Analysis of electrodynamic losses in LTS and HTS conductors for fusion magnets

M. Breschi, L. Cavallucci, A. Macchiagodena

Alma Mater Studiorum - Università di Bologna, Italy

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

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Outline

- Loss mechanisms in technical superconductors
- Models for AC loss computation in LTS magnets
- Model for AC loss computation in HTS magnets
- Comparing losses in LTS and HTS magnets: ITER CS module as a case study
- Conclusions

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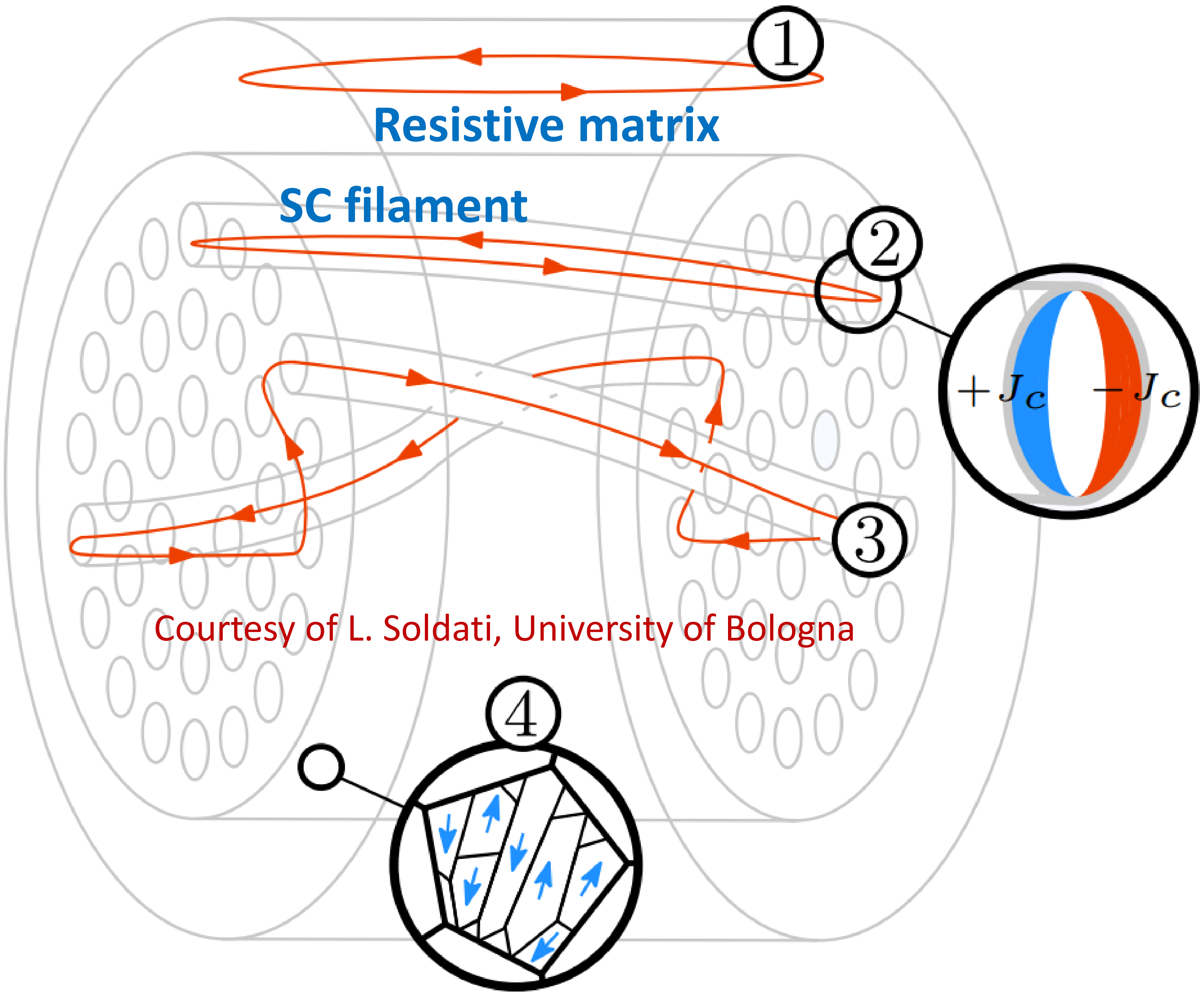
Loss mechanisms in technical superconductors (1/3)

1) Eddy current losses

- Caused by currents induced in normal metals: important contribution in the high frequency range

2)Hysteresis losses in superconducting filaments

- Caused by the non – linear, hysteretic behavior of the SC material



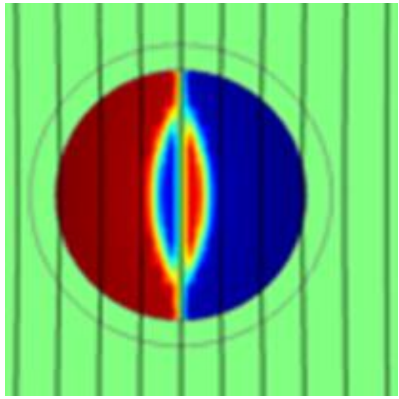
Courtesy of L. Soldati, University of Bologna

Loss mechanisms in technical superconductors (2/3)

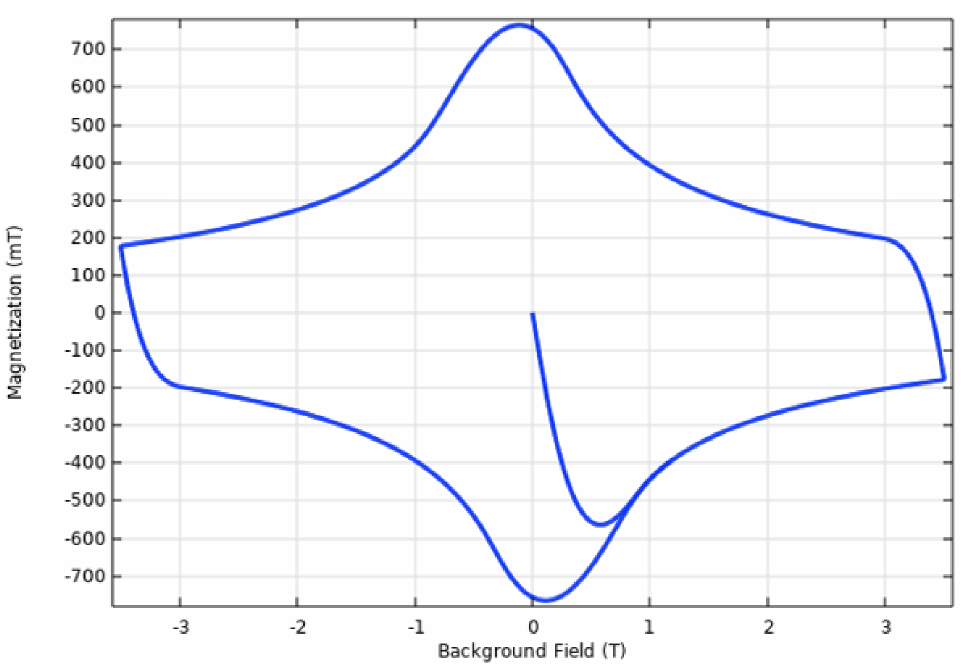
2) Hysteresis losses in superconducting filaments/layers

- In LTS wires, magnetization currents flow in filaments of **3-50 µm** size.
- In 2nd generation REBCO tapes currents flow over the whole tape width (**2 - 12 mm**).

SC filament

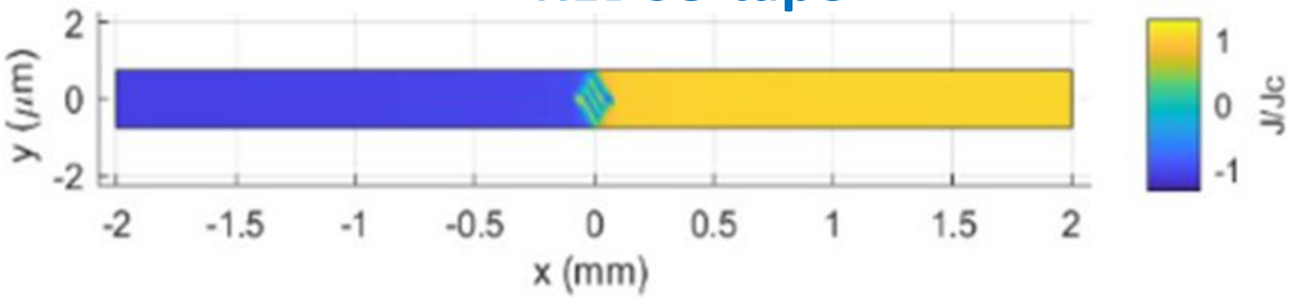


Courtesy of B. Bordini (CERN, Switzerland)



Courtesy of B. Bordini (CERN, Switzerland)

REBCO tape



[*] A. Musso, PhD Thesis, University of Bologna, 2021

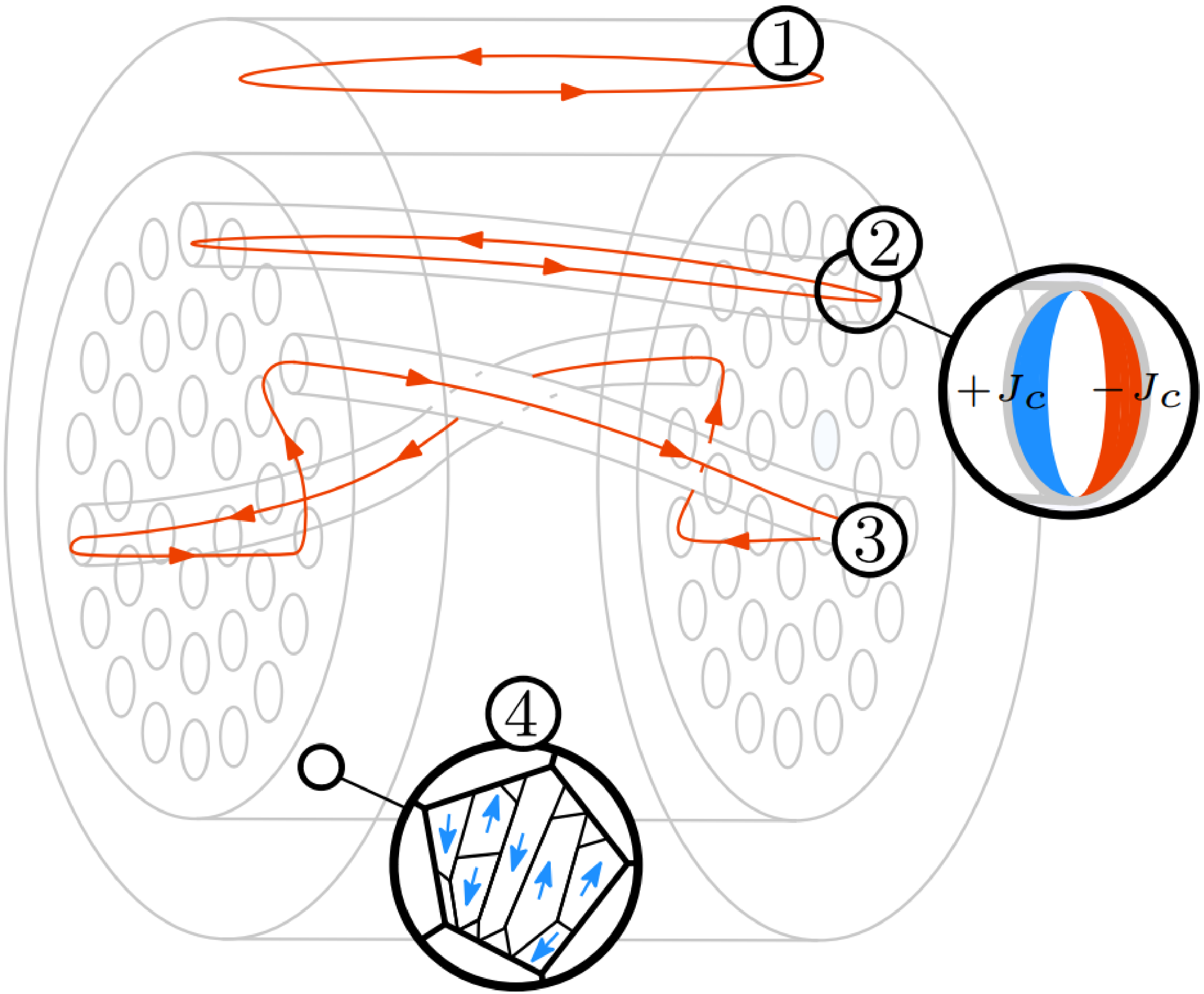
Loss mechanisms in technical superconductors (3/3)

