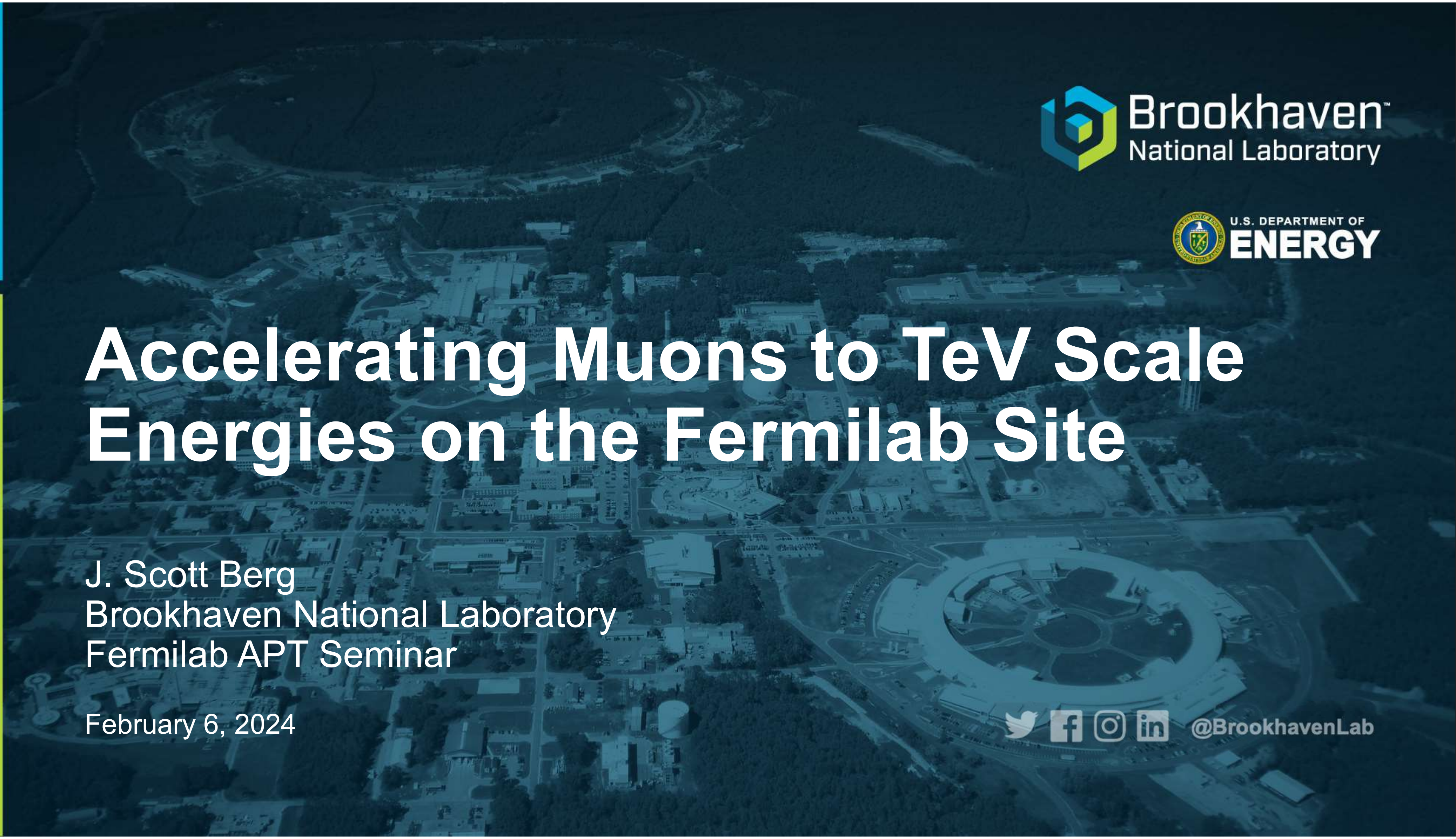

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Accelerating Muons to TeV Scale Energies on the Fermilab Site

