A novel 60 MW Pulsed Power System based on Capacitive Energy Storage

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Workshop Energy for Sustainable Science

Energy Management for Large-Scale Research Infrastructures

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Basic rules to minimize power consumption with particles accelerators

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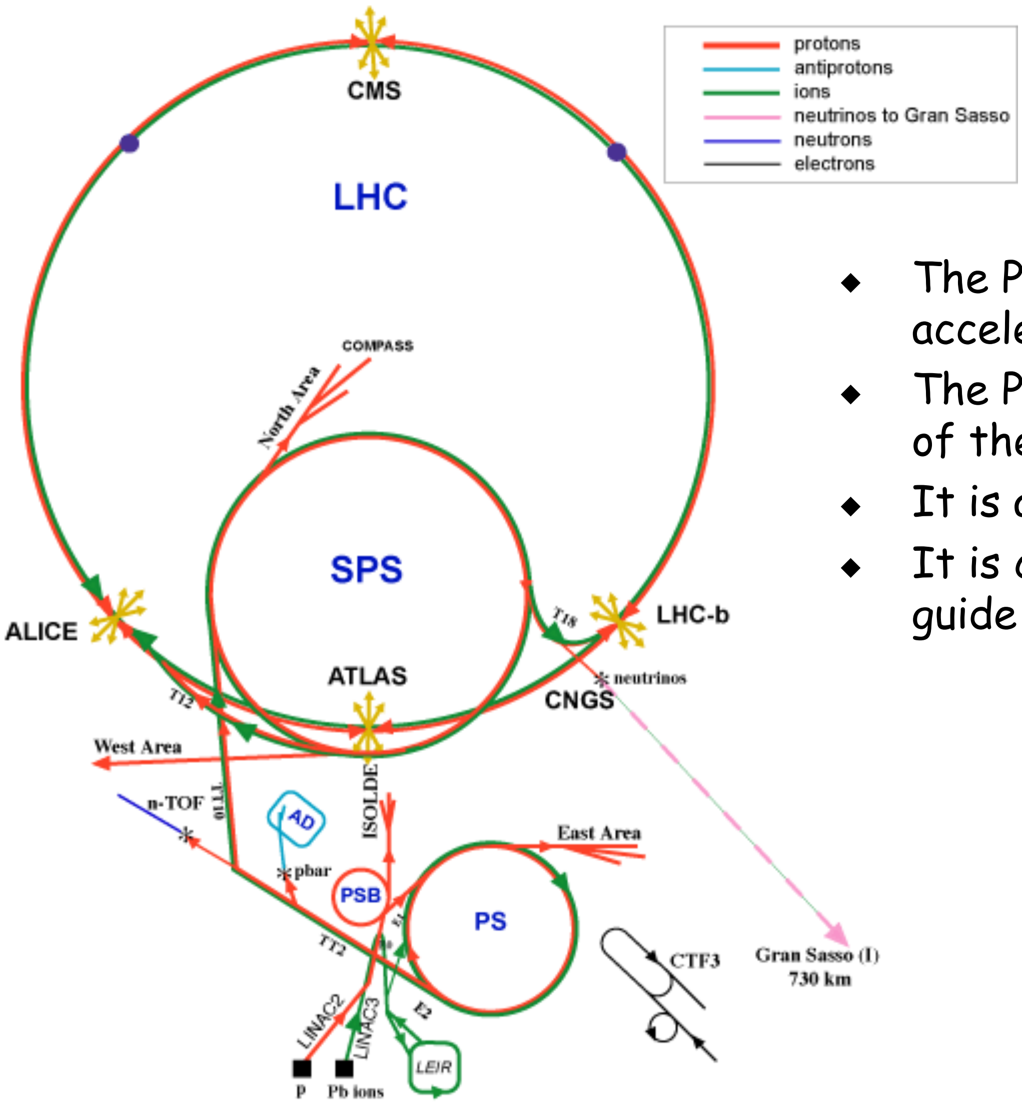
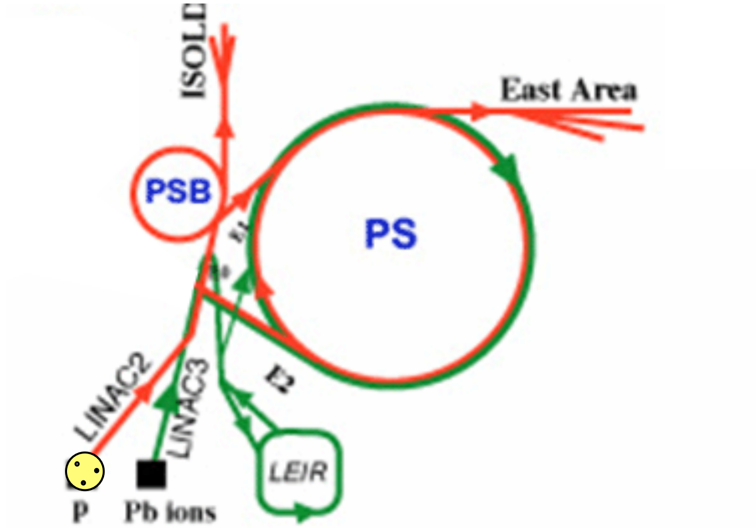
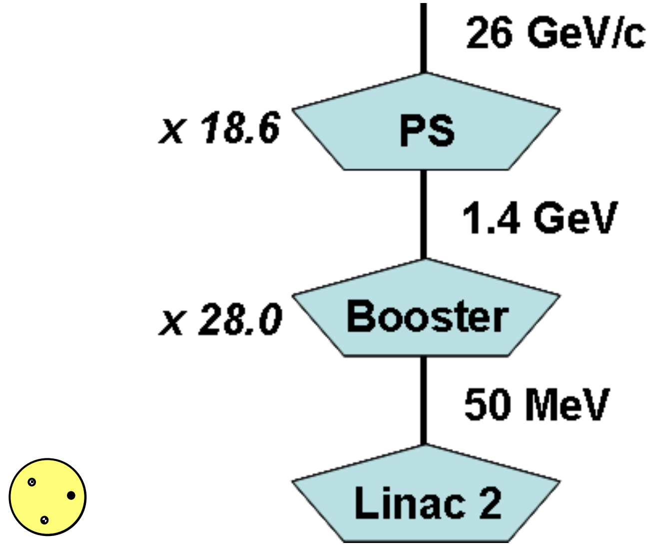
The CERN accelerator complex



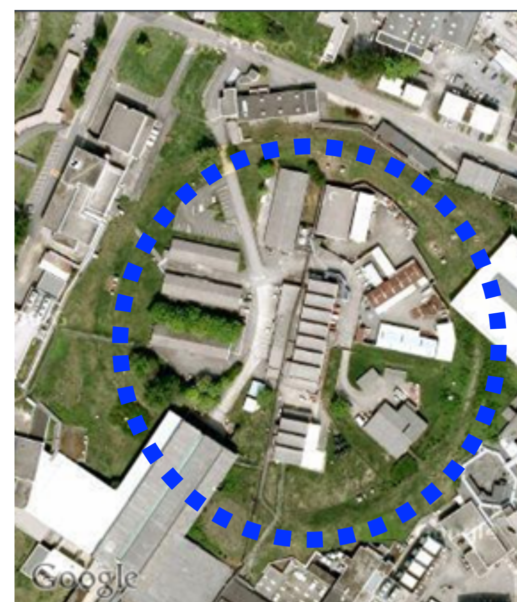
- The PS was the first large accelerator at CERN (1957).
- The PS is a part of the injection chain of the LHC.
- It is a cycling machine (1.2s).
- It is composed of 100 magnets to guide the beam.

