AC loss computation of a dry-cooled MgB_2 SMES coil

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6th International Workshop on Numerical Modelling of HTS

Thursday, June 28, 2018, Caparica - Lisbon , Portugal

Outline

- The DRYSMES4GRID project
- The reference MgB_2 Coil
- Computation of AC loss of the SMES coil
  - Model and assumptions
  - Making the matrix sparse
  - Numerical results
- Conclusion and future work

The DRYSMES4GRID Project

MISE - Italian Ministry of Economic Development

Competitive call: research project for electric power grid

- Transmission and distribution
- Dispersed generation, active networks and storage
- Renewables (PV and Biomass)
- Energy efficiency in the civil, industry and tertiary sectors
- Exploitation of Solar and ambient heat for air conditioning

Project DRYSMES4GRID funded

- **Budget: 2.7 M€**
- **Time: June 2017 – June 2020**
- **developm. of dry-cooled SMES based on MgB_2**
- **500 kJ – 200 kW / full system**

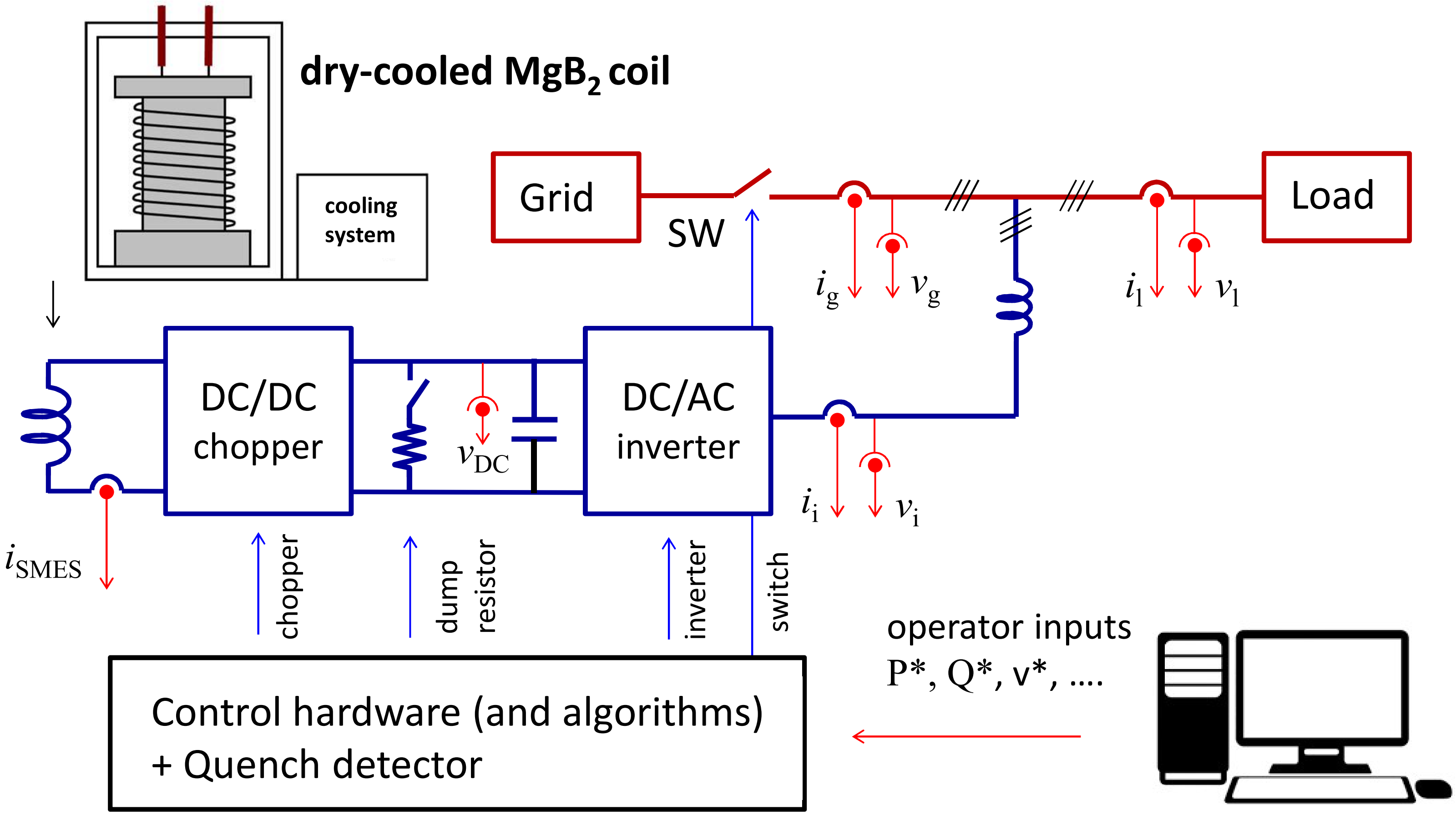
Project Coordinator:

- **Columbus Superconductors SpA, Genova, Italy**

Partners

- **University of Bologna**
- **ICAS - The Italian Consortium for ASC, Frascati (Rome)**
- **RSE S.p.A - Ricerca sul Sistema Energetico, Milan**
- **CNR – SPIN, Genoa**

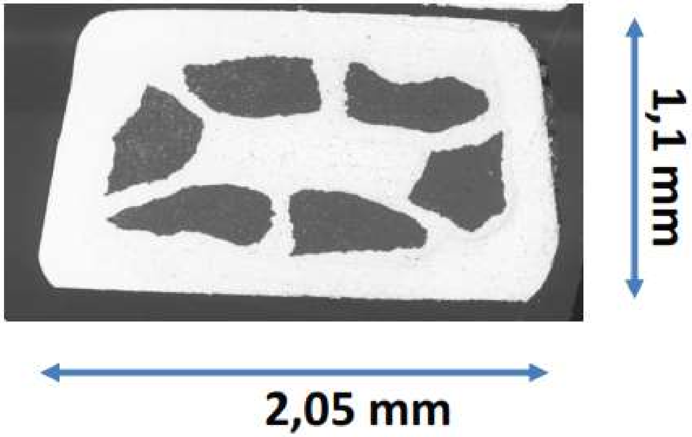
The DRYSMES4GRID system

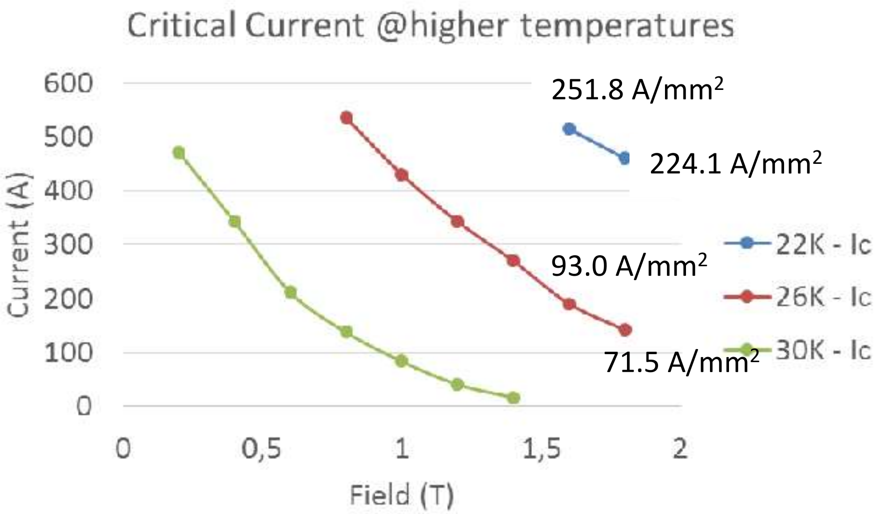


- **Electromagnetic & Mechanical design of the coil completed**
- **Thermal design (connection to cryocooler/s) in progress**
- **Control algorithms (logic, schemes, parameters) defined**

Next
- **Manufacturing of the coil & cooling system**
- **Design and Manufacturing of Power Hardware**

Reference Conductor – Rectangular tape with 6 filaments



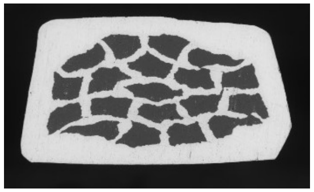


Composition and characteristics	
MgB_2	29 %
Monel 400 (external sheath)	44 %
Nickel 201 (internal matrix)	27 %
Number of filaments	6
Thickness	1.1 mm
Width	2.05 mm
Cross section	2.05 mm^2
Twis pitch	600 mm

Additional external copper
Copper strip with 500 µm thickness applied on one side by tin-soldering Filling factor of protective copper: 0.313 (500 µm strip)

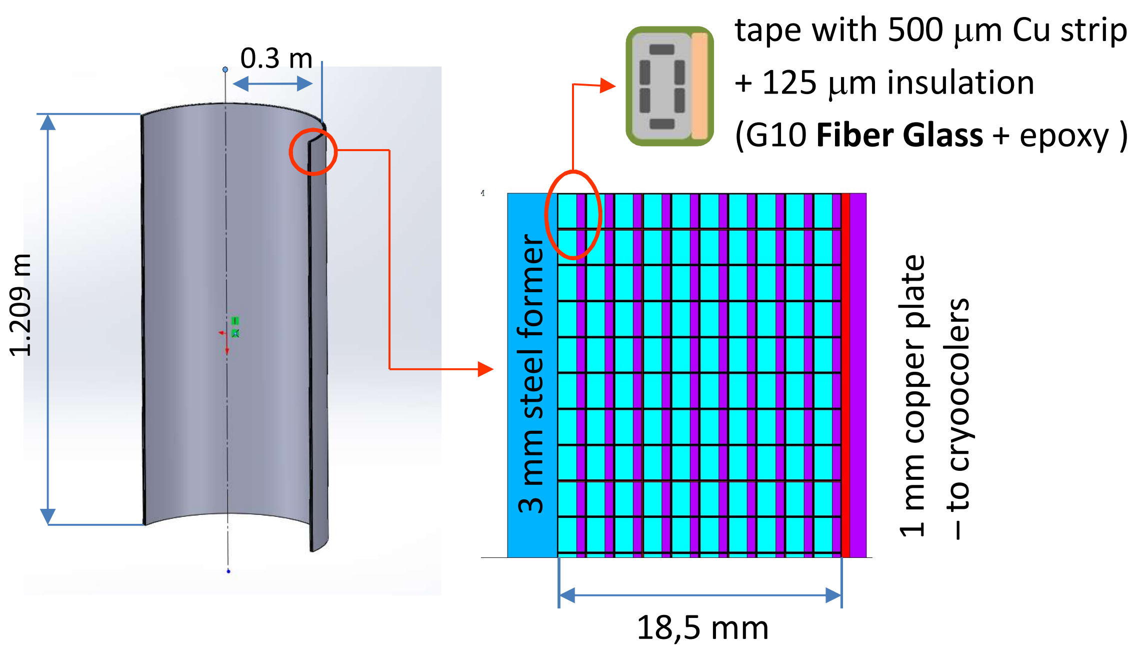
Electrical insulation
125 µm insulating wrapping

A 19 filament tape with same geometrical characteristics and improved I_c vs B,T performance (>30%) could also become available within the time frame of the project

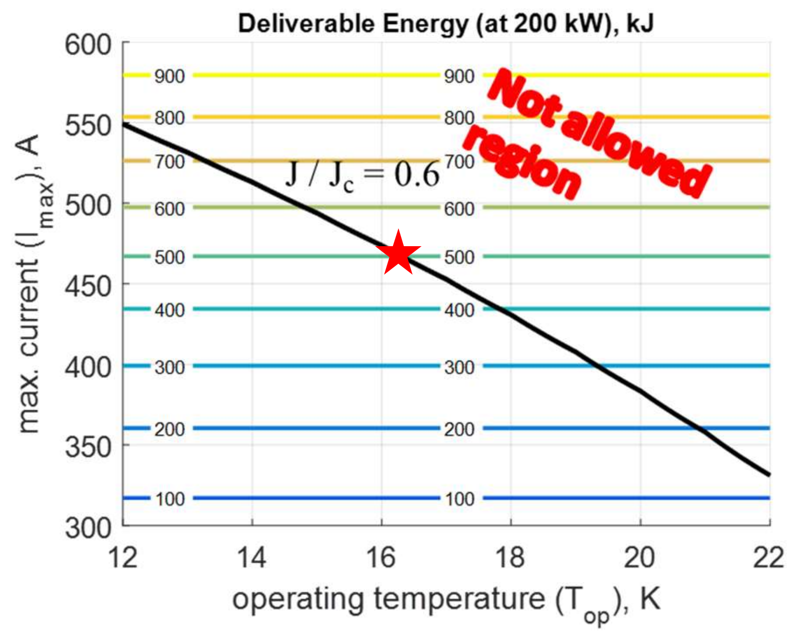


Main characteristics of the designed 500 kJ / 200 kW SMES coil

Inner radius, mm	300
Height, mm	1200.6
Number of layers	10
Number of turns per layer	522
Length of cable, km	10.1
Voltage of the dc bus, V	750
Min Current, A	266.6
Max current, A	467
Field on conductor (at Imax), T	1.63
I/Ic ratio (at Imax)	0.6
Inductance, H	6.80
Total eneregy (at Imax), kJ	741
Deliverable energy, kJ	500.4
Dump resistance, Ω	2,14
Max adiabatic hot spot temp., K	95.6