3) Coupling losses

- Currents flowing between SC filaments (through normal metal matrix in a wire) or different SC wires/tapes (through contact resistances in a cable)

4) Ferromagnetic losses

- Due to the presence of ferromagnetic materials (ex. Nickel and Monel in MgB_2)



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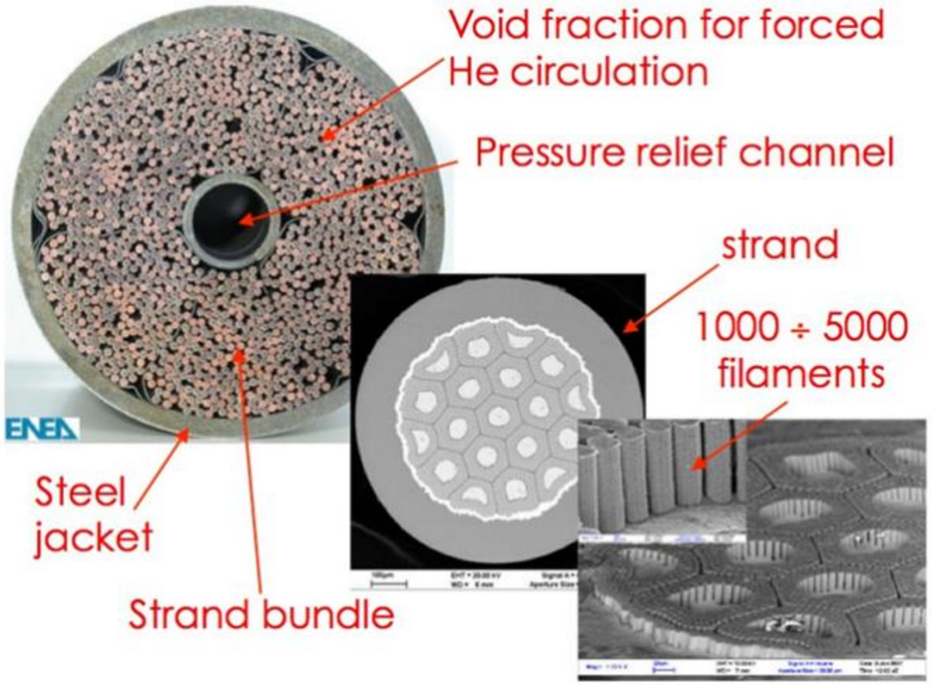
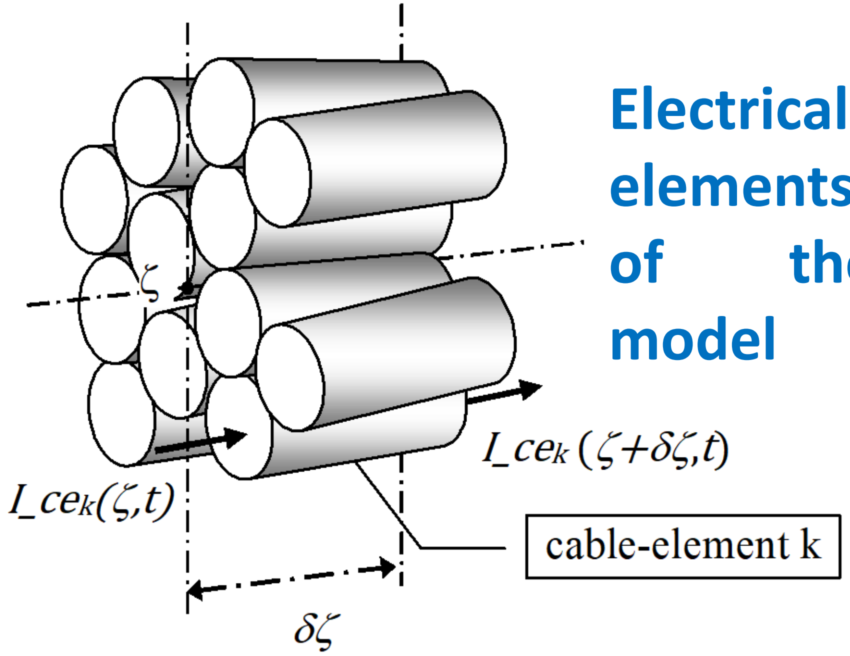
AC loss computation in LTS magnets: THELMA code

- The AC loss computation is a complex task due to the inherent **multiscale structure** of the problem

- The THELMA code is an electromagnetic model based on the **A-V formulation** [*], which computes the current distribution and losses in multistrand cables



Cable in conduit conductor (CICC)



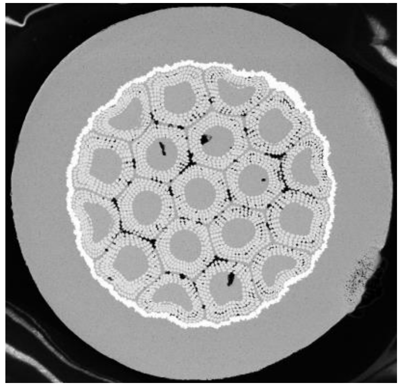
Electrical elements of the model

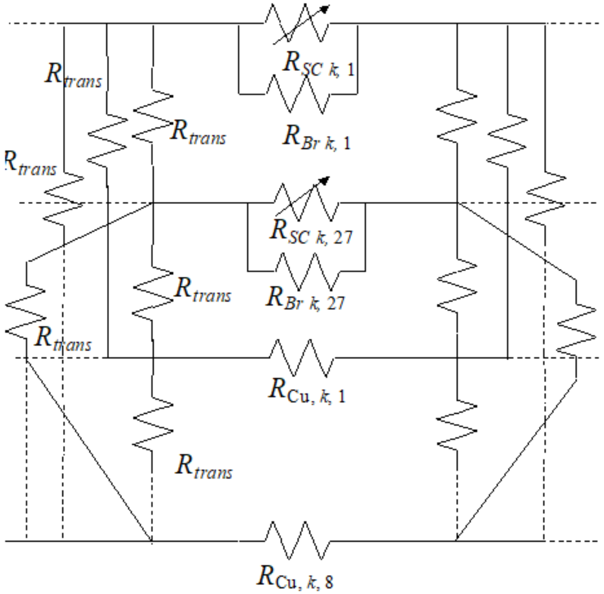
[*] M. Breschi, P. L. Ribani, IEEE Trans. Appl. Supercond., vol. 18, n. 1, pp. 18 – 28, 2008.

THELMA code application

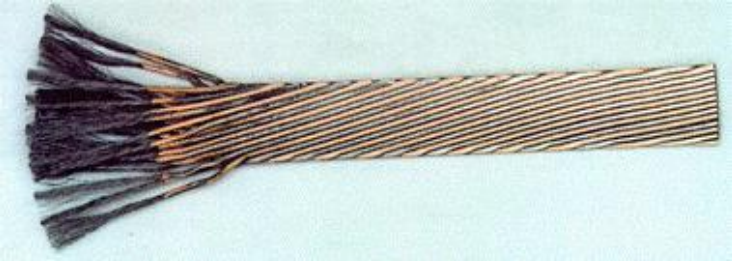
- The **THELMA code** is a powerful tool, which thanks to its **flexibility** can be applied to analyze numerous SC devices

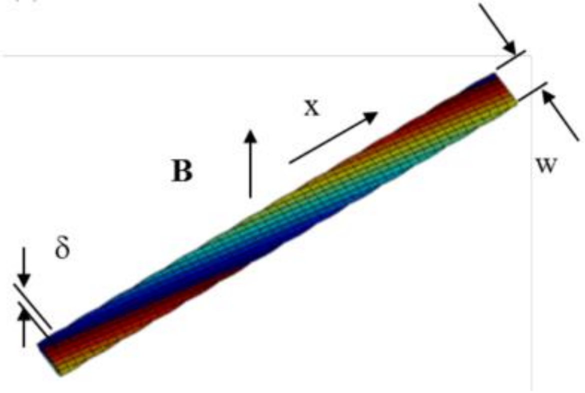
LTS wires (NbTi, Nb_3Sn, MgB_2)



