Increasing Average RF Gradient in FFAGs
Harmonic Number Jump Acceleration

J. Scott Berg
Brookhaven National Laboratory
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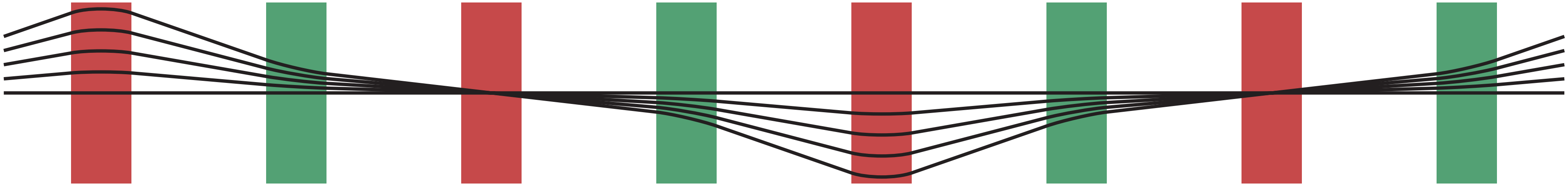
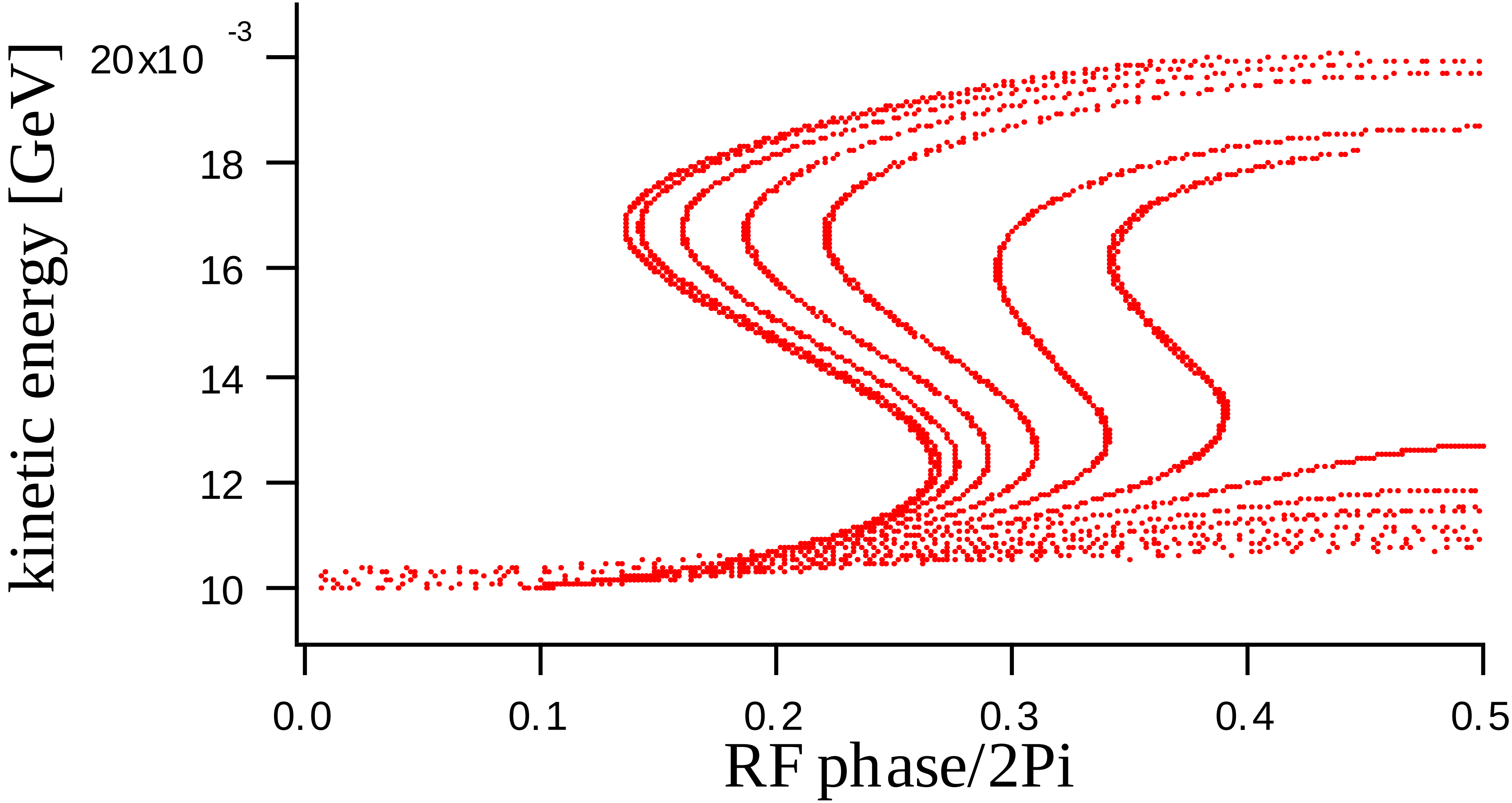
Time of Flight Dependence on Transverse Amplitude: Description of the Problem

