Studies of Alternative TESLA Damping Ring Designs

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and
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Damping ring introduction

TESLA damping ring fast kicker must inject/eject every n^{th} bunch, leaving adjacent bunches undisturbed.

Minimum bunch separation inside damping rings determines size of the damping rings.

It's the kicker speed which limits the minimum bunch spacing.

Damping ring introduction

TESLA TDR:

- linac: 2820 bunches, 337 nsec spacing (~ **300** kilometers)
- damping ring: 2820 bunches, 20 nsec spacing (~ **17** kilometers)

Required vacuum (to avoid ion instabilities) mandates a pump every four meters in the damping ring.

Would a faster kicker and a different extraction technique permit smaller bunch spacing and a smaller damping ring?

Fermilab-centered efforts

FNAL has identified damping rings and kickers as a major area of concentration for its linear collider effort.

March 15-18 working meeting to focus our thinking:

- development of a 6 km damping ring lattice
- improved wiggler field maps
- electron cloud and positive ion instability calculations for a small damping ring
- discussions of how to evaluate the dynamic aperture of a small ring
- discussions of novel kicker schemes, including a brand new idea from Joe Rogers.

We calculated away, and met with FNAL engineers. No PowerPoint!

Participants, either live or via phone

Argonne
Louis Emery
Kwang-Je Kim

Cornell
Joe Rogers

DESY
Winni Decking
Nick Walker

Fermilab
Chris Jensen
George Krafczyk
Shekhar Mishra
David Neuffer
King-Yuen Ng
Jean-François Ostiguy
Kirti Ranjan
Nikolay Solyak
Aimin Xiao

Illinois
George Gollin

LBNL
Andy Wolski

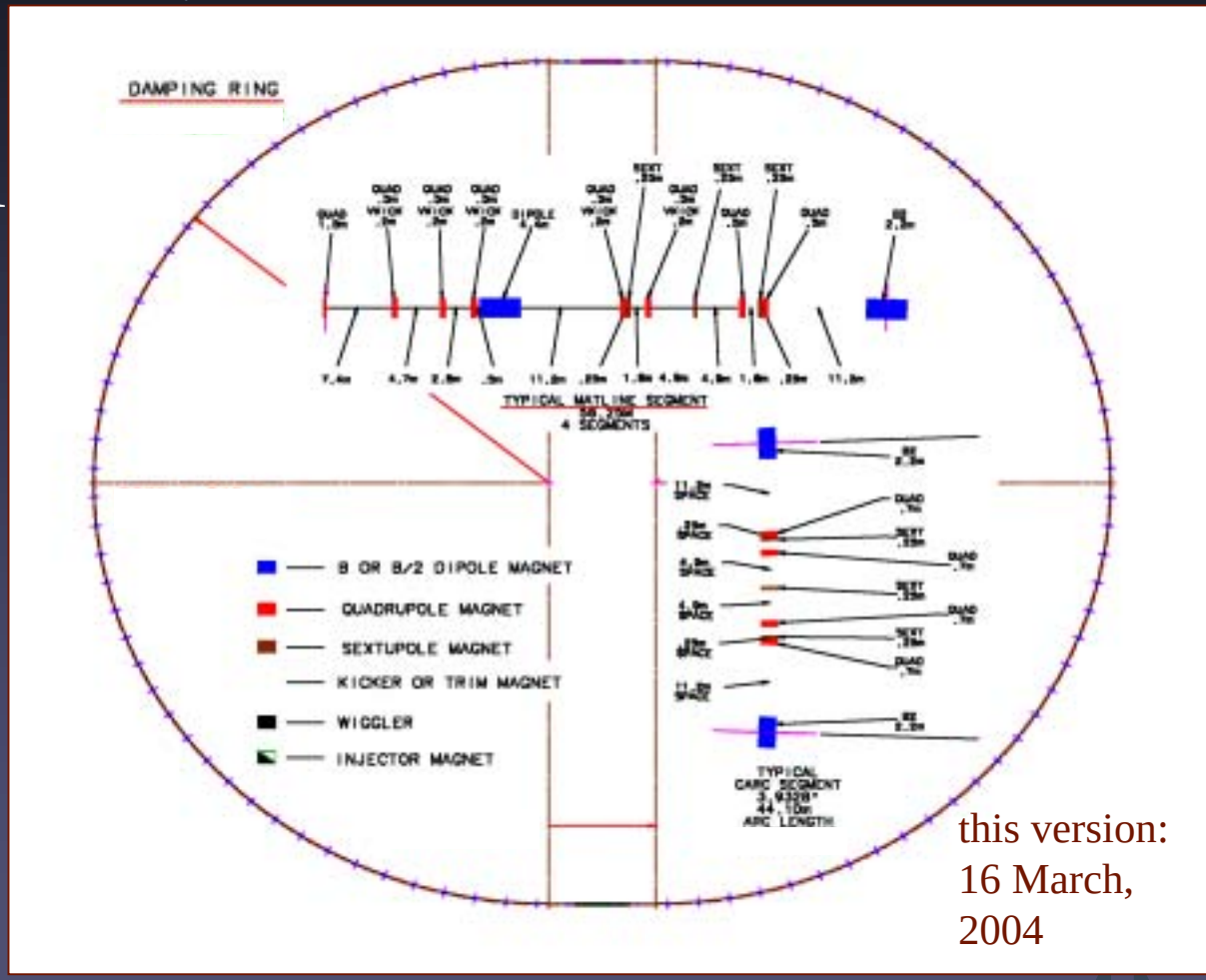
SLAC
Tor Raubenheimer

Damping Ring Lattice

What might a damping ring, small enough to fit into the Tevatron or HERA or tunnels, look like?

In the diagram: an early version, ~4 km circumference, 2 straight sections.

Current version: 6 kms, 6 straight sections, 25 wigglers.



