Design of the MgB_2 coil of a 500 kJ / 200 kW SMES demonstrator with cryogen-free cooling

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CIGRE' WG D1.64 meeting – Milan, April 5, 2019

Outline

- The DRYSMES4GRID project: a 500 kJ / 200 kW MgB_2 SMES
  - Outline of the project
  - Magnet system
  - AC loss
  - Power conditioning system and Test facility

Acknowledgments to all colleagues involved in the project

U. Melaccio, P. L. Ribani, G. Grandi, A. Viatkin, M. Hammami, M. Breschi

University of Bologna, Italy

L. Martini, C. Gandolfi, R. Chiumeo, G. Angeli, M. Bocchi

RSE S.p.A - Ricerca sul Sistema Energetico, Milan, Italy

S. Turtù, L. Affinito, A. Della Corte, A. Anemona,

ICAS S.C. r. l. - The Italian Consortium for Appl. Supercond., Frascati (Rome), Italy

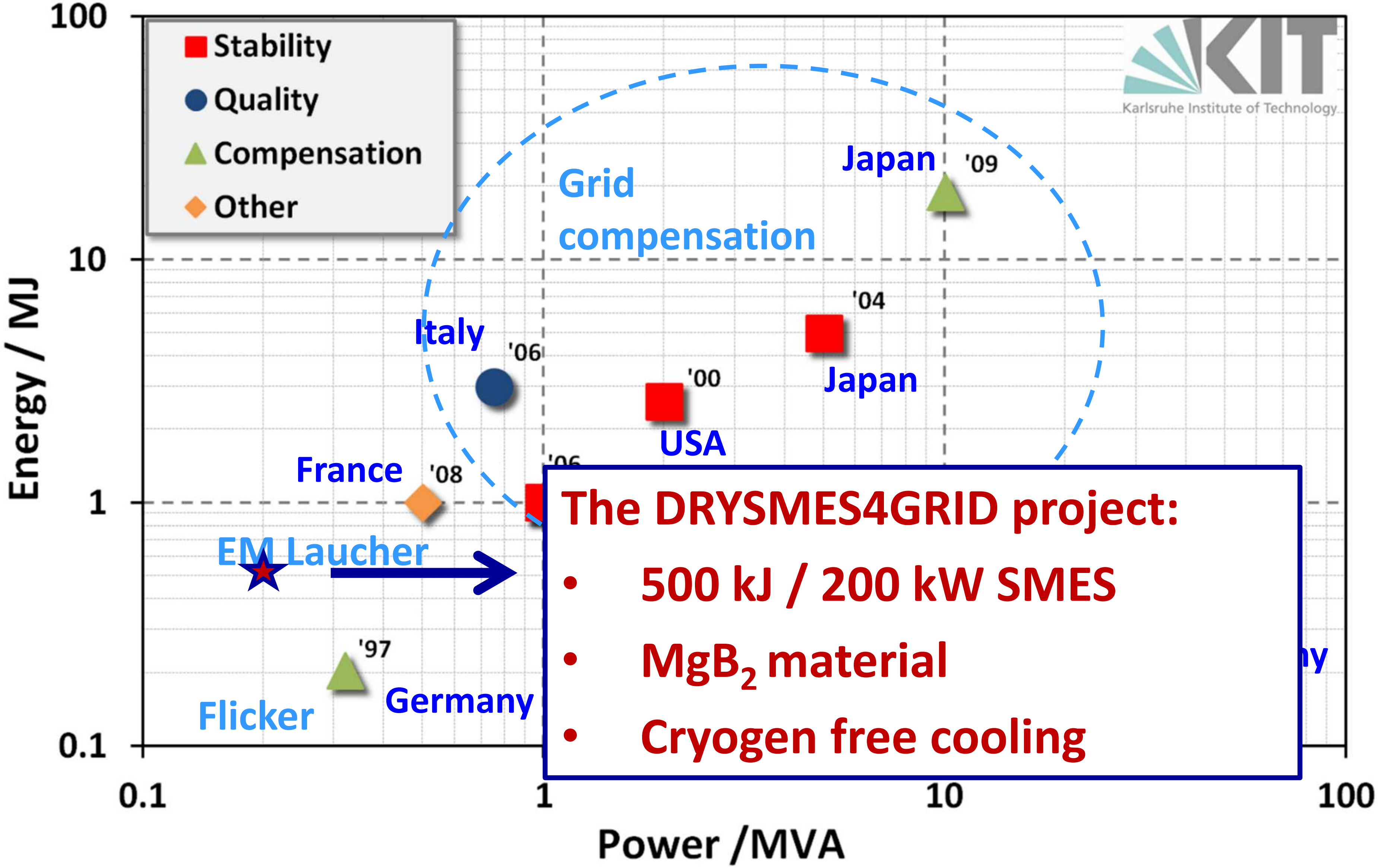
M. Tropeano, A. Capelluto, G. Grasso

ASG Superconductors SpA, Genoa, Italy

C. Ferdeghini, S. Siri, M. Vignolo

CNR – SPIN, Genoa, Italy

The state of the art of SMES technology



The DRYSMES4GRID project:

- 500 kJ / 200 kW SMES
- MgB_2 material
- Cryogen free cooling

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 (+1)**
- **develop. 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**

Project Workplan

Design of the magnet

WP1. Electromagnetic & thermal design

Power conditioning system

WP2. Layout and functions

WP3. Detailed design and manufact. of converters

+ PE industry

Wire, cable and winding

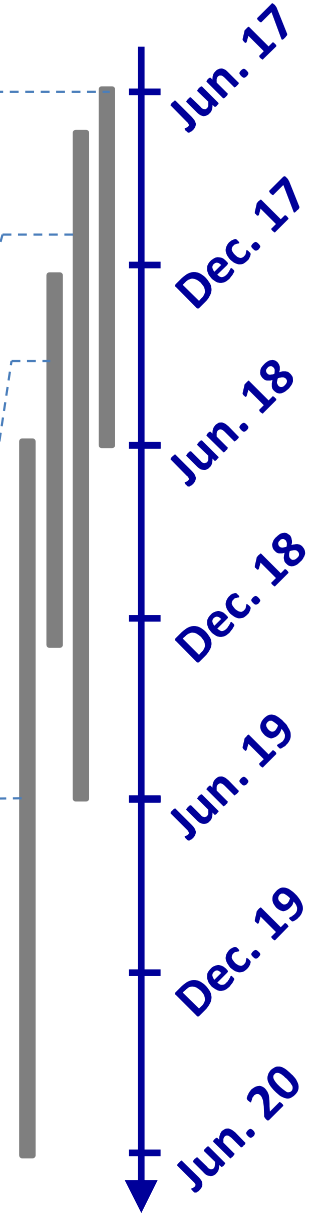
WP4. Optimization of in-field perform. of the wire

WP5. Manufacturing of wire, cable and winding

Assembling and test

WP6. Assembly of coil and cooling & prelim. test

WP7. Assembly of PCS & Experiments in test facility



WP8. Dissemination

WP9. Project management

WP10. Tech.&Econ. analys. of SMES

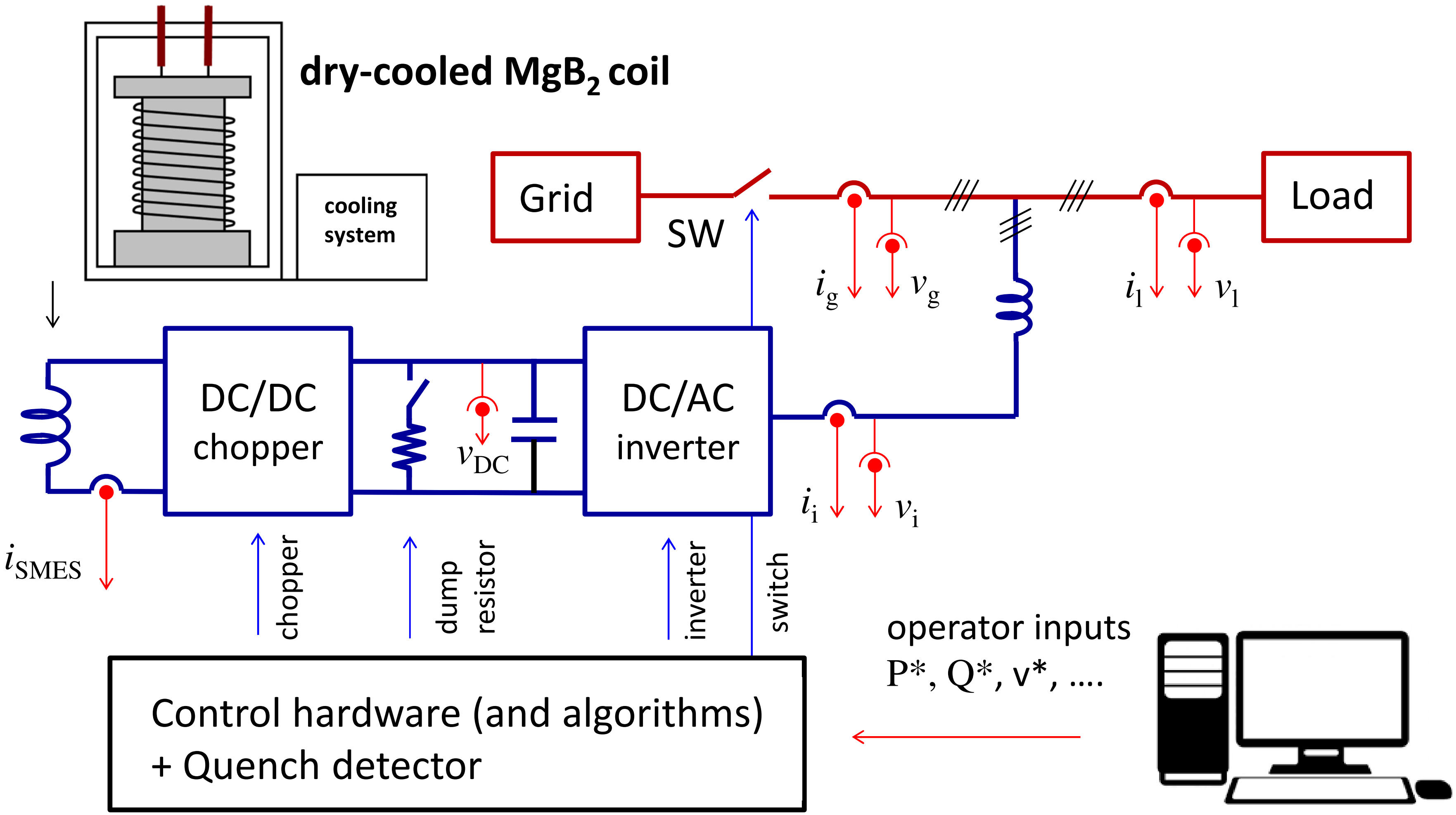
One year extension granted

Columbus and ASG (and Paramed) were merged in a unique company from November 1st, 2018