- Particles with large transverse amplitudes aren't accelerated
- Time of flight depends on transverse amplitude
- Reason: larger amplitudes, angles make longer path length



Acceleration of Particle
Different Transverse Amplitudes (Machida)



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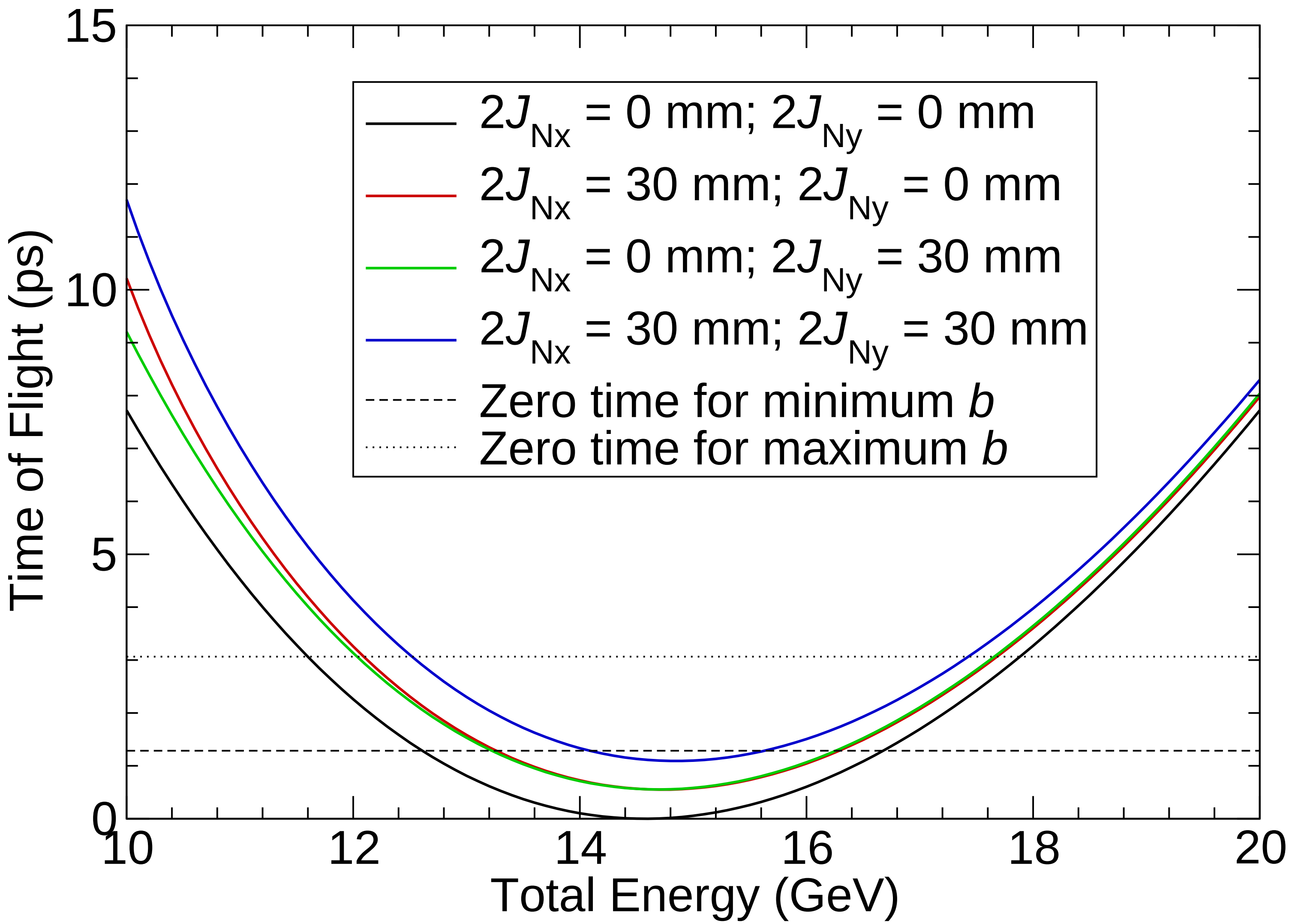
Effect on Linear Non-Scaling FFAGs

- Different times of flight for different amplitudes create acceleration problems in FFAGs
- Small range of phase space that is accelerated at all amplitudes
- Low amplitude and high amplitude particles accelerated in different channels
- Particles start out together, end up spread out in time
- Different paths require different number of cells to complete: energy spread

