AC loss analysis in a stack of non-insulated REBCO tapes

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MDP Advanced Modeling meeting
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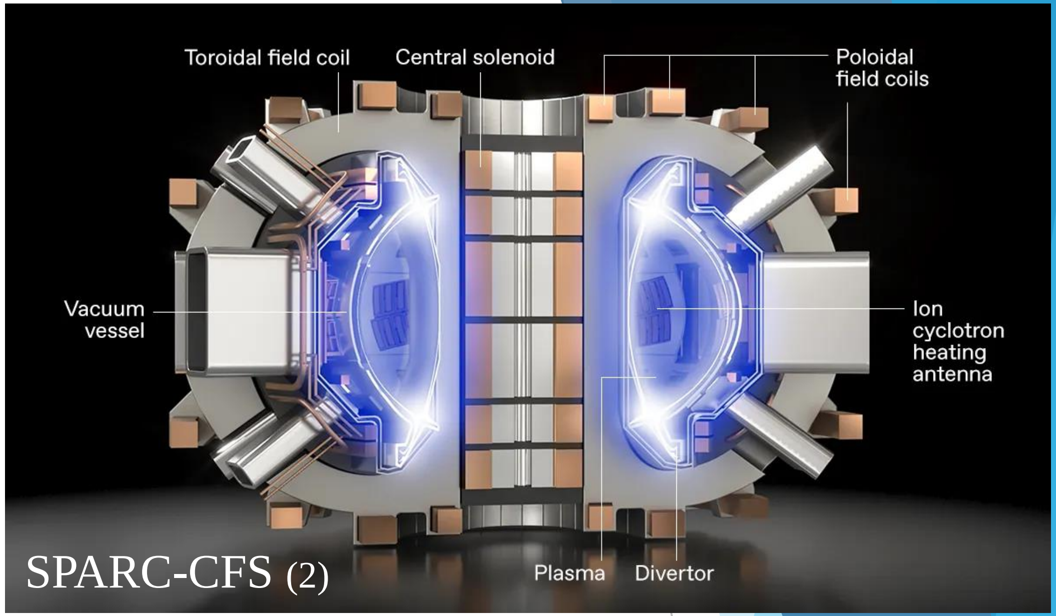
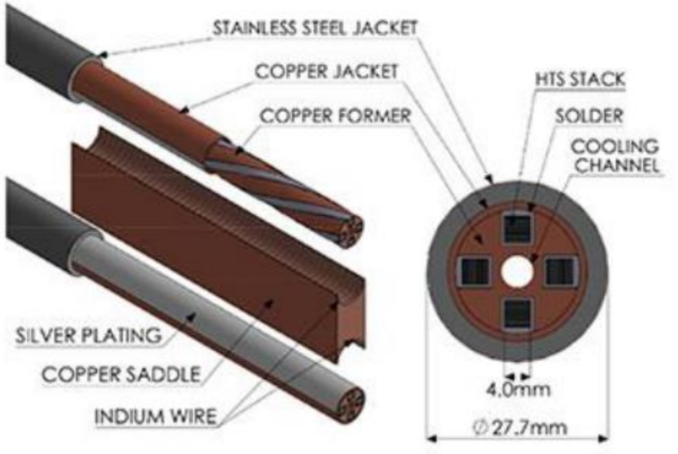
HTS cables and magnets

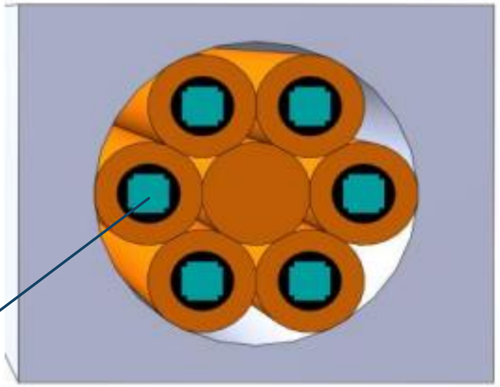
- ➢ Modern interest to Fusion based on HTS magnets:
  - Very large magnets, which require high-current cables.



SPARC-CFS (2)

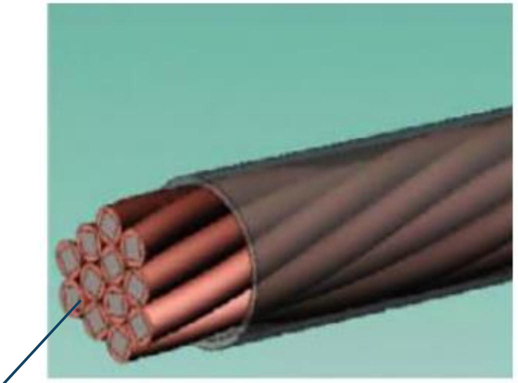


VIPER



HTS stack

KIT



HTS stack

MIT

[Pictures courtesy of MIT, NCEPU, ACT,SPC, NIFS]

Conductor concepts for fusion magnets based on HTS, most based on CICC concept (1)

- ➢ Those cables can be used for other applications, too.

Summary

- Why are we investigating non-insulated REBCO tapes?
- Aim of my thesis.
- State-of-the-art for AC loss computational calculation.
- Geometry of 3D COMSOL model considered, the material properties, with focus on the transverse resistivity of the stack. This latter value has been calculated from a transverse resistance of a bare-REBCO stack, measured through an experiment, at Fermilab's laboratory (brief overview of the experiment conducted will be provided).
- Boundary conditions imposed: changing external magnetic field B.
- Physics of the model: H-formulation and calculation of energy and power loss in COMSOL.
- Mesh selection: Mesh independence.
- Results of AC losses for the stack considered:
  - Dependence on transverse resistivity of the stack.
  - Dependence on stack length.
  - Dependence on stack width.
  - Dependence on the number of tapes of the stack.

Why non-insulated tapes?

- Good for quench protection →"the extra current can bypass the local hot spot and dissipate on the coil during a quench operation"(4)
  - That means less "thermal stabilization problems"

- **Drawbacks**:
- "The complete charging process is much longer than the power supply ramping process itself" (4).
- AC-loss problem

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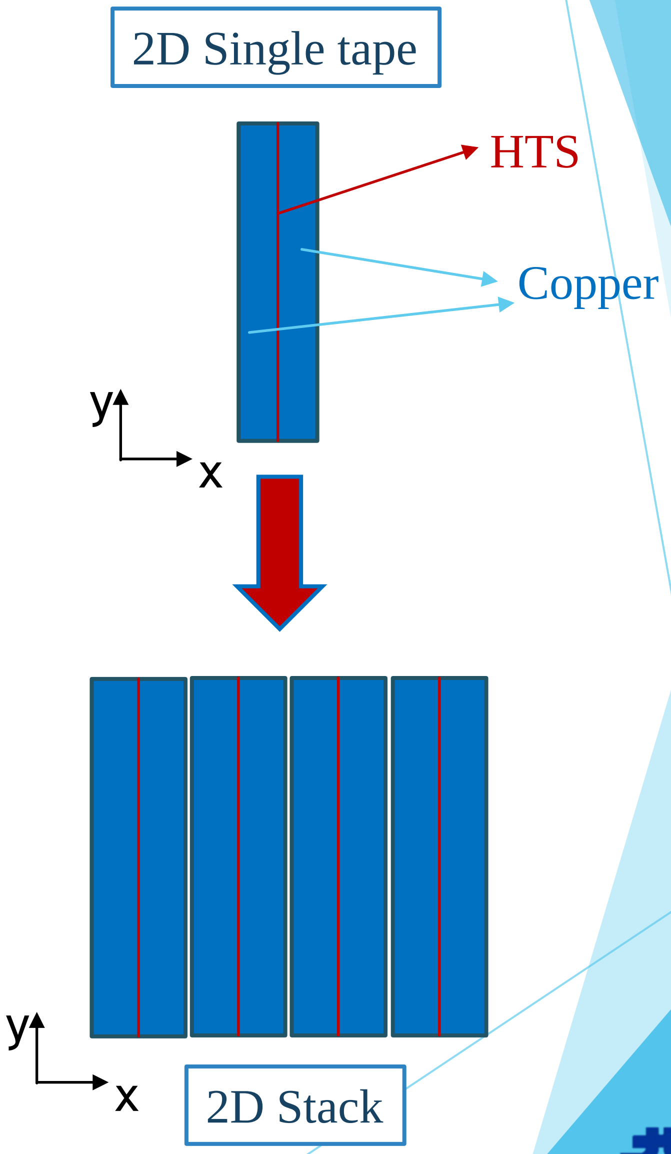
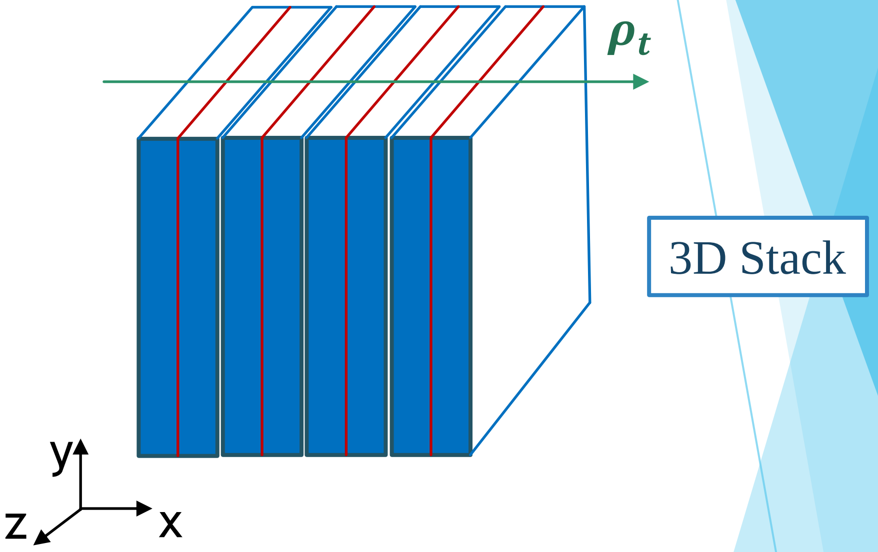
Aim of the thesis

- Calculate and analyze AC-losses for non-insulated REBCO tapes , due to an external, changing magnetic field.
- First, analytically:
  - A single superconducting layer : Critical State Model.
  - A single tape, (approximated as a superconducting layer surrounded by copper layers). In this case, it was possible to calculate AC losses thanks to Faraday's law and the E-J Power's law or considering the Critical State model for the superconductor and eddy current loss for copper.
  - The AC losses of the superconducting layer were then compared to those of the copper layer.
  - At the end, a 2D stack of tapes have been considered. Faraday's law and E-J Power's law have been used for power and energy loss calculations (comparison between B// and B⊥).
- Then, computationally, with COMSOL, 2D models of the superconducting layer, the single tape and the stack have been realized and analyzed. The computational results have been compared with the analytical ones.



Fermilab

- 3D COMSOL model of the stack has been created:
  - For modelling the stack on COMSOL, I need the value of the transverse resistivity.
- Using the TPI (Transverse pressure device, available at Fermilab), the transverse resistance and the effect of pressure on it, have been measured.
- Using transverse resistivity, derived by the transverse resistance, AC loss analysis in a stack of non-insulated REBCO tapes have been conducted.



