Stripline Pickups and Kickers

Accelerator Beam Diagnostics
John Byrd
Lawrence Berkeley National Laboratory
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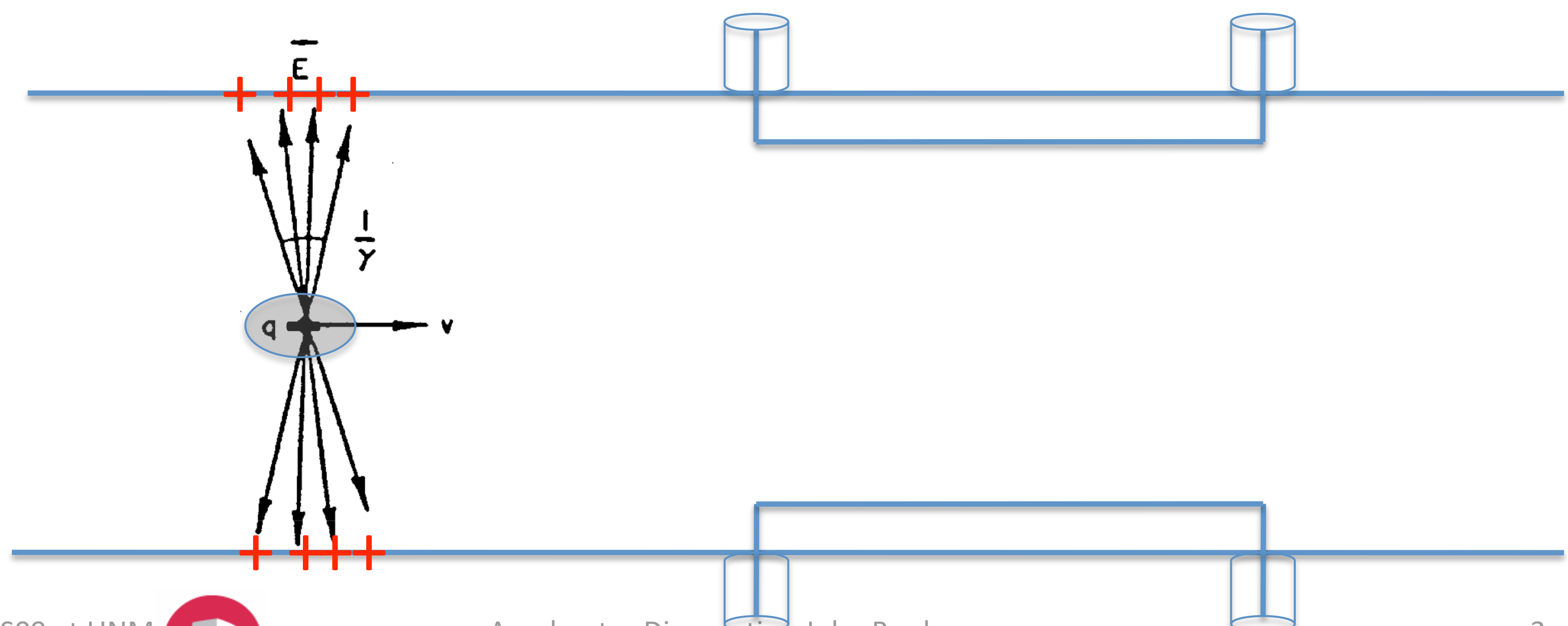
Overview

- Stripline Pickups
  - Basic principles
  - Beam impedance
  - Limitations
- Stripline Kickers
  - Basic principles
- Examples
  - PEP-II
  - BEPC-II
- Beam Impedance
- Signal Processing Techniques

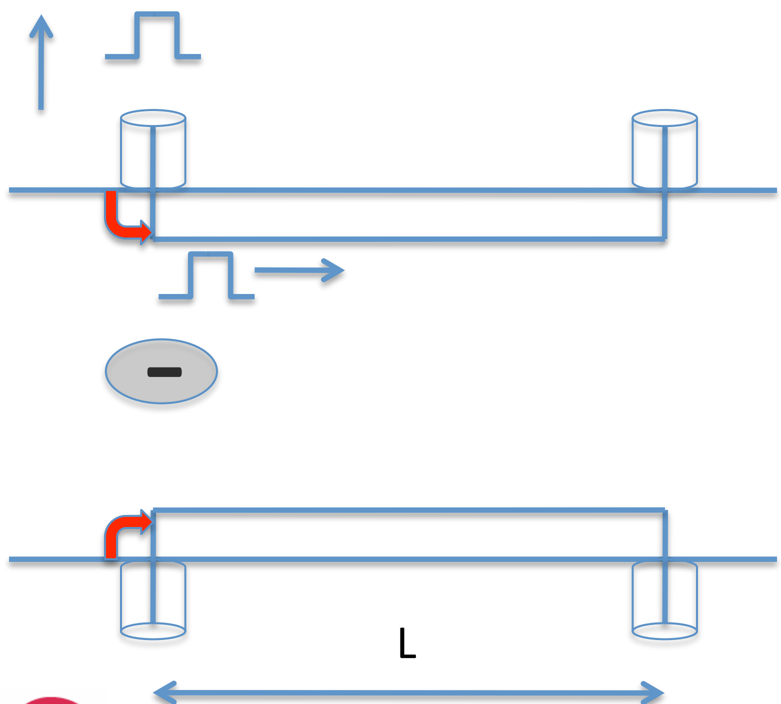
Beam Image Current

- For relativistic beams, the EM fields are flattened to an opening angle of 1/g, approximating a TEM wave.
- Image current flows on the inner surface of the beam pipe.
- A beam pickup (PU) intercepts some fraction of the image current



