IDS-NF Accelerator Systems Overview

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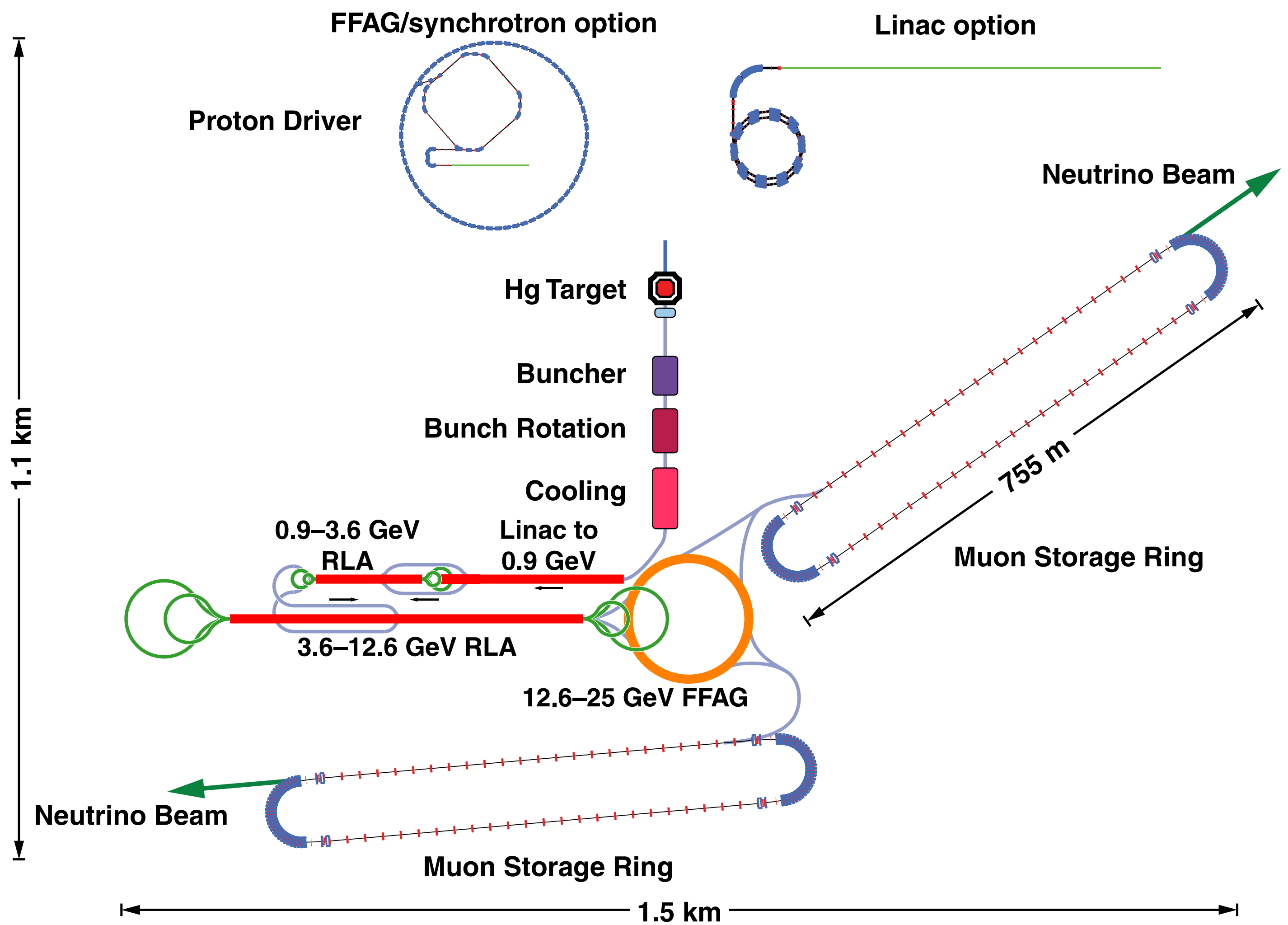
Neutrino Factory Overview
Basic Goals

- Produce neutrinos by muon decay
- Accelerate muons to high energy ($\approx$ 25 GeV)
  - Concentrated beam
  - Higher neutrino cross-section
- Circulate in storage ring with long straight pointed at angle down toward detector

Neutrino Factory Overview



Neutrino Factory Overview

- Proton driver, makes protons that hit
- Target, which produces pions then muons
- Front end: modify phase space for acceleration
- Acceleration, bring to high energy
- Storage ring, direct neutrino decays to detector

Neutrino Beam

- 10^{21} muon decays toward detector per 10^7 s
- 25 GeV muon beam
- Muon angular divergence $0.1/\gamma$
- Two baselines: 3000–5000 km, 7000-8000 km

