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National Laboratory

U.S. DEPARTMENT OF
ENERGY

The Accelerator and Collider

J. Scott Berg, Brookhaven National Laboratory
DPF-PHENO 2024 Minisymposium:
Muon colliders for 10 TeV Center of Mass

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Overview

- We’ve created and captured muons, reduced their emittance without losing too many of them. Now we need to:
  - Get them to a collision energy of ≈5 TeV
  - Collider them in a ring, maximizing luminosity of the beam we have
- Outline
  - Acceleration to high energy in pulsed synchrotrons
  - Alternative: fixed field alternating gradient accelerators
  - The collider ring

Ring Size

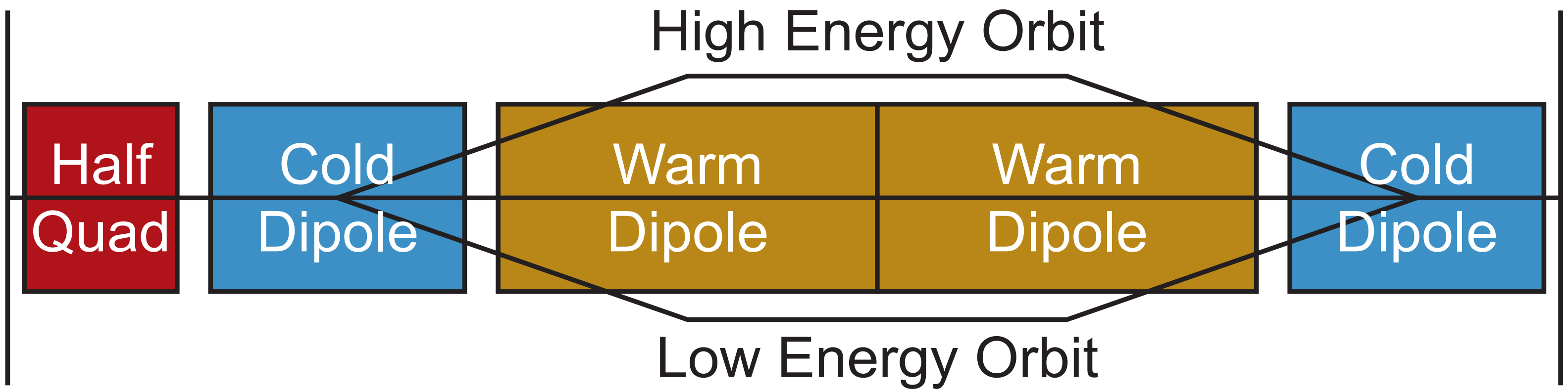
- 50 TeV protons require a ring 10 times larger than 5 TeV muons: right? Well, sort of.
- This is pretty much true for the collider ring. So a 10 TeV center of mass collider ring fits comfortably on the Fermilab site; an equivalent proton collider would not.
- Acceleration is more complicated: muons 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.

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*?
- 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
  - That circumference depends on the pulsed magnet field

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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

Other Components Reducing Bend

- Energy reach is reduced by areas that have zero or reduced bending
- Quadrupoles that focus the beam
  - Using only warm dipoles, ≈20% of circumference in reaching 5 TeV
  - Make hybrid superconducting and pulsed like dipoles; now ≈6%
- Straights for RF cavities
  - More straights, higher average gradient, fewer decays, but less energy reach
- Dispersion suppression (2 cells on each side of straight), half bend
- Sextupoles for chromaticity correction
- Space between components

