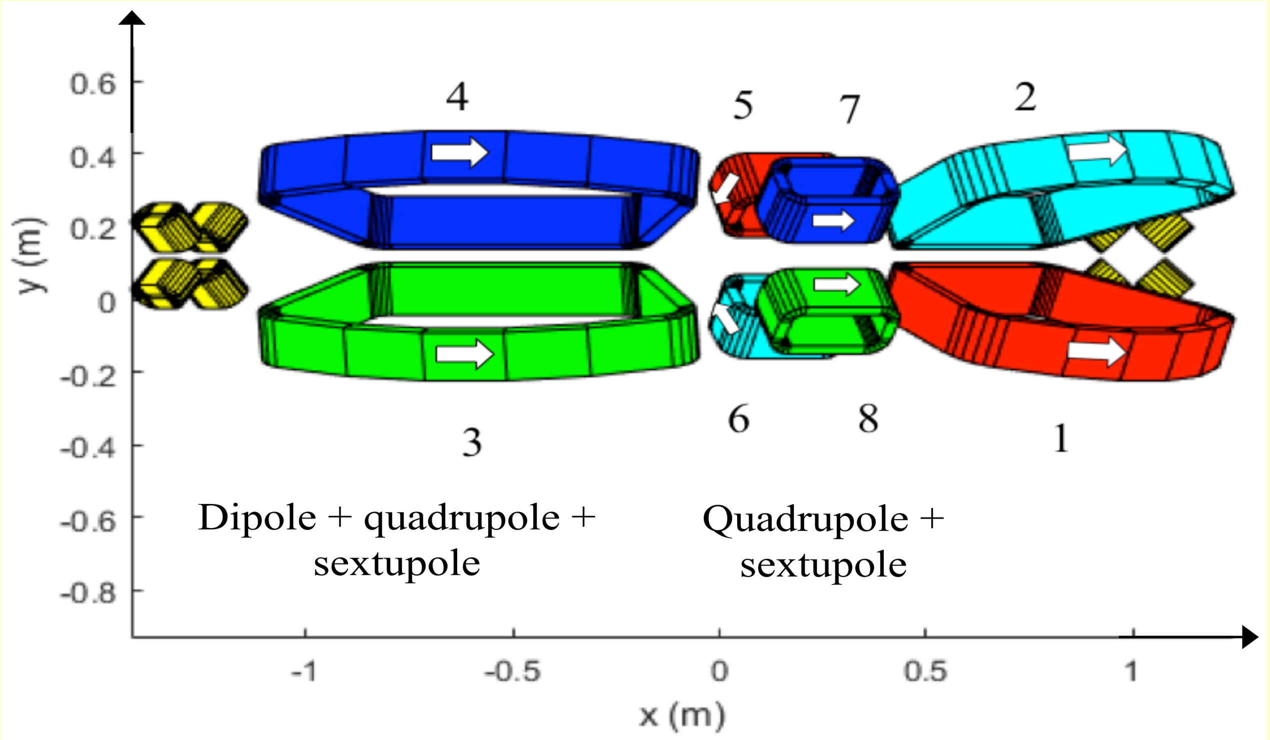
Analysis of losses in superconducting magnets based on the Nb_3Sn Rutherford cable configuration for future gantries

Marco Breschi[1], Lorenzo Cavallucci[1], P. L. Ribani[1], C. Calzolaio[2], S. Sanfilippo[2]
[1]Alma Mater Studiorum - University of Bologna, Italy, [2]PSI, Paul Scherrer Institut, Villigen, Switzerland

