Overview of Magnet Needs for Pulsed Synchrotrons

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1st Muon Community Meeting
20 May 2021

Talk Overview

- Acceleration overview
- Pulsed synchrotrons, including hybrid
- Sample parameters
- Pulsed magnets
- Final thoughts, R&D list

Acceleration Principles

- Limit decays: muons are difficult and expensive to create
- Everything happens fast
  - At lower energies have no time to change magnet fields, RF frequencies, replace RF energy
  - These become possible at high energy, but parameters beyond conventional
- RF cavities are expensive: make as many passes through cavities as possible
- RF power is expensive: consider energy efficiency
- Avoid increasing transverse and longitudinal emittance

Decays: Acceleration Gradient

- Muons decay, rest lifetime 2.2 μs
- Large average acceleration gradient (energy gain divided by beam line length) to avoid decays
- Determine average accelerating gradient from desired transmission for a given energy ratio

$$-\frac{m_\mu c^2/e}{c\tau_\mu}\frac{\log[(E_\mathrm{f}+cp_\mathrm{f})/(E_\mathrm{i}+cp_\mathrm{i})]}{\log(N_\mathrm{f}/N_\mathrm{i})}$$

- Formula involves transmission fraction and energy ratio. Doesn't get relaxed at higher energies.
- To get MAP luminosities, we needed 3.5 MV/m

RF Efficiency

- RF and machine length drive costs
- Muons are bendable leptons: multiple (few to low 10s) RF passes

$$n \sim \frac{\Delta E}{eG_{\text{avg}}L} \sim \frac{1}{2\pi}\frac{B_{\text{avg}}c}{G_{\text{avg}}}\frac{\Delta E}{pc}$$

  - Small circumference of acceleration stages
  - High fields in dipoles
  - Large dipole packing fraction

