Energy Storage
Part 2

- Some case studies
- Alternatives

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CERN PS (proton-synchrotron)

The magnetic field in the 101 bending magnets of the PS is cycled between 0.11 T at injection energy of the protons (1.4 GeV) to 1.25 T at top energy (26 GeV)

The repetition time is 2.4 s
About 6 to 8 million cycles are executed each year

The impedance or the magnets string is 0.32 Ω and 0.9 H
The current at top energy is 5.5 kA

The active power for operating this string peaks at 40 MW at the end of the acceleration, at which time the increase in stored magnetic energy also reaches a maximum

To avoid perturbing the network, from the start, in 1959, a **flywheel motor-generator system** was used

CERN PS From flywheel to capacitors

rotor mass: 90 t
Stored energy 233 MJ
(@ 1000 rpm)

The speed of the rotors decrease by 5% during ramp-up while the generator absorbs 6 MW; during ramp-down, the stored energy flowing from the magnets, peaking at 12 MJ, reaccelerates the rotor to nominal speed

Such a system requires regular maintenance. This was outsourced, but it was increasingly difficult to find a competent supplier.

Studies* of alternative solutions were started in 2003

- Use of batteries was discarded due to the limited lifetime
- SMES was discarded due to **lack of standard industrial products**
- **Energy storage in capacitors was preferred**
  - *Capacitors support practically unlimited discharge cycles*
  - *A modular solution could be* ***based on industrial components***

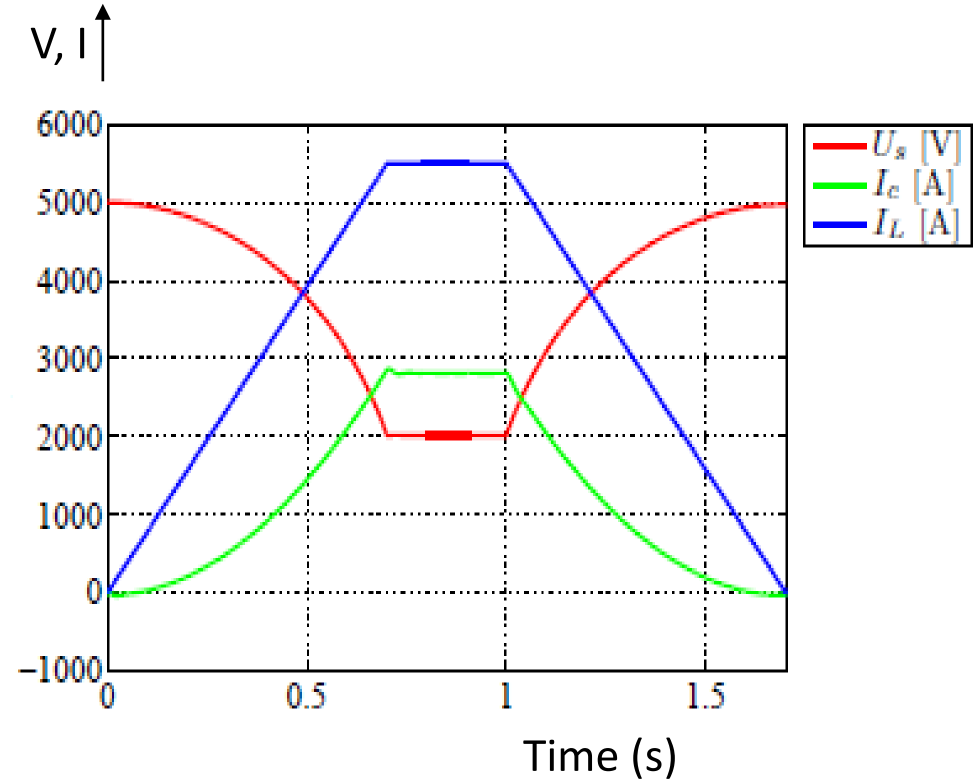
The capacitors are part of a new system, in operation since 2011, which integrates three functions:

- Converts AC current from the network to DC current as required
- Charges the capacitors with energy for pulsing the magnets
- When the energy is not needed it is stored in the capacitor banks

