3-D NUMERICAL MODELLING OF AC LOSSES IN MULTI-FILAMENTARY MGB_2 WIRES

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POLYTECHNIQUE MONTRÉAL LE GÉNIE EN PREMIÈRE CLASSE

4^{th} HTS workshop modelling (2014)

- During the round table of the last workshop, one model was suggested as new 3-D benchmark
  - Twisted round conductors in metal matrix (e.g. MgB_2)

- Our approach for the modelling of multi-filamentary 3-D wires has been
  - 3-D modeling of a simple cable model
  - Characterization of a real MgB_2 wire
  - 3-D modeling of this wire

Our objectives

- To optimize the design of high current SC cables, it is compulsory to calculate the AC losses of the cable
- It is computationally demanding to model in details the complete cable
- One approach is to calculate accurately the AC losses of one wire in detail with transport current and field

Development of a numerical model to calculate AC losses of one MgB_2 wire with transport current and external field

Outline

- 1) Three-filament wire benchmark
- 2) Simulations of MgB_2 wires
  - A) Numerical model
  - B) AC loss calculations
- 3) Improvement of the convergence

1) Three-filament benchmark

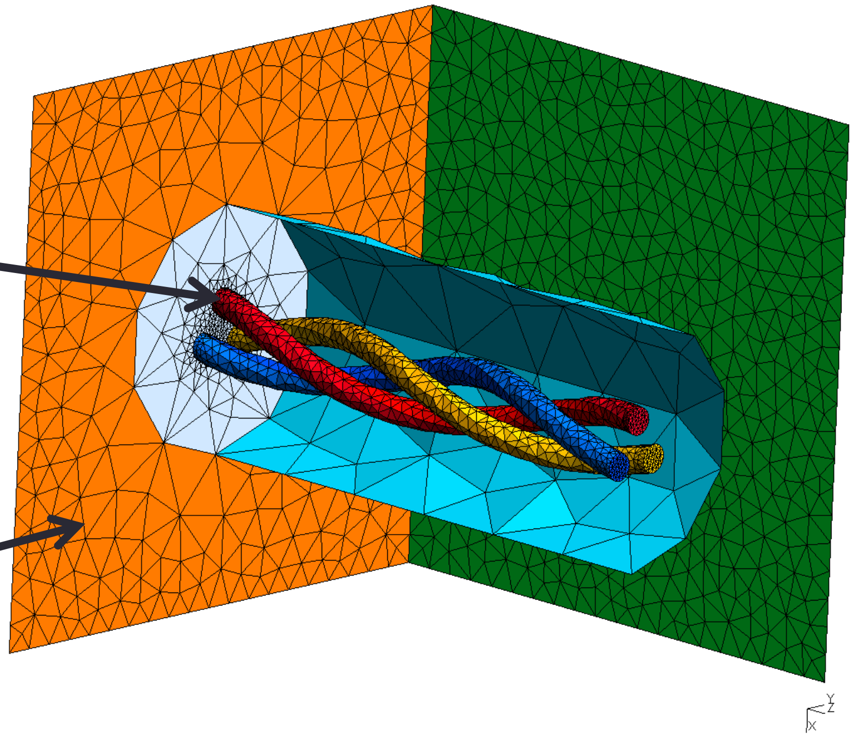
- Simple FEM model
  - 3 filaments in air
  - About 185,000 DoFs

Superconductors

I_c=700 A, n=30

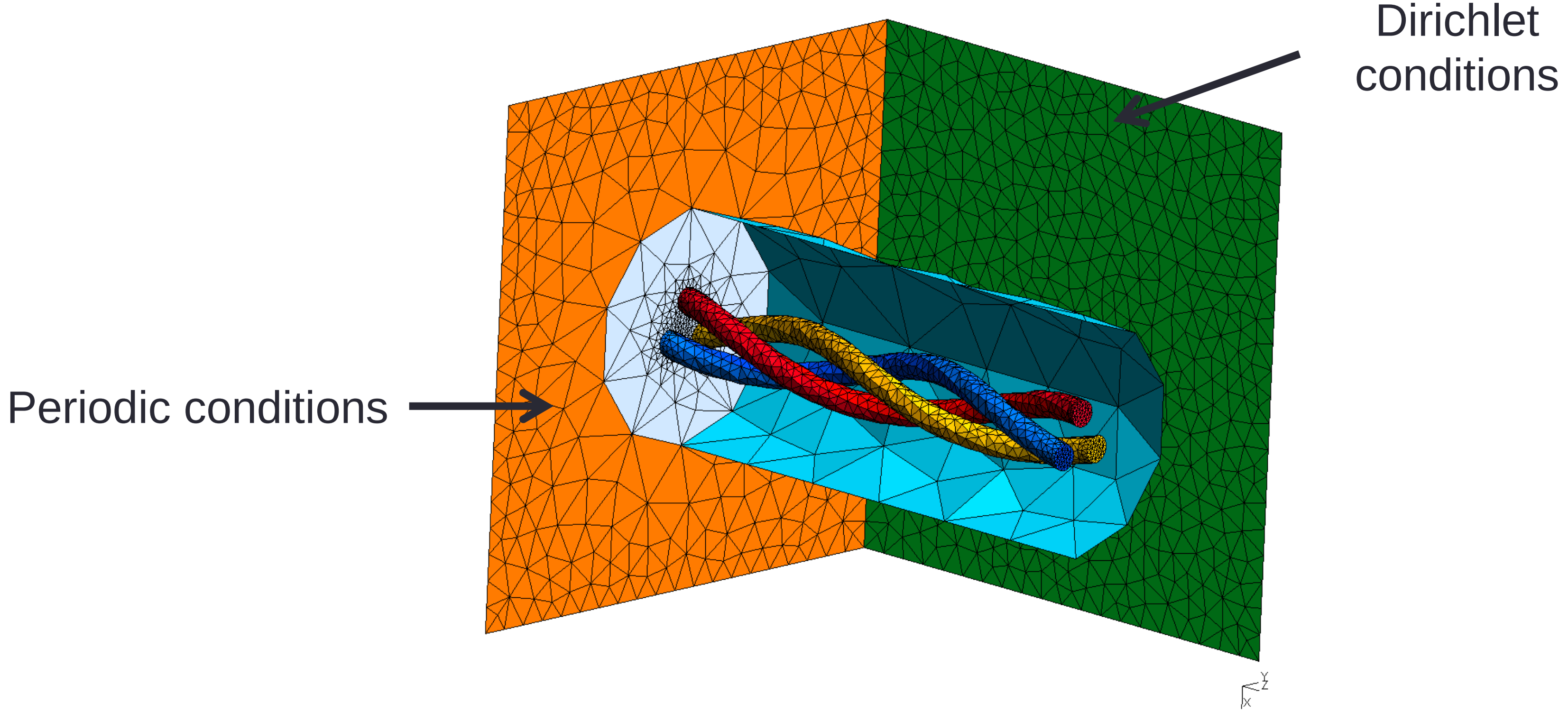
$$\rho = \frac{E_c}{J_c}\left(\frac{|J|}{J_c}\right)^{n-1}$$

Air domain
p=1 mΩ.m
(H formulation)



Numerical model

- Dirichlet conditions are applied on the outside of the box
- Periodic conditions are used on the external faces
- Transport current imposed by integral constraint(s)



List of tests

1) Benchmark for calculations of self-field and external field AC losses (only SC)
2) AC loss with current and applied field
3) Addition of a resistive matrix
4) Addition of a nonlinear relative permeability for the matrix

