BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY
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RLA, RCS and FFA Acceleration Concepts

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Talk Overview

- Acceleration principles
- Types of accelerators
- MAP scenario
- Thoughts on LEMMA scenario

Acceleration Principles

- Limit decays: muons are difficult and expensive to create
- RF is expensive: make as many passes through cavities as possible
- 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

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

- To get MAP luminosities, we needed 3.5 MV/m

Cavity Passes

- RF system cost and overall length generally drive acceleration costs
- Muons are bendable leptons: take advantage of that
- Try to maximize cavity passes

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

  - Small circumference of acceleration stages
  - High fields in dipoles
  - Large dipole packing fraction

Cavity Passes

- Get more turns with lower RF frequencies
  - Time of flight and longitudinal emittance control
  - Cost increases rapidly frequency decreases
- Large bunch currents: beam loading
  - Often no time to top off RF between turns, especially in early stages
  - Good for power efficiency
  - Don't extract more than 50% of stored energy

Longitudinal Emittance

- Preserving longitudinal emittance drives the design of many acceleration stages
- More difficult with larger emittances
- To reduce longitudinal emittance growth
  - Increase circumference
  - Reduce RF frequency (expensive)

Types of Accelerators

- Linac
- Recirculating linear accelerator (RLA)
- Fixed field alternating gradient (FFA)
- Pulsed synchrtrons

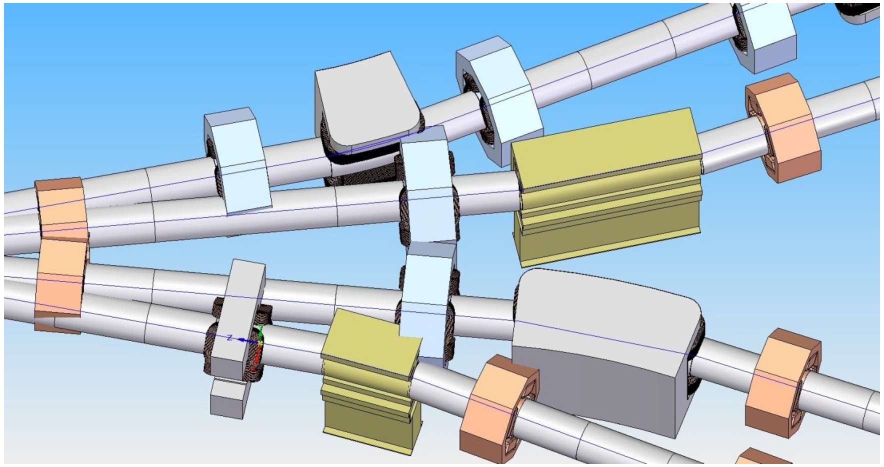
Linac

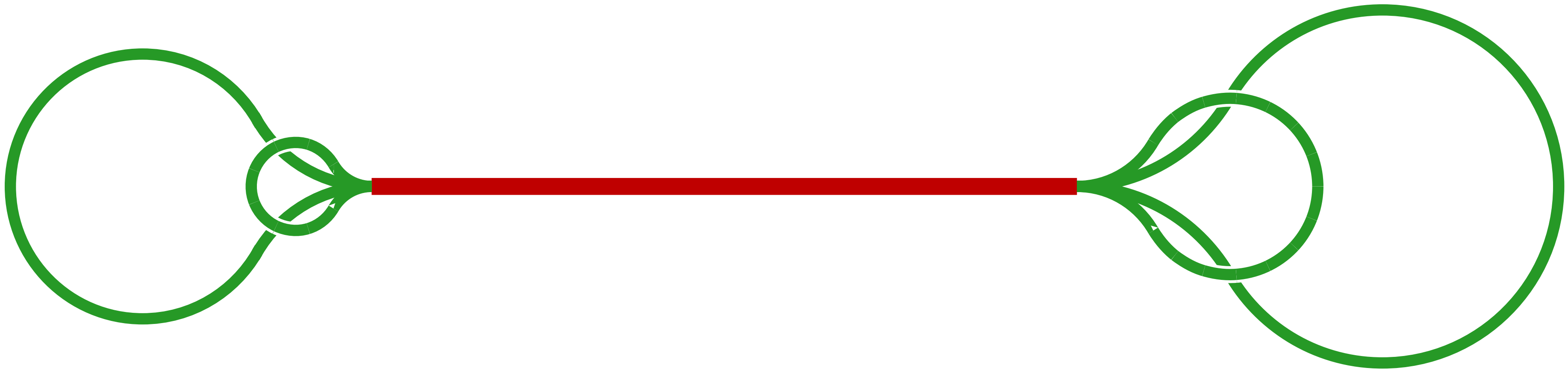
- Only single-pass, so expensive
- MAP muon collider scenarios generally used linacs below about 1 GeV
  - $v < c$ for lower energies creates RF synchronization issues in multi-pass machines
  - Large emittances (transverse and longitudinal) more easily handled
- For smaller emittances at lower energies, a single pass high frequency (1.3 GHz) linac can be more cost effective than a multi-pass system that may require lower frequencies