RF Straights

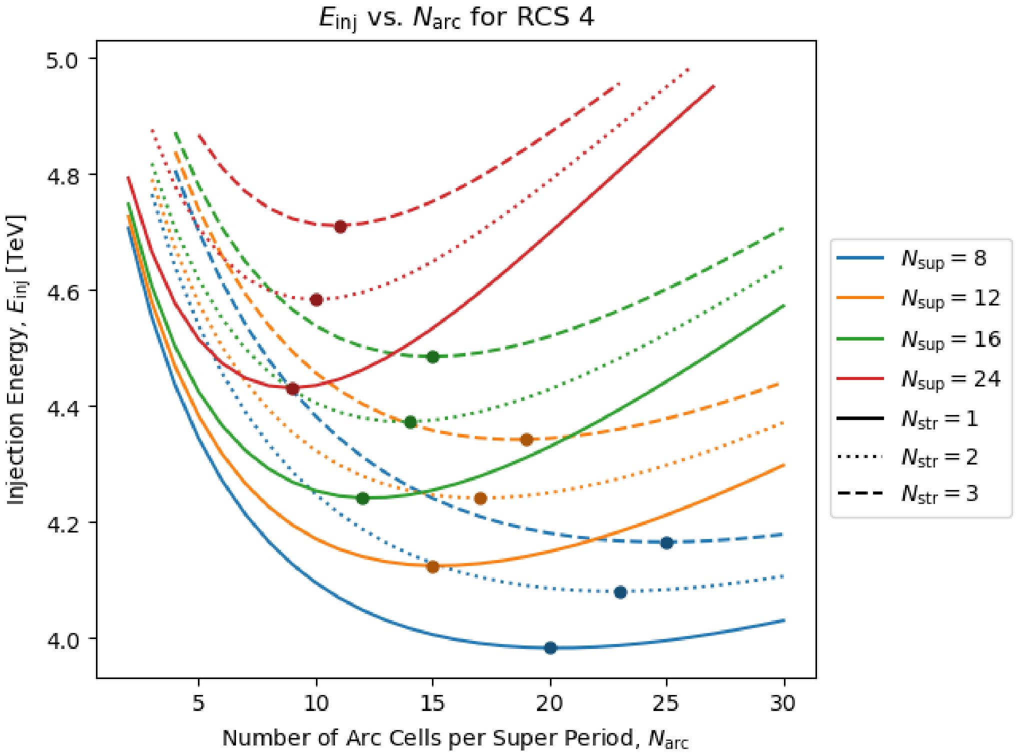
- Need several RF straights (IMCC studies estimated 32)
  - Synchronization between energy and dipole field
  - Synchrotron tune is around 1; RF kick-drift pair must be below 0.16, preferably lower
- Each RF straight needs dispersion suppression, reducing average bend field

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
- Is FeCo usable for the magnet pole? Higher field, better energy reach. Needs radiation simulations
- Power supplies for production systems

IMCC and Other Studies

- Lattice design and parametric optimization, both for green-field designs and Fermilab siting



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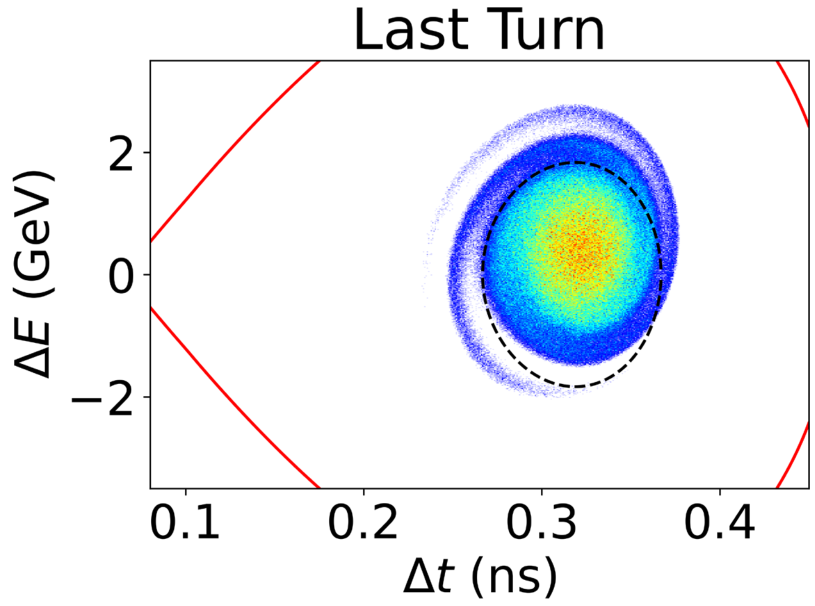
- Longitudinal dynamics, including nonlinear magnet field ramp and impact of number of RF stations