Introduction to PS machine





- 600m of circumference
- The main load of the accelerator is the 101 main magnets connected in series, making a total load 0.9H/0.32Ω



PS cycles

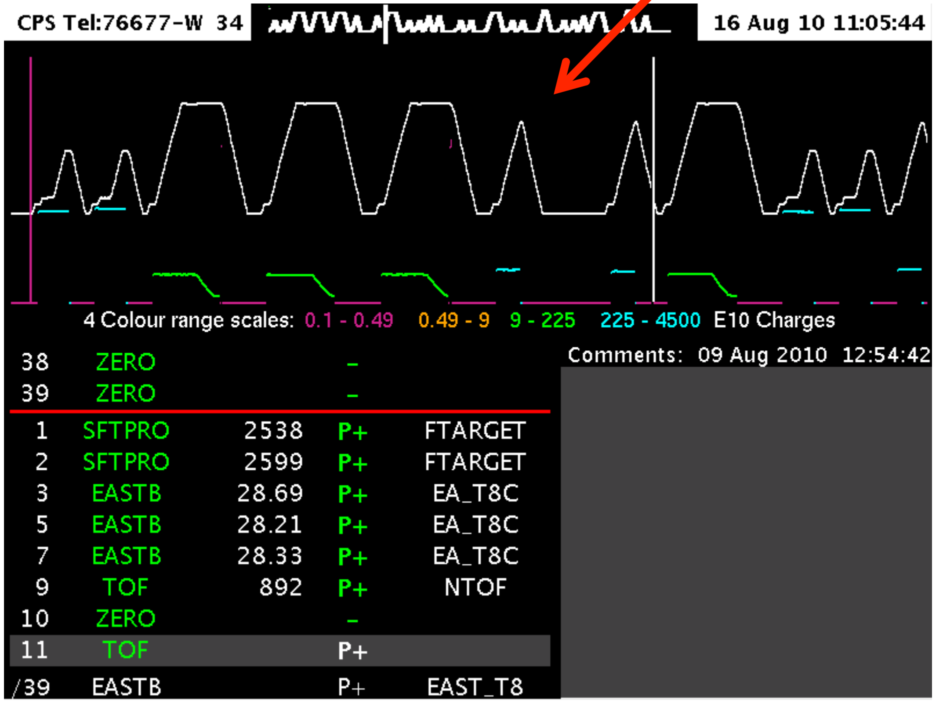
The PS machine is running around 6000h per year, 24h per day, 7 days per week, 8 to 9 months per years.

A technical stop of 8 hours is schedule every 12 weeks.

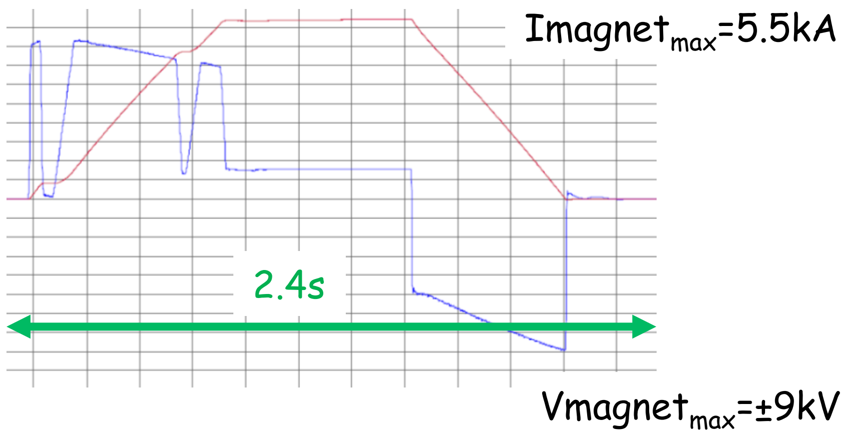
Each cycle takes 1.2s or 2.4s.

6 to 8 millions of cycle are executed per year.

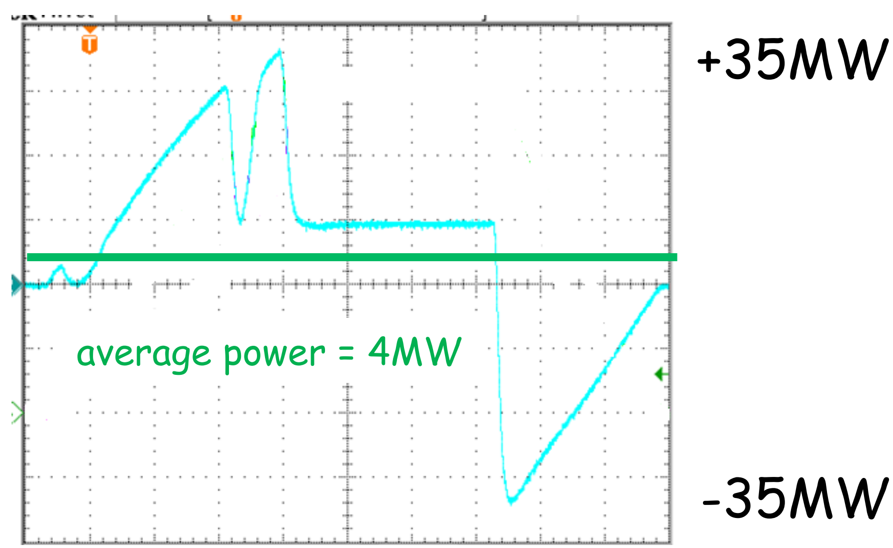
Magnet current



PS cycles



Blue: Umagnet 1 kV / div
Red: Imagnet 500A / div



Light blue: Power_to_magnet 10 MW / div

Power(t) = I_magnet(t) x V_magnet(t)

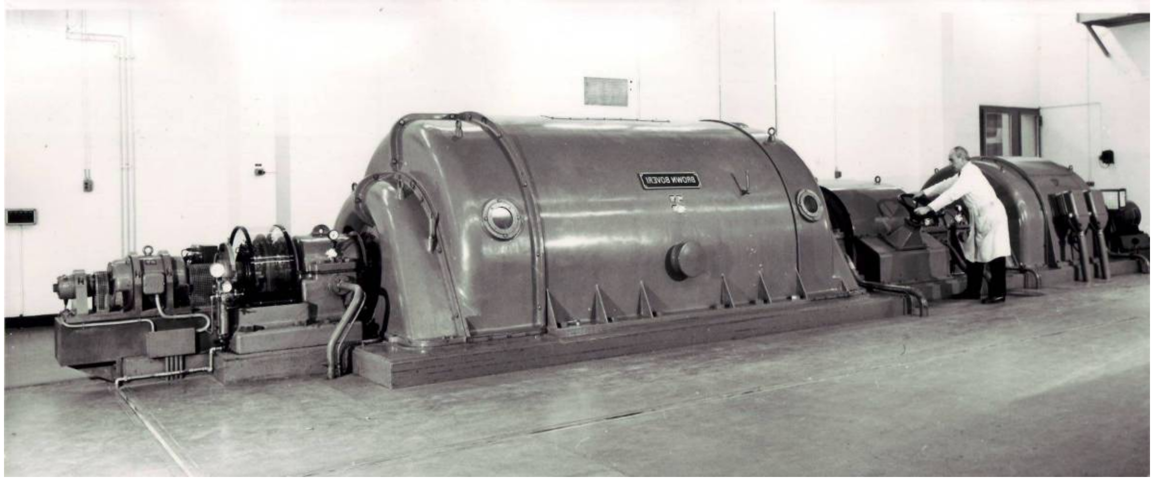
The peak power needed for the main magnets is ±40MW with a dynamic of 1MW per ms
The average power is only 4MW !!!

