Accelerator Physics in the Accelerator and Collider Complex

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Workshop on Muon Collider Testing Opportunities
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Talk Overview

- Acceleration
  - Acceleration principles
  - Types of accelerators
    - Linacs
    - Recirculating linear accelerators
    - Fixed field alternating gradient accelerators
    - Pulsed synchrotrons
  - MAP scenario
  - Collective effects
- Collider ring
  - Overview
  - Specific effects

Acceleration Principles

- Limit decays: muons are difficult and expensive to create
- Everything happens fast
  - At lower energies have no time to change magnet fields, RF frequencies, replace RF energy
  - These become possible at high energy, but parameters beyond conventional
- RF cavities are expensive: make as many passes through cavities as possible
- RF power is expensive: consider energy efficiency
- Avoid increasing transverse and longitudinal emittance

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

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

- 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

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

  - Small circumference of acceleration stages
  - High fields in dipoles
  - Large dipole packing fraction
- RF frequency
  - Higher frequency less expensive
  - More turns with lower frequency
  - Early stages use stored energy (low frequency)
  - Later stages can top off

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)
  - Reduce RF frequency (expensive)

Types of Accelerators

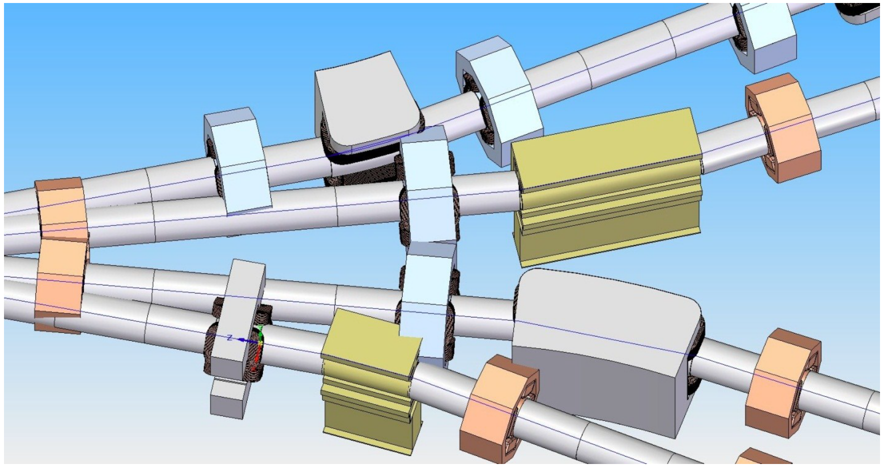
- Linac
- Recirculating linear accelerator (RLA)
  - Make multiple passes through the same linac
  - Separate arc for each energy, returning the beam to the linac
- Fixed field alternating gradient (FFA)
  - All energies in a single beam line whose magnetic fields do not vary in time
- Pulsed synchrotrons
  - Synchrotron with magnets whose fields increase with energy

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
- Early acceleration: cooling lattice without absorbers

