Increasing the efficiency of the CERN accelerators by use of Superconducting Magnetic Energy Storage (SMES)

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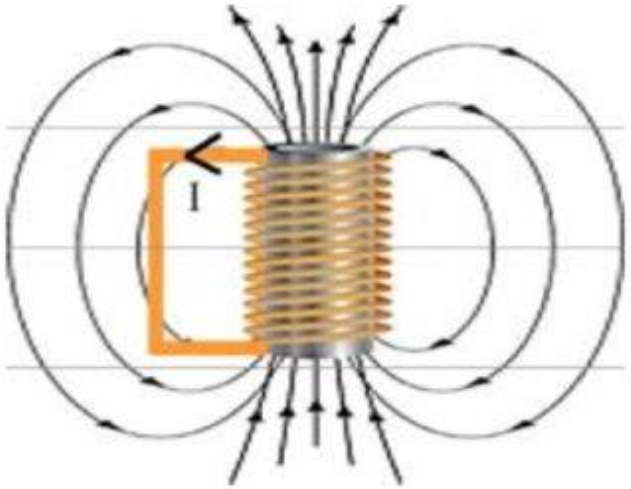
Presentation rundown:

1. Concept of Superconducting Magnetic Energy Storage (SMES), initial idea, history and developments
2. How it works, based on operation of three main components
3. Power quality issues at CERN that can be solved by SMES-systems
4. Design considerations for these SMES-systems
5. Recent developments due to High Temperature Superconductor research
6. Conclusions
7. Questions

Introduction:

- SMES stores energy in the magnetic field generated by a shortened superconducting coil
- The coil can sustain a current for a long time whilst it remains shortened
- The energy is accessed (system is discharged) by unshortening the circuit to include a resistive load
- SMES was first proposed by M. Ferrier in 1969



Orange: Shortened Superconducting Coil
Black: Resulting Magnetic Field

M. Ferriers initial idea (1969):

- 200 m diameter toroidal magnet
- Would operate independently governed by a trigger signal based on electrical power supply and demand - 'load leveling'
- The project was canceled due to exceeding costs of the required cryogenics system

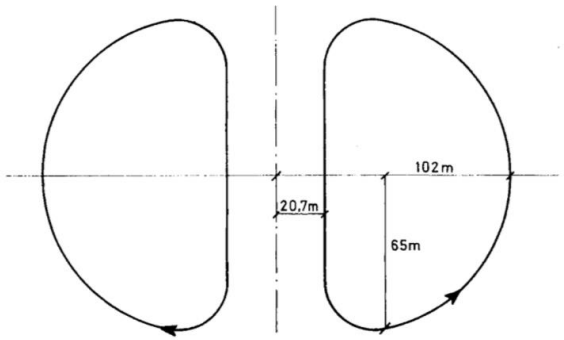


Fig. 1 — Schéma de l'accumulateur à une seule couche dans des plans méridiens.

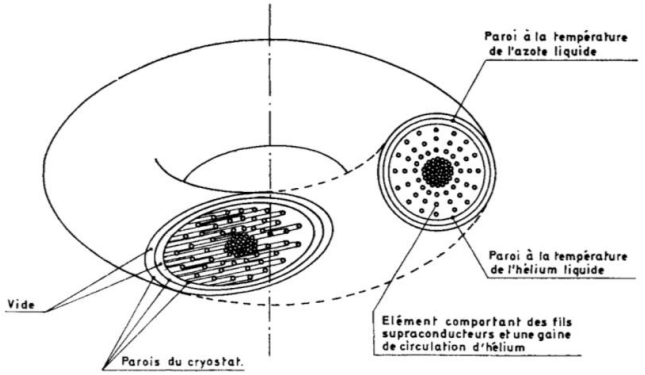


Fig. 2 — Représentation schématique de l'accumulateur à spires dans des plans parallèles. (Les éléments constitutifs du support mécanique ne sont pas représentés).

The firs design of a SMES magnet. Image from: M. Ferrier: "STOCKAGE D'ÉNERGIE DANS UNENROULEMENT SUPRACONDUCTEUR" (1969)

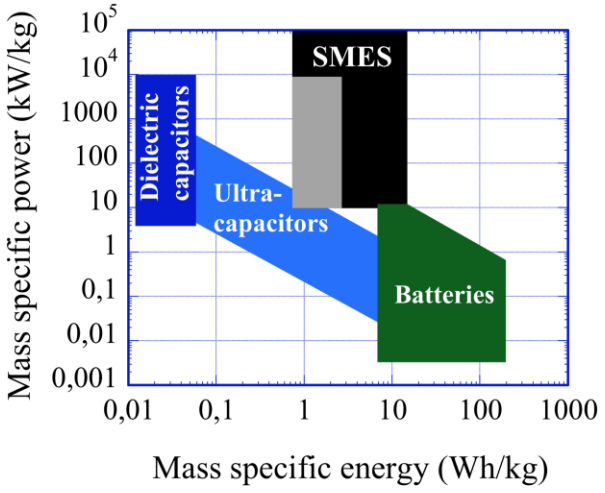
Development, characteristics and contributions:

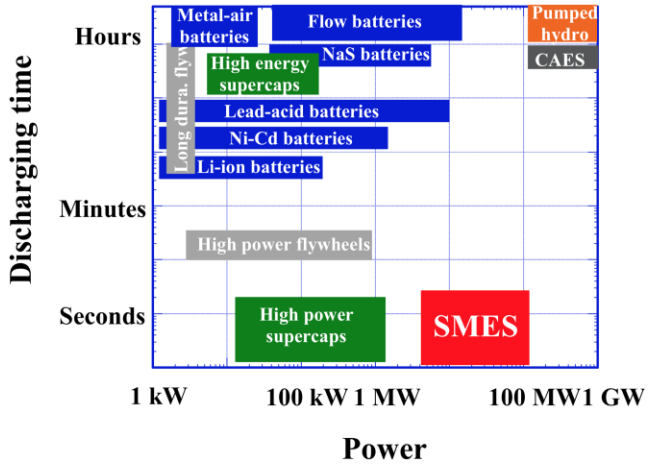
- Research and development has moved its area of application towards other power quality issues such as:
  1. Uninterruptible Power Supply (UPS)
  2. Flexible AC Transmation Systems (FACTS)

- SMES is characterized by:
  1. Many power cycles
  2. Short response time
  3. High conversion efficiency

All because the energy is never converted

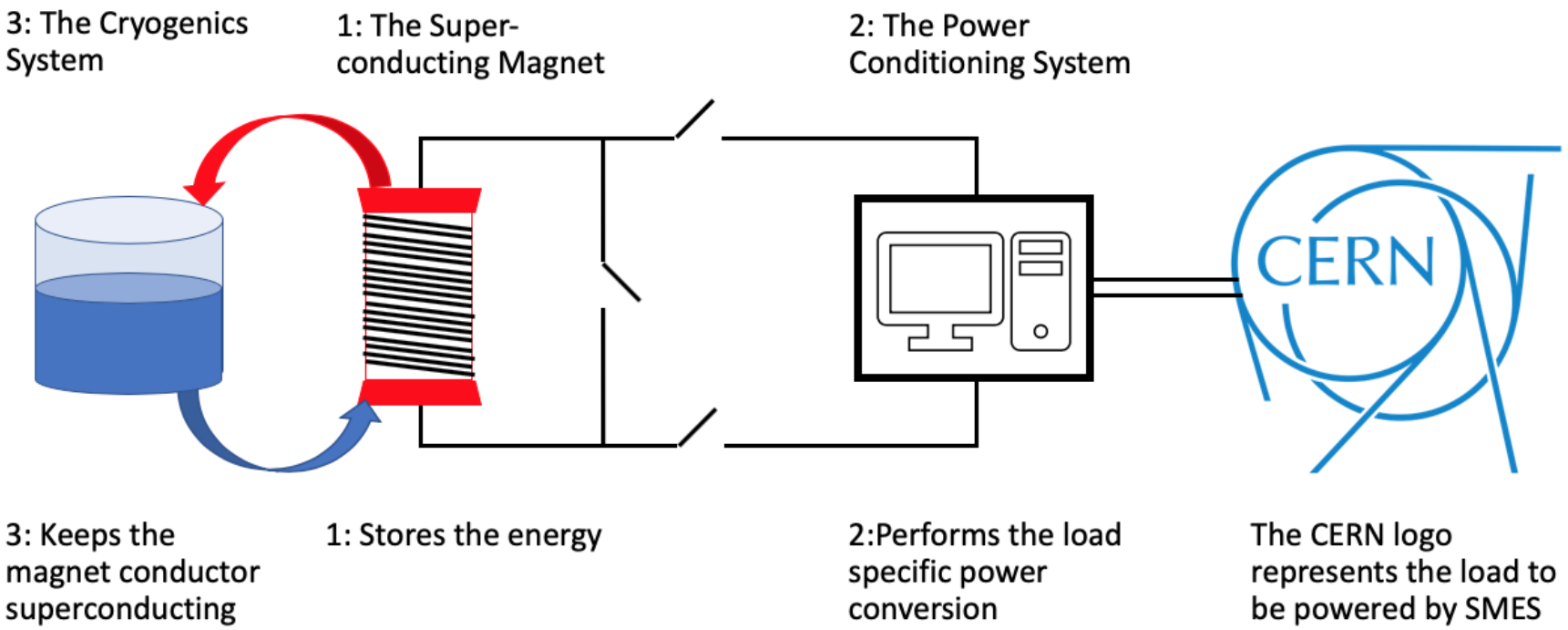
- Technological maturity particularly contributed by American Superconductors and IEEE





Images from: P. Tixador: "Superconducting Magnetic Energy Storage: Status and Perspective" (2008)

SMES operation will be explained in terms of three main components:



The superconducting magnet:

