FFAGs for High-Energy Muon Acceleration

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High Energy Muons for High Energy Physics

- Muons interesting for high-energy physics
  - Energy frontier colliders
  - Create neutrino beams
  - Precision physics (won't address; PRISM)
- Rapidly accelerate muons to high energies
  - Colliders: as much as 2 TeV
  - Neutrino factories: around 25 GeV
  - Muons hard to make
    - Rapid acceleration to avoid decays

Muon Colliders

- How to make the highest-energy colliders?
- Muons point-like: better energy reach than protons
- Larger mass than electrons: can bend
  - Multi-pass acceleration
  - Multiple collisions at IP
- s-channel cross-section enhanced over electrons

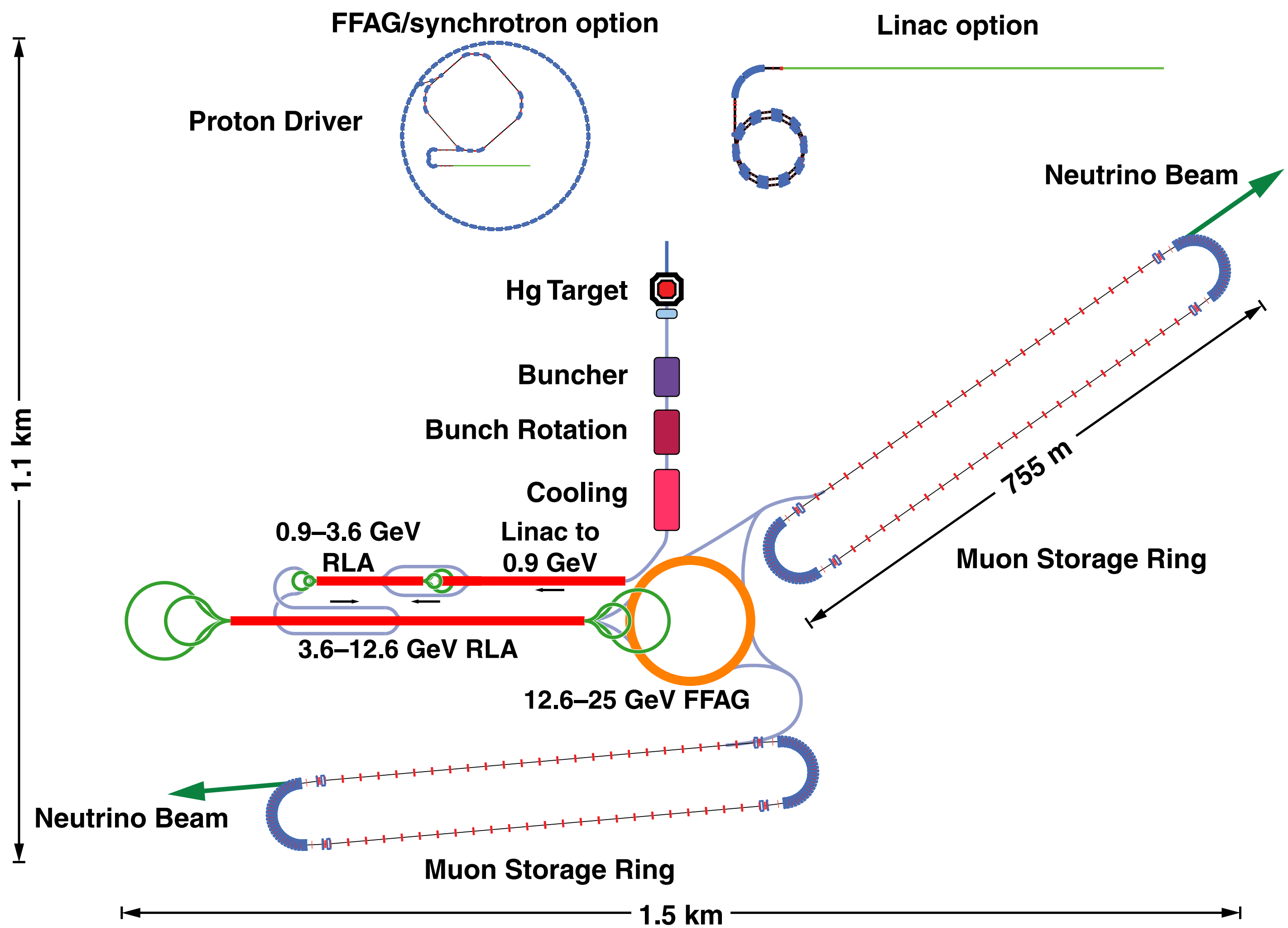
Neutrino Factories

- Neutrino oscillations the clearest recent high-energy physics result
- Muons decay to neutrinos in storage ring
- Look for neutrinos in far detector (1000s of km)
- Produce well-defined neutrino flux
- Only way to measure some quantities at smallest θ_{13}
- High-precision measurements, new physics

The International Design Study of the Neutrino Factory (IDS-NF)

- Design report for a neutrino factory by 2012
- Baseline design
  - 4 MW proton beam hits Hg jet target
  - Capture and phase rotate muons into **200 MHz bunch train**
  - Transverse ionization cooling
  - Accelerate in linac and RLA to 12.6 GeV
  - **Linear non-scaling FFAG to 25 GeV**
  - Two racetrack storage rings

