A Fourier Series Kicker for the TESLA Damping Rings

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LCRD 2.22

Introduction

- The TESLA damping ring fast kicker must inject/eject every n^{th} bunch, leaving adjacent bunches undisturbed.
- The minimum bunch separation inside the damping rings (which determines the size of the damping rings) is limited by the kicker design.
- We are investigating a novel extraction technique which might permit smaller bunch spacing: a "Fourier series kicker" in which a series of rf kicking cavities is used to build up the Fourier representation of a periodic δ function.
- Various issues such as finite bunch size, cavity geometry, and tune-related effects are under investigation.

Outline

Overview

- TESLA damping rings and kickers
- how a "Fourier series kicker" might work

Phasor representation of p_T and dp_T/dt

Flattening the kicker's dp_T/dt

Some of the other points:

- finite separation of the kicker elements
- timing errors at injection/extraction

Conclusions

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Illinois participants in LCRD 2.22

Guy Bresler (REU student, from Princeton)
Keri Dixon (senior thesis student, from UIUC)
George Gollin (professor)
Mike Haney (engineer, runs HEP electronics group)
Tom Junk (professor)

We benefit from good advice from people at Fermilab and Cornell. In particular: Dave Finley, Vladimir Shiltsev, Gerry Dugan, and Joe Rogers.

Overview: linac and damping ring beams

Linac beam (TESLA TDR):

•One pulse: 2820 bunches, 337 nsec spacing (five pulses/second)

•length of one pulse in linac **~300** kilometers

•Cool an entire pulse in the damping rings before linac injection

Damping ring beam (TESLA TDR):

•One pulse: 2820 bunches, ~20 nsec spacing

•length of one pulse in damping ring **~17** kilometers

•Eject every n^{th} bunch into linac (leave adjacent bunches undisturbed)

17 km damping ring circumference is set by the minimum bunch spacing in the damping ring: Kicker speed is the limiting factor.

Overview: TESLA TDR fast kicker

Fast kicker specs (à la TDR):

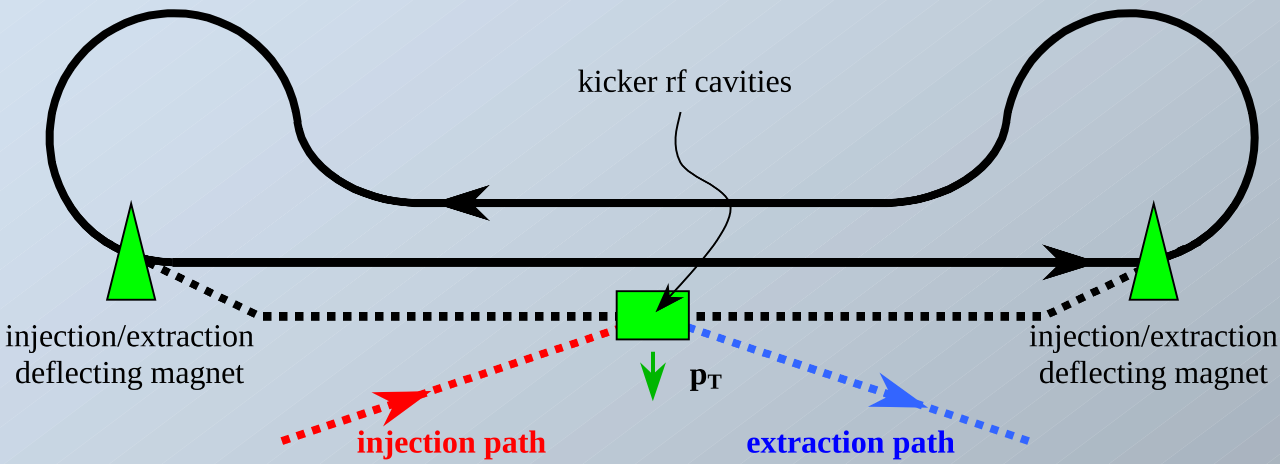
- $\int B\,dl$ = 100 Gauss-meter = 3 MeV/c
- stability/ripple/precision ~.07 Gauss-meter = 0.07%
- ability to generate, then quench a magnetic field rapidly determines the minimum achievable bunch spacing in the damping ring

TDR design: bunch "collides" with electromagnetic pulses traveling in the opposite direction inside a series of traveling wave structures.

TDR Kicker element length ~50 cm; impulse ~ 3 Gauss-meter. (Need 20-40 elements.)

Structures dump each electromagnetic pulse into a load.

Something new: a “Fourier series kicker”

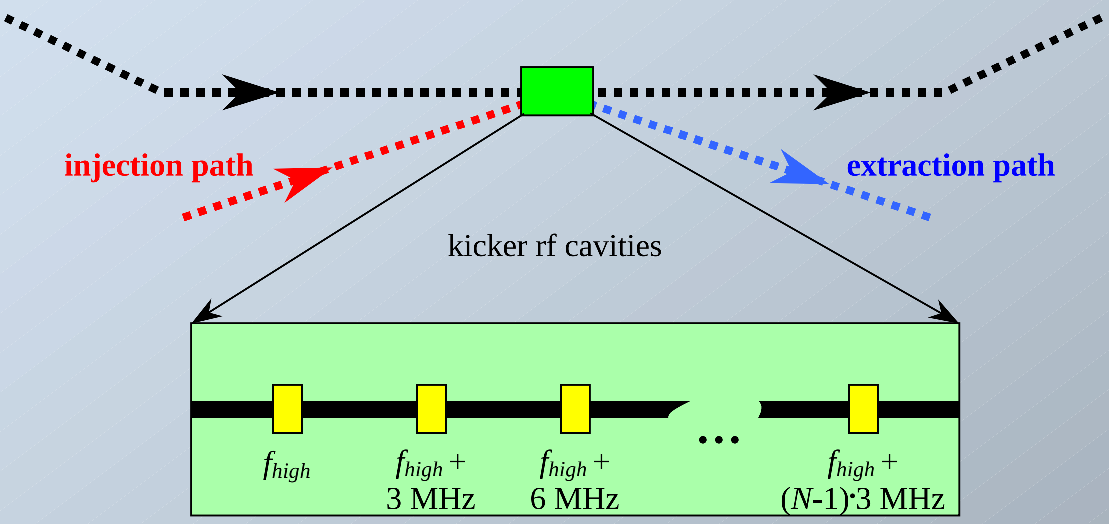


Fourier series kicker would be located in a bypass section.

While damping, beam follows the dog bone-shaped path (solid line).

During injection/extraction, deflectors route beam through bypass (straight) section. Bunches are kicked onto/off orbit by kicker.

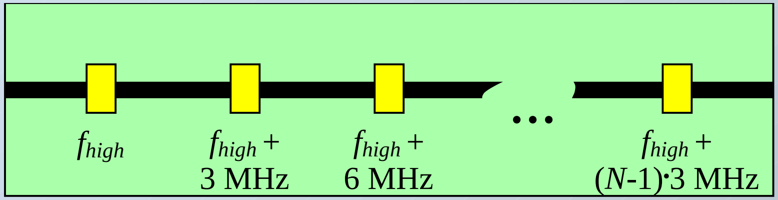
Fourier series kicker



Kicker would be a series of *N* "rf cavities" oscillating at harmonics of the linac bunch frequency 1/(337 nsec) = 2.97 MHz:

$$p_T = A\left[\sum_{j=0}^{j=N_{cavities}-1} A_j \cos\left[\left(\omega_{high} + j\omega_{low}\right)t\right]\right]; \quad \omega_{low} = \frac{2\pi}{337 \text{ ns}}$$

Fourier series kicker



Run them at 3 MHz, 6 MHz, 9 MHz,… (original idea) or perhaps at higher frequencies, with 3 MHz separation: f_{high}, f_{high}+3 MHz, f_{high}+6MHz,... (Shiltsev's suggestion)

Cavities oscillate in phase, possibly with equal amplitudes.

They are always on so fast filling/draining is not an issue.

Kick could be transverse, or longitudinal, followed by a dispersive (bend) section (Dugan's idea).

High-Q: perhaps amplitude and phase stability aren't too hard to manage?

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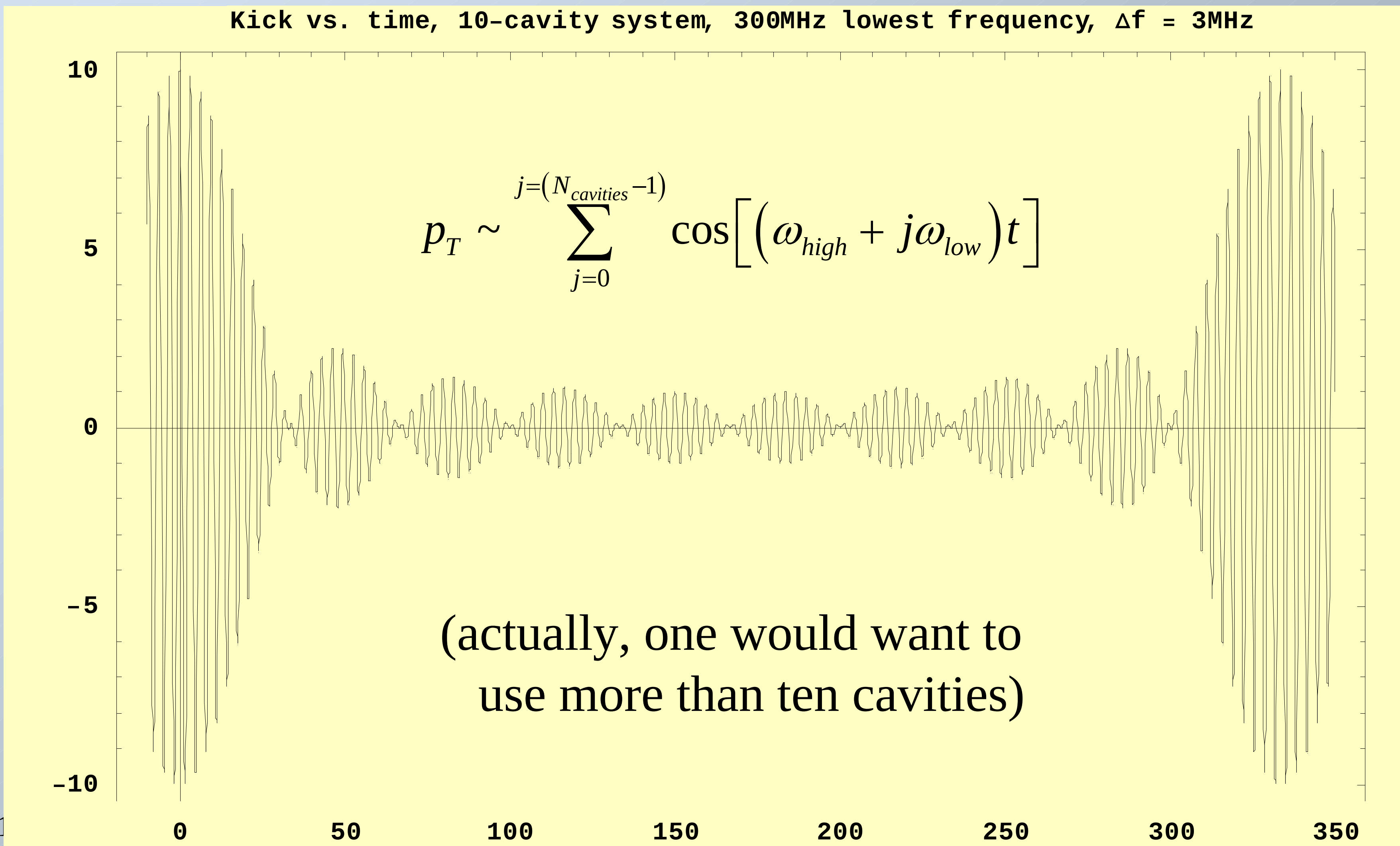
Kicker p_T

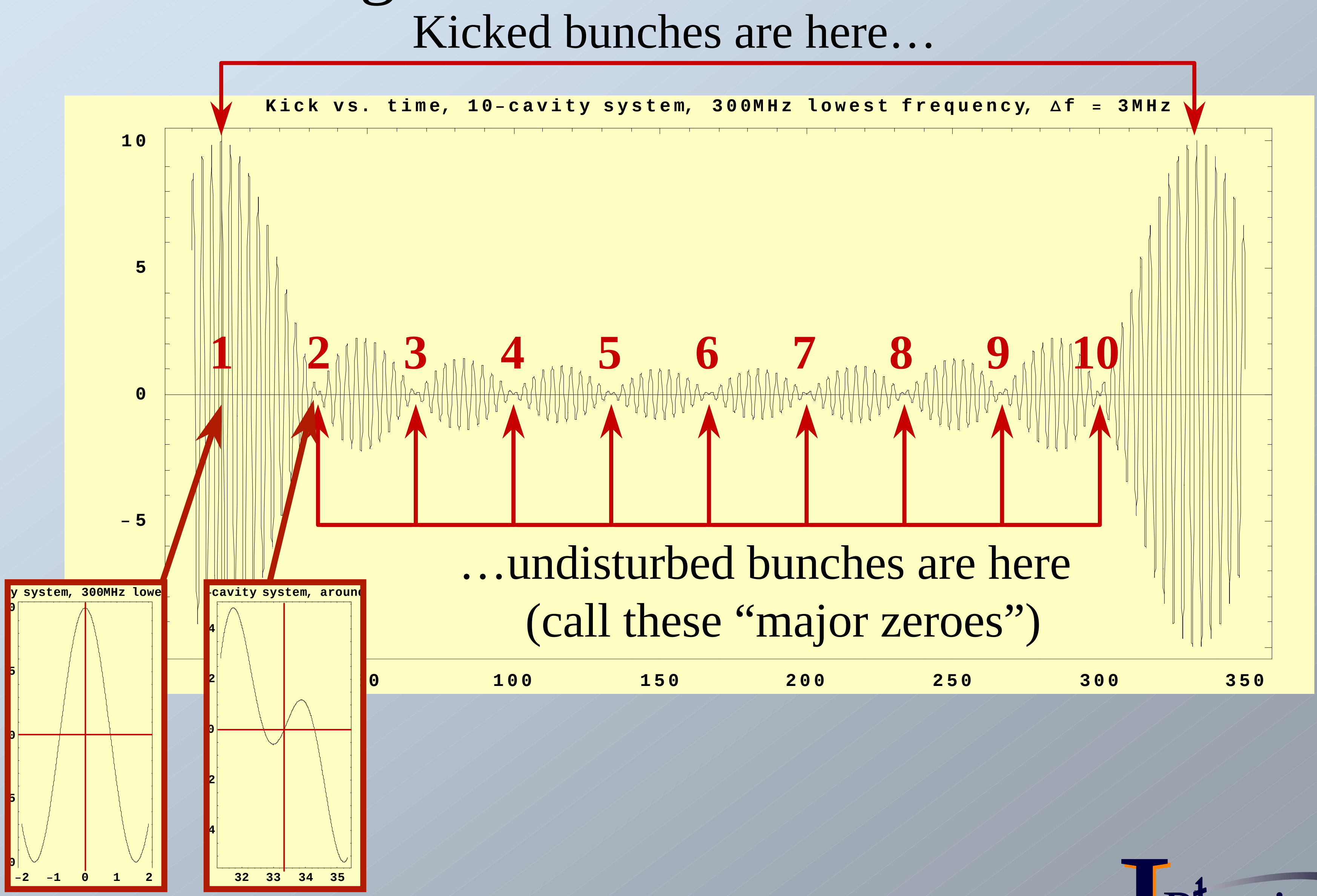
A ten-cavity system might look like this (f_{high} = 300 MHz):



$$p_T \sim \sum_{j=0}^{j=(N_{cavities}-1)} \cos\left[\left(\omega_{high} + j\omega_{low}\right)t\right]$$

(actually, one would want to use more than ten cavities)

Bunch timing

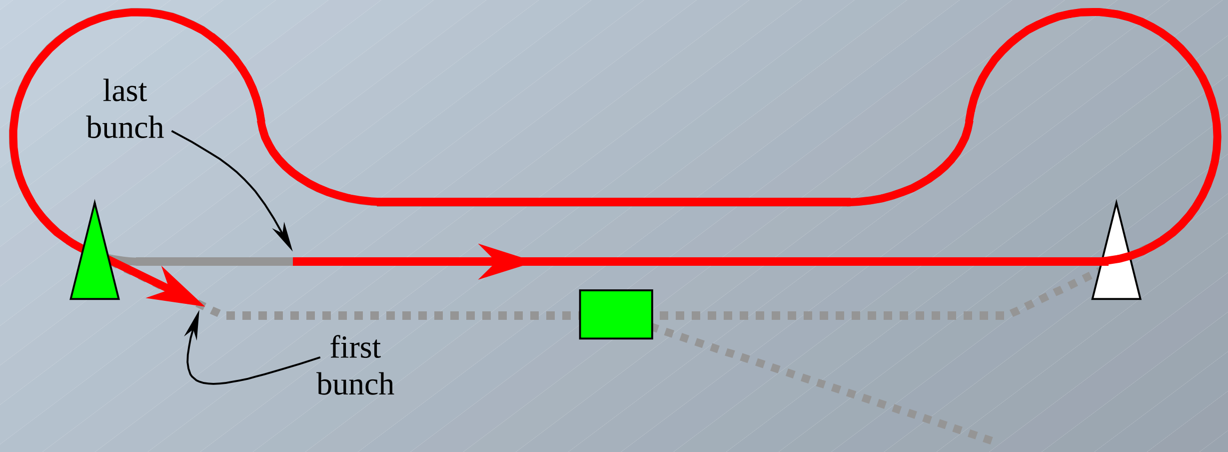


Interval between kick and adjacent "major zeroes" is uniform.