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Fermilab APT Seminar

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Muon Collider Motivation

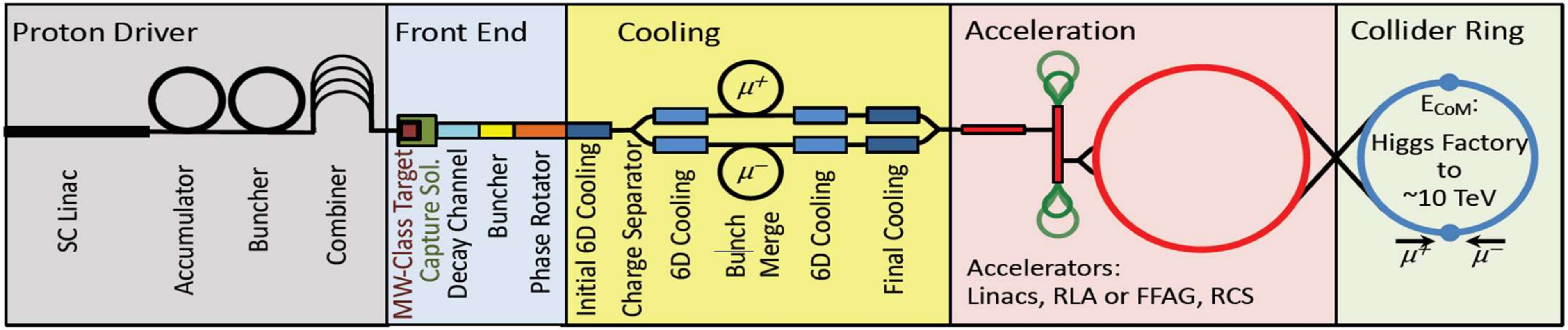
- Recent strengthening of interest in physics at the 10 TeV scale
- Would require ≈100 TeV CoM with protons
- Electrons
  - Would radiate too much in a ring
  - A linear collider is long and expensive, plus beamstrahlung challenges
- So instead use muons
  - Fundamental particles, all energy goes to interaction
  - Higher mass then electrons, so no radiation issues, bend in a ring
  - But they’re unstable: everything must happen fast
  - They’re difficult to make: keep losses low

Muon Colliders and P5

- From the draft report:
  - “we recommend targeted collider R&D to establish the feasibility of a 10 TeV pCM muon collider.” Note they do *not* intend to close off other options for these energies (e.g., 100 TeV protons, plasma acceleration, ...)
  - “With a 10 TeV pCM muon collider at Fermilab as the long-term vision...”
  - “a goal of being ready to build major test facilities and demonstrator facilities within the next 10 years”
  - “The US should pursue a leading role in the muon collider design effort, in concert with the International Muon Collider Collaboration (IMCC)”

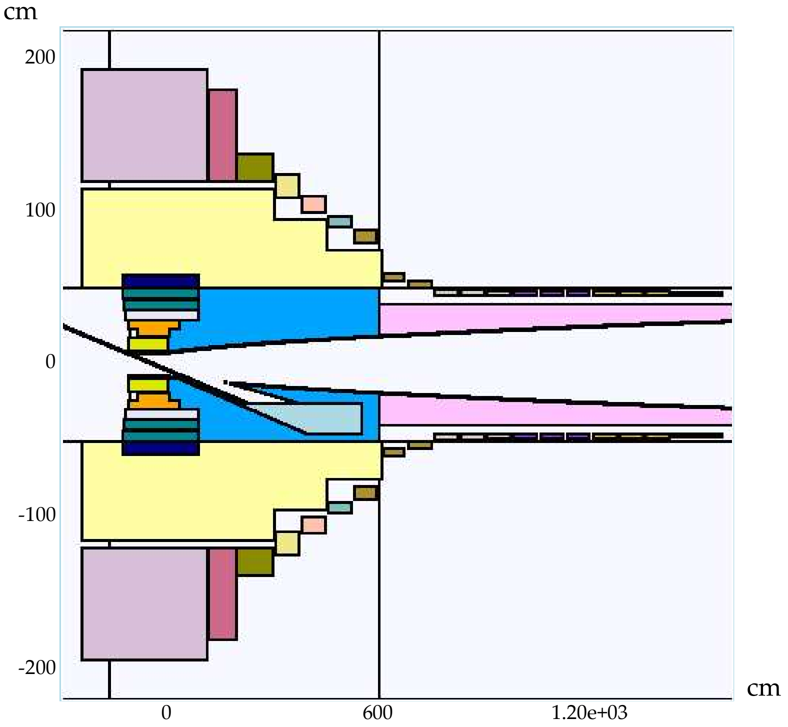
Muon Collider Facility Overview

- Proton driver creating high-power proton beam
- Front end: create pions at target, capture muons, convert to bunch train
- Cooling: reduce emittance, combine into one bunch
- Acceleration: increase energy
- Collider ring



