BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY Office of Science

High Energy Acceleration

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Talk Overview

- Acceleration principles
- Pulsed synchrotron overview
- Collective effects
- Sample scenario
- FFA alternative
- Key R&D issues

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

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

- Formula involves transmission fraction and energy ratio. Doesn't get relaxed at higher energies.
- 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

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

  - Small circumference of acceleration stages
  - High fields in dipoles
  - Large dipole packing fraction
- RF frequency
  - Higher frequency less expensive
  - More turns with lower frequency
  - Top off cavities at high energy

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)

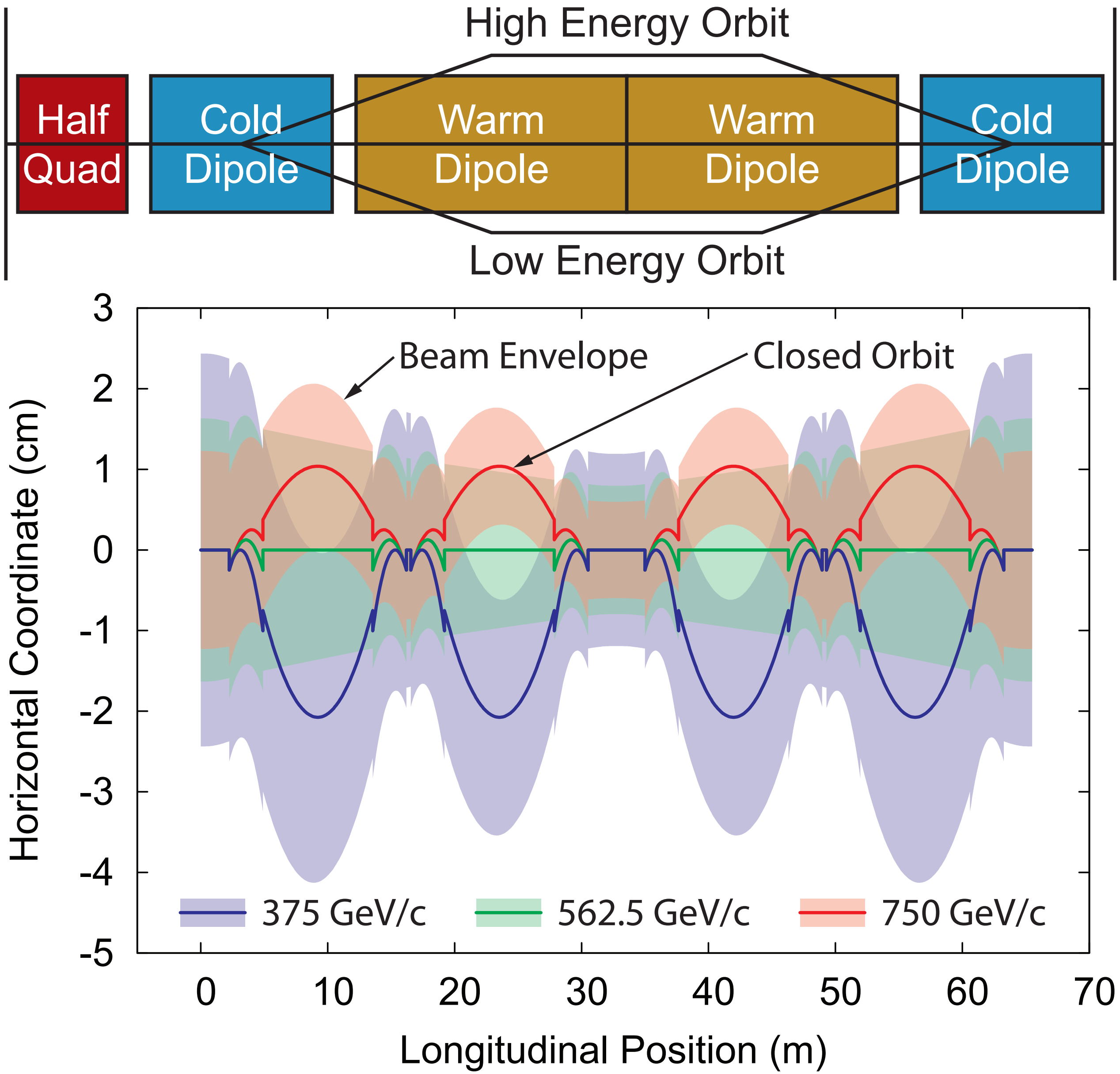
Pulsed Synchrotron

- 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 off RF

Hybrid Pulsed Synchrotron



Collective Effects

- Beam collisions
  - Both beams counter-rotating in same rings
  - Beams collide at two points
  - Small number of collisions
- 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
- Is chromaticity correction needed?

