Acceleration Status and Plans

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MUTAC Review

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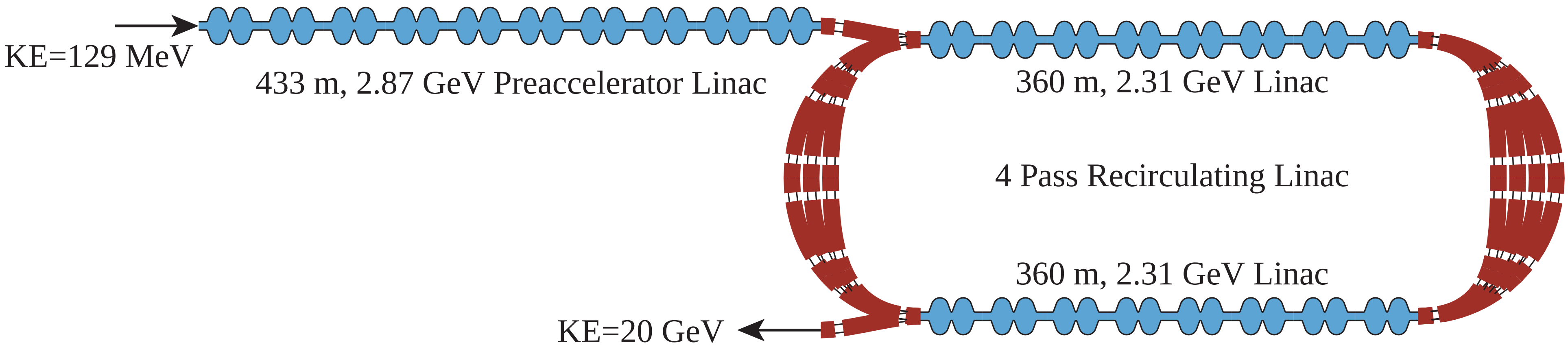
Outline

- Study II acceleration scheme & motivation for FFAGs
- FFAG design principles
- Optimized FFAG designs
- FFAG Tracking Results
- Low Energy Acceleration

Study II Acceleration



- Previous acceleration scheme
  - Linac
  - Recirculating linear accelerator (RLA)
- Acceleration very costly
- Where is that cost coming from?

Motivation for FFAG

- Rough RLA cost model
  - Linac cost inversely proportional to number of turns
  - Arc cost proportional to number of turns
  - Formula for total cost

