Workshop
Energy for Sustainable Science

Energy Management for Large-Scale Research Infrastructures

SMES
(Superconducting Magnetic Energy Storage)
present status & future

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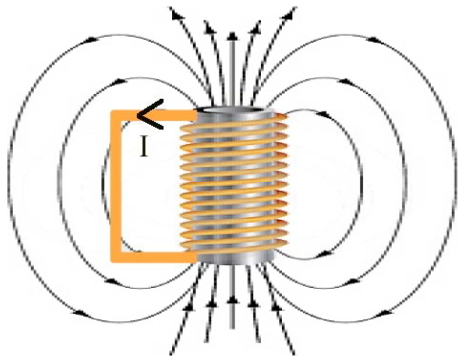
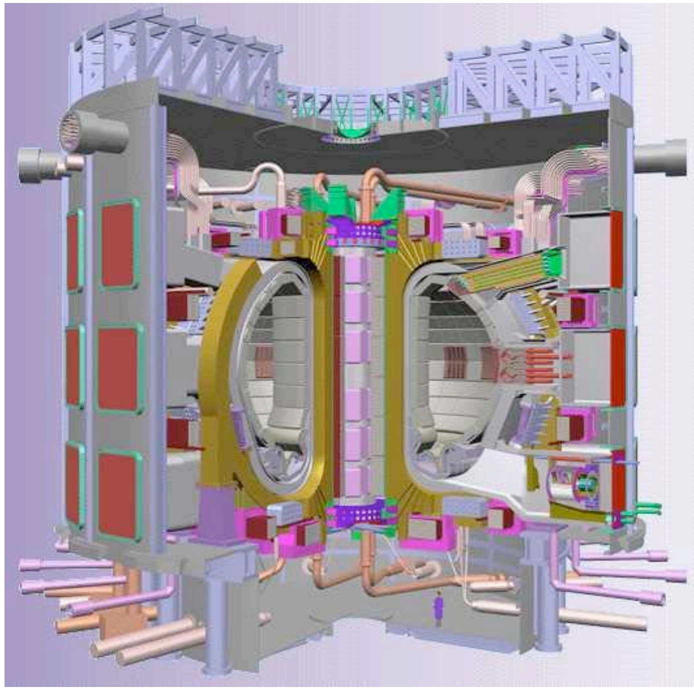


Comparisons, orders of magnitude

1 kg coal	8 kWh
1 kg wood	4 kWh
1 kg oil	10 - 12 kWh
1 kg natural gas	10 - 14 kWh
1 kg enriched uranium	600 000 kWh
1 kg of water - 1000 m fall	0.003 kWh
1 kg Pb battery	0.03 kWh
1 kg lithium battery	0.25 kWh

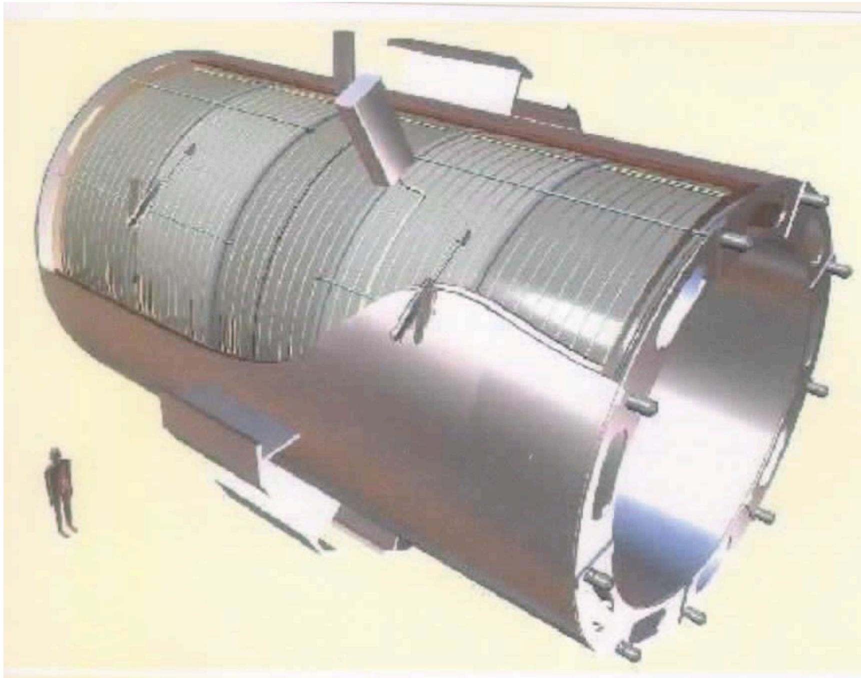
(1 kWh : kinetic energy of a 10 ton truck at 100 km/h)

SC magnets: examples



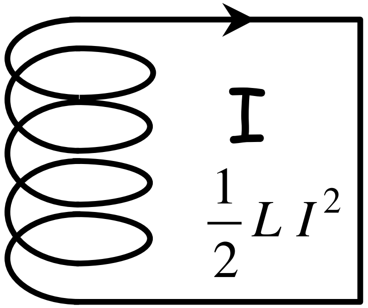
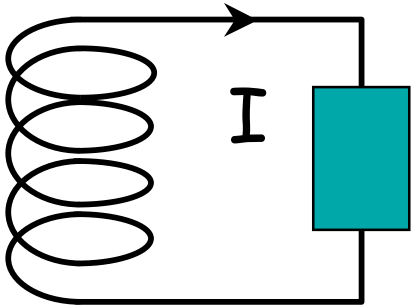
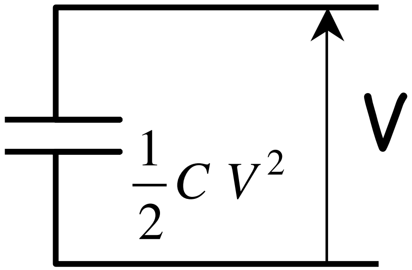
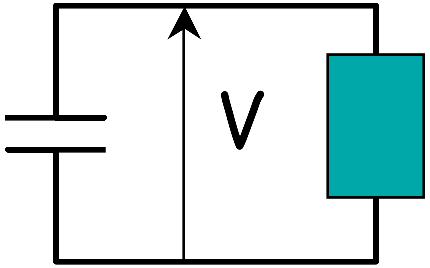
ITER toroid
41 GJ; 5600 tons

(1.14 ton oil, 19 g U)

