An Analytical Framework for Computing AC Losses in the HTS Insert of the EU-DEMO Central Solenoid

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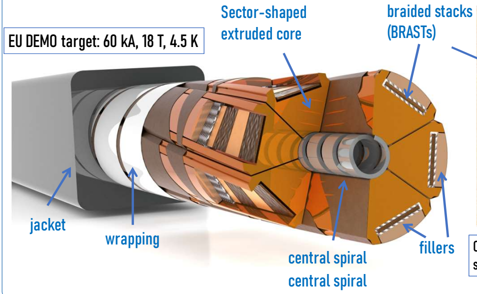
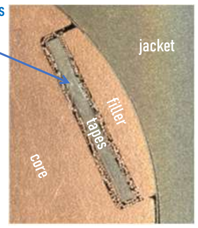
INTRODUCTION – High-temperature superconductors (HTS) are being explored for integration into coil systems for magnetic confinement fusion, due to their ability to extend operational margins in terms of temperature, current, and magnetic field. Recently, a conductor design based on the SECAS concept was proposed for the innermost layer of the central solenoid (CS) module in the EU-DEMO tokamak. The dynamic nature of plasma scenarios, characterized by rapid variations in current and magnetic fields, induces significant AC losses in the superconducting magnets. These losses can be particularly pronounced during phases like plasma start-up and control operation, where field variations can be significant. In this study, we evaluate the instantaneous power losses — both hysteretic and coupling losses — during a baseline plasma scenario using an analytical model that accurately accounts for the temporal evolution of the magnetic field profile within the innermost layers of the CS1 HTS insert. The calculated AC losses will be used in thermal-hydraulic simulations to verify if the temperature margin stays above the design threshold (ΔT_{margin} > 1.5 K), ensuring the safe operation of the HTS conductor.

THE SECTOR-ASSEMBLED CABLE

In recent research developments at ENEA [1], we have designed a novel concept for HTS sector cables, denoted as the SECtor-ASsembled cable (SECAS) based on BRAided Stacks of Tapes (BRAST). Each BRAST sub-unit comprises a stack of an arbitrary number of tapes assembled within a braid of thin, tin coated Cu wires.

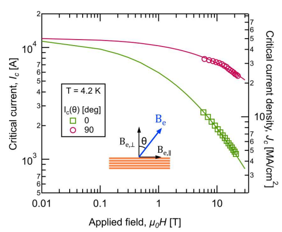




Optical image showing the cross section of a Cu-stabilized SECAS cable

IN-FIELD PROPERTIES OF REBCO COATED CONDUCTORS

Experimental data of 12-mm-wide Ic of commercial tapes at low temperatures (< 5 K) and high fields (> 10 T) are scarcely available in the literature, particularly when the field is parallel to the flat surface of the tapes. In this study, we have reconstructed the field-dependence of Ic in both parallel and perpendicular field configurations by appropriate scaling of the available experimental data under slightly different B-T conditions.



$$I_c(|\boldsymbol{B}|,\theta) = \frac{I_{c0}}{\left[1+\varepsilon(\theta)\left(\frac{|\boldsymbol{B}|}{B_0}\right)^{\alpha}\right]^{\beta}}$$

$$\varepsilon(\theta) = \sqrt{\gamma^{-2}\sin^2(\theta)+\cos^2(\theta)}$$

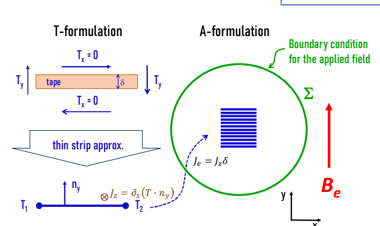
Parameter	Value
I_{c0} [kA]	12.2
α	0.54
β	2.18
B_0 [T]	5.72
γ	5

For the description of the magneto-angular dependence of the in-field critical current of commercial 2G-HTS tapes, $J_c(|B|, \theta)$, we consider an extended version of the conventional Kim model, which has been developed by Zhang *et al.* [2] by taking into account Blatter's angular anisotropy parameter [3]

ANALYTICAL AND NUMERICAL TOOLS

The instantaneous power loss of a twisted, stacked-tape cable is calculated using the theoretical expressions by Halse and Brandt [4, 5] and by London [6] for stacks subjected to an external field, perpendicular or parallel to the tape's wide surface, respectively. The analytical formulation has been extended to the general case where the field varies periodically with time and validated through finite-elements simulations.