Extraction cycle timing

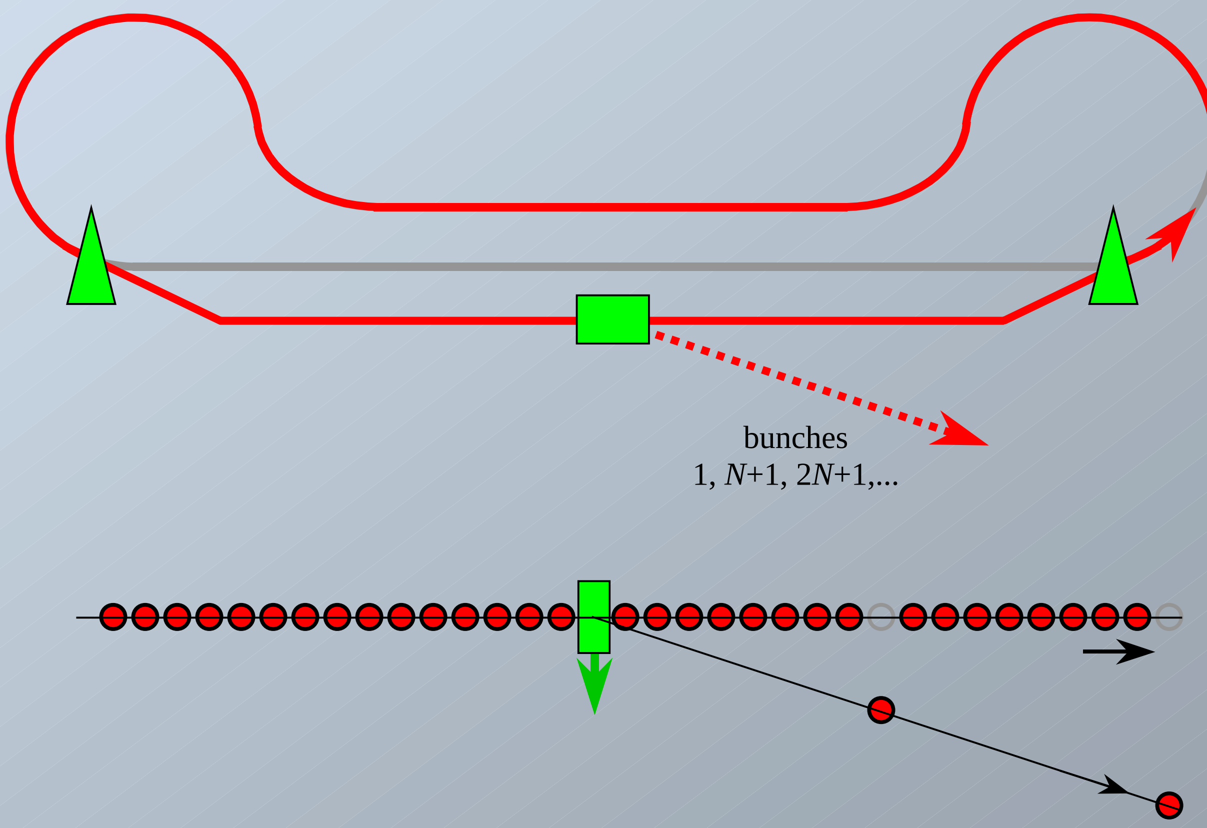
Assume bunch train contains a gap between last and first bunch while orbiting inside the damping ring.

1. First deflecting magnet is energized.



Extraction cycle timing

2. Second deflecting magnet is energized; bunches 1, *N*+1, 2*N*+1,… are extracted during first orbit through the bypass.



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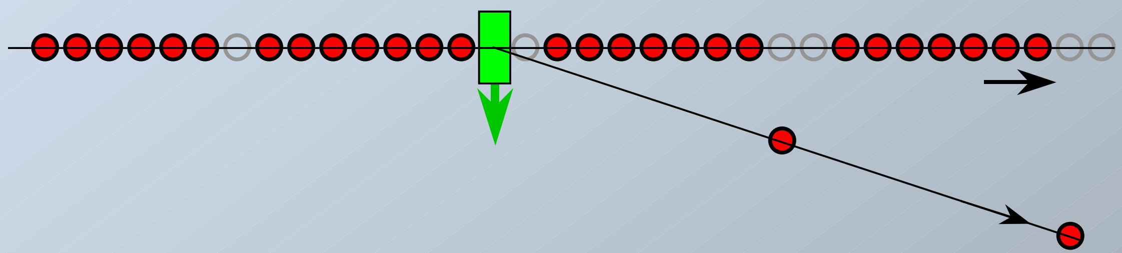
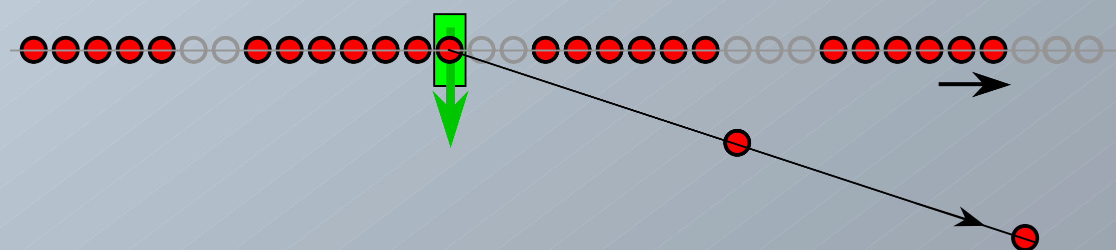
Extraction cycle timing

3. Bunches 2, N+2, 2N+2,… are extracted during second orbit through the bypass.



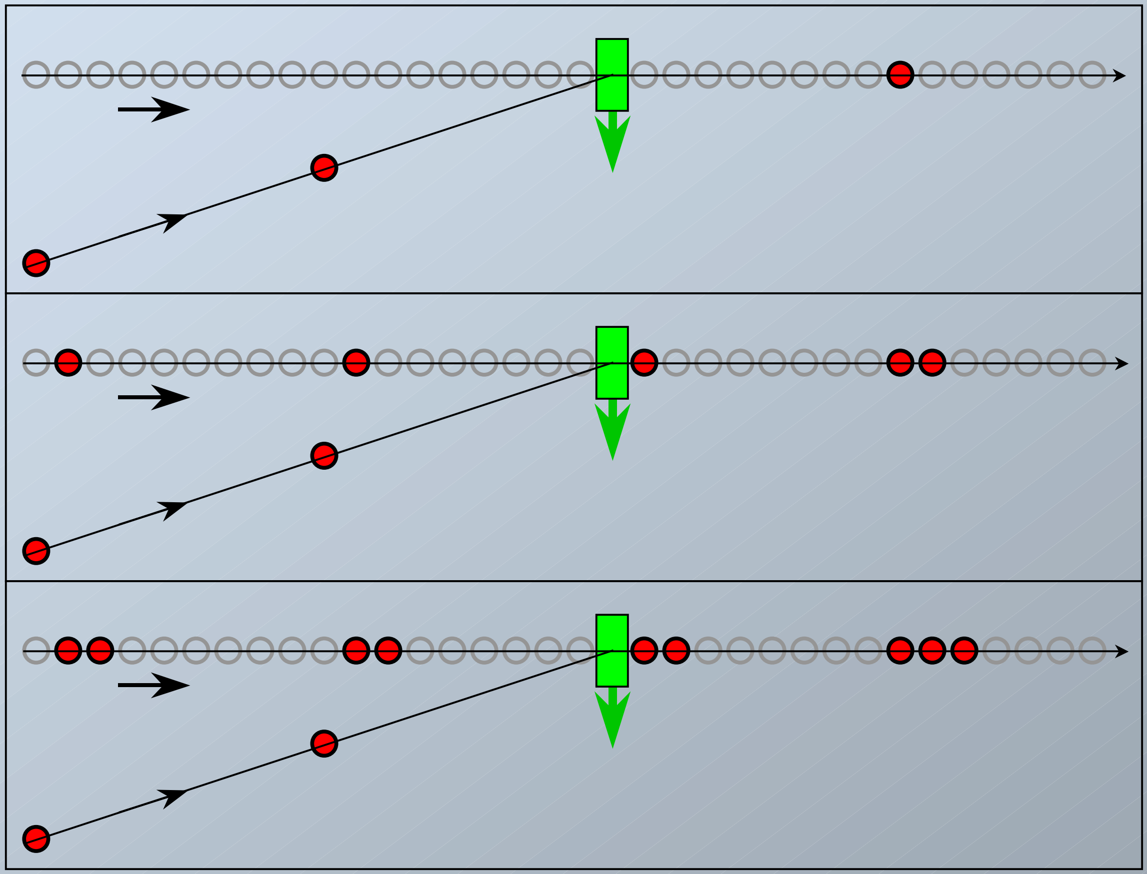
4. Bunches 3, N+3, 2N+3,… are extracted during third orbit through the bypass.



5. Etc. (entire beam is extracted in N orbits)

Injection cycle timing

Just run the movie backwards…



With a second set of cavities, it should work to extract and inject simultaneously.

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Sometimes p_T can be summed analytically…

Here are some plots for a kicker system using frequencies 300 MHz, 303 MHz, 306 MHz,… and equal amplitudes A_j:

Define $\omega_{high} = 2\pi \cdot 300\text{MHz};\ \ \omega_{low} = 2\pi \cdot 3\text{MHz};\ \ K \equiv \omega_{high} / \omega_{low}$

$$p_T \propto \sum_{j=0}^{j=N_{cavities}-1} \cos\left[\left(\omega_{high} + j\omega_{low}\right)t\right]$$

$$= \frac{\sin\left[\left(K - \tfrac{1}{2} + N_{cavities}\right)\omega_{low} t\right] - \sin\left[\left(K - \tfrac{1}{2}\right)\omega_{low} t\right]}{2\sin\left(\tfrac{1}{2}\omega_{low} t\right)}$$

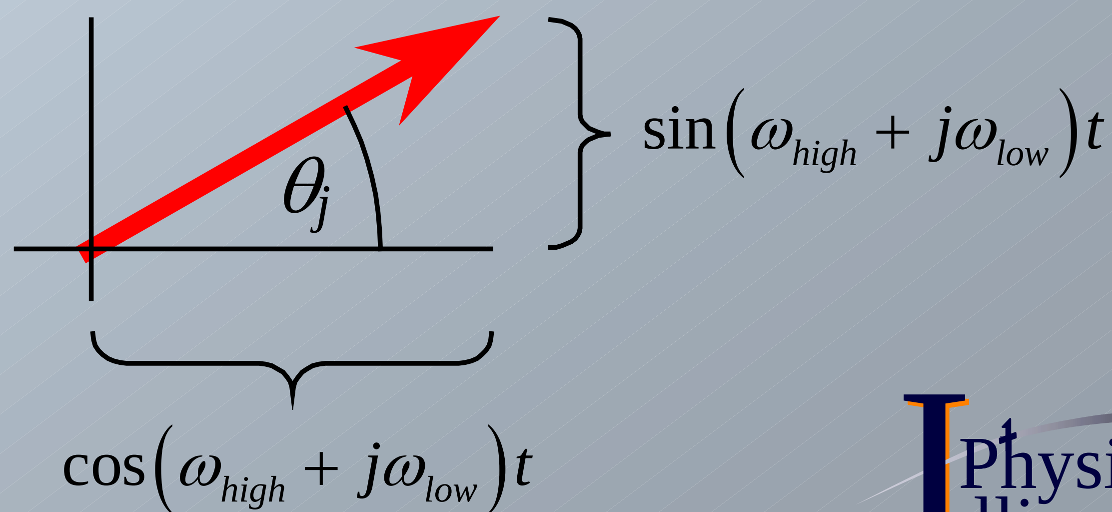
Lots of algebra. Visualizing this…

Represent each cavity's kick as a "phasor" (vector) whose *x* component is the kick, and whose *y* component is not...

$$p_T \sim \sum_{j=0}^{j=(N_{cavities}-1)} \cos\left[\left(\omega_{high} + j\omega_{low}\right)t\right]$$

Each cavity's phasor spins around counterclockwise…

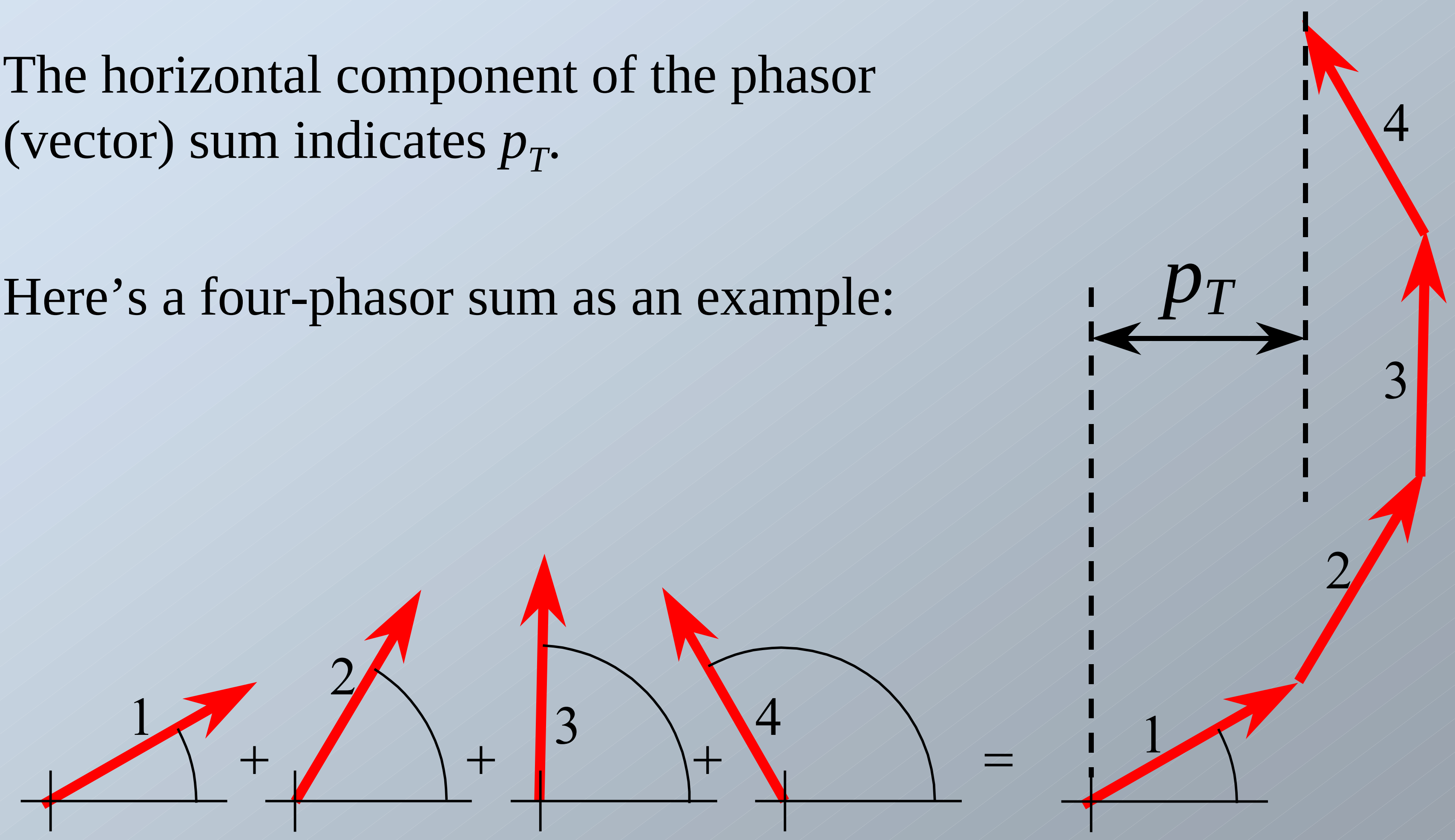
$$\theta_j = \left(\omega_{high} + j\omega_{low}\right)t$$



Phasors: visualizing the p_T kick

The horizontal component of the phasor (vector) sum indicates p_T.