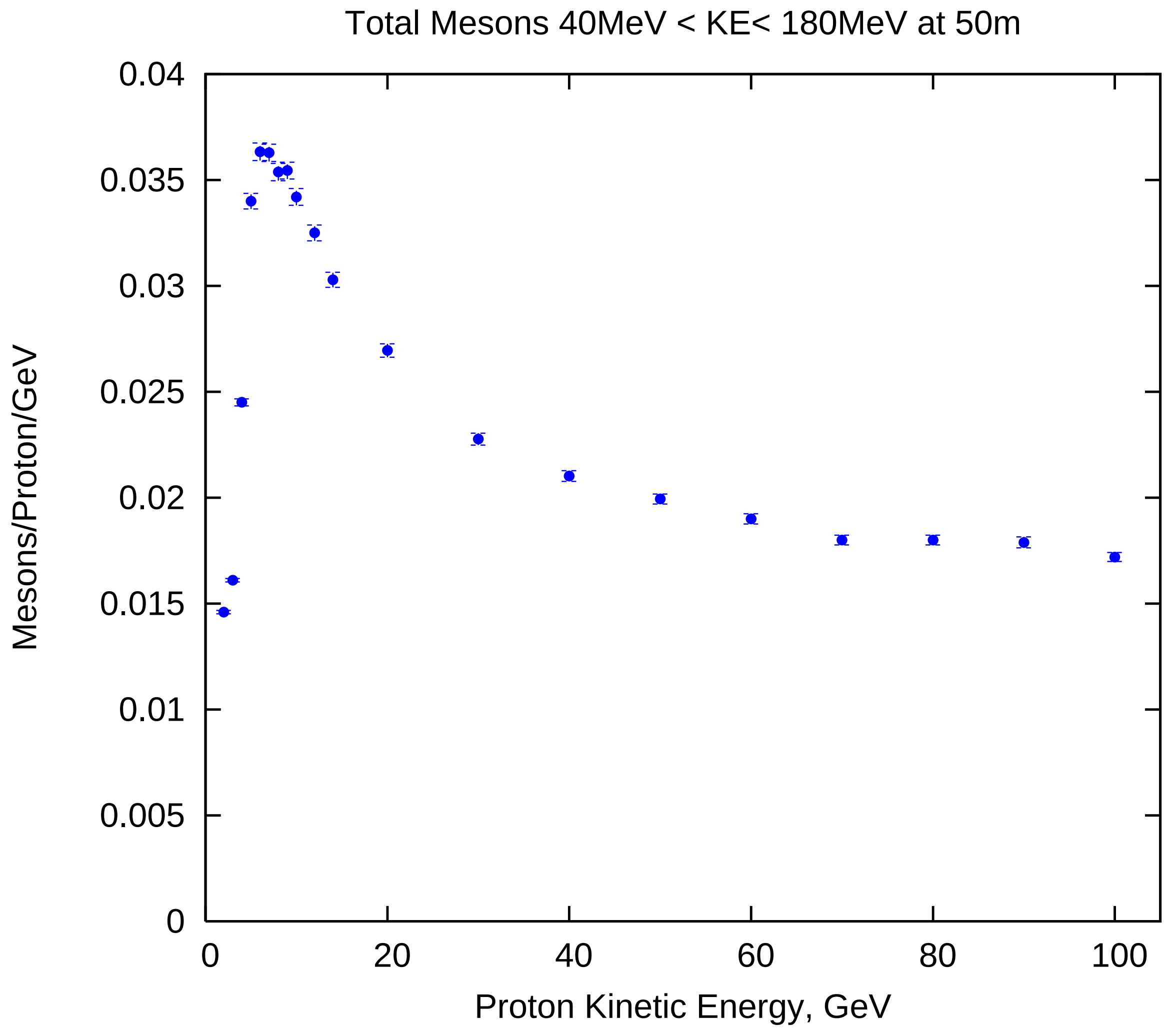
Proton Driver

- Protons hit target, produce pions, decay to muons
- Muons approximately proportional to proton driver power
- Three ways to get power
  - Repetition rate
  - Particles per bunch
  - Energy

Proton Driver Energy

- Proportionality to proton driver power imperfect
- Production per energy depends on energy
  - Hg: peak at 6–7 GeV
  - Rapid decline below 5 GeV, above 10 GeV
- Higher energy machine likely costs more
- High repetition rate harder at high energy
- Early space charge harder at low energy
- Short bunches (1–3 ns!) harder at low energy

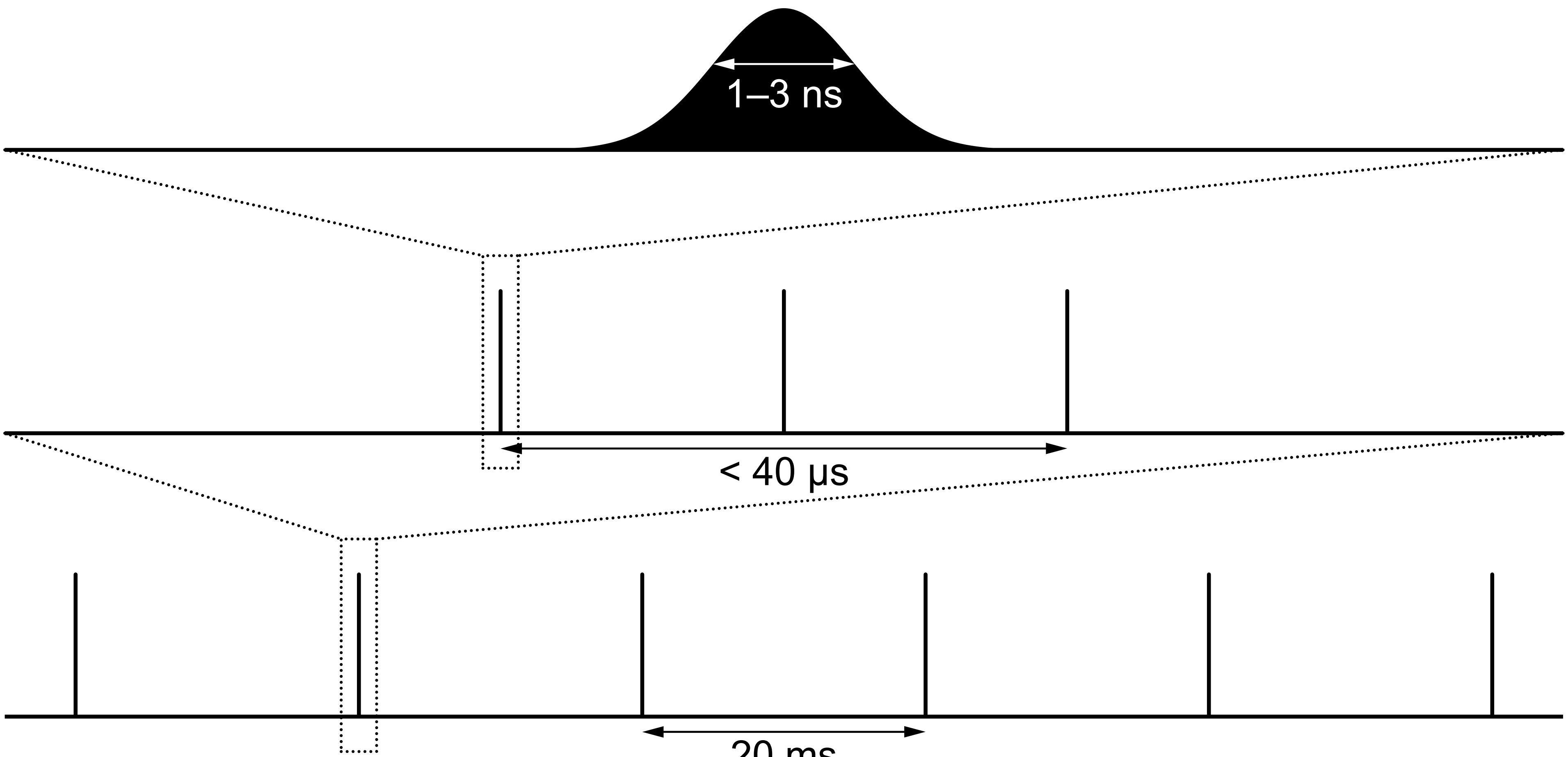
Proton Driver
Production vs. Energy (X. Ding)