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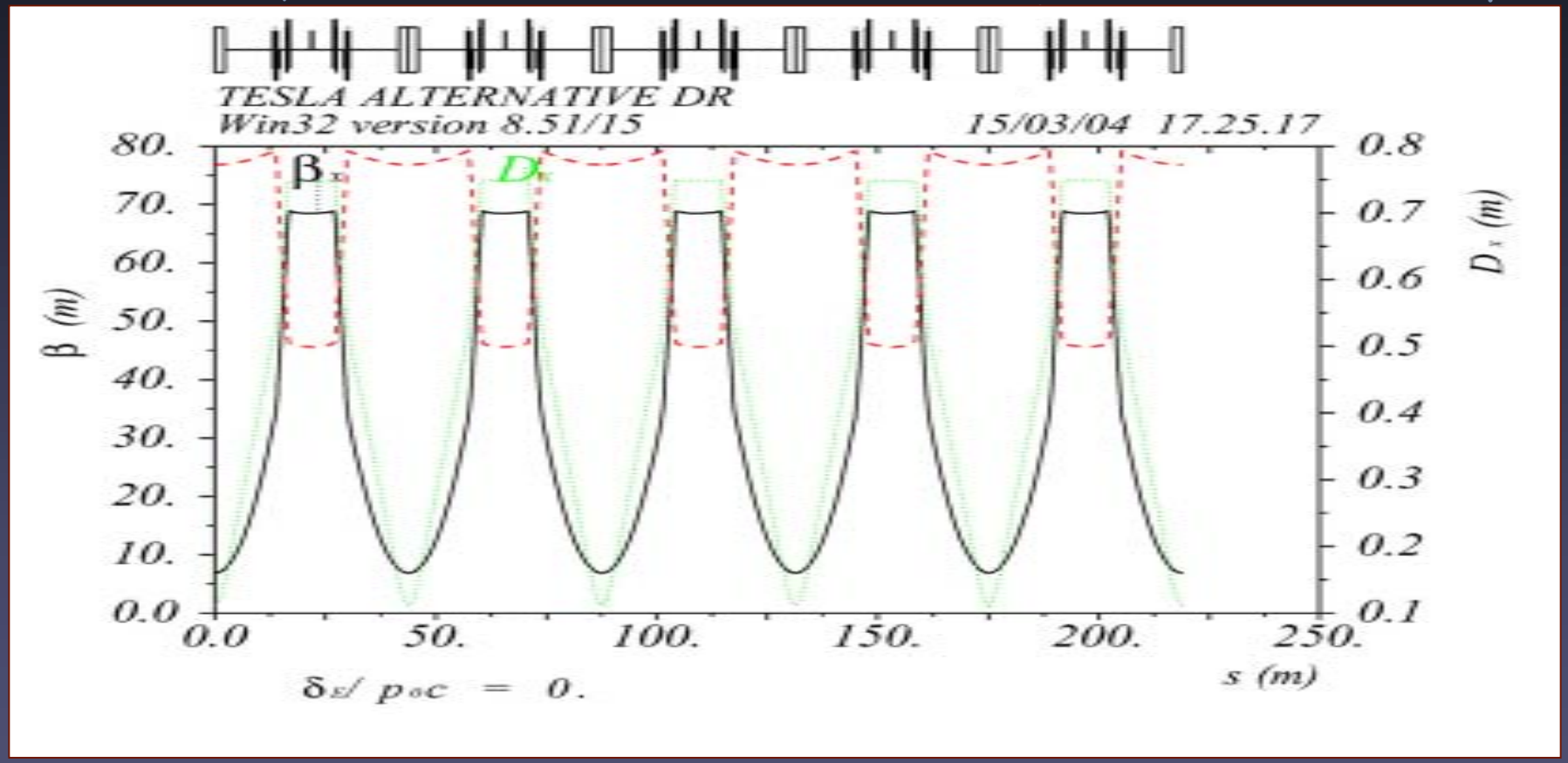
β-functions and dispersion, 6 km ring



Comparison of small ring and dogbone designs

Parameter	Small ring (e^+/e^-)	Dogbone (e^+/e^-)
Energy	5 GeV	5 GeV
Circumference	6.12 km	17 km
Horizontal emittance γe_x	8 mm·mr	8 mm·mr
Vertical emittance γe_y	0.02 mm·mr	0.02 mm·mr
Transverse damping time τ_d	28 ms / 44 ms	28 ms / 50 ms
Current	443 mA	160 mA
Energy loss/turn	7.3 MeV / 4.7 MeV	21 MeV / 12 MeV
Radiated power	3.25 MW / 2.1 MW	3.2 MW / 1.8 MW
Tunes Q_x, Q_y	62.95, 24.52	72.28, 44.18
Chromaticities ξ_x, ξ_y	-112, -64	-125, -68

Other small-ring parameters (1)

Parameter	Value
Revolution frequency	48.986 kHz
RMS bunch length	6.0000 mm, 0.020014 ns
RMS momentum spread	0.00130
Bunch area:	0.000409 eV·s (RMS), 0.002452 eV·s (full)
Bunching factor	0.6930E-02
Synchrotron tune	0.03681
RF voltage	23.91 MV
Momentum compaction	0.00017440
Electrons per bunch	2×10^{10}
Number of bunches	2820
Current/bunch	0.15697 mA
Peak current	63.87 A

Other small-ring parameters (2)

Parameter	Value
Electrons per bunch	2×10^{10}
Number of bunches	2820
Current/bunch	0.15697 mA
Peak current	63.87 A
Space charge tune shift (horizontal)	-0.0046
Space charge tune shift (vertical)	-0.0725 (-0.2015 for 3 GeV)
Longitudinal microwave instability limit	$Z/n = 0.14496\ \Omega$
Transverse coupled-bunch instabilities driven by resistive wall (Al beam pipe)	0.990 ms, 0.045 damping time
Fast-ion instability growth time, beam particles uniformly distributed along train	2.3 ns
Fast-ion instability growth time, inter-train gaps clear trapped ions completely	26 ms

Comments about a small damping ring

The present lattice design of the small damping ring uses 25 wigglers, so the beam dynamics issues associated with wigglers will be less complex.

Preliminary studies (results in the tables a few slides back) indicate that the small ring is stable.

The present lattice has six straight sections. This will allow inclusion of distributed correction schemes which address dispersion, coupling, higher order multipole corrections, and so forth.

It will take a <u>sustained, continuing effort</u> to make steady progress.

Long-term goals

Build a prototype damping ring/kicker system as part of an engineering test facility. Install ring in an existing tunnel at Fermilab.

Show that it works:

- damping ring produces low emittance beam
- kicker injects/extracts beam without destroying emittance
- linac can accelerate the beam while preserving its emittance…

…by building it, making it work, and measuring its properties.

Kicking in new ways

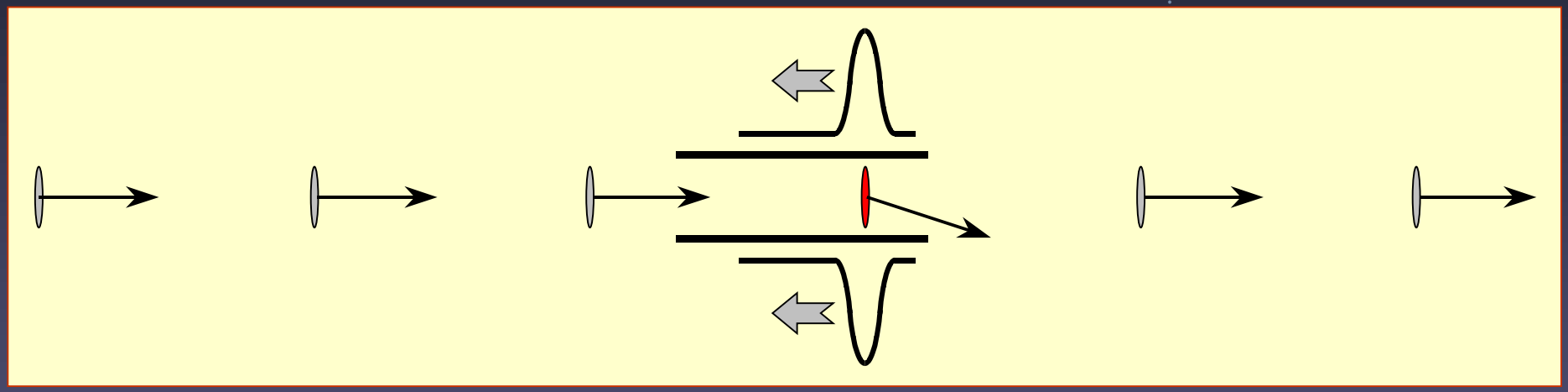
In tandem with damping ring studies we're investigating a few speculative ideas for different kickers and injection/extraction schemes.

Kicker schemes:

- multiple bunch trains with inter-train gaps
- longitudinal RF followed by a dispersive section
- Fourier series kicker
- chirped waveform pulse compression kicker

TESLA damping ring kicker *à la* TDR

TDR design: bunch "collides" with electromagnetic pulses traveling in the opposite direction inside a series of traveling wave structures. Hard to turn on/off fast enough.