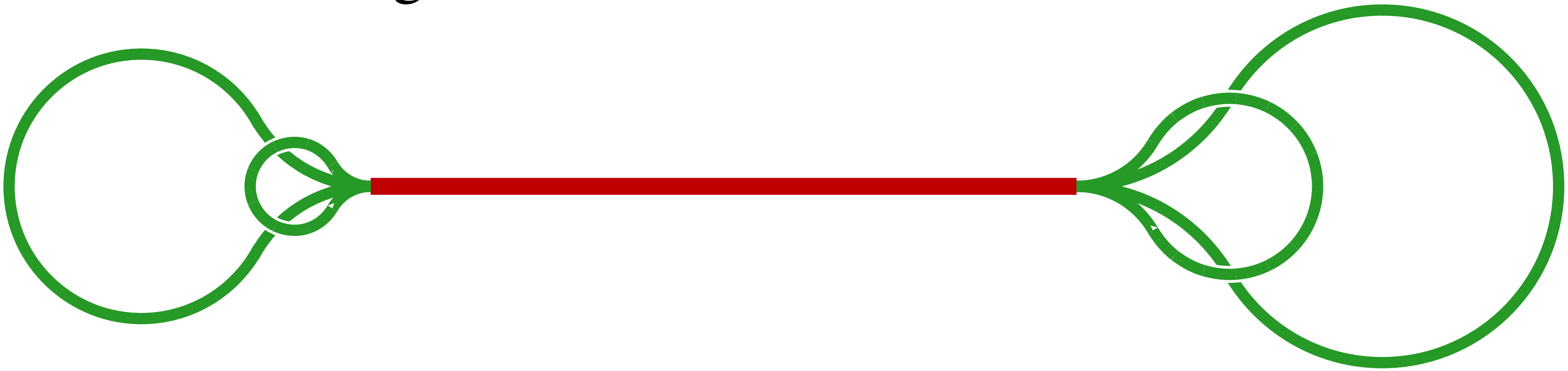
RLA

- Return beam to linac, separate pass for each energy
- Preferred solution at lower (few GeV) energies
- 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



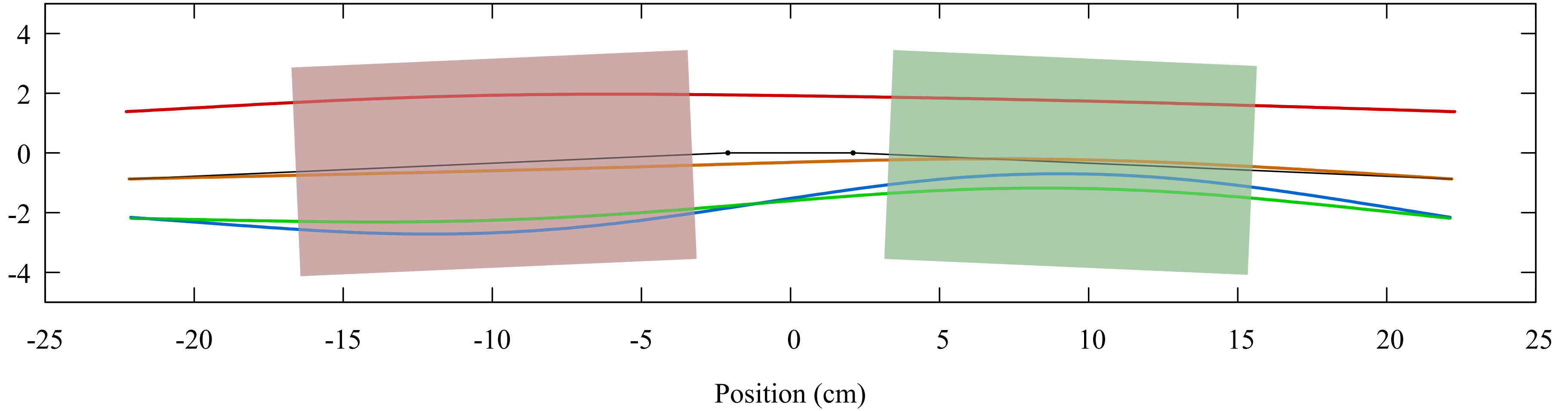
RLA

- 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 length of linac
    - Arcs cross at intermediate points
- Preserving large longitudinal emittance
  - Want short arc cells, but mismatched to linac
  - Forces long arcs

