Status of FFAGs for Muon Acceleration

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Requirements for Muon Acceleration

- Extremely large emittances: 30,000 mm mrad normalized (full)
- Extremely rapid acceleration
  - Avoid excessive decays
  - Real-estate gradients 1 MV/m and above
- Motivation for use: cost
  - To be compared with recirculating linear accelerator (like CEBAF)
  - Save money by making more passes through RF

Types of FFAG Solutions Proposed

- Scaling FFAGs (NuFactJ report)
- Linear Non-Scaling FFAGs
- Isochronous FFAGs

Factors That Drive FFAG Choice

- Cost
- Keeping decays low (this is really cost): high average gradient
- Sufficient Dynamic Aperture
- Keeping RF synchronized
  - Time of flight depends on energy
  - Acceleration too rapid to change RF frequency
  - Must accelerate more quickly: fewer turns, more RF, more cost

Scaling FFAGs

- Traditional form of FFAG
- Tune indenendent of energy
  - Find a good working point away from resonances
  - Time of flight independent of transverse amplitude (more later)
- NuFactJ scheme as it exists seems expensive
  - Optimization has been demonstrated to give significant improvements
  - New ideas on the table (normal conducting spiral sector FFAG even at high energy, for instance)
  - Need to get optimized, trackable scheme defined
- NuFactJ scheme used low-frequency RF
  - System less efficient at capture/transmission of muons (Palmer)
    - Again, may need optimization
  - Difficulty in obtaining high gradients

Scaling FFAGs
High Frequency RF

- Time of flight gives minimum field index: $k = 1220$ for 201.25 MHz, 10–20 GeV scaling FFAG, 1.5 MV/m average gradient

$$\frac{1}{k+1} = \frac{1}{\gamma_0^2} + \frac{16(1-\lambda)V\beta_0^3 E_0 c}{\omega(\Delta E)^2}\frac{2\pi R}{L_0}$$

  - This is not so much larger than existing designs
- This requires many cells (about 180):

$$n \approx 2\pi\sqrt{\frac{k}{\cos\mu_y - \cos\mu_x}} > 2\pi\sqrt{\frac{k}{2}}$$

  - Gradient must be maintained over cells, so very few turns (2.3 GV RF for 10–20 GeV)
- Basically forced to low frequency

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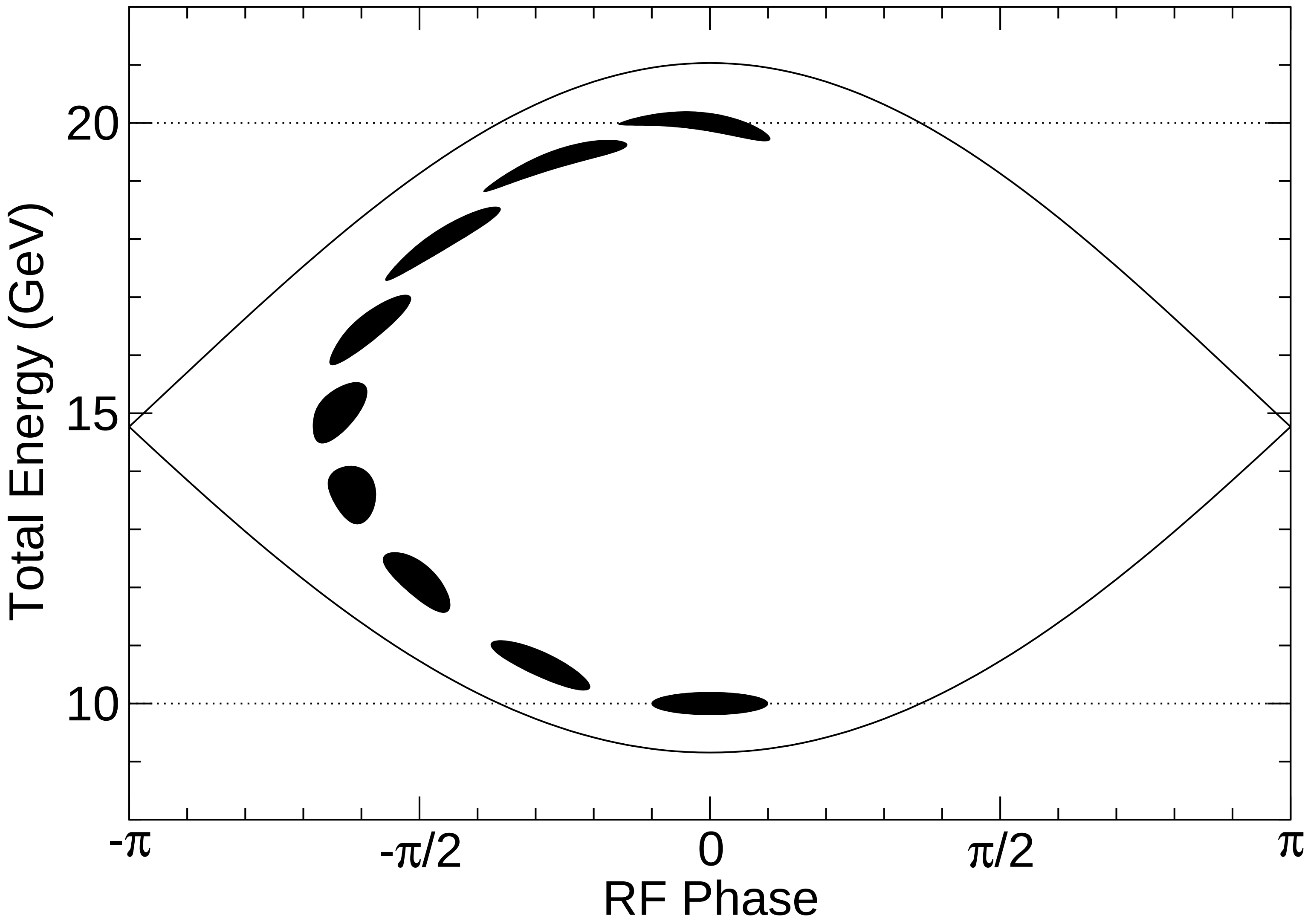
Fixed-Frequency Acceleration in Scaling FFAG