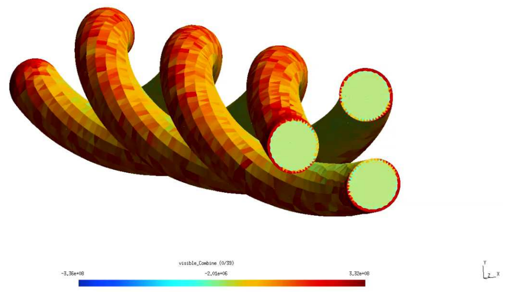
Motivation for the benchmark

- 1) Check the computed quantities of this simple example (no experiment possible)
- 2) Study the performance of software
- 3) Check the difference between various formulations

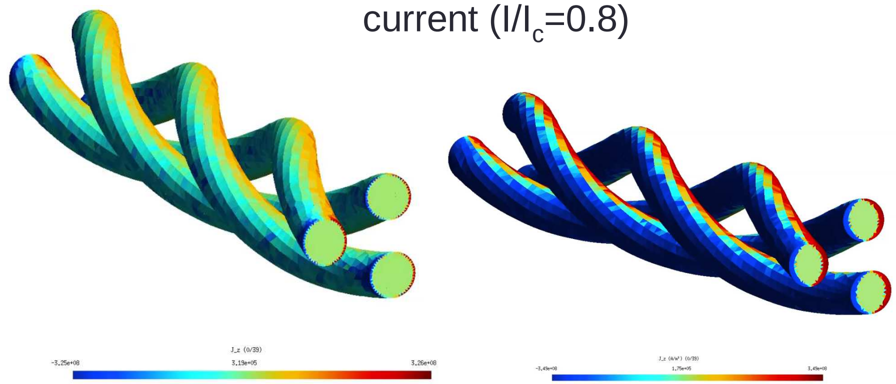
Software packages

- **FLUX (CEDRAT-G2ELab),** commercial code, T-Φ formulation
  - Dedicated for machines, SC package included
- **COMSOL,** commercial code, H formulation
  - Code used in the superconducting communities for 2-D calculations
- **Daryl-Maxwell (Polytechnique Montréal)**, homemade soft,
  - H formulation, developed by R. Rivard, S. Dufour and F. Sirois
- **LoSt (TUT)**, homemade soft, H and H-φ-ψ formulation
  - Developed by V. Lahtinen and A. Stenvall

AC hysteresis losses

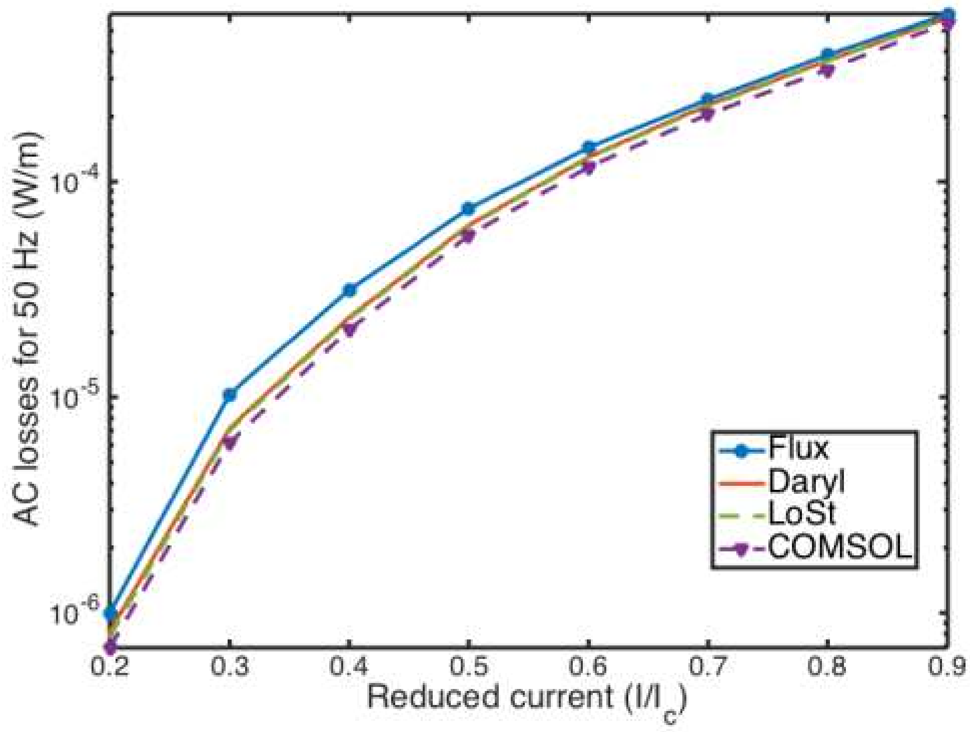


Current density distribution with transport current (I/I_c=0.8)



Current density distributions with external magnetic field (50 mT et 200 mT)

- Computation time: 1-2 days



AC losses in external magnetic field

B(mT)	COMSOL	Flux	Daryl	LoSt
50	6,62	7,69	6,81	7,25
200	1,7	1,7	1,8	1,8

Conclusions of the benchmark

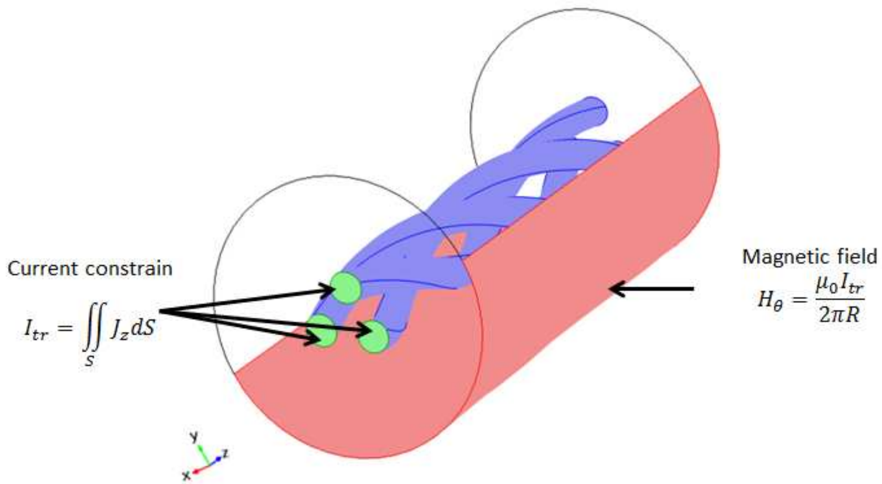
- AC loss calculations are in the range of 8 to 10 %
- No significant difference noticed between T-Φ formulation and H formulation

- For more complicated models
  - COMSOL limits were already reached
  - Fixed time steps necessary