Time of Flight Depends on Transverse Amplitude



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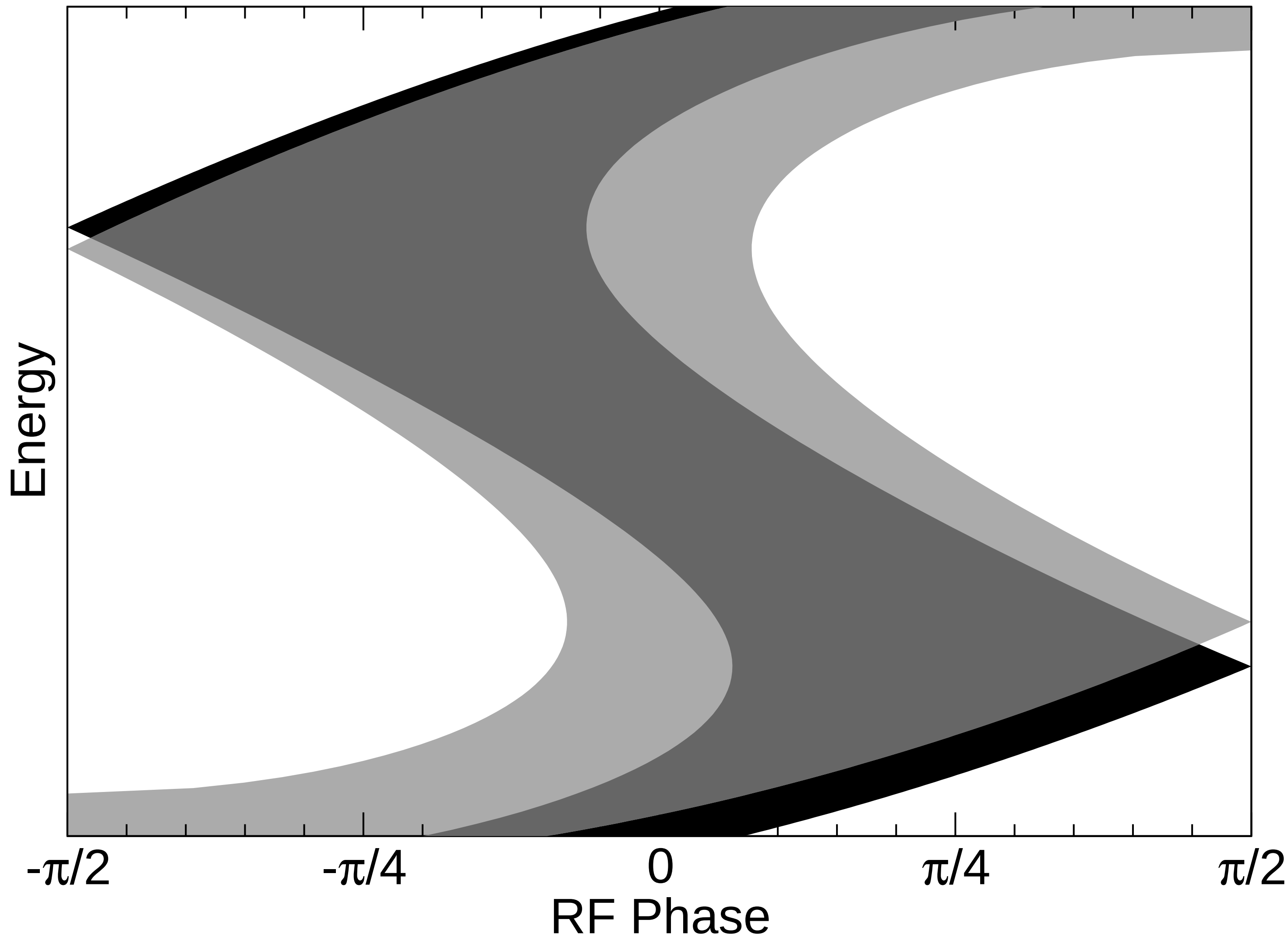
Acceleration Channels in FFAGs



Theory

- Time of flight dependence on amplitude related to chromaticity

$$\frac{d\bar{t}}{ds} = -\partial_E H_T - \frac{2\pi(\partial_E \boldsymbol{\nu}) \cdot \boldsymbol{J}_n}{L} + O(\boldsymbol{J}_n^{3/2}).$$

  - $\boldsymbol{J}_n$ is normalized transverse amplitude (in eV-s)
  - $\boldsymbol{\nu}$ is tune in cell of length L
- Time of flight difference at end for uniform acceleration

$$-2\pi\Delta\boldsymbol{\nu} \cdot \boldsymbol{J}_n/(\Delta E)$$

  - $\Delta\boldsymbol{\nu}$ is tune difference from beginning to end of acceleration, per cell
  - ΔE is energy gain per cell

Addressing the Problem

- Time of flight difference: $-2\pi\Delta\boldsymbol{\nu}\cdot\boldsymbol{J}_n/(\Delta E)$
- Reduce tune range during acceleration
- Increase energy gain per cell
  - More cavities per cell
- Add higher harmonic RF

Increasing Energy Gain per Cell

- Previous baseline had left many cells empty
  - Making the ring longer reduced its aperture and fields, reducing magnet costs
  - Filling every cell with cavities would be very expensive, and decay cost didn't justify this
- Now we want to increase average gradient as much as practical
  - Fill every cell with single-cell cavities
  - Instead, use two-cell cavities to get even more gradient
    - Requires longer drifts

More Energy Gain per Cell
Lattice Parameters

Energy (GeV)	6.25–12.5			12.5–25		
Method	Empty	1/Cell	2/Cell	Empty	1/Cell	2/Cell
Cells	69	61	50	93	78	63
Cavities	48	55	44	58	72	57
Turns	10.8	9.3	5.8	18.2	14.6	9.2
Cost	80.7	82.3	116.8	95.0	98.7	140.2
ΔE/cell (MV)	8.7	11.5	22.4	7.9	11.7	23.0

