AC loss computation of a dry-cooled MgB₂ SMES coil

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Outline

- The DRYSMES4GRID project
- The reference MgB₂ 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€

- developm. of dry-cooled SMES based on MgB₂
- Time: June 2017 June 2020 •
- 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
- Manufacturing of the coil & cooling system
- Design and Manufacturing of Power Hardware



Next

Reference Conductor – Rectangular tape with 6 filaments



2,05 mm

| 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 |

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Additional external copper

Copper strip with 500 μm thickness applied on one side by tin-soldering

Filling factor of protective copper: 0.313 (500 μ m 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

1.209 m

| 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

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Mechanical analysis

Mechanical design includes

- Pretensioning due to winding of the coil ۲
- Thermal contraction during cool down ۲
- 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
- ٠ 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

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

SMES discharged on the dump

• 0.2 s delay before detection



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)





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

 $N_C = N_F N_S$

Unknowns of the discretized problem:

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

$$I_k(x_h, t)$$
 h = 1,..., N_s and k = 1,..., N_F

 $\mathbf{I}(x_{h},t) = [I_{1}(x_{h},t),...,I_{NF}(x_{h},t)]^{T}$

 $\mathbf{I}(t) = \left[\mathbf{I}^{T}(x_{1},t),...,\mathbf{I}^{T}(x_{NS},t)\right]^{T}$

current of filament k-th at position h-th

set of N_F currents at position *h*-th

set of N_C currents of the discretization

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

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



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

$$N_{DP} = N_F (N_S - I)$$
 dual points

Derivative at primal points not lying on the terminal sections

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

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

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



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

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

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

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

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

• Charge conservation

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



A - v formulation and magnetic vector potential

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

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



$$\mathbf{A}^{\text{ext}}(\mathbf{r},t) = \frac{\tilde{\mathbf{r}}_{0}}{4f} \int_{\mathbf{r}_{\text{coil}} - \mathbf{r}_{\text{filaments}}} \frac{\mathbf{J}(\mathbf{r}',t)}{|\mathbf{r} - \mathbf{r}'|} d^{3}r'$$

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

$$\mathbf{A}^{\mathrm{J}}(\mathbf{r},t) = \frac{\tilde{\mathbf{r}}_{0}}{4f} \int_{\mathfrak{f}_{filaments}} \frac{\mathbf{J}(\mathbf{r}',t)}{|\mathbf{r}-\mathbf{r}'|} d^{3}r' + \frac{\tilde{\mathbf{r}}_{0}}{4f} \int_{\mathfrak{f}_{matrix}} \frac{\mathbf{J}(\mathbf{r}',t)}{|\mathbf{r}-\mathbf{r}'|} d^{3}r' \qquad \text{all conducting elements}$$
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:

$$\mathbf{A}^{\mathrm{J}}(\mathbf{r},t) = \frac{\tilde{\mathbf{r}}_{0}}{4f} \int_{\dagger_{filaments}} \frac{\mathbf{J}(\mathbf{r}',t)}{|\mathbf{r}-\mathbf{r}'|} d^{3}r' + \frac{\tilde{\mathbf{r}}_{0}}{4f} \int_{\dagger_{fatrix}} \mathbf{J}(\mathbf{r}',t) |\mathbf{r}-\mathbf{r}'| d^{3}r'$$

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

$$\mathbf{A}^{\mathrm{J}}(\mathbf{r},t) = \frac{\tilde{\mathbf{r}}_{0}}{4f} \int_{\ddagger filaments} \frac{\mathbf{J}(\mathbf{r}',t)}{|\mathbf{r}-\mathbf{r}'|} d^{3}r'$$

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

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

Dependance of $J_{\rm c}$ on B is implicit

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

$$\mathbf{t}_{k}(x_{h}) \cdot \mathbf{E}_{k}(x_{h},t) = -\mathbf{t}_{k}(x_{h}) \cdot \left(\frac{\partial}{\partial t}\mathbf{A}_{k}^{\mathrm{J}}(x_{h},t) - \frac{\partial}{\partial t}\mathbf{A}_{k}^{ext}(x_{h},t) - \nabla v_{k}(x_{h},t)\right) \qquad h = 2, \dots, N_{S} - 1$$

$$k = 1, \dots, N_{F}$$

Which gives

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



Eliminating the potentials – Solving the transverse conduction problem



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





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$$K_m(x_h) = \sum_{n=1}^{N_F} K_{mn}(x_h)$$

