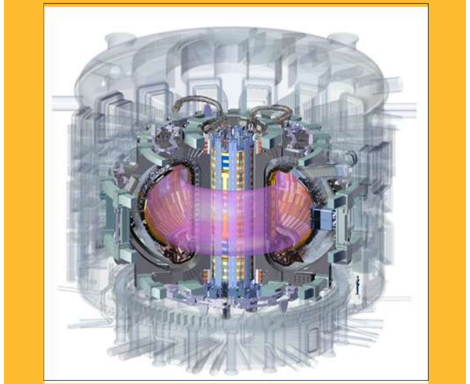
Development of an AC Loss Model for the ITER Central Solenoid during a Plasma Scenario

P. Bauer[1], M. Breschi[2], L. Cavallucci[2], J.L. Duchateau[3], F. Gauthier[1], A. Torre[3], B. Turck[3]
[1]ITER/France [2]University of Bologna/Italy [3]CEA/France

Introduction

- ITER is an international project located in the South of France which aims to demonstrate the feasibility of nuclear fusion for power generation.
- The ITER superconducting magnet system is composed of 18 Nb3Sn Toroidal Field (TF) coils, 6 NbTi Poloidal Field (PF) coils, 6 Nb3Sn Central Solenoid (CS) Coils and 18 NbTi Correction Coils (CC).



3D model of ITER Tokamak.

- The TF coils generate the toroidal field needed for plasma confinement; the PF and CS coils generate the poloidal field required for plasma control and shaping; the CS also acts as the primary of a transformer inducing and maintaining the plasma current. The CC correct field errors due to positioning or manufacturing tolerances of the main coils.
- All these coils are cooled with supercritical Helium flowing at a temperature of ~4.5 K. The thermal loads in the magnet system have to be strictly controlled in order for the coils not to quench.
- These thermal loads are mainly the static heat loads (radiation from the thermal shield and conduction through the supports), neutron heating coming from the fusion plasma and the AC loss (in the superconducting cables and due to eddy currents in the surrounding metallic structures), each representing about a third during a normal plasma scenario.
- AC loss in the coil conductors is the topic of this presentation.

Preparation for testing a CS module in GA/USA

AC loss is a major heat load in the pulsed, super-conducting ITER CS coils, and thus a design driver for the cryo-system and superconductor.

AC Loss in CS Coils

The coupling and hysteresis losses in the ITER CS coils average out to ~6 kW over the 1800 sec reference plasma pulse (which includes ~500 s of fusion burn). This power, which does not include the eddy current heat load in the passive structures (another 1 kW), needs to be compared to the 75 kW @ 4.2 K installed cryo-cooling capacity, For a regular plasma pulse the total AC loss represents 1/3rd of the heat load on the ITER superconducting magnet system.

AC Loss Model

The AC loss power discussed in the following is per unit volume of superconducting strand (pure Copper strands are not counted). To obtain the total power the power density needs to be multiplied by the number of superconducting strands, the strand cross-section and the length of conductor considered. Also to be noted is that the models for the two types of AC losses are somehow related, as the hysteresis loss model is needed to obtain the parameters of the coupling loss from the conductor sample tests, as they are always appear together.

Input Parameters

The following therefore describes analytical approaches in which considerable simplification is achieved by using AC loss parameters measured in standardized tests on conductor- (for coupling loss) or strand- (for hysteresis loss) samples. This phenomenological approach allows to bypass the calculation of the complex in-situ current distributions present in the conductor. Further description of these input parameters as well as the way they are obtained is given in a companion paper to this conference: A. Torre "Review of experimental results and models for AC losses in the ITER PF and CS conductors".

Coupling Loss

$$p = \frac{n\tau}{\mu_0}\left(\frac{dB_i}{dt}\right)^2 \qquad \left[\frac{W}{m^3}\right]$$

$$n\tau = n\tau_0 + \gamma \times B_e(T) + \lambda\left(B_e(T) \times I(kA)\right)\ [s]$$

The coupling loss power density per volume depends on the square of the local ("inner") field variation *dB$_i$/dt*, and the *L/R* (inductance over resistance represented by the time constant τ) of the different coupling loops (first equ. on the left). The temporal behavior of B_i, the "internal" locally applied field after taking into account the shielding by the eddy currents, is obtained from the externally applied field $B_e(t)$ from the solution of the simple ODE $B_i = B_e - \tau * dB_i/dt$. Here it is simply calculated from the previous B_i at time step (t-Δt) by the finite differences method (but other more or less elaborate ways to calculate it exist). The externally applied field $B_e(t)$ along the conductor inside the coils is obtained from numerical analysis with models implementing the entire magnet system (incl. the so-called passive structures) and plasma. The parameter describing the eddy current response of the CICC is represented by nτ, which is typically obtained from AC loss tests on conductor samples as discussed in the companion paper noted above (or insert tests as discussed later). The second equ. On the left gives the phenomenological fit used here.