RLA

- Return beam to a linac with a separate pass for each energy
- Most conventional multi-pass design
- Generally the 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
- Two counter-rotating beams in the same machine
  - True for all multi-pass designs

RLA



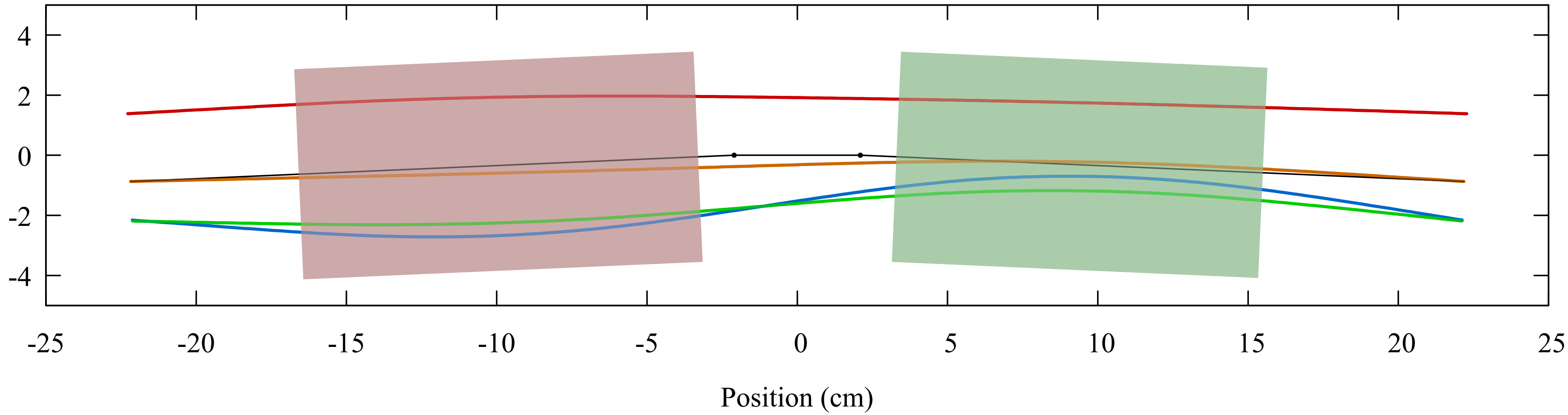


RLA

- 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 number of linac passes.
    - Arcs cross at intermediate points
- Preserving large longitudinal emittance
  - Requires relatively long arcs
  - Large beta function difference between linac and arc, even with focusing in the linac, requires matching

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

- Distribute RF cavities evenly around the ring
  - Drifts containing cavities need to be short
  - Avoid transverse emittance growth from orbit mismatch
- Need fast kickers for injection/extraction
- Preserving large longitudinal emittance
  - Larger emittance or lower emittance growth require longer ring
  - This drives the machine design
- 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