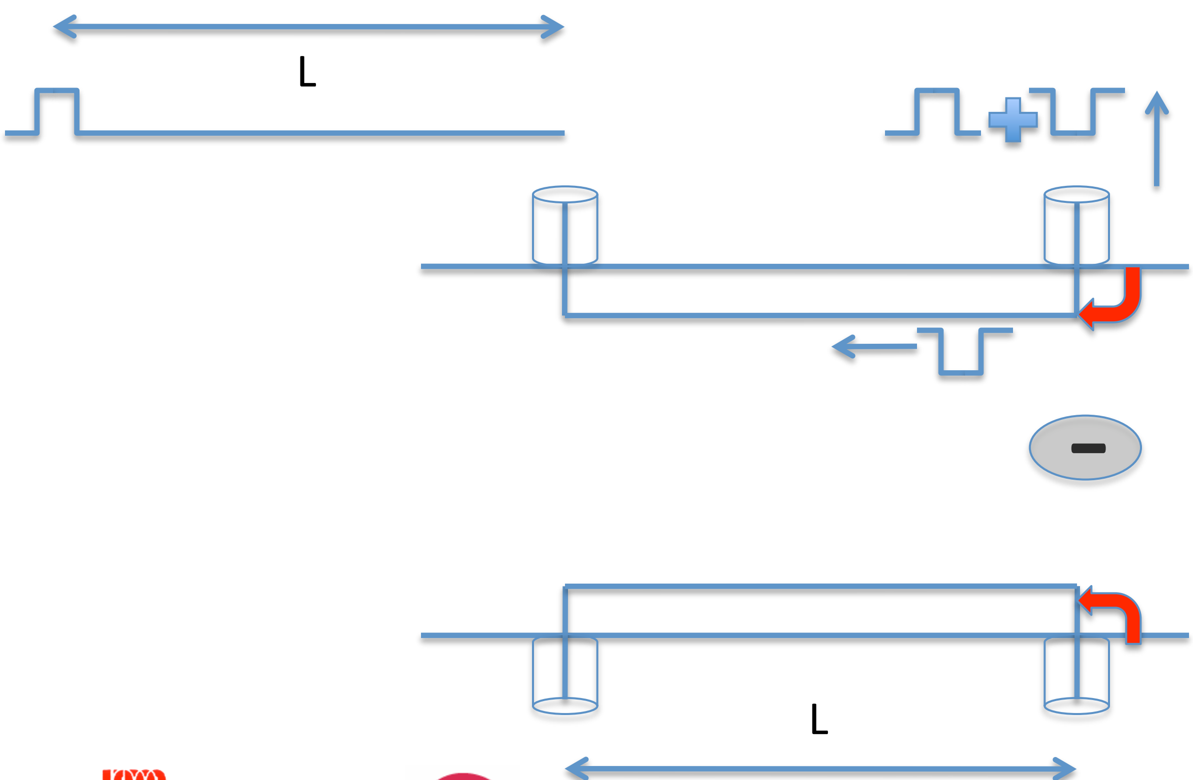
Stripline as a Pickup

- Beam passes upstream port of PU
  - Induced voltage at gap
  - If stripline impedance is matched to upstream output port, half of pulse exits port, the other half travels downstream. For vacuum, pulses moves at c.



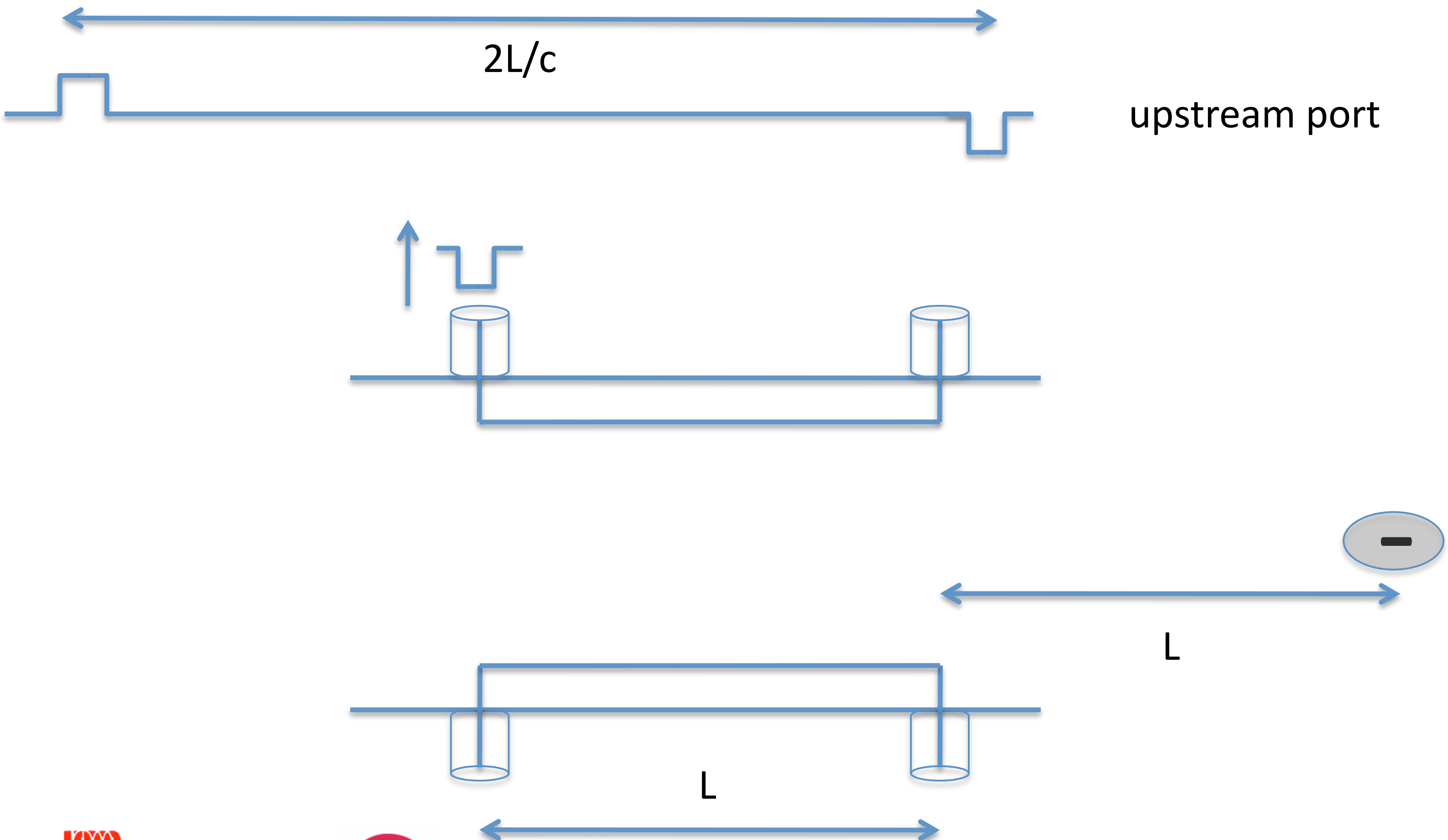
Stripline as a Pickup

- Beam passes downstream port of PU
  - Induced voltage at gap (opposite polarity to upstream port)
  - If stripline impedance is matched to downstream output port, half of pulse cancels pulse from upstream port, the other half travels upstream and is observed at upstream port at a time 2L/c.