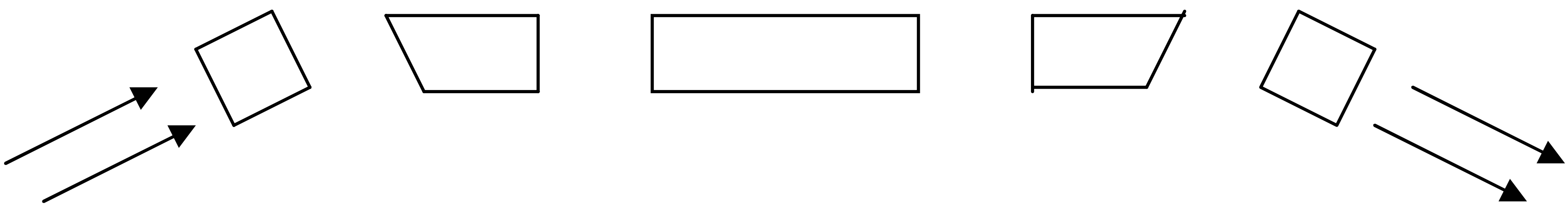


Isochronous FFAGs

- Make time of flight independent of energy
  - Time of flight does not give a minimum amount of RF
- Highly nonlinear fields required
- Tunes depend on energy
- Result: poor dynamic aperture (for muons): $<$ 1000 mm mrad normalized
  - Even have significant losses with these beam sizes
- Plans to address this by correcting chromaticity using two cell types