Pulsed Synchrotron

- Accelerate as usual for a synchrotron: magnet fields proportional to momentum
- Advantages over FFA
  - Dispersion-free straights
    - Eliminate synchro-betatron coupling
    - Reduce or eliminate orbit mismatch
  - Can use higher RF frequencies and/or get more turns
- Distribute cavities uniformly around ring, as many stations as possible
  - Energy increases discretely
  - Field varies continuously
  - Minimize mismatch

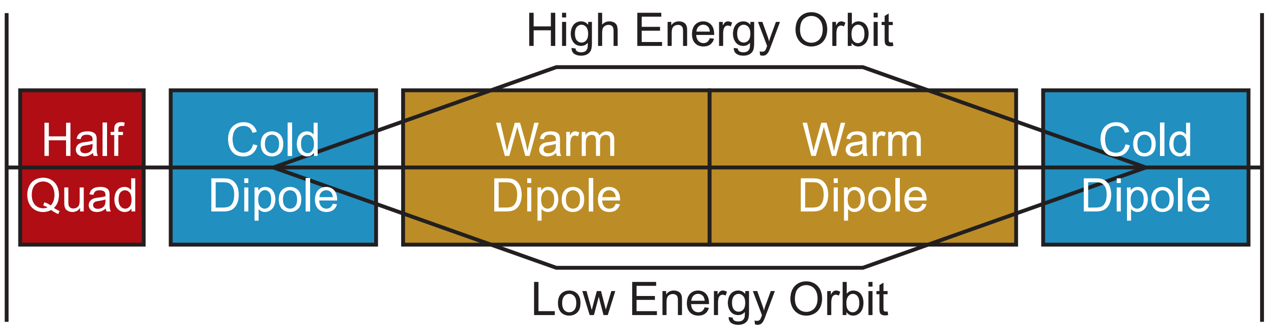
Pulsed Synchrotron

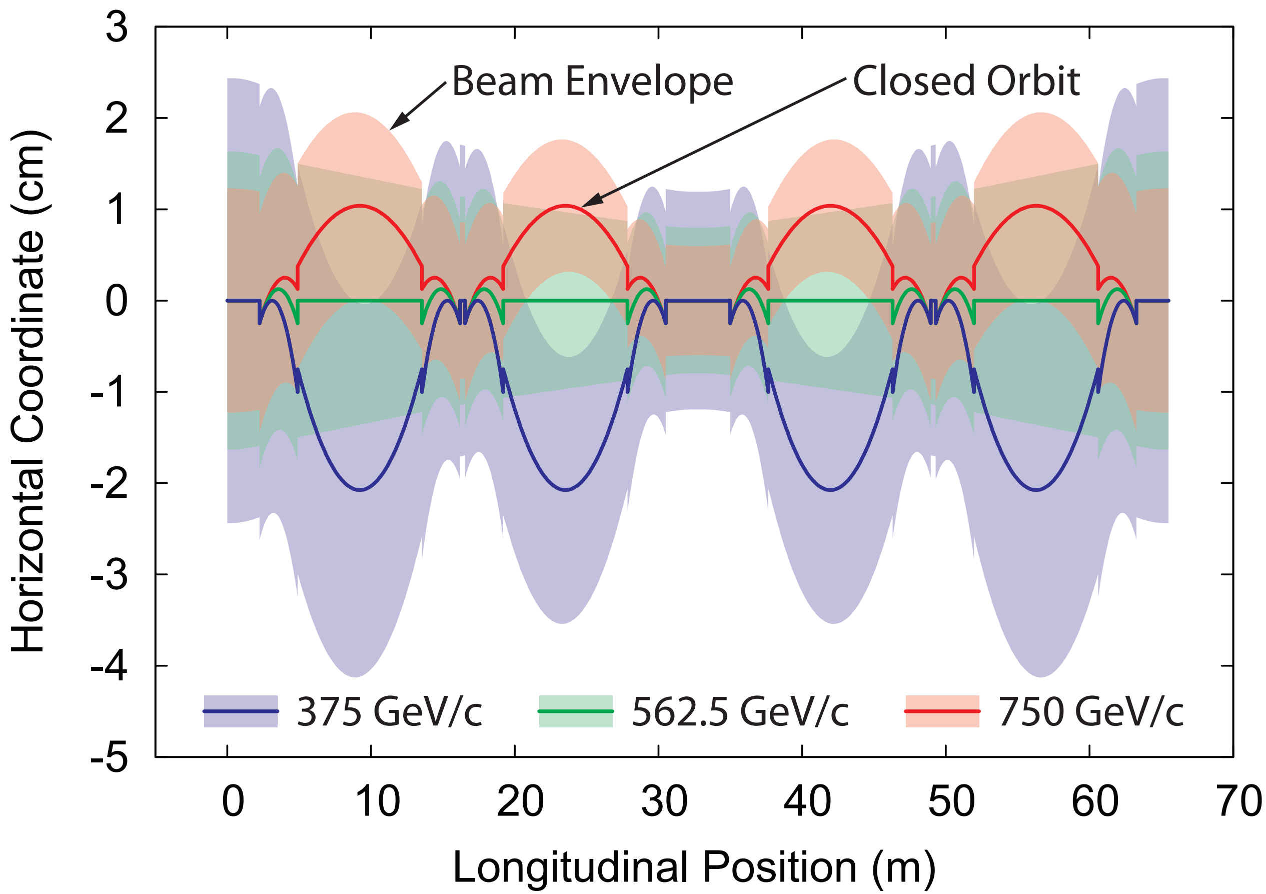
- Maximum field only around 1.5 T: few turns or large number of decays
- Magnet fields increasing rapidly (less than 1 ms)
- Fast pulsed kickers for injection/extraction
- Small adjustments to orbit position with energy to get time of flight synchronization

