Chats 2021
Applied Superconductivity

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

A Numerical Investigation on AC Losses in the first module of the ITER Central Solenoid

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Cadarache, September 23rd 2021

OUTLINE

- **Model description**
  - THELMA model
  - Analytical model

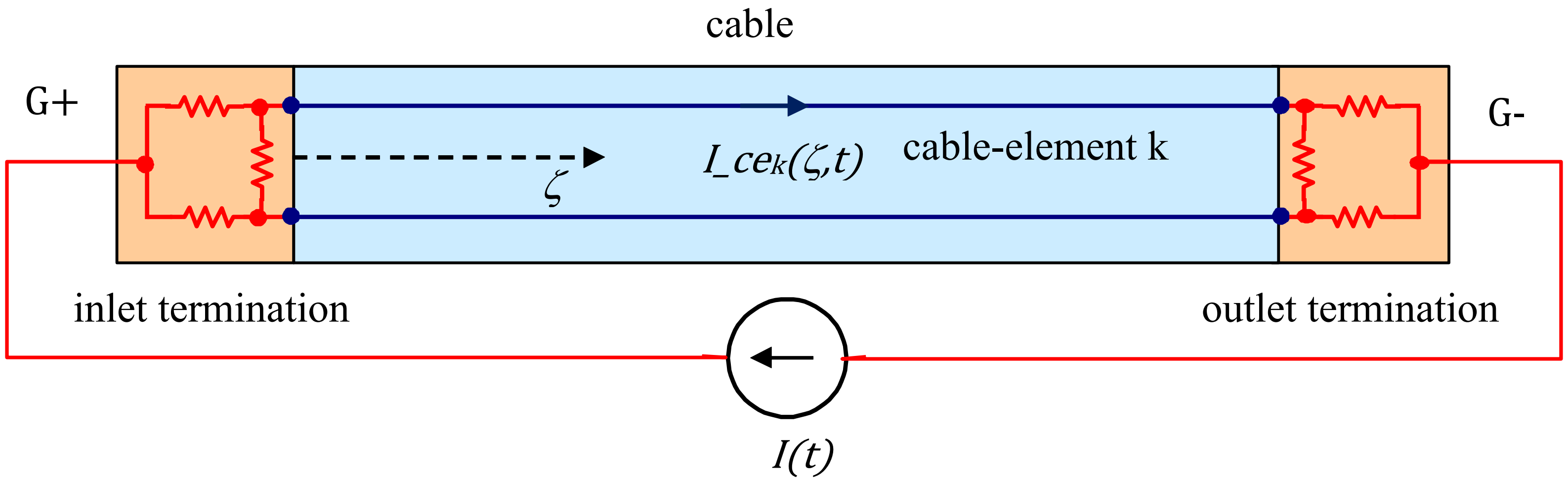
- **Previous application to relevant case (CS Insert)**

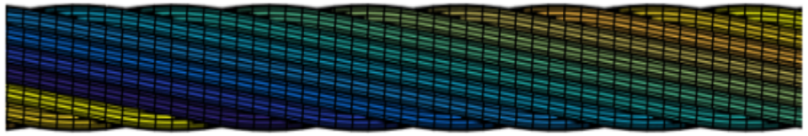
- **Model application to the CSM1 module**
  - Impact of boundary conditions
  - Comparison with experimental results
  - Model simplification

- **Conclusions**

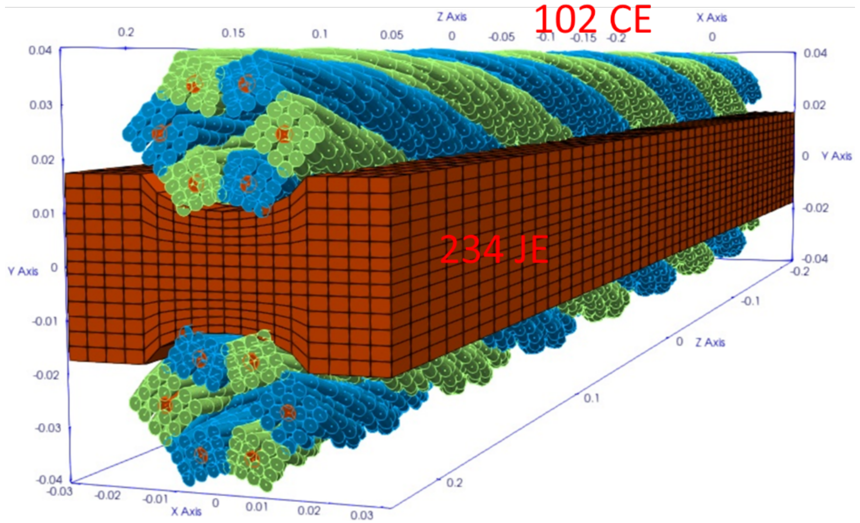
CSM#1 in test station (courtesy N. Martovetsky, US - ITER)

THELMA_UB model: main assumptions





Rutherford cable



CICC + joint

- A **superconducting cable** is connected by two terminations to a power supply, modeled as a current generator [1], [2].
- The conductor geometry can be of any type, **CICC or Rutherford**, wound in different configurations (rectilinear, pancake, layer)
- The cable is modeled with a distributed parameter circuit, with *N_ce* **cable elements** (CE), corresponding to either **individual strands or groups of strands**

[1] F. Bellina, P. L. Ribani, M. Bagnasco, L. Muzzi, E. Salpietro, L. Savoldi Richard, and R. Zanino, IEEE Trans. Appl. Supercond., vol. 12, no. 2, pp. 1798–1802, 2006.
[2] M. Breschi, P. L. Ribani, IEEE Trans. Appl. Supercond., Vol. 18, n. 1, pp. 18 – 28, 2008.

THELMA_UB model: main equations (1/2)

- The longitudinal current in the k^{th} CE is the sum of a uniform component $I\_u_k\ (t)$ and a difference component $I\_d_k\ (t)\ (\zeta,t)$; the latter is the unknown of the problem.

$$I\_ce_k(\zeta,t) = I\_u_k(t) + I\_d_k(\zeta,t) \qquad (1)$$

- The CEs interact through **contact conductances and mutual inductances**

- The electromotive forces are due to the **difference currents at locations 'near'** the selected position, to a **uniform current distribution at locations 'far'** from the selected position, and **to the currents in external coils**

$$\boldsymbol{E}(\boldsymbol{x\_ce}_k(\zeta),t)\cdot\frac{d\boldsymbol{x\_ce}_k}{d\zeta}(\zeta) = -\frac{\partial V\_ce_k}{\partial\zeta}(\zeta,t) - \underbrace{\sum_{h=1}^{N\_ce}\int_0^{\zeta_f}\frac{\partial I\_d_h}{\partial t}(\zeta',t)\, m\_d_{k,h}(\zeta,\zeta')\, d\zeta'}_{\text{difference currents}} - \underbrace{m\_u_k(\zeta)\frac{dI}{dt}(t)}_{\text{uniform current}} - \underbrace{\sum_{i=1}^{N\_ext} m\_e_{k,i}(\zeta)\frac{d\,I\_ext_i}{dt}(t)}_{\text{external coil}} \qquad (2)$$

- The power law is assumed for the superconductor, in **parallel electrical connection with the resistive stabilizer** (made of copper and bronze for the Nb_3Sn wires)

THELMA_UB model: main equations (2/2)

- By **subtracting the equation for the last CE** from those of the first (N_ce-1) CEs, and **inverting the reduced conductance matrix**, the potentials can be removed:

$$\boldsymbol{E\_c}(\zeta,B,T,\varepsilon) = -\frac{\partial}{\partial\zeta}\left\{\boldsymbol{R\_c}(\zeta)\left[\boldsymbol{S}(\zeta,t)+\boldsymbol{C\_d}\frac{\partial\boldsymbol{I\_d}}{\partial\zeta}(\zeta,t)+\int_0^{\zeta_f}\boldsymbol{K}(\zeta,\zeta')\frac{\partial\boldsymbol{I\_d}}{\partial t}(\zeta',t)\,d\zeta'\right]\right\}$$
$$-\int_0^{\zeta_f}\boldsymbol{m\_d\_c}(\zeta,\zeta')\frac{\partial\boldsymbol{I\_d}}{\partial t}(\zeta',t)d\zeta' - \boldsymbol{m\_u\_c}(\zeta)\frac{dI}{dt}(t) - \sum_{i=1}^{N\_ext}\boldsymbol{m\_e}_i(\zeta)\frac{d\,I\_ext_i}{dt}(t) \qquad (3)$$

$$\boldsymbol{E\_c} = [E\_ce_1 - E\_ce_{N\_ce}, \dots, E\_ce_{N\_ce-1} - E\_ce_{N\_ce}]^T$$

- A numerical solution of (3) is obtained by means of discretization with N_el **linear finite elements and a point collocation method**:

$$\boldsymbol{M}\frac{d\boldsymbol{y}}{dt} = \boldsymbol{F}(t,\boldsymbol{y}(t)) \qquad \boldsymbol{y}(t) = \boldsymbol{y_0} \qquad (4)$$

- The unknowns of the problem ($\boldsymbol{y}(t)$) are the values of the **difference currents** in the internal nodes of the 1D domain ((N_el−1)×(N_ce−1) dof)

Analytical model

- The coupling losses were computed both with **THELMA_UB and with an analytical model**
- The **analytical model** is based on a single time constant [3], with calculation of internal field at k[th] turn:

$$\dot{B}_{i,k}(t) = \frac{B_0}{T_d - \tau} \cdot \left(e^{-\frac{t}{\tau}} - e^{-\frac{t}{T_d}} \right) \qquad P_{coup}(t) = \frac{n\tau}{\mu_0} \cdot \left(\dot{B}_i(t) \right)^2$$

- The **hysteresis losses** were computed, both in THELMA_UB and in the analytical model, with two different formulae depending on the value of the cumulative field variation ΔB [4]:

$$\text{if } \Delta B_k < 2B_p \qquad P_{hys,k} = (A_{str} \cdot L_k) \frac{\pi \Delta B_k^2}{2\,\mu_0^2 \lambda\, J_c(B_k,T,\varepsilon)\, d_{eff}} \frac{dB_k}{dt} \left(1 - \frac{\pi \Delta B_k}{3\,\mu_0\,\lambda\, J_c(B_k,T,\varepsilon)\, d_{eff}} \right)$$

$$\text{if } \Delta B_k > 2B_p \qquad P_{hys,k} = (A_{str} \cdot L_k) \frac{2}{3\pi}\, \lambda\, J_c(B_k, T, \varepsilon)\, d_{eff} \frac{dB_k}{dt}$$

where B_p is the penetration field.

