Muon Acceleration

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Workshop on Muon Driven Colliders
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Talk Overview

• Acceleration principles
• Accelerator types, from most efficient to least
  ◦ Pulsed synchrotrons
  ◦ FFAs
  ◦ RLAs
  ◦ Linacs
• Collective effects
Acceleration Principles

- Control cost, maintain beam
- Limit decays: difficult & expensive to make muons
- RF is expensive (hardware, power consumption)
  - Make more passes through cavities
  - Use higher RF frequencies if possible
- Everything happens fast
  - Lower energies: no time to change magnet fields, RF frequencies, replace RF energy
  - These become possible at high energy, but parameters beyond conventional
- Avoid increasing transverse and longitudinal emittance
- Both signs in same accelerator
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

\[
\frac{m_\mu c^2}{e \log[(E_f + cp_f)/(E_i + cp_i)]} \frac{c \tau_\mu}{\log(N_f/N_i)}
\]

- 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 20) RF passes

\[ n \sim \frac{\Delta E}{eG_{\text{avg}}L} \sim \frac{1}{2\pi} \frac{B_{\text{avg}}c}{G_{\text{avg}}} \frac{\Delta E}{\gamma c} \]

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

- Top off cavities (at high energy, more time)
- RF frequency
  - Higher frequency less expensive
  - More turns with lower frequency
Longitudinal Emittance

• Preserving longitudinal emittance drives the design of many acceleration stages
  ▪ Many stages to pass through: successful transmission through a stage is insufficient
  ▪ Transfer lines perform longitudinal matching (RF!)?
  ▪ Think hard about tolerance for longitudinal emittance growth
• More difficult/expensive with larger emittances
  ▪ Think about this in late-stage cooling optimization
• To reduce longitudinal emittance growth
  ▪ Increase circumference (reduce momentum compaction). Less efficient or more decays.
  ▪ Reduce RF frequency (expensive)
Pulsed Synchrotron

- Accelerate as usual for a synchrotron: magnet fields proportional to momentum
- Maximum field (iron dipoles) only around 1.5 T
  - Few turns or large number of decays
  - More turns than other some options (Linac, RLA, FFA)
- Magnet fields increasing rapidly
  - Only suitable for higher energies (1 ms time scale)
- Alternative: hybrid pulsed synchrotron
  - Interleave fixed superconducting dipoles and bipolar warm dipoles
  - Higher average bend field: shorter circumference, more RF passes
  - But less energy gain (typical factor $\approx 2$)
Pulsed Synchrotron Issues

- Need multiple RF stations
  - Energy increases discretely, magnets vary continuously
  - Large synchrotron tune (∼ 1)
  - Bigger problem for non-hybrid synchrotron
- Hybrid vs. normal pulsed synchrotron
  - Normal has larger factor in energy gain
  - Hybrid advantages
    - More passes for given decay
    - Fewer RF stations
    - Smaller circumference
    - Higher maximum energy on site
- Easier at higher energies (more time)
Magnets

- Warm iron magnets fairly straightforward
  - Power loss can be limited to the few MW level
  - 1.5 T maximum field for an efficient design
  - Can push somewhat higher but at a cost (stored energy and loss)
- Pulsed HTS
  - Would need meaningfully higher fields (2.5 T?), and similar ramp times (few ms for higher energies)
  - Right now pretty far from achieving this
Pulsed Power

- Use resonant converters (capacitor banks, inductors)
- Need to have good linearity with time
- $\sim 100$ MJ stored energy in magnets
- Delivered in $\sim 1$ ms
- $\sim 10^9$ lifetime pulses
  - 10 times existing systems
  - Reduce capacitor voltage for better lifetime, need more capacitors
- Hardware costs $\sim 2$ G$\$. 
- More detail, talk by Brauchli et al.,
  https://indico.cern.ch/event/1077393/
Sample Scenario

- Large longitudinal emittance: 25 meV s
- Small transverse normalized emittance: 25 µm
- High bunch charge: $2 \times 10^{12}$ 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

<table>
<thead>
<tr>
<th>Injection Energy (GeV)</th>
<th>63</th>
<th>303</th>
<th>750</th>
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<tr>
<td>Extraction Energy (GeV)</td>
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<td>Circumference (m)</td>
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<td>5210</td>
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<td>Fixed Dipole Length (m)</td>
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<td>2358</td>
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<td>Ramped Dipole Length (m)</td>
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<td>Turns</td>
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<td>Time (ms)</td>
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<td>Cavity Power (kW)</td>
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<td>950</td>
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• Fixed field alternating gradient accelerator
• Single beamline for many energies, magnet fields don’t vary with time
• No switchyard: can get a large number of turns
• Magnets need to be wide: every energy at a different position
FFA