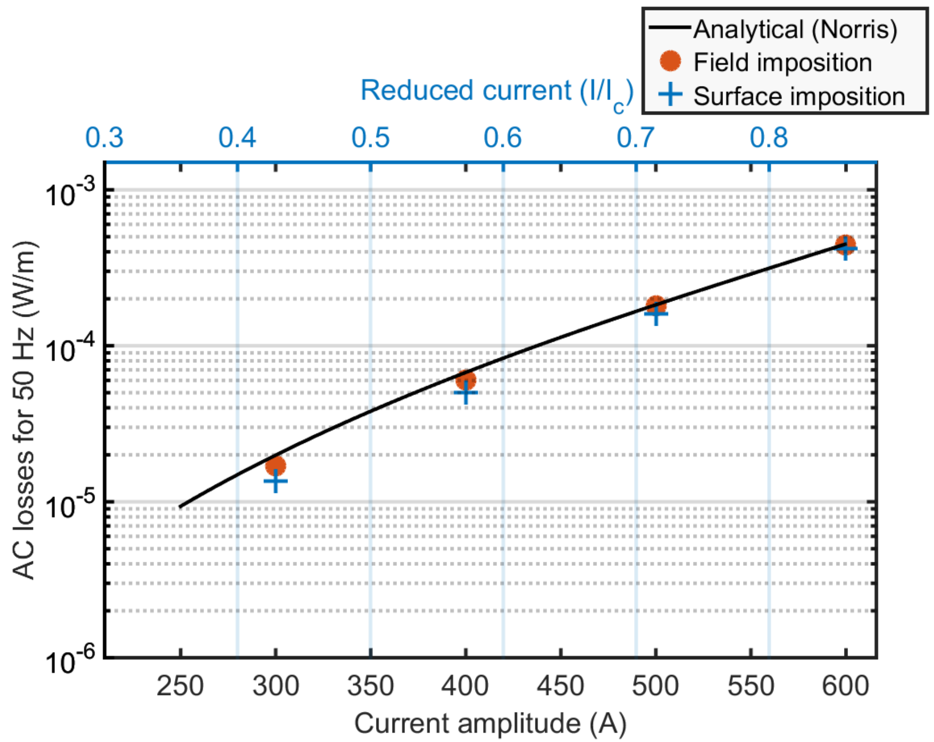
- All the others calculations have been made on Daryl-Maxwell (with the help from V. Lahtinen for validations)
- Multiple examples of more complicated geometries have been tested (EUCAS 2015)

Change of geometry

- To impose a combinaison of transport current and an external field to the model, the model was adapted



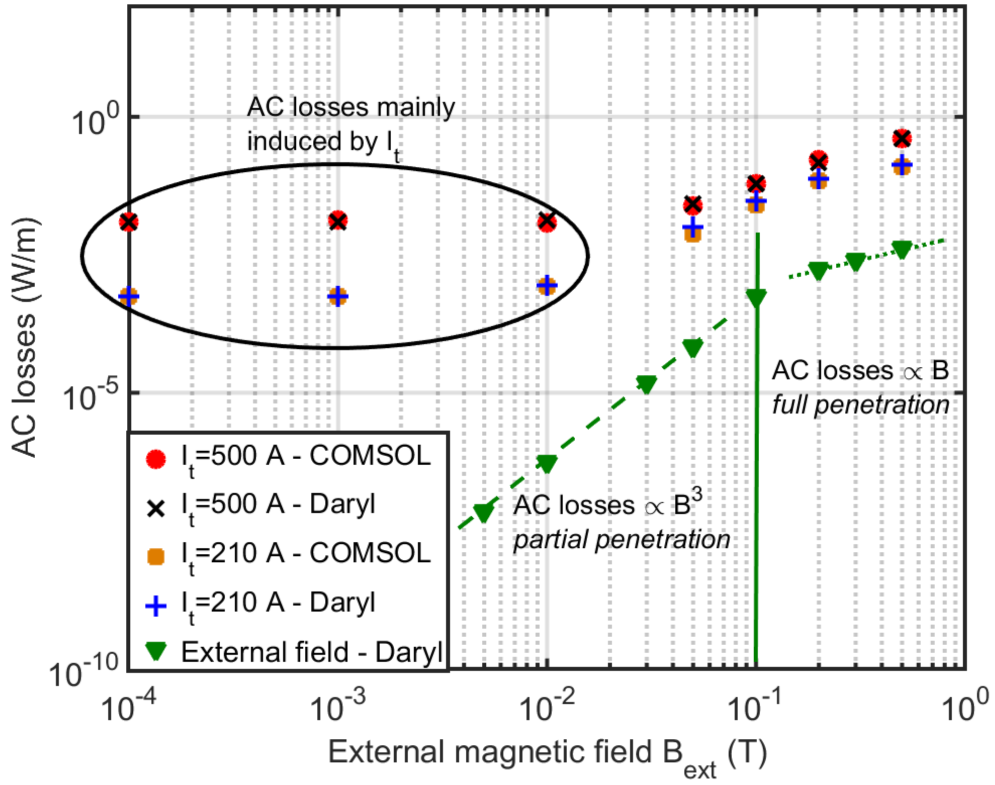
New geometry considered:
The current can be imposed by
- Integral constraint(s)
- Dirichlet conditions (bnd field)

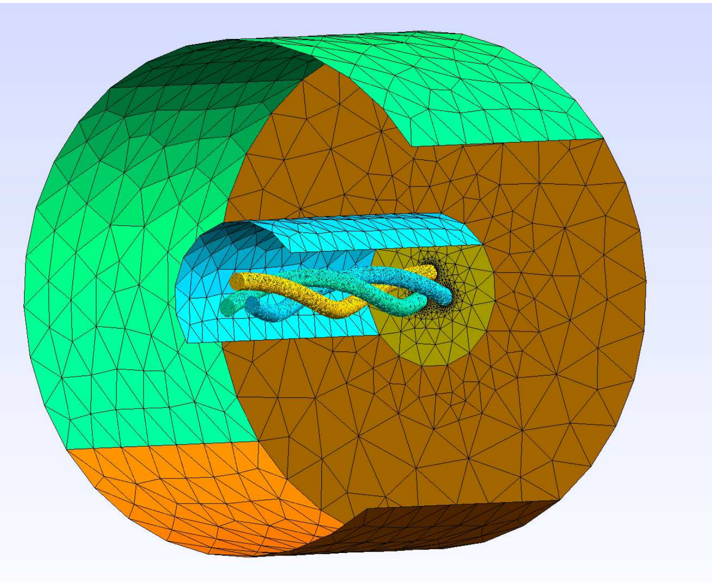


AC losses as a function of the current

AC losses with current and appl. field

- AC loss simulations with transport current and applied field in an air matrix

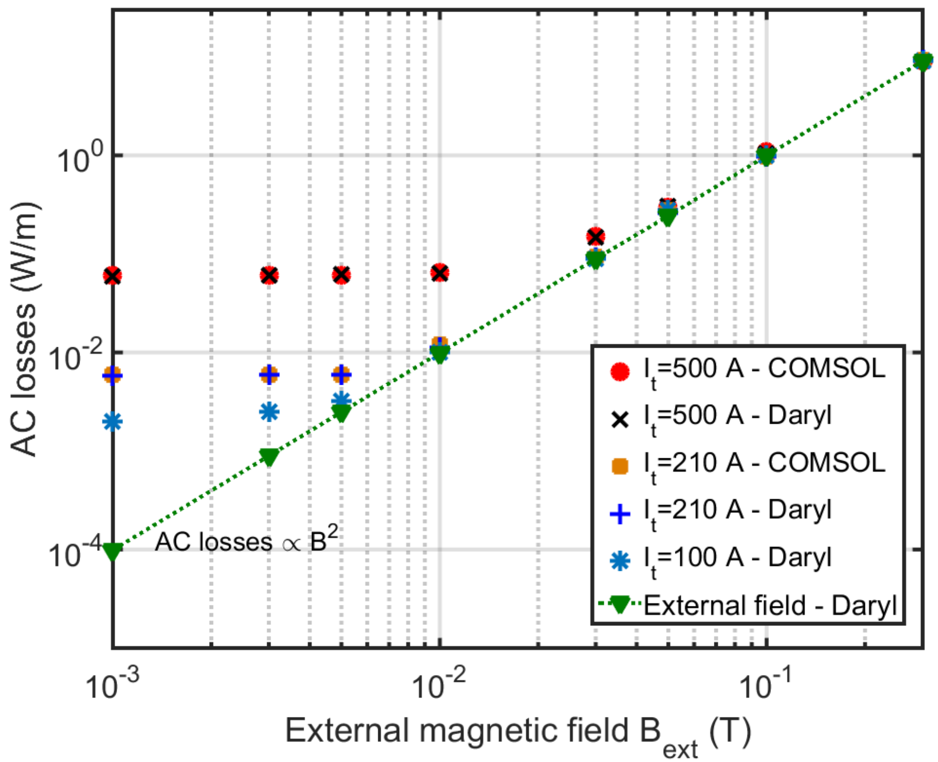




New geometry for the AC loss calculations

Addition of a resistive matrix

- The resistivity of the matrix was defined as p=1 nΩ.m
- Compared to the previous results, the AC losses are the summation of hysteresis losses and coupling losses



