Fast ramping magnet's powering for the Muon Collider

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20/09/2021

Introduction: Problem Statement

Powering dipole magnets with fast rising magnetic field with repetition frequency of 5Hz

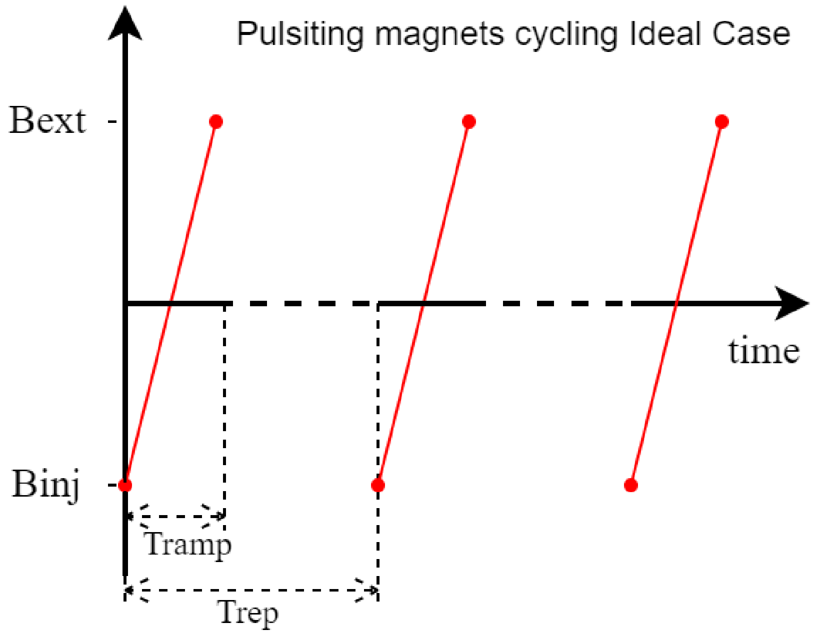
- **Example:**
  - Powering dipoles for a B field swing 4T (-2T → 2T) in 2ms
  - Energy stored in the magnetic fields of the dipoles

$$E_{B_{max}} = \frac{B_{max}^2}{2\ \mu_0} \cdot \underbrace{L_{ramp} . H_{gap} . W_{gap}}_{V_{gap}} = 64\ \text{MJ}$$

  - Linear ramp requires a huge amount of power

$$P(t) = \frac{V_{gap}}{2\mu_0} . \frac{\Delta B^2}{\Delta T} = 128GW$$

- **Solving this with Conventional Power Electronics is virtually impossible**
  - Energy stored in Converter much higher than $64\ \text{MJ}$ (2-3 times more)
  - Complex/costly/lossy converter



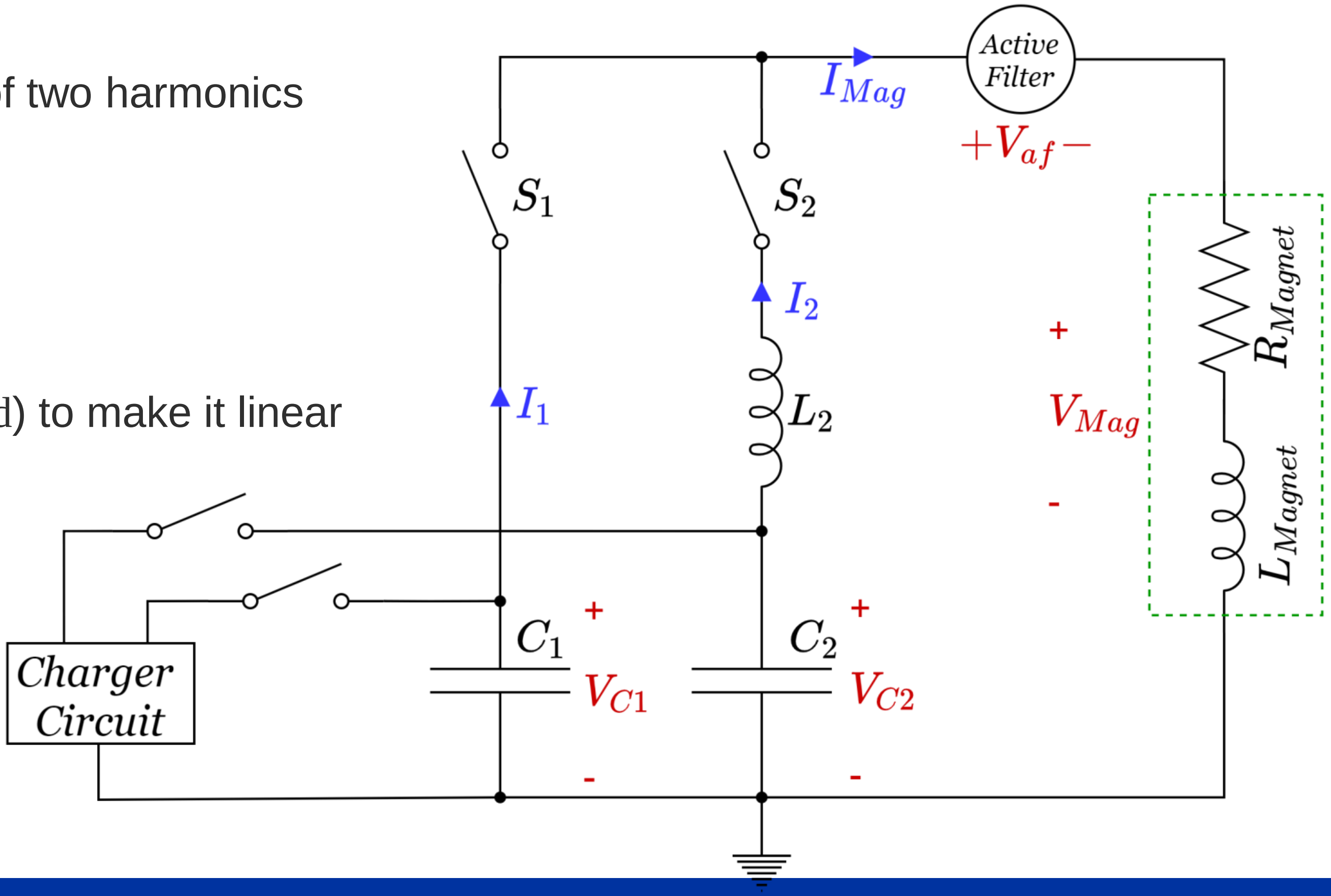
$$\text{Binj} = -2\text{T} \div -1\text{T}$$
$$\text{Bext} = 2\text{T} \div 1\text{T}$$
$$\text{Tramp} = 0.4 \div 12\text{ms}$$
$$\text{Trep} = 200\text{ms}$$

