Muon Acceleration

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Workshop on Muon Driven Colliders
January 25, 2022

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

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

- 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 20) RF passes

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

  - 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

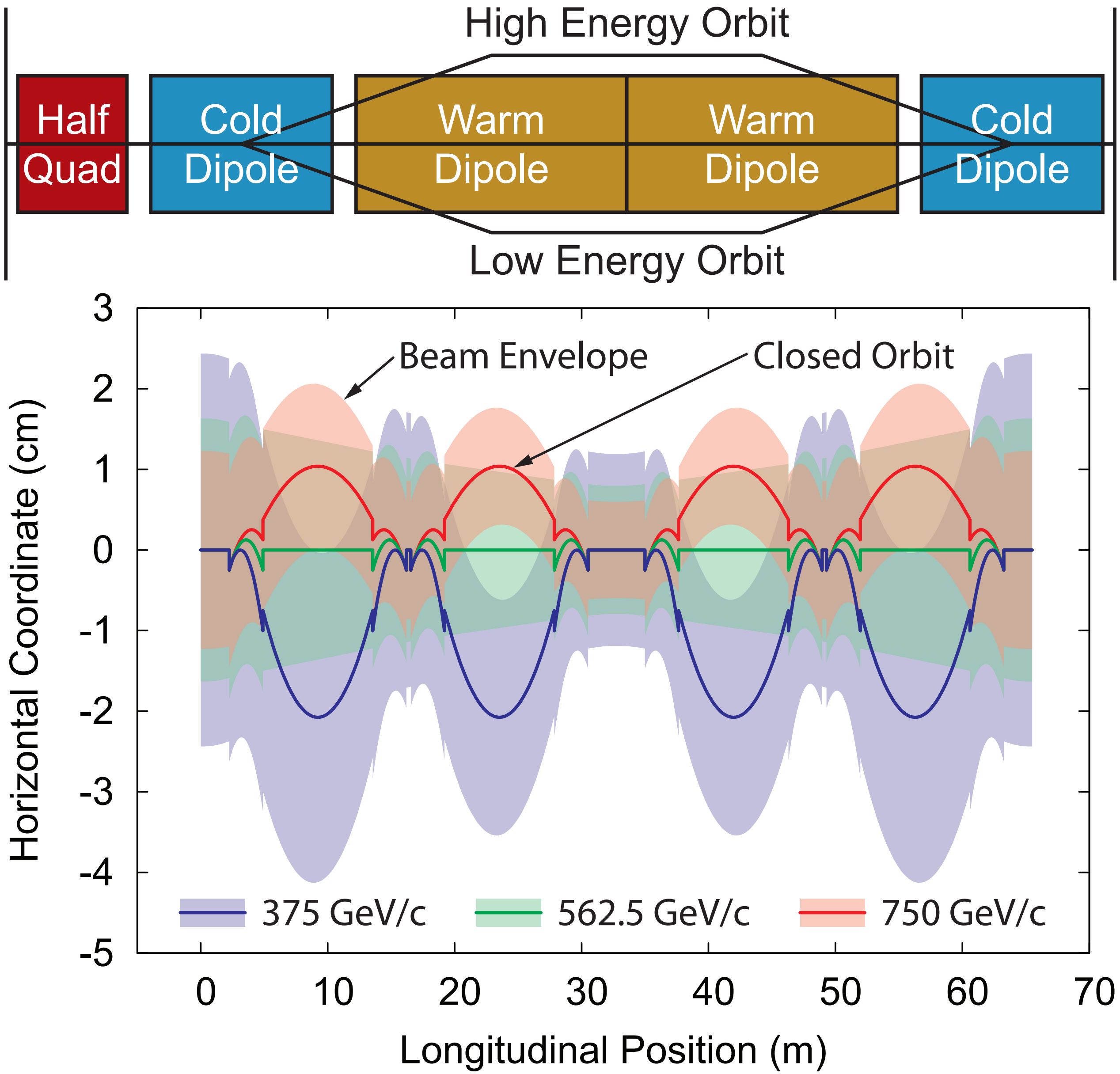
Longitudinal Emittance

- 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 ≈ 2)

Pulsed Synchrotron



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: 2×10^{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