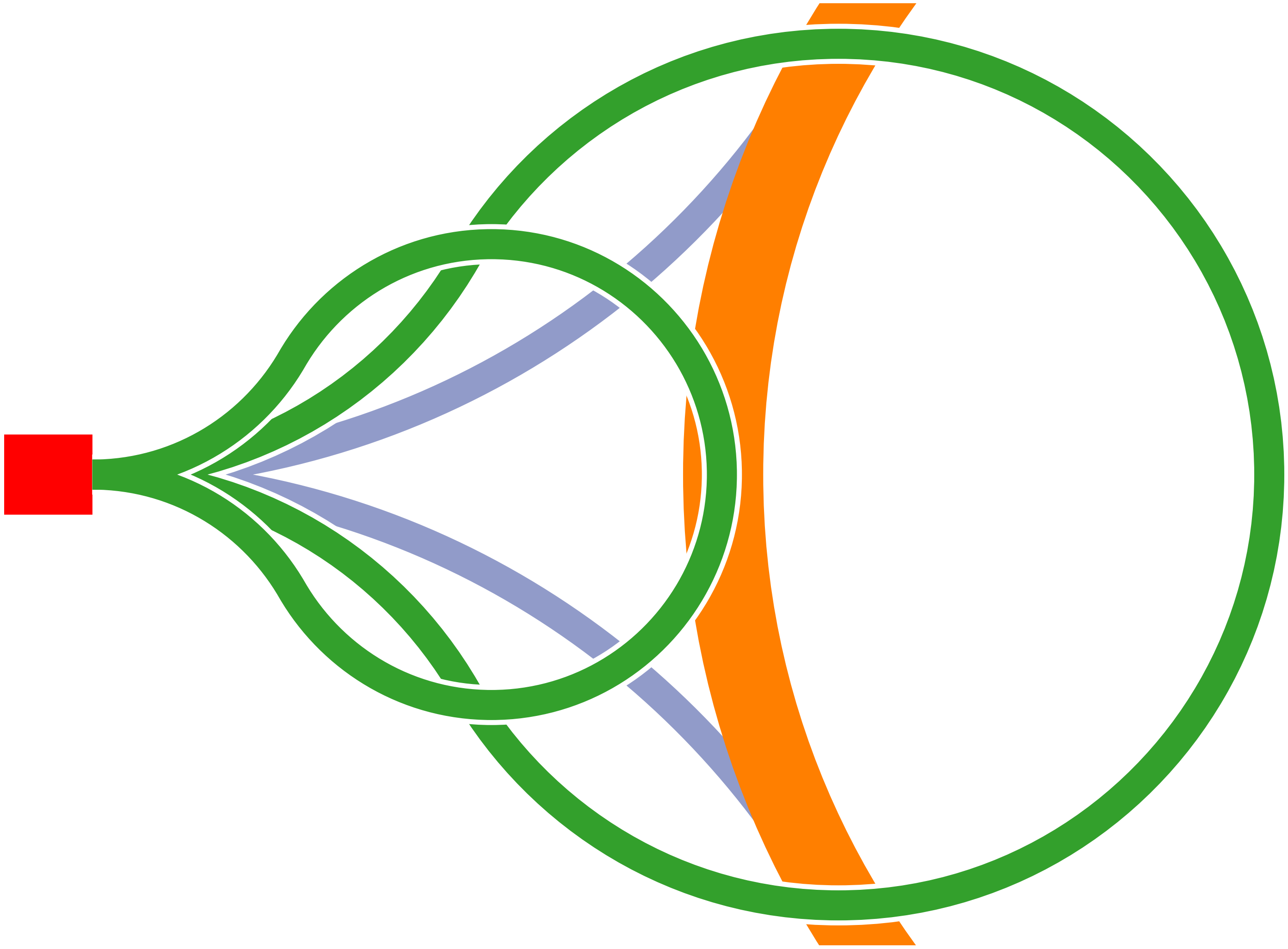
IDS-NF Baseline Layout



Acceleration Challenges for a Neutrino Factory

- Keep machine cost down
- Large transverse and longitudinal emittances
  - Ionization cooling expensive
  - Only muon count matters
- Make multiple passes through RF
  - Switchyard limits number of passes in RLAs
  - FFAGs less efficient at low energies

RLA Switchyard



Time of Flight

- Time of flight depends on energy
- Rapid acceleration with high frequency RF
  - Required for bunch structure, gradients
  - No frequency variation
  - Low tolerance for phase slip
- Lose phase synchronization after some turns

Original FFAG: Scaling Basic Properties

- Except for a linear transform, dynamics independent of energy
- Tune independent of energy
- Momentum compaction constant
  - Relativistic: time increases monotonically with energy
- Closed orbits geometrically similar
  - Radius monotonically increases with energy

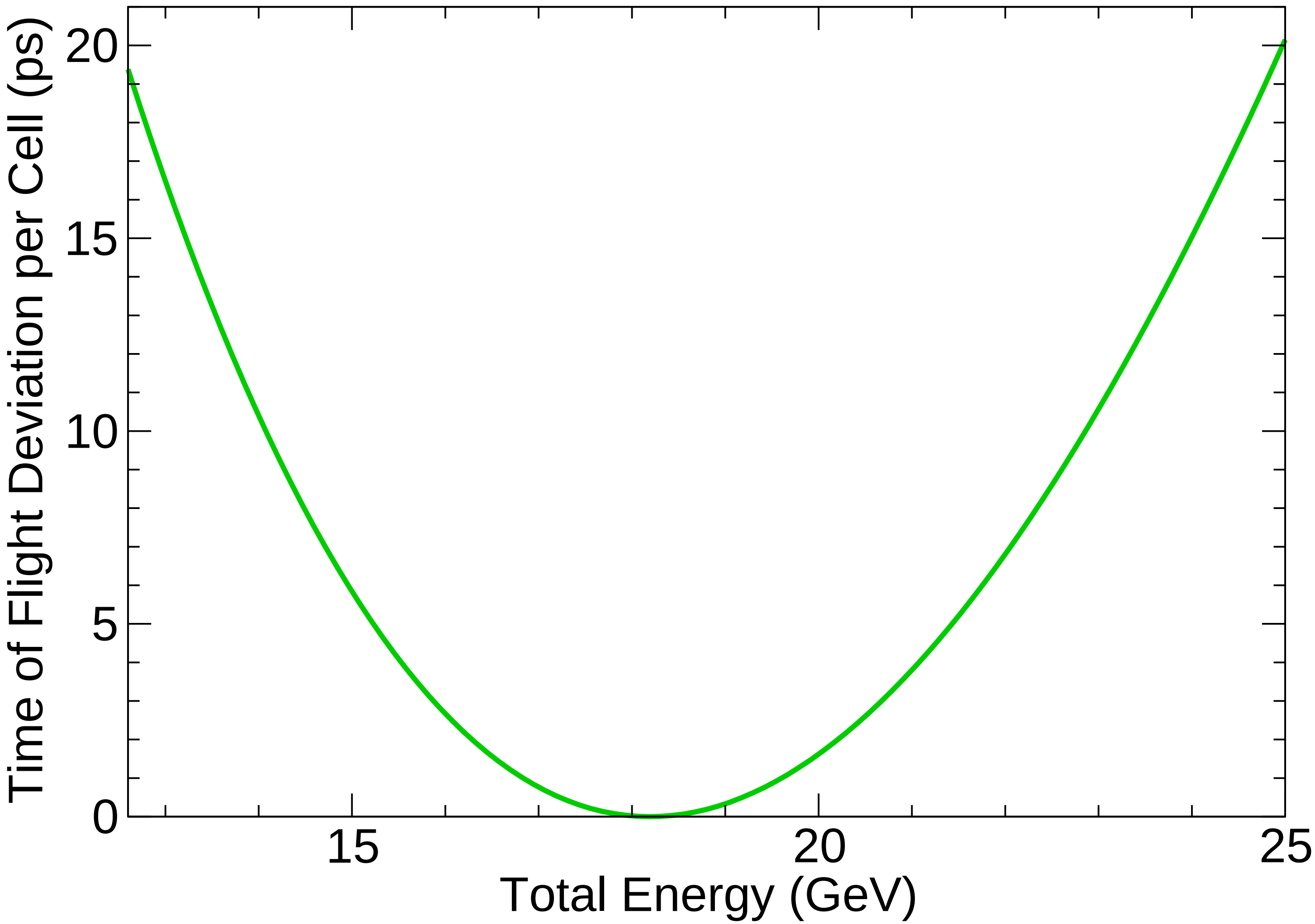
Why not Scaling FFAG?

- Time of flight varies strongly with energy
- Large aperture superconducting magnets required
  - Large transverse emittance
  - Large closed orbit variation
- Low frequency RF required to stay on crest
- Possible workaround discussed later. . .

