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# AC Losses Calculations for the ITER CS and PF Magnet Systems during Plasma Operation

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**Abstract --** While the ITER magnet system assembly is progressing, models are being developed to predict the performances of the coils in support of the preparation of commissioning and operation. In particular, the AC losses generated in the coils during a plasma scenario need to be estimated as input to thermo-hydraulic performance simulations. The largest AC losses during plasma operation are expected in the CS and PF coils. This paper discusses the results of simulations of AC losses in these coils during a representative ITER plasma pulse. These calculations also take into account the electromagnetic shielding of filtering provided by the ITER passive structures, most importantly the vacuum vessel, discussing its impact on the conductor AC losses. The results will also be compared to earlier predictions. Finally, the CS and PF coil AC losses expected during commissioning will be briefly discussed.

**Index Terms—** Superconducting Magnets, AC loss, fusion Magnets, ITER, Nb3Sn, NbTi, LTS, CICC

## I. INTRODUCTION

THE ITER international project located in the South of France aims to demonstrate the technological feasibility of nuclear fusion for power generation. The ITER device uses an array of exceptionally large superconducting magnets, among them the Central Solenoid (CS) and the Poloidal Field (PF) systems, which serve to initiate, maintain, control and shape the magnetically levitated hot nuclear plasma. The CS is made from six large modules wound from Nb3Sn based superconductor, reaching 13 T peak field and each storing up to 800 MJ of energy in its magnetic field [1]. The largest of the six PF ring coils [2] is 24 m in diameter (the PF coils use NbTi superconductor). To attain initial plasma break-down, the CS coils are discharged very quickly at the start of the plasma pulse. Providing the fast plasma position control feedback system the PF (and some CS) coil currents vary significantly. The coils are cooled with supercritical Helium flowing at a temperature of ~4.5 K. The thermal loads in these magnet systems have to be strictly controlled in order not to quench them. In the case of the CS this is mainly the AC loss. The PF coils are also affected by the heat load deposited by stray neutrons and static heat loads (radiation from the thermal shield and conduction through the supports). Three AC loss contributions are being differentiated – the Joule heating due to eddy currents in the passive structures (not discussed further here, see [3] for a recent update) and the two types of AC loss which occur in the superconducting cables, coupling and hysteresis losses, which are the topic of this paper.

In the CS and PF coils this AC loss is the dominating heat load. During a typical ITER plasma scenario, in the CS coils it is shared equally between plasma initiation/termination (short, several sec, but intense) and the burn-phase (longer, ~500 s but less intense). Peak ramp rates in the CS are 1-2 T/s during the plasma initiation and ~0.1 – 0.5 T/s during the burn. In the PF coils (and especially PF2-5) the AC loss occurs predominantly during the plasma burn when the position feed-back is active. It is critical for the operational analysis of the ITER coils performance to assess the AC losses as input to thermo-hydraulic models to predict the minimum temperature margin in the superconductor for the proposed plasma and commissioning scenarios. In some cases it is only ~1 K, making the conductor vulnerable to excessive heat load (risk of quench).

In this paper we describe the CS and PF coupling and hysteresis loss calculated with recently developed analytical models ([4]-[5]) for a standard ITER pulse scenario.

## II. ITER PLASMA PULSE SCENARIO / MODEL INPUT

The first step in the calculation of the AC losses is the calculation of the magnetic field along the conductor during the scenario. The spatial and temporal magnetic field profiles obtained are then used as input to a separate set of codes calculating the AC loss. This study is performed for the case of a recent reference plasma scenario (called “DINA 2016-1”), with the CS, PF (and plasma) currents as shown in Fig. 1. These currents were calculated with the DINA code, which does equilibrium plasma (multi-filament) simulations including the vacuum vessel and the CS and PF coils (this step is not discussed further here, see [6] for more details). The DINA simulation also includes the “noise” in the plasma position feedback system. The magnetic field profile in the CS and PF coils was calculated from these currents with the CARIDDI code (see the field in the CS1 coil in Fig. 2). Note that for perfectly positioned coils, plasma and vacuum vessel, the magnetic fields are axisymmetric around the ITER Tokamak. It is therefore sufficient to calculate the field only in one point for each CS and PF coil turn. Also the field is typically calculated only in the center of the conductor, excluding therefore the self-field (a simplification). Although the DINA 2016-01 scenario takes into account also the so-called In-Vessel-Coils (IVC), these were not modelled in CARIDDI since their contribution to the magnetic field in the CS and PF

