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Energy recovery from magnetic field

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Electrical Power Converters (TE/EPC) group

With valuable inputs from Gijs De Rijk (TE/MSC)

Specifications

- Based on first numbers provided by *Gijs de Rijk* in April's Preparatory Meeting

Acc. length	22	*km*
Pulsed magnet mag length	15.6	*km*
Energy stored in pulsed mag.*	125	*MJ*
Field swing	-2 → 2	*T*
Field swing time	3.8	*ms*
Acc. Repetition rate	6 → 12	*Hz*

*From estimated aperture stored energy: E_{tot}=125 MJ (actually more considering energy stored outside aperture)

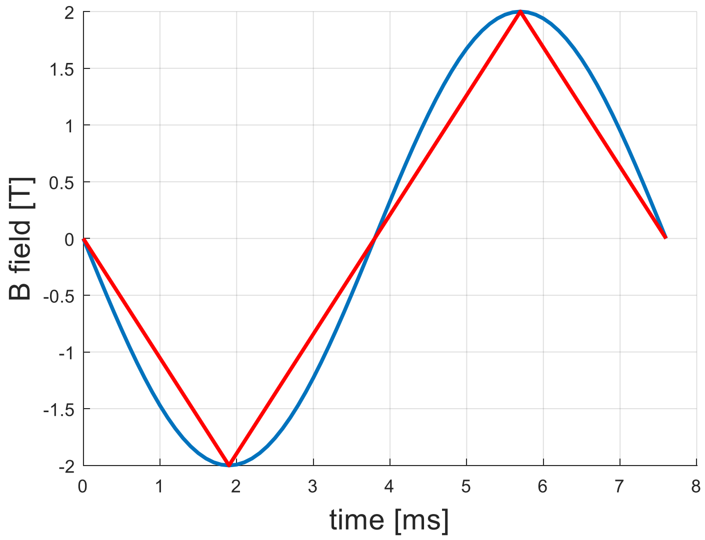
Simple analysis

- Implications on swinging *B* field (4 *T* swing in 3.8 *ms*)

➢ For a perfect current or field ramp
  - ➢ Max instantaneous power 2 x 125 MJ / 3.8 *ms* = **65 GW** !
  - ➢ Energy stored in the converter much higher than 125 MJ (>50% more)
  - ➢ Complex/costly/lossy converter