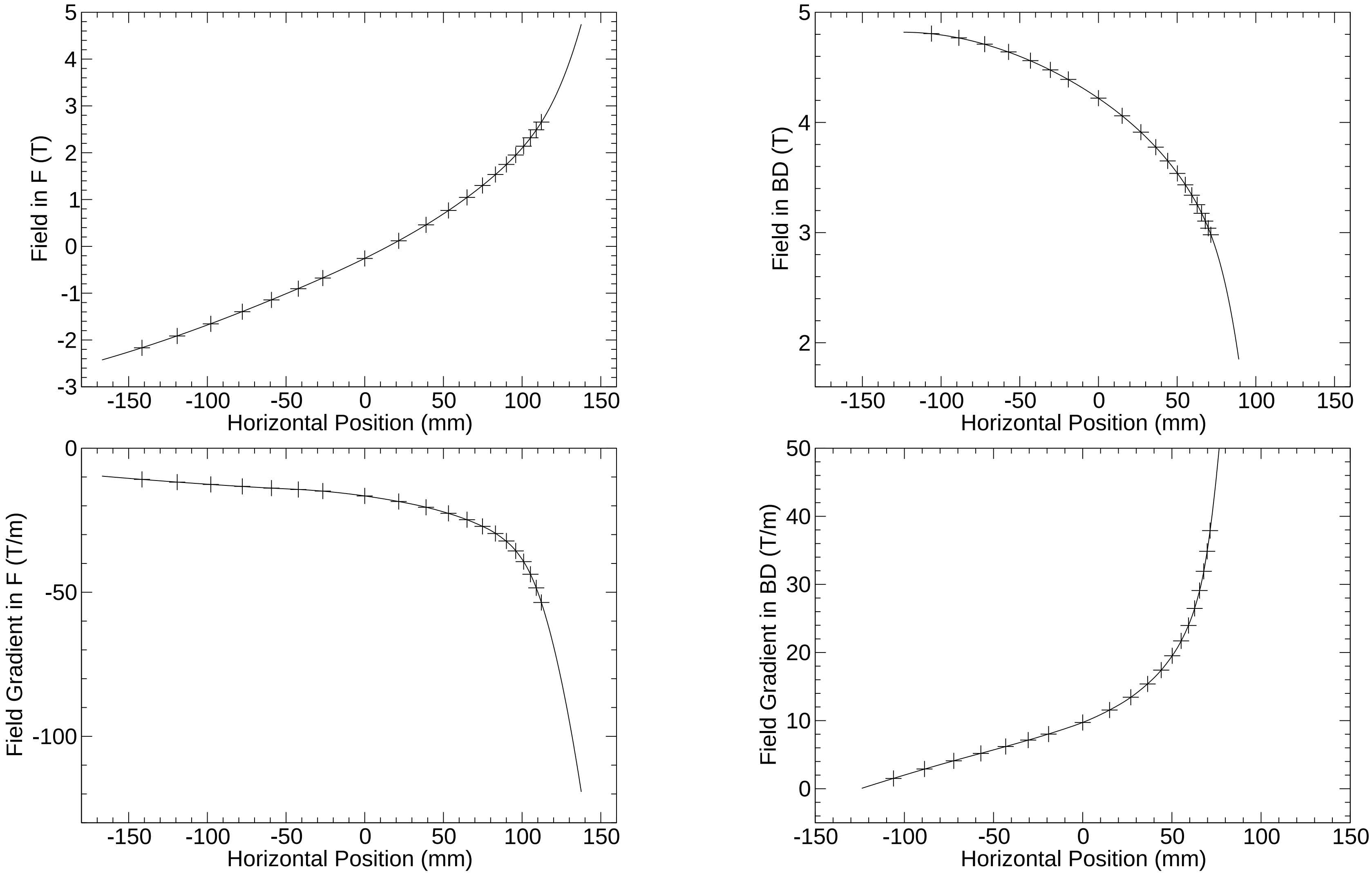
5-Cell Lattice

O bd(-) o F(±) o BD(+) o F(±) o bd(-) O

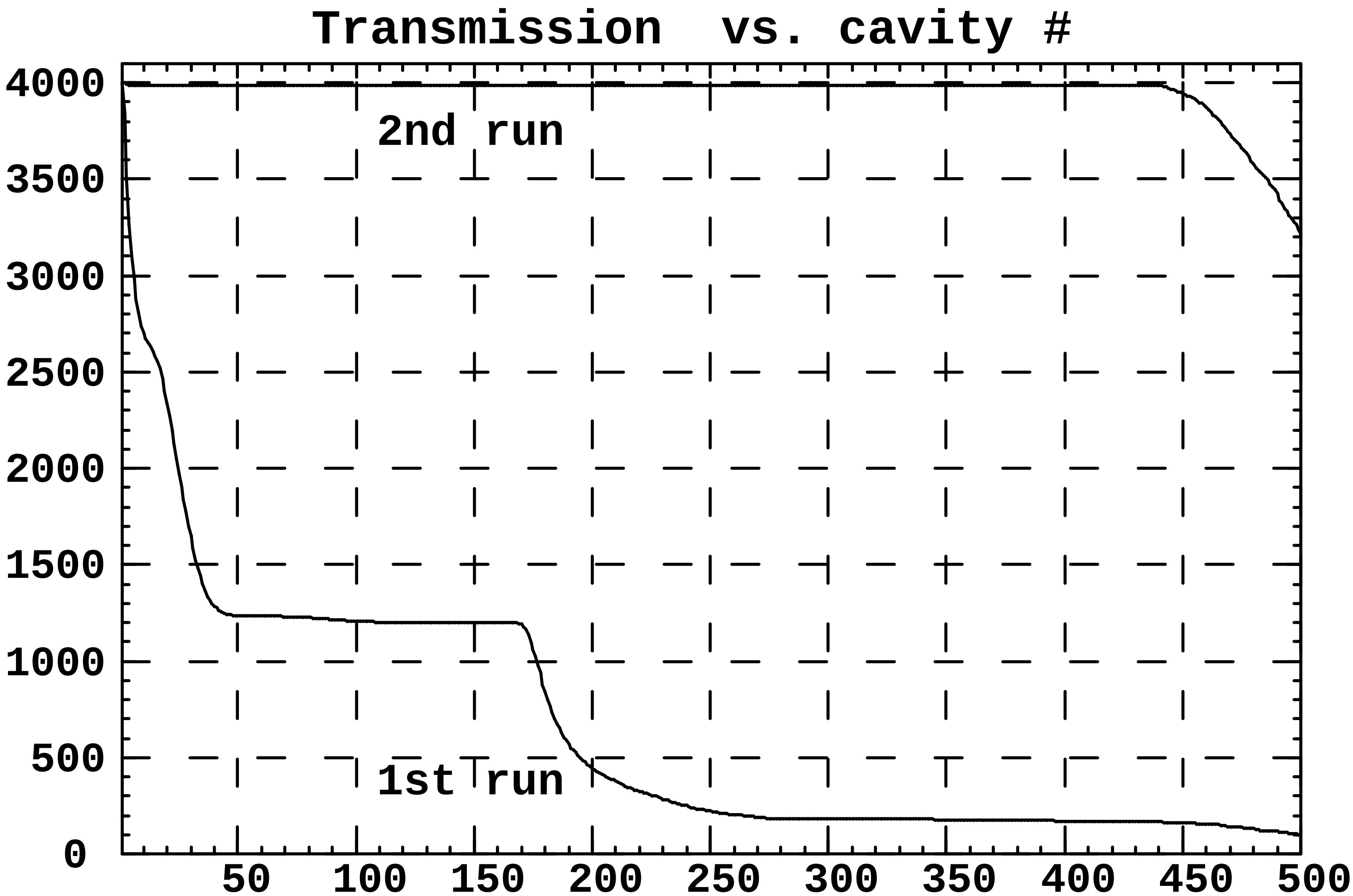


2.4 0.45 0.5 0.62 0.5 1.26 0.5 0.62 0.5 0.45 2.4 m

Field Fits for Isochronous FFAG



Isochronous FFAGs
Particle Transmission



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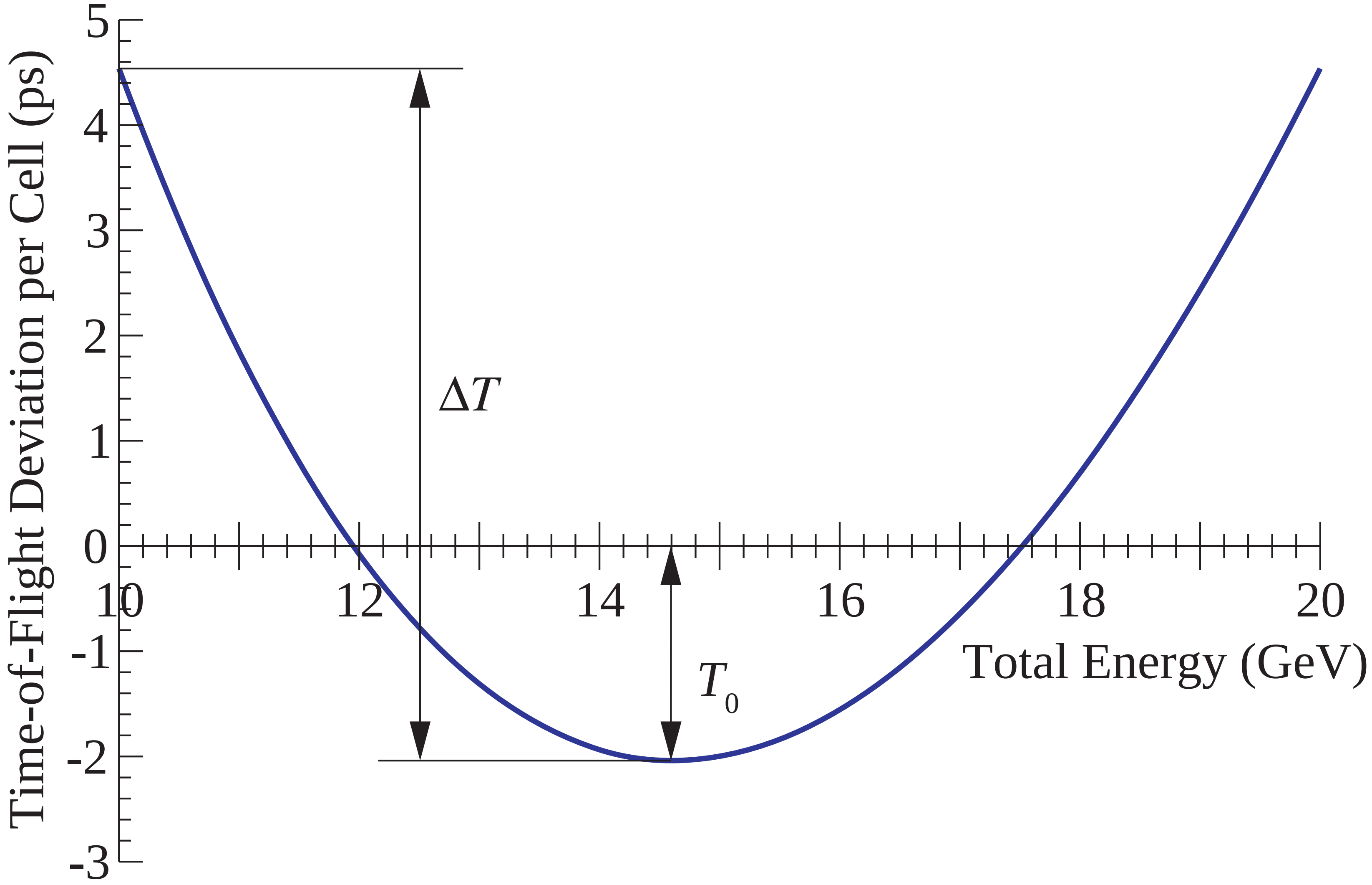
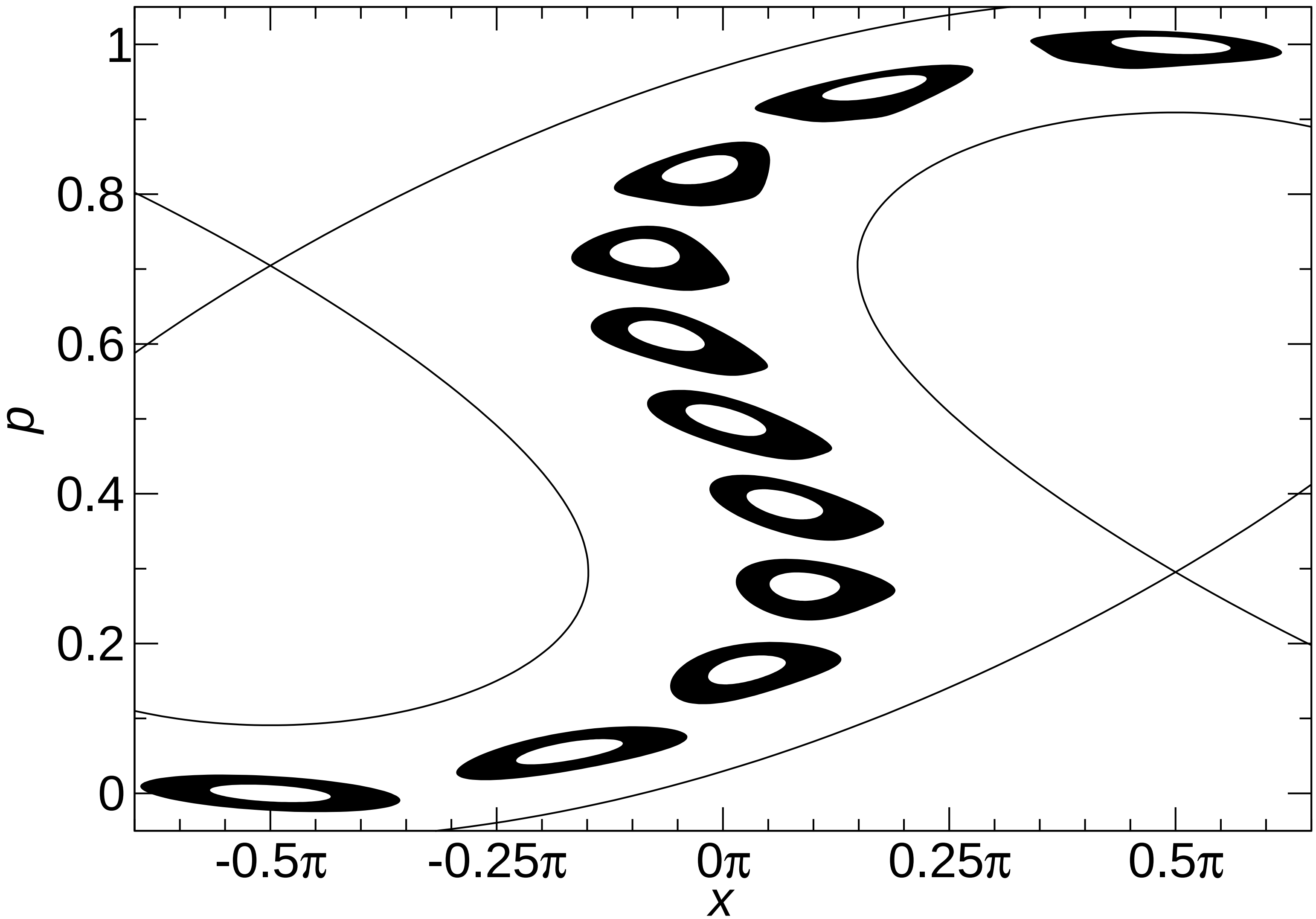
Linear Non-Scaling FFAGs

- Allow the tune to vary. Doesn’t hurt dynamic aperture because:
  - Use linear magnets; resonances not driven strongly
  - Keep every cell the same: only single-cell behavior matters
  - Accelerate rapidly through any (weak) resonance
- Have relatively (for FFAGs) small apertures: lower cost
- Keep time of flight range small by making isochronous within energy range
  - Time of flight is parabolic function of energy
  - Allows the use of high frequency RF
  - Unique “gutter acceleration” mode

