Design of superconducting magnetic energy storage (SMES) for civil applications

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Abstract

We examine the role of energy storage in achieving more sustainable infrastructure, with a focus on electric ship propulsion and hadron therapy facilities. For the maritime sector, the transition to electric propulsion has increased the demand for efficient energy storage systems (ESS) to meet power needs and enhance onboard grid reliability. While industry efforts have prioritized electrochemical batteries, the POSEIDON project explores alternative Fast Response ESS (FRESS) like SMES, supercapacitors, and flywheels. The paper outlines the design of an SMES system for marine environments and explores its potential for energy savings and grid stability in therapy centers.

POSEIDON Project

EU-funded project with the objective of demonstrating the applicability of **3 fast-response ESS in waterborne transport**.

SO1. To build 3 innovative marinized ESS (SMES, Flywheel and Supercapacitors), with power capacities ranging 20-200 kW.

SO2. To demonstrate 200 hours of operation in a maritime environment of a containerized system including the 3 developed ESS systems. A BALEARIA electric ferry will be used as demonstrator

Global Design: Model & BCs

1. **Physical:** temperature, humidity and salinity levels.
2. **Mechanical:** relative movement to the ground, which produces linear and angular accelerations, or vibrations.
3. **Electromagnetic:** Limit for magnetic field value for EMI compatibility and people safety.

Parameters of SMES	Constraints
Storage capacity	$E_{SMES,min} \le E_{SMES,t} \le E_{SMES,max}$
Charging/Discharging Power	$P_{ch,t} \ge P_{SMES,min}; P_{dis,t} \le P_{SMES,max}$
Charging/Discharging quench	$I_t L \frac{dI_t}{dt} < E_{J,t} \quad I_t < I_c;$ $I_t L \frac{dI_t}{dt} + I_t^2 R_{en} \ge E_{J,t} \quad I_t \ge I_c;$
Energy transition	$E_{SMES,t} = E_{SMES,t-1} + (P_{ch,t}\eta_{ch} - P_{dis,t}\eta_{dis})\Delta t$
State of charge	$\lambda_{SOC,t} = E_{SMES,t}/E_{SMES,max}$
Output Voltage Range	$V_{SMES,t}\left(= L\Delta \mathrm{I_{SMES,t}}/\Delta t\right) \le V_{lim,t}$
Marine constraints	
Electromagnetic interference	0.5 mT @ 0.5 m. from cryostat wall
Angle of operation	– List: +/- 15 degrees; Trim: +/- 5 degrees; Roll +/- 45 deg; 12 sec; Pitch +/- 12 deg; 9 sec; Heave 0.4 g; Surge 0.25 g
Vibrations	From 2,0 Hz to 13,2 Hz: displacement amplitude of 1,0 mm From 13,2 Hz to 100 Hz: acc. amplitude of 0,7 g
Ambient temperature, humidity and salinity	$0 \le T_{SMES,t} \le 45ºC$ $25\% \le RH \le 100\%$

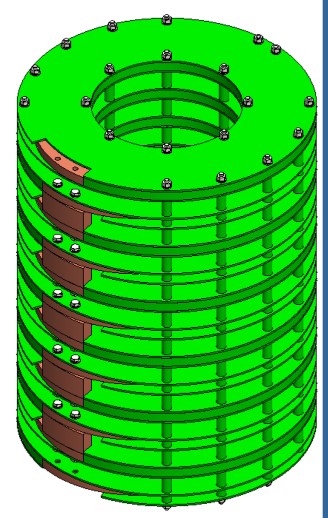
Electromagnetic Design

POSEIDON SMES is based in HTS due to:

- Higher operating temperature: easier & safer cryogen, AC loss impact reduction
- Long term potential: due to favorable market dynamics

