Lumped parameter circuit model for hysteresis losses in sector shaped HTS cables

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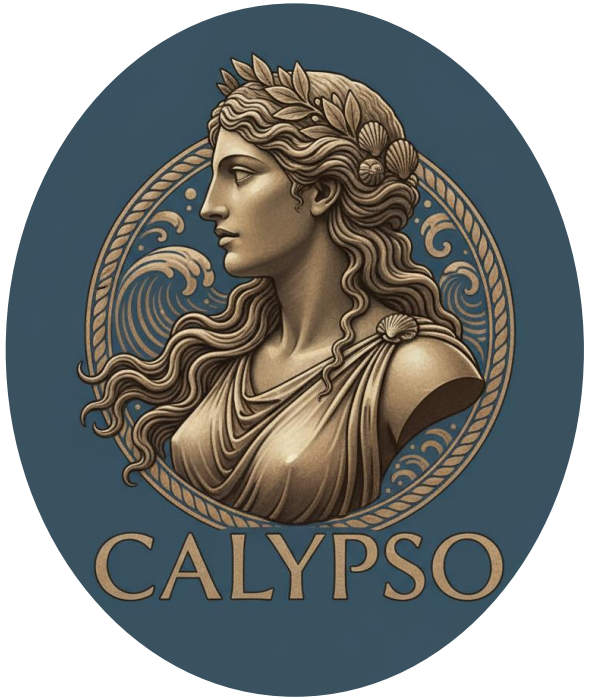
Outline

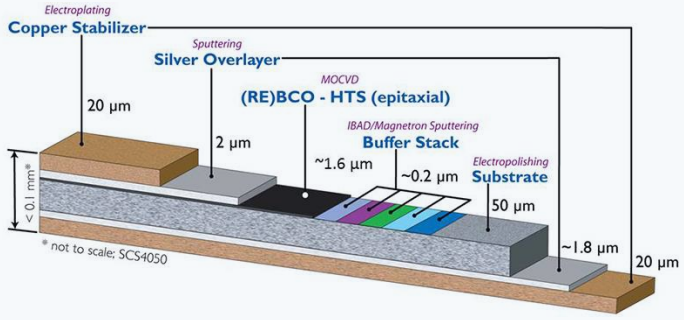
- Evolution of the CALYPSO code for HTS devices modelling
- Model description
- Application to HTS-CICC twisted stacked cables
- Simulation results and benchmarking of numerical codes
- Conclusions & Perspectives



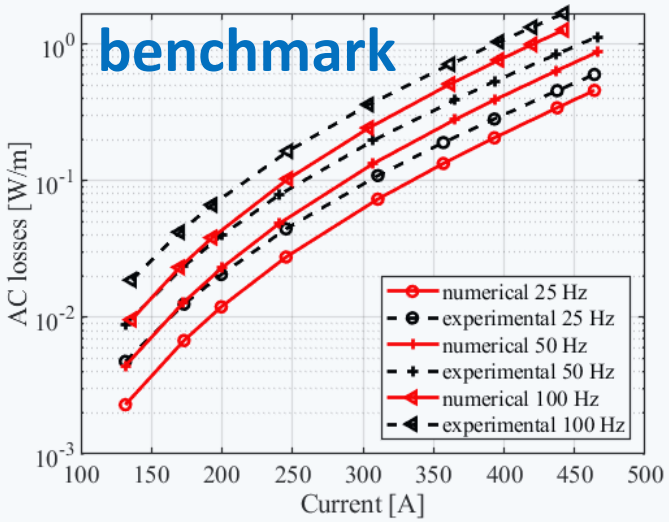
CALYPSO case study

- In recent years, the **CALYPSO** code was developed at UNIBO.

HTS tapes

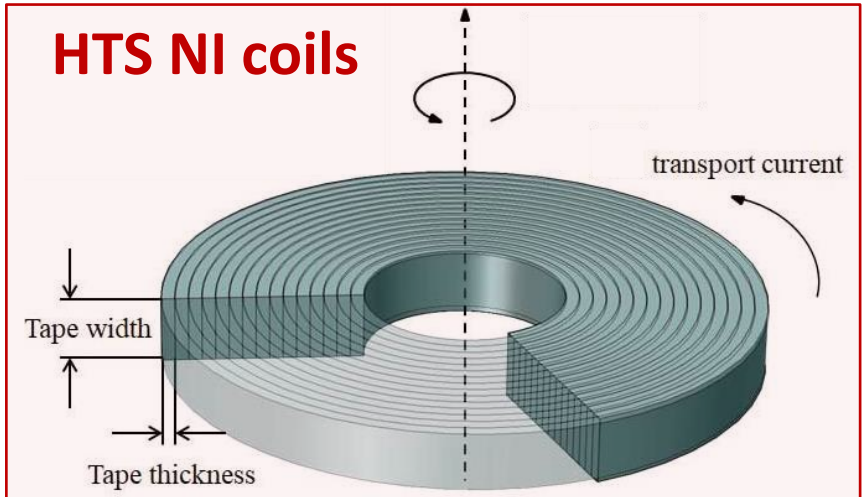


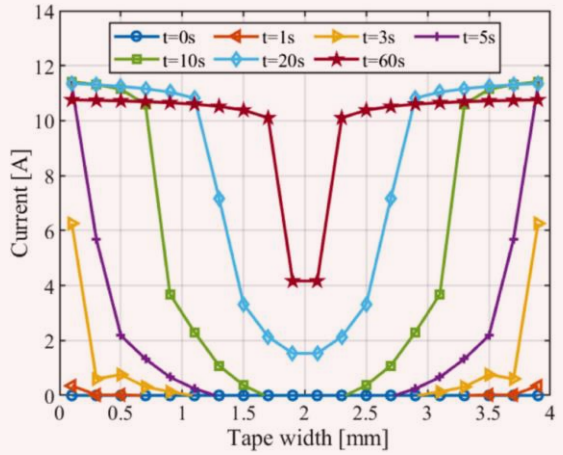
benchmark



[*] M. Breschi, et al IEEE Trans. Appl. Supercond., vol. 34, n. 3, 4604505, 2024.