Proton Driver
Other Considerations

- Repetition rate sufficient to keep space charge reasonable
  - High repetition rate increases costs for muon machine
- Multiple bunches per repetition
  - Short bunches more realistic

Proton Driver
Bunch Structure at Target



Proton Driver
IDS Baseline

- 4 MW power (needed count)
- 50 Hz repetition rate (space charge)
- 5–15 GeV energy (peak production per power)
- 1–3 ns RMS bunch length (production drops for longer bunches)
- 3 bunches per repetition (space charge)

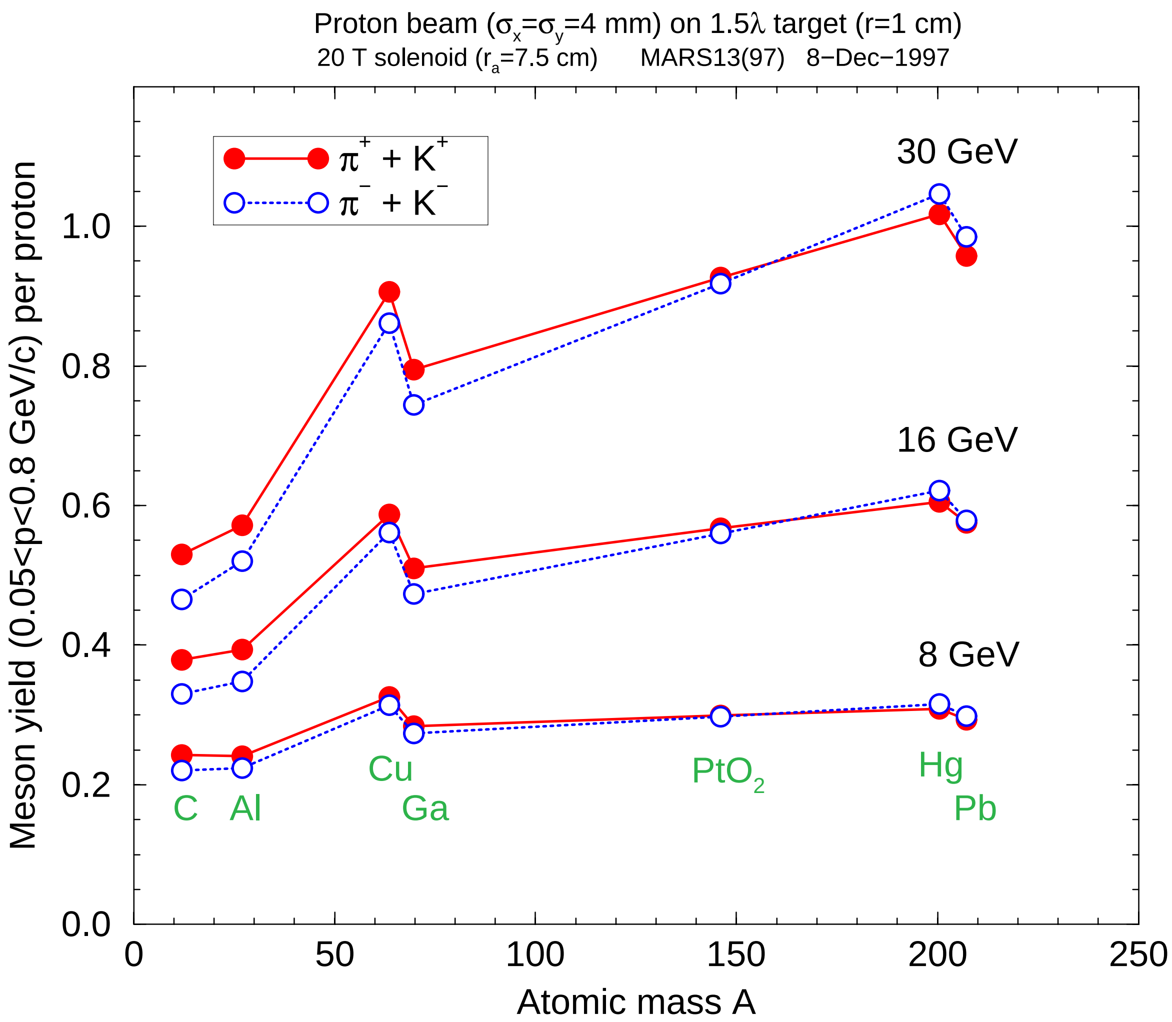
Proton Driver
IDS Goals

- Convince ourselves there is a workable design meeting all requirements
- Muon production is number that matters

Target

- Protons hit target, make pions, decay to muons
- Production different for different materials
  - Prefer heavy metals
- Target damage from proton beam
  - Liquid jet

Target Production vs. Target *A*



Target
Liquid Jet

- Bunches destroy target
- High velocity to replace target
- Multiple bunches per cycle
  - All must arrive before target breaks up

Target
IDS Baseline

- Liquid mercury jet (avoid damage)
- 20 m/s velocity (replace used target in time)
- Bunches arrive within 40 μs (based on older data)