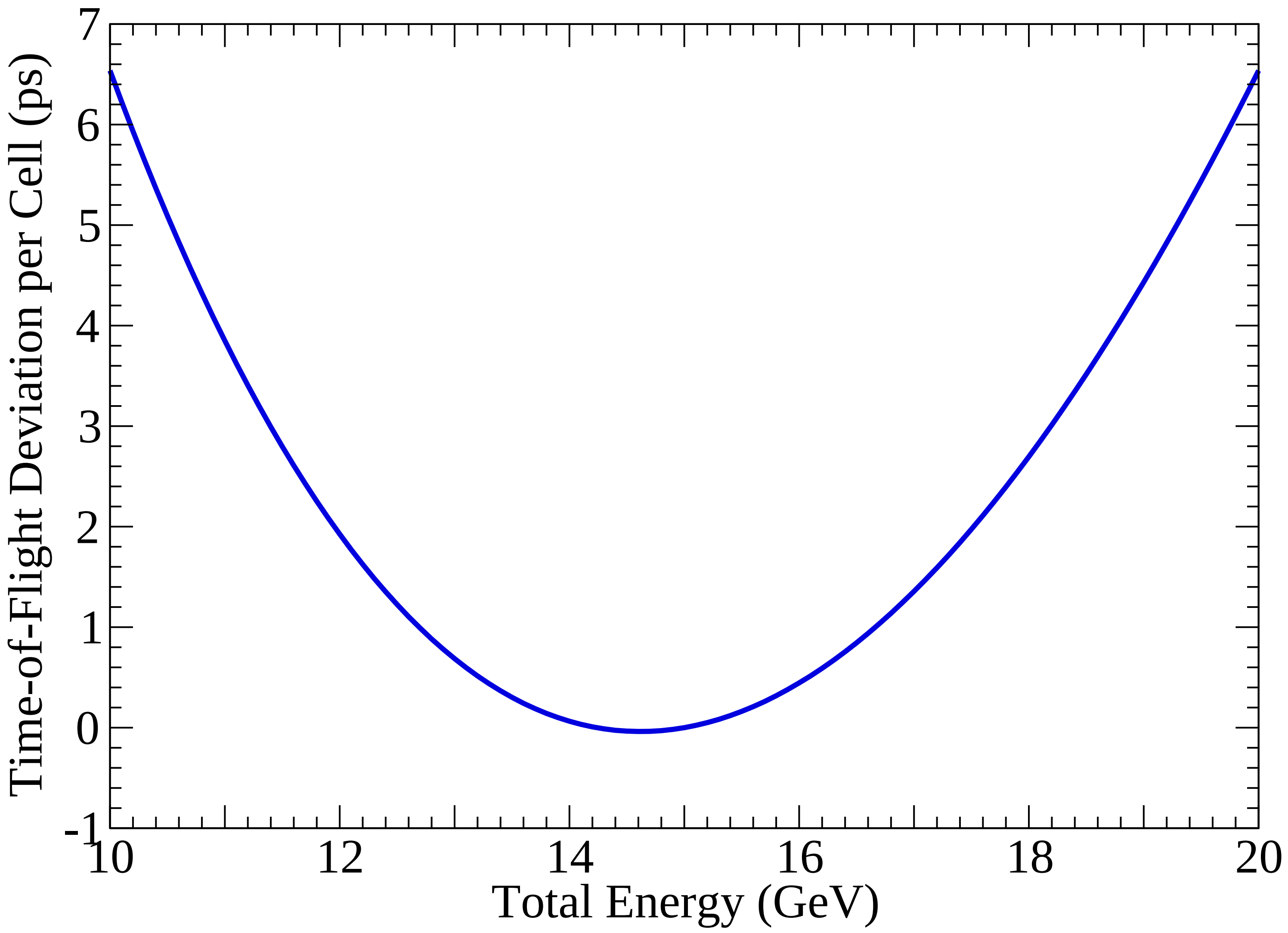
$$C(n) = C_L/n + C_A n$$

    Minimum cost is when linac cost and arc cost are equal
  - Study II design: linac cost significantly more than arc cost: more turns is optimal
  - More turns not possible: switchyard
- Need to make more passes through RF to reduce cost
- Avoid switchyard which limits number of turns
- Our solution: use a **F**ixed **F**ield **A**lternating **G**radient (FFAG) accelerator
  - Single arc with a large energy acceptance: factor of 2 or more

FFAG Design: Longitudinal

- Time-of-flight varies with energy: this limits the number of turns
  - Longitudinal acceptance in scaled variables ($\omega\tau$, $(E - E_0)/\Delta E$) depends mainly on $V/\omega\Delta T\Delta E$
    - V is voltage per turn, ω is angular RF frequency, ΔT is height of time-of-flight parabola, ΔE is energy range of acceleration
  - Lower ΔT, less voltage required, more turns
  - ΔT proportional to cell length: keep magnets, drifts as short as is reasonable
  - ΔT inversely proportional to number of cells: tradeoff between length and voltage required
  - ΔT proportional to $(\Delta E)^2$: prefer smaller energy range
  - Higher voltage per cell, larger ΔT tolerable, more compact ring

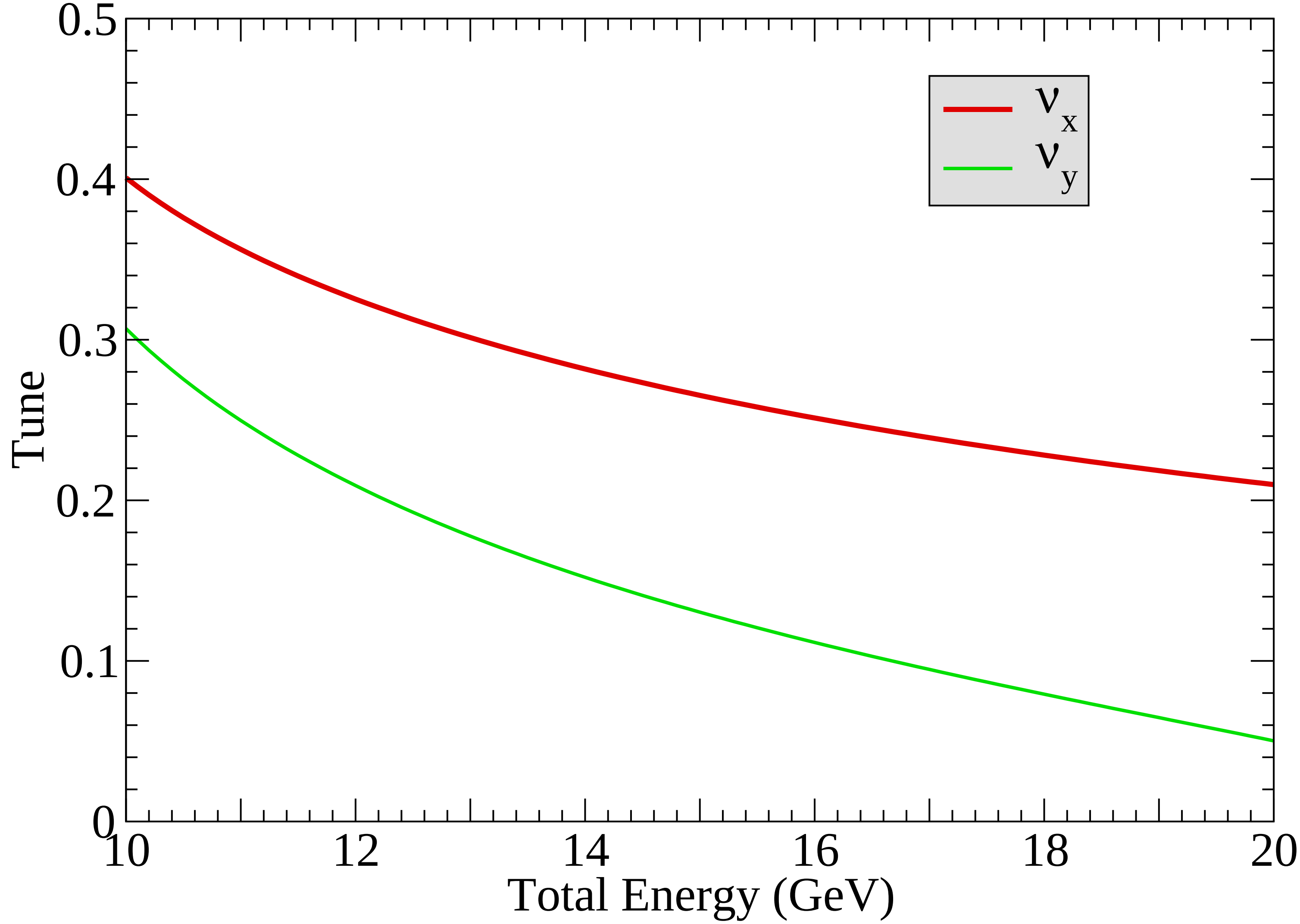
Time-of-Flight vs. Energy



FFAG Design: Resonances

- Tune varies over a large range: resonances
  - Maintain high degree of symmetry: mainly concerned with single-cell resonances
  - Linear magnets minimize driving of resonances
  - Keep single-cell tune below 0.5: avoid rapid loss
  - Rapid acceleration: accelerate through resonances