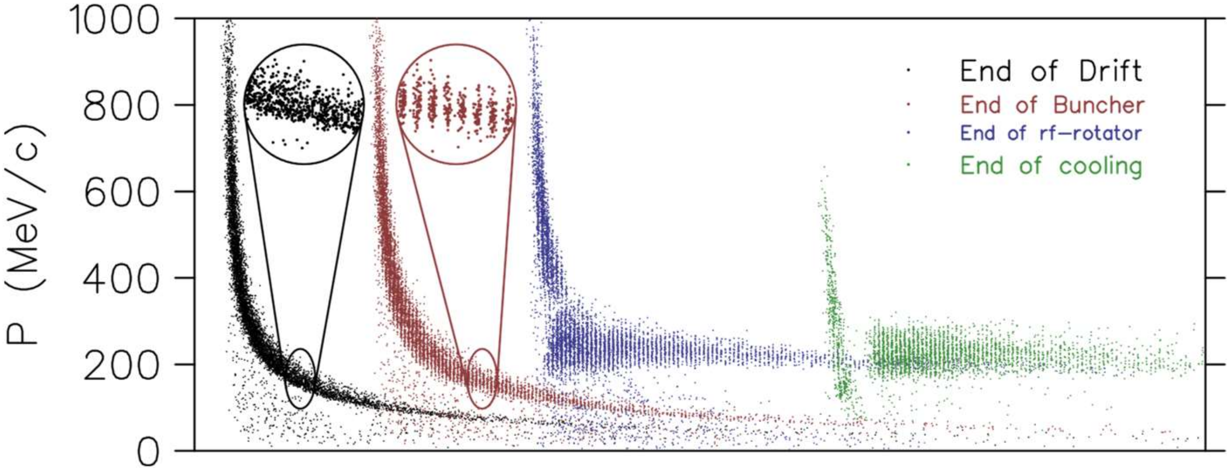
Target and Initial Capture

- Proton beam (1–4 MW) hits target, producing pions, decay to muons
- Pions produced with a large angular and energy spread but a small spot size
- Target is in a high field solenoid (15–20 T), which tapers down to a lower field to capture a large angular divergence



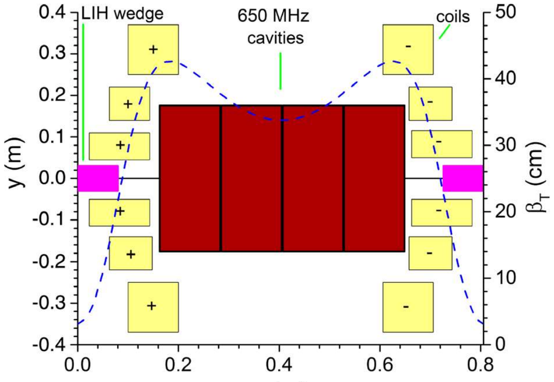
Capture of Bunch Train

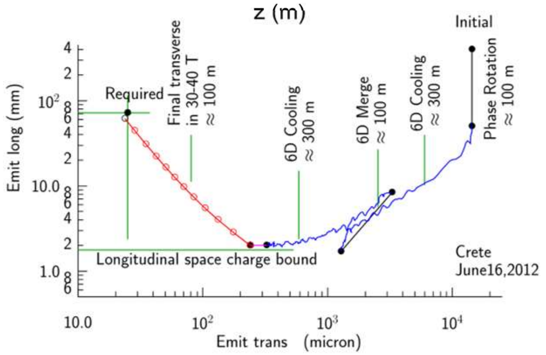
- Beam develops a time-energy correlation
- RF cavities form bunches
- Adjust RF frequencies to give bunches similar energies
- Works for both muon signs



Ionization Cooling

- Lose transverse and longitudinal momentum in absorber
  - Large angular divergence in absorber relative to multiple scattering: strong focusing, high field
- Restore longitudinal momentum in RF cavity
- Dipole field and triangular absorber couple transverse to longitudinal, cool longitudinally
- Cool bunch train, then merge to single bunch and cool more





Acceleration to High Energy: Outline

- High-level factors driving accelerator design
- Pulsed synchrotrons (RCS)
- Fixed field alternating gradient accelerators (FFAs)

Ring Size

- 50 TeV protons require a ring 10 times larger than 5 TeV muons: right? Well, sort of.
- This is pretty much true for the collider ring. So a 10 TeV center of mass collider ring fits comfortably on the Fermilab site; an equivalent proton collider would not.
- Acceleration is more complicated: muons decay
  - Protons: can take hours to ramp superconducting magnets if you want
  - Muons: you’re in a hurry. You have a few ms. You cannot ramp (traditional) superconducting magnets in this time. But you *could* ramp iron-dominated magnets. But they won’t get you fields above about 2 T.