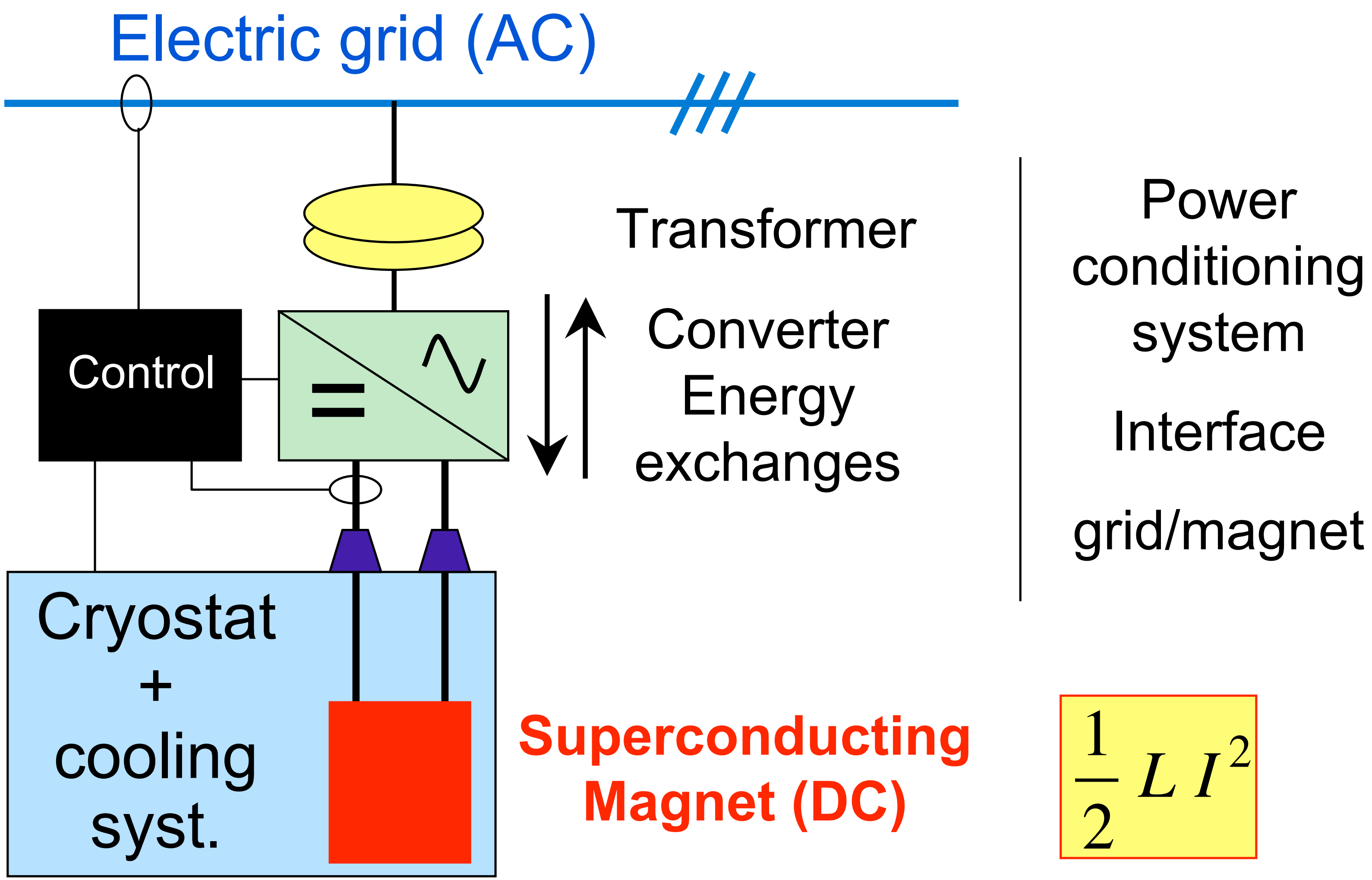


CMS solenoid
2.6 GJ; 225 tons
11 kJ/kg - 0.003 kWh/kg

SMES: dual of capacitor

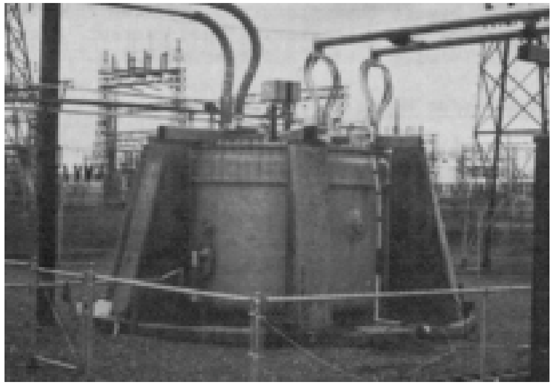
	Storage	Discharge	τ	Source
SMES	 I, $\frac{1}{2} L I^2$	 I	$\frac{L}{R}$	Current
Capaci-tor	 V, $\frac{1}{2} C V^2$	 V	RC	Voltage

SMES for UPS or FACTS



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

First SC device in a grid



P_{max}	10 MW
f	0.35 Hz
W_{max}	30 MJ
W_{exch}	9.1 MJ
I_o - V_o	5 kA - 2.2 kV
$Ø_{magnet}$	2.7 m

BPA SMES on the grid installed in 1979

(transmission stabilization, low frequency power oscillation damping)

One year operation. Cryogenic problems and other solution to damp the oscillations.

