

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

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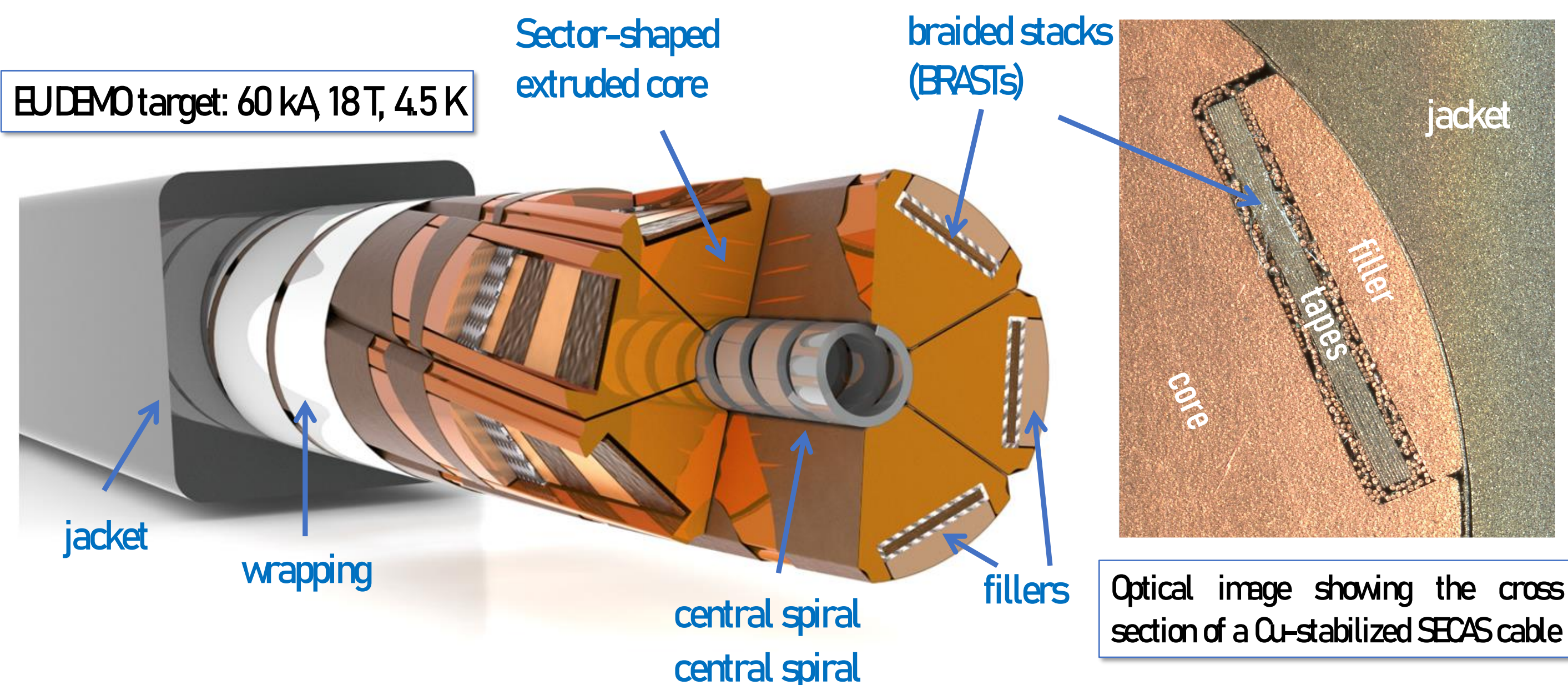
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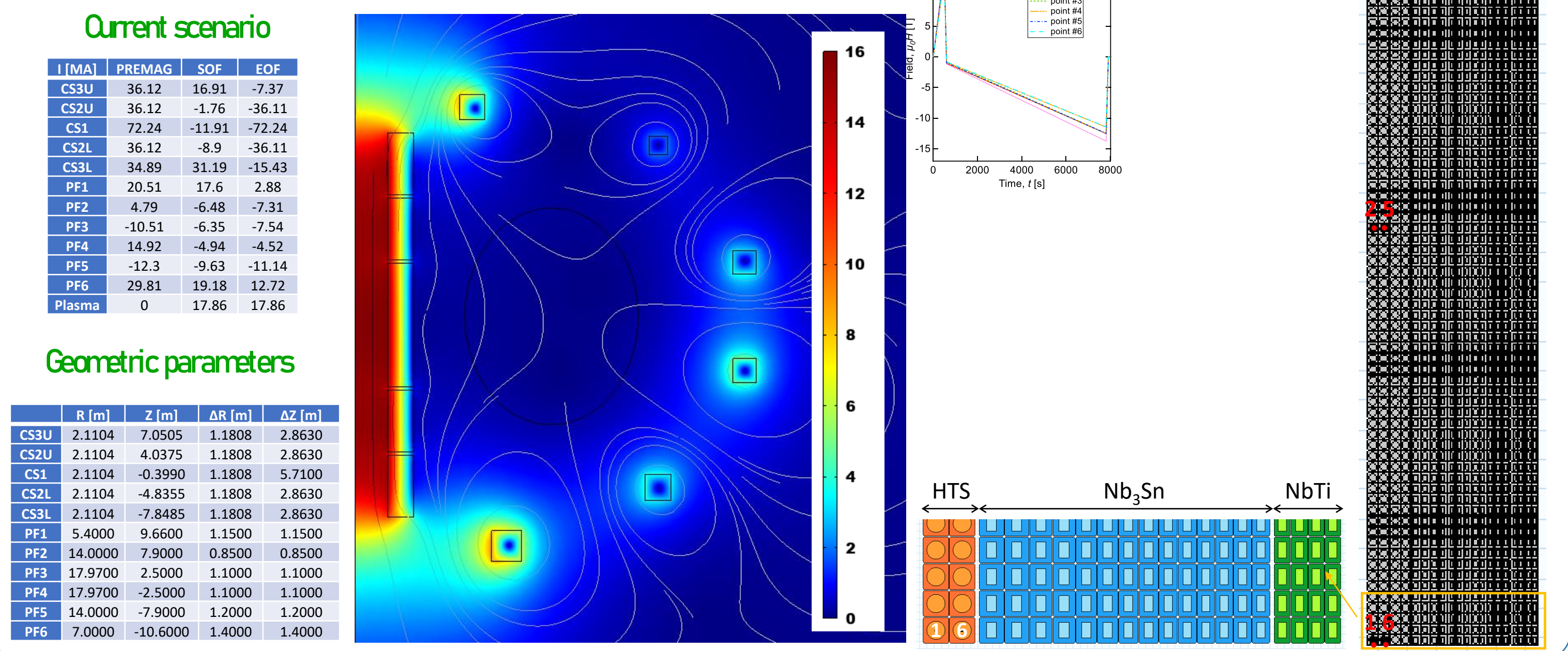
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INTRODUCTION - High-temperature superconductors (HTS) are being explored for integration into coil systems for magnetic confinement fusion, due to their ability to extend operational margins in terms of temperature, current, and magnetic field. Recently, 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 CSI HTS insert. The calculated AC losses will be used in thermal-hydraulic simulations to verify if the temperature margin stays above the design threshold ($\Delta T_{margin} > 1.5$ K), ensuring the safe operation of the HTS conductor.