[3] M. N. Wilson, Superconducting Magnets. Oxford, UK: Clarendon, 1983.
[4] D. Bessette, "Assessment of the conductor AC Losses in the CS modules", 10 Dec 2018, ITER IDM XQB5DS.

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CSM#1 in test station (courtesy N. Martovetsky, US - ITER)

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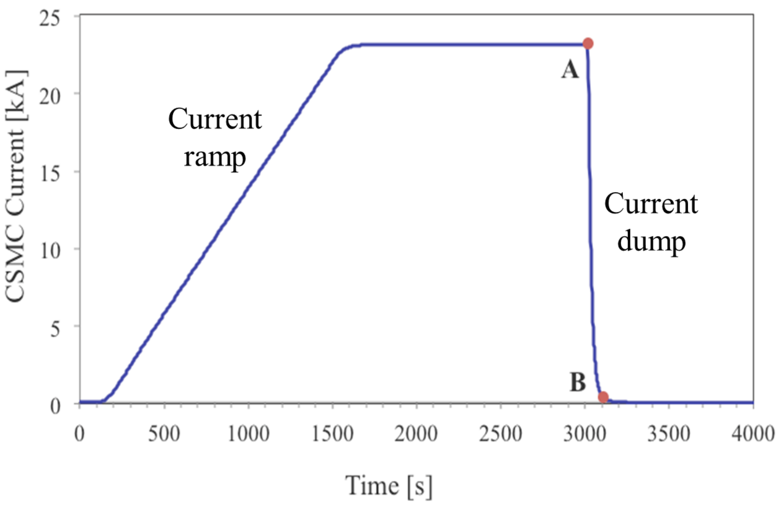
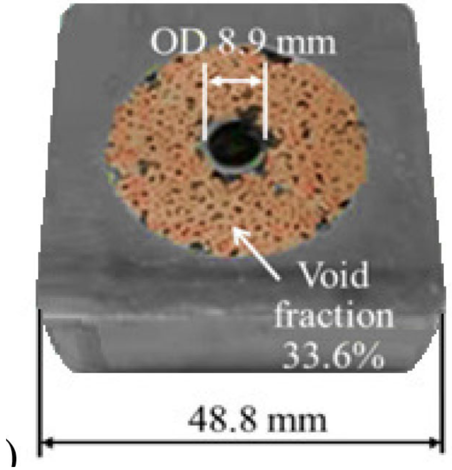
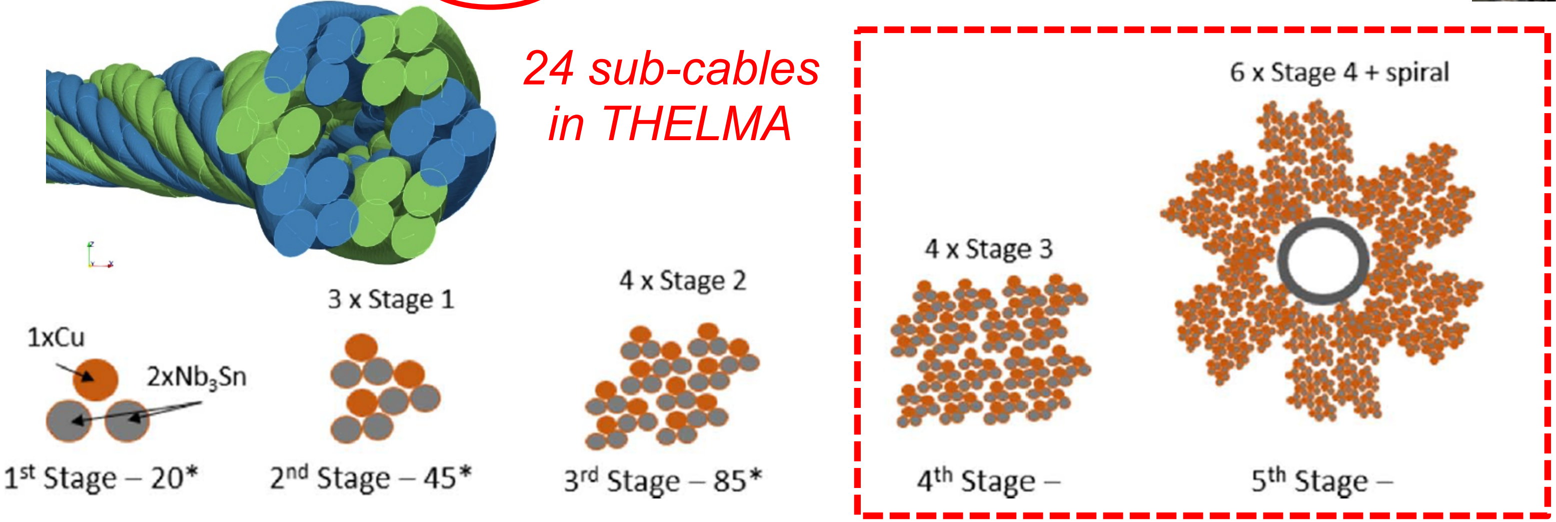
Model application to previous tests of the CS ITER conductor

- The **CS Insert** (CSI) is a **43 m** long **single layer solenoid** wound into **9 turns and** tested in 2015 in the bore of the Central Solenoid Model Coil (CSMC) at QST in Naka (Japan)
- During the **AC loss tests**, the CSMC current is ramped and then kept constant; an **exponential dump** is then triggered with a given time constant
- Conductor winding stages: **(2Sc + 1Cu) × 3 × 4 × 4 × 6**



CS Insert

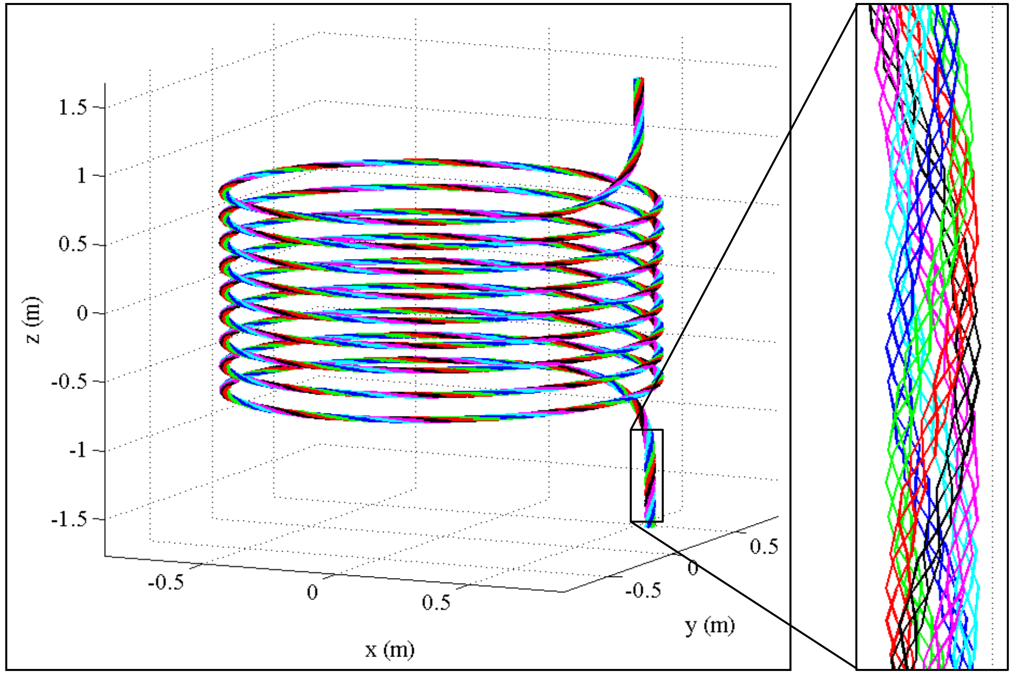




24 sub-cables in THELMA

Model application to previous tests of the CS ITER conductor

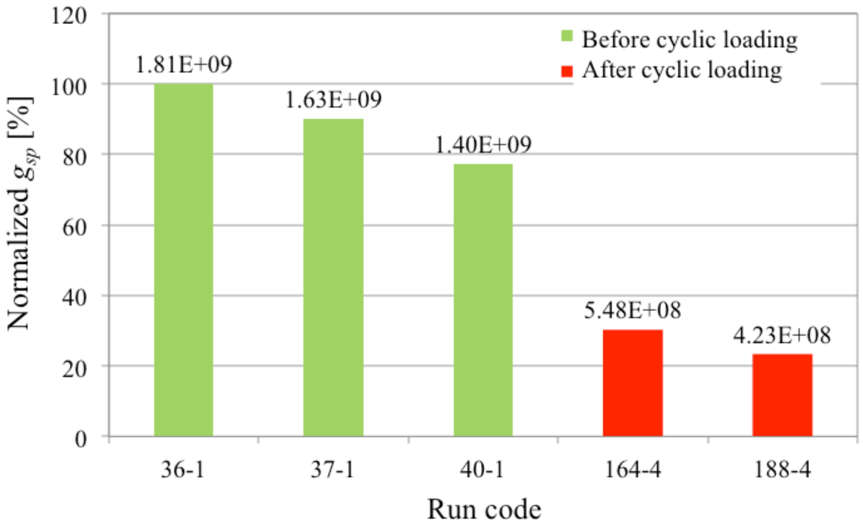
- The mesh includes **1800 nodes** along ~ 43 m, about **7 mesh nodes per twist pitch** of the last-but-one cabling stage.



