EUROFUSION WPMAG-REP(16) 16565

V. Corato et al.

Common operating values for DEMO magnets design for 2016

REPORT

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

MEMO for WPMAG-MCD-2.1

Task Area:	**MCD-2.1**
Deliverable:	**D01**
Title:	**Common operating values for DEMO magnets design for 2016**
IDM Reference:	EFDA_D_2MMDTG
Authors:	V. Corato, R. Bonifetto, P. Bruzzone, D. Ciazynski, M. Coleman, E. Gaio, R. Heller, B. Lacroix, M. Lewandowska, A. Maistrello, L. Muzzi, S. Nicollet, A. Nijhuis, F. Nunio, A. Panin, L. Savoldi, K. Sedlak, A. Torre, S. Turtu, R. Vallcorba, R. Wesche, L. Zani, R. Zanino
Date:	21/06/2016
Version	1.4
Abstract:	The document combines the previous version of the “common operating values for DEMO TF WP memo” for the TF WP designers, and several different versions of “common operating approaches” for the thermal-hydraulic and quench calculations. The document is meant to be valid for all the DEMO coils, with specific paragraphs for individual coil systems. The purpose of this document is to serve as common guideline for the design and analyses to be performed in the year 2016 and beyond. This memo will be paralleled by a detailed technical memo dealing with the equations, friction correlations, etc. for the thermal-hydraulic and quench calculations [1]. -----------------
Distribution list:	

Reviewers	**Name**	**Role**
	P. Bruzzone	WPMAG WGC
	M. Coleman	WPMAG PMU RO
Approver	L. Zani	WPMAG PL

Table of Contents

1 Introduction

The document combines the previous version of the “common operating values for DEMO TF WP memo” for the TF WP designers, and several different versions of “common operating approaches” for the thermal-hydraulic and quench calculations. Contributions about the CS and PF are added, as well as modification of former paragraphs.

2 Proposal of common operating values, analysis tools and criteria for DEMO magnets design

2.1 Nb_3Sn strand J_c law intrinsic parametrization & irreversibility strain

TF Coil: The initial choice of EUTF4 right leg (OST) and its parametrization can be replaced by the actual WST strand (ø = 1.5 mm) used and tested in the DEMO TF prototypes manufactured in 2014 and measured in 2015 and 2016. The EUTF4 OST strand parameterisation can still be employed in the conductor design, if the designers prefer. The parameters are measured in the scope of the 2014 activities [2] and reported below. Compared to the EUTF4 right leg (OST), the performance of the WST at low strain is superior by about 10%. The overall scaling parameter C is normalised per superconducting area, namely C=83075 AT/mm^2. In future, the Nb_3Sn parameters will be updated to the performance of the last strand procured for DEMO prototype manufacture. The ITER scaling law from DDD2009 is also quoted below (from ITER IDM).

Critical current density:

$$J_C = \frac{C}{B} s(\varepsilon)\left(1 - t^{1.52}\right)\left(1 - t^2\right) b^p (1 - b)^q$$

Critical temperature:

$$T_C^*(B,\varepsilon) = T_{C0\max}^* \left[s(\varepsilon)\right]^{\frac{1}{3}} (1 - b_0)^{\frac{1}{1.52}}$$

Critical field:

$$B_{C2}^*(T,\varepsilon) = B_{C20\max}^* s(\varepsilon)\left(1 - t^{1.52}\right)$$

Strain function:

$$s(\varepsilon) = 1 + \frac{1}{1 - C_{a1}\varepsilon_{0,a}}\left[C_{a1}\left(\sqrt{\varepsilon_{sh}^2 + \varepsilon_{0,a}^2} - \sqrt{(\varepsilon - \varepsilon_{sh})^2 + \varepsilon_{0,a}^2}\right) - C_{a2}\varepsilon\right]$$

$$\varepsilon_{sh} = \frac{C_{a2}\varepsilon_{0,a}}{\sqrt{C_{a1}^2 - C_{a2}^2}}$$

Reduced magnetic field:

$$b = \frac{B}{B_{C2}^*(T,\varepsilon)}$$

Reduced magnetic field at zero temperature:

$$b_0 = \frac{B}{B_{C2}^*(0,\varepsilon)}$$

Reduced temperature:

$$t = \frac{T}{T_C^*(0,\varepsilon)}$$

Strand	C_{a1}	C_{a2}	$\varepsilon_{0,a}$ [%]	ε_m [%]	B_{c20m} [T]	T_{c0max} [K]	C [AT/mm^2]	p	q
WST	50.06	0	0.312	-0.059	33.24	16.34	83075	0.593	2.156
EUTF4	44.48	0	0.256	-0.110	32.97	16.06	76189	0.63	2.10