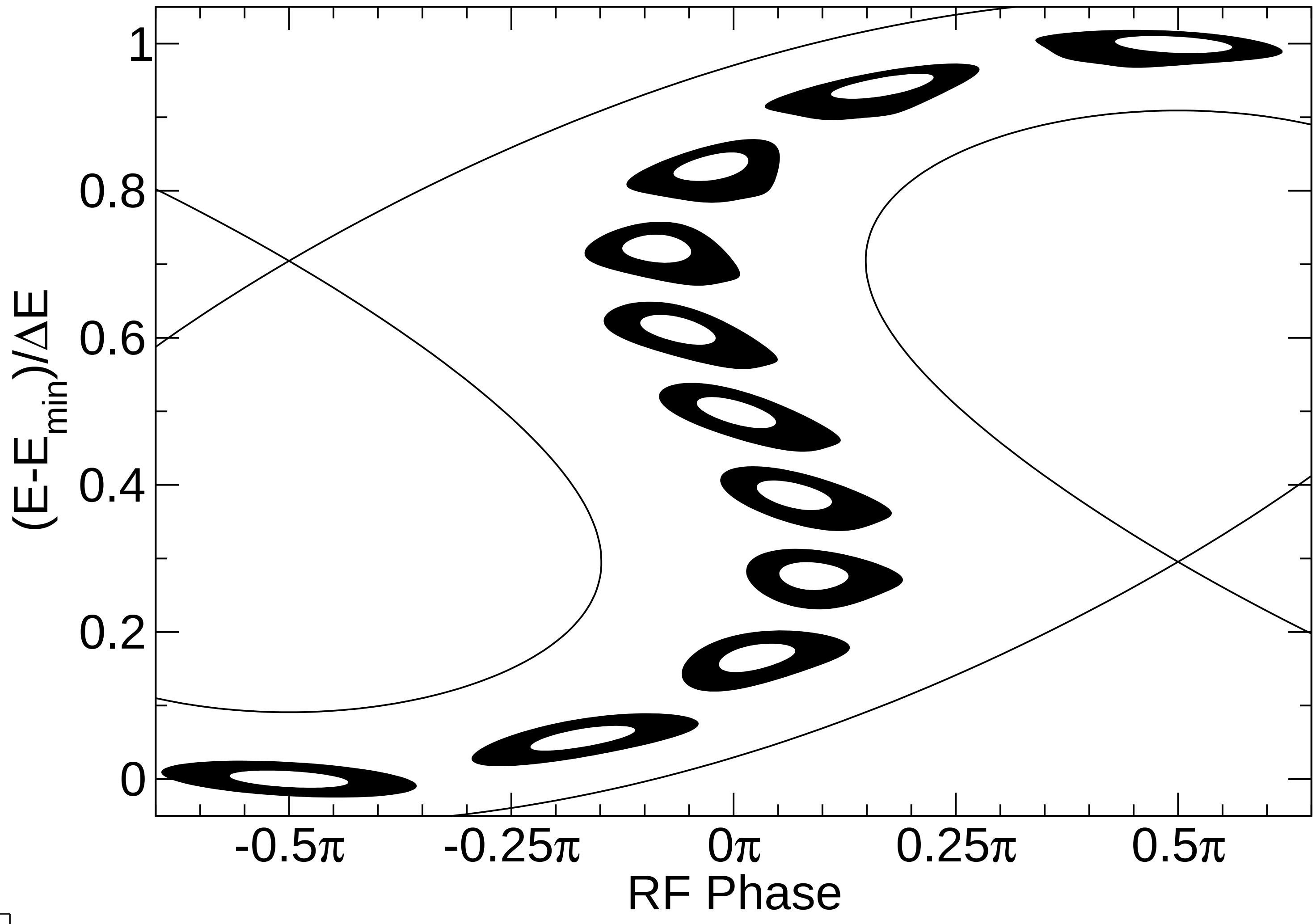
Linear Non-Scaling FFAG

- Original motivation was muon collider
- Reduce orbit variation with energy
  - Smaller aperture magnets
- Reduced time of flight variation with energy
  - Results from reduced dispersion
  - Isochronous within energy range (relativistic)
  - New type of acceleration: serpentine
- Cost: tune depends on energy