These results will be presented here

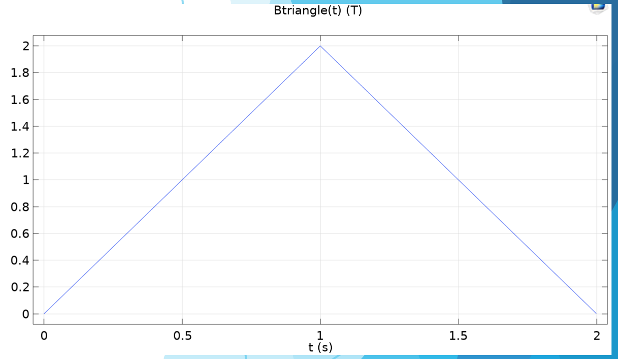
State-of-the-art for computational AC loss calculation

A. Zappatore, N. Bykovskiy and G. De Marzi (2024), "Validation and Application of Hysteresis Loss Model for HTS Stacks and Conductors for Fusion Applications,"

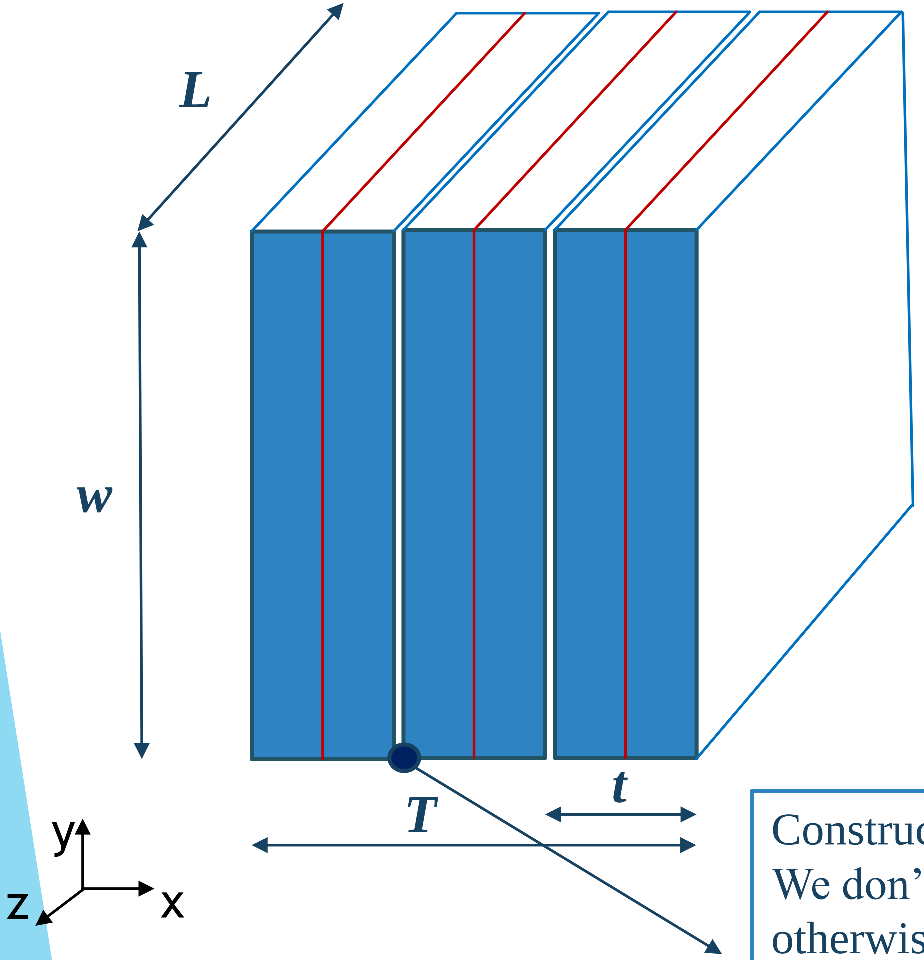
- Done for DEMO-hybrid Central Solenoid (CS).
- BSCCO conductor considered.
- 2D COMSOL model.
- Ampere’s and Faraday’s law as governing equations of the model.
- Stack of tapes homogenized (“Ic homogenized according to the fraction of superconducting area present in the stack”)
- Background DC magnetic field applied perpendicular to the stack, plus sinusoidal AC magnetic field of ± 0.2 $[T]$, f=0.3-1.5 [Hz]

What has been changed

- ➢ REBCO conductor considered.
- ➢ 3D COMSOL model, for the stack.
- ➢ H-formulation: Faraday’s law is governing the equations of the model.
- ➢ Each tape of the stack is approximated with a layer of superconductor and 2 layers of copper (to investigate different power loss distribution).
- ➢ No DC background magnetic field, but only an external changing magnetic field (triangular shape).
- ➢ Transverse resistivity considered.



Model geometry



L= tape length
w=tape width
t=tape thickness
T=stack thickness

L	5	mm
w	1	mm
t	0.1	mm
HTS thickness	1	um
T	0.3	mm

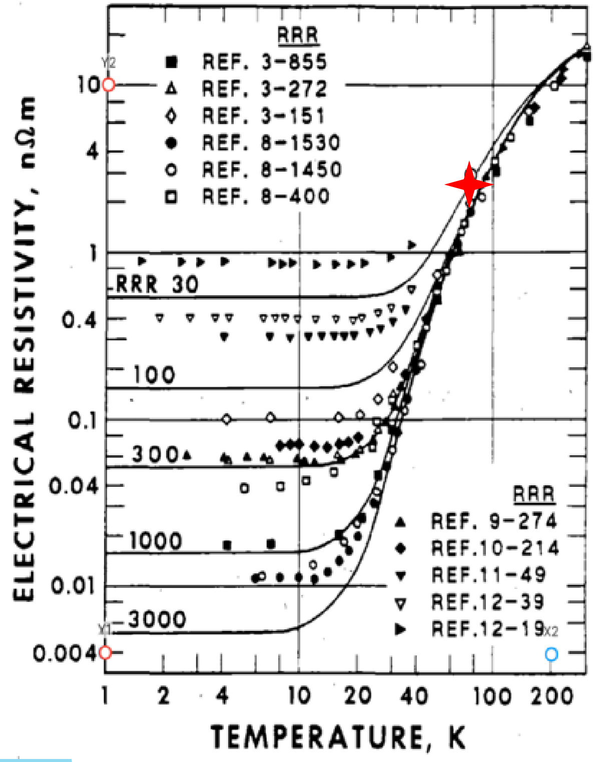
Stack volume=5e-10 [m^3]

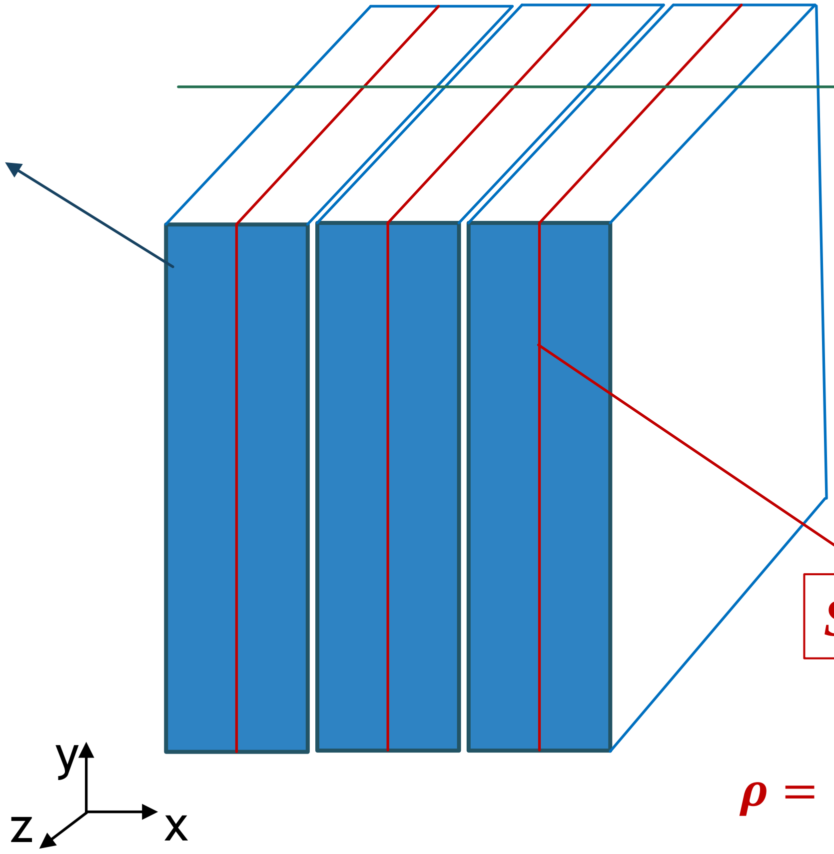
Construction started from here: (0,0, -L/2).
We don't want the SC layer on the center (0,0), otherwise, some instabilities in the AC-loss results could happened (this phenomenon has been observed in previous models).

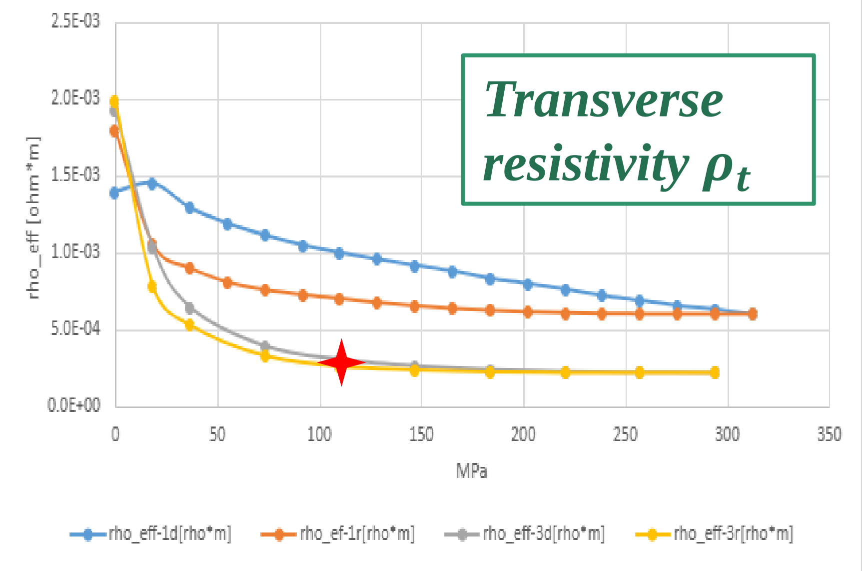
Material properties

Copper

$\boldsymbol{\rho}(\mathbf{77K})$ =*2.9e-9 [Ω*m]*
for **y** and **z**
RRR(Residual Resistivity Ratio)=30