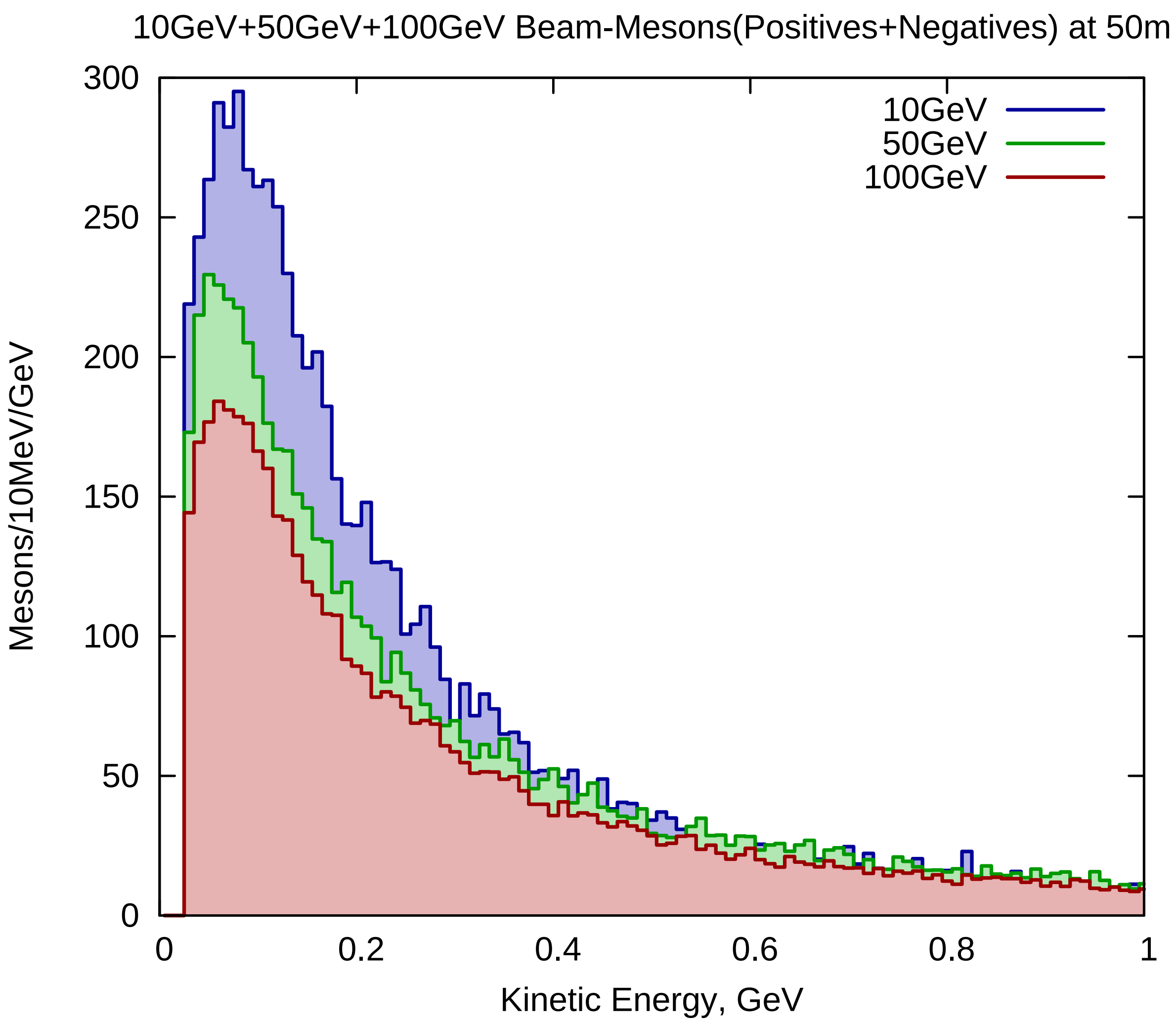
Target Work Plan

- Analyze MERIT data to determine permitted bunch structure
  - If multiple bunches, prefer that they arrive over more than 40 μs; see how long MERIT permits
- Engineering of target infrastructure

Front End

- Produced muons have
  - Large energy spread
  - Large transverse emittance
- Cannot accelerate this beam
- Reduce energy spread
- Reduce transverse emittance (less critical: throw away beam)

Front End
Muon Energy Spectrum (X. Ding)



Front End Functions

- Allow pions to decay to muons
- Reduce energy spread
- Bunch beam suitably for acceleration
- Reduce transverse emittance

Front End Bunching/Phase Rotation

- “Neuffer” phase rotation
- High-frequency ($\approx$ 200 MHz) RF for phase rotation
- Drift: energy correlated with arrival time
- RF creates bunches
- Phases so high energy bunches lose energy, low energy bunches gain energy
- Adjust frequency along length to maintain this