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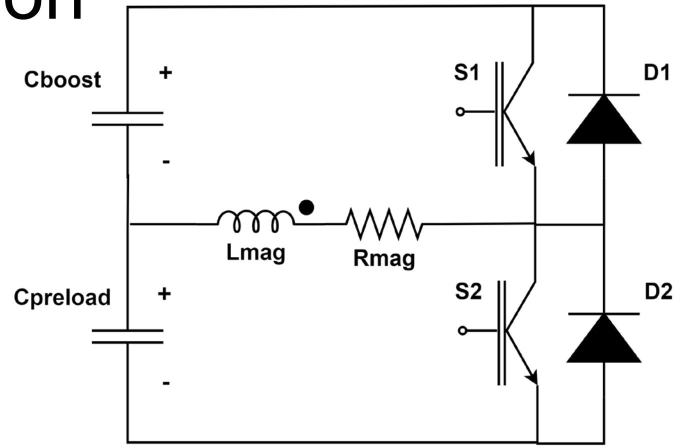

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- Longitudinal dynamics, including non
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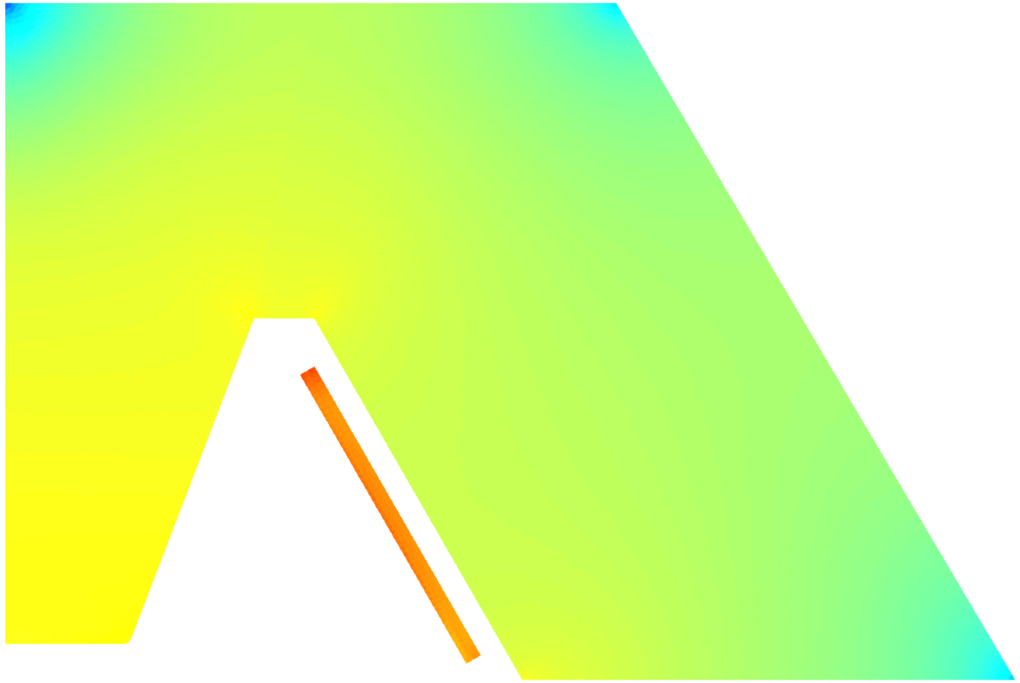
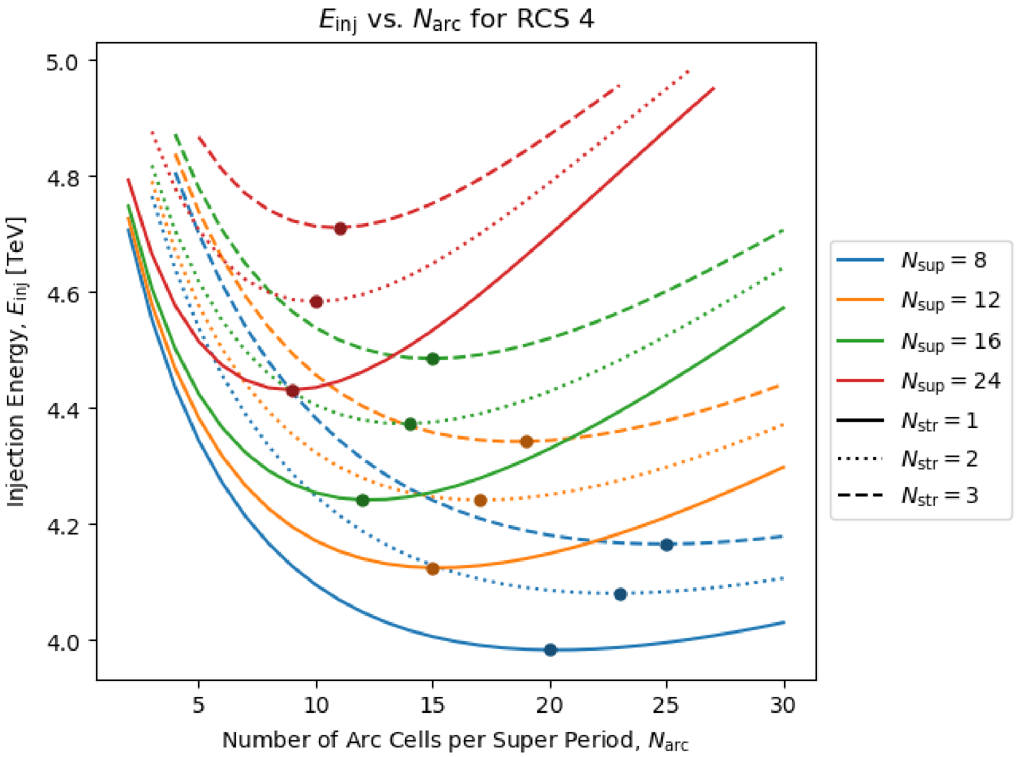
- Collective effects, need for chromatic
- Power supplies for pulsed magnets
- Pulsed magnet design