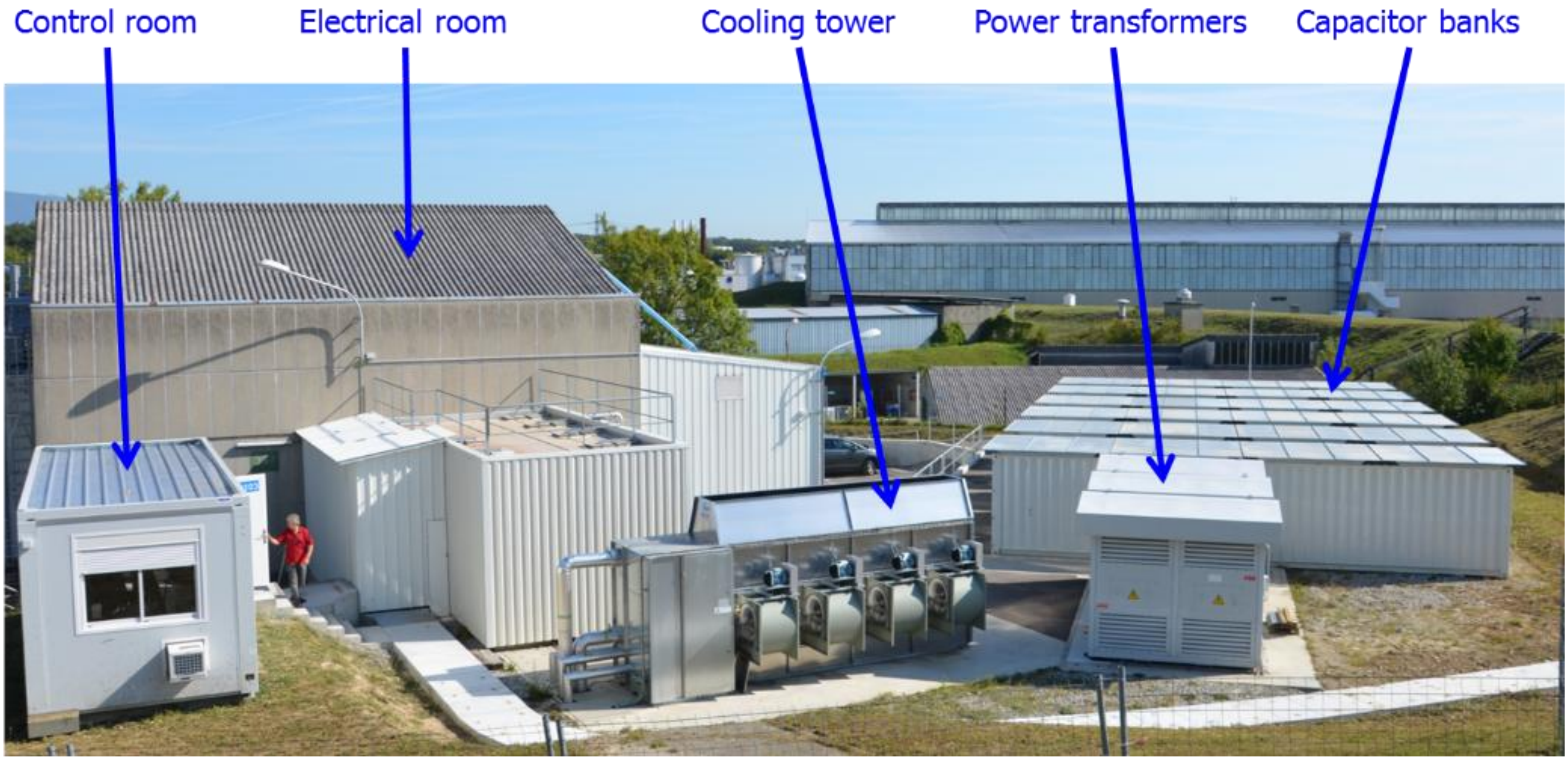
*C. Fahrni, A. Rufer, F. Bordry and JP. Burnet, A Multilevel Power Converter with Integrated Storage for Particle Accelerators, in *Proc. Power Conversion Conf. (PCC '07),* Nagoya, Japan, 2007, p.1480.

The six capacitor banks are connected to the magnet string via six DC/DC converters which precisely control current and voltage in the magnet circuit, independent of the voltage of the capacitors.

