Development status and preliminary test results of a cryogen-free MgB_2 SMES system

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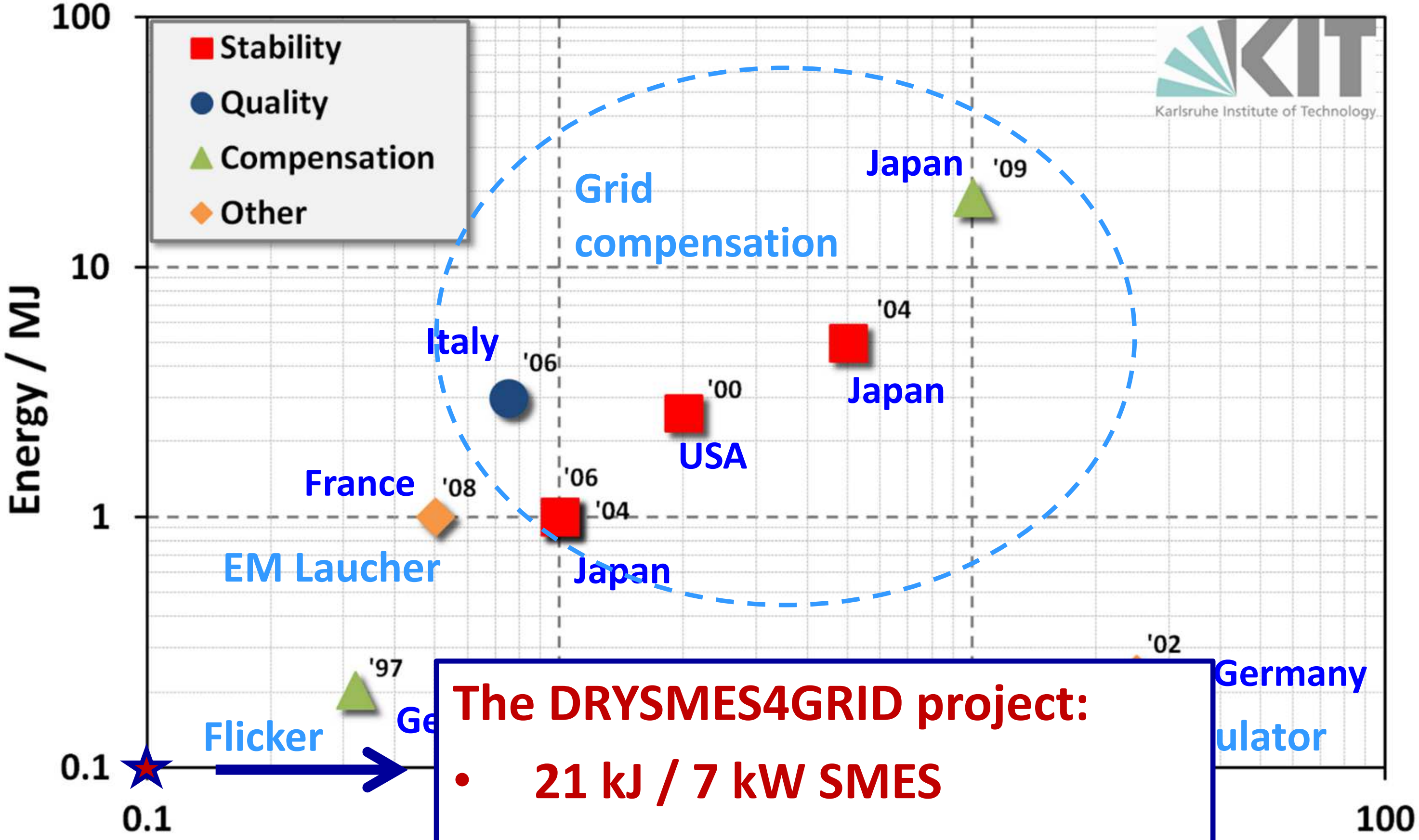
Outline

- SMES Technology status
- The DRYSMES4GRID project: an MgB_2 SMES demonstrator
  - Design methodology and results
- Reducing the demonstrator size - a 21 kJ / 7 kW MgB_2 SMES
  - Manufacturing and assembling
  - First test results

The state of the art of SMES technology



The DRYSMES4GRID project:

- 21 kJ / 7 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**
  - **Extended to September 2021**

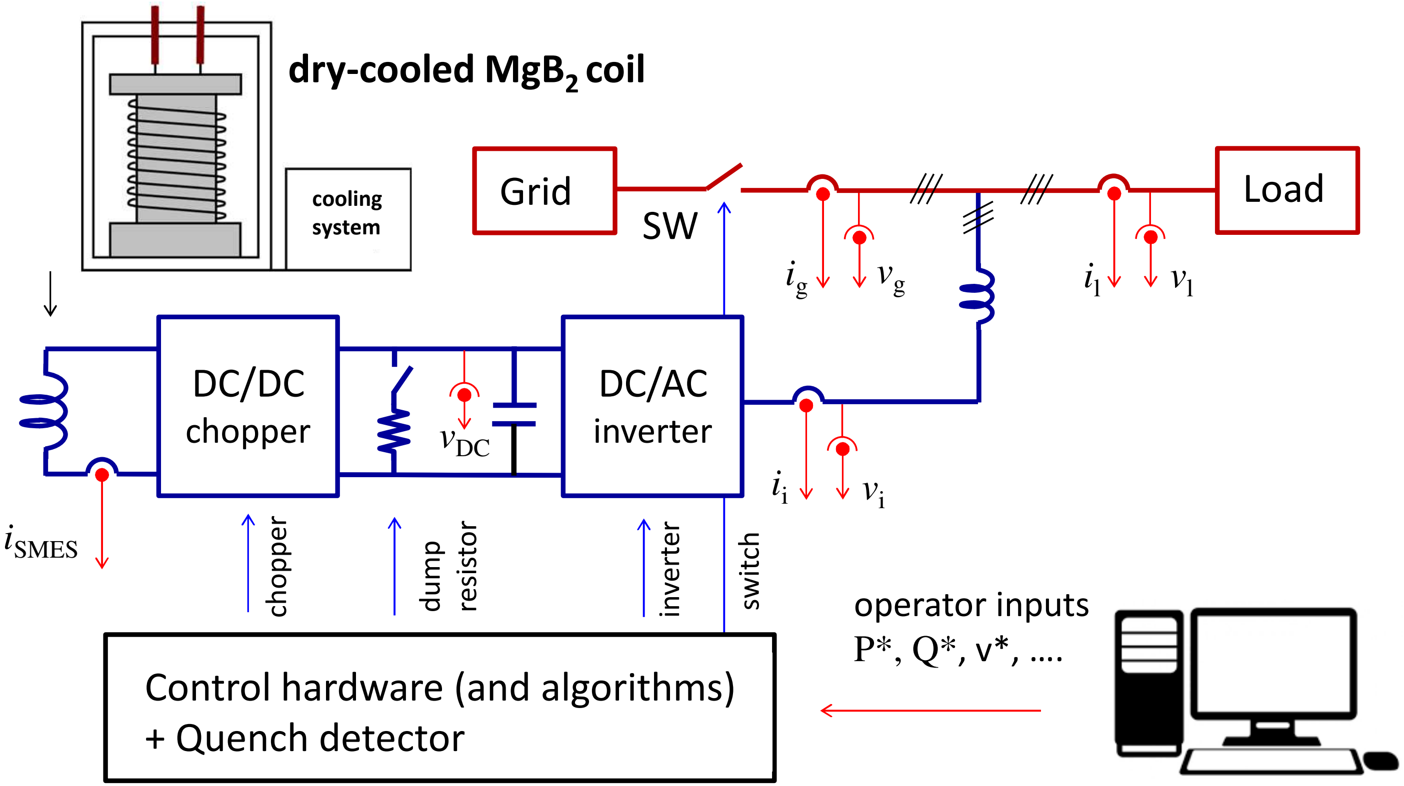
Project Coordinator:

- **ASG Superconductors SpA, Genova, Italy**

Partners

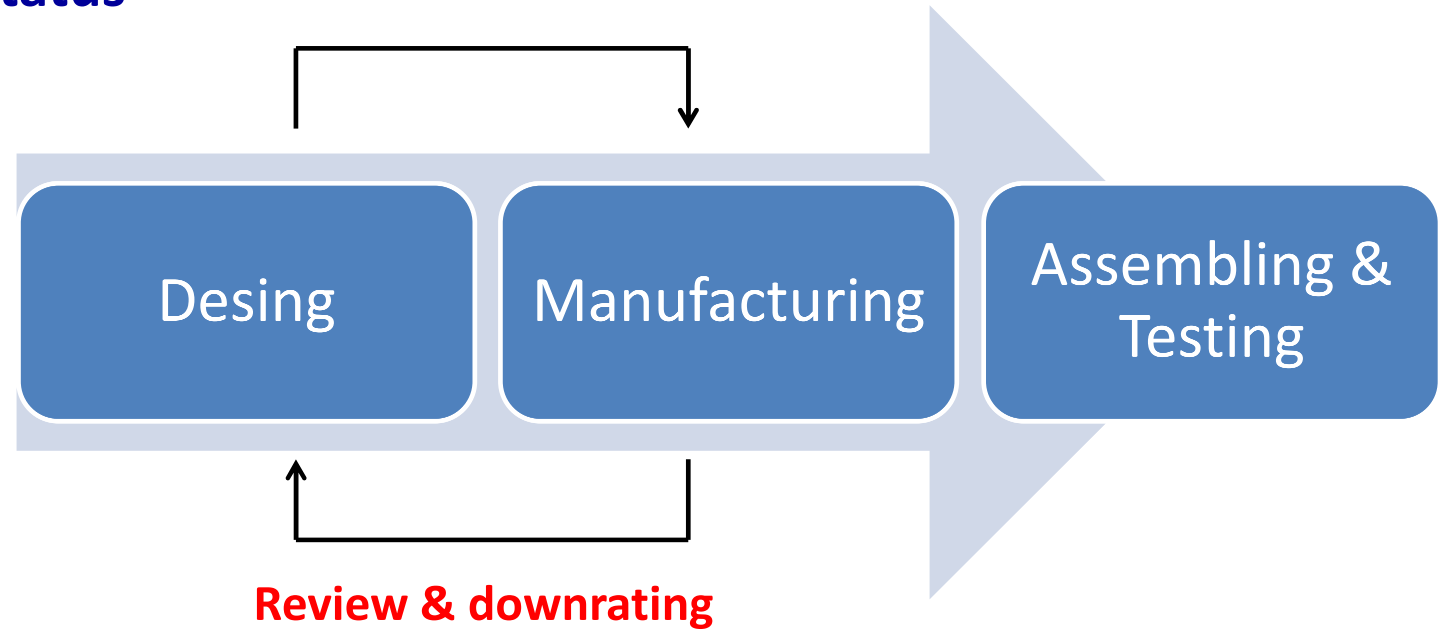
- **University of Bologna**
- **RSE S.p.A - Ricerca sul Sistema Energetico, Milan**
- **CNR – SPIN, Genoa**