Here's a four-phasor sum as an example:



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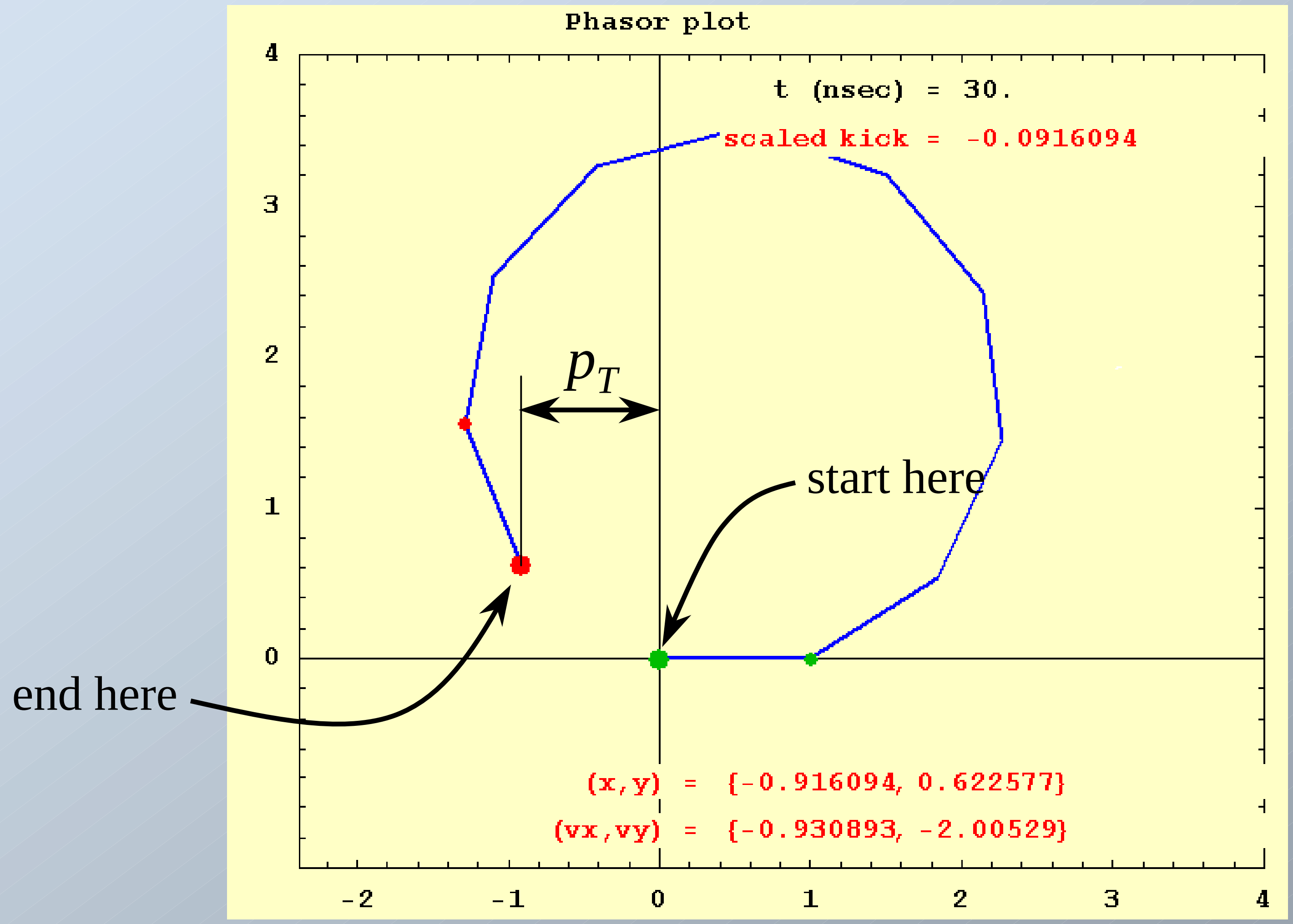
Phasors: visualizing the p_T kick

Here's a 10-cavity phasor diagram for equal-amplitude cavities…



…and 30-cavity animations (30, A, B, C).

Phasors: visualizing the p_T kick

Both the *x* and *y* components of the phasor sum…

$$x: \sum_{j=0}^{j=N_{cavities}-1} \cos\left[\left(\omega_{high} + j\omega_{low}\right)t\right]$$

$$= \frac{\sin\left[\left(K - \tfrac{1}{2} + N_{cavities}\right)\omega_{low}t\right] - \sin\left[\left(K - \tfrac{1}{2}\right)\omega_{low}t\right]}{2\sin\left(\tfrac{1}{2}\omega_{low}t\right)}$$

$$y: \sum_{j=0}^{j=N_{cavities}-1} \sin\left[\left(\omega_{high} + j\omega_{low}\right)t\right]$$

$$= \frac{-\cos\left[\left(K - \tfrac{1}{2} + N_{cavities}\right)\omega_{low}t\right] + \cos\left[\left(K - \tfrac{1}{2}\right)\omega_{low}t\right]}{2\sin\left(\tfrac{1}{2}\omega_{low}t\right)}$$

…are zero when $N_{cavities}\omega_{low}t = m \cdot 2\pi$ (m is integral)

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Phasors: visualizing the p_T kick

Kicks occur when the denominator is zero: $t = 0, \ \dfrac{2\pi}{\omega_{low}}, \ \dfrac{4\pi}{\omega_{low}}, \cdots$

"Major zeroes" between two kicks are evenly spaced and occur at

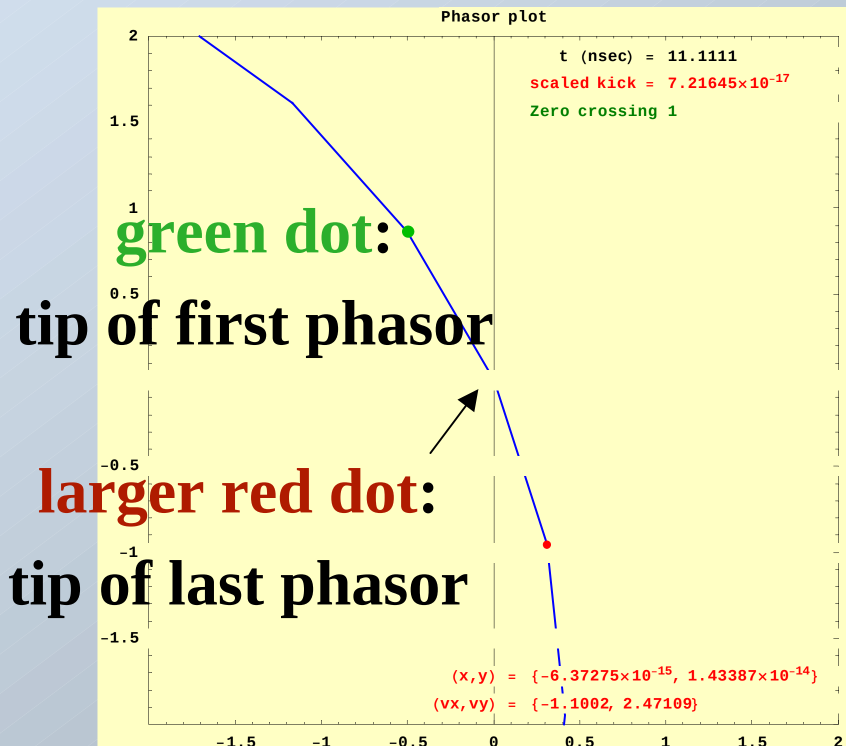
$$t = \frac{2\pi}{N_{cavities}\omega_{low}}, \ \frac{4\pi}{N_{cavities}\omega_{low}}, \cdots \ \frac{(N_{cavities} - 1) \cdot 2\pi}{N_{cavities}\omega_{low}}$$

One kicker cycle comprises a kick followed by ($N_{cavities}$ - 1) major zeroes.

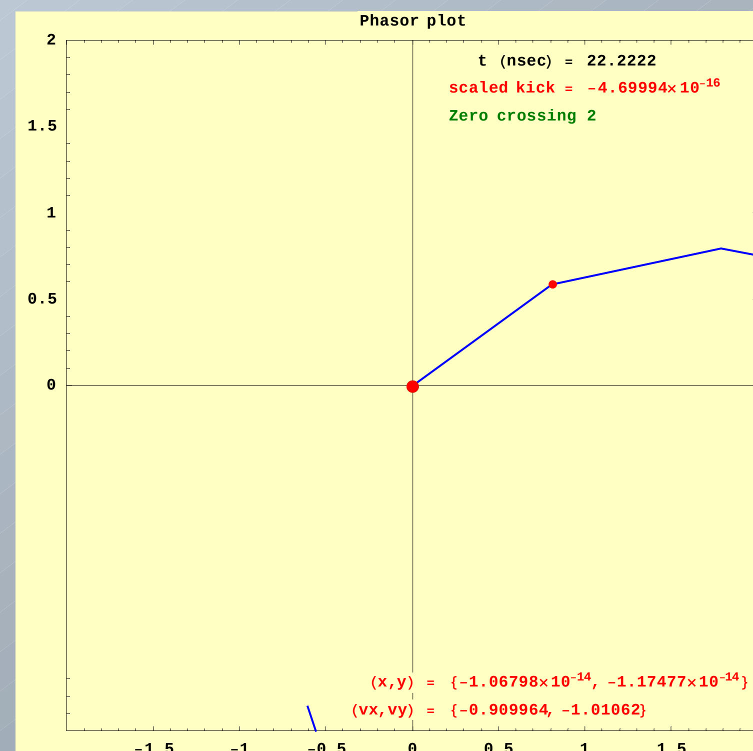
Phasors when $p_T = 0$ (30 cavities)

Phasor diagrams for major zeroes of one specific example:

- 30 cavity system
- 300 MHz lowest frequency, 3 MHz spacing

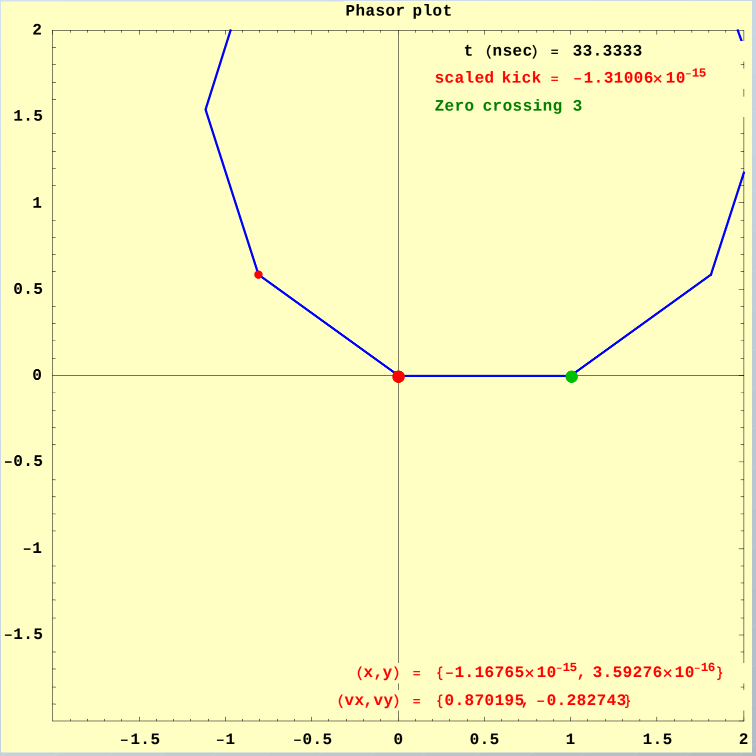


zero #1

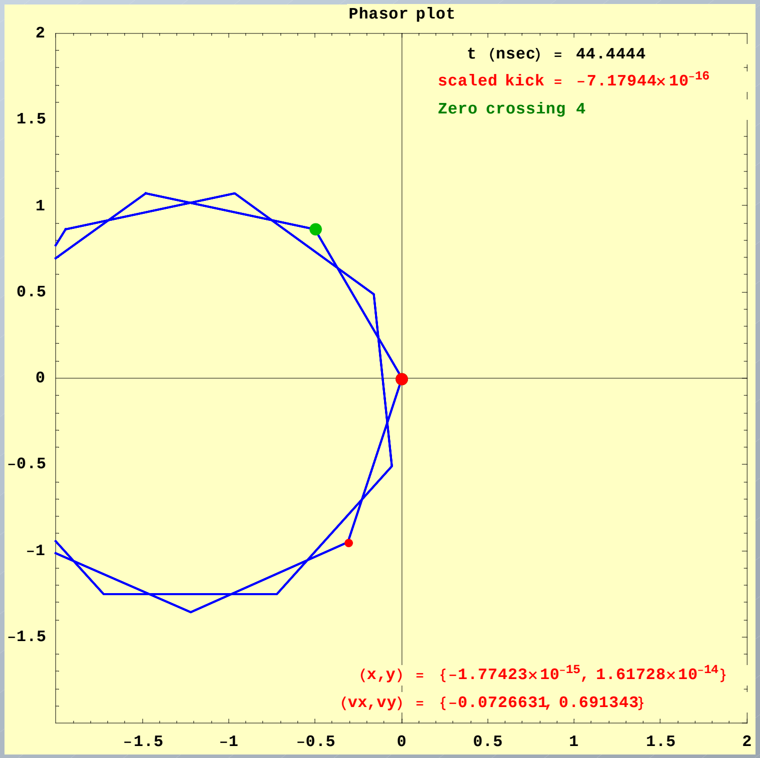


zero #2

Phasors when $p_T = 0$ (30 cavities)

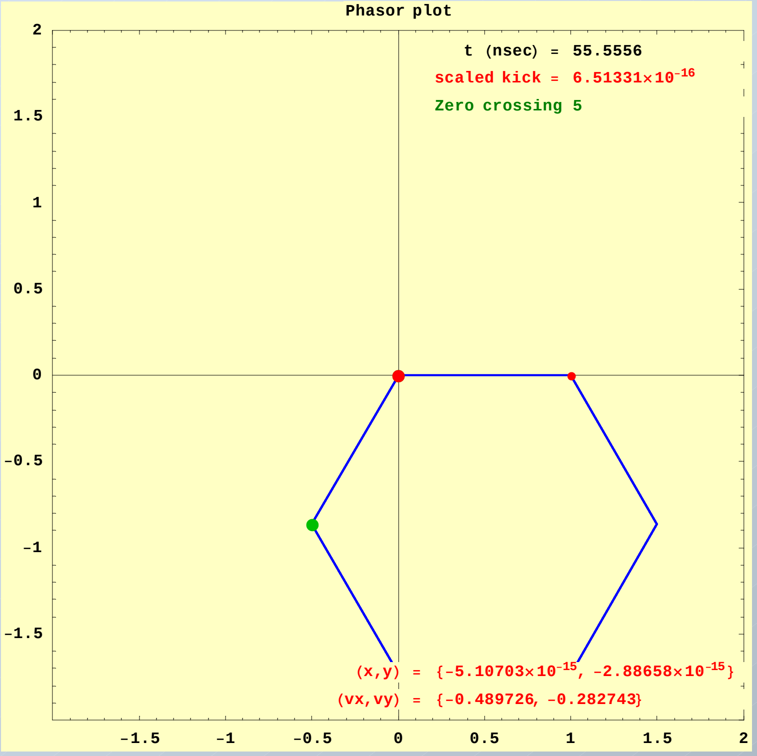


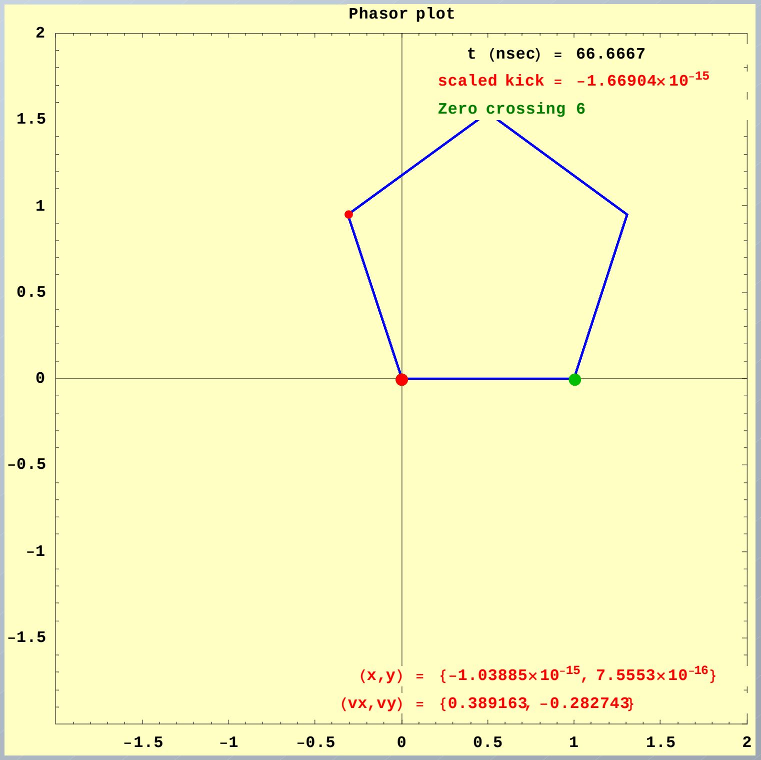
zero #3



zero #4

Phasors when $p_T = 0$ (30 cavities)