The capacitor voltage decreases from 5 kV to 2kV during the ramping to top energy and increases again to 5 kV during ramp-down as shown in the figure.



The capacitor are dry, and made from metalized self-healing polypropylene



The capacitors are housed in six standard 40 ft shipping containers

JT-60 motor generator/flywheel*

The largest of its kind, featuring a vertical shaft, rotary field, water cooled heat-exchanger, with a 650 t flywheel

Specification:

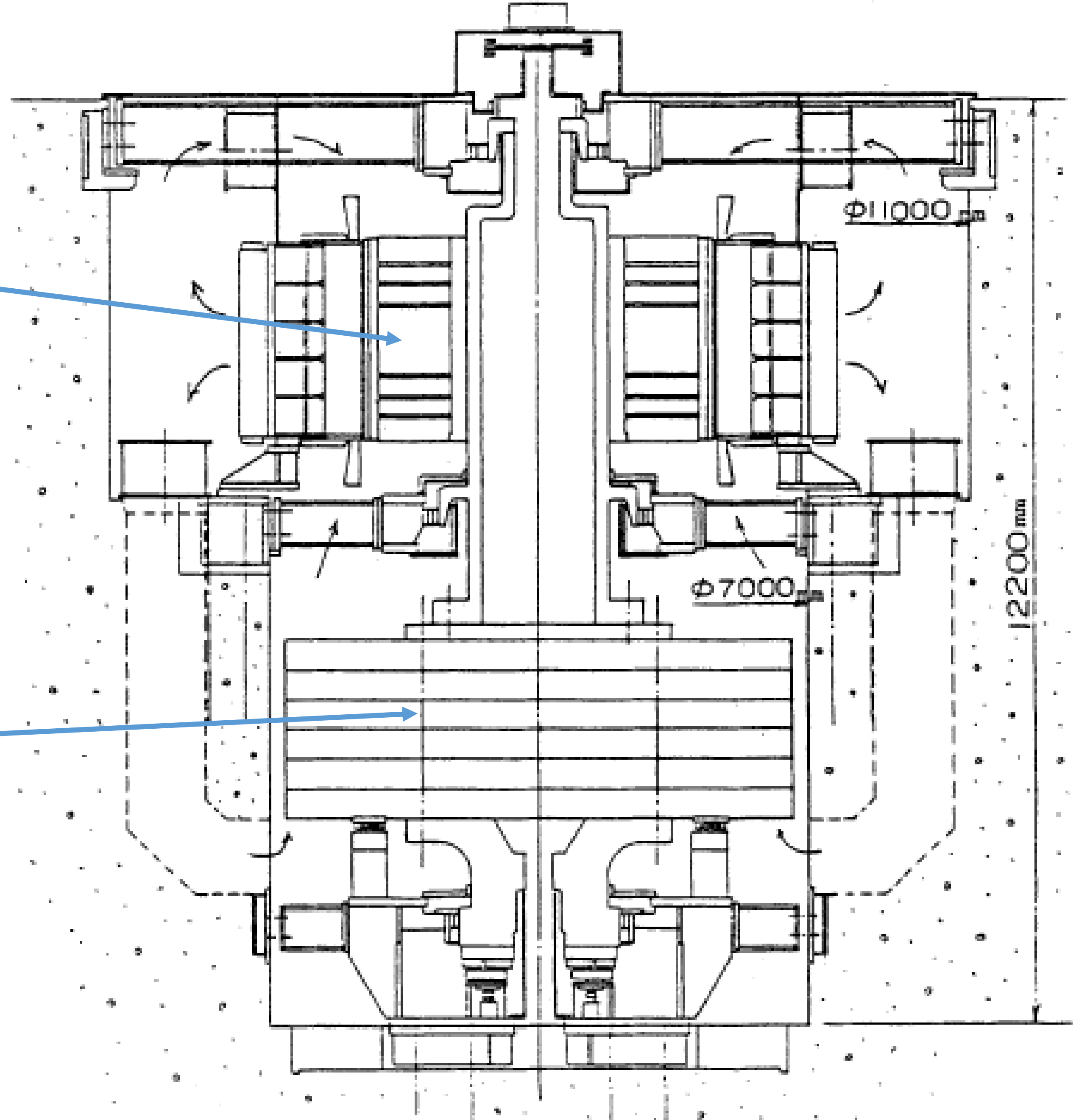
Output	215 MVA
Voltage	18 kV
Current	6,896A
Power factor	0.85
Frequency	80 ∿ 56 Hz
Rotating speed	600 ∿420 r/min
Total flywheel effect(GD^2)	16,000 ton-m^2
Discharge energy	4.02 GJ
Operating frequency	Once every 10 minutes
Exciter	797 kW (Thyristor exciter)
Thyristor starter	19 MW
Number of cycles of operation	
Operation at max rating	150,000 times
Operation at 50% rating	450,000 times
Discharge cleaning operation	300,000 times
Start/stop	3,000 times