The DRYSMES4GRID system



- **Objective: supporting grid and load power both in shunt and in islanded operation**

Project’s status



- Electromagnetic & Mechanical design of the coil
- Thermal design (connection to cryocooler/s)
- AC Loss computation
- Control algorithms (logic, schemes, parameters)
- Design of Power Hardware &Control

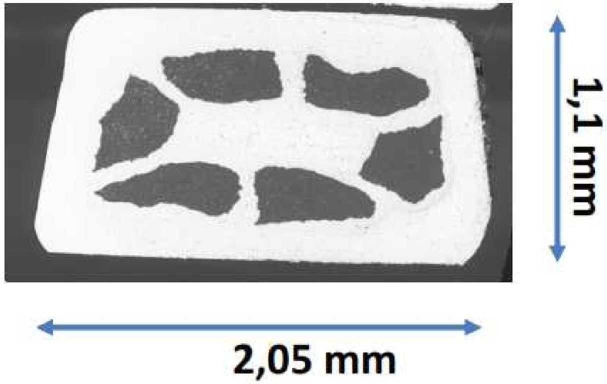
- Manufacturing of the coil & cooling system
- Manufacturing of Power Hardware&Control

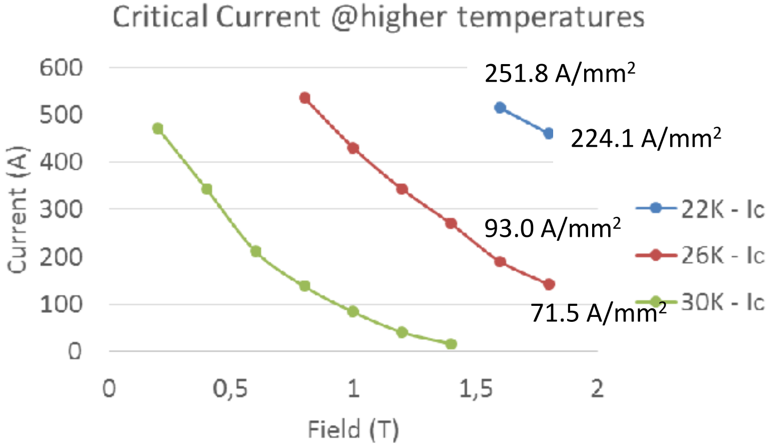
- Assembling
- Testing

Accomplished activities

On going activities

Reference Conductor – Rectangular tape with 6 filaments



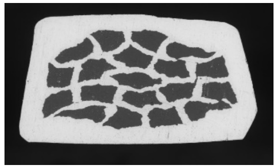


Composition and characteristics	
MgB_2	29 %
Monel 400 (external sheath)	44 %
Nickel 201 (internal matrix)	27 %
Number of filaments	6
Thickness	1.1 mm
Width	2.05 mm
Cross section	2.05 mm^2
Twis pitch	600 mm

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)

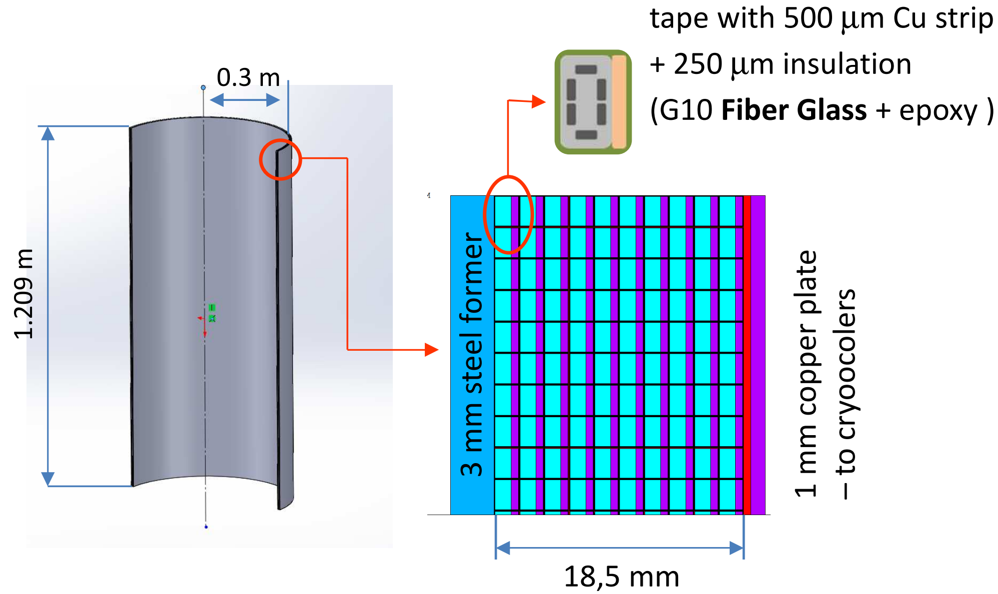
Electrical insulation
125 μm insulating wrapping

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

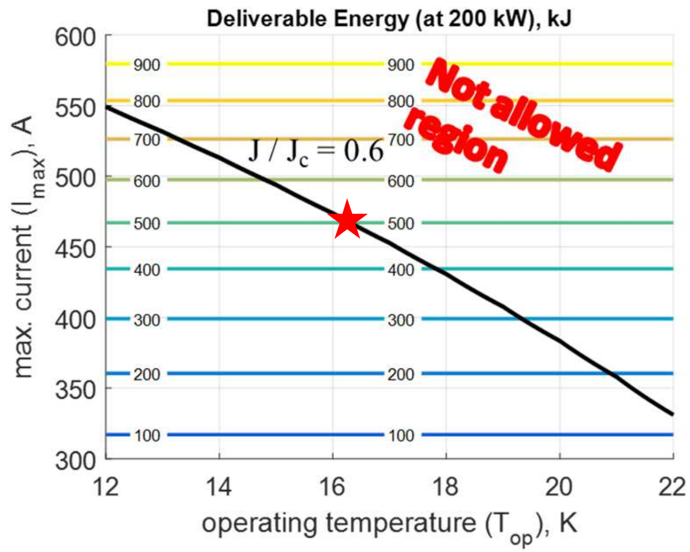


Main characteristics of the designed 500 kJ / 200 kW SMES coil

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

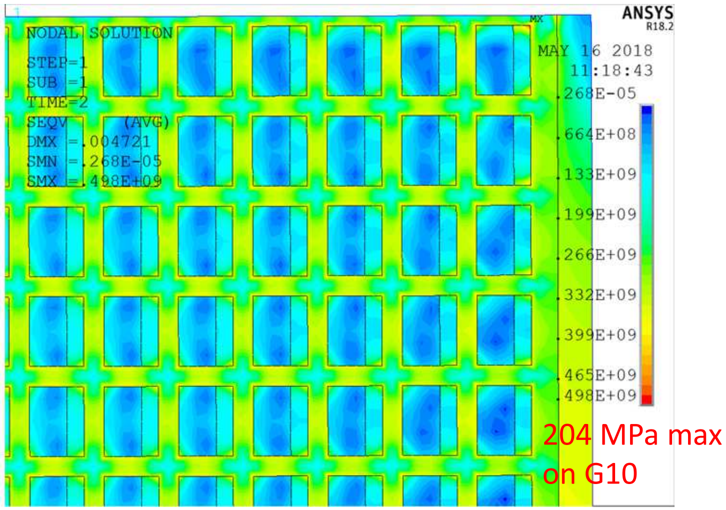
- **Pretensioning due to winding of the coil**
- **Thermal contraction during cool down**
- **Lorentz force**

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

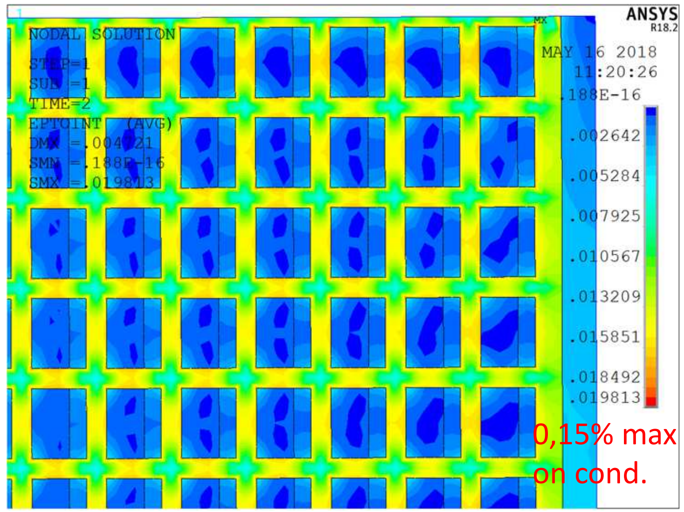
- K Konstantopoulou et al., "Electro-mechanical characterization of MgB2 wires for the SC Link Project at CERN", SUST 2016
- J. W. Ekin, Experim. Techniques for Low Temp. Measurements, OUP, 2006
- *P. Bauer et al.,* EFDA Material Data Compilation for Supercond. Simulation
- CRYOCOMP