Transverse resistivity ρ_t

Applied in x direction for the entire stack
ρ_t=*0.25 [mΩ*m]*

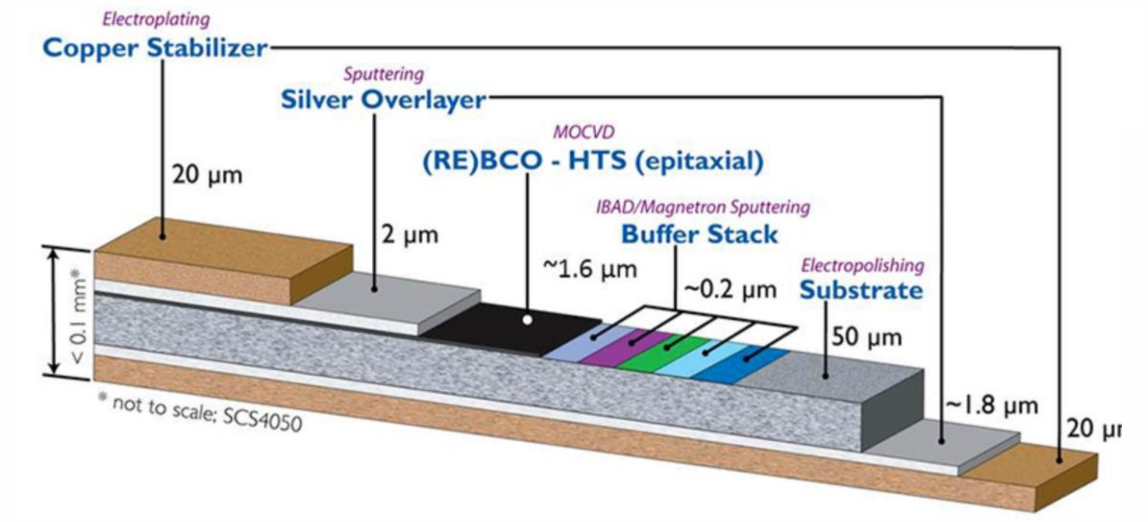
Superconductor

E-J Power's law:

$$\boldsymbol{\rho} = \left(\frac{Ec}{Jc}\right)\left(\frac{|J|}{Jc}\right)^{n-1}, \text{ for } \mathbf{y} \text{ and } \mathbf{z}$$

Jc=2.4e8 [A/m^2]
n=20
Ec= 1e-4 [V/m]

REBCO tapes

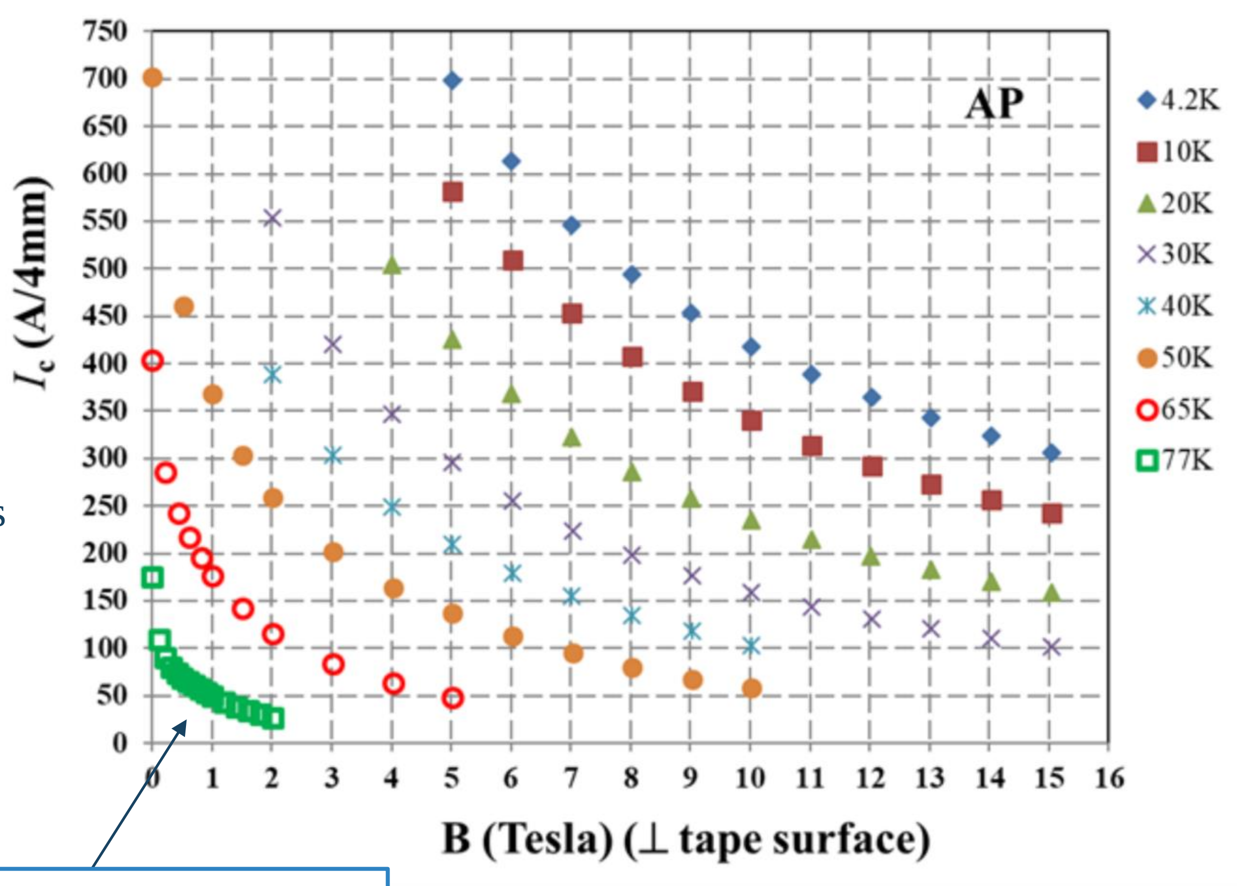


Ic(77K, 0T)	170	A
Ic(77K, 2T)	25	A
Ic(avg)	97.5	A

Range of values for the external B applied

Considering a tape with 0.1[mm] thickness and 4 [mm] width

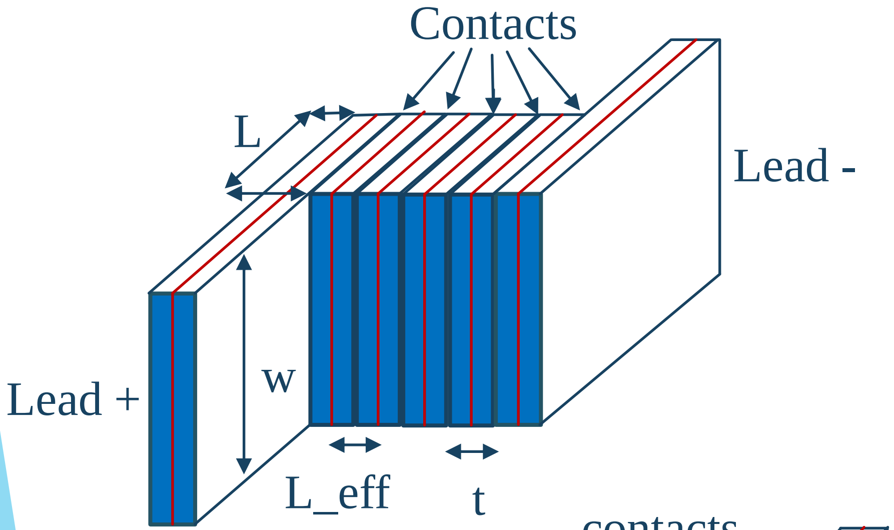
Jc= 2.4e8 [A/m^2]

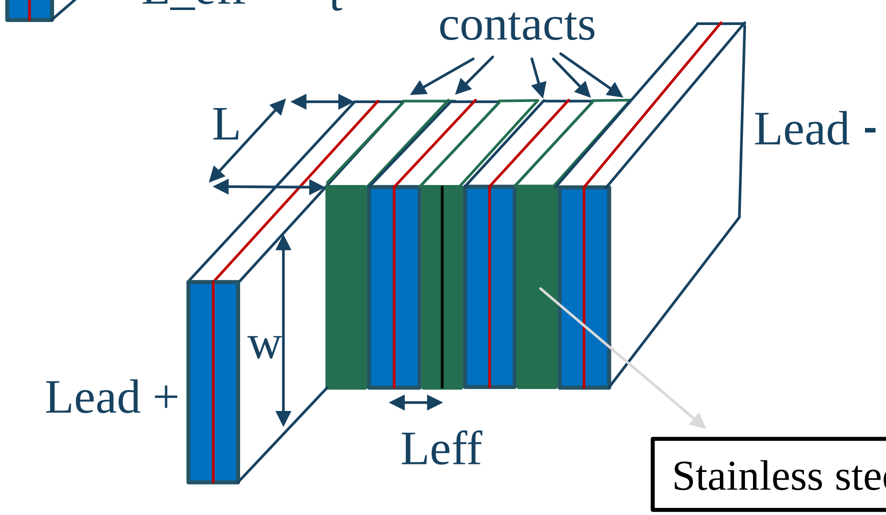


Reference temperature equal to 77K

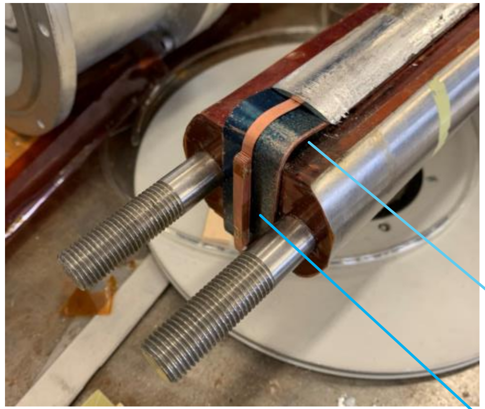
To understand where the value of ρ_t comes from…

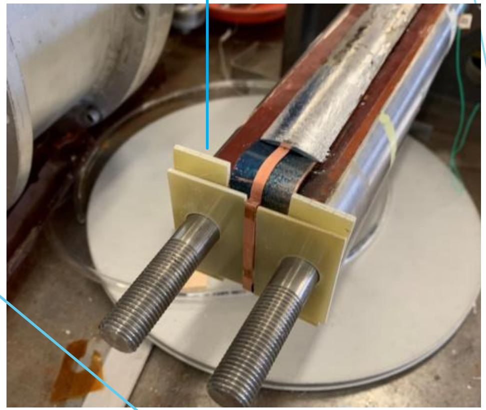
- The *transverse resistance* of a stack of bare REBCO tapes, while applying an increasing transverse pressure, has been measured. The TPI (Transverse pressure device), available at Fermilab's laboratory, was modified and used for this purpose.