Analytical

Shot #	T_d [s]	$I_{0,CSMC}$ [kA]	B_0 [T]	$E_{coup,CSI}$ [kJ]	$n\tau$ [ms]
36-1	19.1	23.1	6.06	0.69	590
37-1	19.2	36.8	9.68	1.58	530
40-1	18.3	46.1	12.1	2.17	470
80-4	18.5	23	6.04	0.20	175
97-4	18	23	6.04	0.16	143
129-1	18.5	22.9	6.02	0.14	124
164-4	18.9	23.0	6.04	0.25	220
188-4	19.6	45.9	12.1	0.69	149

THELMA



- A **good approximation of the experimental results** was obtained, with fitting conductances (and time constants) decreasing by a factor 3 between the beginning and the end of the test campaign.

[5] M. Breschi et al., *IEEE Trans. Appl. Supercond.*, vol. 27, n. 4, Article Number 7762085, 2017.
[6] R. Bonifetto, et al., IEEE Trans. Appl. Supercond., vol. 29, n. 5, Article Number 4200907, 2019.

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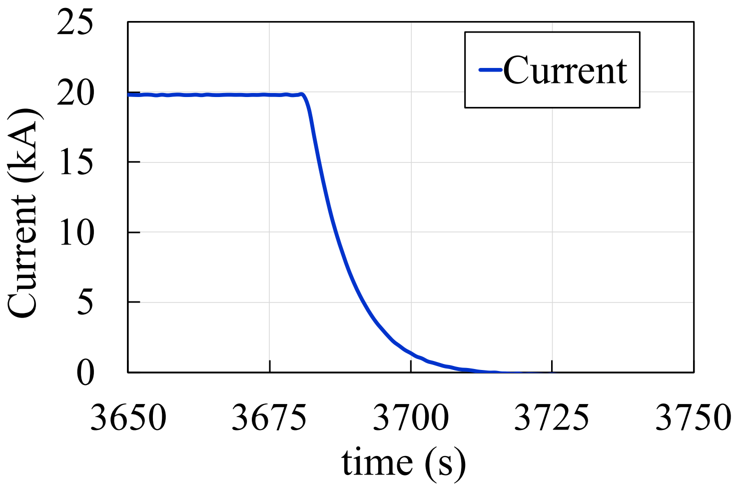
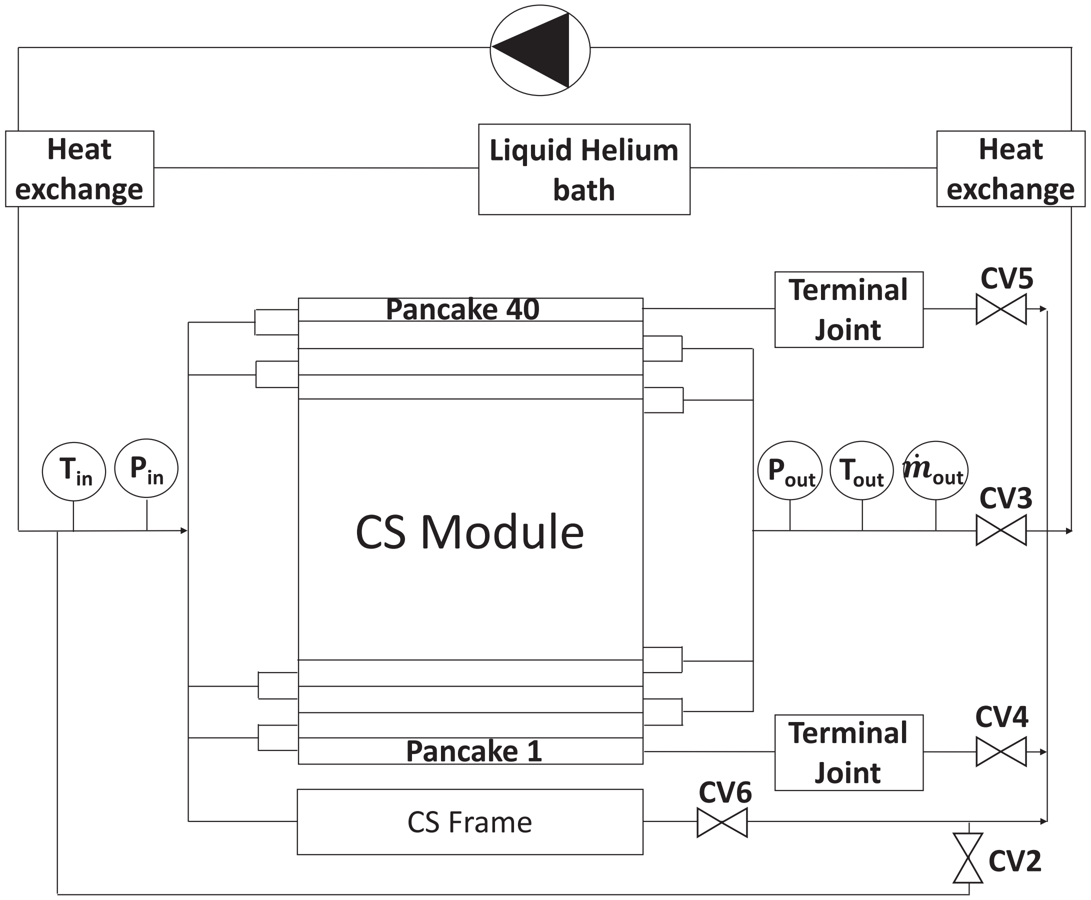
Model application to the CSM1 tests

- The tests of the first module of the CS magnet (CSM1) were performed at General Atomics, Poway (US), in 2020.
- The model consists of **40 pancakes, made of 14 turns each**
- The instrumentation of CSM#1 includes **temperature, pressure and mass flow rate sensors**, at the inlet of all pancakes and at the outlet of pancakes from #2 to #39 [6].
- The AC loss measurements were performed by **exponential dumps of the transport current** of the CSM#1



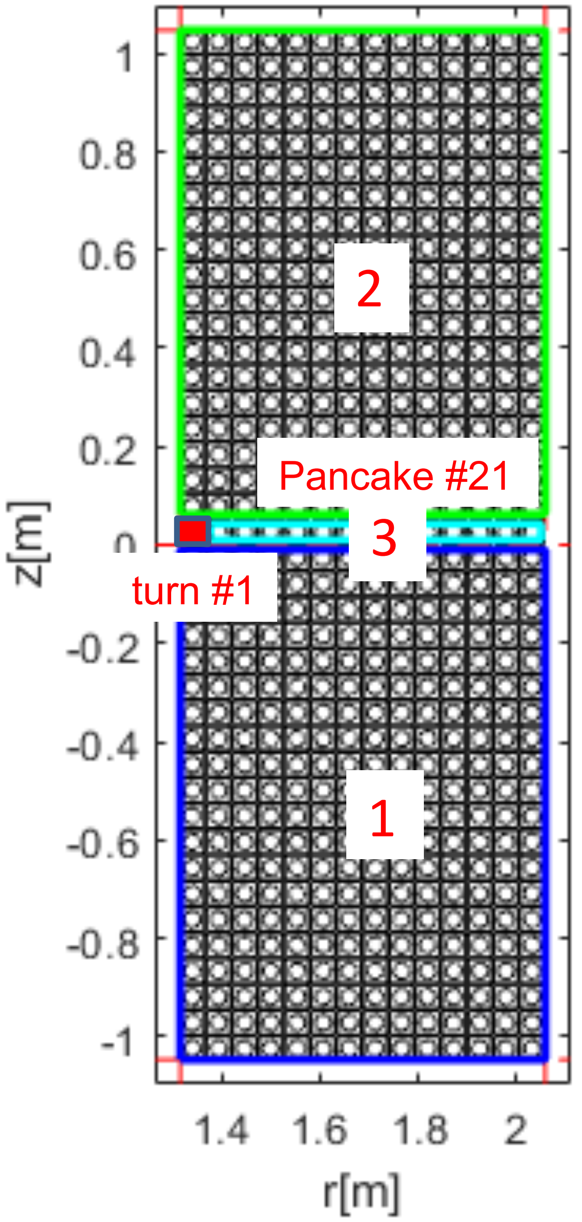
I_{op} (kA)	T_d (s)
10	7.3
15	7.2
20	7.0
25	6.8
35	6.6
40	6.5



[7] M. Breschi, L. Cavallucci, P. L. Ribani, R. Bonifetto, A. Zappatore, R. Zanino, F. Gauthier, P. Bauer, N. Martovetsky,, IEEE Trans. Appli. Supercond., vol. 31, n. 5, Article Number 5900905, 2021

Model application to the CSM1 tests

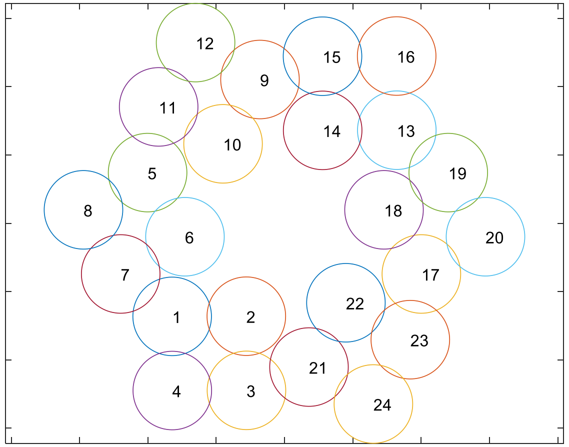
- The losses were computed with THELMA_UB through simulations of all the **individual turns of the CSM1** magnet.
- The magnetic field is computed as the sum of the contributions from a **uniform current distribution in the upper and lower solenoids 1 and 2**, and in the rest of the **same pancake** excluding the analysed turn.
- The magnetic field generated by the turn under analysis accounts for the **non uniform current distribution** in the turn.
- The boundary conditions are either given by a **uniform current distribution or a short circuit (equipotential surface)** at the ends of the turn

