Fourier engineering: progress on alternative TESLA kickers

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Introduction

Linac beam (TESLA TDR):

•2820 bunches, 337 nsec spacing (~ **300** kilometers)

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

Damping ring beam (TESLA TDR):

•2820 bunches, ~20 nsec spacing (~ **17** kilometers)

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

Kicker speed determines minimum damping ring circumference.

We are investigating a "Fourier series kicker": use a series of rf cavities to create a kicking function with periodic zeroes and an occasional spike. Perhaps closer bunches/smaller damping ring will be possible?

Participants

This project is part of the US university-based Linear Collider R&D effort (LCRD/UCLC)

Fermilab

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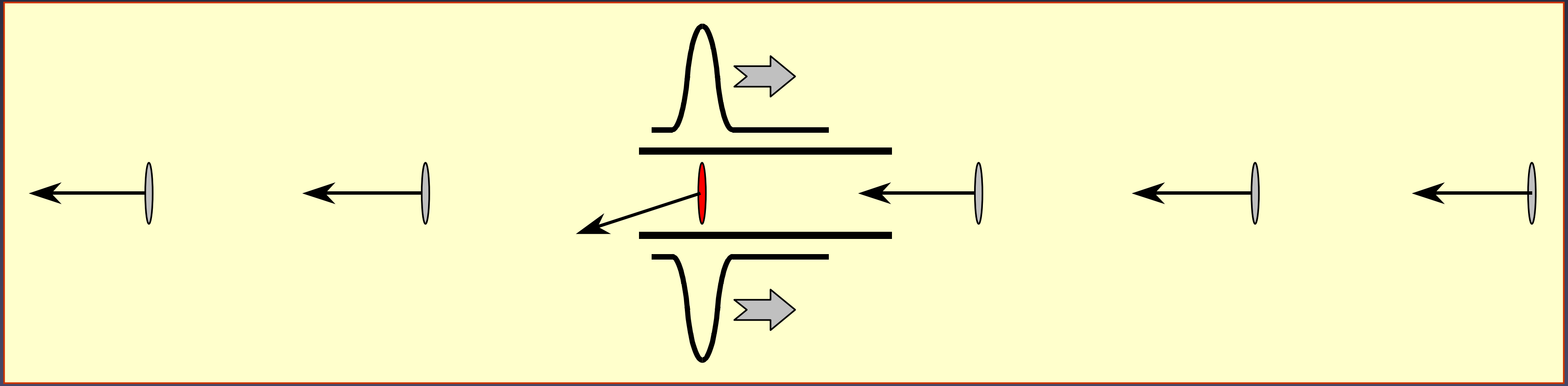
TESLA damping ring kicker *à la* TDR

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%

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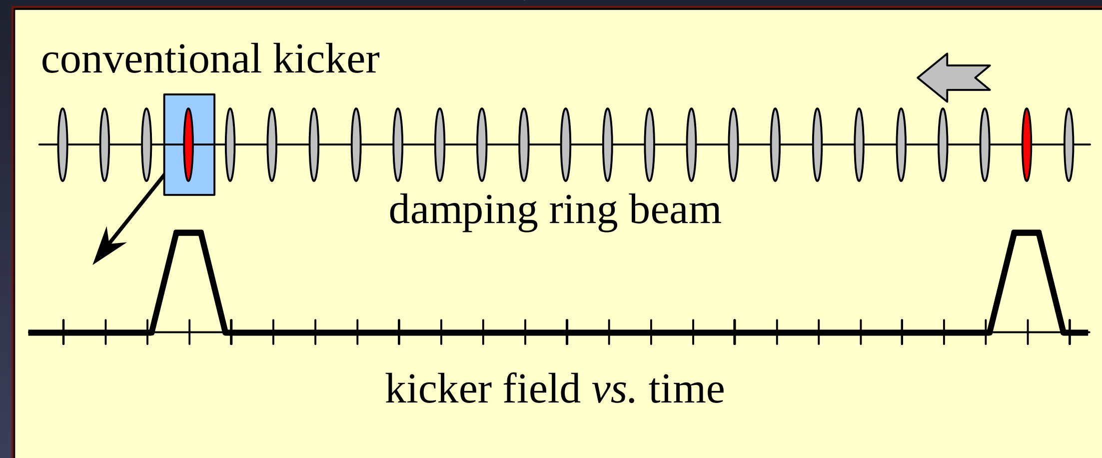
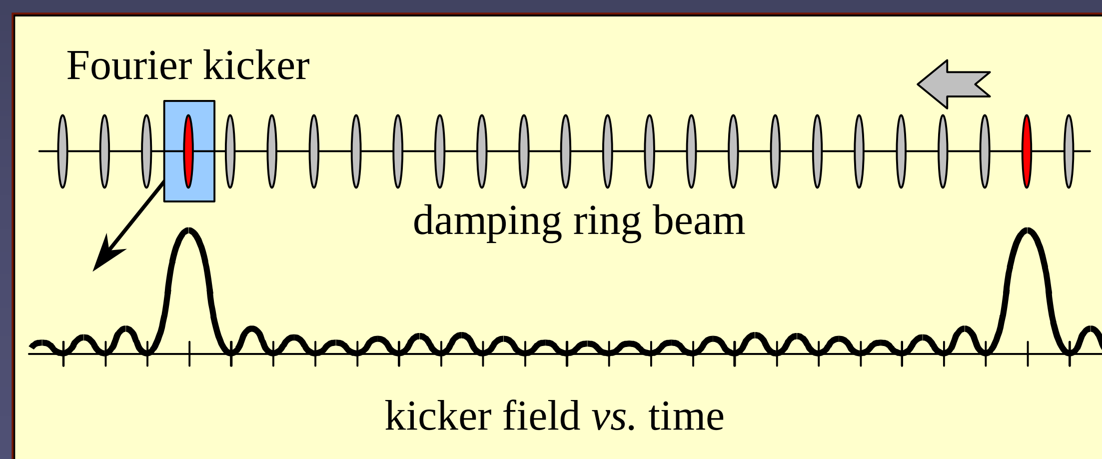
Since it's hard to turn on/off, why not leave it ON all the time?

Kicker field needs to be zero when unkicked bunches pass through.



Fields when kicker is empty of beam are irrelevant.

Synthesize kicker impulse from Fourier components of something with good peaks and periodic zeroes.



Kicker is <u>always</u> on.

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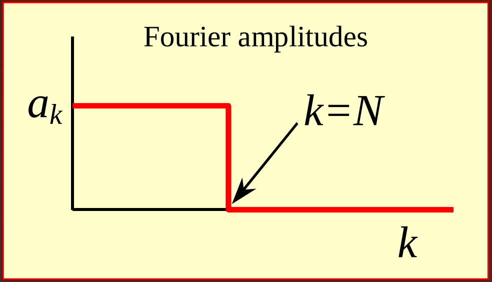
Three functions with good peaks and zeroes: #1

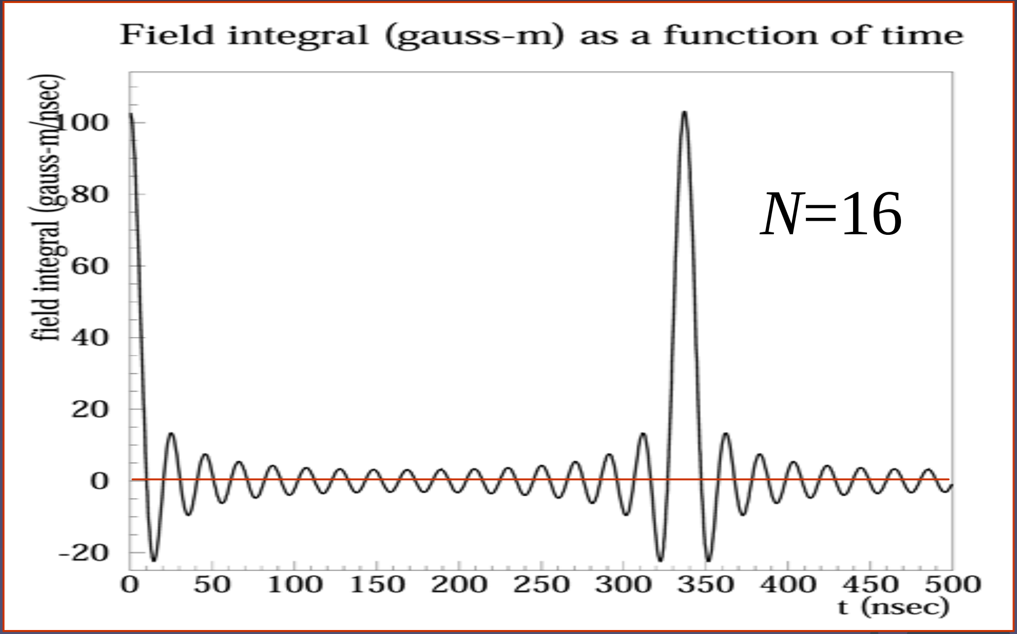
1. part of the series for a periodic δ function (ω is linac frequency):

$$1 + \sum_{k=1}^{N} 2\cos(k\omega t) = \frac{\sin[(N+\frac{1}{2})\omega t]}{\sin(\omega t/2)}$$



"Features" (peaks and zeroes) are evenly spaced.