CS coil:
The scaling law parameters and effective strain values are taken over from ITER CS sample CSJA6 (corresponds to the CS insert test in Naka in 2015) – JASTEC bronze strand, as suggested in [3]. The C parameter normalised to superconducting area is C = 79560 AT/mm^2:

C_{a1}	C_{a2}	$\varepsilon_{0,a}$ [%]	ε_m [%]	B_{c20m} [T]	T_{c0max} [K]	C [AT/mm^2]	p	q
45.74	4.431	0.232	-0.061	29.39	16.48	20193	0.556	1.698

2.2 NbTi J_c law intrinsic parametrization

The scaling law and parameters are kept as in ITER. The scaling law for Jc in NbTi area and the ITER parameters are quoted below (from ITER IDM).

$$J_C(B,T) = \frac{C_0}{B}\left(1-\left(\frac{T}{T_{C0}}\right)^{1.7}\right)^{\gamma}\left(\frac{B}{B_{C2}(T)}\right)^{\alpha} \cdot \left(1-\left(\frac{B}{B_{C2}(T)}\right)\right)^{\beta}$$

$$B_{C2}(T) = B_{C20}\left(1-\left(\frac{T}{T_{C0}}\right)^{1.7}\right)$$

C_0 (A/T/mm^2)	B_{C20} (T)	T_{C0} (K)	α	β	γ
168512	14.61	9.03	1	1.54	2.1

2.3 Nb_3Sn strand in conductor n-value & strain

If measurements of a relevant prototype exist, the measured ε_{eff} and n_{eff} are derived from the prototype. In the absence of prototype results, values from some other sample (typically ITER) will be retained:

TF conductor:

- SPC R&W conductor: ε_{eff} = -0.35% and n_{eff} = 12 (2015 prototype after cycling)

- ENEA W&R conductor: ε_{eff} = -0.55% and n_{eff} = t.b.d. CEA W&R conductor: ε_{eff} = -0.664% and n_{eff} = 5.75 (EUTF4 OST sample after cycling).

The ENEA W&R conductor will soon get the measured values from the tests (to be finished in April 2016), and the ε_{eff} and n_{eff} values will be updated accordingly.

In the absence of prototype data, the CEA W&R uses the values from EUTF4 OST conductor SULTAN tests.

No additional hoop strain (with respect to sample test) coming from the coil deformation is conservatively considered for the TF conductor.

CS coil:
For both, W&R and R&W cases, hoop strain map will be captured after mechanical analyses. The overall effective strain in the conductor is calculated from the ITER CSI test analyses as suggested in as [3]:

$$\varepsilon_{eff} = \varepsilon_{eff0} + 0.78 * \varepsilon_{hoop}$$

where ε_{eff0} is the basic no-hoop strain (from the sample test), and ε_{hoop} is the hoop strain calculated in the mechanical analysis. The corresponding effective n value is set to n_{eff} = 7.0.

2.4 NbTi strand n-value (analysis tool)

Apply a polynomial law of $n(J_C)$ parameterized from Table 2, cond. type B in:

R. Wesche *et al.*, "DC performance, AC loss and transient field stability of five medium size NbTi cable-in-conduit conductors with parametric variations", *Cryogenics* 45, 2005, p.755-779.

$$n(J_c) = 5.16 + 0.0309 \cdot J_c + 9.06 \cdot 10^{-6} \cdot (J_c)^2 - 9.07 \cdot 10^{-9} \cdot (J_c)^3 + 1.53 \cdot 10^{-12} \cdot (J_c)^4$$

where J_c is in A/mm².