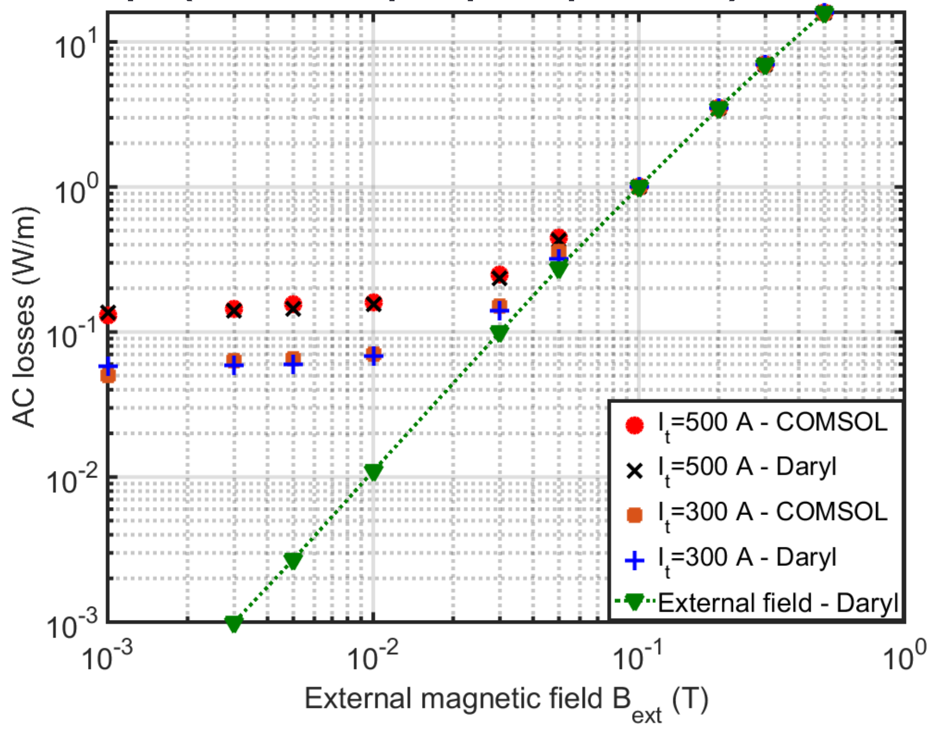
Coupled AC losses

- Addition of a relative permeability dependent of the magnetic field for the matrix (according to [1])
- AC losses are increasing by about 20 %
- Increase of the computation time by about 30 %. In average, 3 to 4 more iterations at each time step (200 steps per period)

Relative permeability of the matrix is following equation :

$$M(H) = \mu_0 (H + \sigma(\mu_{RMAX} - 1)\tanh(H/\sigma))$$

With σ=4.2E3 A/m and μ_{RMAX}=50



[1] Gömöry et al, SuST, (2009)

Conclusion of the three-filament model

- This benchmark and the other examples gave us confidence on our ability to calculate with accuracy the AC losses

- The models can be heavy in terms of computation time

- For the calculation on a real cable, a new model for the real wire had to be created

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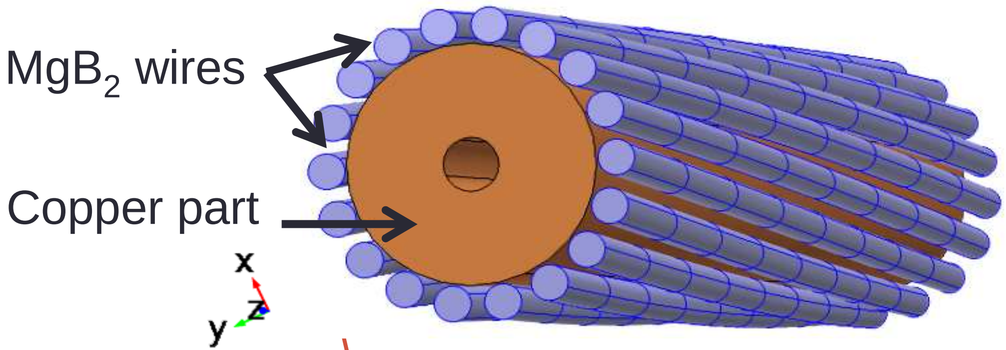
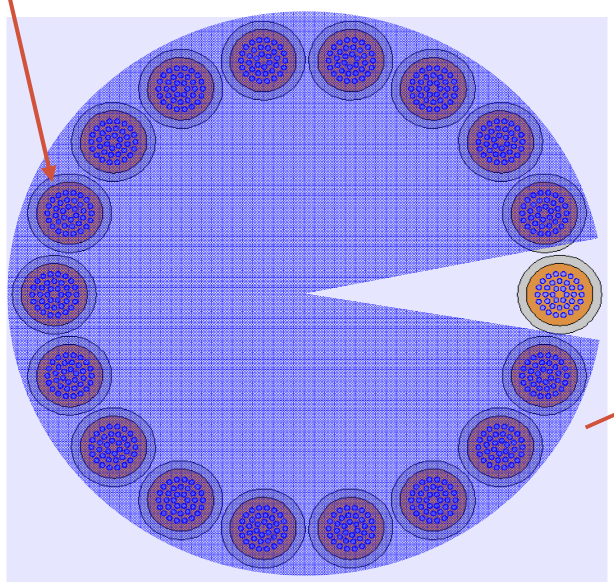
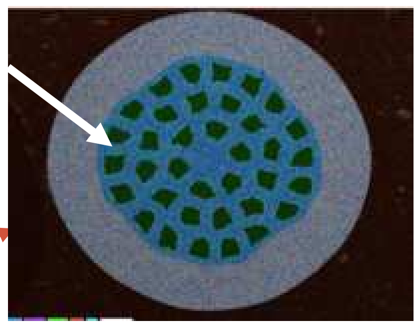
Multi-scale problems



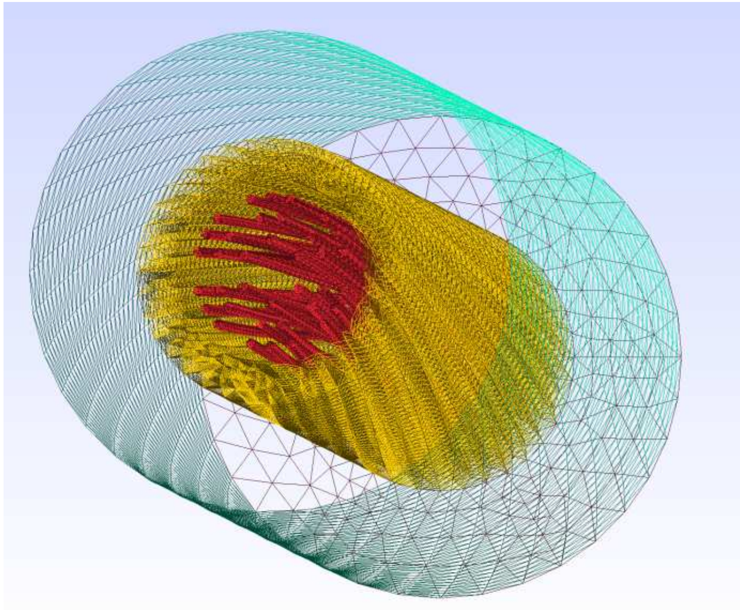
Example of a 10 kA power cable cooled down to 20 K with 18 MgB_2 1.33 mm wires