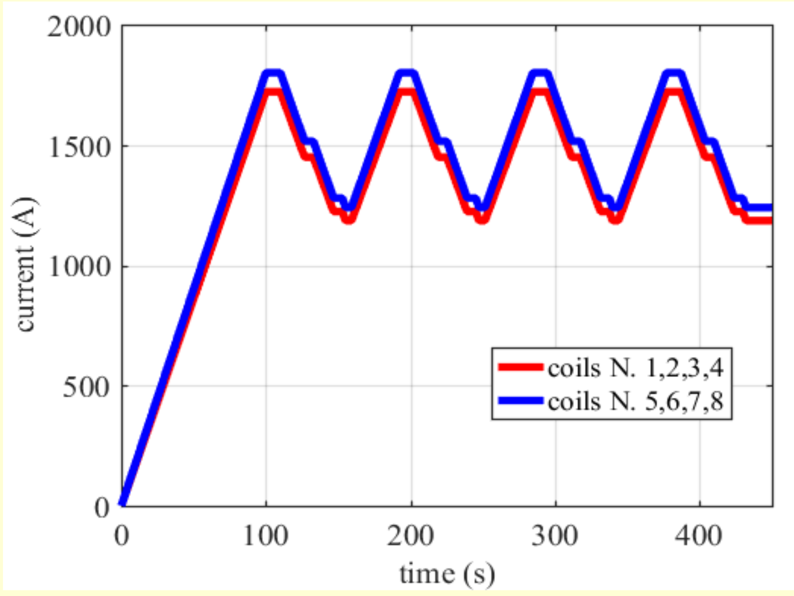
Abstract - Proton therapy for the treatment of cancers adopts a rotating system called gantry to irradiate the tumor from any direction. The gantry system consists of different beamline magnets that bend the proton beam towards the patient. The use of superconducting magnets allows reducing the weight of the last bending section. During the gantry operation, the magnetic field of the last bending section is varied in time to tune the proton penetration depth. This change determines electrodynamic transients in the superconducting strands and cables that generate losses. This work describes the application of the THELMA code to compute the hysteresis and coupling losses in an innovative magnet system designed by PSI for future superconducting gantries.

Gantry magnet system configuration and working scenario

- The combined function **magnet system configuration** includes 8 main coils and two end quadrupoles [1]:



- The reference **working scenario** of the gantry magnet system is characterized by a series of transport current ramps and plateaus :

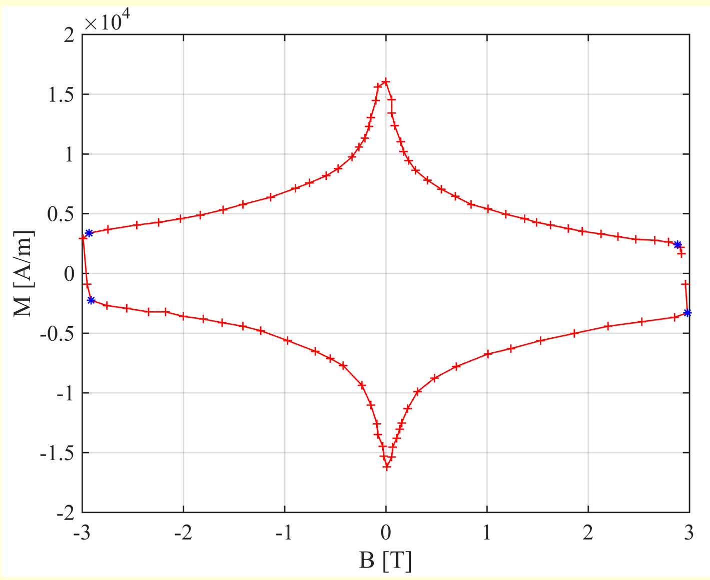


[1] S. Sanfilippo, C.Calzolaio, A.Anghel, A. Gerbershagen and J.M.Schippers, "Conceptual design of superconducting combinedfunction magnets for the next generation of beam cancer therapy gantry", Proceedings of RuPAC2016, St. Petersburg, Russia.