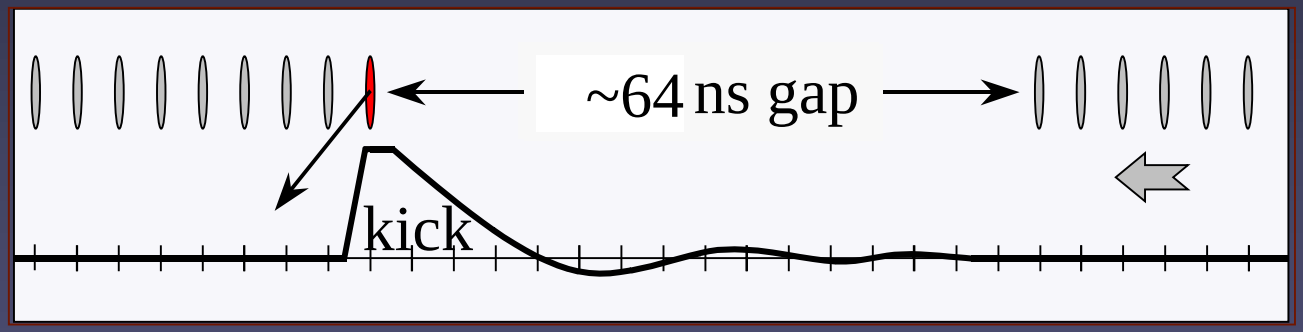
Fast kicker specs (*à la* TDR):

- $\int B\,dl$ = 100 Gauss-meter = 3 MeV/c (= 30 MeV/m × 10 cm)
- stability/ripple/precision ~.07 Gauss-meter = 0.07%

Multiple bunch trains with inter-train gaps
(Joe Rogers, Cornell)

It is easier to turn a kicker on than it is to turn it off.

Beam in DR would be grouped into trains separated by gaps. Eject the last bunch in each train.



Kicker needs to turn on during inter-bunch interval, but can turn off (and settle) during gap between trains.

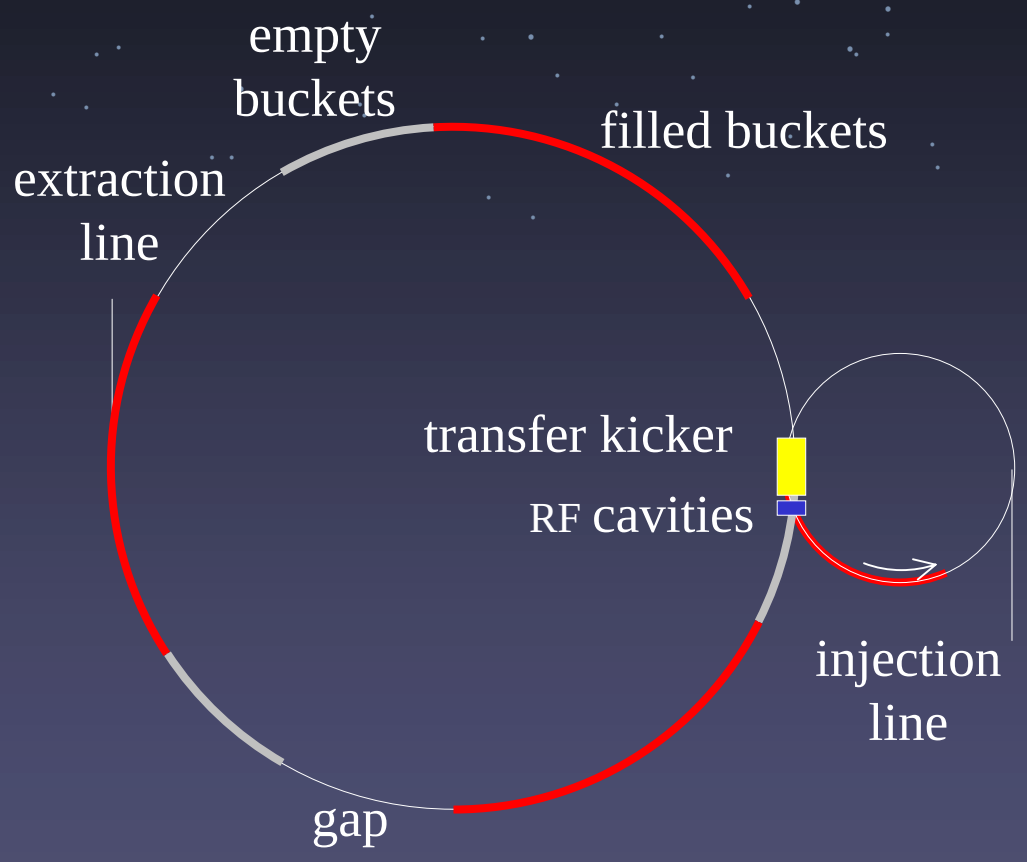
Multiple bunch trains with inter-train gaps

Always inject and eject the last bunch in a train.

If necessary, use a two-ring scheme to keep loading of DR RF constant. (It's a little complicated to explain quickly.)

Large ring ~6 km, filled by transfers of undamped trains from the ~100 m ring

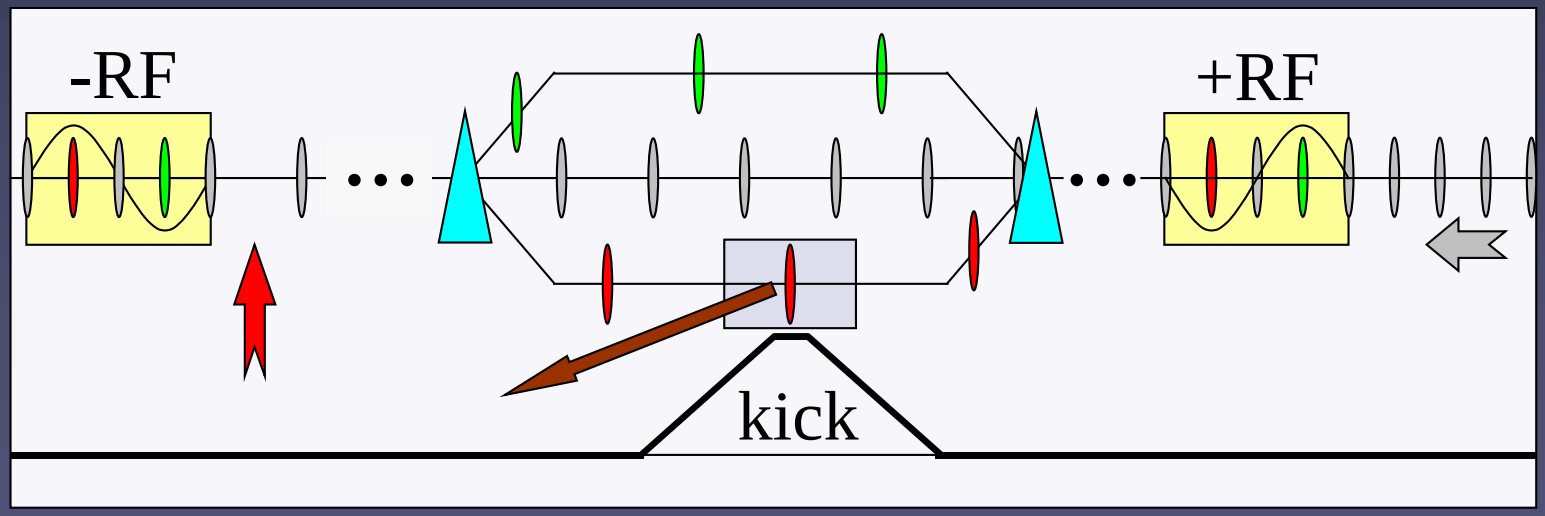
Kicker ideas being discussed at Fermilab.