- **The SMES cannot be discharged below I_{min} = 267 A if the power of 200 kW is to be supplied/ absorbed ($I_{min} = P/V_{dc}$)**
- **The designed coil fullfills the specifics (200 kW – 2,5 s) with an operaing temperature T ≤ 16 K and a max. current I_{max} = 467 A**



Mechanical analysis

Mechanical design includes

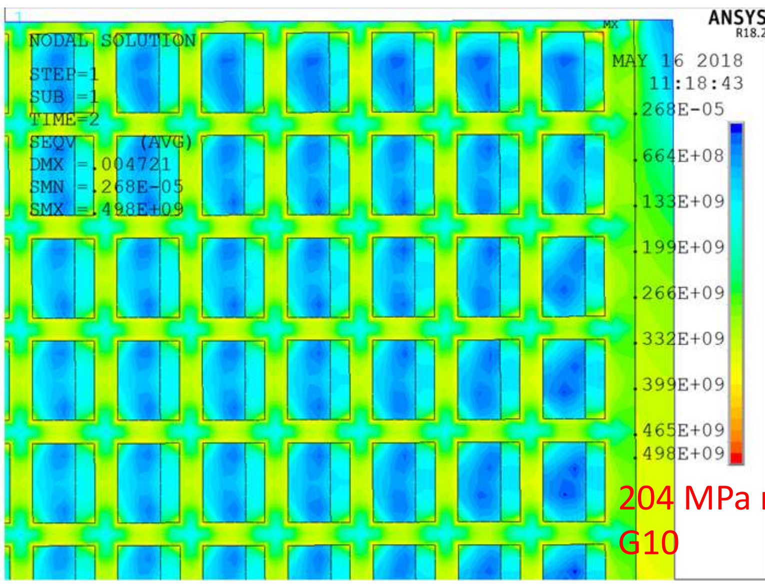
- **Pretensioning due to winding of the coil**
- **Thermal contraction during cool down**
- **Lorentz force**

Elastic’s moduli and thermal expansion coefficients of all materials taken from

- K Konstantopoulou et al., “Electro-mechanical characterization of MgB2 wires for the SC Link Project at CERN”, SUST 2016
- J. W. Ekin, Experim. Techniques for Low Temp. Measurements, OUP, 2006
- *P. Bauer et al.,* EFDA Material Data Compilation for Supercond. Simulation
- CRYOCOMP

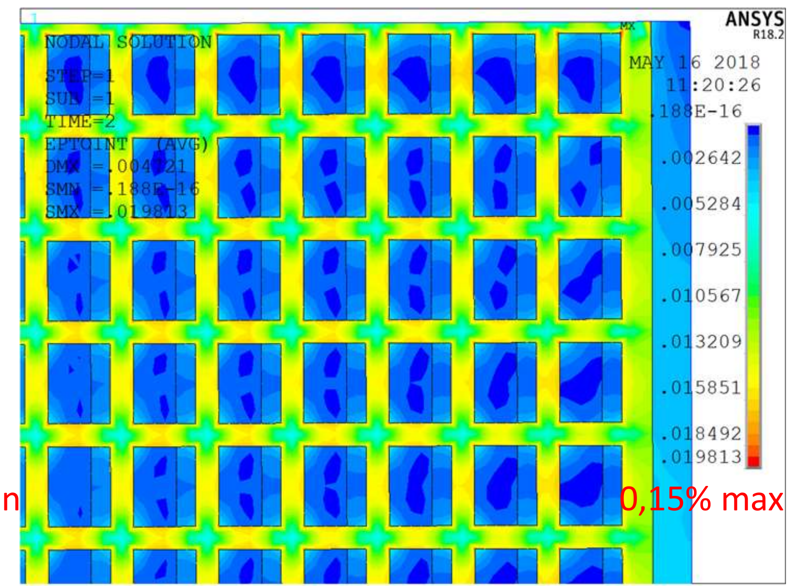
Equivalent Young’s modulus of the tape of 157.3 MPa obtained from weighted average

Von Mises stress



204 MPa max on G10

Strain



0,15% max on cond.

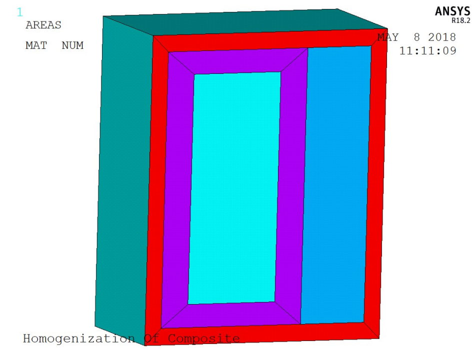
Stress within allowable limit for all materials

Strain below allowable limit

3D Quench Analisys

The composite (MgB2 tape + Cu strip + G10) block is replaced by an equivalent homogeneous one

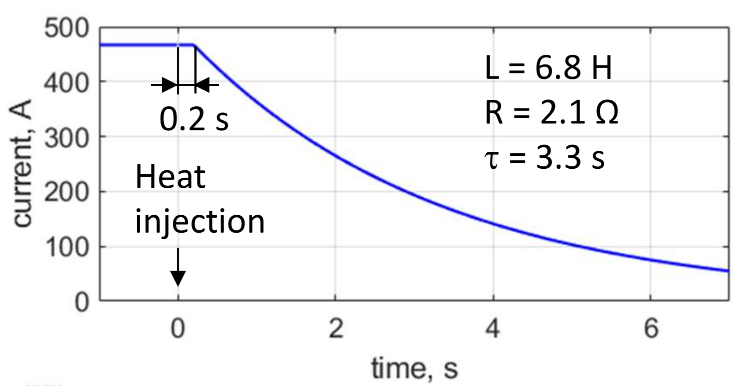
- Equivalent longitudinal resistivity ρ_{eq} from electric parallel
- Equivalent thermal capacity c_{eq} from volume weighted average
- Equivalent thermal conductivities (k_{req}, $k_{\theta eq}$, k_{zeq}) from thermal flux due to unit temperature drop in each direction



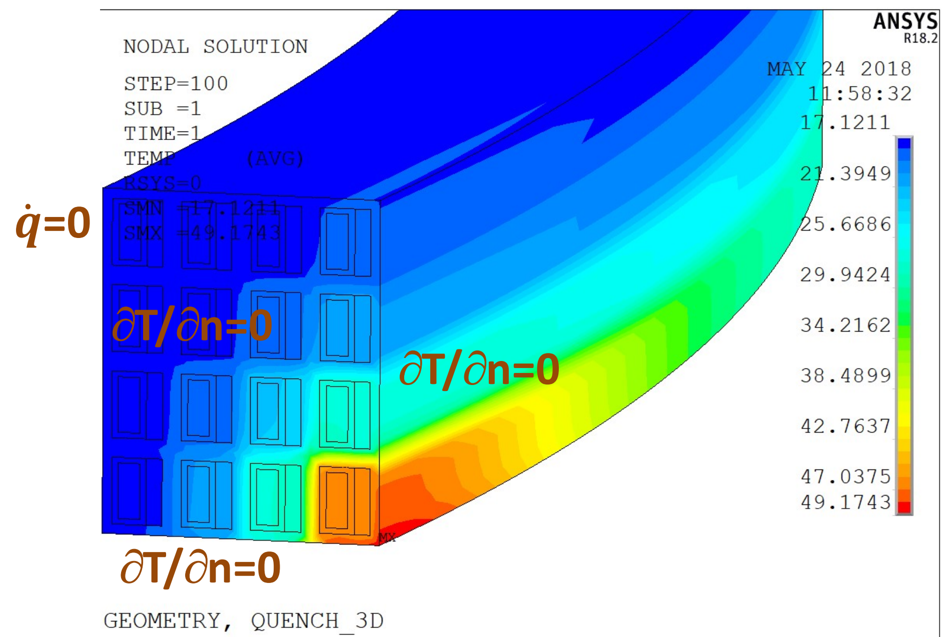
Thermal transient on a 15° sector made of 4x4 strand is calculated

- A 50 J heat relased in a small volume located at the middle radius of the coil
- 0.2 s delay before detection

SMES discharged on the dump resitor by means of the QPS



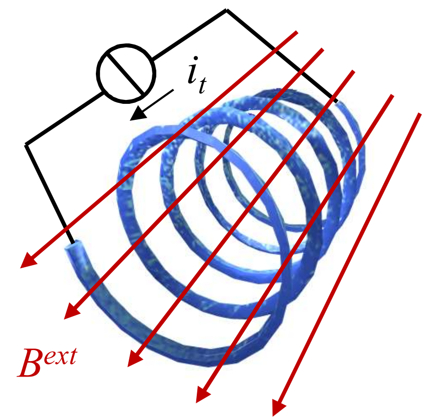
Temperature distrbution at 1 s



A max tempeature of is reached in the coil
Mechanicla stress due to tehrma expansion withn allowable limits

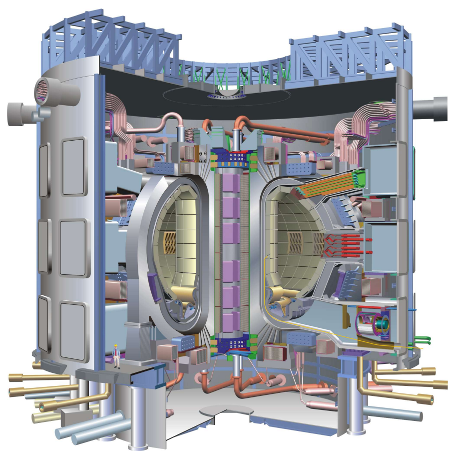
The THELMA model

AC loss of the MgB2 coil during charge and discharge of the SMES are calculated by means of the THELMA electromagnetic model



A in house numerical model for the coupled thermal-hydraulic (TH) and electro-magnetic (EM) analysis of superconductor cables subject to transport current and applied field

Developed in the frame of an Italian initiative, mainly aimed to the analysis of fusion problem

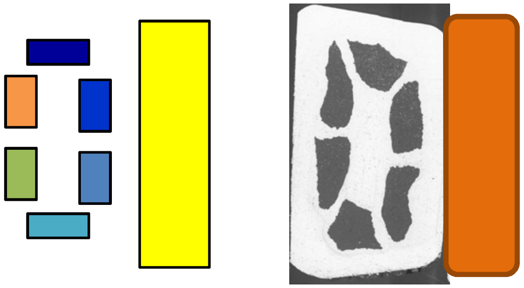


The model is rather general and can be used for a variety of problems

- cable-in-conduit conductor (CICC)
- Rutherford cables
- Multi-filamentary wires/tapes
- HTS tapes

- Ciotti, M., Nijhuis, A., Ribani, P.L., Richard, L.S., Zanino, R., "THELMA code electromagnetic model of ITER superconducting cables and application to the ENEA stability experiment", 2006 Superconductor Science and Technology 19(10),001, pp. 987-997
- Breschi, M., Ribani, P.L., "Electromagnetic modeling of the jacket in cable-in-conduit conductors", 2008 IEEE Transactions on Applied Superconductivity 18(1), 4454197, pp. 18-28

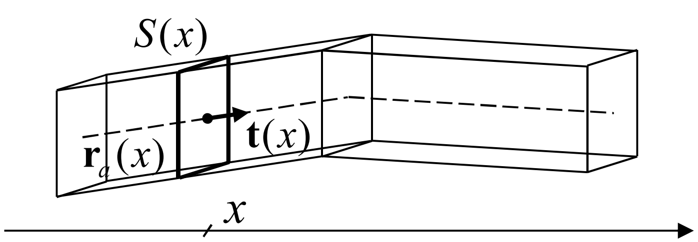
The geometrical model



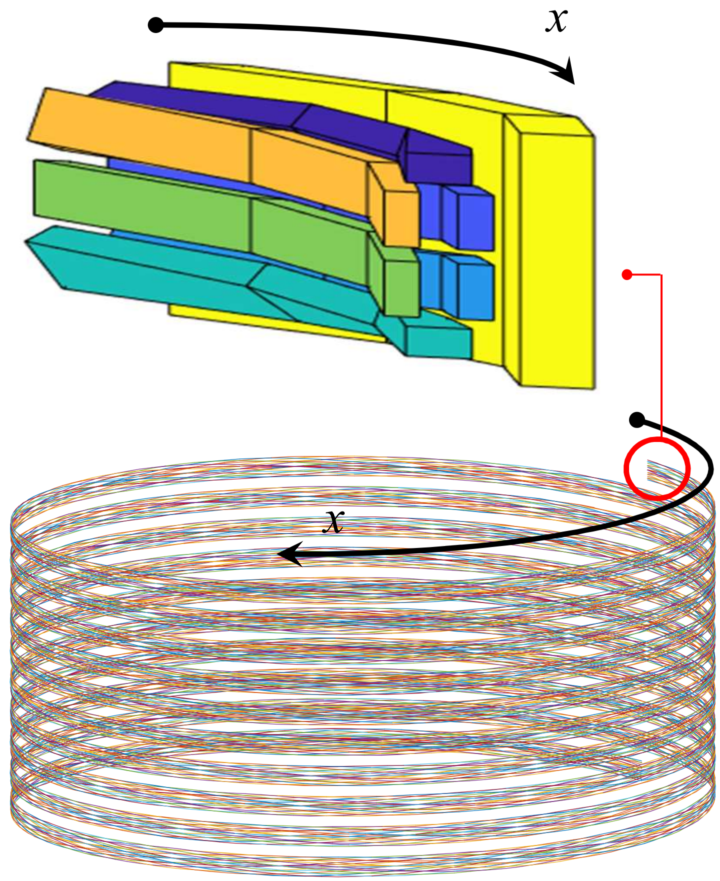
- A 2D model of the conducting elements of the tape (filaments + copper strip) is first introduced
- **Matrix material is not directly included in the geometrical model of the coil**