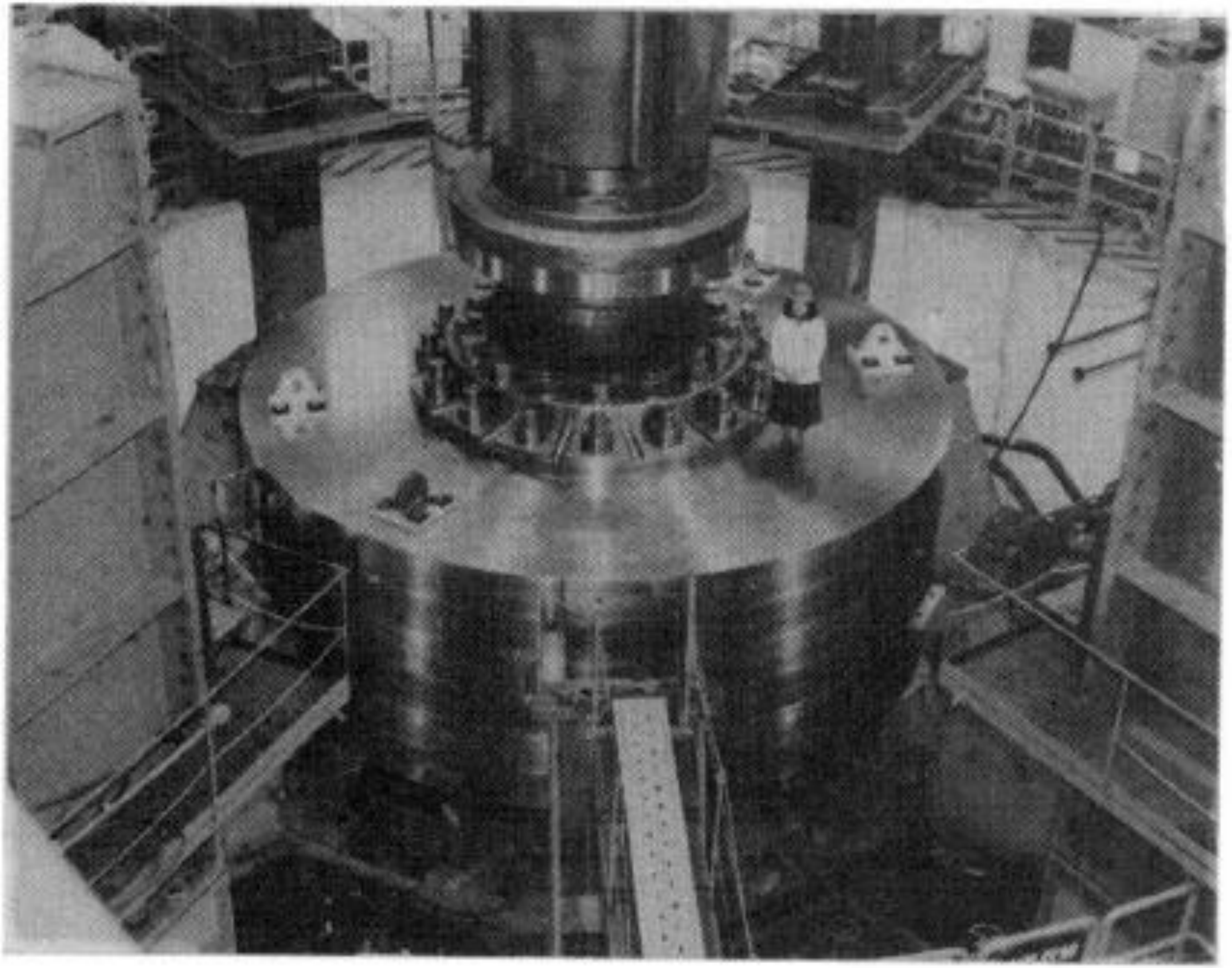
*T. Matsukawa *et al.*, A 215 MVA flywheel motor-generator with 4 GJ discharge energy for JT-60 toroidal field coil power supply system, *IEEE Trans. on Energy conversion*, Vol. EC-2, No. 2, 1987