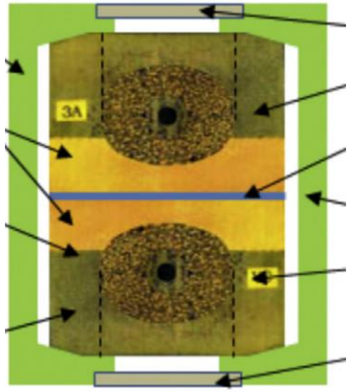


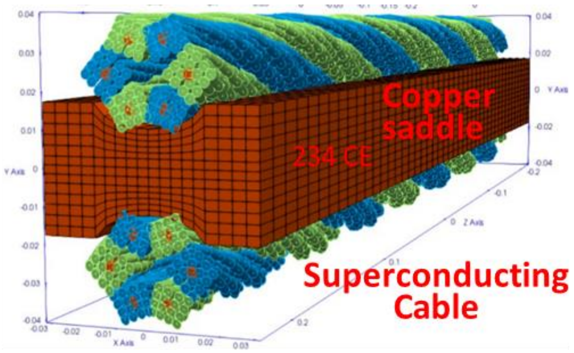
Rutherford cables



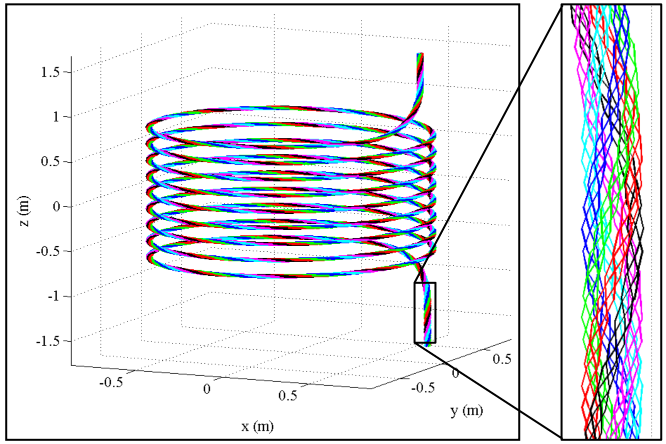


CICC Joints





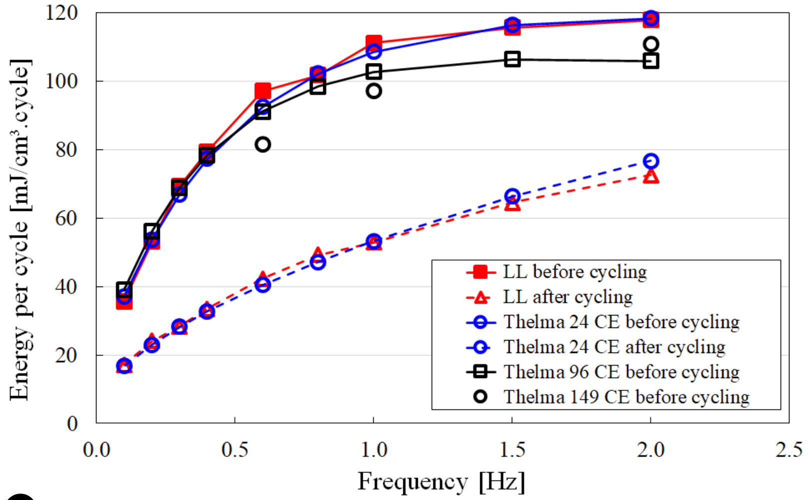
SC magnets



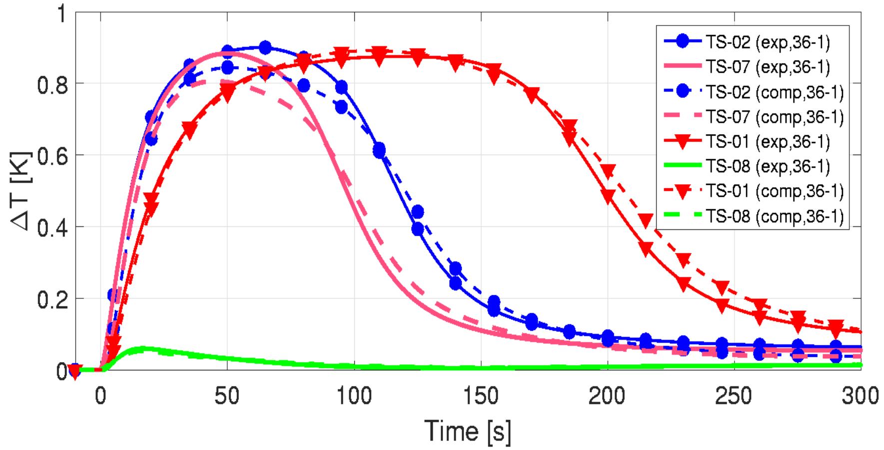
THELMA code validation

- The THELMA model was **validated** against **analytical, numerical and experimental results** in a number of configurations and conditions

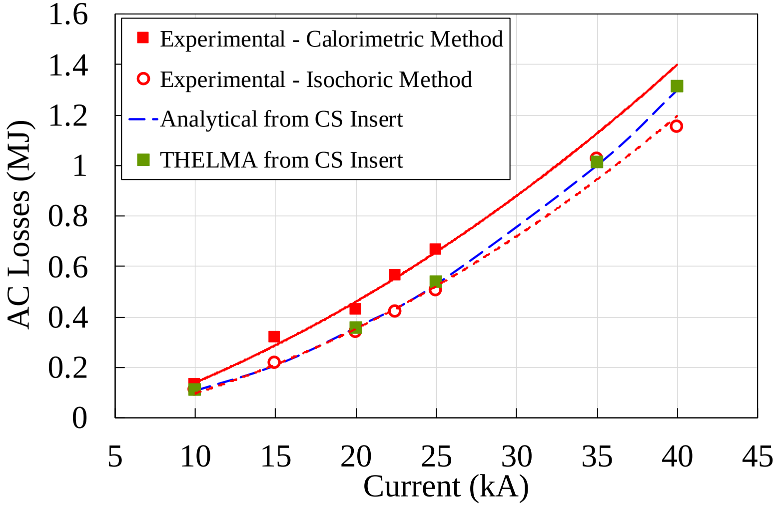
2.5 m



43 m



6 km



- AC loss **data** obtained in the SULTAN facility (SPC, Switzerland) [*]

[*] M. Breschi, et al. IEEE Trans. Appl. Supercond., vol. 28, n. 3, 5900205, 2018

- Temperature rise during AC loss test on the **ITER Central Solenoid Insert** [**]

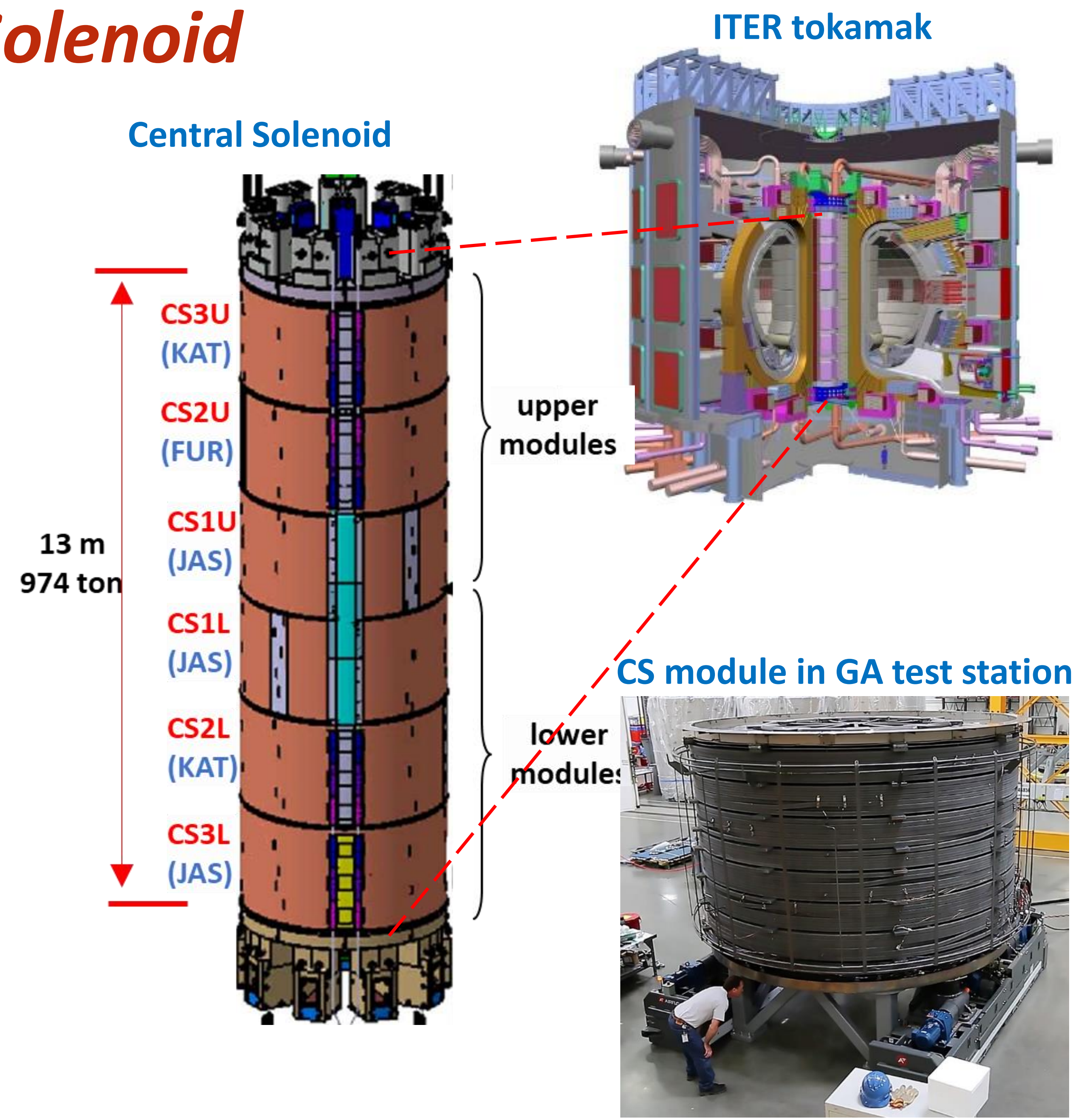
[**] M. Brschi, et al., IEEE Trans. Appl. Supercond., vol. 27, n. 4, 7762085, 2017

- AC losses of the **ITER Central Solenoid Module** [***]

[***] M. Breschi, et al., IEEE Trans. Appl. Supercond., vol. 33, n. 2, 5900212, 2022.

Case study: the ITER Central Solenoid

- For a comparison of losses between LTS and HTS conductors in a coil, we selected the **ITER Central Solenoid** (CS) as a case study
- The CS consists of 6 modules, each made of **40 pancakes** wound with a Nb_3Sn cable in conduit conductor
- The **comparison of AC losses** was performed considering the specific data of the CSM#1

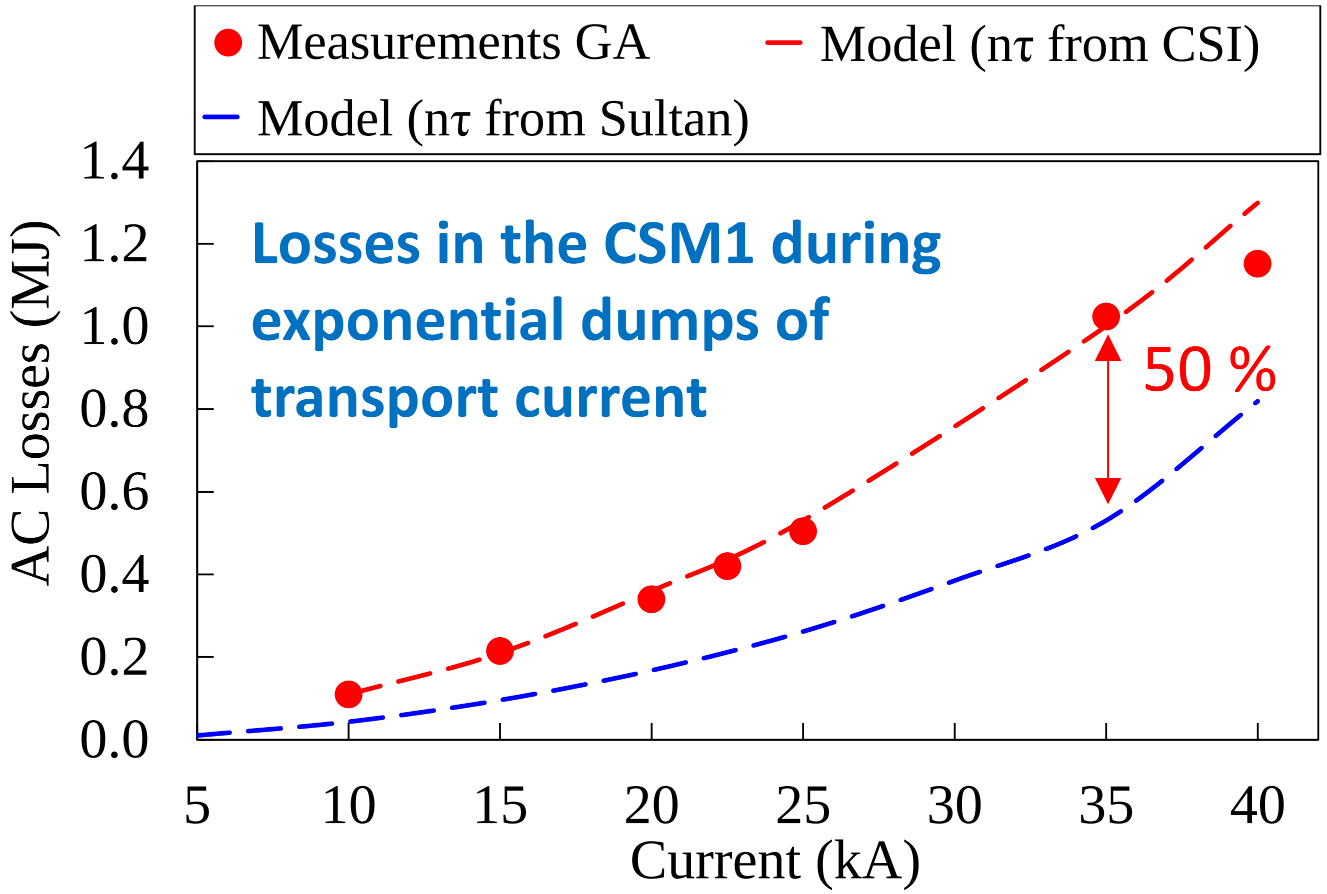


Analytical calculation of losses for LTS magnets (1/3)