- There are two main topologies: Solenoid and Toroid
- The solenoid is simple, small amount of superconductor but large fringe fields
- The toroid requires a lot of superconductor but has minimal fringe field
- Solenoidal developments:
  i. Actively shielded solenoid
  ii. Quadrupolar solenoid arrangement
- Toroidal development:
  i. The force balanced coil
- The strong Lorentz forces limits the mass specific energy of the system
- The Virial Theorem provides a theoretical upper limit for the mass specific energy
- The integration of the cryogenics system is a major design consideration

Stored Energy:

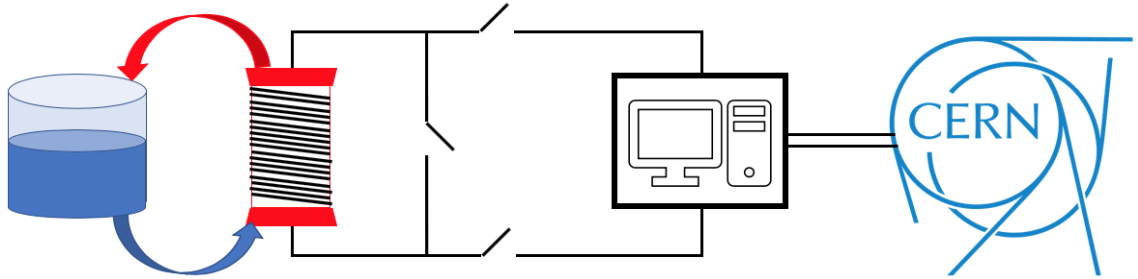
$$E = \frac{1}{2} L I^2$$

Virial Theorem:

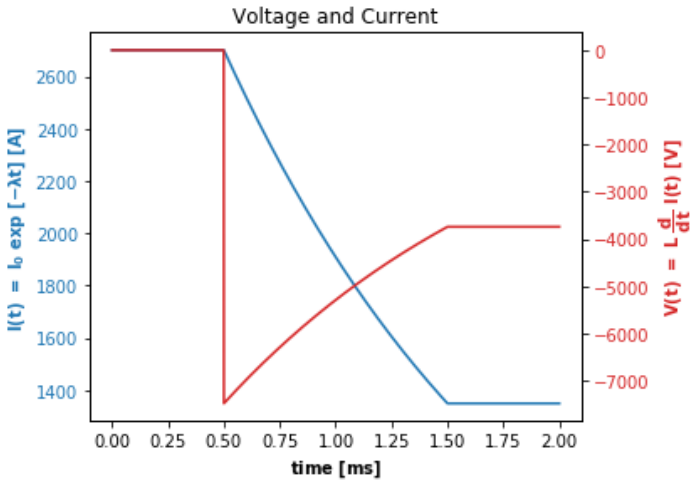
$$\text{sp.E} < \frac{\sigma}{\rho}$$

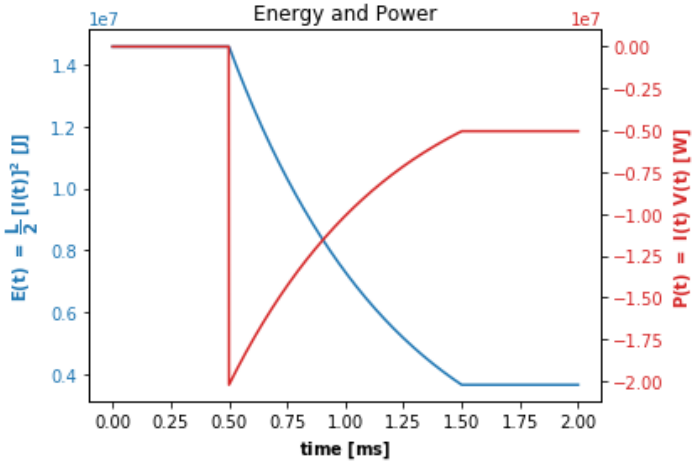
The power conditioning system:

- It delivers the specific power to the load
- It discharges the SMES-system by unshortening the coil and converts the generated power
- Power is calculated as the product of voltage and current
- There will be two different kinds of loads:
  1. AC load: constant power and frequency
  2. DC load: Specific voltage and current profiles: V(t), I(t)



$$I(t) = I_0 \exp[-\lambda t], \quad V(t) = L\,\dot{I}(t)$$





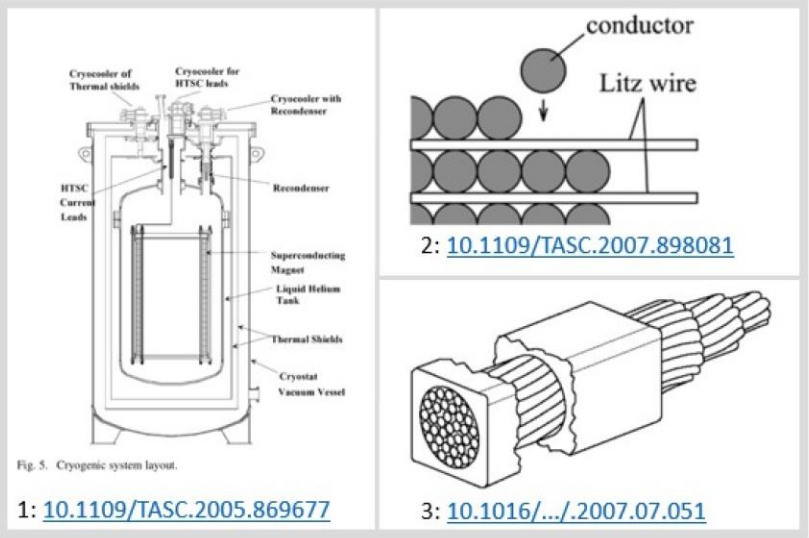
These images show the power and energy transfer of SMES-systems during discharge, without a power conditioning system installed

The cryogenics system:

Three topologies:

1. Bath cooled
2. Conduction cooled
3. Flow cooled

- The high current ratings of flow cooled Cable In Conduit Conductors makes them suitable for these proposed SMES-systems
- A jacket encapsulates the cable and supports the strong Lorentz forces
- The Superconductor is split into fine strands surrounded by thermal and electrical isolation
- Active coolant, Helium or Nitrogen, flows within the jacket
- Heat is generated mainly during charge/discharge
- Runaway quench if superconductor exceeds its critical temperature



1: 10.1109/TASC.2005.869677

2: 10.1109/TASC.2007.898081

3: 10.1016/.../.2007.07.051

Three common topologies for the cryogenics system of superconducting magnets

$$\Delta E = \int_{\dot{B}\neq 0} w_j \, dt$$

$$w_j \left[W m^{-3} \right] \propto \left| \dot{B} \right|^2$$

Deposited energy from Joule heating caused by Eddy-currents induced by a varying magnetic field

CERN has 2 problems (today):

1: Transient glitches

- Voltage dips can result in beam loss and expensive down time at colliders
- Typical duration ~ 100 ms
- Common during thunderstorms
- LHC can today sustain 20 ms voltage dips

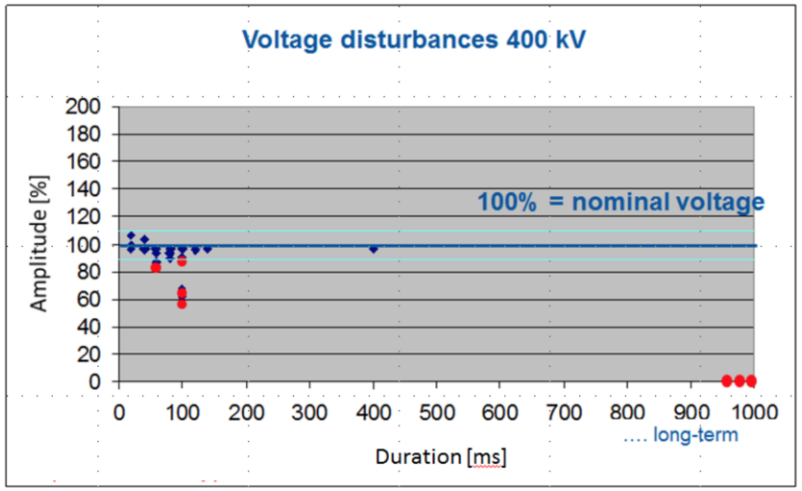
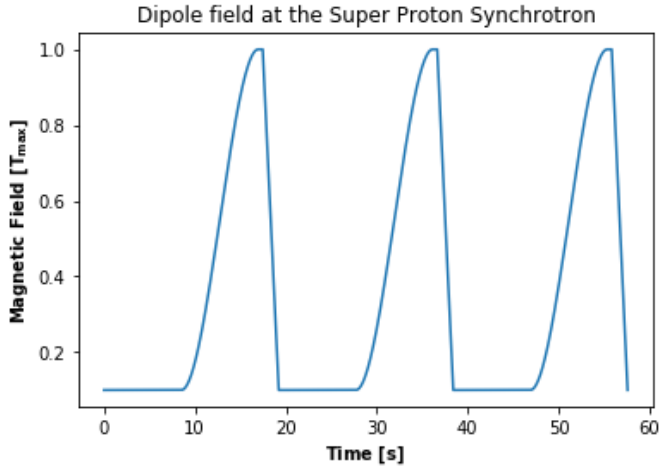


Image from:10.5170/CERN-2015-003.57

2: Periodic power demand:

- The power demand at cyclic accelerators increase with particle momentum
- Pulsing power from mains power grid causes variations on the residual grid
- SPS system is not effective enough



The Future Muon Collider (a problem for tomorrow):

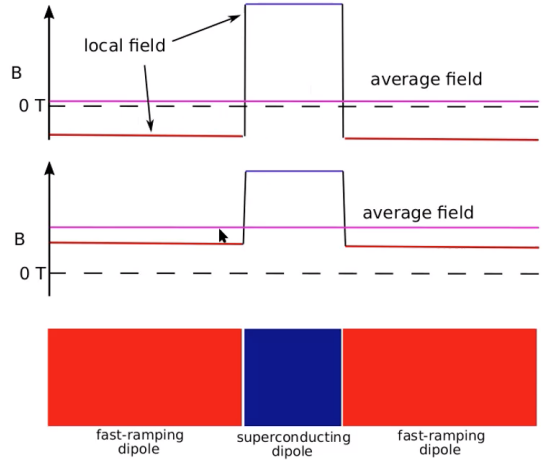
CERN has several proposals for future accelerators