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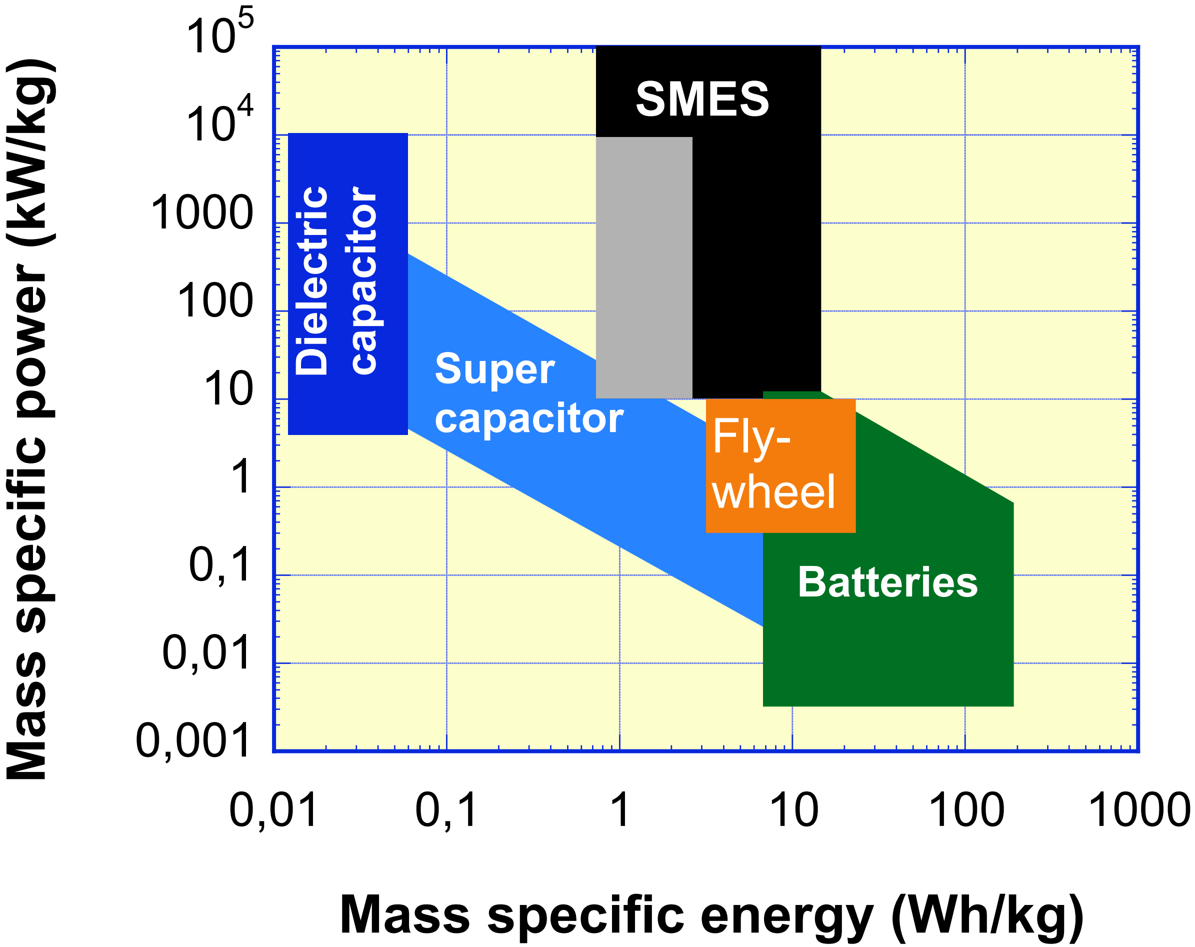
SMES

- Performances
- Applications
- Limits

Energy and power densities



Ragone chart: Performance comparison of storing devices

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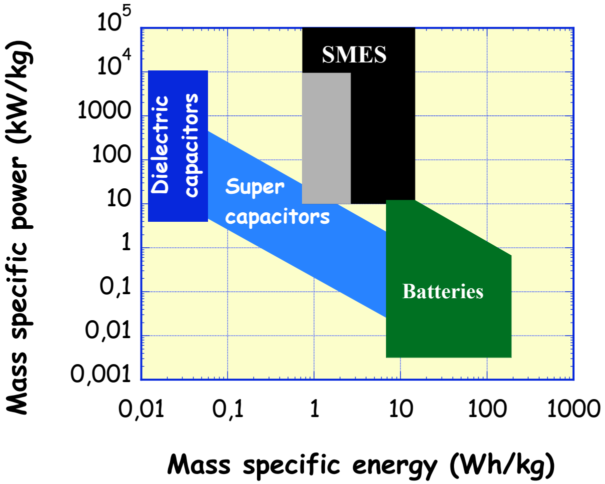
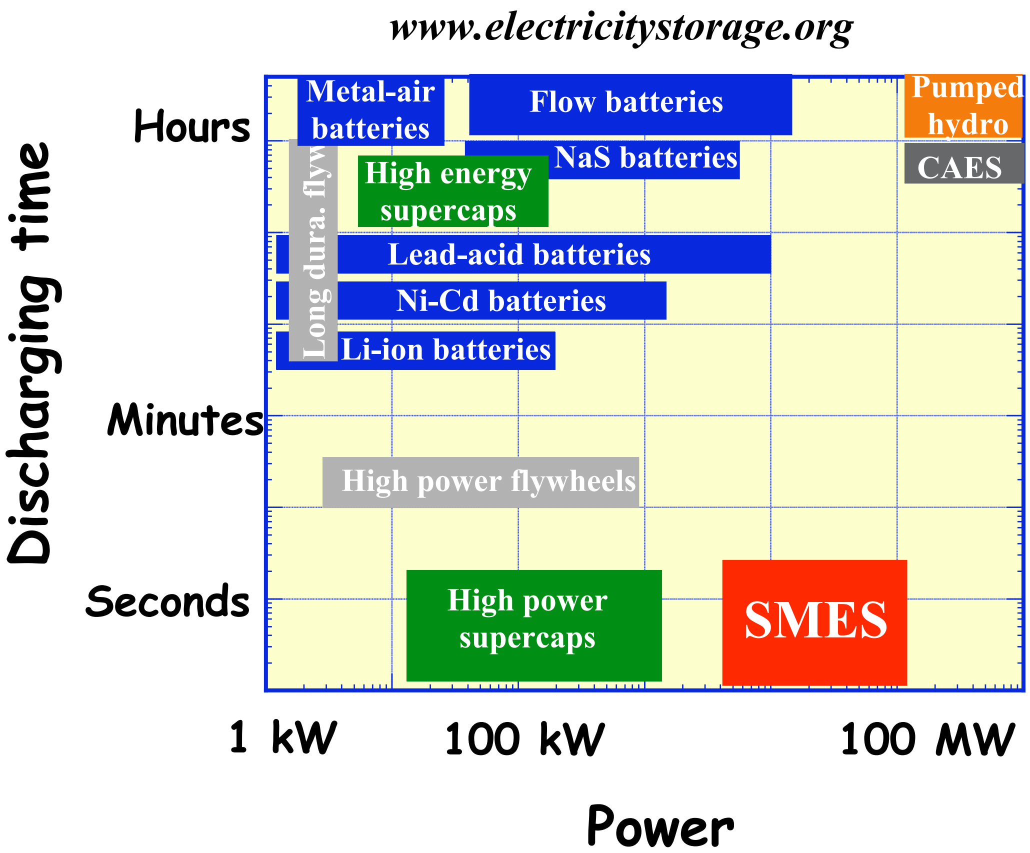
SMES applications





SMES main applications

- **UPS, voltage-power quality & reliability**
  - Protection against voltage drop and sags
  - Relay before the starting of a generating unit
- **FACTS (Flexible AC Transmission System)**
  - Supply/absorption active & reactive powers
  - Grid stability improvement
  - Transmission voltage regulation
- **Pulse power supply**
  - Electric guns
  - Electromagnetic launchers
  - Power Modulator
- **Large energy storage**
  - Daily load leveling
  - Spinning reserve / frequency control

Grids in general requires more reactive than active power

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Energy & power limits

- Energy
  - ✓ Magnetic flux density

$$\frac{W}{Vol} \leq \frac{1}{2}\frac{B^2}{\mu_o}$$

B = 10 T => 40 MJ/m³ (11 kWh/m³)

  - ✓ Mechanical stresses

$$Vol_{structure} \leq \frac{W_{mag}}{\sigma} \text{ (Viriel th)} \qquad [\sigma = J\, B\, R \quad (solenoid)]$$