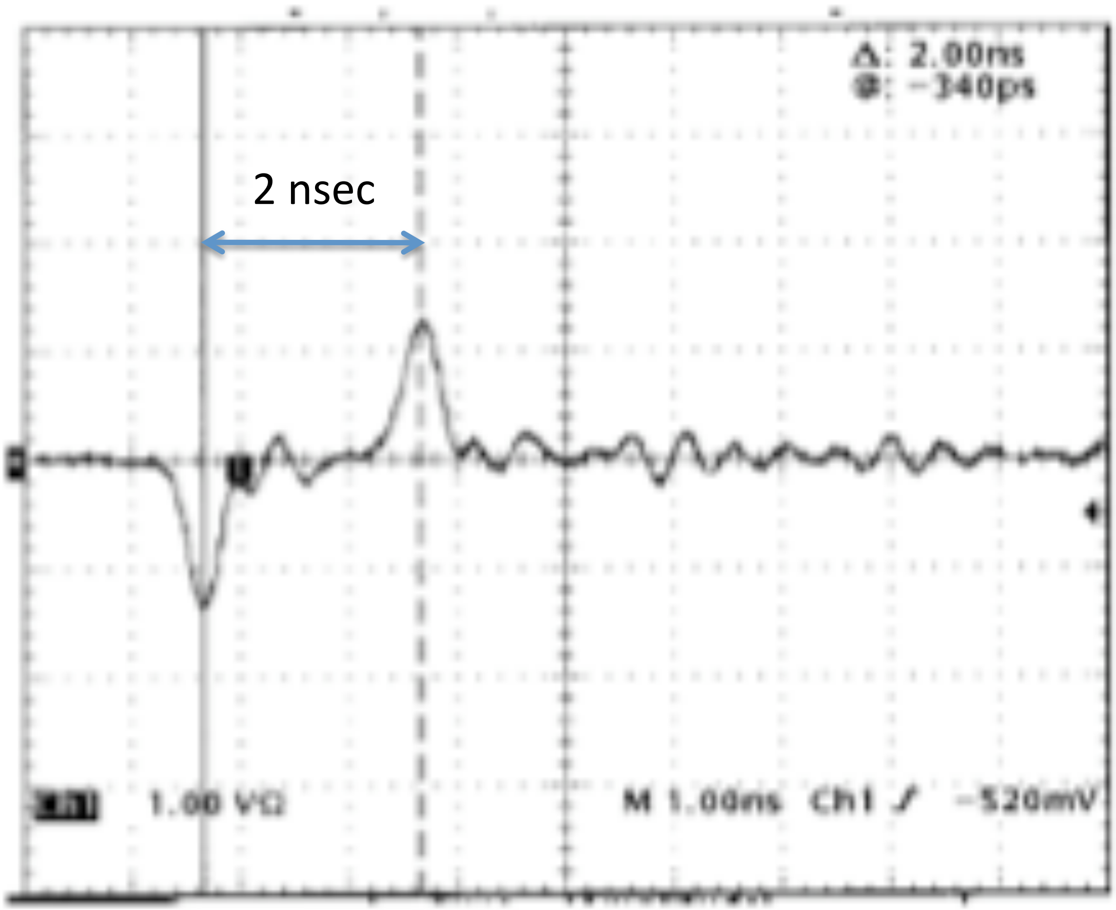
Stripline as Pickup

- The downstream pulse exits through the upstream port at a time 2L/c. No signal from downstream port (ideal case)



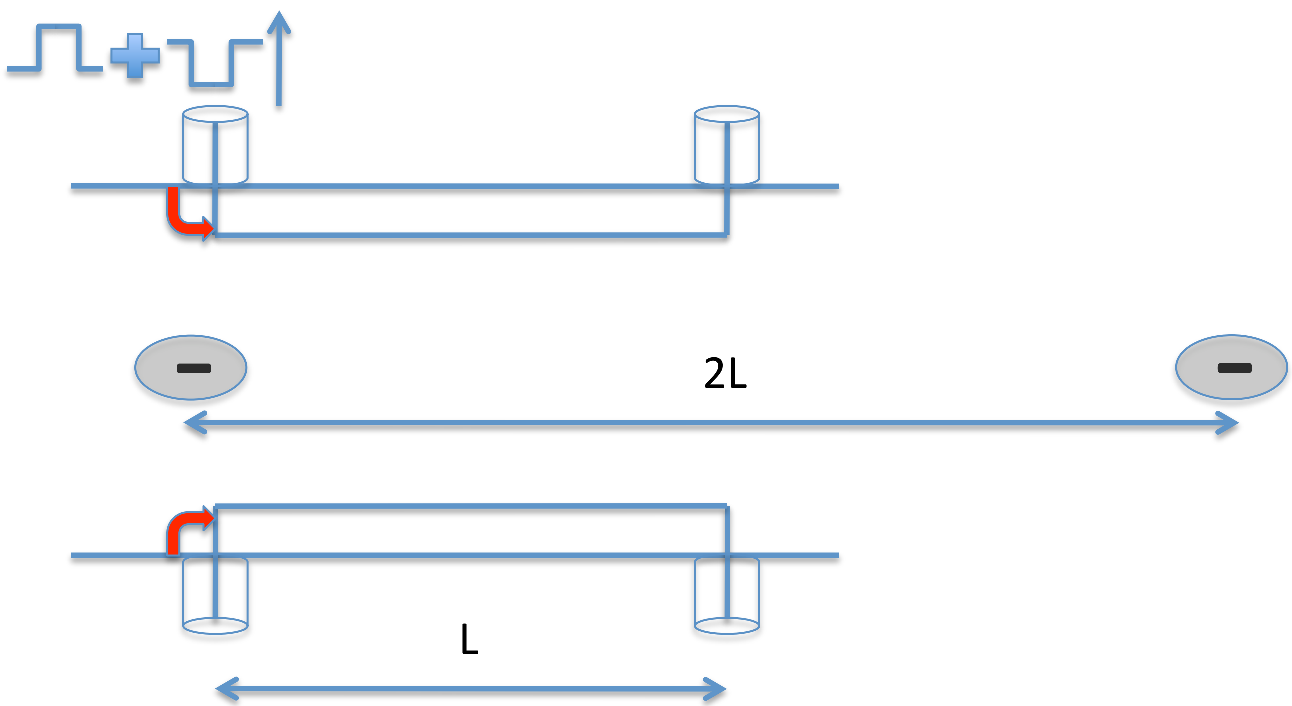
Example Signals

- Advanced Light Source stripline. Signal at the upstream port. Kicker length is 1 nsec (30 cm)