An alternative strategy: resonant converter

- **Natural resonant discharge**
  - The energy initially stored in the capacitors is transfer to the magnets
  - Lineal ramp approximated by resonance of two harmonics

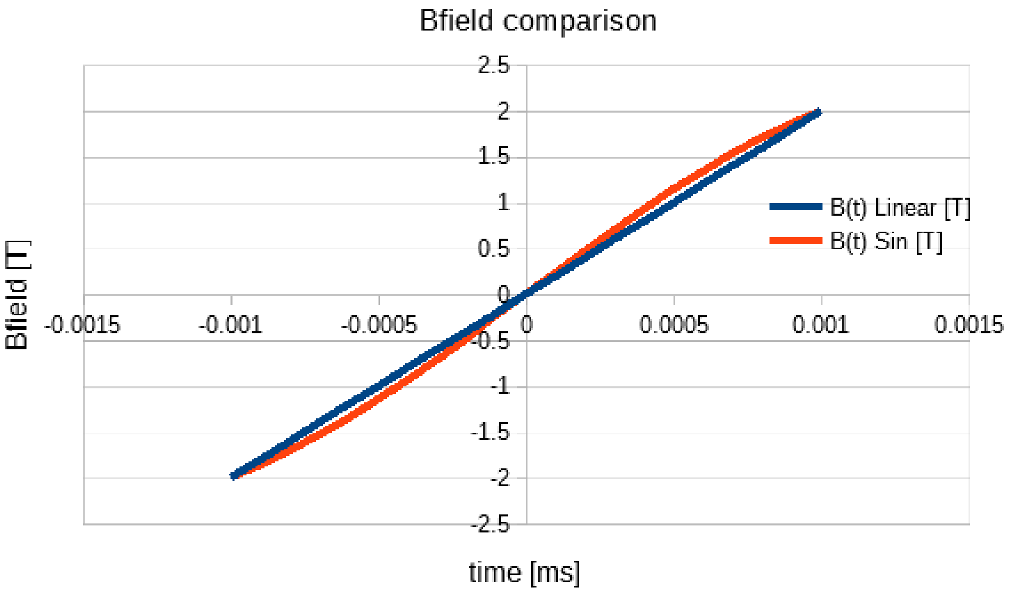
- **Active Filter (AF)**
  - Built with modern power electronics.
  - Corrects current through magnet (α B-Field) to make it linear

- **Advantages**
  - Less power handle by Power Electronics
  - Minimum energy storage configuration

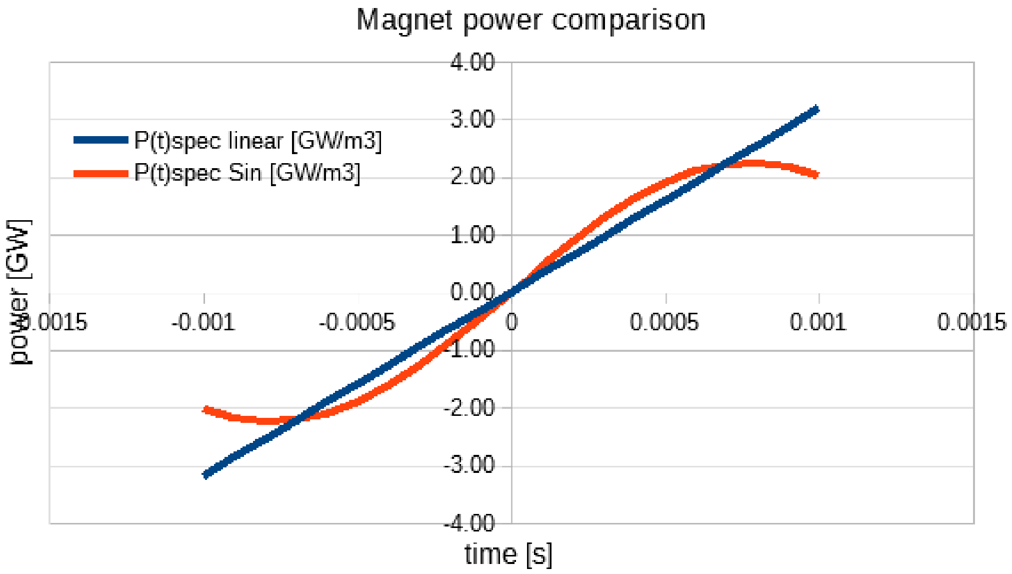


Optimization of the B Field Reference

A further improvement in the design can be achieved if some compromise can be accepted with respect to the linear ramping up of the Bref