A problem: field has non-zero time derivative at the zeroes. Bunch head and tail experience different (non-zero) fields.



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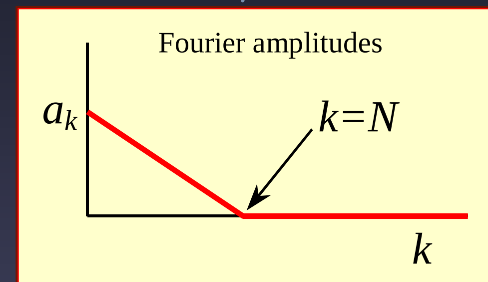
Three functions with good peaks and zeroes: #2

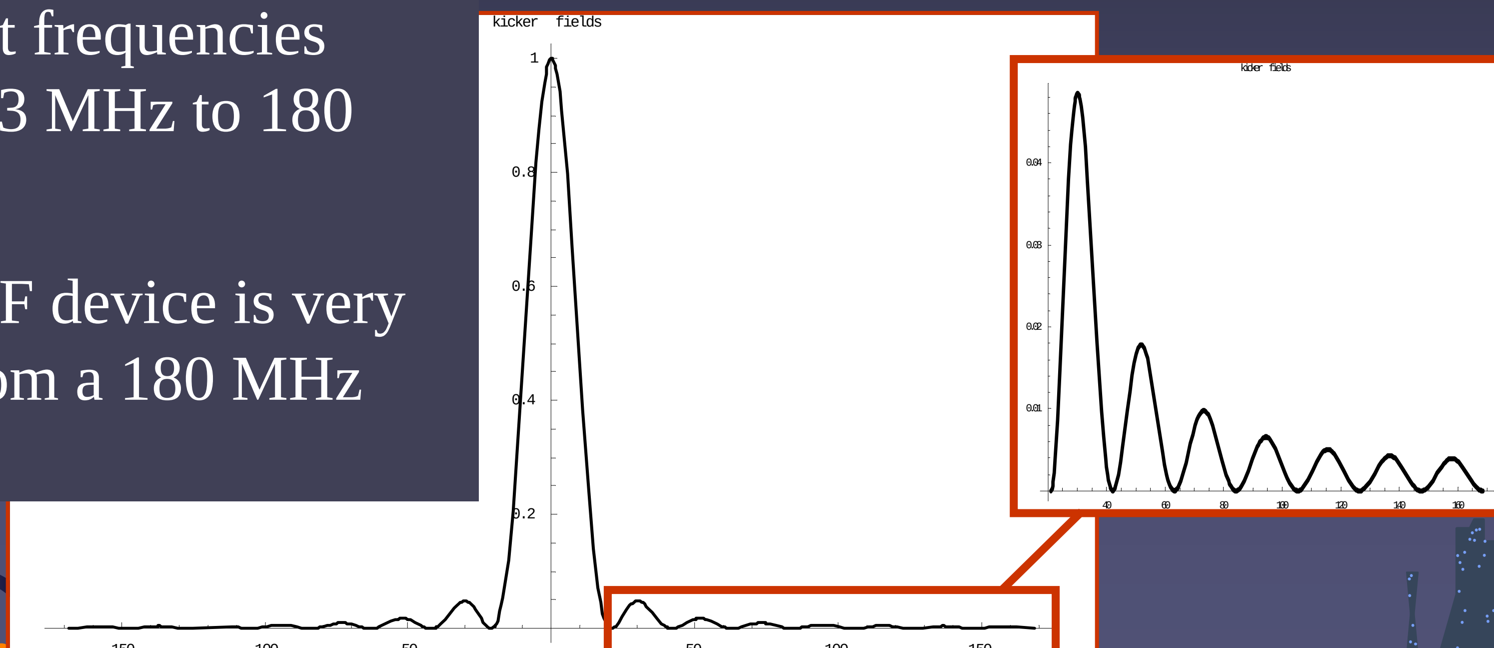
2. "square" of last page: this way zeroes also have zero slope…

$$\text{kick} \sim \frac{\sin^2(N\omega t)}{\sin^2(\omega t)}$$



Better… but frequencies range from 3 MHz to 180 MHz.

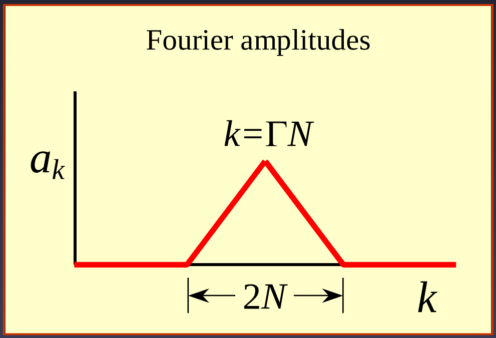
A 3 MHz RF device is very different from a 180 MHz device.



Three functions with good peaks and zeroes: #3

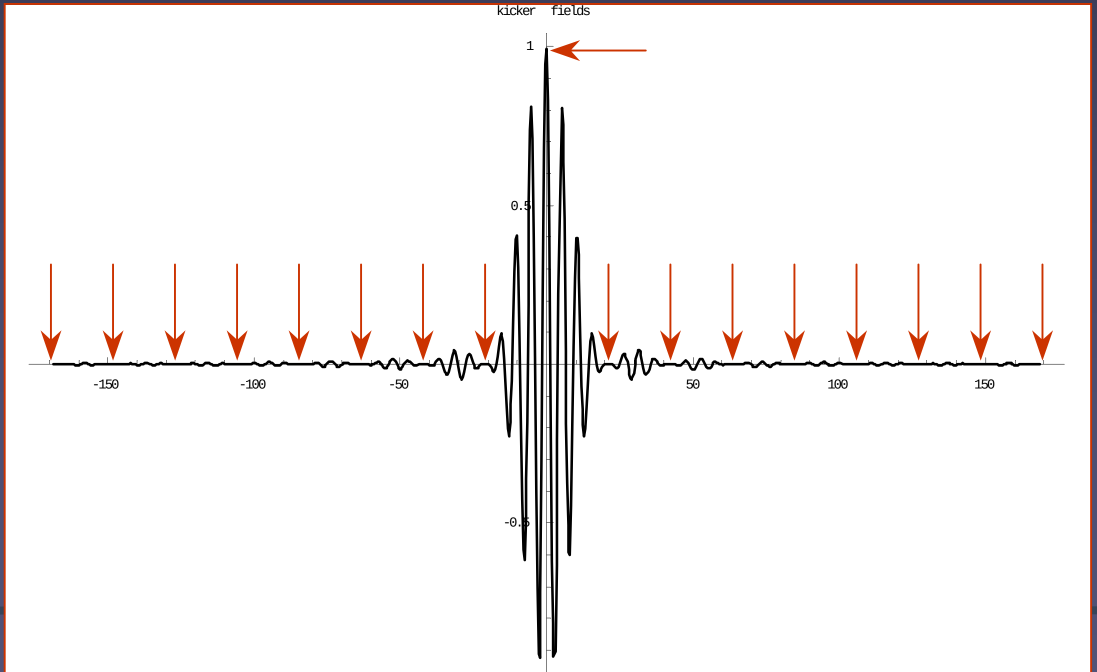
3. high-frequency modulate: this way fractional bandwidth is reduced.

$$\text{kick} \sim \frac{\sin^2(N\omega t)}{\sin^2(\omega t)} \cos(\Gamma N\omega t)$$



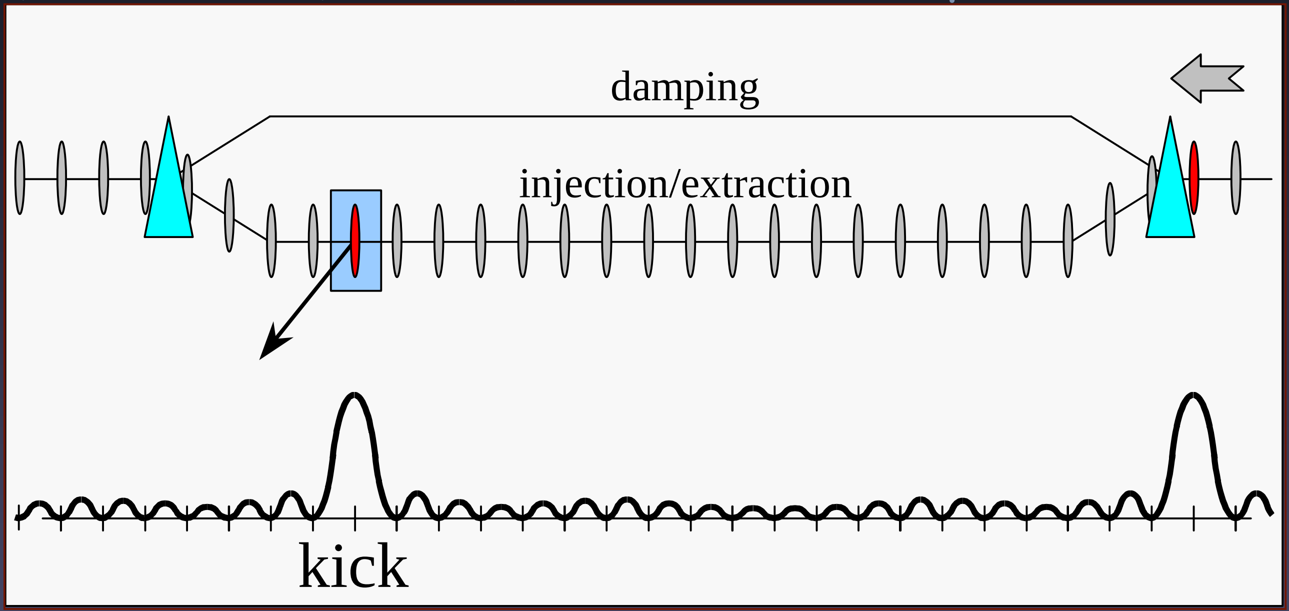
This is what we're actually studying now, but with $N = 60$ and $\Gamma = 10$:
1.78 GHz ± 10% bandwidth