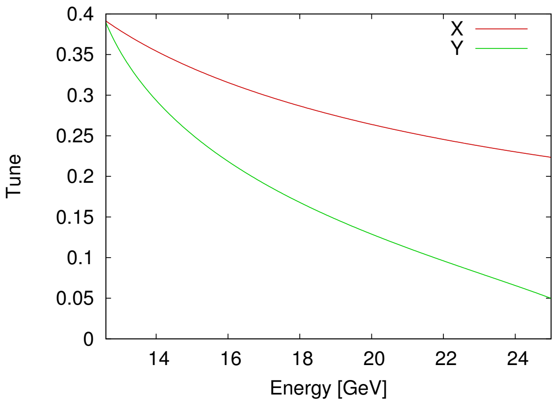


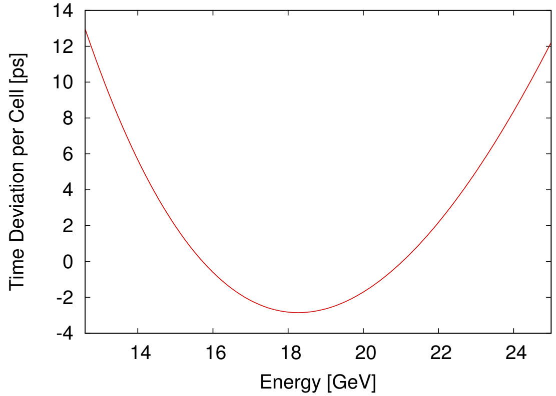
FFA

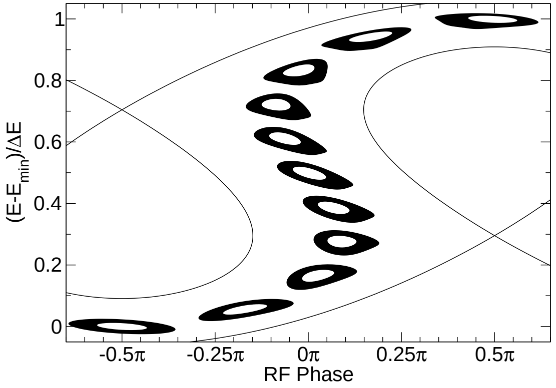
- Fixed field alternating gradient accelerator
- Single beamline for many energies, magnet fields don't vary with time
- No switchyard: can get a large number of turns
- Magnets need to be wide: every energy at a different position



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 (Nakamura?)
- 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