Acceleration at Fermilab

- On-site circumference limited to 16.5 km
- Latest numbers: extraction at 5 TeV requires 4.1 TeV injection
- Have a lower energy accelerator in the same tunnel, will have a larger energy range
- May need to back off 10 TeV CoM a bit if limited to Fermilab site



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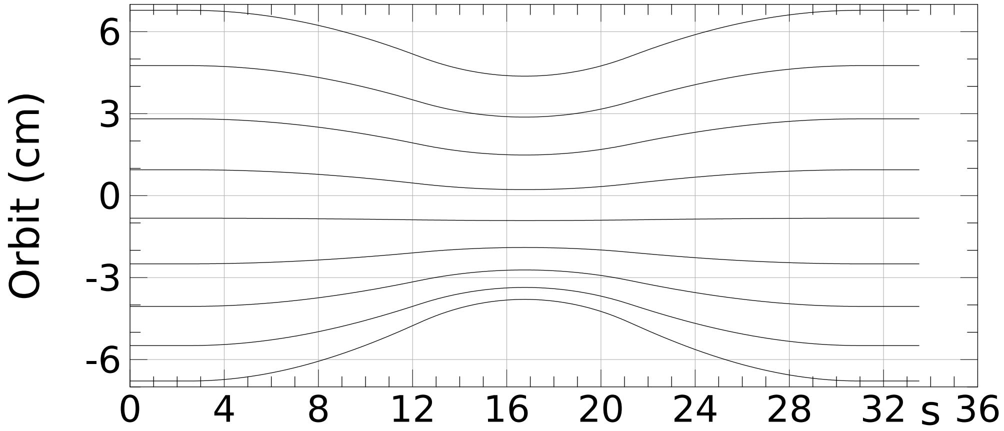
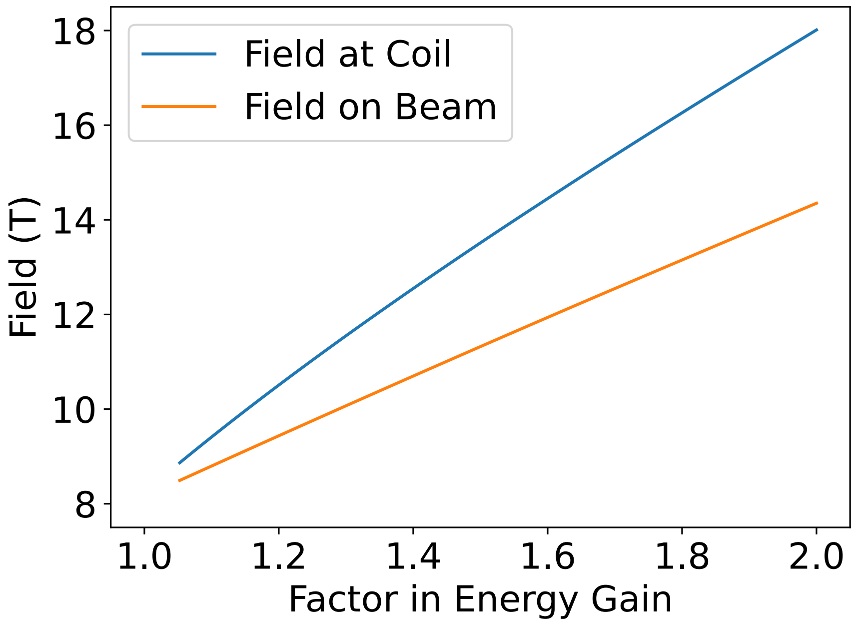
What is an FFA