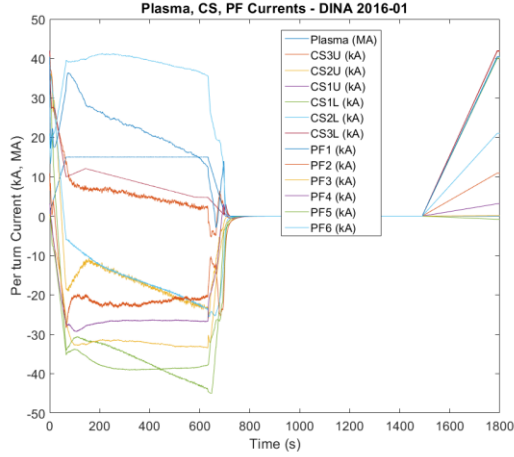


Fig. 1. PF, CS per turn currents (in kA) and plasma current (in MA) during the DINA 2016-01 scenario.

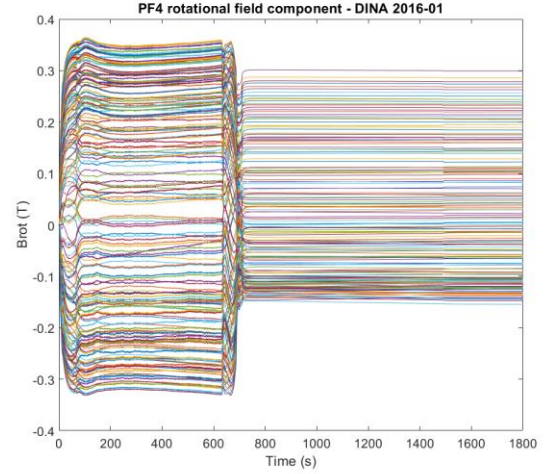


Fig. 3. Rotational magnetic field component of all turns of the PF4 coil during the DINA 2016-01 scenario. Rotating and not rotational everywhere !!!!

coils is negligible. Also, another simplification is that the plasma is described as a single (thin) filament (the plasma is not straying far from this position in this case). The number of time-points of the scenario is very large ( $\sim 100$  k steps), but they need to be retained in this calculation as even minute?? changes of local magnetic field generate AC loss.

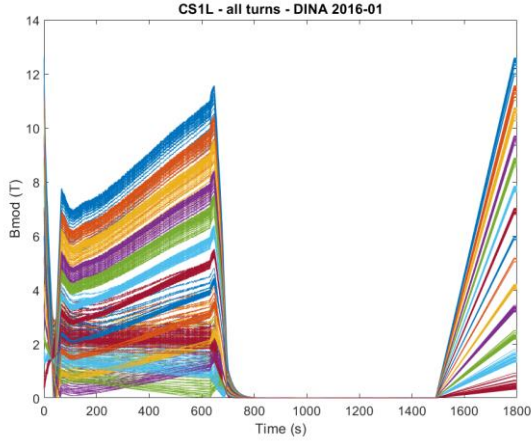


Fig. 2. Magnetic field (modulus) in the center-points of all turns of the lower CS1 coil during the DINA 2016-01 scenario.

### A. Rotating Field Approximation

With purely toroidal (axisymmetric) current distributions the magnetic fields in the turns of the CS and PF coils are either vertical or radial. The coupling loss is indeed calculated separately for the radial and vertical magnetic fields. For the hysteresis loss, however, as discussed in further detail in [4], the loss is calculated with the rotating field approximation. Fig. 3 shows, as an example, the rotating magnetic field component for the 176 turns of the PF4 coil. The so-called normal component is similar to the field modulus.