- **All activity shifted by 12 months**
- **End of the project will be June 2021**

WP1. Electromagnetic & Mechanical Design	**completed**
Thermal Design	**complete in December 2018**
WP2. Layout and functions	**completed**
WP3. Detailed design and manufact. of converters	**start at January 2019**
WP4. Optimization of in-field perform. of the wire	**complete at March 2019**
WP5. Manufacturing of wire, cable and winding	**start at June 2019**
WP6. Assembly of coil and cooling & prelim. Test	**start at December 2019**
WP7. Assembly of PCS & Experiments in test facility	**start at June 2020**

The DRYSMES4GRID system

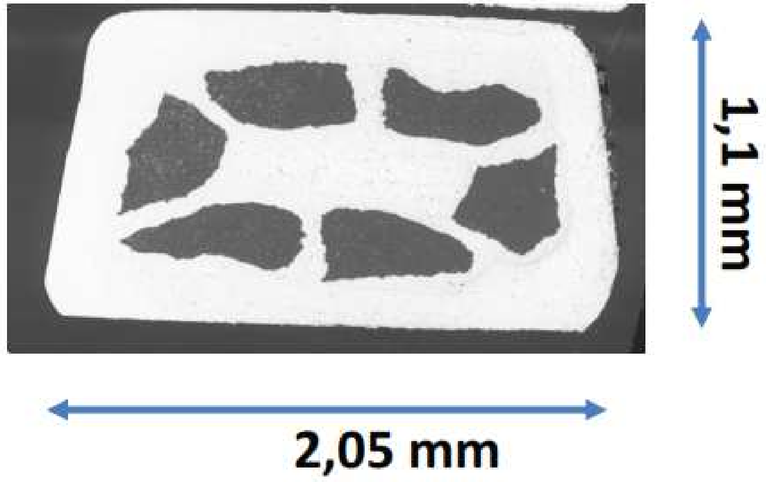


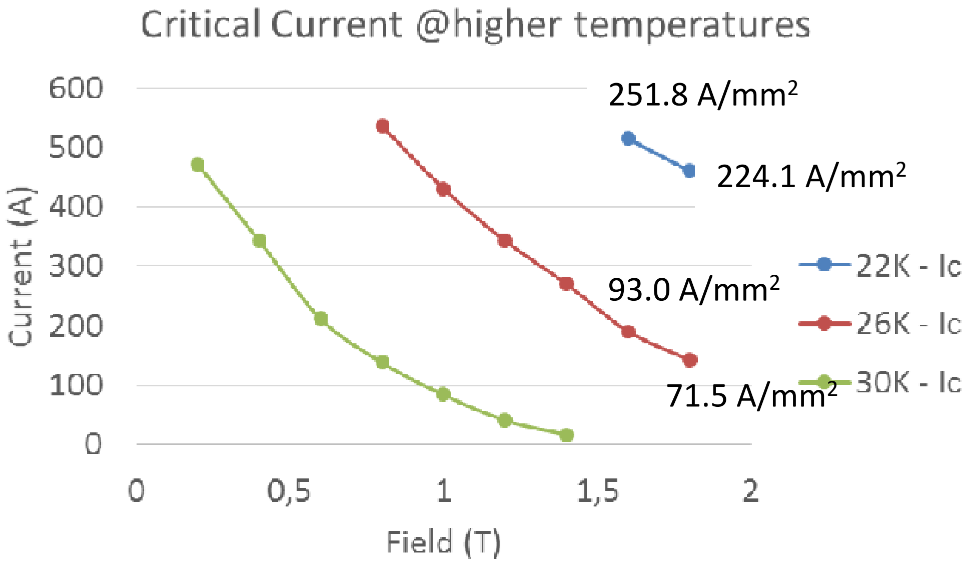
- **Electromagnetic & Mechanical design of the coil completed**
- **Thermal design (connection to cryocooler/s) in progress**
- **Control algorithms (logic, schemes, parameters) defined**

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

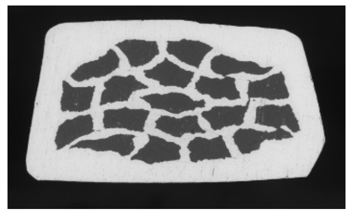
Copper strip with 500 µm thickness applied on one side by tin-soldering

Filling factor of protective copper: 0.313 (500 µm strip)