B-Field: Linear vs. Sine portion



Peak Power: Linear Vs Sine portion

A portion of sinus slightly deviate from a linear acceleration, but the peak power is greatly reduced (30%)

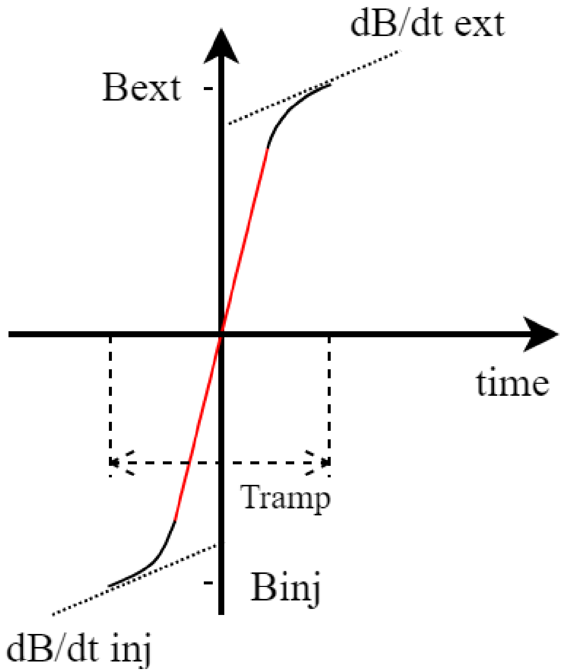
Optimization of the B Field Reference

- **Currently developing an optimization tool for minimizing**
  - Costs (passive components and AF)
  - Volume and energy of the storage means
  - Operational loses (Active Power)

- **Inputs:** $B_{inj},\ B_{ext},\ \left.\frac{dB}{dt}\right|_{inj},\ \left.\frac{dB}{dt}\right|_{ext},\ Tramp$

- **Outputs:**
  - Optimal harmonics to reduce AF utilisation
  - Components values for natural resonance
  - Evaluation of cost function/s

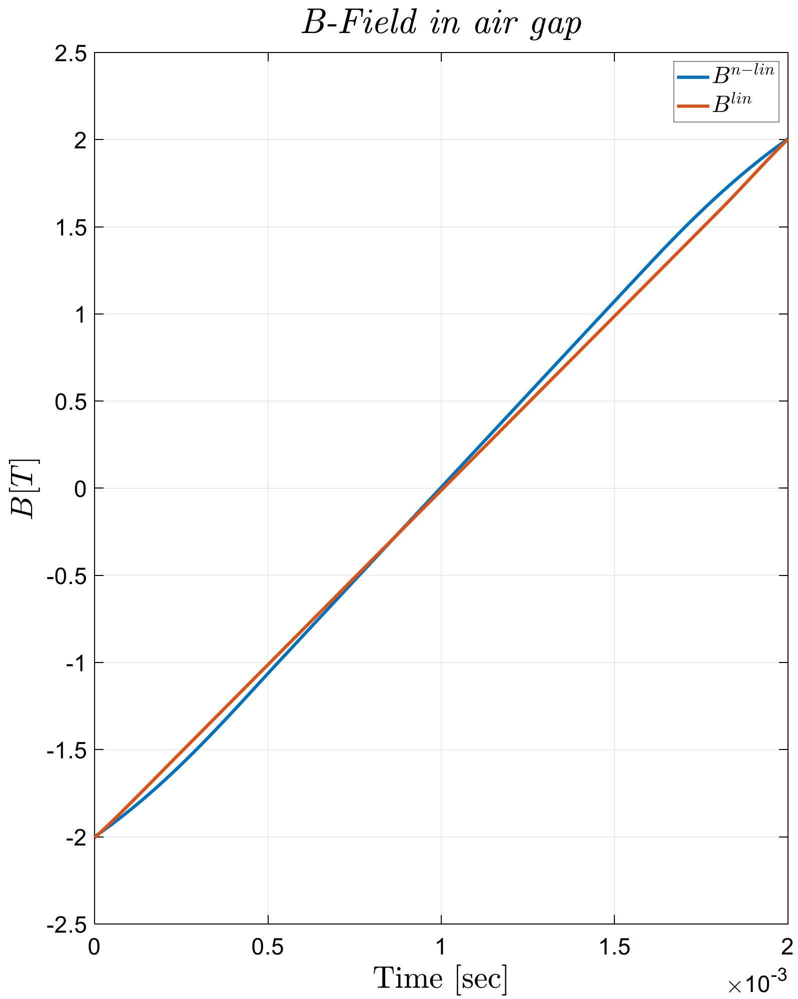
- **Flexible and adaptable tool**
  - Allows you to try different sets of inputs
  - Room for change or improvement of mathematical model of components