Stainless steel

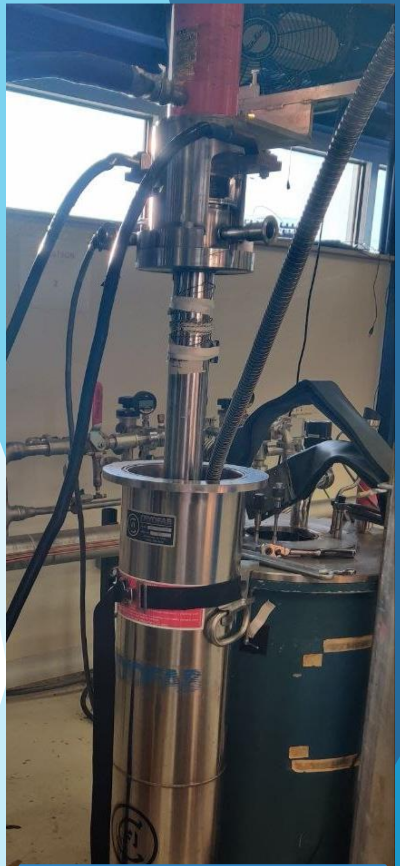




G-10 for stability of the sample

Support with a bending radius >6mm

16 REBCO tapes wrapped in Kapton

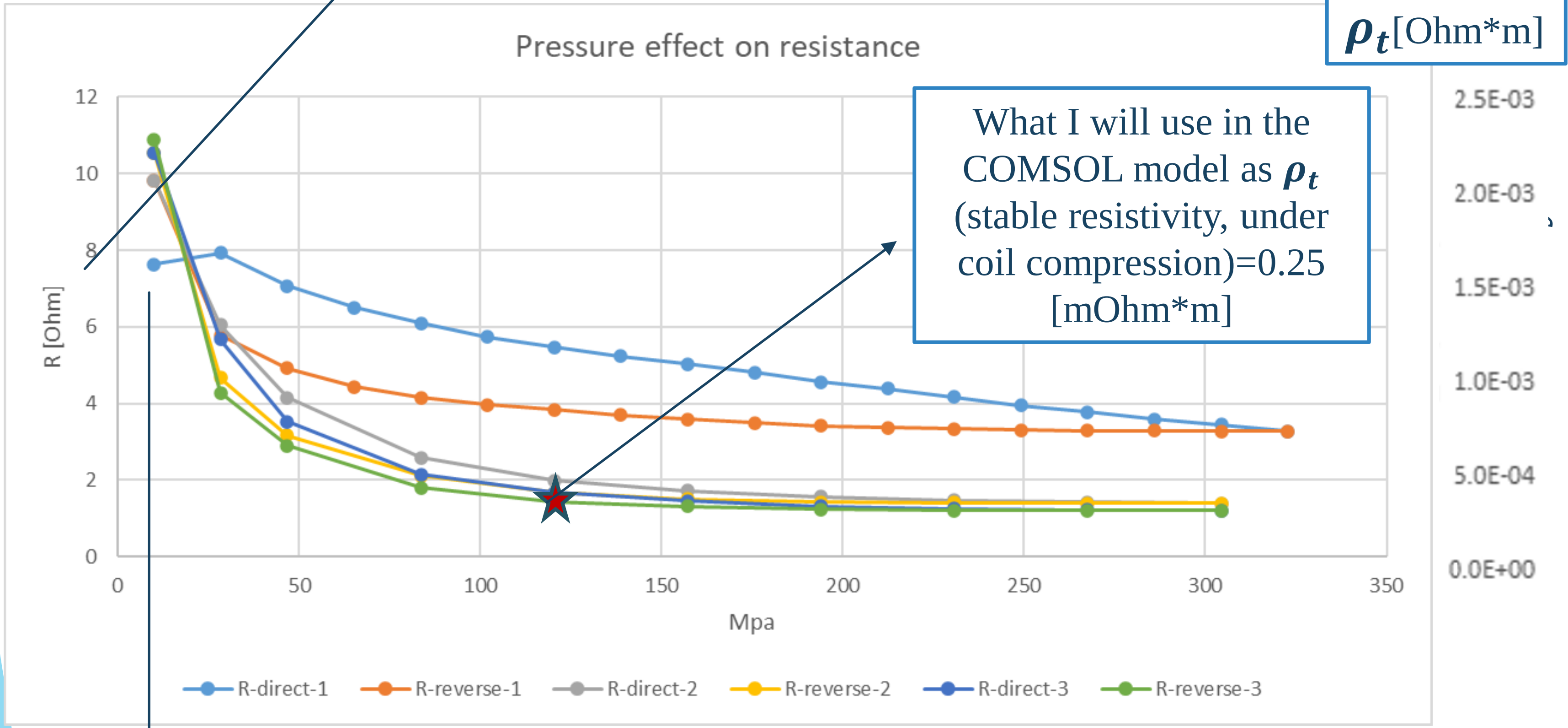


Experiment conducted in liquid nitrogen (77K)

- <u>Transverse resistance R decreases with an increasing pressure</u> (From a microscopic point of view, pressure creates micro-plastic deformations, which increase the contact surface, so the resistance decreases.)

Experiment procedure

1) Apply transverse pressure (about 10 MPa).
2) Ramp current applied on the stack (up to 10 [A]).
3) Measure voltage (voltage taps on leads) with DAQ.
4) Stop current.
5) Repeat from (1) to (4), until reaching maximum pressure (322 MPa).
6) Decreasing pressure, doing (2) -(4) until reaching starting point.
7) Repeat this other 2 times.
8) Post processing: evaluate R for each step.



$\boldsymbol{\rho_t}$[Ohm*m]

What I will use in the COMSOL model as $\boldsymbol{\rho_t}$ (stable resistivity, under coil compression)=0.25 [mOhm*m]

There is a pre-compression (about 10 MPa) due to the TPI weight on the sample.

$$\rho_t = R_{cont} * \frac{A}{L}$$

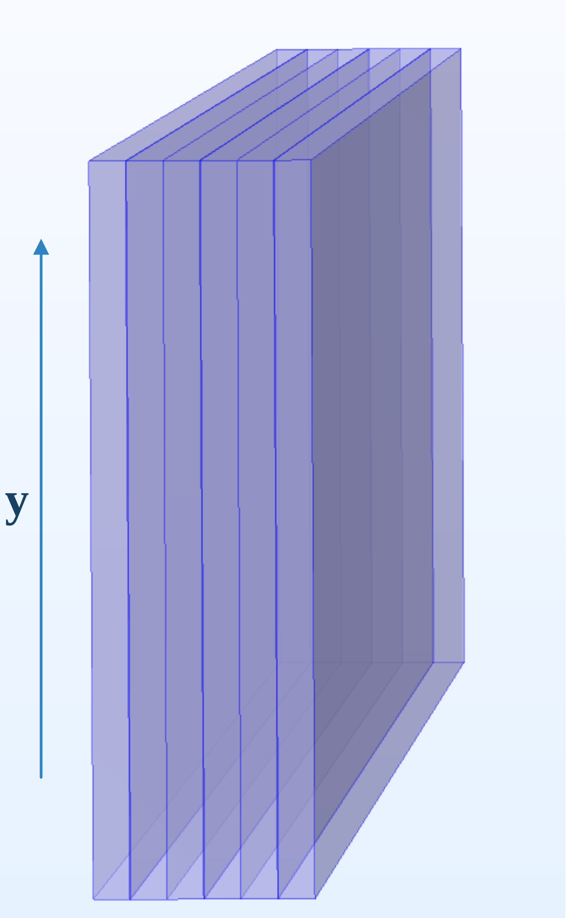
ρ = transverse resistivity

L= effective length of a contact (Cu-Cu)

A= area of contact

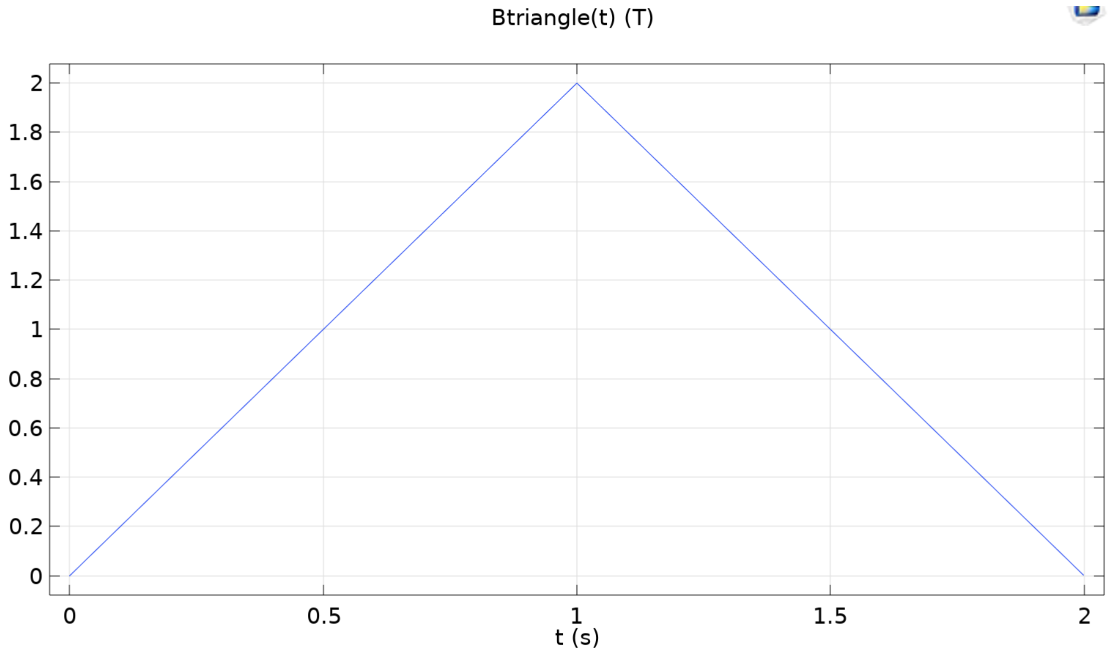
R_{cont}=contact resistance = $\frac{R}{N_{cont}}$

Boundary conditions



An external changing magnetic field B has been applied on the external surfaces of the stack, for 2 [s], parallel to the stack (y-direction)

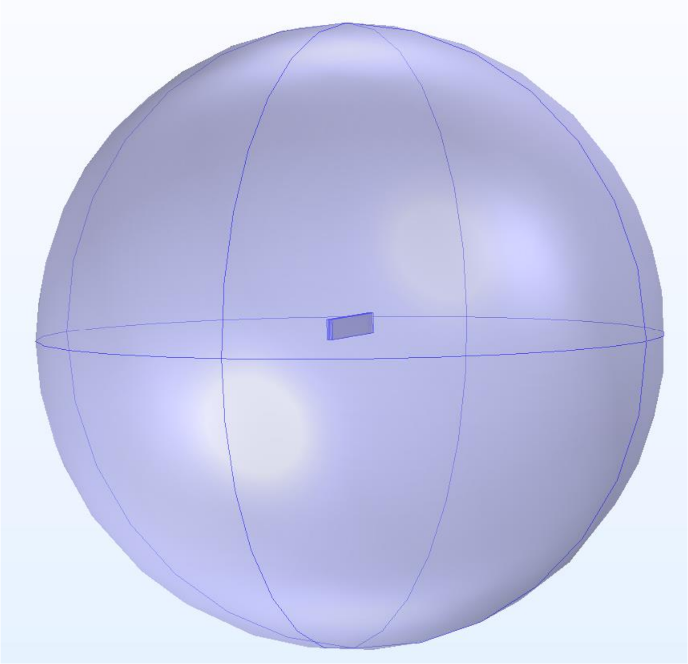
Triangular shape of B



$$\boxed{\frac{dB}{dt} = 2\left[\frac{T}{s}\right]}$$

Together with amplitude: Parameter!