The challenge:
Power a machine which needs a peak power 10 times the average power with a very high dynamic !!!

How to power such a machine ?

❖1959

As the electrical network was too weak, a motor-generator set was chosen.



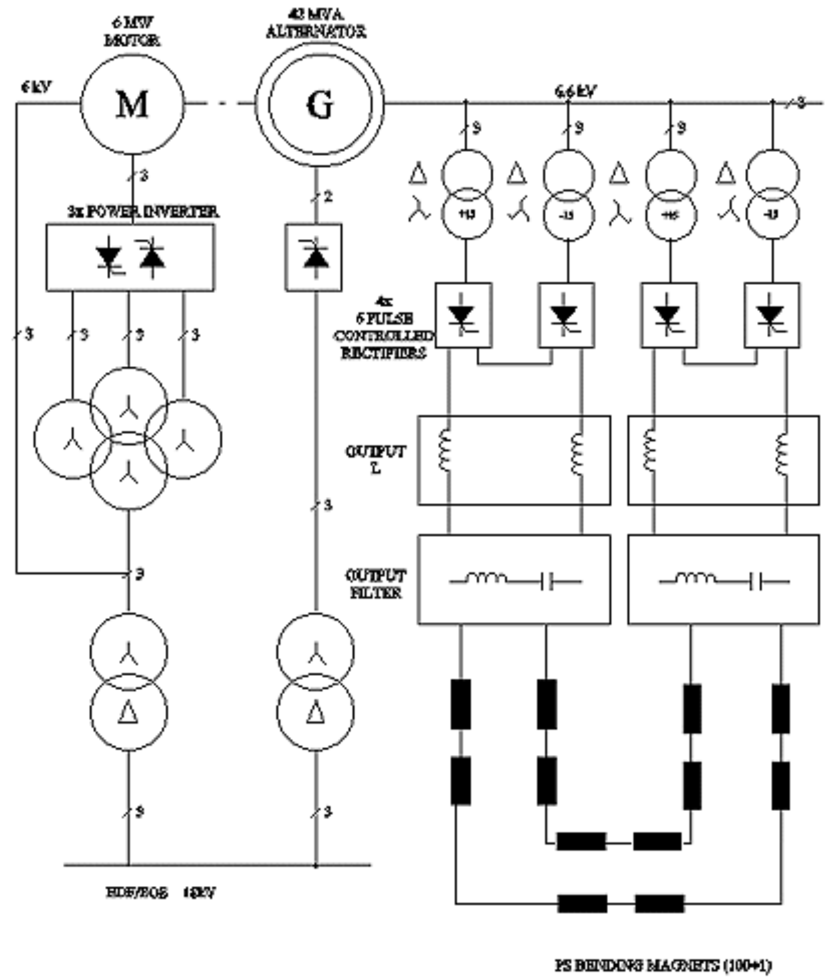
❖1968

A new machine was build to double the power

How to power such a machine ?

<u>Ratings</u>

Load:	0.9 H / 0.32 Ω
DC output:	6 kA / 12 kV
Generator:	90 MVA
Motor:	6 MW
Speed:	1000 rpm
Rotors weight:	80 +10 tons



Few numbers:

Number of cycles per year:	6-8 millions
Number of cycles since 1968:	>300 millions!!!

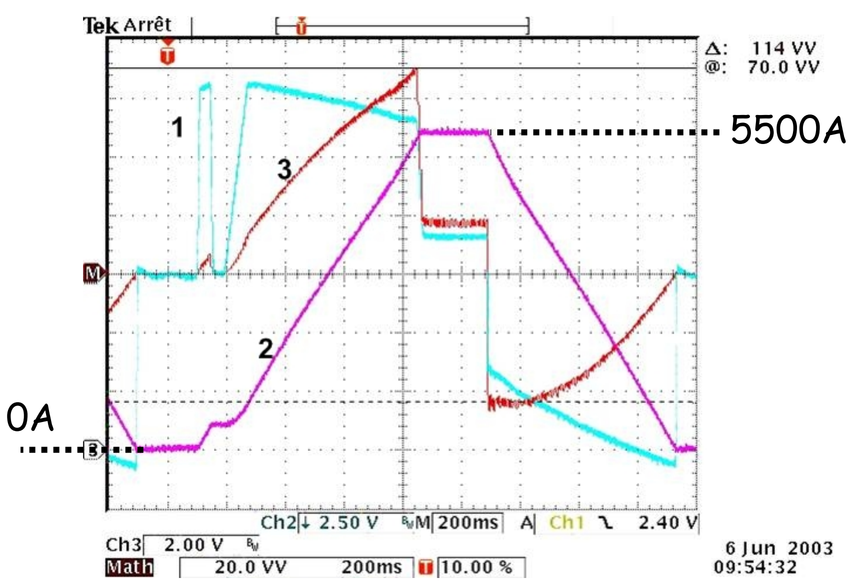
Total losses of the power system 1.5MW

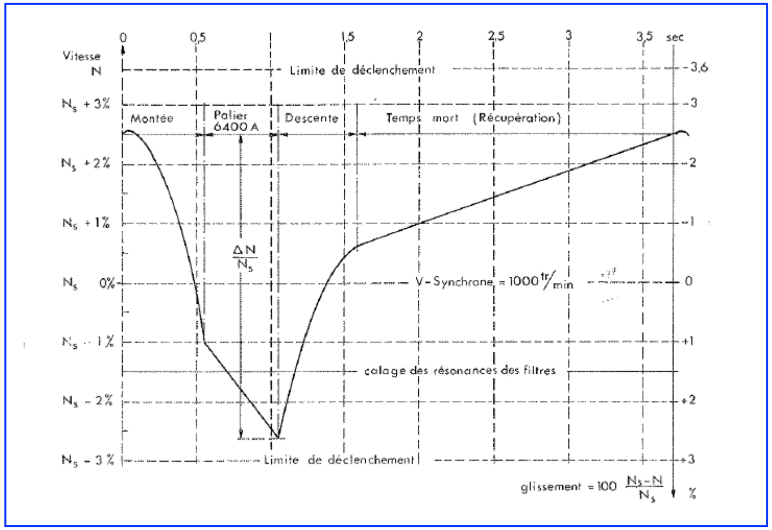
90m^3 of tap water to cool -down the power system

Basic principle with this rotating machine

The 6MW motor drags a heavy (80 tons) rotor of the generator.
The kinetic energy of the rotors is 233MJ at 1000rpm.
When the magnet current ramp to 6kA, the motor will rapidly saturate at 6MW.
Then, the speed of the motor will decrease up to 5%.
When the current returns to zero, the energy of the magnets will reaccelerate the rotor at the nominal speed.