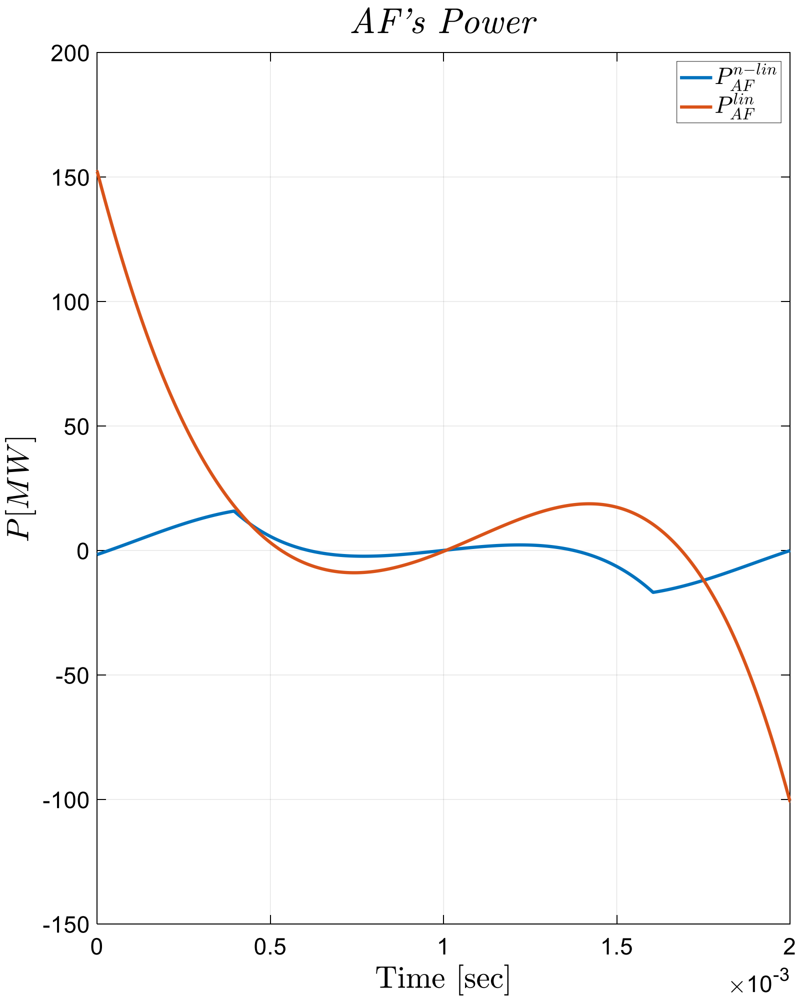


Optimization of the B Field Reference

- **Ramping up**:
  - Sin. + Linear + Sin.

- Inj. and ext. during the sinusoidal portion greatly relaxes the demand on the AF





Ramping up magnets (Warm type)

Magnet characteristics are mandatory for an evaluation of the powering system

The SPS magnet type MBE are our baseline for the moment (also 1.8T - 2T range)

It is very important to correctly evaluate the Energy integral over the total volume of the air gap and not only the vacuum chamber

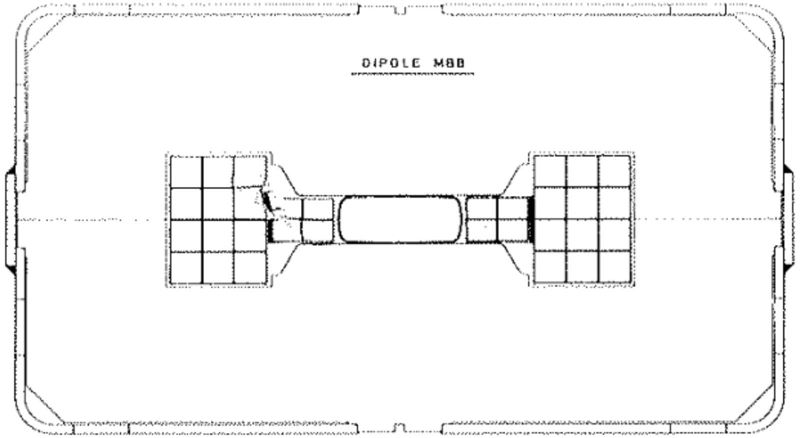


Fig. 2 MBB dipole cross-section

In MBE magnets the total energy is 2.5 times the value calculated only considering the vacuum chamber volume

The input of magnet experts is strongly required!

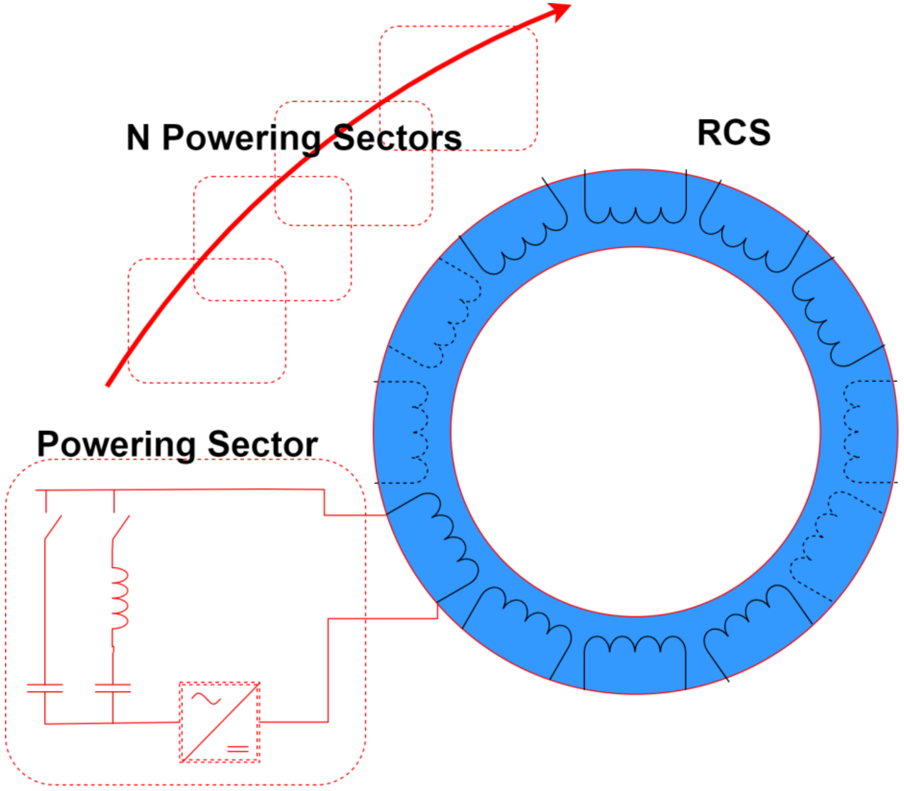
Preliminary results (3TeV collider):