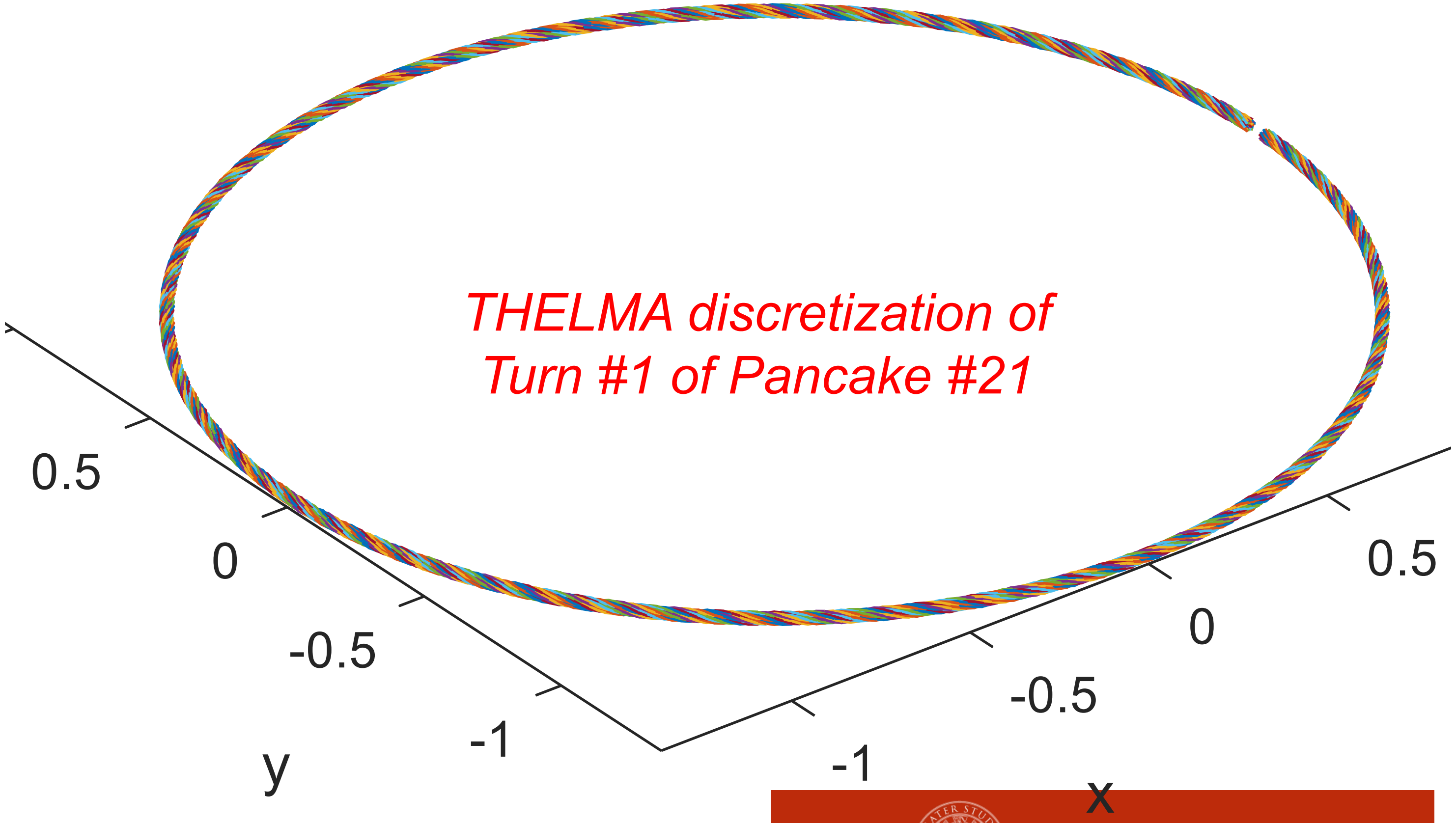


Single Turn model: assumptions

- The simulation of individual turns requires **277 separate runs** (554 turns/2 for symmetry)
- The cable was discretized with **24 sub-cables**, as already done for the simulations of the CS Insert
- Each turn was discretized with **8 mesh nodes per twist pitch** of the last but one cabling stage (150 mm).

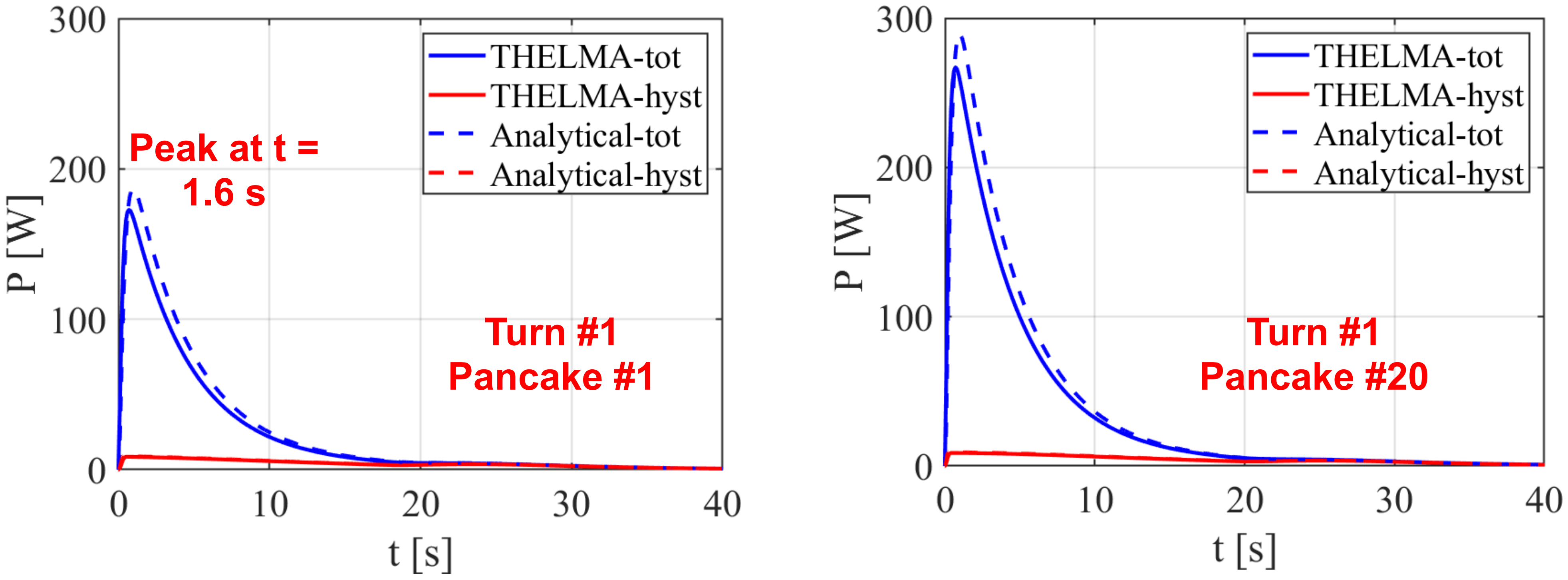
24 sub-cables of the CS conductor





Single Turn model: comparison analytical vs numerical

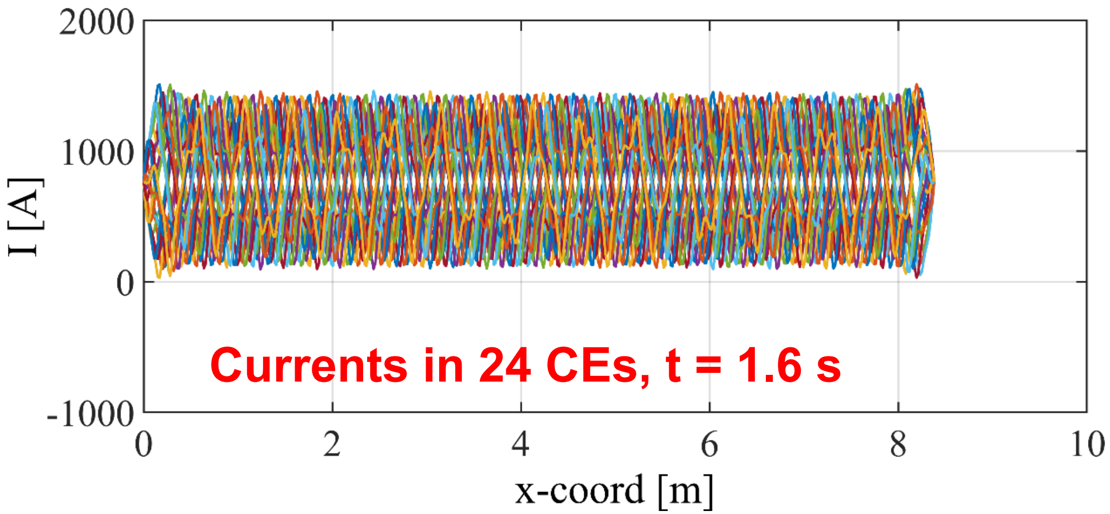
- Exponential dump from **20 kA, with τ = 7.0 s**. The parameters of both THELMA_UB and the analytical model are those used to fit the CS Insert results at virgin conditions