Why was B applied on the external surfaces?



Before: there was a spheric air domain outside the stack and B was applied on its outer surfaces. There were many more mesh elements, so the computational time was much higher (many hours)

⬇

Removing this sphere, and applying B on the outer surfaces of the stack, the power loss [W] was the same, but the computational time has decreased a lot (minutes)

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Physics of the model

- ***H-formulation*** *(7)*:
  - Magnetic field formulation (mfh):

$$\mathbf{J} = \nabla \times \mathbf{H}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

H= magnetic field [A/m]

  - Faraday's law for *SC*
  - Faraday's law for *Copper*

$$\mathbf{J}_c = \sigma \mathbf{E}$$

$$\mathbf{E} = \rho(\nabla \times \mathbf{H} - \mathbf{J}_e)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

Required:
resistivity (x,y,z),
relative permeability (=1),
relative permittivity (=1)

  - Initial values: H=(0,0,0) [A/m]
  - Magnetic field: $H_0 = \frac{B}{\mu_0}$ applied on y direction (BC)

Thanks to H-formulation it is possible to have a more realistic current density distribution in the SC (in A-formulation, for example, the current density is uniformly distributed)

Power loss [W]: $P = \iiint J \cdot E \, dxdydz$

Energy loss [J]: $E = \oint P \, dt$

E[J]= P[W]* Δt

Constant values
1 cycle considered

Power loss density [W/m^3] $= \frac{P}{V}$

Energy loss density [J/m^3]$= \frac{E}{V}$

More fundamental for comparison

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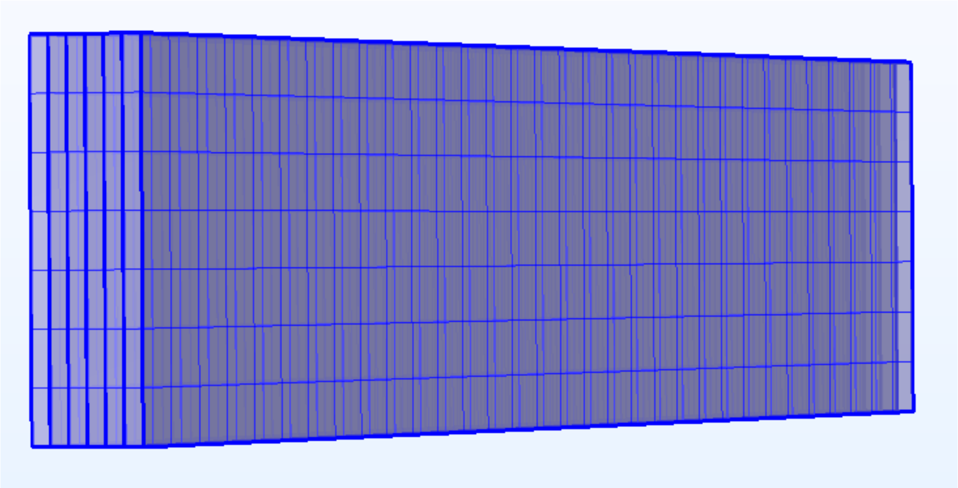
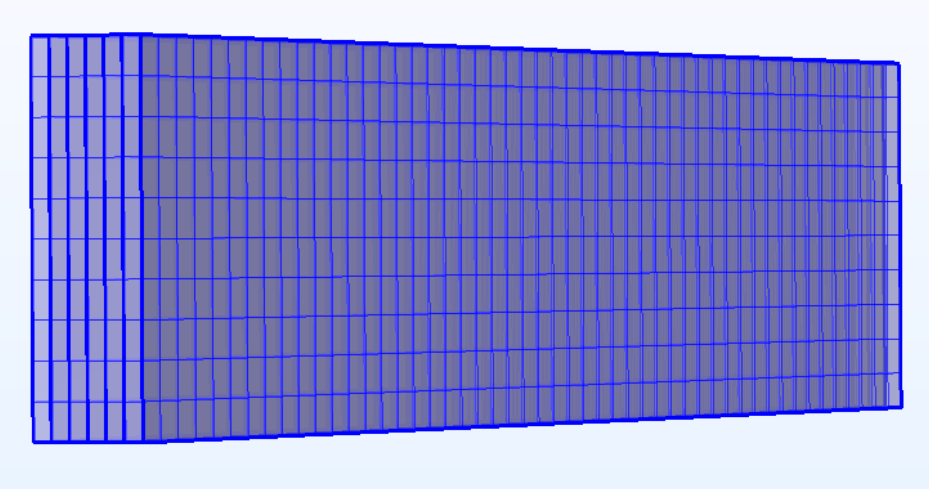
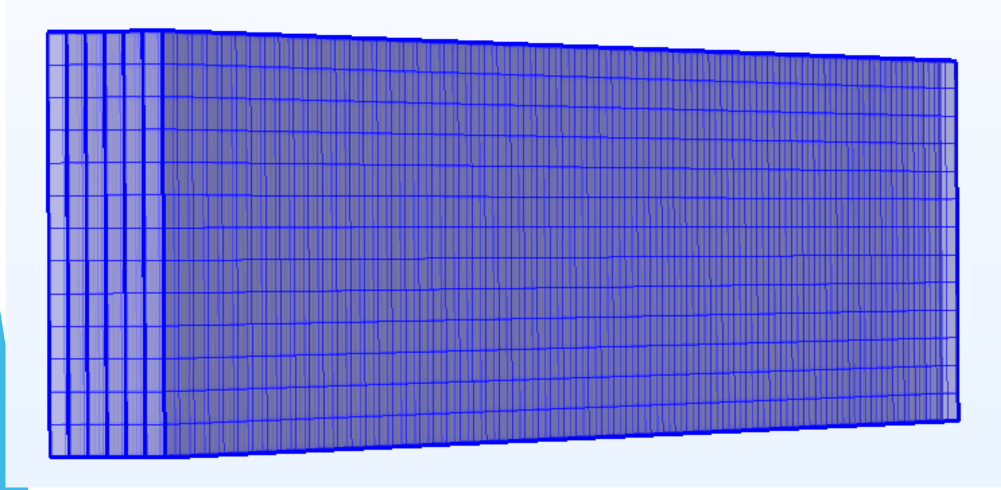
Mesh independence



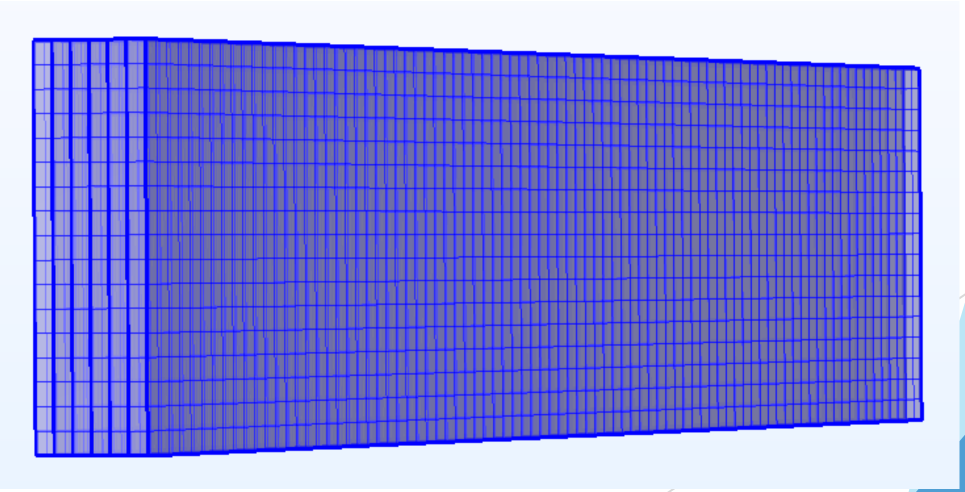
1° mesh, 2016 elements



2° mesh, 4500 elements



3° mesh, 7371 elements



4° mesh, 12852 elements

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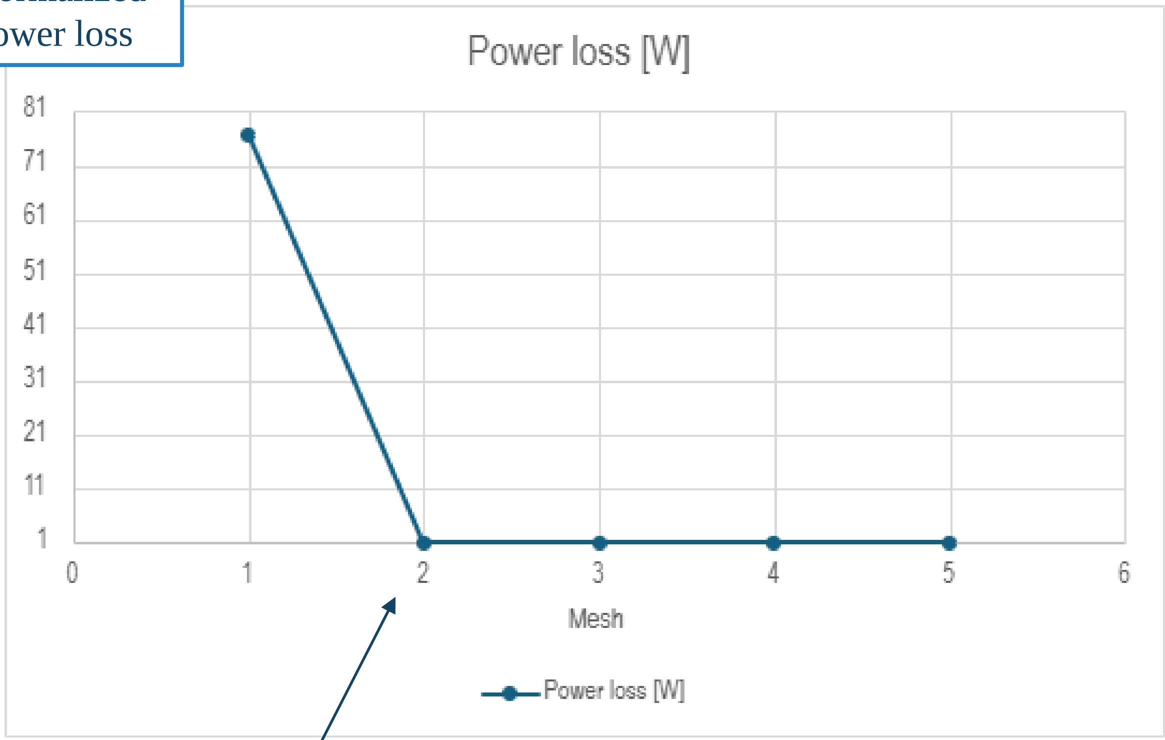
Mesh independence