- A finite number of 3D elements is generated by extrusion along the helix pattern of the coil
- A rotation perpendicular to the helix pattern is added to the filaments to account for twisting

- The arc length x of the coil helix is used to state the problem. The entire discretized domain can be mapped on x (axis of elements, cross section, … are obtained from x)

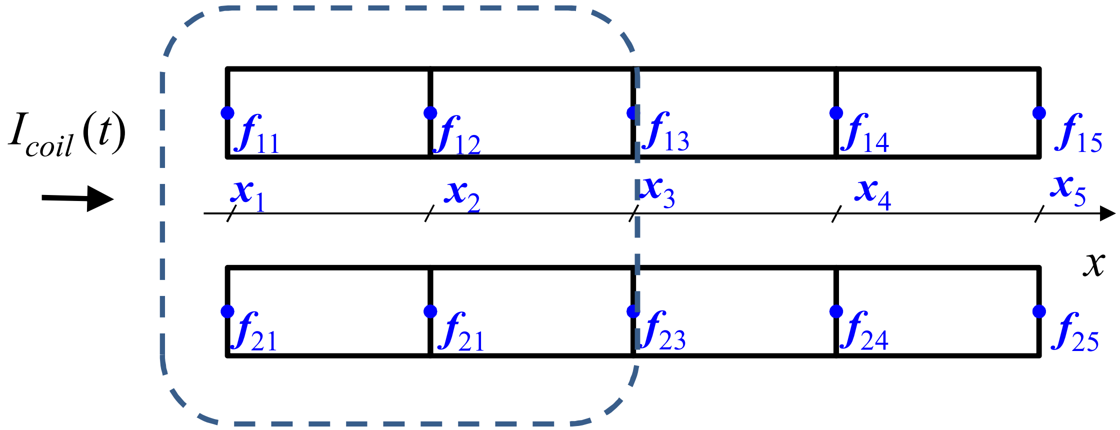


$$\mathbf{t}(x) = \frac{\dfrac{d\mathbf{r}_a(x)}{dx}}{\left|\dfrac{d\mathbf{r}_a(x)}{dx}\right|}$$



Geometrical model of 10 turns

Finite dimensional problem



- N_F **filaments (Cu strip included)**
- N_S **subdivisions along** x
- $N_F(N_S - 1)$ **3D elements**

Unknowns of the discretized problem:

N_C **currents of transverse faces shared by two elements or connecting the coil to the current supply**

$$N_C = N_F N_S$$

$$I_k(x_h, t) \quad \mathrm{h} = 1, \dots, N_S \quad \text{and} \quad \mathrm{k} = 1, \dots, N_F$$

current of filament ***k-th*** **at position** ***h-th***

$$\mathbf{I}(x_h, t) = [I_1(x_h, t), \dots, I_{NF}(x_h, t)]^T$$

set of N_F **currents at position** ***h-th***

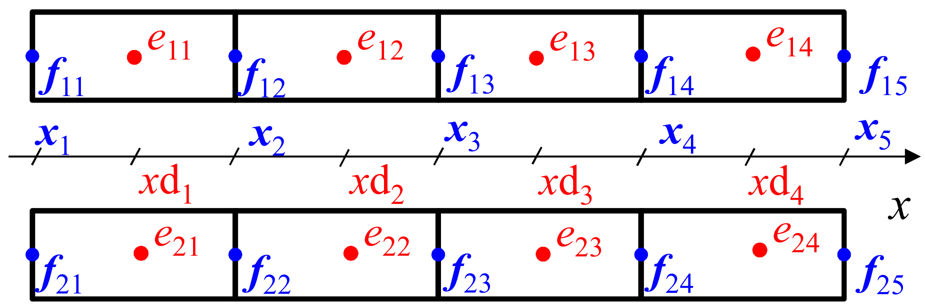
$$\mathbf{I}(t) = [\mathbf{I}^T(x_1, t), \dots, \mathbf{I}^T(x_{NS}, t)]^T$$

set of N_C **currents of the discretization**

Faces corresponding to the same x **coordinate form a cross section of the cable, hence**

$$\sum_{k=1}^{N_F} I_k(x_h, t) = I_{coil}(t) \quad \mathrm{h} = 1, \dots, N_S$$

A dual set of points is further introduced for stating the discrete problem



$N_{DP} = N_F\,(N_S - 1)$ **dual points**

Derivative at primal points not lying on the terminal sections

$$\left.\frac{\partial}{\partial x} q(x,t)\right|_{x=x_h} = \frac{q(xd_{h+1}) - q(xd_h)}{xd_{h+1} - xd_h}$$

$$\left.\frac{\partial}{\partial x} q(x,t)\right|_{x=x_h} = \mathbf{D}\,\left(\mathbf{q}(xd_{h+1},t) - \mathbf{q}(xd_h,t)\right)$$

$\mathbf{D}$: derivative matrix operator

$\mathbf{q}\,(xd_h,\ t)$: set of q values at all dual points at position xd_h

Derivative at dual points

$$\left.\frac{\partial}{\partial x} q(x,t)\right|_{x=xd_h} = \frac{q(x_{h+1},t) - q(x_h,t)}{x_{h+1} - x_h}$$

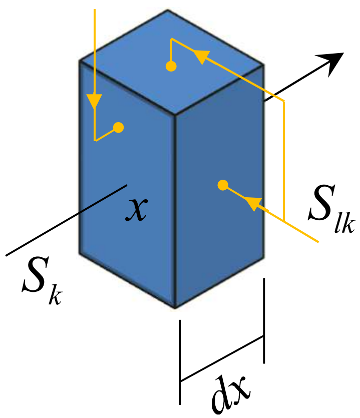
$$\left.\frac{\partial}{\partial x} q(x,t)\right|_{x=x_h} = \mathbf{D}\,\left(\mathbf{q}(x_{h+1},t) - \mathbf{q}(x_h,t)\right)$$

$\mathbf{D}$: derivative matrix operator at dual points

$\mathbf{q}\,(x_h,\ t)$: set of q values at all primal points x_h

Longitudinal and transverse current

- A uniform current density is assumed in the cross section of the element
- **The element can exchange current in the transverse direction through the matrix material**



Longitudinal current of filament k at coordinate x

$$I_k(x,t) = \int_{S_k} \mathbf{J} \cdot \mathbf{n}\, dS \qquad [\,\mathrm{A}\,]$$

Transverse current per unit length of filament k (entering) at coordinate x

$$K_k(x,t) = \frac{1}{dx} \int_{S_{lk}} \mathbf{J} \cdot \mathbf{n}\, dS \qquad [\,\mathrm{A/m}\,]$$

- **Charge conservation**

$$I_k(x,t) - I_k(x+dx,t) + K_k(x,t)\,dx = 0 \quad \longrightarrow \quad \frac{d}{dx} I_k(x,t) = K_k(x,t)$$

$\mathbf{A} - v$ formulation and magnetic vector potential

- The $\mathbf{A} - v$ is used for expressing the electric field at any point of the conducting domain

$$\mathbf{E}(\mathbf{r},t) = -\frac{\partial}{\partial t}\mathbf{A}(\mathbf{r},t) - \nabla v(\mathbf{r},t)$$

- **Magnetic vector potential**

$$\mathbf{A}(\mathbf{r},t) = \mathbf{A}^{\mathrm{J}}(\mathbf{r},t) + \mathbf{A}^{\mathrm{ext}}(\mathbf{r},t)$$

due to currents of the discretized domain

due to external currents

$$\mathbf{A}^{\mathrm{ext}}(\mathbf{r},t) = \frac{\mu_0}{4\pi}\int_{\tau_{coil}-\tau_{filaments}} \frac{\mathbf{J}(\mathbf{r}',t)}{|\mathbf{r}-\mathbf{r}'|}\, d^3 r'$$

Produced by the currents flowing in the part of the coil not included in the discretization

$$\mathbf{A}^{\mathrm{J}}(\mathbf{r},t) = \frac{\mu_0}{4\pi}\int_{\tau_{filaments}} \frac{\mathbf{J}(\mathbf{r}',t)}{|\mathbf{r}-\mathbf{r}'|}\, d^3 r' + \frac{\mu_0}{4\pi}\int_{\tau_{matrix}} \frac{\mathbf{J}(\mathbf{r}',t)}{|\mathbf{r}-\mathbf{r}'|}\, d^3 r'$$

all conducting elements
filaments + Cu strip

matrix material

Though the matrix material is not explicitly included in the discretization coupling currents flow through it and contribute, strictly, to the vector potential

The key assumption:

$$\mathbf{A}^{\mathrm{J}}(\mathbf{r},t)=\frac{\mu_0}{4\pi}\int_{\tau_{filaments}}\frac{\mathbf{J}(\mathbf{r}',t)}{|\mathbf{r}-\mathbf{r}'|}\,d^3r'+\cancel{\frac{\mu_0}{4\pi}\int_{\tau_{matrix}}\frac{\mathbf{J}(\mathbf{r}',t)}{|\mathbf{r}-\mathbf{r}'|}\,d^3r'}$$

The vector potential due to transverse coupling currents flowing through the matrix is negligible with respect to the one due to currents flowing in the conducting filaments

$$\mathbf{A}^{\mathrm{J}}(\mathbf{r},t)=\frac{\mu_0}{4\pi}\int_{\tau_{filaments}}\frac{\mathbf{J}(\mathbf{r}',t)}{|\mathbf{r}-\mathbf{r}'|}\,d^3r'$$

This is a suitable approximation in problems where a dominant direction of current exists

Longitudinal problem - Weak form

The power law is assumed modeling the superconductor

$$\mathbf{E}(\mathbf{r}) = E_0 \left(\frac{J}{J_{\mathrm{c}}} \right)^n \frac{\mathbf{J}(\mathbf{r})}{J}$$

Dependance of J_{c} on B is implicit

A solution is looked for in the weak form by imposing at the internal subdivisions

$$\mathbf{t}_k(x_h) \cdot \mathbf{E}_k(x_h, t) = -\mathbf{t}_k(x_h) \cdot \left(\frac{\partial}{\partial t} \mathbf{A}_k^{\mathrm{J}}(x_h, t) - \frac{\partial}{\partial t} \mathbf{A}_k^{ext}(x_h, t) - \nabla v_k(x_h, t) \right) \qquad \begin{array}{l} h = 2, \ldots, N_S - 1 \\ k = 1, \ldots, N_F \end{array}$$

Which gives

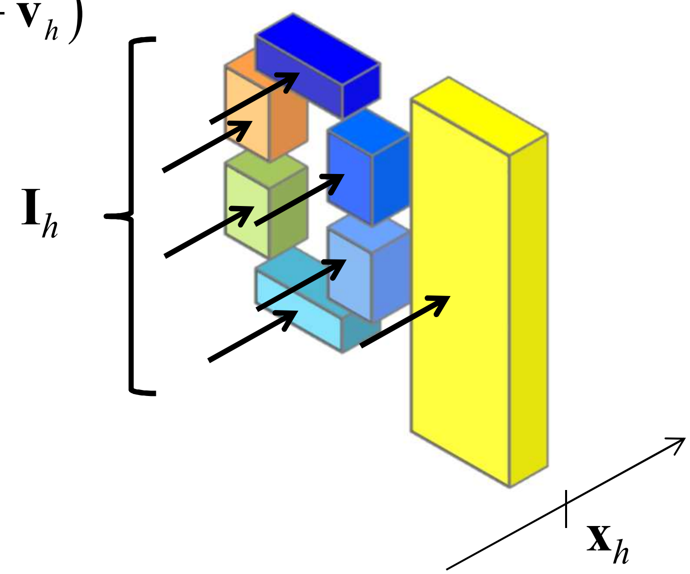
set of N_F scalar potentials at dual position *h+1-th* and *h-th*

$$\mathbf{f}_h\left(\mathbf{I}_h\right) = -\sum_{j=1}^{N_S} \mathbf{m}_{hj} \frac{d}{dt} \mathbf{I}_j - \mathbf{u}_h \frac{d}{dt} I_{coil} - \mathbf{p}_h \mathbf{d}_h \left(\mathbf{v}_{h+1} - \mathbf{v}_h \right)$$