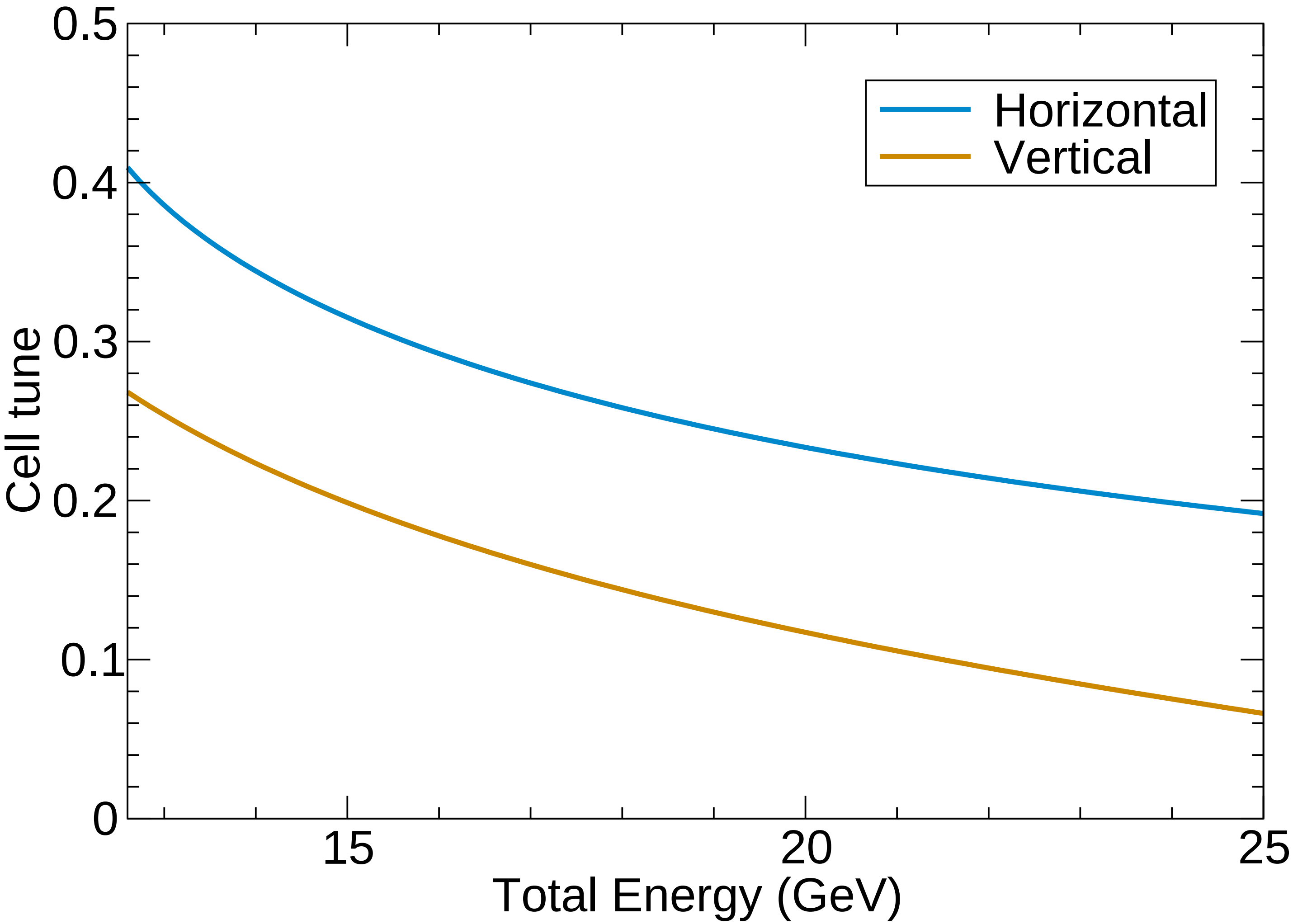
Linear Non-Scaling FFAG
Time of Flight



Linear Non-Scaling FFAG Serpentine Acceleration



Linear Non-Scaling FFAG Tunes



Linear Non-Scaling FFAG Tune Variation

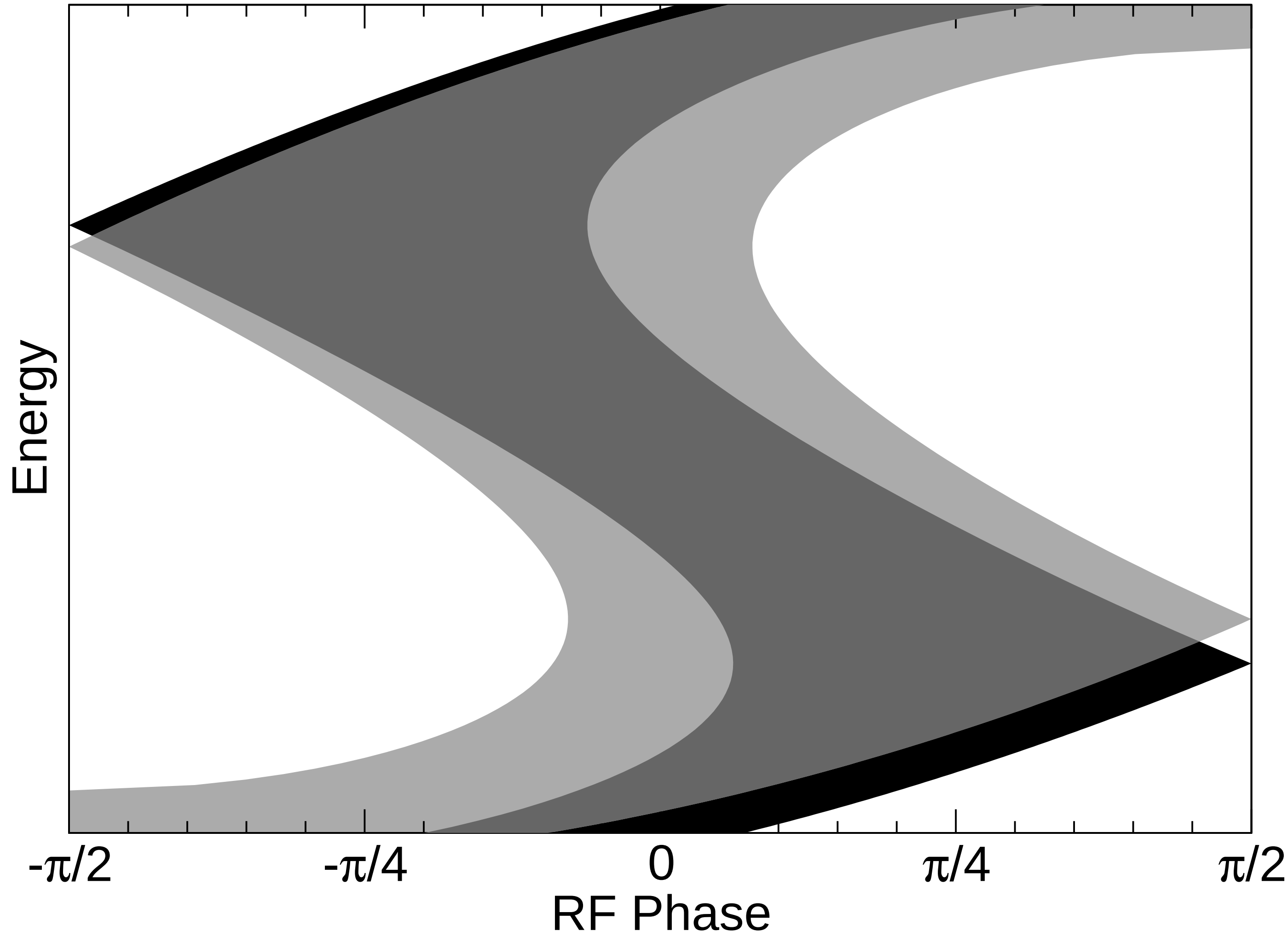
- Problem with tune variation: resonance crossing
- High degree of symmetry: single cell
  - Perfect lattice: only single-cell nonlinear resonances
  - Imperfection resonances driven weakly
- Use only linear magnets: avoid driving nonlinear resonances
- Accelerate rapidly: cross resonances quickly

Time of Flight Variation with Transverse Amplitude

- Time of flight depends on transverse amplitude
- Neutrino factory transverse emittance large enough to see this
- Longitudinal dynamics depends on transverse amplitude
- Total effect proportional to
  - Change in tune with energy
  - Acceleration time (in lattice cells)
  - Hamiltonian term proportional to $\xi \cdot J\,\delta$

Time of Flight Variation with Transverse Amplitude

Longitudinal Dynamics vs. Transverse Amplitude



Neutrino Factory FFAG Parameters

- Accelerate 12.6–25 GeV total energy
- Both signs simultaneously accelerated
- 30 mm normalized transverse acceptance
- 150 mm normalized longitudinal emittance
- 201.25 MHz SCRF, 17 MV/m
- Simple lattice cell: FODO or triplet

Neutrino Factory FFAG Design Principles

- Fill all available drifts with RF
  - Reduce transverse effect on longitudinal
- Need enough voltage for longitudinal emittance
- Longer ring: magnets less expensive
  - Aperture reduction
  - But more RF with all drifts filled
    - Longer ring needs less RF without this

Neutrino Factory FFAG Design Principles

- Reduce cell length, reduce time of flight variation
  - Minimize drift lengths
  - Use combined-function magnets
- High horizontal tune: lower dispersion
  - Low vertical tune reduces magnet strengths, improves stability
- Optimize for “cost” (including decays)

IDS-NF FFAG Parameters

	FCDC	FDFCC	FDFC
Cells	68	60	80
D radius (mm)	94	102	87
D field (T)	6.4	7.9	7.0
F radius (mm)	200	144	115
F field (T)	3.1	4.0	4.0
Average Gradient (MV/m)	2.8	2.6	1.6
turns	9.0	13.0	17.3
Length (m)	521	393	479
Cost (A.U.)	170	155	142

IDS-NF FFAG Design Notes

- No doublet: two-sign injection/extraction
- Note large aperture high-field magnets
- Average gradient: trans./long. coupling
- One or two cavities per cell
  - Cost vs. transverse/longitudinal coupling
  - Longer drifts in two-cavity triplet
- More turns, more efficient
- Injection/extraction also affects choice