2.5 Definition of temperature & current margin (analysis tool)

- The B map calculation is carried out along the conductor length, and using the actual TF coil geometry and operating current.
- Temperature margin: $\Delta T_M = T_{cs} - T_{op}$.
- For Nb_3Sn & NbTi the T_{cs} is calculated by the average electric field E of 10 µV/m over the cable cross section taking into consideration the magnetic field distribution and uniform current density distribution. Equivalent to B_{eff} definition (see further).
- T_{op} depends on many interleaved causalities: the thermal-hydraulic analysis provides the actual value of T_{op} . Joule-Thomson effect and nuclear heat load must be taken into account. Unless the joint resistance is measured or specified by the designer of the joint, it is recommended to assume that any conductor joint has a resistance of 1 nΩ. The joint near outlet location can be neglected when calculating ΔT_M (i.e. only the joints at inlet need to be considered). For the determination of the cryogenics load, the outlet joint ohmic heating should be considered.

2.6 Minimum value of temperature margin / maximum current ratio) (criteria)

- $\Delta T_M \geq 1.5$ K for both NbTi and Nb_3Sn conductors.
- $I_{op}/I_c(T_{op})$ ratio is reported and spotted in conductor section where it exceeds 0.5. (This is not a design criterion.)

2.7 Maximum terminal voltage and voltage to ground for normal operation

For TF coils (1.5 times higher than ITER DDD):

- Nominal and maximum voltage terminal to terminal at current dump (QPS intervention, no fault) is below 10 kV. (Here nominal voltage corresponds to R·I voltage, while different maximum voltage might be generated by QPS circuit). If the analysis of the QPC leads to the maximum voltage above the specified limit, the limits on maximum voltage will be rediscussed.
- Nominal and maximum terminal voltage to ground at current dump (QPS intervention, no fault) is below 5 kV. If the analysis of the QPC leads to the maximum voltage above the specified limit, the limits on maximum voltage will be rediscussed.
- Inductance can be deduced from stored energy (source PROCESS) and from the operating current selected by the designers, for the high-precision calculations from the real WP geometry.

For each CS module and PF coil (1.5 times maximum value of ITER DDD):

- Nominal and maximum voltage terminal to terminal at current dump (normal operation, no fault) is below 20 kV. If the analysis of the QPC leads to the maximum voltage above the specified limit, the limits on maximum voltage will be rediscussed.
- Nominal and maximum terminal voltage to ground at current dump (normal operation, no fault) is below 10 kV. If the analysis of the QPC leads to the maximum voltage above the specified limit, the limits on maximum voltage will be rediscussed.

2.8 Maximum terminal voltage and voltage to ground for fault operation

The voltage to ground applicable for acceptance test by the coil manufacturer (the maximum of twice the normal operation ground voltage plus 1kV or fault ground voltage plus 1kV) will not exceed 29 kV. Should the fault voltage analysis identify a fault voltage larger than 28 kV, a revision of the allowable voltage will be considered. In general, the electric design criteria of ITER (ITER_D_22GRQH v1.2) are retained.

2.9 Insulation and winding pack area (criteria)

- Conductor insulation (wrap) = 1 mm (minimum turn steel-to-steel separation = 2 mm).

- Pancake-wound coils: Inter-pancake insulation = 2 mm; double-pancake wrap insulation = 1 mm (the metal-to-metal separation for conductors belonging to different pancakes = 4 mm).
- Layer-wound coils: Insulation between layers = 2 mm (the metal-to-metal separation for conductors belonging to different layers = 4 mm).
- Ground insulation wrap = 8 mm.
- Insertion gap for TF coils = 10 mm on three sides. No insertion gap on the plasma facing side.

2.10 RRR values (criterion)

- RRR = 100 for copper in strands.
- RRR ≤ 400 for segregated copper.

2.11 Nb_3Sn Cu : non-Cu ratio limits (criteria)

- Cu : non-Cu ratio ≥ 1.
- Cr plating is 2 µm thick and should be considered in overall strand diameter.

2.12 NbTi Cu : non-Cu ratio limits (criteria)

- Cu : non-Cu ratio ≥ 1.
- Ni plating (if any) is 2 µm thick and should be considered in overall strand diameter.

3 Thermal-Hydraulic analysis in burn and quench conditions

3.1 Material database

If widely used/accepted programs (4C, THEA, FLOWER, …) are used for the thermal-hydraulic analyses, the material properties implemented in these programs can be employed. Otherwise the material properties from EDFA database [5] are the default choice.

3.2 He pressure drop and mass flow in normal operation

- The inlet pressure is 6 bar.
- The maximum pressure drop from inlet to outlet (manifolds) of the winding pack in normal operation is targeted at 1 bar. A figure of merit for the cooling is the product of pressure drop at inlet-outlet manifolds, Δp, by the total volumetric flow rate in the winding.