Time of Flight



Tracking in Linear Non-Scaling FFAGs
Longitudinal Phase Space Channel



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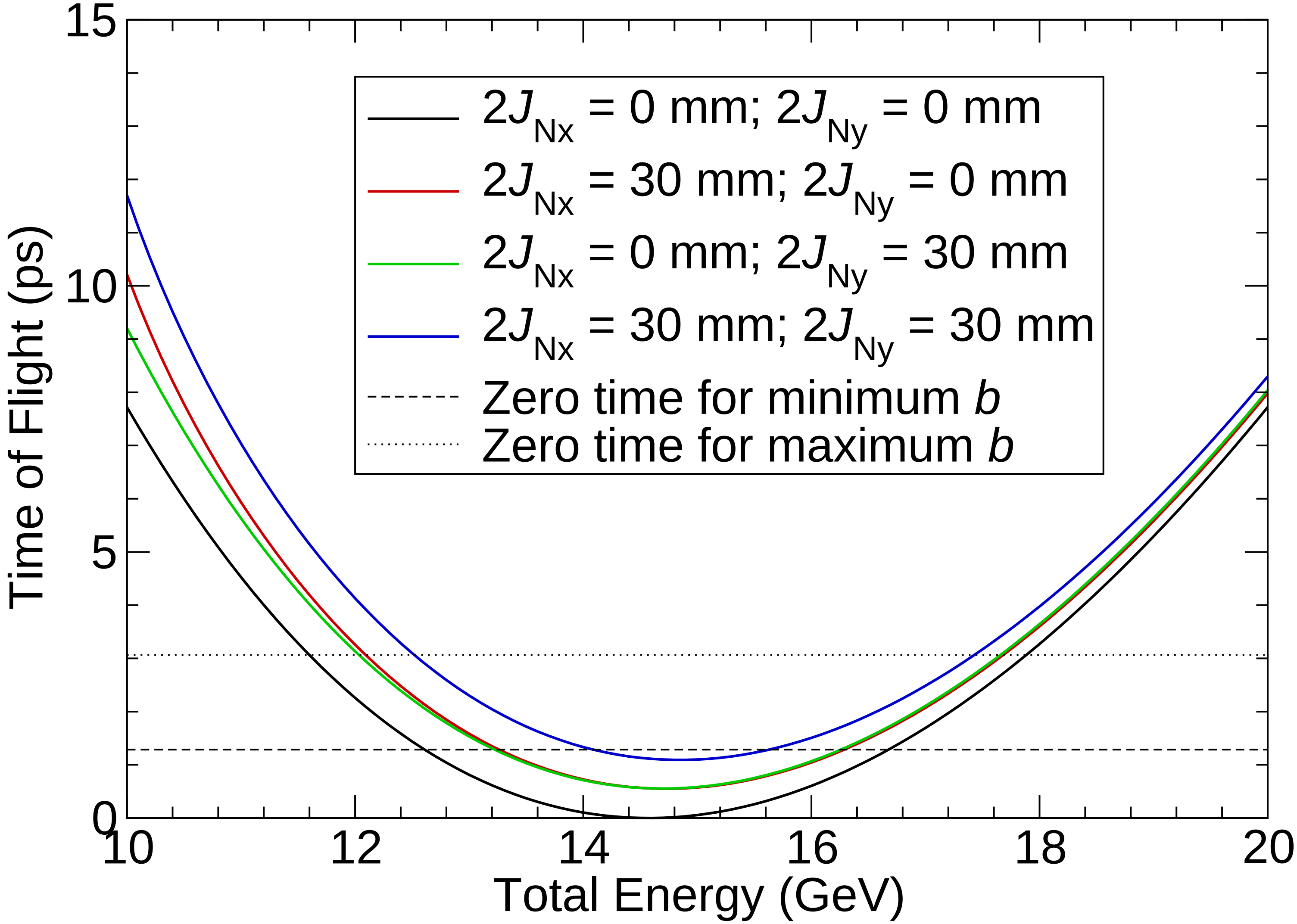
Linear Non-Scaling FFAGs
Time of Flight Dependence on Transverse Amplitude

- Problem with time of flight depending on transverse amplitude

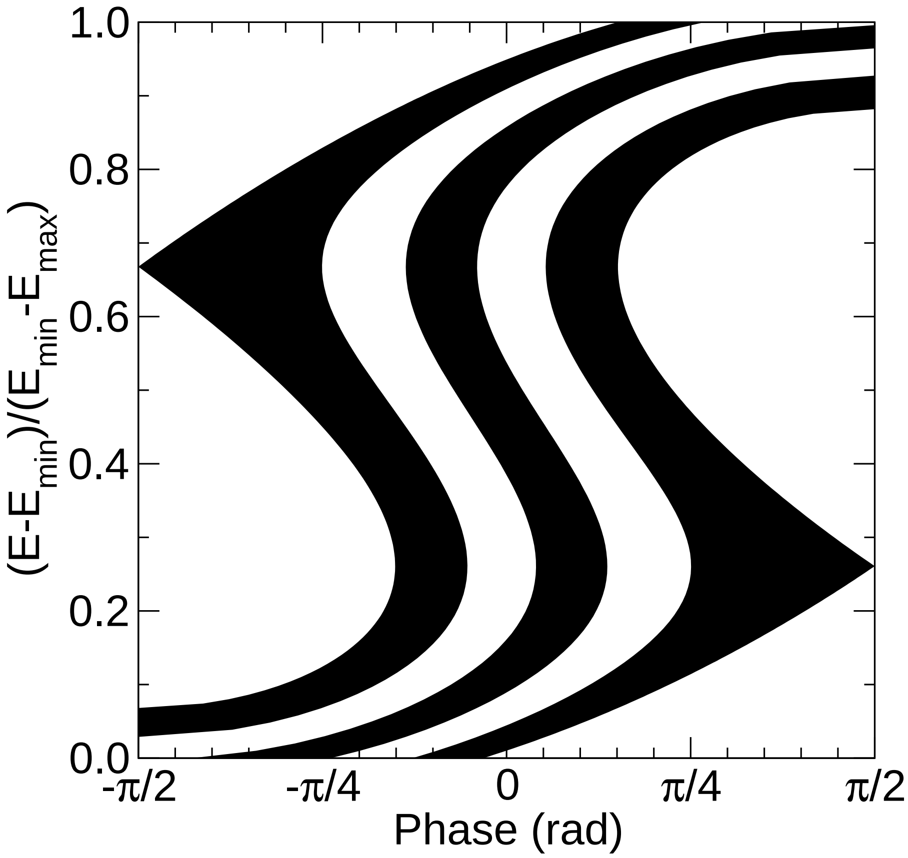
$$T = T_0(E) - 2\pi mc\frac{d\nu}{dE}J_n$$