(Graph uses $N = 16$, $\Gamma = 4$.)



Damping ring operation with an FS kicker

We don't want the beam to go through the kicker until we're ready to extract.

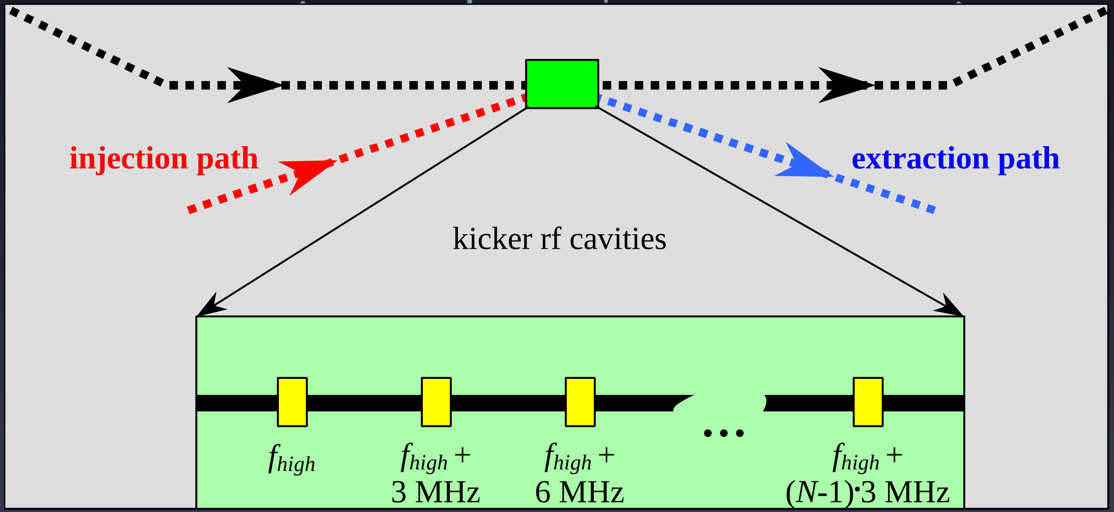


Fourier series kicker would be located in a bypass section.

While damping, beam follows the upper path.

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

So what is it, actually?



Original idea: kicker would be a series of 60 “rf cavities,” each oscillating at one of the desired Fourier components. (60 cavities would allow the damping ring to fit into the Tevatron tunnel.)

A bunch “sums” the impulses as it travels through the system.

There are lots of cavities, but they’re all nearly the same.

Is there another way to sum the Fourier components?

Well yes, maybe…

Summing signals in a single cavity…

- dumb: build a 3MHz cavity and drive it so that multiple modes are populated. (cavity is huge, lots of modes to control…)

- promising: launch different frequencies down a long (dispersive) waveguide to a low-Q cavity. Send the frequency with slowest group velocity first, fastest last. Signals arrive at cavity properly phased to make a short pulse. Q ~ 25 cavity can support an acceptable range of frequencies. (This was originally Joe Rogers' idea.)

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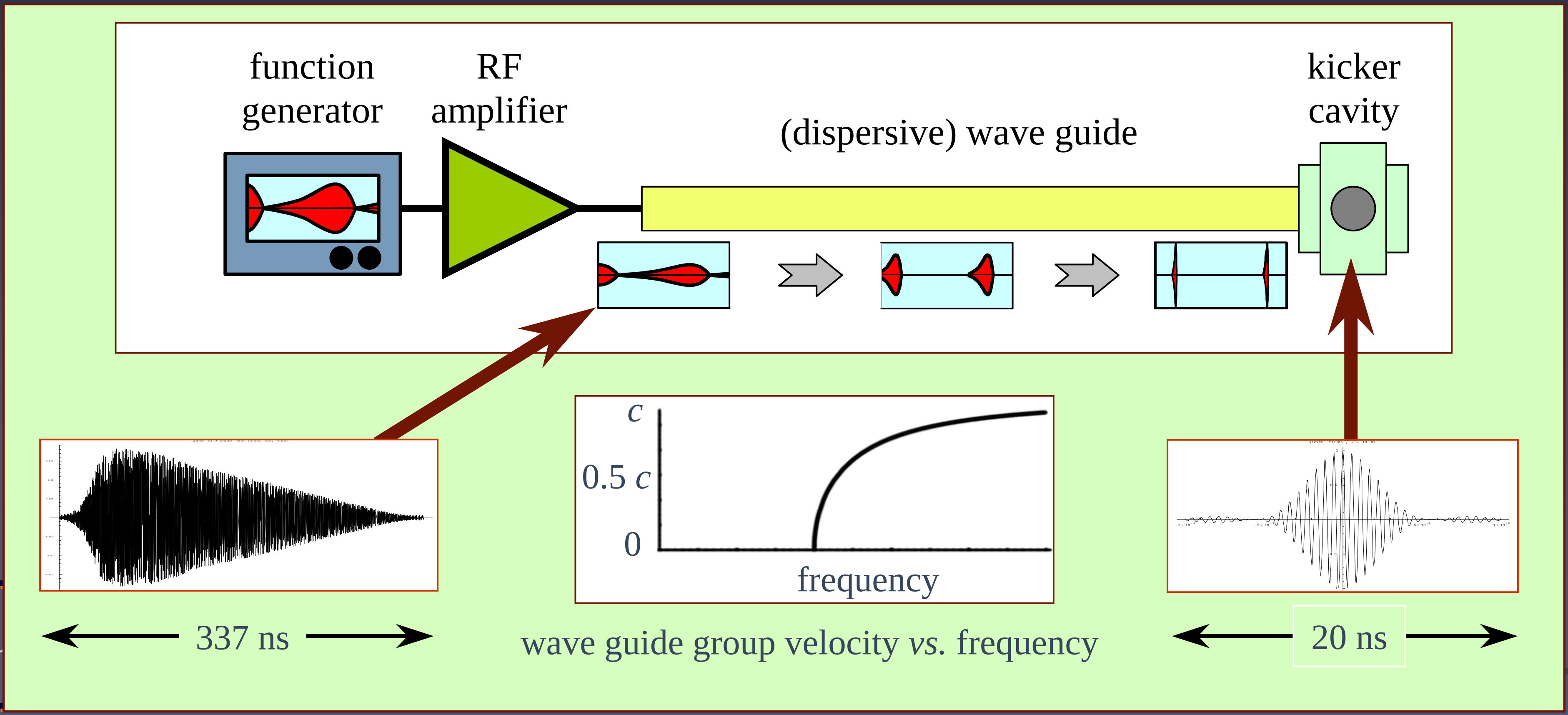
Pulse compression kicker

Dispersive wave guide compresses chirped RF signal.

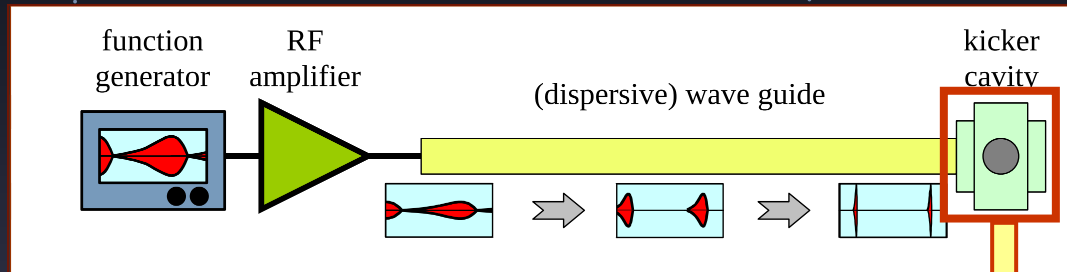
(Commercial broadcast?) RF amplifier ~100kW, but compression generates large peak power for kicking pulse in low-Q cavity.