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

Von Mises stress



Strain

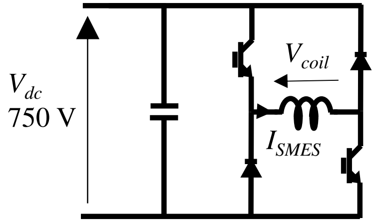


Stress within allowable limit for all materials

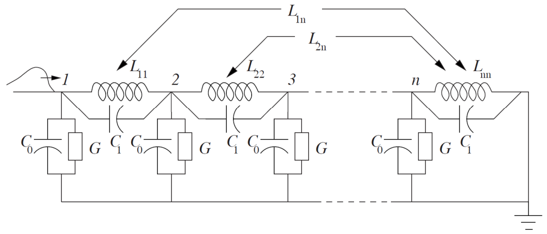
Strain within allowable limit for all materials

Electrical insulation

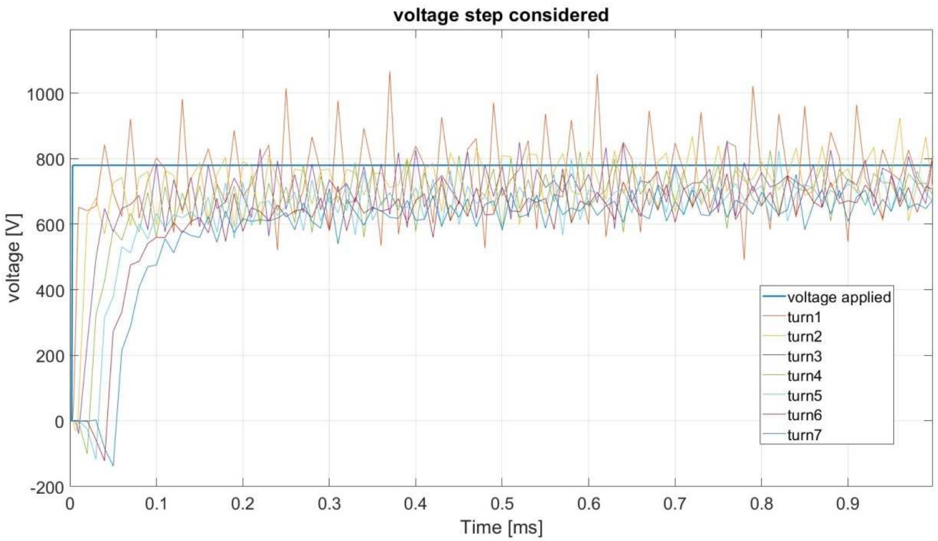
Voltage surge (1 us) on the coil due to switching
Uneven distribution of voltage among turns



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

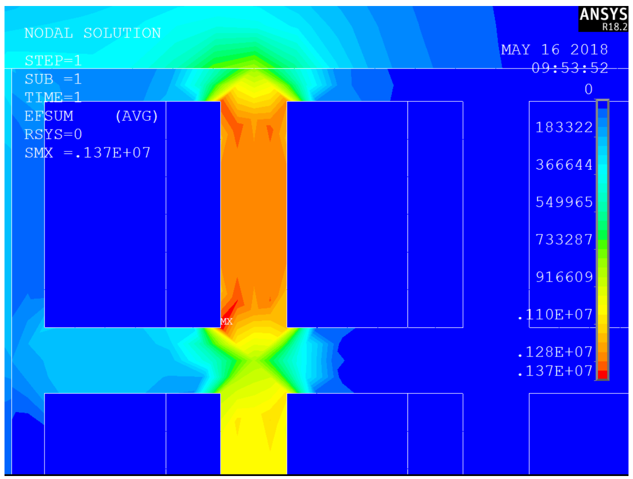


Actual vs. ground voltage distribution of turns after at chopper switching



Electric field

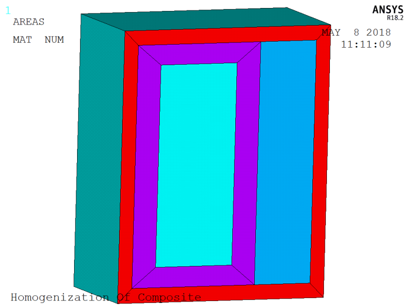
E_{max} within allowable limit of 1.2 kV/mm



3D Quench Analisys

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

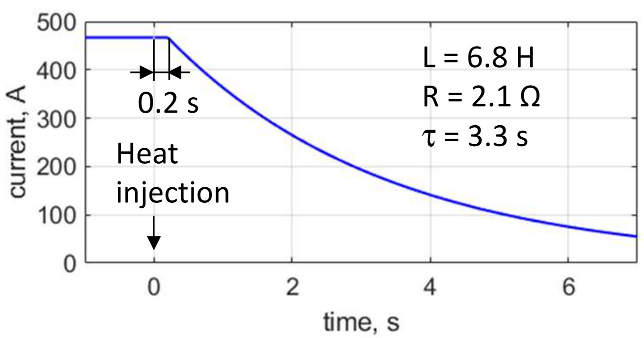
- Equivalent longitudinal resistivity ρ_{eq} from electric parallel
- Equivalent thermal capacity c_{eq} from volume weighted average
- Equivalent thermal conductivities (k_{req}, $k_{\theta eq}$, k_{zeq}) from thermal flux due to unit temperature drop in each direction



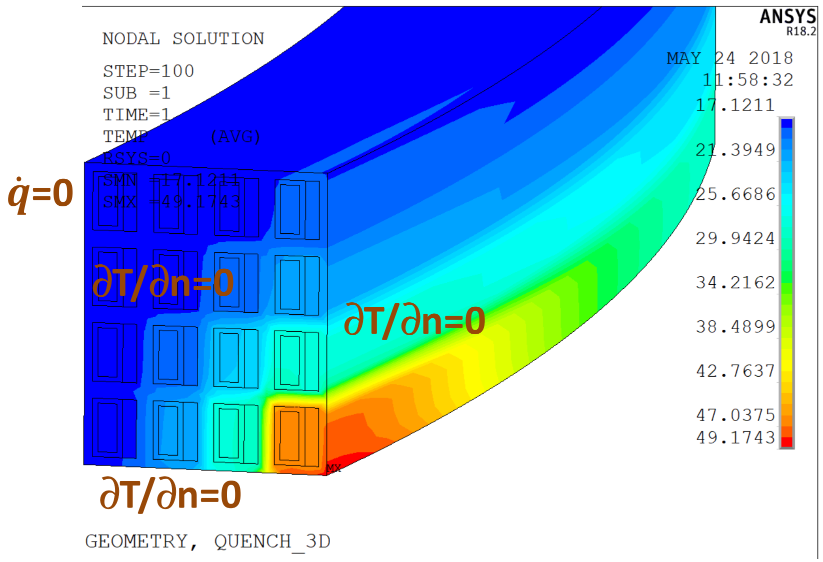
Thermal transient on a 15° sector made of 4x4 strand is calculated

- 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

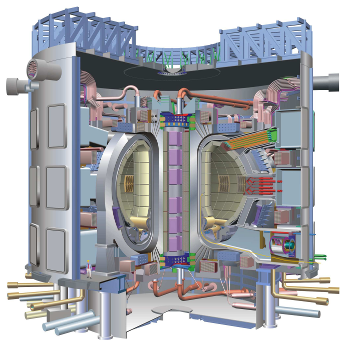


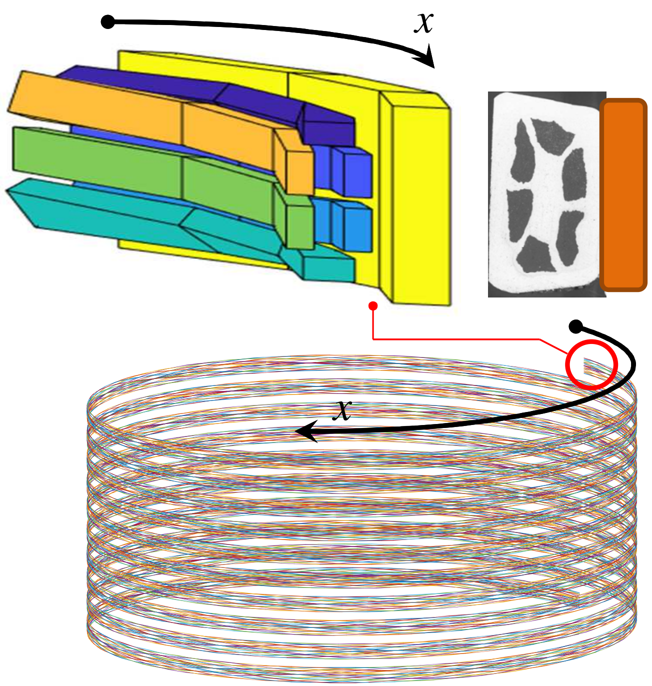
A max temperature of 108 K is reached in the coil
Mechanical stress due to thermal expansion within allowable limits