- **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
- Each energy follows a different orbit
- 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



FFA: 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



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FFA: Injection/Extraction

- For 0.2 T kickers, about 3 straights for extraction
- 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

Muon Collider Luminosity

- Luminosity for a muon collider

$$L=\frac{N_0^2 f\gamma}{4\pi\beta^*\epsilon_{\perp n}}\frac{c^2\tau_\mu B}{4\pi\left(m_\mu c^2/e\right)}$$

- Inversely proportional to transverse emittance
- Second factor: effective number of turns, proportional to average bend field (about 150 times the field in T)
- β^* should be larger than the bunch length
  - Bunch length times fractional energy spread is longitudinal emittance
  - Reducing β^* reduces energy acceptance
  - Longitudinal emittance impacts luminosity

Muon Collider Luminosity

- Luminosity for a muon collider

$$L = \frac{N_0^2 f \gamma^2 \sigma_\theta^2}{4\pi\epsilon_{\perp n}^2} \frac{c^2 \tau_\mu B}{4\pi\left(m_\mu c^2/e\right)}$$

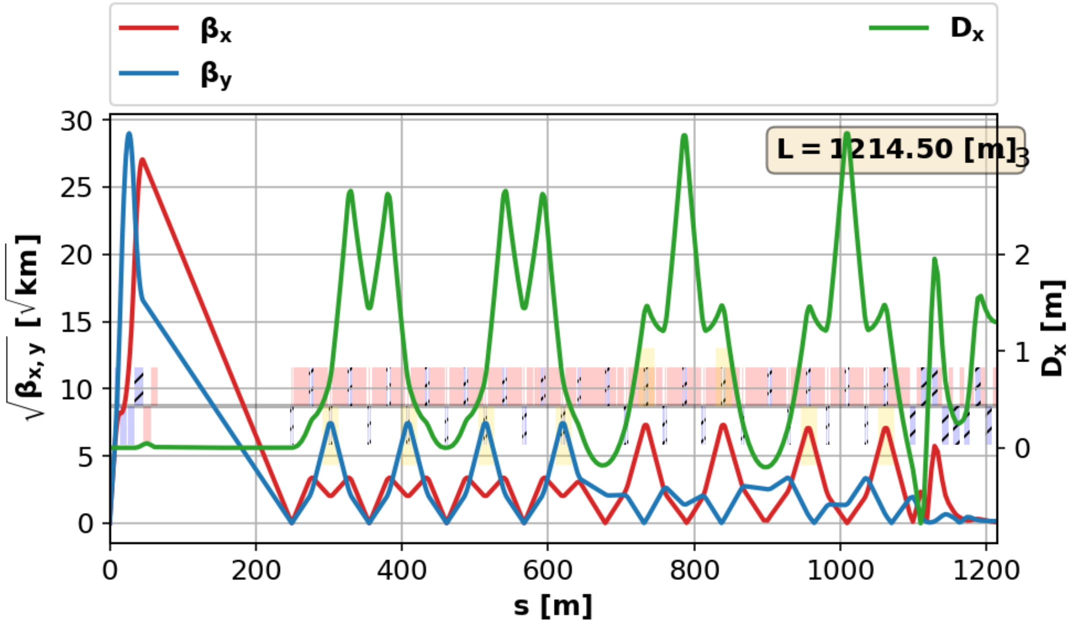
- $\epsilon_\perp/\beta^*$ is the square of the RMS angular divergence
- σ_θ^2 is roughly proportional to $B_Q r_Q/\gamma$
  - Want high IR quadrupole pole tip field B_Q
  - Large IR quadrupole radius, but that means lower B_Q
- Luminosity depends strongly on fields in collider magnets, both arc dipoles and IR quarupoles