3.3 Inlet and outlet temperature

T_{in} = 4.5 K. The outlet temperature for each channel of flow (cooling channels and bundle) within the winding pack is determined by the thermal-hydraulic analysis. If the case cooling is considered, the case cooling circuit is separated from the WP cooling circuit, assuming the same inlet temperature of 4.5 K, but with different outlet temperature and different pressure drop (not necessarily 1 bar).

3.4 Definition and maximum value of hotspot temperature (analysis tool & criterion)

To limit the thermal-mechanical stress in the winding pack, the hot spot temperature at the steel jacket, $T_{hs\,jt}$ must be $\leq$ 150 K (as in ITER criteria). (This criteria is considered roughly equivalent to a maximum temperature of 250 K in the strand bundle, when calculated adiabatically, based on the enthalpy of the strand bundle alone, i.e. disregarding Helium and steel).

As the correlation between hot spot temperature at the jacket and transient maximum temperature at the cable may vary depending on conductor layout and dump time constant, the analysts use $T_{hs\,jt} \leq 150$ K as a criterion and report the maximum transient temperature of the cable in the analysis results.

3.5 NH load map

The latest available document predicting the NH load map is [6], and will be used for TF coils until a new updated document is released (expected in 2016).

The poloidal distribution of the NH load (due to casing front case wall thickness variation) on the TF winding must be accounted in the analysis (e.g. by considering at least 2 different sections).

The analysis of L. Savoldi *et al.* [7] indicates that the entire NH load in the case can be removed by the case cooling circuit. It is therefore assumed that there is no heat transfer from the TF case to the TF WP. The active contribution of the case cooling to the winding cooling [7] is conservatively neglected.

For the CS coil, the NH load can be neglected.

3.6 Friction Factors

The friction factors are specified in the detailed technical memo [1].

3.7 Heat Transfer Coefficients

The heat transfer coefficients are specified in the detailed technical memo [1].

3.8 Boundary Conditions

In the TF burn simulations, the analysts can assume fixed "reservoir" boundary conditions, with constant temperature and constant pressure.

For other simulations (PF, CS operation and quench studies for all magnets), a simple circuit model should be adopted, including at least return line, pump, heat exchanger and supply line, as shown in Fig. 1. The dimensions (diameter and length of the pipes) should be chosen in such a way to account for the He volume in the DEMO circuit (rescaled to a single TF coil if one WP is considered), e.g. one can get inspired by the cooling circuit proposed in Fig. 9 of [7]. The cryolines can be assumed adiabatic, and the HX is modelled as ideal. In the simplest approximation, the pump can be a volumetric pump that forces a prescribed (constant) volumetric flow rate. The pipelines are assumed to be smooth pipes.