Structure with 100 MPa and d = 8: 12.5 kJ/kg (3.5 Wh/kg)

Present world record: 14 kJ/kg

Mechanics: very important for SMES

Energy limit: viriel theorem & protection

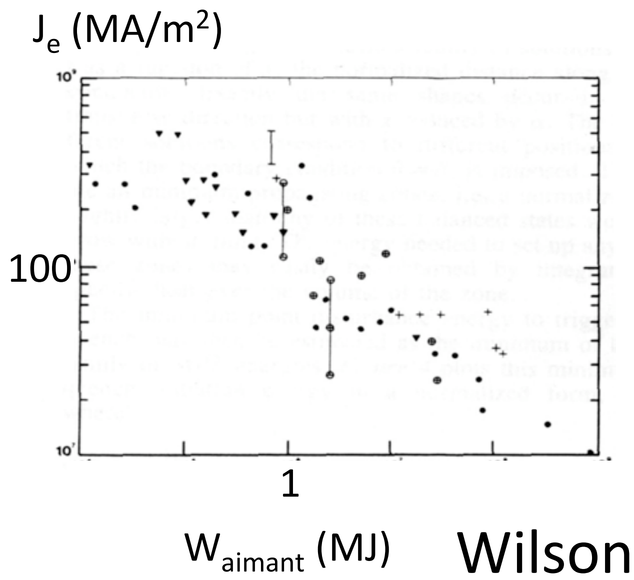
Ultimate limit: $W_{mag} \leq \frac{\sigma}{d} Mass_{traction}$ Rather low limit

Very important to combine functions:
Mechanical support & current transport

Reduced mass:
protection may become an issue then a limitation

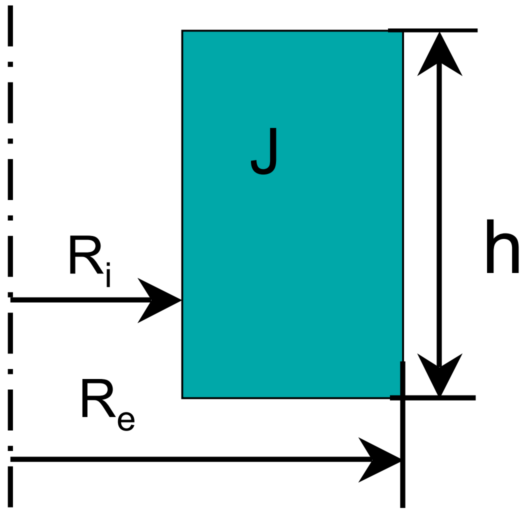
Protection: no damage during a quench

$$F(T_{\max}) = J_o^2 \left[\frac{W_{mag}}{V_{\max} \ I_o} + t_{det\,ection} \right]$$

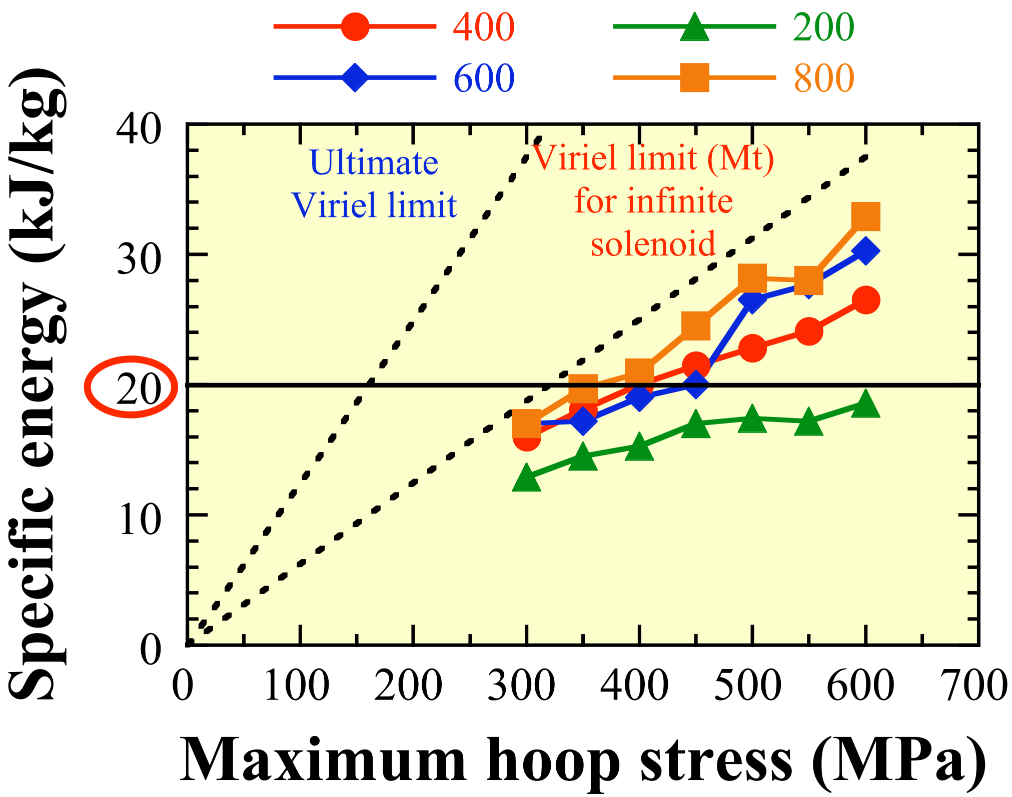


Wilson

Conditions to reach 20 kJ/kg



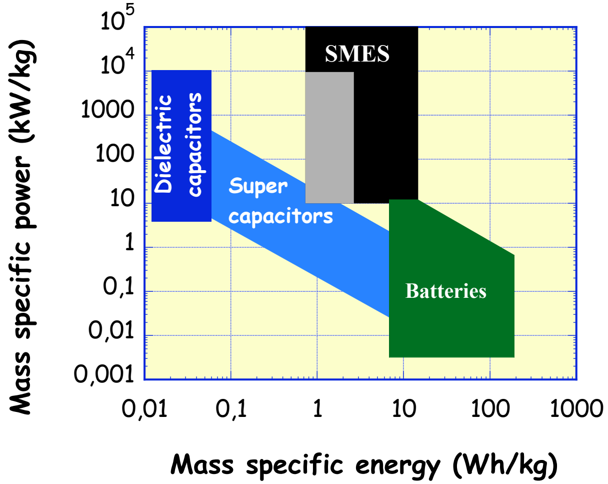
5 MJ



Possible with NbTi & YBaCuO HTS
=> protection issues (LTS & HTS)

Energy & power limits

- Power (VI)
  - ✓ Voltage & current
    - Good electric isolation
      - He gas bad dielectrics
    - High current conductor
  - ✓ Eddy current losses
    - Cryostat
    - Conductor (coupling losses)