### B. Effect of Passive Structures

Two cases were investigated – one with the ITER passive structures (the vacuum vessel and the coil cases) and one without. Since the calculation with the passive structures requires much more computing resources it is of interest to investigate if it is actually required. The result as shown in Fig. 4 for the particular case of one inner turn of the lower CS3 coil is that the

TABLE I  
COUPLING AND HYSTERESIS LOSS PARAMETERS (FROM [4])

Coil	Strand	$n\tau_0$ (s)	$\alpha$ (s/T)	$\beta$ (s/T/kA)	$d_{\text{eff}}$ ( $\mu\text{m}$ )	$J_{c,NCu}^{**}$ (A/mm <sup>2</sup> )	$d_{\text{eff}}J_c$ (A/m)	$A_{\text{cond}}^*$ (mm <sup>2</sup> )
CS3L, CS1L, CS1U	JASTEC	0.2632	-0.0138	0.0001127	14.5	61400	890300	312.4
CS2L, CS3U	KAT	0.1335	-0.0062	0.0000905	24.6	19936	490425	304.2
CS2U	FURUKAWA	0.078	-0.0003	0.0001016	12.6	26411	332779	311.7
PF1&6	ChMP	0.2042	-0.0156	0.000153257	6.7	9495	63615	604.4
PF2-4	WST	0.0993	-0.0207	0.000495050	7.7	24846	191314	301.4
PF5	WST	0.1246	-0.0193	0.000275229	7.7	24846	191314	482.2

\*  $A_{\text{cond}}$  is combined cross-sectional area of all superconducting strands in the cable \*\*  $J_{c,NCu}$  at 4.5 K, 0.1 T, -0.6% strain (strain parameter only for Nb3Sn)

Is it really 0.1 T ? why JcNcu (which is not in [4] and further Jc ?

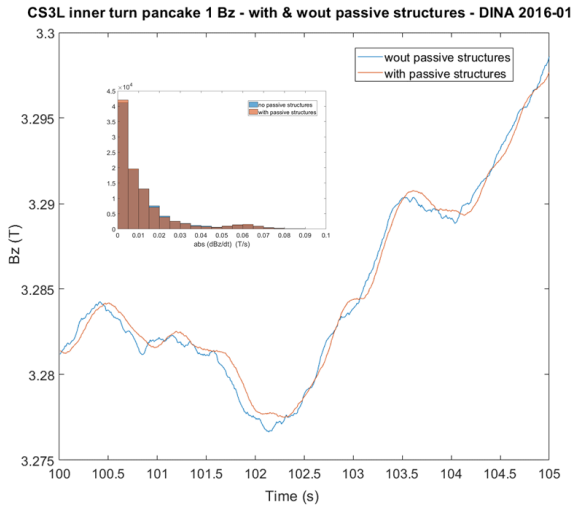


Fig. 4. Vertical magnetic field in pancake 1 innermost turn during the burn-phase of the 2016-01 scenario, with and without the effect of the vacuum vessel.

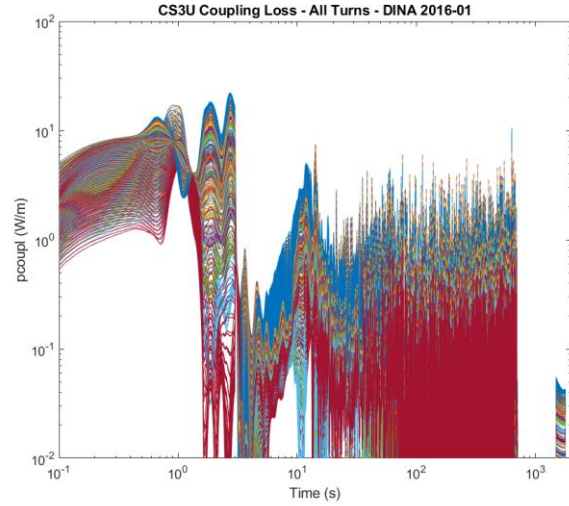


Fig. 6. Coupling loss power in the CS3U coil during the DINA 2016-01 scenario.

impact is minor. Some filtering by the passive structures is visible on the field traces, but the  $\text{dBz}/\text{dt}$  distribution is hardly affected as can be seen by the histogram insert.