Tune vs. Energy



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Optimized FFAG Design

fact Muon Collaboration

- Produce design with minimum cost: Palmer's formula
- Fix RF drift length, inter-magnet spacing to minimum tolerable values
- Use combined-function magnets to keep cell compact
- Fix voltage per cell
  - 7.5 MV/cell: pessimistic, assumes only gradients achieved to date
- Allow 8 empty cells for injection/extraction
- Make time-of-flight parabola symmetric, height determined by giving $V/\omega\Delta T\Delta E$ specific values
- Choose 30 mm normalized transverse acceptance (15 mm before)
  - Marginal cost of acceptance in acceleration small (roughly 20%)
  - Cooling cost high

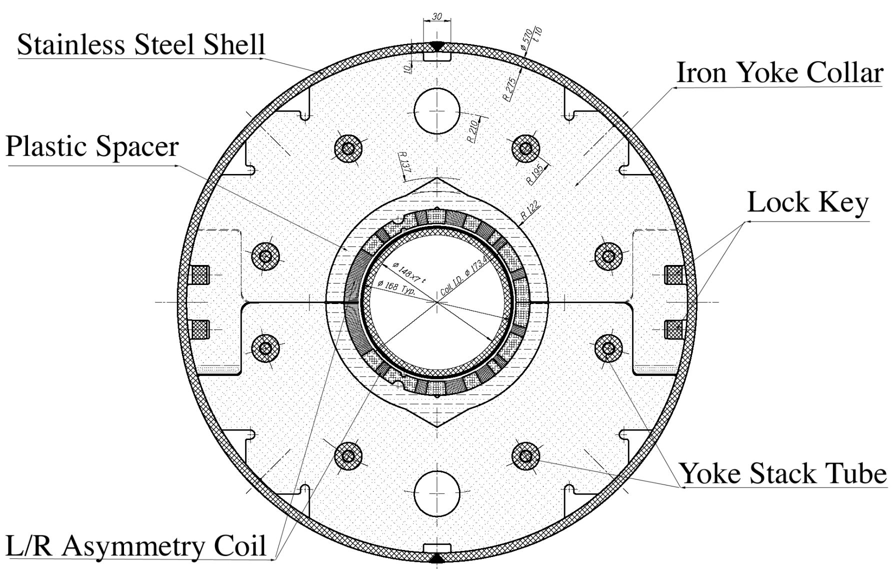
Choice of Lattice Type

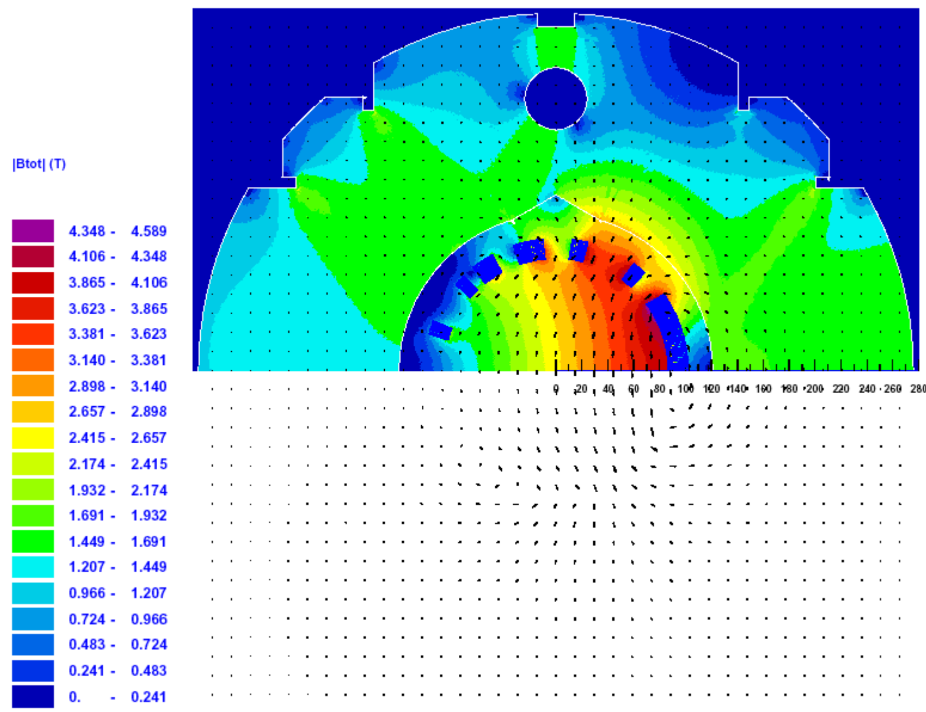
Type	FDF	FD	FODO
Cells	108	113	127
D Length (cm)	175	137	130
D Radius (cm)	10.2	8.7	9.7
D Pole Tip (T)	4.4	4.6	4.0
F Length (cm)	118	221	213
F Radius (cm)	11.9	13.8	15.5
F Pole Tip (T)	2.4	2.3	1.9
RF Voltage (MV)	811	849	950
$c\Delta T$ (cm)	23.1	24.1	27.1
Circumference (m)	768	688	941
Magnet cost (PB)	39	34	33
RF cost (PB)	53	55	62
Linear cost (PB)	19	17	24
Total cost (PB)	111	106	118

- 10–20 GeV, low energy tunes fixed at 0.35
- Doublet has lowest cost
  - Triplet requires lower voltage
  - More magnets in triplet than in doublet
  - FODO wastes space
  - Differences not large
- Triplet used here for historical reasons
- Have more optimized lattices available
  - Triplet, low-energy tunes not fixed
  - Working on full comparison

Magnets: Compare J-PARC

- KEK designed combined-function magnets for J-PARC (Ogitsu *et al.*, with BNL consultation)
- Apertures slightly smaller (8.7 cm radius), magnets longer (3 m). Not drastically different.