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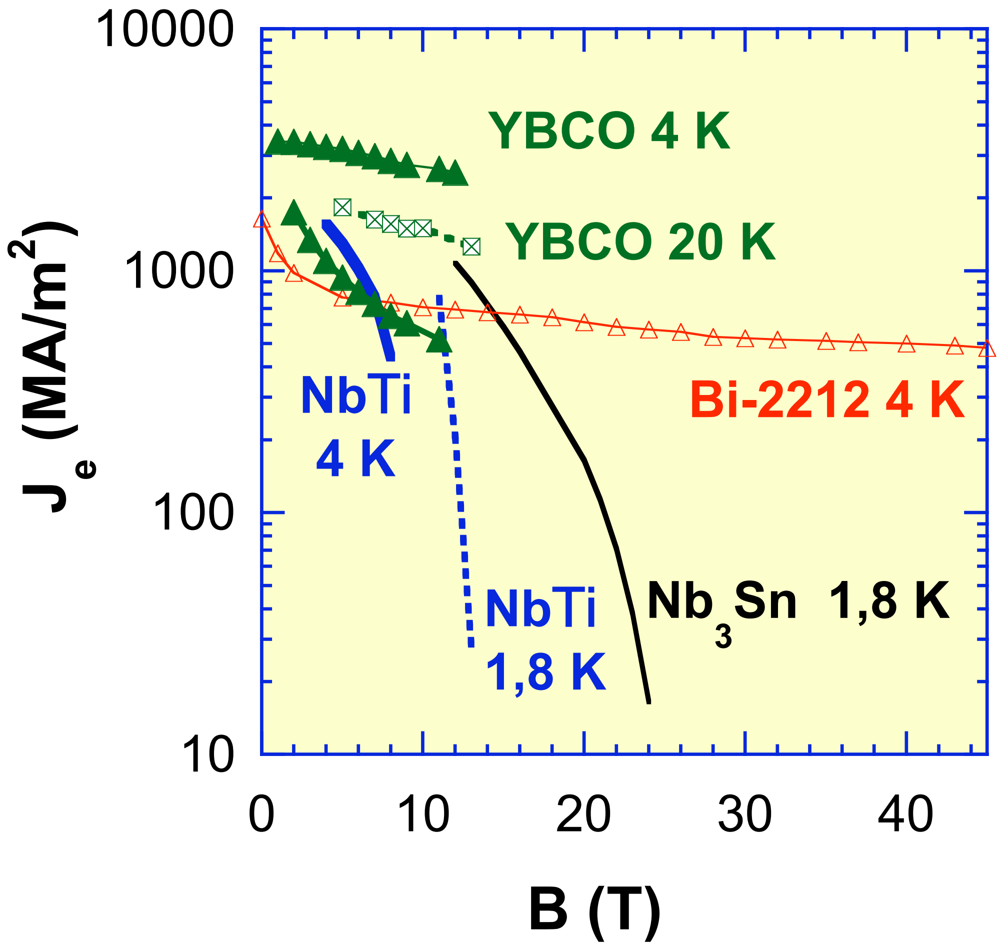
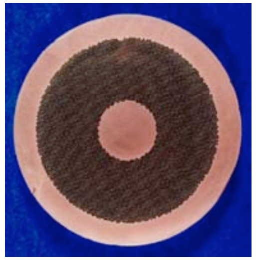
SMES

Superconducting materials

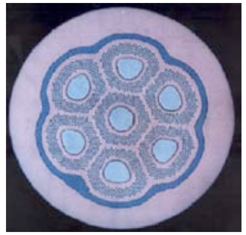
Superconducting materials



======= LTS =======

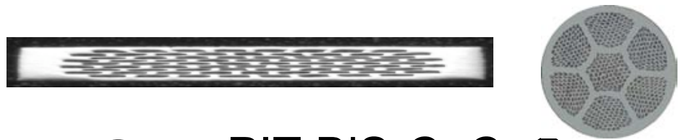


NbTi

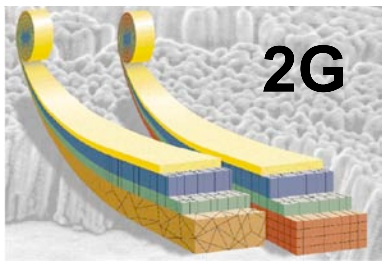


Nb_3Sn

======= HTS =======



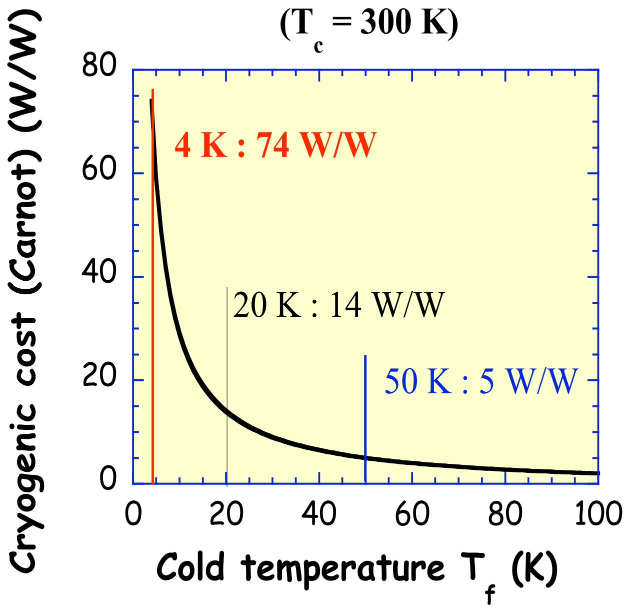
1G PIT BiSrCaCuO
Bi-2212 & Bi-2223

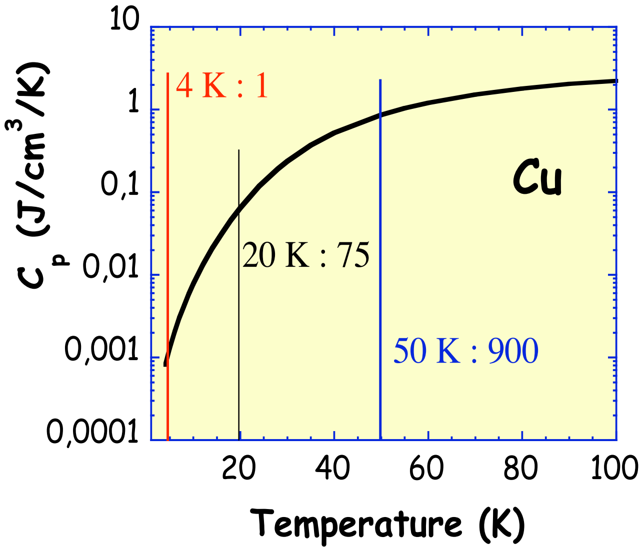


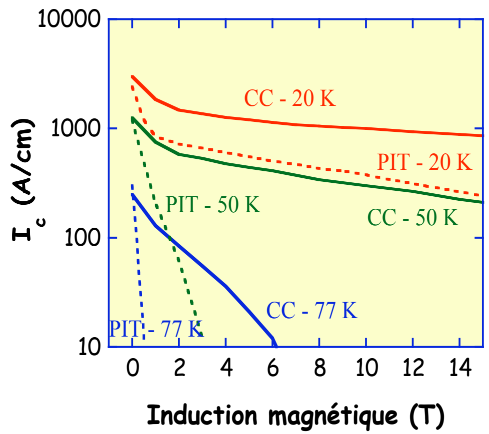
2G Coated conductor
YBaCuO

σ = 700 MPa

Operating temperature







- ✓ Cryogenic cost
  - running
  - investment

- ✓ Stability
  - margins & perturbations
- ✓ Isolating thickness
  - voltage => power