Muon Decay in Acceleration

- Muon decays behaves logarithmically:

$$\frac{N_1}{N_0} = \left(\frac{E_1 + p_1 c}{E_0 + p_0 c}\right)^{-\frac{mc^2}{Gc\tau}}$$

- Average accelerating gradient G determines relation between transmission factor and energy gain factor. Can't relax at high energy.
- In MAP we specified 3.5 MV/m; IMCC study is using 2.5 MV/m and even lower

RF Cavities

- Minimize RF for cost and efficiency
- Make many passes through same cavities

$$n \sim \frac{\Delta E}{GL} \sim \frac{1}{2\pi} \frac{\bar{B}c}{G} \frac{\Delta E}{pc}$$

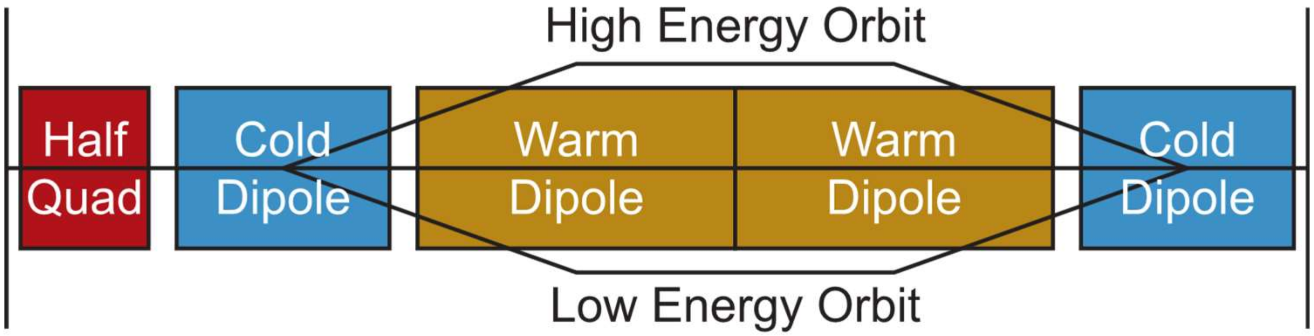
  - Minimize circumference of accelerating stages
  - High fields in dipoles, large dipole packing fraction
- Cost and efficiency drive you toward higher frequency
  - But large longitudinal emittance may get in the way

Pulsed Synchrotrons

- Pulsed magnets need to be iron-dominated to change fields on a ms time scale
- Iron dipoles will be limited to a bend field of 1.75 T
  - 2.0 T if you use Fe-Co, but cobalt might be a radiation problem
- With *only* iron dipoles, could only accelerate to 1.3 TeV on the Fermilab site
  - Not even accounting for quadrupoles, RF, etc.
- Need to get a higher average bend field

Hybrid Dipoles

- Need a higher average bend field with changing magnetic field
- Mix constant field superconducting magnets with iron magnets that bend backward at low energy and forward at high energy
- More SC magnet: higher energy; more iron magnet: more range



Dipole Field and Circumference

- What is the circumference from dipoles *only*?
- Starting point:

$$\frac{q}{p_+}(B_C L_C + B_W L_W) = \frac{q}{p_-}(B_C L_C - B_W L_W) = 2\pi$$

- Circumference

$$L_C + L_W = \frac{\pi}{q}\left(\frac{p_+}{B_W} - \frac{p_-}{B_W} + \frac{p_+}{B_C} + \frac{p_-}{B_C}\right)$$

- Even for infinitely high superconducting fields, there’s a minimum circumference for a given energy range: e.g., 2.5–5 TeV, 15 km

Dipole Field and Circumference

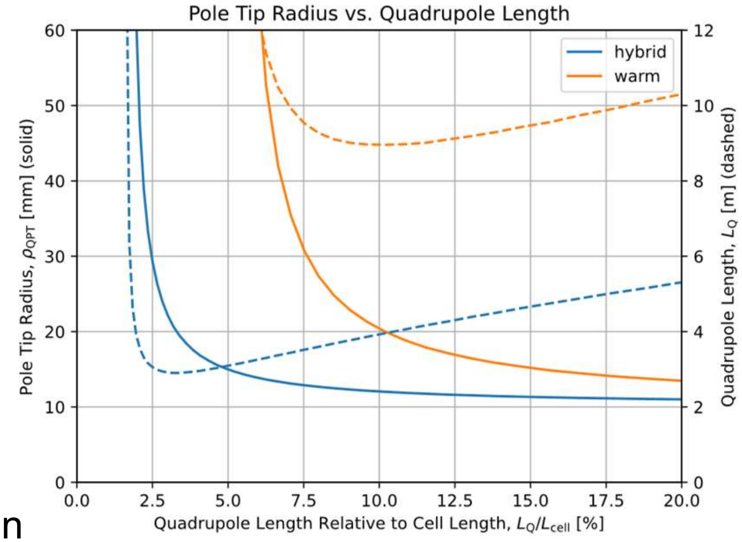
- Another point of view: average dipole field at high energy:

$$\frac{2B_C B_W}{B_C + B_W - (B_C - B_W)(p_-/p_+)}$$

  - With $p_- = p_+$, B_C as you would expect
  - With $p_- = 0$, get $2B_C B_W/(B_C + B_W)$ (e.g., $B_W = 1.75\ \mathrm{T}$, $B_C = 14\ \mathrm{T}$, get $3.11\ \mathrm{T}$)
  - With $p_- = p_+/2$, number would be 5.1 T
- A tradeoff between energy range and average bend field
- As energy range increase, fraction of warm dipole increases