- The basic **analytical model** for **coupling losses** is based on **single time constant** :

$$P(t) = \frac{n\tau}{\mu_0} \dot{B}_i^2(t)$$

- The coupling losses originally predicted from the ***nτ*** found on **Sultan samples** exhibit a discrepancy wrt experimental data on **ITER CS module #1** [*]
- Extrapolating the ***nτ*** from the test of the **CS Insert**, a 43 m long single layer solenoid, a good agreement was found [*]



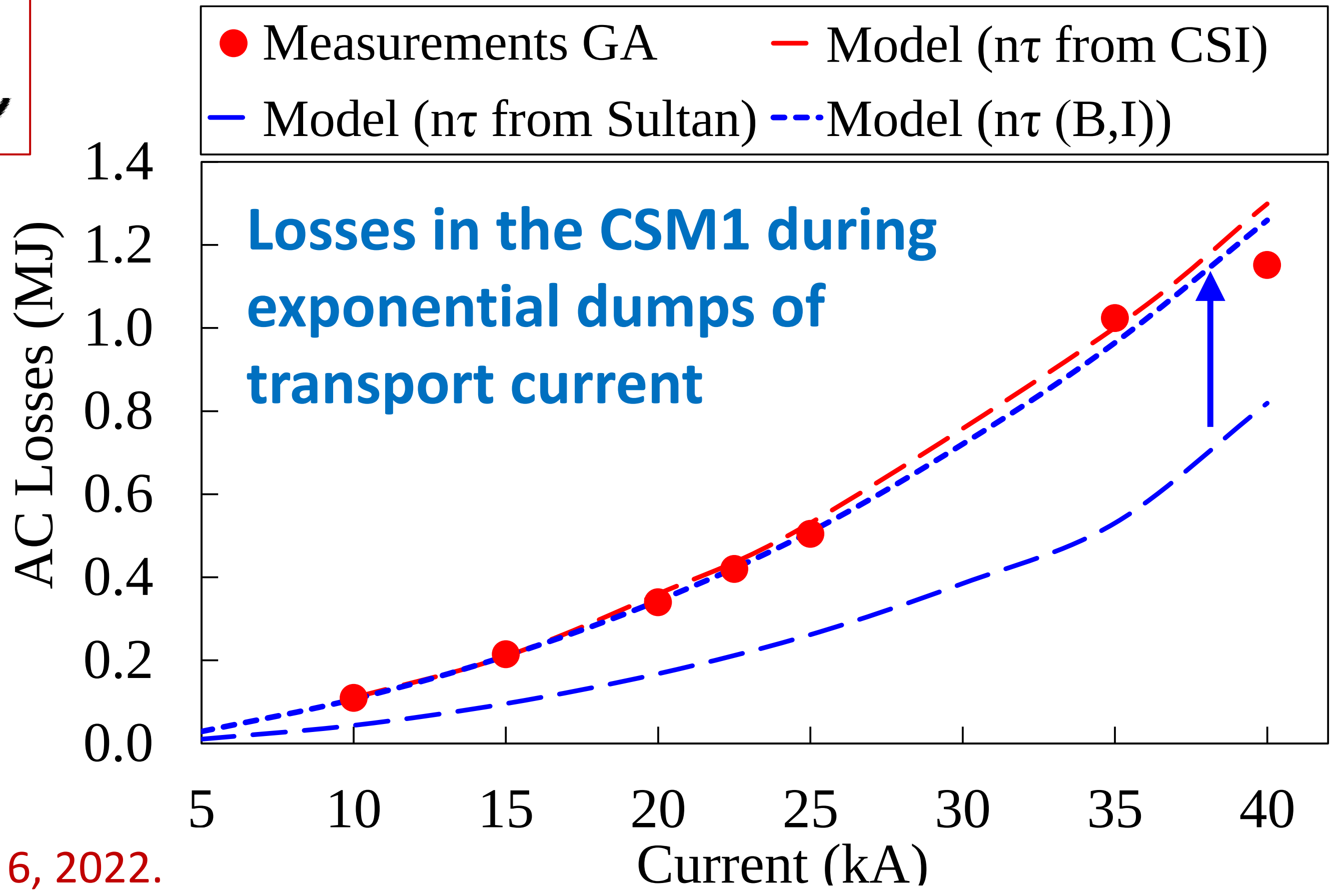
[*] M. Breschi et al., IEEE Trans. Appl. Supercond., vol. 33, no. 2, 2023.

Analytical calculation of losses for LTS magnets (2/3)

- The discrepancy found for the extrapolation from SULTAN data was resolved accounting for the impact of the **B-field** and the **Lorentz-force** on the $n\tau$ [*, **]:

$$\mathrm{n\tau[s]} = \underbrace{\mathrm{n\tau_0} - \beta \cdot B[\mathrm{T}]}_{\text{from SULTAN samples}} + \underbrace{\gamma \cdot I[\mathrm{kA}] \cdot B[\mathrm{T}]}_{\text{from Twente press}}$$

- The value of the $n\tau$ is obtained as a combination of the time constants of the multi-time constant model [***]



[*] P. Bauer et al., IEEE Trans. Appl. Supercond., vol. 32, no. 6, 2022.
[**] A. Torre et al., IEEE Trans. Appl. Supercond., vol. 32, no. 6, 2022.
[***] B. Turck, L. Zani, Cryogenics, vol. 50, pp. 443-449, 2010

Analytical calculation of losses for LTS magnets (3/3)

- The **hysteresis losses** are computed with two different formulae depending on the value of the cumulative field variation ΔB with respect to the penetration field B_p:

$$B_p = \frac{\mu_0 \, \lambda \, J_c(B,T,\varepsilon) \, d_{eff}}{\pi}$$

penetration field

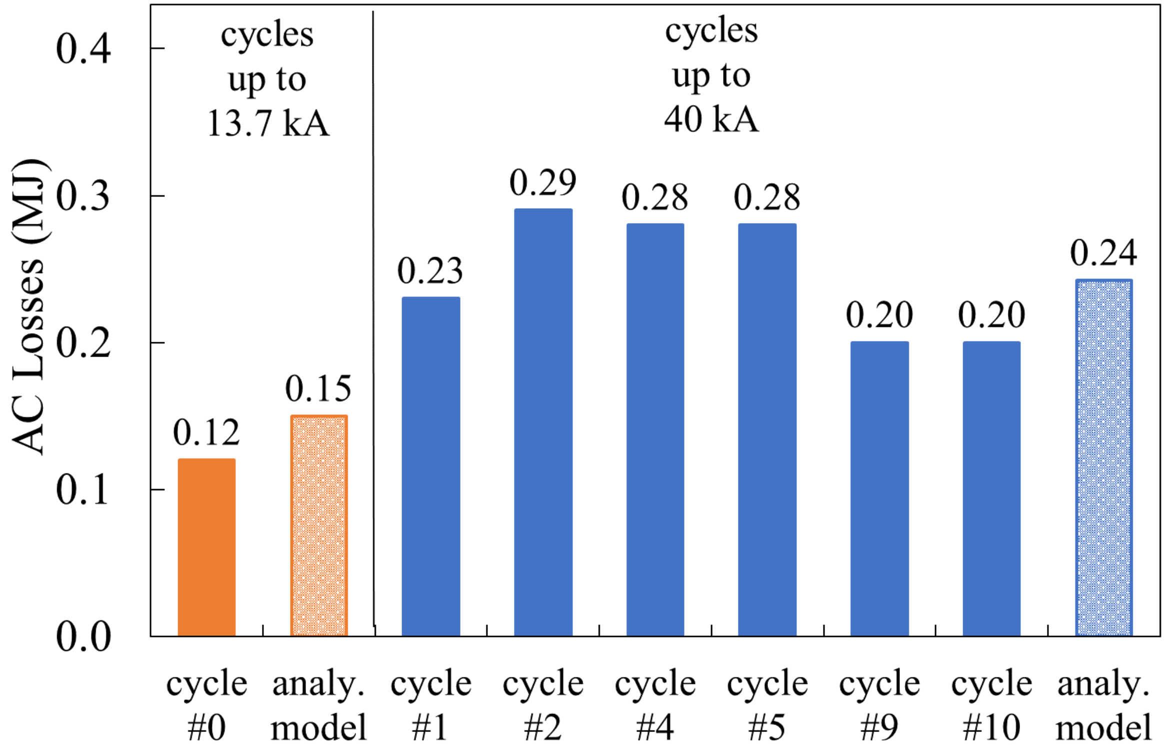
if $\Delta B_k < 2B_p$

$$P_{hys} = \frac{\pi \Delta B^2}{2\,\mu_0^2 \lambda \, J_c(B,T,\varepsilon)\, d_{eff}} \frac{dB_k}{dt} \left(1 - \frac{\pi \Delta B}{3\,\mu_0\,\lambda\, J_c(B,T,\varepsilon)\, d_{eff}}\right)$$

if $\Delta B_k > 2B_p$

$$P_{hys} = \frac{2}{3\pi} \lambda \, J_c(B,T,\varepsilon)\, d_{eff} \frac{dB}{dt}$$

Losses in CSM1 during slow current cycles



[*] M. Breschi et al., IEEE Trans. Appl. Supercond., vol. 33, no. 2, 2023, 5900212.
[**] P. Bauer et al., IEEE Trans. Appl. Supercond., vol. 32, no. 6, 2022, 4701305

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AC loss computation in HTS magnets: analytical approach

- Starting from [*] a **set of analytical formulae** to compute **hysteresis losses** in a superconducting slab was developed [**], accounting for **transport current** and **magnetic field**