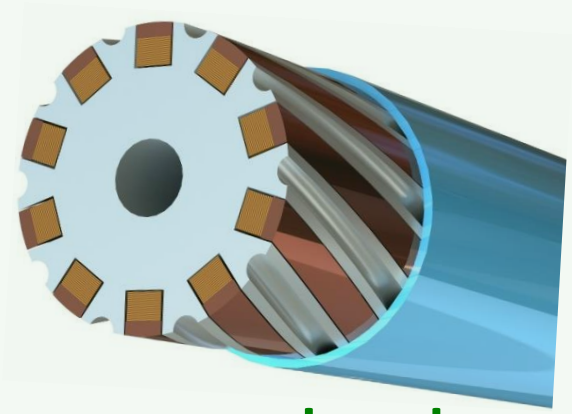
HTS NI coils



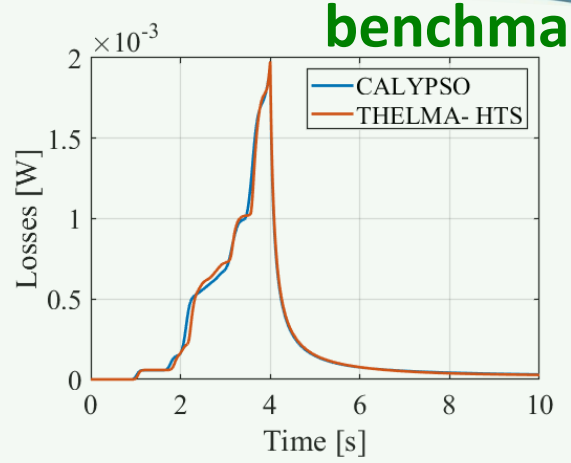


[*] M. Breschi, et al. IEEE Trans. Appl. Supercond., vol 35, n. 5, 4902305 2025.

HTS Twisted Stacked Cables



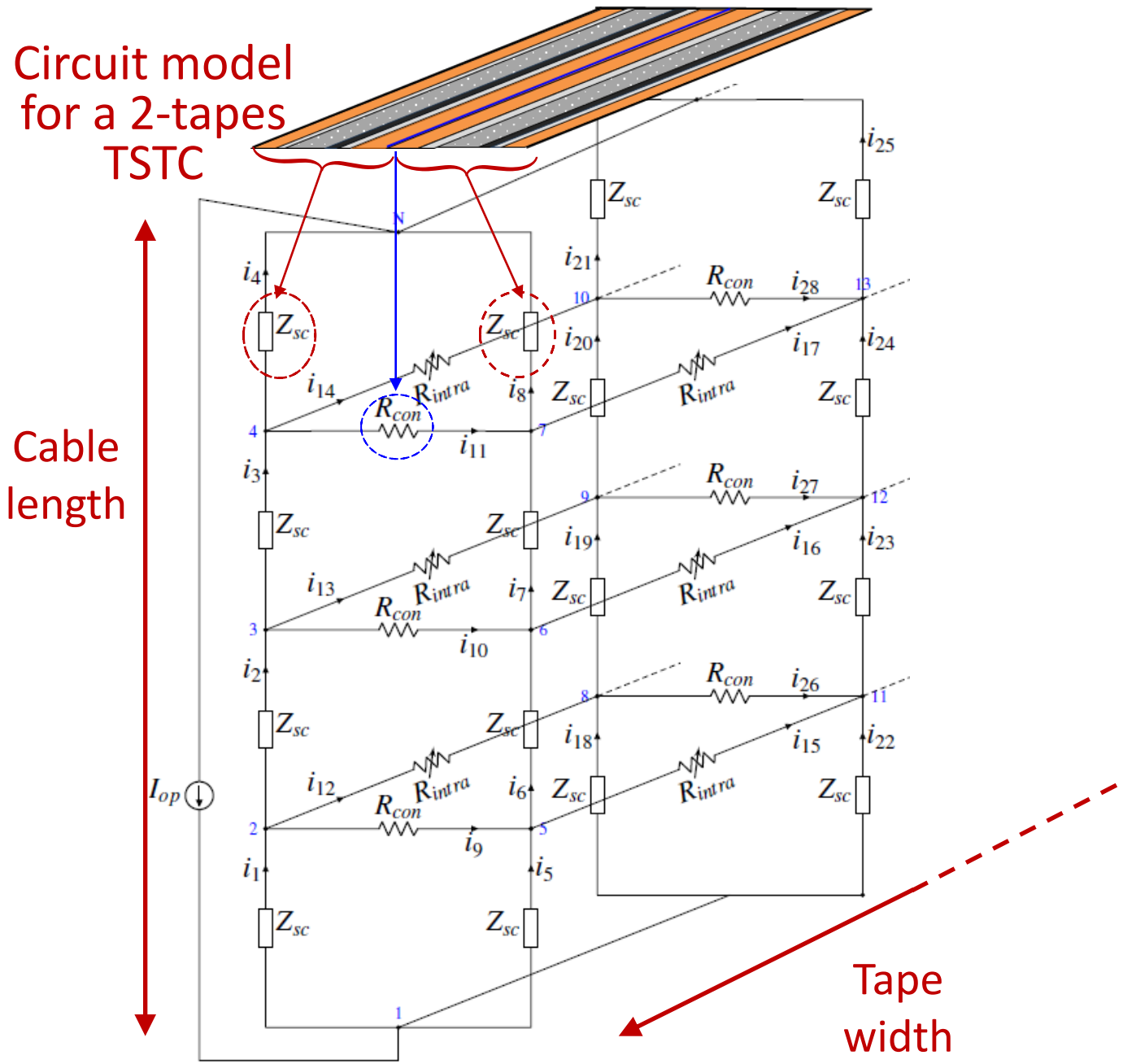
benchmark



[*] A. Macchiagodena, et al. accepted for publication on IEEE Trans. Appl. Supercond.