Hybrid Pulsed Synchrotron

- Average bend field for pulsed synchrotron low: few turns or significant decays
- Increase average bend field by interleaving fixed-field superconducting dipoles and pulsed warm dipoles
  - More RF passes and shorter circumference than ordinary pulsed synchrotron
- Larger adjustments of orbit position with energy to get correct bend angle and time of flight
- 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

Hybrid Pulsed Synchrotron

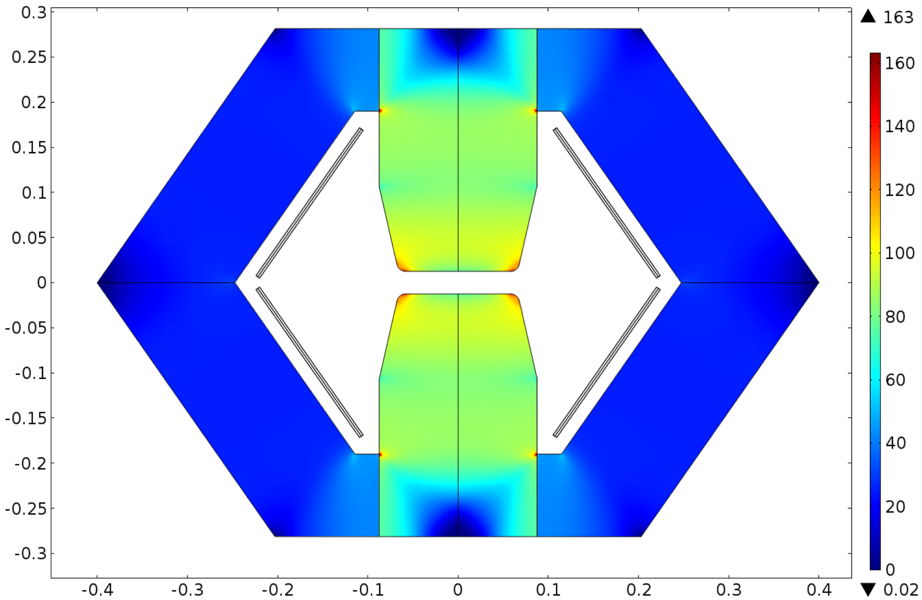


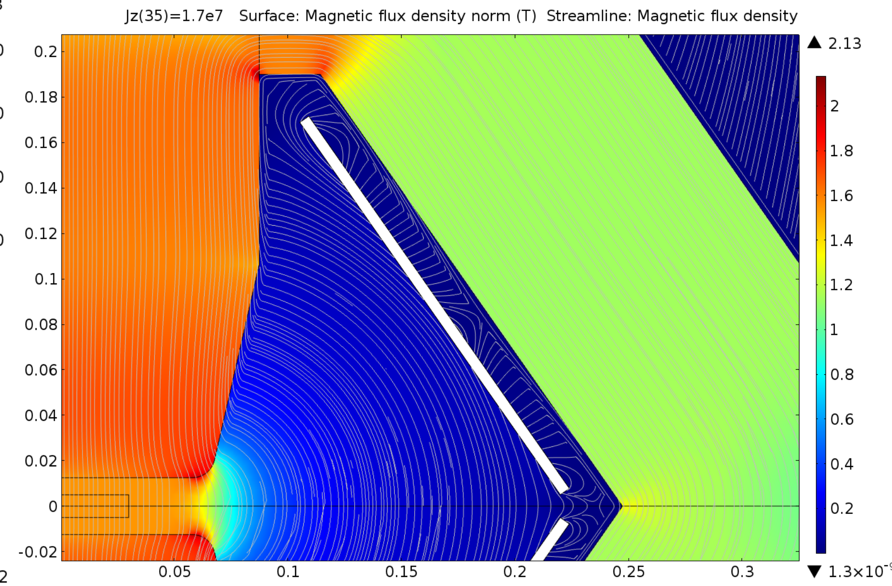


Pulsed Magnets

- Acceleration times around 1 ms
- Need to deal with energy losses
  - Eddy current, hysteresis, and anomalous losses
  - Higher fields preferred for lower circumference, but give greater losses
  - Material choices for magnet
    - Pure iron or Fe-Co give high fields (1.75/2.0 T) but high losses
    - 6.5% Si steel significantly reduces losses, but lower maximum field (1.4 T)
- Low-loss magnet design with high fields (Witte)
  - Losses primarily confined to high-field Fe or Fe-Co pole
  - Back yoke with 6.5% Si steel to reduce losses
  - Align "coils" parallel to field lines to minimize induced currents in coils (can also use Litz wire)

Pulsed Magnets





- 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

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 5 GeV
  - Match to neutrino factory energy
- Dogbone RLA to 63 GeV
  - Higgs factory
  - 650 MHz RF
- Pulsed synchrotrons to high energy