Hysteresis Loss

$$J_{c,nonCu}(B_e,T,\varepsilon) = J_{c,nonCu,mag}(B_e) \times \frac{J_{c,nonCu,transp}(B_e,T,\varepsilon)}{J_{c,nonCu,transp}(B_e,T_0,-0.0022)} \quad \left[\frac{A}{m^2}\right]$$

$$p_{hyst,full} = \frac{2}{3\pi(1+CuNCu)} J_{c,nonCu}(B_e,T,\varepsilon) d_{eff} \frac{dB_e}{dt} \quad \left[\frac{W}{m^3}\right]$$

$$p_{hyst,part} = \frac{\pi \frac{dB_e}{dt}\Delta B^2}{2(1+CuNCu)\mu_0^2 k_{fil}^2 J_{c,nonCu}(B_e,T,\varepsilon) d_{eff}}\left(1 - \frac{\pi\Delta B}{3\mu_0 k_{fil} J_{c,nonCu}(B_e,T,\varepsilon) d_{eff}}\right) \quad \left[\frac{W}{m^3}\right]$$

The most straight forward way to calculate the hysteresis loss consists of integrating the magnetization *M* as a function of the applied field B_e. The instantaneous loss power is then as in $p_{hyst} = \frac{1}{2}\Delta M(B_e,T,\varepsilon)\frac{dB_e}{dt}\ \left[\frac{W}{m^3}\right]$, where *ΔM* is the width of the hysteresis loop from up- to down-field branch (the factor ½ assumes the hysteresis loop is up/down symmetric). The practical approach chosen is to measure the magnetization loop of a single strand exposed to an applied field and use this magnetization loop to calculate the hysteresis loss of a cable where it is assumed that the applied field is the same for all strands in the cable. Alternatively magnetization measurements could also be performed for entire cable samples, but this requires larger equipment (and for this reason these measurements are less common). As also before for the coupling loss the magnetization is the response to the internal field B_i, which is not the same as the applied field B_e because of the shielding effect. For the single strand case it is relatively straightforward to estimate B_i from B_e.

Two issues complicate the computation of the hysteresis loss, however. The first is that the superconductor magnetization depends not only on magnetic field, but also on temperature *T* and in Nb3Sn on strain ε. Measurements of the magnetization for varying temperature and strain is experimentally complex. The work-around is provided by the known dependence of the magnetization on $J_c \times d_{eff}$, the product of the critical current density and the "effective" filament diameter. J_c is usually measured in strands as a function of *T* and ε (and B_e) in a transport measurement setting (recording the super-to-normal-conducting transition during a current ramp at fixed field). The transport type of measurement underestimates the J_c at low field, however, because the higher transport current a) produces a non-negligible magnetic self-field and b) combines with the shielding currents in a complex way making it difficult to relate B_i and B_e. The equation above gives the J_c function finally used here, which combines the field dependence obtained with $J_{c,mag}$ obtained from the magnetization test with the temperature and strain dependence from the $J_{c,transp}$, which is normalized to a reference temperature and strain to suppress the field dependence. The two equations used to calculate the instantaneous hysteresis loss power per volume of sc strand as a function of J_c are given above are for the fully and partially penetrated case (see below for further explanation). There the d_{eff} parameter is in fact a fitting parameter, which allows to bring into agreement the magnetization $J_{c,mag}$ (for low field) and the transport $J_{c,transp}$ (for high field) measurements. Note that J_c is always referred to the non-Cu area in the superconducting strand. In Nb3Sn in which the non-Cu area is further differentiated (diffusion barriers, non-reacted Sn,.. etc) an additional parameter is introduced, k_{fil}, which is the non-Cu area divided by the Nb3Sn area.