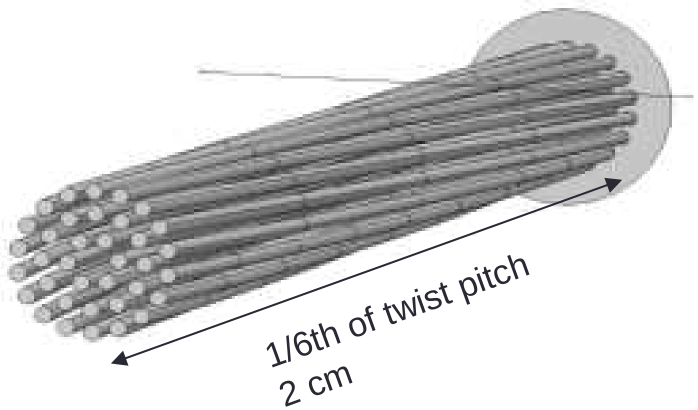




3-D numerical modelling

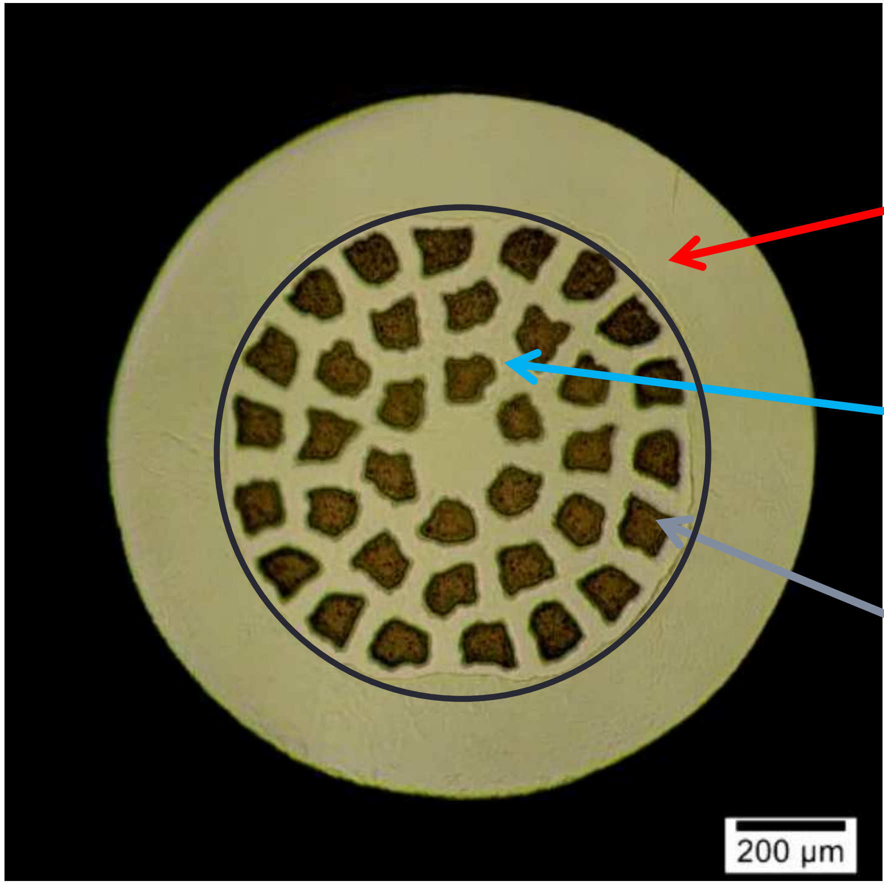
- Numerical model
  - 682 560 elements
  - 798 520 DoFs
- I_c function of B
- Twist pitch 20 mm (1/6th of the twist pitch)
  - Periodic conditions applied on the external faces
- Monel and Nickel
  - ρ at operating temperature
  - M(H) taken into account





Experimental characterization

- Measurements realized to identify material parameters



Monel:
- Electrical resistivity ρ
- Relative permeability μ_R

Nickel:
- Electrical resistivity ρ
- Relative permeability μ_R

MgB_2:
- Critical current I_c

Numerical considerations

- Model made on Daryl-Maxwell
- Three nonlinearities
- Alternative material law used for SC (percolation)[1]

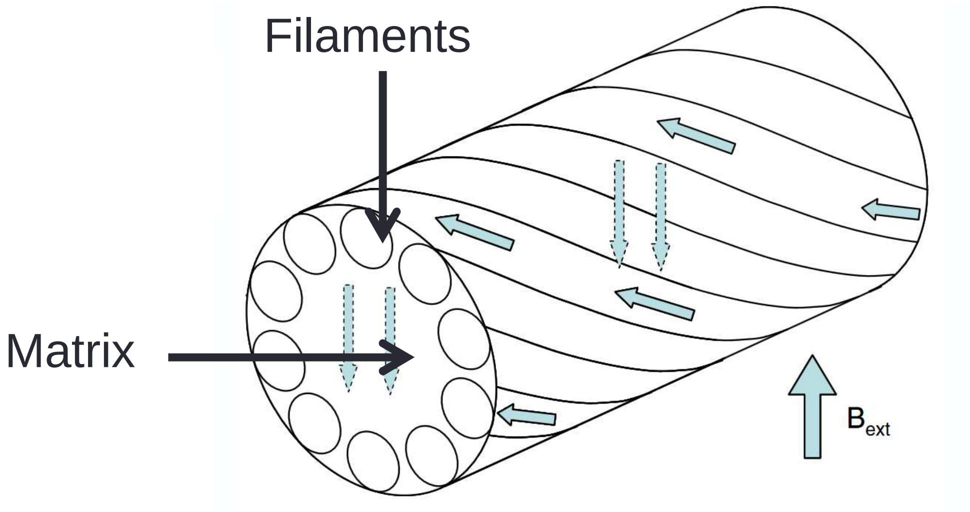
$$E = E_0 \left(\frac{J}{J_{c_0}} - 1 \right)^{n_0}$$

- Fixed time step (800 steps per period) – Direct solver PARDISO
- Computation time 13 days

[1] Zeimetz et al, SuSt (2001)

AC loss calculations in the model

- In the model, we compute
  - Hysteresis losses coming from the superconducting filaments
  - Eddy current losses
  - Coupling loss in the matrix
- The AC losses are computed with : $p_{AC} = \iiint_V \vec{J}\vec{E}\,dV$
- Analytical calculations exist for all these losses under certain hypothesis