Loss computation methodologies

Hysteresis losses

The computation of the **hysteresis losses** starts from the calculation of the effective diameter (d_{eff}) of the strand



- A Nb_3Sn bronze strand is selected for the magnet system design

➡ $d_{eff} = 7.8\ \mu m$

- The power dissipated per unit volume is computed as:

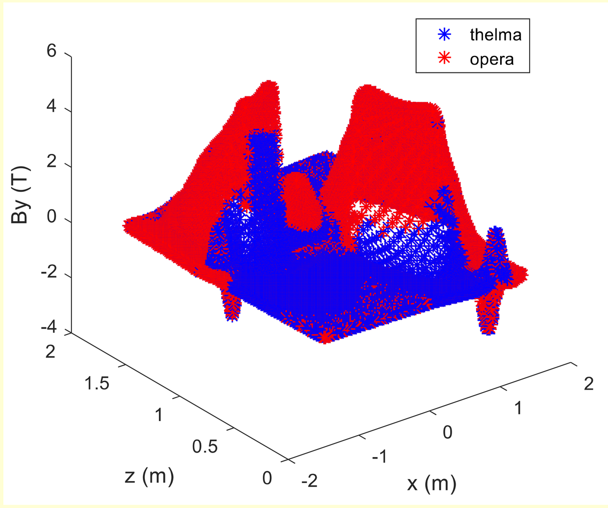
$$P_{hyst} = \frac{2}{3\pi} J_c\left(B_k, T, \varepsilon\right) d_{eff} \left|\frac{dB}{dt}\right|$$

Coupling losses

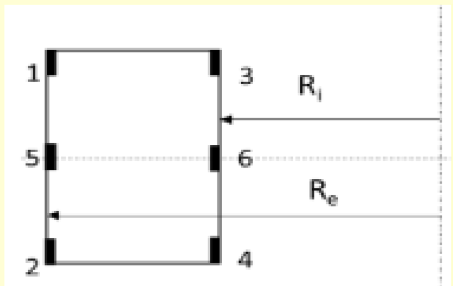
Coupling losses are computed by means of the THELMA code [2], which calculates the magnetic field distribution and **current distribution between strands**.

RUTHERFORD CABLE DATA

Parameter	Values
Number of strands	12
Strand diameter	0.81 mm
Cu/non Cu	0.93
Width	4.9 mm
Thickness	1.45 mm

