Thoughts on Acceleration for a Muon Collider

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Muon Collider vs. Neutrino Factory

- Muon collider has only a single bunch
- Transverse acceptance
  - Neutrino factory: 30000 $\mu$m
  - Muon collider: 50 $\mu$m
- Longitudinal
  - Neutrino factory: 150 mm acceptance
  - Muon collider: 68 mm emittance
    - For comparison: 150 mm acceptance would be $1.5\sigma$ with this emittance
- The difficulty is clearly going to be the longitudinal emittance
Emittance vs. Acceptance

- What matters to first order for neutrino factories is acceptance
  - The size (in phase space) of the hole that the beam needs to fit into
  - Any distortion to the ellipse gets clipped (square peg/round hole)
  - Square of radius in phase space gets third-order correction from nonlinearities

- What matters for muon colliders is emittance
  - Computed from second order moments
  - Third order moments don’t affect emittance
  - Fourth order moments give lowest order correction from nonlinearities
  - If get too close to dynamic aperture (bucket edge): blow up emittance significantly

- Small emittance growth easier than small acceptance growth, but for given emittance, muon colliders require larger acceptance
Types of Acceleration

- Recirculating Linear Accelerators (RLAs)
- Fixed Field Alternating Gradient (FFAG) Accelerators
- Fast Ramping Synchrotrons
Recirculating Linear Accelerators (RLAs)

- Essentially arbitrarily large longitudinal acceptance
  - Lots of RF available
  - Going off-crest increases bucket height significantly while affecting acceleration little

- Each arc designed separately: get cavity phases right

- Switchyard is the problem
  - Lots of beamlines, but small aperture
  - Small energy spreads and beams may make easier
Fixed Field Alternating Gradient (FFAG) Accelerators

- Get less expensive per unit acceleration at higher energy
- At higher energy, can shift cavity frequency (piezo, ...)
  - Instead of fancy “gutter acceleration,” have something more like standard synchrotron oscillation
  - Longitudinal acceptance ceases to be a problem
- At lower energies, worry about acceptance
  - May be forced to lower frequencies than other designs
- Large aperture beamlines
- Limited energy range: many stages
- Small emittance: nonlinear magnets?
Fast Ramping Synchrotrons

- Stored energy, length \( L \) of magnets with field \( B \) and aperture \( a \): 
  \[
  \frac{B^2 L \pi a^2}{2\mu_0}
  \]

- Revolution time, average gradient \( G \): 
  \[
  \frac{\Delta E}{q G c}
  \]

- Relate dipole length \( L \) to field: 
  \[
  L = \frac{2\pi (pc/q)}{B c}
  \]

- Peak power (\( \Delta E \sim pc \)): 
  \[
  \frac{\pi^2 B a^2 G}{\mu_0}
  \]
  - Should add factor of 2 for other magnets
  - Independent of energy!
  - Magnet aperture is critical
  - 1 cm aperture, 1 T field, 6 MV/m gradient, result is 4.7 GW
● Aperture increases at lower energy, power requirement increases

● Acceleration time
  ♦ For 1 TeV, about 0.5 ms total cycle time
    ★ Long time to hold the peak power
  ♦ Note at 1 T, just the bends give a period of 0.07 ms.
    ★ Multiply by 4 at least: only a couple turns!
    ★ Can go to higher fields, but more peak power, still few turns

● With all this RF, can make bucket arbitrarily large

● RF phasing a non-issue at high energy
● Longitudinal acceptance is a significant issue at low energy
● Linac acceptance: 150 mm is already pushing it at 200 MHz
  ♦ Need closer to 1 m for collider
  ♦ Probably can’t even accelerate required acceptance in cooling lattice at 200 MHz
  ♦ Lower frequencies required
● FFAGs also have acceptance problem
  ♦ Probably can’t start FFAGs until higher energy (10 GeV?)
● Working on computing the correct relationship between FFAG parameters and emittance transmitted