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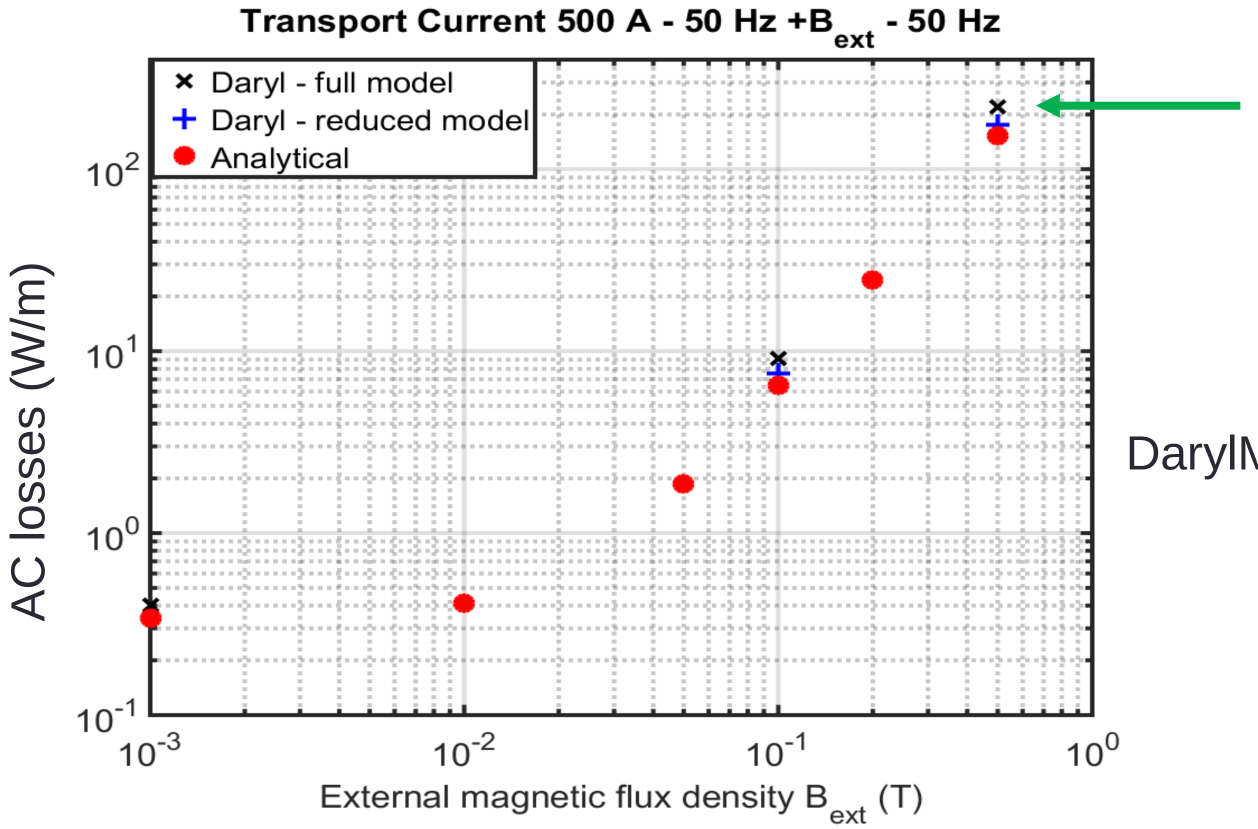
In case of pure AC (50 Hz) loss calculations

- First test case : pure AC excitations (currents and fields)



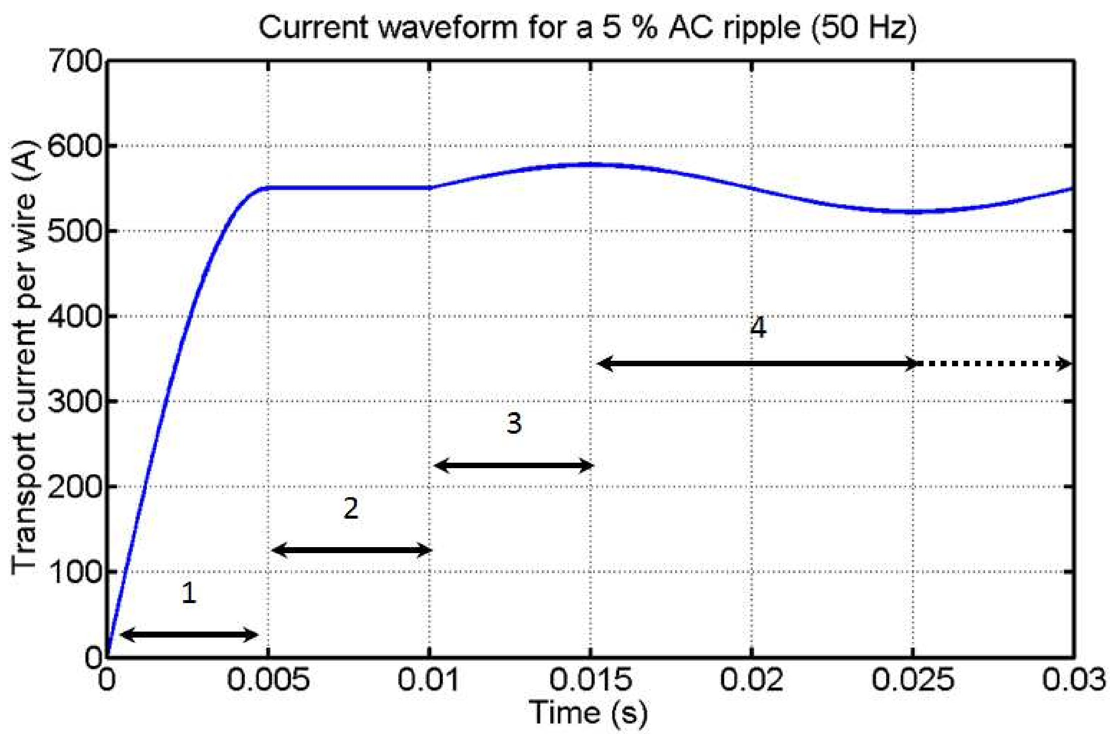
30 % difference between analytical and FEM

DarylMaxwell reduced model
No μ_R

Very high losses in AC cable applications => DC cables

Simulations AC+DC

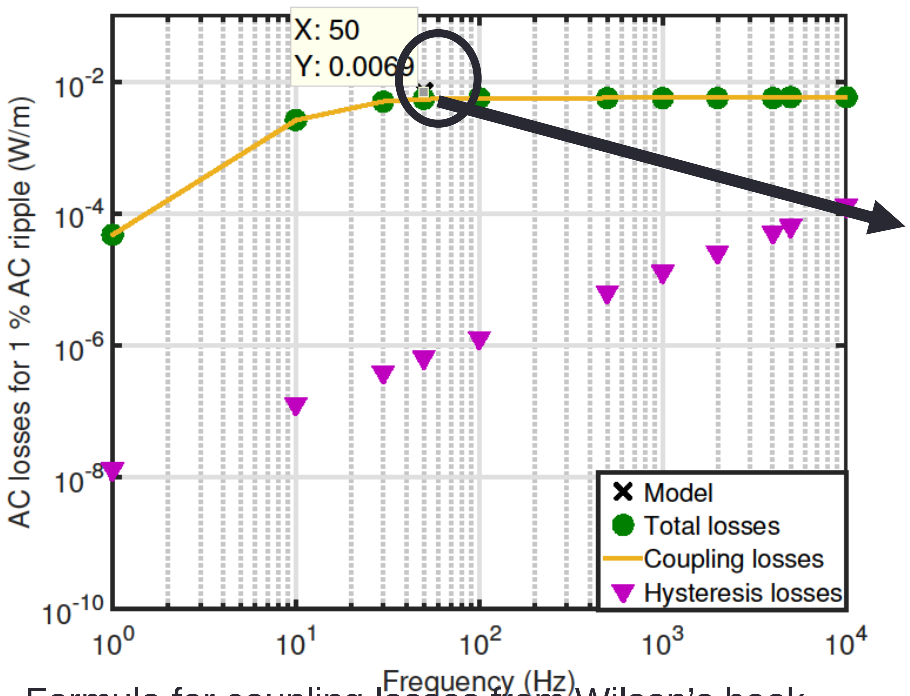
- AC ripples (harmonics) can be superposed to DC current
- Change of excitation waveforms
- Computation of the losses between 20 ms and 30 ms