IDS-NF FFAG Injection and Extraction

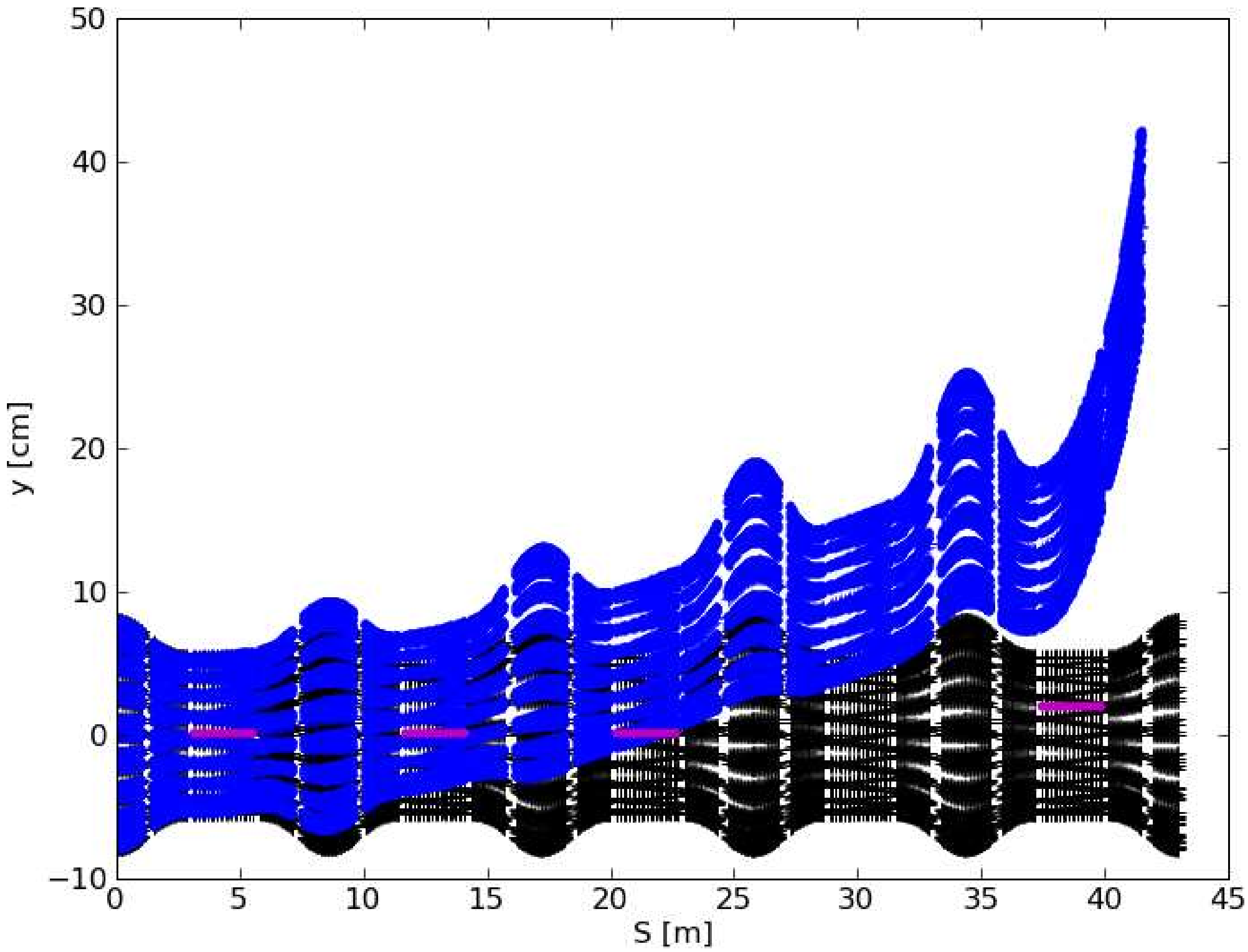
- Injection/extraction very challenging
- Large aperture magnets
- Very short drifts (2 or 3 m)
- Design parameters
  - Field below 0.1 T
  - 1.4 or 2.4 m kicker length
  - Kickers shared by both signs
- More in later talk

Injection and Extraction Parameters (Pasternak/Kelliher)

	FCDC inj. vert.	FCDC ext. vert.	FDFCC inj. horiz.	FDFCC ext. horiz.	FDFCC ext. vert.
Kickers	10	6(4)	3	6	4
Kicker field (T)	0.08	0.1	0.0855	0.085	0.08
Septum (T)	2.5	4	2	2	2

- Triplet seems easier: longer drifts

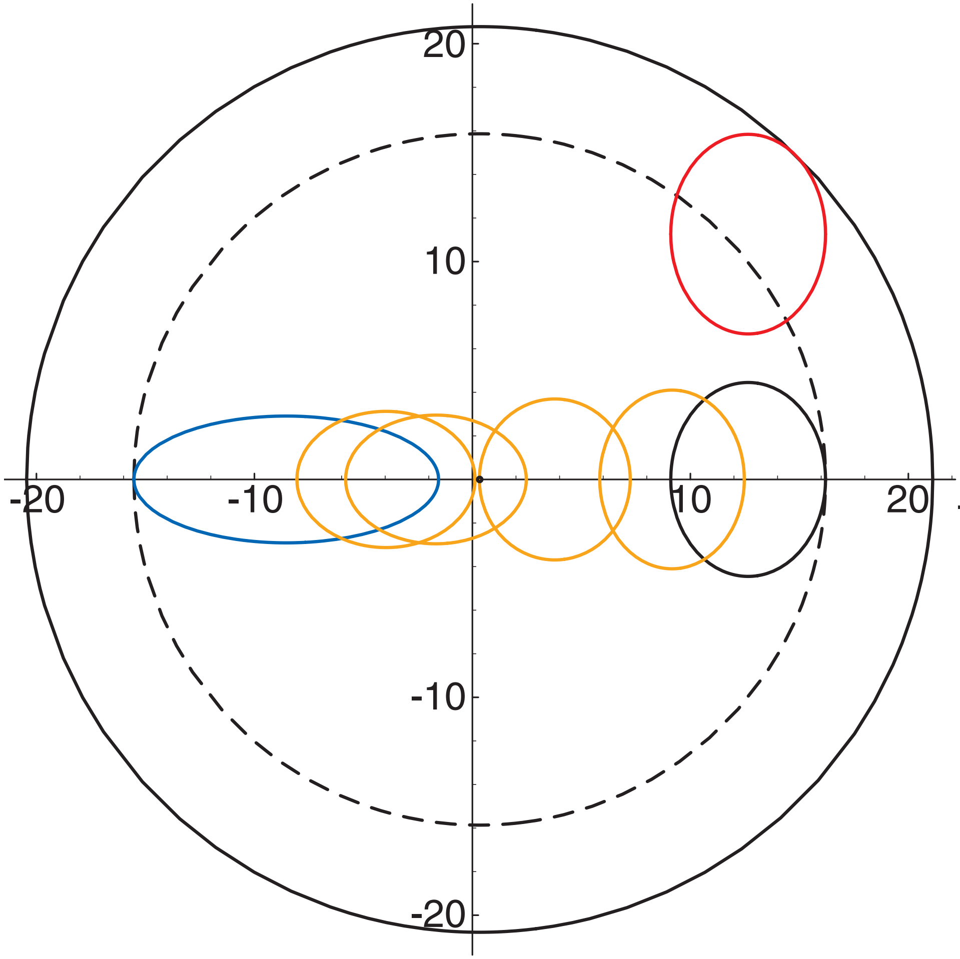
Extraction Orbits (Kelliher/Pasternak)