### C. AC Loss Model Input Parameters

The input parameters for the coupling and hysteresis loss models are listed in Table 1 for reference. These material parameters are as published (and explained) previously in [5]. Note that for the CS conductor the coupling loss parameters are for the “cycled” case (i.e. reduced compared to the “virgin” or non-cycled case).

## III. CS COIL LOSSES

The AC losses in the CS modules during the DINA 2016-01 scenario are shown in Fig. 5. The total sum of coupling and hysteresis AC loss during the DINA 2016-01 scenario is 9.26 MJ, shared equally between hysteresis and coupling loss. In the

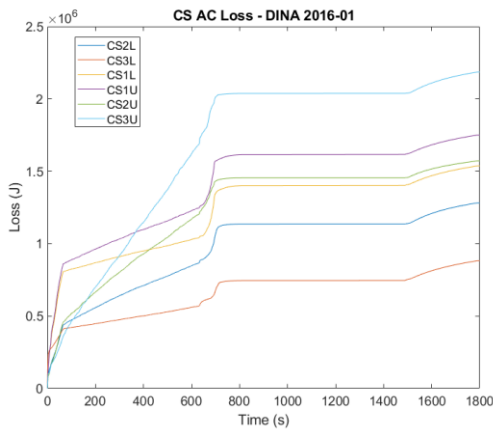


Fig. 5. AC loss in the CS coils during the DINA 2016-01 scenario.

CS the main contribution to the coupling loss occurs during the plasma initiation and termination phases, with the power reaching up to  $\sim 20$  W/m in CS3U (Fig. 6). In other modules the peak coupling loss powers can reach 60 W/m. Only the upper two modules also show a significant coupling loss contribution during the plasma burn. The hysteresis loss is generally distributed equally over the plasma initiation/termination and the plasma burn. CS3U is an exception again, with a lot of loss during the burn (as for the coupling loss). The peak hysteresis loss rates are generally lower,  $\sim 10$  W/m, but again, as stated above, the hysteresis loss is more evenly distributed as it is also significant during the burn.

## IV. PF COIL LOSSES

The AC losses in the PF coils during the DINA 2016-01 scenario are shown in Fig. 7. The total sum of coupling and hysteresis AC loss in the PF coils during the DINA 2016-01 scenario is 3.55 MJ. 60% is coupling loss, while 40% is hysteresis loss.

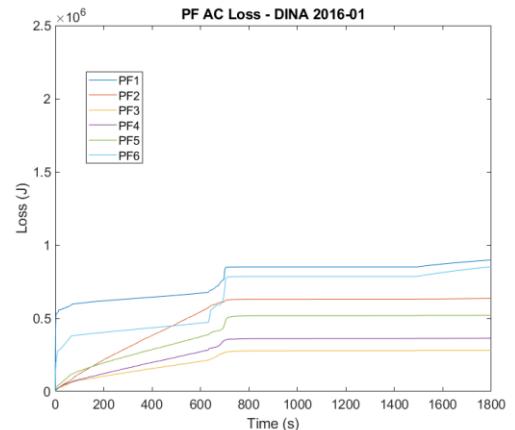


Fig. 7. AC loss in the PF coils during the DINA 2016-01 scenario.

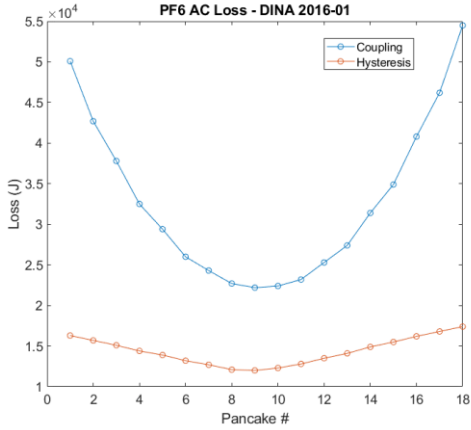


Fig. 8. AC loss in the PF single pancakes during the DINA 2016-01 scenario.