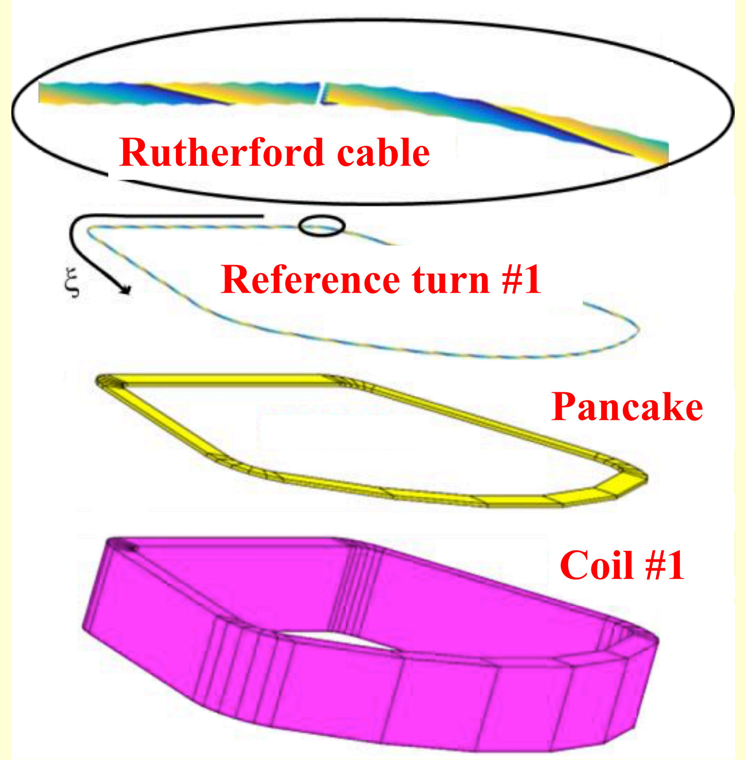


Field distribution



Reference turns

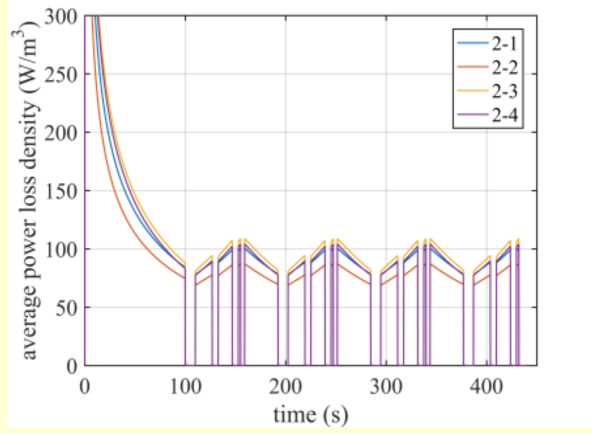
Coil #1



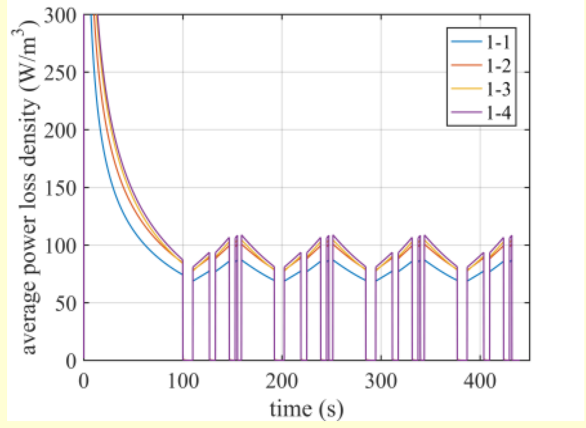
[2] M. Breschi, P. L. Ribani, *IEEE Trans. Appl. Supercond.*, Vol. 18, n. 1, 2008

Magnet system symmetry

- Coils **#1** and **#3**, and coils **#2** and **#4** exhibit the same losses
- Coils **#1** and **#2** (**#3** and **#4**) are identical exchanging the numbering of the turns



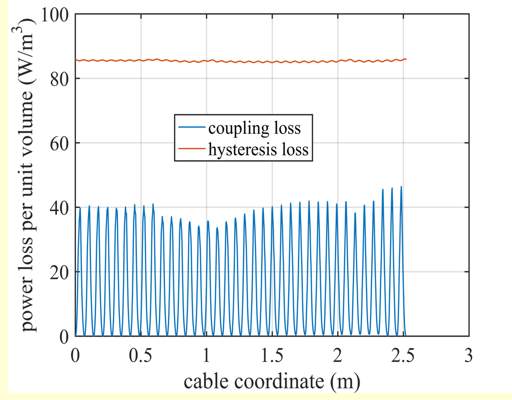
- Coils **#5** and **#6**, and coils **#7** and **#8** exhibit the same losses
- Coils **#5** and **#7** (**#6** and **#8**) are identical exchanging the numbering of the turns



➡ Coils **#1** and **#5** analyzed in detail

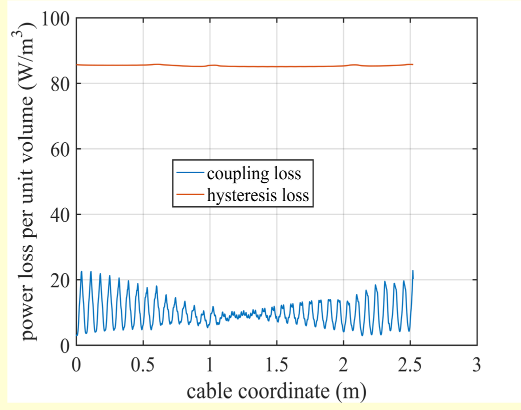
Impact of boundary conditions

- A **uniform current** and a **short circuit** boundary conditions at the turn ends were imposed to compare the losses