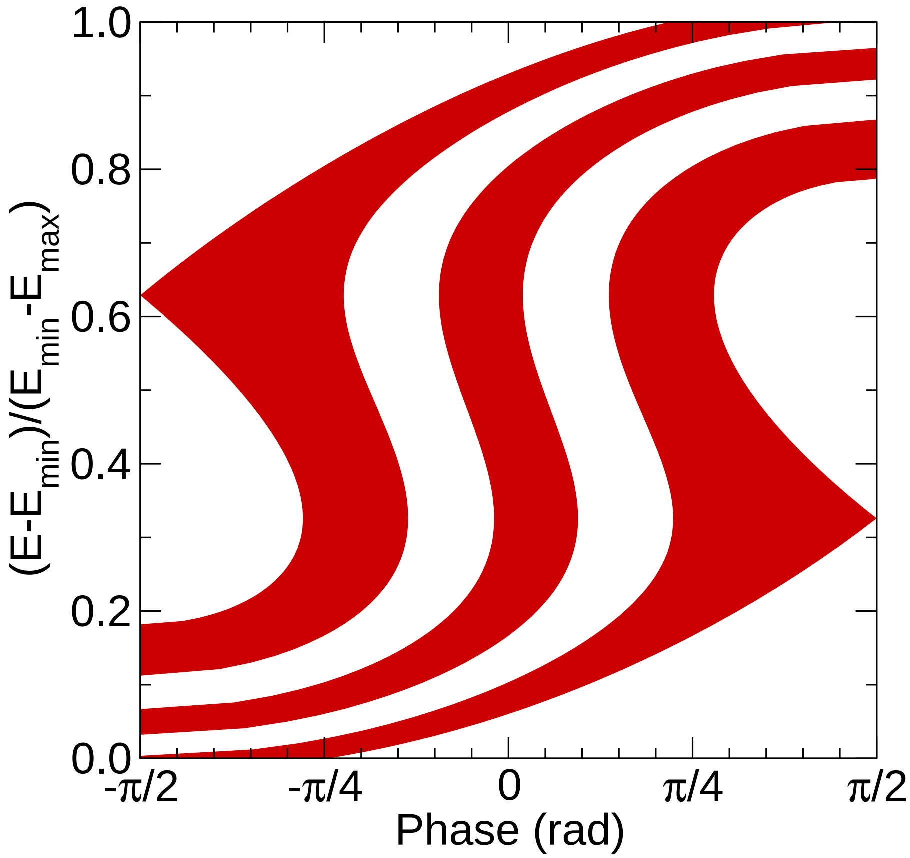
- High amplitude particles take longer than low amplitude
- Need to insure that RF is synchronized for both low and high amplitude
  - Limits range of allowed RF frequencies (b)
  - Must increase voltage (a) to be able to accelerate all amplitudes to full energy
- Passing to next stage a problem: larger time spread, high ampliutde start late