Electrical insulation

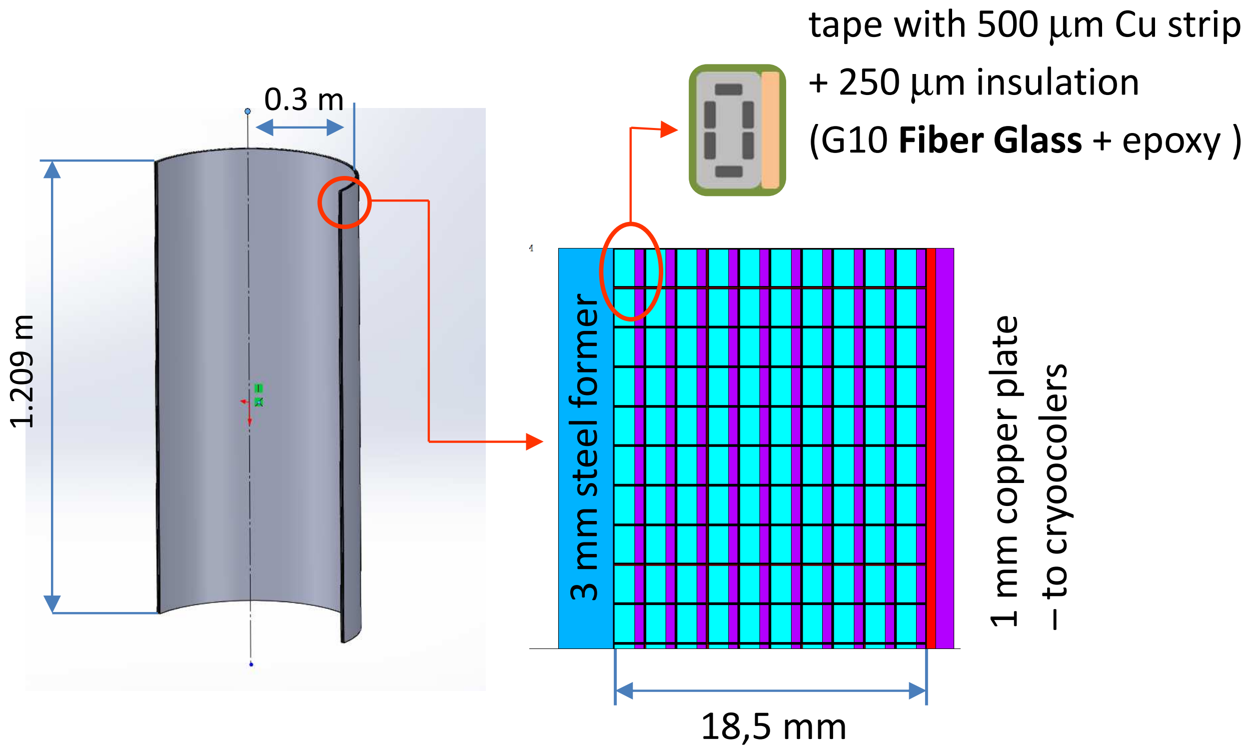
125 µm insulating wrapping

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

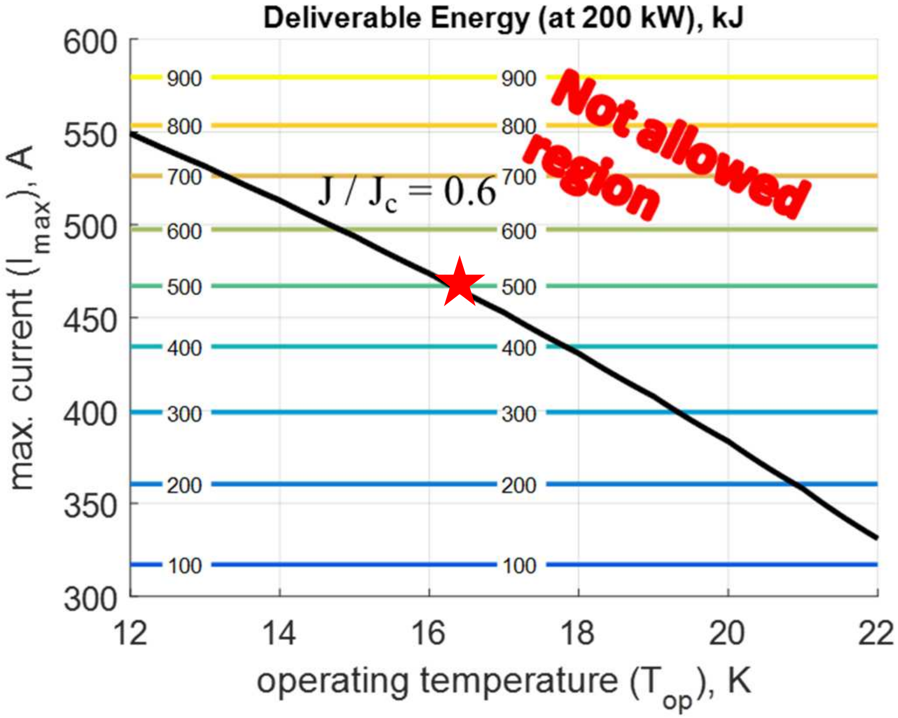


Main characteristics of the designed 500 kJ / 200 kW SMES coil

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**



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Mechanical analysis

Mechanical design includes

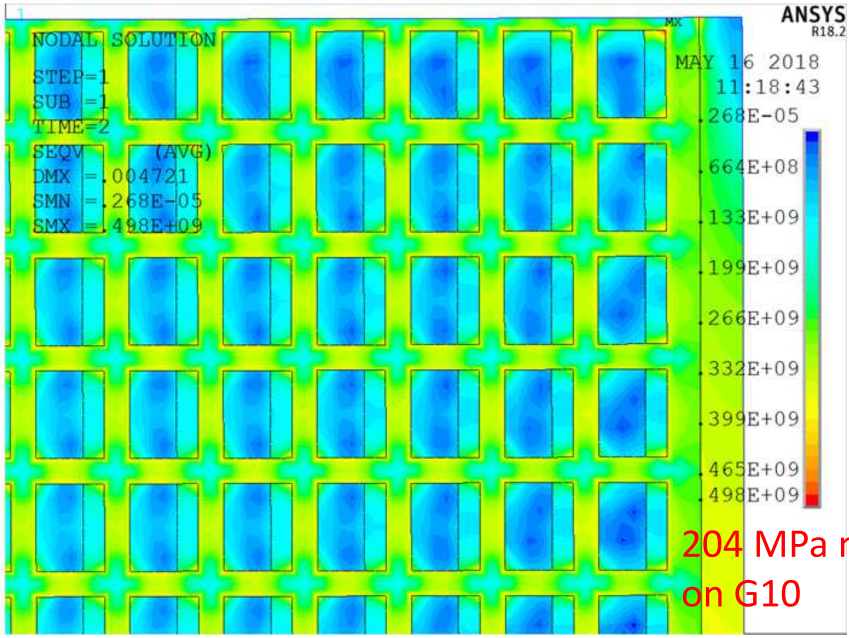
- **Pretensioning due to winding of the coil**
- **Thermal contraction during cool down**
- **Lorentz force**

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

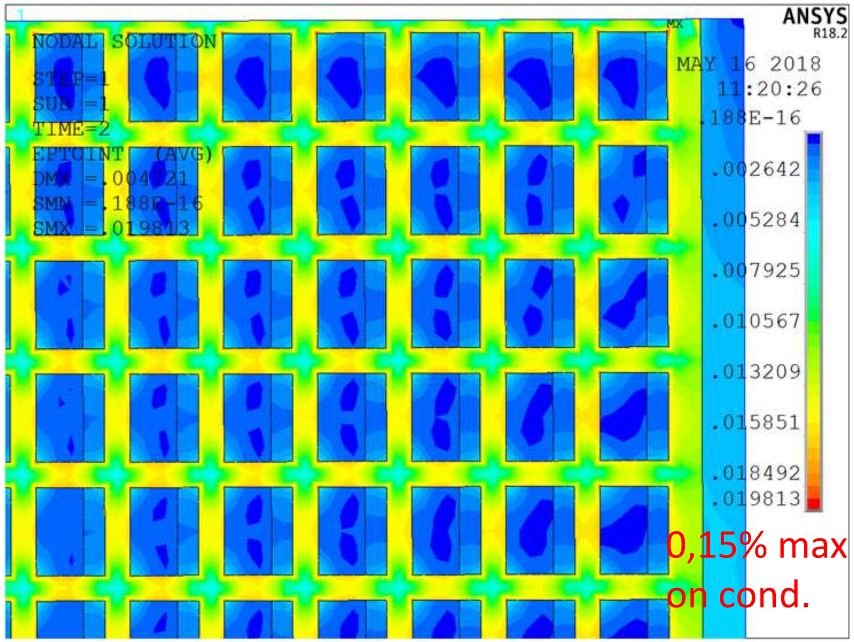
Equivalent Young's modulus of the tape of 157.3 MPa obtained from weighted average

Von Mises stress



Stress within allowable limit for all materials

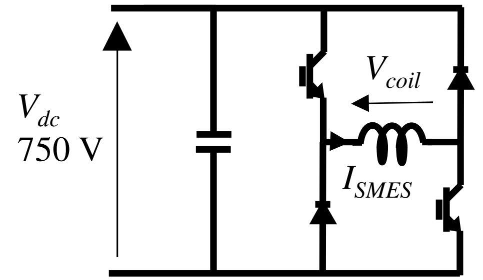
Strain



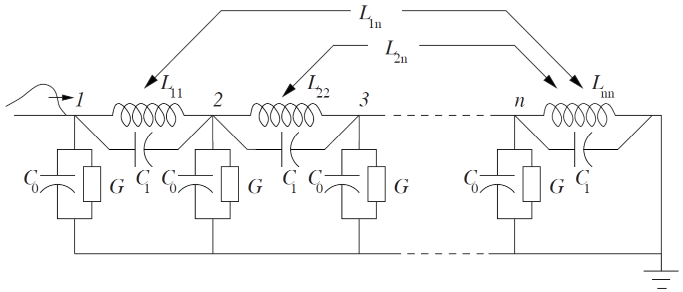
Strain within allowable limit for all materials

Electrical insulation

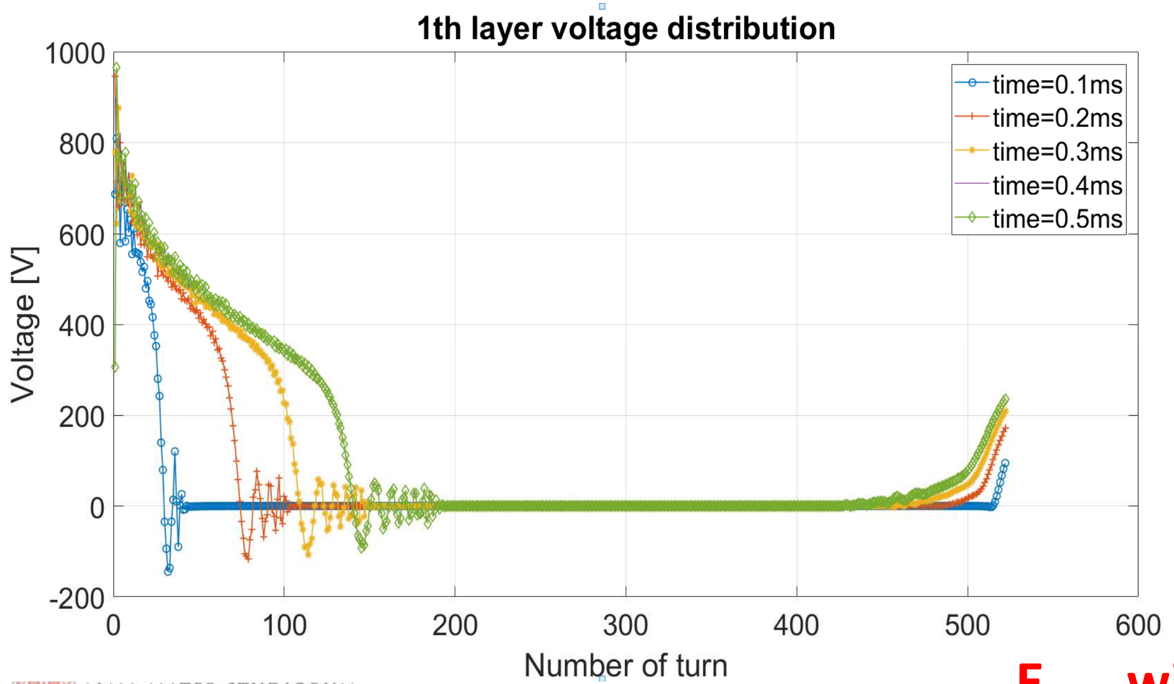
Voltage surge (1 us) on the coil due to switching
Uneven distribution of voltage among turns



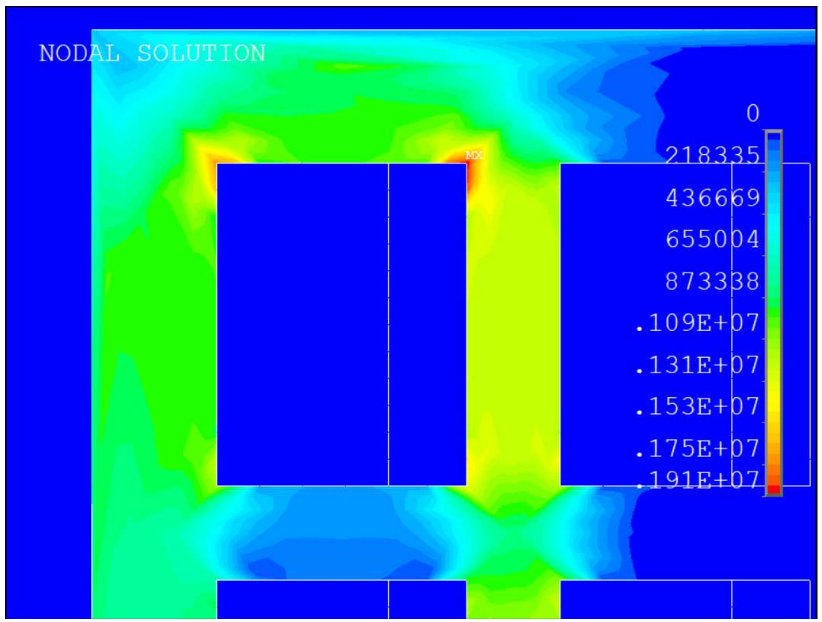
Versus ground voltage distribution of the coil calculated via lumped parameter circuit