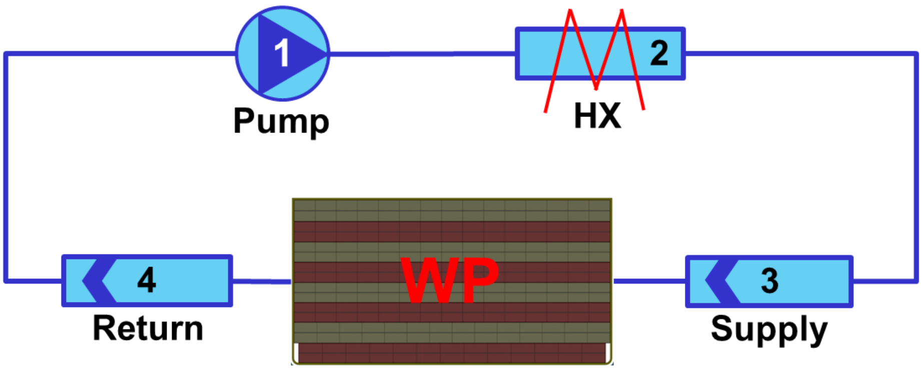
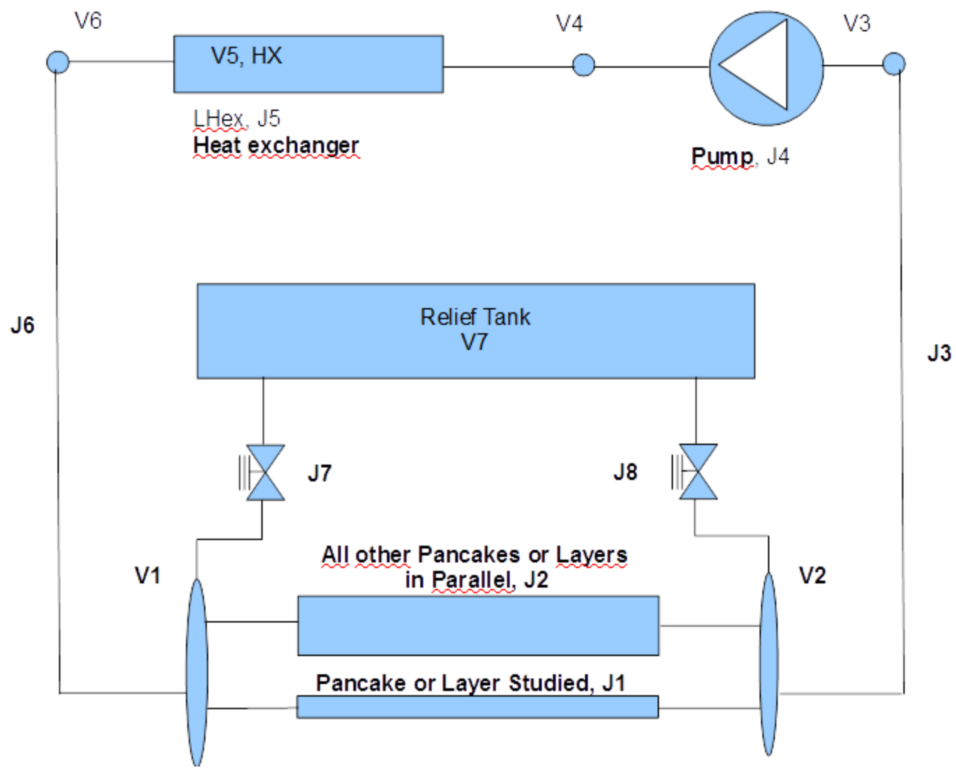


Fig. 1. Simplified circuit for the analysis of a DEMO TF coil , reproduced from [R. Bonifetto, B. Lacroix, M. Lewandowska, L. Savoldi, K. Sedlak, R. Vallcorba, R. Zanino, "Common approach for thermal-hydraulic analyses in burn conditions," EFDA_D_2MYEEZ v1.0, 26/01/2015].

For a more realistic quench calculation, the following cryogenic circuit proposed by CEA could be adopted with a detailed analysis of the pancake or the layer studied and an equivalent hydraulic circuit for all the other pancakes or layers in parallel. The circuit comprises two burst disks (to be open at DP> 2.0 MPa) connected to a quench helium discharge volume at a determined pressure and temperature.



The analysts are free to implement the cooling circuit according to their choice, also a circuit not mentioned in this memo, e.g. Fig. 9 of [7] used by POLITO team. More detailed/realistic models are allowed/welcome.

3.9 Magnetic Field

Space distribution of the magnetic field (the output of an electromagnetic analysis) should be specified along the conductor length, from the conductor inlet to the conductor outlet.

The overall magnetic field should include contributions from PF, CS and Plasma, namely at the End of Flat-top (EOF) time (= end of burn). The currents in individual PF and CS coils during EOF are defined in the last table of [8]. The plasma current during flat-top is defined in the same document ("plasmacur") = 19.6 MA.

For CS and PF coil, the designers must retain the operation point with the worst combination of B_{op} and I_{op} (with respect to the minimum T_{cs}) over the duty cycle.

In case of a fast discharge, the magnetic field contribution of the discharged magnet follows the changes in the current (i.e. the current decay):

$$B(x_1,t) = B(x_1,0) \cdot I(t) / I(0)$$

3.10 Effective Magnetic Field

To calculate the effective magnetic field B_{eff}, the general approach described in [9] and [10] should be used. The analysts can deviate in details in the way how he/she iterates over the cable space (e.g. whether a full 2D distribution of magnetic field is used or just some 1D approximation).

In order to assess B_{eff} along the full conductor length, the analysts may also use the following approach:

1. Calculate the effective field at one position of the given conductor (e.g. inboard leg, equatorial plane) = $B_{eff}^{nominal}$, and the field at the conductor centre at the same position = $B_c^{nominal}$.
2. Calculate the field on the central line (i.e. at the conductor centre) along the conductor length, $B_c(x)$.
3. Scale the $B_c(x)$ to $B_{eff}(x)$ using the ratio of $B_{eff}^{nominal}$ to $B_c^{nominal}$ for calculating the effective field along the conductor length: $B_{eff}(x) = B_c(x) \cdot B_{eff}^{nominal}/B_c^{nominal}$.