Time of Flight vs. Amplitude

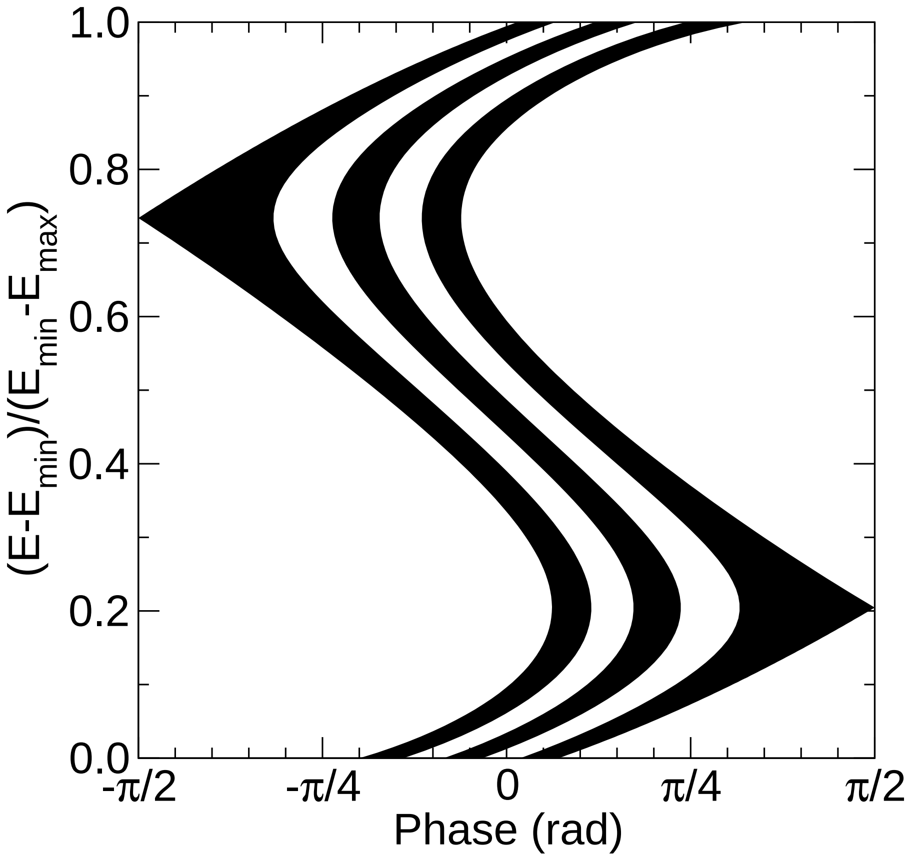


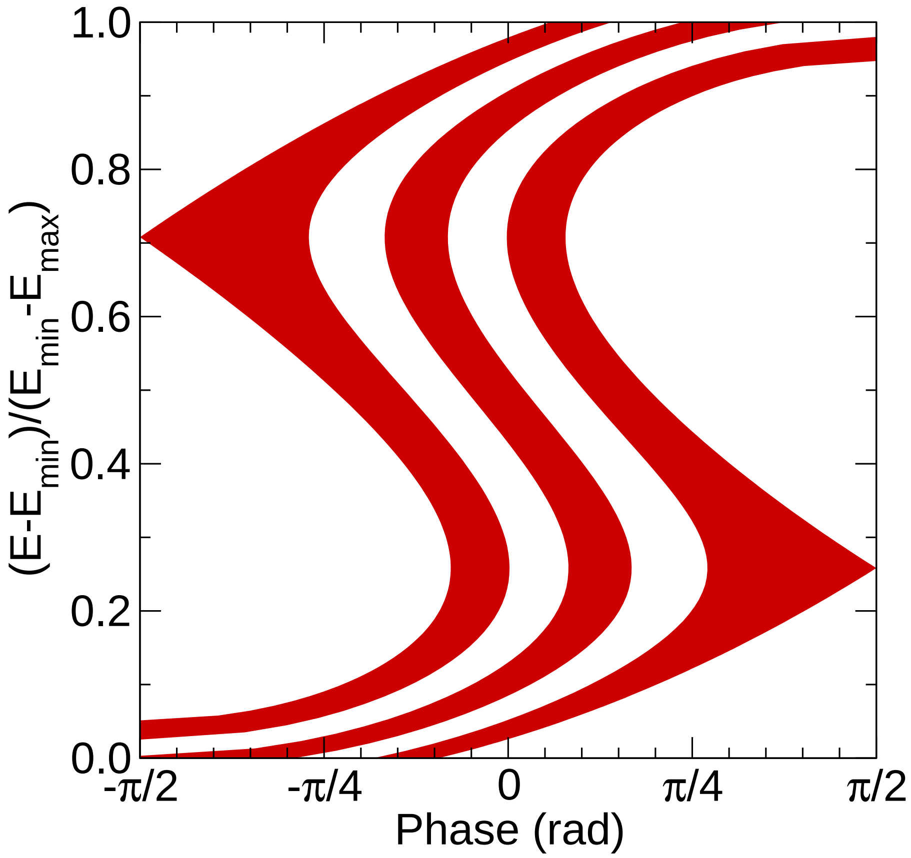
Longitudinal Phase Space
Baseline



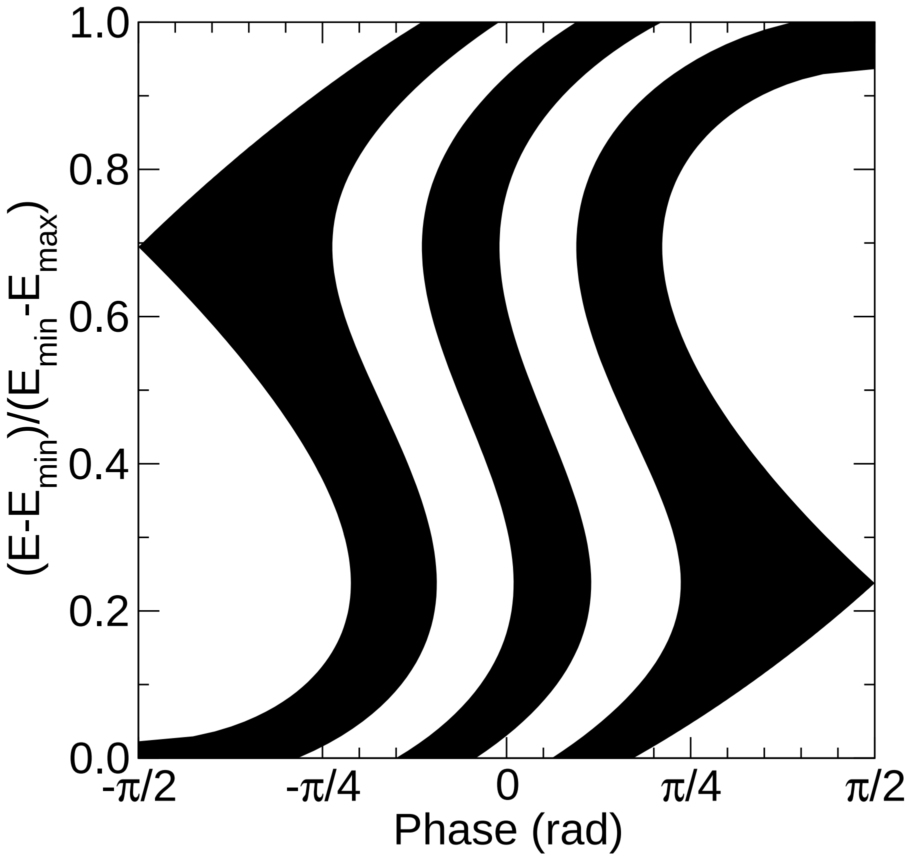


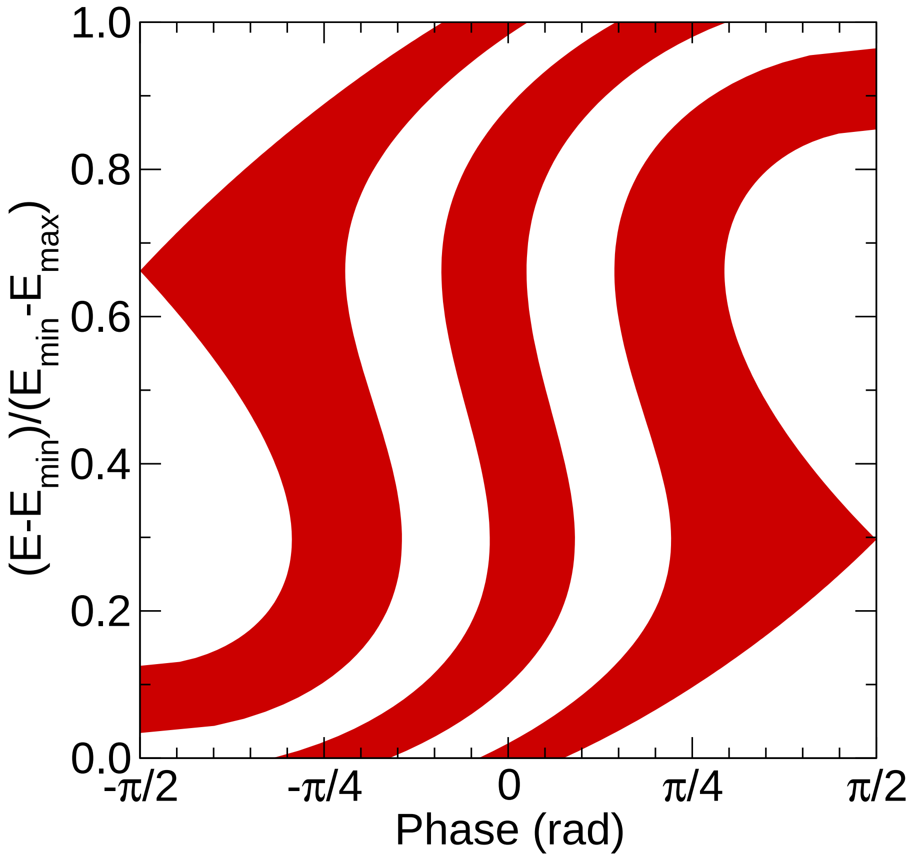
Longitudinal Phase Space
Increased b





Longitudinal Phase Space
Increased Voltage





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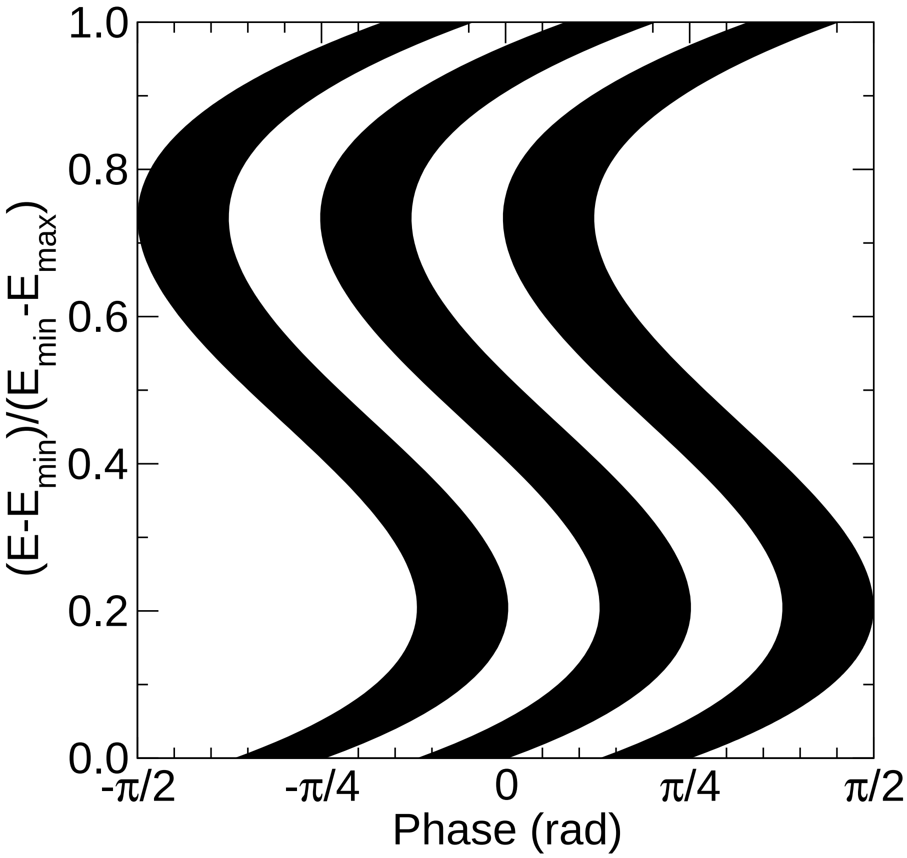
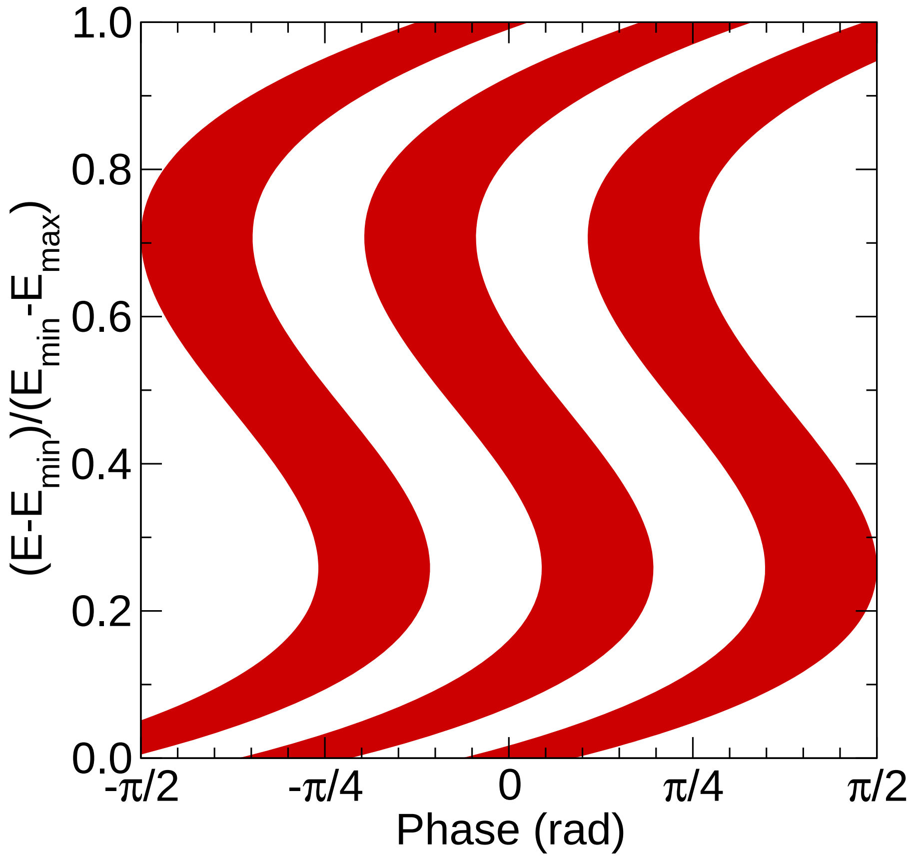
Linear non-scaling FFAGs
Addressing Problems

- Reducing time of flight range alone will ***not*** improve this effect
  - Phase space improves for low amplitude
  - High amplitude gets worse: more cells per turn
- Introduce small nonlinearities to correct chromaticity
  - Initial attempts don't do so well
- Time slip simply proportional to number of cells we go through
  - Fill maximum number of cells with RF
  - Make fewer turns: more voltage
- Introduce higher harmonic RF
  - Reduces energy spread correlated to different times of flight
  - Increases time of flight range that is accelerated
- Only promise ellipsiodal distribution transmitted: large longitudinal amplitude, low transverse amplitude

Longitudinal Phase Space
Square Wave RF





Concluding Observations

- Isochronous FFAGs, like all highly nonlinear non-scaling FFAGs studied so far, seem to have transverse dynamic aperture problems for large muon emittances
- Scaling FFAGs currently showing poorer performance and higher cost than other solutions
  - A significant optimization effort may help this
  - Cannot overcome being forced to use lower RF frequencies
- Linear non-scaling FFAGs must address the dependence of time of flight on transverse amplitude
  - We have several methods to attack the problem, and we will probably need to employ them all
  - Costs will be higher than originally envisioned
  - May lead us to avoid using FFAGs at lower energies where they are less efficient