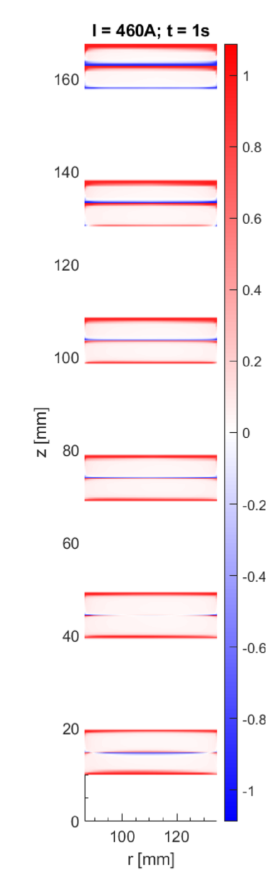
MAIN PARAMETERS OF POSEIDON SMES

	Parameter	Value
SC material	Material	2G HTS Tape
	Supplier	Shangai Superconductors
	Dimensions	4.8 mm width & 0.2-0.25 mm thickness Cu laminated
SC coil	Internal radius	86 mm
	Cross section	49x10 mm^2
	Turns	144 per coil (200 m. of tape)
Magnet	Nº of Double pancakes	12
	Topology	Solenoidal
	Inductance	1.68 H
	Nominal current	457A @4.2K (235A @20K)
SMES	Energy	275 kJ (@ 4.2K)



EM Optimization:

- Maximization of the specific energy per meter of superconducting tape.
- Constraints: Maximum diameter limited to application constraints.
- Optimization variable: Pancake distance.



EM model: A-ϕ integral formulation

- Mathematical formulation

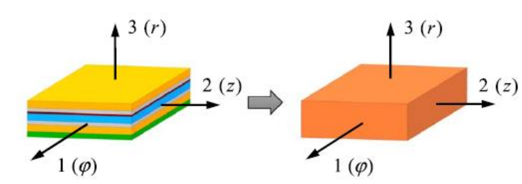
$$\sum_{\substack{k=1\\k\neq e}}^{E}\sum_{j=1}^{N}\left(K_{kij}\frac{dJ_{ej}}{dt}\right) = -\left(E_c\frac{J_{ei}}{J_{c_{ei}}}\left|\frac{J_{ei}}{J_{c_{ei}}}\right|^{n-1} + \gamma\left(I(t) - \sum_{i=1}^{N} J_{ei}dS_{ei}\right)\right)$$

- Coded in MATLAB and validated in COMSOL Multiphysics using H formulation
- Screening currents included
- AC loss computation included

Figure. Current density distribution at nominal operation

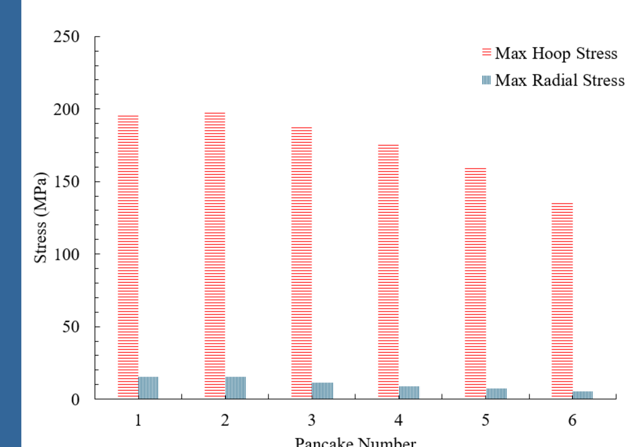
Mechanical Design

Homogenized material properties of the coil winding are considered.