=> Protection <=

Interest HTS & CC

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SMES

History
Examples

History

- Introduced by Ferrier in 1969 to meet peak demands
- 30 MJ BPA experience
- 5-20 MWh / 100-500 MW ETM in the 80’ (SDI context)
- 3-6 MJ / 1 MW SMES in the 90’
  - More secure sources for critical/sensitive loads (no voltage sags)
  - FACTS
- First HTS « large » SMES in the 00’

SMES evolutions

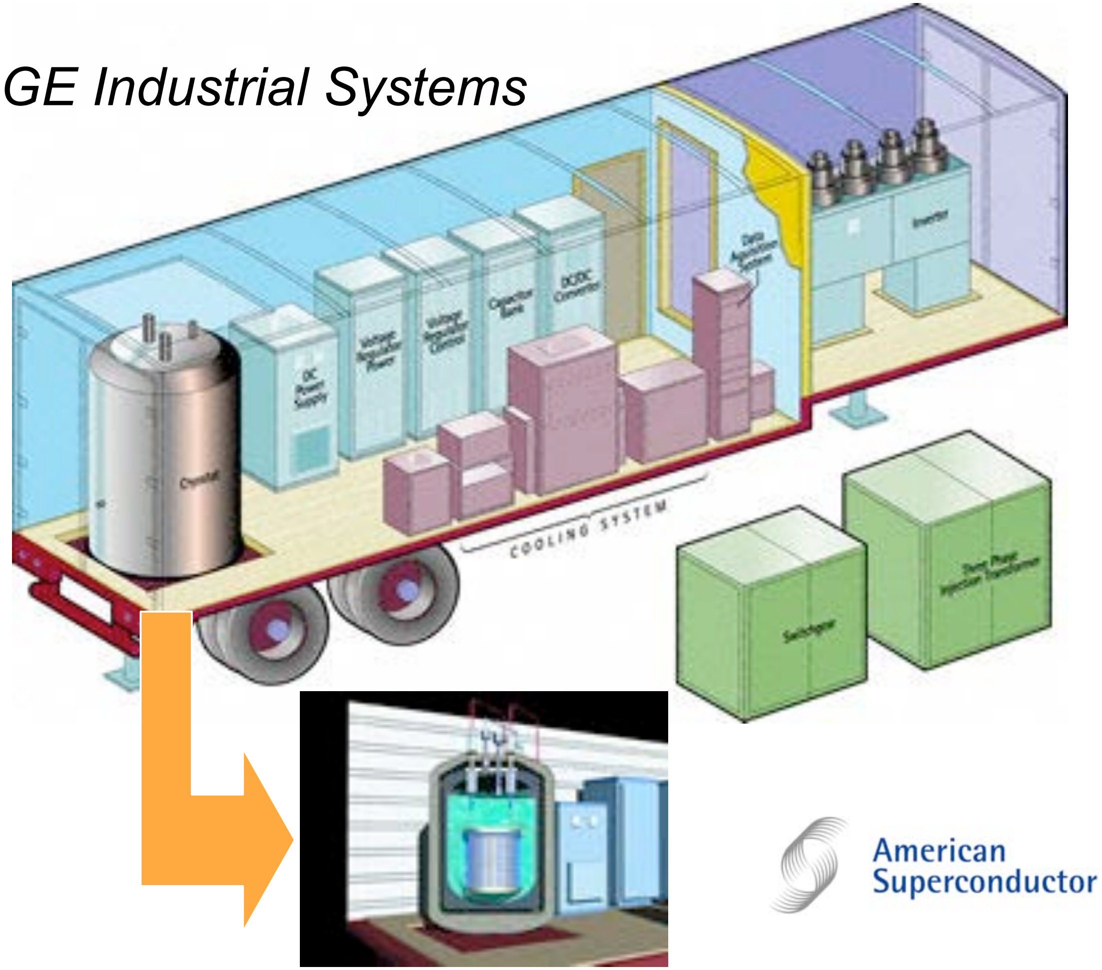
- LTS SMES
  - HTS current leads
  - Cryocoolers
  - Power conditioning systems and control

- HTS SMES
  - Conductor developments (YBCO CC)
    - Low cost
    - Mechanical properties
    - High current conductor