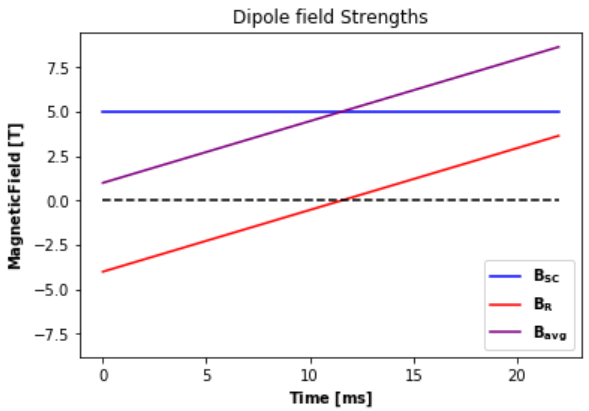
a) The Future Circular Collider

b) The Future Muon Collider

- A proposal for the Future Muon Collider aims at TeV Center of Momentum collision energy and a repetition rate of 5 Hz
- May require dipoles supporting 10^2 T/s
- Possible by combining 'warm' and 'cold' magnets
- High Temperature Superconductor research shows promising results
- May use SMES to support the cyclic operation

Potential dipole configuration:
Image from private correspondance

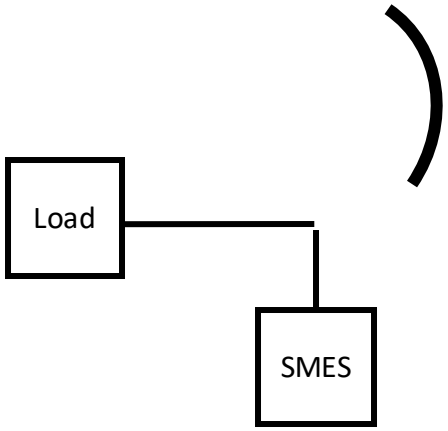




SMES operation for two different situations at CERN:

1: Uninterruptible Power Supply SMES

- When a hazardous voltage drop is detected the SMES-system will discharge to power the load



2: Cyclic machine SMES

- Intermediate energy storage to avoid pulsing power from the mains power grid
- Energy will be transferred in both directions between the SMES magnet and its load

Uninterruptible Power Supply SMES for the Large Hadron Collider:

- The LHC is connected to a CERN internal 18 kV 50 Hz AC network at four locations
- LHC Consumes ~ 100 MW as the beams are colliding
- LHC cryogenic system requires 40/100 MW
- Accelerator shut down if voltage dip > 20 ms
- Prolonged downtime if voltage dip > 300 ms
- Two suggested loads to be powered by SMES:
    1. The entire LHC operating at 100 MW to avoid accelerator shut down
    2. LHC cryogenics operating at 40 MW to avoid prolonged down time

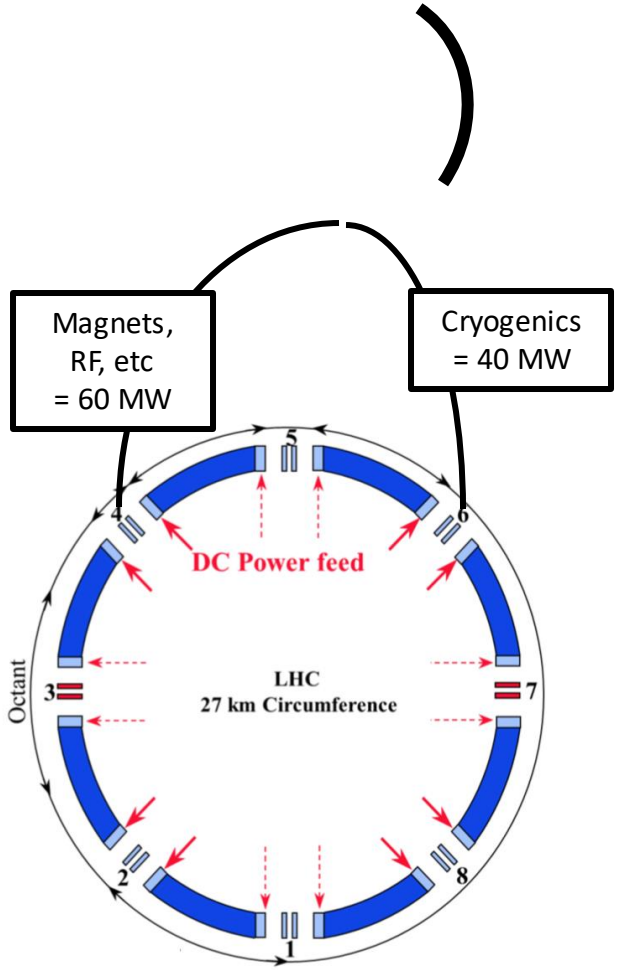


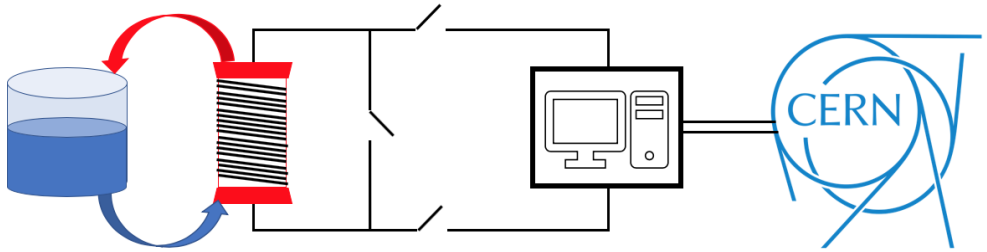
Image from: 10.5170/CERN-2015-003.1

System specifications for Uninterruptible Power Supply SMES:

- Two suggested SMES-systems, LHC_{20} and LHC_{300}, for two different loads
- 1000 ms discharge to statistically cover most voltage dips
- Distributed installation in accordance with LHC 4 pt connection to the 18 kV AC network
- Only three quarters of the stored energy can be delivered because of the exponentially decaying current during discharge

UPS SMES Sub-systems

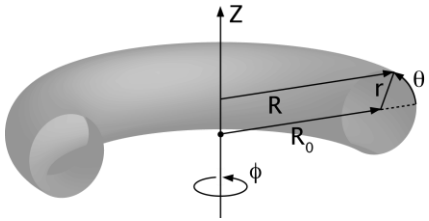
	E_S [MJ]	E_D [MJ]	P [MW]	t_r [ms]	t_D [ms]
LHC^{8}_{20ms}	16.67	12.5	12.5	20	1000
LHC^{4}_{300ms}	13.34	10	10	300	1000



Design considerations for the two UPS SMES magnets

- Conceptually similar systems with identical energy density and power density
- The magnets will have to be toroidal to minimize the fringe fields
- Same poloydal radius, different toroidal radii
- Will use Cable In Conduit Conductor with a high rated current capacity

Magnet:	$\mathbf{LHC^{8}_{20ms}}$	$\mathbf{LHC^{4}_{300ms}}$
Shape	Toroid	Toroid
Stored Energy [MJ]:	16.67	13.34
Inductance [H]:	0.156	0.125
Magnetic Field [T]:	5.24	5.24
Length [m]:	9.51	7.61
Inner radius [m]:	0.55	0.55
Outer radius [m]:	0.9	0.9
no. Layers	10	10
no. Turns/Layer:	272	217
Conductor:	Cable In Conduit	Cable In Conduit
Diameter [m]:	0.035	0.035
Length of Superconductor [m]:	12077	9664
Rated Current [kA]:	14.6	14.6



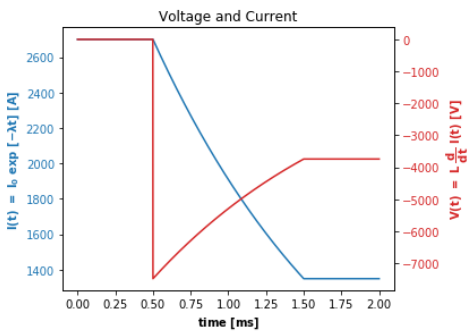
R_0 – Toroidal radius

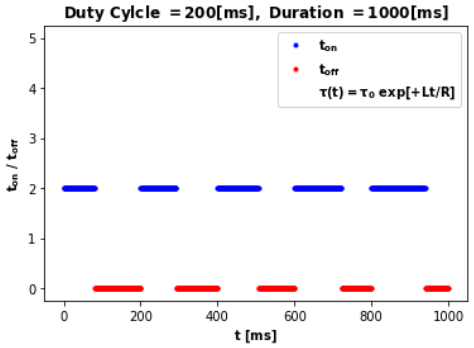
r – Poloydal radius

Image from: FusuinWiki - Toroidal Coordinates

- <u>Design considerations for the two UPS SMES power conditioning systems:</u>

- The SMES-system will intercept an 18 kV, 50 Hz AC network
- The power conditioning system takes current and voltage profiles from the SMES-magnet as input parameters
- A chopper will disrupt the current by discrete segmentation
- The effective current decay becomes linear
- The effective induced voltage becomes constant
- The discretized current and voltage must be *pulse width modified* by filters to resemble trigonometric functions
- The tolerated *Total Harmonic Distortion* is 5%
- The SMES-system will be charged by a separate power converter connected to the same AC network





Input parameters: $I(t) = I_0 \exp[-\lambda t]\,, \qquad V(t) = L\,\dot{I}(t)$

Chopper operation: $T(t) = \dfrac{t_{on}(t)}{t_{on} + t_{off}}$

Averaged delivered power: $P_{avg} = T(t)\ I(t)\ V(t)$

Box diagram of Power Conditioning System for Uninterruptible Power Supply SMES:

- Design considerations for the two UPS SMES cryogenics systems:

- 2.62 T/s during discharge may induce Eddy-currents and Joule heating within the Cable In Conduit Conductor
- The effect of Joule heating varies for the different composites of the conductor
- It is tolerated within the jacket, but must be avoided within the thermal isolation
- Flow of active coolant to avoid accumulation of heat
- Finite Element Methods to properly calculate the heat transfer properties of the system

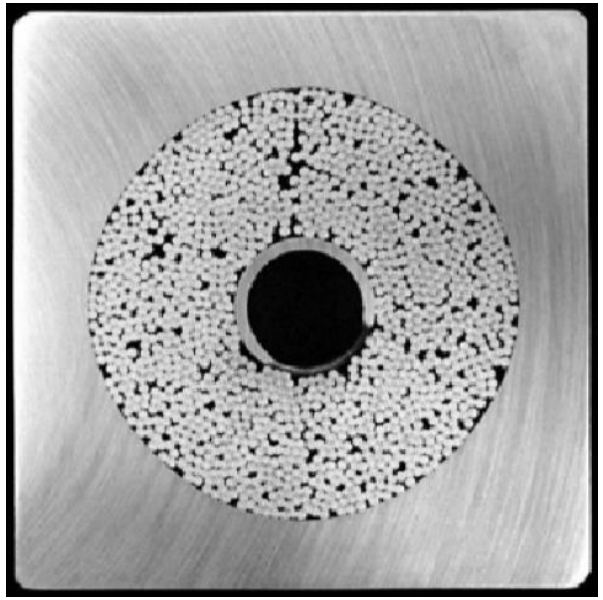
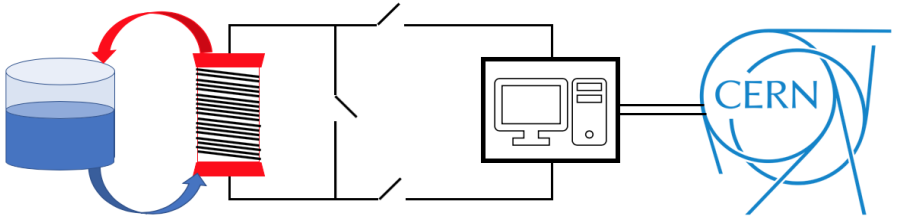


Image of CICC cross-section from: IEEE: C. Marinucci et al - Pressure Drop In CICC

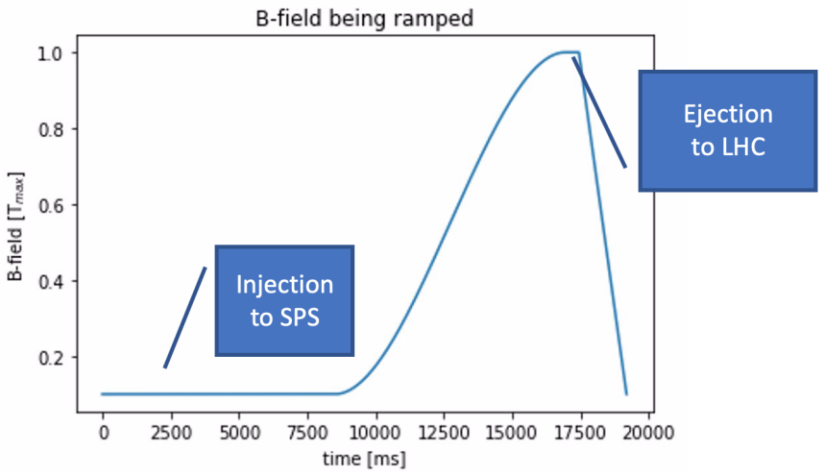
Summary of Uninterruptible Power Supply SMES to bridge voltage dips at the Large Hadron Collider:

- Voltage dips can cause beam loss at the LHC
- 100 MW for 1 second = 100 MJ can bridge these voltage dips
- Or 40 MW for 1 second = 40 MJ can cut the subsequent down time
- Distributed installations
- Power must be transformed to 18 kV AC
- dB/dt cause Joule heating during discharge which needs to be removed by flow of active coolant within the Cable In Conduit Conductor



Cyclic machine SMES to power the dipoles at the Super Proton Synchrotron:

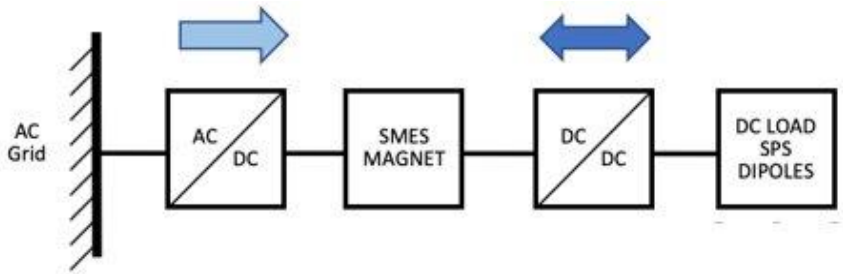
- Accelerators operating in cycles constitute *Fluctuating Loads*
- Pulsing high power directly from the mains power grid is prohibited
- The Super Proton Synchrotron use a static var-compensator
- The Proton Synchrotron use capacitor banks for intermediate energy storage
- SPS operate at ≈ 0.05 Hz, and the periodic power consumption is largely contributed by its dipole magnets



Magnetic field strength supplied by the SPS dipoles as a function of time

System specification for cyclic machine SMES:

- By transferring power between a SMES magnet and the SPS dipoles, one can mitigate the periodic power demand
- Normal conductive dipoles: $V_{Dipole} = V_{Inductive} + V_{Resistive}$
- Power transfer is given by the product of voltage and current
- The energy transfer between the SMES magnet and the dipoles is not 1:1 because of the resistive losses
- The current through the SPS dipoles must be precise within 1 ppm



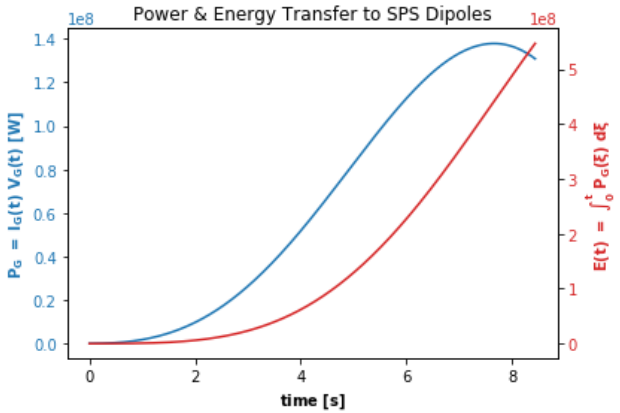
The arrows represent the power flow between the power network, the SMES magnet and the SPS dipoles

Dipoles at the Super Proton Synchrotron

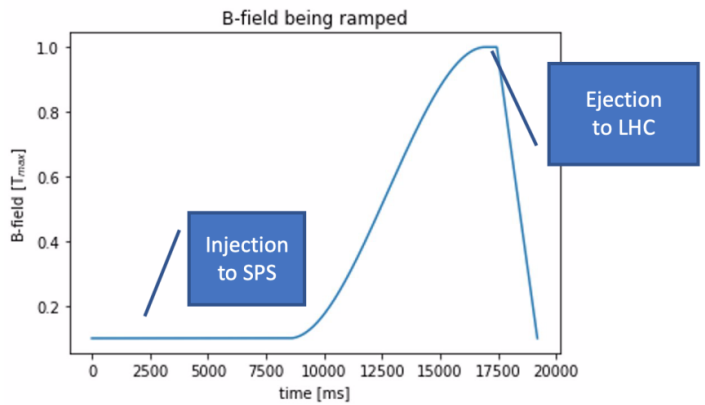
R [Ω]	L [H]	I_{max} [A]	I_{min} [A]	$\dot{I}_{max}$ [A/s]
3.25	6.6	5754	38	1900

Design suggestions for cyclic machine SMES:

- The power delivered by SMES during discharge must be very precise in terms of voltage and current profiles **[This has been modelled]**
- The SPS dipoles will deliver energy to the SMES magnet during field ramp down
- The SMES magnet will continue to charge during the subsequent proton injection to cover the resistive losses



1. The SMES system will deliver ≈ 600 MJ during ramp up and flat top
2. The SPS dipoles will return ≈ 110 MJ during ramp down
3. The SMES system will draw ≈ 490 MJ from mains during proton injection



- The power demand of the dipoles will be shifted from the acceleration phase to the injection phase

Design suggestions for cyclic machine SMES:

- High energy storage capacity and specific power delivery
- A modular system to facilitate maintenance
- 40 magnets storing 20 MJ each, distributed across 8 DC to DC converters
- The Cable In Conduit Conductor will be used, where the flow of active coolant must remove heat continuously
- The power conditioning system will employ a chopper, a DC to DC converter and a filter

System Charracteristics for $\mathbf{SPS_{SMES}}$	
Stored Energy	0.8 GJ
Delivered Energy	0.6 GJ
Delivered Power (Peak)	138 MW
Charge Rate	
During dipole ramp down	63 MW
Charge Rate	
During proton Injection	70 MW
Period	19.2 s
no. Magnets	40
Inductance per Magnet	0.1 H
Circulating Current (I_0) per Magnet	20 000 A
Magnetic field	7.18 T.