Longitudinal RF followed by a dispersive section
(Dave Rubin, Cornell)

Split the energies of successive bunches, then send bunches down energy-dependent (separate, equal-length) paths.

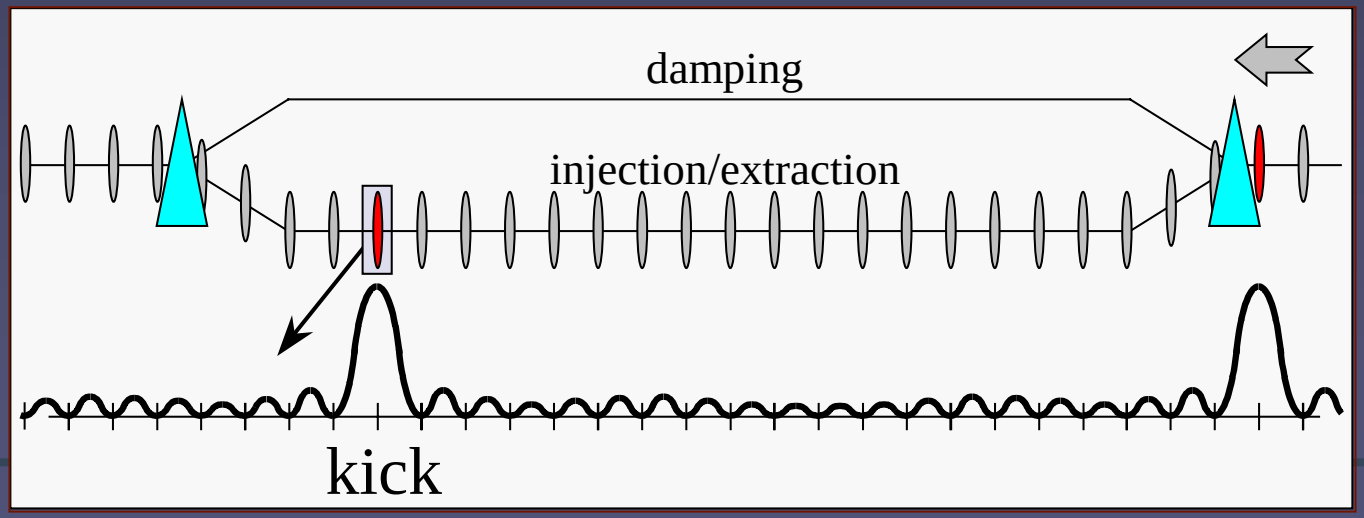
- kicker rise, fall times can be 4× bunch spacing
- could be combined with Joe Rogers' idea to accommodate longer fall-time kicker



Fourier series kicker
(George Gollin, Illinois)

Kicker is a series of *N* transverse RF cavities tuned to frequencies which differ by ~3 MHz.

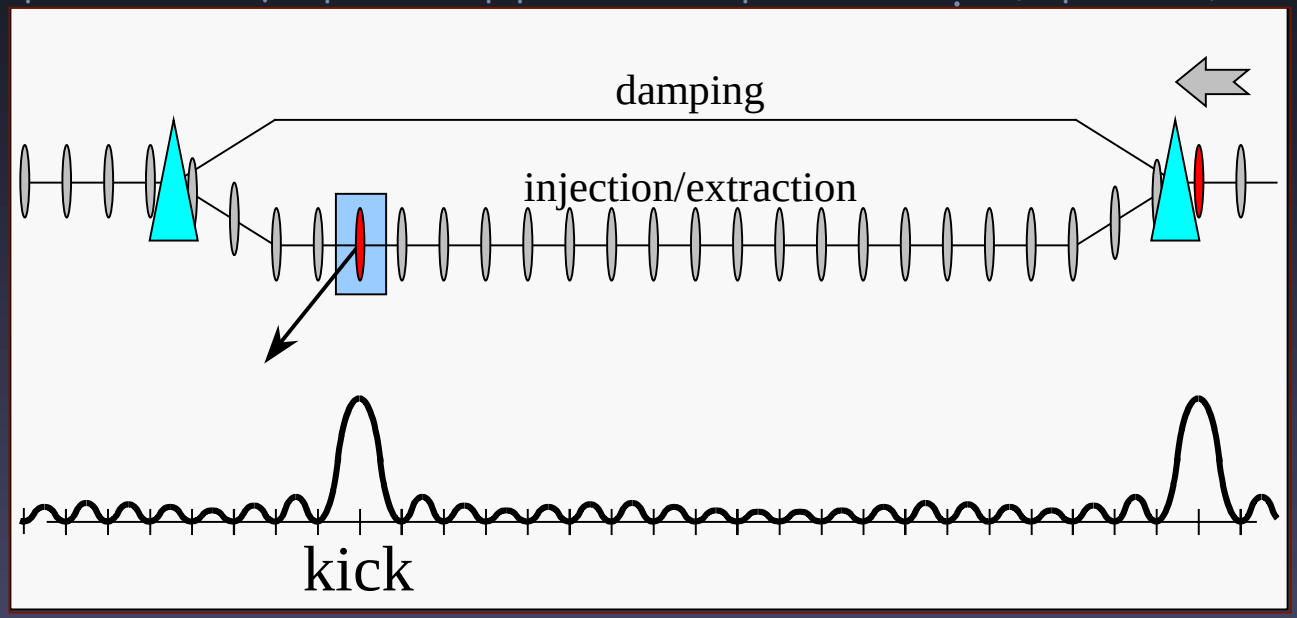
- proper adjustment of amplitudes and phases kicks one bunch while leaving the next (*N*-1) undisturbed.
- intelligent choice of amplitudes permits $p_T = 0$ <u>and</u> $dp_T/dt = 0$ for unkicked bunches.
- transverse kick minimizes beam-induced fields in cavities.



Damping ring operation with an FS kicker

Fourier series kicker would be located in a bypass section.

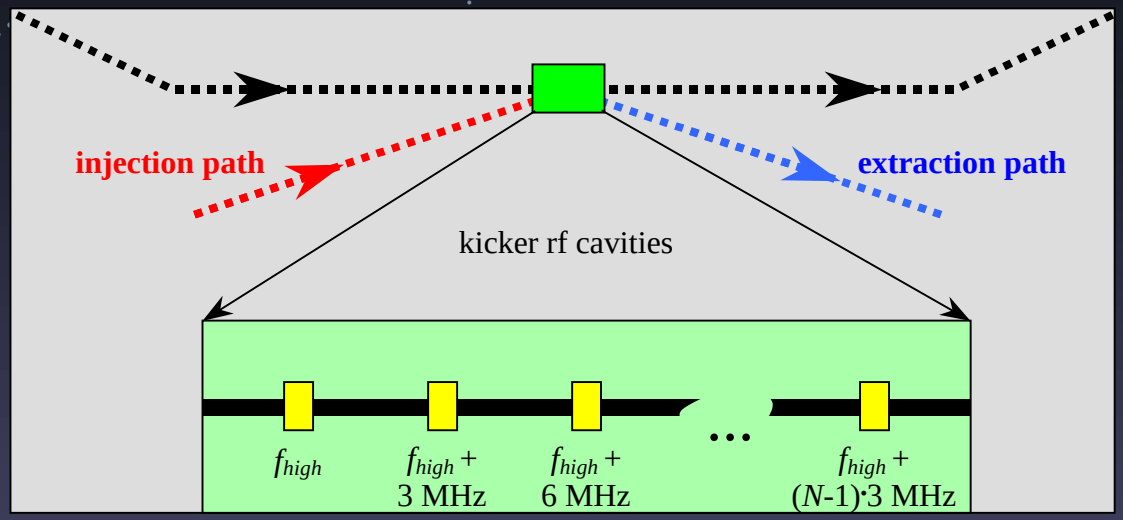
While damping, beam follows the upper path.