Add Quadrupoles

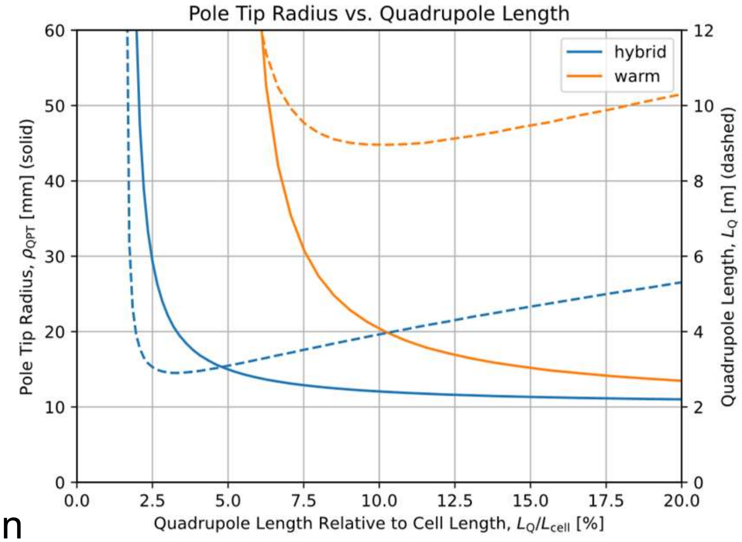
- Can’t only have dipoles, need quadrupoles. What fraction of the circumference do they require?
- Assume iron quadrupoles pulsed to maximum 1.2 T pole tip, 5σ aperture plus 1 cm overhead, factor of 2 energy gain, 5 TeV max
- End up with 9 m quadrupoles, and 20% quadrupole occupancy



Kyle Capobianco-Hogan

Add Quadrupoles

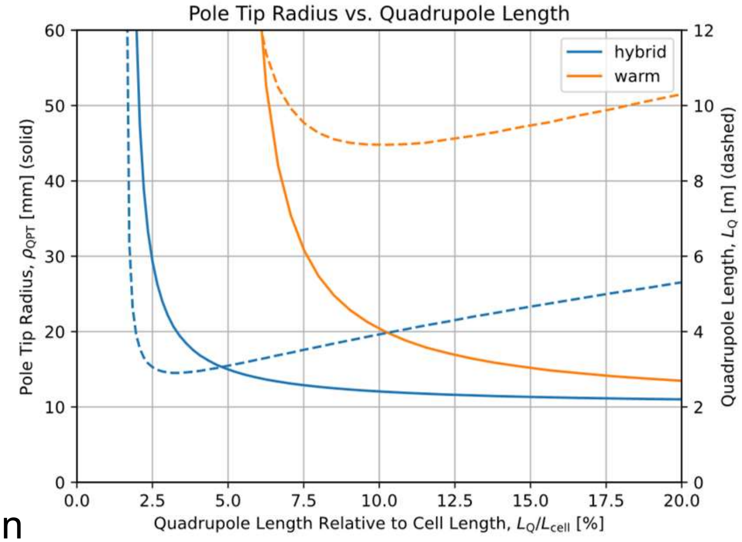
- Instead, interleave superconducting and warm quadrupoles like with the dipoles
  - Downside: need extra drifts between magnets
- Use similar formulas to dipoles, assume 12.5 T superconducting pole tip field
  - Effective max pole tip field is 3.7 T
- Now roughly 3 m long dipoles, 6% occupancy or so



Kyle Capobianco-Hogan

Add Quadrupoles

- As cells get shorter, quadrupoles must get longer due to stronger focusing, thus higher occupancy fraction
- But as cells get longer, occupancy fraction goes down, but beam size grows as well
  - Quadrupoles start getting longer at some point
- Optimum is somewhat near minimum quadrupole length