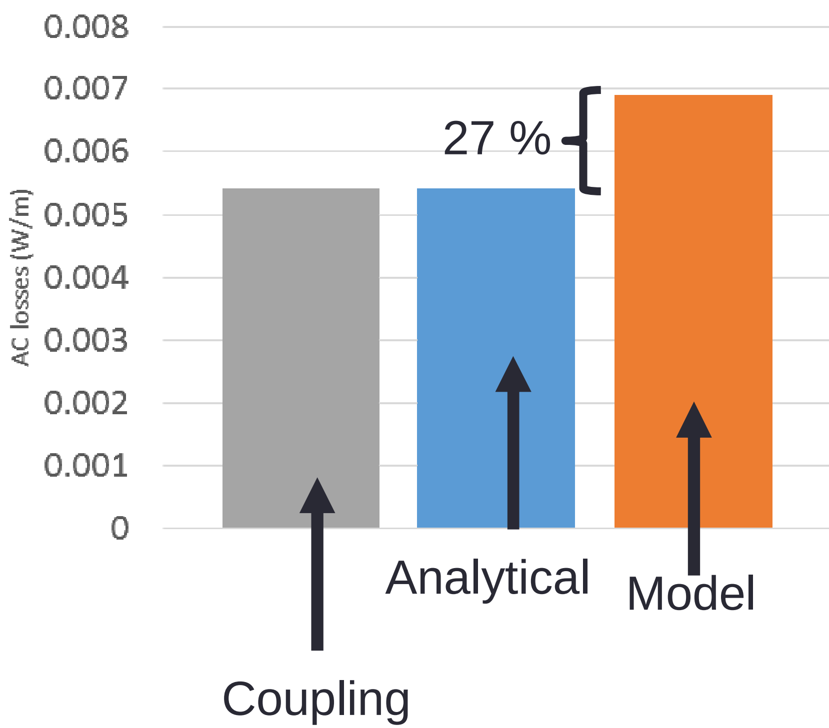


Current waveform

Results

- AC loss calculation and analytical calculations for 1 % AC ripples
- Error between analytical calculations and numerical models = 27 %
- Transverse resistivity considered as pure nickel





Formula for coupling losses from Wilson's book
Formula for hysteresis losses from Norris

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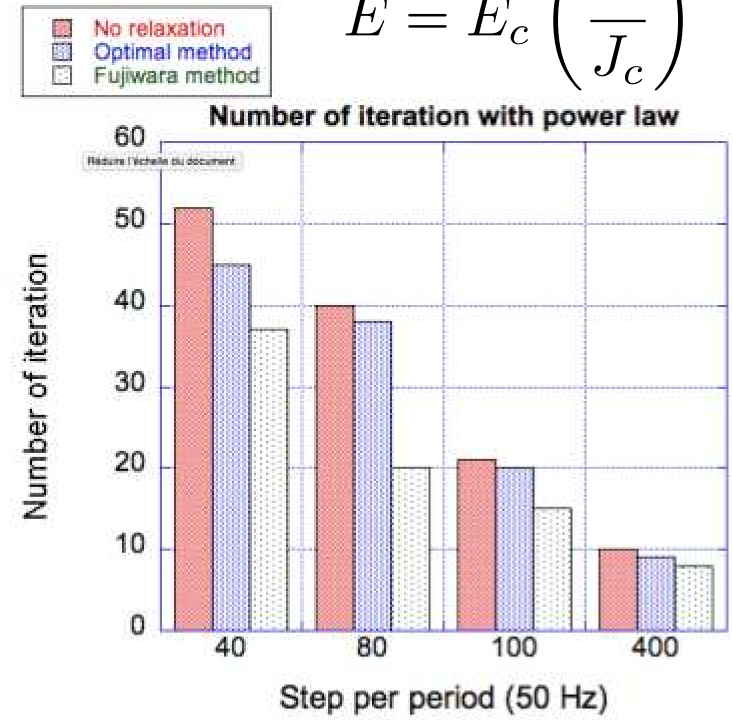
Improvement of the convergence

- To improve the convergence of the model, it is possible to adapt the relaxation coefficient of Newtown-Raphson
- Two methods are suggested
  - Fujiwara method
  - Optimal method
- Simulations on the three-filament wires have been made to see the improvement of the convergence

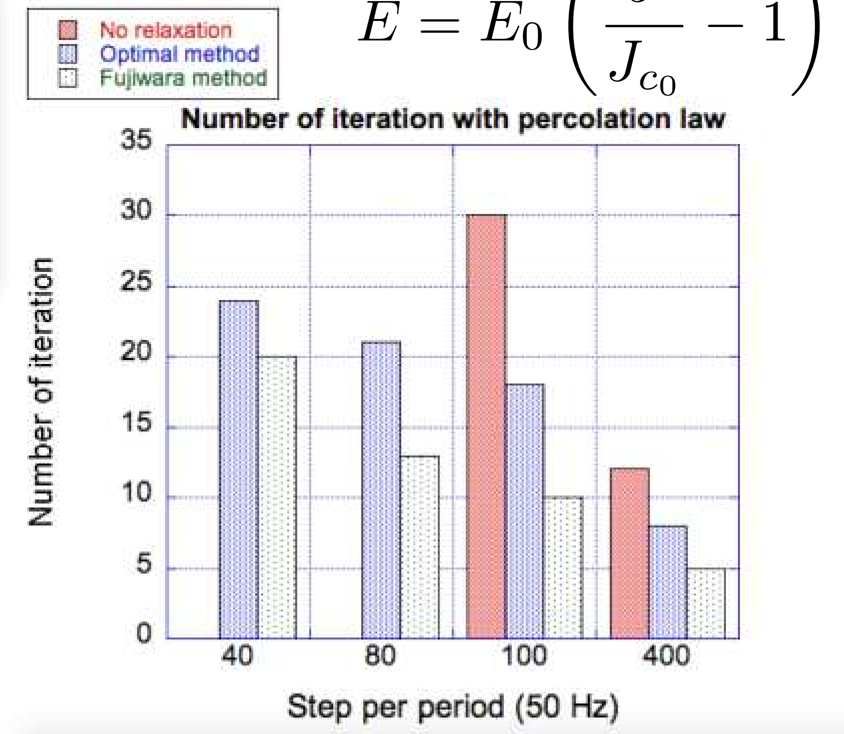
Results for the three-filament model

- Results: time steps and Newton method (*T-φ* only)
  - Without relaxation factor: harder to converge with percol. model
  - With rela… percol. model conver…