JT-60

Motor-generator

Flywheel
Mass: 650 t
6 disks of carbon steel





Difficulty of choice of power control for large accelerators…

Type	characteristics
Motor-generator/flywheel	+ fast response - repetitive stress - maintenance
SMES	+ fast response + efficient - AC loss - prototype stage - cost
Capacitor	+ fast response - low energy density -/+ lifetime?
Battery	+ fast developing -/+ lifetime??

Small accelerators

Reducing the power footprint of medical synchrotrons

The cost performance of a **4 MJ SMES** system to compensate load fluctuation of synchrotrons for medical use has been studied*

The study was based on a small scale SMES that had already been demonstrated technically as being suitable for this application.

- Power is saved by compensating input and output using SMES.
- The depreciation time of the SMES **system** (cost $3M) was found to be about 20 years, assuming an annual maintenance cost $50k.

It is nevertheless interesting, as the power saving would be about 1.2 GWh per year per facility. It is planned to construct a medical facility in every prefecture, i.e. 50 facilities in Japan, so there is the potential for a saving of 60 GWh/year nation-wide…

*Sato et al., Application of energy storage system for the accelerator magnet power supply, Proc. IPAC-10, 2010.

Typical features of the medical facility accelerators

Hyogo Ion Beam Medical Center	**Gunma University Heavy Ion Medical Center**
H, C H: 70 – 230 MeV C: 70 – 320 MeV/u	C 140 – 400 MeV/u
6 treatment rooms 2 gantry rooms 1 horizontal treatment room 1 45-degree treatment room 1 seated treatment room	3 treatment rooms (4 ports) 1 horizontal & vertical treatment room 1 vertical treatment room 1 horizontal treatment room
95 m × 80 m	60 m × 50 m
1 ~ 2 sec **2.5 MW**	**3.5 sec** **3 MW**

What we take away from this study

If the SMES system cost could be halved, it would clearly be the way to go!

There are no moving parts, so maintenance is easy

It is environmentally friendly!

However, from both the economic and environmental standpoints it is important to plan to install the SMES system at the beginning of the planning of construction.

(Magnet designers should pay more attention to this…)

Another study* in Japan addressed the opportunity of using SMES on a larger scale (as an alternative to the flywheel solution for the energy upgrade of the J-PARC accelerator)

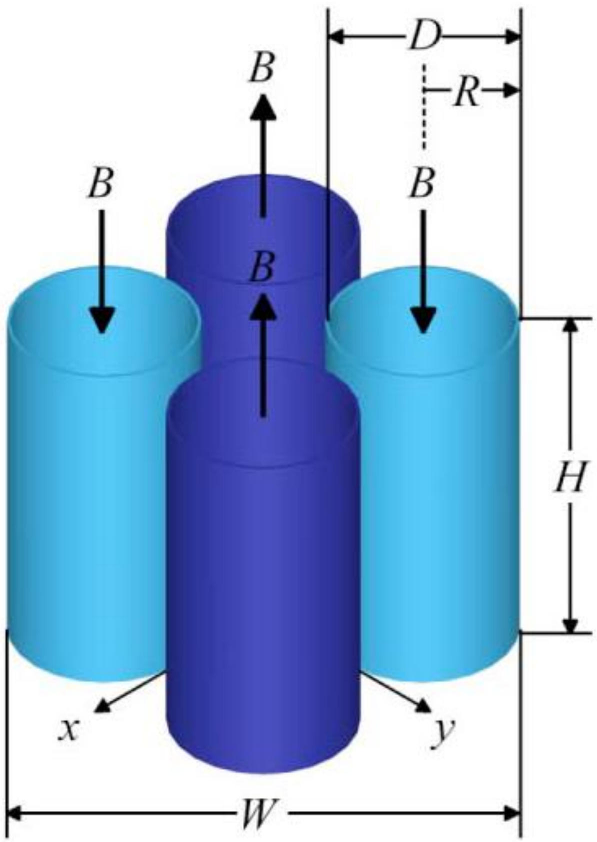
For this accelerator, the energy to be delivered by SMES is 21 MJ. If it is assumed that 30% of the capacity of the SMES system is used for this purpose, the system must be designed to store 70 MJ