Variation with Energy Range

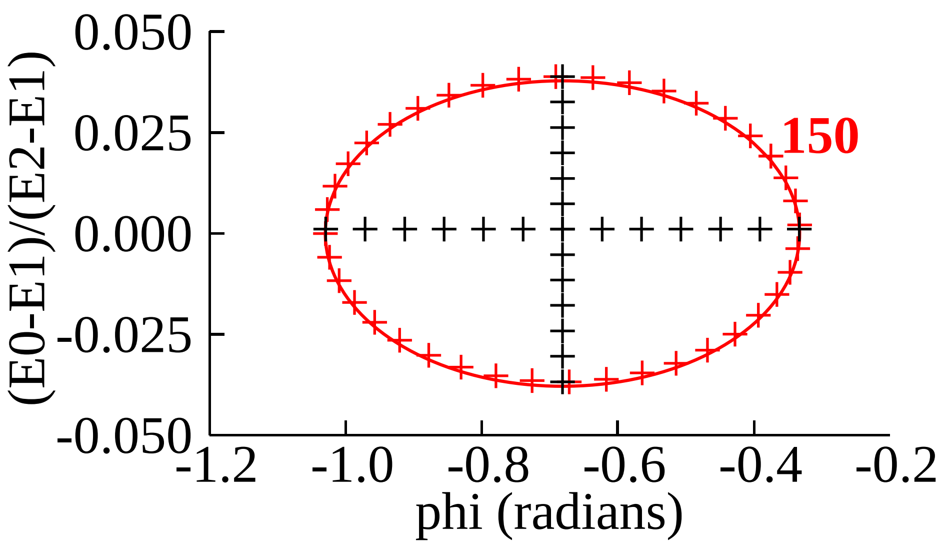
Min Energy (GeV)	2.5	5	10
Max Energy (GeV)	5	10	20
$V/\omega\Delta T\Delta E$	1/6	1/8	1/12
Cells	80	93	108
D Length (cm)	144	158	175
D Radius (cm)	19.0	13.8	10.2
D Pole Tip (T)	2.0	3.1	4.4
F Length (cm)	84	96	118
F Radius (cm)	18.2	14.4	11.9
F Pole Tip (T)	1.2	1.8	2.4
RF Voltage (MV)	604	695	811
$c\Delta T$ (cm)	34.3	26.4	23.1
$\Delta E/V$	4.1	7.2	12.3
Circumference (m)	493	603	768
Magnet cost (PB)	25	31	39
RF cost (PB)	39	45	53
Linear cost (PB)	12	15	19
Total cost (PB)	77	91	111
Cost per GeV (PB)	30.8	18.2	11.1

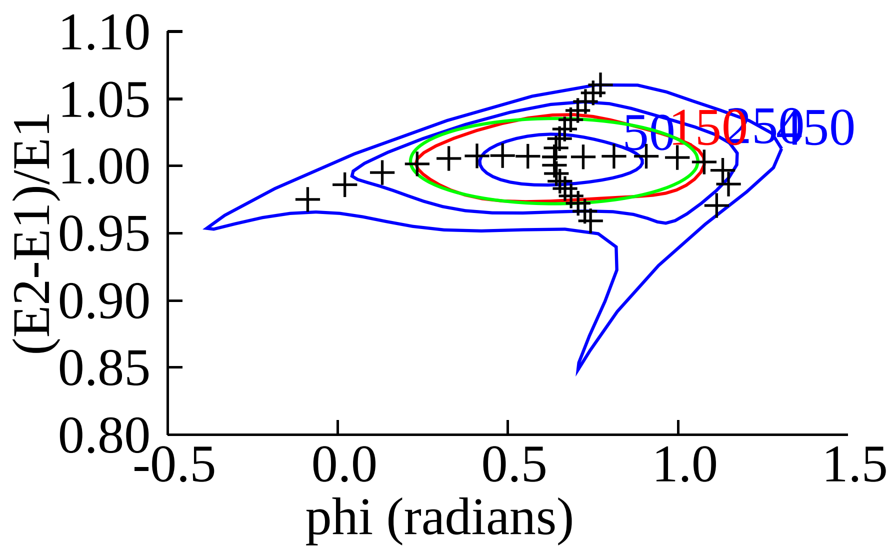
- Triplet lattices, low-energy tunes fixed at 0.35
- Cost per GeV increases substantially as energy lowers
  - Increasing magnet apertures
  - Increasing $V/\omega\Delta T\Delta E$
  - Number of cells decreases very slowly
- 2.5–5 GeV not cost-effective: only 4 "equivalent turns"
  - Need to use a different acceleration method below 5 GeV