Normalized Power loss

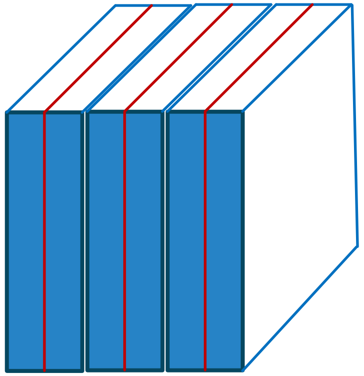


From here, the results are stable

Mesh	Power loss [W]
1	7.2221E-09
2	9.4384E-11
3	9.4378E-11
4	9.4384E-11

The mesh selected for the following models

Power loss [W]: $\iiint J \cdot E \, dxdydz$



Evaluated in the entire volume of the stack

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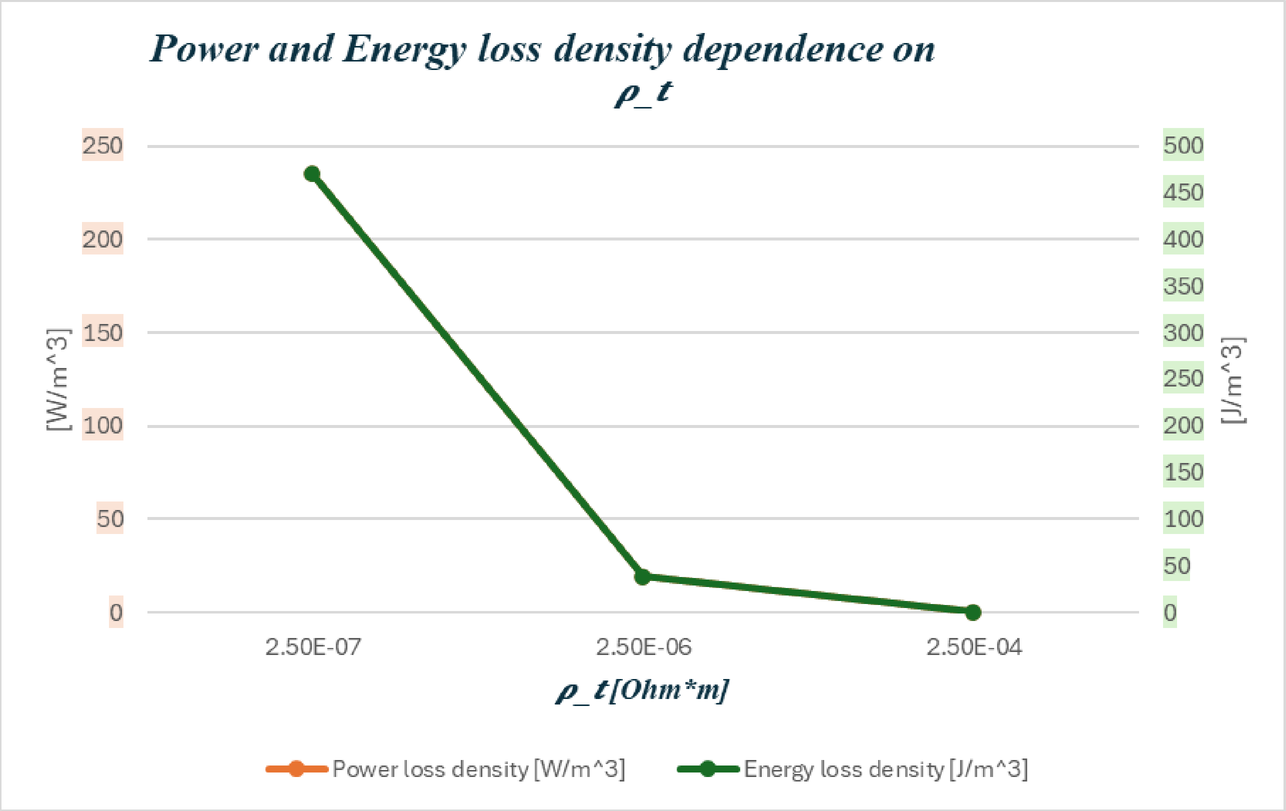
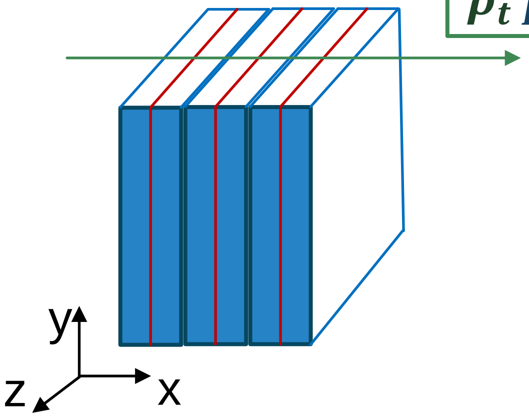
Power and energy loss density dependence on transverse resistivity



ρ_t [Ohm*m]	Power loss density [W/m^3]	Energy loss density [J/m^3]
2.50E-07	2.35E+02	4.70E+02
2.50E-06	1.92E+01	3.84E+01
2.50E-04	2.59E-01	5.18E-01

ρ_t parameter



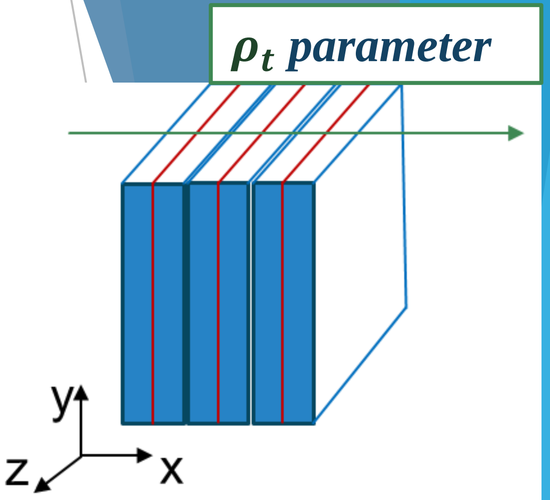
L	5	mm
w	1	mm
t	0.1	mm
HTS t	1	um

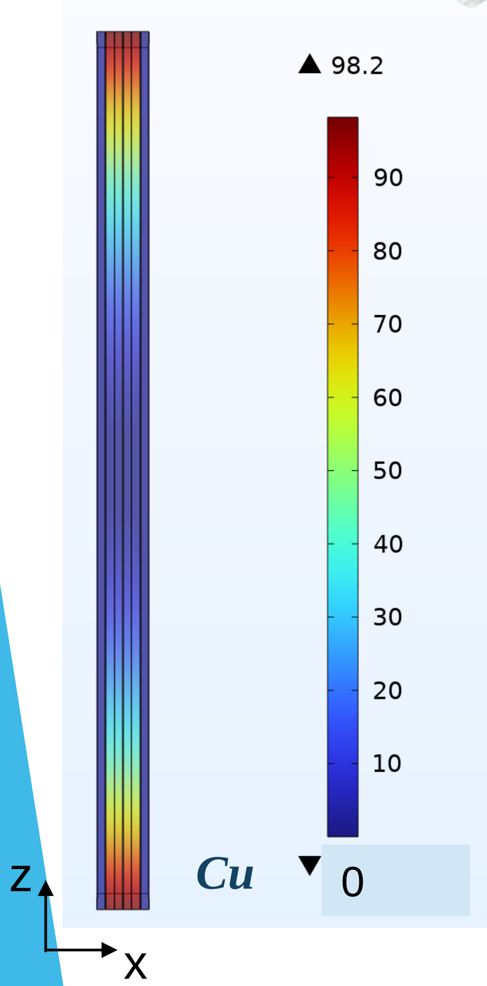
- Power and energy loss are inversely proportional to $\boldsymbol{\rho_t}$ (remember power loss density due to eddy currents)

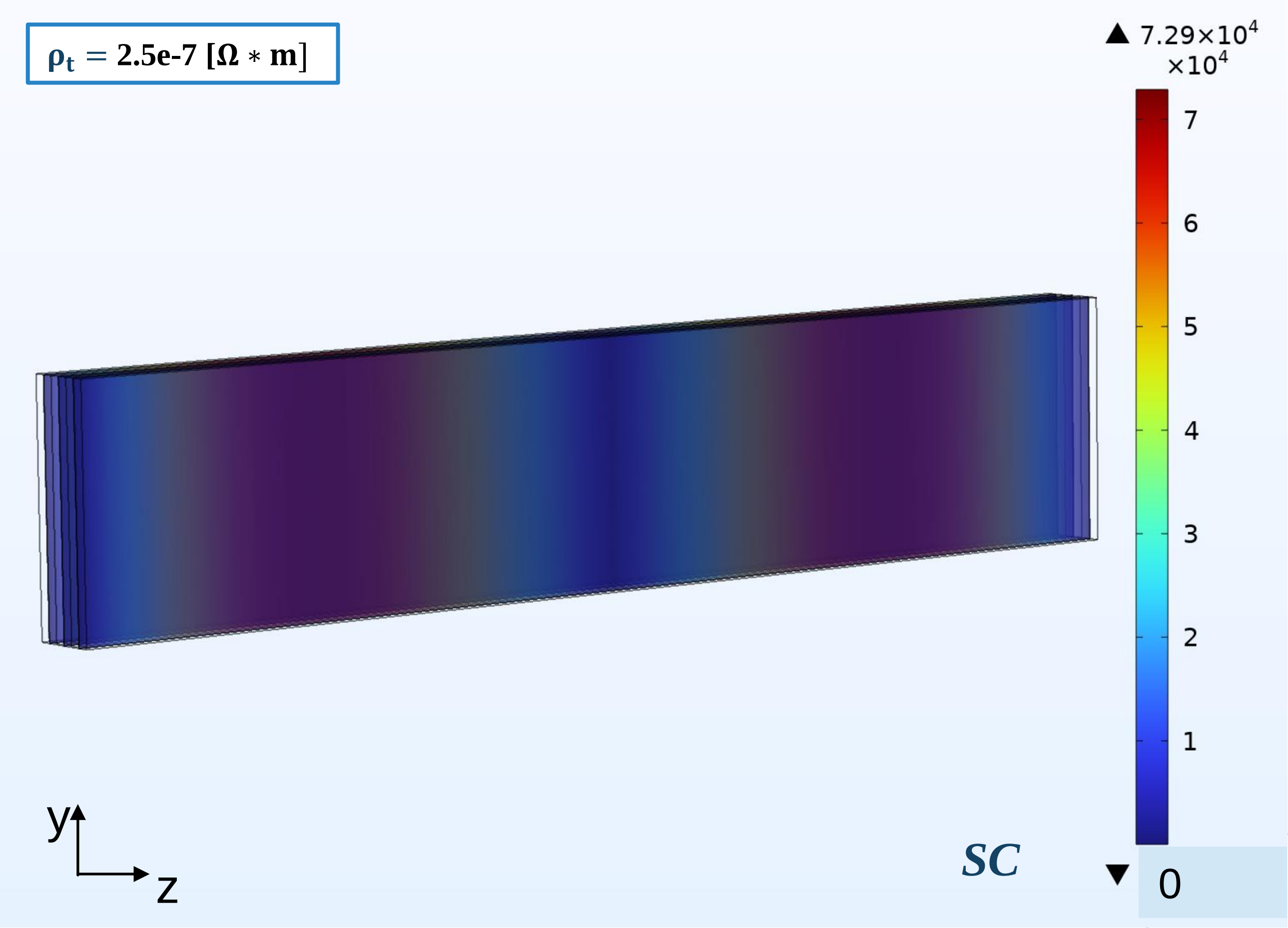
$$\frac{P}{V}=\frac{1}{12}\left(\frac{d^2}{\rho}\right)\left(\frac{dB}{dt}\right)^2$$

$$\frac{E}{V}\,\alpha\left(\frac{\mathrm{dB}}{\mathrm{dt}}\right)\mathrm{dB}$$

Power loss density [W/m^3] distribution in Cu and SC







- *Power losses [W/m^3] in copper layers are much smaller than the ones in SC. This has been observed also in previous analytical calculations.*
- *Symmetric distribution.*