The study proposed using a modular solution –
As there are six power converter modules, six SMES modules

A magnet design suitable for series production was studied

*H. Sato, T. Shintomi *et al*., Electric power compensation of the large scale accelerator using SMES, *IEEE Proc. Particle Accelerator Conference* (PAC'07) (2007) 239

Proposed design
for a SMES module



Possible parameters of SMES units

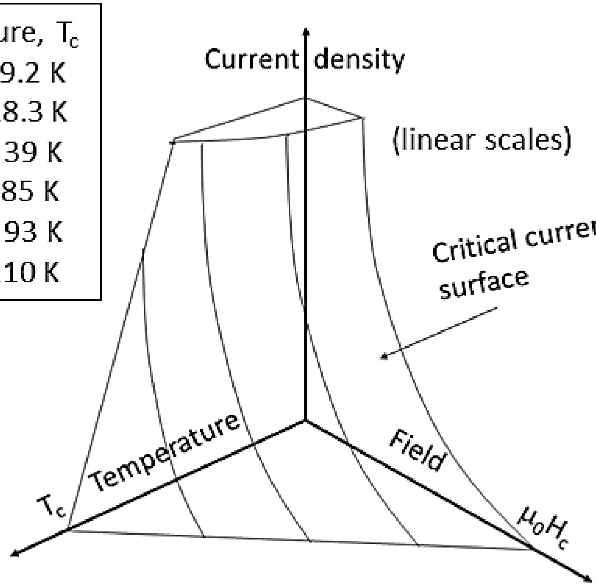
Stored Energy of Each Coil(MJ)	2.0	5.0
Maximum Magnetic Flux Density(T)	5.0	5.0
Coil Current (kA)	10	10
Average Diameter of Coil (m)	0.51	0.69
Height of Coil (m)	0.924	1.407
Number of Turn	440	603
Magnetomotive Force (MAT)	4.4	6.0
5G Line Radius of 4 Pole (m)	3	4
Total Stored Energy of 6 Units (MJ)	48	120
Radius of 6 Units SMES (m)	9	12

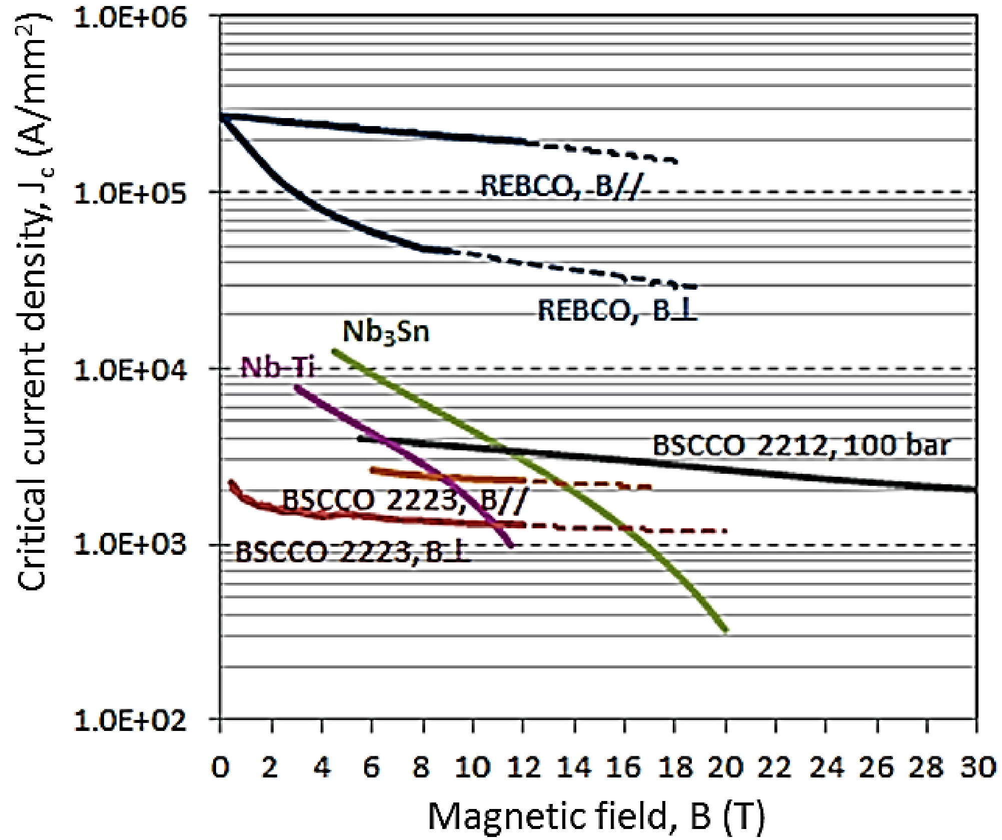
This design was based on the use of Nb-Ti superconductor in the form a flat cable, as used for the LHC dipoles