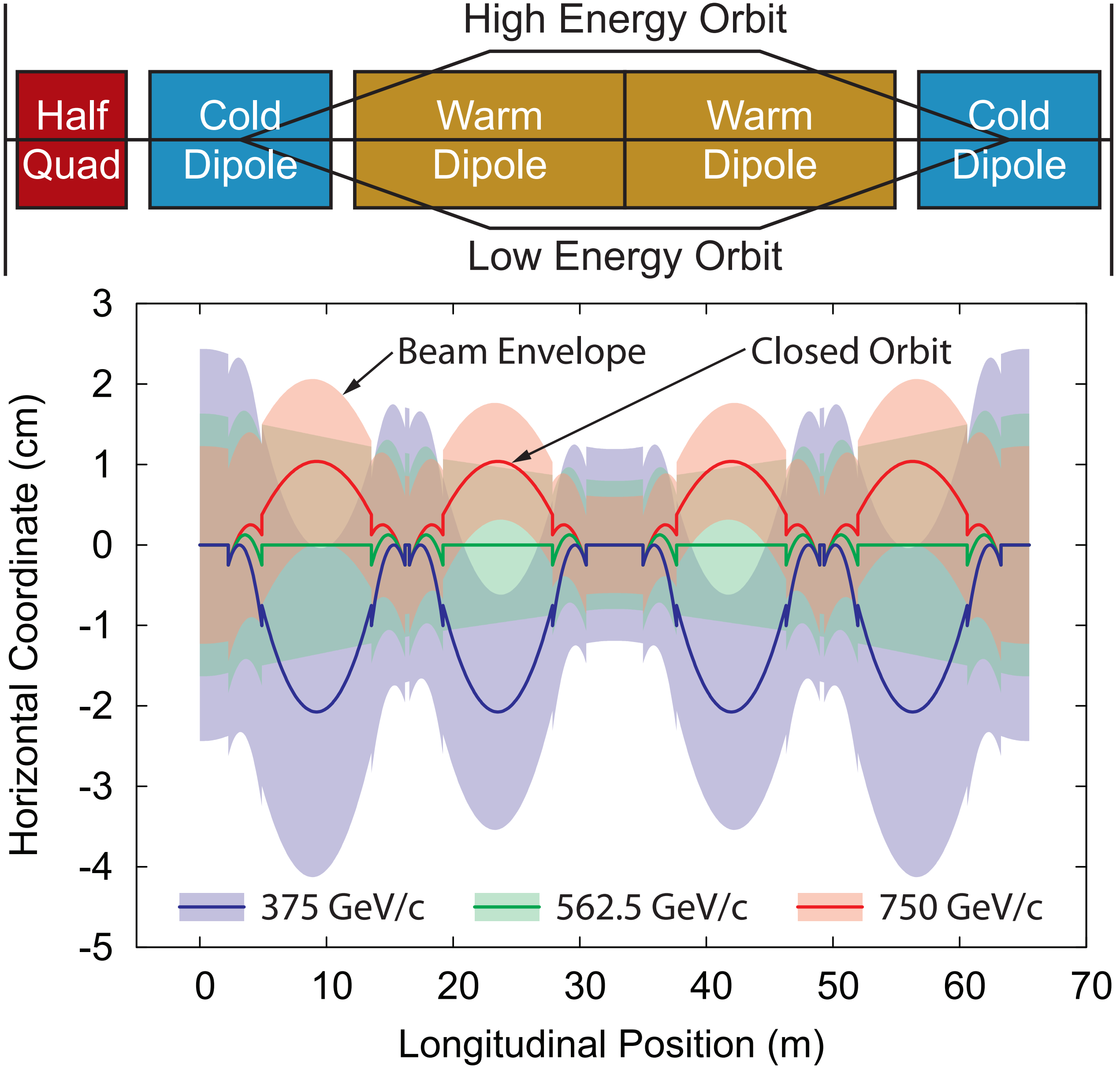
Pulsed Synchrotron

- Accelerate as usual for a synchrotron: magnet fields proportional to momentum
- Advantages over FFA
  - Dispersion-free straights: reduce orbit mismatch, synchro-betatron coupling
  - Can use higher RF frequencies and/or get more turns
- Distribute cavities uniformly around ring, as many stations as possible to minimize mismatch
  - Energy increases discretely
  - Field varies continuously
- Maximum field only around 1.5 T: few turns or large number of decays
- Magnet fields increasing rapidly (around 1 ms)

Hybrid Pulsed Synchrotron

- Increase average bend field: interleave fixed superconducting dipoles and bipolar pulsed warm dipoles
  - More RF passes and shorter circumference
- Larger energy gain factor has significant penalties
  - Lower average bend field, so longer ring
  - Wider aperture required in magnets
  - Energy discretization problems at lower energies
- Easier at higher energies: more time
- Adjust orbit position to keep time of flight constant
- High synchrotron tune (approaching 1), far off-crest ($\approx 45°$)
- Top of RF

Hybrid Pulsed Synchrotron



Pulsed Magnets

- Acceleration times around 1 ms
- Need to deal with energy losses
  - Combine high-field pole with 6.5% Si steel back yoke
  - HTS-based SC solutions
- Power supply
  - Need good control of current ramp
  - Large peak power
  - High efficiency (below 2% loss per pulse) to keep losses below magnet losses
  - Keep magnet apertures small to minimize stored energy
- Losses and power supply capabilities lead to lowest tolerable energy for pulsed synchrotrons

MAP Requirements

- 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
- Initial beam energy 100–200 MeV

MAP Scenario

- Initially use something like cooling channel
- Superconducting linac at 325 MHz to 1.25 GeV
- RLAs to 5 GeV (neutrino factory) then 63 GeV (Higgs)
  - 650 MHz RF, extracting stored energy
  - FFAs had to be long to control longitudinal emittance
    - RLA arcs need to be long for the same reasons…
- Pulsed synchrotrons to high energy
  - Hybrid synchrotrons at high energy
  - Loss in magnets: a few MW per stage
  - 1.3 GHz RF systems. Heavy beam loading.
    - Good for efficiency, but large collective effects
  - Top off cavities at each turn

Collective Effects

- Beam collisions
  - Both beams counter-rotating in same rings
  - Beams collide at two points
  - Small number of collisions
  - Electrostatic separators?
- 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

Acceleration: Final Thoughts

- Key issues driving designs
  - Preventing excessive decays
  - Limiting longitudinal emittance growth
  - Power efficiency
  - Cost, particularly RF
- Large longitudinal emittance pushes up costs
- Very efficient systems have small energy gain factor
- Things get easier, more efficient at higher energies
- Push FFA designs into lower/higher energy
  - Revisit RLA/pulsed synchrotron tradeoffs
  - Addition of nonlinearity to extend energy range
- Hardware challenge: pulsed magnet power supplies; pulse control and efficiency