- Cost reduced to account for fewer decays
- Filling every cell with cavities gives substantial increase in voltage per cell for very little cost
- Two cavities per cell gives even voltage per cell, but at a substantial increase in cost
- FODO with 2 single cell cavities slightly better than 2/cell doublet

Other Techniques
Higher Harmonic Cavities

- Don't attack the time of flight problem directly
- Instead reduce some of its ill effects
  - Increase region of phase space successfully accelerated
  - Reduce energy spread
  - Reduces ellipse distortion
- Higher harmonic cavities have less stored energy than main cavities
  - Could be problem when there are many turns
  - Lower fill times may allow use of NC cavities in multiple-train schemes
- Will reduce average gradient from main cavities

The Overall Plan

- Add some chromaticity correction, as much as dynamic aperture will tolerate.
- Fill every cell with cavities. Probably use two cells per cavity.
- Study higher harmonic RF
  - Seems to help substantially
  - May have practical concerns
- Make the best use of what we have: set up machine parameters and initial conditions optimally

Time of Flight Dependence on Energy

- In FFAGs, Time of Flight Depends on Energy
- If RF frequency stays constant during acceleration, particles will arrive at different phases each turn
- Classic solution: vary RF frequency during acceleration
- Problem in muon acceleration: can't vary frequency fast enough
- One solution: use nearly isochronous non-scaling FFAG

Scaling FFAG

- Problems with time of flight dependence on transverse amplitude
- At lower energies, linear non-scaling FFAGs don’t look cost effective
- Solution: scaling FFAGs (Mori)
  - Have no chromaticity, so no time of flight dependence on transverse amplitude
  - Lower energies, use warm magnets, don’t worry about aperture so much
- Problem: these are highly non-isochronous
  - Not isochronous enough to use high-frequency RF
  - Forced to low frequency RF, not practical

Harmonic Number Jump

- Originally proposed by Kolomenskii for microtrons, resurrected by Ruggiero for FFAGs
- If on each turn, time of flight varies by integer number of RF periods, still arrive at same phase
- Works fine if only one cavity in the ring
- Need to fill the ring with cavities for muon acceleration
- When there are cavities all around the ring, can we meet the harmonic number jump condition everywhere?
  - The answer is no
  - But how good can we do?

Basic Equations

- We have a number of cavities at position θ_k in the ring, with maximum energy gain V_k, frequency f_k, and phase ϕ_k.
- The revolution time as a function of energy is given by $T(E)$
- We can write equations of motion for time t and energy E

$$\frac{dt}{d\theta} = \frac{T(E)}{2\pi} \qquad \frac{dE}{d\theta} = V(\theta)\cos\bigl(2\pi f(\theta)t + \phi(\theta)\bigr)$$

$$V(\theta) = \sum_k V_k \delta_{2\pi}(\theta - \theta_k) \qquad \delta_{2\pi}(\theta) = \sum_m \delta\bigl(\theta - 2\pi m\bigr)$$

$$f(\theta_k) = f_k \qquad \phi(\theta_k) = \phi_k$$

Single Cavity

- Single cavity located at $\theta_0 = \pi$
- We want to arrive at the cavity with the same phase each time

$$E(2\pi k) = E(0) + kV_0 \cos\phi_0 = E(0) + k\Delta E$$

$$t(2\pi k + \pi) = \sum_k T\bigl(E(0) + k\Delta E\bigr) - \frac{1}{2}T\bigl(E(0)\bigr)$$

- To have the same arrival phase each time

$$fT\bigl(E(0) + k\Delta E\bigr) = h_k$$

h_k an integer

- $T(E)$ linear in E: $T(E) = T\bigl(E(0)\bigr) + \Delta T[E - E(0)]/\Delta E$
- Thus $f\bigl[T\bigl(E(0)\bigr) + k\Delta T\bigr] = h_k$
- Harmonic number jump condition: $f\Delta T = m$, m an integer

Cavities Everywhere

- Energy gain distributed uniformly

$$E(\theta) = E(0) + \Delta E \frac{\theta}{2\pi}$$

- Assuming time depends linearly on energy,

$$t(\theta) = t(0) + T\bigl(E(0)\bigr)\frac{\theta}{2\pi} + \frac{\Delta T}{2}\left(\frac{\theta}{2\pi}\right)^2$$

- We want to come back to the same phase on each turn

$$f(\theta)[t(\theta + 2\pi) - t(\theta)] = f(\theta)\left[T\bigl(E(0)\bigr) + \frac{\Delta T}{2} + \Delta T\frac{\theta}{2\pi}\right] = h(\theta)$$

$h(\theta)$ is an integer

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Cavities Everywhere
Mathematical Contradictions

- Can compute the cavity frequencies:

$$f(\theta) = \frac{h(\theta)}{T\bigl(E(0)\bigr) + \frac{\Delta T}{2} + \Delta T \frac{\theta}{2\pi}}$$

- Harmonic number jump condition

$$h(\theta + 2\pi) - h(\theta) = f(\theta)\Delta T = m$$

- Combining these

$$\frac{m}{\Delta T} = \frac{h(\theta)}{T\bigl(E(0)\bigr) + \frac{\Delta T}{2} + \Delta T \frac{\theta}{2\pi}}$$