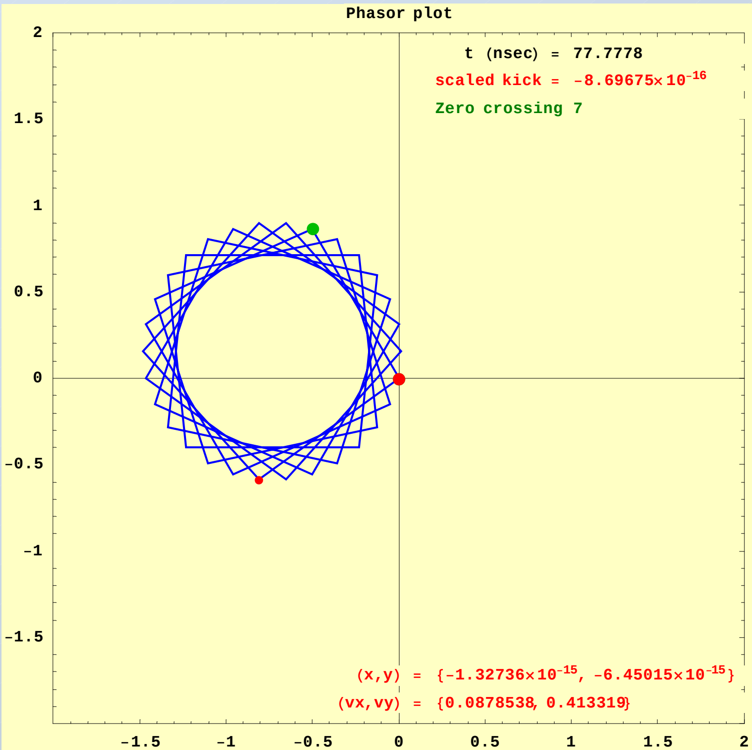




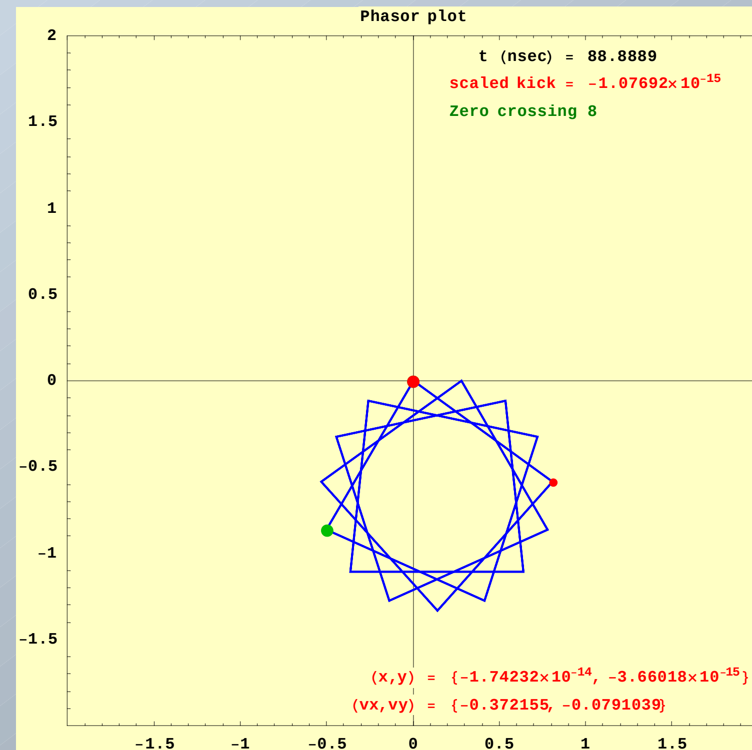
zero #5

zero #6

Phasors when $p_T = 0$ (30 cavities)

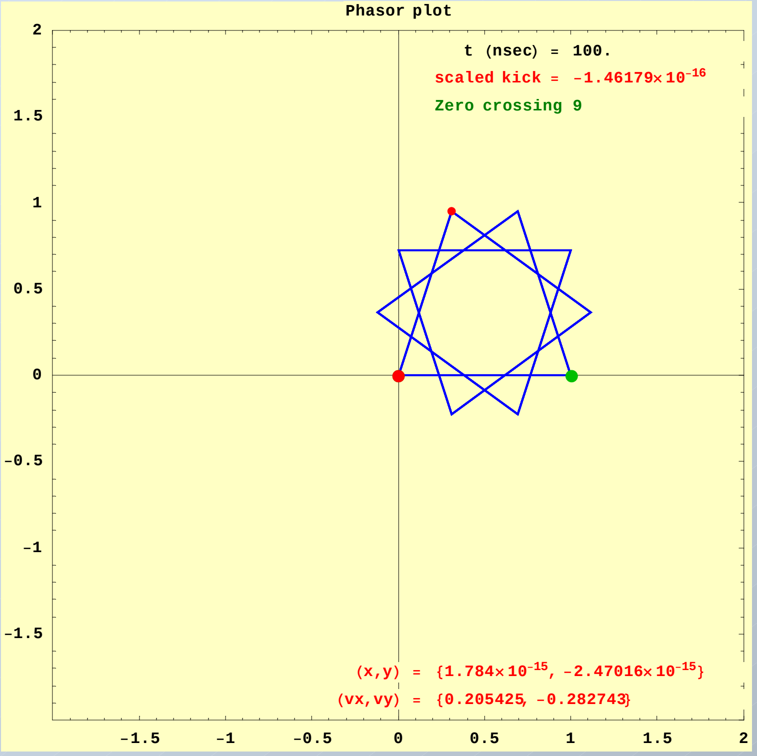


zero #7

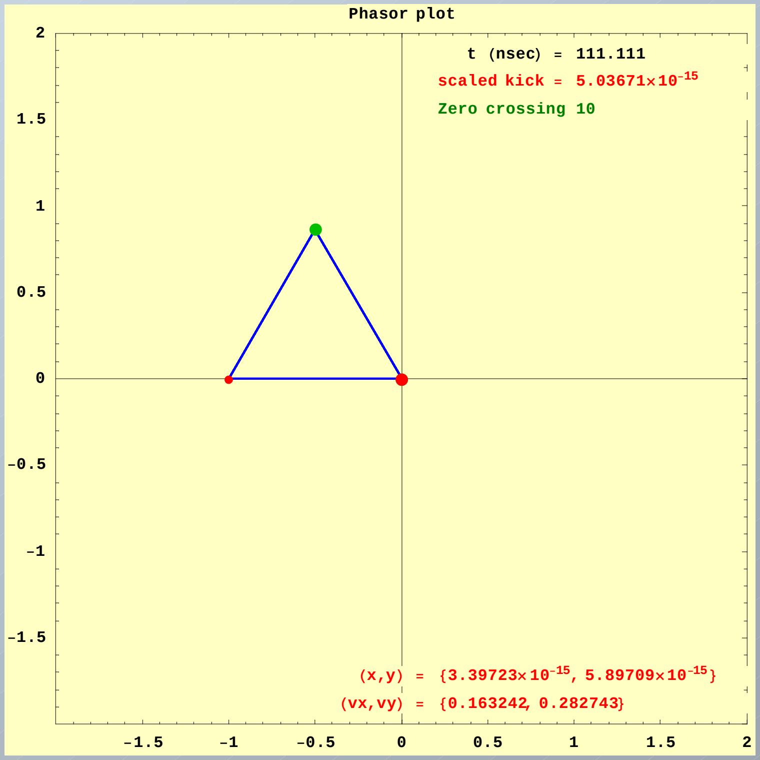


zero #8

Phasors when $p_T = 0$ (30 cavities)

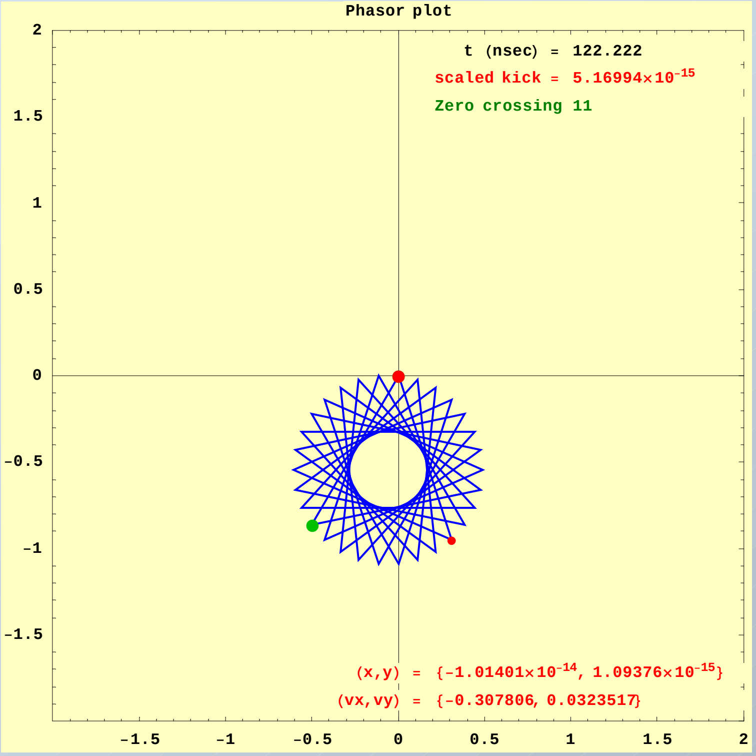


zero #9

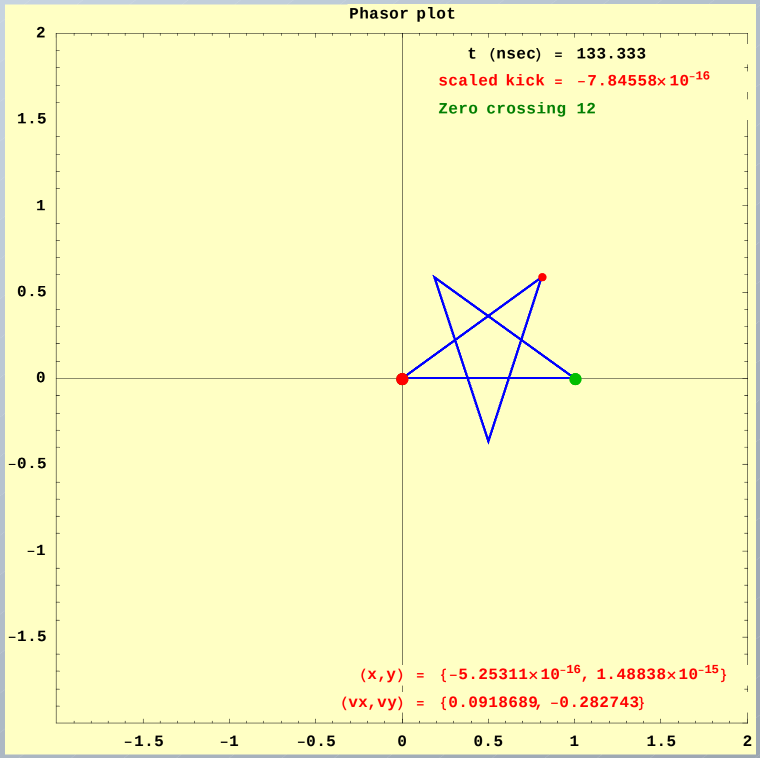


zero #10

Phasors when $p_T = 0$ (30 cavities)



zero #11



zero #12

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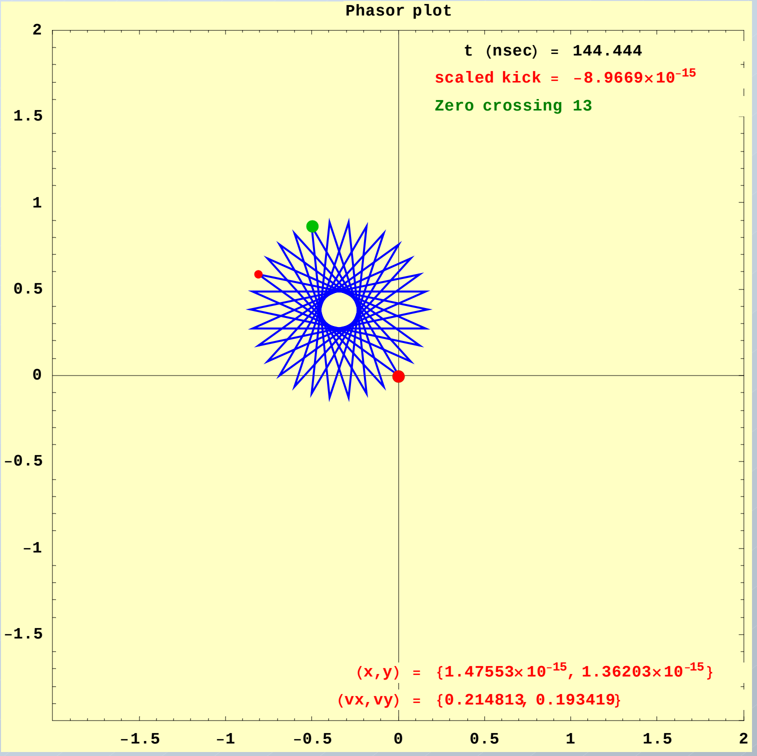
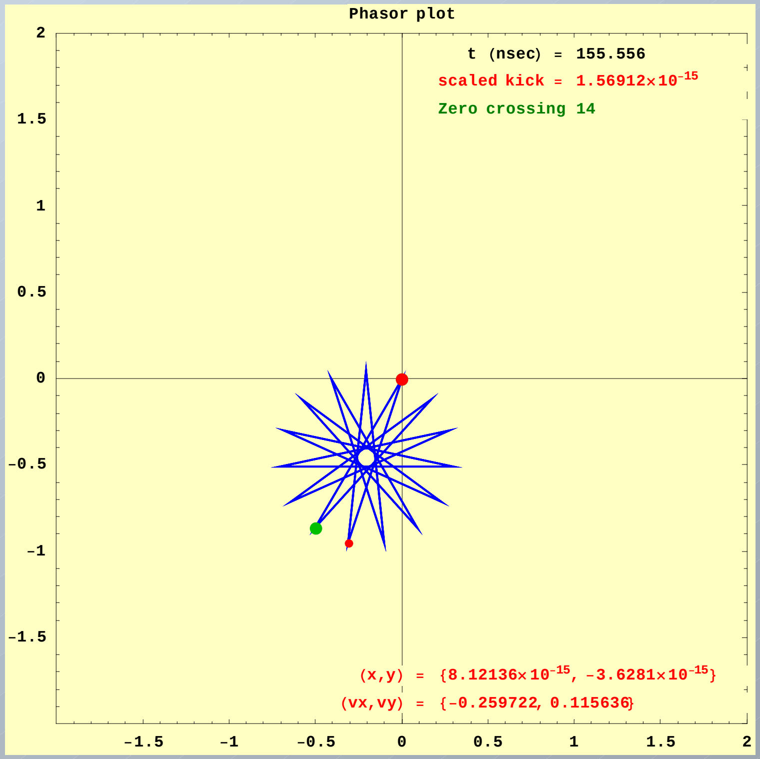
Phasors when $p_T = 0$ (30 cavities)