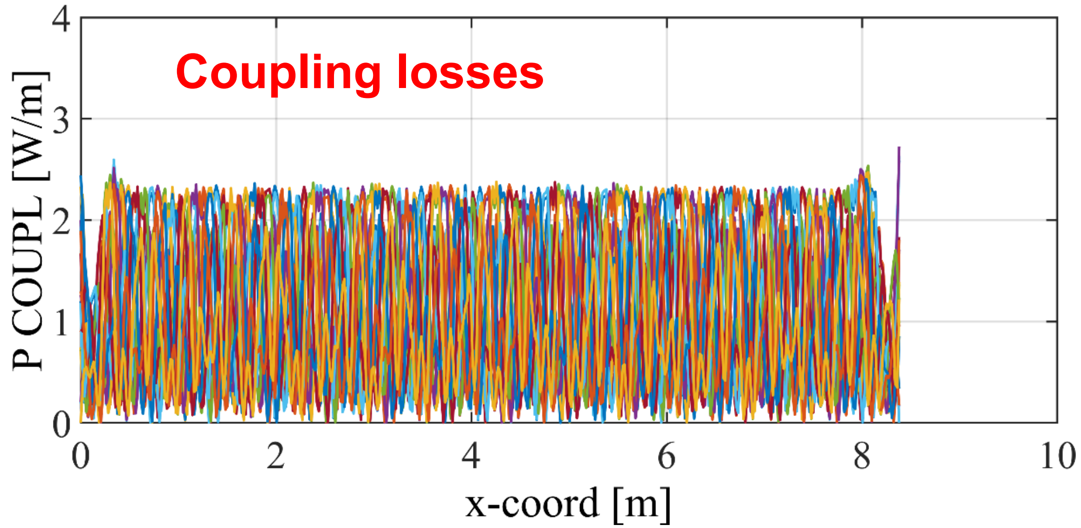
- A **good agreement** is found between the two models, with a maximum difference of about 10 % on the total energy of each turn

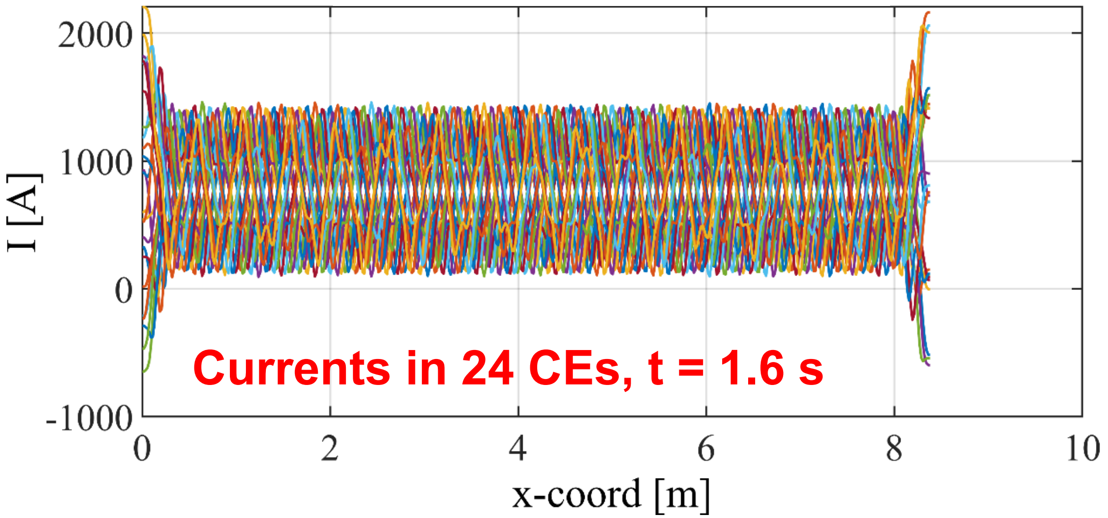
Single Turn model: impact of the boundary conditions

- **Exponential dump from 20 kA**, with τ = 7.0 s, turn 1 of pancake 1: current and coupling losses at *t* = 1.6 s