Subject to

$$\mathbf{1} \cdot \mathbf{I}_h = I_{coil}$$

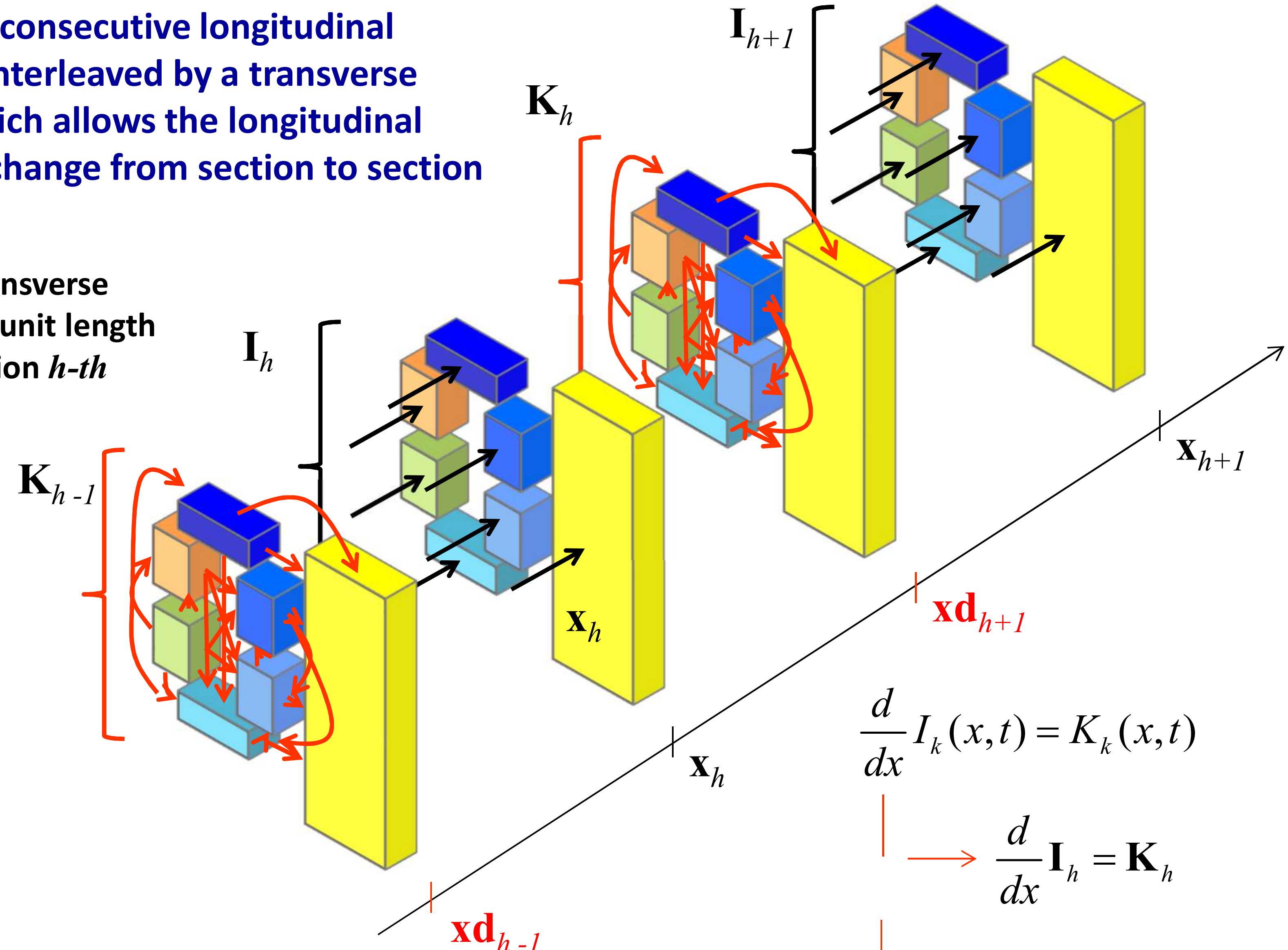
set of N_F currents at position *h-th*



Eliminating the potentials – Solving the transverse conduction problem

Each pair of consecutive longitudinal problem is interleaved by a transverse problem which allows the longitudinal currents to change from section to section

set of N_F transverse currents per unit length at dual position ***h-th***



$$\frac{d}{dx} I_k(x,t) = K_k(x,t)$$

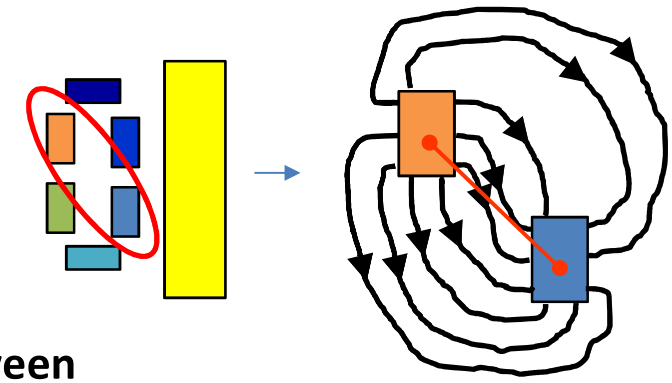
$$\frac{d}{dx}\mathbf{I}_h = \mathbf{K}_h$$

$$\mathbf{d}_h \mathbf{I}_h = \mathbf{K}_h$$

For solving the transverse problem line integral along a transverse path connecting two dual points is considered

$$\int_{\mathbf{r}_m(xd_h)}^{\mathbf{r}_n(xd_h)} \mathbf{E}\cdot\mathbf{t}\,dr = -\int_{\mathbf{r}_m(xd_h)}^{\mathbf{r}_n(xd_h)} \frac{\partial \mathbf{A}^J}{\partial t}\cdot\mathbf{t}\,dr - \int_{\mathbf{r}_m(xd_h)}^{\mathbf{r}_n(xd_h)} \frac{\partial \mathbf{A}^{ext}}{\partial t}\cdot\mathbf{t}\,dr + \left(v_m(xd_h) - v_n(xd_h)\right)$$

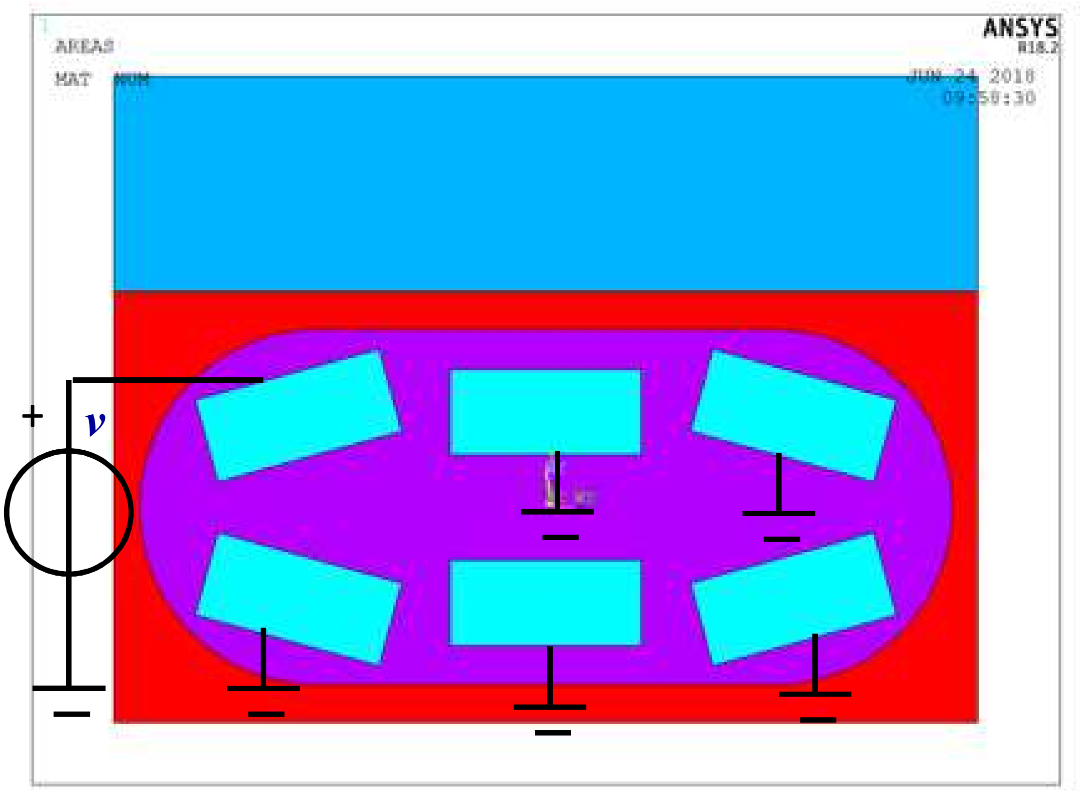
We assume that current distribution in the transverse cross sections is the same as it would be in the case of steady current conduction, hence



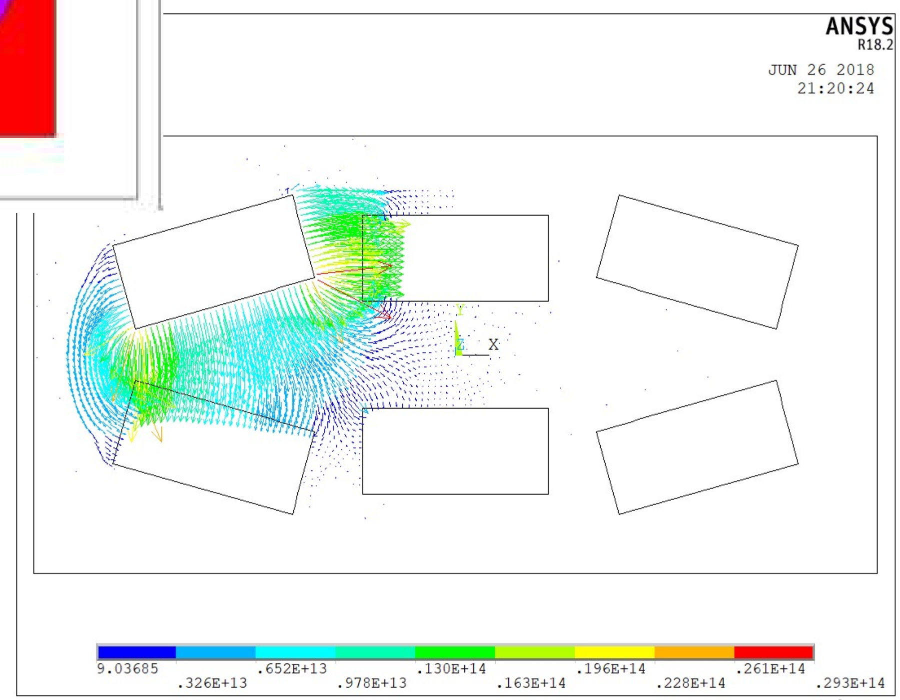
Transverse conductance per unit length between filaments *m* and *n* at position x_h

$$K_{mn}(x_h) = g_{mn}(x_h)\left(-\sum_{j=1}^{N_S}\sum_{k=1}^{N_F} m^t{}_{mn,k,j}(x_h)\frac{d}{dt}I_k(x_j,t) - u_{mn}(x_h)\frac{d}{dt}I_{coil}(t) + \left(v_m(x_h) - v_n(x_h)\right) \right)$$

- **No derivative of the transvers currents appear in the equation**
  - **The transverse problem can be solved as a series of static problems in which the derivative of longitudinal currents act as forcing terms**



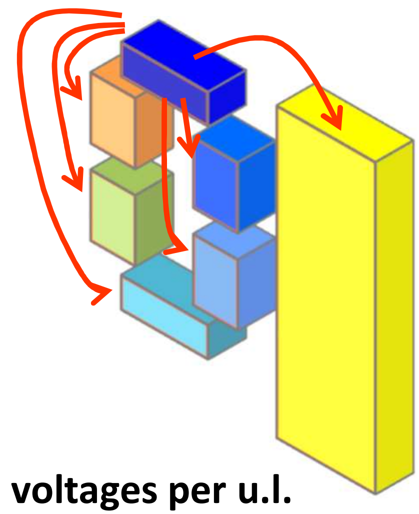
Conductances are calculated during the preprocessing by means of a commercial software



ρ_{monel} (20K) = $4.2\times10^{-7}\ \Omega$m
ρ_{nickel} (20K) = $11\times10^{-9}\ \Omega$m

Due to model very small conductance, and hence current, is found toward the copper filament

$$K_m(x_h) = \sum_{n=1}^{N_F} K_{mn}(x_h)$$ **total current of filament m**



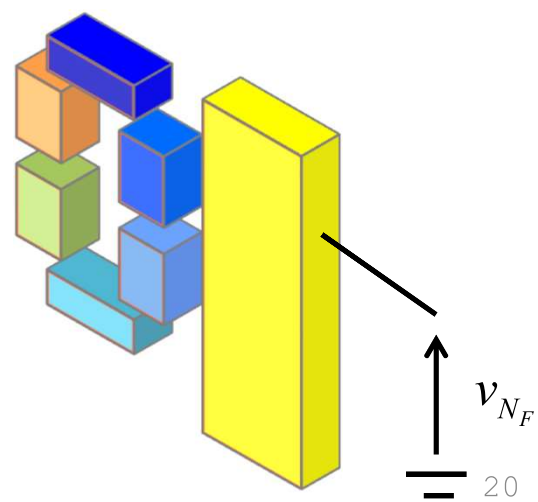
By assembling the transverse voltage balances referring to all filaments but the last one we obtain

set of $N_F - 1$ transverse currents per u.l. set of $N_F - 1$ transverse voltages per u.l.