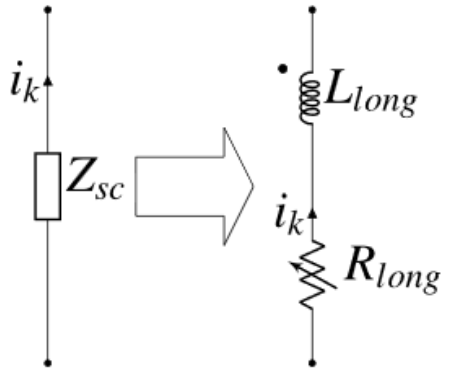
Model description (1/2)

- Each tape is **subdivided across its width** into **N_N sub-elements**.
- The tapes are further **divided along their length** into **N_D longitudinal elements.**



Model description (2/2)

- **Longitudinal elements** modeled as a superconducting element in parallel with the stabilizer and in series with an inductor.
- All inductors are **mutually coupled.**



$$\rho(J) = \frac{\rho_n \rho_{sc}(J_{sc})}{\rho_n + \rho_{sc}(J_{sc})}$$

$$\frac{\rho_n}{E_c}(J - J_{sc}) - \left(\frac{J_{sc}}{J_c}\right)^n = 0$$

$$\rho_{sc} = \frac{E_c}{J_c}\left(\frac{J_{sc}}{J_c}\right)^{n-1}$$

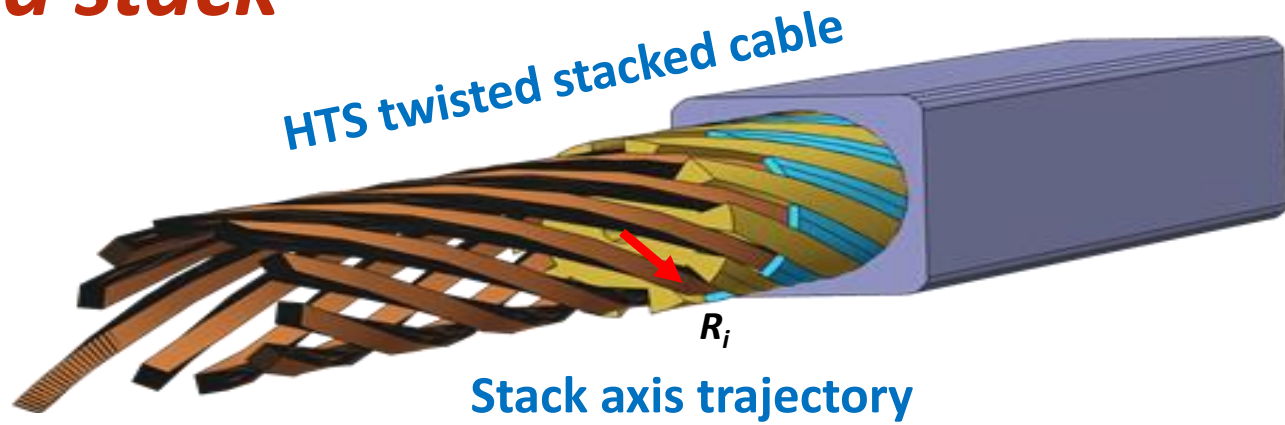
- Numerical calculation of the **mutual inductance matrix.**
- Integration over the cross-section of the superconducting layer of the longitudinal elements, and along the **local axial coordinate ζ**.

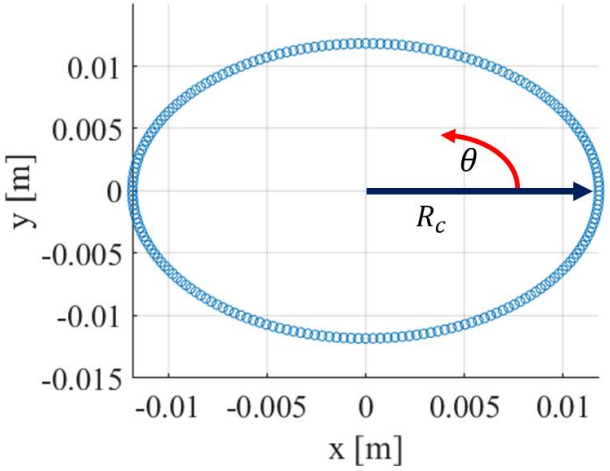
$$M_{ij} = \iiint_{V_i} \boldsymbol{J_i} \cdot \boldsymbol{A_j}\, dV = \int_{\zeta_i} \iint_{S_i} \boldsymbol{J_i} \cdot \boldsymbol{A_j}\, dS d\zeta$$

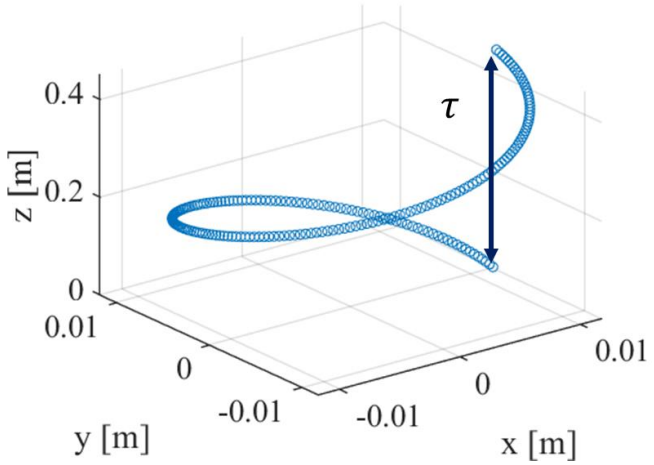
Analysis of REBCO tapes twisted stack

- The CALYPSO model was applied to the study of **one twist pitch** of an HTS-CICC with twisted stacked configuration.