	D. Schulte Muon Collider Collaboration, IPAC 2021		*H,Damerau MC RF WG meeting #3: RF for HEC*		
Collider COM energy	**3TeV collider**		**3TeV collider**		
	RCS1	RCS2	RCS1	RCS2	RCS3
peak ramping field [T]	2	2	1.5	1.5	1.5
length [km]	1.26	6.28	4.193	3.094	5.13
Ramping dipole gap size [cm2]	32	32	32	32	32
Magnetic field energy in vacuum chamber [MJ]	6.4	32.0	12.0	8.9	14.7
Tramp [ms]	0.4	2	0.33	0.63	1.05
N sector	40	200	75	56	92
DATA per Sector:					
Peak current on RCS magnets [A]	6.36E+04	6.37E+04	4.77E+04	4.78E+04	4.78E+04
Peak current resonating inductor [A]	4.06E+04	4.07E+04	3.05E+04	3.06E+04	3.05E+04
Peak voltage on resonating capacitors [V]	7.98E+04	1.59E+04	1.29E+05	6.69E+04	4.04E+04
Peak Power on Magnets [W]	1.68E+09	3.37E+08	2.04E+09	1.06E+09	6.41E+08
Peak power of the Active Filter [W]	1.25E+08	2.51E+07	1.51E+08	7.88E+07	4.76E+07
Peak Energy of the capacitors [J]	4.49E+05	4.49E+05	4.49E+05	4.46E+05	4.48E+05
Peak Energy of the inductors [J]	1.27E+05	1.27E+05	1.27E+05	1.26E+05	1.27E+05

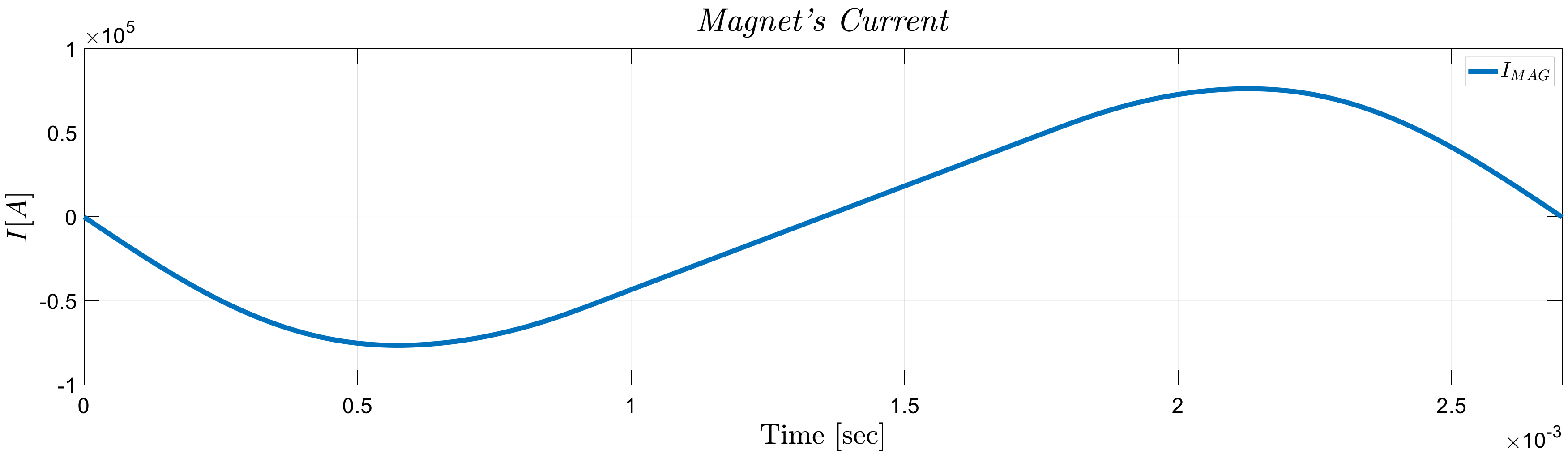
Acceleration in 2 steps (per sector)
Current on magnets → 60kA
NRG capacitors (total) → 0.9MJ
NRG on inductors → 0.25 MJ
Power of Active Filter (peak) →150MW