$$\mathbf{K}'_h = \mathbf{g}'_h \left(-\sum_{j=1}^{N_S} \mathbf{m}^{t}_j \frac{d}{dt}\mathbf{I}_j - \mathbf{u}_h \frac{d}{dt} I_{coil} + \mathbf{v}'_h - \mathbf{1} v_{N_F} \right)$$

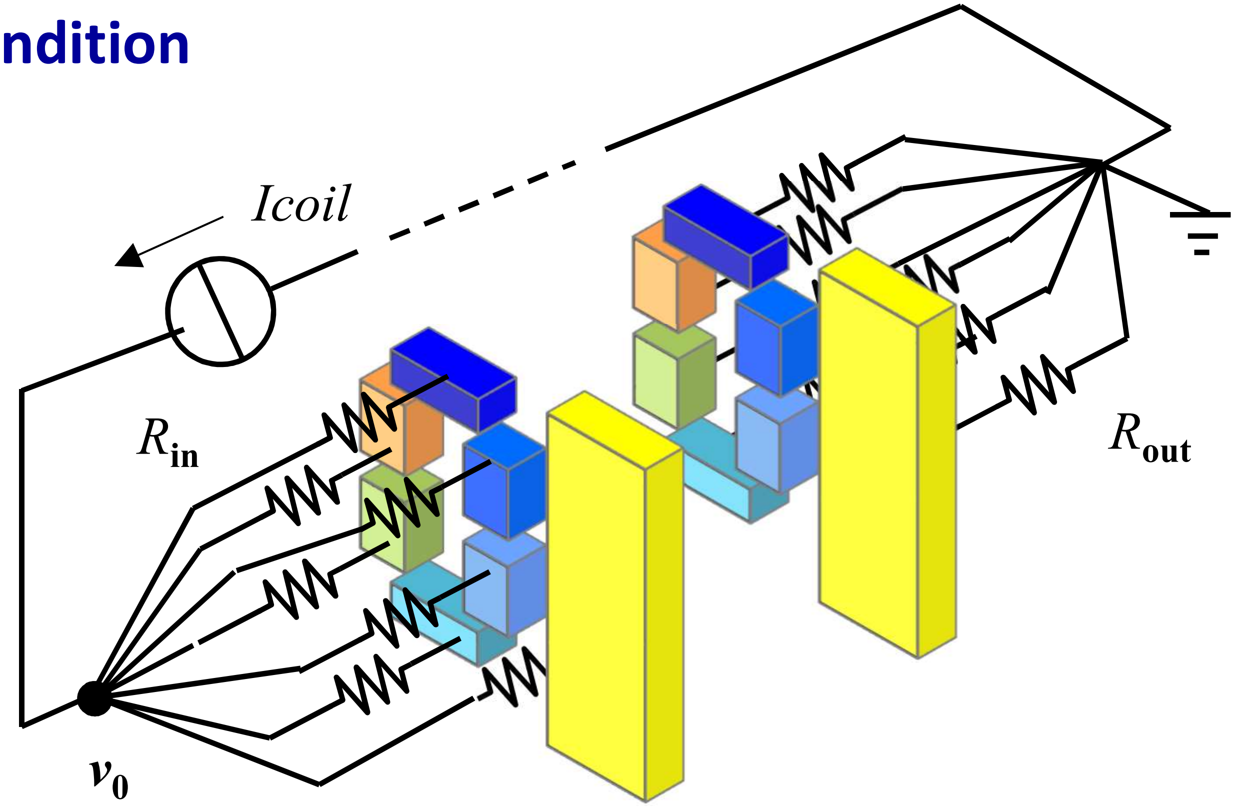
with $g_{h,mm} = \sum_{\substack{m=1 \\ m\neq n}}^{N_F} g'_{mn}(x_h)$ and $g_{h,mn} = -g'_{mn}(x_h)$

Finally, by using charge conservation, the potentials at all nodes of each section but the last are related to the longitudinal current as



$$\mathbf{v}'_h = \mathbf{g}_h^{-1}\mathbf{d}_h \left(\mathbf{I}'_{h+1} - \mathbf{I}'_h \right) + \sum_{j=1}^{N_S} \mathbf{m}^{t}_j \frac{d}{dt}\mathbf{I}_j + \mathbf{u}_h \frac{d}{dt} I_{coil} + \mathbf{1} v_{N_F h}$$

Boundary condition



- **Two further nodes are added for calculating the derivative of voltage at the input and output sections**
- **A resistive model of the terminations is added in order to calculate the potential of the additional nodes at the input and output section**

$$\mathbf{v}_1 - \mathbf{1}v_0 = -diag(R_{in})\mathbf{I}_1 \qquad \mathbf{v}_{NS-1} - \mathbf{1}v_{NS} = +diag(R_{out})\mathbf{I}_{NS-1}$$

Assembling of the solving system

$$
\begin{cases}
\mathbf{f}_h(\mathbf{I}_h) = -\sum_{j=1}^{N_S} \mathbf{m}_{hj} \frac{d}{dt}\mathbf{I}_j - \mathbf{u}_h \frac{d}{dt} I_{coil} - \mathbf{p}_h \mathbf{d}_h (\mathbf{v}_{h+1} - \mathbf{v}_h) \\
\mathbf{1} \cdot \mathbf{I}_h = I_{coil} \\
\mathbf{v}'_h = \mathbf{g}_h^{-1} \mathbf{d}_h (\mathbf{I}'_{h+1} - \mathbf{I}'_h) + \sum_{j=1}^{N_S} \mathbf{m}^{t}_j \frac{d}{dt}\mathbf{I}_j + \mathbf{u}_h \frac{d}{dt} I_{coil} + \mathbf{1} v_{N_F h} \\
\mathbf{v}_1 - \mathbf{1}v_0 = -diag(R_{in})\mathbf{I}_1 \quad \mathbf{v}_{NS-1} - \mathbf{1}v_{NS} = +diag(R_{out})\mathbf{I}_{NS-1}
\end{cases}
$$

$N_F \times (N_s - 2)$ equations

N_s equations

$(N_F - 1) \times (N_s - 1)$ equations

$2N_F$ equations

$N_F \times N_s + (N_F - 1) \times N_S + 1$ equations

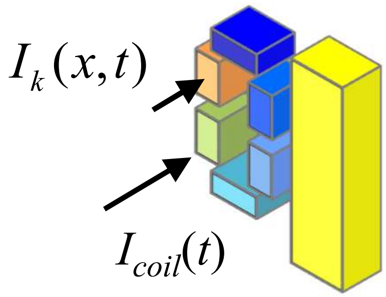
$N_F \times (N_s - 2) + (N_F - 1) \times N_S + 2N_F$ unknowns

- The last of longitudinal voltage balance equations of each sections is used for eliminating the potential v_{NF} from the corresponding dual sections
- Current balance at all sections is used for eliminating current I_{NF} at all sections

$$
\begin{cases}
\mathbf{M} \frac{d}{dt}\mathbf{I}(t) = -\mathbf{f}\big(\mathbf{I}(t)\big) - \mathbf{U} \frac{d}{dt} I_{coil} \\
\mathbf{I}(0) = \mathbf{I}_0
\end{cases}
$$

$(N_F - 1) \times N_s$ state equations

Making the problem sparse – introducing constant and deviation current



The total longitudinal current carried by the elements at any coordinate x must coincide with the coil current

The constant current (independent on x) of element k is introduced

$$I_k^c(t) = \frac{S_k}{S_{tot}} I_{coil}(t) \qquad \mathrm{k} = 1,\ldots,N_F$$

same for all elements of one filament

The longitudinal current of element at coordinate x is expressed as the sum of the constant current plus a deviation current with respect to it

$$I(x_h,t) = I_h^c(t) + i_h(x_h,t)$$

Deviation current at coordinate x of element k

An assigned, time dependent, term

That is

set of N_F deviation currents at position h

set of N_F total currents at position h

$$\mathbf{I}_h = \mathbf{s}_h I_{coil} + \mathbf{i}_h$$

set of N_F constant currents

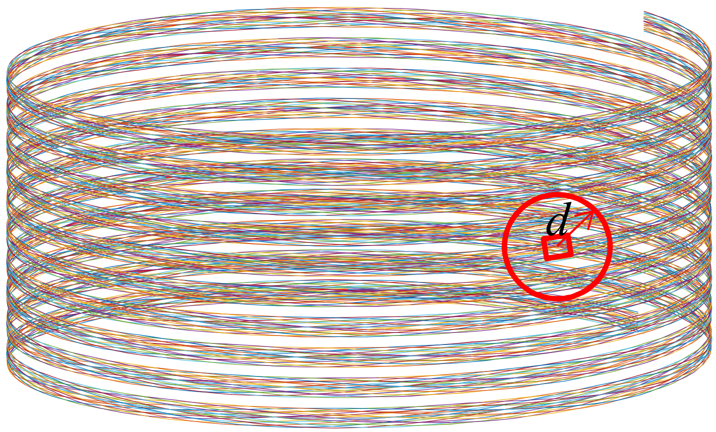
- **By substituting in the voltage balance equation at position h**

$$\mathbf{f}_h(\mathbf{I}_h) = -\sum_{j=1}^{N_S} \mathbf{m}_{hj} \frac{d}{dt}\mathbf{i}_j - \sum_{j=1}^{N_S} \mathbf{m}_{hj}\mathbf{s}_j \frac{d}{dt} I_{coil} - \mathbf{u}_h \frac{d}{dt} I_{coil} - \mathbf{p}_h \mathbf{d}_h (\mathbf{v}_{h+1} - \mathbf{v}_h)$$

$$\begin{bmatrix} \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} \\ \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} \\ \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} \\ \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} \\ \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} \end{bmatrix} \longrightarrow \begin{bmatrix} \mathbf{m} & \mathbf{m} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{m} & \mathbf{m} & \mathbf{m} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{m} & \mathbf{m} \end{bmatrix}$$

The coefficients matrix of the compete problem is made by the assembling of full $N_F \times N_F$ blocks

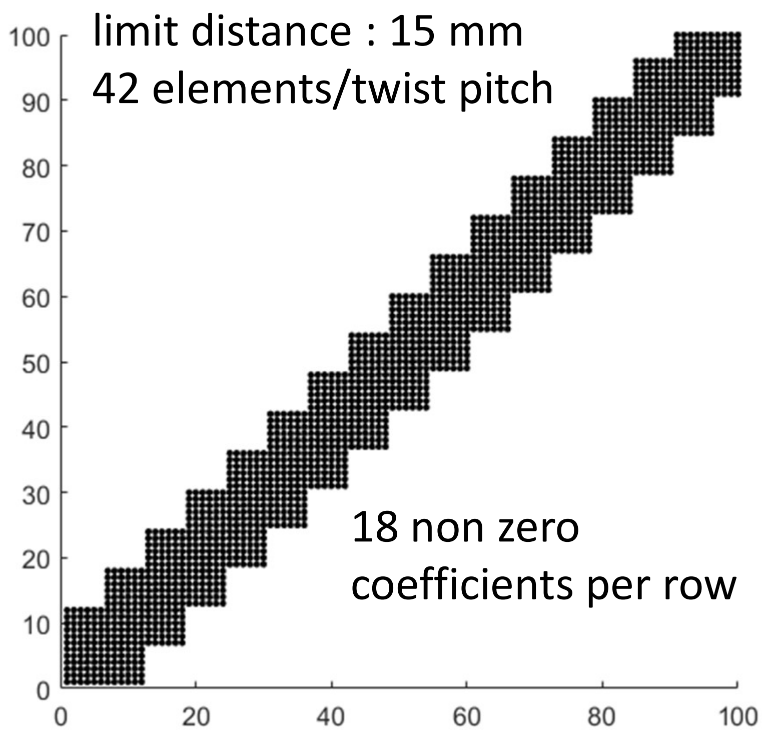
The coefficients matrix becomes sparse

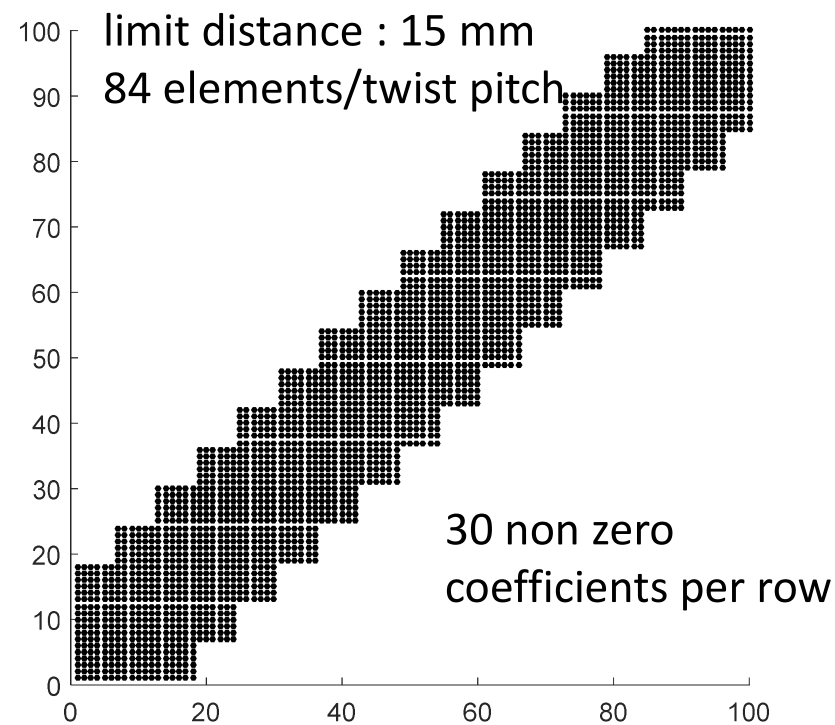


- **If the distance between two blocks is greater than a given value we disregard the corresponding blocks of the coefficients matrix**
- **We are not completely neglecting the long term interactions since this is considered via the additional term related to the constant current which acts as forcing term**

$$
\begin{cases}
\mathbf{M}\dfrac{d}{dt}\mathbf{i}(t) = -\mathbf{f}\left(\mathbf{s}\,I_{coil} + \mathbf{i}(t)\right) - \left(\mathbf{M}\,\mathbf{s} + \mathbf{U}\right)\dfrac{d}{dt}I_{coil} \\
\mathbf{i}(0) = \mathbf{i}_0
\end{cases}
$$