- CALYPSO was benchmarked against the results of the **validated THELMA code** developed at UNIBO [*], and a **2D COMSOL model** (*T-A formulation*).







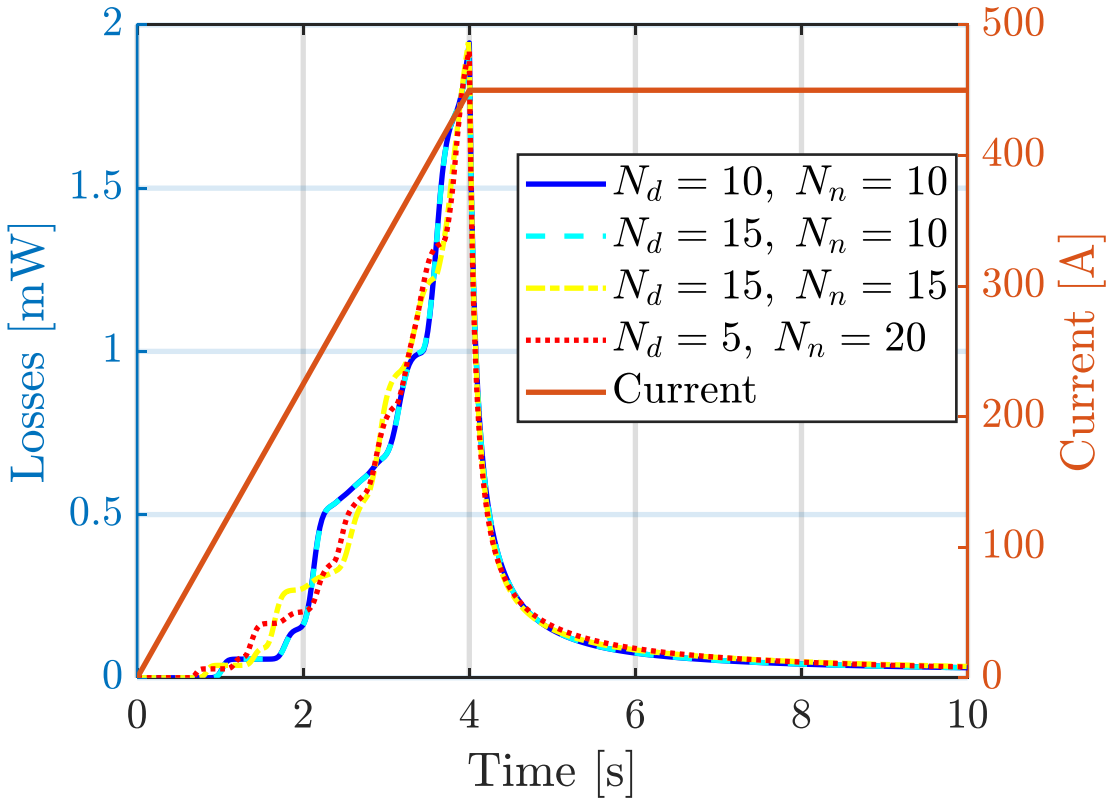
Tape thickness t_{tape} [µm]	Superconductor thickness t_{sc} [µm]	Tape Width w [mm]	I_c tape [A]	n index [-]	Twist Pitch τ [m]	Number of tapes N [-]	Number of twist pitches N_p [-]	Bending Radius R_i [cm]	Contact conductivity [S/m]
150	1.5	4	120	40	0.45	5	1	1.25	$2.22\ 10^6$

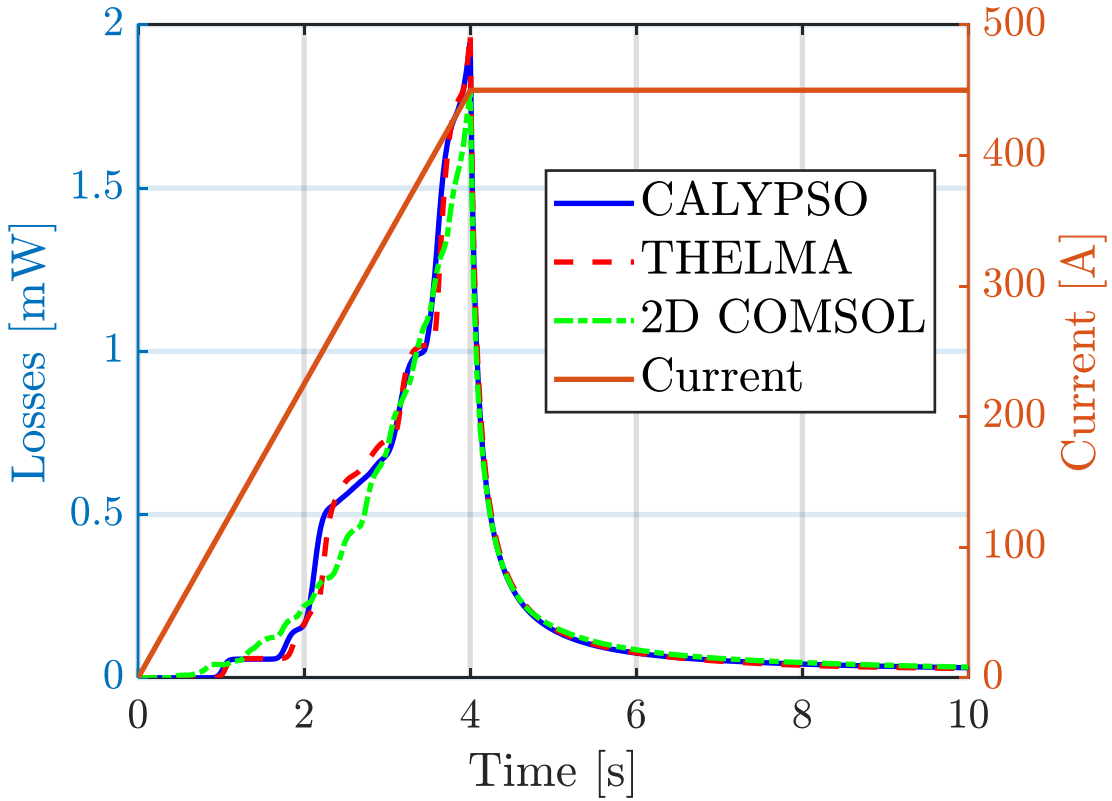
[*] P. Ribani, et al "Thelma code analysis of bronze route Nb_3Sn strand bending effect on Ic," IEEE trans. on app. Supercond., vol. 16, no. 2, 2006.

