε_{eff}	Strand-in-cable effective strain	[%]
		n_{eff}	Strand-in-cable effective n-value	[-]
	Cable Parameters	V_f	Cable void fraction	[%]
		$Cos(\theta)$	θ = Mean cabling angle	[-]
		D_{cool}	Central spiral outer diameter	[mm]
Outputs	Strand Parameters	d_S	Diameter of the strands	[mm]
		CuNCu	Copper ratio in the Nb_3Sn strand	[-]
	Conductor parameters	γ	Cable aspect ratio	[-]
		I_{TF}	Cable current	[A]
		N_{Sc}, N_{Cu}	Number of Sc and copper strands	[-]
		L_C	Square cable dimensions	[m]
		w_{jack}	Jacket thickness (w/o 0.16mm wraps)	[mm]
	WP structure	N_{tr}, N_{pk}	Number of turns and pancakes	[-]
	TF system	N_{sub}	Number of subdivisions in the TF coil electrical circuit	[-]

III. DESIGNING STEPS

A. Initiation

Since the tool has an iterative structure, we initiate the design with an approximate target current for the conductor I_{TF}. This choice should be justified by considerations on ITER's TF conductor current, scaling the current using the magnetic energy or the size of the tokamak. We know from ITER experience that we should go toward the maximum current to decrease the space used for insulation of conductors and pancakes, but we also should consider conductors which are not too far from what has been tested up to now (i.e. 68kA for ITER TF).

B. Superconducting Strands

First of all, we choose an initial value of the strands diameter (copper and superconductive) inspired by existing strands, and a copper/non-copper ratio set to its minimum practical value of 1. Then, knowing the strand properties, we calculate the strand current which gives an average electric field of E_C=10µV/m over the cross-section of the innermost conductor. The magnetic field over the cable cross-section is calculated in a first step from Ampere's law, giving rise to the following quasi-linear formula:

$$B(r) = B_{max}\frac{r_e}{r}\left(\frac{r - r_i}{r_e - r_i}\right)$$

With r_i and r_e respectively the inner and outer radius of the WP space in the radial built. Furthermore, B is considered invariant in the toroidal direction. The strand current is then calculated by:

$$I_{strand} = \left[\frac{1}{L_{CR}}\int_{r_e - L_{CR}}^{r_e}\left(\frac{1}{I_C\left(B(r), T_{calc}, \varepsilon_{eff}\right)}\right)^{neff} dr\right]^{-\frac{1}{neff}}$$

Where $T_{calc}=T_{op}+\Delta T_{margin}$, and L_{CR} is the cable radial size, derived automatically from the initial value of I_{TF}. I_{strand} is then used to calculate the number of superconducting strands in the cable through: $N_{Sc}= I_{TF} / I_{strand}$.

C. Hotspot Calculation

To compute the copper area A_{Cu} needed for the protection of the conductor, we have included in our approach an adiabatic Hotspot calculation module which takes into account only the cable materials areas and thermal properties. The coil current is driven by $I_{TF} = I_{TF0} \quad for\ t \leq \tau_{hold}$ and:

$$\frac{dI_{TF}}{dt} = -\left(\frac{R_{dis}}{L}\right)I_{TF} \quad for\ t > \tau_{hold}$$

Where L is the coil effective inductance, calculated from the magnetic energy as $L=2E_{mag}/(N_{TF}*I_{TF}^2)$, R_{dis} is the discharge resistance, calculated so that $L/R_{dis}=\tau_{dump}$. The module has a fixed computation step in temperature ΔT, and calculates the related times step using the following power balance:

$$\Delta t\left[\frac{\rho_{Cu}(B,T)}{A_{Cu}}{I_{TF}}^2\right] = \left[\sum_{cable\ material\ K} C_{pK}\, d_K A_K\right]\Delta T$$

Where C_{pK}, d_K and A_K are respectively the heat capacity, the density and the area of cable component k, ρ_{Cu} is the electrical resistivity of copper. The same module calculates the evolution of the coil voltage $V_{TF}=I_{TF}.R_{dis}$ where R_{dis} must comply with the requirements from the minimum dump time constant and maximum voltage, so:

$$R_{dis} \leq min\left(L/_{\tau_{dump\ min}}; {}^{2\Delta V_{max}N_{sub}}/_{I_{TF}N_{TF}}\right)$$

Where N_{sub} is the number of subdivisions (current breakers) in the TF coils electrical circuit. In order to limit the maximum temperature to: $T_{hotspot} \leq 250K$, one generally needs to add a number of pure copper strands N_{Cu}, R_{dis} is then fixed at the maximum value fulfilling the above inequalitiy. Refinements have been added to include the heating of the dump resistor and the associated increase of R_{dis} (made of stainless steel), which gives a slight beneficial effect by reducing the effective dump time constant without increasing the voltage to ground.