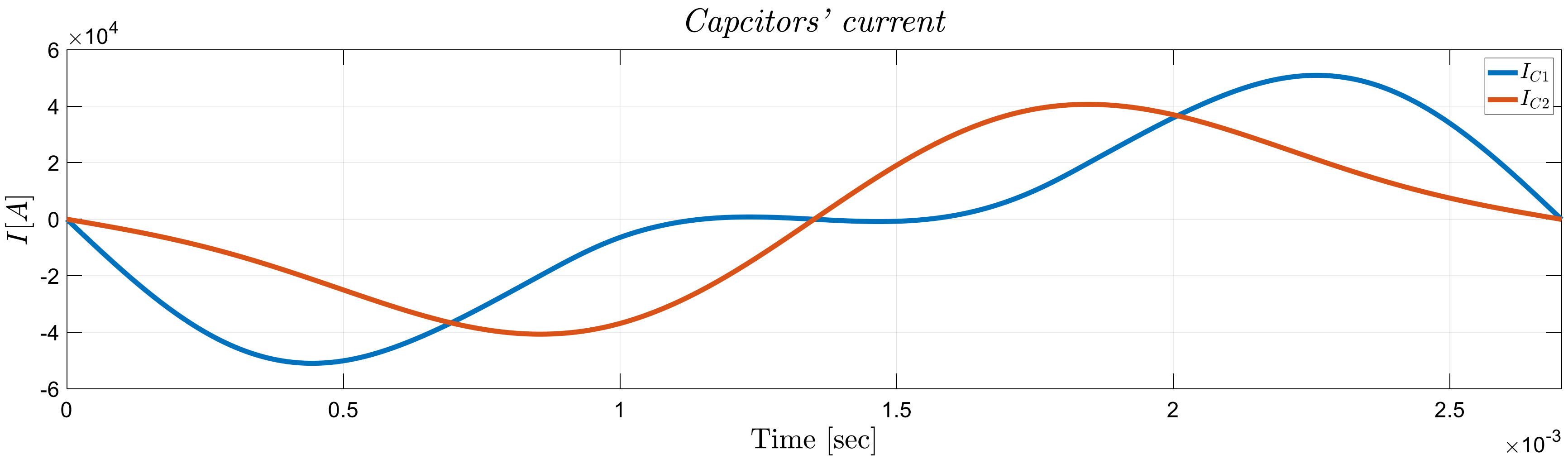
Acceleration in 3 steps (per sector)
Current on magnets → 40kA
NRG capacitors (total) → 1.3MJ
NRG on inductors → 0.38 MJ
Power of Active Filter (peak) →280MW

Low inductance magnet (# of turns = 1)
200 Powering Sector
Pulsed operation @5Hz

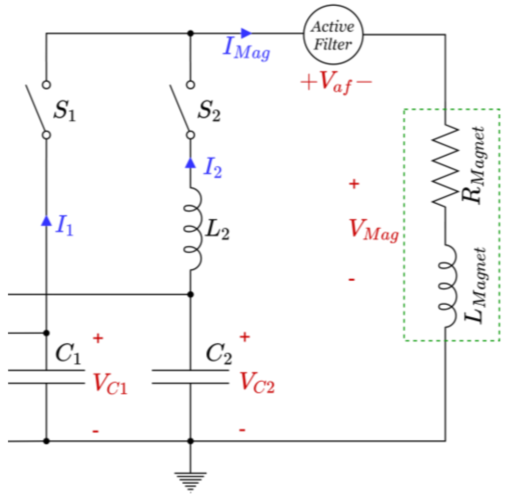


Preliminary results: RCS2 Waveforms





I_{MAG}^{max}	60 kA
I_{L2}^{max}	40.7 kA (127 kJ)
I_{MAG}^{RMS}	8.46 kA
I_{2}^{RMS}	4.23 kA



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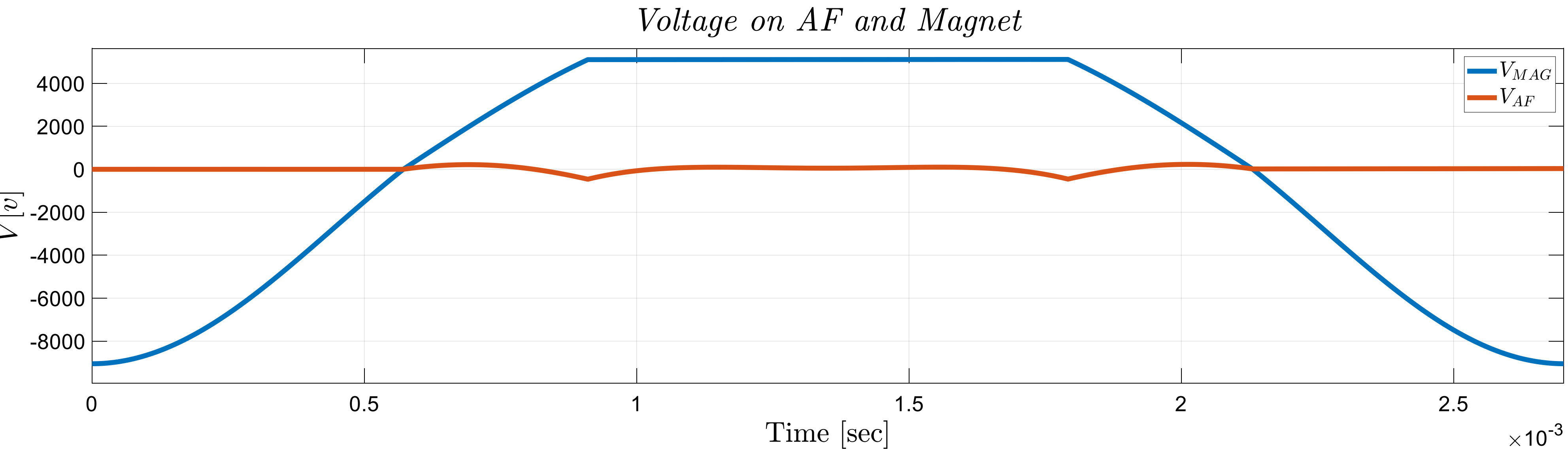
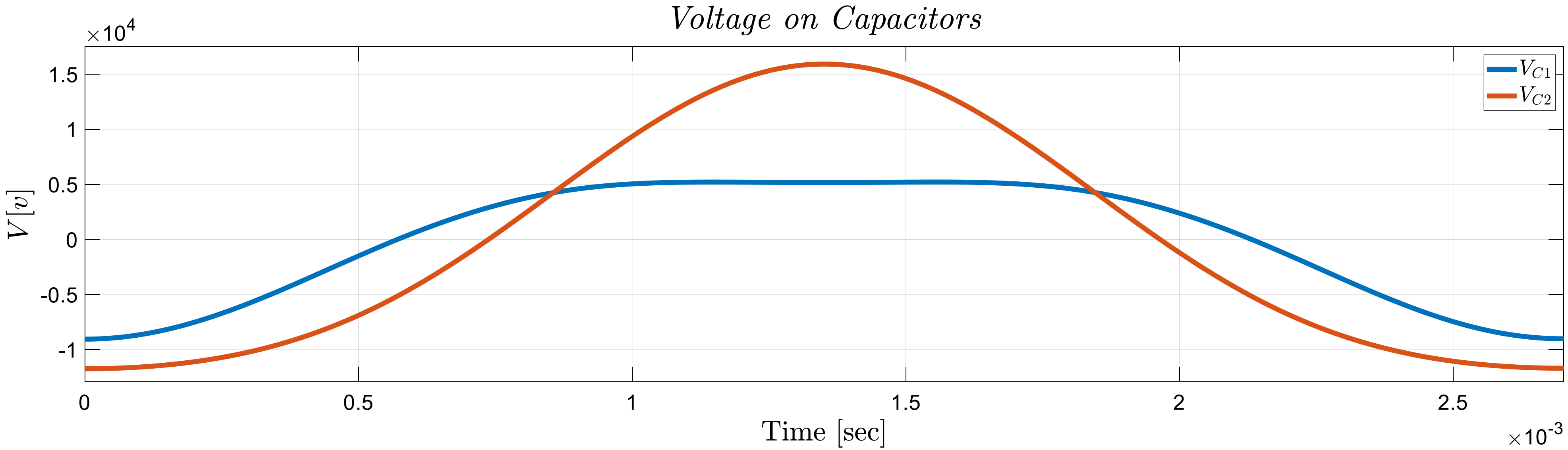
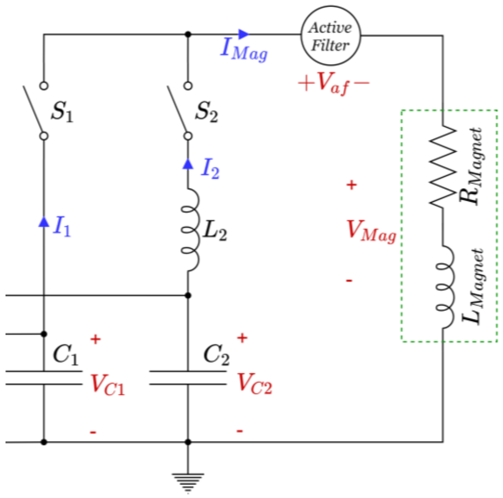