Model benchmark

Case study

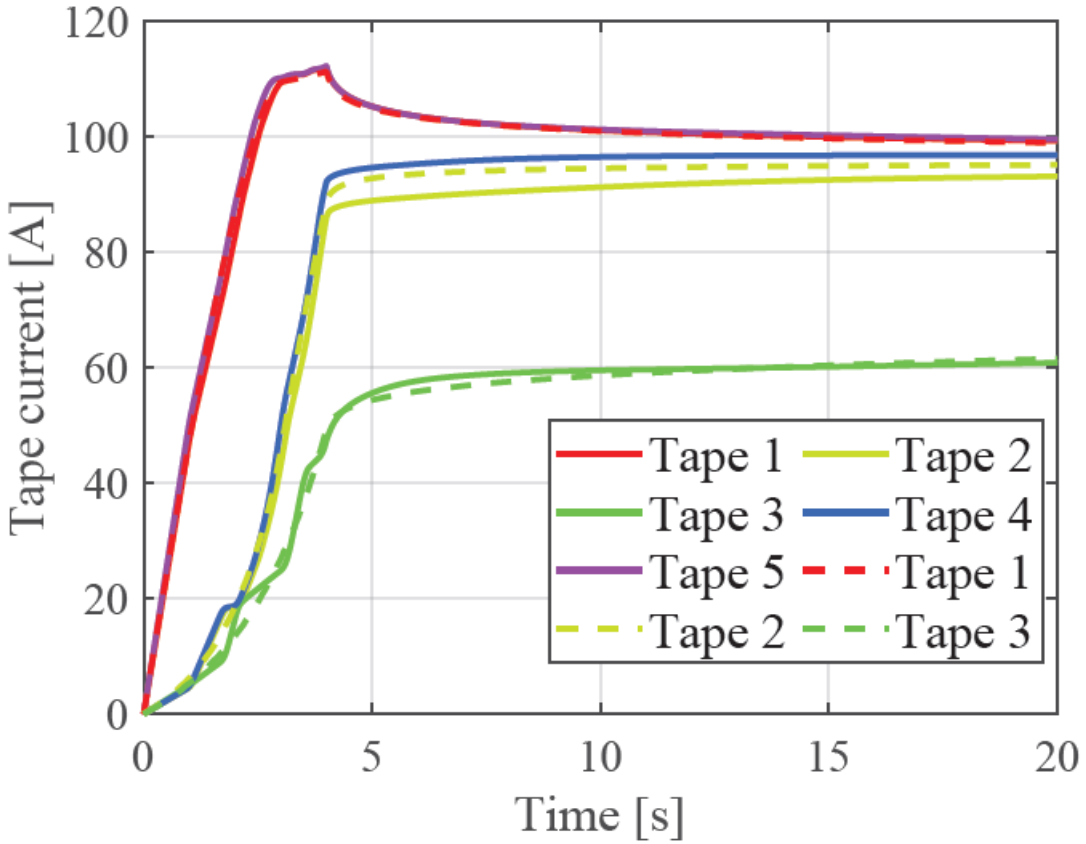
- A set of simulations was performed with a **transport current ramp** up to 75 % of the stack critical current (450 A) **in 4 s**, followed by a **current plateau of 196 s**.
- J_c is kept **constant** throughout the simulation.