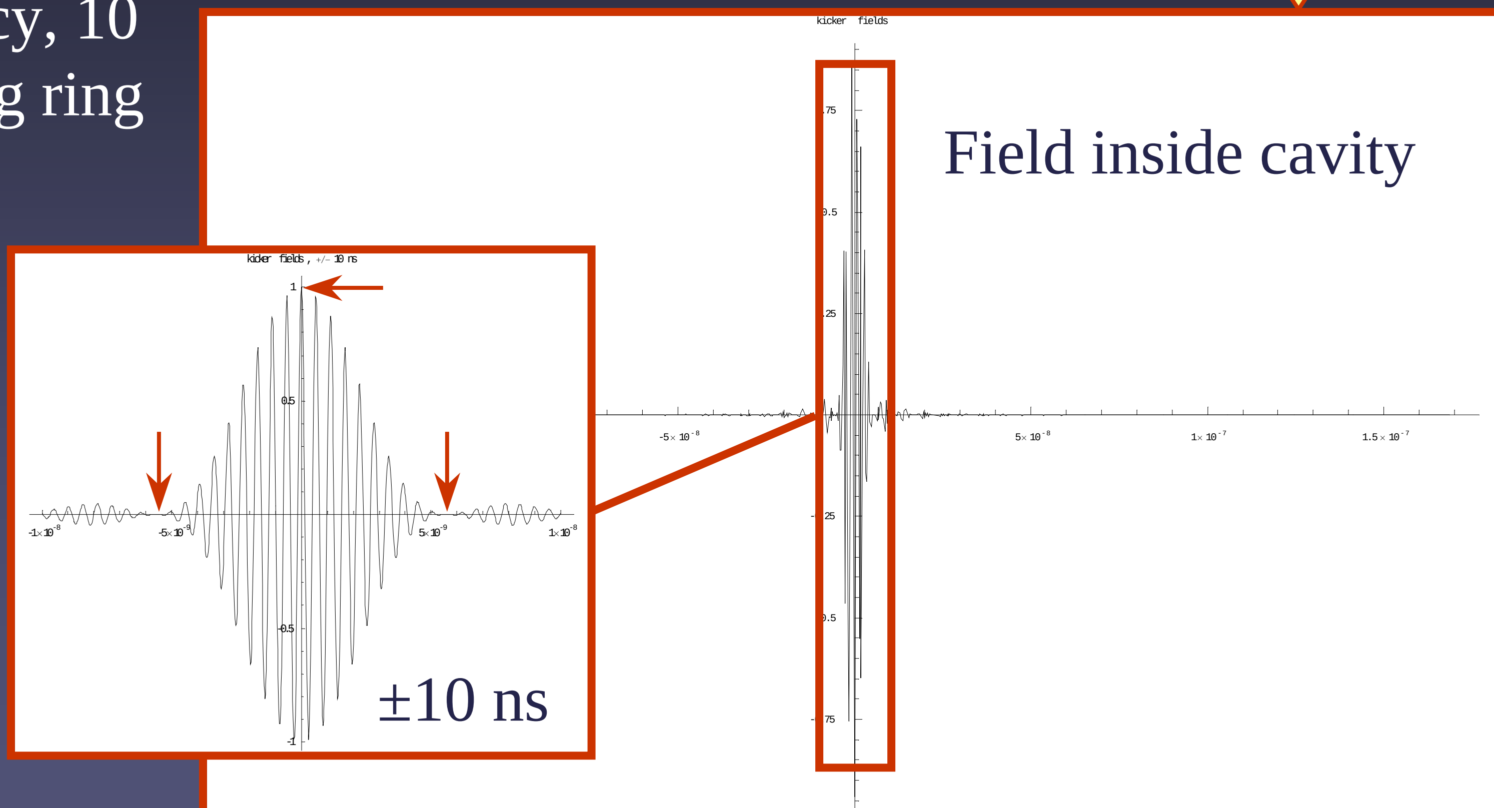


Trace the signal from kicker back to amplifier

Kicker cavity field for ~6 ns bunch spacing.

Cavity center-frequency is 600 times linac frequency, 10 times damping ring frequency.

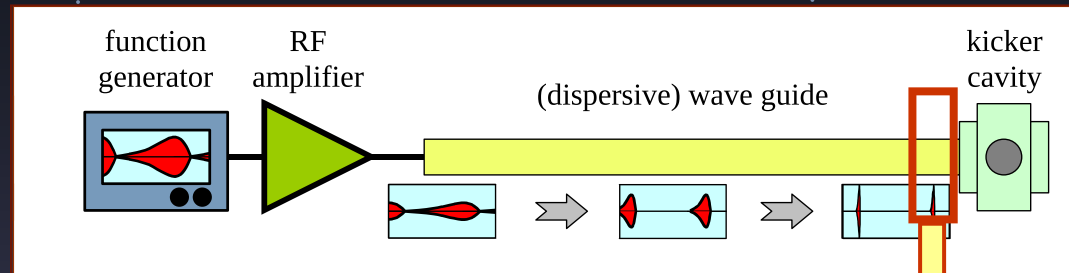


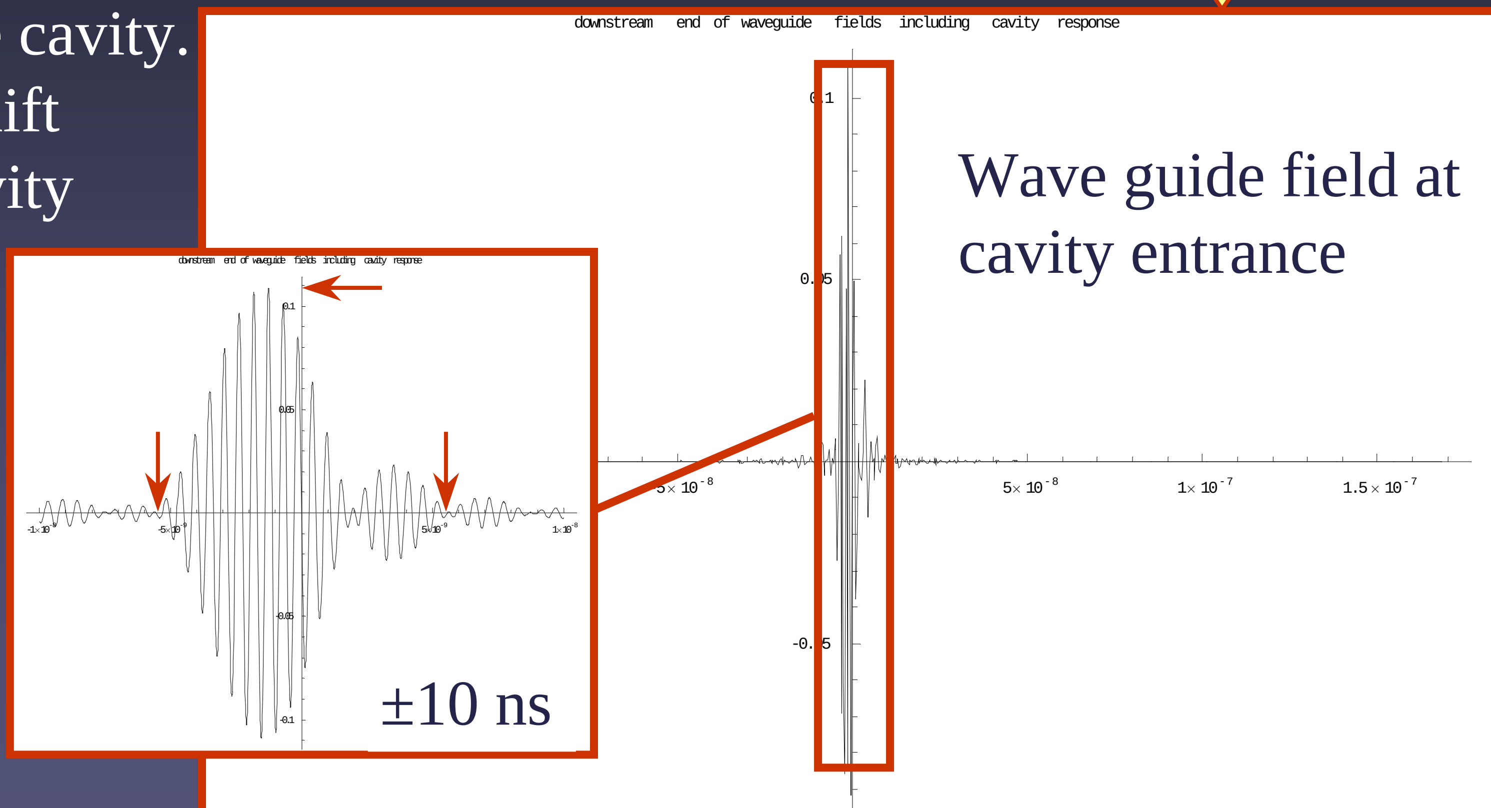


Field at the downstream end of the wave guide

Wave guide field at cavity entrance.