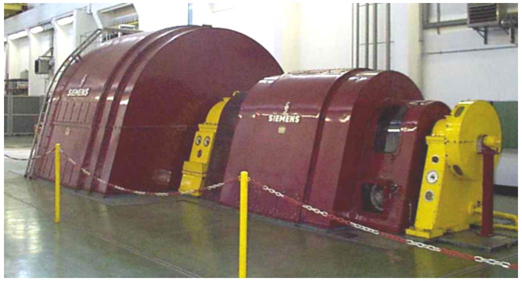
With this system, only the losses of the magnets is taken of the electrical network.
During each cycle, up to 14MJ is exchanged between the kinetic energy of the rotors and the magnets.

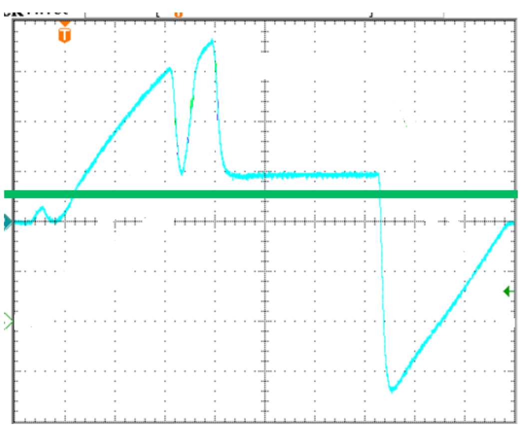




Generator speed variation during a cycle

Basic principle with this rotating machine





Intermediate stored energy

Kinetic energy= 1/2.m.v^2
=233MJ at 1000rpm

Magnetic energy=1/2.LI^2
=12MJ at 5.4kA

Losses of the magnet= R*I^2
=10MJ at 5.4kA per cycle

Energy from the mains

Magnet energy

Research of new power system

Many studies were done between 2003 - 2007

Electrical network:

Connect the load directly to a very high power network (400kV)

Kinetic storage:

Is it still a solution for this type of load?

We didn't find any interested supplier

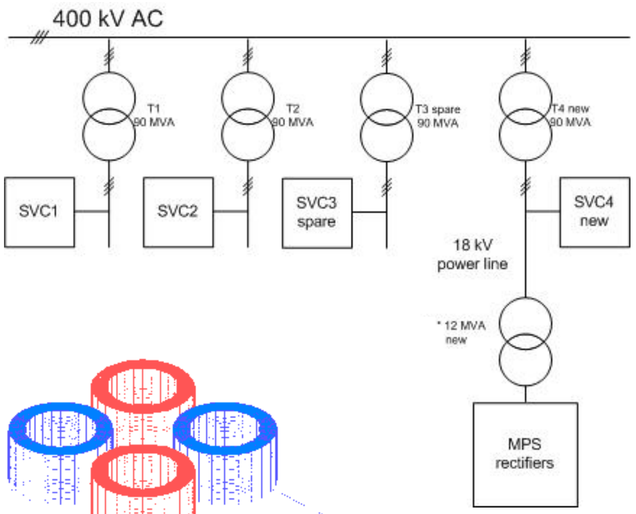
New types of local energy storage system

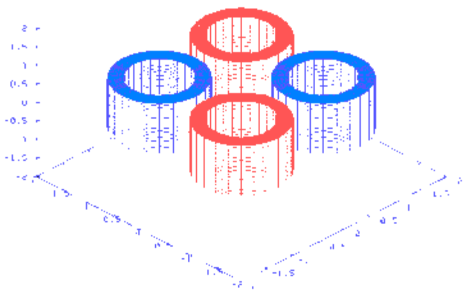
Batteries

Capacitors

Supercaps

SMES: Superconducting Magnetic Energy Storage

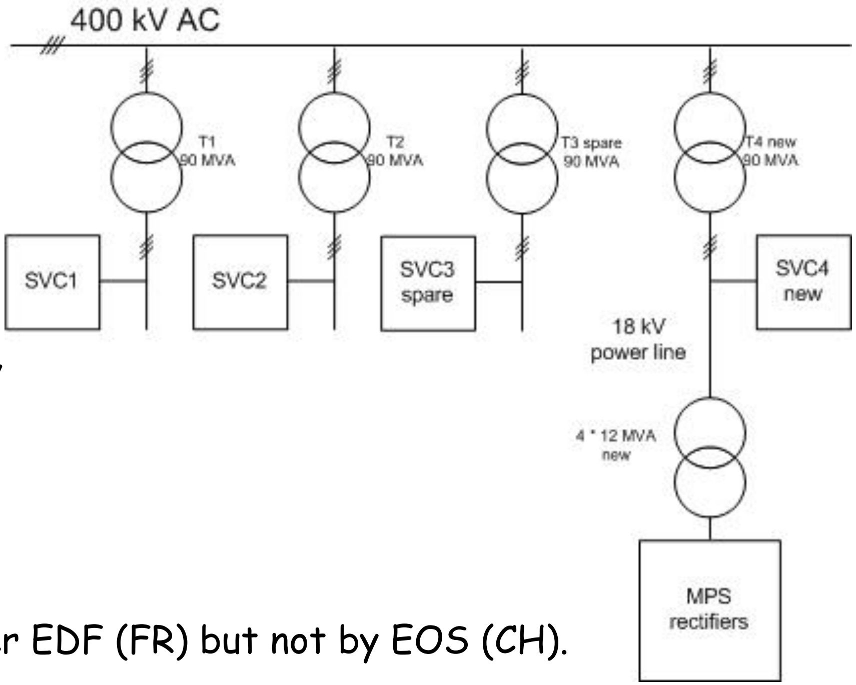




Electrical network solution

The full power comes from the network.
Requires a very high power network: Peak power < 1% Short-circuit Power of the network.

The thyristor rectifiers are connected via transformers to the 400kV network
Needs a reactive power compensation (SVC)



Advantages:
- Industrial solution but not off-the-self
- Return of the magnet energy to the network

Drawbacks:
- Limit of the performances due to thyristor technology
- Exchange of energy with a power plant
- Bad use of a 400kV power line

Proposal approved by one of the CERN electricity supplier EDF (FR) but not by EOS (CH).

Examples of this type of powering:
- SPS at CERN, 140MW peak power, 40MW average, 14s cycle
- ITER

Local energy storage system

The idea is to reproduce the same principle as with the present rotating system.

- Need energy storage devices
    - Batteries
    - Capacitors
    - Supercapacitors
    - SMES (see next slide)

	Batteries	Capacitors	Supercaps
Energy Density	100-700kJ/kg	300J/kg	100-500kJ/kg
Charge Discharge cycles	Limited < 10000	Unlimited	Limited < 100000

Only power capacitors can do millions of charge discharge cycles !!!!