The stiffness matrix of the state equation is obtained by algebraic manipulation from the coefficients matrix and follows the same behavior



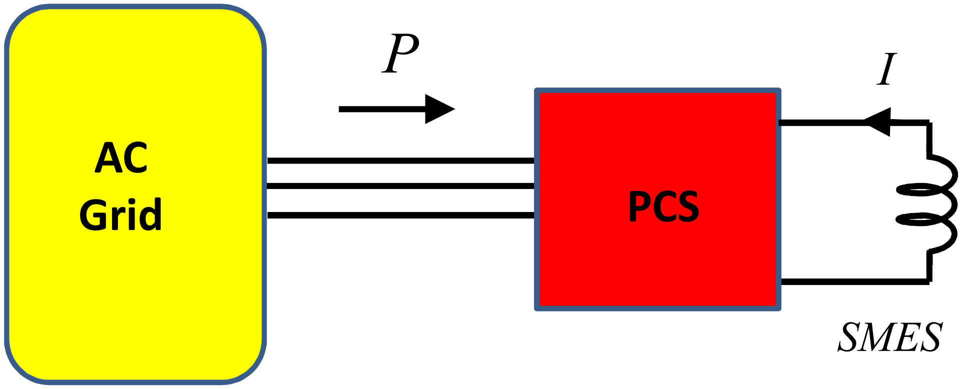


ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Outline

- The DRYSMES4GRID project
- The reference MgB_2 Coil
- Computation of AC loss of the SMES coil
  - Model and assumptions
  - Making the matrix sparse
  - **Numerical results**
- **Conclusion and future work**

Simulated cases



$$\frac{1}{2} L\, I^2 - \frac{1}{2} L I_0^2 = \mp P(t - t_0)$$

$$I = \sqrt{I_0^2 \mp \frac{2}{L} P(t - t_0)}$$

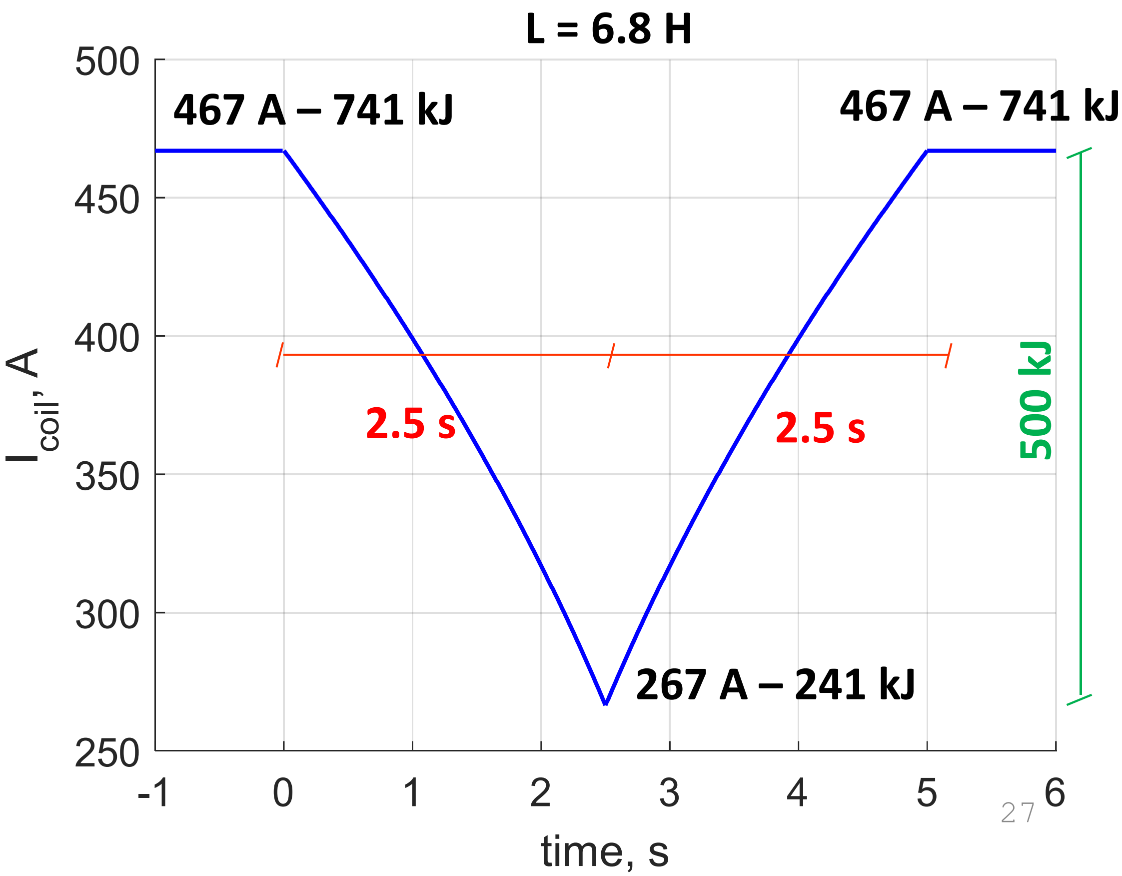
Discharge

@ 200 kW – 2.5 s

Charge

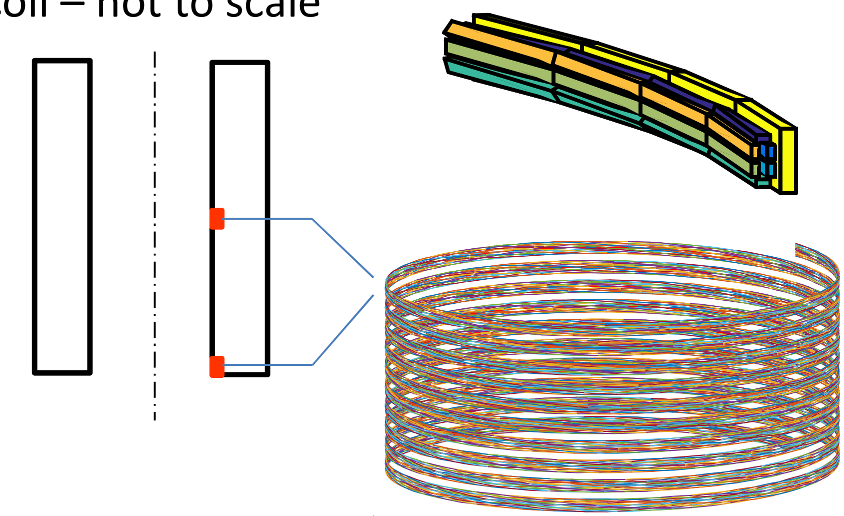
@ 200 kW – 2.5 s

Waveform of coil current is obtainded from operating conditions



Mesh and computation time

Coil – not to scale



~ 19 m of conductor

Ten turns of the coil are modeled

- Turns are located at the bottom and at the middle of the layer
- All layers are considered (20 cases in total)

Mesh

- 42 elements per twist pitch (600 mm)
- 1323 elements in total

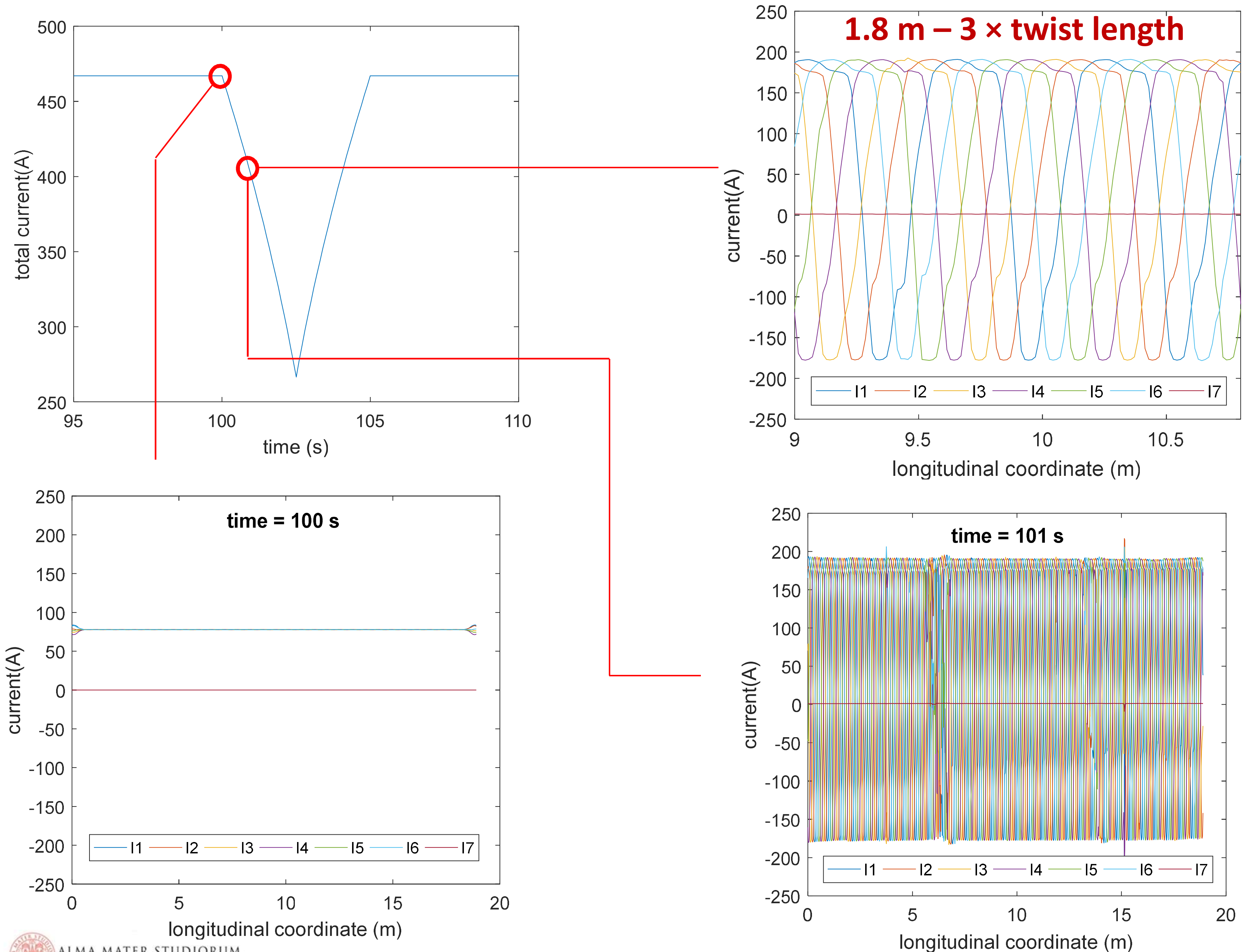
Convergence analysis shows that same results are obtained with a higher number of elements per twist pitch and/or with a larger number of turns (up to 58)