MAP Specifications

- 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
- Average gradient: 3.5 MV/m
  - 1.3 GHz cavities at 35 MV/m
- Pulsed dipole maximum field: 1.5 T
- Fixed dipole field: 10 T

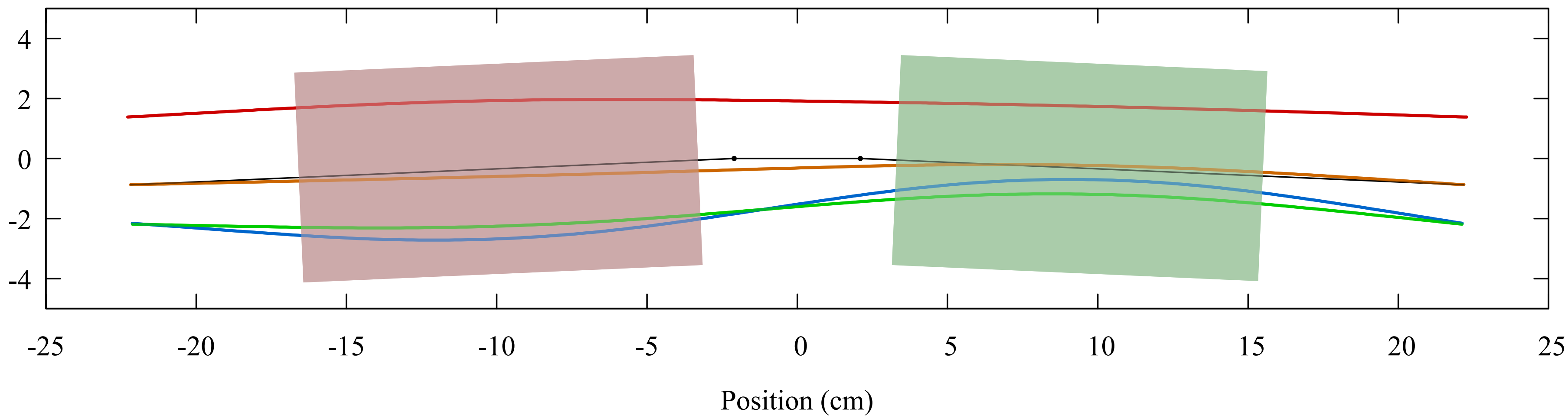
Sample Scenario

- Accelerate from 63 to 1500 GeV
- Three stages, first two share a tunnel
- Very hand-waving calculation
- Dwell times in particular will be somewhat longer

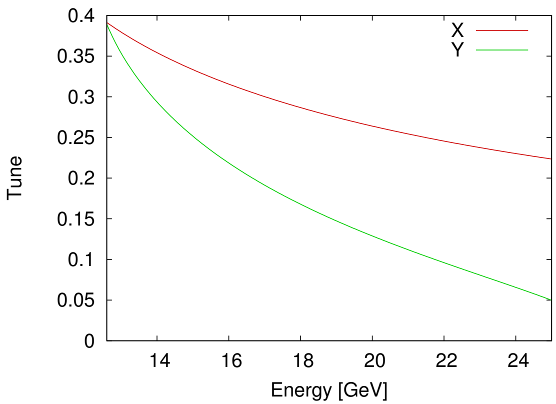
Injection Energy (GeV)	63	303	750
Extraction Energy (GeV)	303	750	1500
Circumference (m)	5210	5210	9361
Fixed Dipole Length (m)	—	1103	2358
Ramped Dipole Length (m)	4229	3126	5240
Turns	13	25	23
Time (ms)	0.23	0.43	0.72
Cavity Power (kW)	950	950	530

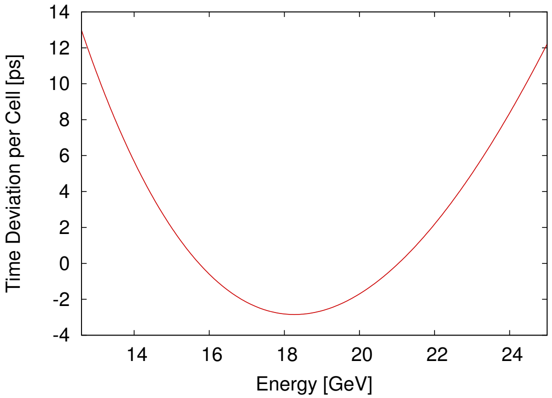
Alternative: FFA

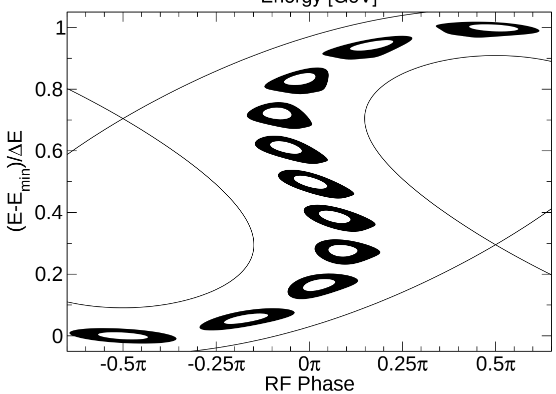
- Fixed field alternating gradient accelerator
- Single beamline for many energies, magnet fields don't vary with time
- No switchyard: can get a large number of turns
- Magnets need to be wide: every energy at a different position



Alternative: 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

Alternative: 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

RF in FFA

- FFA probably uses lower RF frequencies
- Short cell length important
  - Cavities as close as possible to magnets
  - Operate with up to 0.1 T on cavities?
- Sample parameters:

Injection Energy (GeV)	63	173
Extraction Energy (GeV)	173	375
RF Frequency (MHz)	975	975
Cells/cavity	3	3
Gradient (MV/m)	30	30
Turns	6.5	8.5
Cavities/drift	1	2

Key R&D Issues

- Beam dynamics
  - Dynamics with large single bunch loading/wake
  - Are sextupoles needed in pulsed synchrotrons?
  - Beam crossing: beam-beam and wakes
  - FFAs with increased energy range (nonlinearity)
  - Design of a full acceleration chain
    - Emphasis on longitudinal dynamics
- RF
  - Very high beam loading from each bunch
  - High power into coupler
  - High SC gradient at lower frequencies
  - FFAs: operating with exclusion of small magnetic field