- Linear non-scaling FFA
- Tunes vary with energy
- Time of flight parabolic with energy
- Serpentine acceleration: pass three times over RF crest
- Increase width of channel to reduce longitudinal emittance growth. Do this with
  - More voltage (fewer turns)
  - More cells (longer ring)
  - Tolerated decay and emittance growth determine circumference/turns
• Distribute RF cavities evenly around the ring
  ◦ Drifts containing cavities need to be short
  ◦ Avoid transverse emittance growth from orbit mismatch
• Fast kickers for injection/extraction
• Usually prefer stages with factor of 2–3 energy gain
  ◦ Aperture increases rapidly with energy gain factor
  ◦ Longitudinal acceptance decreases rapidly with energy gain factor
• Add nonlinearity
  ◦ Reduce time of flight range: open serpentine channel
  ◦ Reduce chromaticity: more energy range
  ◦ Watch dynamic aperture
FFA

- FFA probably uses lower RF frequencies
- Short cell length important
  - Cavities as close as possible to magnets
  - Operate with up to 0.1 T on cavities?
- Sample parameters:

<table>
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<tr>
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<th>Injection Energy (GeV)</th>
<th>Extraction Energy (GeV)</th>
<th>RF Frequency (MHz)</th>
<th>Cells/cavity</th>
<th>Gradient (MV/m)</th>
<th>Turns</th>
<th>Cavities/drift</th>
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</table>

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Vertical FFAs

- In a vertical FFA, orbits change vertically with energy, not horizontally
- Path length nearly independent of energy
  - Path length variation with energy limits turns (longitudinal emittance growth) in traditional FFA
- Difficulties
  - Relatively larger vertical orbit excursions. Require large cavity apertures.
  - Magnets are challenging
• Return beam to a linac with a separate pass for each energy
• Most conventional multi-pass design
• Preferred solution at lower (few GeV) energies
• Large factor of energy gain
• Primary limitation is the switchyard where each energy enters/exits a different arc
  • Large emittances
    • Need focusing magnets close to separation
    • Energy overlap between passes
  • Space at switchyard end gets very crowded
  • Limits turns
• Geometry to improve switchyard crowding
  • Conventional racetrack: two linacs connected by 180° arcs
  • “Dogbone”: loops at each end of a single linac. Separation twice as good for a given number of linac passes.
    • Arcs cross at intermediate points

• Preserving large longitudinal emittance
  • Requires relatively long arcs
  • Large beta function difference between linac and arc, even with focusing in the linac, requires matching
  • Focusing in linac to keep beta function reasonable
    • Focusing strength at injection, including energy spread
    • Injecting into linac center can help
Linac

- Only single-pass, so expensive, inefficient
- MAP muon collider scenarios generally used linacs below about 1 GeV
  - $v < c$ for lower energies creates RF synchronization issues in multi-pass machines
  - Large emittances (transverse and longitudinal) more easily handled
- For smaller emittances at lower energies, a single pass high frequency (1.3 GHz) linac can be more cost effective than a multi-pass system that may require lower frequencies
- Early acceleration: cooling lattice without absorbers
Collective Effects

- **Beam collisions**
  - Both beams counter-rotating in same rings
  - Beams collide at two points
  - Small number of collisions

- **Heavy beam loading in cavities**
  - High frequency RF good for power efficiency, cost
  - $1.3 \text{ GHz}$ cavity, $2 \times 10^{12}$ muons extract $15\%$ of the stored energy
  - Significant short-range wake
  - Opposite signs passing through same cavities, relative timing depends on which cavity
  - Small number of passes compared with storage ring

- Is chromaticity correction needed?
Summary

- Hybrid pulsed synchrotrons most efficient, in terms of RF, circumference
  - High average bend field
  - Larger number of turns
- Pulsed power costs look large: may need to revisit cost tradeoffs
- FFAs may be a good alternative, particularly more advanced designs
- More decays allowed, better efficiency
- Longitudinal bunch manipulation between stages could be expensive: consider in stage design
- Collective effects may be significant