FFAG Tracking Results

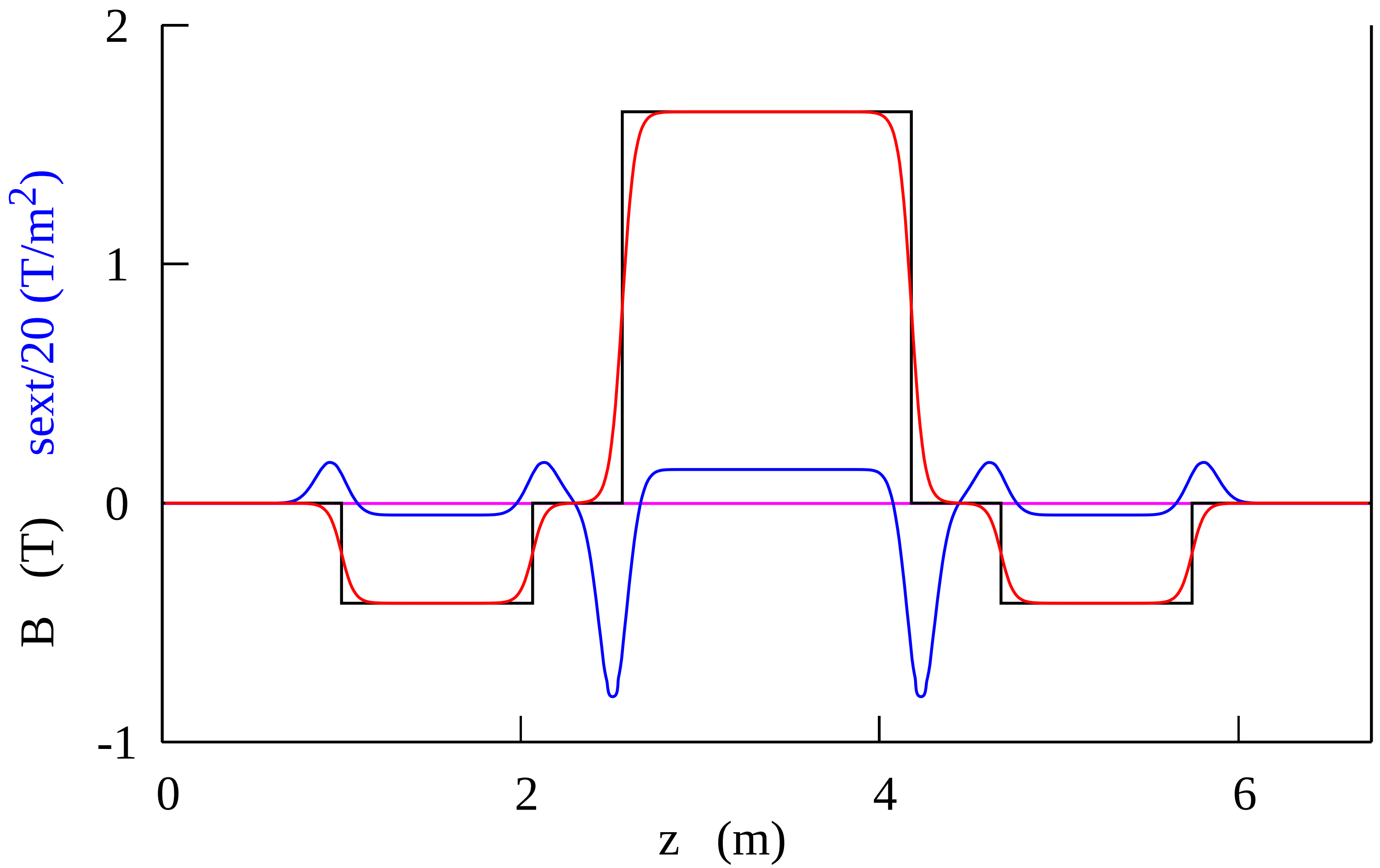
- Values of $V/\omega\Delta T\Delta E$ conservative
  - Using lower values would reduce cost further
  - For 5–10 GeV, $V/\omega\Delta T\Delta E = 1/12$ seems to work
    - Third harmonic RF system required!
  - Need to optimize
- Relatively short magnets: end fields primary source of nonlinearity
  - Geometric nonlinearity due to coil symmetry at ends: can compensate in body
    - Insufficient space between magnets to fix directly
  - Nonlinearity at ends due to Maxwell's equations: can't be compensated directly
  - Need to do tracking with realistic magnet ends: ICOOL
- With sextupole compensated appropriately in the body, get good dynamic aperture