High Temperature Superconductor research and development:

- Maintaining superconductivity at high temperature enables:

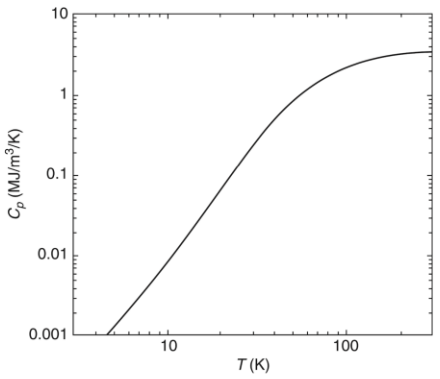
1. Larger operating temperature margin
2. Less power from cryogenics system

- This allows for higher energy density and power density
- HTS research for the Future Muon Collider which may require dipoles sustaining 10^2 T/s.
- Obtained results by IEEE and Fermi lab using 'YBCO' Cable In Conduit Conductor:

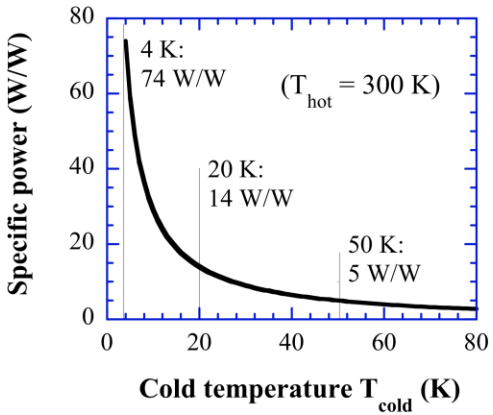
1. Radially segmented coil sustains stresses of 1000 MPa from Lorentz forces
2. Approximately linear relation between generated Joule heating and magnetic field ramp rate: 0.4 W per T/s

$$\Delta T = \frac{d}{c_p}\,\Delta E$$

$$\mathrm{MQE} \approx c_p(T_o)[T_{cs} - T_o][1 - \frac{I_{sc}}{I_c}]$$



Mass specific heat capacity of copper. Image from: 10.1533/9780857097378.3.442



Carnot efficiency for cryogenics system. Image from: snf.ieeecsc.org/-/CR5_Final3_012008.pdf

Conclusions

- SMES installations are expensive and require a lot of research and development
- CERN chose capacitors rather than SMES for intermediate energy storage at the Proton Synchrotron partly due the novelty of the technology
- Var-compensators are established industrial products and therefore much cheaper to install
- All proposed SMES-systems will be large

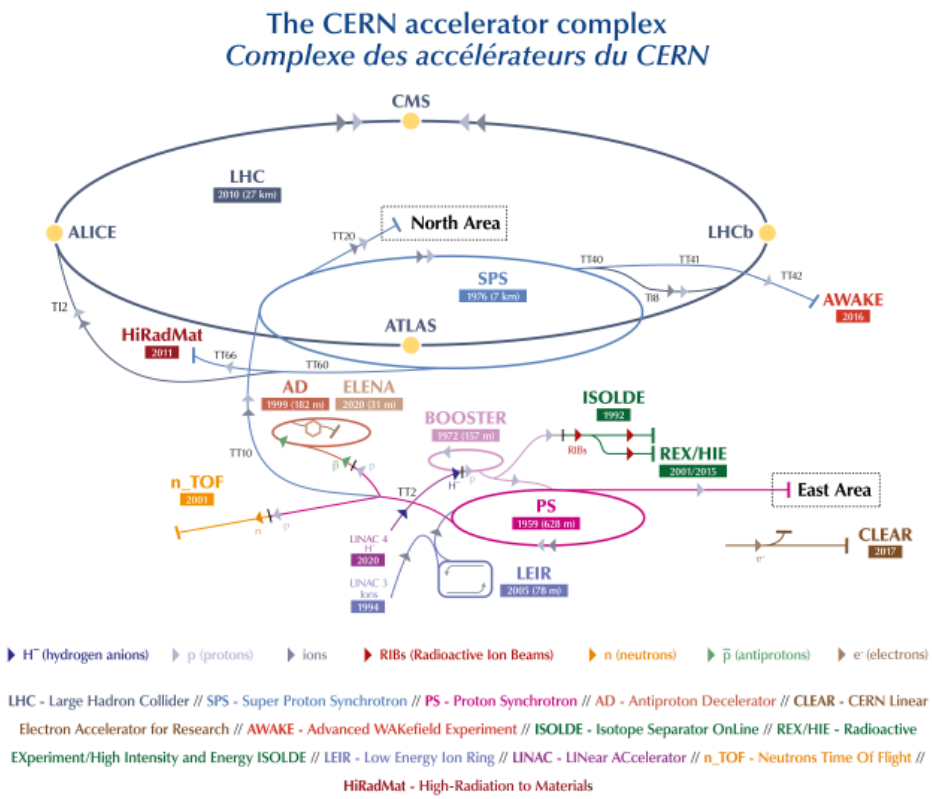


Image from: [Complexe des accélérateurs du CERN - 2019]

Energy Density:

- Storing this amount of energy will require large systems
- The energy density of SMES is superior to capacitor banks
- SMES volume is usually estimated as 2 * Magnet volume
- Higher energy and power densities with HTS SMES-systems

System:	LHC_{20}	LHC_{300}	SPS_{SMES}	POPS
Stored Energy:	133.34 MJ	53.34 MJ	800 MJ	15 MJ
Delivered Energy:	100 MJ	40 MJ	600 MJ	12.6 MJ
Delivered Power:	100 MW	40 MW	138 MW (peak)	60 MW
Total Magnetic Volume:	201.4 m^3	81.6 m^3	644.7 m^3	100 m^3*
no. Magnets:	8	4	40	6 Banks*
Energy Density:	0.49 MJ/m^3	0.49 MJ/m^3	0.93 MJ/m^3	0.126 MJ/m^3
Power Density:	0.49 MW/m^3	0.49 MW/m^3	0.22 MW/m^3	0.6 MW/m^3

POPS = POwer for the Proton Synchrotron. Use 6 large capacitor banks for intermediate energy storage during cyclic operation

Energy Density:

- Energy density proportional to square of magnetic field
- Power density proportional to magnetic field × magnetic field rate of change
- SPS_{SMES} Magnets: 0.376 T/s (average)
- LHC_{20} & LHC_{300} Magnets: 2.62 T/s during discharge
- SPS_{SMES} has higher energy density but lower power density as its cryogenics system must remove heat continuously

System:	LHC_{20}	LHC_{300}	SPS_{SMES}	POPS
Stored Energy:	133.34 MJ	53.34 MJ	800 MJ	15 MJ
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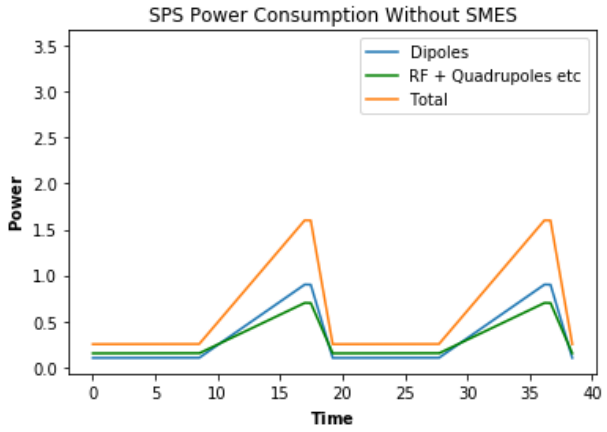
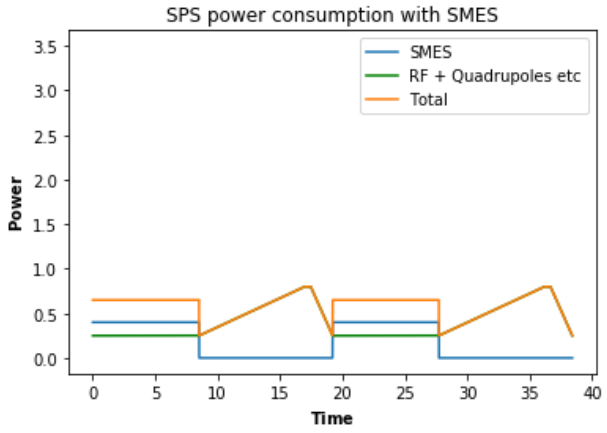
Delivered Power:	100 MW	40 MW	138 MW (peak)	60 MW
Total Magnetic Volume:	201.4 m^3	81.6 m^3	644.7 m^3	100 m^3*
no. Magnets:	8	4	40	6 Banks*
Energy Density:	0.49 MJ/m^3	0.49 MJ/m^3	0.93 MJ/m^3	0.12 MJ/m^3
Power Density:	0.49 MW/m^3	0.49 MW/m^3	0.22 MW/m^3	0.6 MW/m^3

POPS = POwer for the Proton Synchrotron. Use 6 large capacitor banks for intermediate energy storage during cyclic operation

SPS resistive losses:

- SPS dipoles power demand largely contributed by their resistive voltage
- 600 MJ consumed during ramp up and flat top
- 110 MJ stored within dipoles during peak magnetic field
- Gives an energy ratio of 6:1.1
- The capacitor bank at the Proton Synchrotron has an energy ratio ≈ 3:1
- With superconducting dipoles at the SPS the energy ratio would approach 1:1
- Removes 1/6 of the dipoles power demand
- Shifts the power demand of the dipoles to the injection phase





The plotted power consumtions are not accurately scaled!

Thank you for listening!

Main References:		
Area:	Contributed by:	Selection:
SMES concept, operation and design:	IEEE, special thanks to Pascal Tixador	10.1533/9780857097378.3.442
		snf.ieeecsc.org/-/CR5_Final3_012008.pdf
SMES-system experience:	IEEE	10.1109/TASC.2003.812894
		10.1109/TASC.2007.898081
		10.1109/TASC.2005.869677
Power Conversion:	Wikipedia:	wikipedia - uninterruptible power supply
		wikipedia - chopper (electronics)
	Frédérick Bordry:	10.1109/EPE.2007.4417398
CERN accelerators:	CERN Yellow Reports	10.23731/CYRM-2020-0010
	CERN Accelerator Summer School	10.5170/CERN-2015-003.57

Questions?