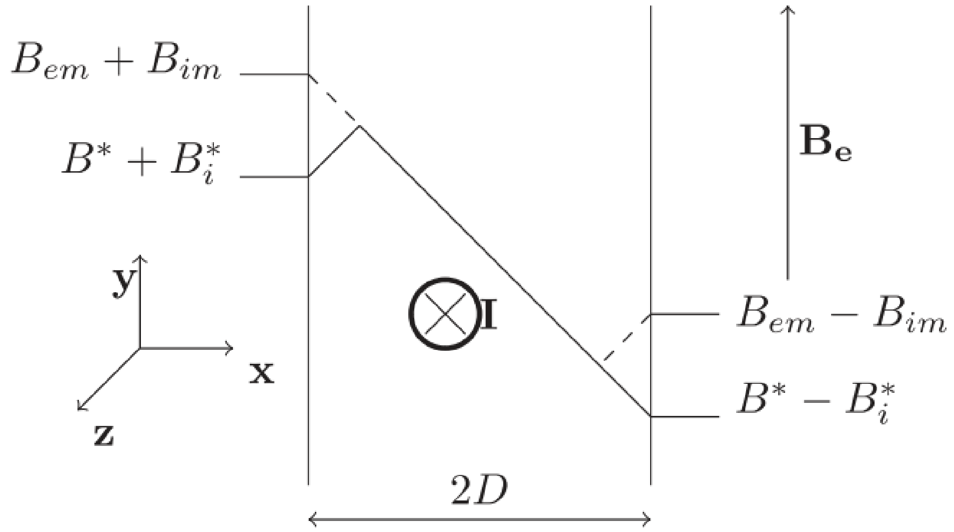
Losses per unit of volume of a slab [W/m³]

$$P = \frac{\mathrm{sgn}(\dot{I})}{16\mu_0 B_p} \begin{cases} A_1 & \text{for} \quad B_e < B_i \\ A_2 & \text{for} \quad \mathrm{sgn}(\dot{I}) B_e \leq -B_{em} \left(\frac{B_{em}+B_{im}-2B_p}{B_{em}-B_{im}} \right) \\ A_3 & \text{for} \quad \mathrm{sgn}(\dot{I}) B_e > -B_{em} \left(\frac{B_{em}+B_{im}-2B_p}{B_{em}-B_{im}} \right) \end{cases}$$

$$A_1 = (\dot{B}_e + \dot{B}_i)\left(B_{em} + B_{im} + \mathrm{sgn}(\dot{I})(B_e + B_i)\right)^2 - (\dot{B}_e - \dot{B}_i)\left(\mathrm{sgn}(\dot{I})(B_{im} - B_{em}) - B_e + B_i\right)^2$$

$$A_2 = (\dot{B}_e + \dot{B}_i)\left(B_{em} + B_{im} + \mathrm{sgn}(\dot{I})(B_e + B_i)\right)^2 + (\dot{B}_e - \dot{B}_i)\left(\mathrm{sgn}(\dot{I})(B_{im} - B_{em}) - B_e + B_i\right)^2$$

$$A_3 = 4{B_p}^2 \left[(\dot{B}_e + \dot{B}_i)\left(1 + \mathrm{sgn}(\dot{I})\frac{B_i}{B_p}\right)^2 + (\dot{B}_e - \dot{B}_i)\left(1 - \mathrm{sgn}(\dot{I})\frac{B_i}{B_p}\right)^2 \right]$$



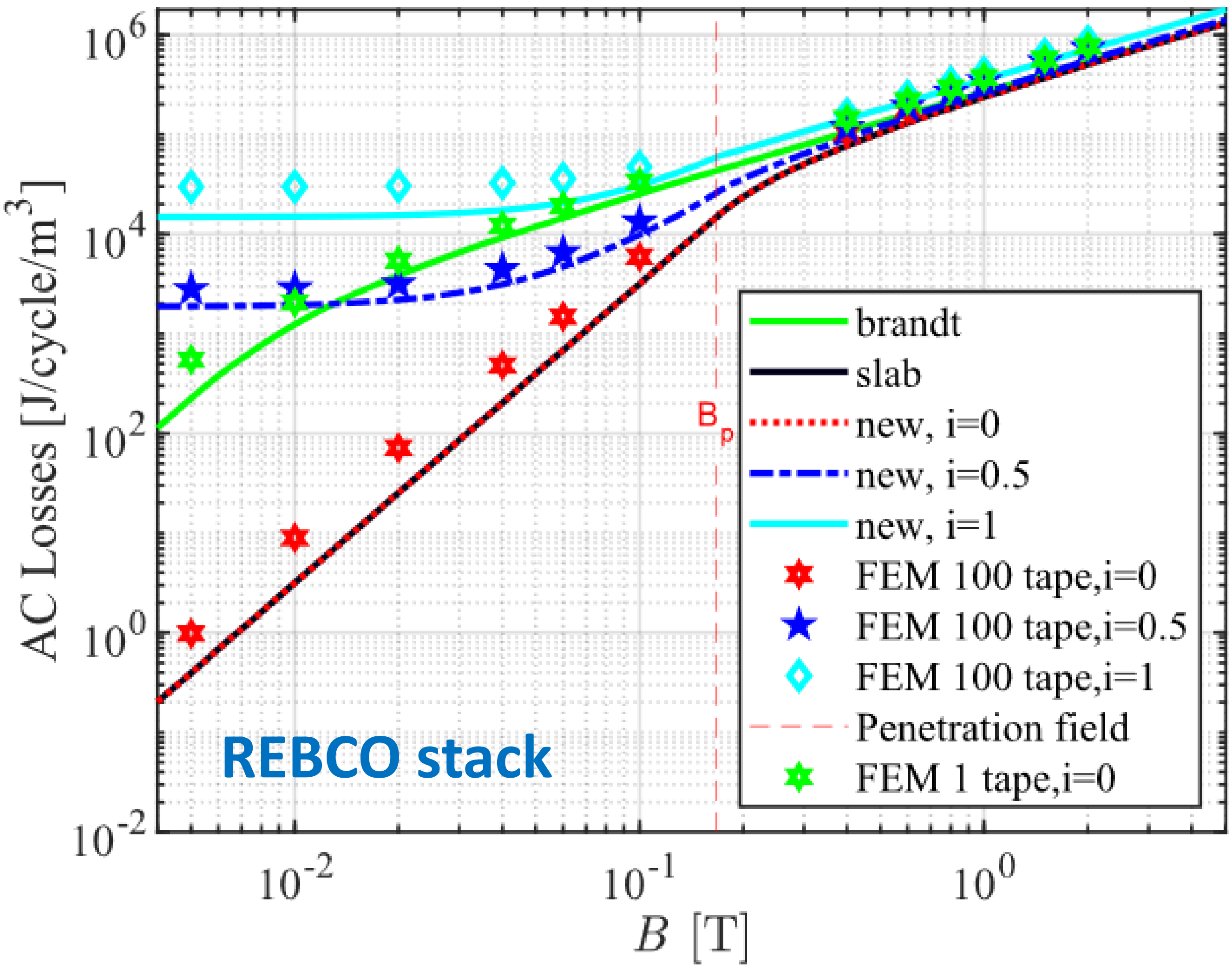
Superconducting slab

Total losses [W]

$$Q \approx Q_{\perp} + Q_{\parallel}$$

[*] K. Kajikawa et al., Cryogenics, vol. 80, no. 2, pp. 215-220, 2016.
[**] A. Macchiagodena et al, IEEE Trans. Appl. Supercond., vol. 33, n. 5, 2003, 5900705.

AC loss computation in HTS magnets: model validation



- The analytical model was validated by comparison **with a 2D FEM** model based on the H-formulation
- Computations performed for a **100-tape stack** subjected to 50 Hz sinusoidal transport current and orthogonal applied field [*]
- The **impact of transport current on hysteresis losses** in a REBCO stack is significant

[*] A. Macchiagodena et al, IEEE Trans. Appl. Supercond., vol. 34, n. 3, 2024, 8200305.

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Comparing losses in the ITER CS module as a case study

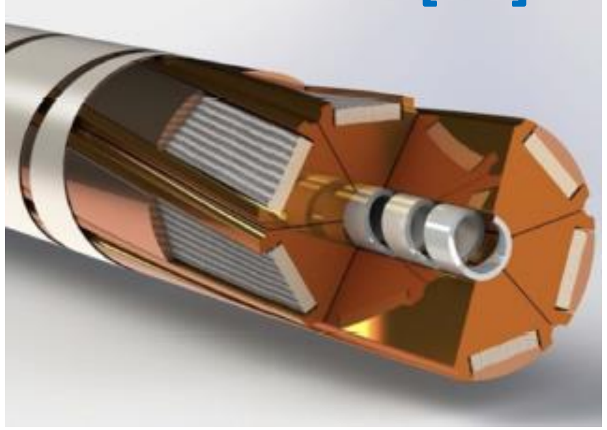
- The LTS cable is the **ITER CS conductor**, consisting of 576 SC strands and 288 Cu strands wound in 5 stages [*]
- The HTS cable is a SECtor-ASsembled (SECAS) conductor based on BRAided STacks (BRAST), obtained **scaling down the design of the DEMO CS-conductor** (ENEA) [**]
- The same **ratio of transport to critical current** of the DEMO CS conductor was kept, adapting the cable to the **ITER CS magnet operating conditions**

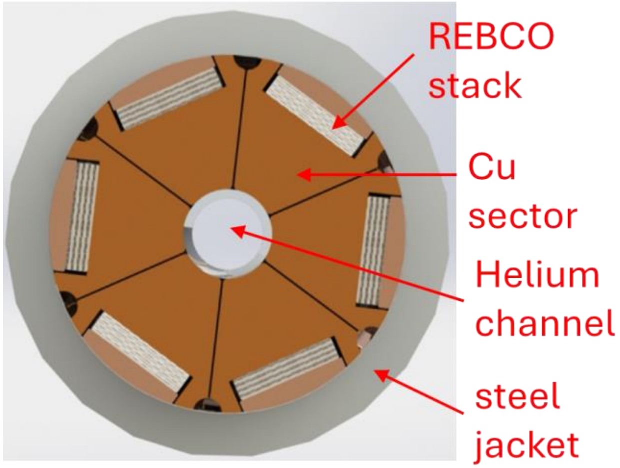
ITER CS, 45 kA, 13 T, 4.5 K

ITER LTS cable

ENEA HTS SECAS cable [**]