D. Cable Design

The cable design is finalized by imposing a void fraction V_f, a mean cabling angle in cos(θ) and a cooling channel outer diameter D_{cool}, based on ITER design. For a square geometry, the cable side L_C can thus be calculated. The cable can also be made rectangular by introducing the aspect ratio $\gamma = L_{CA}/L_{CR}$ (A and R subscripts indicating azimuthal and radial directions, respectively). We limit ourselves to $\gamma \geq 1$ to limit stress (pressure under Lorentz force) in cable but also to $\gamma \approx 1$ because too large aspect ratios could lead to deformation of the central spiral during manufacturing.

E. Conductor finalization and WP structure

Taking into account the cable size, the insulation requirements and the available WP space, we choose an initial jacket thickness w_{jack}, inspired by extrapolation from ITER conductors, to get the insulated conductor dimension L_{Ci}, and calculate the number of turns and pancakes in the WP:

$$N_{tr} = \lfloor (WP_R - 2(Ins_G + Ins_{Gap} + Ins_{PK}))/L_{Ci} \rfloor$$

$$N_{pk} = \lfloor (WP_A - 2(Ins_G + Ins_{Gap}) - Ins_{PK})/(L_{Ci} + Ins_{PK}) \rfloor$$

Whereas tokamak level codes often consider homogeneous winding pack for initial design, we see here that the detailed layout imposes an integer number of turns and double-pancakes. From ITER design, we know that the load in the radial direction, supported by the conductor jacket walls, leads generally to a hard mechanical constraint, and thus any final radial free space is used to increase the jacket thickness. At this point, it is also possible to calculate the total magnetomotive force as $N_{tr}.N_{pk}.I_{TF}$, and update the I_{TF} value to match the NI_{tot} from the tokamak scale requirement. The coil inductance can also be refined by calculating the inductance of a Princeton-D coil as expressed in [2]. Finally, a check of the magnetic energy of the system is also performed at this point.

F. Mechanical calculation

To calculate the maximum centering stress, we integrate the Lorentz load on the winding pack cross-section and divide the total force by the jacket walls thickness:

$$\sigma_{rmax} = \frac{B_{max}}{2} \frac{N_{tr}.I_{TF}}{2.w_{jack}}$$

The hoop vertical force F_z, and thus the maximum poloidal stress, is calculated from the Princeton-D shape relationships in [4]:

$$\sigma_{zmax} = \frac{{B_{max}}^2}{\mu_0} \frac{\pi\, {r_1}^2}{N_{pk} N_{tr} 4 w_{jack} (L_C + w_{jack})} Ln\left(\frac{r_2}{r_1}\right)$$

It should be noted that at this point, the associated Tresca stress ($\sigma_{tresca} = \sigma_{rmax} + \sigma_{zmax}$) is compared to stainless steel yield stress (see Table II), but since all other design parameters are fixed, this last step is only a cross-check that the whole design is sound. If the WP does not comply with this last point, it should either undergo further optimizing, or be rejected.

IV. APPLICATION TO EU DEMO

A. Context and initial design choices

The data model and design approach presented above were applied to propose the 2014 and 2015 Eurofusion DEMO TF WP3 reference designs. In this context, the Tokamak-level inputs were provided by the Eurofusion PROCESS code. A first design choice was to base the conductor designs on the TFEU4 ITER conductor sample: its design, strand scaling law and effective parameters are reported in [1]. Since they vary with cycling the “after cycling”, hence conservative, values were retained with $\varepsilon_{eff} = -0.66\%$ and $n_{eff} = 5.75$.