Left side constant, right side is not

How Good Can We Do?
Same Frequencies

- First attempt: make all cavities have the same frequency f
- Harmonic number jump condition: $f\Delta T = m$
- Cavity at $\theta = 0$ is synchronized

$$f\left[T\big(E(0)\big) + \Delta T/2\right] = h$$

- Cavity at $\theta = \pi$, the phase difference (divided by 2π):

$$f[T\big(E(0)\big) + \Delta T] = h + m/2$$

For m odd, it is completely out of phase

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How Good Can We Do?
Get First Turn Right

- Adjust cavity frequencies to get first turn right: on $\theta \in (0, 2\pi)$,

$$f(\theta) = \frac{h(0)}{T\bigl(E(0)\bigr) + \dfrac{\Delta T}{2} + \Delta T \dfrac{\theta}{2\pi}}$$

- Now check harmonic number condition

$$h(\theta) = f(\theta)[t(\theta + 2\pi) - t(\theta)] =$$

$$h(0)\frac{T\bigl(E(0)\bigr) + \dfrac{\Delta T}{2} + \Delta T \dfrac{\theta}{2\pi}}{T\bigl(E(0)\bigr) + \dfrac{\Delta T}{2} + \Delta T \left(\dfrac{\theta}{2\pi} - \left\lfloor \dfrac{\theta}{2\pi} \right\rfloor\right)}$$

Would like this to be an integer, but it isn't for all θ

How Good Can We Do?
Get First Turn Right (cont.)

- Compute harmonic number jump condition

$$h(\theta+2\pi)-h(\theta)=\frac{h(0)\Delta T}{T\bigl(E(0)\bigr)+\dfrac{\Delta T}{2}+\Delta T\left(\dfrac{\theta}{2\pi}-\left\lfloor\dfrac{\theta}{2\pi}\right\rfloor\right)}$$

- Make this an integer when $\theta=2\pi n+\pi$

$$m=\frac{h(0)\Delta T}{T\bigl(E(0)\bigr)+\Delta T}$$

- Now write jump in terms of $h(0)$ and m

$$h(\theta+2\pi)-h(\theta)=\frac{h(0)m}{h(0)+m\left(\dfrac{\theta}{2\pi}-\left\lfloor\dfrac{\theta}{2\pi}\right\rfloor-\dfrac{1}{2}\right)}$$

How Good Can We Do? Get First Turn Right (cont.)