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

SCRF and transverse kick minimize beam-induced fields in cavities.

Fourier series kicker



N "rf cavities" oscillating at harmonics of the linac bunch frequency:

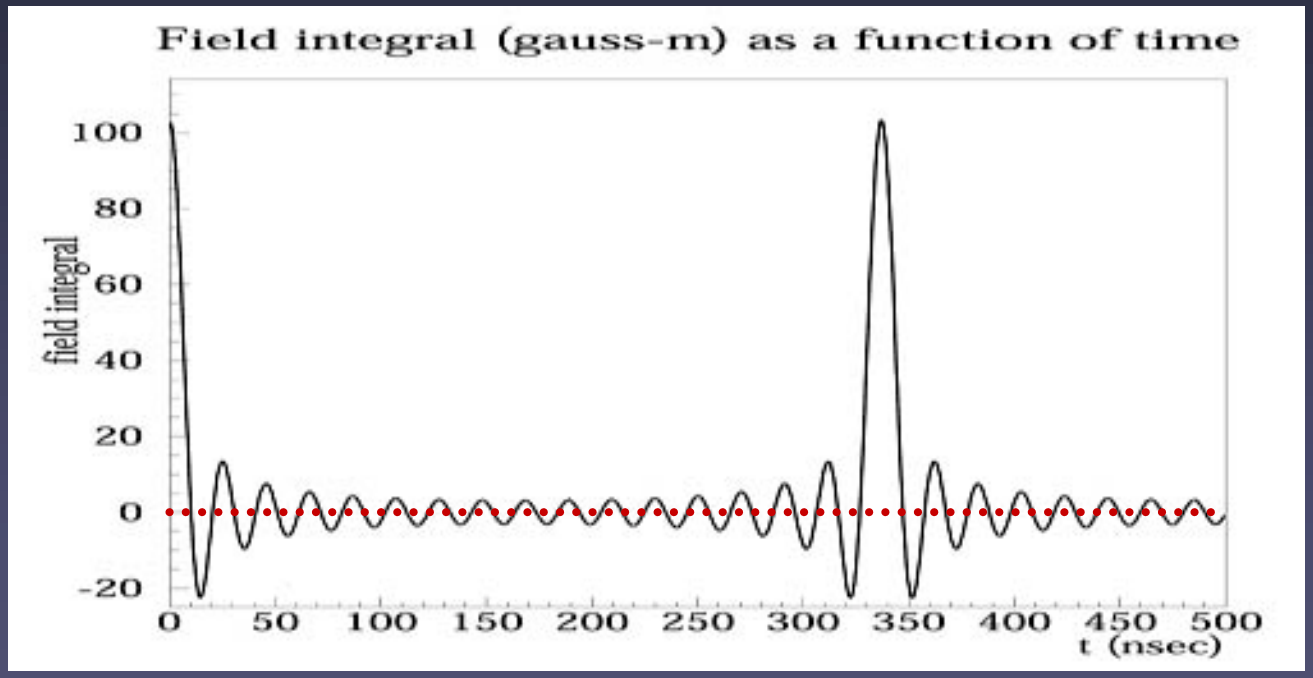
$$p_T = A\left[\sum_{j=0}^{j=N_{cavities}-1} A_j \cos\left[\left(\omega_{high} + j\omega_{low}\right)t\right]\right]; \quad \omega_{low} = \frac{2\pi}{337\ \text{ns}}$$

Version 1

Run transverse kicking cavities at 3 MHz, 6 MHz, 9 MHz,… in phase with equal amplitudes. Unkicked bunches traverse kicker when field integral sums to zero.

Problems with this:

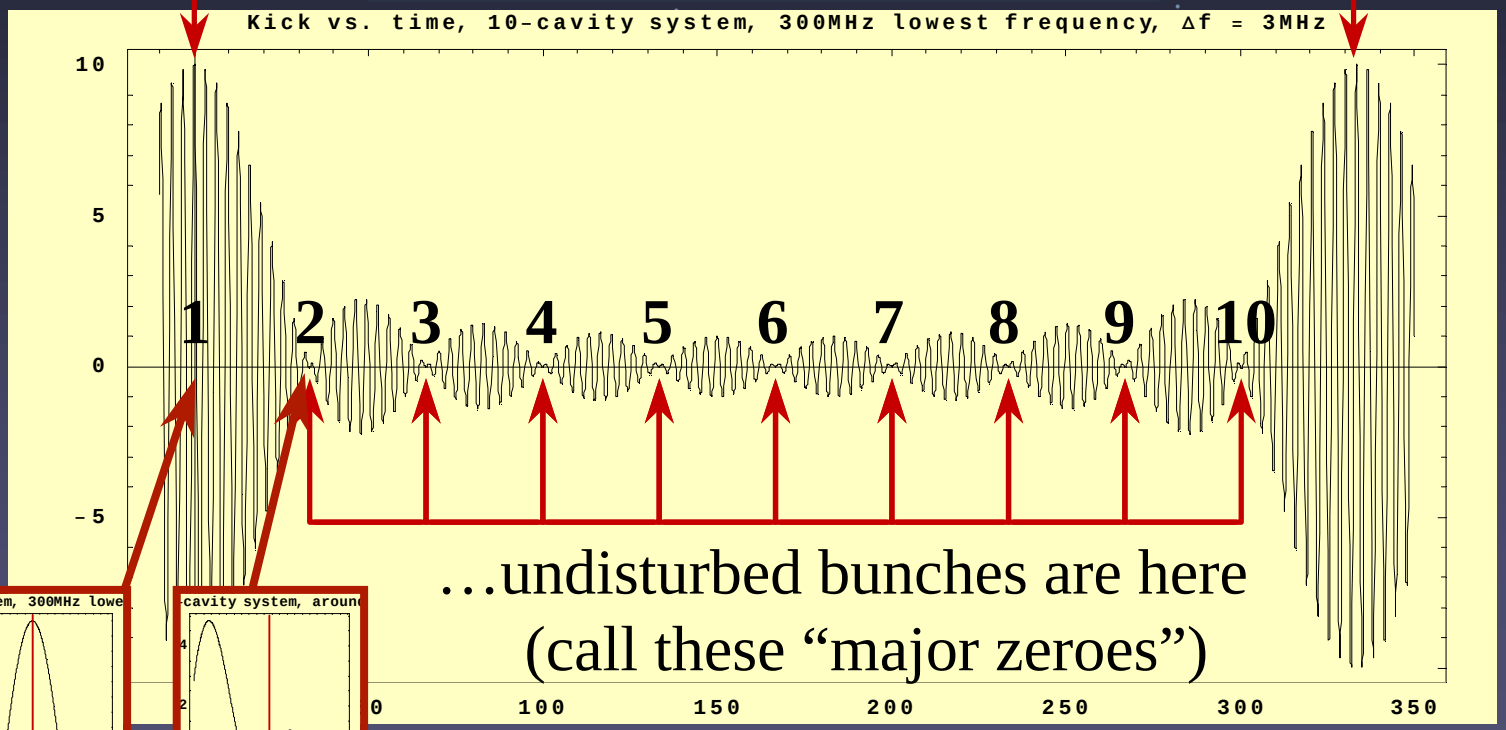
- slope at zero-crossings might induce head-tail differences
- LOTS of different cavity designs (one per frequency)