3.11 Quench Detection Voltage, Reaction Time and Discharge time

Motivation

Till 2015, the quench detection (resistive) voltage threshold V_{thr} was set to 0.5 V. It has been learnt that ITER uses much lower threshold of 0.1 V. The high voltage threshold in DEMO in combination with the relatively long delay time of 3 s makes the fulfilment of the quench requirement very challenging (ITER would not satisfy the hot spot temperature criteria with the previous DEMO assumptions). According to ITER representatives [11], thorough simulation studies were done in order to confirm the feasibility of the 0.1 V threshold detection.

The V_{thr} = 0.1 V criteria is now adopted. It makes easier to protect all sections of the coils, even those with large temperature margin ΔT (as in ITER).

In the quench analysis, the resistive voltage over the full layer or pancake is detected. Once the voltage exceeds the V_{thr} = 0.1 V, the full operating current is provided for the sum of "quench validation time" and "QPC reaction time".

The value for dump time constant of the TF current, τ, is defined in [12] and depends on DEMO parameters. The following relation is inferred from [12]:

$$\tau \sim \frac{B_{tor} \cdot I_{TF(total)} \cdot a^2}{R_{VV} \cdot \sigma_{VVallowable}}$$

where $\sigma_{VVallowable} = 91\ MPa$, seems to be reasonable for a safety class pressure vessel with welds, and the remaining parameters are given by PROCESS: $B_{tor} = 5.667\ T$, $a = 2.927\ m$, $R_{VV} = 5.091\ m$, $I_{TF} = 257.1\ MA$. This leads to $\tau = 27\ s$.

Common values:

- Quench detecting voltage: V_{thr} = 0.1 V.
- The time between quench initiation and reaching the quench detection voltage depends on the specific situation (magnetic field, current, quench initiation conditions, …) and is implicitly treated case-by-case in the quench analysis.
- QPC reaction time consisting of the validation time t_v = 0.1 s and breakers opening time t_d = 1.0 s (i.e. the time between voltage reaches $V_{threshold}$ and start of the current dump): t_v+t_d = 1.1 s.

- Current dump time for TF coils: τ = 27 s, which corresponds to DEMO aspect ratio of 3.1. The current Fast Safety Discharge can be simulated by a more sophisticated formula (for example taking into account the heating of discharge resistance) if available.
- Current dump time for other coils. Unless a value is specified, the designers may deduce the dump constant from the maximum allowed voltage to ground, the selected operating current and the actual inductance of the winding pack.

3.12 Stability and Hot Spot Temperature Calculation associated with Quench (Maximum Temperature)

Motivation

The aim of these analysis is to identify the maximum hot spot temperature that could be found anywhere in the WP. As in real life, the quench initiation is very local, with a very short normal zone. It is expected that the most critical location of the normal zone is at the conductor section with the largest temperature margin ΔT_{max} (which is also the most unlikely quench location). In such situation the local "hot spot" becomes the weak point of the conductor, and its temperature reaches the highest value. Depending of the WP layout, the ΔT_{max} may occur in different location, e.g. at the lowest field for pancake wound coils or in any of the graded layers for the layer wound coils. However, several locations should be investigated in order to clarify whether the coil is protected in the full volume.

Common values:

- The quench is initiated by heat deposition in the selected zone. The perturbation is 10 cm long and has the duration 100 ms. The power deposition used for the quench initiation is 2×MQE. The MQE values should be reported in the report.
- A realistic magnetic field profile is considered, preferentially using B_{eff} rather than B_{center}, if possible.
- The heat conduction between neighbouring turns and layers must be considered.
- The locations, in which the quench should be initiated, are:
  - Location where ΔT_m is largest.
  - Location where ΔT_m is smallest.
  - Some intermediate location depending on the analyst's choice.
- Minimum output of the analysis is $T_{hs\ jt}$ (to be compared to 150 K criterion) of steel jacket and $T_{hs\ str}$ of strands.

