Fast ramping magnet’s powering for the Muon Collider

F. Boattini, D. Aguglia and G. Brauchli

Electrical Power Converters (SY/EPC) group

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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
    \[
    \frac{E_{B_{\text{max}}}}{2 \mu_0} \cdot L_{\text{ramp}} \cdot H_{\text{gap}} \cdot W_{\text{gap}} = 64 \text{ MJ}
    \]
  - Linear ramp requires a huge amount of power
    \[
    P(t) = \frac{V_{\text{gap}}}{2 \mu_0} \cdot \frac{\Delta B^2}{\Delta T} = 128 \text{ GW}
    \]
  - Solving this with Conventional Power Electronics is virtually impossible
  - Energy stored in Converter much higher than 64 MJ (2-3 times more)
  - Complex/costly/lossy converter

B_{\text{ext}} = 2T \div 1T
T_{\text{ramp}} = 0.4 \div 12\text{ms}
T_{\text{rep}} = 200\text{ms}
An alternative strategy: resonant converter

- **Natural resonant discharge**
  - The energy initially stored in the capacitors is transferred 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.

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: $B_{inj}$, $B_{ext}$, $\frac{dB}{dt}|_{inj}$, $\frac{dB}{dt}|_{ext}$, 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

![Graph of B-Field in air gap and AF's Power](image-url)
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.

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):

<table>
<thead>
<tr>
<th>Collider COM energy</th>
<th>D. Schulte Muon Collider Collaboration, IPAC 2021</th>
<th>H. Damereau MC RF WG meeting #3: RF for HEC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3TeV collider</td>
<td>3TeV collider</td>
</tr>
<tr>
<td>RCS1</td>
<td>RCS1</td>
<td>RCS1</td>
</tr>
<tr>
<td>RCS2</td>
<td>RCS2</td>
<td>RCS2</td>
</tr>
<tr>
<td>RCS3</td>
<td></td>
<td>RCS3</td>
</tr>
<tr>
<td>Peak ramping field [T]</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Length [km]</td>
<td>1.26</td>
<td>6.28</td>
</tr>
<tr>
<td>Ramping dipole gap size [cm²]</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Magnetic field energy in vacuum chamber [MJ]</td>
<td>6.4</td>
<td>32.0</td>
</tr>
<tr>
<td>Tramp [ms]</td>
<td>0.4</td>
<td>2</td>
</tr>
<tr>
<td>N sector</td>
<td>40</td>
<td>200</td>
</tr>
</tbody>
</table>

**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
  - 1.20E+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

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**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
Preliminary results: RCS2 Waveforms

- \( I_{\text{MAG}}^{\text{max}} \) = 60 kA
- \( I_{L2}^{\text{max}} \) = 40.7 kA (127 kJ)
- \( I_{\text{MAG}}^{\text{RMS}} \) = 8.46 kA
- \( I_{L2}^{\text{RMS}} \) = 4.23 kA

![Magnet's Current](image)

![Capacitors' Current](image)
Preliminary results: RCS2 Waveforms

Voltage on AF and Magnet

$$V_{\text{MAG}}^\text{max} = 9.05 \text{ kV}$$

$$V_{\text{C1}}^\text{max} = 9.05 \text{ kV}$$

$$(179 \text{ kJ})$$

$$V_{\text{C2}}^\text{max} = 15.9 \text{ kV}$$

$$(268 \text{ kJ})$$

$$V_{\text{AF}}^\text{max} = 462 \text{ V}$$
Preliminary results: RCS2 Waveforms

Magnet and AF’s Power

\[ P_{\text{MAG}} \]
\[ P_{\text{AF}} \]

- \( p_{\text{MAG}}^{\text{max}} = 337 \, \text{MW} \)
- \( p_{\text{AF}}^{\text{max}} = 25 \, \text{MW} \)
Cost Estimation: example of Capacitors

Muon Collider N of pulses $\rightarrow 10^9$ 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 $\approx$ 400MJ

One CBM: 860kJ @ 24kV; 360us wide 240kA current pulse; 1 pulse every 25min; 2500 kg; estimated price 70kCHF

total lifetime $\rightarrow$ 200’000 pulses (12h of the MC)

Cost $\approx$ 0.09 CHF/Joule

**POPS (CERN)**

6xCapacitorContainers $\approx$ 20MJ

One CC: 3.2MJ @ 5kV; 2ms wide 2kA current pulse; 1 pulse every 1.2; 25000 kg; estimated price 500kCHF

total lifetime $\rightarrow$ 120’000’000 pulses (1 year of the MC)

Cost $\approx$ 0.15 CHF/Joule
Cost Estimation: example of Capacitors

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total lifetime $\rightarrow 120\,000\,000$ pulses (1 year of the MC)
Cost $\approx 0.15$ CHF/Joule

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

With the same large approximation

Cost Capacitor $\approx 1.5$ CHF/Joule
Cost Inductance $\approx 0.8$ CHF/Joule
Cost Active Filter $\approx 0.2$ CHF/Wpk

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

Only Material, no Civil Engineer no installation:

Acceleration for 3TeV collider in 2 stages $\rightarrow 2.2$BCHF
Acceleration for 3TeV collider in 3 stages $\rightarrow 4.2$BCHF
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