Vs. ground voltage of 1st layer's turns at chopper switching



Electric field

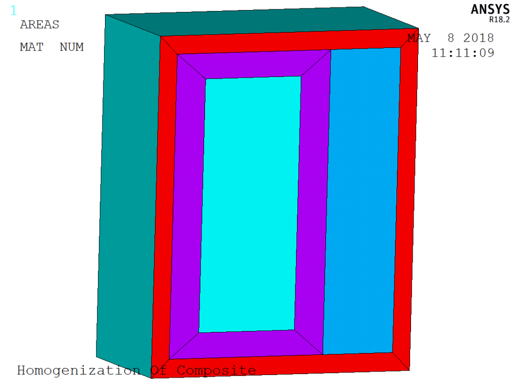


E_{max} within allowable limit of 1.2 kV/mm

3D Quench Analisys

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

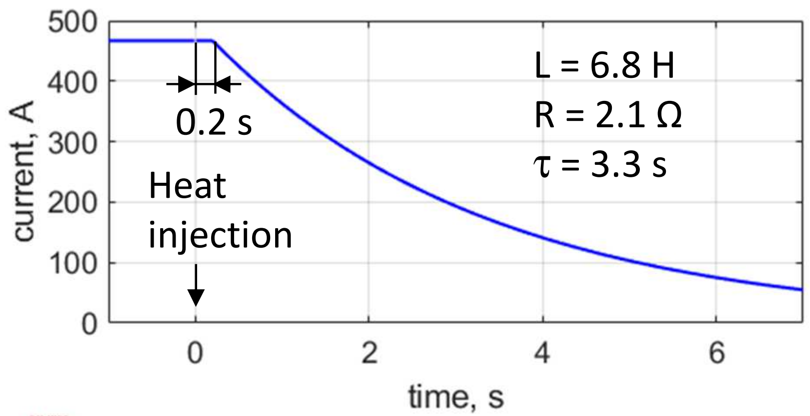
- Equivalent longitudinal resistivity ρ_{eq} from electric parallel
- Equivalent thermal capacity c_{eq} from volume weighted average
- Equivalent thermal conductivities (k_{req}, $k_{\theta eq}$, k_{zeq}) from thermal flux due to unit temperature drop in each direction



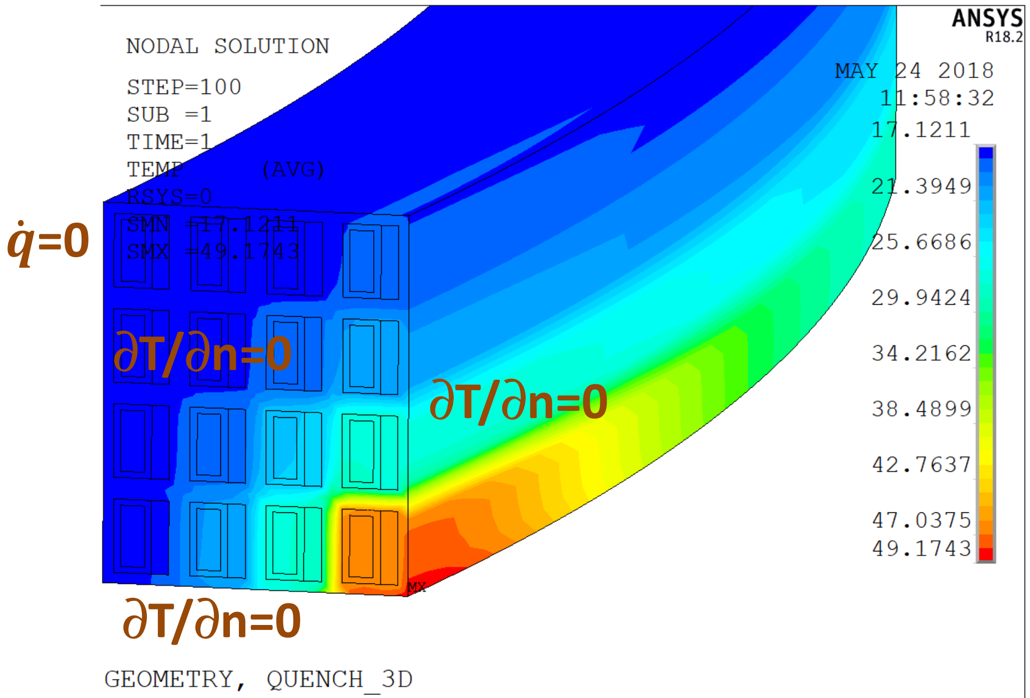
Thermal transient on a 15° sector made of 4x4 strand is calculated

- 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

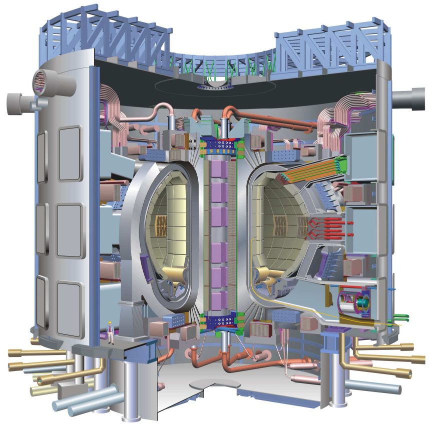


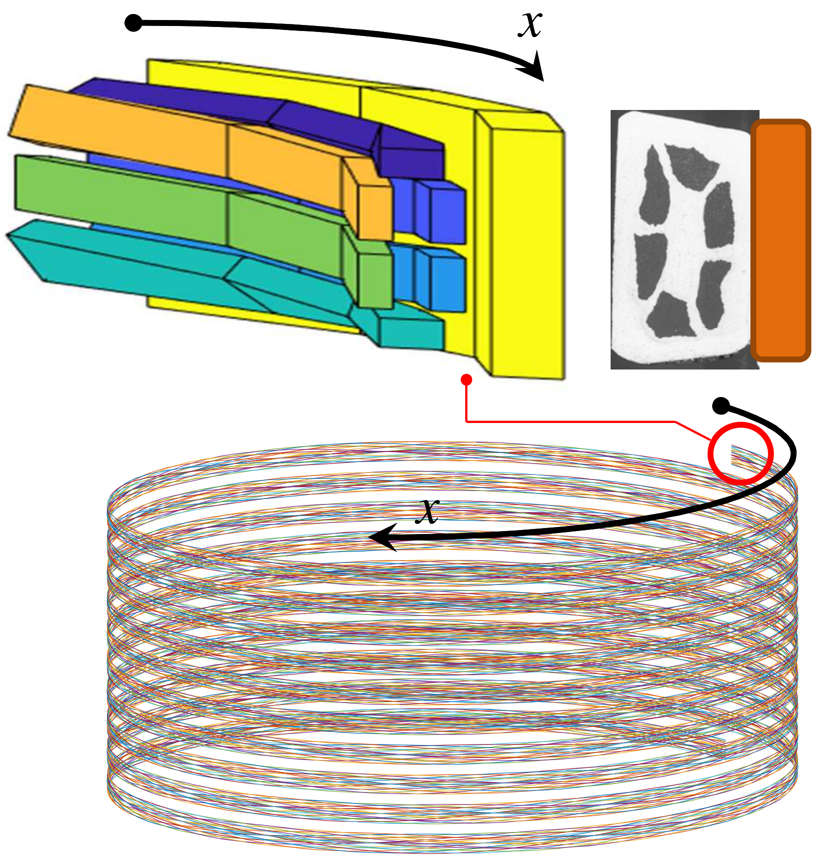
A max temperature of 108 K is reached in the coil
Mechanical stress due to thermal expansion within allowable limits

AC loss calculation - the THELMA model

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

A in house numerical model developed in the frame of an Italian initiative, originally for fusion problem

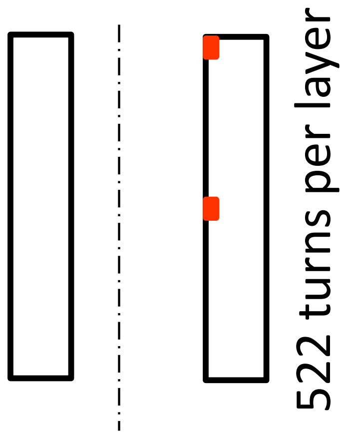




10 turns – 19 m of conductor

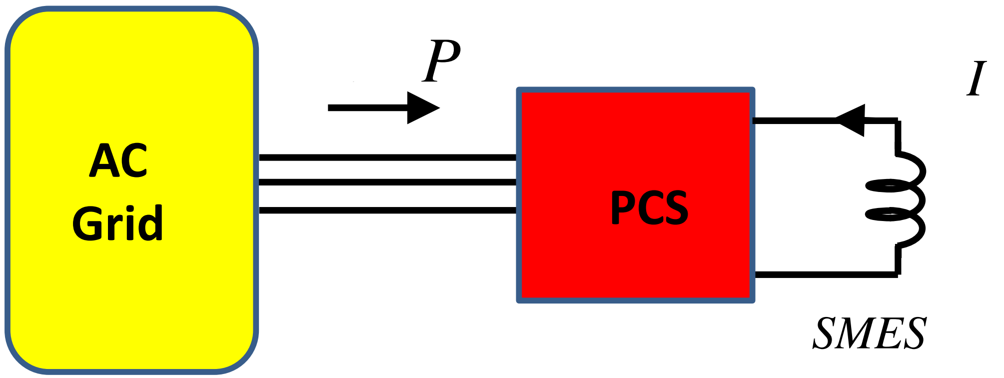
- A 3D mesh of 10 turns is generated by extrusion along the helix pattern of the coil (the remain of the coil act as a field source)
- A 3D FEM simulation based on integral formulation is performed