EU DEMO, 60 kA, 18 T, 4.5 K

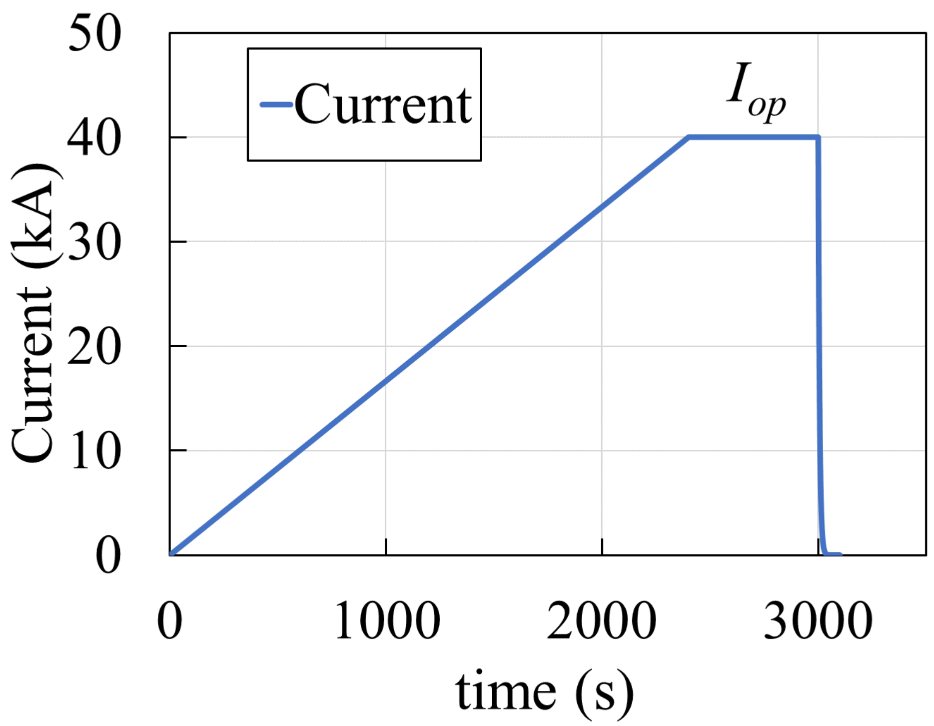


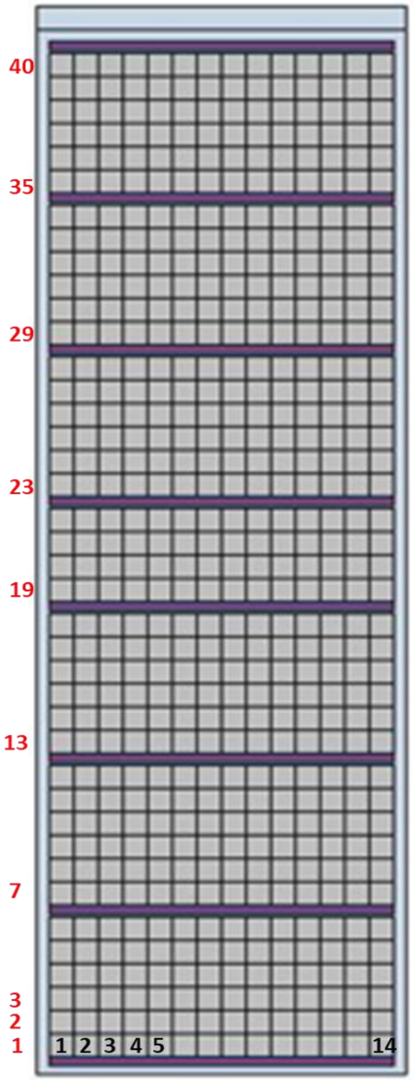


[*] M. Breschi., et al. in Superconductor Science and Technology, 2023, 36, 035007
[**] L. Muzzi et al., in IEEE Trans. Appl. Supercond., vol. 33, no. 5, 2023, 4200106

Comparing losses in LTS and HTS magnets: simulation data

- The designed HTS conductor includes **6 stacks of 21 REBCO tapes, 4 mm wide**, embedded in a braid of copper wires (to be compared with 6 stacks of 25 tapes, 12 mm wide, of the DEMO conductor)
- The **outer radius** of the HTS cable was kept at the value of the previous CS ITER conductor
- The AC losses were computed during a **cycle of the transport current**, **from 0 kA to I_{op}** with a ramp-rate of 1 kA/min, followed by an **exponential dump**





Comparing losses in LTS and HTS magnets: models for HTS (1/2)

- The **hysteresis losses in HTS** were computed with **two analytical approaches**:
  1) The formula for **superconducting slabs** [*], accounting for both field and transport current
  2) The **formula widely used for LTS**, adapted to HTS twisted stacked cable in [**], which does not account for the transport current

[*]

$$P = \frac{\mathrm{sgn}(\dot{I})}{16\mu_0 B_p} \begin{cases} A_1 & \text{for} \quad B_e < B_i \\ A_2 & \text{for} \quad \mathrm{sgn}(\dot{I}) B_e \le -B_{em}\left(\frac{B_{em}+B_{im}-2B_p}{B_{em}-B_{im}}\right) \\ A_3 & \text{for} \quad \mathrm{sgn}(\dot{I}) B_e > -B_{em}\left(\frac{B_{em}+B_{im}-2B_p}{B_{em}-B_{im}}\right) \end{cases}$$

[**]

$$P_{hys} = \frac{2}{3\pi} \lambda J_c(B,T,\varepsilon)\, d_{eff} \frac{dB}{dt} \frac{2}{\pi}$$

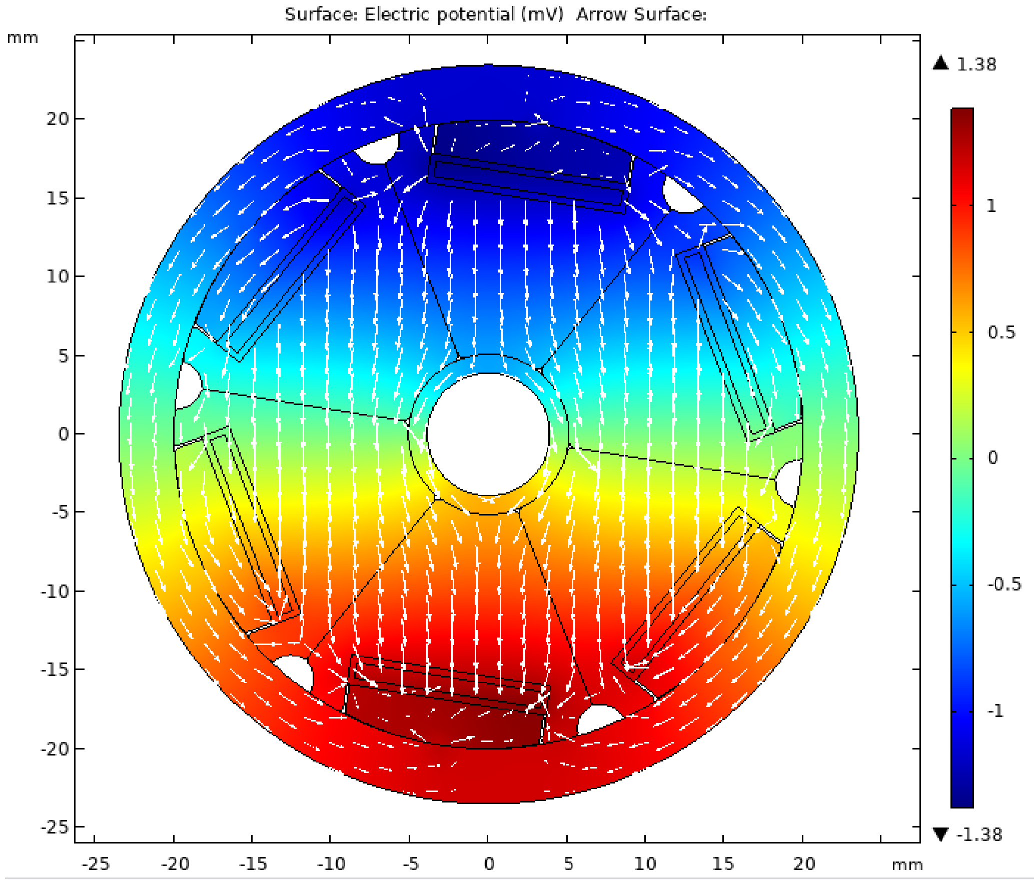
$$d_{eff} = w_{tape}$$

[*] A. Macchiagodena et al, IEEE Trans. Appl. Supercond., vol. 33, n. 5, 2003, 5900705.
[**] M. Takayasu, et al. Supercond. Sci. Technol. vol 25 no. 1, 2011,014011.

Comparing losses in LTS and HTS magnets: models for HTS (1/2)

- Coupling losses **between tapes in the stack were neglected** due to their low time constant (2.5 ms) [*]
- The **coupling losses** between stacks were computed via the **single time constant model, with nτ = 300 ms** [**]
- The **current** inside a SECAS HTS cable **is highly affected** by the **contact resistance** between sectors and between the stacks and the sectors [**]