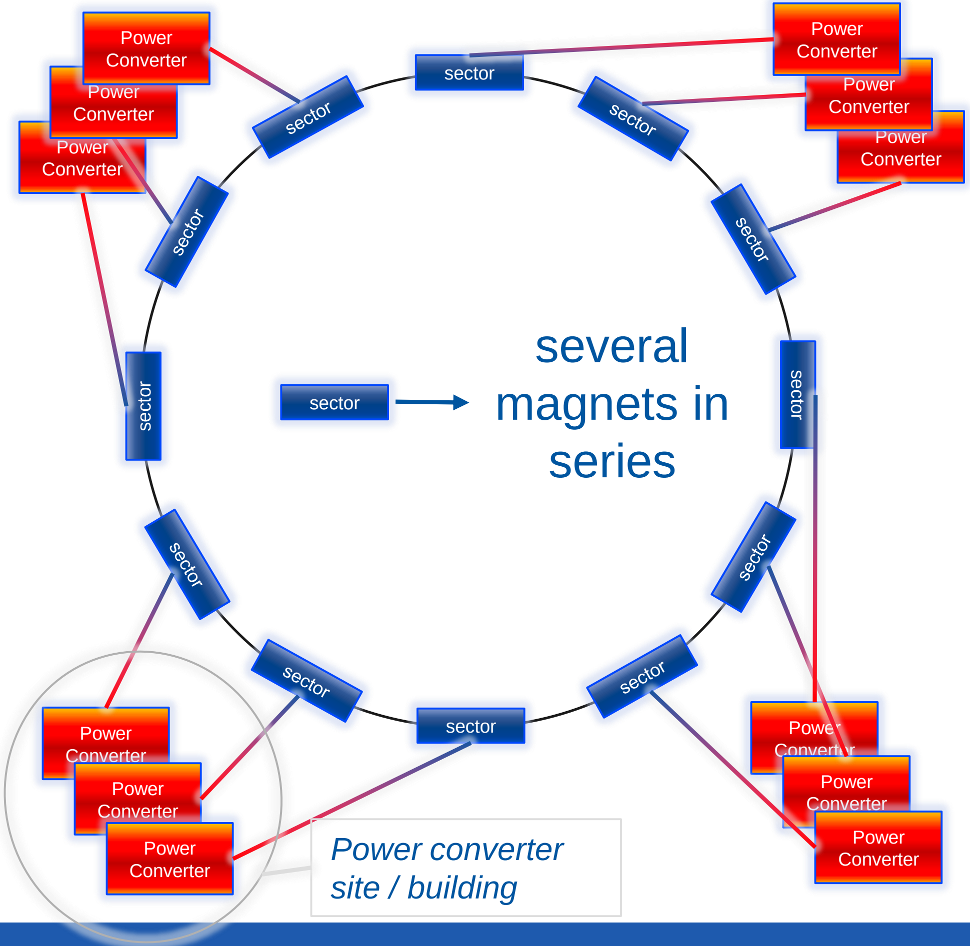
➢ For a sine shaped increase of current & field
  - ➢ $P = \frac{d}{dt}\left(\frac{E}{2} + \frac{E}{2}\sin(2\omega t)\right)$ → **100 GW**
  - ➢ Energy stored in the converter is 125 MJ - minimal energy storage configuration
  - ➢ Viable/Simpler/More efficient converter

Two “extremes” swing shapes analysed



Simple analysis

- Most important variable Number of sectors (Nos) to explore feasible Voltages & Currents
  - ➢ Proceed with a sensitivity analysis w.r.t. the *Nos*
- Main questions to be answered first:
  - How many powering sectors?
  - What voltage – current per sector?
  - How many power converter sites? (cable length)



Simple analysis

- SPS magnet type MBE as baseline (also 1.8T - 2T range)
- Inductance / meter / turn is L_{mt}=*6.2 µH* – this wont really change
- A simple system of equations for deriving voltages & currents combinations:

Dipole characteristics MBE

Magnet type		B1	B2	B2/2
Basic parameters				
Magnetic length	(m)	6.26	6.26	3.13
Maximum field	(T)	1.8	1.8	1.8
Aperture height	(mm)	39	52	52
Aperture width	(mm)	129	92	92
Core characteristics				
Length	(m)	6.200	6.200	3.07
Lamination height	(mm)	2x225	2x225	2x225
Lamination width	(mm)	800	800	800
Packing factor	(%)	97	97	97
Core weight	(ton)	16	15.5	7.7
Block weight	(ton)	20	20	10
Coils characteristics				
Maximum length	(m)	6.507	6.476	3.346
Number of turns		2+10	4+12	4+12
Conductor inner coil	(mm^2)	24x33	32x22.5	32x22.5
Conductor outer coil	(mm^2)	32x32	33.5x33.5	33.5x33.5
Cooling hole inner coil	(mm)	6.5	10.2	10.2
Cooling hole outer coil	(mm)	10	11	11
Number of water circuits		3	3	3
Amount of cooling water	(m^3/h)	1.9	2.59	3.6
Temperature rise	(°C)	14	14	6
Pressure drop	(kg/cm^2)	6	6	6
Copper weight	(ton)	1.38	1.88	1.05
Excitation				
Peak ampere-turns	(A)	58800	78400	78400
Peak current	(A)	4900	4900	4900
Rms current	(A)	3102	3102	3102
Average current density (rms)	(A/mm^2)	3.42	3.36	3.36
Resistance	(mΩ)	3.23	4.42	2.47
Inductance maximum	(mH)	7.73	9.9	5.0
Inductance at 1.8 T	(mH)	7.35	9.4	4.7
Losses	(kW)	31.1	42.3	23.6
Peak stored energy	(kJ)	88.2	113	57
Ampere-turns in iron (1.8 T)	(%)	5	5	5