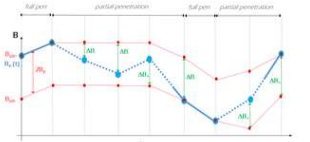


Illustration for how *ΔB* is defined for the hysteresis loss calculation

The second issue is that the magnetization response may not be fully developed, i.e. one is between the two branches of the magnetization loop (commonly referred to as the "partially penetrated" case). This condition is reached after a reversal of the sign of the dB_e/dt as long as ΔB_e has not allowed to reach the other side of the magnetization loop which by definition is $2B_p$ wide with $B_p=\mu_0/\pi\ k_{fil}\ d_{eff}\ J_{c,nonCu}\ (B_e,T,\varepsilon)$ the so-called penetration field. During an ITER scenario the evolution of B_e can be very complex due to the plasma position feedback (incl. noise) and the complex electromagnetic interaction of the many (pulsed) coils and plasma. It is possible that the dB_e/dt changes sign a lot of times while in between the two branches. This kind of back and forth of the field produces very complex shielding current patterns with alternating signs inside the sc filaments (like onion layers) and a simplification is needed here also. The key parameter which will be simplified is *ΔB*, which is the change of applied field accumulated since the last sign reversal of dB_e/dt. Here the simplification applied is the following (see the illustration on the left): as a dB_e/dt sign reversal occurs the magnetization loop branches are kept in memory for reference, denoted B_{sat+} and B_{sat-}, the first being the up-field branch and second the down branch. The difference B_{sat+}-B_{sat-}=$2B_p$ per definition. As a simplification the *ΔB* for a down-step in B_e is $\Delta B_- = B_{sat+} - B_e$ and for an up-step $\Delta B_+ = B_e - B_{sat-}$. When $\Delta B_\pm \geq 2B_p$ the fully penetrated case is reached and $B_{sat\pm}$ are redefined until the next sign reversal occurs. The formulas used for the fully or partially penetrated case are as described above. Note that the simplification used for the *ΔB* parameter results in an over-estimation of the hysteresis loss, it is thus a conservative model.

Rotating Field

$$B_{e,mod}(t) = \left|\overrightarrow{B_e}\right| = \sqrt{B_{e,r}(t)^2 + B_{e,z}(t)^2} \quad [T]$$

$$B_{e,rot}(t) = \sum dB_{e,rot}(t) = \sum \overline{B_{e,mod}(t)}\,\partial\alpha(t) \quad [T]$$

$$\partial\alpha(t) = \mathrm{acos}\left(\frac{\overrightarrow{B_e(t)}\,\overrightarrow{B_e(t-\Delta t)}}{B_e(t)B_e(t-\Delta t)}\right) \quad [rad]$$

For the case of the ITER CS (and PF) coils the applied field can be decomposed into the two projections perpendicular to conductor, i.e. vertical and radial (there is no field component along the conductor). It is assumed here that the coupling loss can be calculated separately for the two components and added. This assumes that the shielding currents excited in the two planes do not interfere with each other and the respective applied fields. In the case of the hysteresis loss this assumption does not hold, however, because the shielding current distribution in the superconducting filaments will always arrange in such a way as to cancel the applied field, i.e. it rotates with the field in the case of a rotating field. Calculating the loss from the sum of transverse field projections would generate a hysteresis loss that is overestimated. A good example is the case of a purely rotating field. Assuming that the loss is driven by the applied field modulus would give zero loss, which is certainly too little. The so-called "rotating field" approach, which strictly speaking applies only to small rotations, projects the field onto a non-rotating and a rotating component. Only the rotating component produces loss in purely rotating field. The components of this applied field de-composition for which the separately computed hysteresis losses are added are as given on the left. They are $B_{e,mod}$ and $B_{e,rot}$. The angle increment for each time step is α.

AC Loss General Explanation

Coupling Loss:

The coupling losses are the result of induced currents flowing between filaments in the multi-filamentary strands, and between strands within various cable stages as well as between sub-cables. The loss causing coupling currents partially flow inside superconductor, which enhances their time constants and thus their strength as compared to a normal conductor*. Therefore, in pulsed superconducting magnets as in ITER, all means possible to suppress these coupling currents are applied. This includes twisting of the filaments, strands and sub-cables to cut down on the inductance and increase the contact resistance with resistive coating on the strands (Cr or Ni). Finally stainless steel foil wraps over the sub-cables are also effective. But the effect cannot be suppressed entirely, as it would lead to electrically insulated strands (or filaments), preventing the transfer of currents from saturated strands and can thus lead to degraded cable performance and quench margin.

Hysteresis Loss:

Hysteresis (or "magnetization") loss is caused by the diamagnetic shielding effect inside the superconductor in which persistent currents are induced to expel the applied magnetic field. The loss causing mechanism is the re-arrangement of screening currents and pinned magnetic field vortices due to a change of applied field. The hysteresis loss depends on the so called "effective" filament diameter and the critical current density in the superconductor. The reduced filament sizes typical for LTS type strands (order 10 microns) cannot fully suppress this loss as the filaments are coupled through the Cu matrix (needed for electro-thermal stability of the strands) and thus behave like a larger filament. The critical current density should obviously be high enough to allow a large transport current to limit the superconductor cost. Since the superconductor is designed for the highest field region it can be over-designed for the low field regions in non-graded coil designs (as in ITER), additionally enhancing the hysteresis loss.

*but then at comparable performance the superconducting cable have much smaller cross-section, the AC loss in the superconductor, however, occurs at low temperature for which a penalty applies due to the limited Carnot efficiency.

Summary

- Simple analytical AC loss models are needed for fast turn-around calculations for the large superconducting coils in the ITER device.
- Once validated on conductor and coil measurements such models can be used to simulate the AC loss heating inside the superconducting coils for the ITER device during the plasma pulses.
- Such models have been presented here for the CS type ITER coils. In these coils the magnetic field transients are always transverse to the conductor, resulting in the simplest possible models.

Pierre Bauer - Pierre.Bauer@iter.org