$$E = E_c \left(\frac{J}{J_c}\right)^n$$

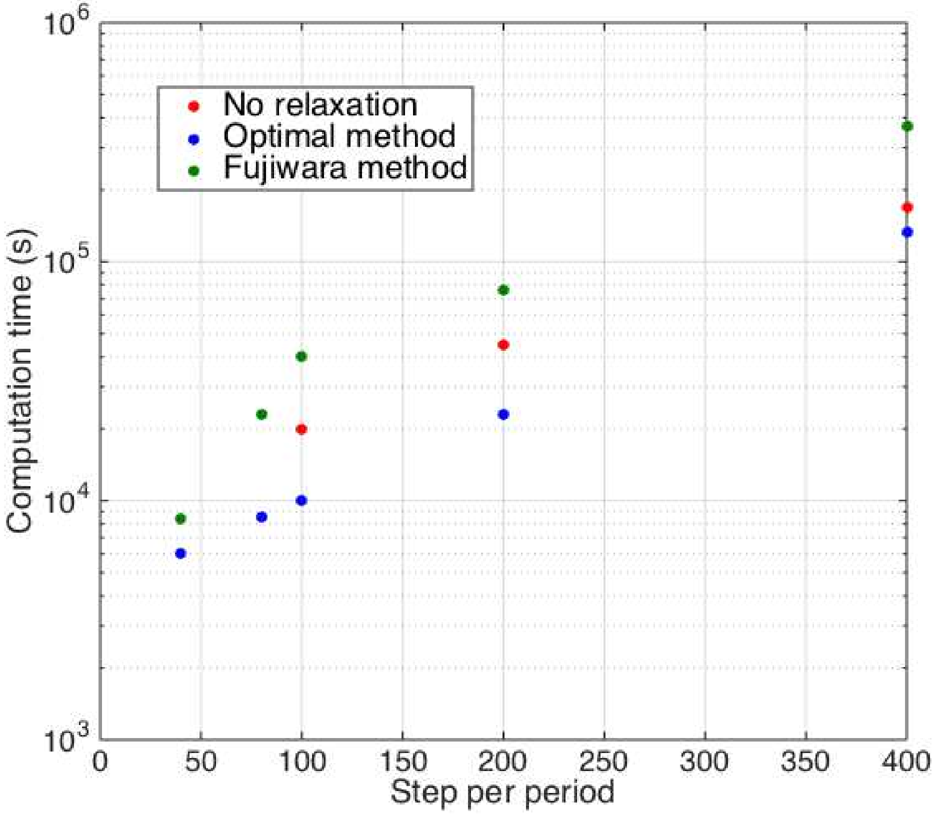


$$E = E_0 \left(\frac{J}{J_{c0}} - 1\right)^{n_0}$$



Numerical considerations

- Results: computation times vs. Newton method
  - Sensitive to relaxation scheme chosen
  - Fujiwara method: requires less iterations, but more time overall
  - Optimal method: variant of Fujiwara method implement in FLUX



Conclusions

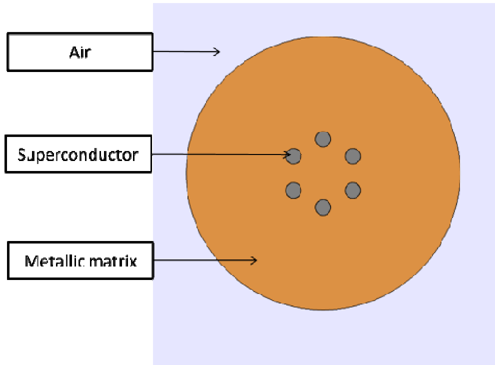
- 3-D numerical have been developed and tested on various geometries
- We created a full realistic numerical model based on experimentally characterized material models (article in progress)
- Ways exist to improve the convergence and to speed up the computation

- Feel free to contact us if you want to join this benchmarking initiative ☺

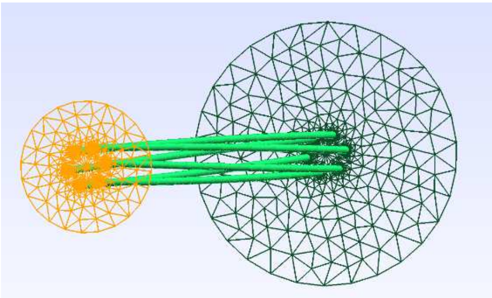
THANK YOU

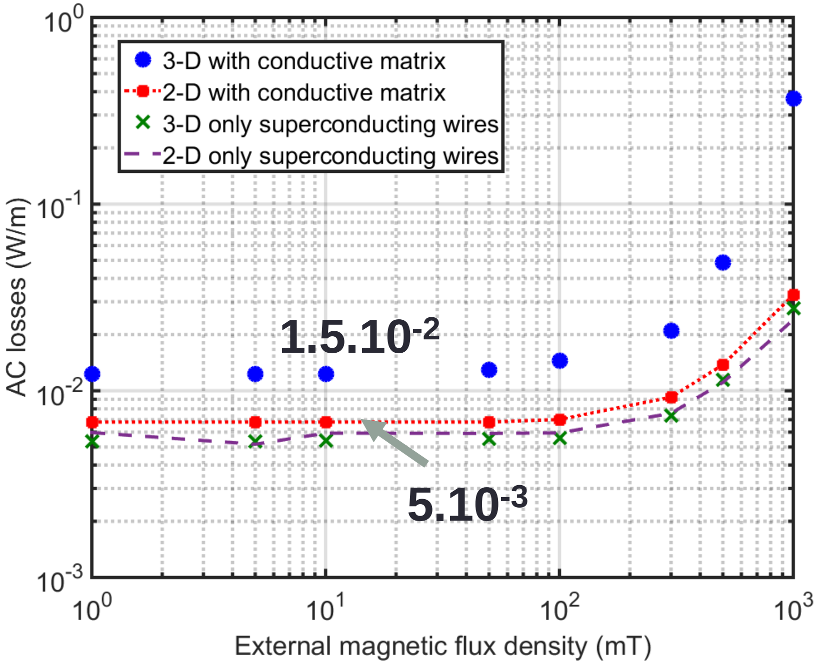
- In a 2-D model, only the AC losses in the superconducting filaments are calculated
- In a 3-D model, the coupling AC losses are also computed

2-D model
(hysteresis losses
+ eddy current in matrix)



3-D model
(hysteresis losses +
Eddy current in matrix +
Coupling losses)

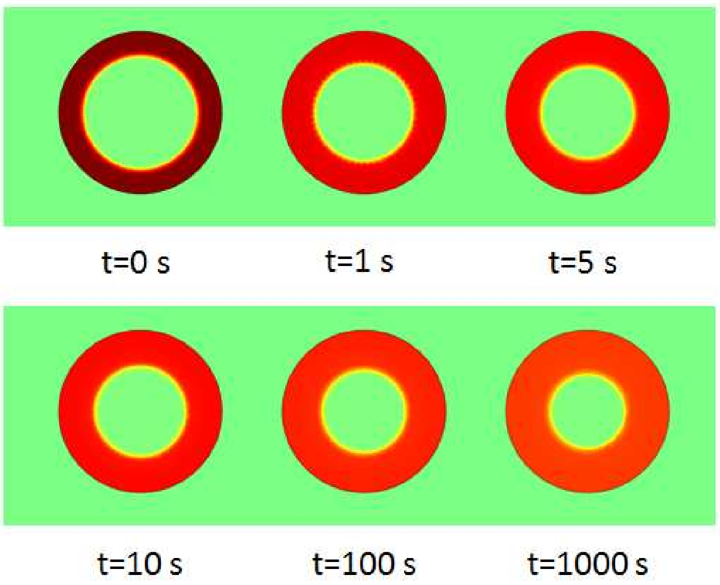


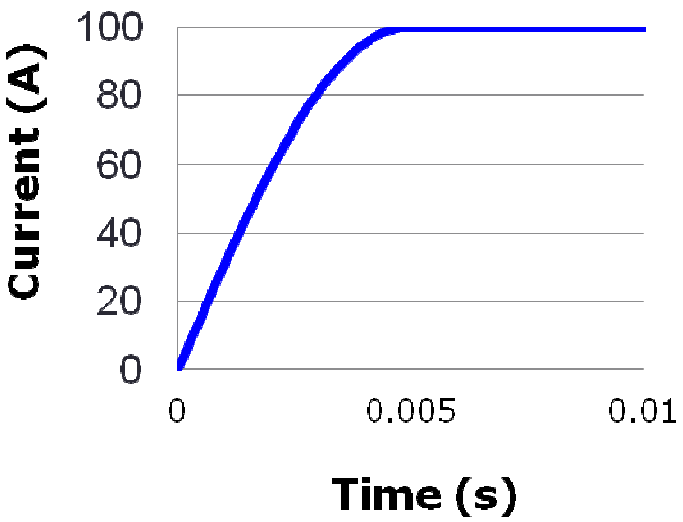


AC external field (50 Hz) +
500 A transport current (50 Hz)

The power law in DC

- Using the power law with DC signals leads to a problem at an infinite time.
- When the superconductor is full -> no more superconducting





Use of another E-J law

- We suggested another law called percolation law

H. Gonzáles-Jorge *et al.*, "Evidence of current stabilization after long-time decay in High-T_c superconductors", Cryogenics, 2004