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

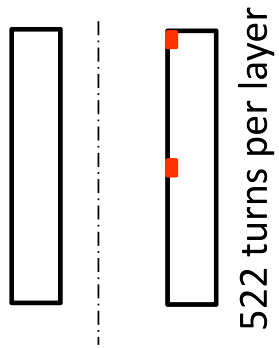




10 turns – 19 m of conductor

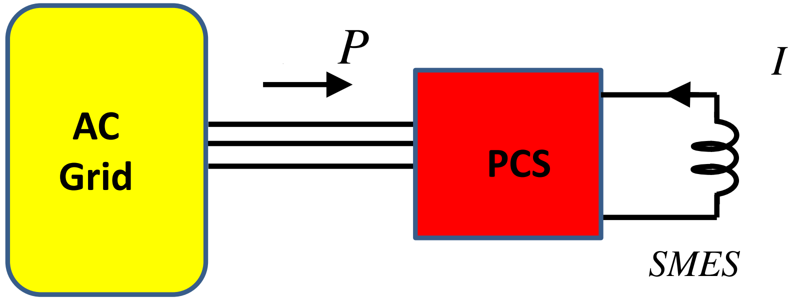
- A 3D mesh of 10 turns is generated by extrusion along the helix pattern of the coil (the remain of the coil act as a field source)
- A 3D FEM simulation based on integral formulation is performed

- **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



$$\frac{1}{2}L\,I^2 - \frac{1}{2}LI_0^2 = \mp P\,(t - t_0)$$

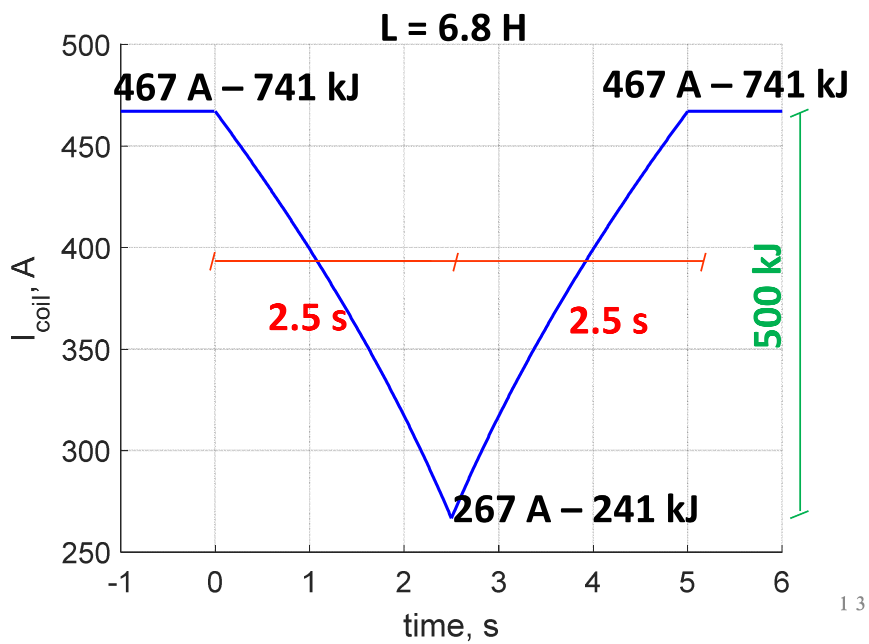
$$I = \sqrt{I_0^2 \mp \frac{2}{L}P\,(t - t_0)}$$

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

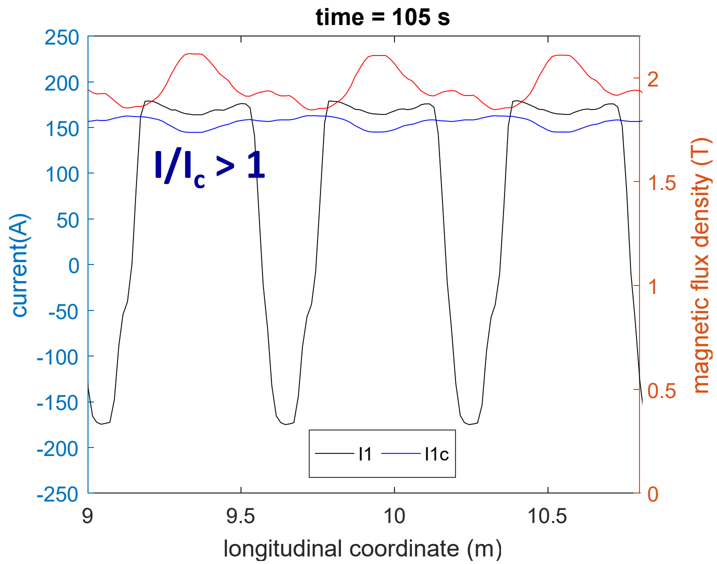
One Discharge/Charge cycle is simulated

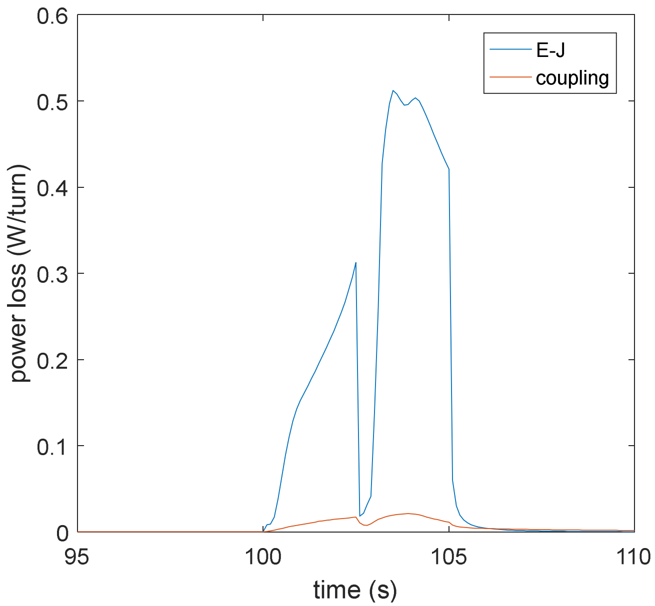
Discharge
@ 200 kW – 2.5 s

Charge
@ 200 kW – 2.5 s



Dissipated power

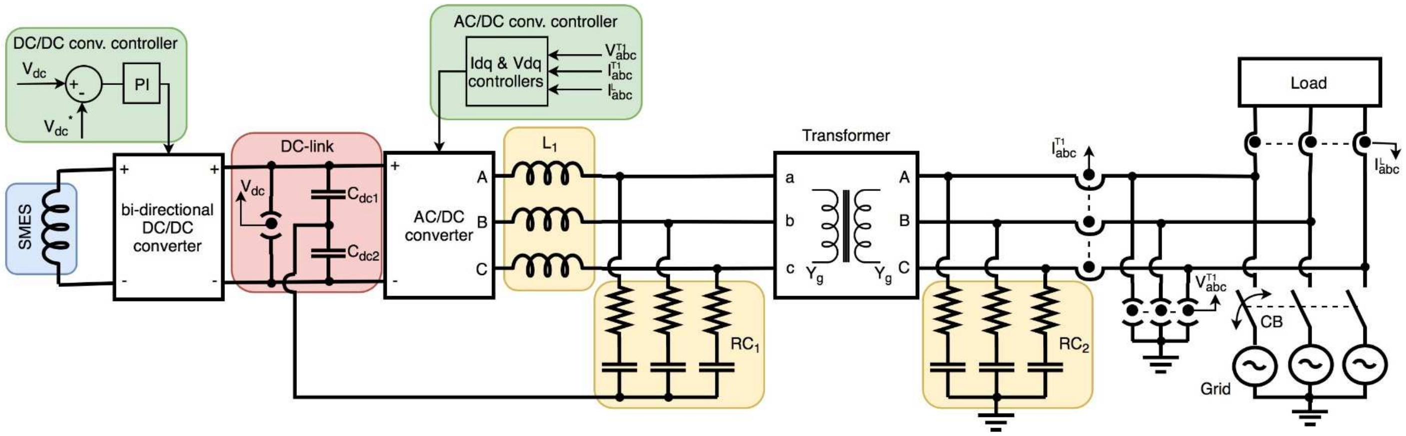




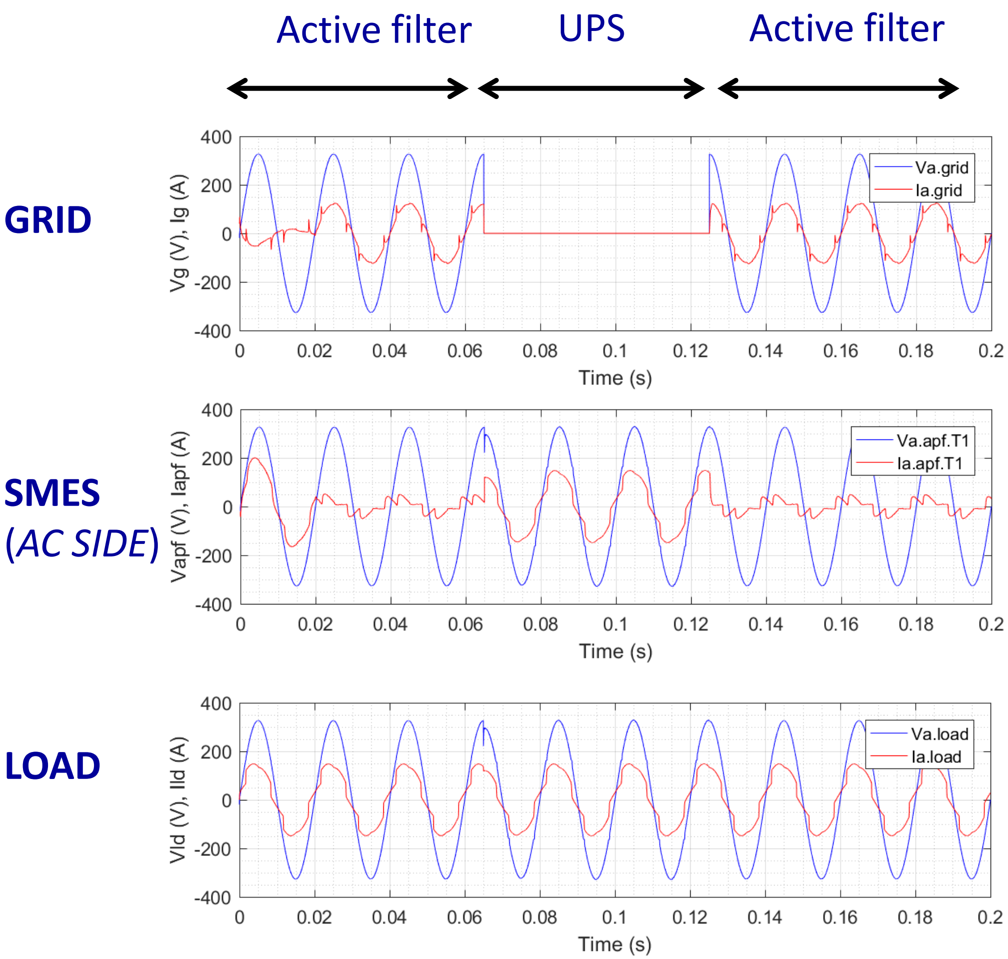
- **Current of filaments below the critical value during steady SMES operation**
- **Critical current largely overcome during ramp due to coupling currents**