Waveguide peak field is about 1/10 that inside the cavity. Note phase shift relative to cavity field.

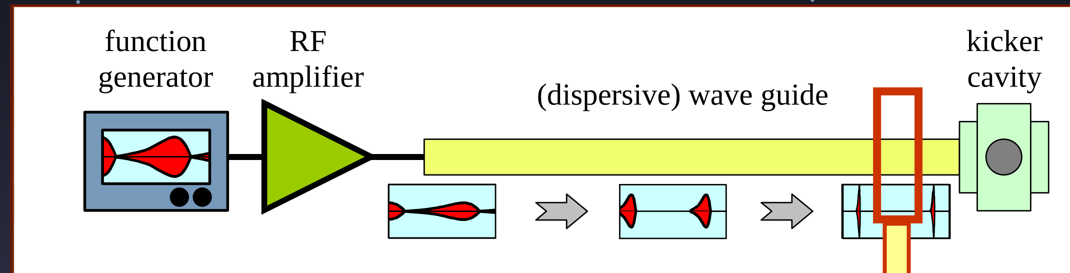


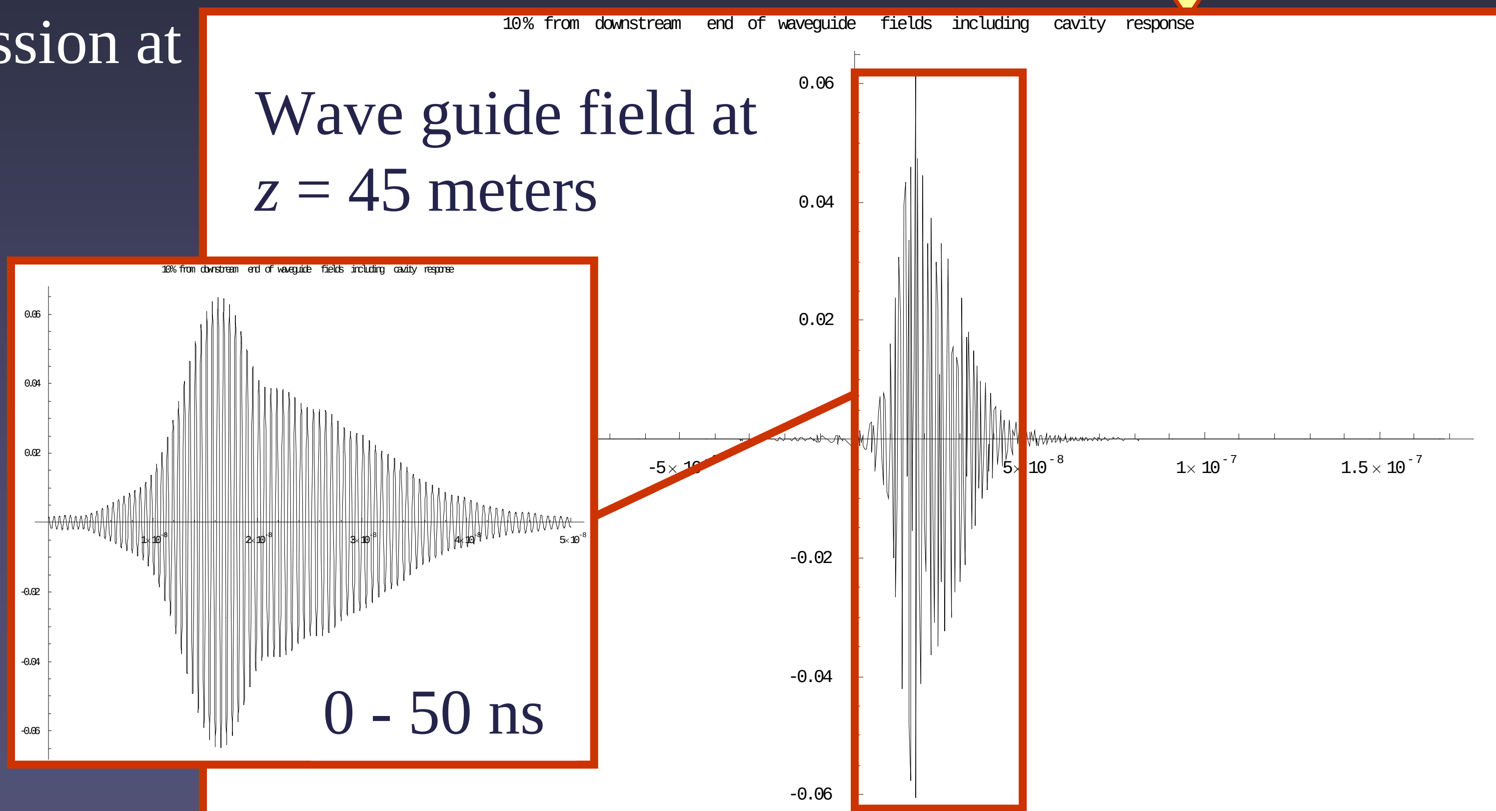


Field 4/5 of the way down the wave guide

Wave guide field 90% down the length of the wave guide.

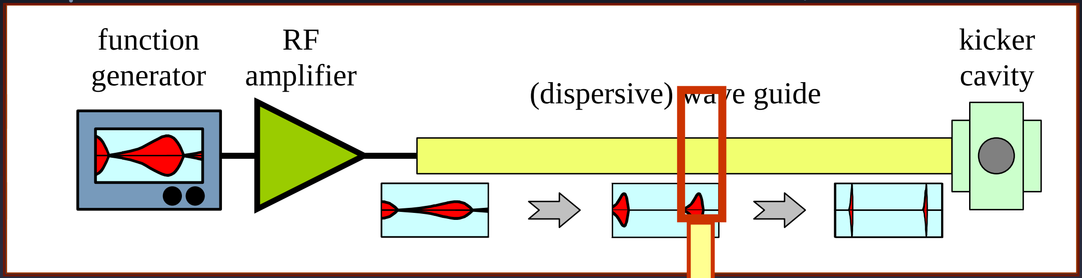
Note incomplete pulse compression at this point.

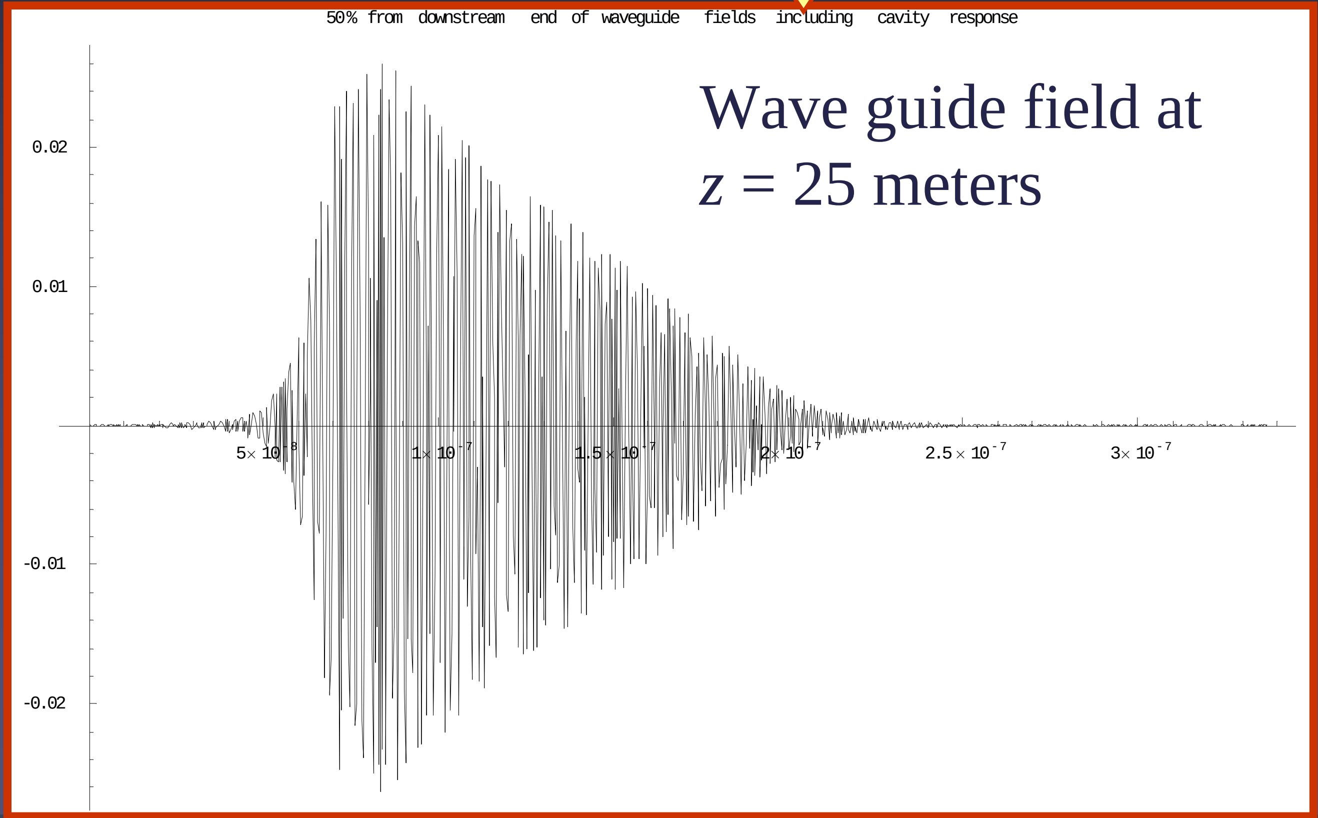




Field half-way down the wave guide

Wave guide field 50% down the length of the wave guide.