Short circuit

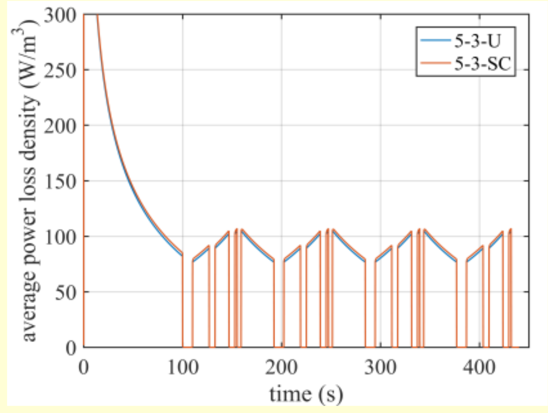
Coil # 1, turn #4 at t = 90 s



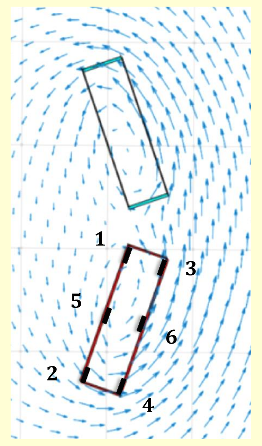
Uniform current

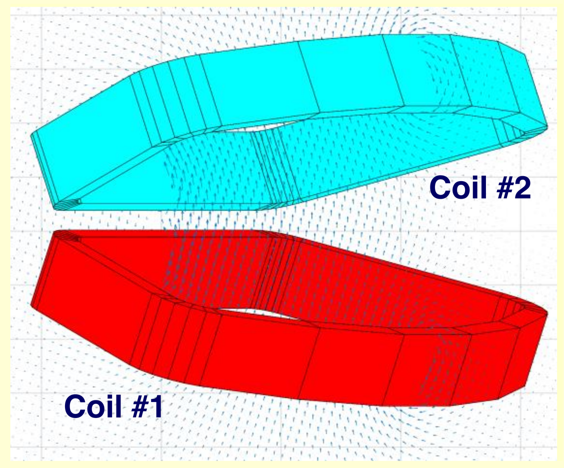
- The boundary condtions affect the **coupling losses**
- **Hysteresis** losses dominant