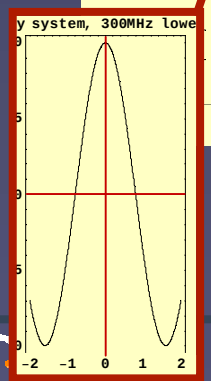
Better idea: permits one (tunable) cavity design

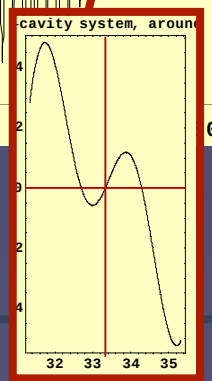
Run transverse kicking cavities at much higher frequency; split the individual cavity frequencies by 3 MHz. (V. Shiltsev)

Kicked bunches are here



…undisturbed bunches are here
(call these "major zeroes")





Still a problem: finite slope at zero-crossings.

Eliminating head-tail effects

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

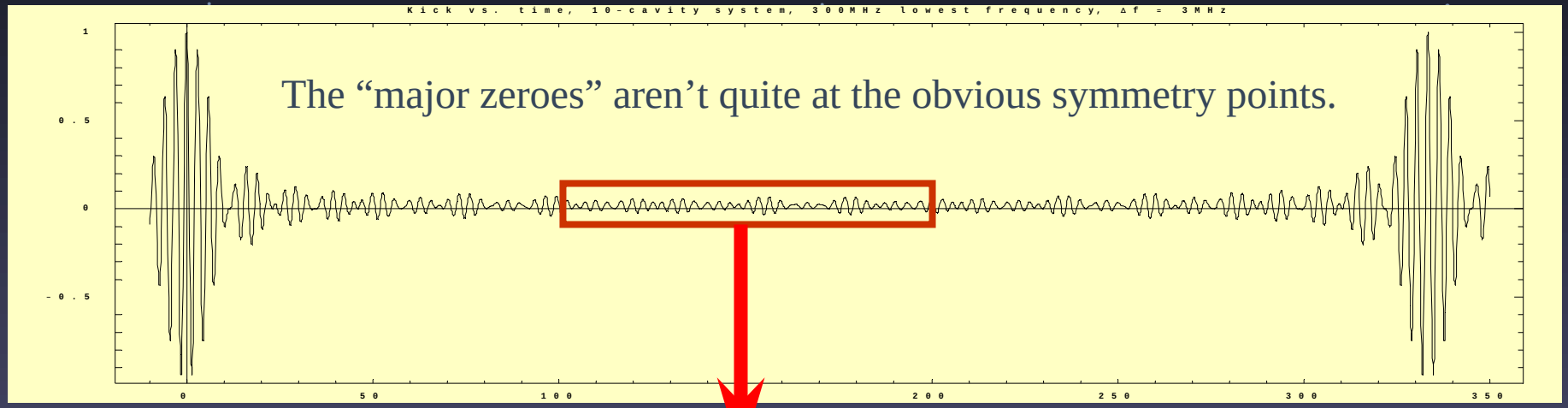
We (in particular Guy Bresler, an undergraduate[!!]) figured this out last summer

Bresler's algorithm finds sets of amplitudes which have $dp_T/dt = 0$ at evenly-spaced "major zeroes" in p_T.

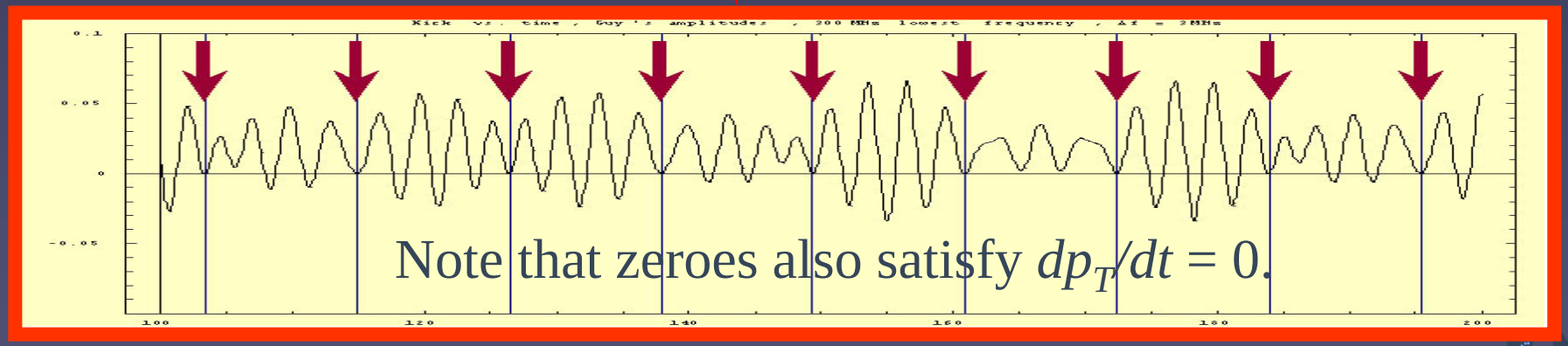
There are <u>lots</u> of different possible sets of amplitudes which will work.

Kick corresponding to those amplitudes

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



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



Note that zeroes also satisfy $dp_T/dt = 0$.

Is there an even better way to do this?

In a Fourier series kicker, the beam sums the effects of the different (high-Q) cavities.

60 cavities would allow the damping ring to fit into the Tevatron (or HERA) tunnel.

That's a lot of cavities to stabilize.