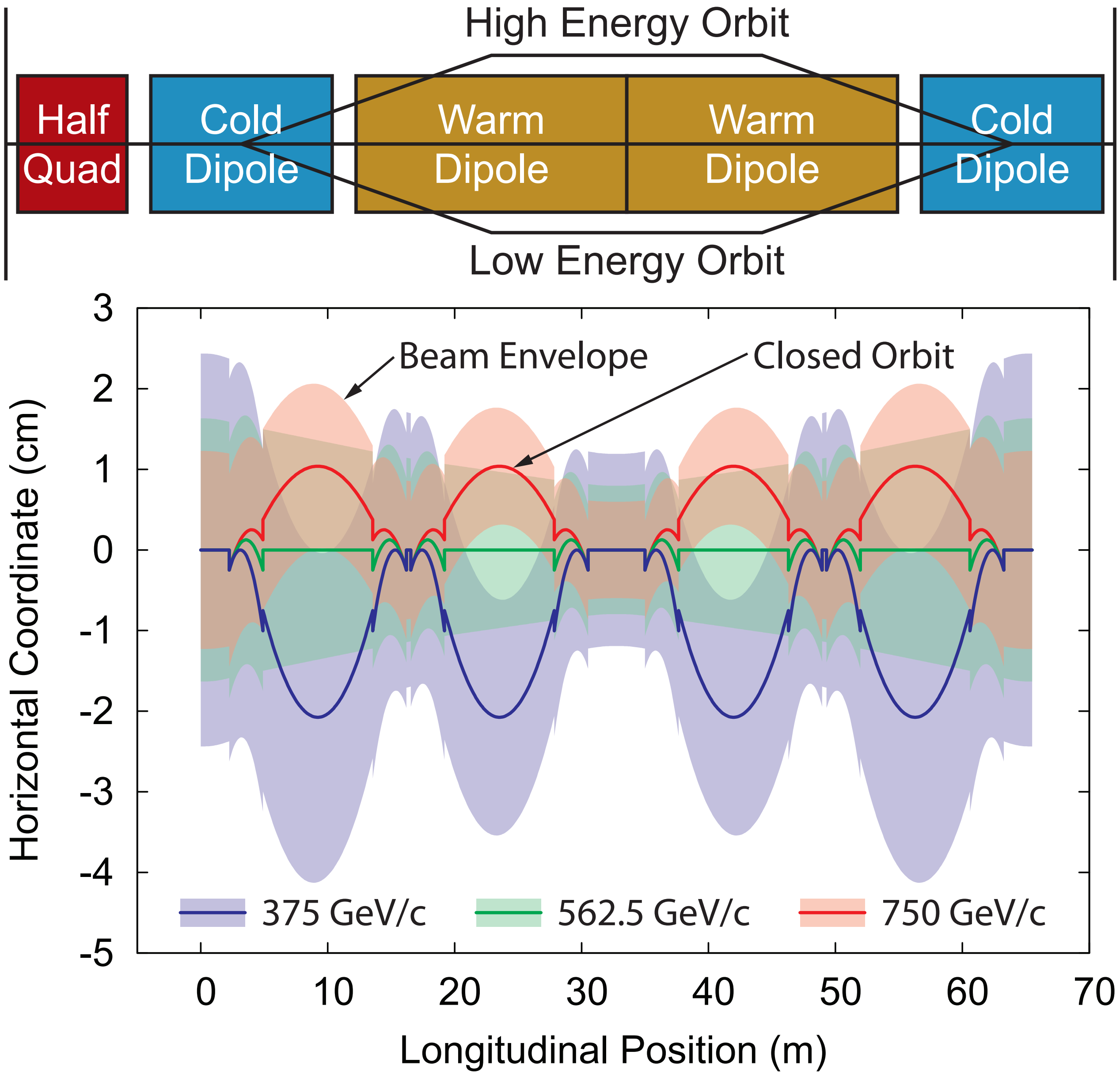
Pulsed Synchrotron

- Accelerate as usual for a synchrotron: magnet fields proportional to momentum
- Distribute cavities uniformly around ring, as many stations as possible to minimize mismatch
  - Energy increases discretely
  - Field varies continuously
- Maximum field only around 1.5 T: few turns or large number of decays
- Magnet fields increasing rapidly (1 ms and below)

Hybrid Pulsed Synchrotron

- Increase average bend field: interleave fixed superconducting dipoles and bipolar pulsed warm dipoles
  - More RF passes and shorter circumference
- Larger energy gain factor has significant penalties
  - Lower average bend field, so longer ring
  - Wider aperture required in magnets
  - Energy discretization problems at lower energies
- Easier at higher energies: more time
- Adjust orbit position to keep time of flight constant

Hybrid Pulsed Synchrotron



MAP Specifications

- Large longitudinal emittance: 25 meV s
- Small transverse normalized emittance: 25 µm
- High bunch charge: 2×10^{12} per sign
- Low repetition rate: 15 Hz
- Average gradient: 3.5 MV/m
  - 1.3 GHz cavities at 35 MV/m
- Pulsed dipole maximum field: 1.5 T
- Fixed dipole field: 10 T

Sample Scenario

- Accelerate from 63 to 1500 GeV
- Three stages, first two share a tunnel
- Very hand-waving calculation
- Dwell times in particular will be somewhat longer

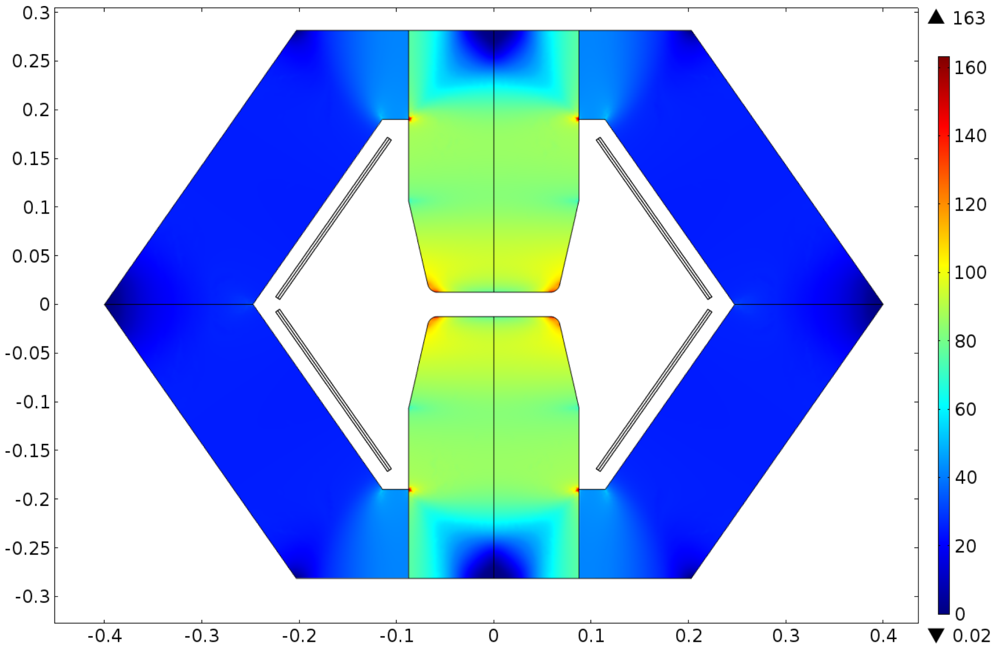
Injection Energy (GeV)	63	303	750
Extraction Energy (GeV)	303	750	1500
Circumference (m)	5210	5210	9361
Fixed Dipole Length (m)	—	1103	2358
Ramped Dipole Length (m)	4229	3126	5240
Turns	13	25	23
Time (ms)	0.23	0.43	0.72