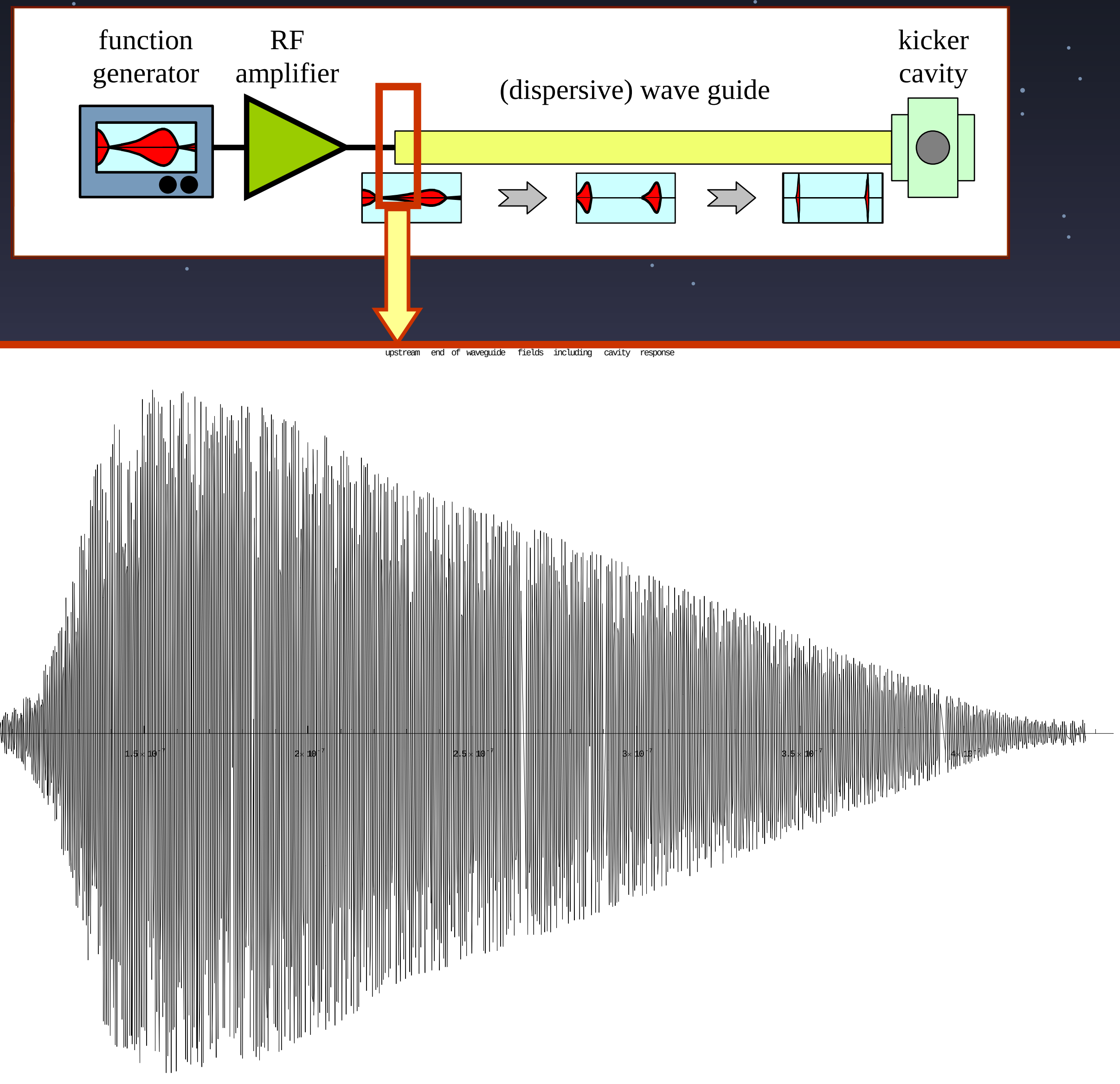


Field at entrance to the wave guide

Field at upstream end of the wave guide.

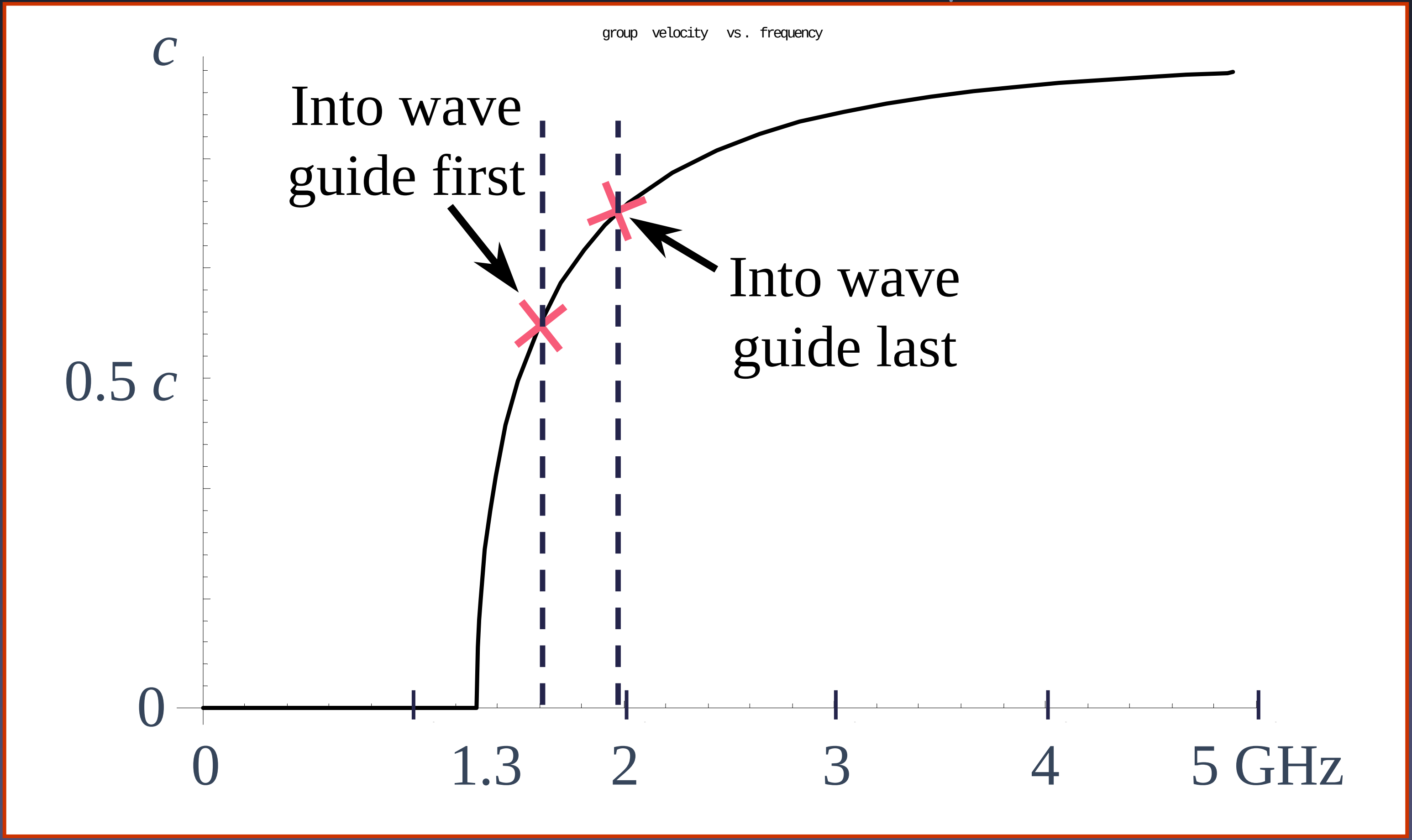
Note that peak field is about .018 here, in comparison with 1.0 inside cavity.

Pulse compression, plus energy storage in the cavity!



Group velocity vs. frequency

1.3 GHz cutoff frequency wave guide



Pulse compression kicker

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.)