TABLE IV – INITIAL CABLE DESIGN CHOICES

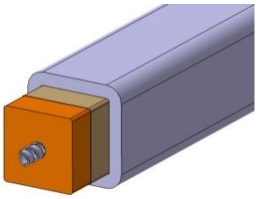
V_f	Void fraction	29%
cos(θ)	Cos(average cabling angle)	0.95
D_{spi}	Cooling channel dimensions (o.d./i.d.)	10x8 mm

B. 2014 TF WP3 Reference Design

Applying our methodology to the initial 2014 PROCESS inputs, we identified that the inner corner radius R_{WP} of the WP space (initially R_{WP}=150mm) specified by Eurofusion PMU was unjustifiably large. Using our tool as feedback to show that decreasing this value to 38mm (as in ITER TF casing) we could optimize the filling of the WP space, we called for a change that was accepted by PMU. We then converged on the conductor structure depicted below:

TABLE V – 2014 TF WP3 REFERENCE CONDUCTOR DESIGN

I_{TF}	Conductor Current	95500 A
d_S	Strand diameter	1.024 mm
N_{Sc}	Number of Sc. Strands	1350
N_{Cu}	Number of Cu Strands	324
L_C	Cable Size	46.07 mm
w_{jack}	Jacket thickness	8.15 mm
ΔV_{max}	Max voltage to ground	7965 V
σ_{tresca}	Tresca stress	669 MPa



This conductor gives a structured winding pack with N_{tr}=10 and N_{pk}=20. As shown in Fig. 2, the radial gap is not fully filled, essentially because the conductor’s aspect ratio is fixed to a square shape in this first analysis. However, some steel area could be refund here to the casing.

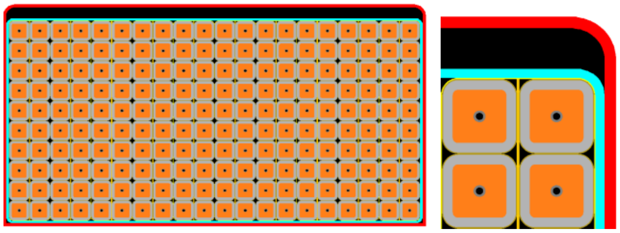


Fig. 2. 2014 TF WP3 reference design with the insertion gap (red), the ground insulation (blue) and conductors (orange and grey).

Using this layout, we could use our fine magnetic field computation tool (TRAPS code, used in [4] and [5]) in which every conductor is discretized (10000 points along the D-shape) to issue a detailed field map, considering only the TF system. This calculation revealed that B_{max} had been underestimated by PROCESS (13.33T) and was about 13.69T in this specific design. On the other hand, we got a slight beneficial effect from a larger field gradient computed through the cable area. Nevertheless, this revision led to slightly increase N_{Sc} and to reduce w_{jack} to 8.07 mm with an increase of σ_{tresca} to around 714.

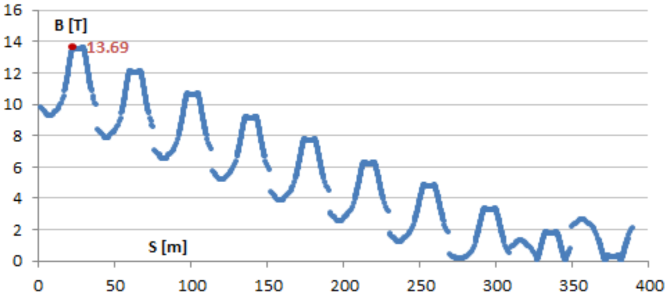


Fig. 3. Detailed magnetic field map on a central pancake for reference TF WP3 2014 layout.

This last calculation shows that as part of a larger scale design process, our approach is also able to interface rapidly with refined magnetic analyses that are then used as inputs by thermohydraulic analyses [6]. This refined field map also led to a new iteration on the conductor geometrical parameters.

C. *2014 TF WP3 Variant Design*

Following the initial design presented as the 2014 reference case, we used our design approach as an optimization tool in order to best fill the allocated WP space. This was achieved by adding one turn per pancake except on two side pancakes with 10 turns (vs. 11) each to cope with the corner radius. This also implies to have a rectangular conductor with a lower current. We assumed here the previous detailed field map unchanged.

TABLE VI – 2014 TF WP3 VARIANT CONDUCTOR DESIGN

I_{TF}	Conductor current	87610 A
d_S	Strand diameter	0.983 mm
N_{Sc}	Number of Sc. strands	1386
N_{Cu}	Number of Cu strands	302
L_{CR}	Radial cable size	43.14 mm
L_{CA}	Azimutal cable size	45.85 mm
w_{jack}	Jacket thickness	8.26 mm
ΔV_{max}	Max voltage to ground	8849 V
σ_{tresca}	Tresca stress	669 MPa

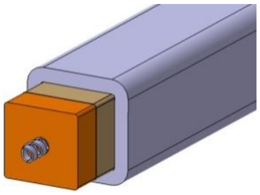


Fig. 4 shows the WP layout for this variant configuration.