Numerical



Governing equations

$$\boldsymbol{J} = \nabla\times\boldsymbol{T}; \qquad \boldsymbol{B} = \nabla\times\boldsymbol{A}$$

In Σ, Maxwell-Ampere's law is applied to solve the *A*-formulation

$$\nabla\times\nabla\times\boldsymbol{A} = \mu_0\mu_r\boldsymbol{J}$$

Maxwell-Faraday's and power laws are applied on the HTS domains

$$\nabla\times\boldsymbol{E} = -\partial_t\boldsymbol{B}; \qquad \boldsymbol{E} = E_c\frac{\boldsymbol{J}}{J_c(B)}\left|\frac{\boldsymbol{J}}{J_c(B)}\right|^{n-1}$$

Analytical

Halse-Brandt model for thin strip

$$P_{strip} = \frac{1}{4}J_c w|\partial_t B_e|[\tanh(\xi)-\xi\,\mathrm{sech}^2(\xi)]$$

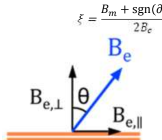
$$\xi = \frac{B_m+\mathrm{sgn}(\partial_t)B_e}{2B_c}$$

London-Bean model for infinite slab

$$P_{slab} = \frac{B_p^2}{2\mu_0}|\partial_t B_e|\begin{cases}(B_m+\mathrm{sgn}(\partial_t B_e)B_e)^2/4B_p^3 & (1)\\ 1/B_p & (2)\end{cases}$$

$$B_p = \mu_0 J_c\,\delta/2 \qquad (1)\quad \mathrm{sgn}(\partial_t B_e)B_e \le 2B_p - B_m$$

$$B_c = \mu_0 J_c\,\delta/\pi\,N_{tapes} \qquad (2)\quad \mathrm{sgn}(\partial_t B_e)B_e \ge 2B_p - B_m$$



$$P_{cable} = \frac{2}{\pi}\int_0^{\pi/2}\left[P_{slab}(B_{e,\parallel})+P_{strip}(B_{e,\perp})\right]d\theta$$

Twisted stack

ELECTROMAGNETIC ANALYSIS

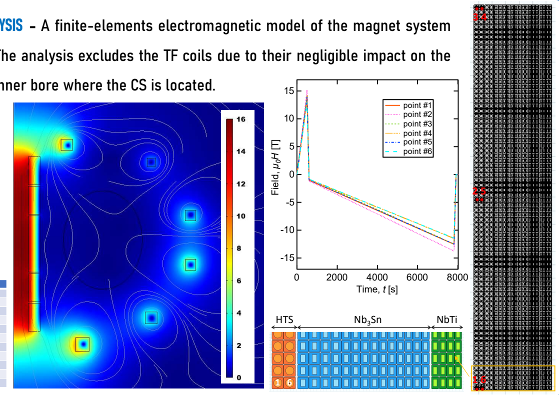
A finite-elements electromagnetic model of the magnet system has been developed. The analysis excludes the TF coils due to their negligible impact on the magnetic field at the inner bore where the CS is located.