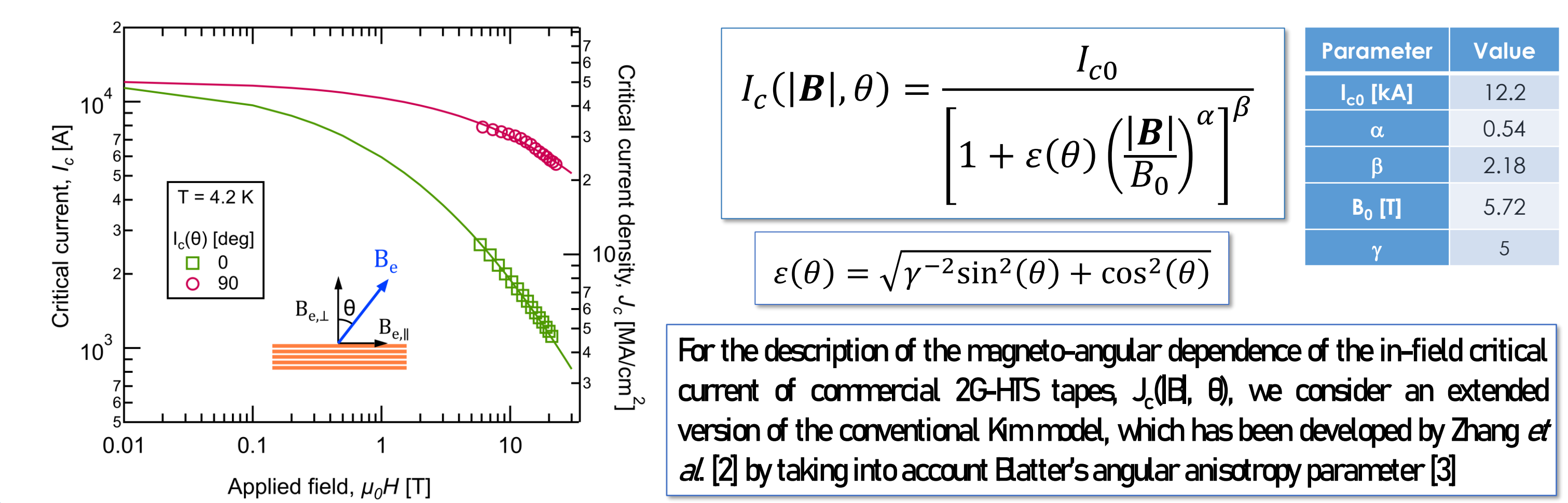
THE SECTOR-ASSEMBLED CABLE - In recent research developments at ENEA [1], we have designed a novel concept for HTS sector cables, denoted as the SECTOR-ASsembled cable (SECAS) based on BRAIDed Stacks of Tapes (BRAST). Each BRAST sub-unit comprises a stack of an arbitrary number of tapes assembled within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