- **Ten turns located at the top and at the middle of the layer**
- **All layers (20 cases in total)**



Coil – not to scale

Simulated case



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

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

Waveform of coil current is obtainded from operating conditions – no details of the PCS needed

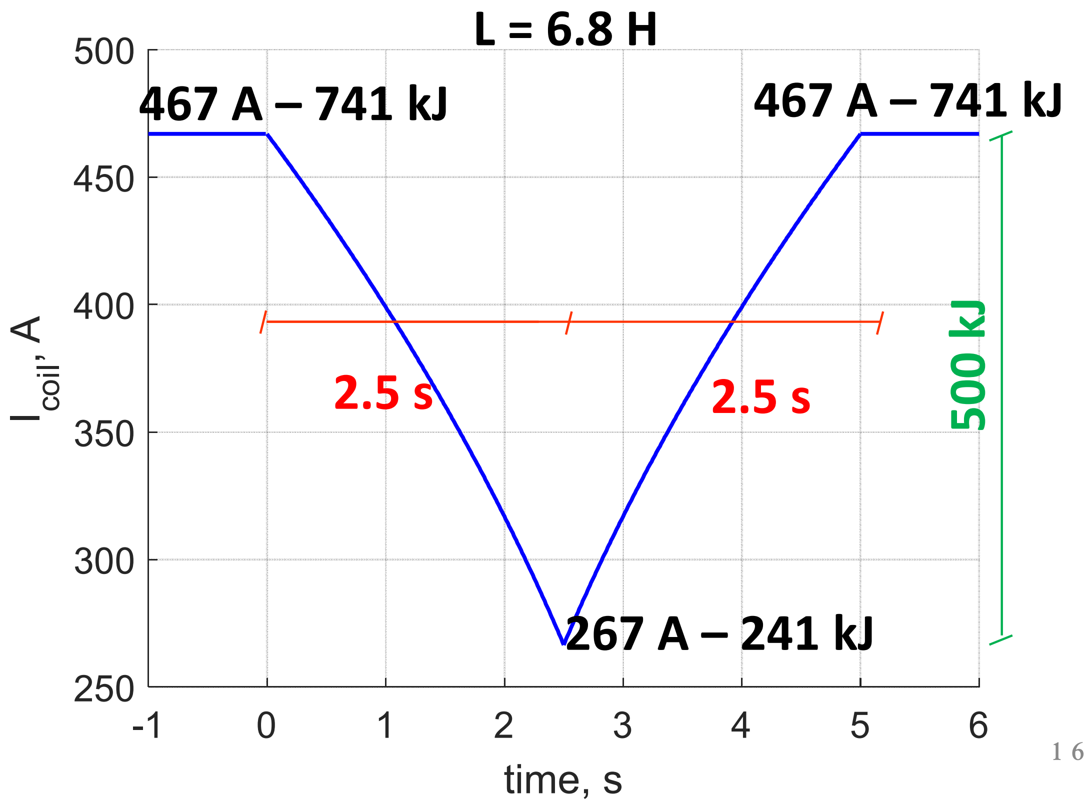
One Discharge/Charge cycle is simulated

Discharge

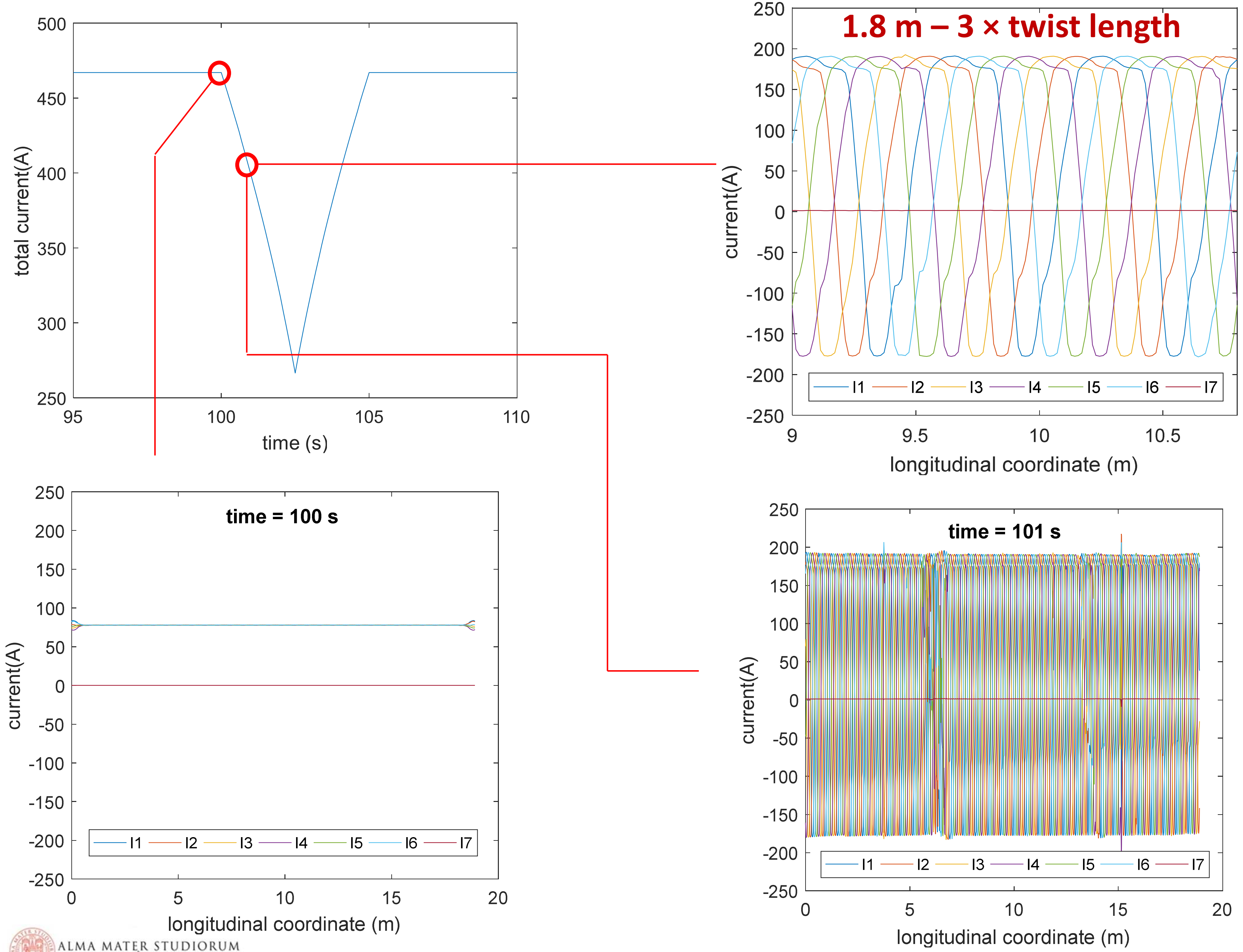
@ 200 kW – 2.5 s