V_{MAG}^{max}	9.05 kV
V_{C1}^{max}	9.05 kV (179 kJ)
V_{C2}^{max}	15.9 kV (268 kJ)
V_{AF}^{max}	462V





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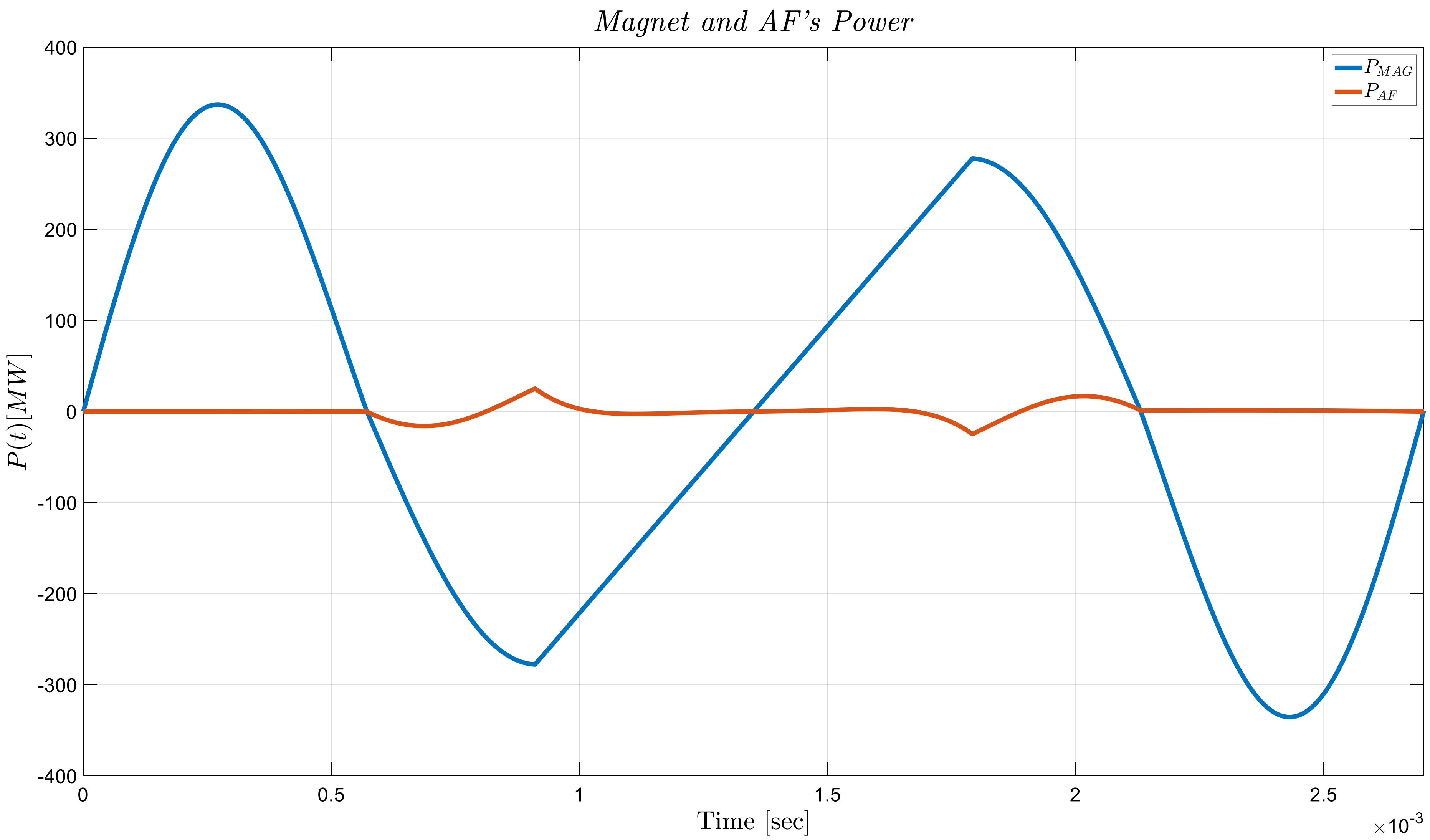
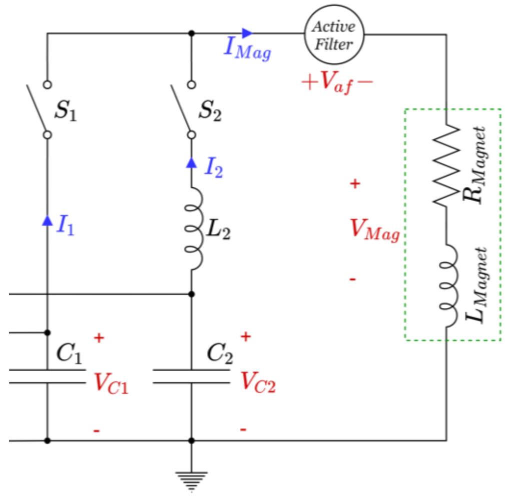