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

$$\mathbf{v'}_{h} = \mathbf{g}_{h}^{-1} \mathbf{d}_{h} \left(\mathbf{I'}_{h+1} - \mathbf{I'}_{h} \right) + \sum_{j=1}^{N_{s}} \mathbf{m}_{j}^{t} \frac{d}{dt} \mathbf{I}_{j} + \mathbf{u}_{h} \frac{d}{dt} \mathbf{I}_{coil} + \mathbf{1} v_{N_{F}h}$$







- 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

$$\mathbf{v}_1 - \mathbf{1}\mathbf{v}_0 = -diag(R_{in})\mathbf{I}_1 \qquad \mathbf{v}_{NS-1} - \mathbf{1}\mathbf{v}_{NS} = +diag(R_{out})\mathbf{I}_{NS-1}$$



Assembling of the solving system

$$\mathbf{f}_{h}(\mathbf{I}_{h}) = -\sum_{j=1}^{N_{s}} \mathbf{m}_{hj} \frac{d}{dt} \mathbf{I}_{j} - \mathbf{u}_{h} \frac{d}{dt} I_{coil} - \mathbf{p}_{h} \mathbf{d}_{h} (\mathbf{v}_{h+1} - \mathbf{v}_{h}) \qquad N_{F} \times (N_{s} - 2) \text{ equations}$$

$$\mathbf{1} \cdot \mathbf{I}_{h} = I_{coil} \qquad N_{s} \text{ equations}$$

$$\mathbf{v}_{h}' = \mathbf{g}_{h}^{-1} \mathbf{d}_{h} (\mathbf{I}'_{h+1} - \mathbf{I}'_{h}) + \sum_{j=1}^{N_{s}} \mathbf{m}^{t}_{j} \frac{d}{dt} \mathbf{I}_{j} + \mathbf{u}_{h} \frac{d}{dt} I_{coil} + \mathbf{1} v_{N_{F}h} \qquad (N_{F} - \mathbf{I}) \times (N_{s} > \mathbf{I}) \text{ equations}$$

$$\mathbf{v}_{1} - \mathbf{1} v_{0} = -diag(R_{in}) \mathbf{I}_{1} \qquad \mathbf{v}_{NS-1} - \mathbf{1} v_{NS} = +diag(R_{out}) \mathbf{I}_{NS-1} \qquad 2N_{F} \text{ equations}$$

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

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

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



22

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

$$I_{k}^{c}(t) = \frac{S_{k}}{S_{tot}} I_{coil}(t)$$
 $k = 1, ..., N_{F}$

same for all elements of one filament

23

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

$$I(x_h,t) = I_h^c(t) + i_h(x_h,t) \longrightarrow \begin{array}{c} \text{Deviation current at coordinate } x \text{ of element } k \\ \uparrow \\ \text{An assigned, time dependent, term} \\ \text{That is} \\ \text{set of } N_F \text{ total currents at position } h \\ \text{set of } N_F \text{ deviation currents at position } h \\ \text{i} \\ \text{i} \\ \text{set of } N_F \text{ constant currents} \\ \text{set of } N_F$$

• By substituting in the voltage balance equation at position h

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

$$\begin{bmatrix} \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} \\ \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} \\ \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} \\ \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} \\ \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} \\ \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} \\ \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} \\ \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} \\ \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} \\ \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} \\ \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} \\ \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} \\ \mathbf{m} & \mathbf{m} & \mathbf{m} \\ \mathbf{m} & \mathbf{m} & \mathbf{m} & \mathbf{m} \\ \mathbf{m}$$

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



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- 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

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

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





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Simulated cases



$$\frac{1}{2}L I^{2} - \frac{1}{2}LI_{0}^{2} = \mp P(t - t_{0})$$

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

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

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



• 19 m of conductor

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



Mesh



Layer 1 – bottom - current distribution

29



Relaxation of coupling currents





Relaxation of coupling current nearly completed after 150 s

Current vs critical current



2

1.5

0.5

0

2

1.5

0.5

0

longitudinal coordinate (m)

32

magnetic flux density (T)

magnetic flux density (T)



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



Conclusion

- The THELMA model was used for investigating the AC loss of a large coil made of a multifilamentary MgB₂ 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