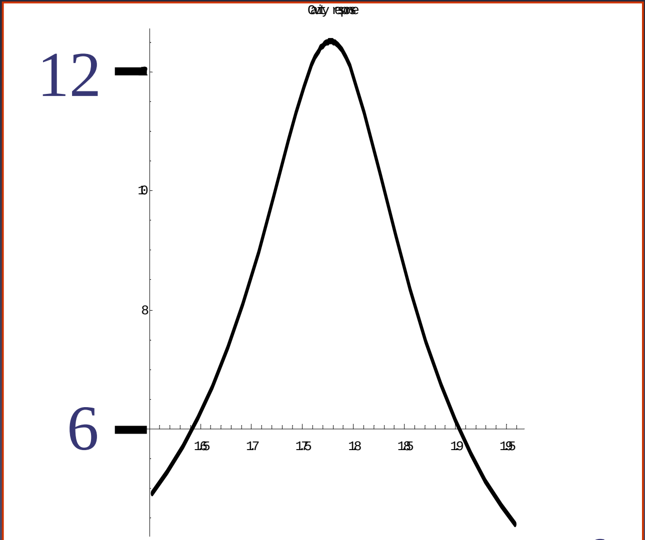
Programmable function generator can be reprogrammed to compensate for drifts and amplifier aging.

Underway: studies of how sensitive kicker is to parameter errors:

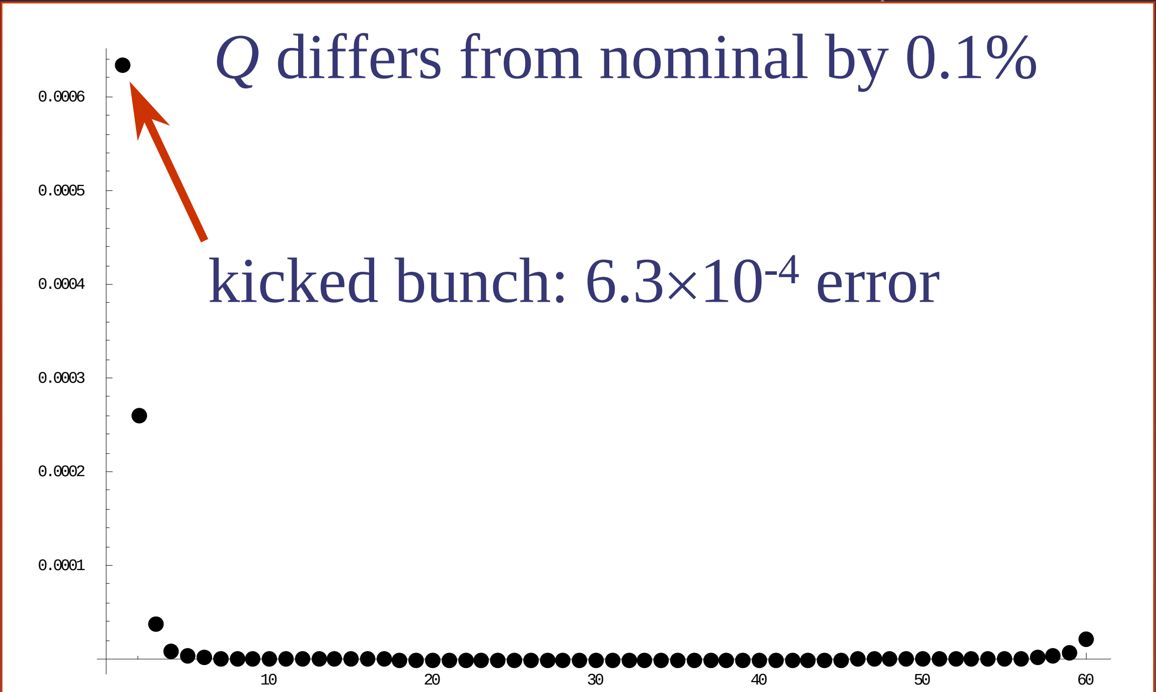
- What if Q isn't exactly 25?
- What if amplitude, phase, losses in wave guide,… drift?

An example: what if $Q \neq 25$?

Cavity response to drive fields delivered by wave guide depends on Q. If Q is different from nominal value, cavity fields are not as expected.



Cavity response *vs. f*

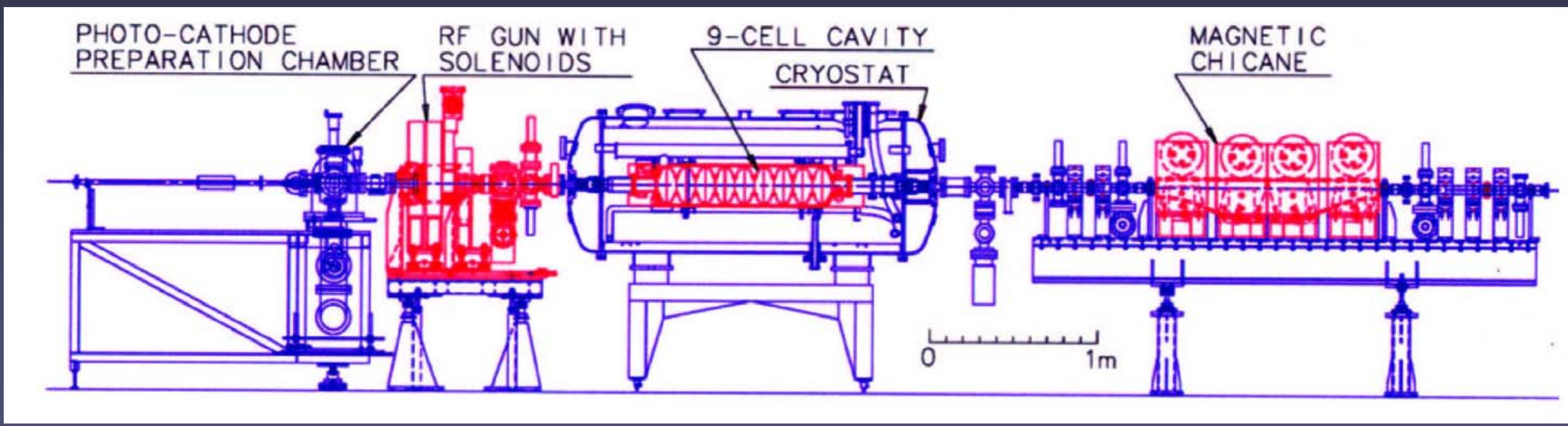


p_T error *vs.* bunch number ($< 7\times10^{-4}$)

EOI submitted to Fermilab to begin tests

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!

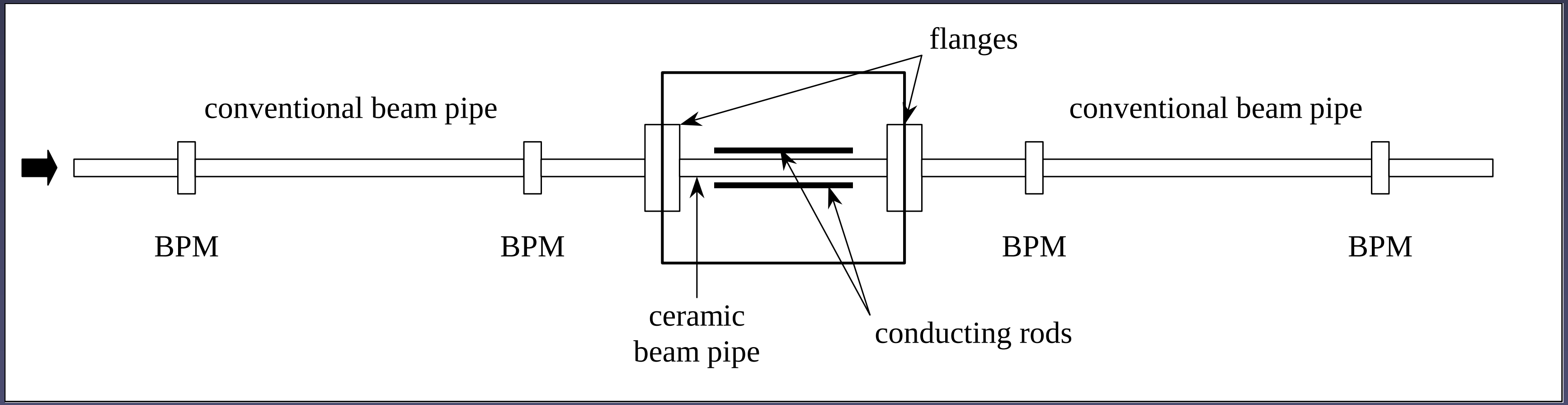


First order of business: understand how well the A0 beam will work for kicker tests

Simple kicker for initial tests

Start with a simple kicker whose properties are calculable and can be measured independently of its effects on the A0 electron beam.

Most important: how well can we measure a device’s amplitude and timing stability with the A0 beam?