- Worst case error in harmonic number difference looks like

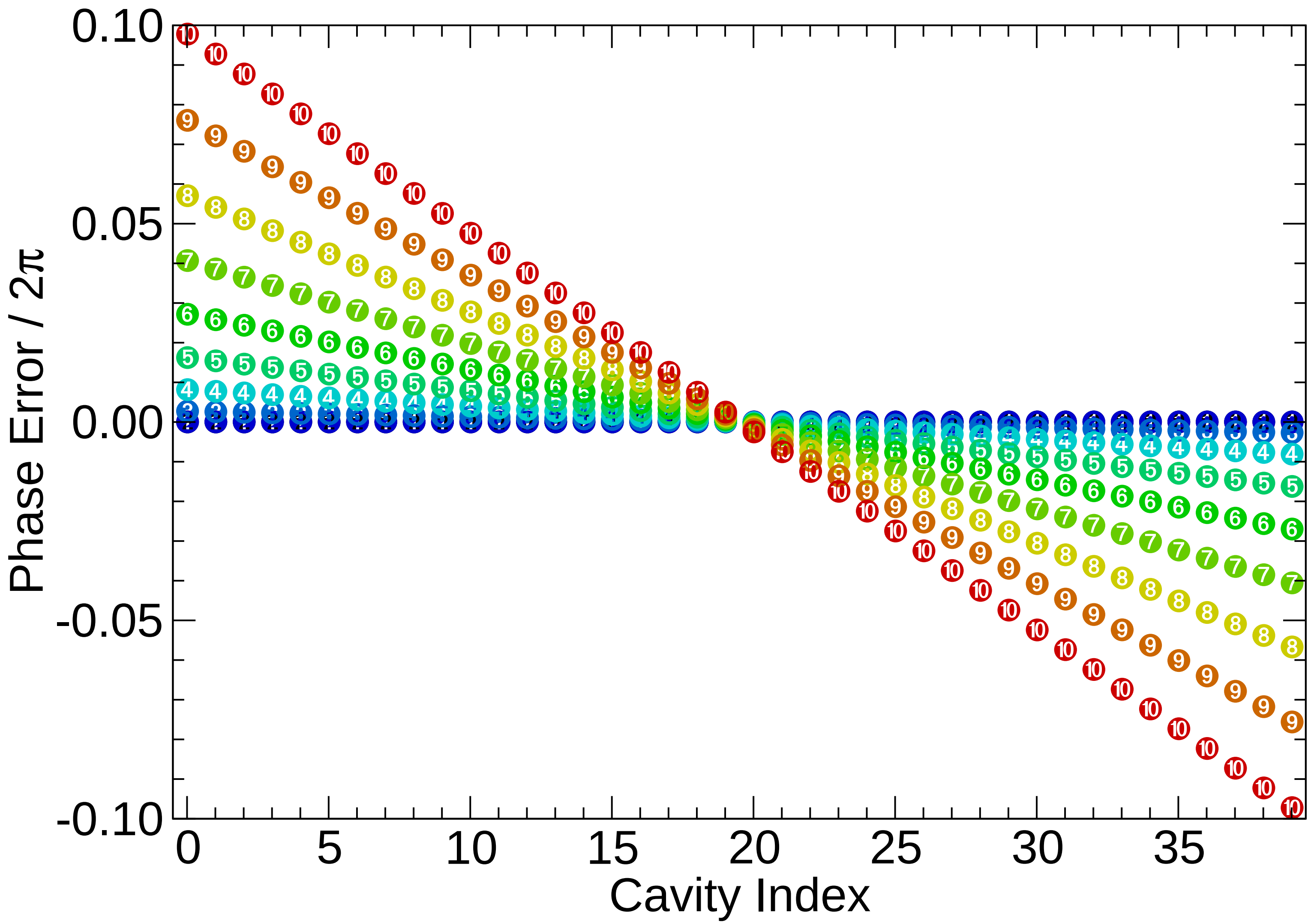
$$\frac{m^2}{2h(0) \pm m}$$

  - This is the **increase** in the **period** error on each turn
  - The phase error is the sum of the period errors
- After n turns, the worst phase error is thus

$$2\pi\frac{(n-1)(n-2)}{2}\frac{m^2}{2h(0) \pm m}$$

Approximately $\sqrt{h(0)}/m$ turns before some cavities start decelerating

Cavity Phases
Synchronized to First Turn



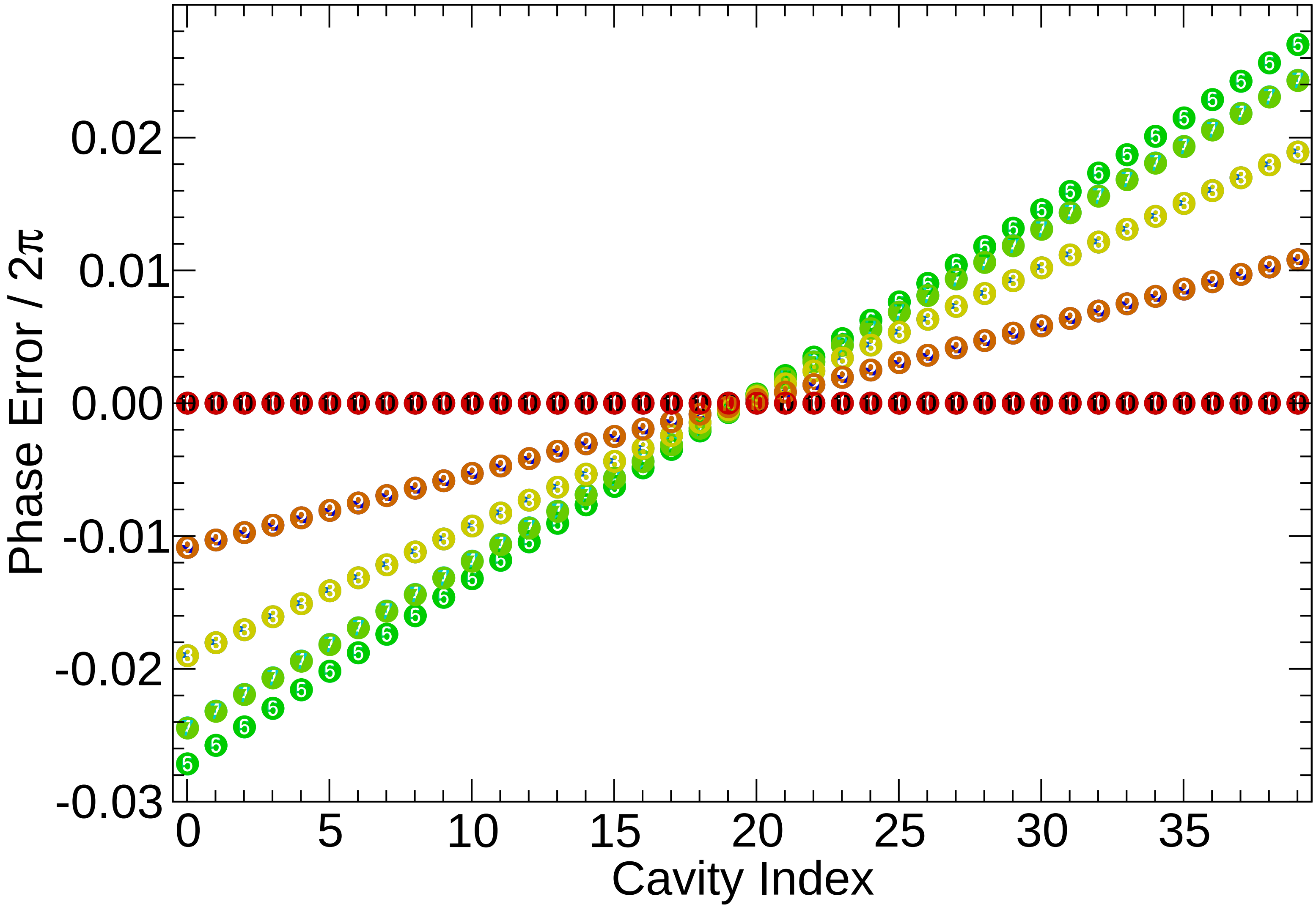
How Good Can We Do?
Get Middle Turn Right