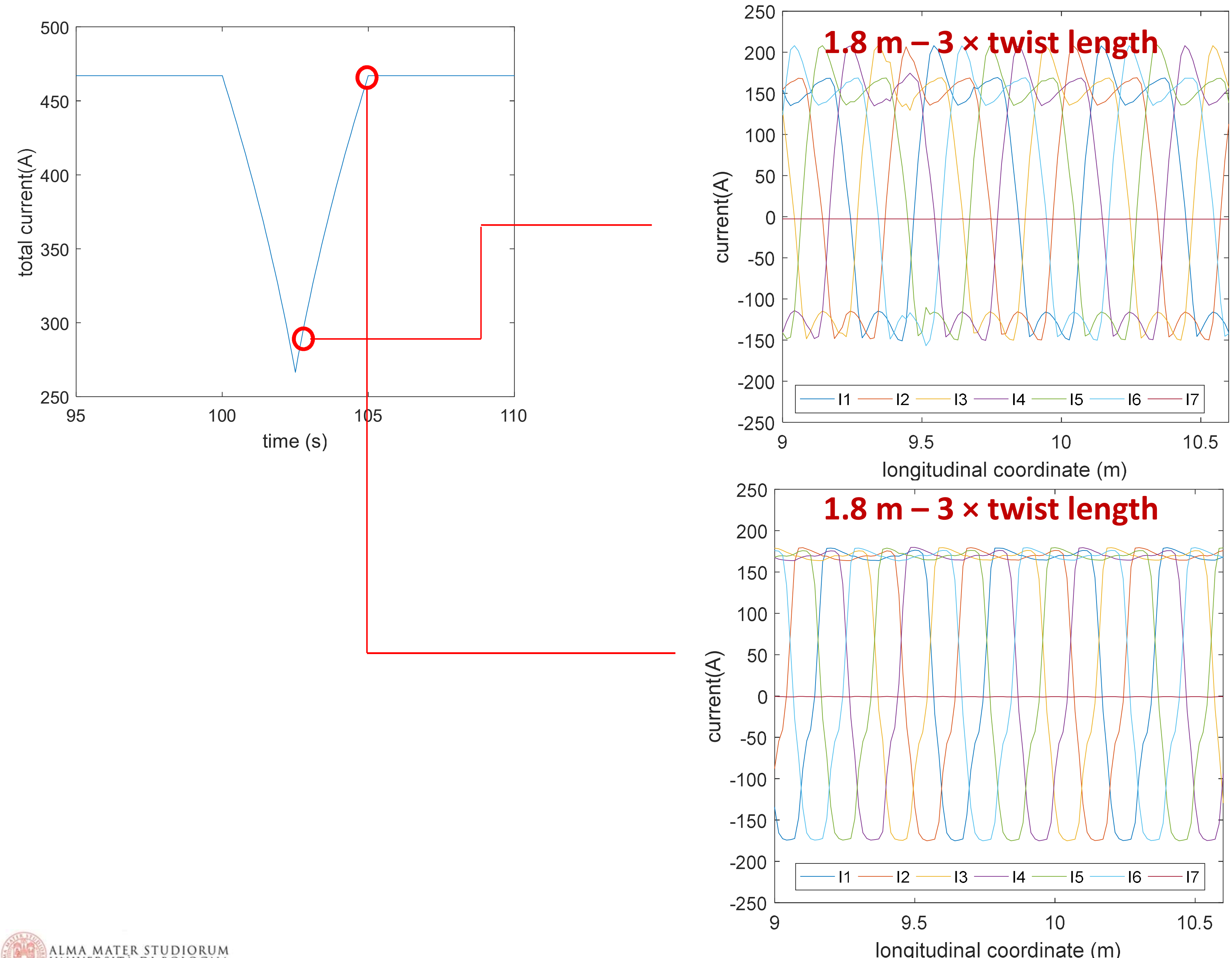
Uniform current in the filaments (no transverse current) is assumed as initial condition

Computation times

- 10 turns – 42 elements per twist pitch – 1323 unknowns — 50 m
- 10 turns – 84 elements per twist pitch – 2646 unknowns — 4h 5 m
- 58 turns – 42 elements per twist pitch – 7663 unknowns — 30h 48 m

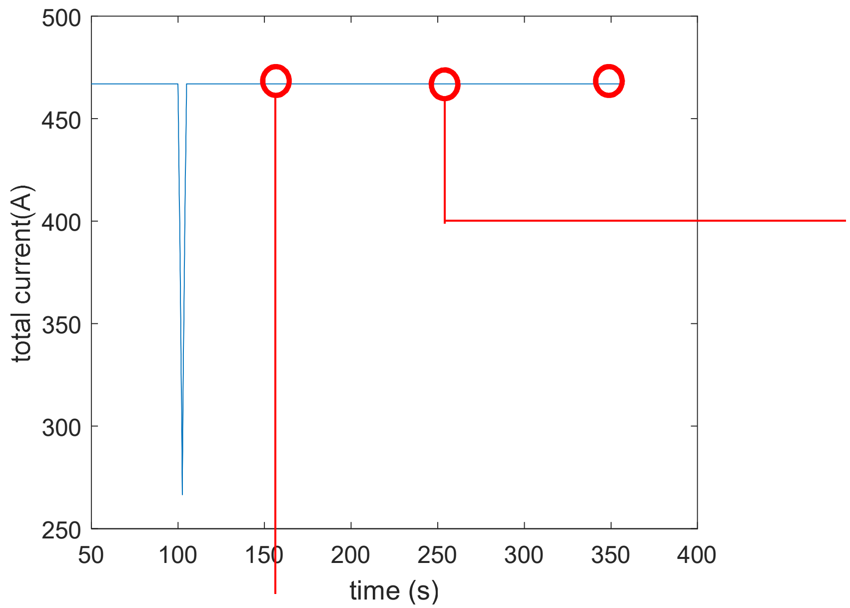
Layer 1 – bottom - current distribution

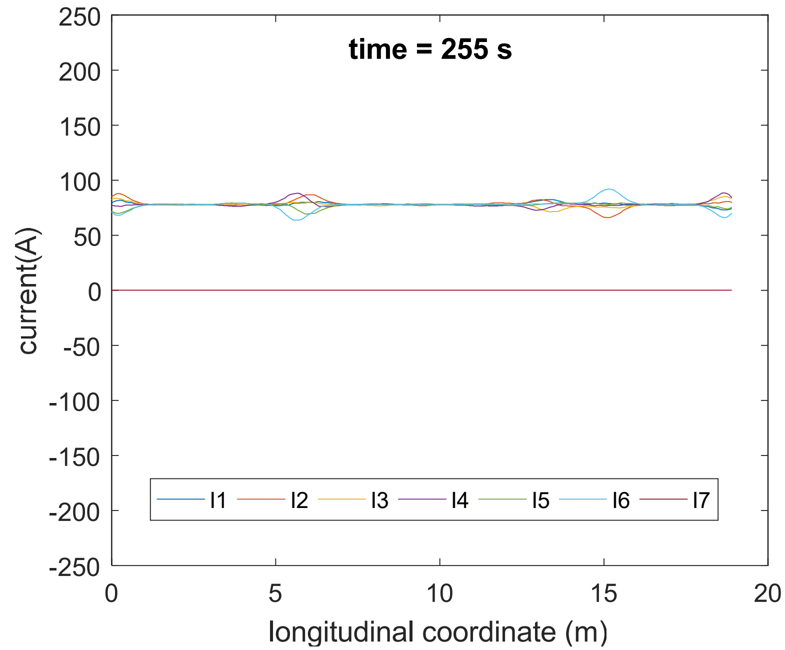


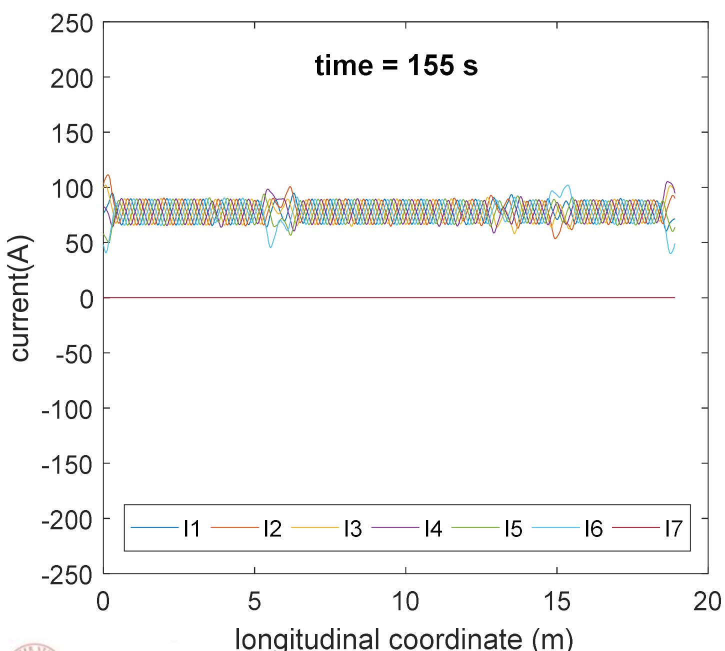


total current(A)
time (s)
1.8 m – 3 × twist length
current(A)
longitudinal coordinate (m)
I1 I2 I3 I4 I5 I6 I7
1.8 m – 3 × twist length
current(A)
longitudinal coordinate (m)
I1 I2 I3 I4 I5 I6 I7