Collider Ring

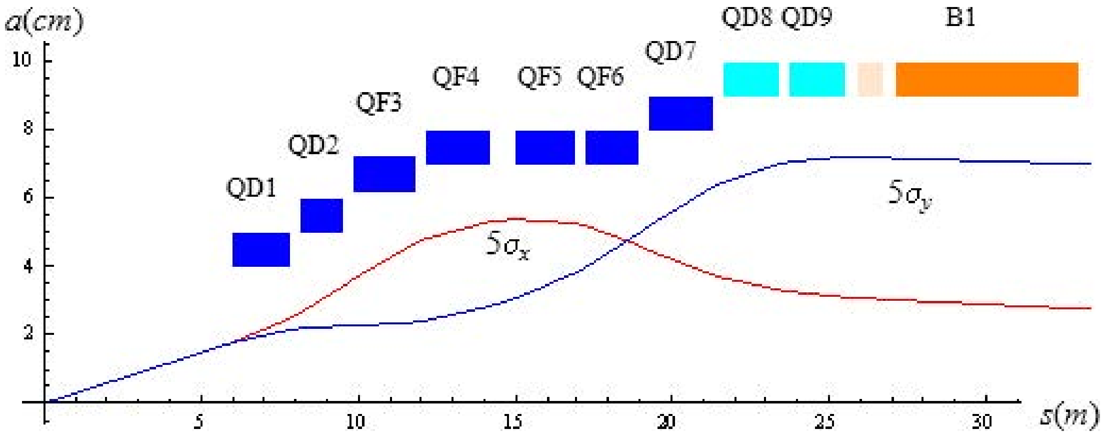
- Small β^*: short bunch (3–10 mm)
- Large longitudinal emittance
    - With short bunches, large energy spread ($\sim 10^{-3}$)
- Neutrino radiation
    - Minimize straights
    - Combined function magnets
- Shield SC magnets from electrons (muon decay)
    - Large magnet aperture for shielding, and/or
    - Open midplane magnets
- Large bunch charge
- High average bend field (turns for luminosity)

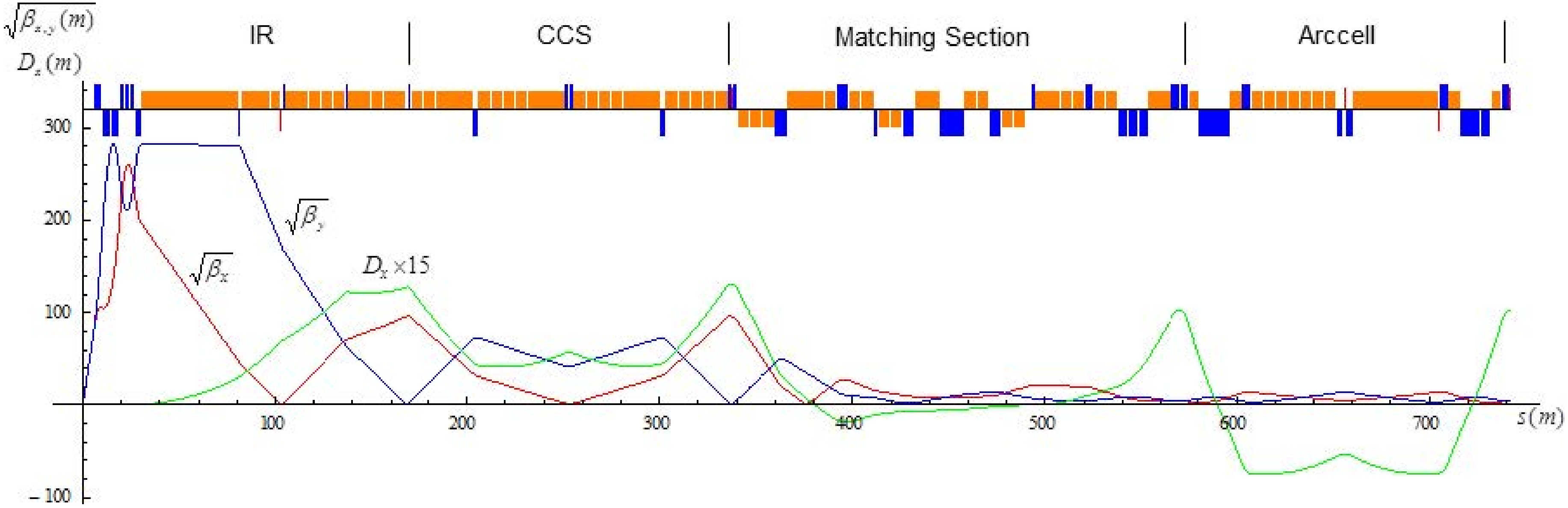
Collider Ring

- Around 1000 turns
  - Small compared to most storage rings
  - Much larger than other muon collider systems
- Two IPs
- Mostly pulling from papers by Alexahin and co-authors, occasionally adding my own thoughts