« Commercial » SMES

Trailerized Installation

GE Industrial Systems



Voltage Sag Protection

Power ratings

Load voltage: 400 V to 20 kV

Unit Output: 1.3 MVA

Response Time: subcycle

System efficiency: > 97 %

Magnet (NbTi) data

Stored energy: 3 MJ

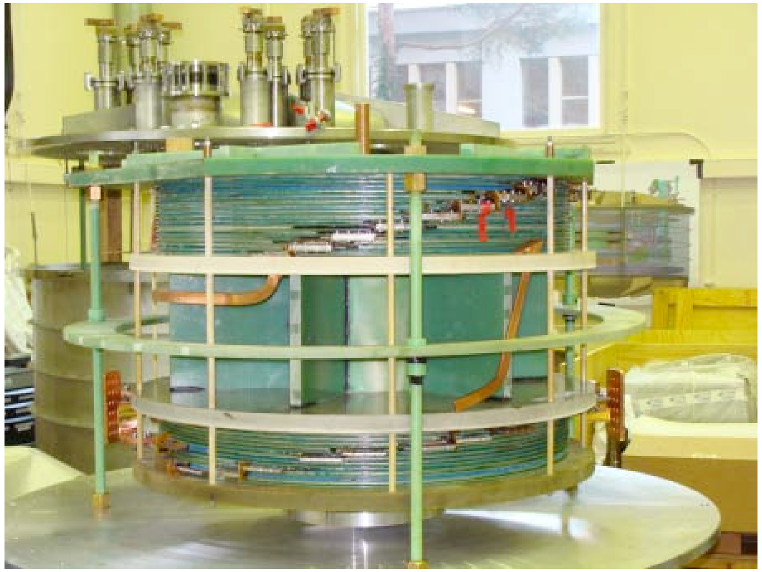
Recharging time: < 90 s

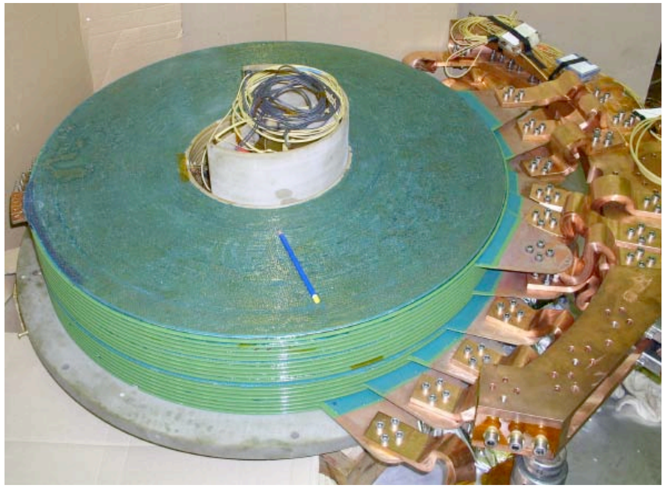
Duty cycles nber: unlimited

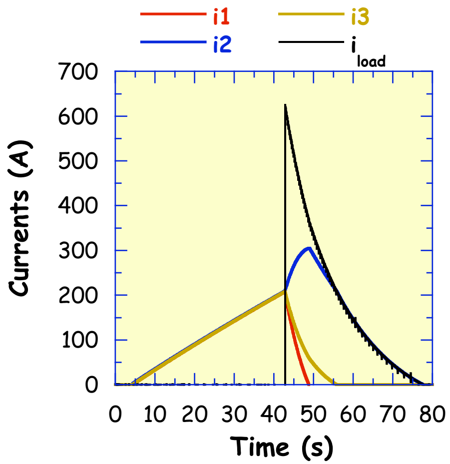
Some HTS SMES

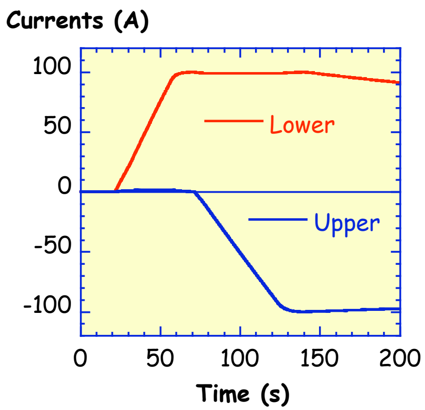
Organ.	Country	Year	Data	SC	Application
Chubu	Japan	2004	1 MVA, 1 MJ	Bi-2212	Voltage stability
CAS	China	2007	0.5 MVA, 1 MJ	Bi-2223	
KERI	Korea	2007	0.6 MJ	Bi-2223	Power, voltage quality
DGA CNRS	France	2007	0.8 MJ	Bi-2212	Pulse appl. Electric gun
KERI	Korea	2011	2.5 MJ	YBCO	Power quality
Chubu	Japan	2012	MJ class	YBCO	Grid stabilization