In the PF1 and PF6 coils the coupling loss is largest during the plasma initiation/termination phases, which is expected as these coils participate in the plasma break-down process. For all other PF coils the AC is mostly generated during the plasma-burn, again as expected, as their main function is to keep the plasma rotating stably within the vessel. As shown in Fig. 8 there can be up to a factor 2 difference in the loss between different pancakes (parallel cooling loops).

## V. DISCUSSION OF THE RESULTS

Fig. 9 shows a calculation of the AC loss for the CS3L module using the transient magnetic field as calculated with and without the passive structures (note that the coupling loss is different from Fig. 4 because this calculation is for the conductor in the virgin case, which generates higher loss). The case using the magnetic field transient without the passive structure effect gives only  $\sim 5$  larger loss, so the effect is quite limited as expected.

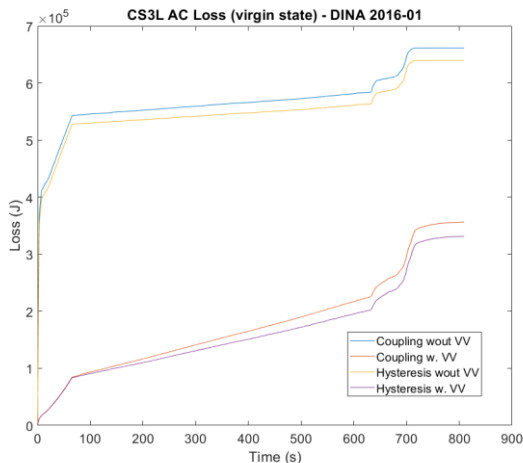


Fig. 9. CS3L AC Loss during DINA 2016-01 scenario with and without VV effect (virgin condition).

### A. Uncertainty on Hysteresis loss

Given the recent experimental evidence of increased hysteresis loss in the factory cold test of the second CS module ([4], [7]) -  $\sim 2$  times larger than predicted - it is recommended to apply a margin factor on the hysteresis heat loads computed above before performing updated thermo-hydraulic analysis until the above issue is resolved.

### B. Comparison to Earlier Calculations

Although similar data were not published previously, a number of such calculation were performed in the context of the ITER design. Table 2 gives the results of such a representative study [8] in comparison to the data here. Both simulations were for the same DINA 2016-01 scenario.

Case	CS	PF
previous model [8]	10.11	4.96
this model	9.26	5.06

### C. Brief Discussion of AC Loss during Commissioning

Table 3 presents AC losses as calculated for scenarios that are typical of the single coil commissioning – fast linear ramps and fast discharges. For the case of the CS, it is assumed that the conductor is in non-cycled condition, which gives larger losses. Also, the conductor chosen for this calculation is the one giving the largest losses (not all modules are made from this conductor). Only the PF6 coil is considered for the PF coils, as again, this coil gives the largest losses. The heat loads measured during the commissioning need to be carefully assessed against these predictions, as the AC loss parameter is one of the few performance parameters indicating the overall condition of the conductor.

## VI. SUMMARY AND OUTLOOK

The conductor AC loss was calculated for the ITER CS and PF coils using previously described analytical models for the case of a typical ITER plasma scenario. These AC loss data are readily available for thermo-hydraulic models to calculate the temperature margin inside the CS and PF coils during operation. Similar results for the ITER superconducting TF coils are presented in a different paper at this conference [9].

Case	CS mod*	PF6**
Fast discharge from 20 kA	0.42	0.18
Fast discharge from 40 kA	1.41	0.57
Linear ramp down from 20 kA	0.28	0.22
Linear ramp down from 40 kA	0.56	0.43

\* discharge time constant 6.5 s, ramp rate 1 kA/s,

\*\* discharge time constant 14 s, ramp rate 1 kA/s

## DISCLAIMER

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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