- **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**

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]

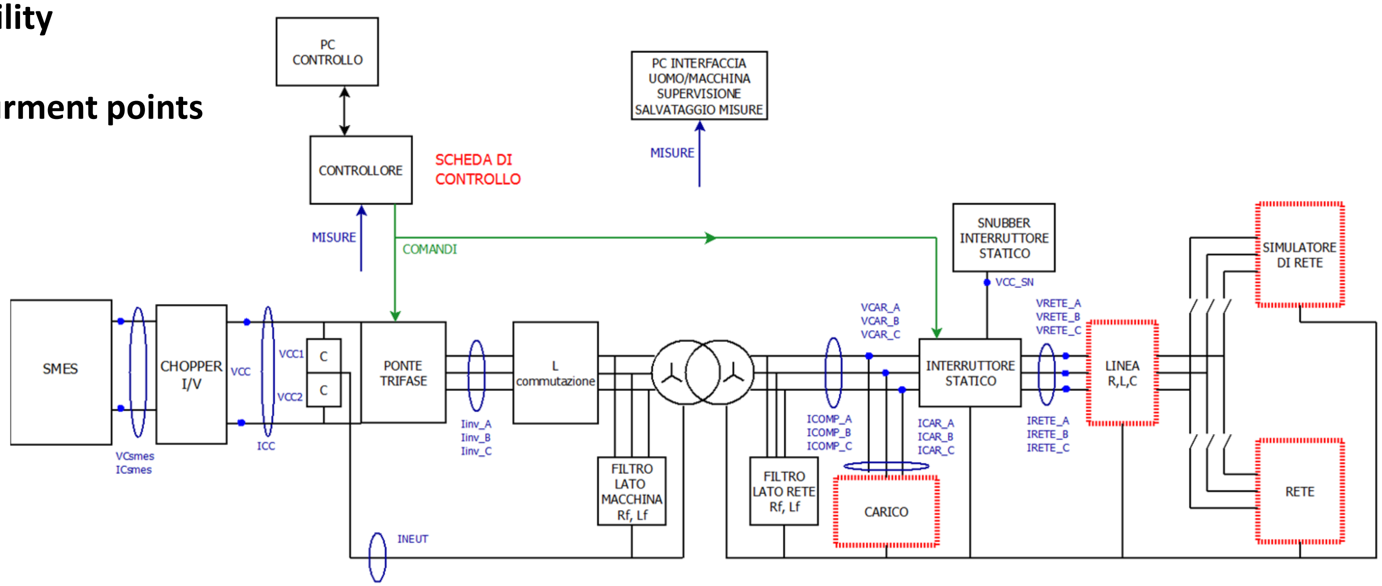
Idq PI controller [1.4, 200]
Vdq PI controller [5, 1000]
Vdc PI controller [200, 10000]

- **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**

Power conditioning system – power hardware

Definition of power hardware

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



Technical specifics for commissioning and type testing issued

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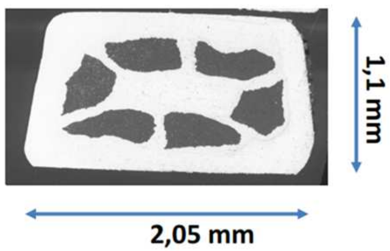
Motivation – critical production process



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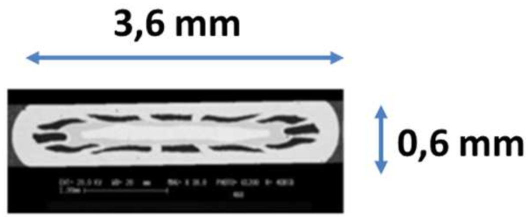


Material	Area (mm^2)	%
MgB_2	0.23	10
Ni	1.55	65
Iron	0.23	10
Copper	0.36	15
Total	2.37	100
Dimension	3.65 x 0.65	

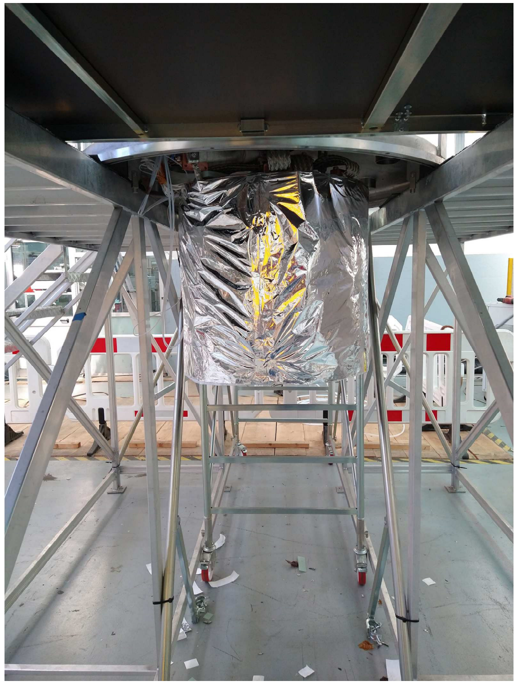
Main characteristics of the reduced size SMES coil

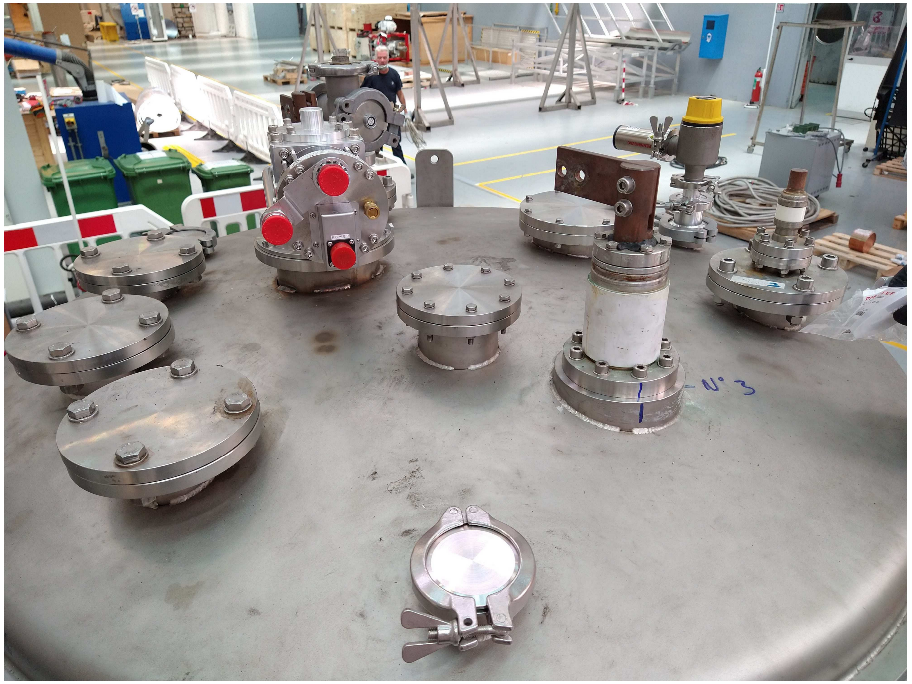
Min Current, A	120
Max current, A	240
I/Ic ratio (at Imax)	0.6
Inductance, H	0.75
Total eneregy (at Imax), kJ	21.6 kJ
Deliverable power, kW	7 (for 2.3 s)
Dump resistance, Ω	3,0

- Production of the selected conductor in long the long lengths needed for manufacturing the designed magnet resulted critical
- A substitute conductor with improved in-field performance and established producibility was selected
- Downrating of the SMES system to 21 kJ / 7 kW was selected in order to simplify and speed up project conclusion

Demonstration of SMES technology based on dry-cooled MgB_2 achieved if tests are successful