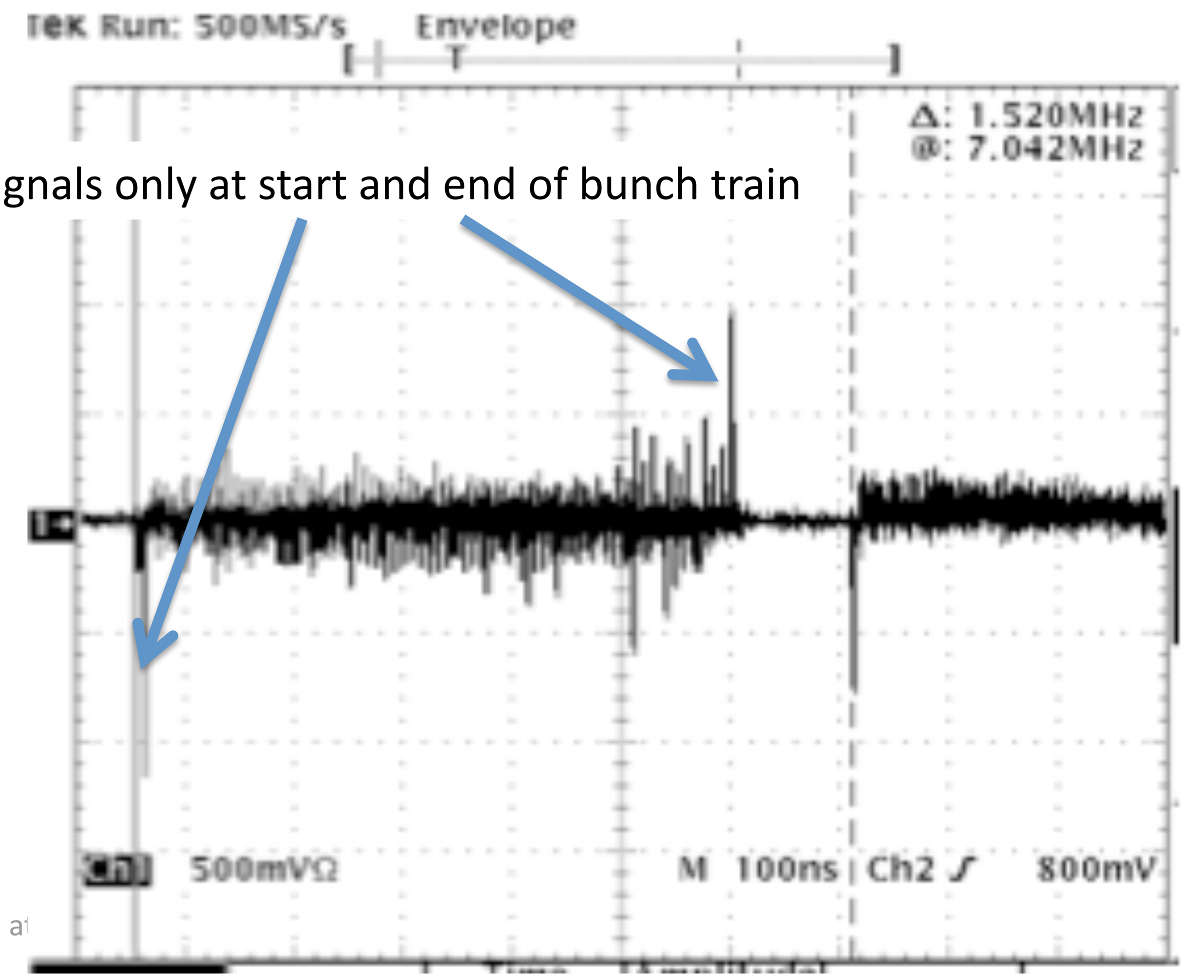
Multibunch signals

- Multibunch beam with bunches separated by 2L/c. The next bunch signal cancels the downstream signal from the previous bunch. Therefore, NO SIGNAL for this bunch spacing! Maximum signal power for a bunch spacing of L/c.



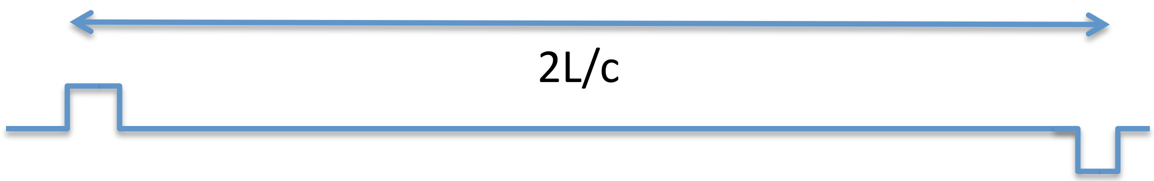
Example Multibunch Signal

- ALS stripline kicker (used as a PU, upstream port)
- L=30 cm (1 nsec), Bunch spacing 60 cm (2 nsec)