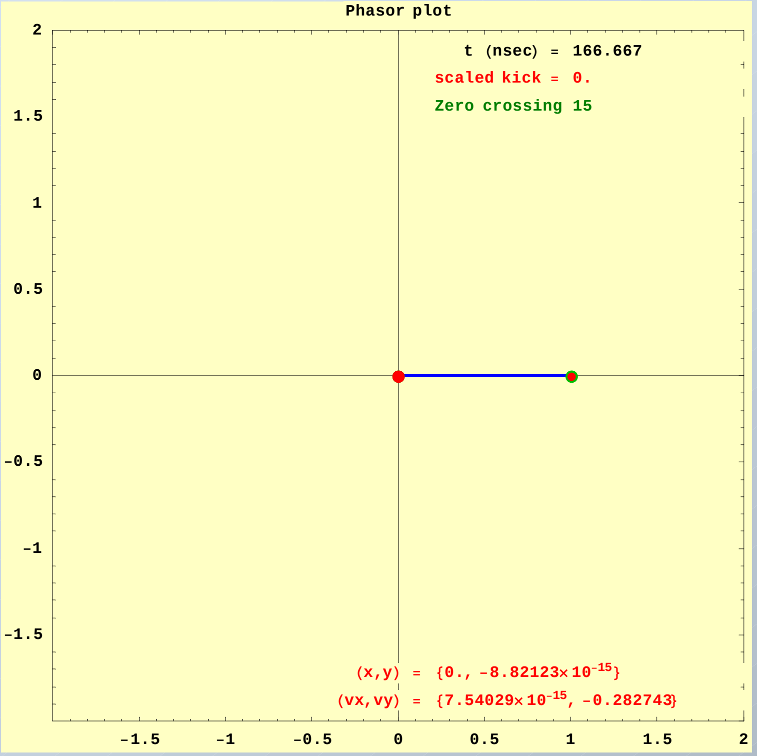


zero #13

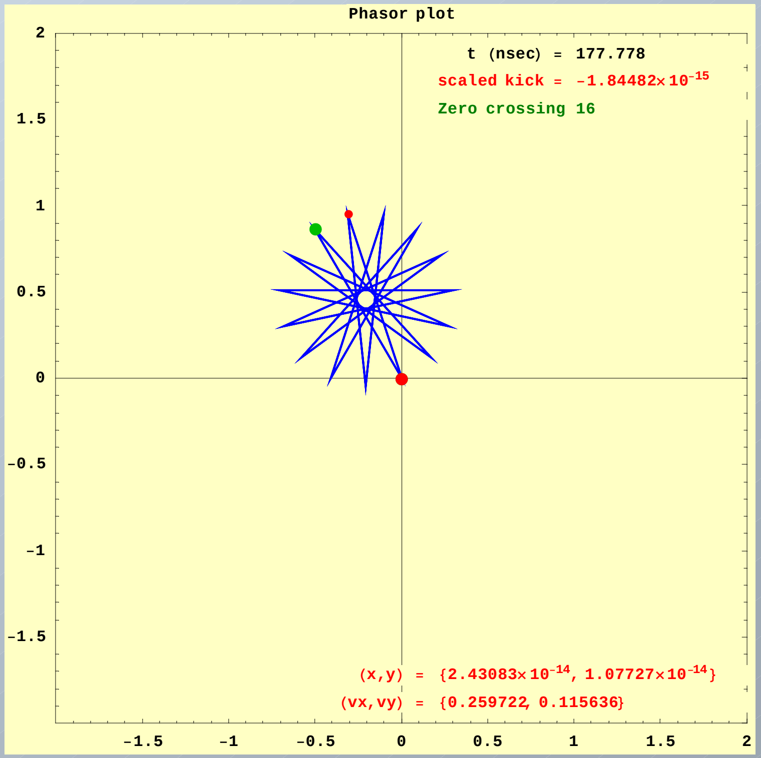


zero #14

Phasors when $p_T = 0$ (30 cavities)

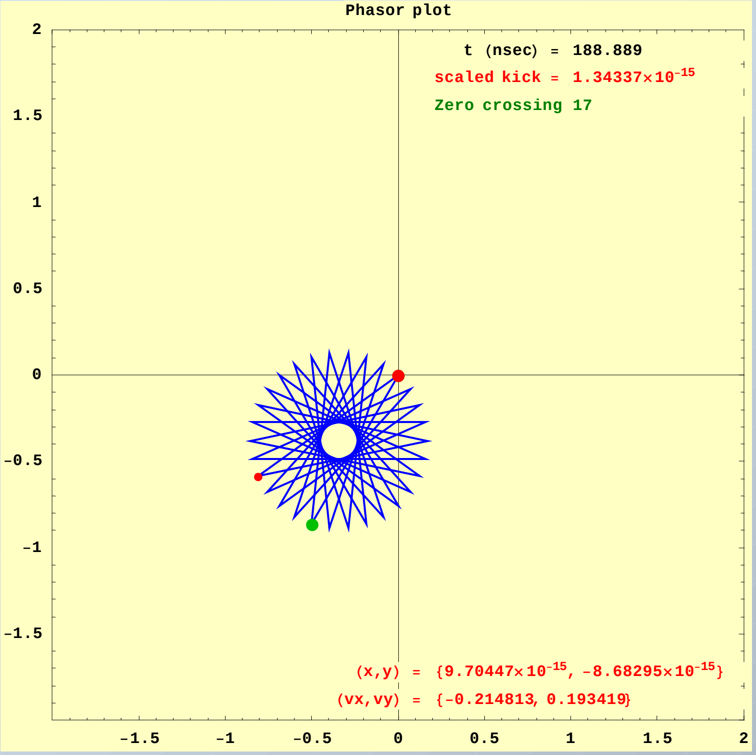


zero #15

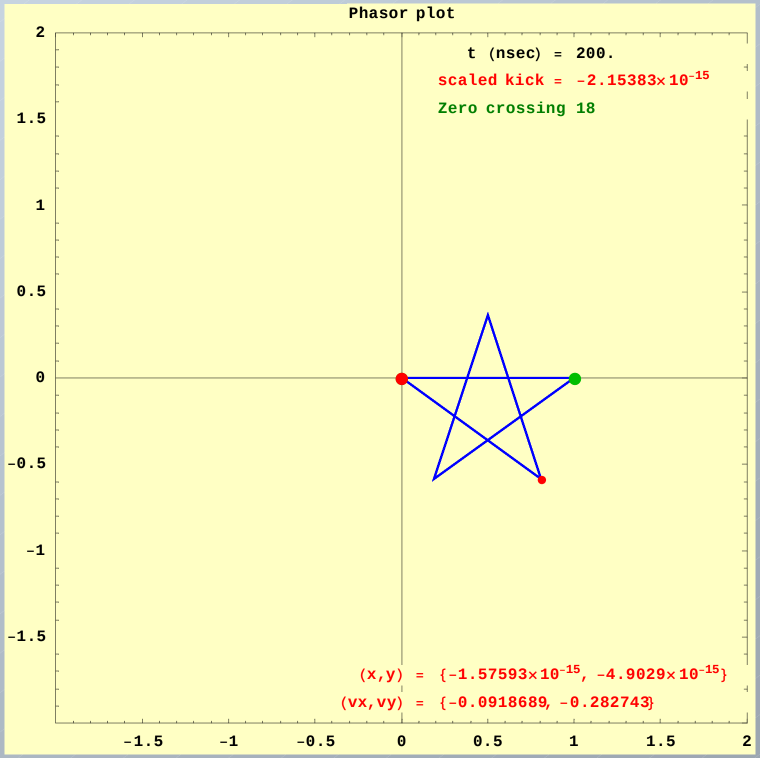


zero #16

Phasors when $p_T = 0$ (30 cavities)



zero #17

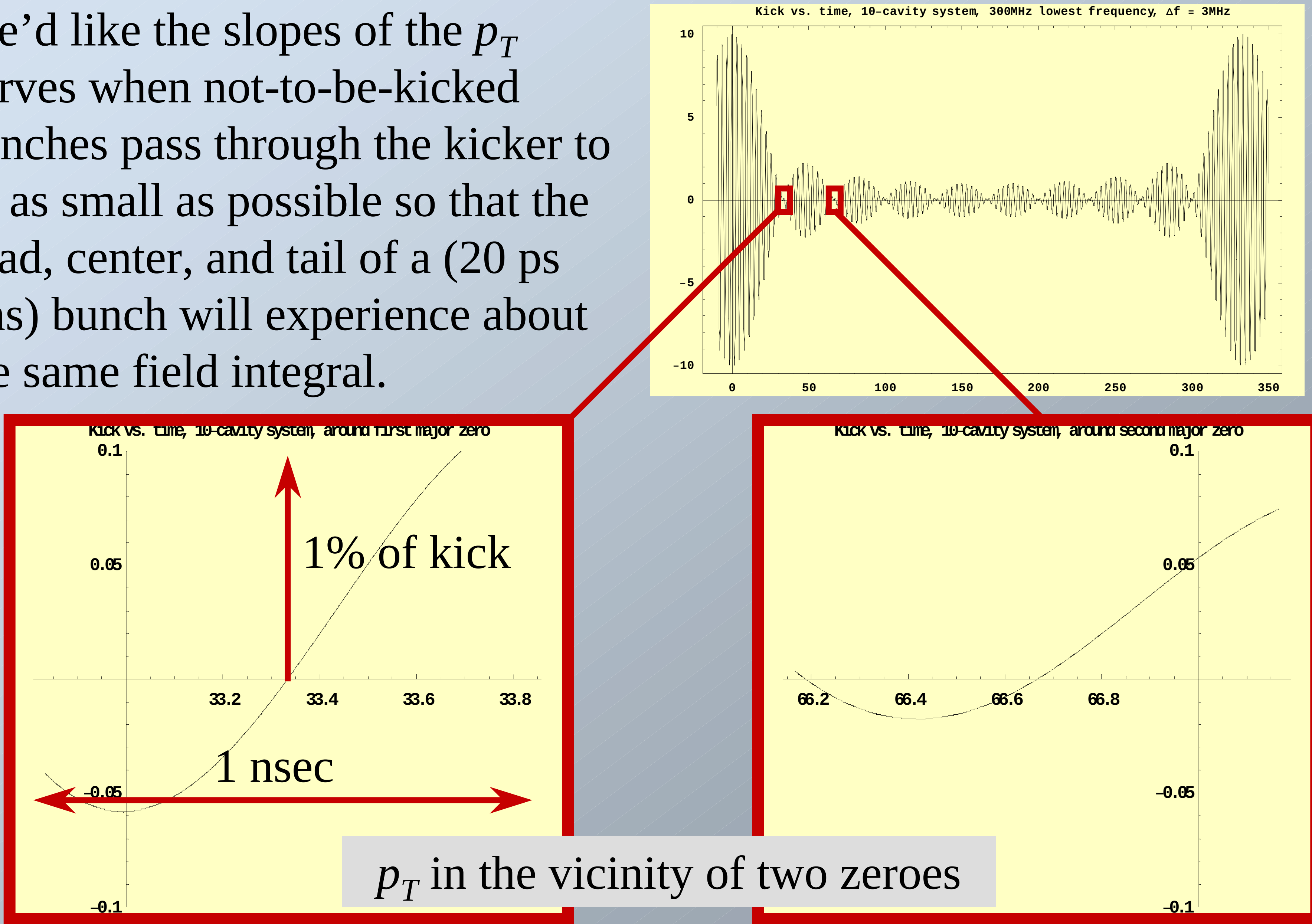


zero #18

…and so forth. (There are 29 major zeroes in all.)

dp_T/dt considerations

We'd like the slopes of the p_T curves when not-to-be-kicked bunches pass through the kicker to be as small as possible so that the head, center, and tail of a (20 ps rms) bunch will experience about the same field integral.



p_T in the vicinity of two zeroes

Sometimes dp_T/dt at zeroes can be calculated…

$$\frac{dp_T}{dt} \propto \frac{d}{dt}\left\{ \sum_{j=0}^{j=N_{cavities}-1} \cos\left[\left(\omega_{high} + j\omega_{low}\right)t\right] \right\}$$

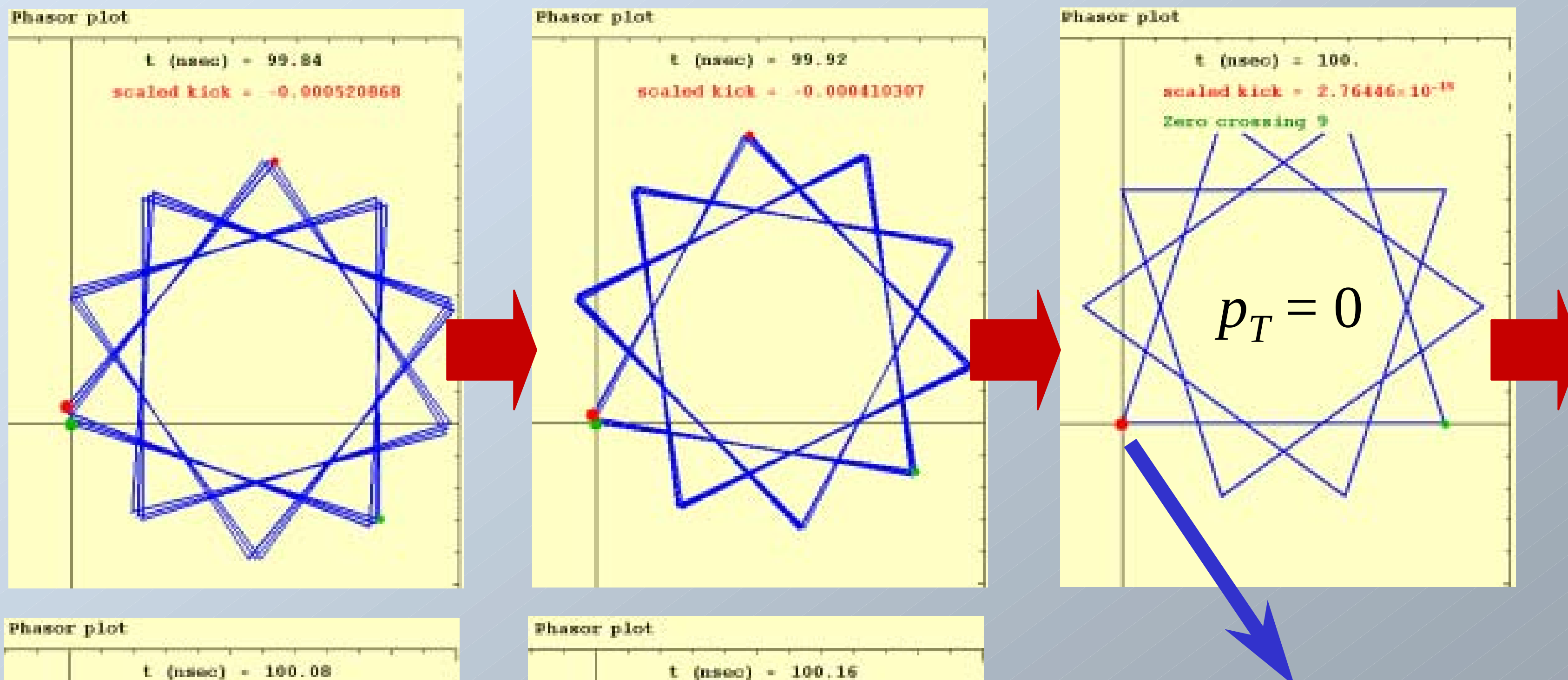
At the m^{th} “major zero” the expression evaluates to

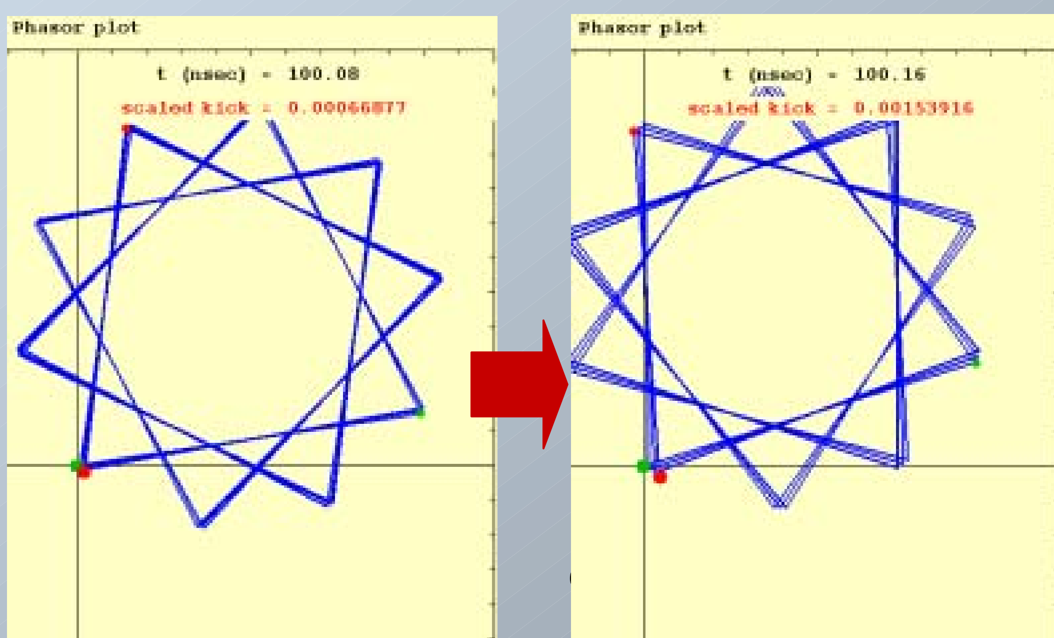
$$\frac{dp_T}{dt} \propto \frac{N_{cavities}\,\omega_{low} \cos\left[m \cdot 2\pi \frac{\left(K - \frac{1}{2}\right)}{N_{cavities}} \right]}{2\sin\left(\frac{m\pi}{N_{cavities}} \right)}$$

$$\left(K \equiv \omega_{high} / \omega_{low} \right)$$

Note that magnitude of the slope <u>does not</u> depend strongly on ω_{high}. (It does for the other zeroes, however.)

Flattening out dp_T/dt





Endpoint is moving this way at the zero in p_T

(80 psec intervals)

Flattening out dp_T/dt

In terms of phasor sums: we want the endpoint of the phasor sum to have as small an *x* component of "velocity" as possible.

Endpoint velocity components (*m* ranges from 1 to $N_{cavities} - 1$):

$$v_x = \frac{N_{cavities}\omega_{low}}{2\sin\left(\frac{m\pi}{N_{cavities}}\right)}\cos\left[m \cdot 2\pi \frac{\left(K - \frac{1}{2}\right)}{N_{cavities}}\right]$$

$$v_y = \frac{N_{cavities}\omega_{low}}{2\sin\left(\frac{m\pi}{N_{cavities}}\right)}\sin\left[m \cdot 2\pi \frac{\left(K - \frac{1}{2}\right)}{N_{cavities}}\right]$$

Flattening out dp_T/dt

How large a value for v_x is acceptable?