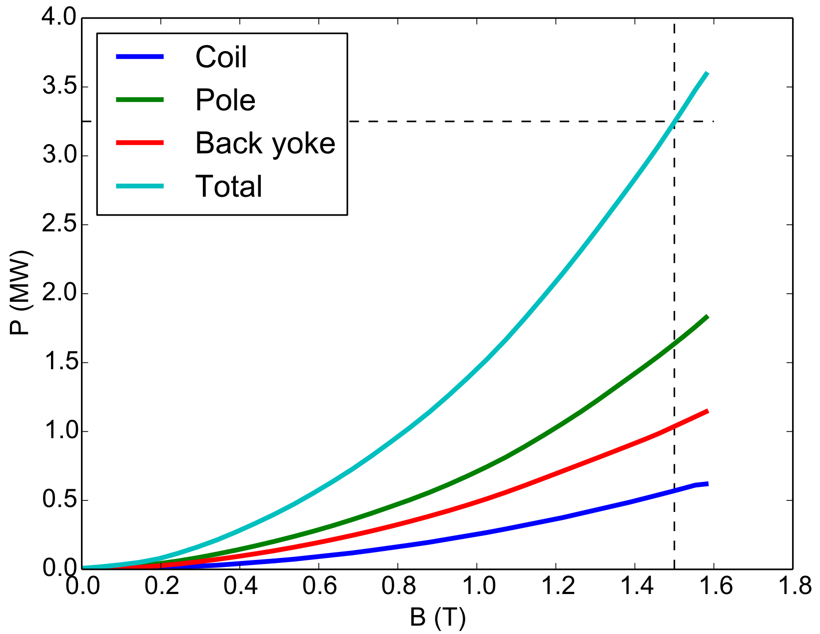
Pulsed Magnets

- Acceleration times 1 ms and below
- Need to deal with energy losses
  - Combine high-field pole with 6.5% Si steel back yoke
  - HTS-based SC solutions
- Power supply
  - Need good control of current ramp
  - Large peak power
  - High efficiency (below 2% loss per pulse) to keep losses below magnet losses
  - Keep magnet apertures small to minimize stored energy
- Losses and power supply capabilities lead to lowest tolerable energy for pulsed synchrotrons

Pulsed Magnet Design

- 3% Si pole (moderate loss, high field)
- 6.5% Si back yoke (low loss)
- Losses dominated by pole
- Low eddy current loss in coil





Pulsed Power Supply

- Stored energy in pulsed magnets of a few to low 10s of MJ per ring
- Peak power delivered in the GW range per ring (individual supply per magnet?)
- Must store energy between pulses with decent efficiency
- Ramp should be linear and well-controlled. Difficult to control acceleration rate (rapid phase change, bucket area).
- Ramping either from something above zero to maximum, or from negative to positive

Final Thoughts

- High field, fixed field magnets for hybrid designs
- Things get easier, more efficient at higher energies
- Pulsed power supply is the biggest challenge
  - High ramp rate, power
  - Controlling the current pulse
- Can slow down, but more decays or money
- If pulsing too scary at low energies, we have other (probably more expensive) options: FFAs
- Higher field pulsed magnets would be nice
  - Different pole materials:
    - Pure iron: higher losses
    - Fe-Co: activation?
  - Can SC options (HTS) ramp in these sorts of times?

Magnet R&D Items

- Power supplies
  - Short pulse times
  - Efficiency
  - Tightly controlled linear ramp
- Higher field pulsed magnets
  - Higher fields in conventional design
  - Rapid pulsing of HTS magnets?
- High field fixed magnets