Frequency Response

- The signal from the upstream port is a bipolar pulse separated by 2L/c

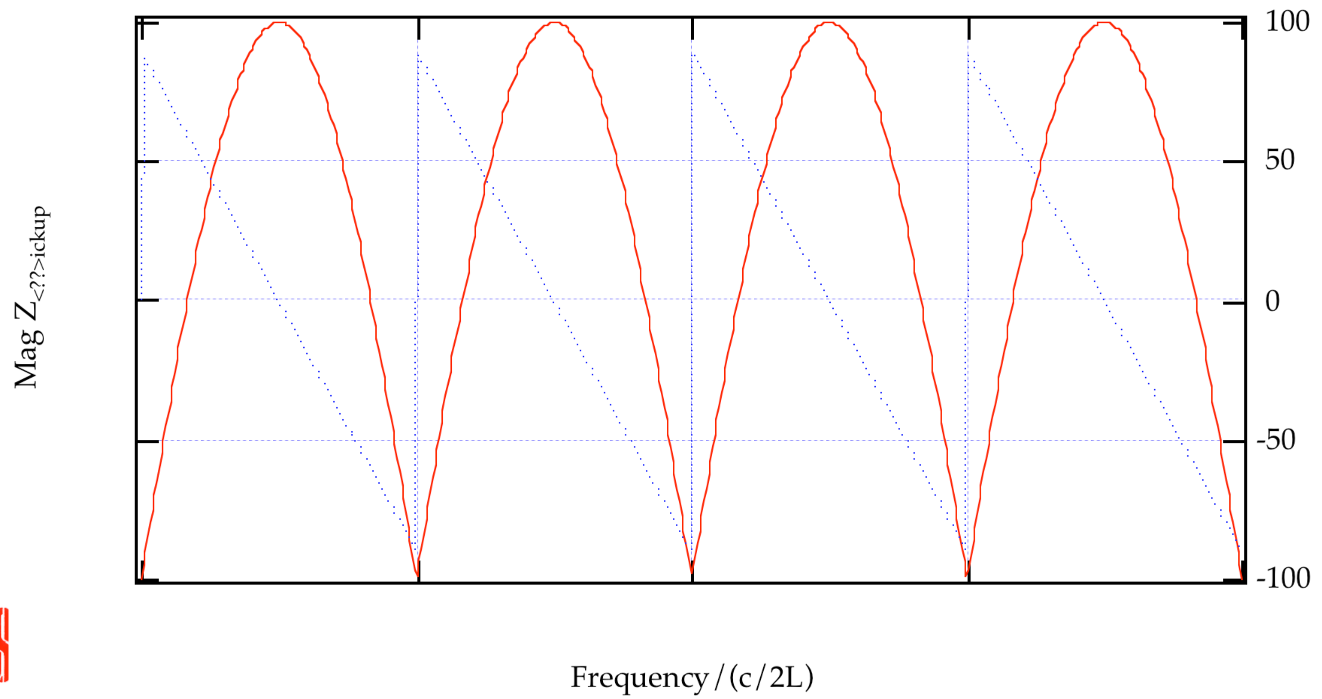


- This signal in the frequency domain is given by (assume the pulses are delta functions)

$$V_1(\omega) = \frac{1}{2} g R_0 I_b \left(1 - e^{-2jkL}\right)$$

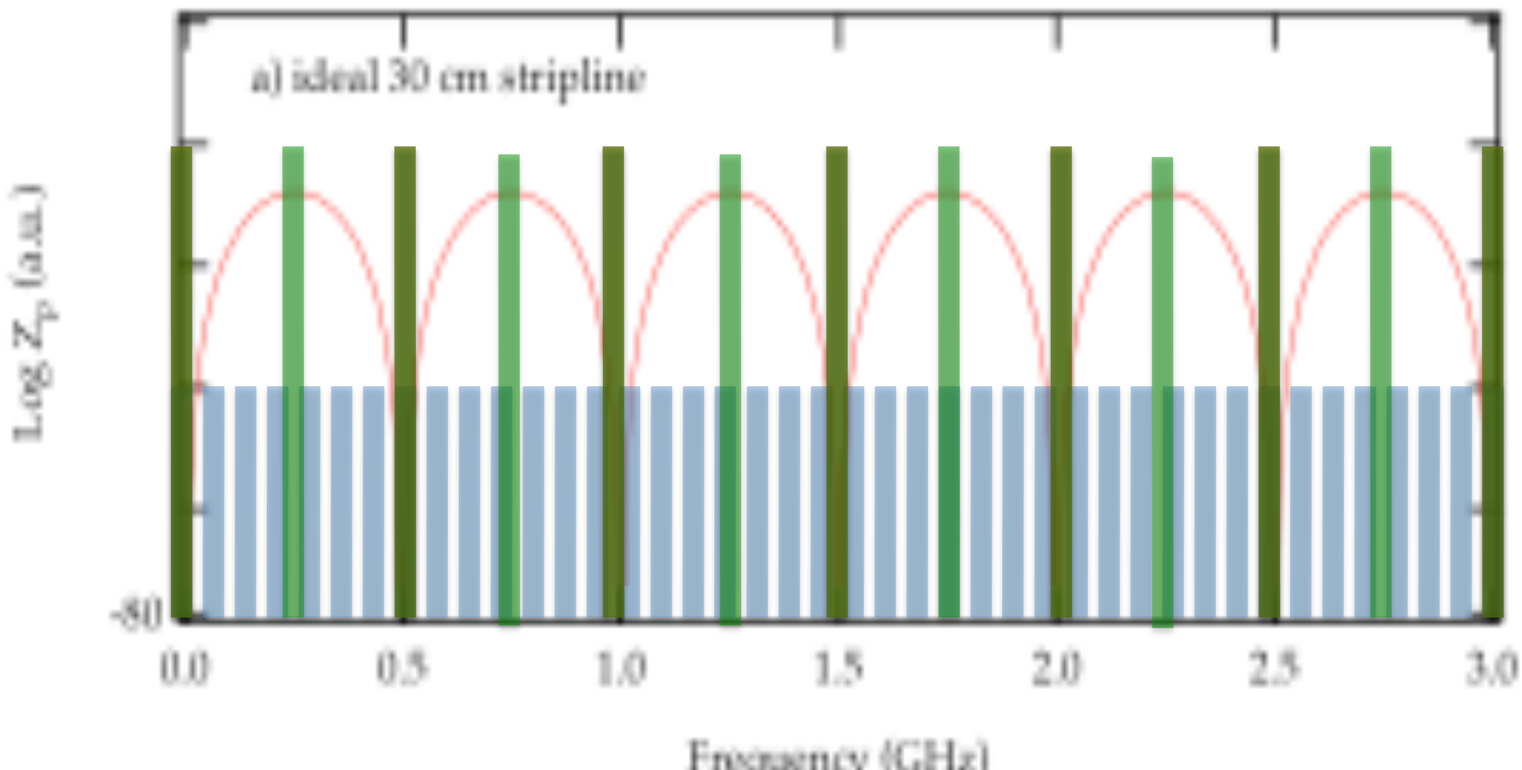
g=fraction of image current intercepted by stripline