- Follow the same procedure, but make harmonic number jump correct for central turn
- After n turns, the worst phase error is thus

$$\pi \left\lfloor \frac{n}{2} \right\rfloor \left\lfloor \frac{n-1}{2} \right\rfloor \frac{m^2}{2h(0) \pm m}$$

  - About 1/4 of the phase slip compared to getting first turn right
  - Twice as many turns possible

Cavity Phases
Synchronized to Middle Turn



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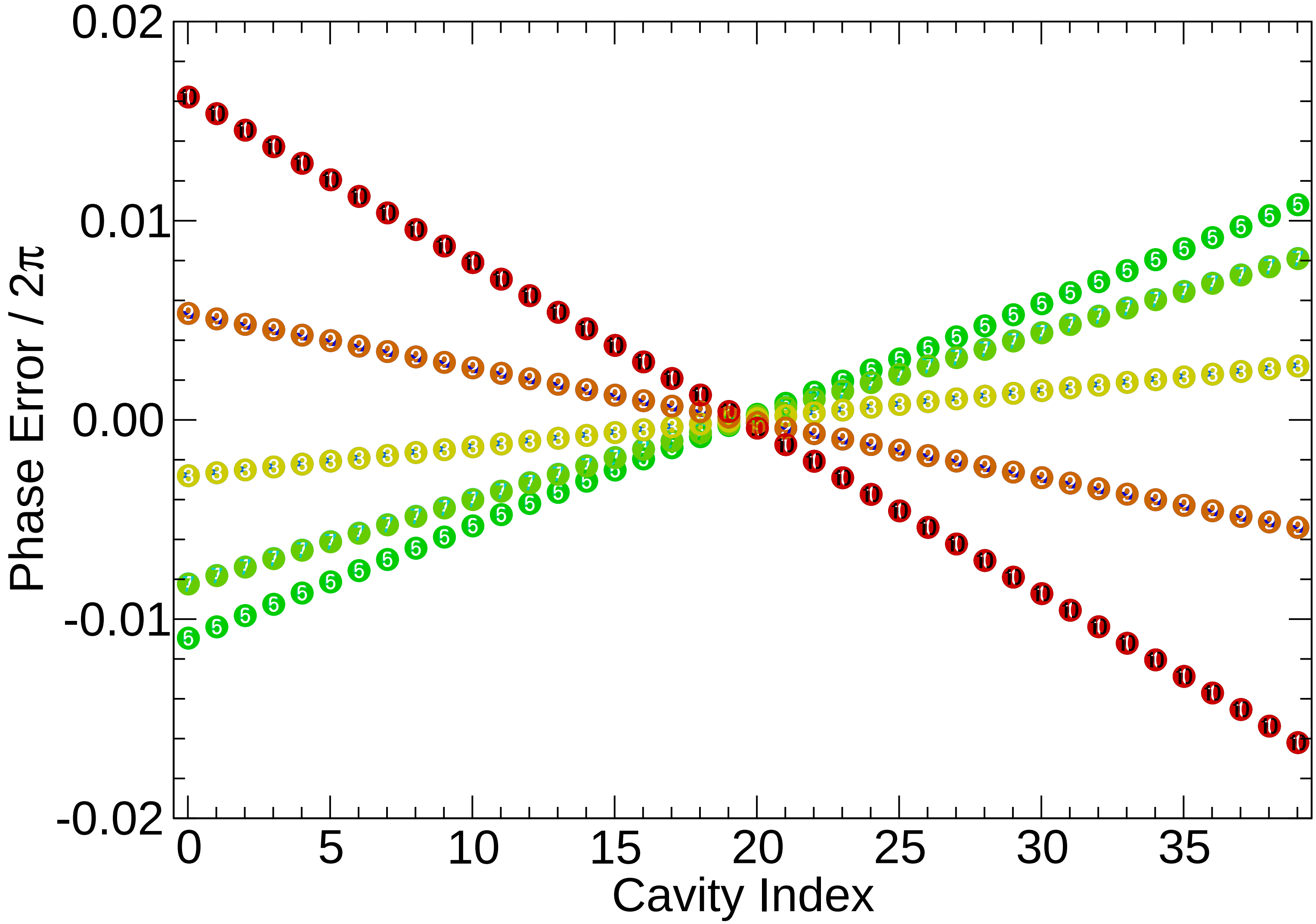
How Good Can We Do?
More Ideas

- Could make average phase slip zero at each cavity
- Note that in all cases, average phase error is zero
  - On linear RF, average effect is small
  - On crest, unsynchronized turns gain less energy
    - Exploit to vary energy gain with time?
- Note that this trick is directional
  - Won’t work for both signs