Thermo switch : 75°C

$$\begin{cases} V_{ps} = L_{ps}\dfrac{di_{ps}}{dt} \\ P_{pc} = V_{ps} i_{ps} \end{cases}$$

$$L_{ps} = L_{mt} S_l$$

Simplifying (constant voltage during current and power ramps)

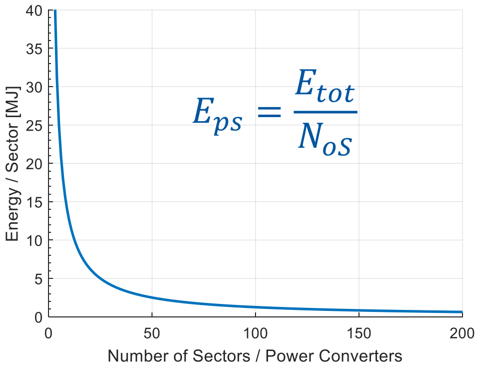
Ramp case

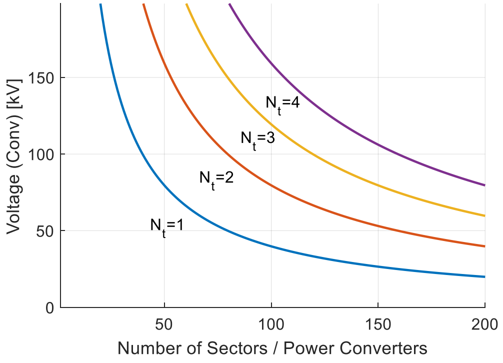
$$\frac{di_{ps}}{dt} = \frac{d\left(P_{pc}/V_{ps}\right)}{dt} = \frac{\Delta P_{pc}}{V_{ps}\Delta t} \Rightarrow V_{ps} = \sqrt{\frac{L_{ps}\Delta P_{pc}}{\Delta t}}$$

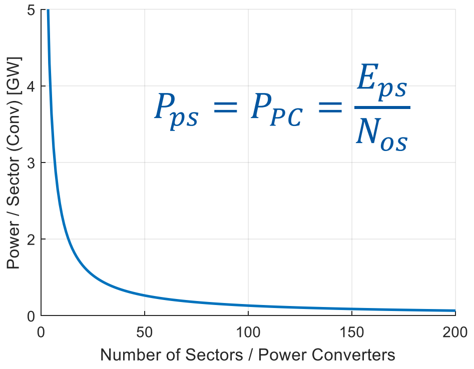
Sine case

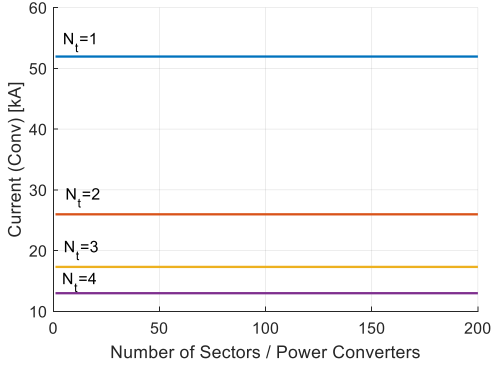
$$\frac{di_{ps}}{dt} = j2\omega\frac{P_{pc}}{V_{ps}} \Rightarrow V_{ps} = \sqrt{L_{ps} 2\omega P_{pc}}$$

Simple analysis: vs. number of sectors









Clear need for:

- low magnet inductance (turns number = 1)
- High number of power converters to reduce Magnets voltage insulation (to ground)

- Either distributed power converters along the ring or centralization with long cables…