Collider: IR Design

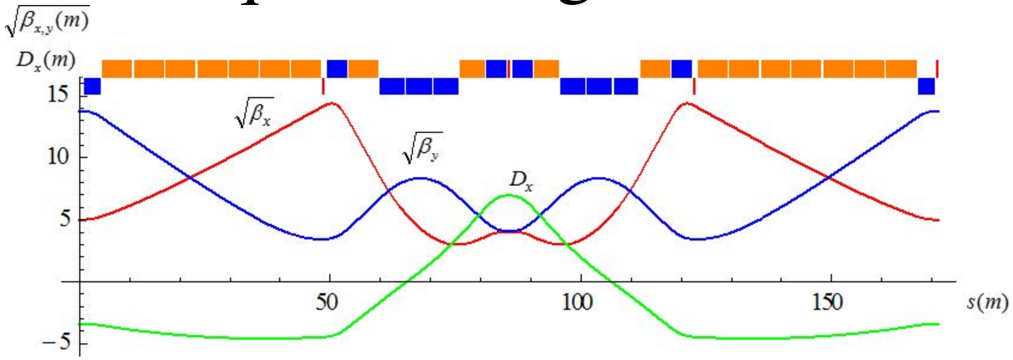
- Small β^*
- Large chromaticity: $\gtrsim 100$ (per IP!)
- Local chromaticity correction



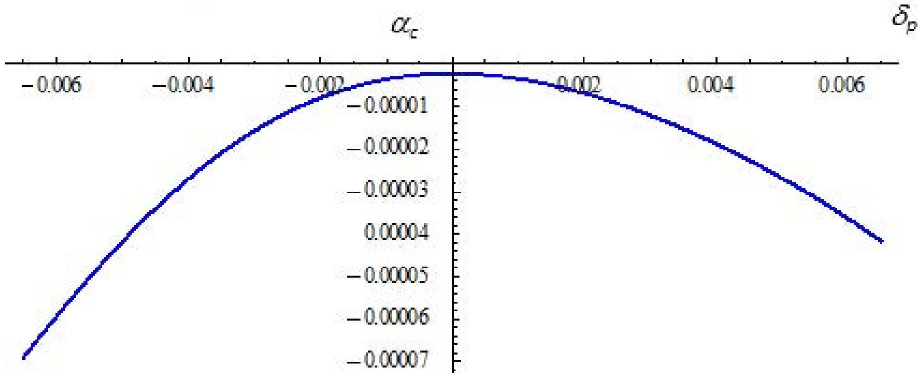


Collider: Longitudinal

- RF to maintain short bunch length.
  - Minimize voltage to reduce required straight
- Small α_C
  - Large energy range
  - Never isochronous (?)
  - FMC arc cell

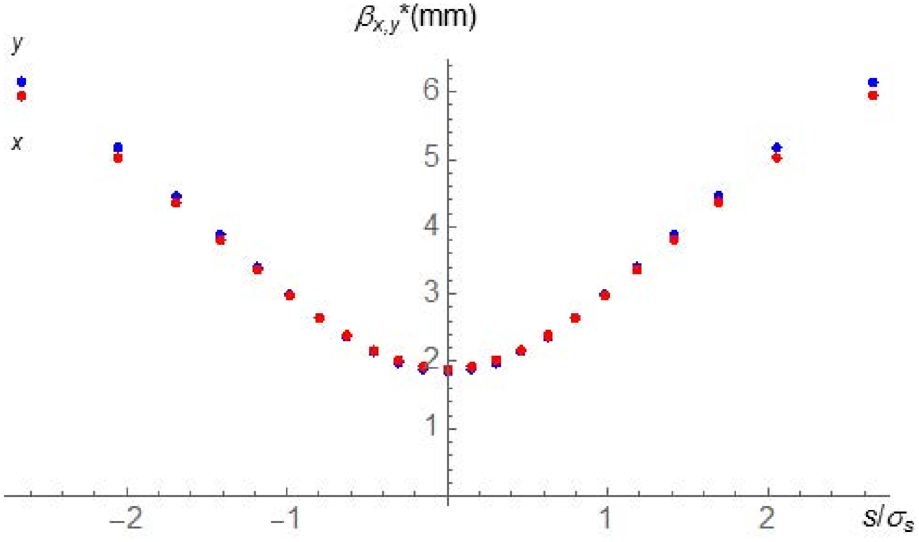


- Nonlinear α_C
  - Amplitude-dependent longitudinal match
  - Large amplitudes: longer bunch, higher synchrotron tune
  - Incoming distribution not properly correlated