➡ **No relevant effect** of boundary conditions on total losses



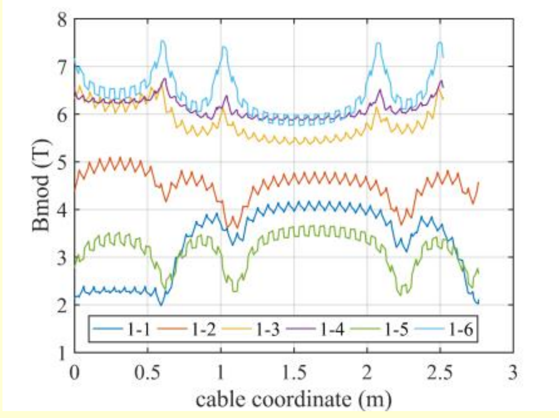
Magnetic flux density and losses



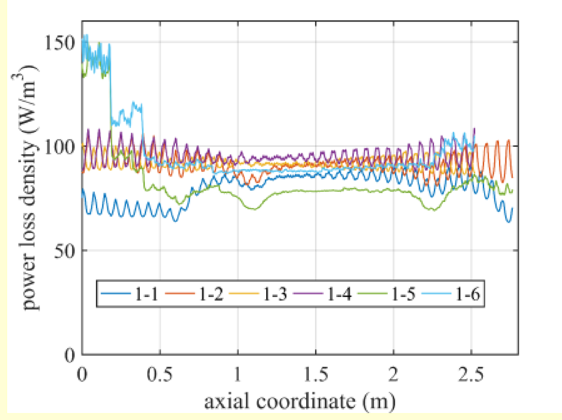


- High field locations with higher **dB/dt** but lower **Jc**

➡ Compensation effect



Field distribution along strand axis



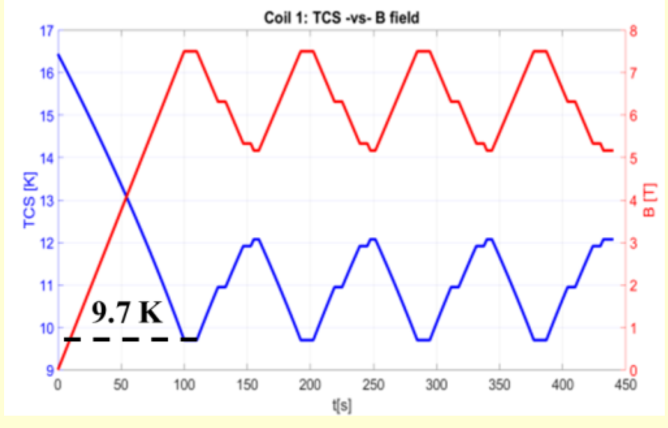
Power loss along reference turns

Thermal analysis: coil #1

- The peak temperature in coil **#1** is **8 K**, the current sharing temperature at the peak field location is **9.7 K**

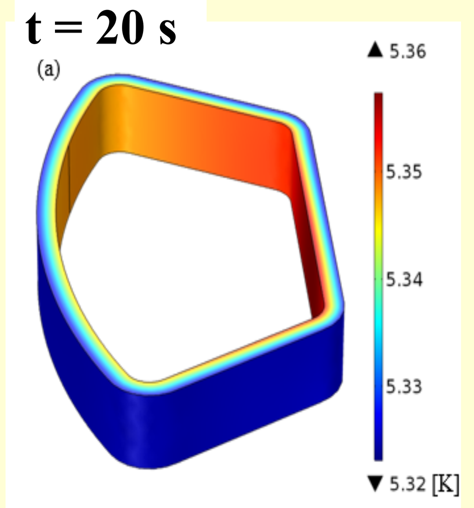
⬇

ΔT = 1.7 K

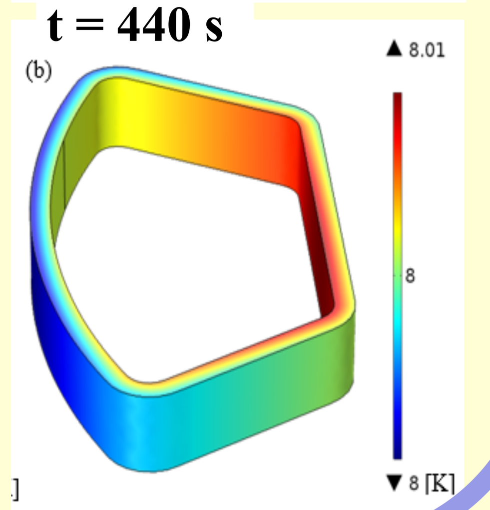


Current sharing temperature

t = 20 s



t = 440 s



Summary

- A collaboration between **PSI** and the **University of Bologna** was established to study power losses in Nb_3Sn Rutherford cables for future gantry magnet systems
- The THELMA code was adapted to the analysis of the **Rutherford cable** configuration and validated vs **analytical formulae**
- **Two coils** of the gantry magnet system were selected for detailed loss analysis due to **symmetry conditions**
- In this configuration the **hysteresis losses** in the strand are dominant with respect to the interstrand losses
- The computed losses were implemented in an adiabatic **thermal model**: the available temperature margin guarantees a **safe magnet design**

Acknowledgment

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