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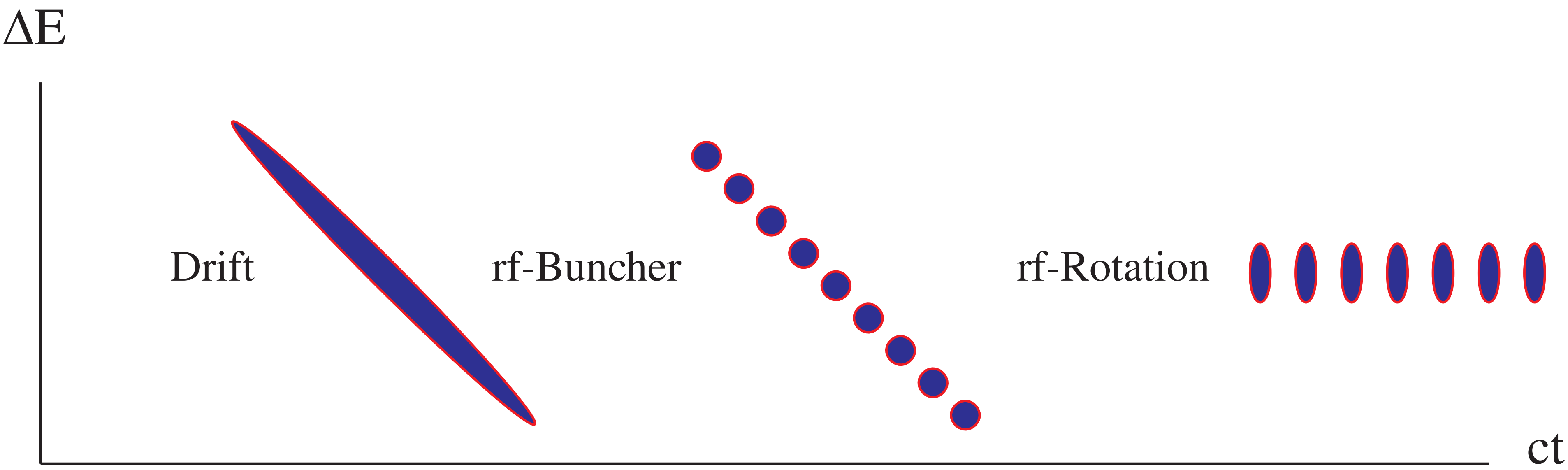
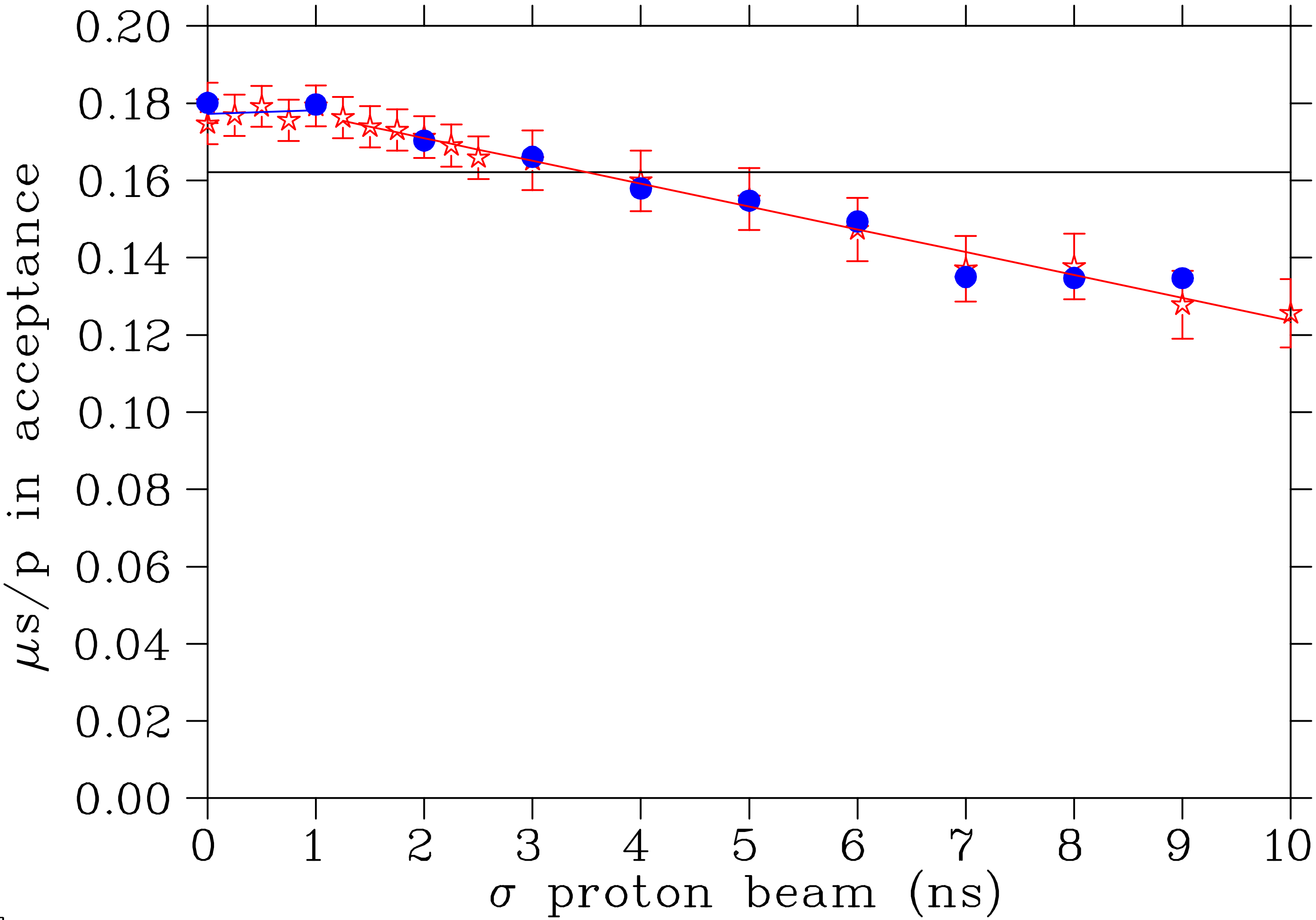
Front End
Neuffer Phase Rotation



Front End
Bunch Length

- Longitudinal phase space area preserved
- Longer proton bunch: larger muon phase space area
  - Inherent time spread from pion decay
- More time spread, longer phase rotation to reach energy spread: decays
- Lose capture efficiency above 1 ns rms proton bunch length