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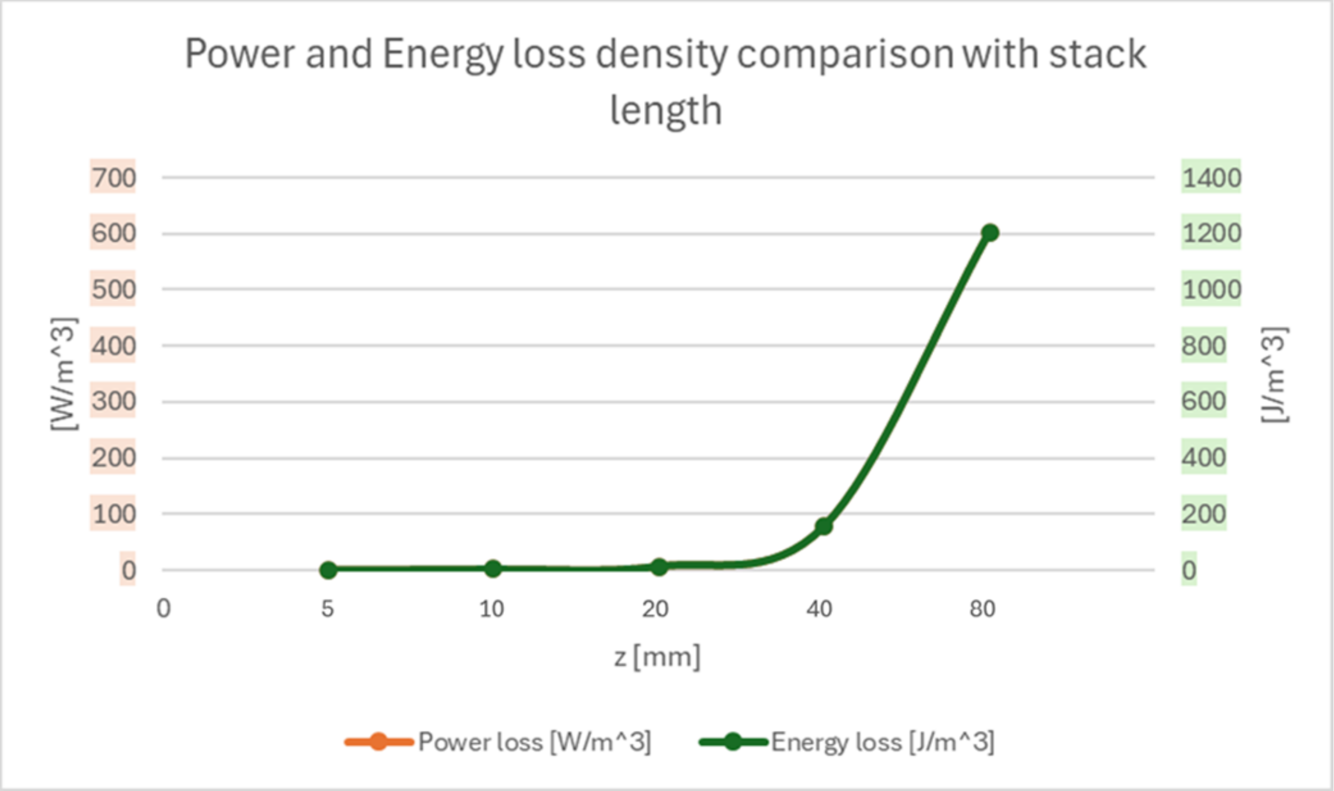
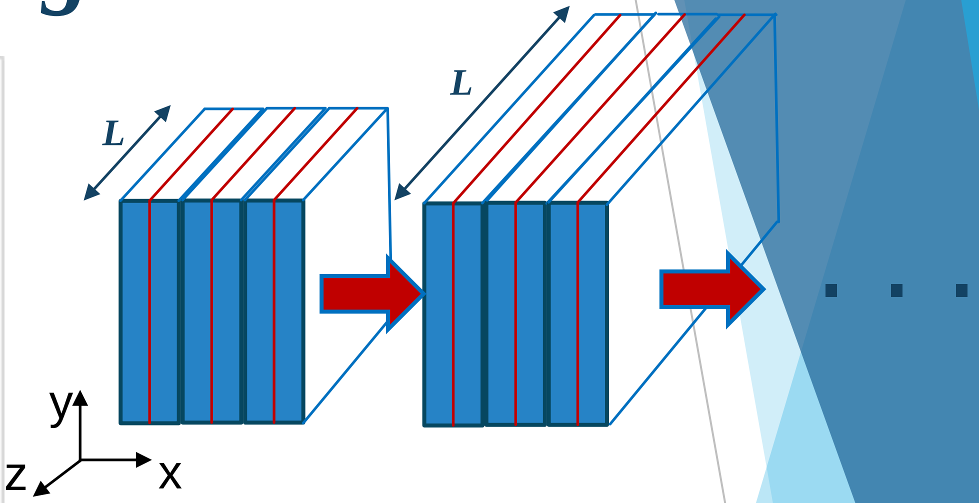
Power and energy loss density dependence on stack length





L	***Parameter z***	mm
w	1	mm
t	0.1	mm
HTS t	1	um
ρ_t	0.25e-3	[Ohm*m]

z [mm]	*Power loss density [W/m^3]*	*Energy loss density [J/m^3]*
5	2.59E-01	5.17E-01
10	1.52E+00	3.04E+00
20	6.76E+00	1.35E+01
40	7.83E+01	1.57E+02
80	6.03E+02	1.21E+03

- Considering an infinite stack, Power loss density = 342 [W/m^3]→ ρ_t ***effect is not considered!***

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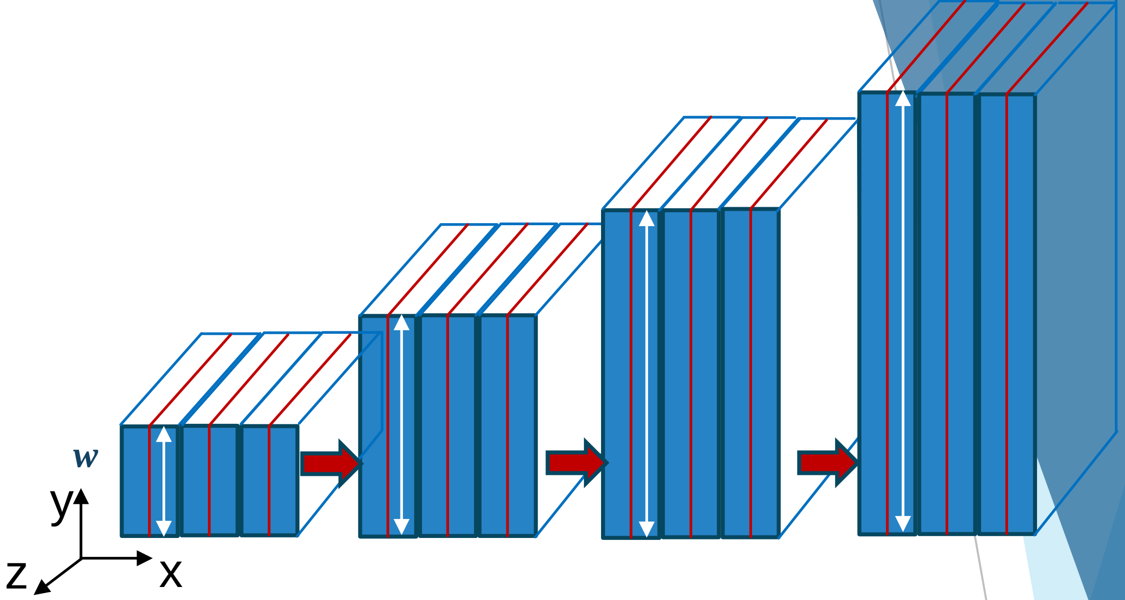
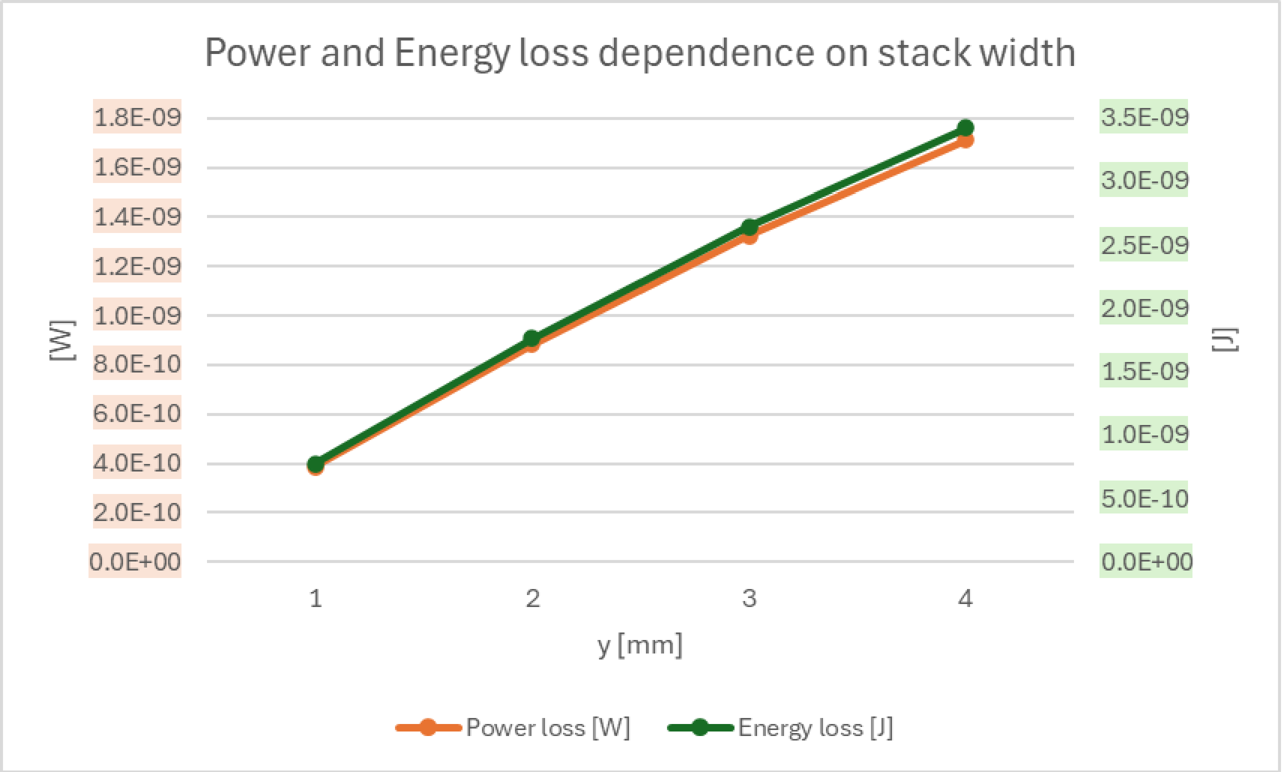
Power and energy loss dependence on stack width





y [mm]	Power loss [W]	Energy loss [J]
1	3.88E-10	7.75E-10
2	8.83E-10	1.77E-09
3	1.32E-09	2.65E-09
4	1.71E-09	3.42E-09