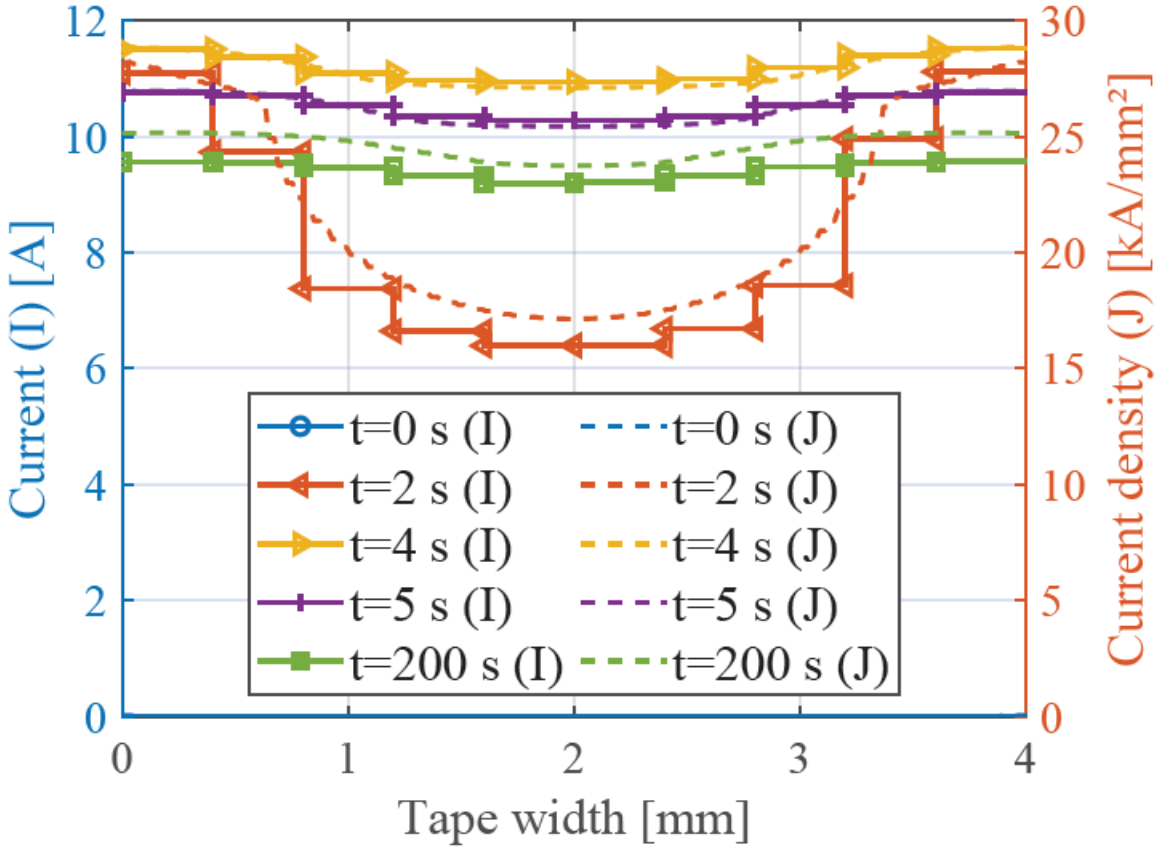




Current distribution inside the tape/stack

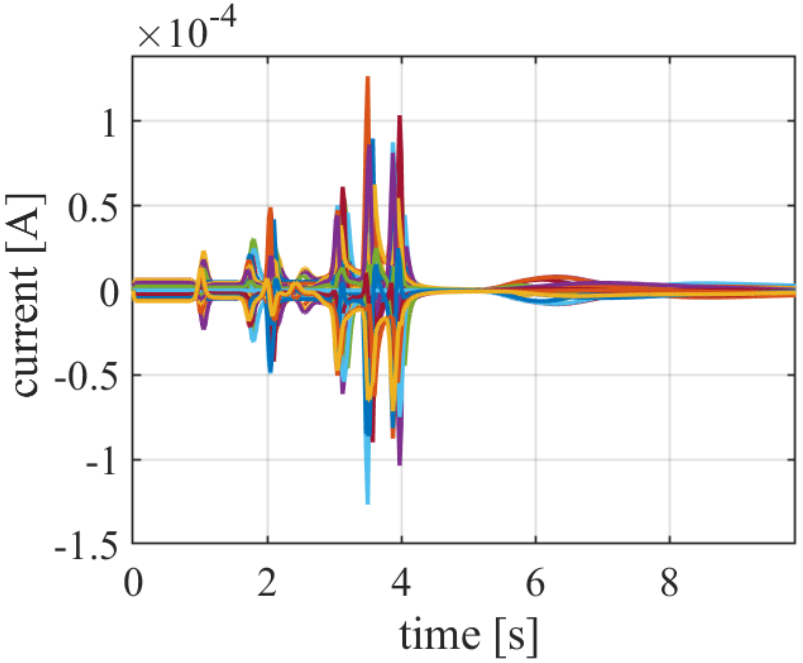
- Within each tape, a larger fraction of the transport current concentrates **near the edges.**
- In the stack, tapes in the **outermost position** exhibit higher current levels.
- **Uneven current distribution** between the tapes persists even after 200 s.