One module for a medical facility,
six modules for a large accelerator

Importance of superconductivity

Critical temperature, T_c	
Nb-Ti	9.2 K
Nb_3Sn	18.3 K
MgB_2	39 K
BSCCO 2212	85 K
REBCO	93 K
BSCCO 2223	110 K





The plots on the right show the critical current density of superconductors at 4.5 K (except for Nb-Ti, at 1.9 K)

Applications of electrical energy storage

- Cost minimization for utilities
- Improving efficiency of wind generation
- Community energy storage
- Distributed grid + PV integration
- Domestic storage to minimize cost
- Plug-in vehicles
- Uninterruptable power systems
- Reliable power in remote locations

“A next-generation smart grid without energy storage would be like a computer without a hard drive”

Why do we need energy storage?

Reduce risk of power outages: Today's electricity grid is vulnerable to threats from nature, terrorists, and accidents.

To save consumers money: Energy storage (ES) lets customers avoid premium pricing that utilities charge during times of peak demand.

For clean energy integration and energy independence: ES supports the integration of renewable power. By reducing the load on fossil-fuel generation ES helps cut emissions. (Peak capacity is wasteful)

For the economy: In addition to reducing economic losses from major and minor annual outages, ES will be a critical technology in the electricity grids of the future, and thereby create economic activity.

BUT…

There are alternatives to storage

(which could also serve to complement…)

The problem of requiring very high peak power capacity to all demands at all times could be addressed (partially) in other ways

Hard-nosed

- Accepting a few short periods (hours, days?) of power outage
- Massive increase of tariffs during bad peaks to "train" consumers

Technological

- Adopt long distance power transmission to address daily peaks by delivering the power to locations in other time zones

To flatten demand by distributing consumption, adopt

High voltage DC power transmission

- 800 kV overhead lines are in operation in Korea and China
- Problem (in Europe): “not-in-my-backyard” (**NIMBY**)

or

High current DC power transmission in superconducting links

- Virtually loss-free transmission of GW proportions
- Can be buried like pipelines

CERN, needing to power its high current magnet systems from distant radiation-free locations of power converters

- Has developed a conductor and cable for 20 kA for its own use. ***This has been done****

* A. Ballarino, Final design report, *CERN-ACC-2015-0134* (2015); https://cds.cern.ch/record/2063726/files/CERN-ACC-2015-0134.pdf.

Further to the CERN initiative, MgB_2 superconducting technology was proposed by Prof. Carlo Rubbia, erstwhile scientific director of the Institute for Advanced Sustainability Studies (IASS) in Potsdam, for an innovative transmission line for long-distance transport of green power

The idea is to use superconducting cables of **magnesium di-boride (MgB_2)** , cooled with **liquid hydrogen**, for use in underground power transmission lines, with permanent cryogenic cooling stations.