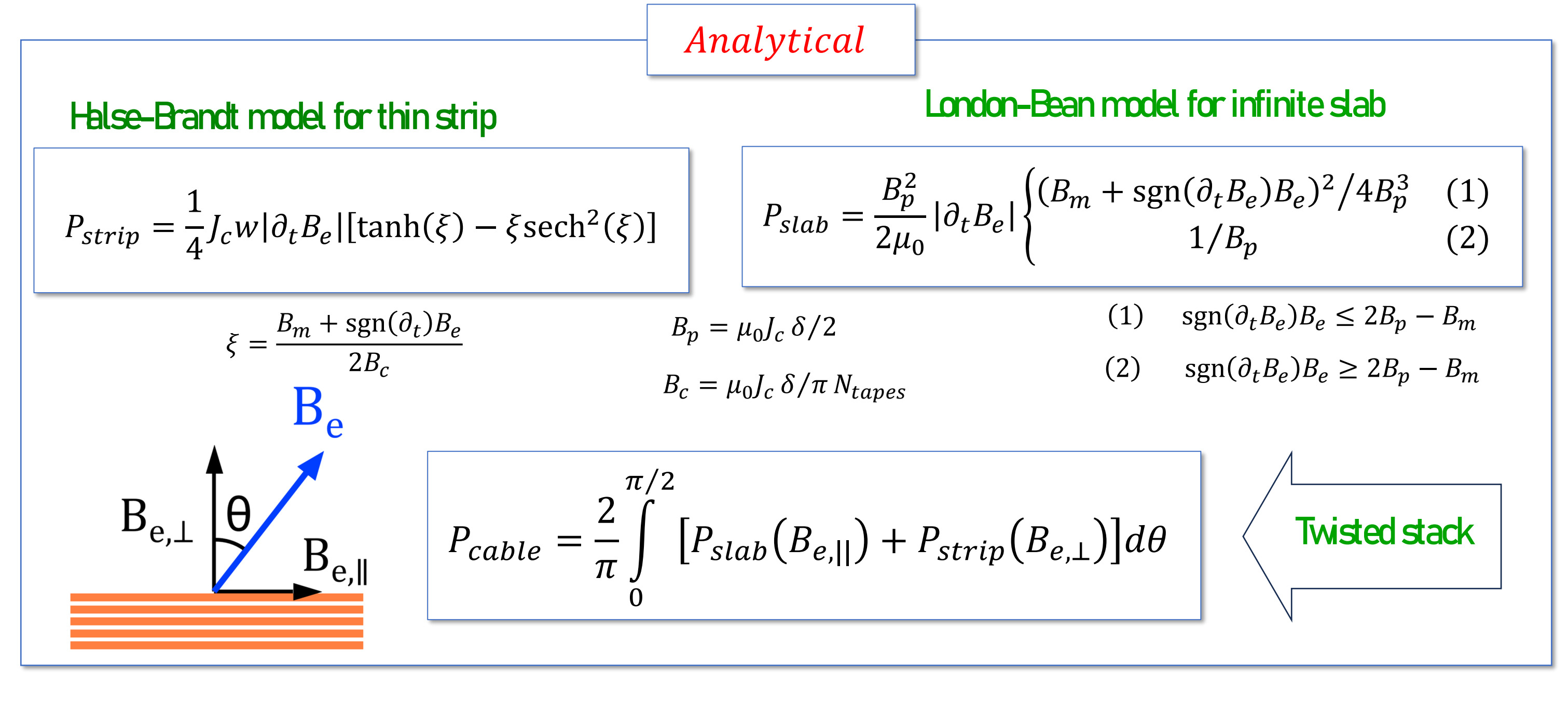
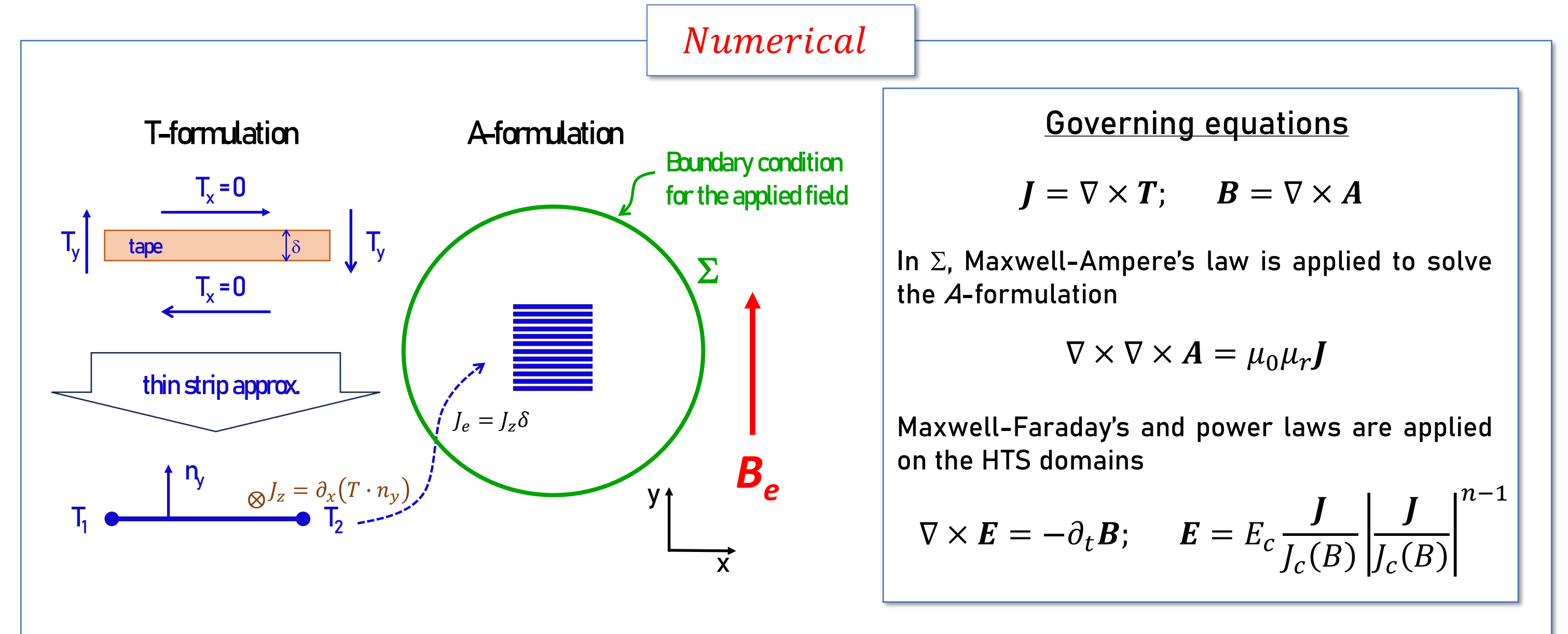
ELECTROMAGNETIC ANALYSIS - A finite-elements electromagnetic model of the magnet system has been developed. The analysis excludes the TF coils due to their negligible impact on the magnetic field at the inner bore where the CS is located.