Front End Bunch Length



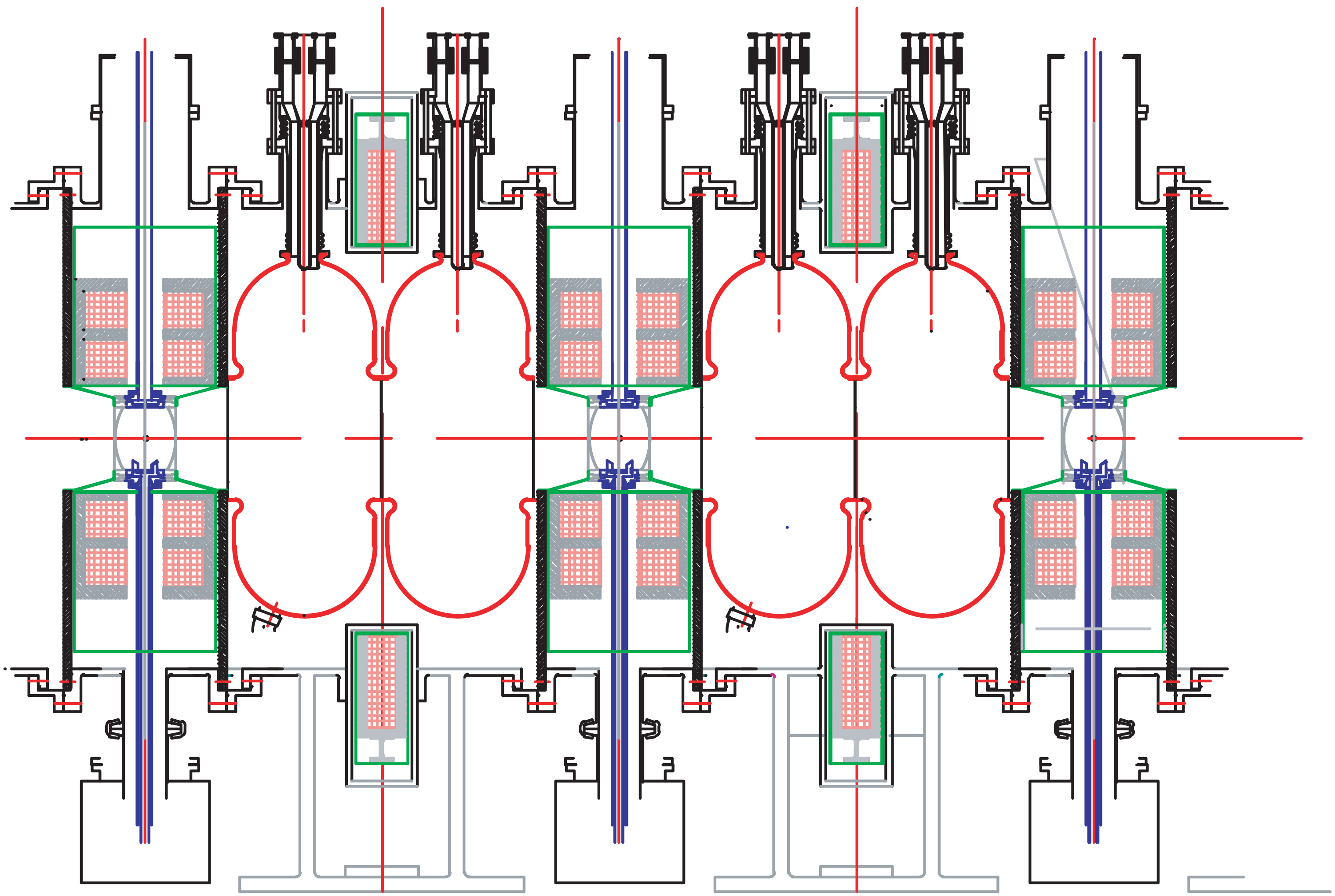
Front End
Ionization Cooling

- Transverse emittance too large for acceleration and storage ring
- Reduce transverse emittance: ionization cooling
- Ionization cooling expensive: use only small amount

Front End
RF and Magnetic Fields

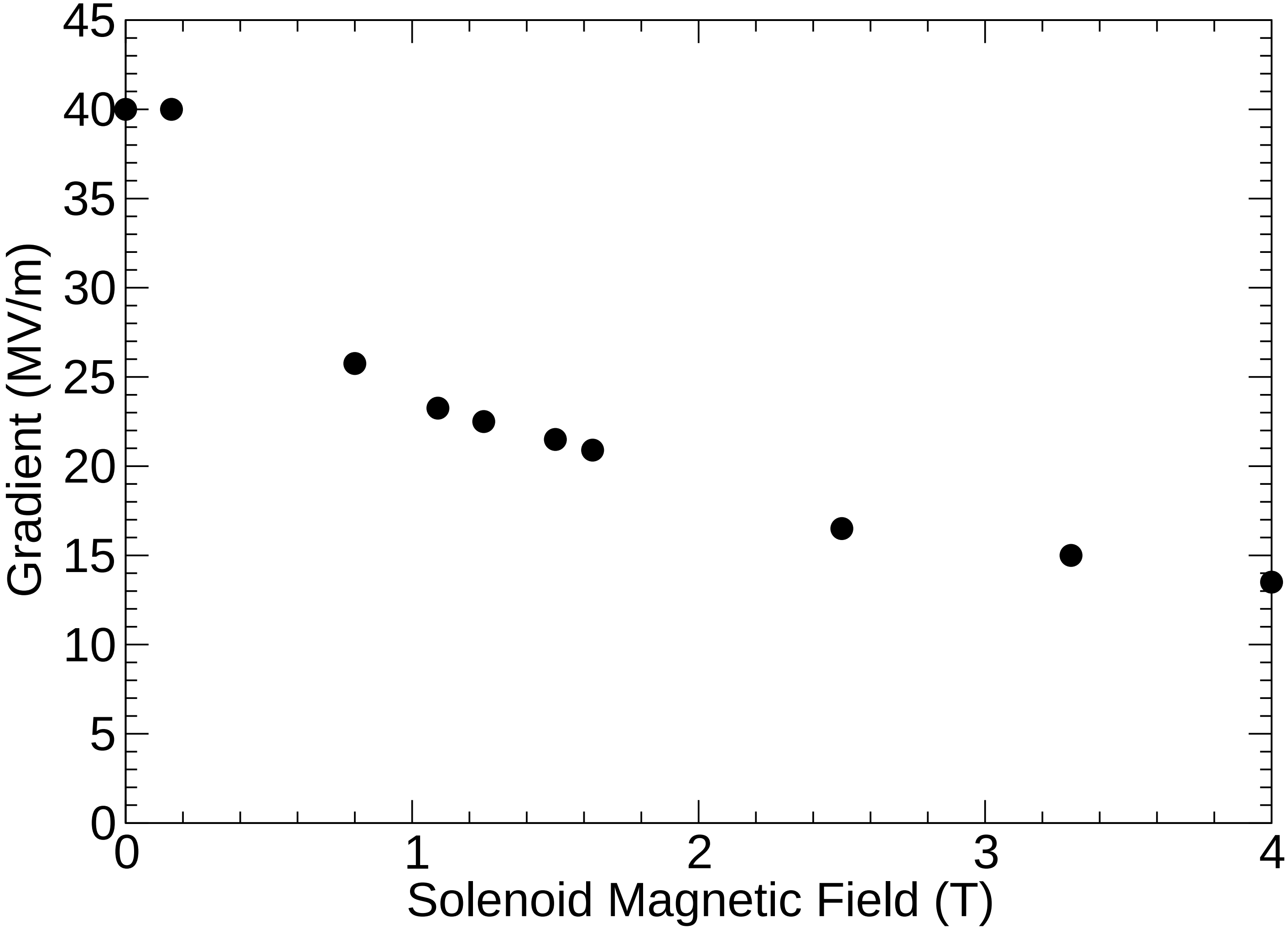
- Neuffer phase rotation and ionization cooling
  - Compact solenoid-based lattice cells
  - Large magnetic fields in RF cavities
- Cooling performance proportional to RF gradient
- Achievable RF gradient reduced in magnetic fields