- Need the associated power electronics
    - Design a topology which can integrate the energy storage inside the power converter

SMES

CERN did a study to design a SMES for the PS machine with ITP Karlsruhe (DE)

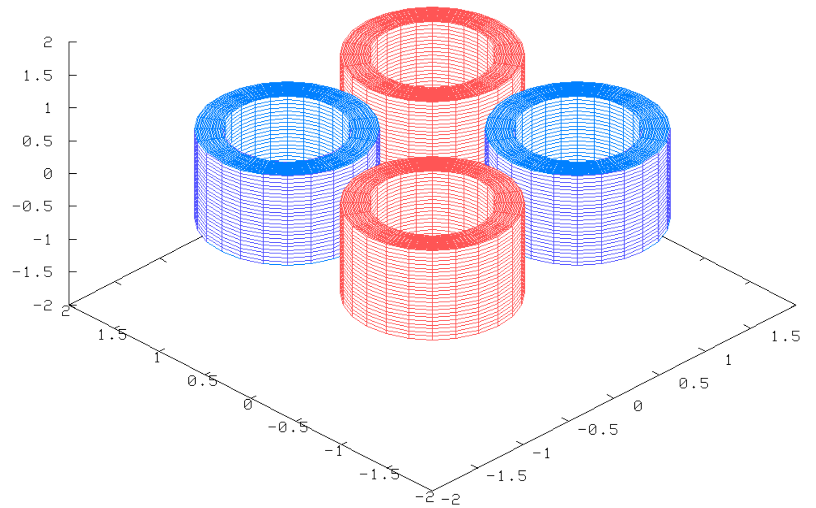
Seems possible but the stored energy must be very high to limit the variation of magnetic field.
Typically, 80 MJ to exchange 14 MJ with the magnets

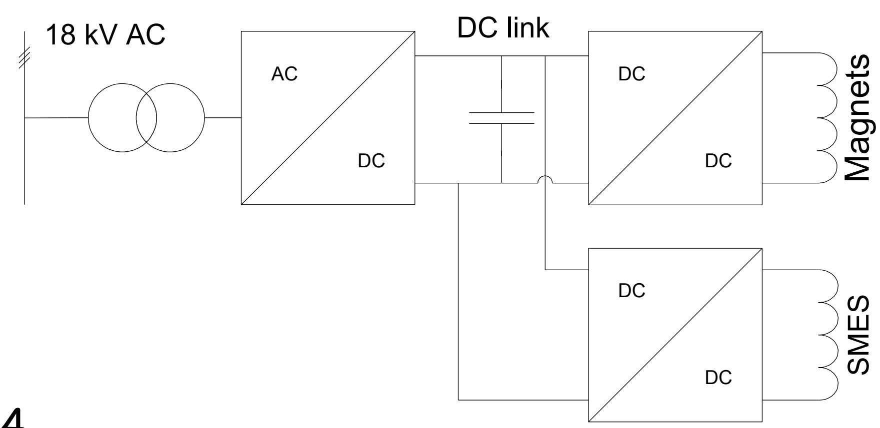
Advantages:

- compact solution
- High discharge rates possible for a reasonable size
- Can be integrated in many topologies

Drawbacks:

- No industrial product above 100kJ
- R&D efforts to be done
- No experience on fatigue with high discharge rates



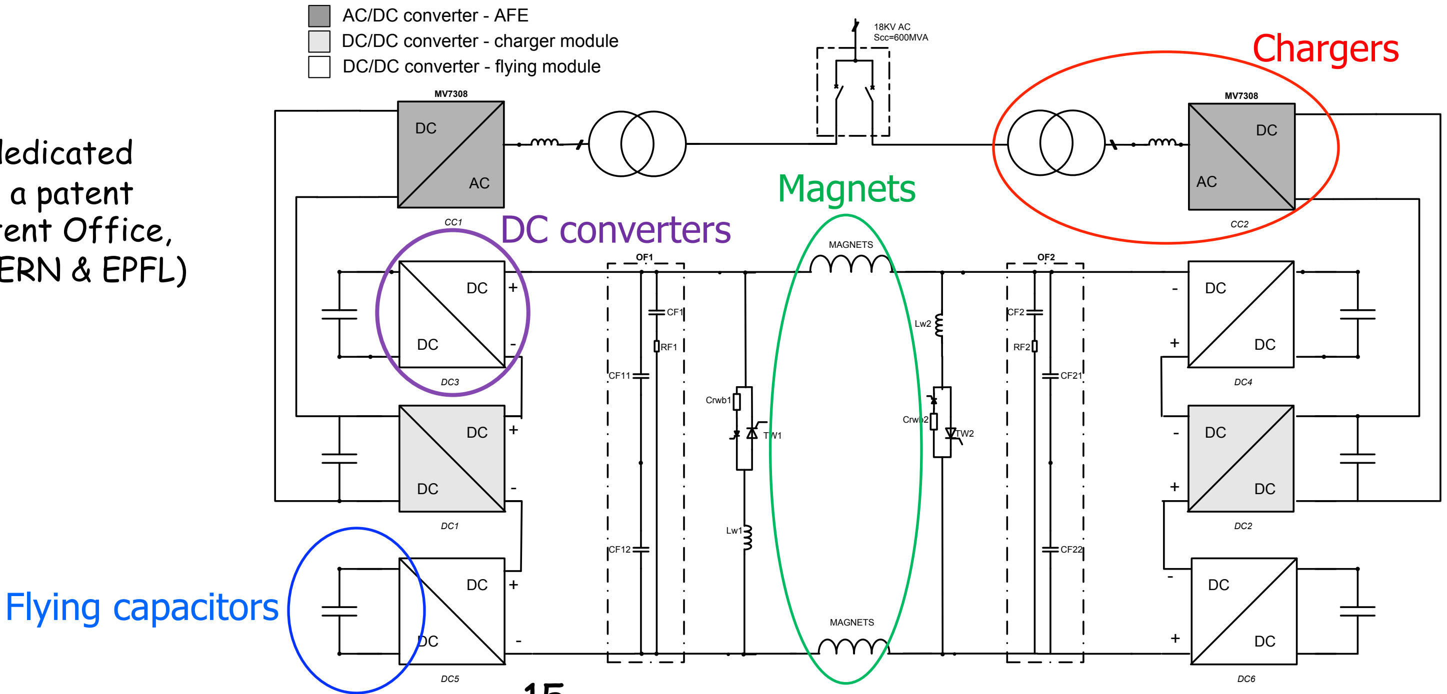


New power system designed by CERN

The energy to be transferred to the magnets is stored in capacitors
The capacitor banks are integrated in the power converter

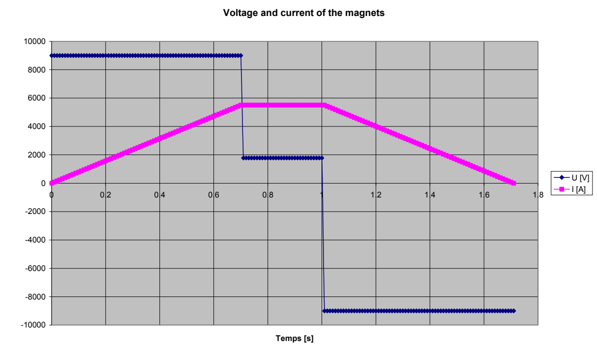
- DC/DC converters transfer the power from the storage capacitors to the magnets.
- Four flying capacitors banks are not connected directly to the mains. They are charged via the magnets
- Only two AC/DC converters (called chargers) are connected to the mains and supply the losses of the system and of the magnets.