- Size of kick: $N_{cavities}$
- rms bunch length: 20 psec (6 mm)
- maximum allowable kick error: ~.07%

$$\Rightarrow .020 \text{ nsec} \cdot v_x < 0.07 \times 10^{-2} \cdot N_{cavities}$$

Work in units of nsec and GHz… for 30 cavities: $v_x < 1.05 \text{ nsec}^{-1}$.

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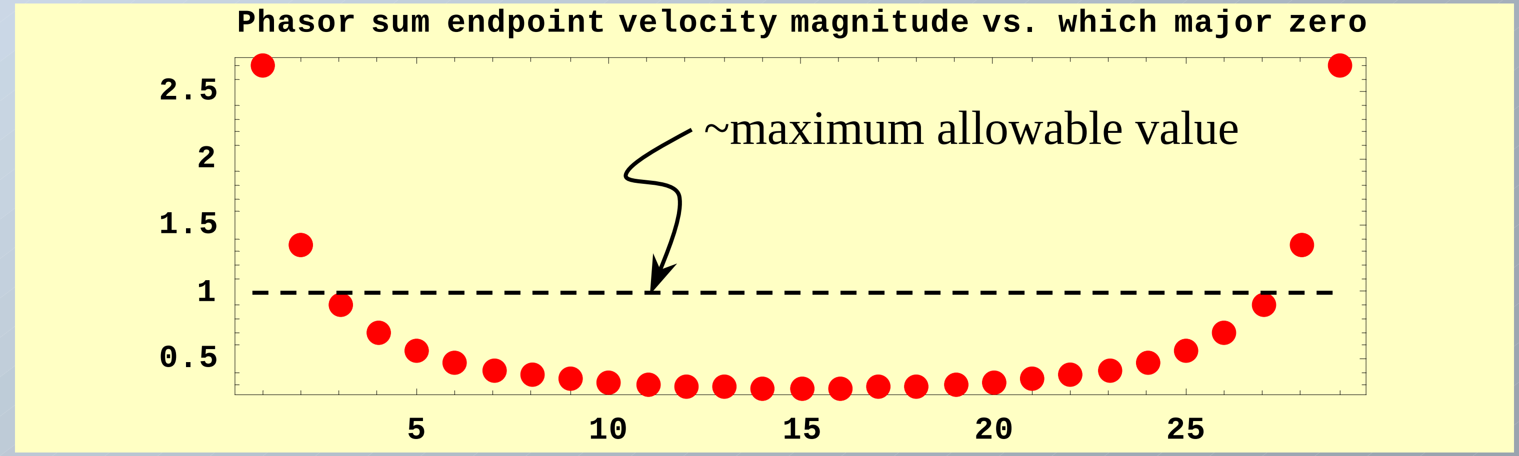
Phasor plots for dp_T/dt

Phasor magnitude for m^{th} zero's dp_T/dt:

$$|\vec{v}| = \frac{N_{cavities}\,\omega_{low}}{2\sin\left(\frac{m\pi}{N_{cavities}}\right)} \qquad m = 1,\ 2,\ \ldots,\ N_{cavities} - 1$$



Phasor angle: $\theta_m = m \cdot 2\pi \frac{\left(K - \frac{1}{2}\right)}{N_{cavities}}$ $\qquad v_x = |\vec{v}|\cos\theta_m$

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Phasor plots for dp_T/dt

Phasor plot for dp_T/dt, including the phasor angles…

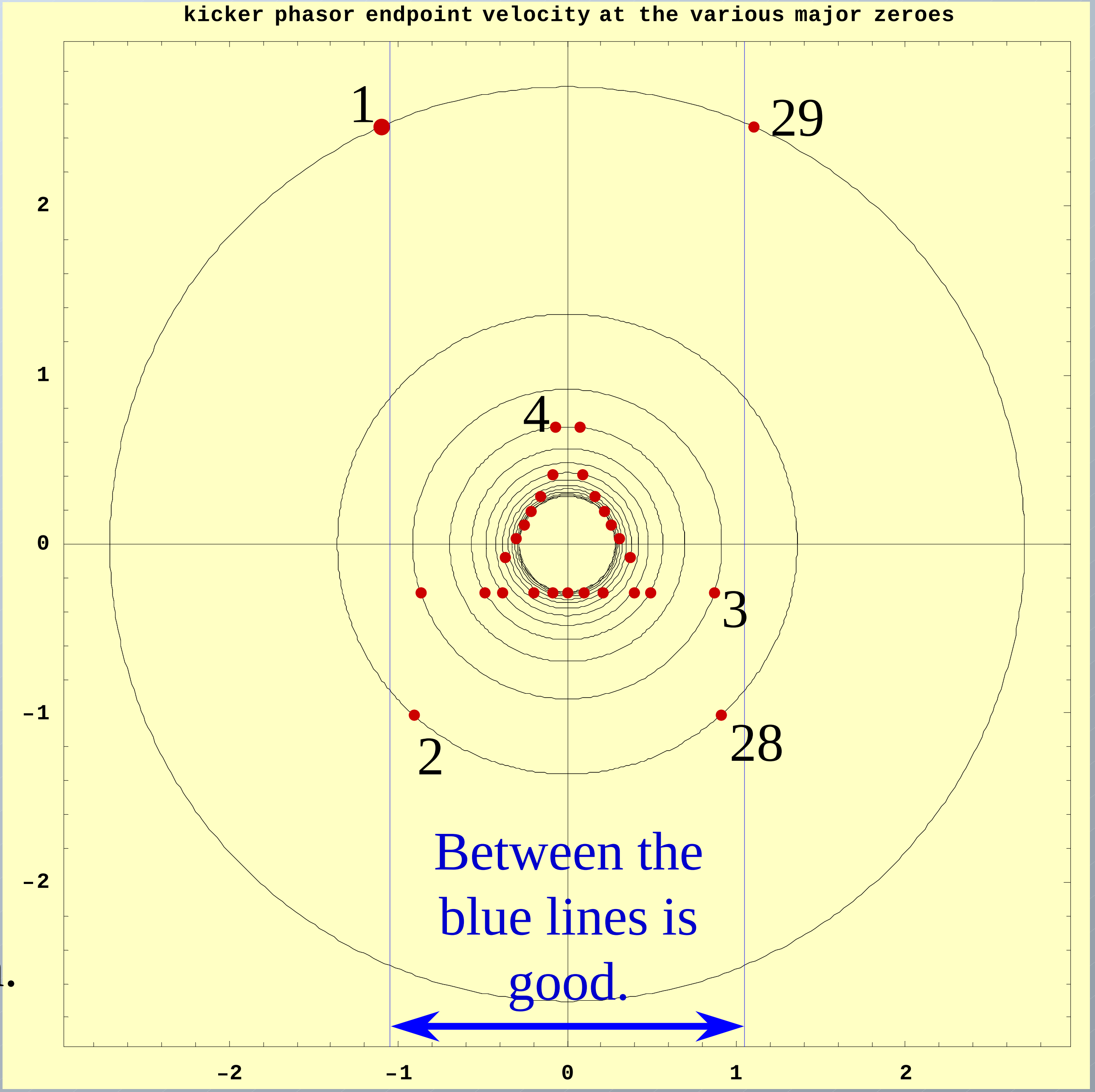
$$\theta_m = m \cdot 2\pi \frac{\left(K - \frac{1}{2}\right)}{N_{cavities}}$$

$$K \equiv \omega_{high} / \omega_{low}$$

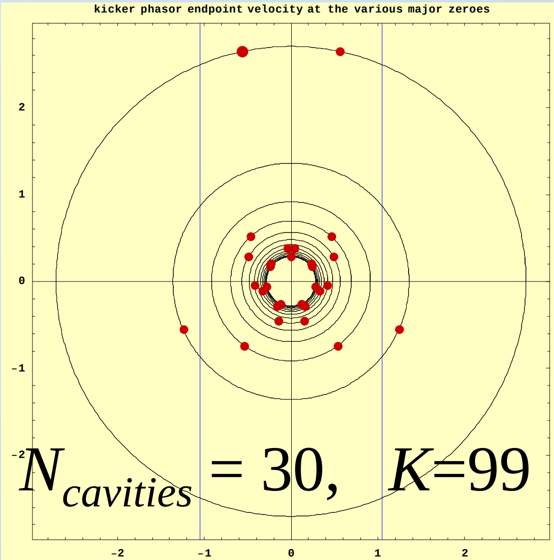
$$N_{cavities} = 30$$

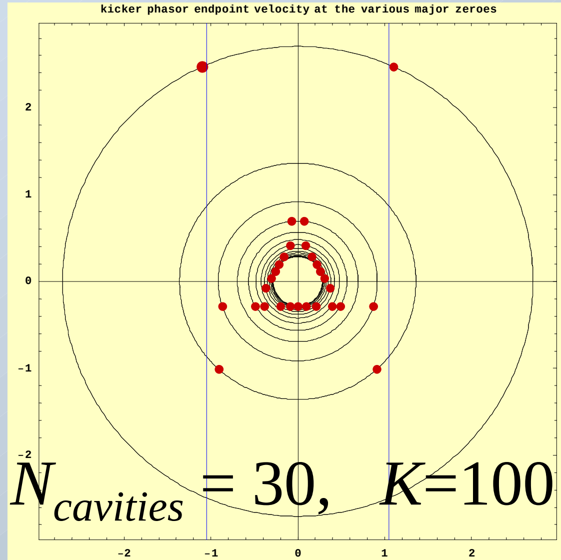
K=100 (300MHz, 3 MHz)

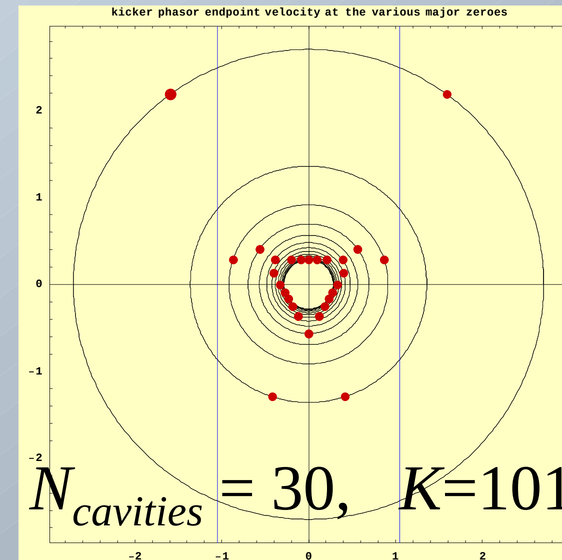
There are lots of parameters to play with.

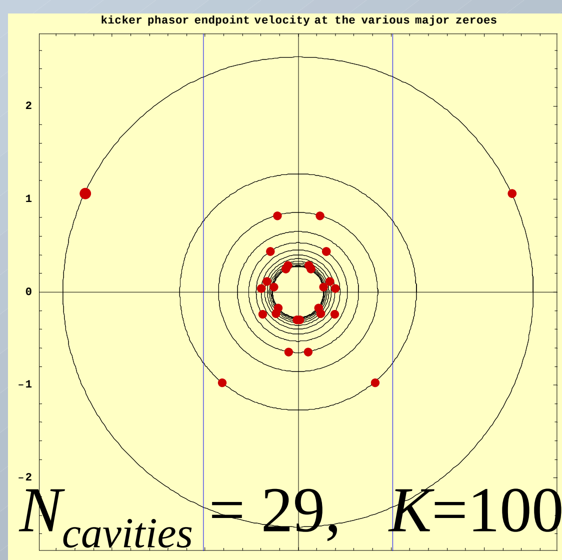


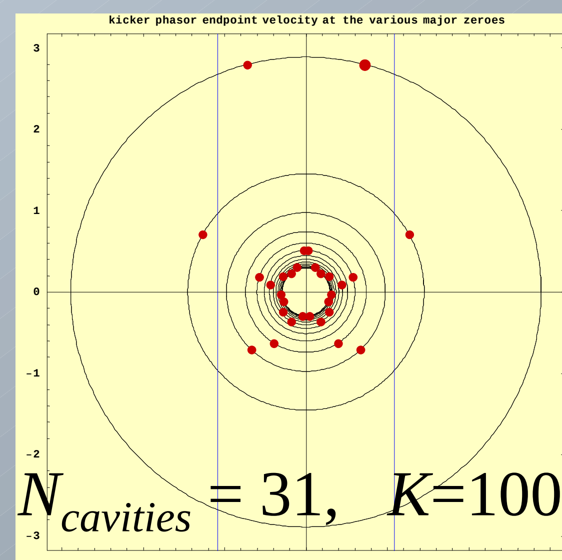
Changing parameters











More dramatic dp_T/dt reduction…

…is possible with different amplitudes A_j in each of the cavities.

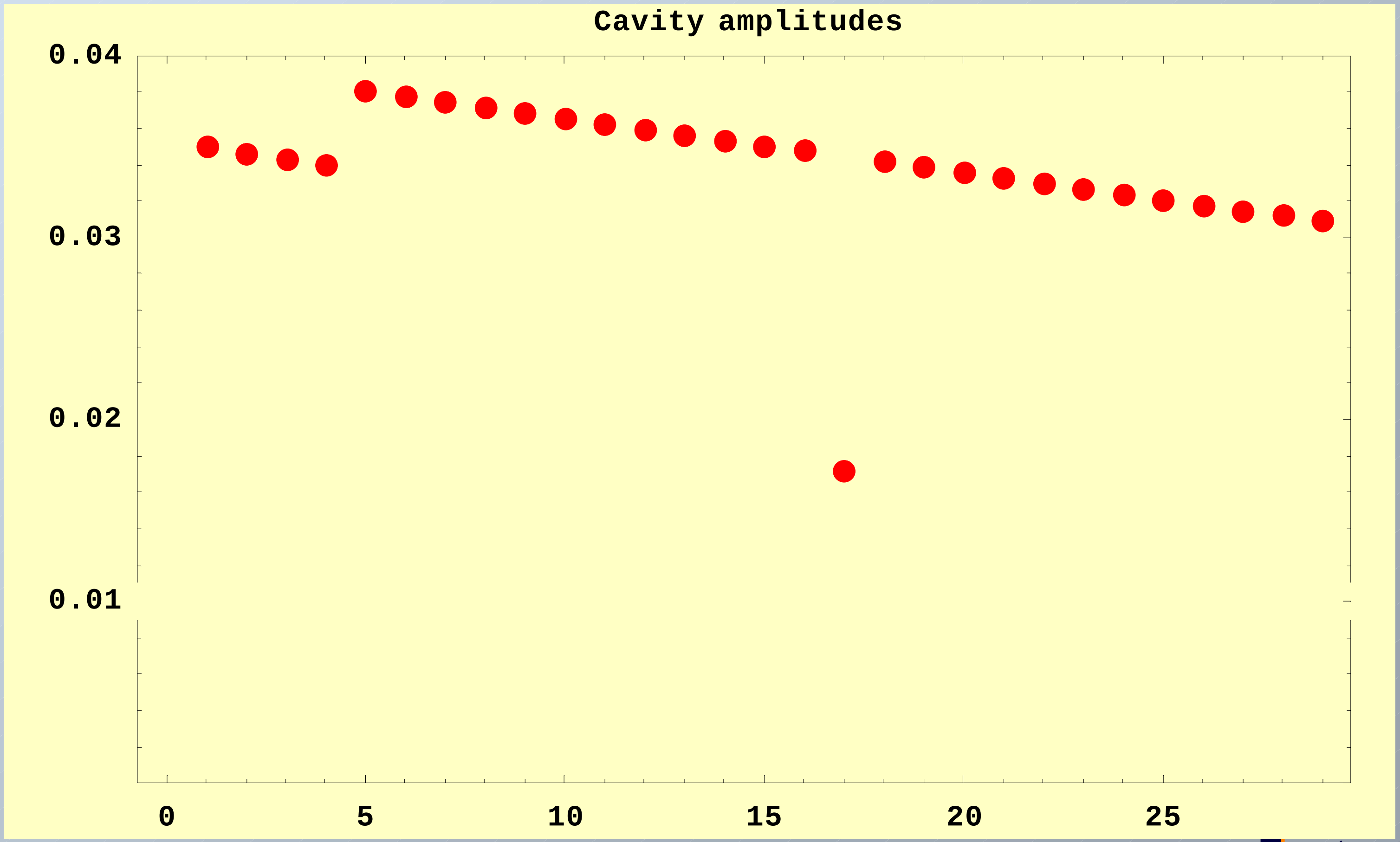
We (in particular Guy Bresler) are investigating this right now. It looks very promising!

Guy has constructed an algorithm to find sets of amplitudes which have $dp_T/dt = 0$ at evenly-spaced "major zeroes" in p_T.