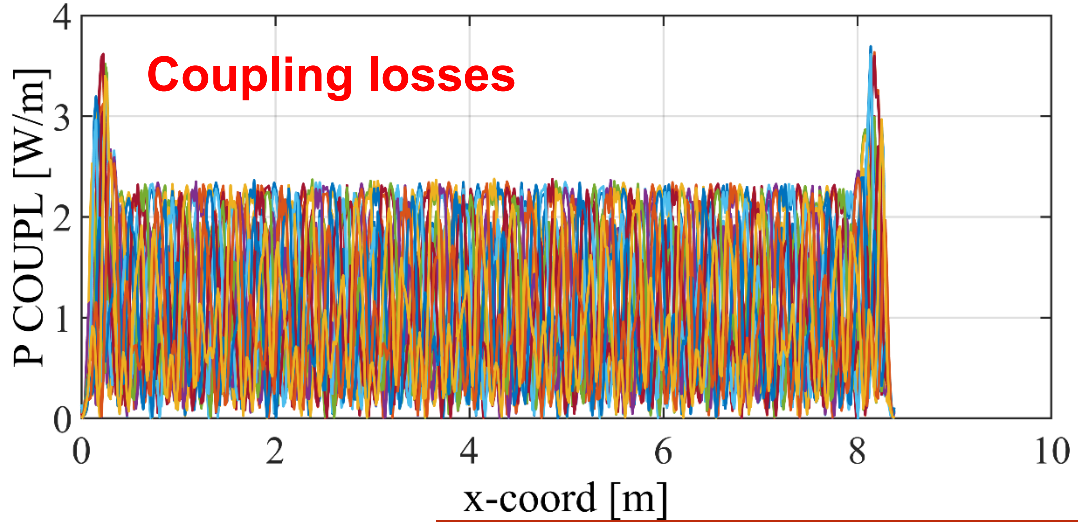


Uniform current →



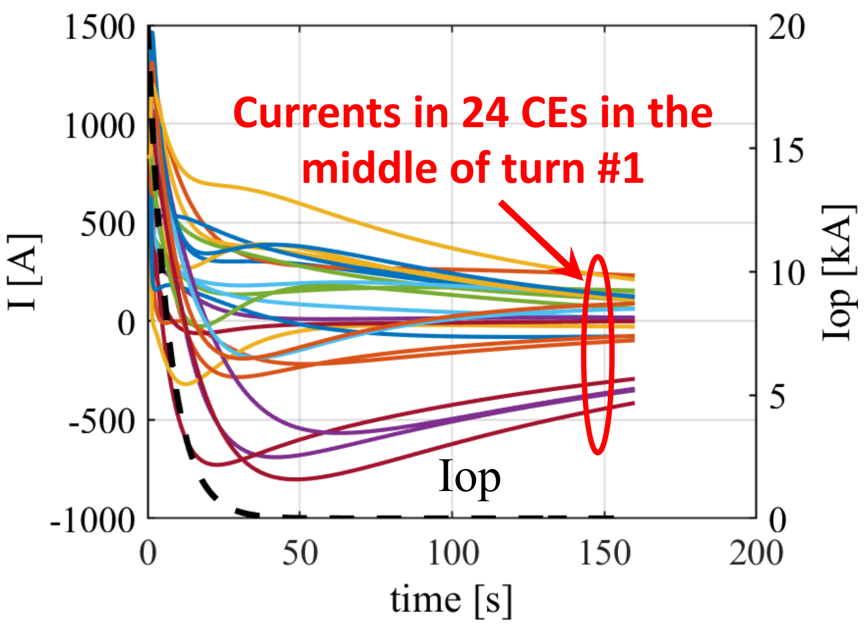


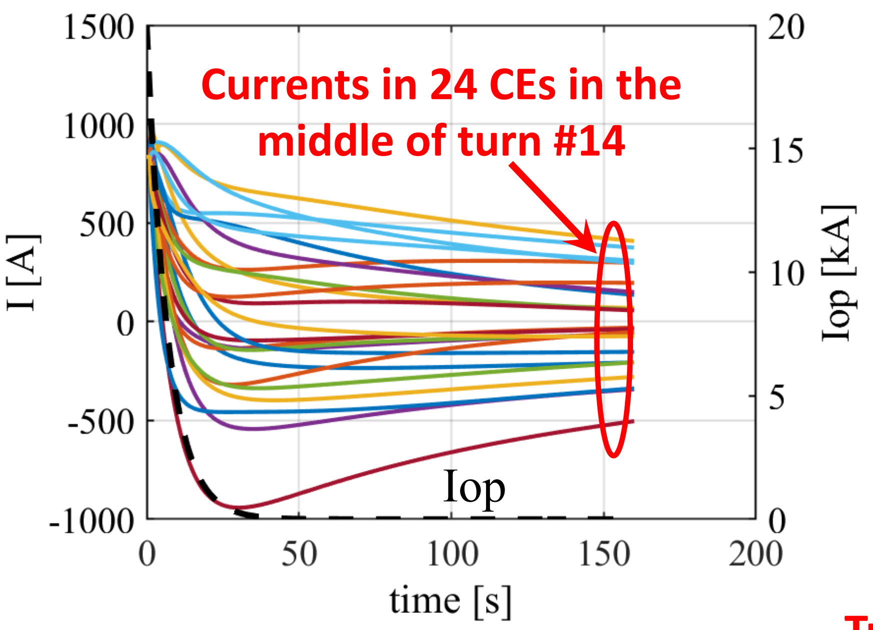
Short circuit →



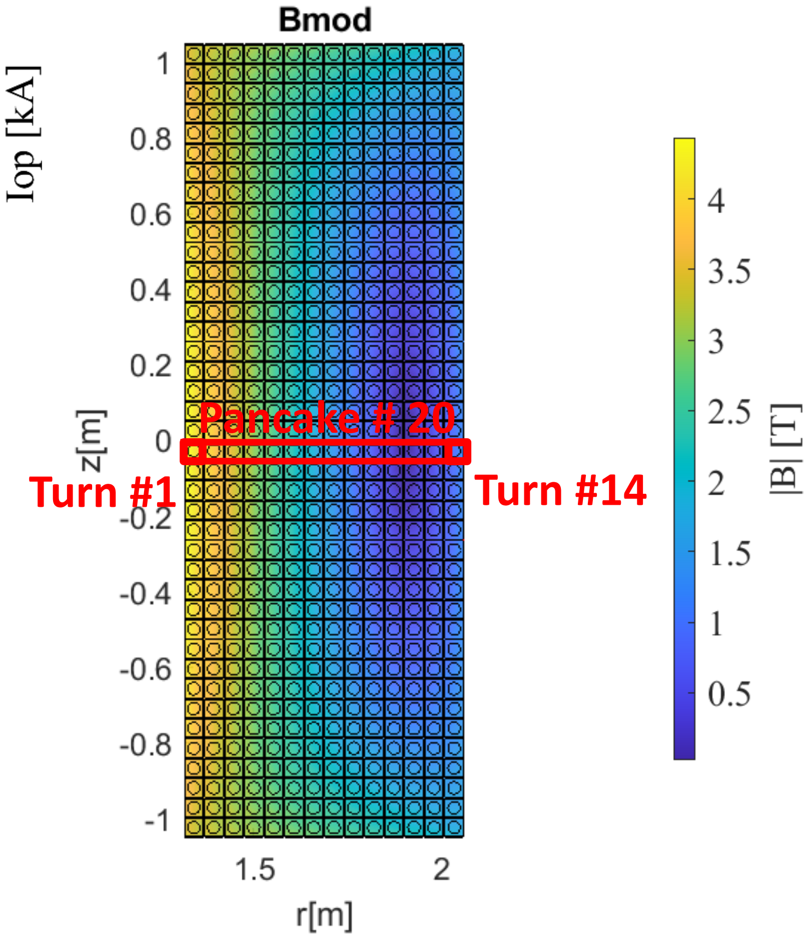
- The **impact of boundary conditions** is limited to about 0.3 m, and affects the total energy deposited in the turn by about **10 %**

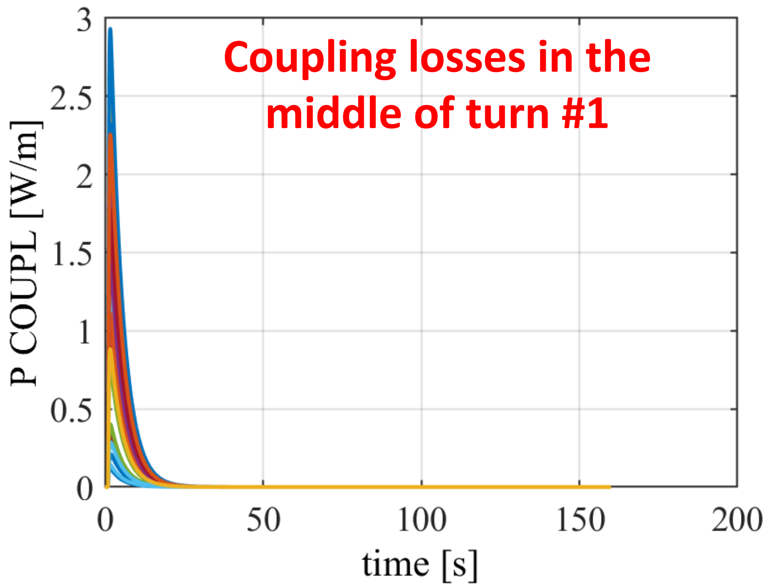
Single Turn model: time evolution of currents and losses

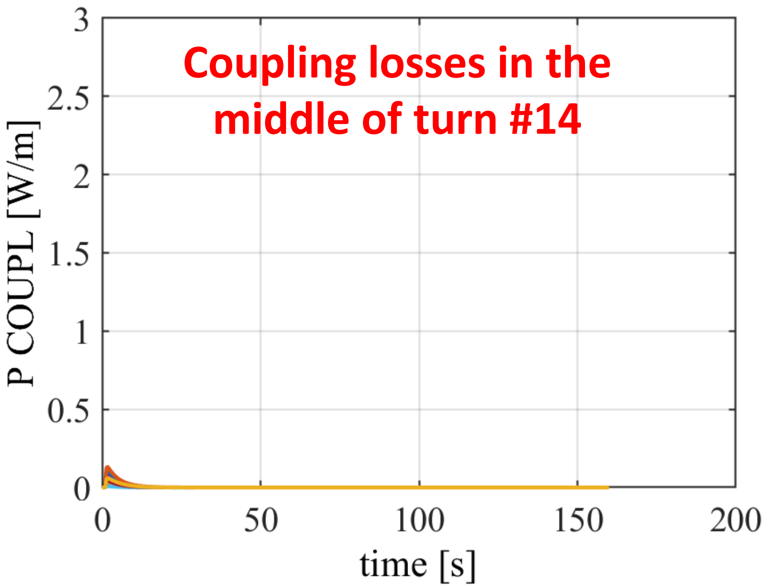




Exponential dump from 20 kA, with τ = 7.0 s, pancake 20







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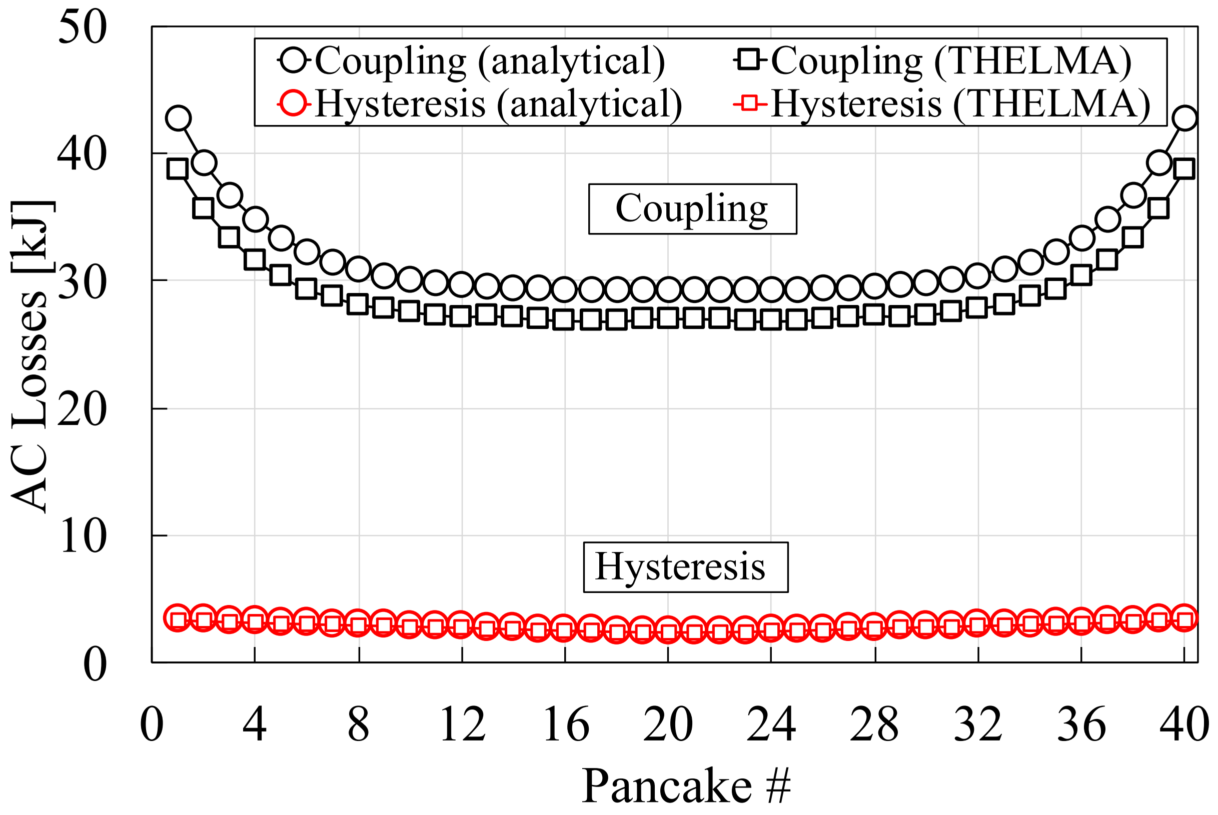
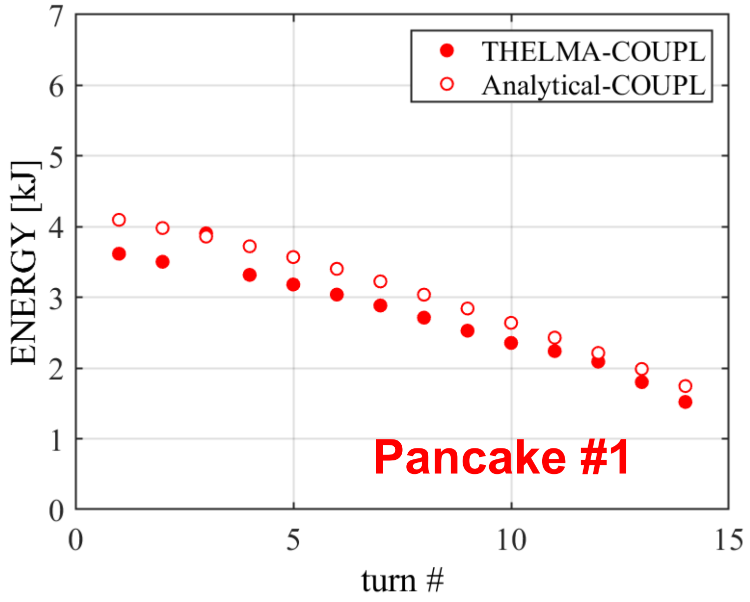
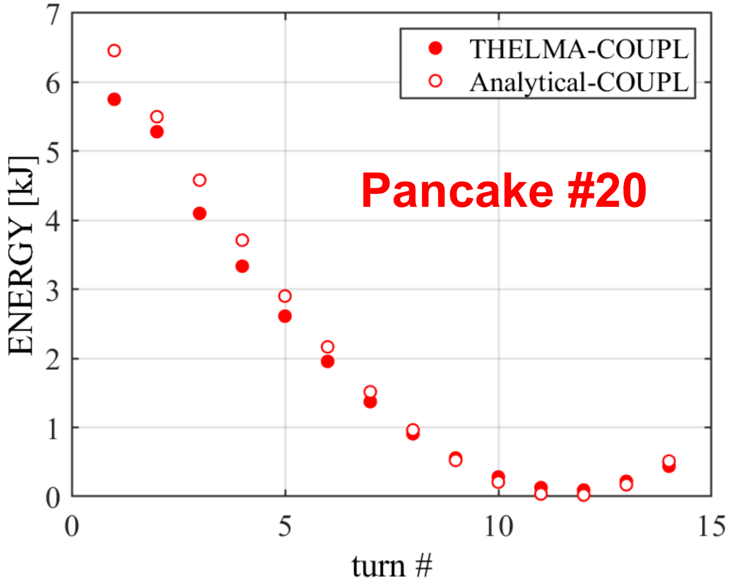
Single Turn model: spatial distribution of the deposited energy