Relaxation of coupling currents

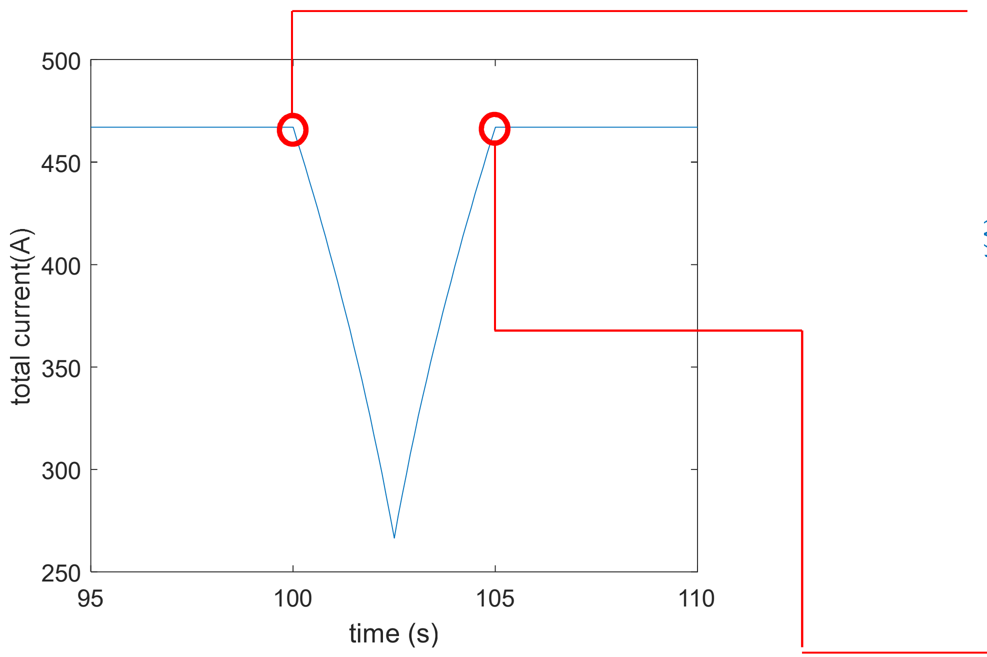


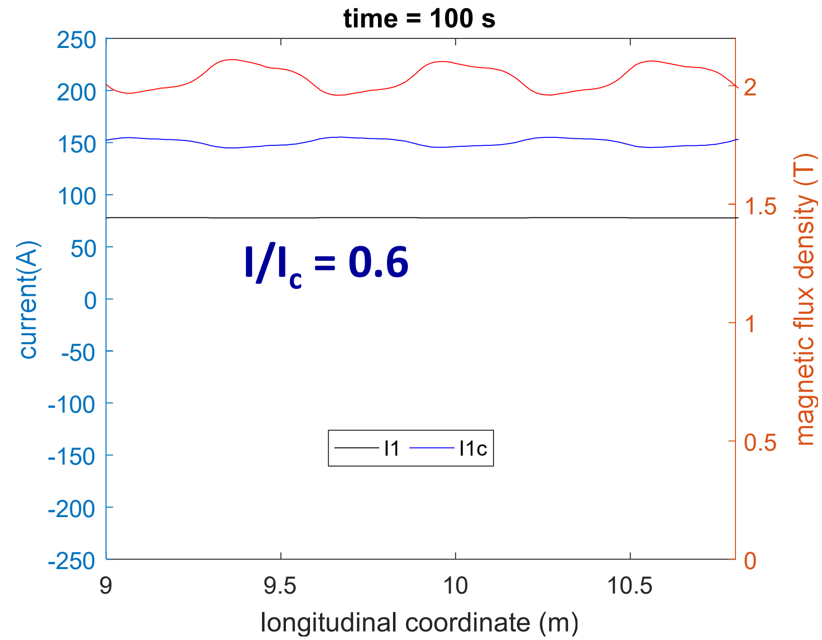


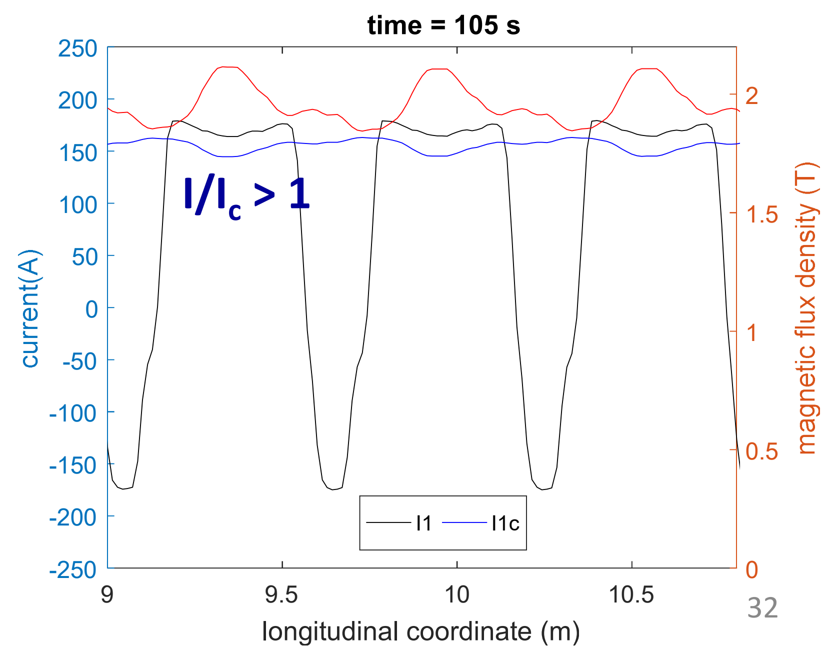


Relaxation of coupling current nearly completed after 150 s

Current vs critical current

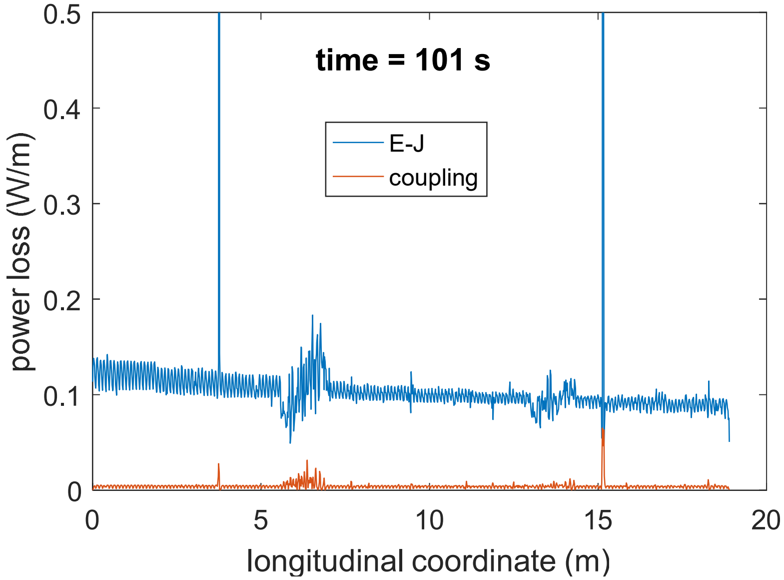


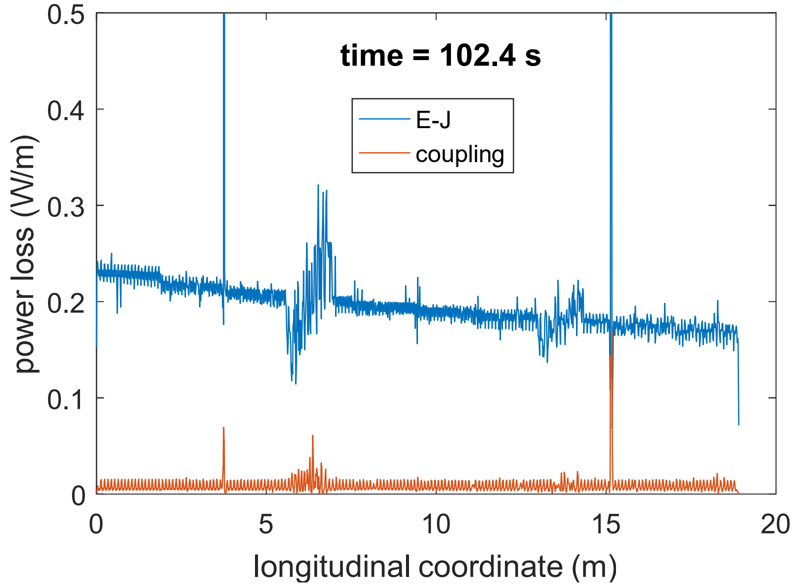


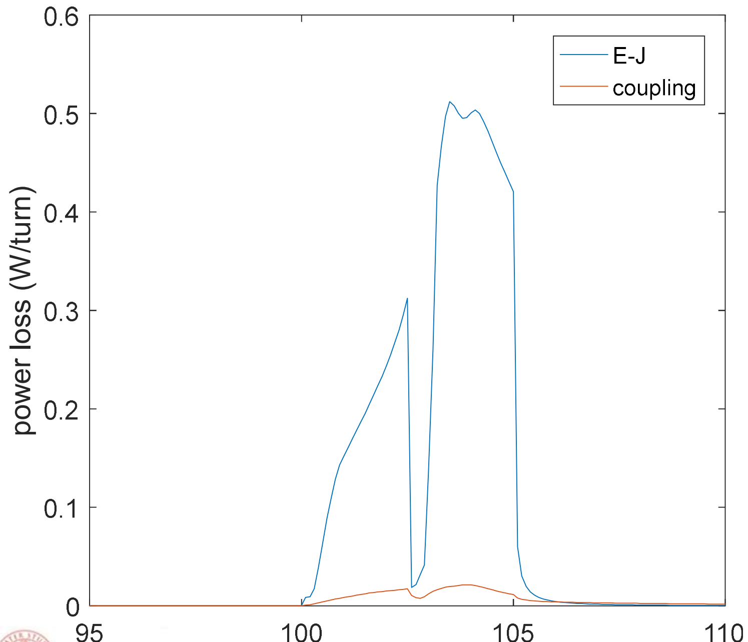


- **Current of filaments below the critical value during steady SMES operation**
- **Critical current largely overcome during ramp due to coupling currents**

Dissipated power



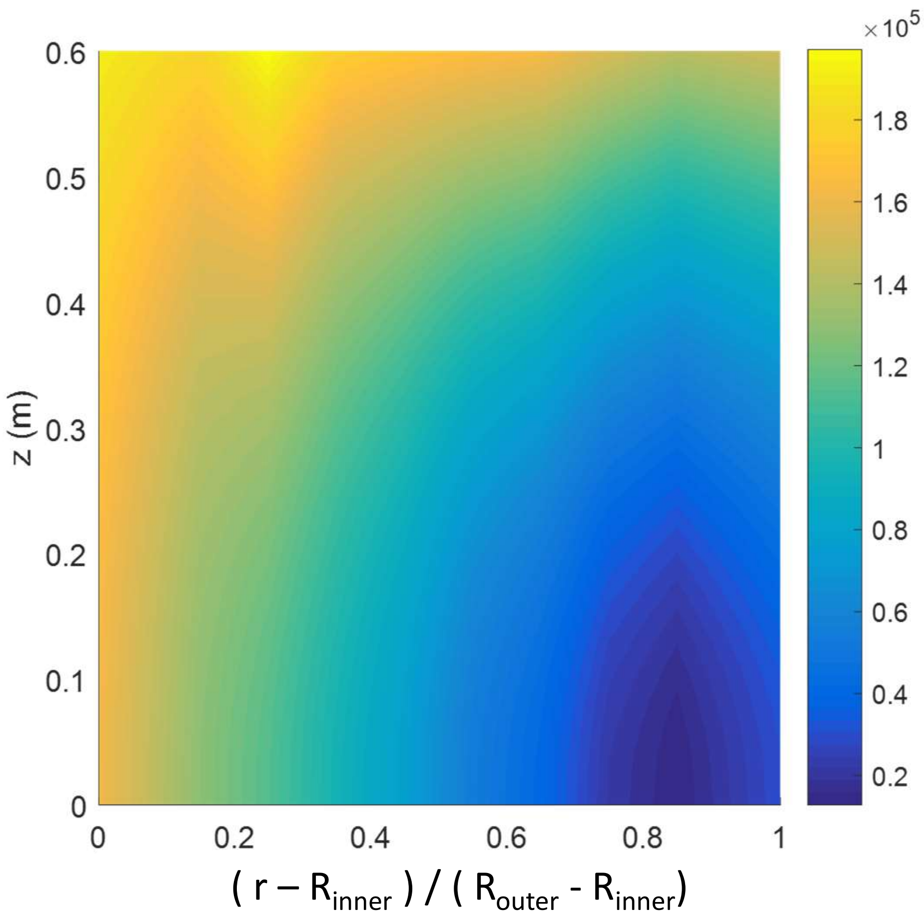




- **Loss due to coupling current are negligible compared to loss in the superconductor filaments**
- **An average power of about 155 mW / turn occurs at the bottom of the coil**

Loss distribution and recovery

Energy loss per unit volume of coil (J/m³)
in one discharge/ charge cycle

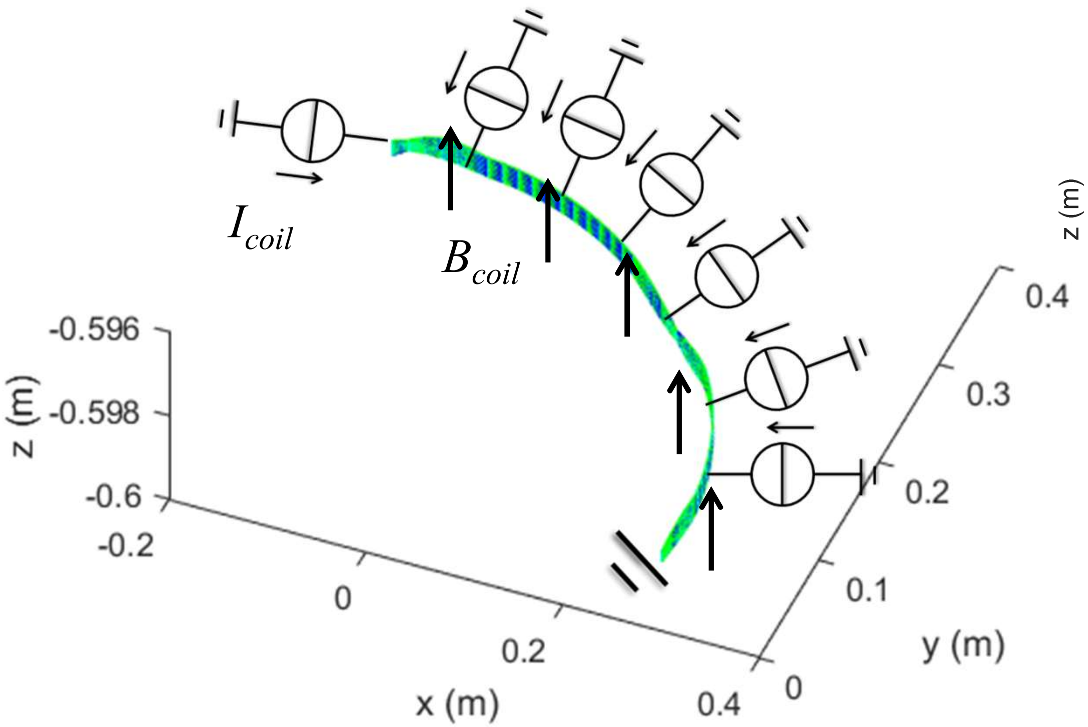


- **Higher losses are obtained at the innermost end of the coil**
- **The total loss of the SMES coil in one cycle is 5.2 kJ**
- **By assuming a cooling power of 2 × 20 W @ 20 K this loss can be removed in about 130 s**
- **A waiting time in the order of the minutes is needed before the next cycle**

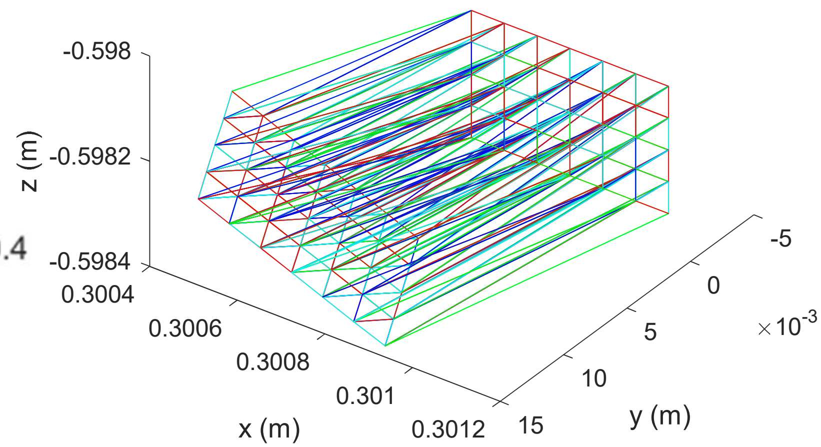
Future work

- **Coupling currents and overall current of SC filaments can be obtained by means of the Thelma model**
- **No detail of the distribution of current in the filament's cross section can be obtained**
- **A refined calculation can be set up a posteriori based on the results obtained with the Thelma code**

- **Detailed 3D simulation of one fiament one twist pitch**



Cut-off of the mesh



Applied field and current injection extraction along the length available from thelma

Conclusion

- **The THELMA model was used for investigating the AC loss of a large coil made of a multifilamentary MgB_2 cable with conduction cooling**
  - **Coupling currents and overall current of SC filaments were obtained by means of the model**
  - **Instantaneous AC loss and total heat load after one charge discharge cycle was calculated**
  - **Based on standard cooling system a waiting time in the order of the minutes is needed for recovering the normal operating temperature**
- **A refined calculation allowing to investigate diffusion of current within the filaments is being set up a posteriori based on the results obtained with the Thelma code**