Smart coil configurations for SMES magnets:

The force balanced coil has a combination of toroidal and poloidal conductor turns

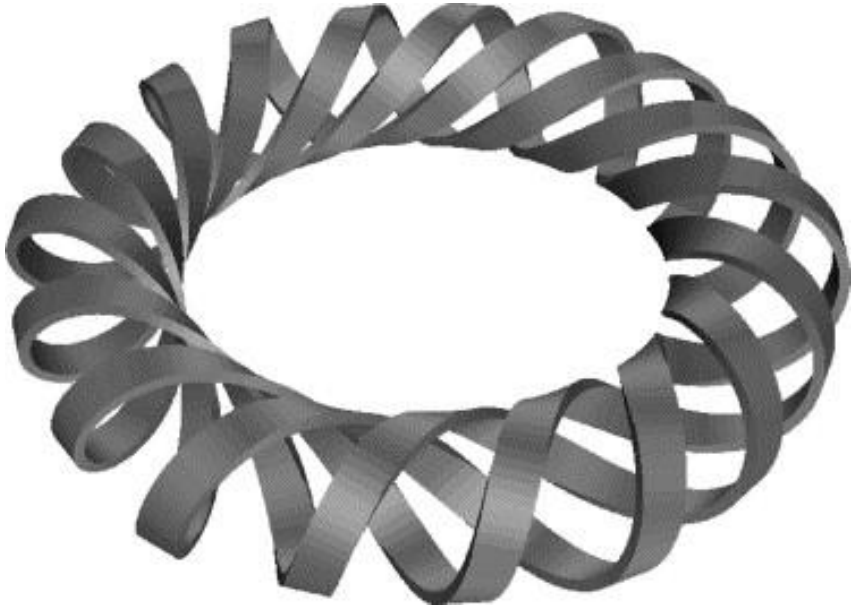


Image from: https://doi.org/10.1016/j.energy.2004.08.017

This decreases the net Lorentz Forces, and thereby the mechanical stresses

Virial theorem: sp.E < stress/density

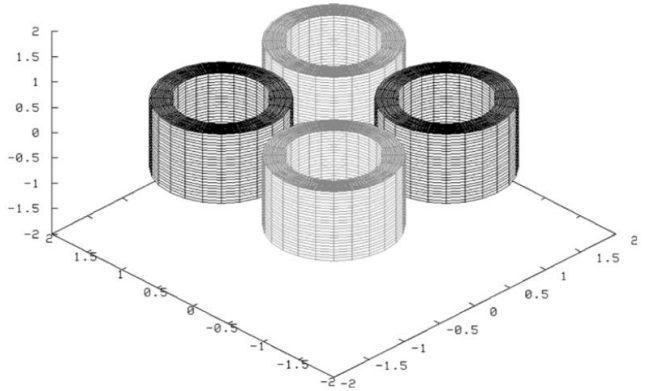


Fig. 4. Quadrupole coil arrangement for a SMES, the two darker coils have the field vector pointing up, the other two pointing down. All coils are connected in series. Scales are in meter.

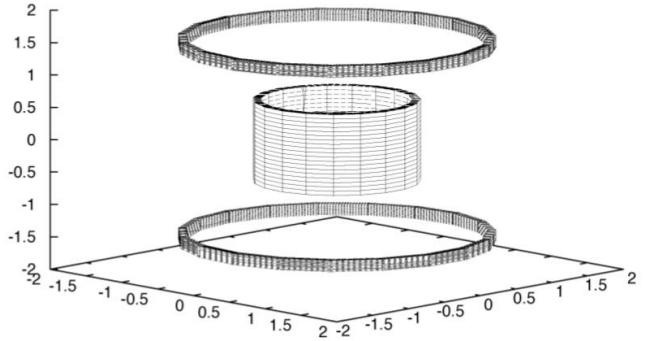


Fig. 5. Actively compensated SMES configuration. The two ring coils have the opposite field direction as the main solenoid. Scales are in meter.

Top: Quadrupolar arrangement where the fringefields of solenoids of different polarity counteract eachother
Bottom: Actively shielded solenoid with smaller solenoids of opposite polarity counteracting the fringefield of the larger coil
Image from: 10.1109/TASC.2006.871330

Electrodynamics of Eddy-currents:

$$J = \sigma E \ , \quad \nabla \times E = -\dot{B}$$

$$\iint (\nabla \times J) \cdot ds = \iint \sigma(-\dot{B}) \cdot ds$$

$$\oint J \cdot dl = \iint \sigma(-\dot{B}) \cdot ds$$

$$\iint ds = \text{area SC penetrated by } \dot{B}$$

$$\oint dl = \text{circumference of } \iint ds$$

$$J = -\sigma \dot{B} \cdot \left(\frac{A'}{l'} \right)$$

$$w = J^2/\sigma \ [Wm^{-3}]$$

Because of the chopper, the effective rate of change of the magnetic field will be constant during discharge

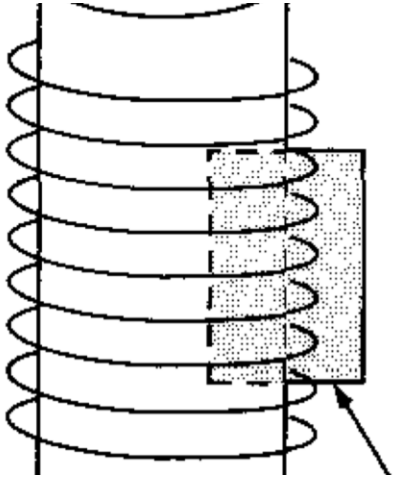


Image from: David J. Griffiths - Introduction To Electrodynamics

$$I(t) = I_0 \ \exp[-\lambda t]$$

$$B(t) = \mu_0 N_l I(t)$$

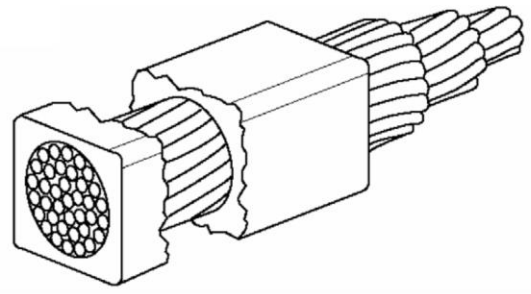


Image from: L. Bottura et al: A poroud medium analogy for the Helium flow in CICCs

Superconducting cables have highly inhomogeneous material composition. Therefore, F.E.M is used to estimate the heat transfer properties of SMES-systems

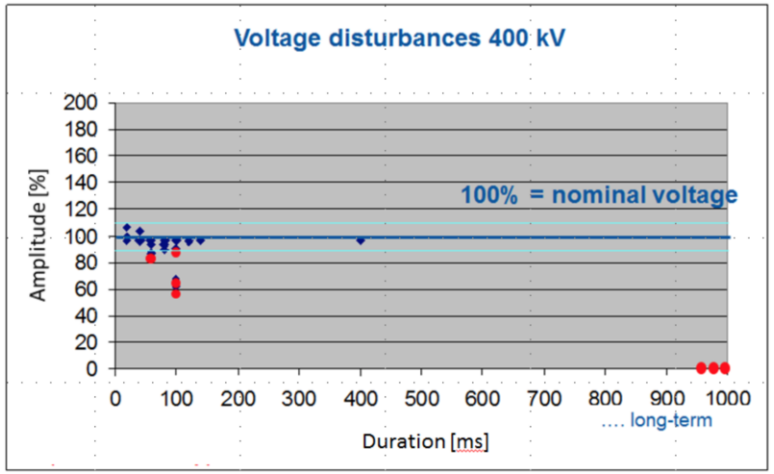
AC Losses in SC cables

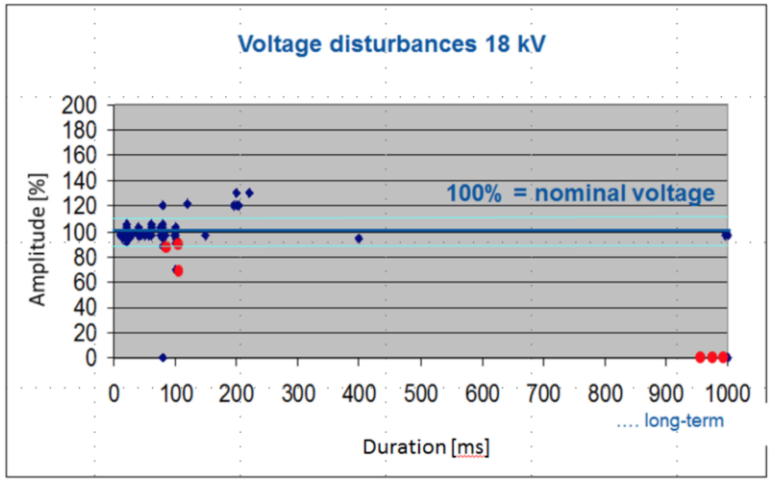
- SMES suggestion for the proton synchrotron would've sustained 1.17 T/s during discharge and generate 1150 J per cycle – 445 W AC Losses (62.3 mJ/m Rutherford cable) 10.1109/TASC.2006.871330

- 600 kJ, 1 second = 600 kW SMES discharge generate 7.53 kJ AC Losses, current from 400 A to 0 A (Generic HTS SMES) https://doi.org/10.1016/j.cryogenics.2007.04.011

Voltage variations within the CERN power network:

- There are various reasons for voltage dips within the different power networks at CERN
- 400 kV on the mains (regional) power grid
- The first intermediate internal power network at CERN operates at 18 kV
- Most voltage variations resulting in 'Major Events' = Accelerator stop (red dots) originate from disturbances on the 400 kV, common during thunderstorms
- Voltage variations often propagate downwards but rarely upwards
- 1 s ride through capability should statistically cover most voltage dips
- Data from June – November 2013

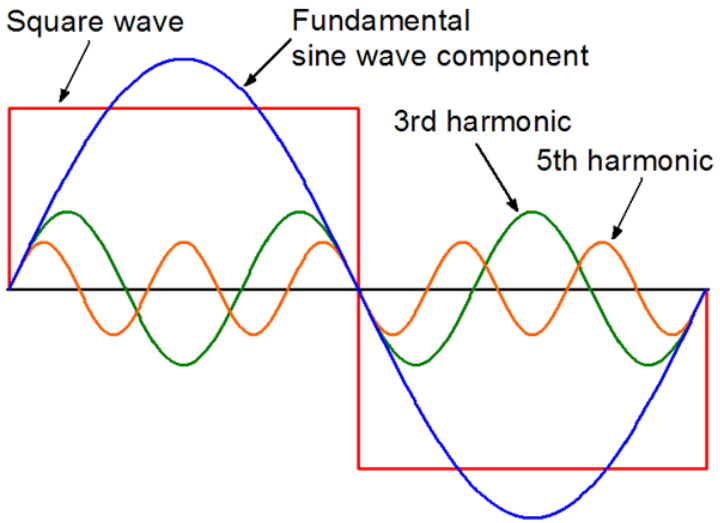




Images from:10.5170/CERN-2015-003.57

Pulse Width Modification (how to achieve the blue sine-wave)