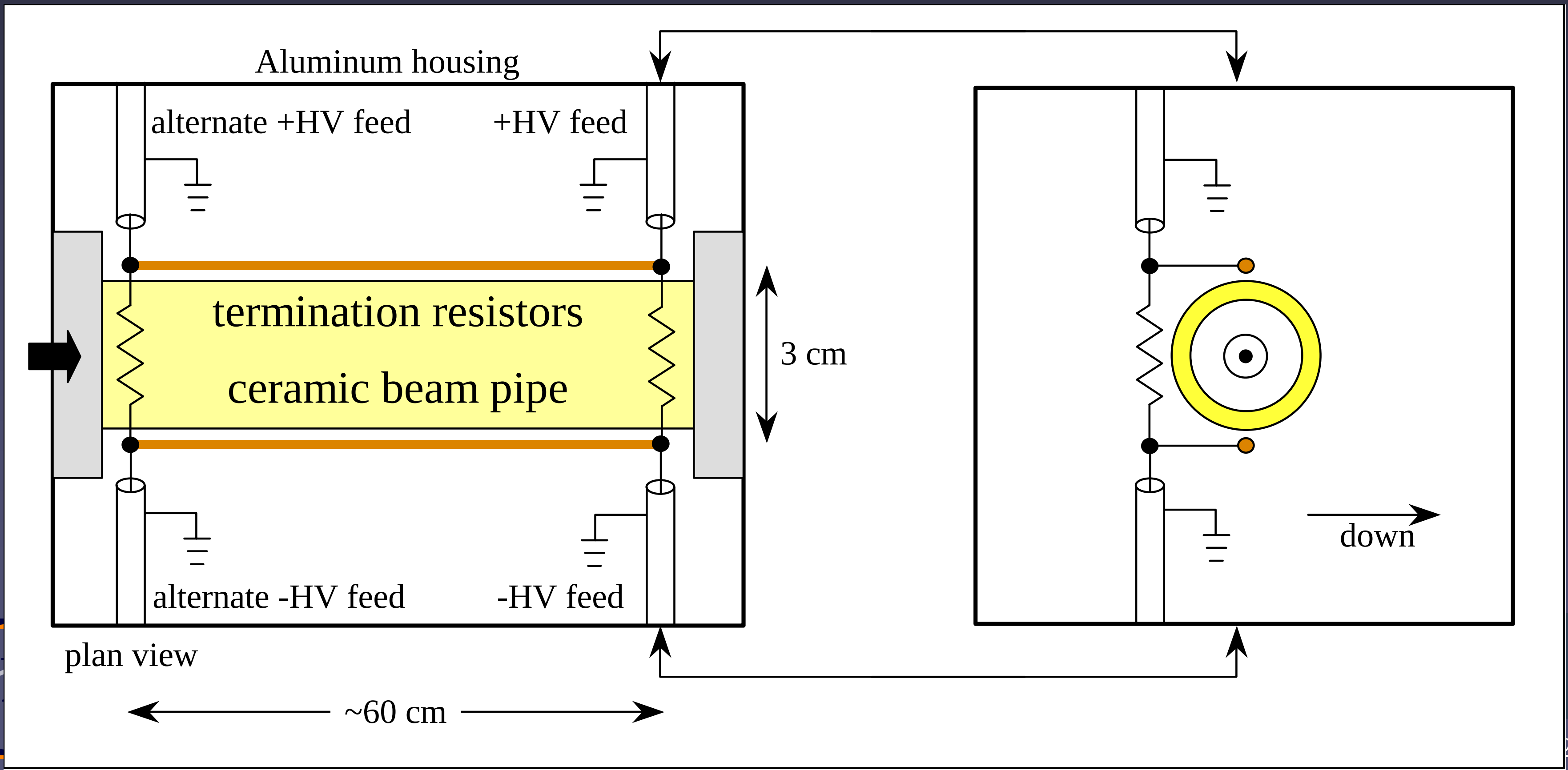


BPM’s are separated by about a meter.

Simple kicker

Driving kicker with ±750 volt pulse from FNAL linac chopper pulser will deflect 16 MeV beam by 3.3 mrad. (See EOI for calculations.)

Two pairs of 50 μ resolution BPM’s determine deflection to ± 100 μrad



Simple kicker instrumentation

Most kicker parts are on hand at Fermilab. SLAC sent us a ceramic vacuum pipe which is already flanged.

We would like to assemble the kicker, developing instrumentation to measure ("on the bench") its field strength and time dependence in collaboration with Fermilab's technical division.

After we feel we understand the kicker we would like to install it in the A0 beam to measure its properties there.

Rough estimate of running time

The performance demands on a real TESLA damping ring kicker are shown in the following table.

quantity	value	precision
kicking field integral	100 Gauss-meters	±0.07 Gauss-meters
"off" field integral	0	±0.07 Gauss-meters
kicking pulse "flattop"	at least 40 ps	
pulse rise time	less than 6 ns	
pulse fall time	less than 64 ns	

Rough estimate of running time

A most naïve calculation is based on the estimated 3% single pulse accuracy from the BPM's and the kicker stability goal of 0.07%.

If only BPM precision contributed to the measurement uncertainties (we should be so lucky!), it would take $(3\% / 0.07\%)^2 \approx 2000$ pulses per measurement point to reach this level of accuracy.

Arbitrarily increasing this by a factor of three to 6000 pulses would allow the 10 Hz A0 repetition rate to deliver one point's data in 10 minutes.

A scan of 100 points in which the relative timing of the arrival of the beam and the firing of the kicker is varied could be done in a few shifts.

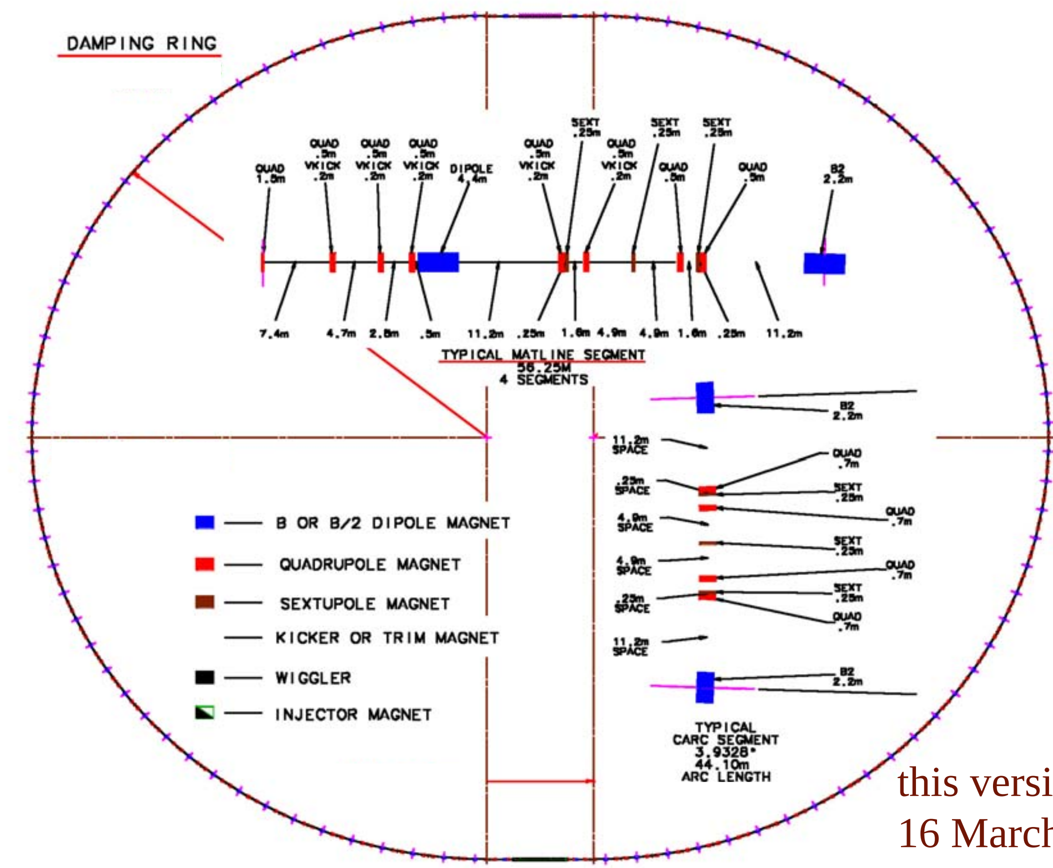
Small Damping Ring Studies at Fermilab

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

We had a small workshop in March at Fermilab to think about this.

Participants: ANL, LBNL, SLAC, Cornell, DESY, FNAL…

6 kms, 6 straight sections, 25 wigglers.



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Comparison of the two 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

Comments about damping rings

It will be interesting to see how various optimizations turn out if it is possible to remove the 20 ns minimum bunch spacing requirement.

A small damping ring could be built and tested before linac construction was complete. (Independent tunnels) This is an appealing idea! It could allow beam to be injected into the linac as soon as the main linac was under construction.

Exploration of technical issues associated with damping rings is becoming a major focus of LC activity at Fermilab.

Fermilab damping ring studies

•Lattice design

•Dynamic aperture studies

•Instability studies

•Kicker work…

…all are underway.

Summary/conclusions

It is possible that alternative TESLA damping ring 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.

Kicker and damping ring are planned to become major activities at Fermilab.

Stay tuned!