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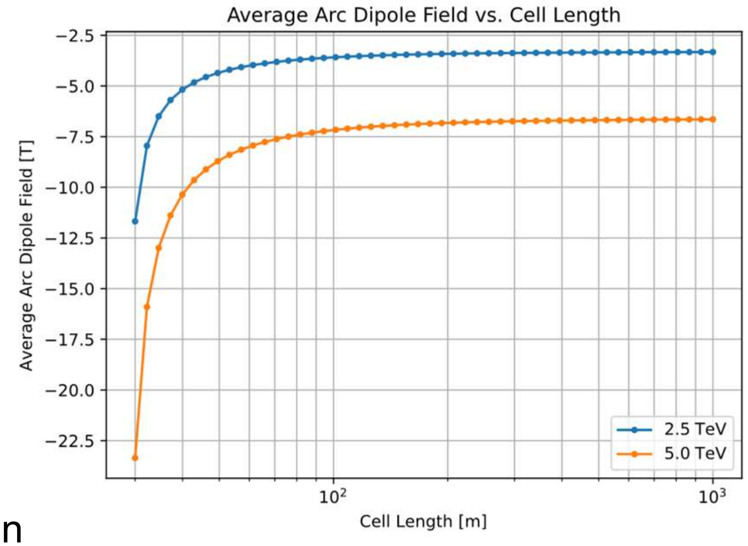
Add Quadrupoles

- Now do things more carefully: put 50 cm drifts between magnets
- Minimum quad length at ~12% occupancy
- Quadrupole apertures growing rapidly for lower occupancy
- Roughly 90 m long cells
- 7 T dipole fields to reach 5 TeV



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Dipole Field and Energy Range

- From before: factor of 2 energy gain, average bend field at high energy of 5.1 T, not 7 T. Choices:
  - Factor of 2 accelerating from 1.75 TeV to 3.5 TeV
  - Or accelerate from 3.6 TeV to 5 TeV
  - But with these lower energy ranges, dipoles occupancy fraction will get better. Need to close the loop (work in progress).
- But let’s not forget RF...

Rough RF calculation

- Rough starting assumptions
  - Low average gradient of 1 MV/m (90% transmission for a factor of 2)
  - 25 MV/m real estate RF gradient (roughly ILC number)
  - 45 degrees off-crest for the bucket
    - Careful with low average RF gradients: you spend a larger fraction of your voltage on keeping the RF bucket large enough
- Result is 6% occupancy for RF
- Now average bend for 5 TeV goes to 7.5 T
  - Slight reduction in maximum energy for factor of 2 or energy range for 5 TeV

Additional RF Complications

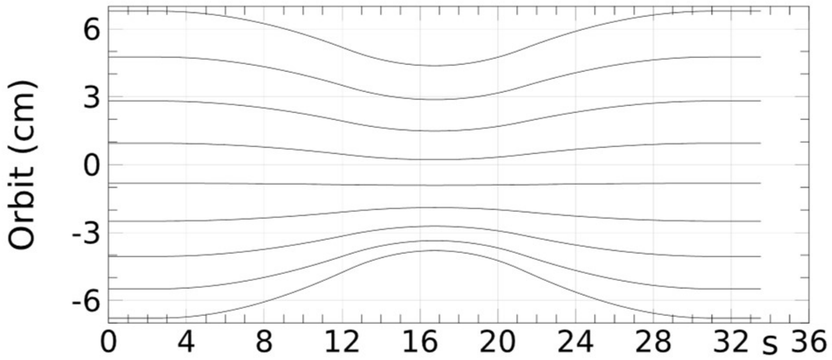
- Need several RF straights (CERN studies estimated 32)
  - Synchronization between energy and dipole field
  - Synchrotron tune is around 1; RF kick-drift pair must be below 0.16, preferably lower
- Making magnet drive current linear with time is expensive
  - Make up for it by changing RF phase to keep acceleration rate and field change rate synchronized
  - Need excess bucket area for this: more RF voltage

Putting it all Together

- Need to put together designs with more factors considered
    - Spaces between warm and cold dipoles
    - Compute RF phase from required bucket area
    - Add dispersion suppression between RF and arc
    - Chromatic correction sextupoles
- Kyle Capobianco-Hogan (student, SBU) is working on putting together a design that takes all this into account self-consistently
    - Plots show here are from some of his initial studies

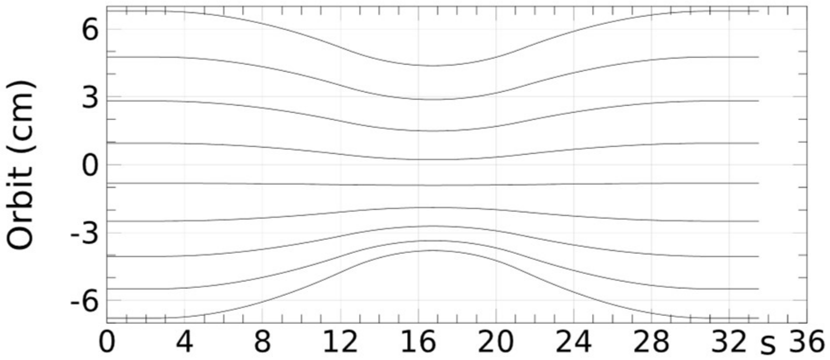
What is an FFA

- **F**ixed **F**ield **A**lternating gradient accelerator
- Large energy range (e.g., factor of 2) in a single beamline
- Magnet fields do not vary with time
- Alternating gradient focusing in compact cells for small orbit excursion
- Motivation for muon acceleration: superconducting-only solution that will scale with magnet technology; overcome the limited field in iron