Current scenario

I [MA]	PREMAG	SOF	EOF
CS3U	36.12	16.91	-7.37
CS2U	36.12	-1.76	-36.11
CS1	72.24	-11.91	-72.24
CS2L	36.12	-8.9	-36.11
CS3L	34.89	31.19	-15.43
PF1	20.51	17.6	2.88
PF2	4.79	-6.48	-7.31
PF3	-10.51	-6.35	-7.54
PF4	14.92	-4.94	-4.52
PF5	-12.3	-9.63	-11.14
PF6	29.81	19.18	12.72
Plasma	0	17.86	17.86

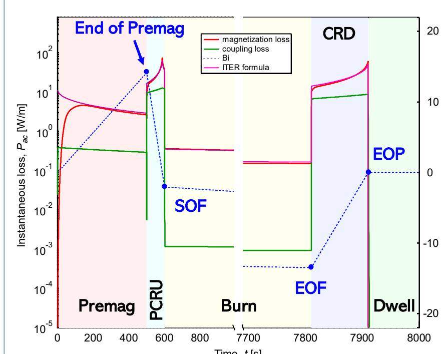
Geometric parameters

	R [m]	Z [m]	ΔR [m]	ΔZ [m]
CS3U	2.1104	7.0505	1.1808	2.8630
CS2U	2.1104	4.0375	1.1808	2.8630
CS1	2.1104	-0.3990	1.1808	5.7100
CS2L	2.1104	-4.8355	1.1808	2.8630
CS3L	2.1104	-7.8485	1.1808	2.8630
PF1	5.4000	9.6600	1.1500	1.1500
PF2	14.0000	7.9000	0.8500	0.8500
PF3	17.9700	2.5000	1.1000	1.1000
PF4	17.9700	-2.5000	1.1000	1.1000
PF5	14.0000	-7.9000	1.2000	1.2000
PF6	7.0000	-10.6000	1.4000	1.4000



RESULTS

We have calculated hysteresis and coupling losses in a DEMO plasma scenario [7]. A comparison was made with the formulas used in the ITER project [8]. The dominant losses are due to hysteresis, which are approximately four times higher.



Phases of plasma scenario [7]

0-500 s
Premagnetisation phase (Premag)

500-600 s
Plasma current ramp-up (PCRU)

600-7810 s
Burn phase (between the Start of Flat Top, SOF, and the End of Flat Top, EOF)

7810-7910 s
Conductor current ramp down (CRD, between EOF and end of plasma, EOP)

7910-8010 s
Dwell time between EOP and next Premag

Hysteresis loss

The hysteresis loss is compared with that obtained using the ITER formula [8] for fully penetrated strands:

$$P_h[W\cdot m^{-3}] = \frac{2}{3\pi}J_c d_{eff}|\partial_t B_e|\cdot\frac{2}{\pi}$$

where the *"effective diameter"*, d_{eff}, is the tape thickness, and the correction factor $2/\pi$ accounts for twisting and anisotropy [9].

Coupling loss

The coupling loss in a field ramped was calculated as:

$$P_c[W\cdot m^{-3}] = \frac{2\tau}{\mu_0}|\partial_t B_i|^2$$

where the internal field B_i is the solution of the differential equation:

$$B_e - B_i = \tau\partial_t B_i$$

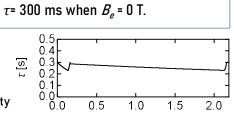
We assumed that τ = 300 ms when B_e = 0 T.

Loss [kJ/m]	Value
Q_h	8.2
$Q_{h,ITER}$	9.0
Q_c	2.0

$$Q_h = \int dtP_h \qquad Q_c = \int dtP_c$$

$$\tau = \frac{\mu_0}{2\rho_t}\left(\frac{L_p}{2\pi}\right)^2$$

ρ_t = transverse resistivity
L_p = twist pitch



CONCLUSIONS

The instantaneous power loss of the SECAS conductor, designed by the ENEA team for the innermost layers of the hybrid CS coils of EU-DEMO, was simulated using a recently developed analytical framework. A simplified current scenario, excluding the fast breakdown phase, was considered. Our results show that hysteresis losses dominate, while coupling losses also contribute significantly during both the PCRU and CRD plasma phases. Additionally, we applied the ITER formulas using the tape width in place of the "*effective diameter*" and introduced a corrective factor to account for twisting. Future work will involve thermo-hydraulic analyses to ensure the temperature margin remains above the design threshold.

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