Patent
The global system with dedicated control has been filed as a patent application. European Patent Office, Appl. Nr: 06012385.8 (CERN & EPFL)

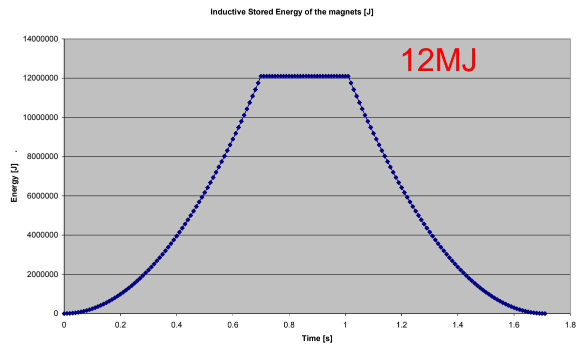


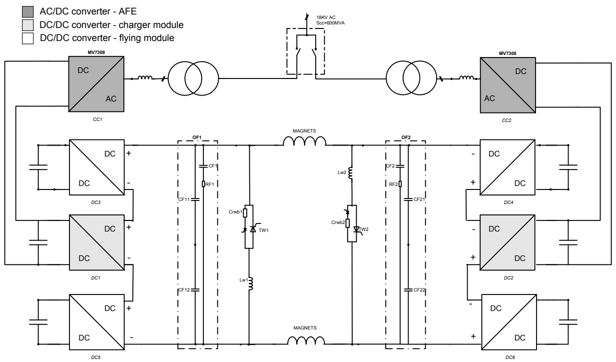
How POPS works

Magnets current and voltage

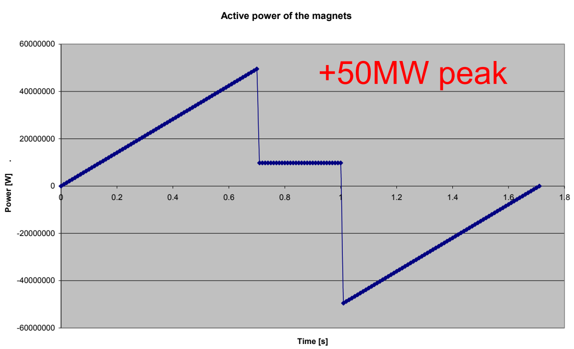


Stored magnetic energy

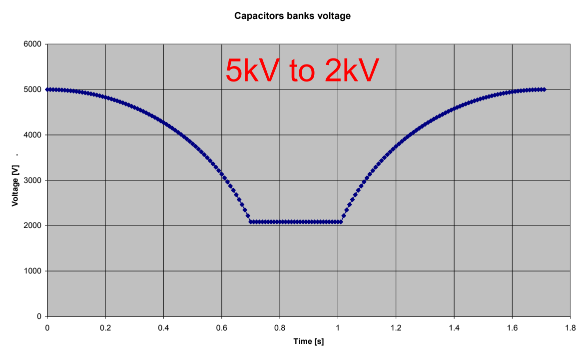




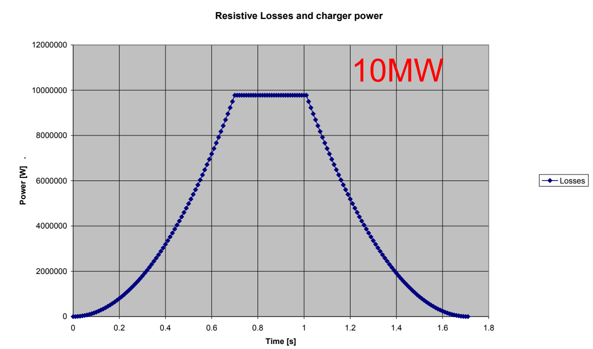
Power to the magnets



Capacitor banks voltage



Power from the mains = Magnet resistive losses



POPS is the name of this new power system.
POwer converter for the PS main magnets.

How POPS looks like

Control room Electrical room Cooling tower Power transformers Capacitor banks

Capacitor banks

Capacitor banks

- 5kV Dry capacitors
- Polypropylene metalized self healing
- Outdoor containers: 2.5m x 12m, 18 tons
- 0.247F per bank, 126 cans
- 1 DC fuse
- 1 earthing switch
- 3 MJ stored per bank

60 tons of capacitors divided in
6 capacitor banks making in total 18.5MJ

Up to 14MJ can be extracted during a cycle!

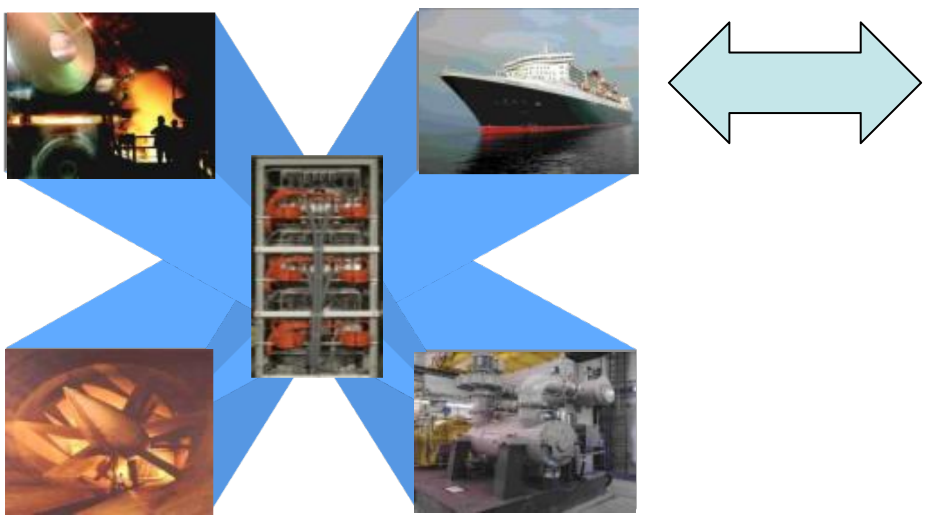
The capacitors represent 20% of the total system cost.