MgB_2 has a critical temperature of 39 K

- CERN collaborated with a producer (Columbus) to develop a round wire suitable for cabling
- Sufficient wire was purchased to make two 20 m lengths of cable

The cable was assembled at CERN. It was installed and tested in helium gas at various temperatures in a special long cryostat

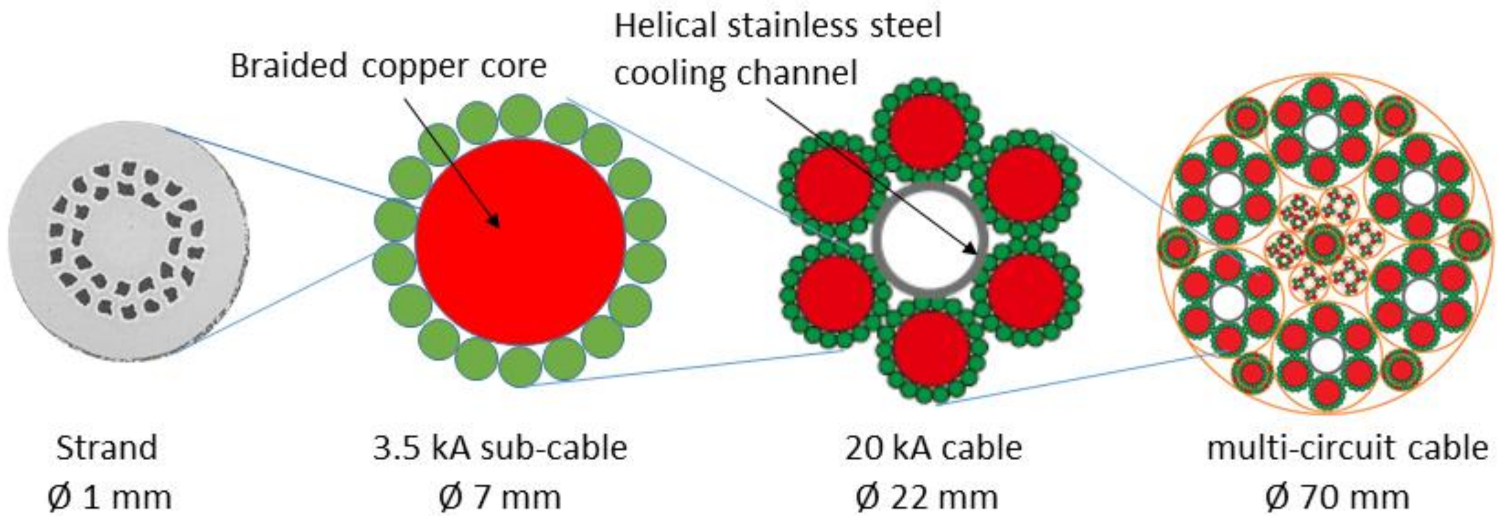
The development was aimed at testing a 20 kA DC line operated at 20 K (-253 °C), which was also conveniently close to the CERN requirement for powering the magnets.

The result of the tests was a demonstration that such high-current cables can be operated at and above the temperature of liquid hydrogen, and that the basic related technology is proven.

At CERN it is planned to use such cables for the LHC luminosity upgrade project; gaseous helium will be used to cool the cables.

For power transmission in conjunction with solar power it is interesting to envisage **cooling with liquid H_2**. Surplus energy at the source could be used to ***produce liquid H_2 by electrolysis*** and this could be stored for use as energy to produce back-up power.

For efficient cold powering of the magnet system of the high luminosity upgrade of the CERN-LHC several cables are grouped



Possible build-up of the proposed multi-circuit cable.
Twisted strands consist of 30 filaments of MgB_2 superconductor embedded in a Monel matrix.

Transmission lines carrying up to 100 kA could be envisaged…

According to market research, **the energy storage market is set to rise** to an annual installation size of 6 GW in 2017 and over 40 GW by 2022, from a base of 0.34 GW installed in 2012 and 2013.

Over a thousand companies serve the energy storage industry

Pumped water, heat, flywheel, battery and capacitor energy storage systems are operating today in the competitive ancillary services power market with fast and accurate response to distribution signals

The market for storing power from solar panels – which was less than $200 million in 2012 – will be about $19 billion in 2017

Pay attention to minimizing the amount of storage needed,
e.g. by increasing **long distance power transmission** capacity
within a smart grid

Thank you for your attention!