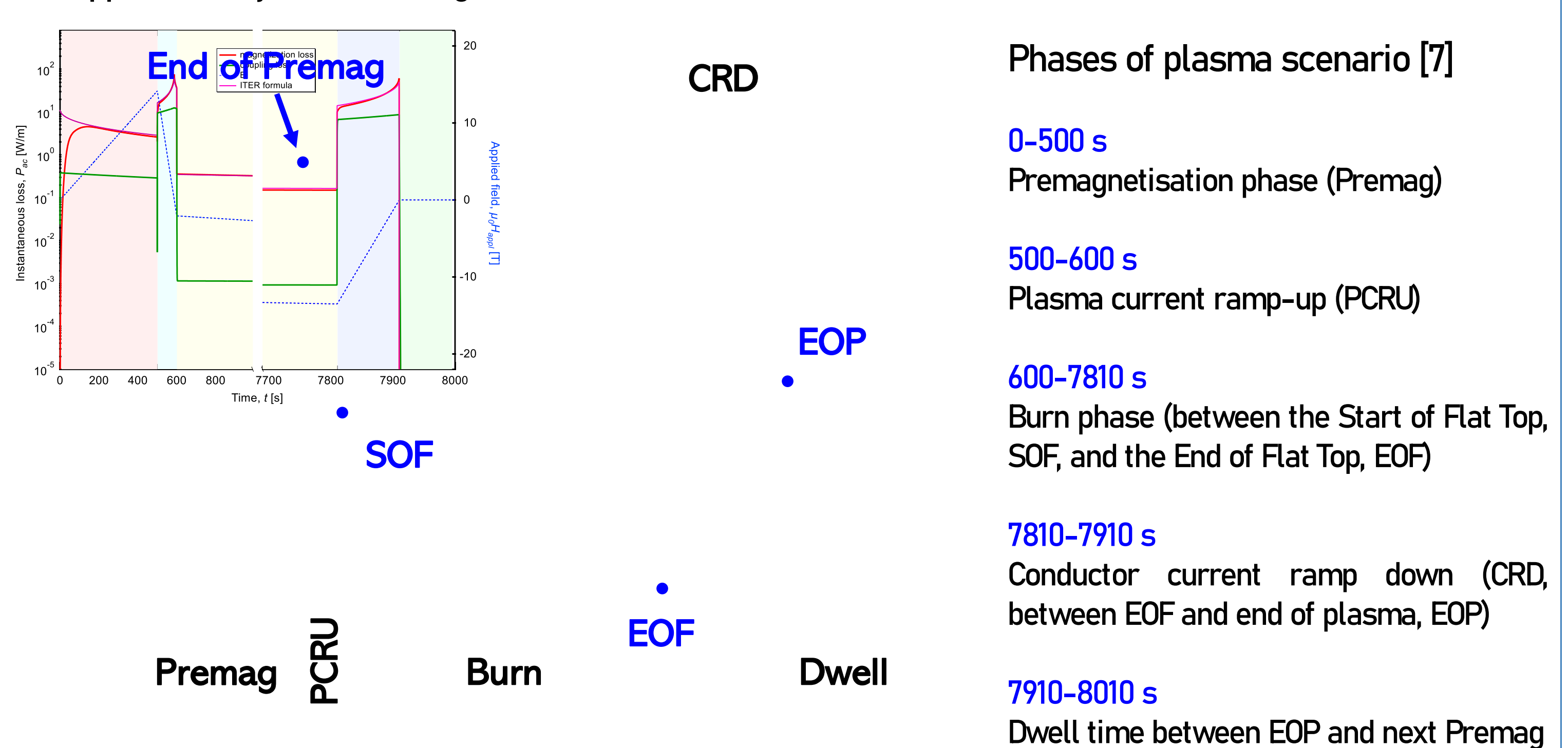
IN-FIELD PROPERTIES OF REBCO COATED CONDUCTORS - Experimental data of 12-mm-wide Ic of commercial tapes at low temperatures (< 5 K) and high fields (> 10 T) are scarcely available in the literature, particularly when the field is parallel to the flat surface of the tapes. In this study, we have reconstructed 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.



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.



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.



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].

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

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 $\tau = 300$ ms when $B_e = 0$ T.

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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