- By use of filters (a combination of inductors and capacitors) one can alter the shapes of voltage and current profiles
- By harmonic analysis one calculates the Total Harmonic Distortion of the system, which is a measure of how far from the blue sine wave your voltage and current profiles are
- The size of the required inductors and capacitors decreases with increasing frequency
- LHC engineering specifications require THD < 5% in accordance with international power regulation



$$\mathrm{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2}}{V_1}$$

From: [wikipedia - power inverter]

Box diagram of Power Conditioning System for Uninterruptible Power Supply SMES:

Chopper:

- Input current & input voltage at the SMES magnet
- Linear current decay, constant voltage, constant power at input side
- Output current & Output voltage constant on the other side of chopper
- Inverter and PWM filter

This example is from an IEEE report on the operation of a UPS SMES installation: 10.1109/TASC.2007.898081

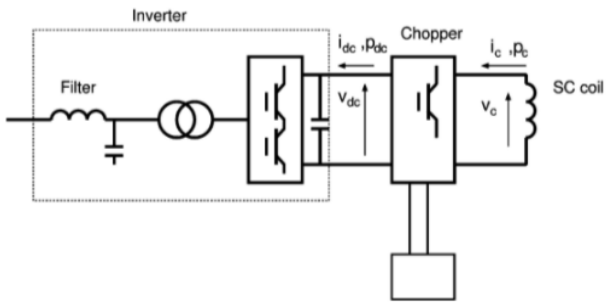


Fig. 1. Test circuit diagram for the prototype 100 kJ UPS-SMES system.

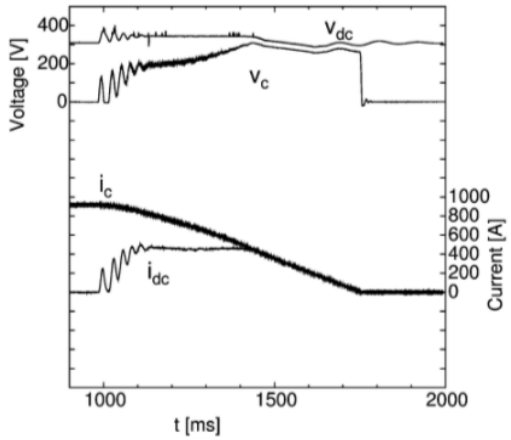


Fig. 2. Coil voltage, current and power for 150 kW discharge operation.

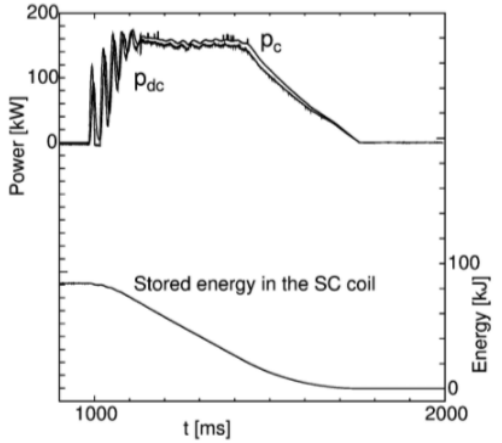


Fig. 3. DC power flows in the dc link of the converters and stored energy in the coil.

POwer for the Proton Synchrotron (POPS)

- Capacitive cyclic energy storage to power the Proton Synchrotron
- Delivers 60 MW to the PS (peak)
- Draws maximum of 10 MW from mains to cover resistive losses
- Symmetric period: 0.6 s discharge, 0.6 s charge
- 6 capacitor banks of total 100 m^3
- +2 AC to DC converters as chargers
- System can operate with:

  5/6 capacitor banks

  5/6 DC to DC converters

  1/2 chargers

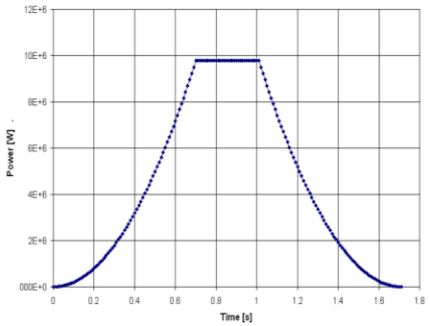


Fig. 8: Power of the two chargers

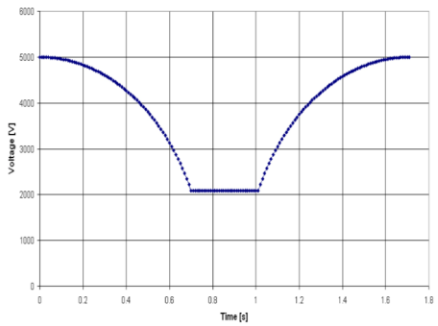


Fig. 10: Capacitor banks voltage

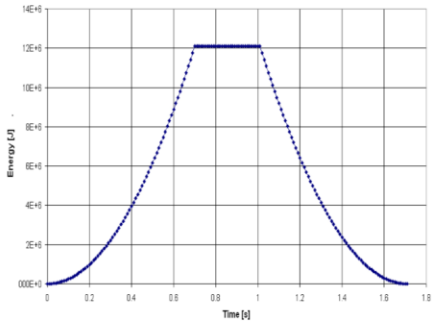


Fig. 9: Energy stored in the magnets

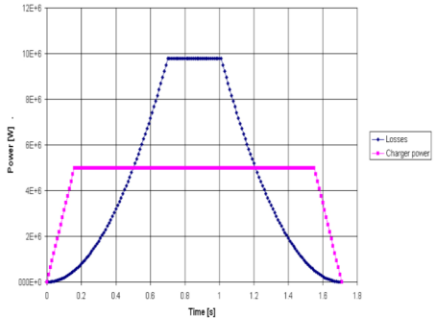
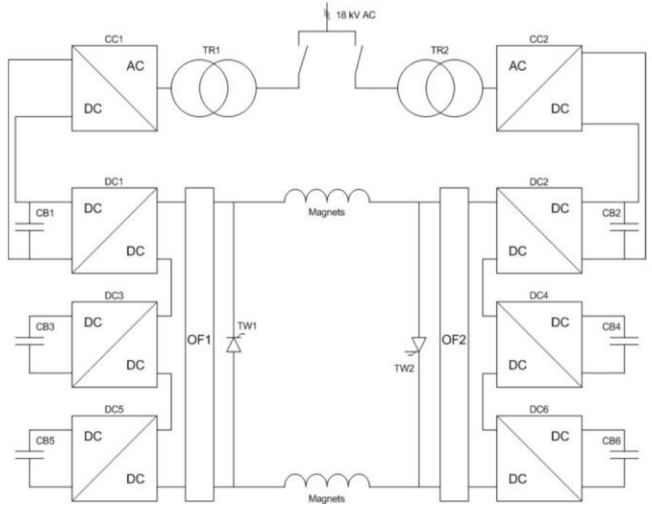


Fig. 11: Charger power with only one working



Images from: [10.1109/EPE.2007.4417398](10.1109/EPE.2007.4417398)

Further specifications of the SPS SMES-system:

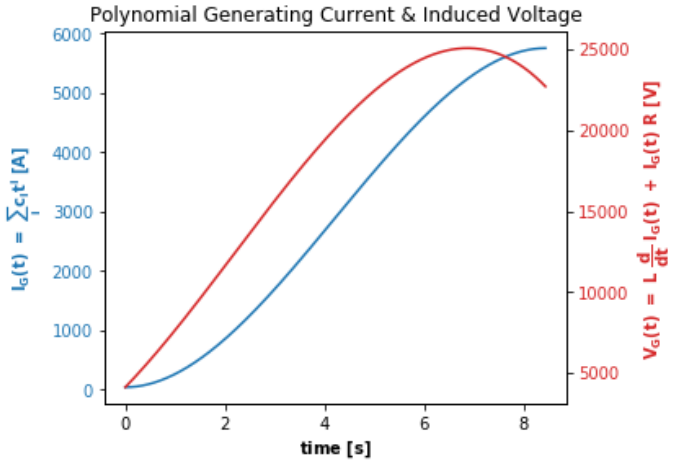
- High energy density allowed because of the low power density
- Energy density proportional to B^2
- Power density scales with magnetic field strength and magnetic field rate of change
- Magnetic field rate of change disrupted by chopper
- Higher current but lower inductance compared to UPS SMES
- Same Cable In Conduit Conductor is used
- 40 toroidal magnets

$\mathbf{SPS_{SMES}}$ Magnet	
Shape	Toroid
Stored Energy [MJ]:	20
Inductance [H]:	0.1
Magnetic Field [T]:	7.18
Length [m]:	6.09
Inner Radius [m]:	0.55
Outer Radius [m]:	0.9
no. Layers:	10
no. Turns/Layer:	174
Conductor:	CICC
Diameter [m]:	0.035
Length of Superconductor [m]:	7731
Rated Current [kA]:	20

Box diagram of Power Conditioning System for Cyclic Machine SMES:

My model for the SPS power demand:

- I modelled the generating current through the SPS dipoles by a polynomial subjected to given restrictions (table)
- I then expressed the voltage as an inductive part + an Ohmic part
- The power demand was estimated as the product of voltage and current
- Shows good agreement with J.D. Pahud: CAS - CERN