R_0=stripline characteristic impedance



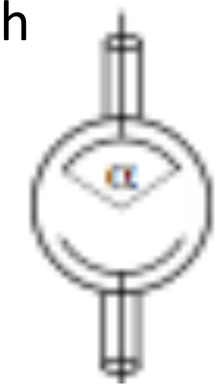
Beam Signal in Frequency Domain

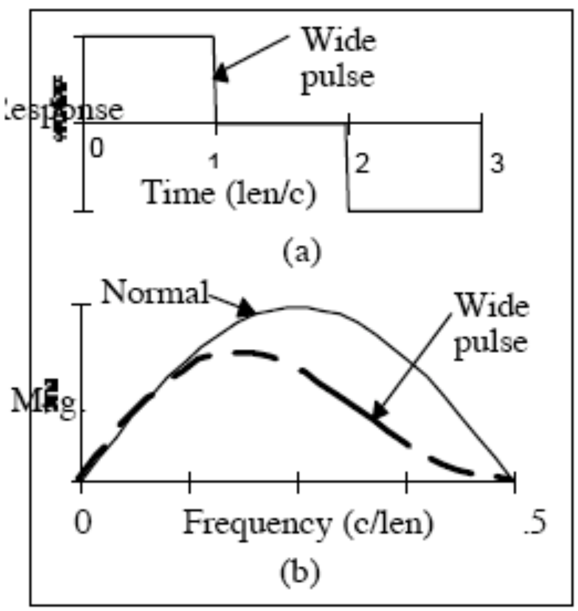
- Frequency domain signal is the product of the beam spectrum with the pickup impedance
  - Signal bunch
  - Multibunch
    - Separation by 2L/c
    - Separaction by 4L/c

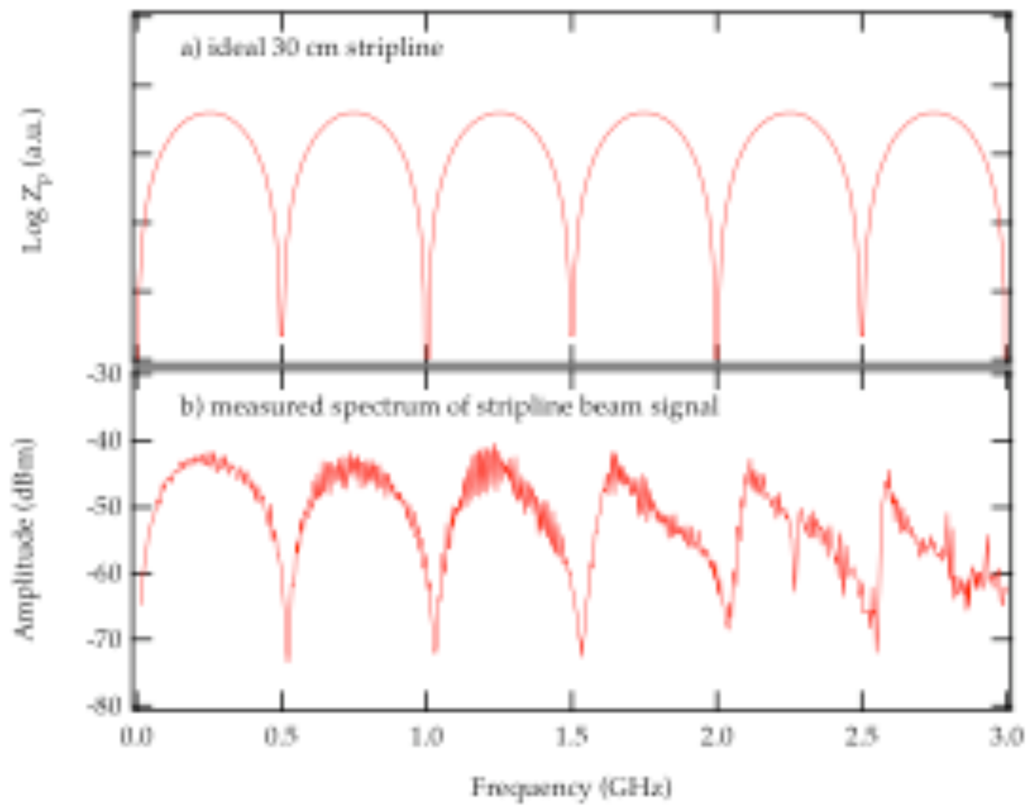


Bandwidth Limitations

- At higher frequencies, the stripline deviates from the ideal response.
- One issue is width of the pickups broadening the delta function response at the pickup. Wider pickups have larger signal but lower bandwidth







Stripline kickers: a simplified model

- We apply an alternating voltage between the plates:

$$V = V_0 e^{i\omega t}$$

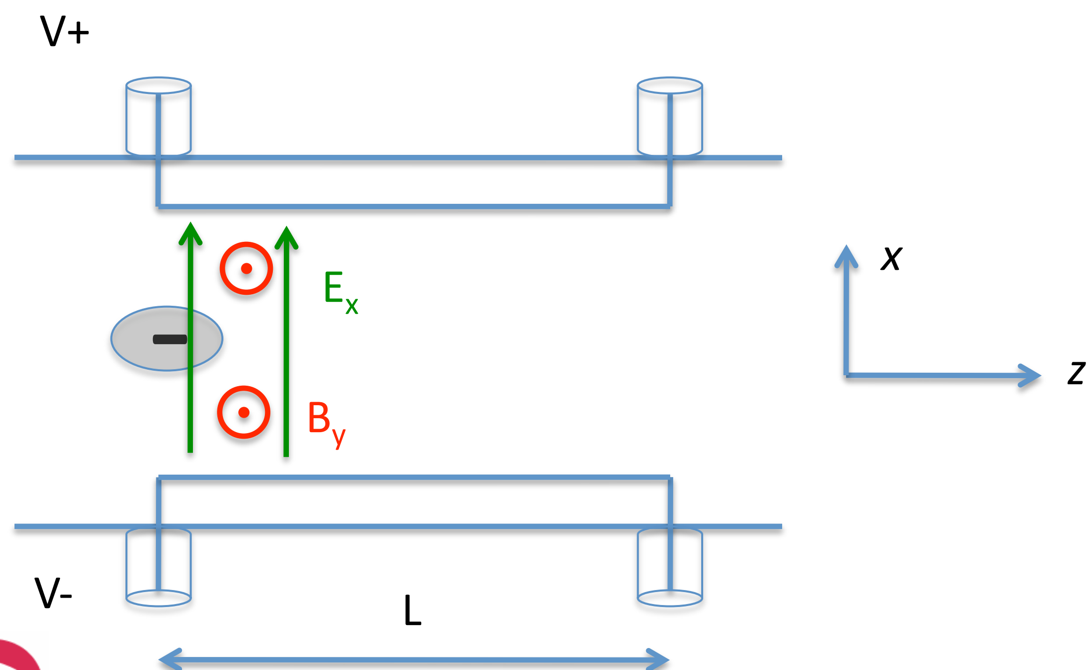
- From Maxwell's equations, there are electric and magnetic fields between the plates:

$$E_x = E_0 e^{i(kz-\omega t)} \qquad B_y = \frac{E_0}{c} e^{i(kz-\omega t)}$$

  A particle traveling in the $+z$ direction with speed c will experience a force:

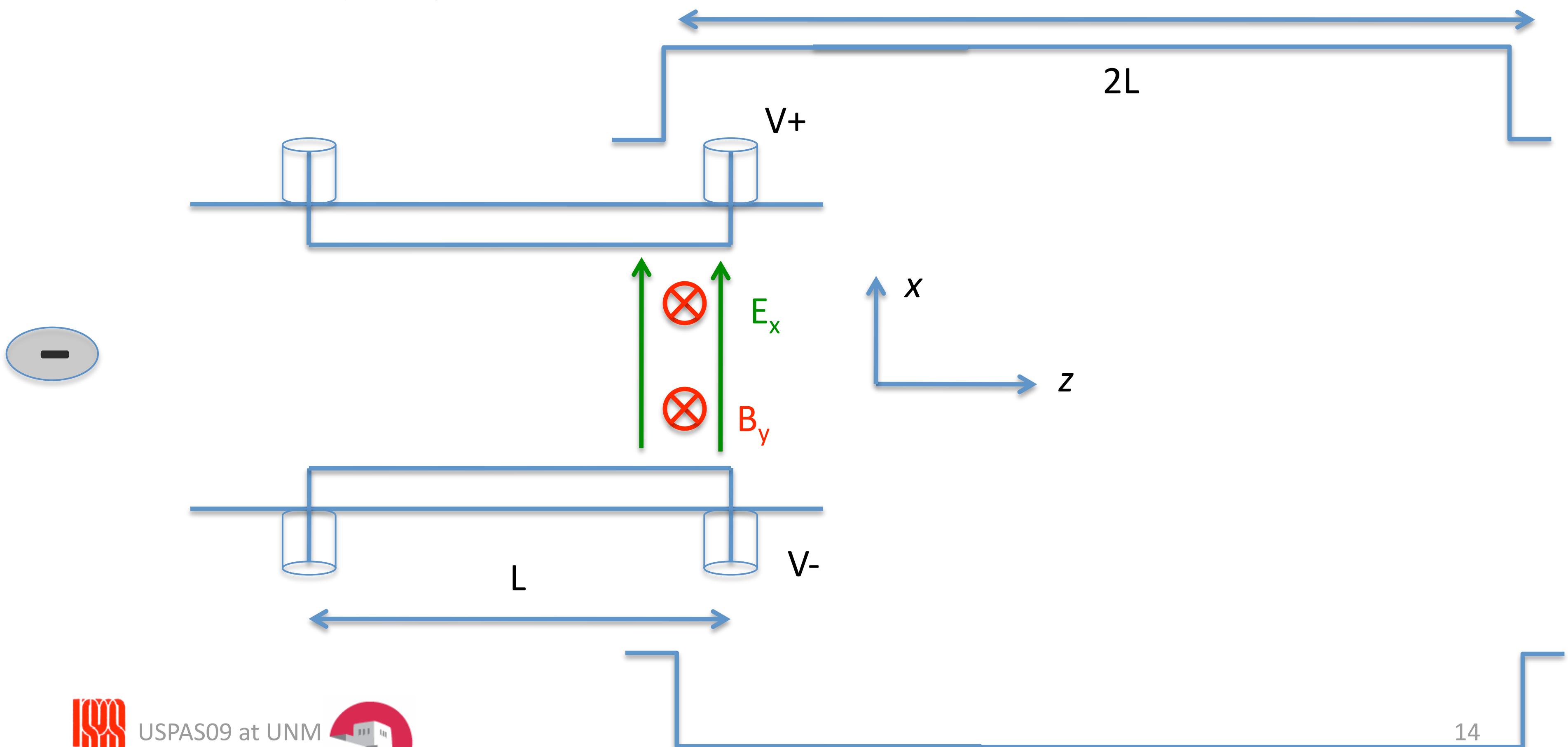
$$F_x = q(E_x - v_z B_y) = q(1-\beta)E_0 e^{-i(1-\beta)\omega t}$$

- For an ultra-relativistic particle, and the electric and magnetic forces almost exactly cancel: the resultant force is small. But for a particle traveling in the opposite direction to the electromagnetic wave, and the resultant force is twice as large as would be expected from the electric force alone.



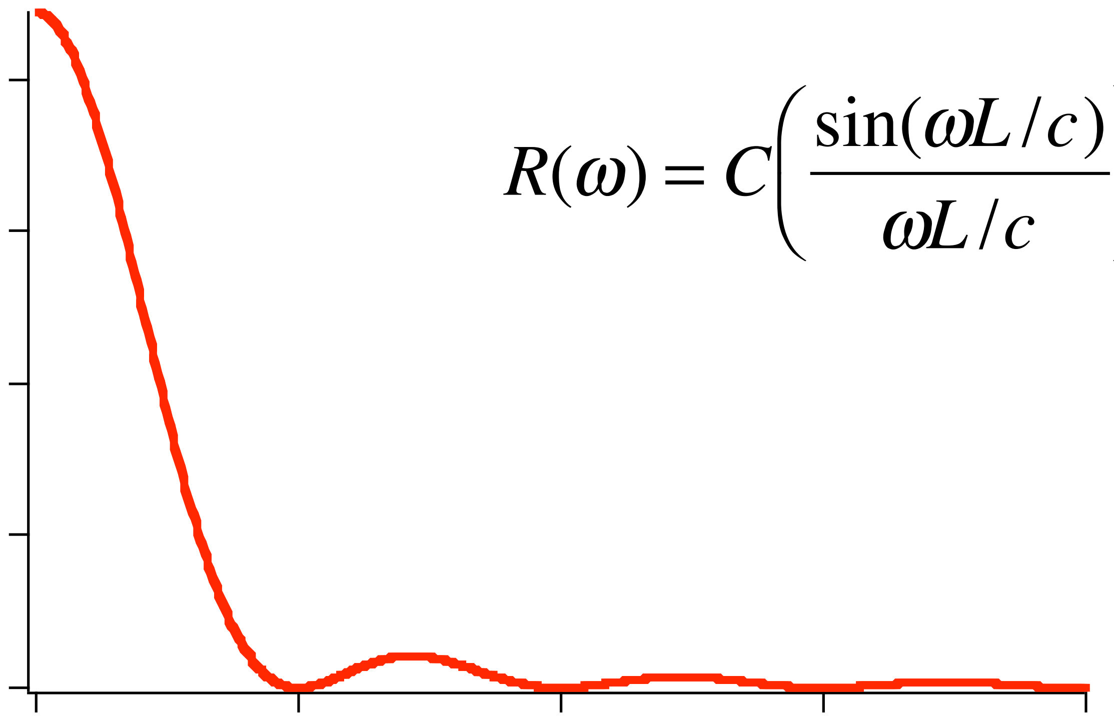
Stripline Kickers

- Consider a differential voltage pulse into the downstream port
  - Forces from E and B fields are equal and in the same direction
  - Pulse must be twice as long as kicker length for greatest efficiency
  - To give individual bunches separate kicks, kicker must be less than twice the bunch spacing.