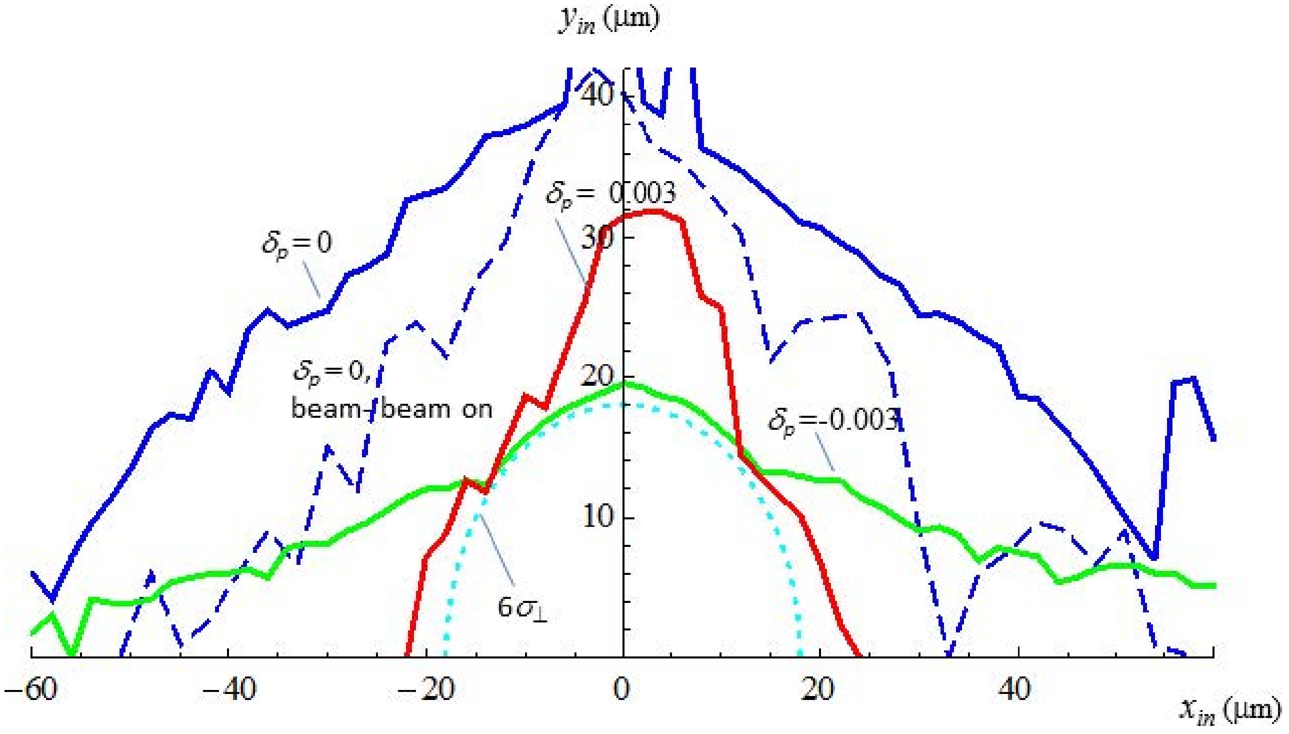
Collider: Beam-Beam

- Large beam-beam parameter (≈ 0.09 *per ip*)
- Only need to survive 1000 turns
- Significant dynamic beta
- Initial transients from beam-beam force
- Phase advance between IPs
    - Near π gives beneficial cancellations, dynamic beta
    - But near π means near-integer tunes



Collider: Dynamic Aperture

- Only need to survive 1000 turns
- Only need about 4σ
- But very strong beam-beam, highly nonlinear
- Initial results (fixed energy) look good



Collider: Final Thoughts

- Push parameters to extremes, relying on
  - Only 1000 turns
  - Only 4σ
- Initial transient could be important
  - Nonlinear mismatch, particularly longitudinal
  - Beam-beam transient and nonlinear mismatch
- Practical issues are important
  - Energy deposition in SC magnets
  - Neutrino radiation
- Skew combined-function lattice? For radiation.
- Hardware R&D
  - Nb_3Sn or HTS magnets
  - Complex: combined function, open midplane