Model:

$$I_G(t) = \sum_{i=0}^{3} c_i t^i$$

$$c_{0,1,2,3} = [38, 0, 241, -20]$$

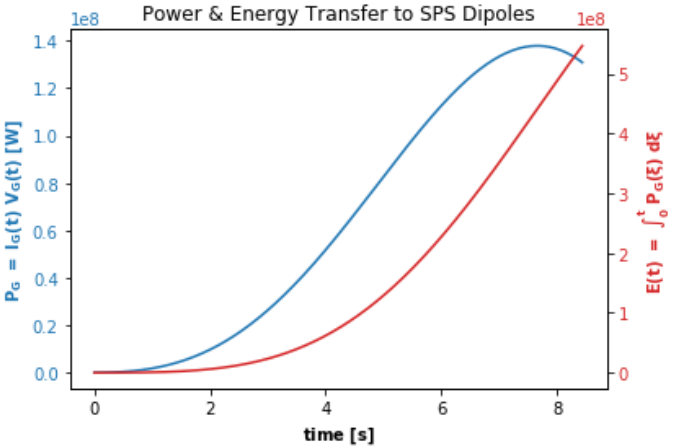
Restrictions:

$$I_G(t=0) = 38 \qquad I_G(t=8.439) = 5754$$

$$\dot{I}_G(t=0) = 0 \qquad \dot{I}_G(t=8.439) = 0$$

Dipoles at the Super Proton Synchrotron

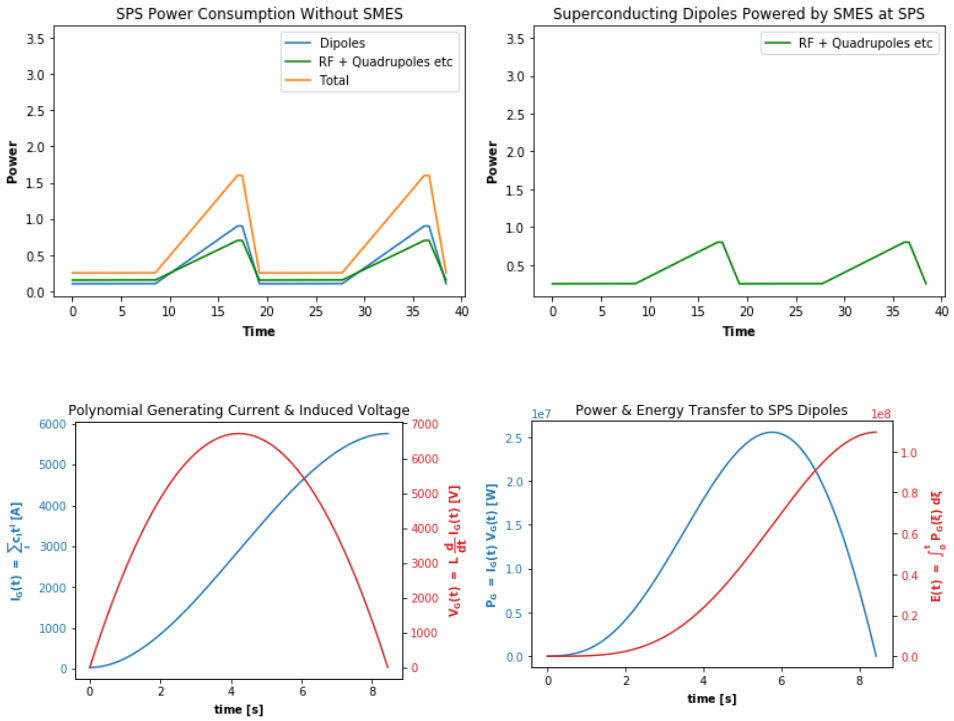
R [Ω]	L [H]	I_{max} [A]	I_{min} [A]	$\dot{I}_{max}$ [A/s]
3.25	6.6	5754	38	1900



Source: J.D. Pahud: CAS - CERN

For Superconducting dipoles at the Super Proton Synchrotron:

- If the Future Circular Collider becomes reality there is a suggestion to raise the ejection energy of SPS from 0.45 TeV to 1.3 TeV, which may require installation of superconducting dipoles
- $V_{Dipole} = V_{Inductive} + V_{Resistive}$
- SMES to Dipole energy transfer approach the energy stored within dipoles at peak magnetic field (110 MJ today)
- Delivered during the 8439 ms proton acceleration gives average power of 13 MW
- Very low losses
- Some inherent energy losses associated with inductance powering another inductance



Var-Compensator solution for SPS

- CERN investigated var-compensator solution for the Proton Synchrotron
- A var-compensator draws power from the mains whilst the load does not
- It then returns power to the mains whilst the load draws power from the mains
- Often used for loads with high resistive losses
- Places high requirements on power converter to avoid harmonic distortion that could pollute the CERN power network
- The benefit is that var-compensators are established industrial products
- The idea to use SMES as a var-compensator for the LHC or the SPS was raised

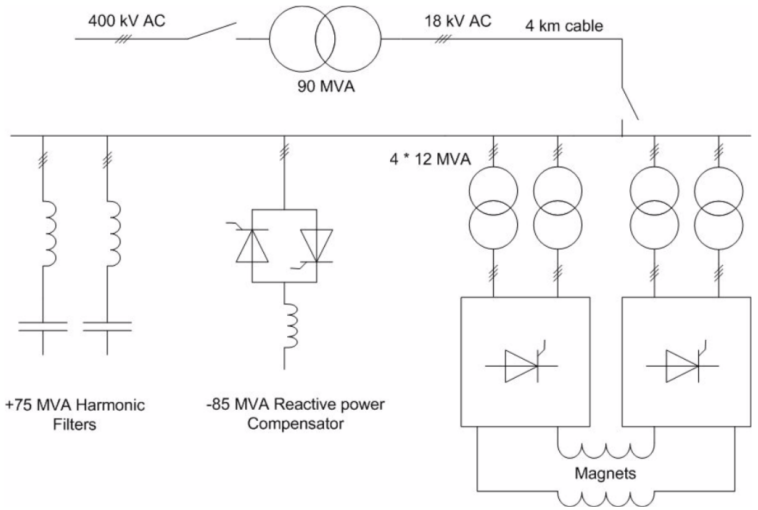
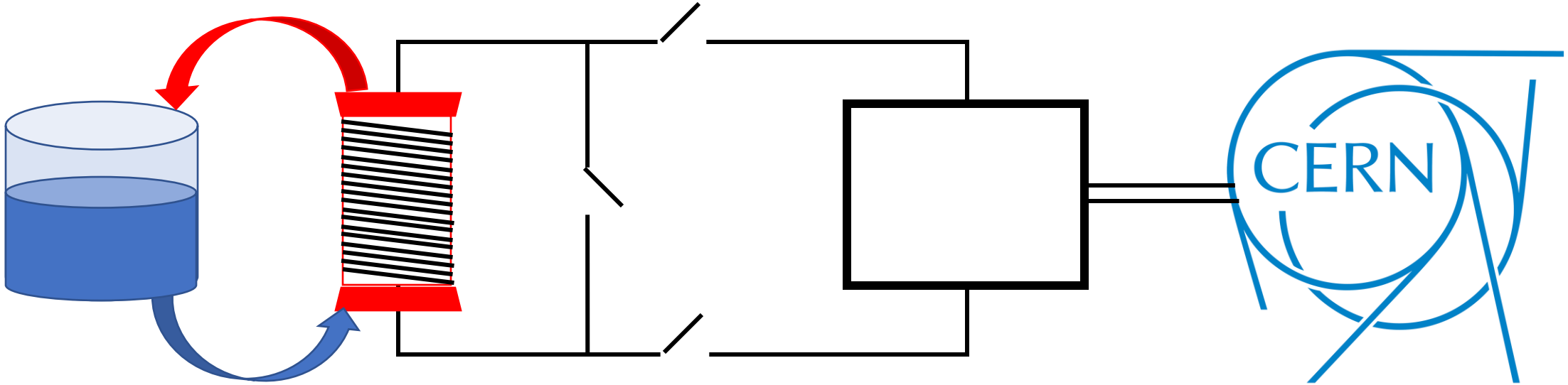


Image from: 10.1109/EPE.2007.4417398

3: The Cryogenics System

1: The Super-conducting Magnet

2: The Power Conditioning System



3: Keeps the magnet conductor superconducting

1: Stores the energy

2:Performs the load specific power conversion

The CERN logo represents the load to be powered by SMES

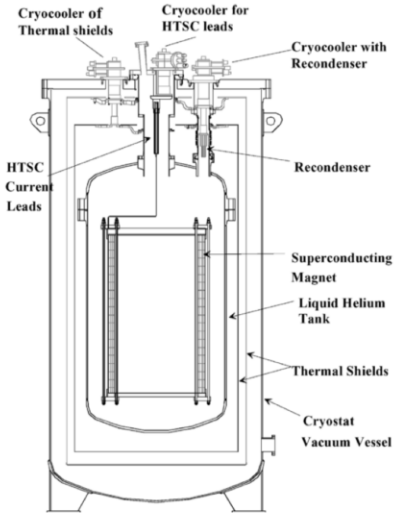
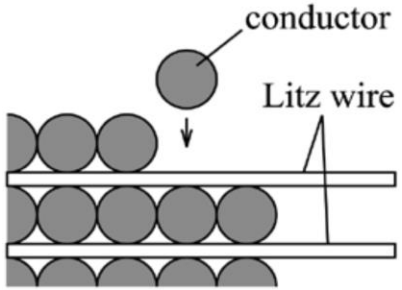
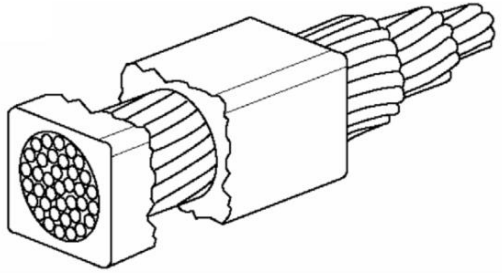


Fig. 5. Cryogenic system layout.

1: 10.1109/TASC.2005.869677



2: 10.1109/TASC.2007.898081



3: 10.1016/…/.2007.07.051