What is an FFA

- A single cell is duplicated around the ring
- Each cell has a long drift that can contain an RF cavity
  - Also used for injection/extraction/etc.
- For muons: accelerate both signs, requires reflection symmetry for consistent injection/extraction
- An FDF triplet with a long RF straight is the simplest solution

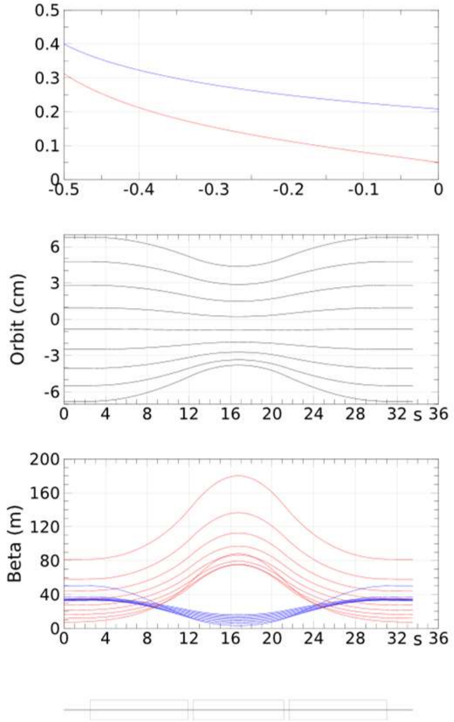


FFA to Accelerate to 5 TeV

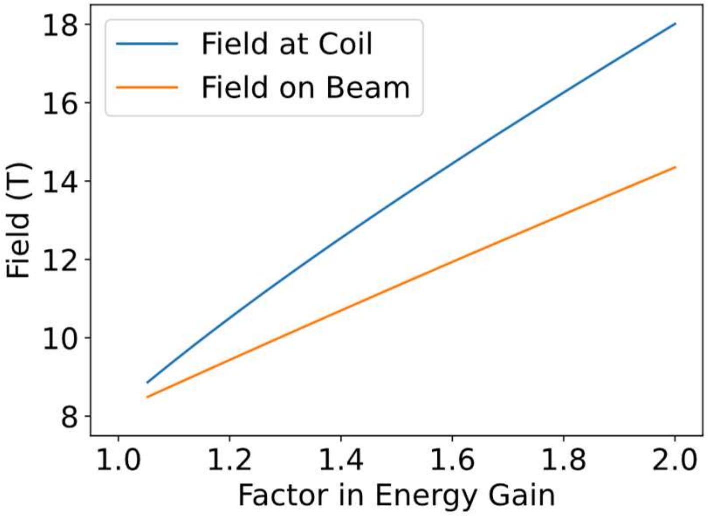
- Older study, parameters are inconsistent with pulsed synchrotron study
- 12% of circumference occupied by RF
- 50 cm between objects
- Optimize to minimize the maximum field at the magnet coil
  - Defined so that 4.5σ is at 2/3 of coil radius

Sample Result

- Note tunes, orbits vary with energy
- Sample result for factor of 2 energy gain
- Just under 480 cells
- 4 m for RF (or injection/extraction)
- Optimization for field
- F field is 12.4 T at outside
- D field is −5.3 T at outside
    - Reverse bend



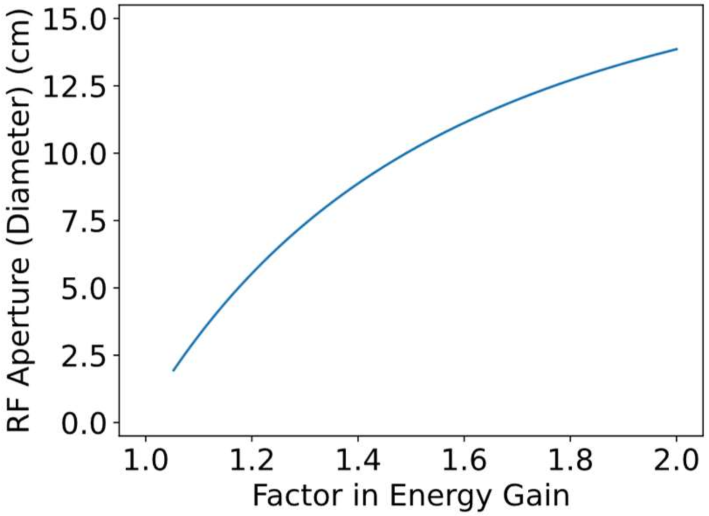
Field and Energy Range



- Assume maximum energy of 5 TeV
- Magnet field depends on minimum energy
- Plot shows field at coil, at 1.5 times beam radius, and field at beam
- Factor of 2 energy gain possible, but high fields
- Limitations similar to pulsed synchrotron
  - Minimum energy 3.1–3.6 GeV for 5 TeV max for 12.5 T max
  - Factor of 2, maximum energy 3.5–4.4 TeV for 12.5 T max
- Remarkably similar to pulsed synchrotron numbers