L	5	mm
w	***Parameter y***	mm
t	0.1	mm
HTS t	1	um
ρ_t	0.25e-3	[Ohm*m]

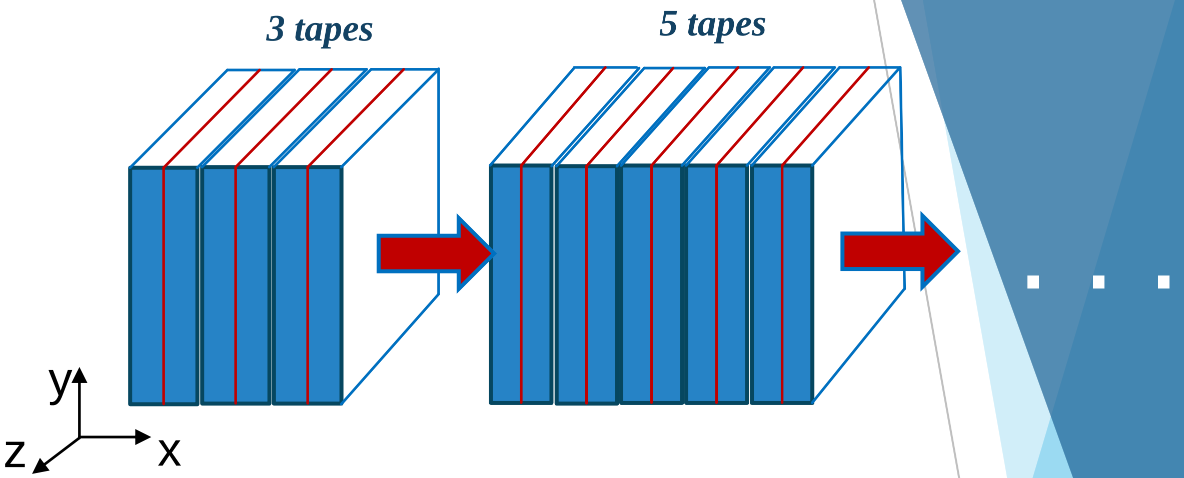
- Stack width independent:

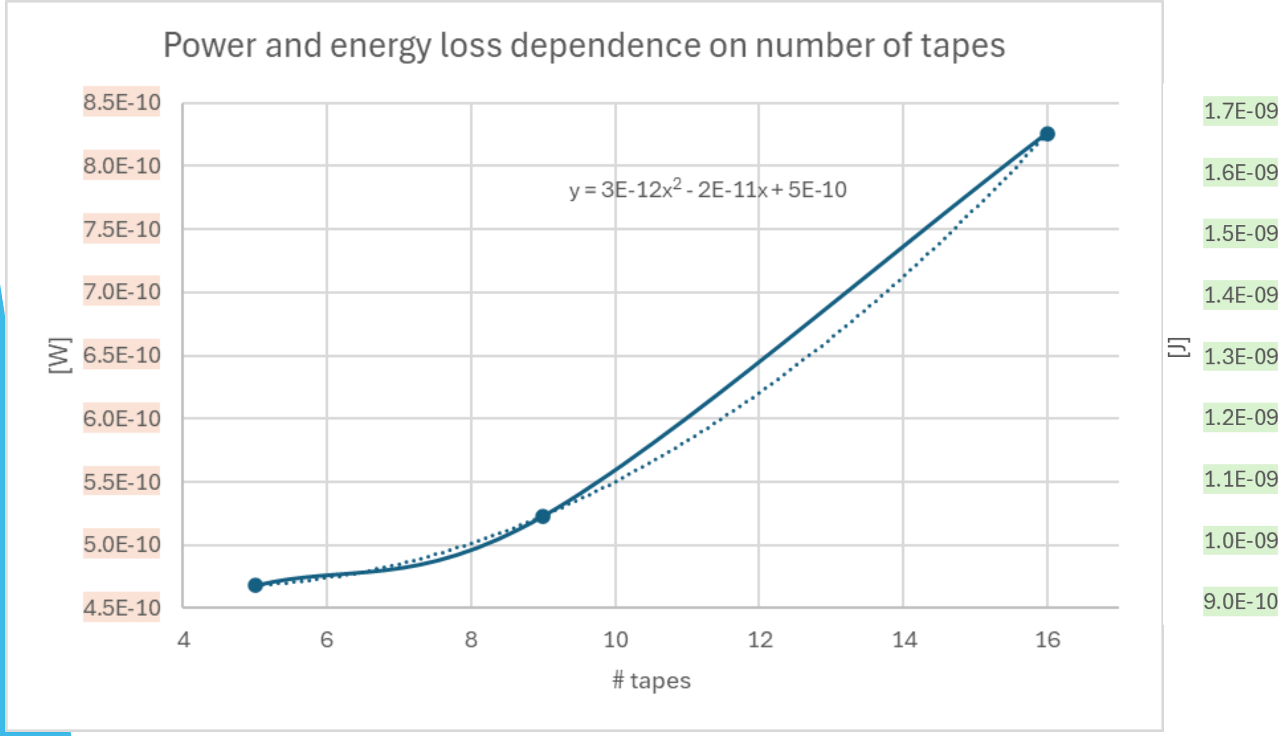
Power loss density[W/m^3]	*Energy loss density [J/m^3]*
2.58E-01	5.17E-01

Constant for different width!

Power and energy loss dependence on number of tapes

Tapes	Power loss [W]	Energy loss [J]
5	4.6837E-10	9.3674E-10
9	5.2315E-10	1.0463E-09
16	8.2585E-10	1.6517E-09

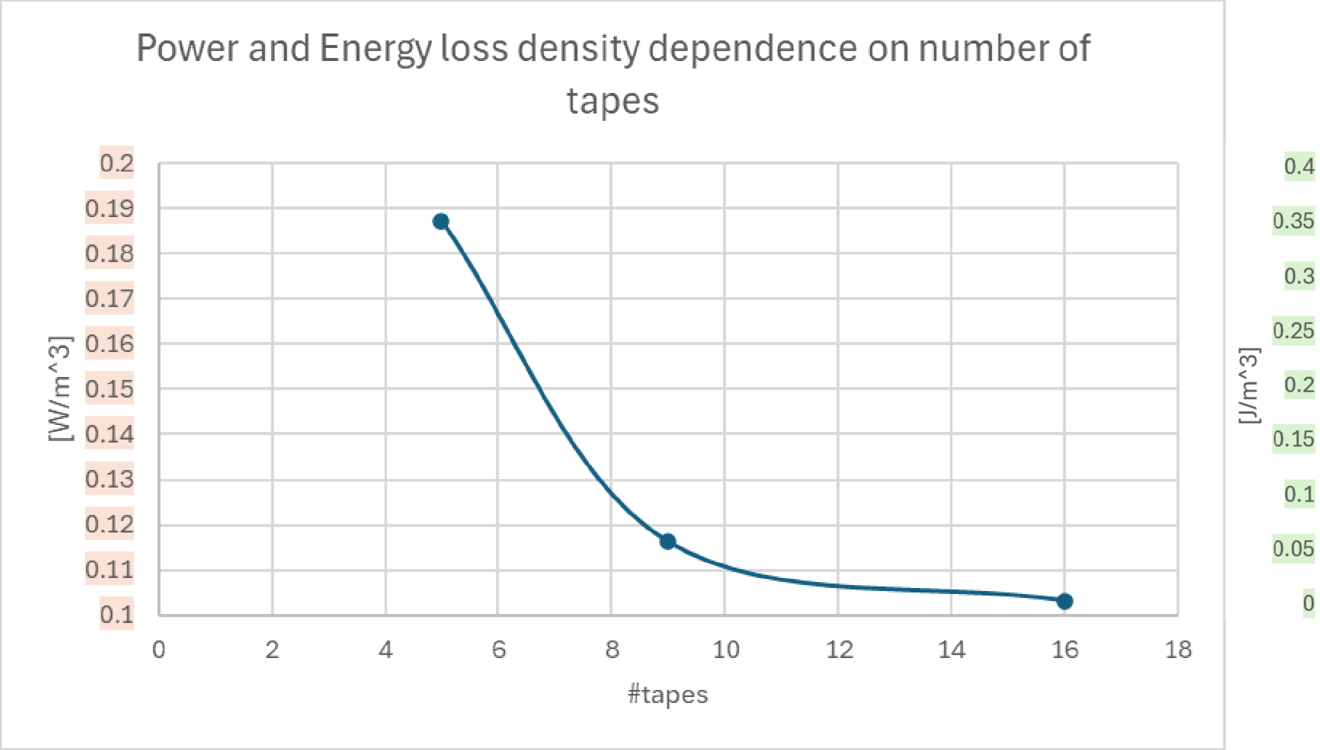




L	5	mm
w	1	mm
t	0.1	mm
HTS t	1	um
ρ_t	0.25e-3	[Ohm*m]
# tapes	***parameter***	/

$$\frac{P}{V} = \frac{1}{12}\left(\frac{d^2}{\rho}\right)\left(\frac{dB}{dt}\right)^2$$

*Power and energy loss **density** dependence on number of tapes*



- Increasing the number of tapes could lead to an increase of transverse resistivity, which results in a decrease of AC losses.

Volume [m^3]	Tapes	Power loss density [W/m^3]	Energy loss density [J/m^3]
2.50E-09	5	1.8735E-01	3.7470E-01
4.50E-09	9	1.1626E-01	2.3251E-01
8.00E-09	16	1.0323E-01	2.0646E-01

Next steps

- Use different values of dB/dt and see how it affects AC losses.
- Evaluate AC losses with a perpendicular magnetic field. From analytical calculations, AC losses should increase, especially in superconductor layers, where the losses are always larger than the copper ones.
- Consider a stack with stainless steel tapes between the REBCO ones and evaluate AC losses. This is possible because in the experiment, the transverse resistance of a reinforced stack (SS+REBCO), has been measured, too.

Conclusions

- Non-insulated REBCO tapes are an interesting field of research, for HTS magnets, which could give less "thermal stabilization problems" .
- This study represent a first, significant step to understand AC losses in HTS stacks, which could be used for magnet systems, for Fusion and accelerator applications.
- Thanks to this model, AC losses main dependences have been studied:
  - Inverse proportionality to the transverse resistivity of the stack.
  - Quadratic dependence on stack length.
  - Power and Energy loss density are stack width independent.
  - Inverse proportionality of power and energy loss density, with respect to the number of tapes of the stack.

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Thank you for the attention!