Neutrino Radiation

- Neutrinos from muon decays shower in matter where they exit surface, leading to small but relevant does to stationary observer
- Increases rapidly with energy: E_μ^3 to E_μ^4
- Ways to manage
  - Collider ring deep underground
  - Insure there are dipole fields everywhere
  - Vary beam trajectory with time, using fields or moving beamline
  - Large beam divergence
  - Choose or control problematic beam exit locations

Current IMCC Studies

- Work on 10 TeV collider lattice design
  - Including dipoles to reduce BIB



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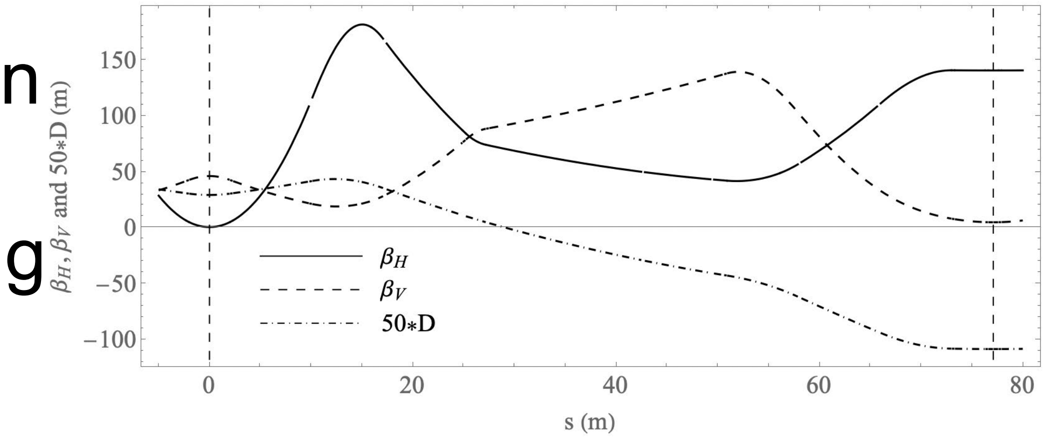