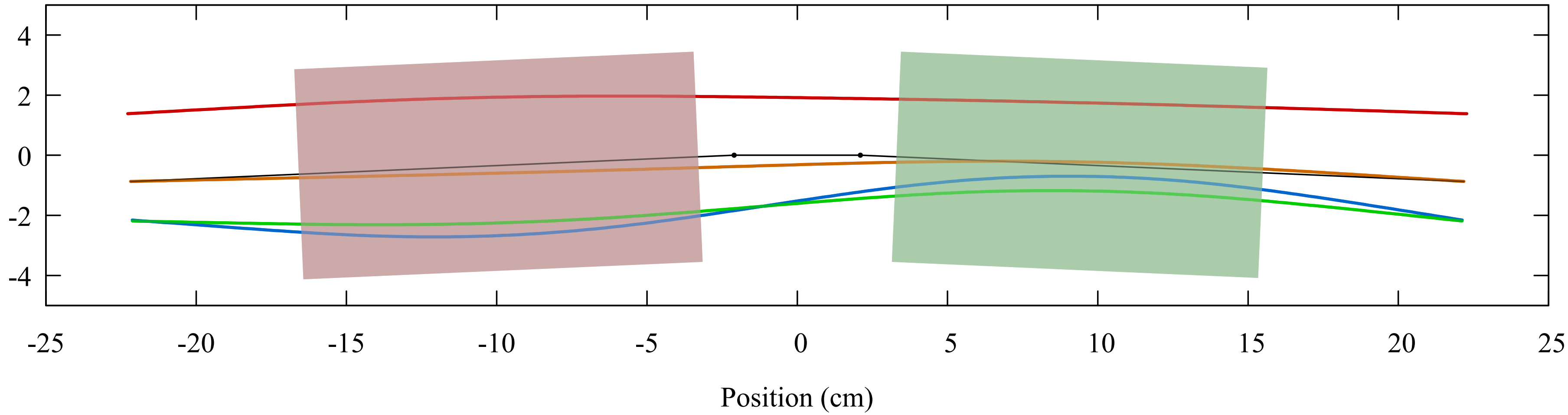
Sample Scenario

- 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

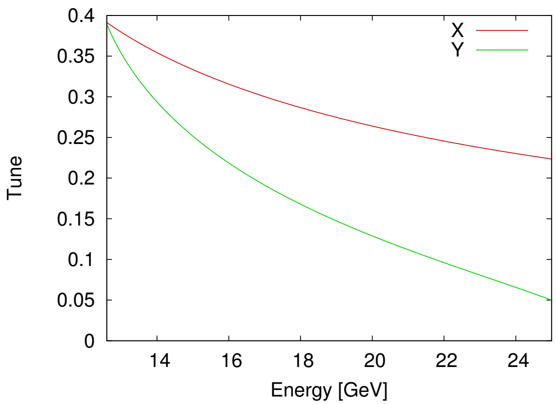
Injection Energy (GeV)	63	303	750
Extraction Energy (GeV)	303	750	1500
Circumference (m)	5210	5210	9361
Fixed Dipole Length (m)	—	1103	2358
Ramped Dipole Length (m)	4229	3126	5240
Turns	13	25	23
Time (ms)	0.23	0.43	0.72
Cavity Power (kW)	950	950	530

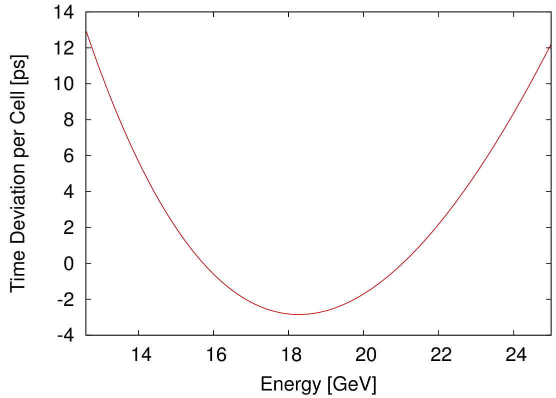
FFA

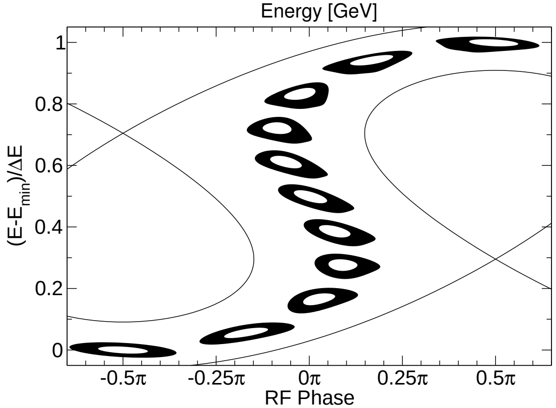
- Fixed field alternating gradient accelerator
- Single beamline for many energies, magnet fields don't vary with time
- No switchyard: can get a large number of turns
- Magnets need to be wide: every energy at a different position