Charge

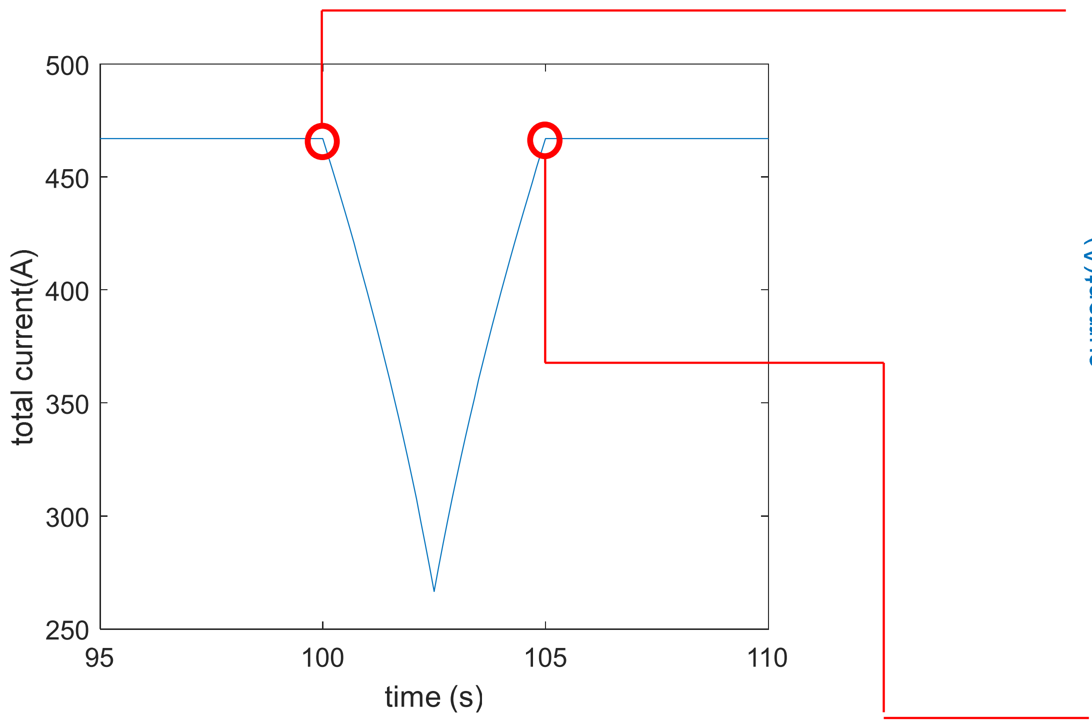
@ 200 kW – 2.5 s

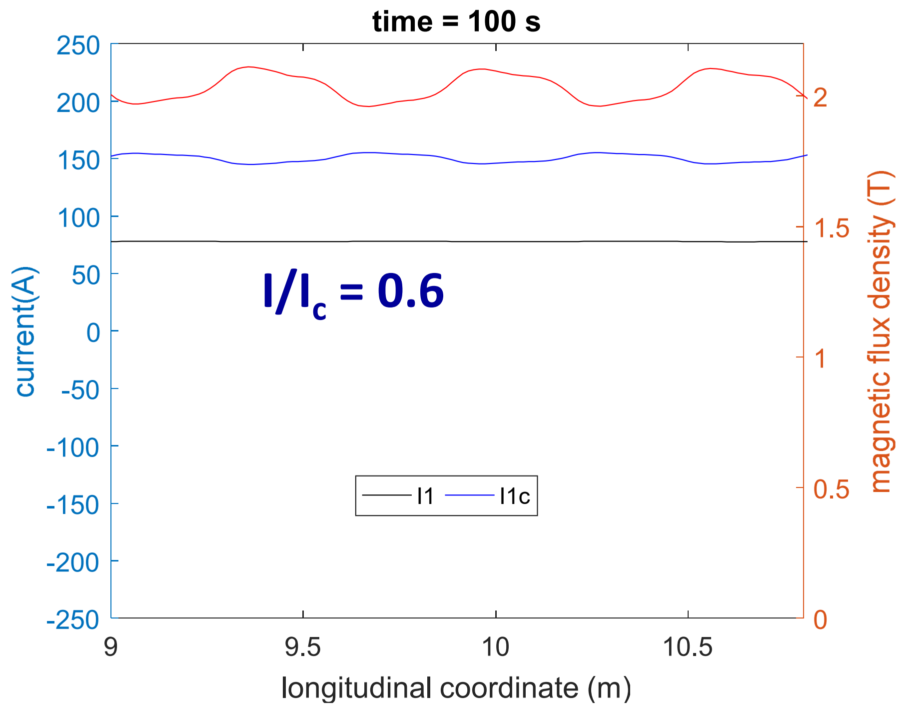


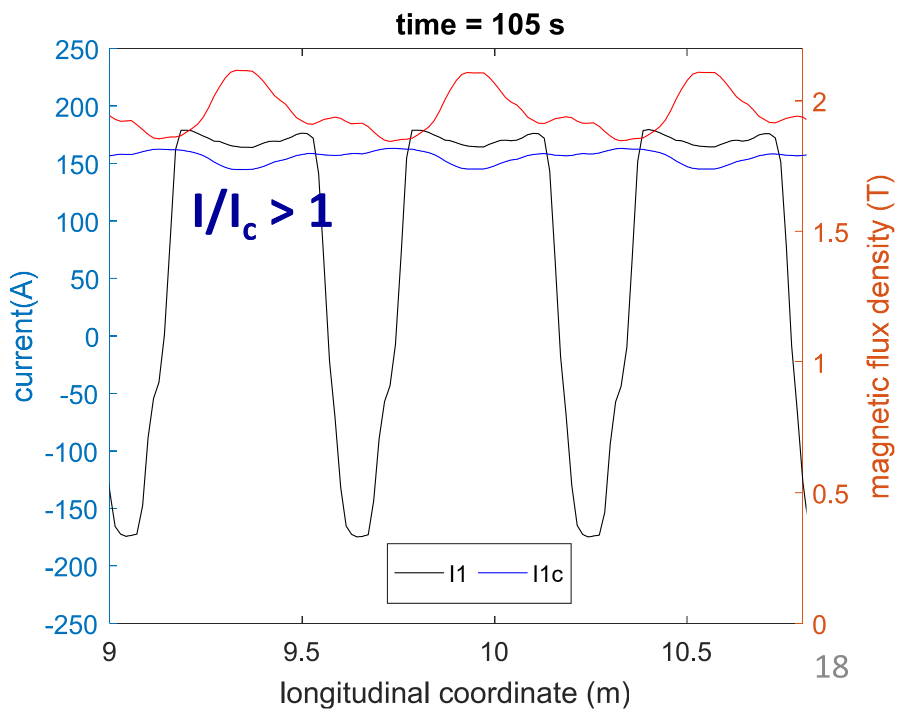
Layer 1 – bottom - current distribution



Current vs critical current

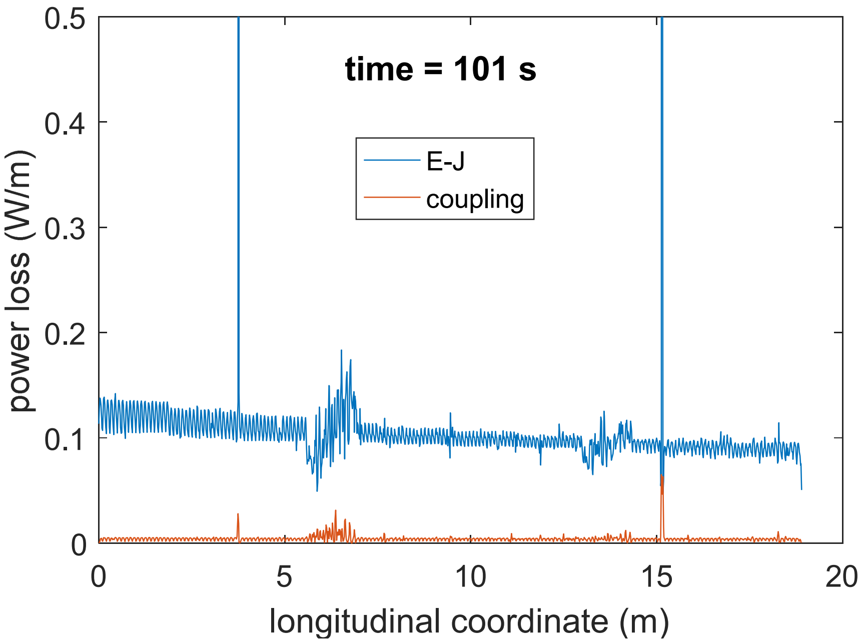


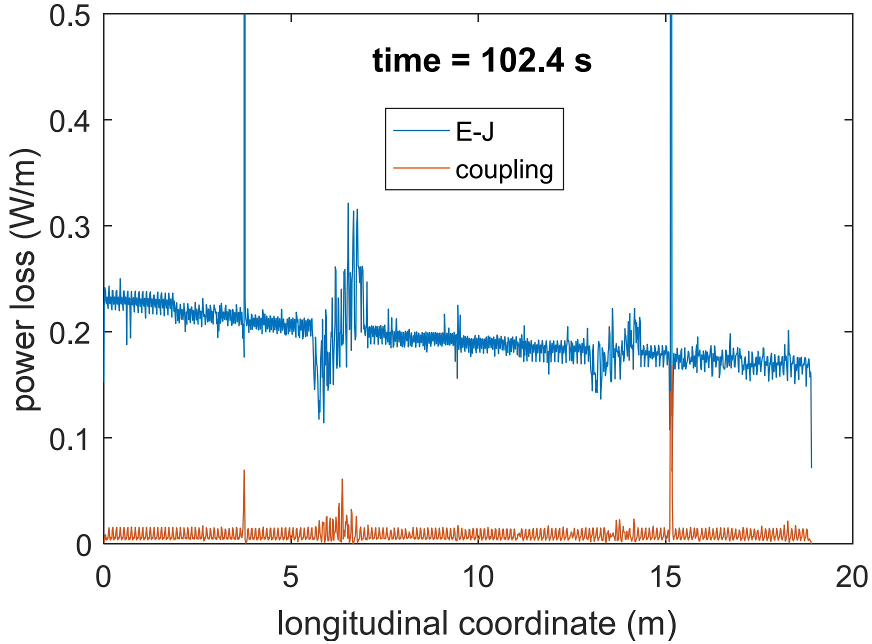


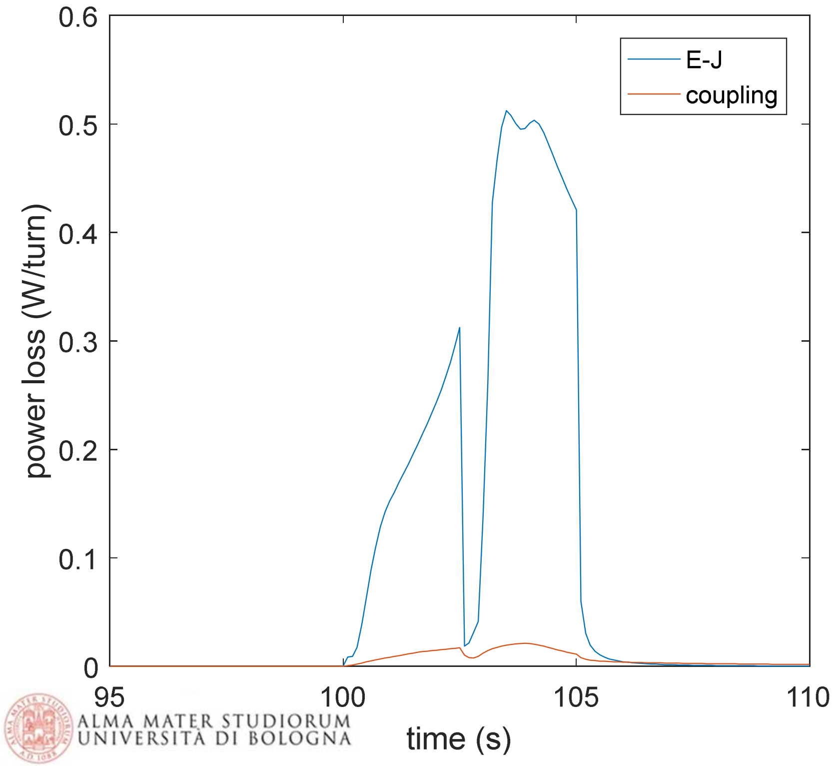


- **Current of filaments below the critical value during steady SMES operation**
- **Critical current largely overcome during ramp due to coupling currents**