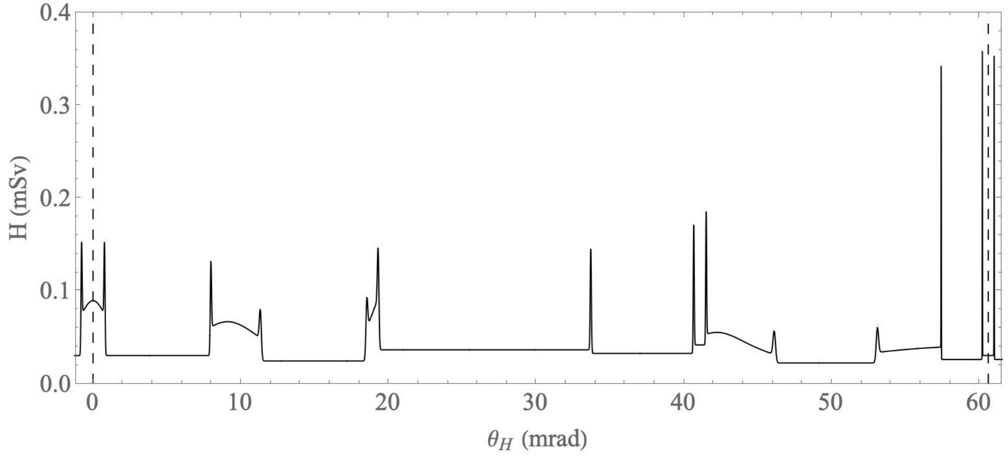

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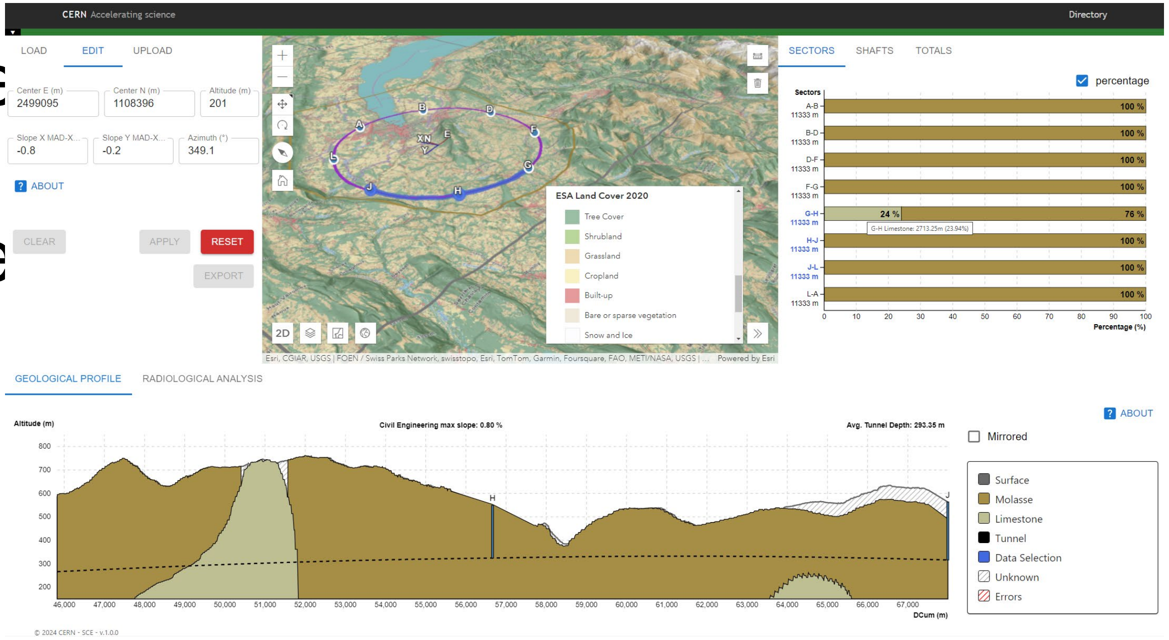
- Tools to incorporate geography, topography, underground composition in siting and radiation does calculations



Center E (m): 2499095
Center N (m): 1108396
Altitude (m): 201
Slope X MAD-X…: -0.8
Slope Y MAD-X…: -0.2
Azimuth (°): 349.1

☑ percentage

G-H Limestone: 2713.25m (23.94%)

Civil Engineering max slope: 0.80 %

Avg. Tunnel Depth: 293.35 m

☐ Mirrored

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R&D Topics for Collider Ring

- Collider lattice design. In addition to the usual:
    - Neutrino radiation mitigation plan (partially site specific)
    - Injection (need a straight!). Do we need to dump?
    - Determine if RF needed (would also need a straight)
    - Interaction with magnet design
    - Shielding requirements
- Magnet design
    - Determine what is feasible
    - Many magnets to design, each a major effort
- Interactions with detector: beam induced background, etc.

Summary

- We can accelerate muons rapidly to high energies with hybrid pulsed synchrotrons
  - But we may be limited in energy reach if confined to the Fermilab site
  - FFAs provide an alternative that scale well with superconducting magnet fields, but need to find an injection/extraction solution
- Good progress is being made on collider ring designs
  - Magnet fields have a direct impact on luminosity
  - Need a site-specific plan for addressing neutrino radiation
- Much work is still needed before we can build a muon collider. Plenty of areas where people can contribute.