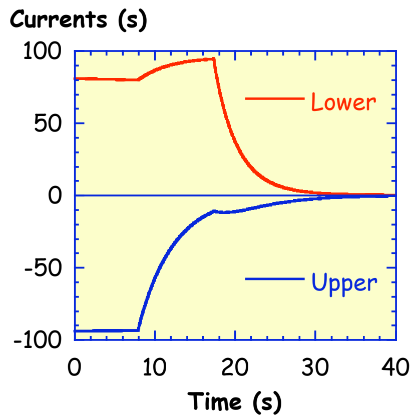
SMES HTS DGA/CNRS/ Nexans





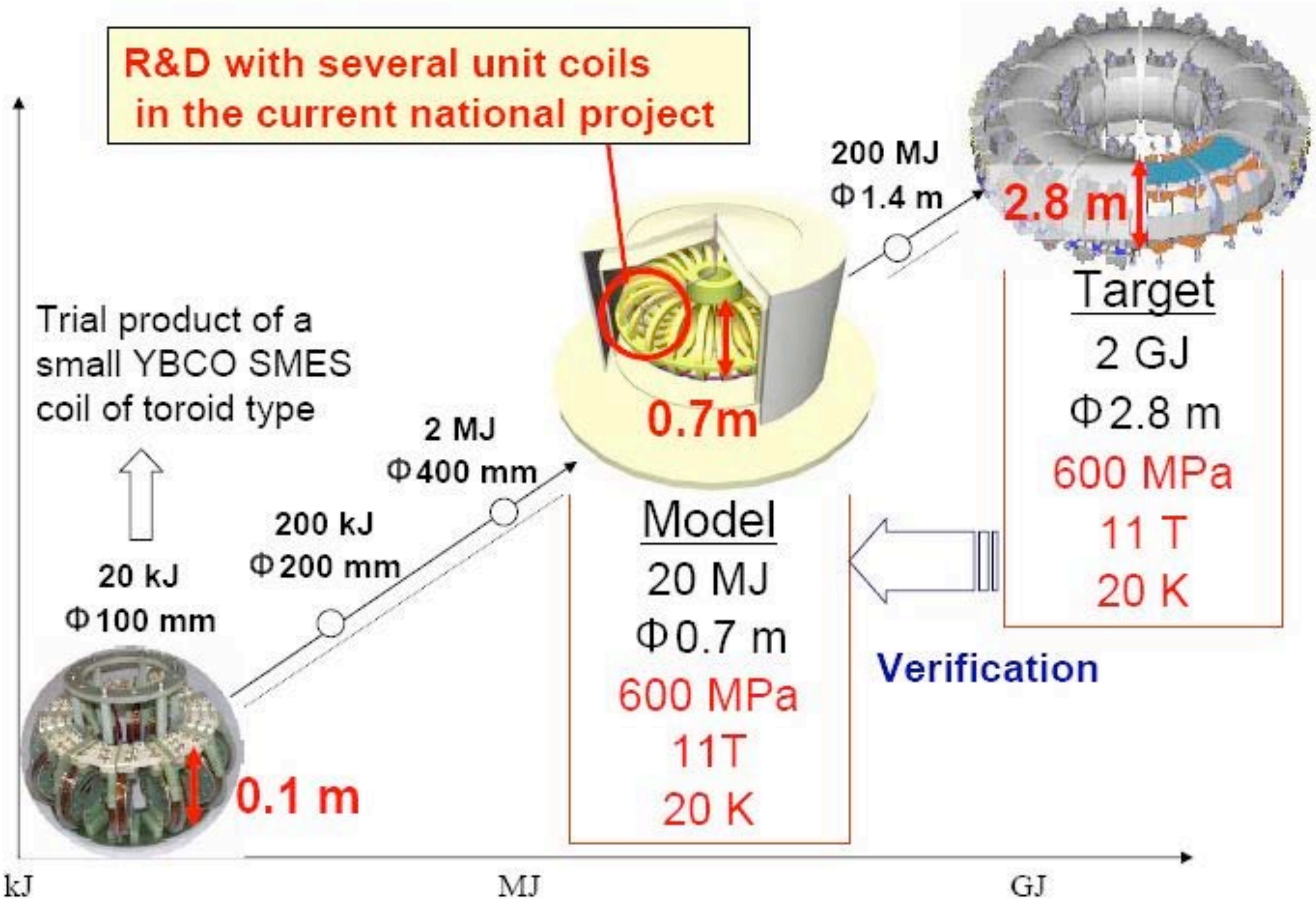






Japanese project

Courtesy of Chubu Electric



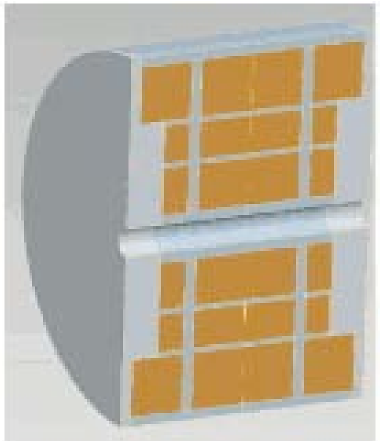
FACTS

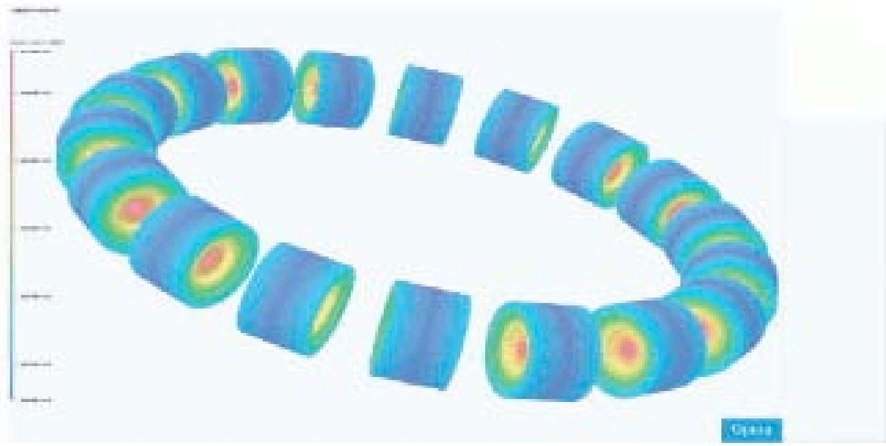
Syst

control

New US SMES project (arpa)

Partners: ABB, Brookhaven, SuperPower, Houston university





$$\sigma = J\ B\ R$$

Specifications:

- 2.5 MJ / 20 kW
- Up to 25 T (4 K)
- 2G wires

Objective:

- Load levelling on the grid with renewable energies

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SMES

Conclusions

Summary: SMES

- **High power density** & large energy density
  - Directly usable current source
- **Quick response time**
- Number of charge-discharge cycle very high (infinite)
- Static system / low maintenance
- Specific application of superconductivity
- **Conversion efficiency may be high (> 97 %)**
- « Correct » from environmental point of view
- Security of operation
- **High costs (cryogenics - superconductor)**
- **Losses in storage mode (but not really a storage system!)**

SMES : pulse current source

- SMES, best solution
  - In the intermediate range of power-energy plan or for extreme powers
  - for current type load

(batteries: energy sources, capacities: pulse voltage sources)

- Application examples
  - **Electromagnetic launcher/catapult/gun**
  - Some FACTS, UPS (Uninterruptible Power Supply)
  - **Pulse applications (electron lasers, pulse field, ...)**

Conclusions

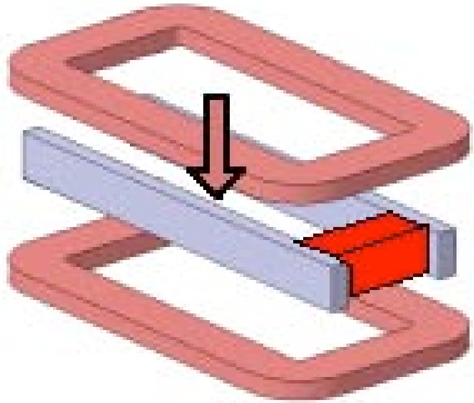
- Technology status
  - Currently available for short term power
  - Capability of SMES demonstrated
  - **Successful experiences on years, large test exp.**
  - **Too high initial cost: the major bottleneck**
  - Competition by more mature technologies

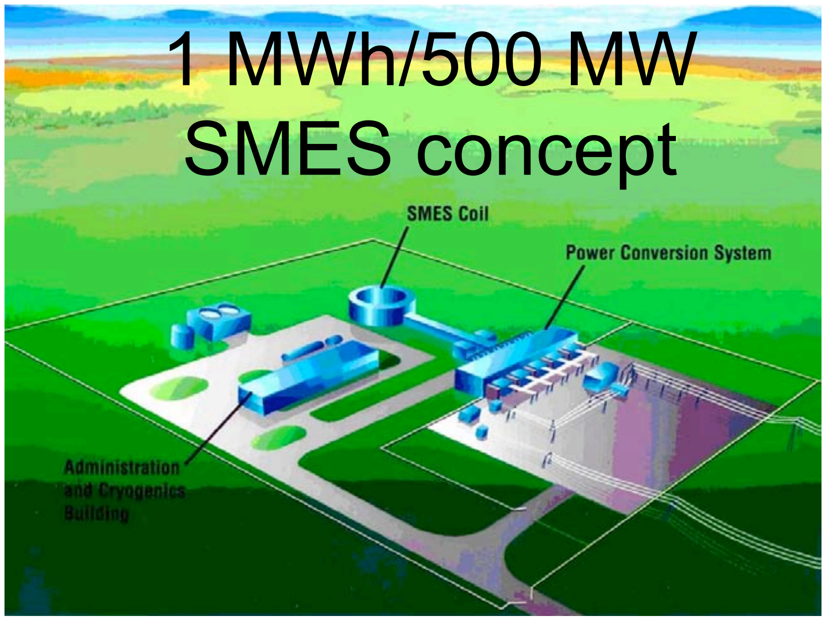
- Future
  - HTS, YBaCuO coated conductors
    - Specific energy improvement
    - Reduced cryogenics
    - Protection issues

Cost

Perspectives: function combining

S^{3}EL : Superconducting Self Supplied Electromagnetic Launcher





C. Luongo

Thanks !