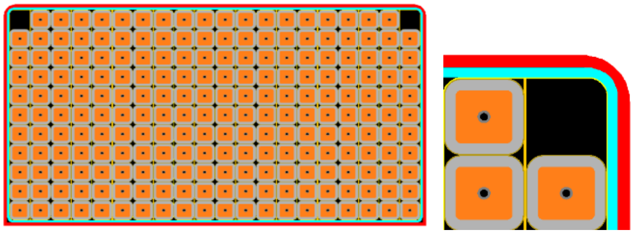


Fig. 4. 2014 TF WP3 variant design with the insertion gap (red), the ground insulation (blue) and conductors (orange and grey).

This new layout is advantageous because it better fills available space, it has a slightly increased jacket wall thickness (8.26 vs. 8.07 mm), and it also has a lower current. It is nevertheless more complicated to manufacture because of the two types of pancakes and of the longer conductor unit lengths required. The maximum discharge voltage is also slightly increased because of the higher inductance.

D. *2015 TF WP3 Reference Design*

In 2015, we were faced with a new full set of PROCESS inputs [7], with radical changes in the tokamak design (e.g. 18 TF coils instead of 16, B_{max} = 12.32 T) and within an allocated space decreased by 36% in cross-section, which was found insufficient to fit both current carrying capacity (Sc cross-area) and stainless steel to support the various loads. We thus decided to use our Design Tool to perform a parametric study on the required radial space extension that would be needed to ensure a mechanically-relevant WP layout. This gave us the opportunity to introduce a new mechanical safety coefficient λ defined as:

$$\lambda = {}^{\sigma_{maxSS}}\!\big/\!\left(1.02\ \sigma_{rmax} + 1.6\ \sigma_{zmax}\right)$$

This particular combination of the stresses was adjusted to fit a detailed mechanical analysis [8] assuming no friction between WP and casing (conservative assumption). It had previously shown on the 2014 reference layouts that our former calculations were optimistic [9]. This permitted to rapidly perform the parametric study which results are given below:

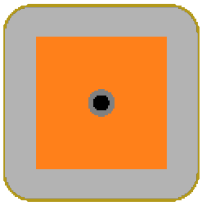
TABLE VII – PARAMETRIC STUDY ON WP RADIAL SPACE

	Square (γ=1)				Rectangular (γ>1)			
WP_R (mm)	600	612	620	623.5	600	612	620	623.5
N_{Sc}	1048	1039	1033	1029	1068	1056	1049	1046
N_{Cu}	832	838	842	844	846	854	858	862
L_{CR} (mm)	48.72	48.69	48.66	48.64	47.57	48.26	48.72	48.93
L_{CA} (mm)					50.77	49.96	49.40	49.22
w_{jack} (mm)	9.6	10.37	10.88	11.1	10.17	10.58	10.85	10.94
λ	0.977	1.023	1.053	1.065	0.991	1.019	1.038	1.045

From this analysis, we agreed to ask for an extension of the WP radial free space up to at least 624mm to have a mechanically sound WP design. On this basis, we proposed the following layout for our 2015 TF WP3 reference design:

TABLE VIII – 2015 TF WP3 REFERENCE CONDUCTOR AND WP DESIGN

I_{TF}	Conductor current	111560 A
d_S	Strand diameter	1.024 mm
N_{Sc}	Number of Sc. strands	1029
N_{Cu}	Number of Cu strands	844
L_C	Cable size (square)	48.64 mm
w_{jack}	Jacket thickness	11.1 mm
ΔV_{max}	Max voltage to ground	5154 V
N_{pk}	Number of pancakes	16
N_{tr}	Number of turns	8



V. CONCLUSION

In this paper, we presented the tool that has been developed at CEA to design TF magnets winding pack and conductor components. This simple analytically-based approach is meant to refine tokamak-scale system codes and propose winding packs relevant with respects to electrical properties, geometrical constraints, thermal and mechanical characteristics, to be further evaluated by dedicated detailed codes (thermohydraulics or mechanical). It was applied to the Eurofusion DEMO 2014 and 2015 TF magnet configurations, proposing WP layouts with a sound level of definition that could interface easily with detailed analysis tools. We used it to provide feedback, optimize designs and perform parametric studies. This tool should be further developed to include other refinements into a unified magnet design platform.

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