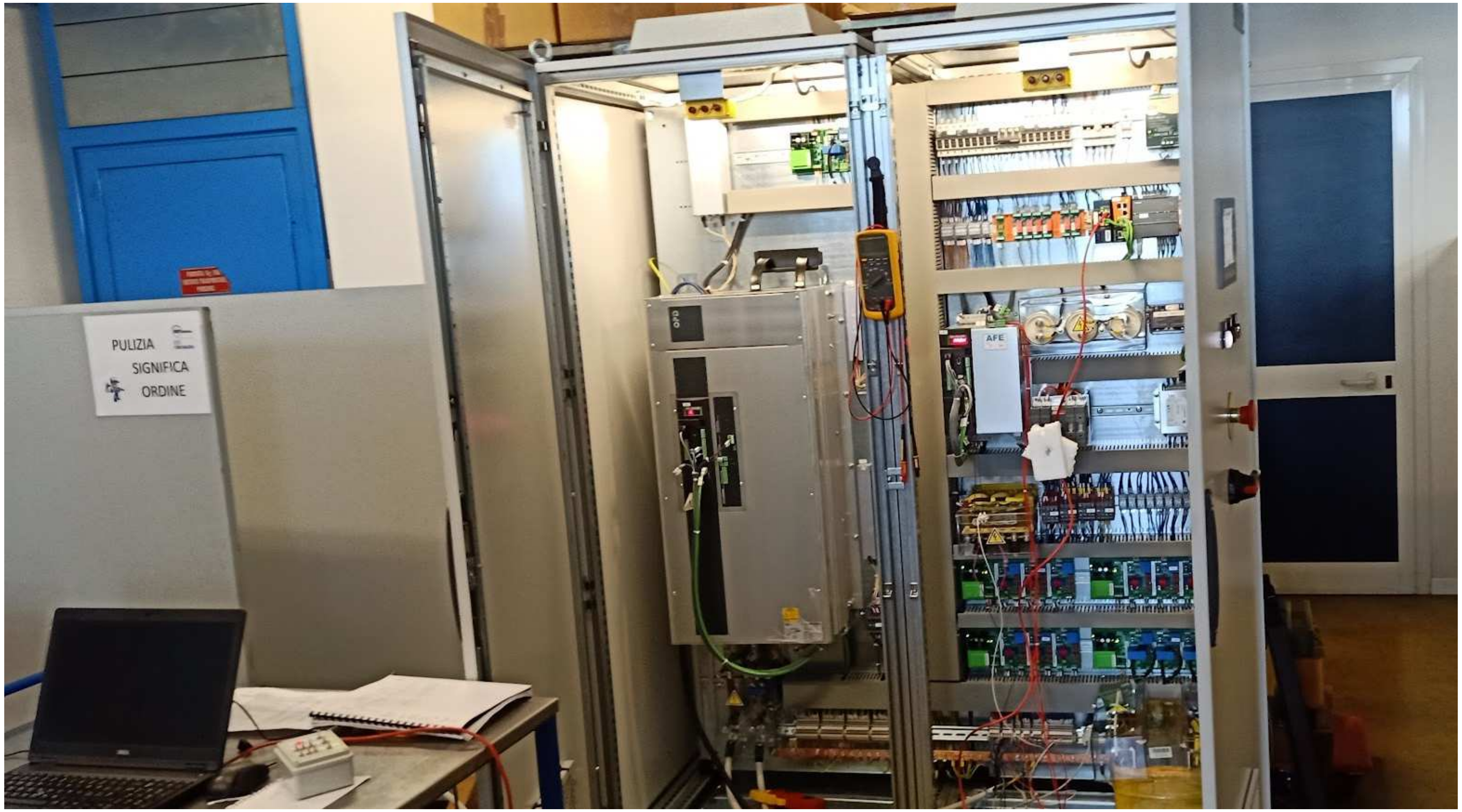
SMES coil





Manufacturing and assembling of the 21 kJ SMES coil completed during April-August 2021

Power conditioning system

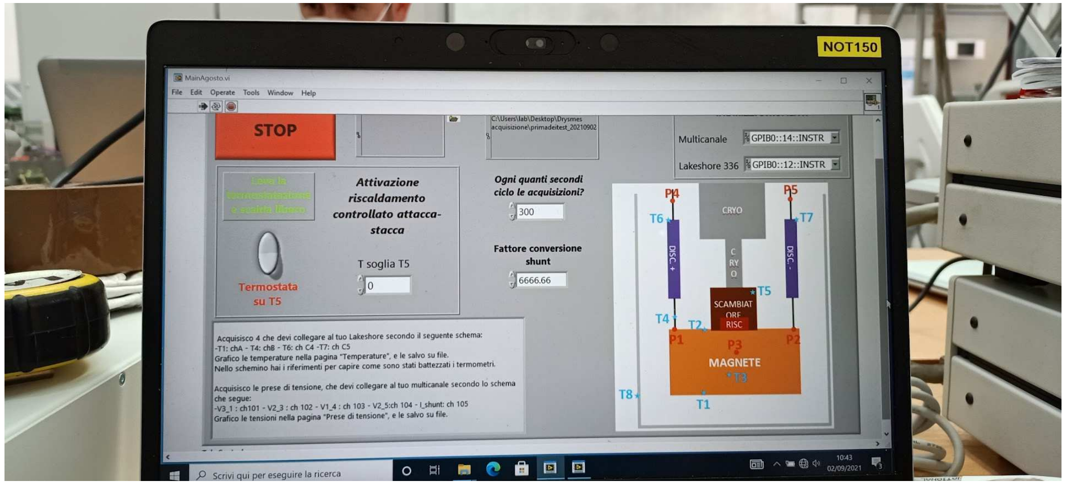


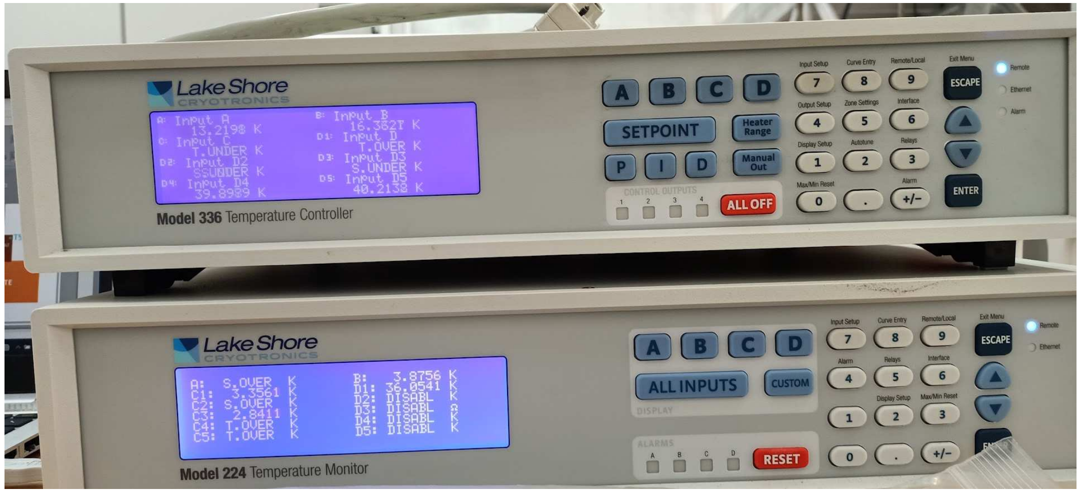
Manufacturing and assembling of the 7 kW PCS completed during April-August 2021

Assembling of the SMES system

Assembling of the 21kJ / 7 kW SMES system completed at ASG premise in August 2021