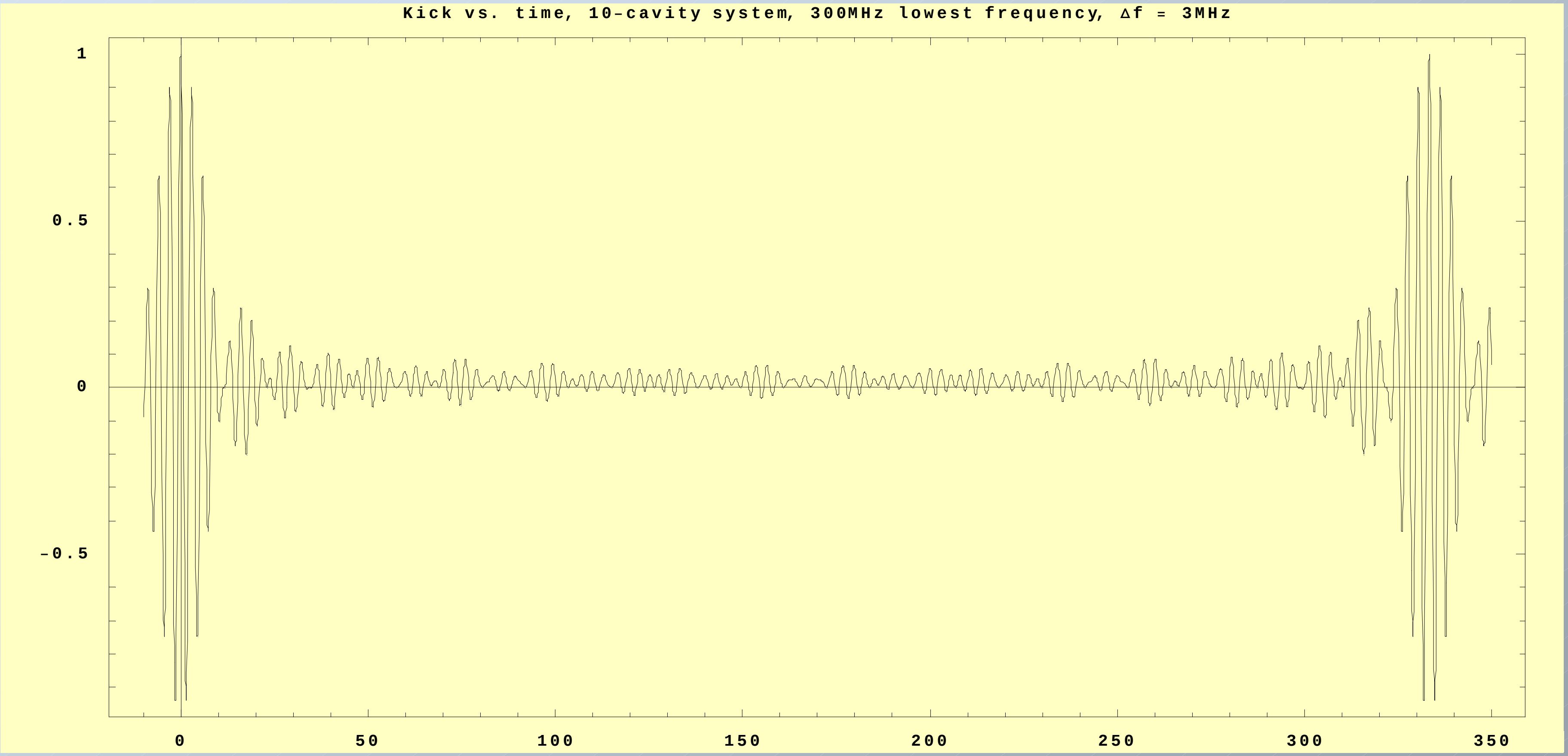
There are lots of different possible sets of amplitudes which will work.

More dramatic dp_T/dt reduction…

Here's one set for a 29-cavity system (which makes 28 zeroes in p_T and dp_T/dt in between kicks):

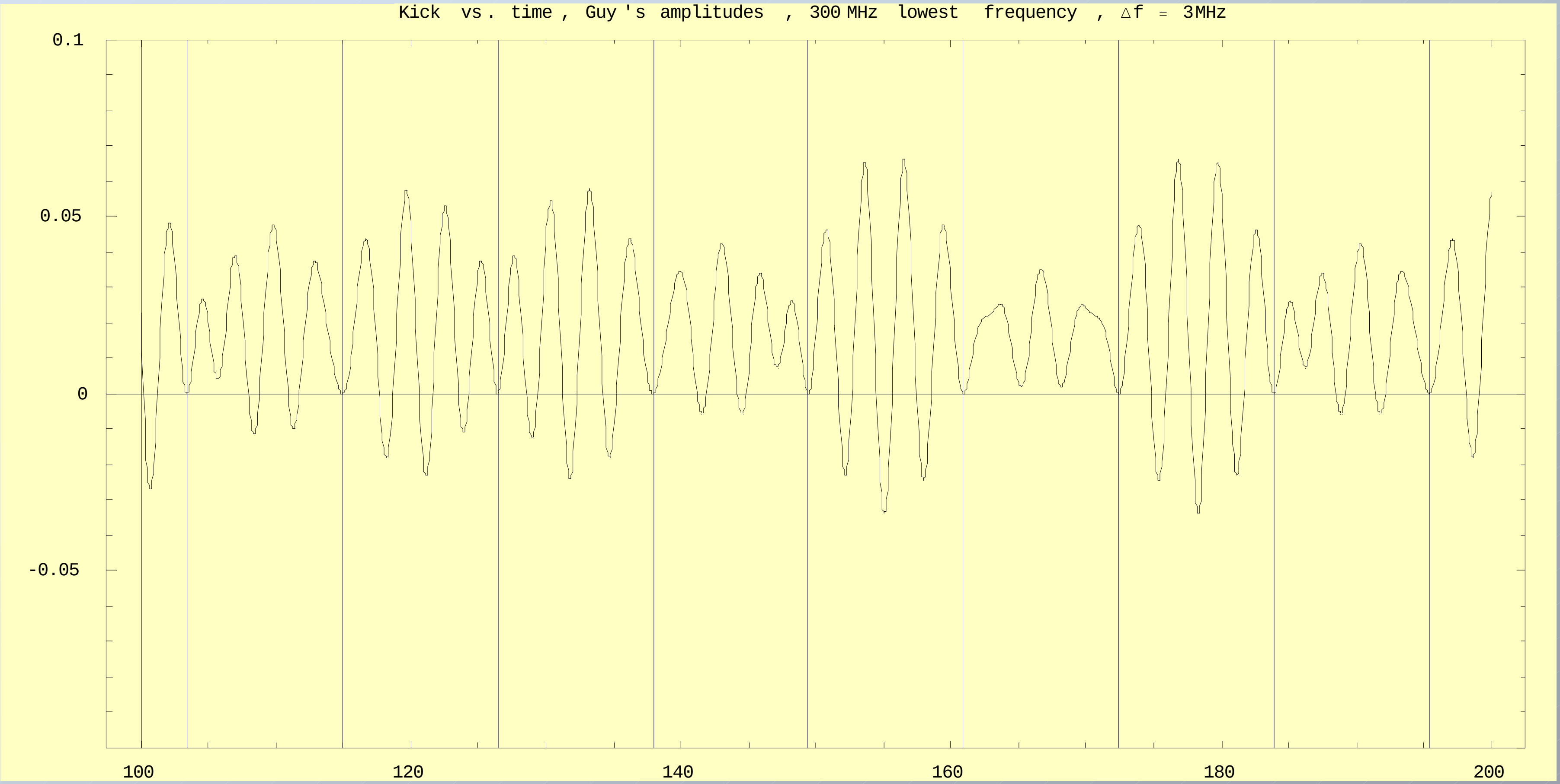


Kick corresponding to those amplitudes



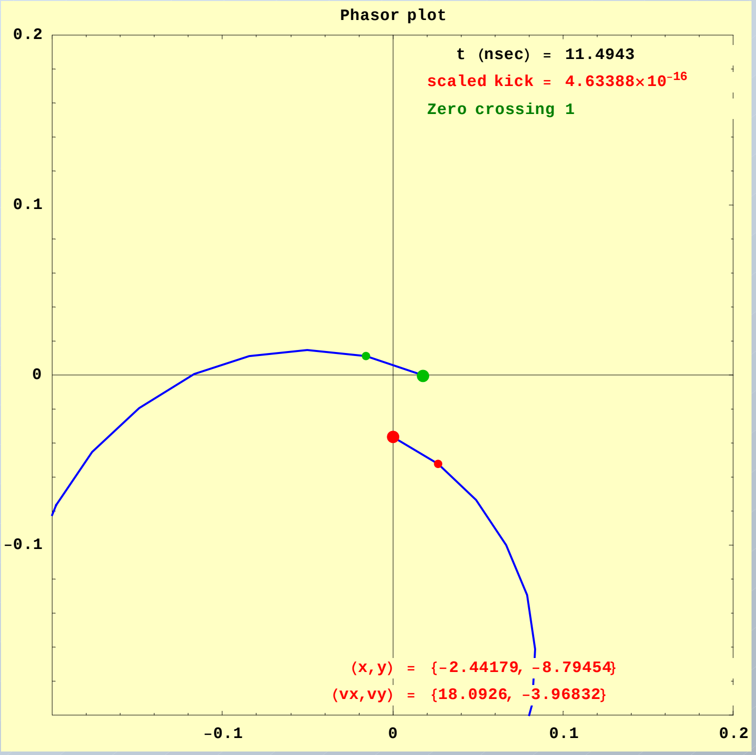
The “major zeroes” aren’t quite at the obvious symmetry points.

Kick corresponding to those phasors

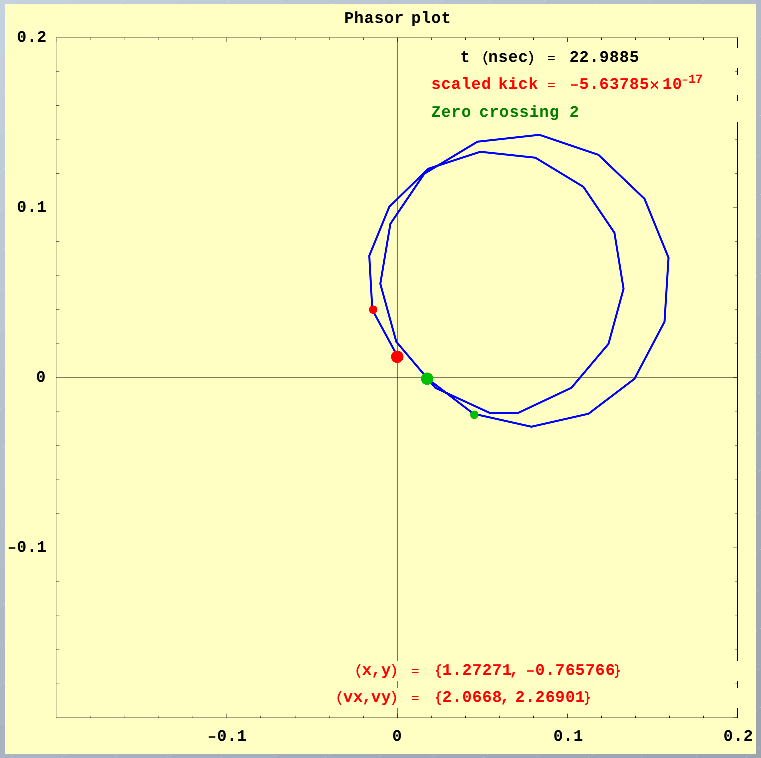


Here's where some of them are.

Phasors with amplitudes chosen to give $dp_T/dt = 0$ and $p_T = 0$ (29 cavities)



zero #1



zero #2

The phasor sums show less geometrical symmetry.

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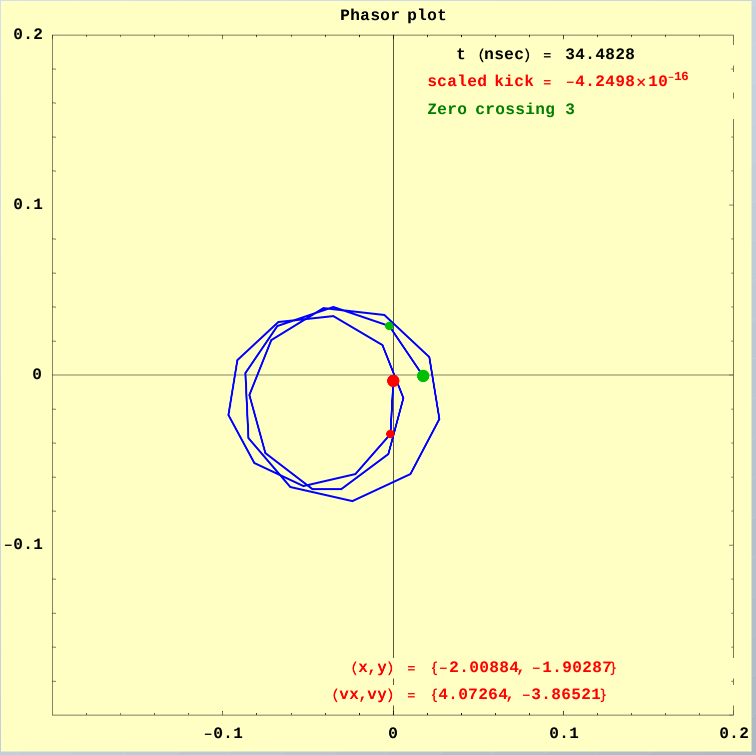
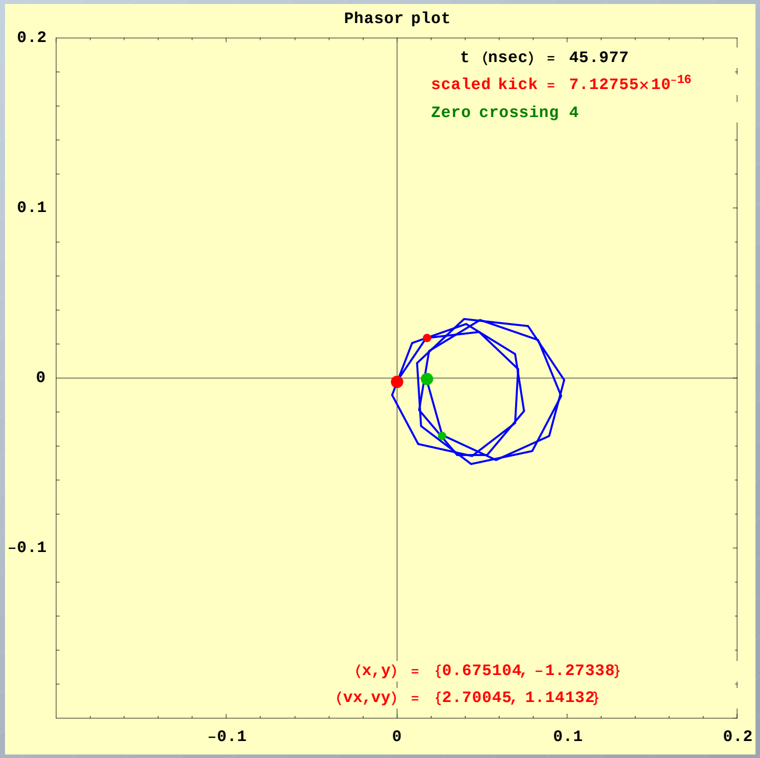
Phasors with amplitudes chosen to give $dp_T/dt = 0$ and $p_T = 0$ (29 cavities)



zero #3



zero #4

etc.