p_{MAG}^{max}	337 MW
p_{AF}^{max}	25 MW

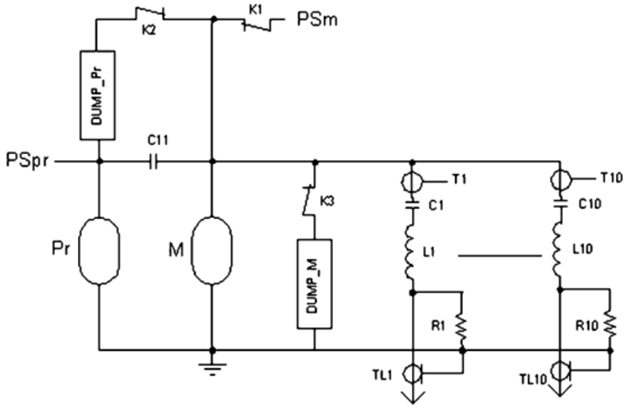


Cost Estimation: example of Capacitors

Muon Collider N of pulses → 10^9 pulses in 10 years with current peak of 60kA and a repetition period of 200ms

There is **no existent application** with very high current pulses and fast repetition rate.

Laser Mega Joule (France)
480xCapacitorBankModule ≈ 400MJ
One CBM: 860kJ @ 24kV; 360us wide 240kA current pulse;
1 pulse every 25min; 2500 kg; estimated price 70kCHF
total lifetime → 200’000 pulses (12h of the MC)
Cost ≈ 0.09 CHF/Joule



POPS (CERN)
6xCapacitorContainers ≈ 20MJ
One CC: 3.2MJ @ 5kV; 2ms wide 2kA current pulse; 1 pulse every 1.2; 25000 kg; estimated price 500kCHF
total lifetime → 120’000’000 pulses (1 year of the MC)
Cost ≈ 0.15 CHF/Joule

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Applying POPS to the MC, we need to reduce the Efield in the capacitor by a factor of 2-3, therefore the energy density by a factor 4-9

→

Attempt for order of magnitude
Cost ≈ 1.5 CHF/Joule
Is that enough? Too much?

With the same large approximation

Cost Capacitor ≈ 1.5 CHF/Joule
Cost Inductance ≈ 0.8 CHF/Joule
Cost Active Filter ≈ 0.2 CHF/Wpk

→

Only Material, no Civil Engineer no installation:

Acceleration for 3TeV collider in 2 stages → 2.2BCHF
Acceleration for 3TeV collider in 3 stages → 4.2BCHF

Next Steps and Conclusions

- Define a R&D Road Map
  - Power electronics for Active Filter and Switches
  - High voltage storage capacitor with fast pulse discharge and high repetition rate
  - Inductor design
  - Samples testing is required to determine limits of NRG storage elements in MC application conditions
- Necessary cooperation with magnet’s expert for a combined optimisation
  - NRG of the airgap versus vacuum chamber (how can we minimize it?)
  - Magnets’ design should aim at reducing the total inductance due to pulsed operation (voltage levels)
  - Can we increase the peak current above that required for injection-extraction? (beneficial for the powering system)

Conclusion

- **Power scheme not addressable with standard power converters**
  - Resonant circuit relieves power demands on the electronics
- **Reach a compromise in the waveform of B-Field**
  - To reduce linear portion as much as possible
- **Need for input from magnet's expert in the near future**
- **High number of power sectors/converters (>200)**
  - To prevent large voltage levels and isolation issues.
  - Power of individual sector still challenging
- **R&D greatly required in many fields (storage means, power switching, …)**
  - To determine the feasibility of the powering and estimate costs

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