Losses (rough) analysis

- Magnets losses
  - If current density 3 MA/m^2, 6 kW/m of losses if continuously fed with DC or RMS current - **10 MW losses @ 6 Hz rep. rate or 20 MW @ 12 Hz rep. Rate**
  - Using SPS magnets: 4.3 MW @ 6 Hz rep rate, 8.6 MW @ 12 Hz rep rate – but these magnets have a lot of copper for higher average currents
- Converter losses
  - ~ 0.1 – 0.5% (continuous operation) for a simple topology providing a quasi-linear current excursion
- Cable losses
  - Very important depending on the integration of the sector powering – centralization of powering for several sectors? Need for long cables. Global study needed to give some figures
  - Estimation: same losses amount as Magnets: 10 MW – 20 MW
- Distribution losses (transformers, bus bars, AC lines feeding all sectors) : 1%
- **Global losses / Average power needed from grid: 25 MW – 60 MW range (assuming 125 MJ!)**
- **Energy recovery efficiency: 92% - 95% range**

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PS and SPS energy cycling

	PS	SPS	Muon
Magnetic energy	12 MJ	90 MJ	125 MJ
Power losses	3.3 MW	32 MW	25-60 MW
Field rise time	0.5s	3s	3.8/2ms
Power (magnetic on average slope)	24 MW	30 MW	65 -100 GW
Peak Power losses	12 MW	80 MW	Depends upon the design of magnets
Peak Design power of power converter	60 MW	150 MW	Too big anyways !!

Energy exchange and losses don't seem to be dramatically high

On the contrary the peak power is huge with respect to what has been done with ordinary power electronics bridges. It is clear that a much simpler power converter concept than POPS or SPS mains must be identified.

The simpler one is the resonating discharge whereby the power converter acts as switch to start and stop the resonance with the magnets.

Some application exists in the laser experiment field (ex LMJ Bordeaux) but repetition rate is orders of magnitude lower than with an accelerator. (few pulses per week)

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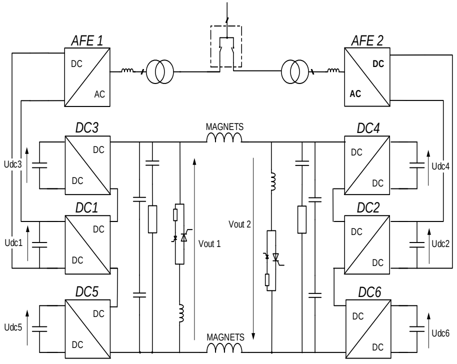
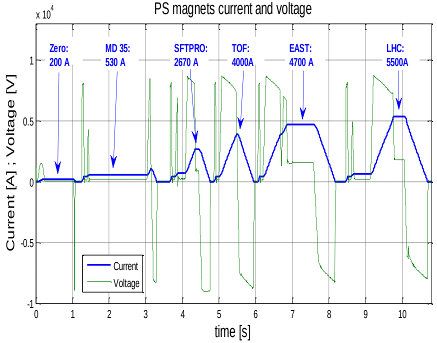
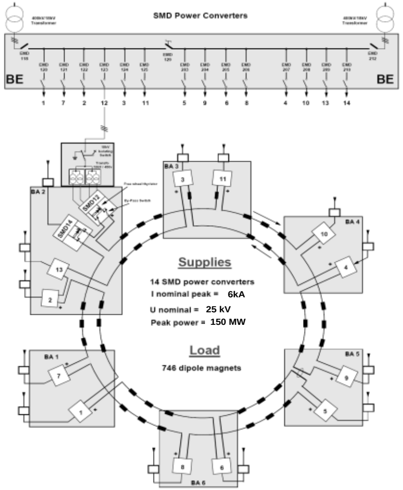
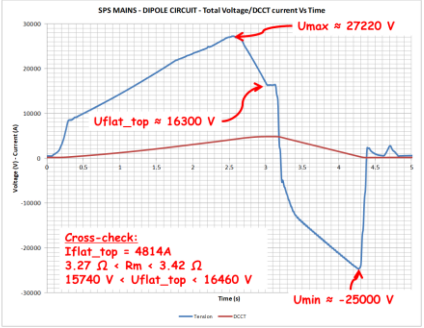
PS and SPS main power converters



