U.S. DEPARTMENT OF ENERGY
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Brookhaven National Laboratory

Midplane-Symmetric FFA Option for High Energy Muon Collider Acceleration

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Motivation

- There is a renewed interest in the physics community muon colliders with a center of mass around 10 TeV
- The largest rings for a muon collider will be the acceleration rings
  - Space occuped by RF: muons decay, so lots of RF per turn
  - Multiple passes in a single aperture requires compromises in average bend field
- Desire to keep accelerating ring as compact as possible
  - Space considerations (e.g., fit on Fermilab site)
  - Longer ring means more RF for given number of decays

What I will (not) be Discussing

- Constraints for this talk (*very* early studies)
  - A final FFA acceleration stage
  - Linear non-scaling FFA
  - Fit onto the Fermilab site
    - Optimize to minimize field
- What I will not talk about
  - Improvements with nonlinear magnets
  - Longitudinal dynamics
  - Green-field solution
  - Lower energy stages (may be favorable!)
  - Vertical FFAs (someone else's job…)
  - More complex cells (pumplet, etc.)

Muon Decays

- 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.
- For U.S. Muon Accelerator Program (MAP) luminosities, we needed 3.5 MV/m

Pulsed Synchrotron

- A pulsed synchrotron is the baseline and the preferred solution
- Simplistically, magnets ramp in proportion to beam energy, times around 1 ms
    - Dipole fields limited to below 2 T
    - Interleave bipolar pulsed dipoles with fixed SC dipoles
- Numbers for Fermilab site (16 km circumference):
    - 2.5–5 TeV for 2 T pulsed dipoles not viable
    - 10 T dipole, can only do 4.2–5 TeV
    - 10 T dipole, factor of 2, 3.3 TeV max energy
- The big challenge: power supplies!
    - Very high peak power
    - Very large stored energy

Parameters for this Study

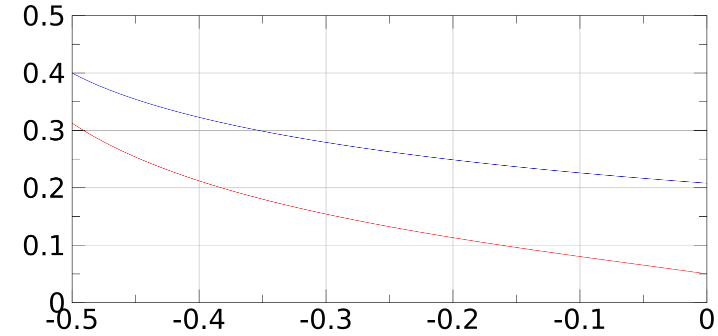
- Fits on the Fermilab site: 16 km circumference
- Goal of a 10 TeV center of mass collider, so 5 GeV per beam
- 12% of the circumference occupied by RF
  - 3.5 MV/m average accelerating gradient
  - 30 MV/m in cavities (roughly ILC numbers)
- 50 cm space between objects
- Both muon signs accelerated
  - Need reflection symmetric lattice for injection/extraction: use triplet

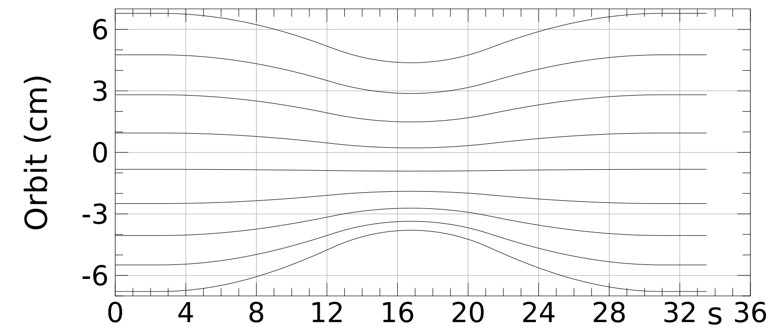
Parameters for this Study

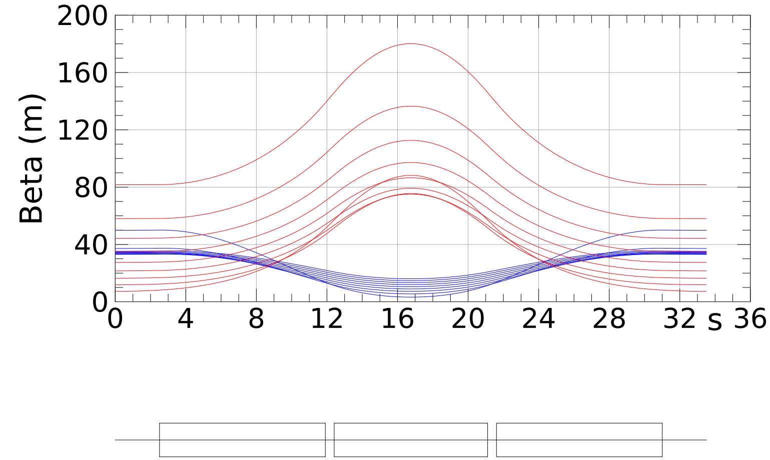
- Optimize to minimize maximum field at magnet coil
  - Defined so that maximum beam (4.5σ) is at 2/3 of coil radius
- FDF triplet
  - DFD fields slightly higher, but may have advantages
- End tunes fixed
  - Low energy horizontal tune set to 0.4
  - High energy vertical tune set to 0.05
  - Optimization to minimize field will push these to their limits, but benefits are only a couple percent in field