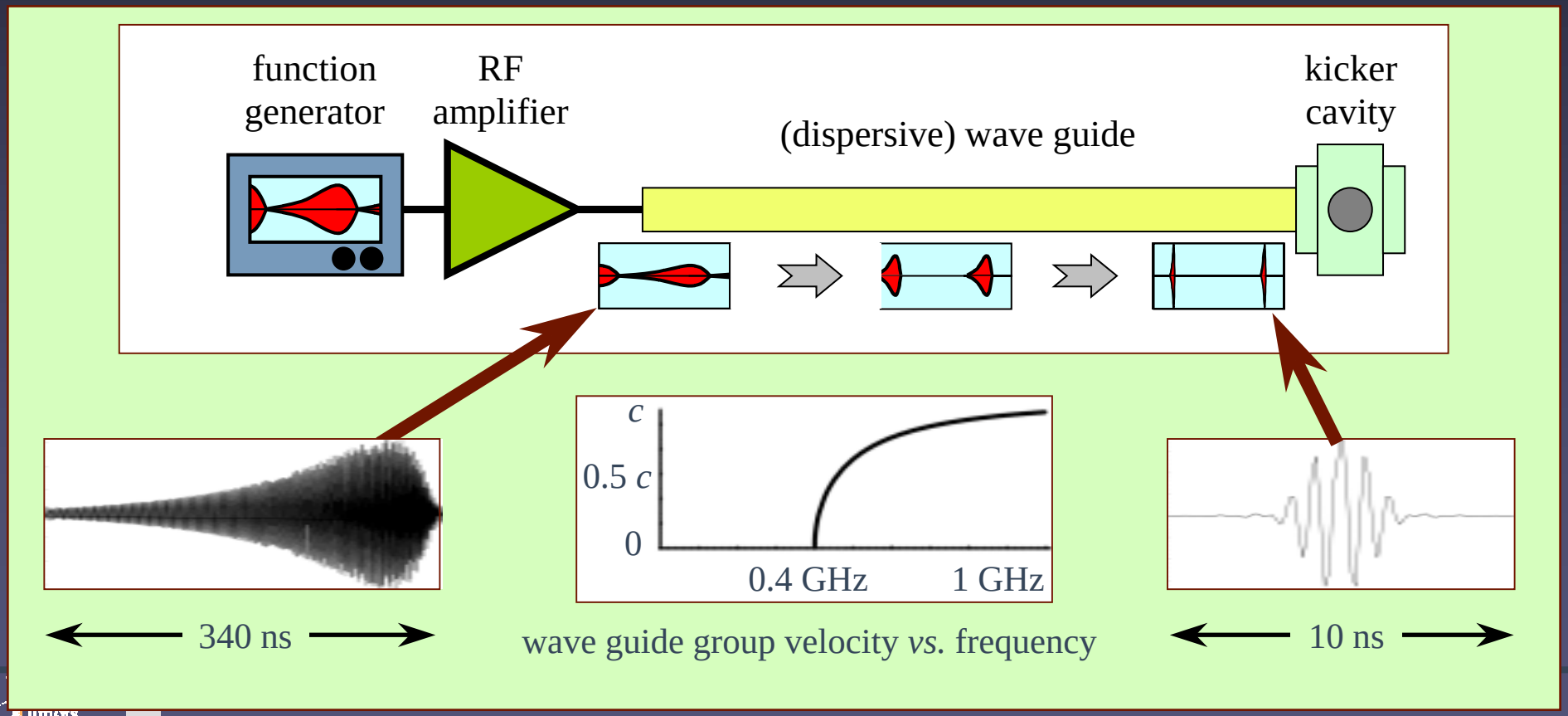
Is there a way to sum the different frequencies in a <u>single</u> cavity?

Yes, maybe…

Chirped waveform pulse compression kicker
(Joe Rogers, Cornell)

Dispersive wave guide compresses chirped RF signal.

Commercial broadcast RF amplifier ~100kW, but compression generates large peak power for kicking pulse in low-Q cavity.



Chirped waveform pulse compression kicker

In effect, the amplifier launches different frequencies down the waveguide at different times. Slowest-traveling frequency is injected first, fastest-traveling frequency last.

All frequencies arrive simultaneously at the cavity.

Unlike Fourier series kicker, in which bunches “sum” the effects of different frequencies, this design uses the cavity to form the sum.

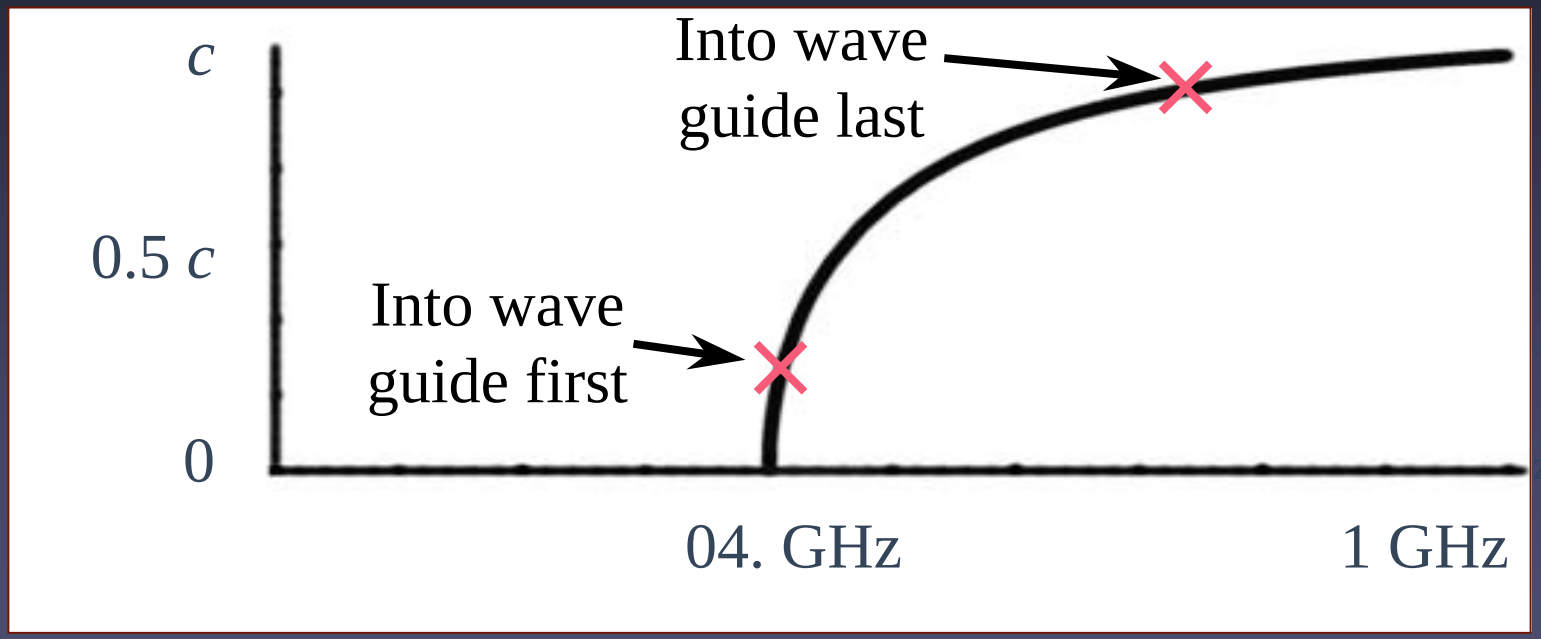
System is linear, so low-power tests can be used to evaluate concept. (Fermilab is interested in pursuing this.)

Programmable function generator can be reprogrammed to compensate for drifts and amplifier aging

Group velocity vs. frequency

Dispersive wave guide compresses chirped RF signal.