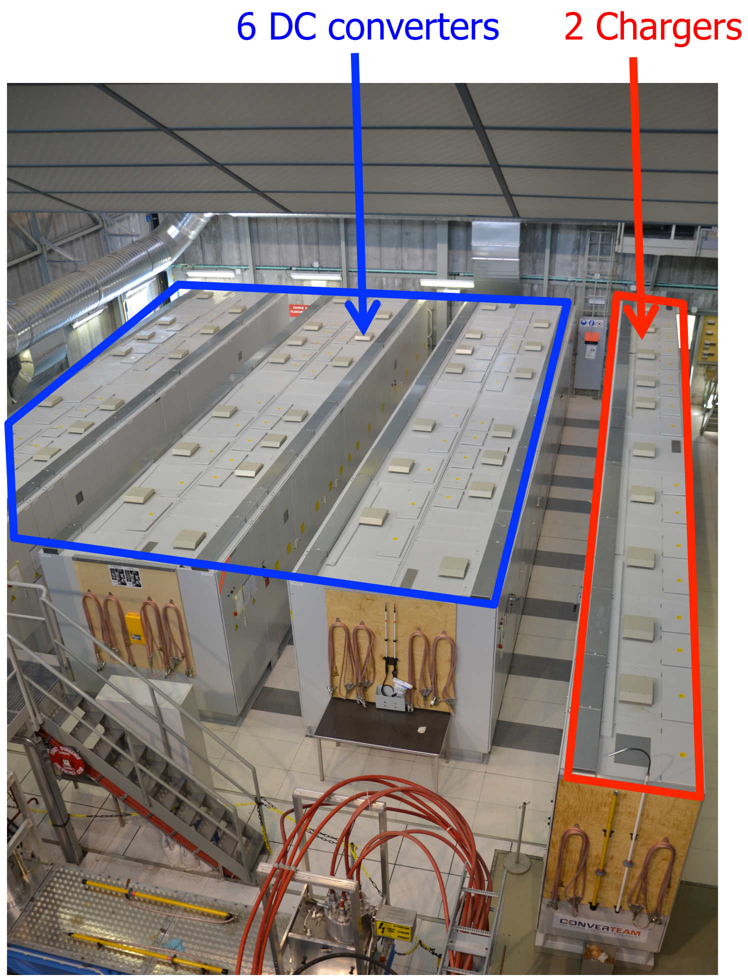
Power electronics

The DC/DC converters are built with industrial motor drives produced in series.
CONVERTEAM have 5GW of this drive in operation!!!

- Two industrial drives (2.6kA /5kV) makes a DC converter
- NPC topology, press-pack IGBT
- 14 industrial drives making a total installed power of 120MW
- 168 power IGBTs are working together!
- Main developments were done for the control

Queen Mary 2 = 4 * 21 MW

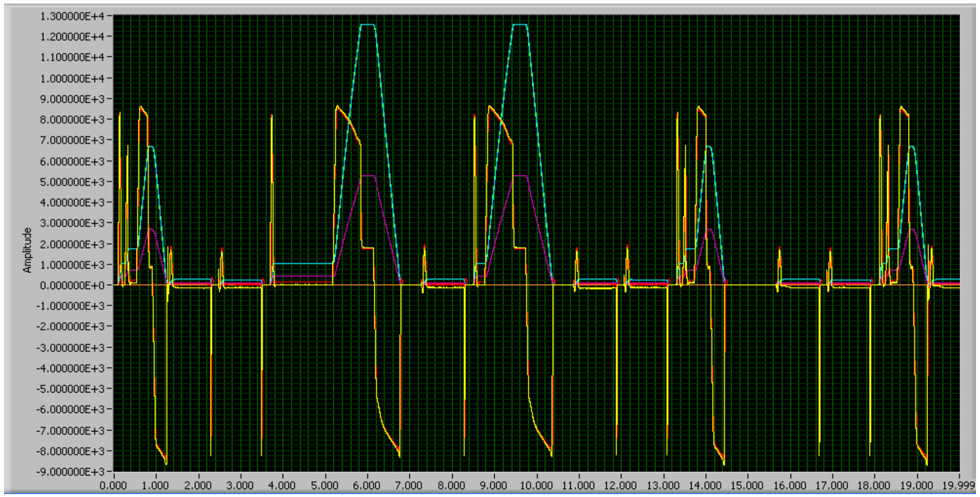


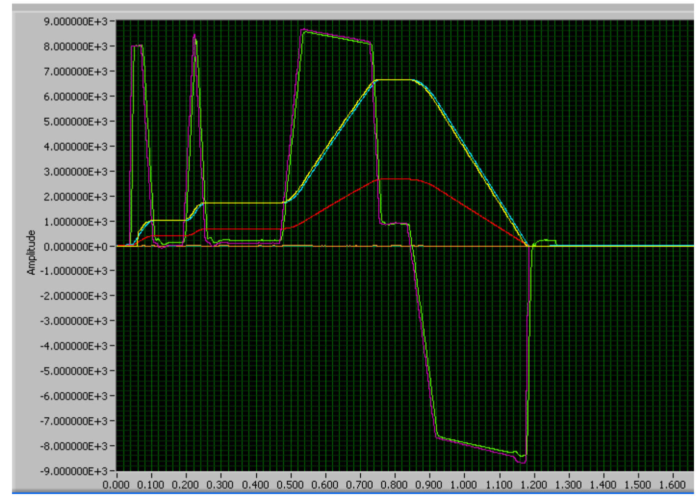


Total losses of the power system: 600kW
1 MW saved compared to previous system
+ 90m^3 of tap water!
Energy is only consumed when pulsing!

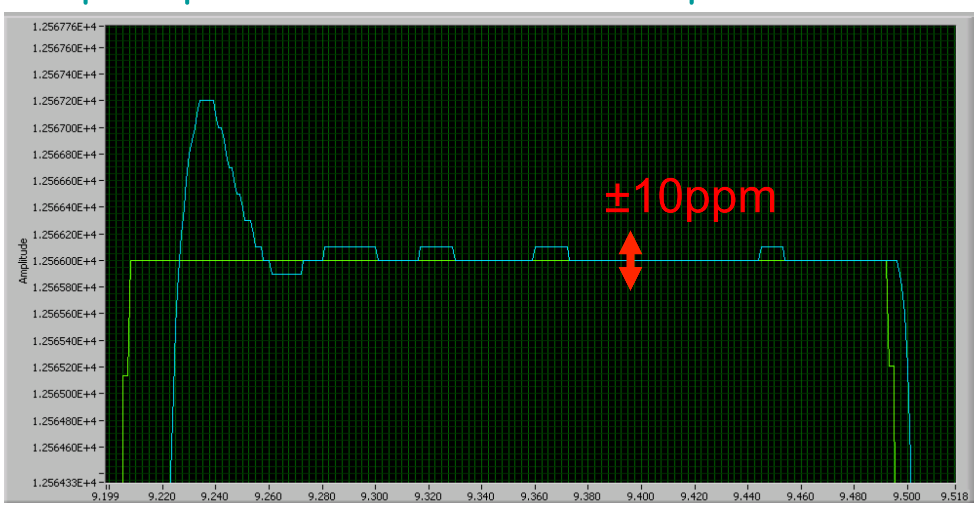
POPS in operation

Friday 11 February 2011 at 11H11: First beam with POPS !!!





http://op-webtools.web.cern.ch/op-webtools/vistar/vistars.php?usr=CPS



Reminder: it is a high-precision power supply

the output current shall be controllable with a precision of 10ppm, 10^{-5} of IMax = 60mA !!!

New rules for new facilities

With POPS, CERN demonstrated that it is possible to design a power system which takes the strict minimum required energy from the electrical network, avoiding large power fluctuation on the mains.