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

FFA

- 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:

Injection Energy (GeV)	63	173
Extraction Energy (GeV)	173	375
RF Frequency (MHz)	975	975
Cells/cavity	3	3
Gradient (MV/m)	30	30
Turns	6.5	8.5
Cavities/drift	1	2

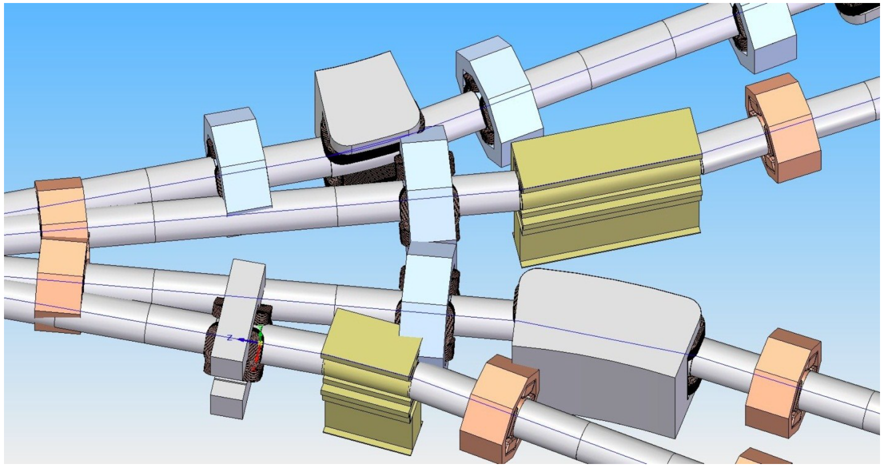
Vertical FFAs

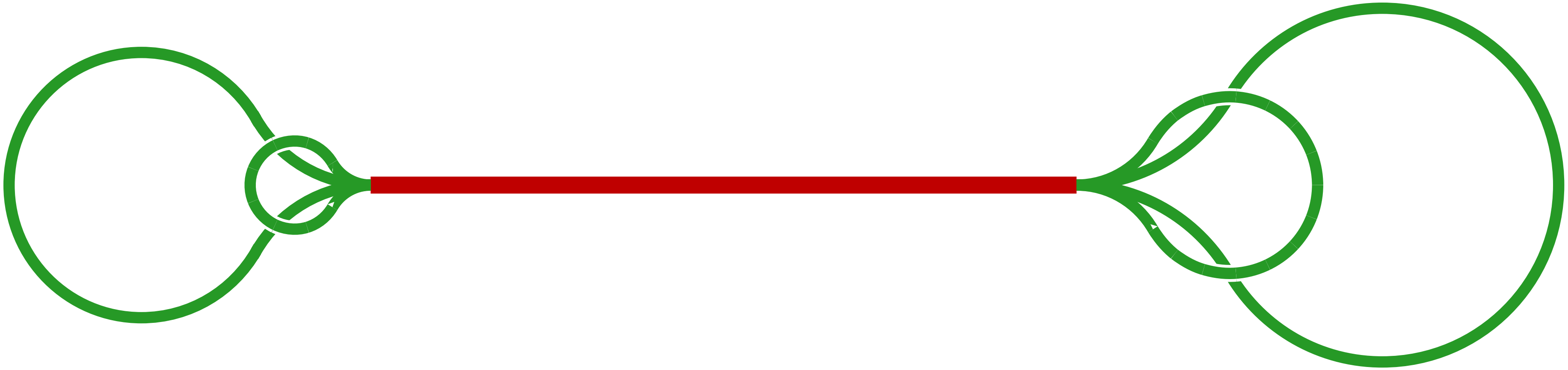
- In a vertical FFA, orbits change vertically with energy, not horizontally
- Path length nearly independent of energy
  - Path length variation with energy limits turns (longitudinal emittance growth) in traditional FFA
- Difficulties
  - Relatively larger vertical orbit excursions. Require large cavity apertures.
  - Magnets are challenging

RLA

- 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

RLA





RLA

- 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 GHz cavity, 2×10^{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