Component	Thickness (mm)	E_m (GPa)	v_m	G_m (GPa)	$\Delta L/L$ (@296-4.2K)
Copper	170	138	0.34	52	2.9e-3
Ag+Buffer	4	90	0.3	35	4.1e-3
REBCO	1.6	125	0.34	69	-
Hastelloy C-276	50	210	0.3	81	3.1e-3
Kapton	100	2.5	0.35	0.93	1.0e-2
Resin	2	7	0.28	2.75	6.4e-3
HTS axial (XY)	--	98.9	0.32	39.8	3.4e-3
HTS long. (YZ)	--	98.9	0.016	4.49	3.4e-3
HTS trans. (XZ)	--	6.15	0.016	4.49	4.6e-3

- Analysis: Analytical and FEM model
  - Boundary Conditions: Contact with friction (μ=0,2) is considered between coils and inter-module plates made of G10.
  - Forces exported from electromagnetic model
  - Addition of Screening Current increase stresses by a factor of 2



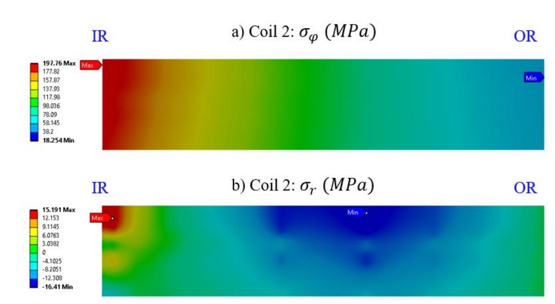
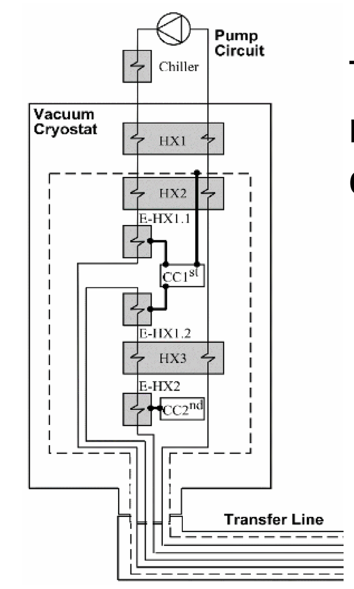


Figure. Hoop and radial stress of most stressed coil

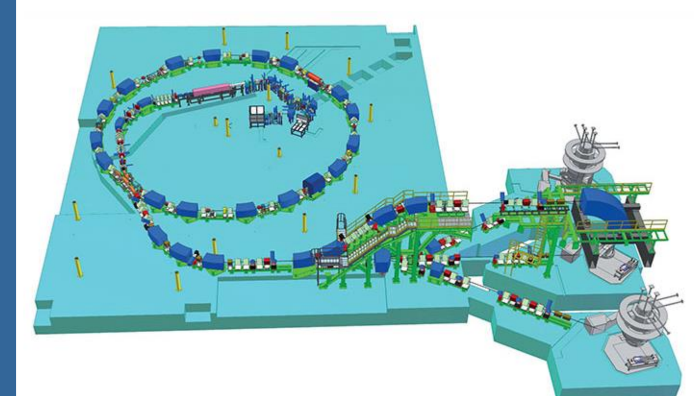
Cooling system



The cooling system will be based on flow refrigeration providing forced convection cooling:

1. Autonomous, easy to use, and cheap cooling system.
2. High safety, and reliability. Essential for marine applications
3. Capable of rejecting heat locally → Essential to provide high power.

Sustainable Infrastructure: CNAO



CNAO is a hadron therapy medical center situated in PAVIA.

<u>Use case</u>: CNAO accelerator is capable of accelerating protons and carbon ions to 250 MeV and 4800 MeV respectively.

Power consumption: Est. consumption of 100 kW for the dipole magnets.

<u>**Advantages:**</u> Incorporating a 100 kW SMES (Est. CAPEX: 80-100k€):

- <u>Energy savings</u>: Energy can be recovered in the deceleration phase of the pulsed load and used in the next acceleration. 7.5k€ savings per year. Pay-back of 11 years.
- <u>Grid stability</u>: According to CNAO a voltage dip of just 3% is sufficient to cause a perturbation of the output current impeding patient treatment. An SMES can provide dynamic stability during or act as a UPS.

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