Here are some rules for pulsed machine which can be retained for new facilities:

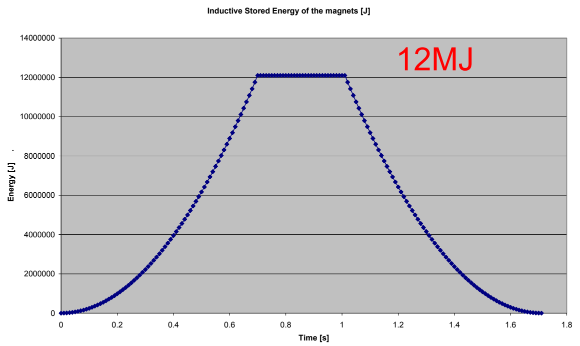
- Rule 1: Power factor = 1
- Rule 2: The stored magnetic energy of the magnets shall be recuperated (no dissipation)
- Rule 3: The stored magnetic energy of the magnets shall be recuperate locally for the next cycle no return to the mains
- Rule 4: The peak power taken on the mains shall not exceed the maximum power dissipated in the magnets
- Rule 5: The peak power taken on the mains shall be very close to the average power of the magnets

Rule 1 and 2 saves energy.
Rule 3 saves energy on the distribution network and reduces power fluctuation.
Rule 4 needs an energy management
Rule 5 saves energy and reduces the energy taken on the mains to the strict minimum.

Rule 1 to 5, from simplicity to complexity, from basic technology to advanced technology

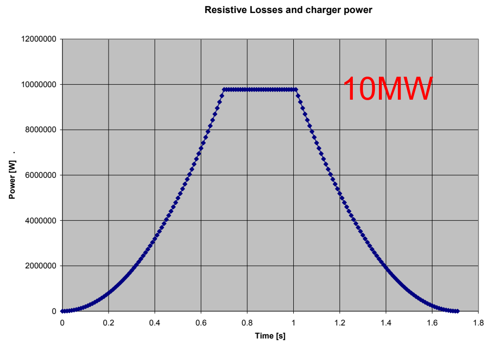
Explanation of these rules with POPS

Stored energy of the magnets



Rule 2 and 3: energy to be recuperated locally

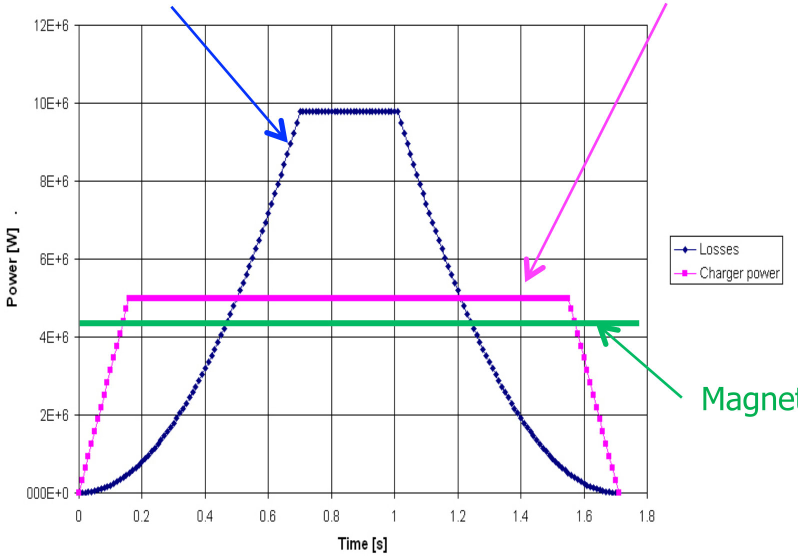
Resistive losses of the magnets



Rule 4:
peak power on the mains ≤ Losses of the magnets

Resistive losses of the magnets

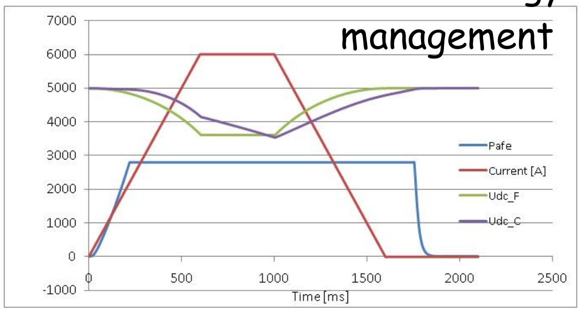
Power demand on the mains



Magnet average power

Rule 5:
power taken on the mains ~ magnet average power

POPS energy management



New rules for new facilities

Case study 1: CNAO (the Italian Hadrontherapy center)
Thyristor converters with reactive power compensator
peak power 10MVA
Average power 4MVA
±5MVA (main dipoles)
Cycle duration 1.2s
Network fluctuation controlled by reactive power compensator

The main dipoles are the biggest load of the machine (50%).
The thyristor converters allow the return of the energy to the mains but require a reactive compensator. The energy is recuperated but the flow of power is very high on the network.

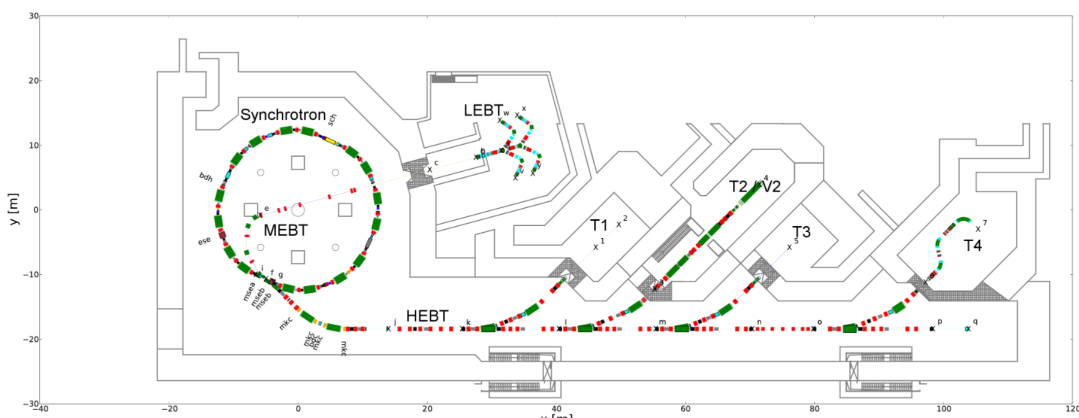
Rules 1 and 2 are respected.

New rules for new facilities

Case study 2: Medaustron (new centre for ion-therapy, Austria)
Switch-mode converters with capacitor bank
machine peak power 11MWA
Average power 4.5MVA
Cycle duration 1.2s
power factor = 0.95
Network fluctuation not controlled <2%
Power transformer 16MVA (110kV / 20kV)

All the power converters for magnets will have a capacitor bank to recuperate the magnetic energy during each cycle.
Only the main power converter for the dipoles will have an energy management and will respect rule 4.

Medaustron respects rule 1, 2, 3 and partially 4 (only the dipoles).



Conclusions

Advanced power electronics associated with storage devices allow a better energy management between the load and the network.

With POPS, CERN demonstrated that it is possible to design a power system which takes the strict minimum required energy from the electrical network, avoiding large power fluctuation on the mains, and minimizing the total losses.

Electrical storage devices are key elements, Will SMES can play a major role in a near future?.

Power quality is a critical issue for particles accelerators, a local energy storage helps to solve this problem.

5 rules are proposed to build new facilities.

Smart power management is possible for particles accelerators. !

Be smart, choose the most advanced technology!