Preliminary testing / 1

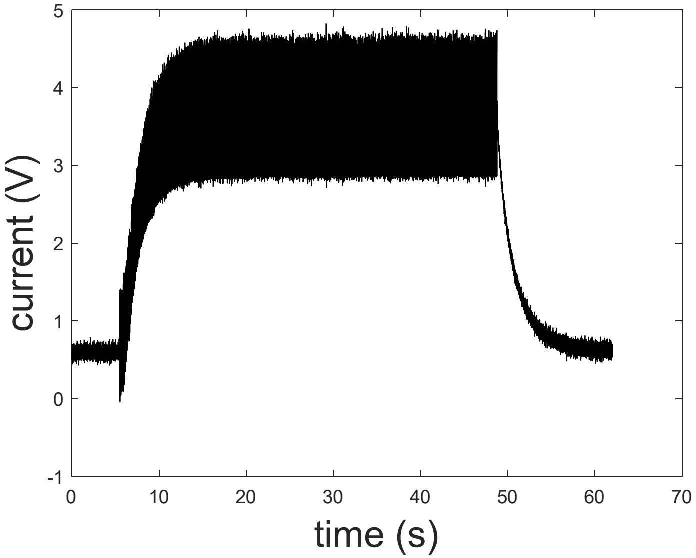


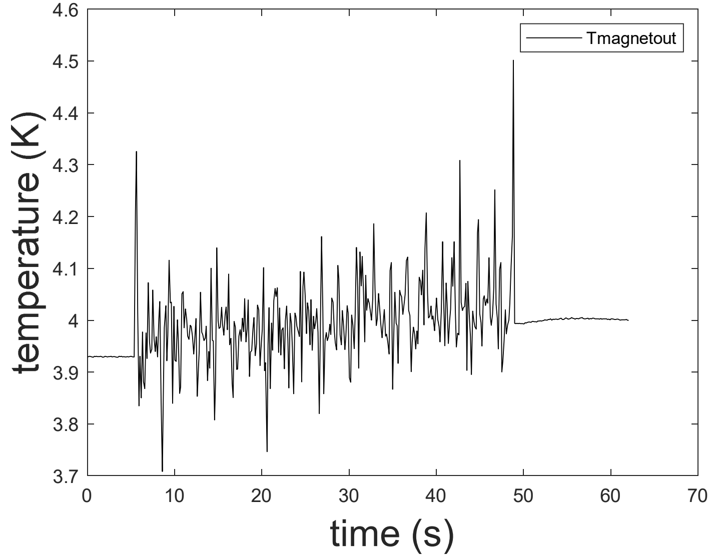


3.9 K reached on the coil in no load condition

Magnet cooldown successfully completed in September 2, 2021

Preliminary testing / 2

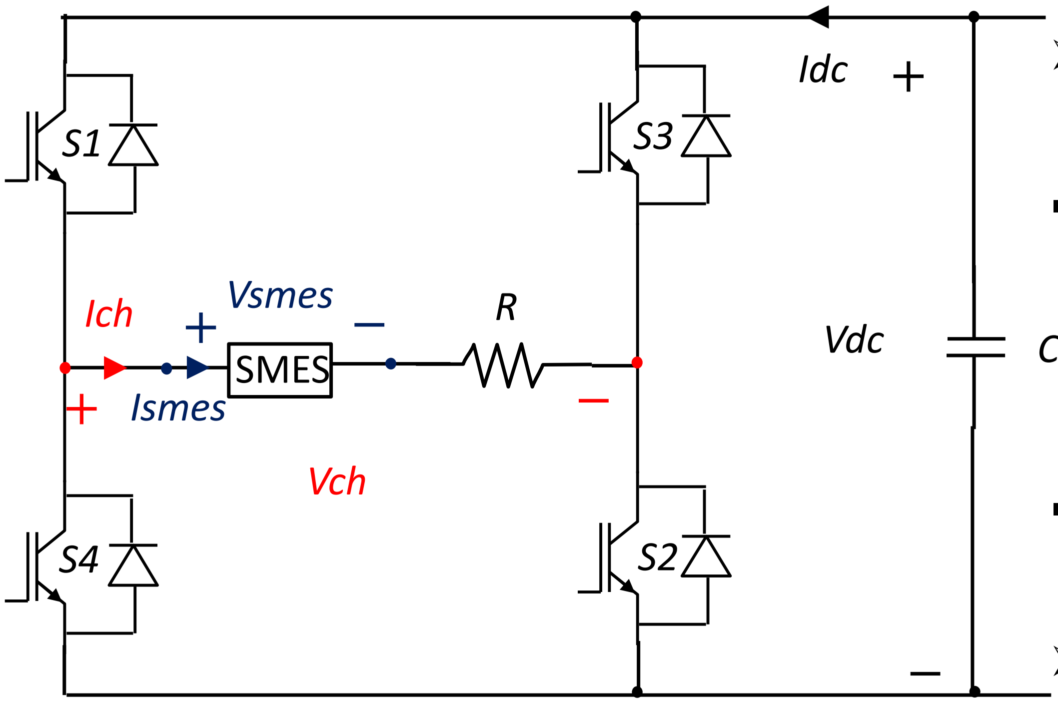




Controlled charge up to 6 J (4A) reached via the PCS

First magnet energization up to 4 A completed via the PCS in September 2, 2021

TEST 10/09/2021:PROVA-40

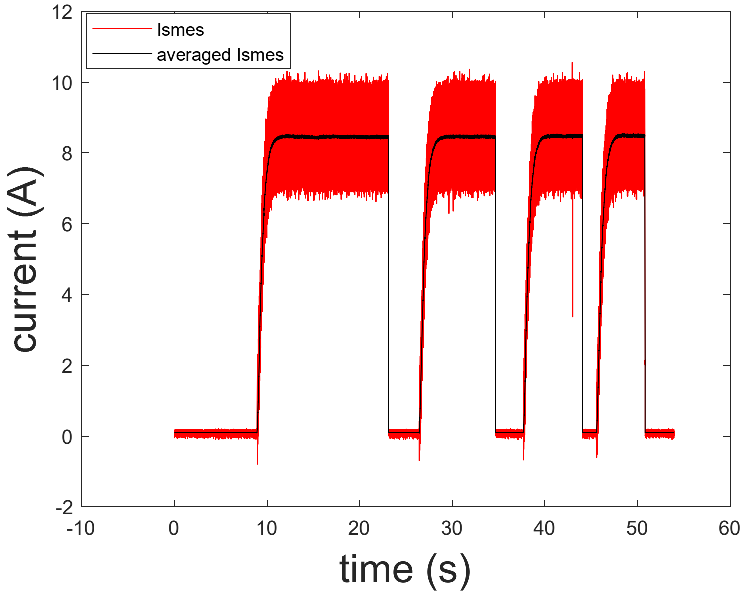


- ***Ismes*** e ***Ich*** sono la stessa corrente ma misurata da due diversi sensori:
  - ***Ismes*** è misurata prendendo il segnale dal sensore esterno al quadro in cui il cavo della corrente era stato fatto passare 6 volte (f = (40/6) A/V)
  - ***Ich*** è misurata prendendo il segnale dal sensore nel quadro (f = 40 A/V)
- ***Vsmes*** è misurata prendendo il segnale dal sensore differenziale di RSE (f = 200 A/V)

Layout del test:

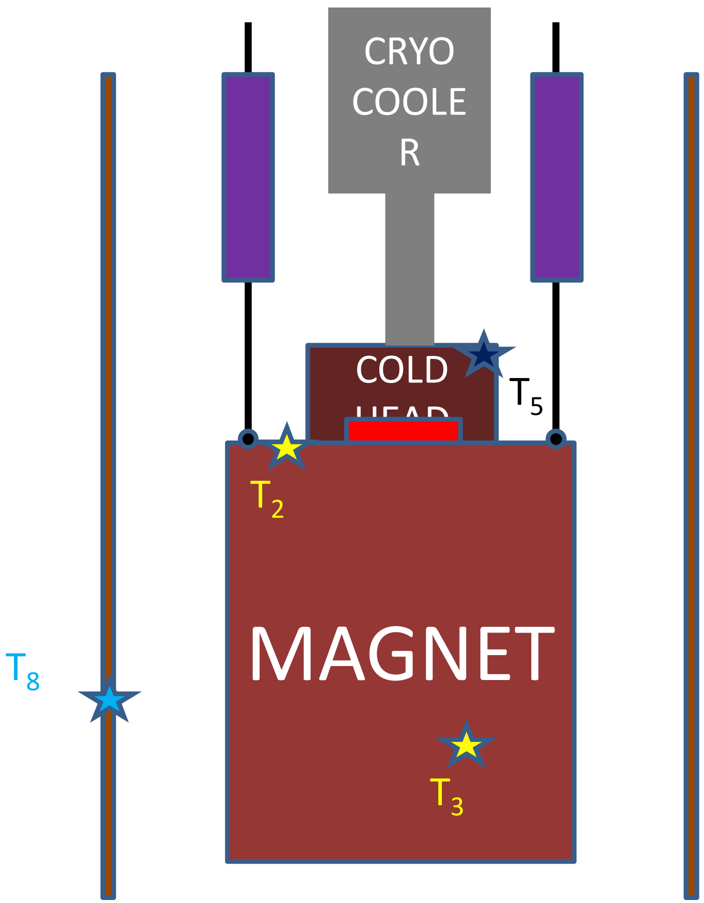
- R = 8.6 Ω,
- frequenza di lavoro del chopper 2 kHz,
- frequenza di campionamento dei segnali di tensione e corrente 60 kHz
- Il chopper funziona nella modalità «controllo della corrente»

Ismes



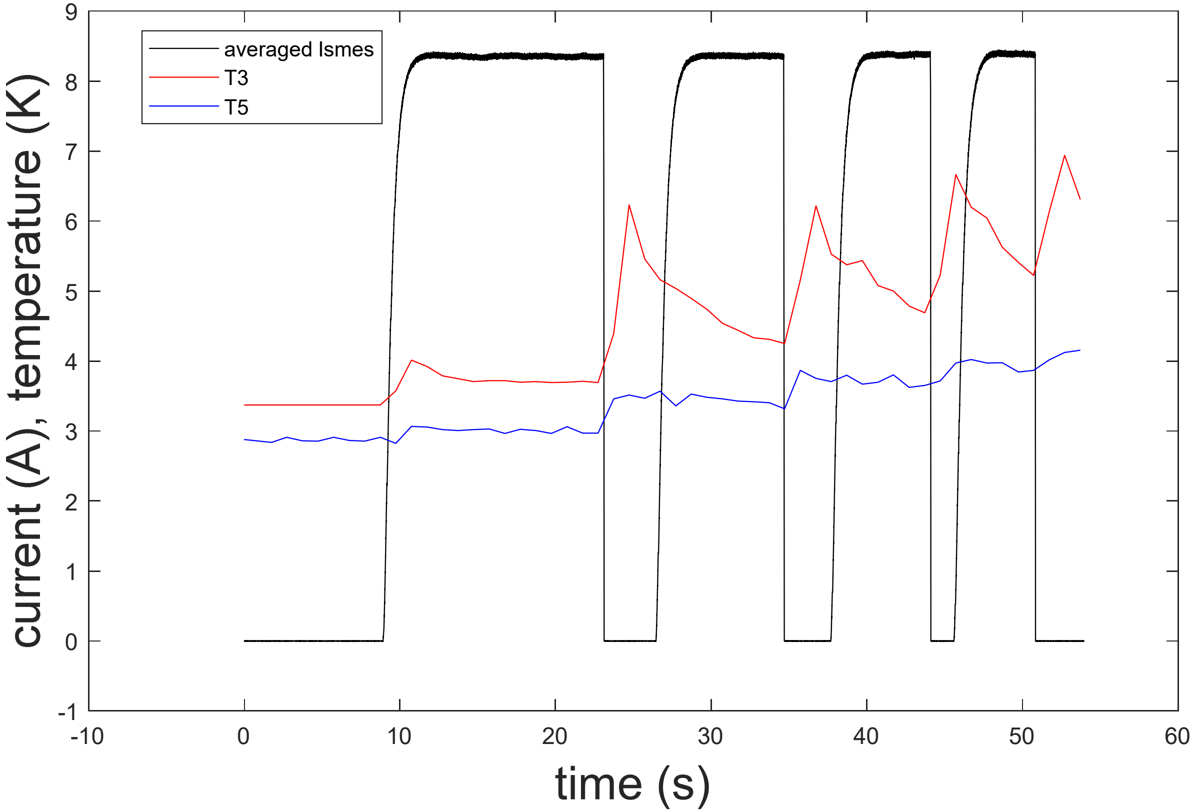
- Il segnale proveniente dalla sonda esterna risulta più preciso perché più vicino al fondo scala del sensore (grazie alle 6 spire di corrente realizzate)
- Offset di ***Ismes***: 0.096 A
- Offset di ***Ichopper***: -0.63 A
- ➢ La corrente nello SMES raggiunge un valore massimo medio di **8.35 A**