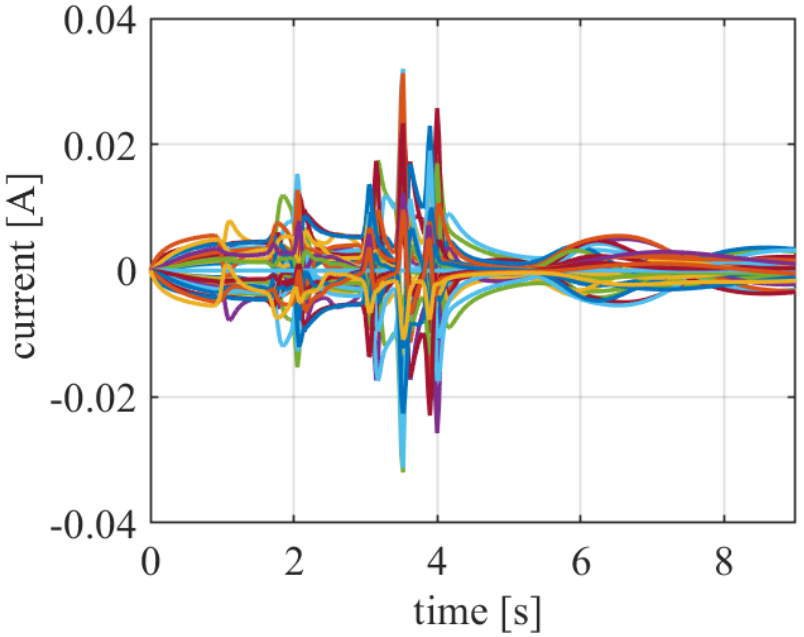


Losses dependence on contact resistance

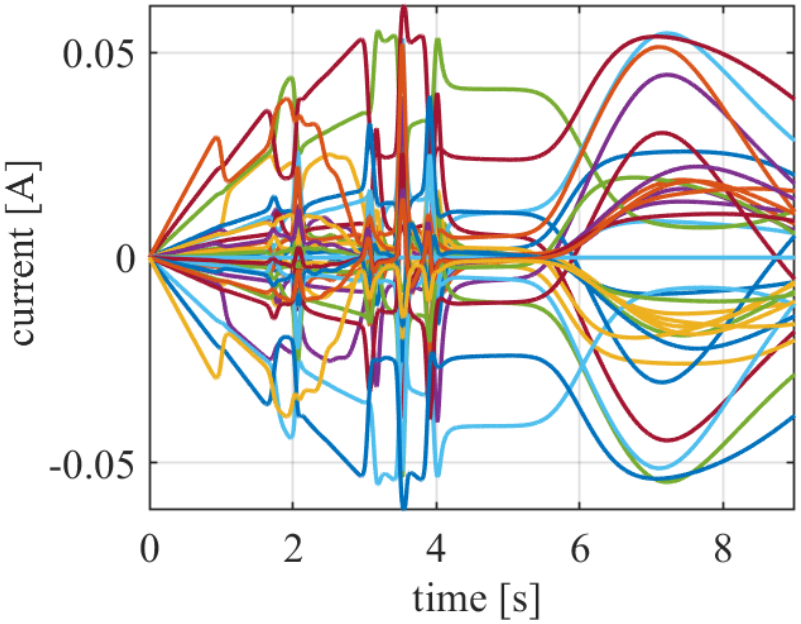
- The **current in the contact resistances** between tapes increases with the contact conductance.
- The impact of the **coupling losses between tapes** on the total losses is, however, **negligible**.



Reference case



Contact resistance x 10^{-3}



Contact resistance x 10^{-6}

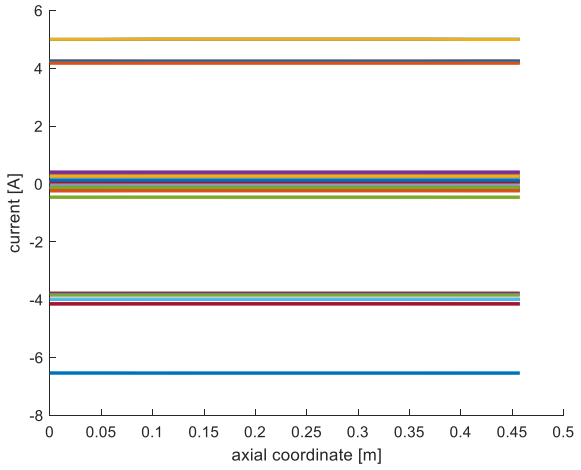
External magnetic field

- **External magnetic** fields are **incorporated** into the model through inductive coupling with **three large solenoids**, which reproduce the three components (Bx, By, Bz) of the desired magnetic field. Two cases were investigated, field parallel/orthogonal to the cable axis, without transport current.

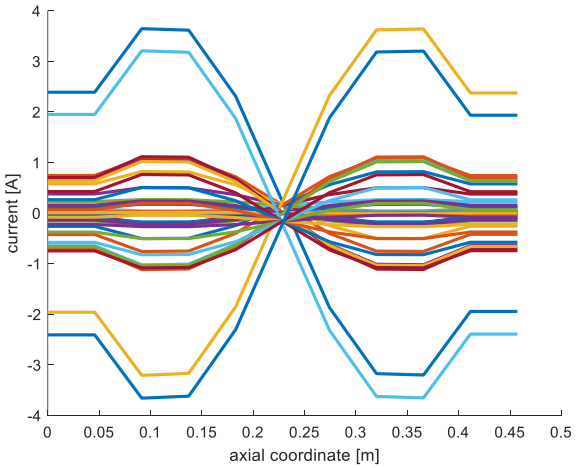
- Mutual inductances have also been introduced for the **non-longitudinal** elements. These **mutual inductances** are only between the **considered elements and the external solenoids**.

THELMA results

Parallel field

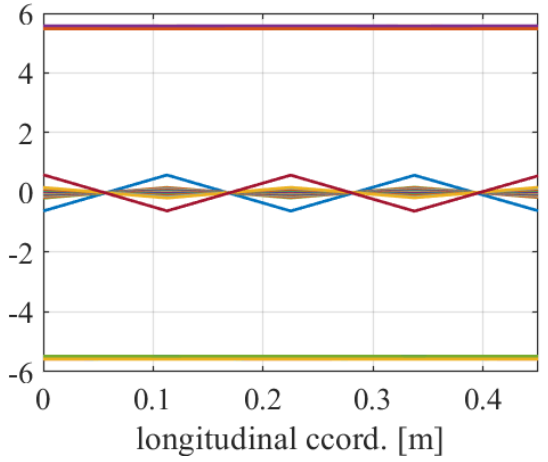


Orthogonal field

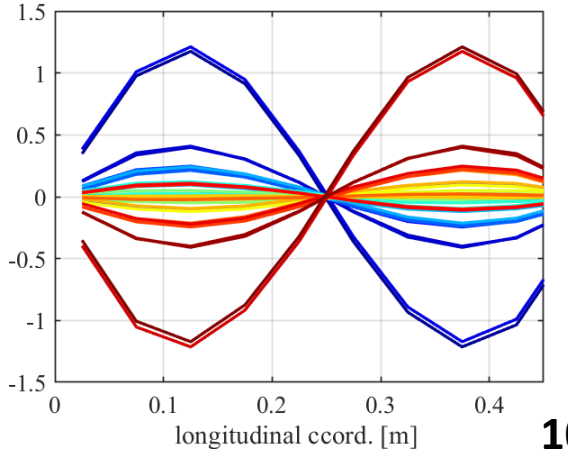


CALYPSO results

Parallel field



Orthogonal field



Conclusions & Perspectives

- The **CALYPSO code** developed at UNIBO was adapted to compute AC losses during electrodynamic transients in twisted stacked conductors.
- The model computes both the **magnetization currents flowing in individual tapes and the transverse currents** flowing from tape to tape.
- **CALYPSO results were successfully benchmarked** against those of the **THELMA** code and of a **2D COMSOL** model.
- The simulations indicate that the **losses during the transport-current plateau** are not negligible with respect to those computed during the ramp-up phase and should therefore be included in loss estimations.
- The **introduction of an external time varying magnetic** field in the model was completed. Given some discrepancies with other models, **further investigations are required** on the updated model and results.