AFE 1 ; AFE 2 — AC/DC rectifiers
DC1; DC2 — DC/DC converters "Charger" type
DC3 ; DC4 ; DC5 ; DC6 — DC/DC converters "Floating" type







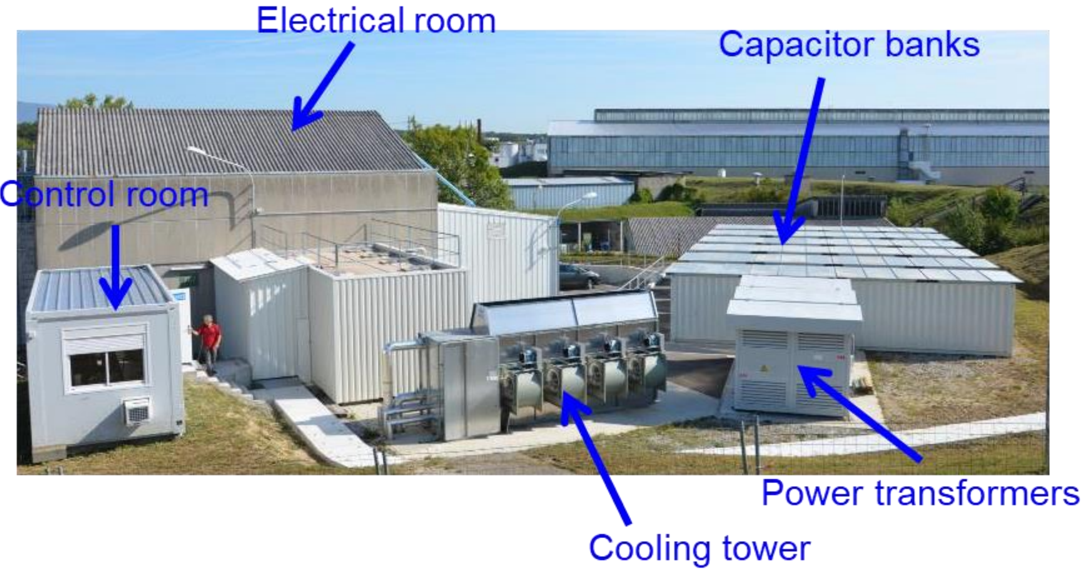
Rmag=0.37 Ω
Lmag $_{(unsat)}$=0.97 H
Vpk = 9000 V
Ipk = 5500 A

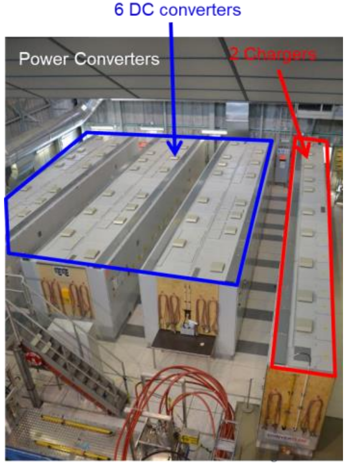
Energy storage

Rmag = 3.4 Ω
Lmag$_{(Unsat)}$ = 6.4 H
Vpk = 27000 V
Ipk 4800 A

Reactive power compensation

Energy storage: the POPS example





70 tonnes of power converters.
1200 m^2 of land
16 MCHF (building included)

90 tonnes of capacitors.
300 m^2 of land
3 MCHF

Energy storage for Muon collider

CERN has experience with capacitors so far.
A simple scale up from POPS capacitor energy will give a factor ten in volume and cost

	POPS	Muon linear ratio
Capacitor energy	20 MJ	200 MJ
Capacitor weight	92 tonnes	920 tonnes
Capacitor land area required	300 m^2	3000 m^2
Capacitor cost estimation	3 MCHF	30 MCHF (capacitors only!)