Representative Result

- Sample result for factor of 2 energy gain
- Just under 480 cells
- 4 m for RF (or injection/extraction)
- Optimization for field: field profile different from usual:
    - Inside F field near zero (normally about negative of outside)
    - Outside D field negative (−5.3 T vs. 12.4 T at outside, normally about zero)

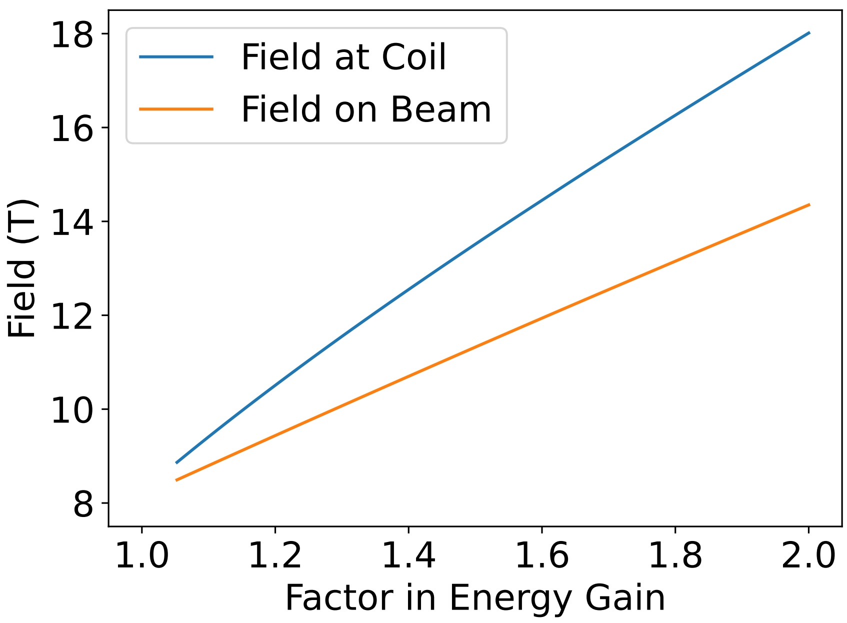






Field Range

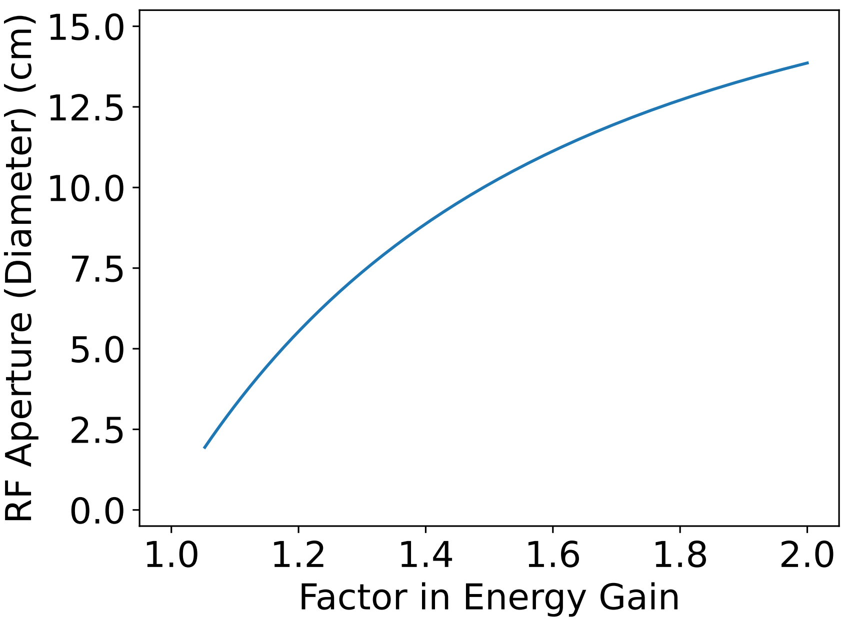
- Coil field assumes beam to 2/3 coil radius
- Magnet fields required depend on energy range
- Factor of 2 possible, but high fields



- With 10 T limitation, limits similar to synchrotron
  - Minimum energy 3.9–4.3 TeV for 5 TeV max
  - Factor of 2, maximum energy 2.8–3.5 TeV

Aperture

- For factor of 2, too large for Tesla cavities
- 650 MHz probably possible
  - But gradient may be reduced, so greater straight fraction



- SC magnet apertures also large, making magnets challenging
  - F magnet is larger and higher field

Injection/Extraction

- Horizontal for this configuration
  - FDF makes horizontal favorable
  - Beam near outer radius of magnet
- Number of straights for kickers reasonable to get separation
  - If 0.2 T (Nakamura), about 3 for extraction
  - Injection harder due to tune near 0.5
  - Lowering horizontal tune: higher main magnet fields
- But: how to get beam out with a septum?
  - Generate angle in oscillation as well
  - Pipe penetrating into aperture
  - Longer straights
    - Requires larger fields
    - More magnets in cell?

Final Comments

- Not so much worse than pulsed synchrotrons.
  - Biggest disadvantage related to larger aperture
    - Lower frquency RF
    - Larger magnet apertures
  - But no pulsed magnet power supplies
- This is a *very* early study
- Need to look at longitudinal dynamics
  - Can possibly shift phase for late stages
- Look at DFD triplet
- Nonlinear fields *must* help, but I suspect by not much
- Optimizing for field in a green-field design may not be best

Final Comments

- Should revisit lower energy FFAs
  - Older designs looked at neutrino factory with large transverse emittance
  - May work better with smaller collider transverse emittance