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Thank you for your kind attention !

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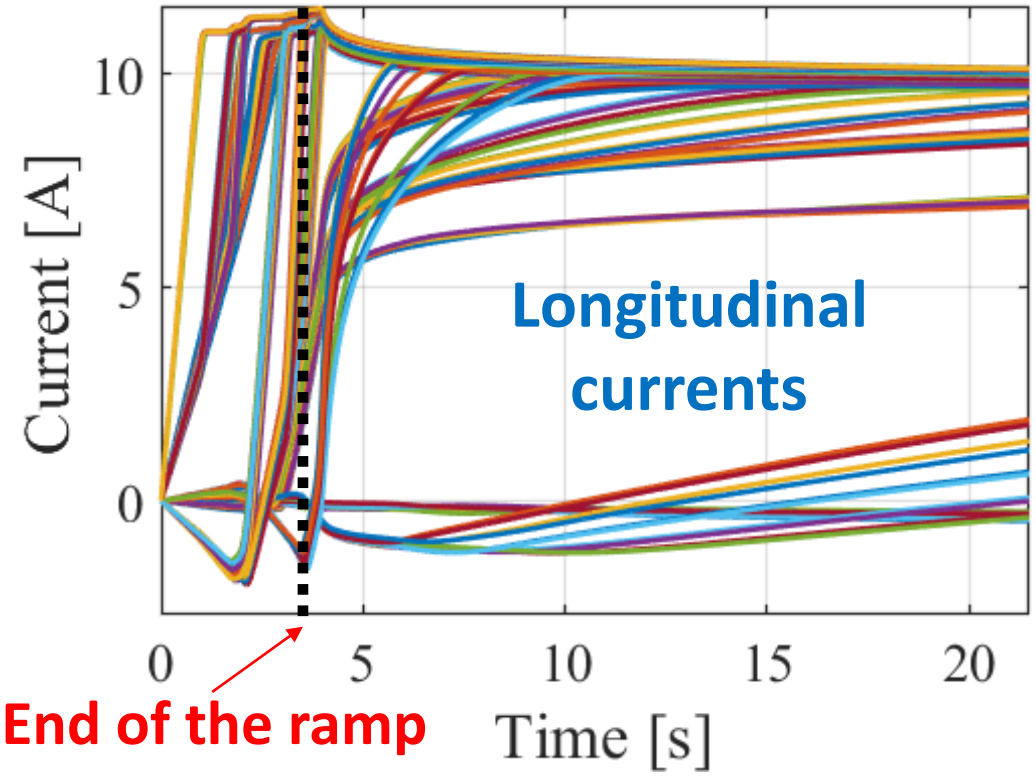
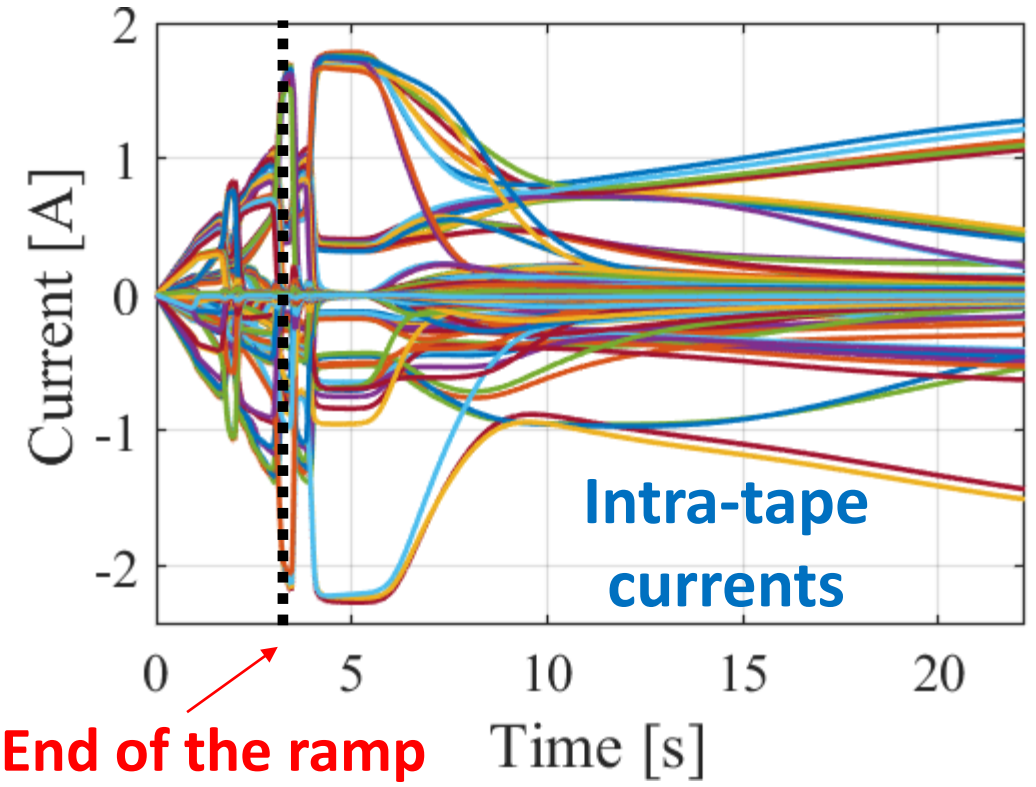
Results on HTS twisted stack (2/3)

- Convergence is reached with at least **10 elements across the tape width** and **10 along the twist pitch.**
- While analytical models predict zero losses during the plateau, simulations show **magnetization losses during the plateau** comparable to those of the ramp-up.