Dissipated power



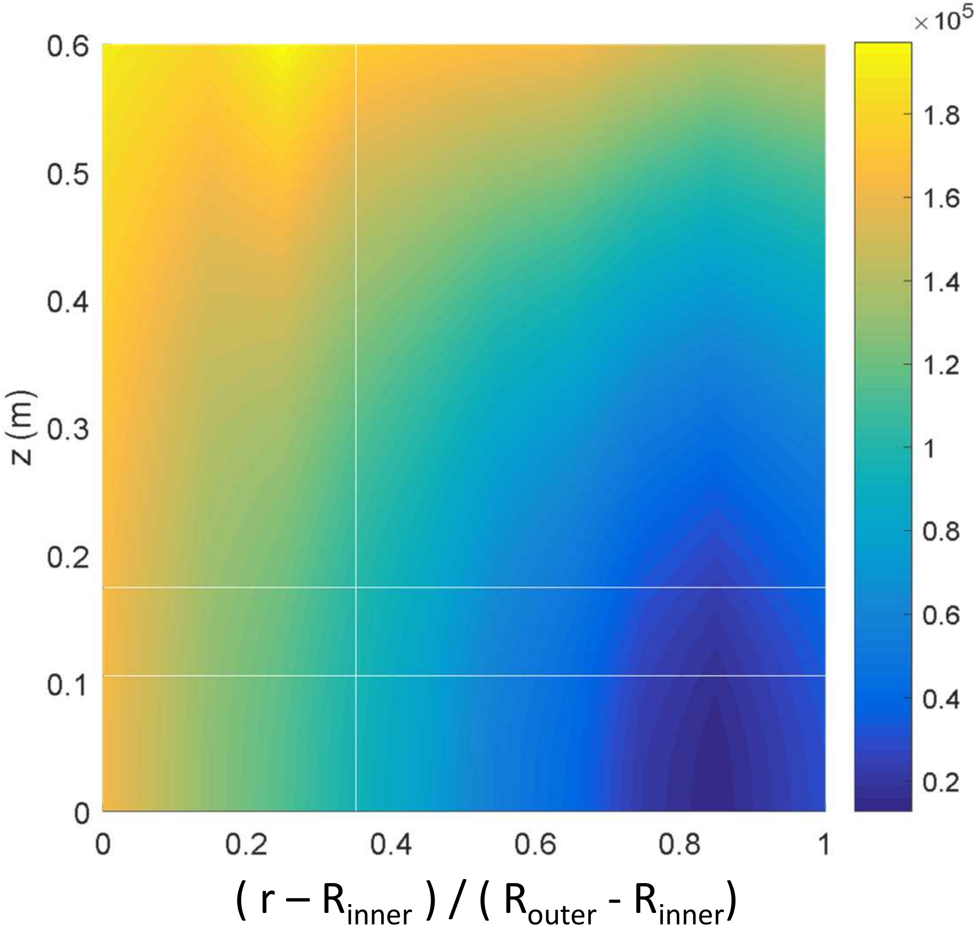




- **Loss due to coupling current are negligible compared to loss in the superconductor filaments**
- **An average power of about 155 mW / turn occurs at the bottom of the coil**

Loss distribution and recovery

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



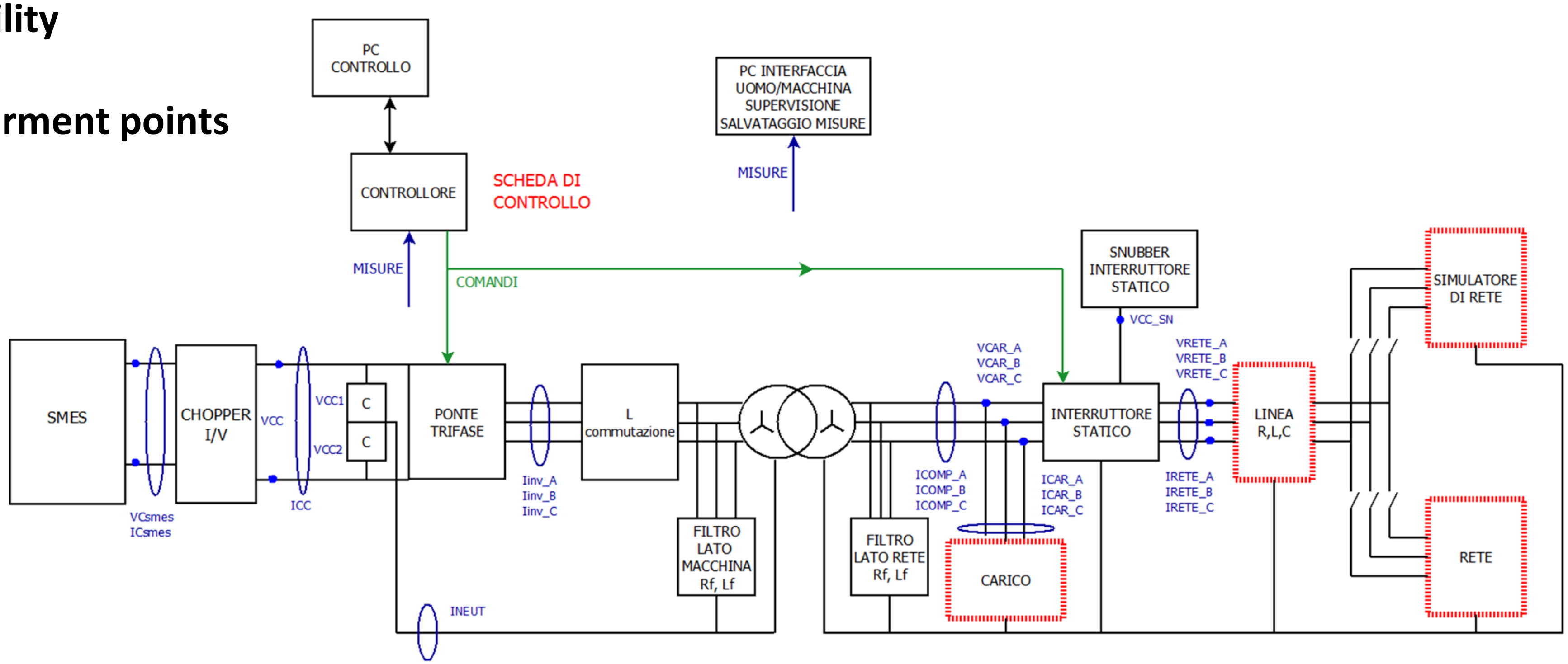
- Higher losses are obtained at the innermost end of the coil
- The total loss of the SMES coil in one cycle is 5.2 kJ
- By assuming a cooling power of 2 × 20 W @ 20 K this loss can be removed in about 130 s
- A waiting time in the order of the minutes is needed before the next cycle

Steady state and dynamic thermal analysis and definition of thermal connection of the coil with the cryocooler to completed soon (December 2018)

Power conditioning system – power hardware

Definition of power hardware completed

- Converters architecture
- Switch technology
- Capability
- Filter
- Measurment points



Technical specifics for commissioning and type testing issued
Negotiation with possible suppliers in progress