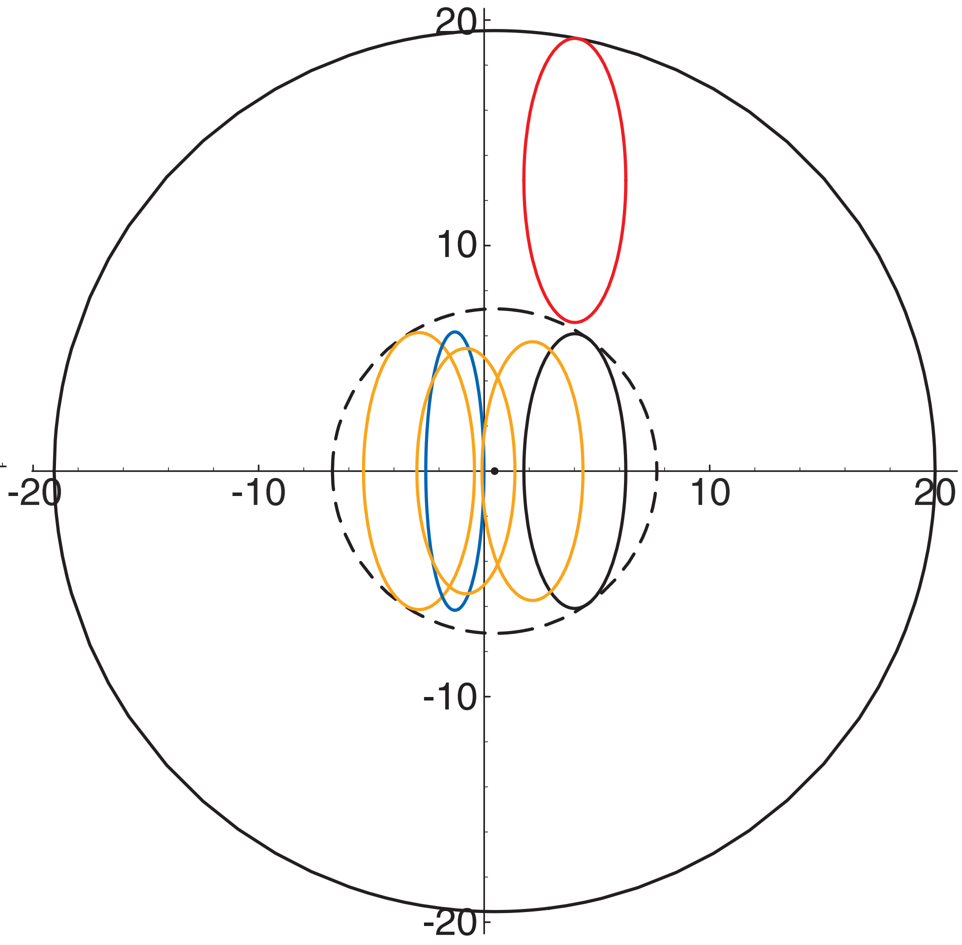


Injection/Extraction: Special Magnets (Kelliher/Pasternak)

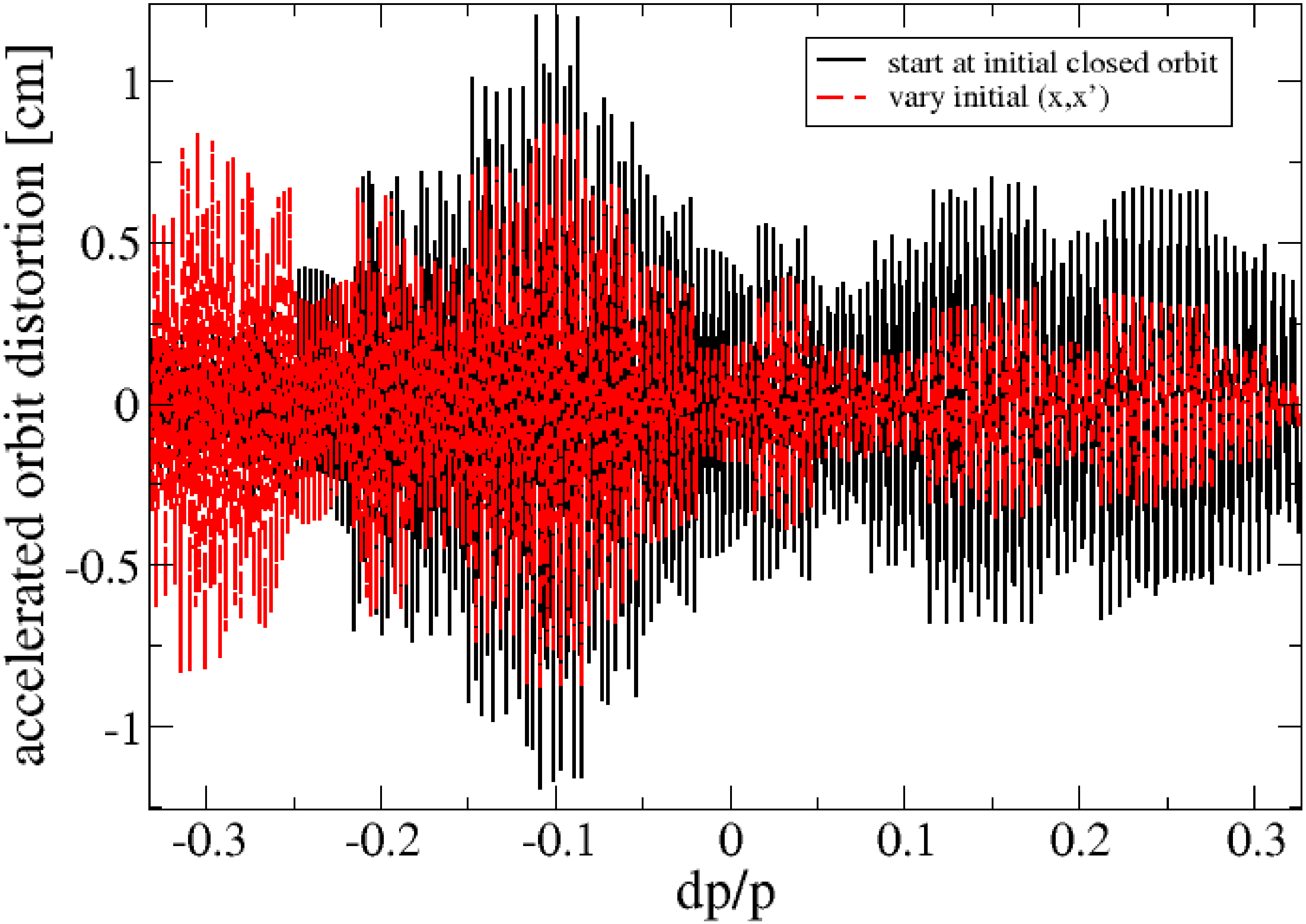
- Larger beam excursion in injection/extraction regions
- Need larger magnets in these regions
  - Increased aperture less for triplets
- Breaks symmetry in lattice
- Leads to closed orbit distortions
  - Appear modest: $\approx$1 cm

Magnet Aperture in FFAG Extraction Region (Kelliher)





Accelerated Orbit Distortion (Kelliher)



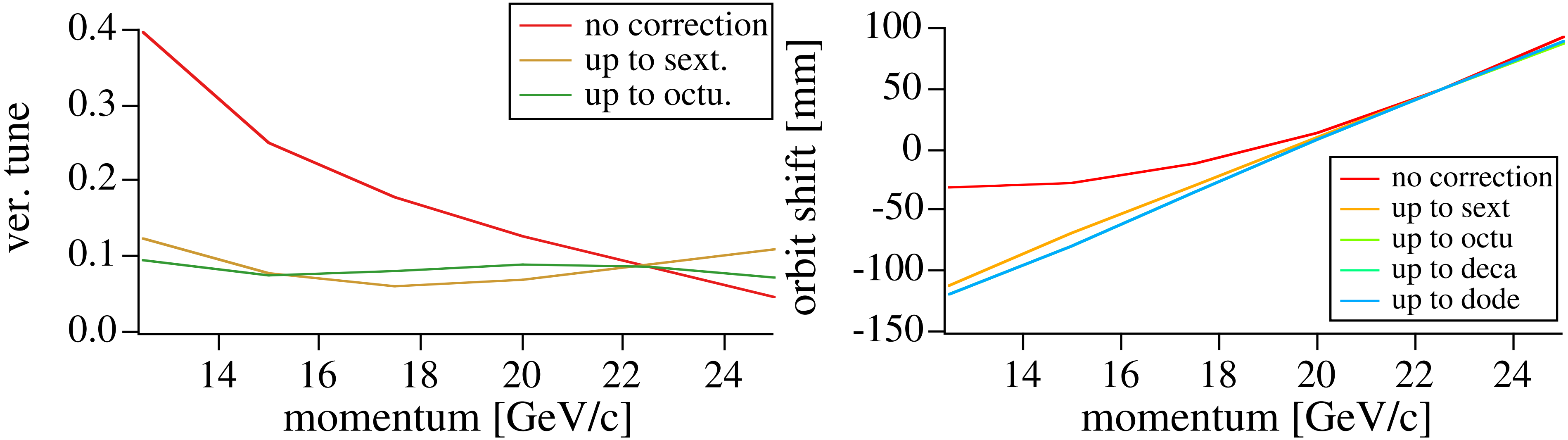
IDS-NF FFAG Chromaticity Correction

- Time dependence on transverse amplitude
  - Proportional to chromaticity
  - Significant longitudinal emittance growth
  - Large transverse emittance in neutrino factory
- Nonlinearity required for correction
  - Reduced dynamic aperture
  - Nonlinear resonances stronger