Longitudinal Distortion

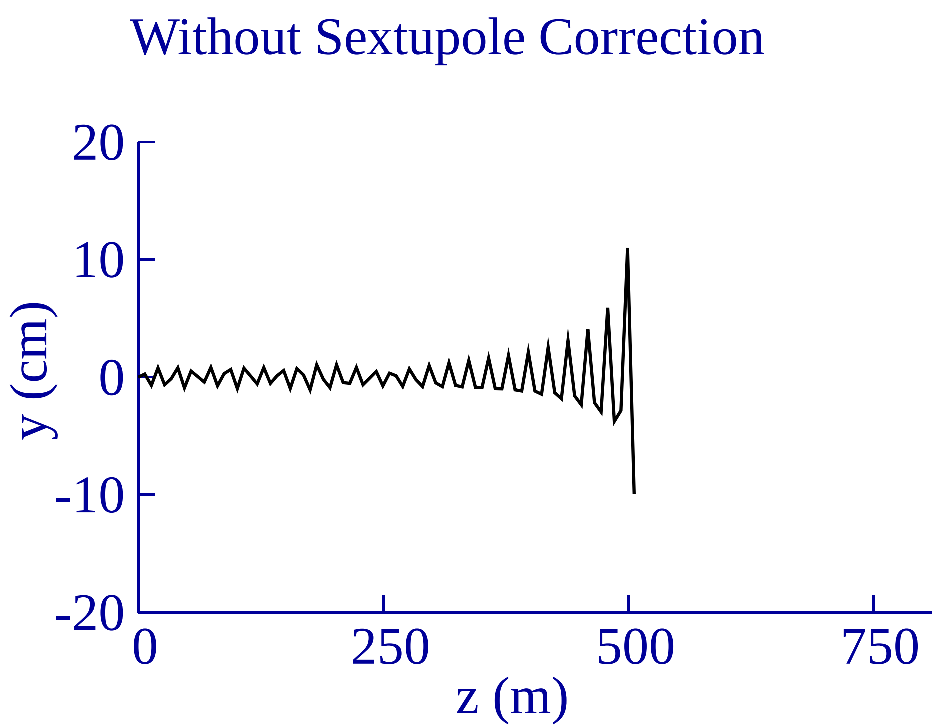


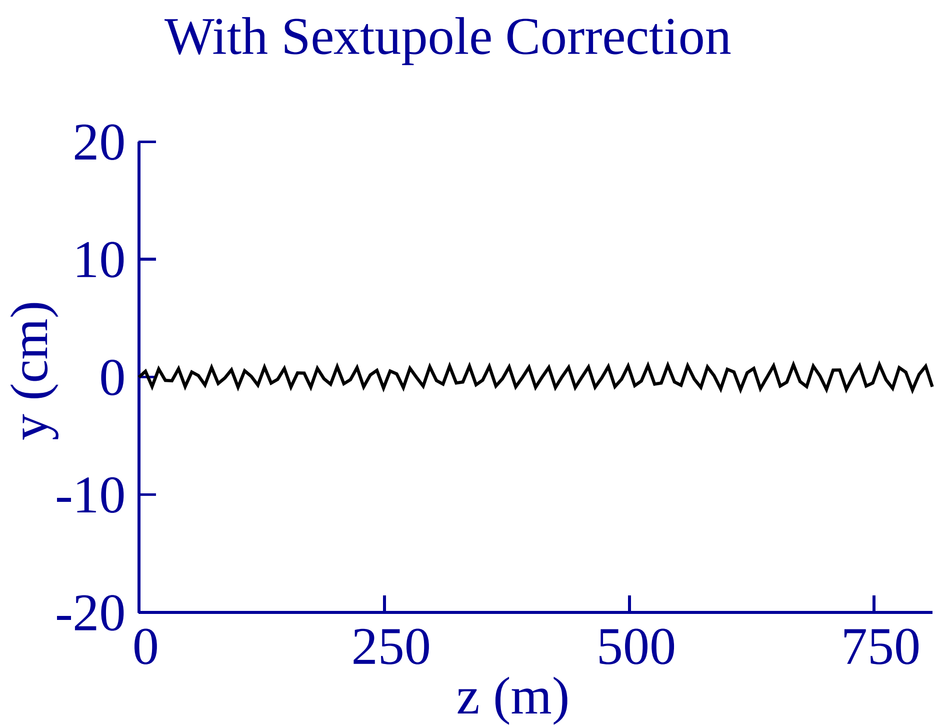


Field Profile



Emittance Growth at Resonance

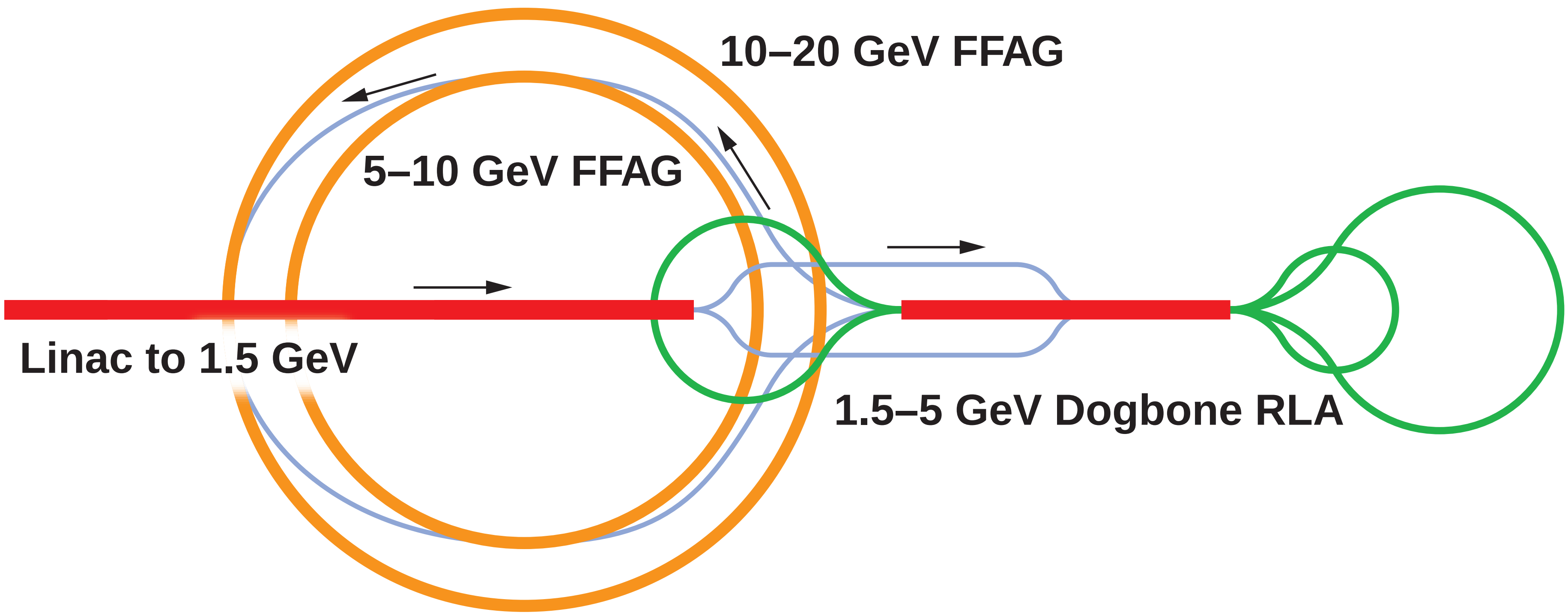




Low-energy acceleration

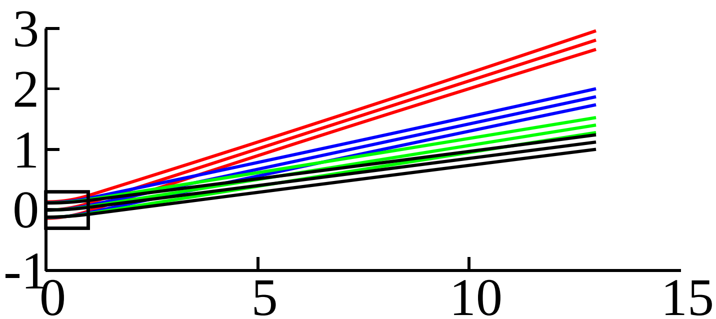
- FFAGs at very low energy not cost effective
- Need alternative methods of acceleration
- As before: linac followed by recirculating accelerator
- Linac to low energy (1.5 GeV)
- Recirculating accelerator to get up to 5 GeV
  - Consider dogbone design: easier switchyard
- Getting to 5 GeV with this scheme uses about as much linac as getting to 2.5 GeV in Study II linac