Front End
Lattice Cell



Front End

Gradient vs. B (Moretti)



Front End
IDS Baseline

- Based on “Study IIa” (APS study)
- Taper in 12 m to 1.75 T, then 100 m decay
- 100 m Neuffer bunching/phase rotation
- 80 m cooling at 220 MeV/*c*
  - 201.25 MHz 15 MV/m RF
  - 2.8 T magnetic field
  - Final emittance: 7.4 mm normalized
  - LiH absorbers

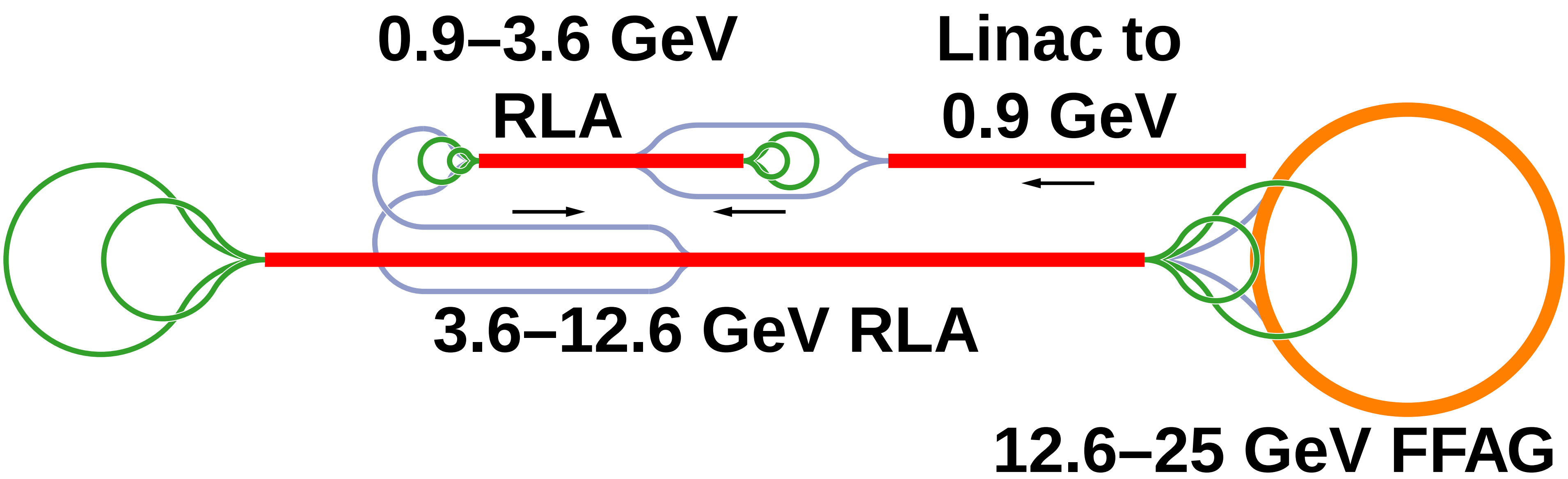
Front End
IDS Task List

- Evaluate experimental data for relationship between magnet fields and achievable RF gradient
- Re-design front end to meet these requirements
  - Experimental program won't be finished
  - Base on best estimates

Acceleration

- Accelerate to 25 GeV
- Maintain emittances
- Keep costs low
  - Efficiency: multiple passes through cavities
- Multiple stages: optimize efficiency
  - Linac
  - Two recirculating accelerators
  - FFAG

Acceleration Scenario



Acceleration Stage Choices

- Linac: only one pass, works all energies
- RLA: multiple passes through RF
  - Switchyard limits passes: 4 or so
  - Problems at very low energy
- FFAG: avoid switchyard
  - No switchyard: 8–16 passes
  - Inefficient at low energy
  - Induces longitudinal distortion

Acceleration IDS Baseline

- 201.25 MHz 17 MV/m superconducting RF
- Linac to 0.9 GeV
- Dogbone RLAs to 3.6 GeV and 12.6 GeV
- FFAG to 25 GeV
- System normalized acceptance: 30 mm transverse, 150 mm longitudinal

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Acceleration Challenges

- FFAG: injection and extraction
  - Short drifts
    - Needed for efficiency
    - Must keep symmetry
  - Kickers must be strong, large aperture, fast
- RLA: switchyard, beam crossings
- Must top off RF between bunch trains
  - Prefer 200 μs for trains, not 40