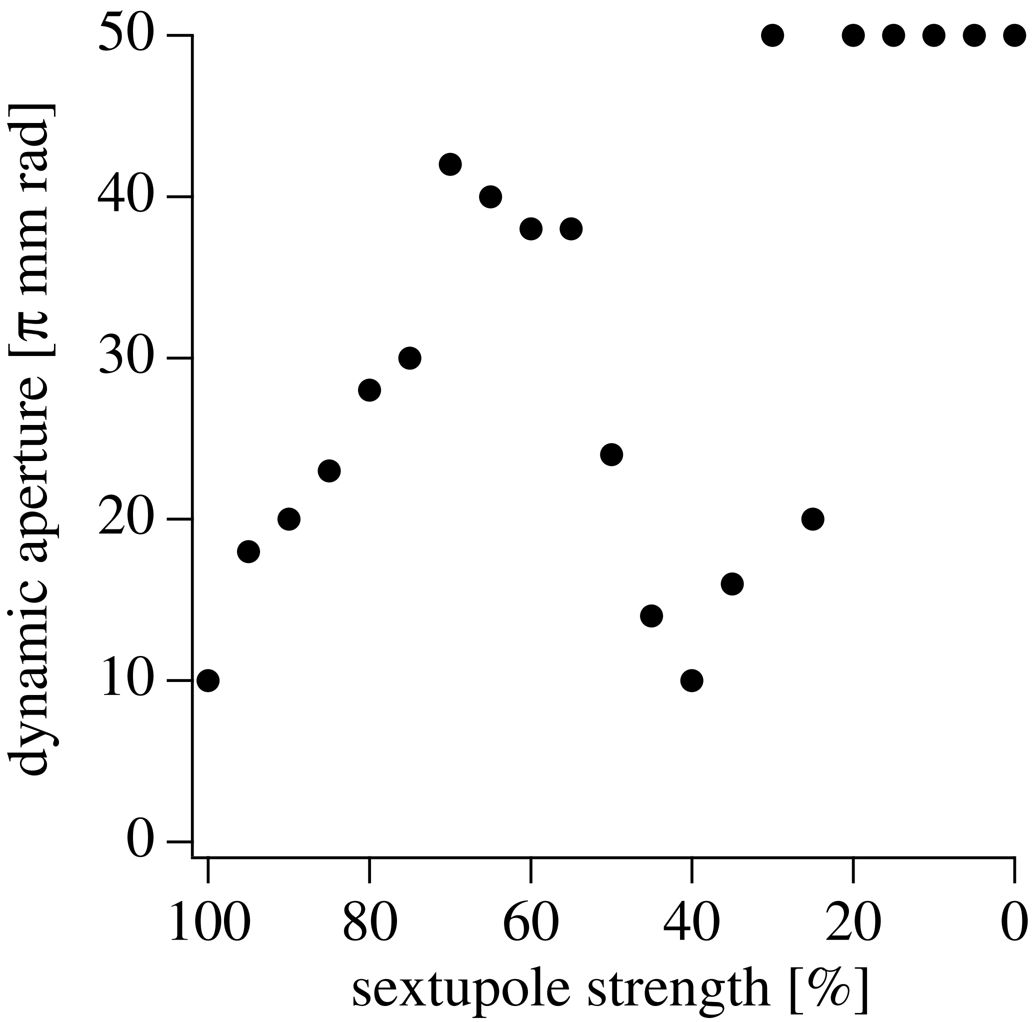
IDS-NF FFAG: Chromaticity Correction (Machida)

- Add chromatic correction to lattice
- Full chromatic correction
  - Significantly reduced dynamic aperture
  - Increased horizontal aperture (lower tune)
- Partial chromatic correction
  - Effect on longitudinal proportional to chromaticity
  - Dynamic aperture rises to acceptable levels
  - Horizontal aperture increase reduced

Chromaticity Correction (Machida)



Chromaticity Correction Dynamic Aperture (Machida)



IDS-NF FFAG Insertions (Machida)

- Long drifts better for kickers
- Longer drifts, larger time variation
- Longer drifts only in some cells
- Introduces additional resonances
- Can avoid crossing with chromaticity correction
- Result: insertion sections seem possible with chromaticity correction
  - Even possible with partial chromaticity correction

Scaling FFAGs

- Recall problems
  - Large time of flight variation
    - Prevents high frequency RF
  - Large aperture variation
- No problem with transverse/longitudinal coupling: no chromaticity
- Interesting solutions
  - Harmonic number jump
  - Use at lower energy with warm magnets

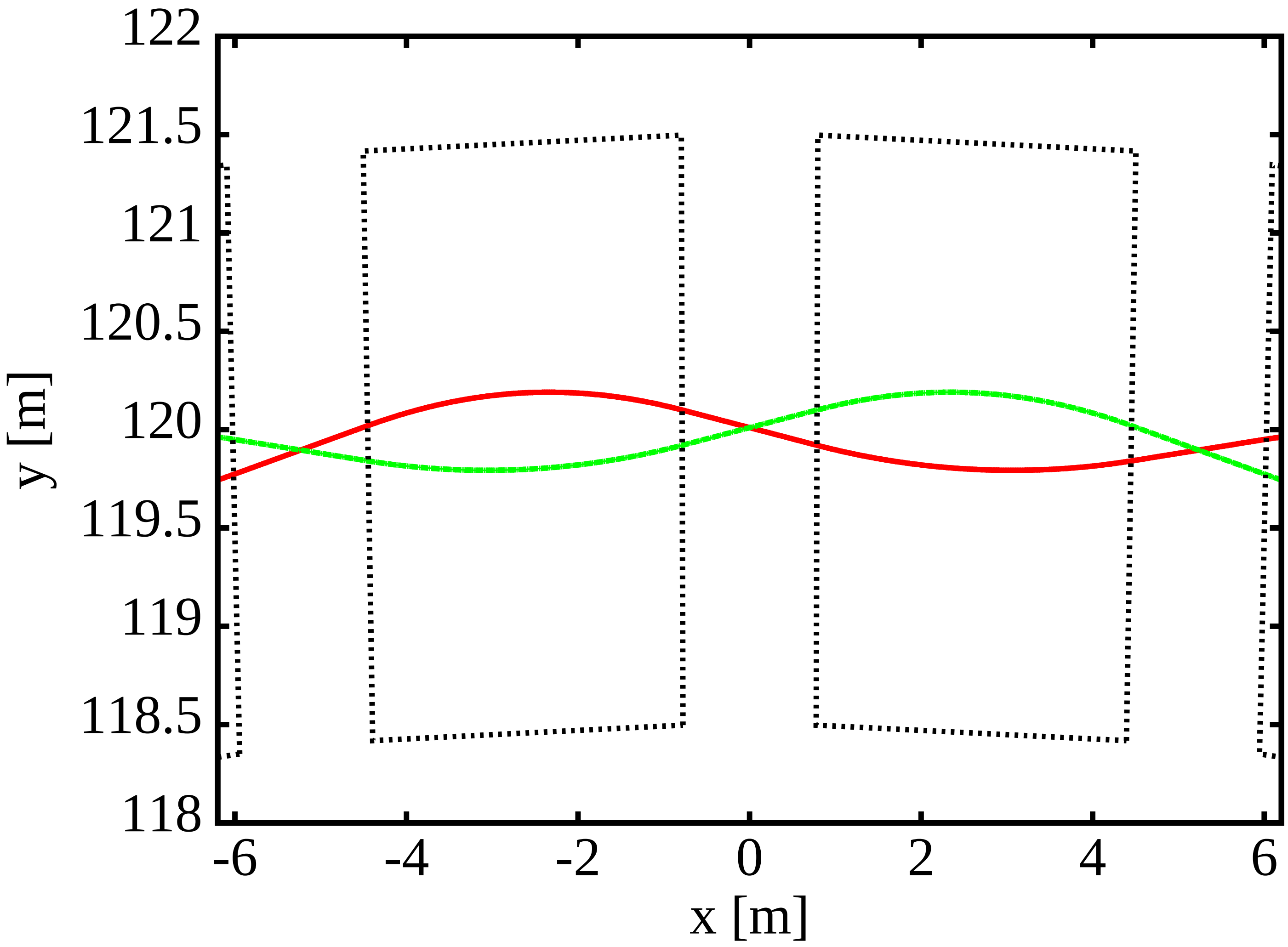
Harmonic Number Jump (Mori, Planche)