Acceleration Layout

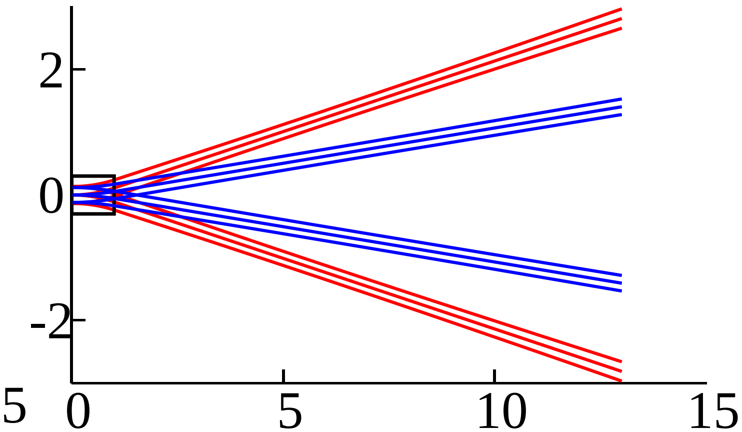


Switchyard

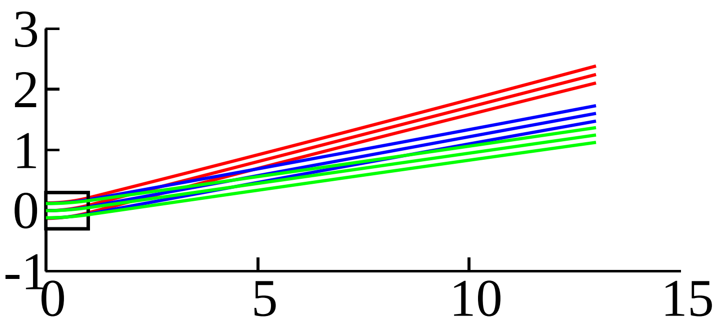
Racetrack End 1



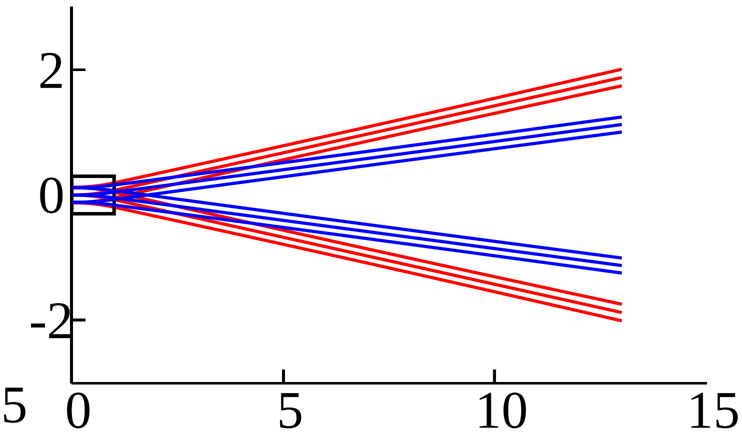
Dogbone End 1



Racetrack End 1



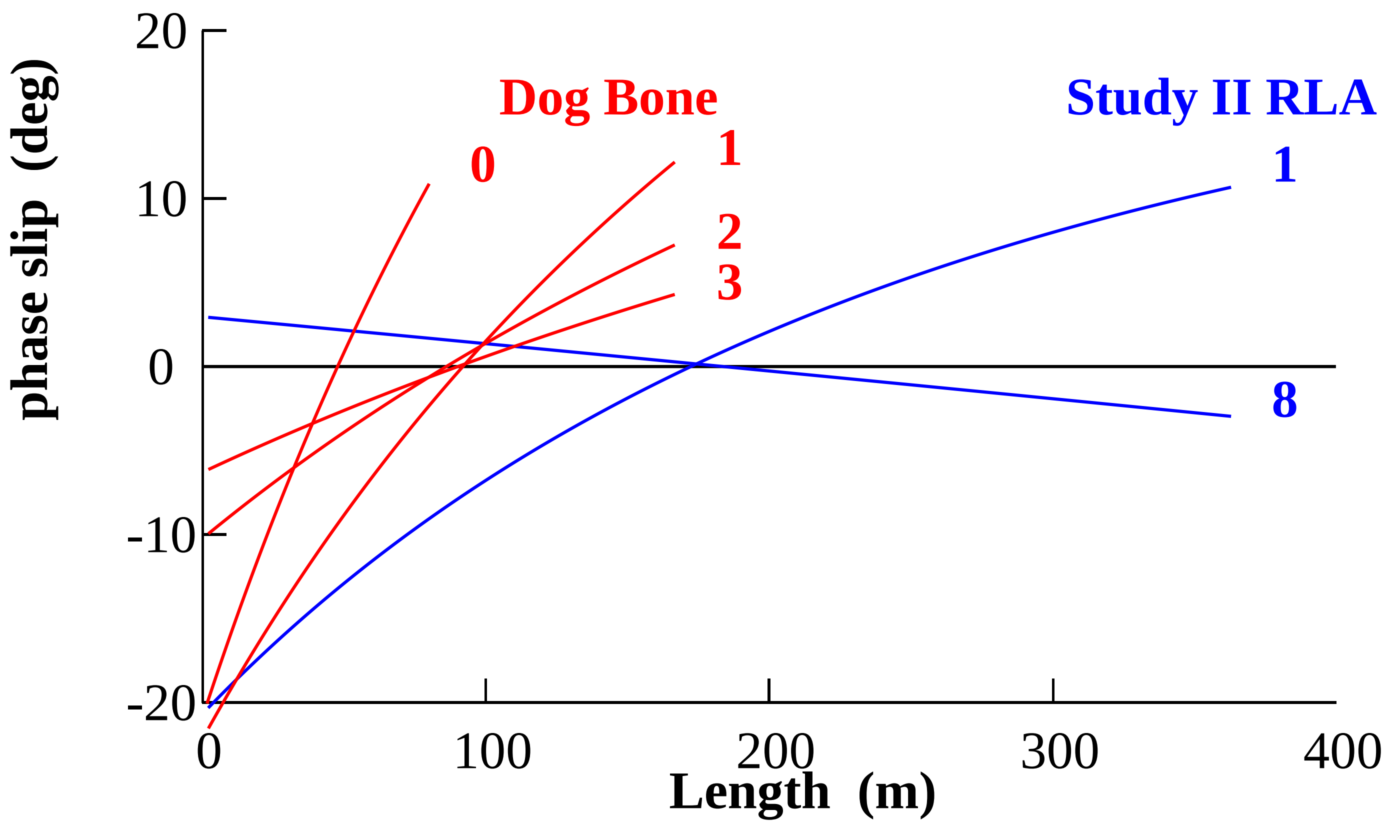
Dog End 2



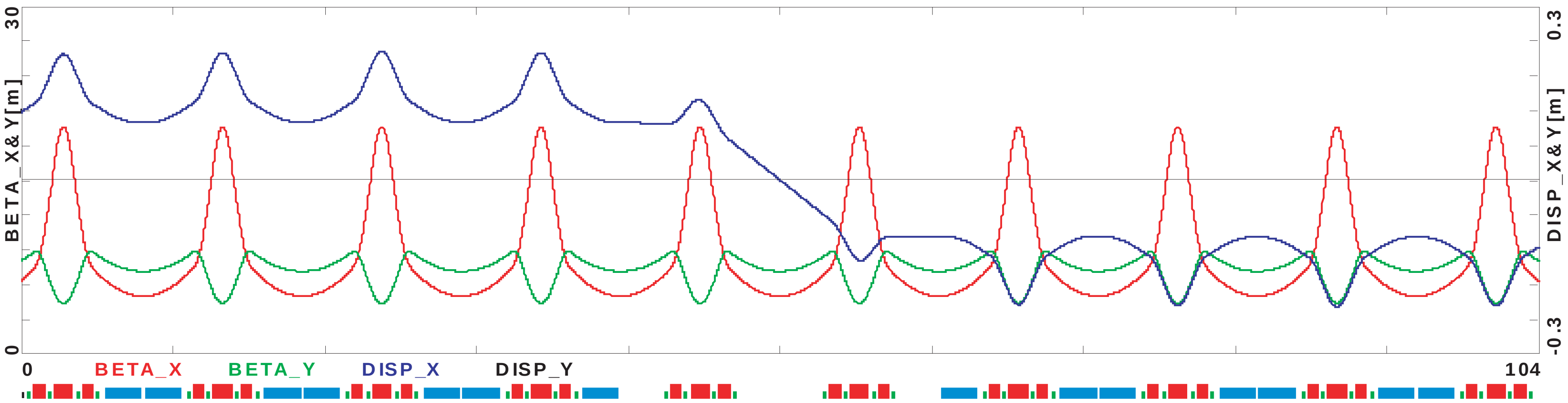
Low-Energy Acceleration Design

- Larger acceptance: must introduce shorter (compared to Study II) cells at beginning of linac
  - Single-cell cavities needed; already used in FFAG
- Inject at center of dogbone linac
  - Velocity variation with energy leads to phase slip along linac
  - Lower energy than Study II: larger effect
- Choose 90° phase advance per arc cell
  - Easy to flip dispersion when bend changes direction
  - Cancellation of nonlinear/chromatic effects
- First design, all arcs same length: avoid vertical bending, but costly

Phase Slip in Dogbone Linac



Dispersion Flip in Arcs



Conclusions

- We have incorporated FFAGs into the muon acceleration design
- We can produce FFAG parameter sets which are in some sense optimized
- We have begun more detailed studies of the dynamics in these FFAGs
- We have begun work on a new low-energy acceleration section designed to work with the FFAG acceleration

Future Work

- Finalize FFAG design parameters
  - Compare cost models
  - Determine best value for $V/\omega\Delta T\Delta E$
  - Study how to choose stage energies
- Further work in tracking
- More work on low-energy acceleration stages
  - Study how to choose transition from linac to RLA
  - Study more turns in RLA
  - Study shorter low-energy arcs: vertical bend
- Injection/extraction (next talk)
- Electron model of non-scaling FFAG (next talk)