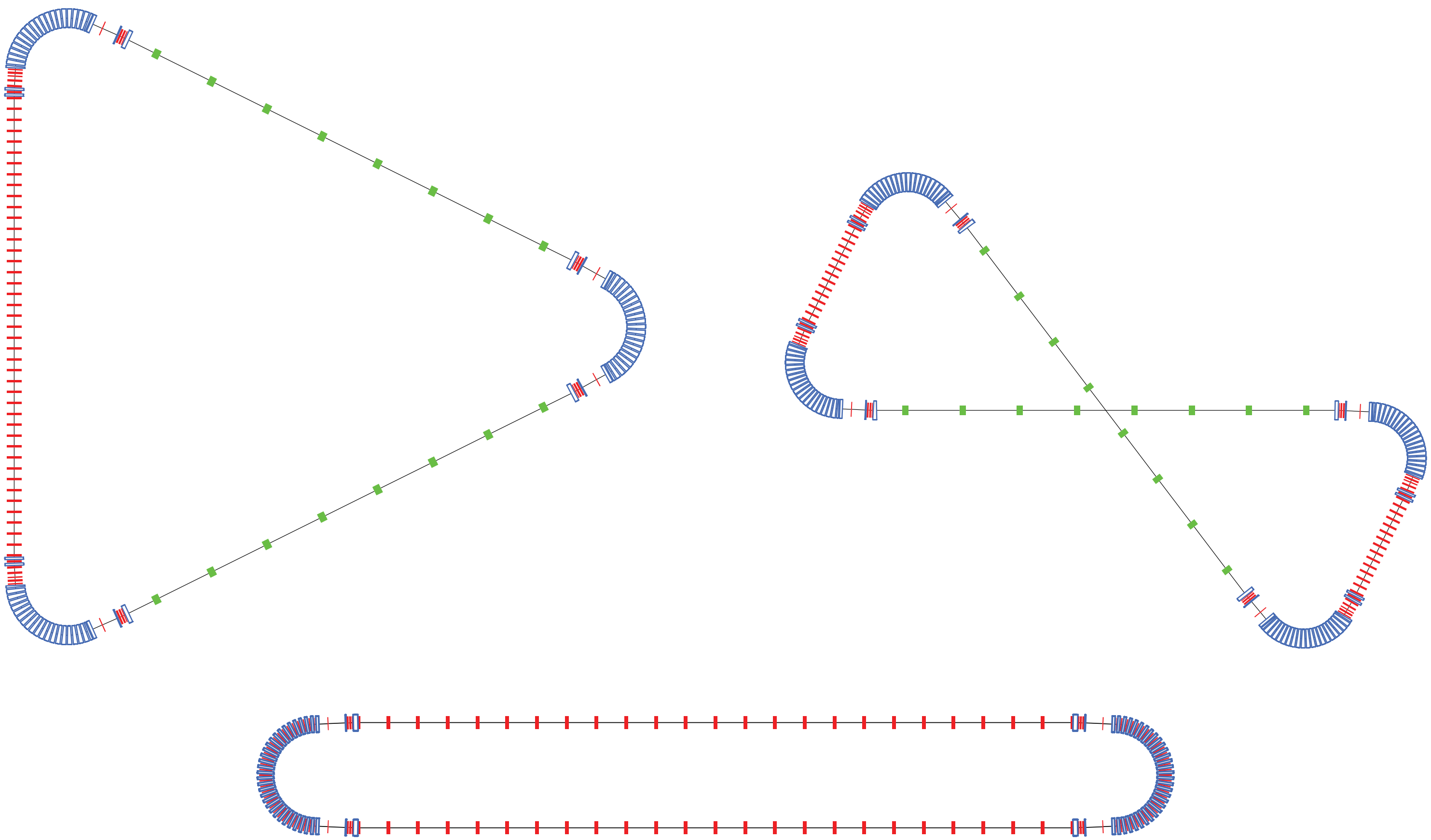
Acceleration
IDS Work Plan

- Complete designs of RLA and FFAG
- Design switchyard and beam crossings for RLA
- Find realistic injection/extraction scenario for FFAG
- Deal with inability to top-up RF if necessary
- Get costs to determine cost advantage (if any) of FFAG

Storage Ring Design and Issues

- Triangle or bowtie shape can improve efficiency over racetrack
- Racetrack more versatile
  - Arbitrary direction choice
  - Can run both signs in one
  - Bowtie: preserves polarization (bad if unknown)
- Depth creates geological problems

Storage Ring Geometry

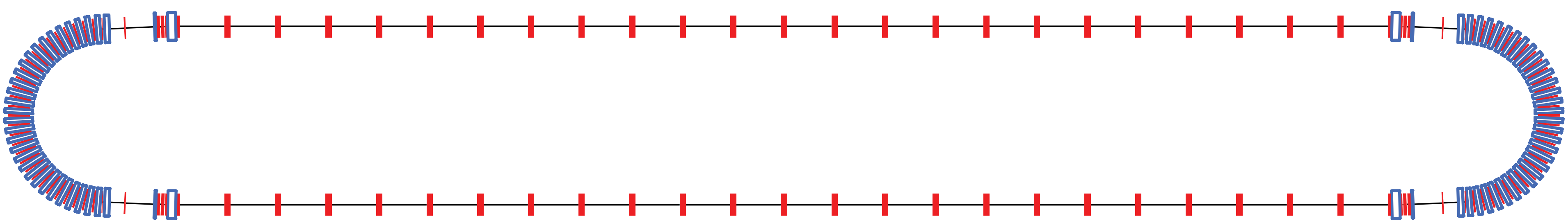


Low Energy Neutrino Factory

- Consider accelerating only to 4 GeV
- Reduced storage ring depth
  - Lower energy, shorter circumference
    - Problem for multiple bunch trains
  - Shorter baseline, smaller angle
- Must answer question of physics reach
- Not too much extra work for accelerator end

Storage Ring
IDS Baseline

- Two racetracks to two baselines
- 25 GeV muon beam
- 0.1/γ angular divergence
- Each holds three bunch trains, both signs
- 100 ns between trains
- 1600 m circumference



Storage Ring Work Items

- Work out design details
  - Try to reduce circumference
- Injection/extraction
- Evaluate whether RF needed
- Find beam distribution for production

Overall System
IDS Work Items

- Get cost estimate of entire system
- Track through entire system
- Identify R&D items
- Timeline
  - Preliminary report by 2010
    - Have information for engineering
  - Final report by 2012