- The time of flight is an integer number of RF periods
- That integer changes on every turn
- Allows (requires!) high-frequency RF
- Difficulties
  - Must fill ring with RF
    - HNJ works only in one direction
  - Cavity aperture small compared to orbit swing

Harmonic Number Jump (Mori, Planche)

- Possible solutions to problems
  - Unidirectional two-sign FODO lattice
  - Lattice with two cell types
    - Short arc cells without cavities
    - Longer straight(er) cells with cavities
    - Straighter cells: less horizontal orbit swing
- Collaboration forming to study this
- More later in Mori's talk(?)

Unidirectional Scaling FODO FFAG (Mori/Planche)



Muon Colliders

- Beams have small transverse emittance
- Transverse coupling to longitudinal not a problem
- Non-scaling FFAGs efficient at high energy
  - Smaller transverse beam size
  - More cells, smaller dispersion
  - Longitudinal emittance relatively smaller
- Can go to higher RF frequency

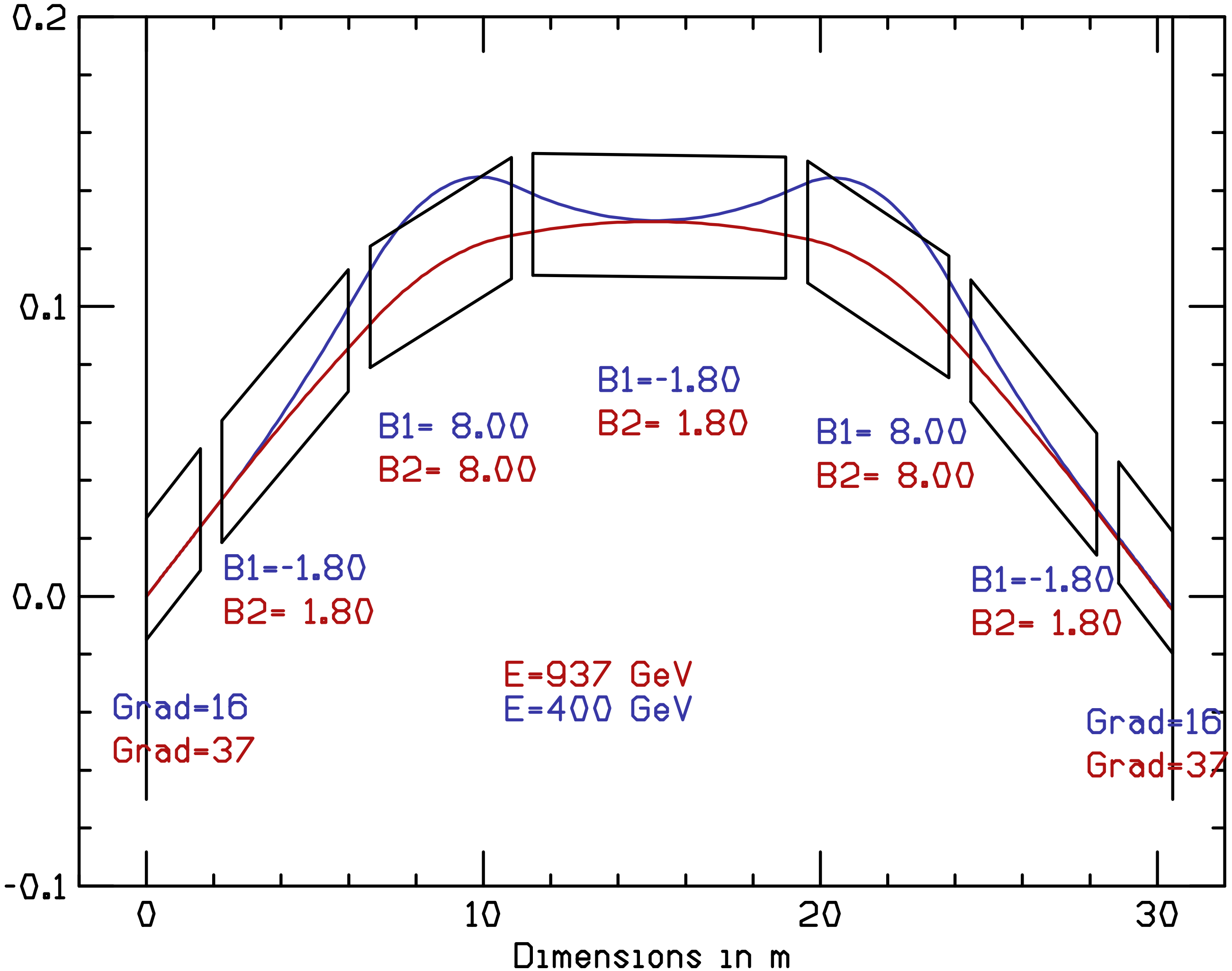
Muon Colliders

- High single-bunch currents
  - Collective effects significant
  - Serpentine acceleration: no synchrotron oscillation
  - Synchrotron oscillation stabilizes collective
- Possible alternatives
  - Run non-isochronous (scaling?)
  - Harmonic number jump
  - Ramp some magnets

Muon Colliders: Fast Ramping Hybrid Synchrotrons

- Not true synchrotrons
  - Orbit not fixed during acceleration
  - Time of flight should be kept constant
- Design similar to non-scaling FFAG
  - Have “knobs” to ramp during acceleration
  - Improve desired properties
    - Tune variation
    - Orbit swing
    - Keep time of flight constant

Fast Ramping Hybrid Lattice (Summers)



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Summary

- FFAGs increase efficiency and reduce cost in muon acceleration
- Preliminary IDS-NF linear non-scaling FFAG designs exist
  - Two-cavity triplet configuration looks best
  - Some chromaticity correction likely
  - Injection/extraction being studied
- Scaling designs also of interest
- FFAGs and similar useful for a muon collider