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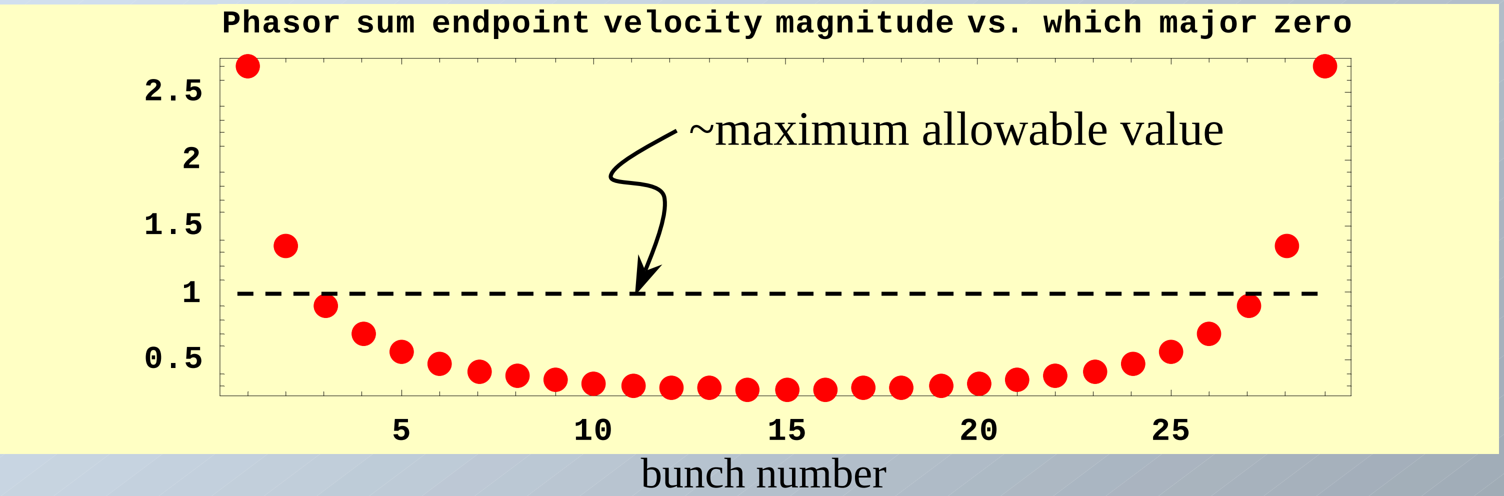
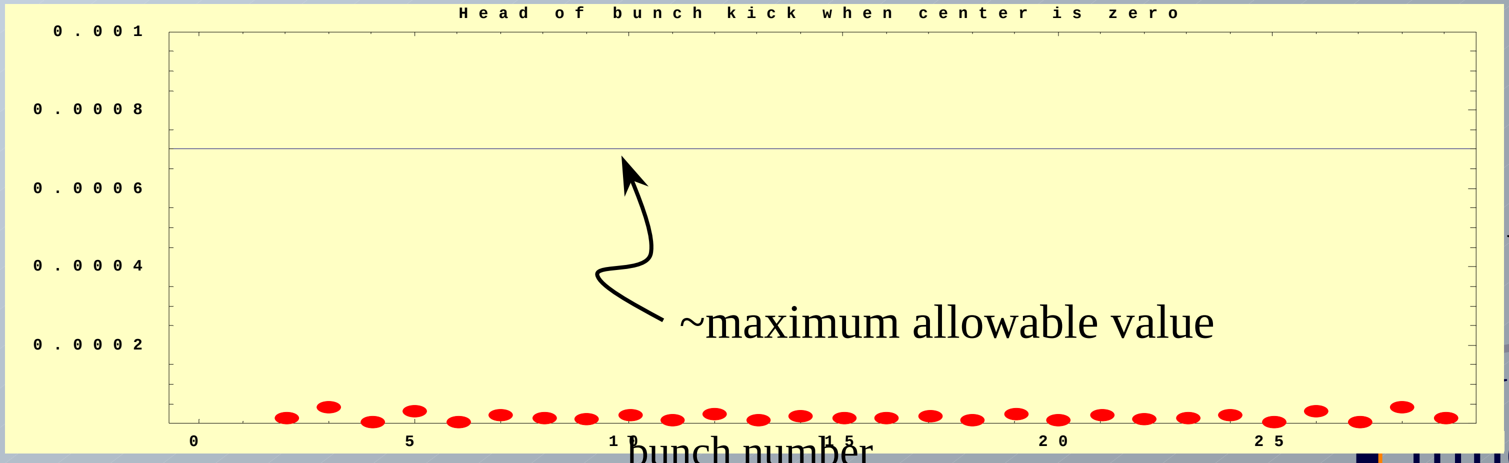
How well do we do with these amplitudes?

Old, equal-amplitudes scheme:



New, intelligently-selected-amplitudes scheme:



Wow!

Multiple passes through the kicker

Previous plots were for a single pass through the kicker.

Most bunches make multiple passes through the kicker.

Modeling of effects associated with multiple passes must take into account damping ring's

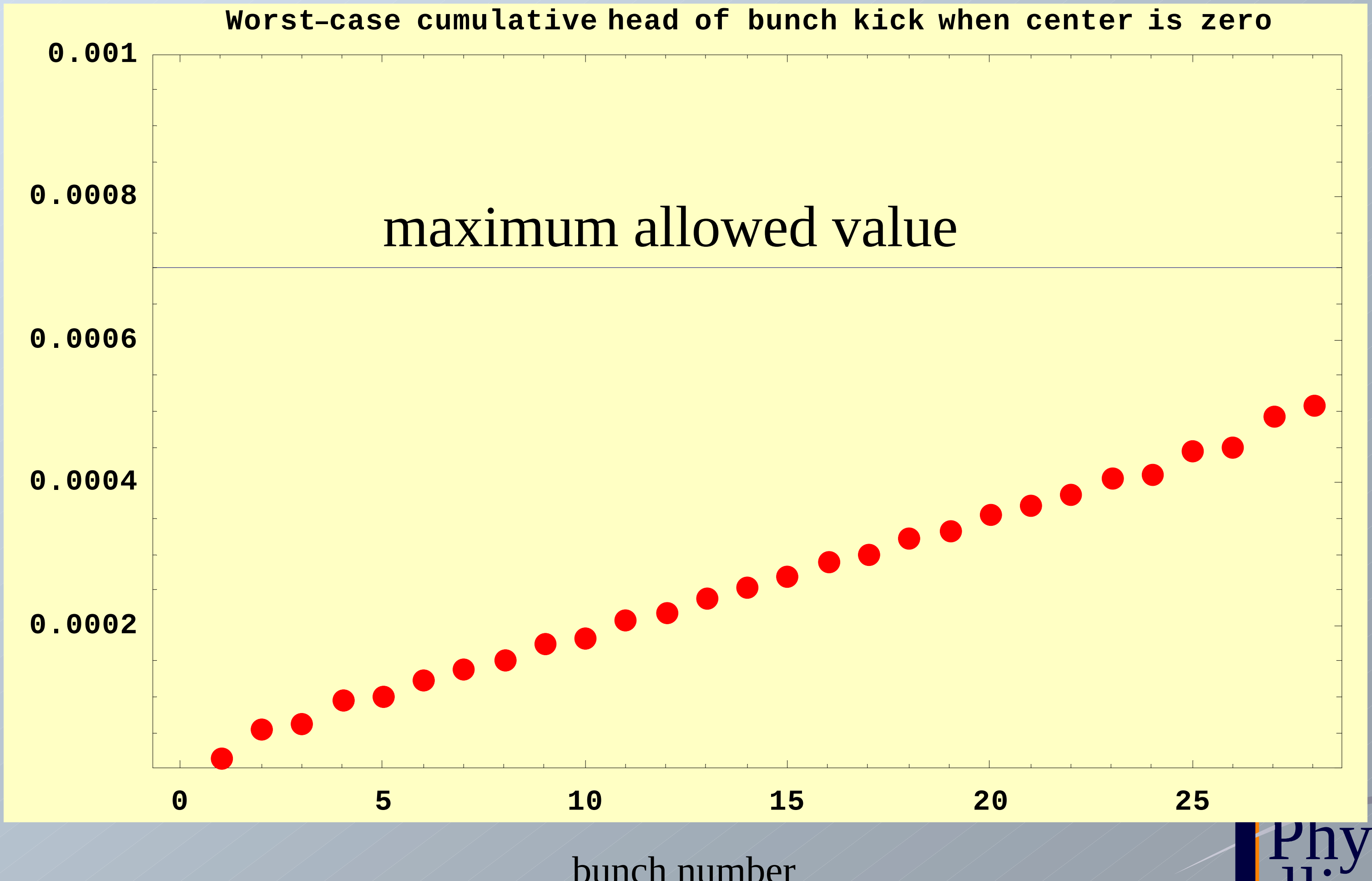
- synchrotron tune (0.10 in TESLA TDR)
- horizontal tune (72.28 in TESLA TDR)

We (in particular, Keri Dixon) are working on this now.

With equal-amplitude cavities some sort of compensating gizmo on the injection/extraction line (or immediately after the kicker) is probably necessary. However…

Multiple passes through the kicker

…selecting amplitudes to zero out p_T slopes fixes the problem! Here’s a worst-case plot (assumes tune effects always work against us).



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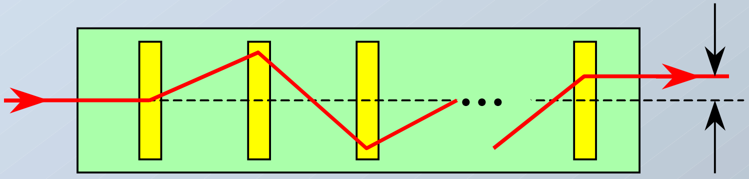
Some of our other concerns

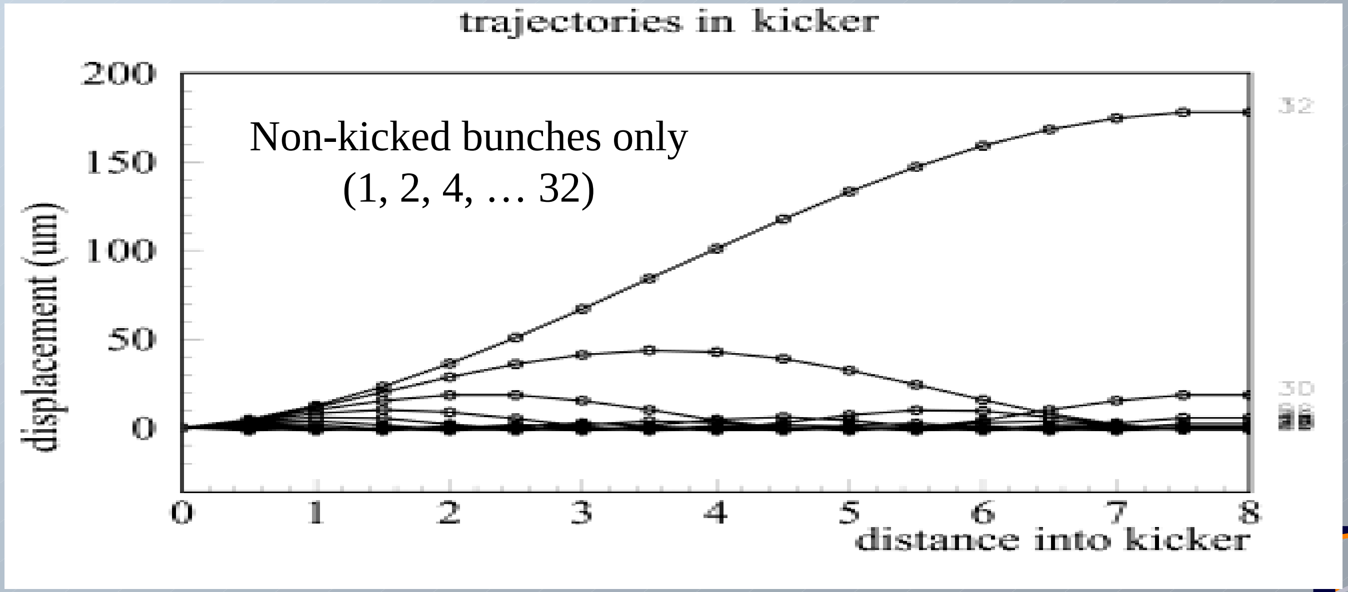
1. Effect of finite separation of the kicker cavities along the beam direction (George)
2. Arrival time error at the kicker for a bunch that is being injected or extracted (Keri)
3. Inhomogeneities in field integrals for real cavities (Keri)
4. What is the optimal choice of cavity frequencies and amplitudes? (Guy)

Finite separation of the kicker cavities



Even though net p_T is zero there can be a small displacement away from the centerline by the end of an N-element kicker.

For N = 16; 50 cm cavity spacing; 6.5 Gauss-meter per cavity:



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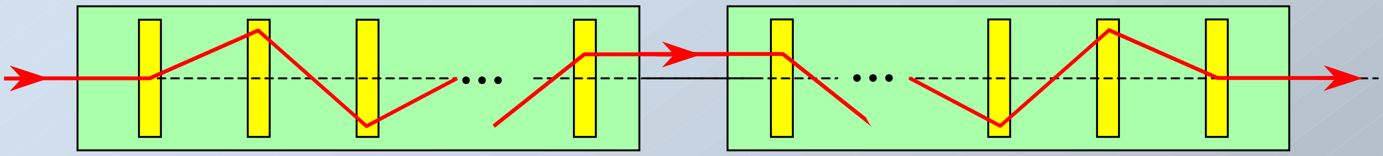
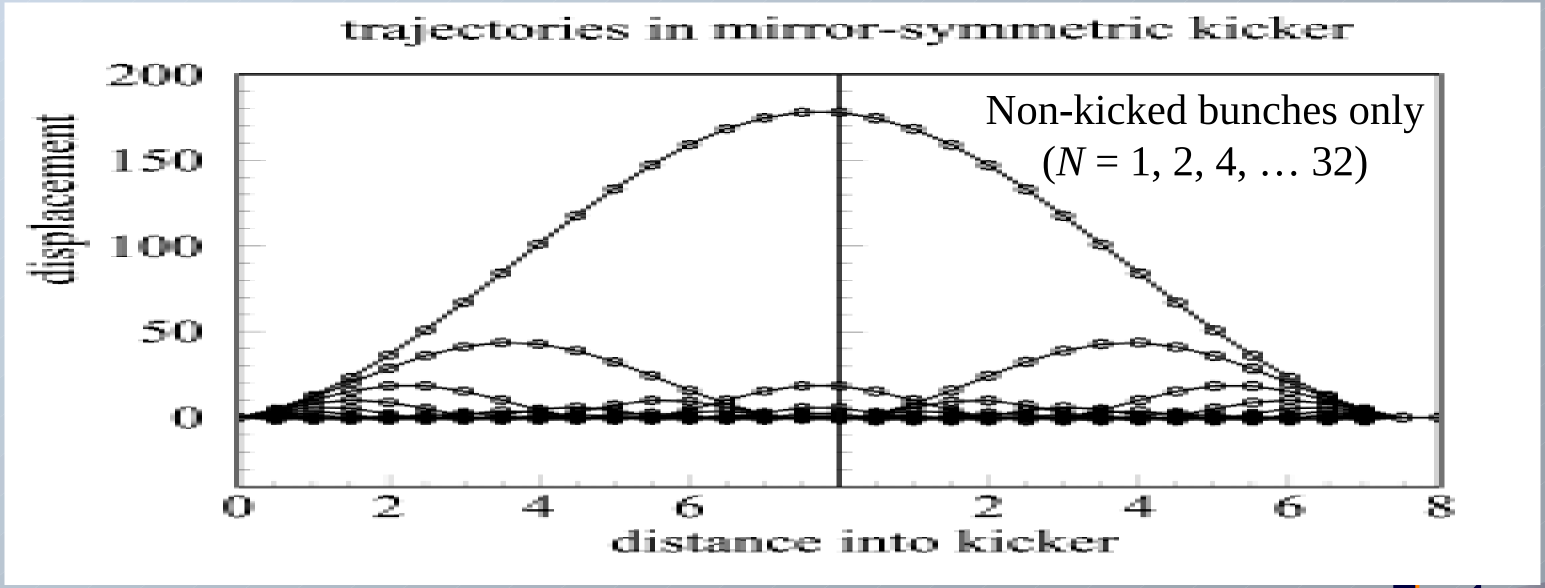
Finite separation of the kicker cavities



Compensating for this: insert a second set of cavities <u>in phase</u> with the first set, but with the order of oscillation frequencies reversed: 3 MHz, 6 MHz, 9MHz,… followed by …, 9 MHz, 6 MHz, 3 MHz.



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Arrival time error at the kicker for a bunch that is being injected or extracted

What happens if a bunch about to be kicked passes through the kicker cavities slightly out of time?

It depends on the details of the kicker system:

- 16-cavity system with 3MHz, 6MHz,… cavities:

  $\delta p_T/p_T \sim 6 \times 10^{-6}$

- 30-cavity system with 3.000GHz, 3.003GHz,… cavities:

  $\delta p_T/p_T \sim 9 \times 10^{-4}$ so an extraction line corrector is probably necessary

What we're working on now

- Lately we've been working with models using high-frequency cavities, split in frequency by multiples of the linac bunch frequency.
- We want to better understand how to select the best set of cavity frequencies an geometries.
- We are in the process of incorporating tune effects into our models.
- We will investigate the kinds of corrections necessary to compensate for tune and cavity-related effects.
- We will look into the relative merits of horizontal and longitudinal kicks.

Comments on doing this at a university

- Participation by talented undergraduate students makes LCRD 2.22 work as well as it does. The project is well-suited to undergraduate involvement.
- We get most of our work done during the summer: we're all free of academic constraints (teaching/taking courses). The schedule for evaluating our progress must take this into account.
- Support for students comes from (NSF-sponsored) REU program. We have borrowed PC's from the UIUC Physics Department instructional resources pool for them this summer.
- LCRD 2.22 requested $2,362 in support from DOE (mostly for travel). In spite of a favorable review by the Holtkamp committee, DOE has rejected the proposal. (We don't know why.) We're continuing with the work, in spite of this.

Conclusions

- We haven’t found any obvious show-stoppers yet.
- It seems likely that intelligent selection of cavity amplitudes will provide us with a useful way to null out some of the problems present in a more naïve scheme.
- We haven’t studied issues relating to precision and stability yet. later this summer…
- This is a lot of fun.