Current density for a SECAS cable

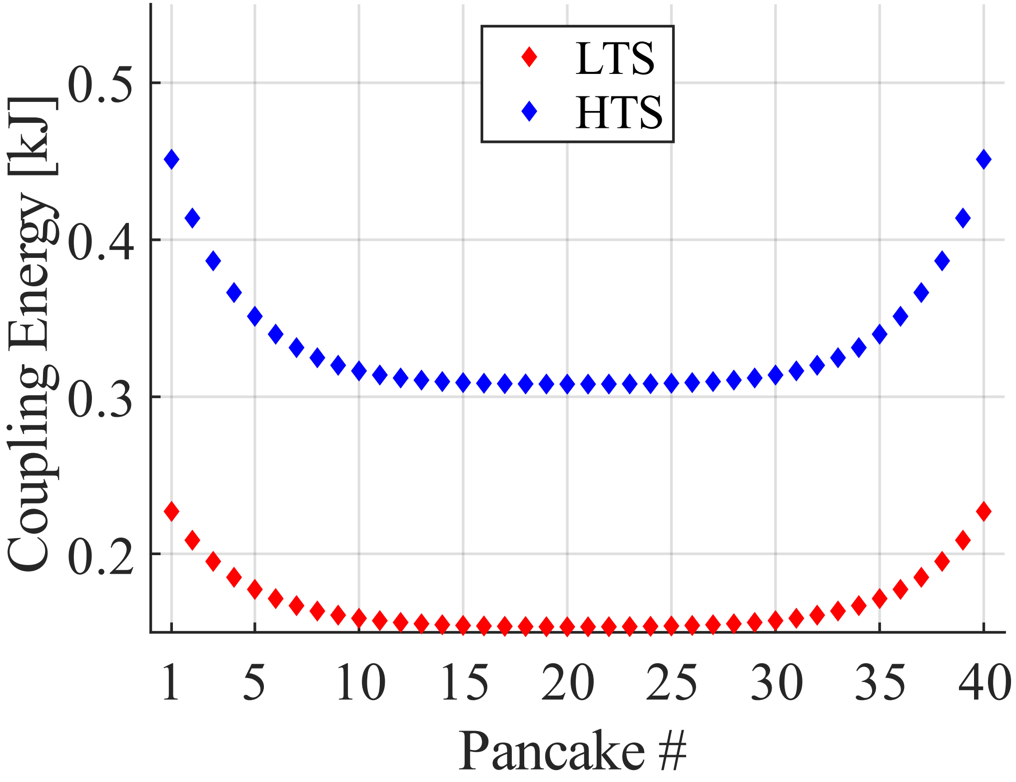


[*] Y. Ueno, et al. Plasma and Fusion Research, 2021, 16: 2405071

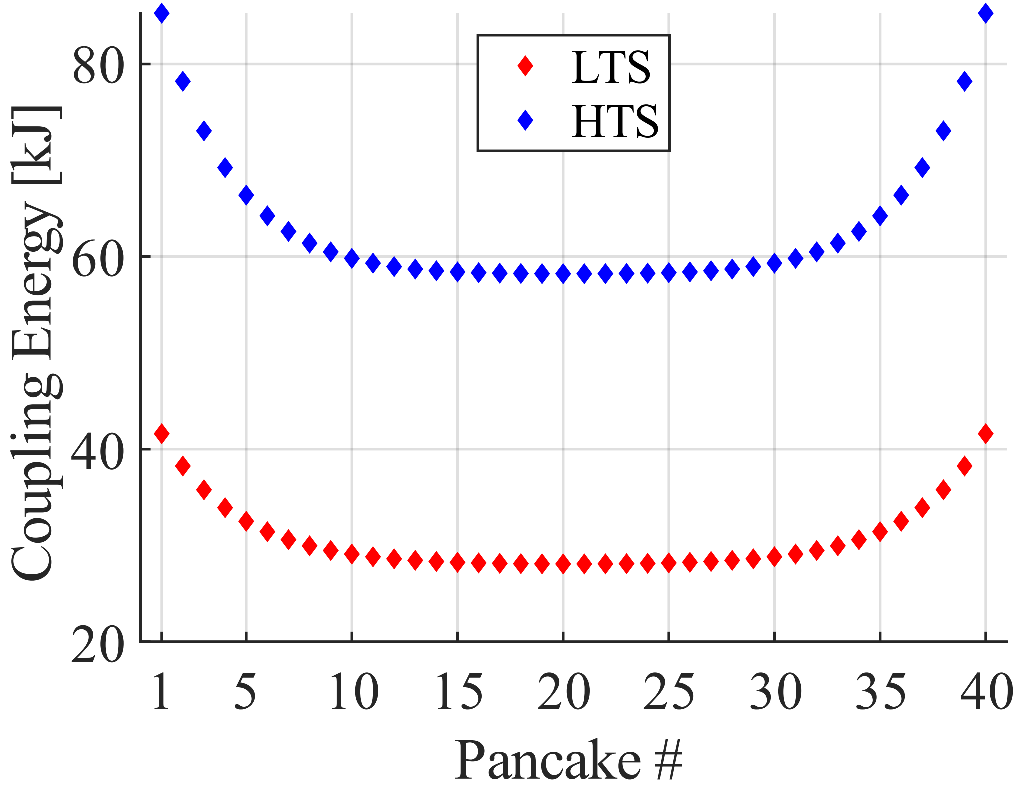
[**] G. De Marzi, DEMO intermediate meeting 02/10/2024

Comparing losses in LTS and HTS magnets: coupling (1/2)

- The total coupling loss energy **follows the same distribution** in the pancakes for both the LTS and HTS coils.
- The **coupling losses** in the HTS coil are about a factor of 2 greater than in the LTS one.



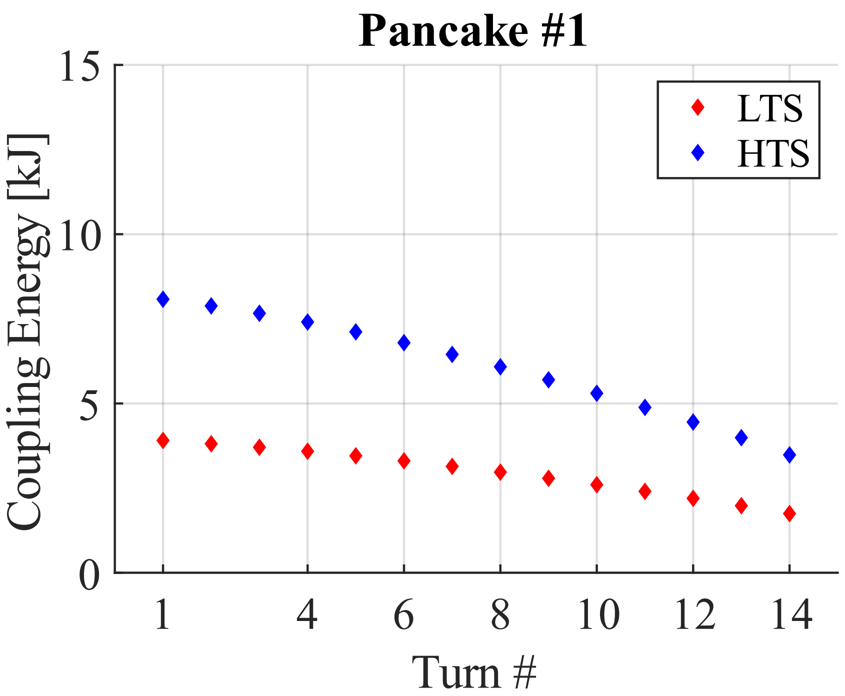
Ramp up 0 - 40 kA (1 kA/min)

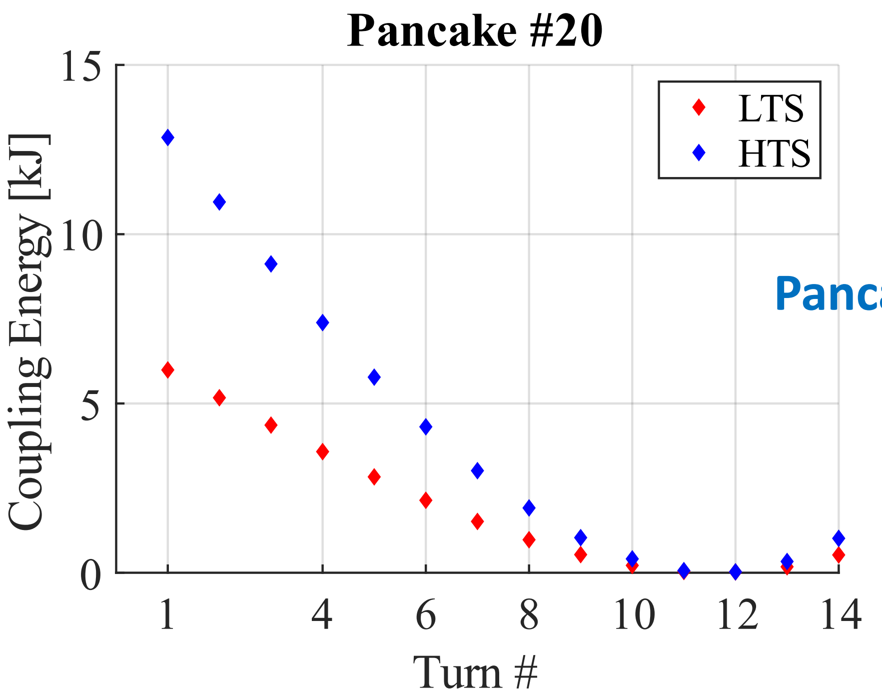


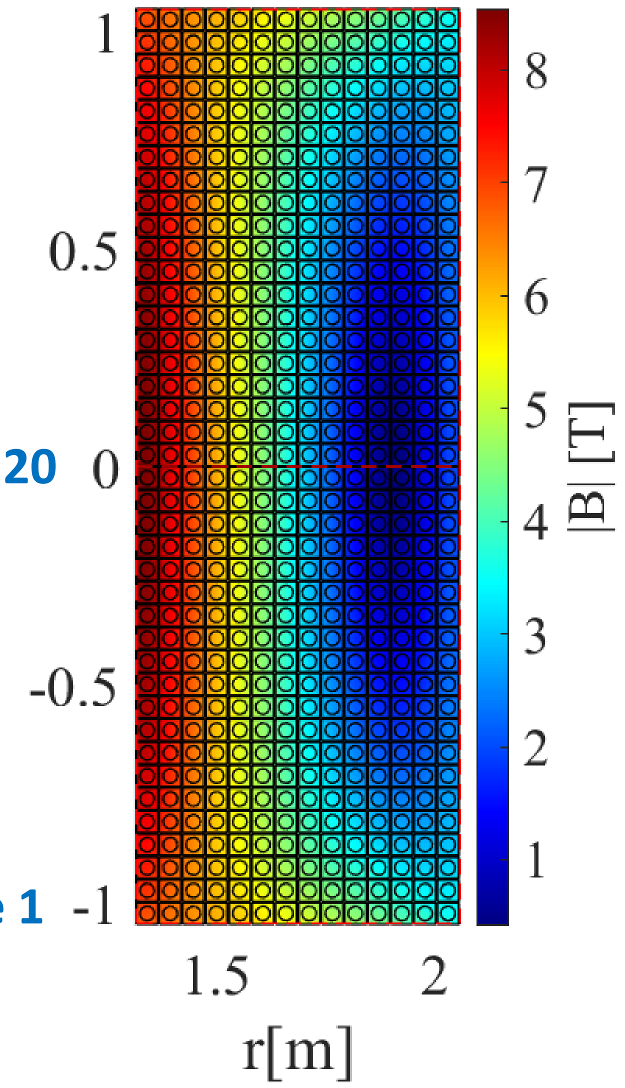
Exponential dump from 40 kA (T_d = 6.2 s)

Comparing losses in LTS and HTS magnets: coupling (2/2)

- The **upper** and **lower pancakes** exhibit higher losses than the central ones, due to their higher average value of the field







Exponential dump from 40 kA (T_d = 6.2 s)

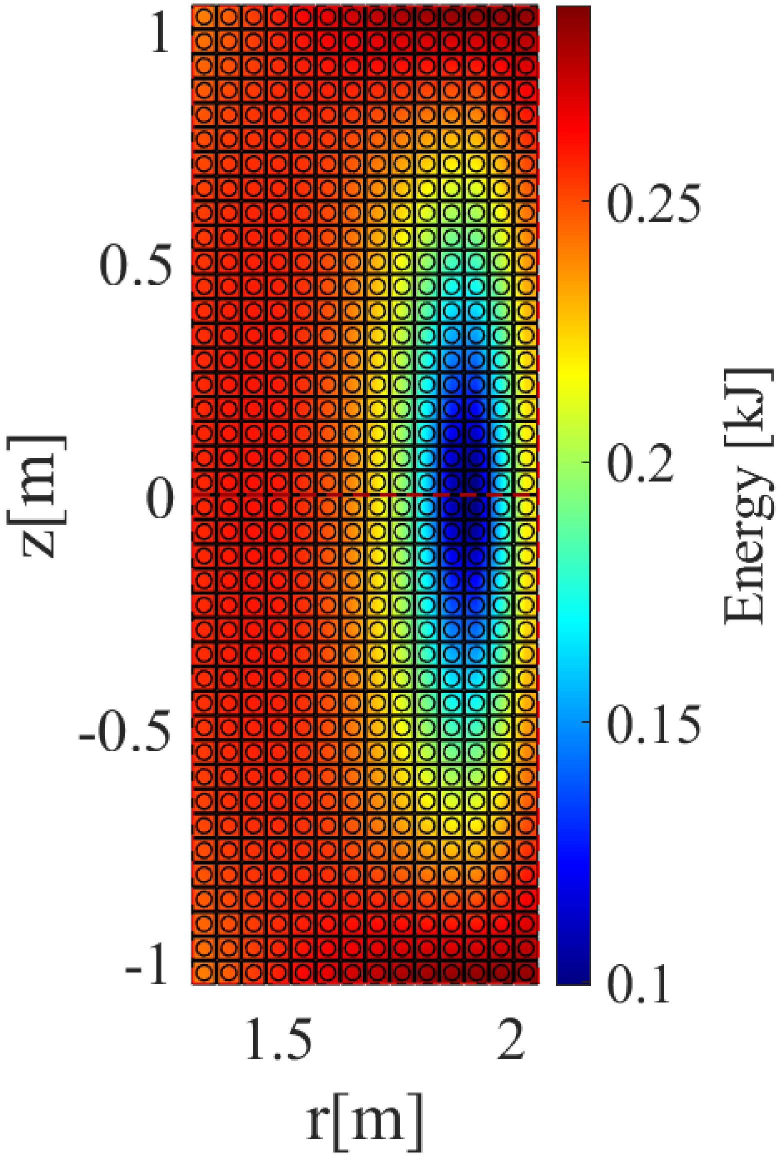
- The **loss distribution over turns** is more uniform in the pancakes at the coil ends