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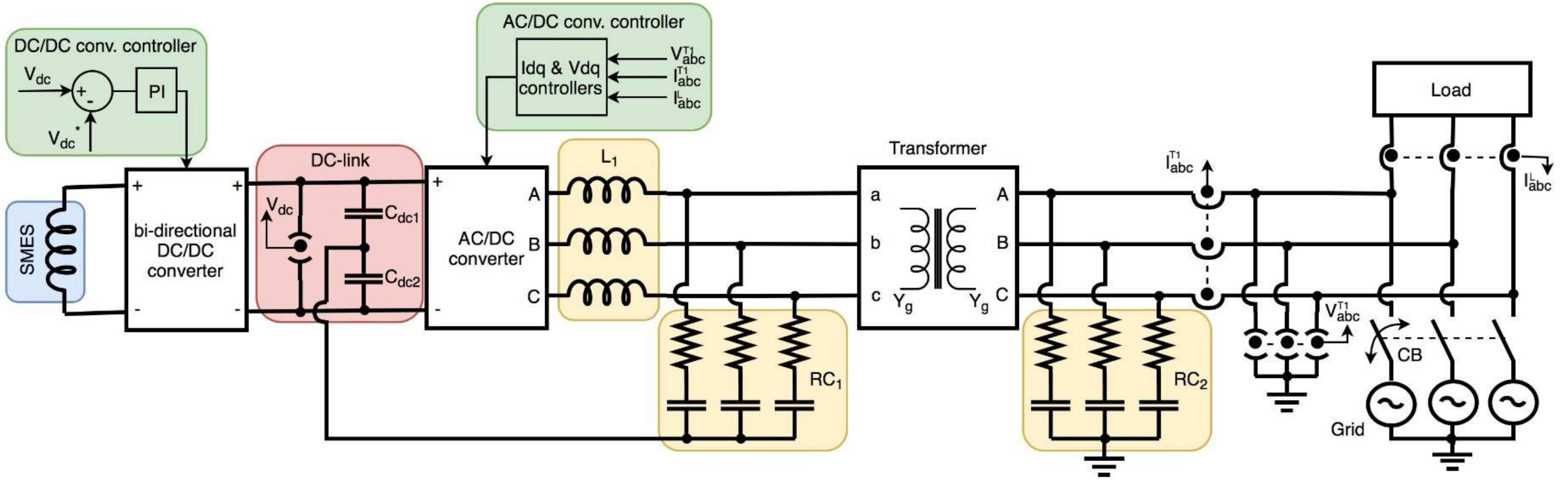
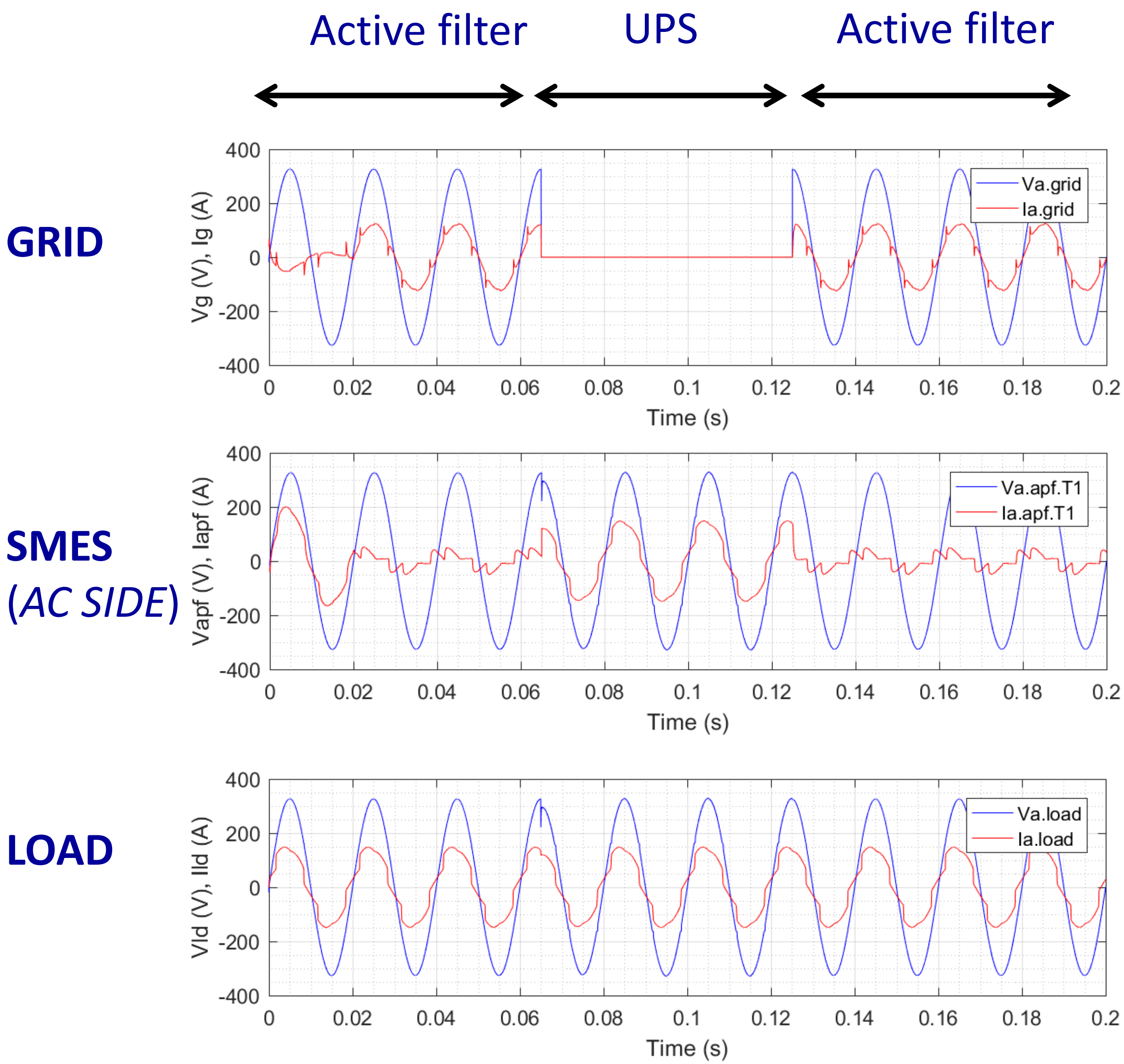
Power conditioning system – control hardware and algorithms



- **Detailed definition of control algorithms (logic, schemes, parameters) completed by means of SIMULINK and ATP simulations**
    - Shunt operation (power modulation, active filter) and islanding operation
    - Shift from shunt to islanding operation

- **Integration of the magnet protection system**

- **Control hardware in the loop testing planned**



Regulator proportional and integral gains [Kp, Ki]

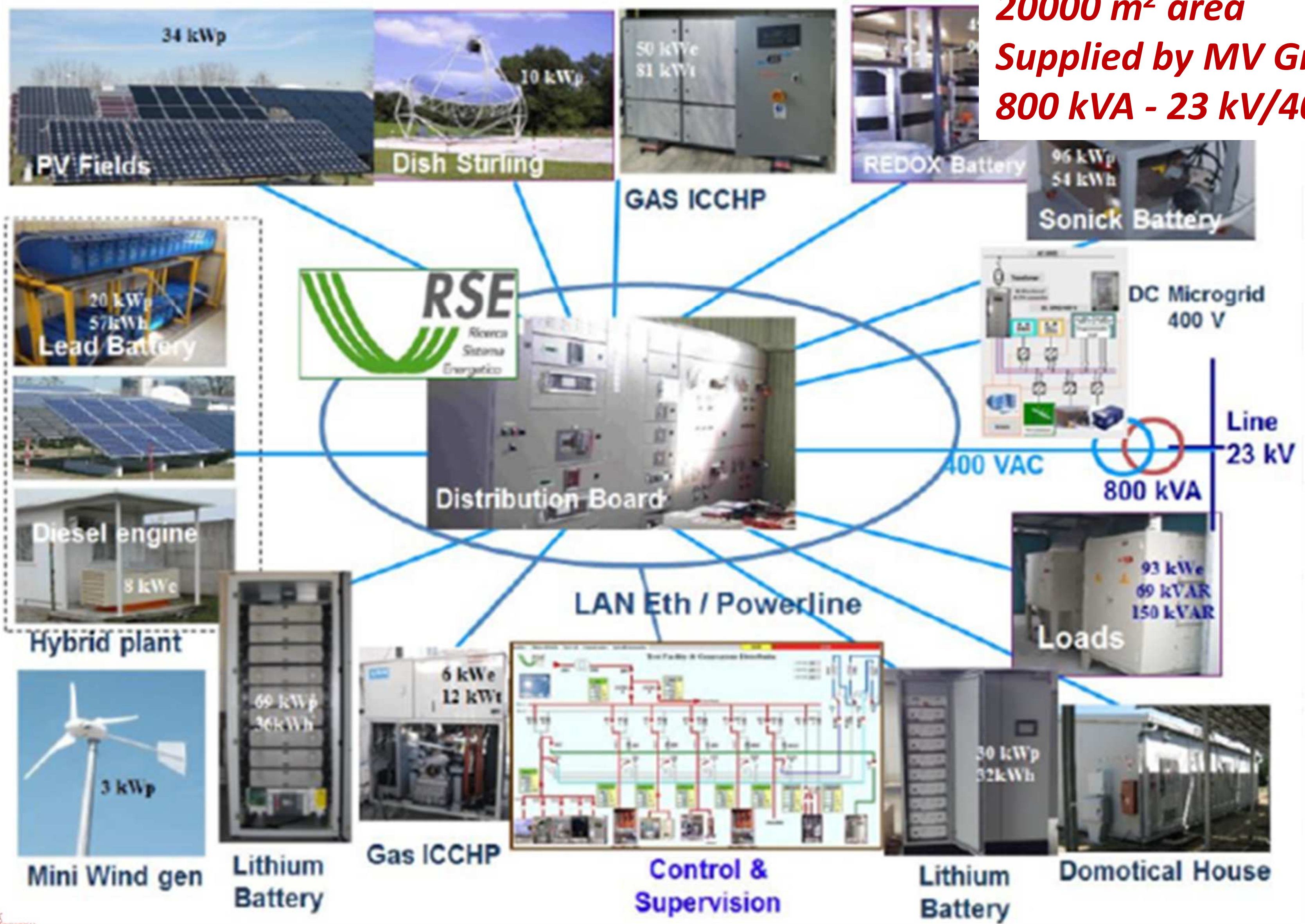
Idq PI controller [1.4, 200]
Vdq PI controller [5, 1000]
Vdc PI controller [200, 10000]

- **Effective compensation of load current harmonics and reactive power (SAPF)**
- **Effective compensation of voltage interruption (UPS)**
- **Smoot transition (small current and voltage surges) between SAPF and UPS**

Test Site: RSE Distributed Energy Resources Test Facility

A real low voltage microgrid that interconnects different generators, storage systems and loads to develop studies and experimentations on DERs and Smart Grid solutions.

20000 m^2 area
Supplied by MV Grid
800 kVA - 23 kV/400 V transf.



Conclusion

- SMES is an established technology based on low temperature superconductor materials
- Improvements of SMES technology can be obtained by means of HTS superconductors compatible with cryogen free cooling
  - A three year (+1) research project has been recently started in Italy aimed at developing a 500 kJ / 200 kW SMES demonstrator with cryogen free cooling based on MgB2
  - The design phase of magnet and cooling system and power conditioning system completed. Manufacturing phase to be started soon

Thank you for your attention

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