  - Best solution when they work
  - Hybrid synchrotrons at high energy
  - Lowest energy stage may be non-hybrid, sharing tunnel with first hybrid stage
  - 1.3 GHz RF systems
  - Loss in magnets: a few MW per stage

MAP Scenario

- Thoughts on 5–63 GeV acceleration
  - FFAs had to be long to control longitudinal emittance: thus RLA preferred
  - Late studies: longitudinal emittance control in dogbone RLA required long arcs
  - Should revisit alternatives: racetrack RLA, FFA
  - Short acceleration time: only use stored energy in cavities
- Pulsed synchrotrons
  - Beam loading extracts a large fraction of the energy
  - Beam loading is good for efficiency, but significant collective effects
  - Top off cavities at each turn
    - Early stages may reduce cells per cavity

LEMMA-Based Scenario

- Longiduainal emittance much smaller
  - Exclusively use high-frequency (1.3 GHz) RF
  - Rings more compact, more turns
- Lower bunch currents, beam loading and collective effects less of a concern
- High repetition rate (around 1 kHz)
  - Run RF CW: lower gradients, but good efficiency
- Pulsing magnets becomes a problem
  - Similar ramp times, but 60 times the power consumption
  - Switch pole to lower-loss material (e.g., 6.5% Si steel)
    - Lower fields and thus longer ring
    - Only pick up a factor of 2 or so

LEMMA-Based Scenario

- FFAs look attractive: low emittance
  - Larger energy range per stage
  - Use nonlinear magnets to extend range
  - Larger number of turns