Comparing losses in LTS and HTS magnets: hysteresis (Takayasu)

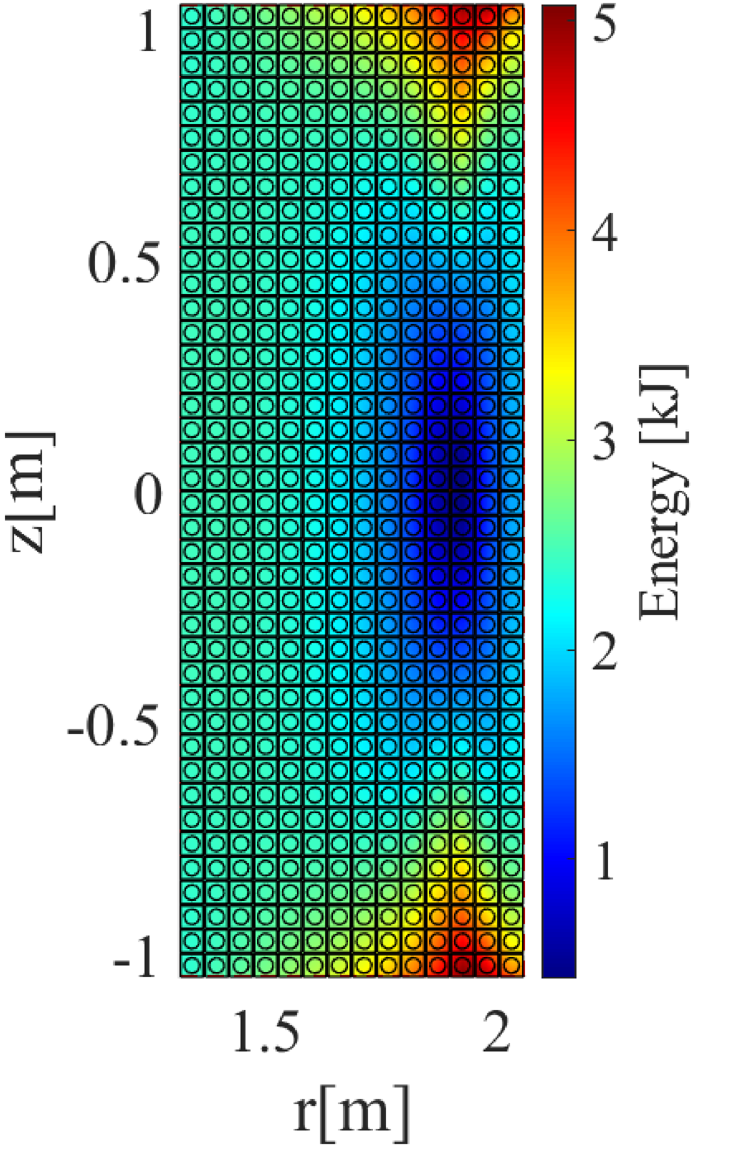
Exponential dump from 40 kA (T_d = 6.2 s)

- The **hysteresis losses** in the HTS coil are one order of magnitude higher than in the LTS one

Hysteresis losses LTS



Hysteresis losses HTS [*]



[*] M. Takayasu, et al. Supercond. Sci. Technol. vol 25 no. 1, 2011,014011.

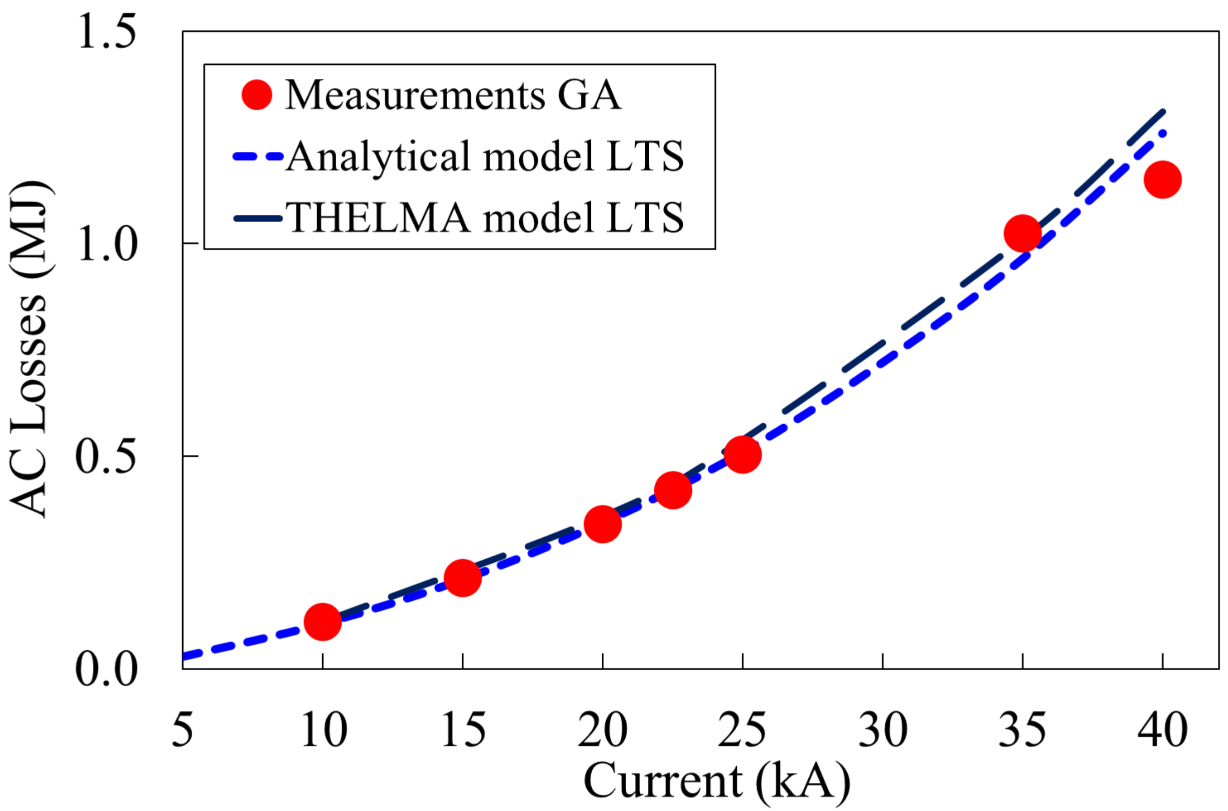
Comparing losses in LTS and HTS magnets: exponential dumps (1/2)

Iop [kA]	Td [s]	LTS coupling [kJ]	LTS hysteresis [kJ]	HTS coupling [kJ]	HTS hysteresis Takayasu [kJ]	HTS hysteresis Macchiagodena [kJ]
10	7.3	65	41	135	531	1079
20	6.95	267	77	566	862	1788
30	6.55	623	97	1350	1108	4554
40	6.2	1140	111	2532	1305	*

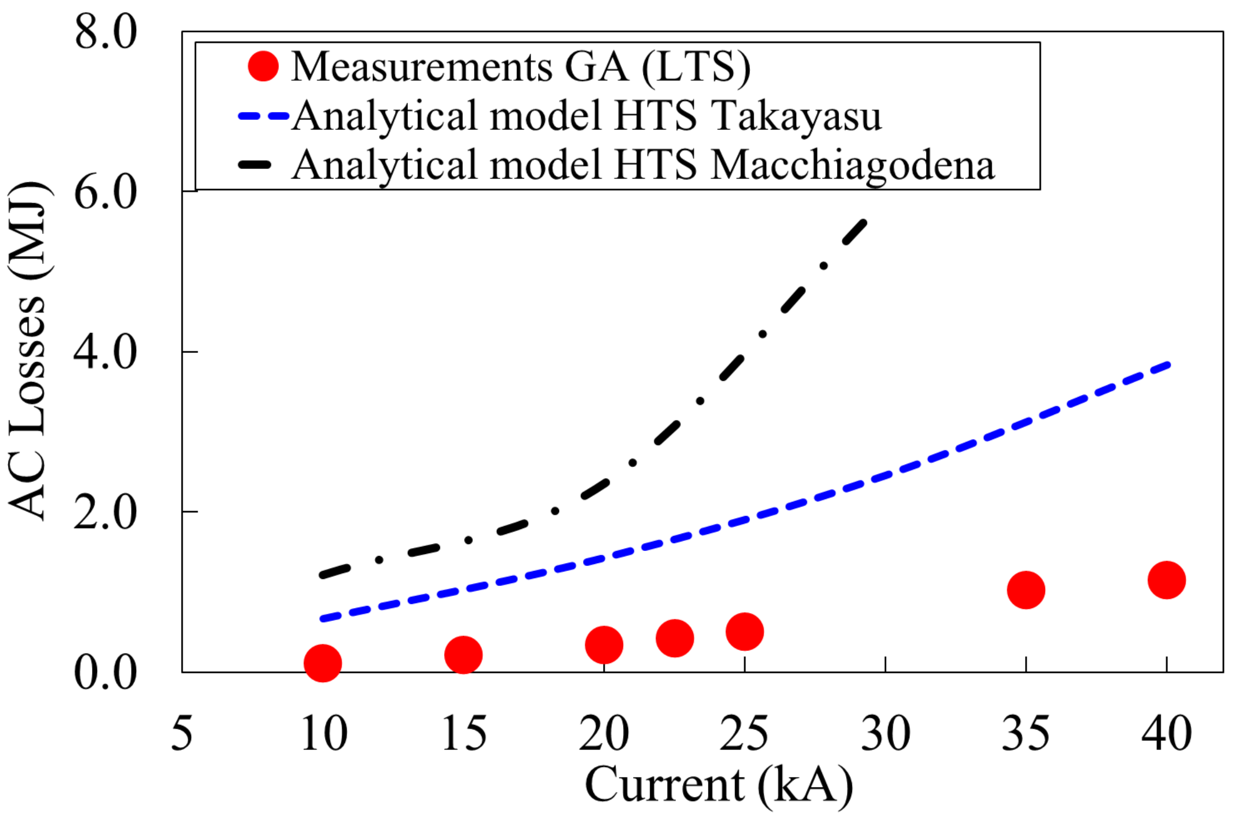
- For dumps from low transport current, the **hysteresis losses in the HTS conductor** are greater than the coupling ones
- The hysteresis losses in the HTS conductor computed with the 2 analytical formulae considered **differ by a factor up to 4**

Comparing losses in LTS and HTS magnets: exponential dumps (2/2)

Total losses LTS



Total losses HTS



- The overall **losses in the HTS conductor are greater than in the LTS one** by a factor from 2.5 to 8 depending on the formula adopted for hysteresis losses

Summary

- After many years of work on modeling and experiments, the community reached the ability to **predict with reasonable accuracy the losses in large LTS fusion magnets**
- A comparison of losses between LTS and HTS conductors is not straightforward, due to their different typical working conditions
- In the case study of the CS ITER Module in standalone configuration, the **coupling losses** of LTS and HTS conductors **have the same order of magnitude**, while the **hysteresis ones are one order of magnitude higher** in the HTS case
- Further **validation vs numerical and experimental data** is required for the hysteresis loss formulae for twisted stacked HTS conductors

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Thank you for your kind attention !

M. Breschi, L. Cavallucci, A. Macchiagodena

marco.breschi@unibo.it