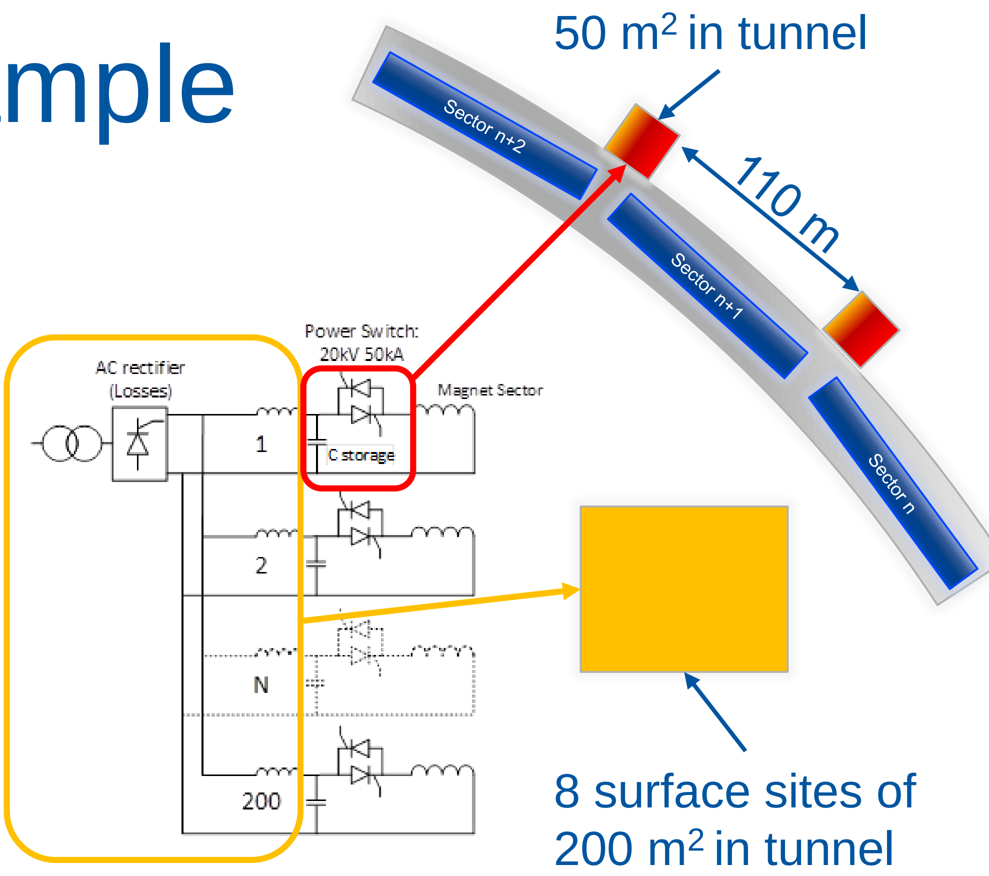
Capacitor dimensioning depends strongly on voltage-current shape. No experience exists in the field.

You need to find how to protect the capacitors (against short circuit). High voltage fuses in DC is also unknown.

A case study example

- 200 sectors with sinusoidal field (the feasible one)
- 20 *kV* – 50 *kA* each sector (power converter)
- Need for 50 m^2 for local energy storage + discharge circuit
- Sector length 22 *km*/200=110 *m*
- Need for surface building for electrical distribution & rectifier

Back of the envelope analysis



Conclusion

- Powering seems possible but:
  - Lot of R&D needed in strong collaboration with civil eng., power distribution eng., magnet eng., etc.
  - Lot of R&D needed for fast energy storage technology
  - Due to technological challenges an experimental proof of principles shall be addressed. R&D efforts look very high.
- Magnets should present the smallest possible inductance due to pulsed operation (voltage levels)
- Number of power Sectors or Converters > 150 - 200
- Current/field swing shape has an impressive impact on technology, and cost. No viable solutions found with a perfect current ramp!
- Total losses of pulsed magnet system in the range of 25 – 60 MW
- Energy recovery efficiency: 92% - 95% range

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