Dump from 40 kA

Total energy deposited in the pancakes



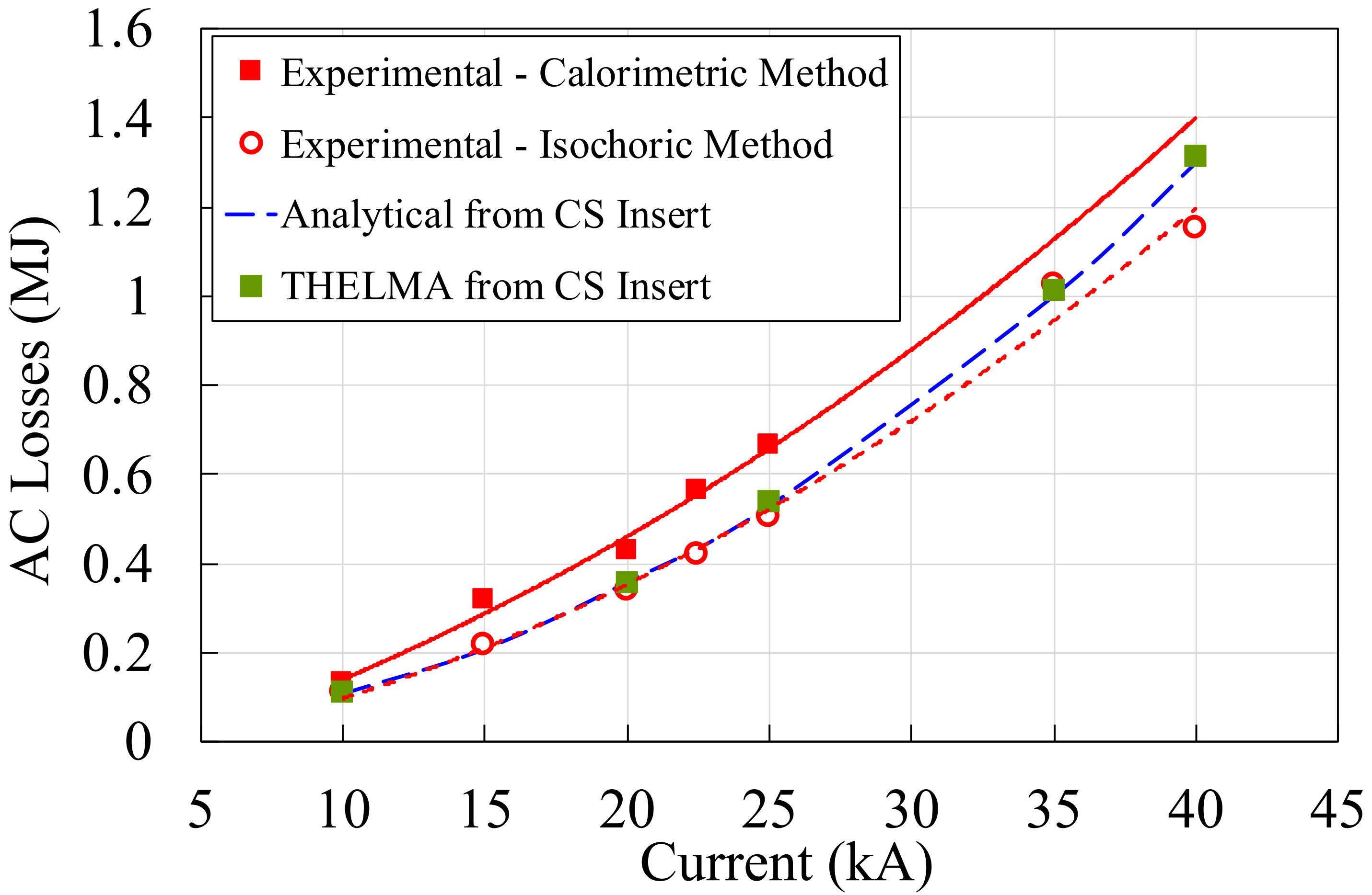




- A **predictive analysis** based on the simulations of the individual turns was carried out before the CSM#1 tests.
- The pancakes with **highest AC losses are those at the top and bottom** of the module

Single Turn model: comparison with experimental results

- The only modification applied here with respect to the predictive analysis is the change of the **dump time constants from the nominal (7.8 s)** to the measured values, in the range from 6.5 to 7.3 s

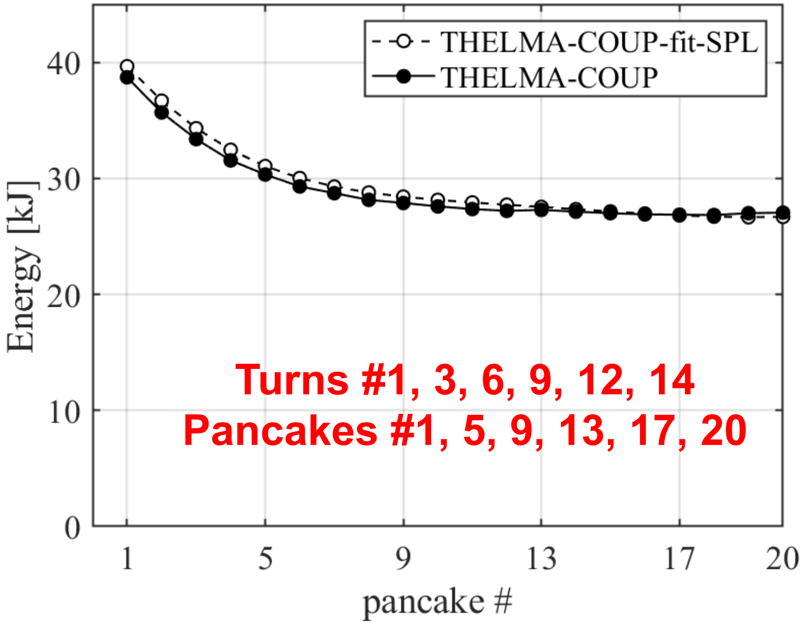


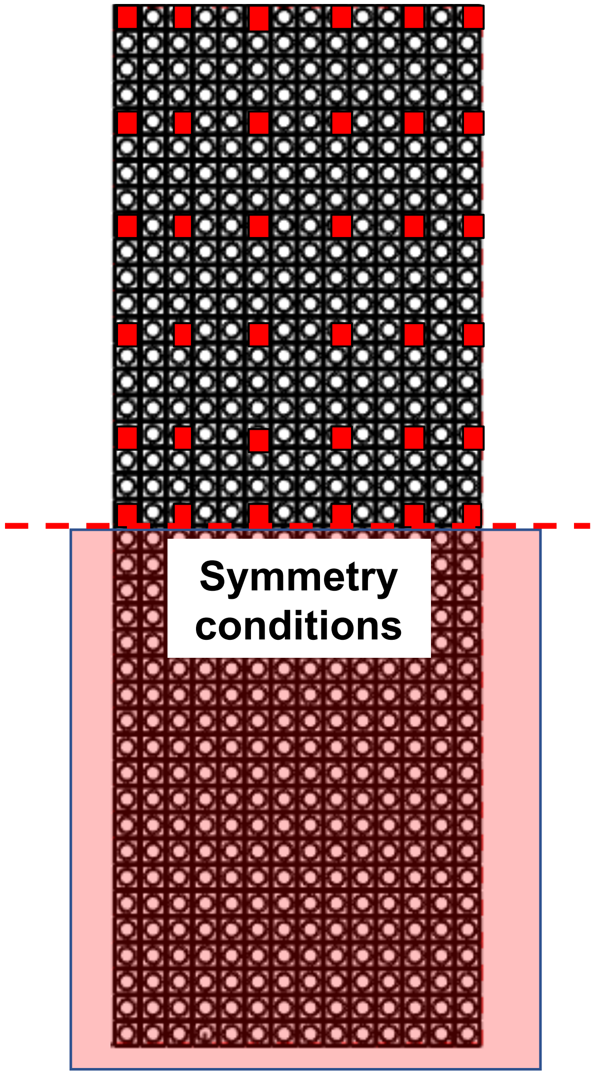
- The numerical and analytical results are in good agreement with the **experimental data**