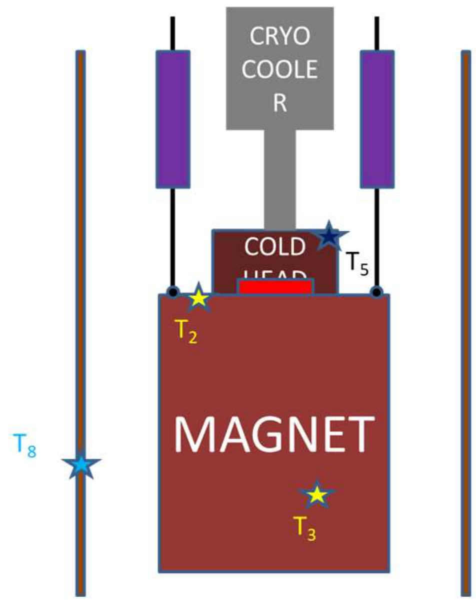
Temperature



- Tutte le temperature vengono lette mediante GPIB dal lettore Lakeshore 224

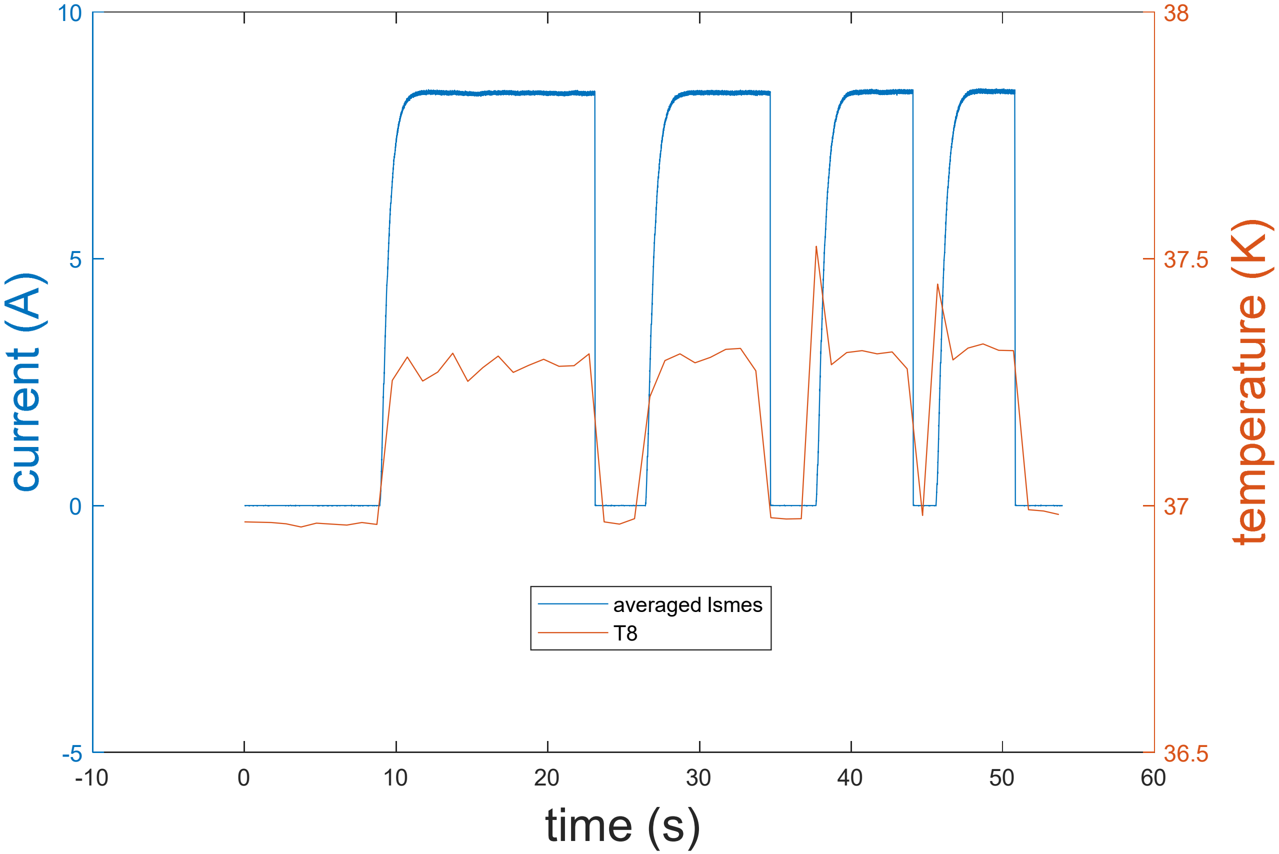
T3 - T5 - Ismes

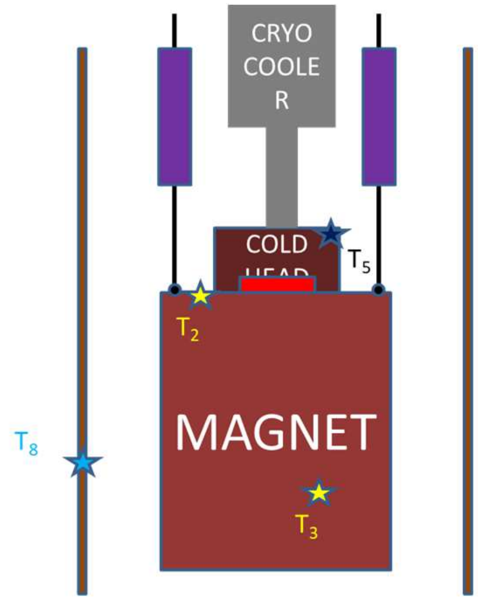




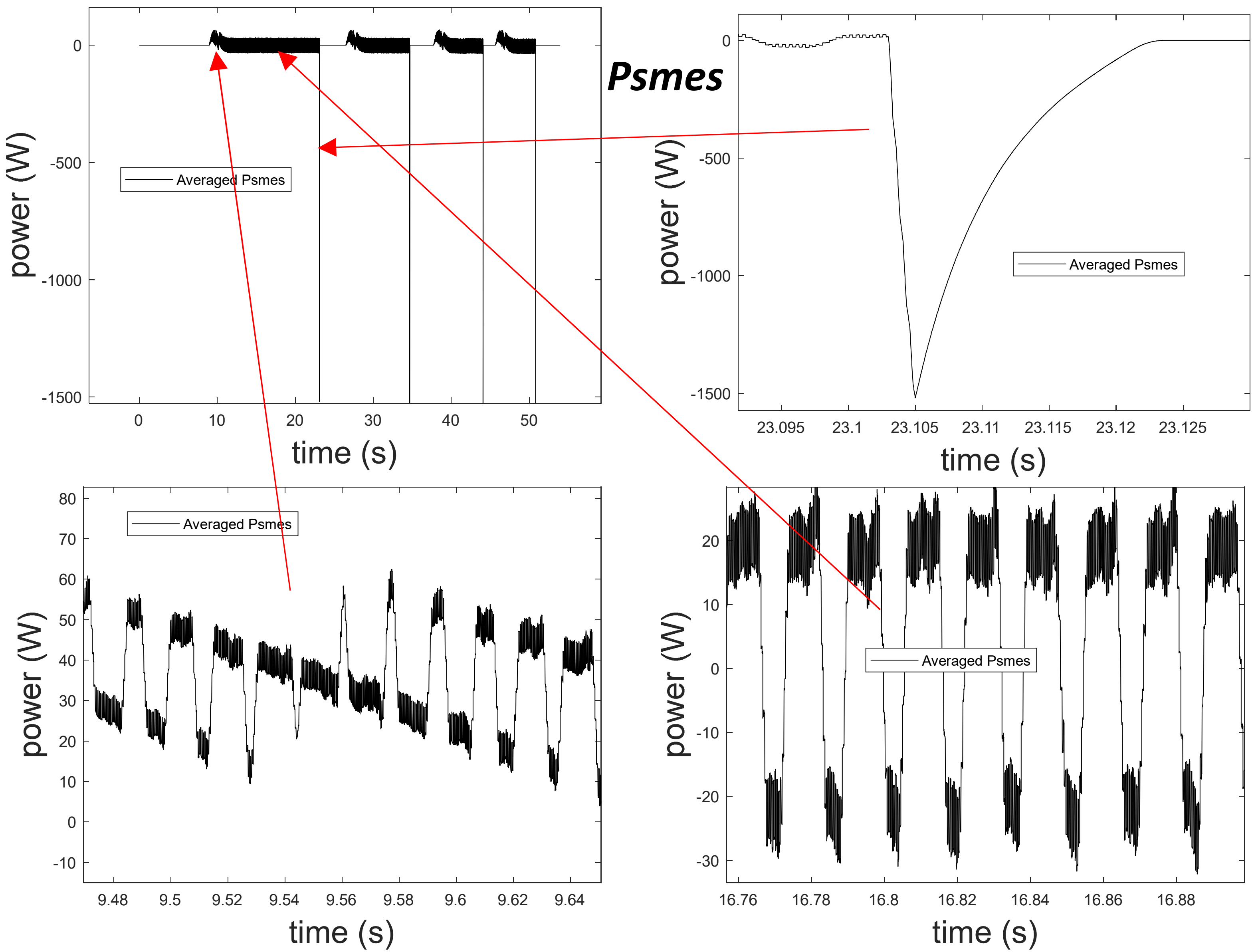
- La temperatura che più risente del calore dissipato è la T2.
- La potenza maggiore viene rilasciata dallo smes nella fase di scarica a causa dell'elevata derivata temporale della corrente ($dI/dt \cong 420$ A/s in fase di scarica, $dI/dt \cong 4.2$ A/s in fase di carica)
- **È presente un ritardo di circa 1.5 s fra il picco della temperatura e la fine della scarica** ?

T8 - Ismes





- **La temperatura dello schermo cresce di circa 0.5 K in corrispondenza della carica dello SMES e cala della stessa quantità in corrispondenza della scarica dello SMES ?**



Psmes
Averaged Psmes
power (W)
time (s)

Conclusion

We are very excited to report on the complete test of the SMES system to be completed in September 2021