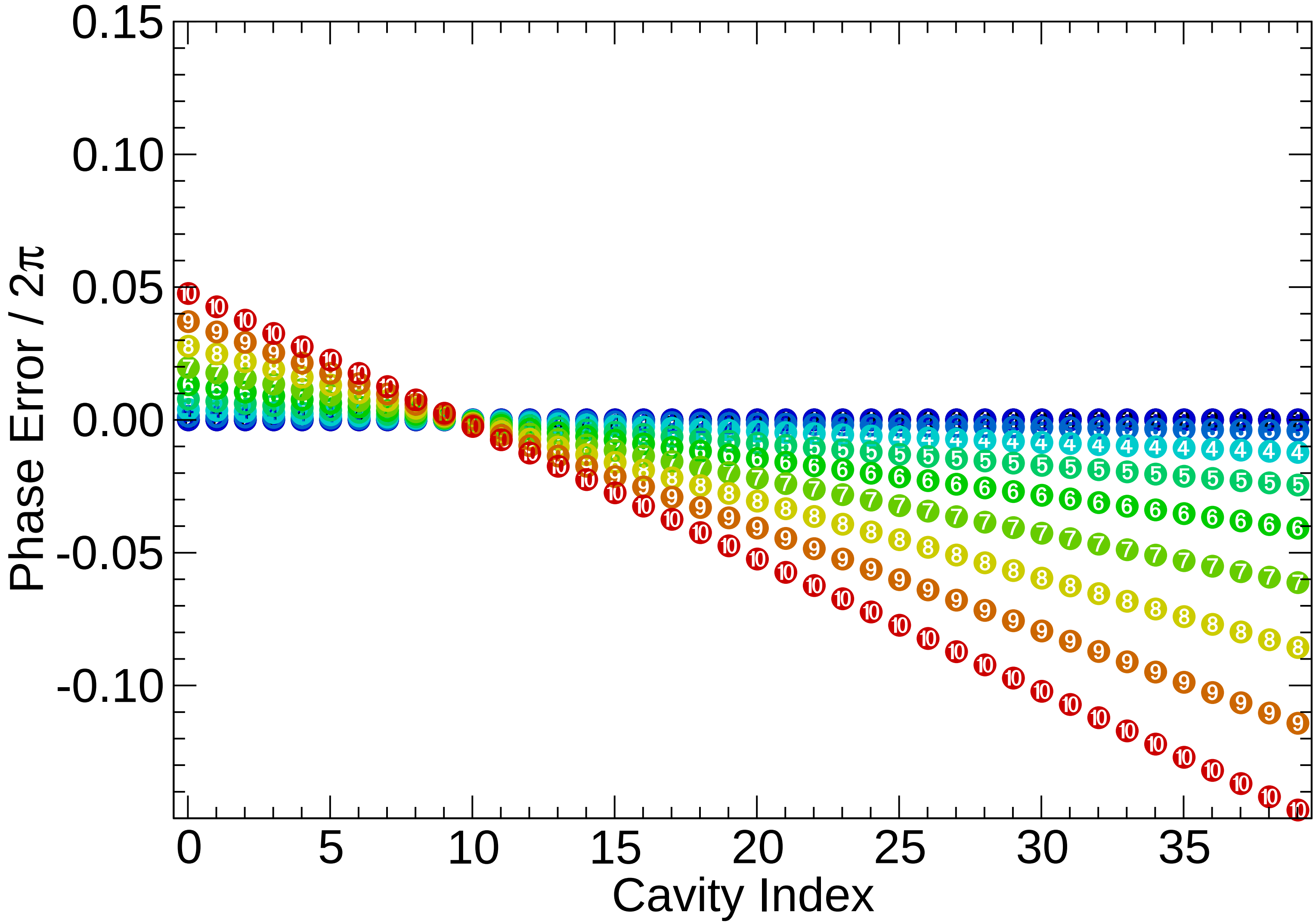
Cavity Phases
Synchronized to Middle Turn, Average Zero



Exploiting This Effect

- Time of flight is nonlinear function of energy: energy gain must vary during acceleration
- Use this to construct desired energy gain vs. time profile?
- Have three knobs
  - Which cavity is synchronized
  - Which turn has “zero” phase error
  - Which turn meets the harmonic number condition
- These control, respectively
  - The size of the average phase error on each turn
  - At a given cavity, the phase averaged over all turns
  - What phase you spend more time at, how phase varies during acceleration
- Could also use different phases or frequencies than these

Cavity Phases
Synchronized to Middle Turn, Average Zero



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Application to Non-Muon Rings

- Other rings don't need the ring filled with cavities
- However, could intentionally add additional cavities near, but not right next to, first cavity
  - May allow control of energy gain with turn number
  - If cavities too far apart, will not work for many turns

What is Lacking: the To-Do List

- No variation of energy gain with arrival time
- Time of flight must vary nonlinearly with energy
- No computation of RF bucket
- What happens with a long bunch train?

Conclusions

- When the ring is filled with cavities, the harmonic number jump conditionn cannot be satisfied, even when time of flight depends linearly on energy
- By choosing the cavity phases and frequencies correctly, one can do very well
  - Problematic for both signs
- One may even be able to exploit this to vary the energy gain with turn number
  - One may even be able to exploit this for a ring needing very few cavities
- This is a highly simplified calculation at this point, and there is more work to be done.