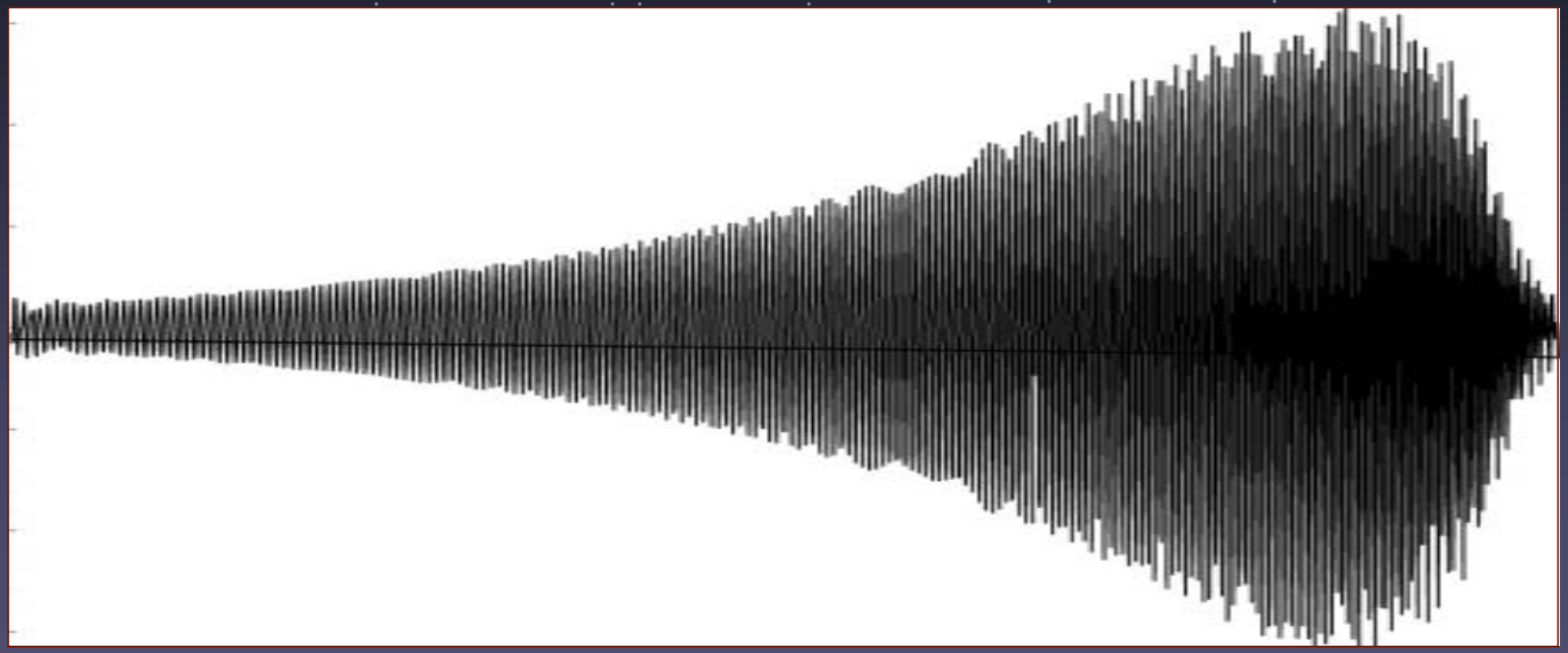
500 MHz signal travels more slowly than 1 GHz signal.



wave guide group velocity *vs.* frequency

Chirped signal into the wave guide…

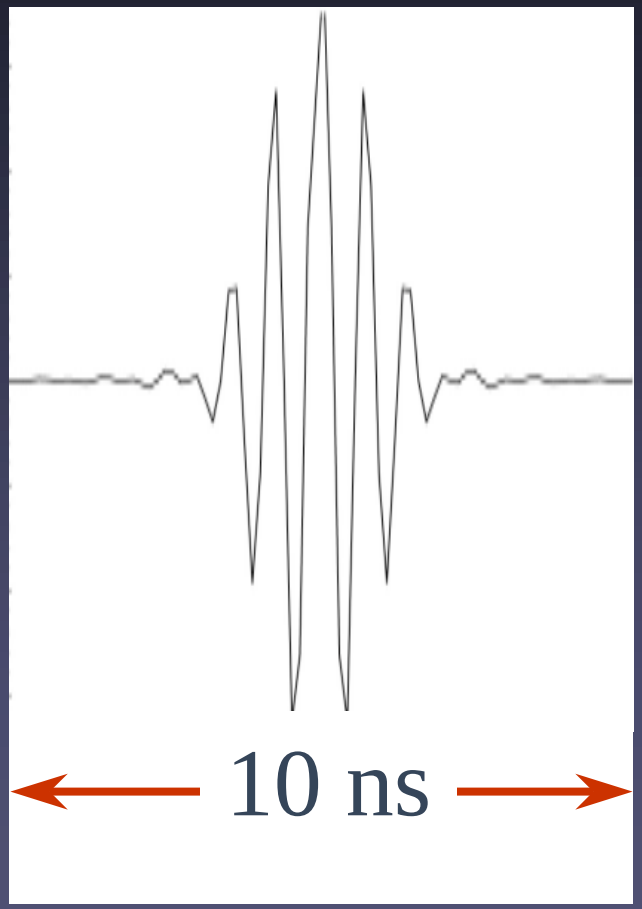
Wave guide input signal (not from actual measurements!):



340 ns

Signal at the far end of the wave guide…

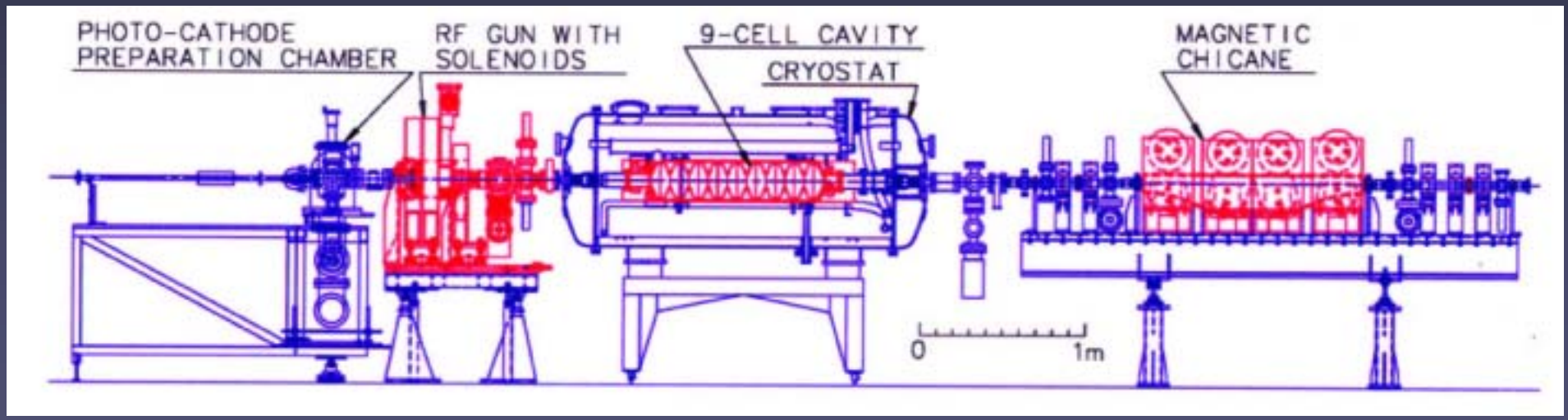
Narrow!



Testing our kicker ideas

A0 photoinjector lab at Fermilab produces a relativistic (16 MeV now, 50 MeV in a few months), bunched low-emittance electron beam. (It's rather like a TESLA injector.)

This should be an excellent facility for kicker studies!



Fermilab resources

Fermilab's EE Department has assigned an engineer (with significant experience in kicker design and fabrication) to develop ideas for a small damping ring's kicker system.

Fermilab's Magnet Design Group is also investigating kicker designs.

Beam Physicists at FNAL are developing detailed maps of wigglers for damping ring beam dynamics calculations.

We are collaborating with physicists from ANL, BNL: their light source experience and modeling tools will aid in the development of an improved lattice as we study the properties of a small damping ring.

Fermilab expects to develop a full design for a small damping ring (including design of accelerator components and cost estimates), in order to allow meaningful comparison with the present TESLA damping ring design.

Summary/conclusions

It is possible that alternative TESLA damping ring and kicker designs will allow the construction of smaller rings.

Simulations are encouraging; we will begin testing some of these ideas over the next few months at Fermilab. Stay tuned!