4 Specific CS Coil Issues

The CS coil is composed of five modules (CS3U, CS2U, CS1, CS2L, CS3L). The winding packs of these modules are separated by 100 mm. The total height of the CS coil is 17350 mm, while the height of the CS1 module is 5710 mm and that of the other modules 2810 mm.

The outer radius of the CS assembly is R=3309 mm [13], i.e. leaving a room temperature gap of 42 mm to the TF coil case (at R=3351 mm). This gap between the two assemblies is needed for lowering the CS into the pit and is reduced in operation at low temperature because of the centering loads of the TF coils and the hoop load on the CS. The actual maximum outer radius for the CS winding pack must account for the outer pre-compression tie plates and the busbars (both pancakes and layer winding). Here it is suggested to retain a maximum radius R=3200 mm for the insulated winding pack, including ground insulation, leaving 109 mm for busbars/tie plates (≈85 mm in ITER). The designers are free to consider a smaller outer radius, provided that the flux requirement is fulfilled.

The CS coil provides together with the 6 PF coils a magnetic flux of 320 Vs at the plasma during pre-magnetization. The values of the currents in the CS modules and the PF coils for the plasma equilibrium description are provided by the IDM document [14]. The specifications in [14] are given as a useful information but are not constraining for the CS WP designer since the magnetic flux is already imposed. For pre-magnetization, the currents in CS3U, CS2U, CS2L modules are 28.07 MA-turns, while the current of the CS3L module is only 20.18 MA-turns. Finally, the current of the central CS1 module is 57.14 MA-turns [15]. The discharge time constant is determined by the inductances and maximum tolerable terminal-to-terminal voltage.

References

[1] L. Savoldi and R. Zanino, "Common approach for thermal-hydraulic calculations", https://idm.euro-fusion.org/?uid=2LMECE .

[2] A. Nijhuis, "TF conductor samples strand thermo mechanical critical performances tests", https://idm.euro-fusion.org/?uid=2M5SMM v1.0.

[3] D. Ciazynski, "CEA TF and CS winding pack designs", Final Report, https://idm.euro-fusion.org/?uid=2MRUHR .

[4] N. Martovetsky, "ITER Central Solenoid Insert Test Results", IEEE Transactions on Applied Supercond., vol. 26, no. 4, 2016.

[5] P. Bauer, H. Rajainmaki, E. Salpietro: EFDA Material Data Compilation for Superconductor Simulation.

[6] L. Zani, U. Fischer, "Advanced definition of neutronic heat load density map on DEMO TF coils", https://idm.euro-fusion.org/?uid=2MFVCA .

[7] L. Savoldi *et al.*, "Development of the 4C model of a DEMO TF coil, including casing and casing cooling channels", https://idm.euro-fusion.org/?uid=2MXVRN .
and/or
R. Zanino, R. Bonifetto, O. Dicuonzo, L. Muzzi, G. F. Nallo, L. Savoldi, S. Turtù, "Development of a Thermal-Hydraulic Model for the European DEMO TF Coil," IEEE Transactions on Applied Superconductivity, vol. 26, issue 3, Apr. 2016, Art. ID 4201606.

[8] R. Wenninger, "EU DEMO1 2015 Plasma and Equilibrium Description", https://idm.euro-fusion.org/?uid=2LJFN7 .

[9] N. Mitchel, private communication.

[10] N. Mitchel, N. Mitchel "Steady state analysis of non-uniform current distributions in cable-in-conduit conductors and comparison with experimental data", Cryogenics vol. 40, pp. 99–116, 2000.

[11] R. Wesche, A. Anghel, B. Stepanov, M. Vogel, P. Bruzzone, "DC performance, AC loss and transient field stability of five medium size NbTi cable-in-conduit conductors with parametric variations", Cryogenics vol. 45, pp. 755–779, 2005.

[12] C. Bachmann, "Estimate of the Main EM Loads in DEMO Depending on the Aspect Ratio" https://idm.euro-fusion.org/?uid=2MBSE3

[13] "DEMO1 Reference Design - 2015 April ("EU DEMO1 2015") - PROCESS One Page Output ", https://idm.euro-fusion.org/?uid=2LBJRY .

[14] "Plasma and Equilibrium description", https://idm.euro-fusion.org/?uid=2LJFN7 .

[15] "DEMO1 Reference Design - 2015 April ("EU DEMO1 2015") - SOF and EOF equilibria", https://idm.euro-fusion.org/?uid=2AQ5GP .