Aperture

- For factor of 2, too large for Tesla cavities
- 650 MHz probably possible
  - Reduced gradient may require longer straight
- SC magnet apertures are also large

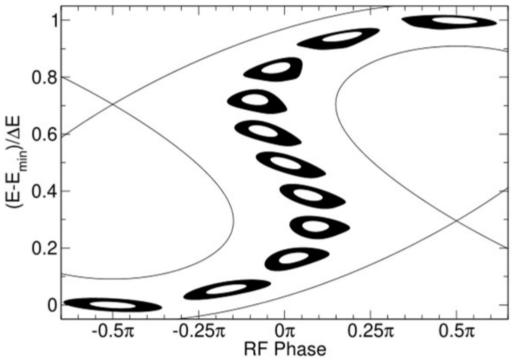


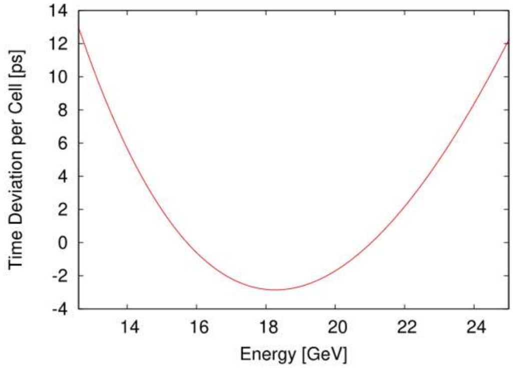
Injection/Extraction

- This configuration (FDF) makes horizontal favorable
  - Beam near inner/outer edge of magnet
- Number of straights for kickers to get separation
  - For 0.2 T kickers, about 3 straights for extraction
  - Injection harder due to tune near 0.4. Reducing tune would lead to higher main magnet fields
- Challenge is extraction septum. Ideas to manage:
  - Generate angle and position at septum
  - Pipe penetrating into aperture
  - Special magnets with larger apertures (higher fields!)
  - Longer straights (larger fields); maybe taper straight length

Acceleration

- Design is optimized for peak field
- Need to consider longitudinal dynamics
- One option is to shift RF phase
- Without shifting phase, can do serpentine acceleration
  - Requires designing for a more symmetric time of flight vs. energy
  - Will lead to higher fields





Further FFA Studies

- This was just a first look
- Additional areas of study needed
  - Look at longitudinal dynamics; do we need to adjust the lattice?
  - Look at DFD triplet
  - To what extent to nonlinear fields help?
  - Need a concrete injection/extraction design
  - Look at tapered design to get longer drifts for injection/extraction

Pulsed Magnet Studies

- Iron response
  - No good data on iron response at high ramp rates and approaching saturation
  - Losses are important, but should also understand response
  - Measure material response to single pulse for various ramp rates and maximum fields
  - Build a small prototype, measure voltage/current/field with a range of drive pulse amplitudes and ramp rates
- Power supplies for production systems

Collaboration with the IMCC

- IMCC has contributed incredibly to the pulsed synchrotron design
- Extensive studies of power supply design
- Studies of many aspects of lattice design and beam dynamics
    - Longitudinal dynamics, coupled with power source limitations
    - Impact of the number of RF stations
    - Collective effects
    - Lattice design framework
- A program looking at iron magnets

Conclusions

- The largest ring in a muon collider is the one that accelerates beams to the highest energy
- Pulsed synchrotrons or FFAs both appear able to accelerate beams to similar energies near 5 TeV
- There is a tradeoff between energy gain and maximum energy in the acceleration design
- A likely scenario seems to be roughly a factor of 2 energy gain to some energy below 5 TeV, then later a second ring in the same tunnel to reach a higher energy

Acknowledgements

- David Neuffer proposed an acceleration scenario pointing out much of what you see here; there’s just a bit more detail here
- I’m working with a Stony Brook University graduate student, Kyle Capobianco-Hogan, on a scenario accelerating with pulsed synchrotrons on the Fermilab site; the plots came from his work
- The IMCC has contributed greatly to advancing pulsed synchrotron studies
- Al Garren worked out an earlier lattice design for a lower energy hybrid pulsed synchroton
- The idea for the hybrid dipole configuration came from Don Summers