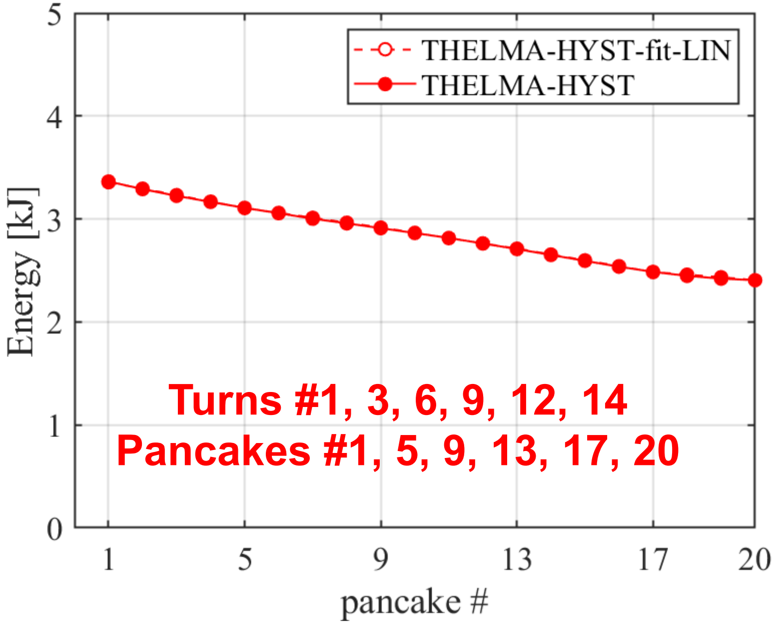
Single Turn model: how many turns are needed ? (1/2)

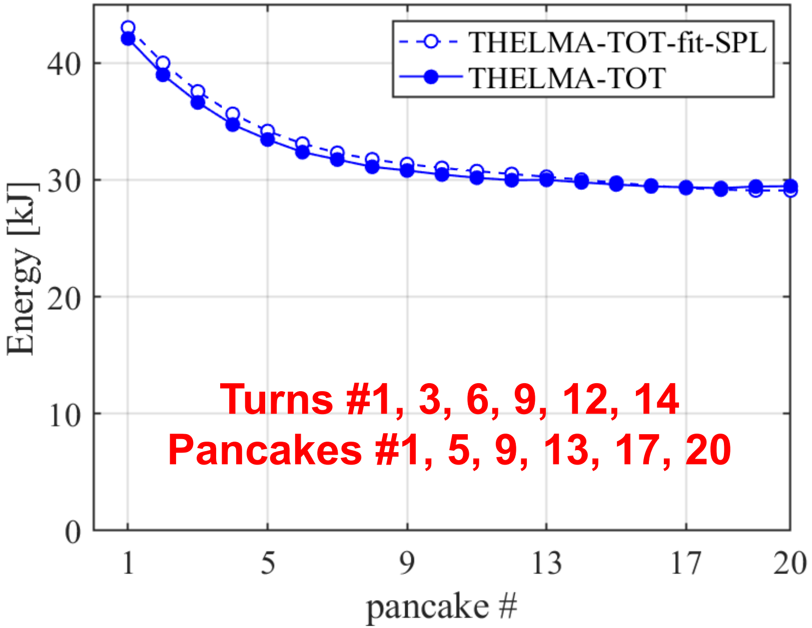
- A **2D fitting procedure** was applied to determine the error committed if reducing the number of simulated turns.

- The computations were performed by **skipping 1, 2, 3 pancakes** along the magnet height and **1, 2, 3 turns** along the magnet radius.

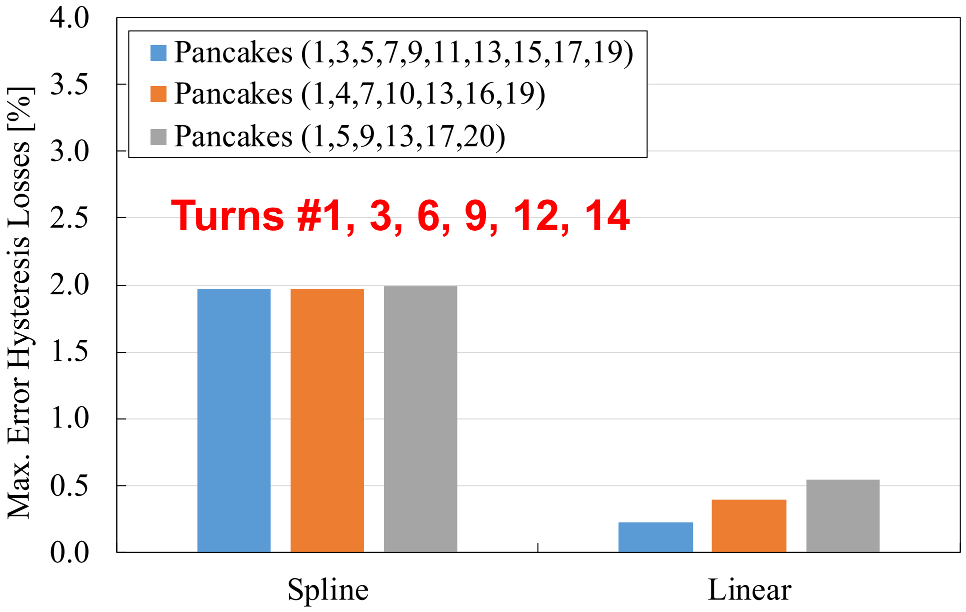






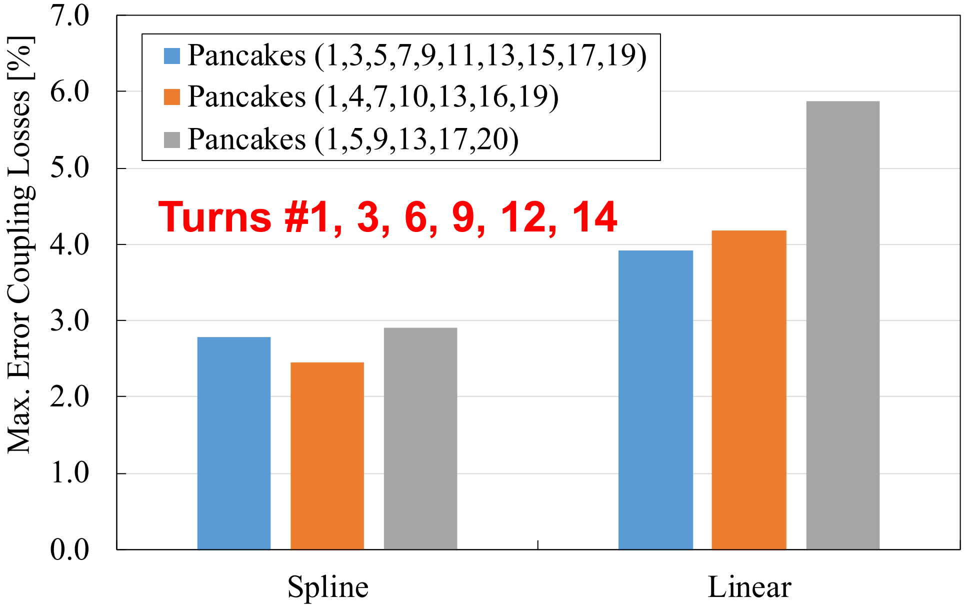


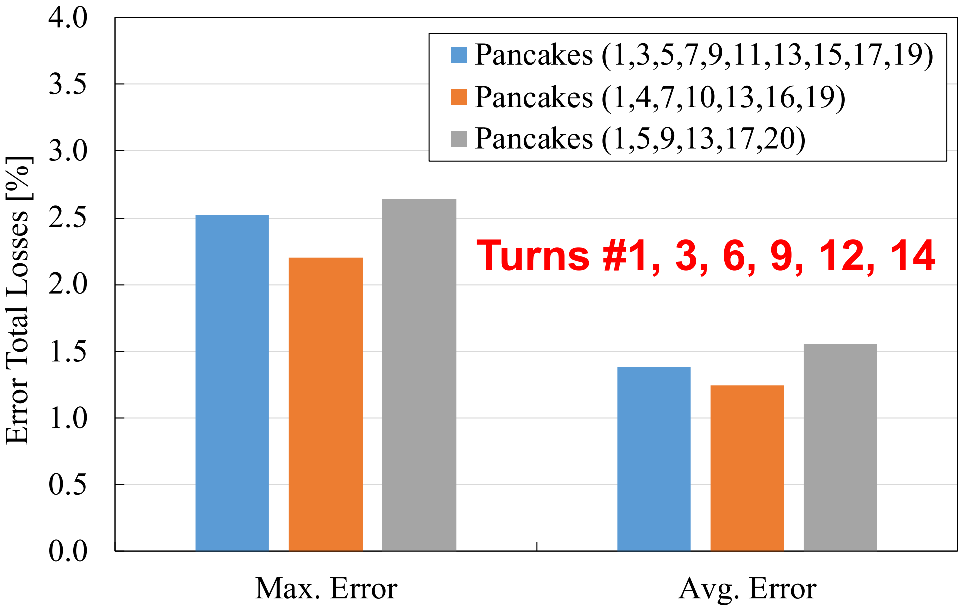
Single Turn model: how many turns are needed ? (2/2)



- The **best fitting of hysteresis losses** is obtained with a **linear fitting**, while for the **coupling losses** the best fitting is obtained with the **spline approximation**

- Using **36 turns in total** (out of 277) it is possible to approximate the AC loss results with an **average error of 1.5 %** and a **maximum error of 2.5 %** on the total energy deposited in **each pancake**.





Conclusions and perspectives

- A **numerical model** for the computation of AC losses in a full scale fusion magnet was developed and successfully implemented to the ITER Central Solenoid module.

- The **impact of the boundary conditions** on the results is limited below 10 %. The preferred choice of the boundary conditions is the uniform current distribution.

- The **number of turns** to be analysed **can be reduced from 277 to 36** with a maximum error less than 2.5 % on the losses in each pancake through a **suitable 2D interpolation.**

- The results of the THELMA model with parameters obtained from tests of the 43 m long CS Insert can be scaled up to the 6 km long CSM#1, with a good **agreement with the experimental data**.

- In **perspective** we plan to apply the model **to other CS modules,** and to improve it for the **projection of results from tests in SULTAN (SPC)**. **Full pancake simulations** are under way.

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Thank you for your attention !

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