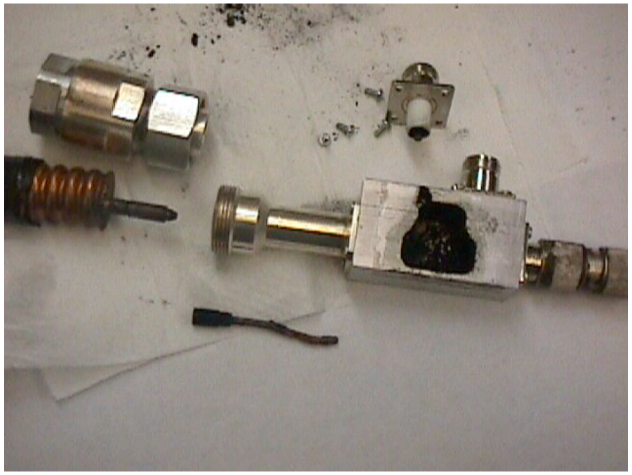
Transverse kicker frequency response

- Transverse kicker frequency response can be found from transform of square pulse
  - Nonzero DC response (i.e. works as constant deflector)
  - First zero in response at f=c/2L
  - Best response at baseband. Reduced response in upper bands.

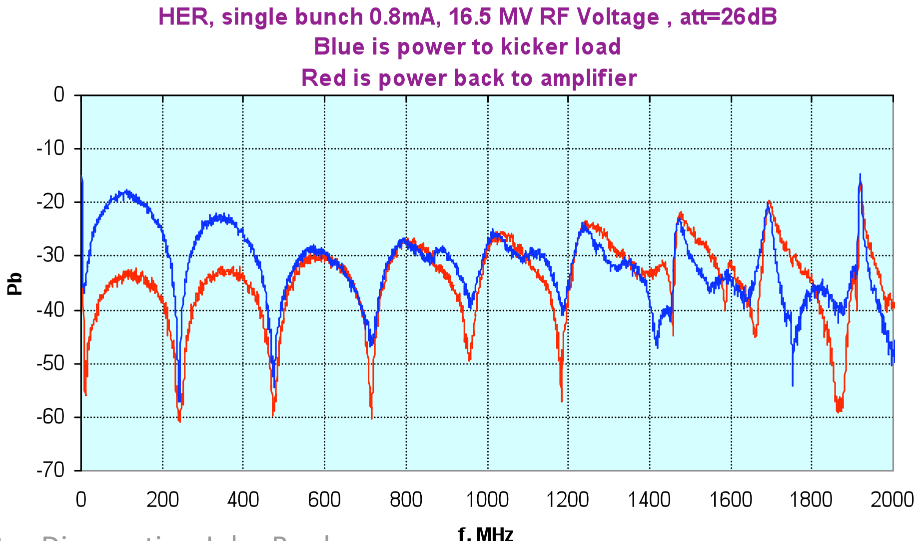


$$R(\omega) = C\left(\frac{\sin(\omega L/c)}{\omega L/c}\right)^2$$

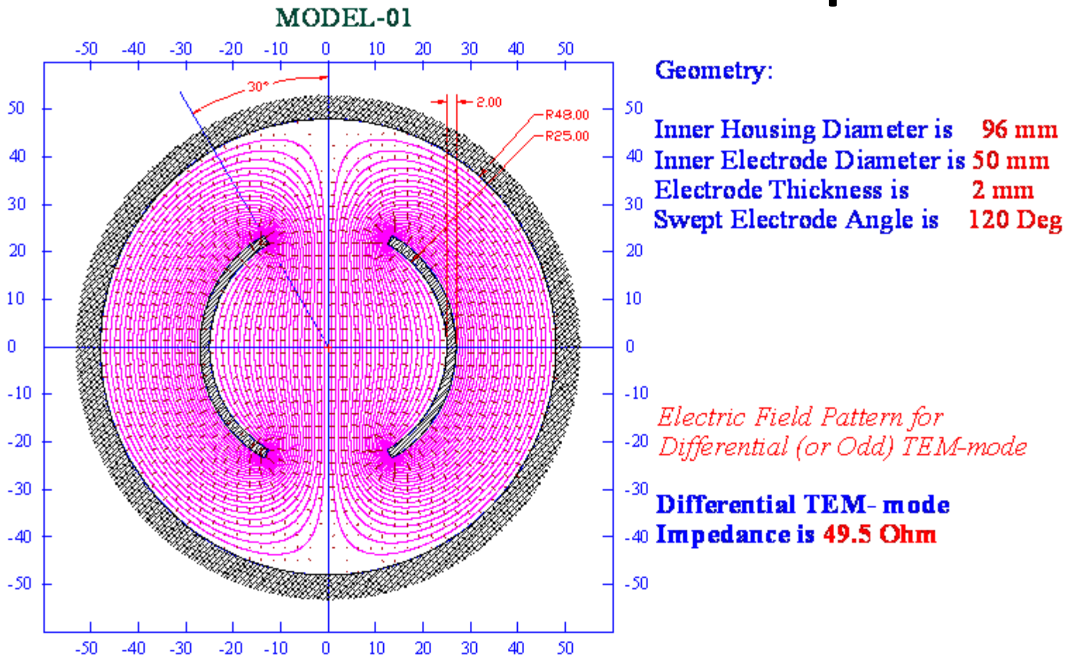
- Kicker is an efficient Higher Order Mode (HOM) power extractor. HOM power will go to the load when well matched, otherwise power can go back to drive amplifier.
- Peak HOM voltage and average power reflected back to the drive amplifier can cause damage if not handled properly.
- Input and output transition imperfections (cable, connectors, feedthroughs, kicker electrodes, loads) can cause build up of energy from bunches passing through the kicker structure.
- Shorter bunch lengths broaden the HOM spectrum



Burnt amplifier protection filter

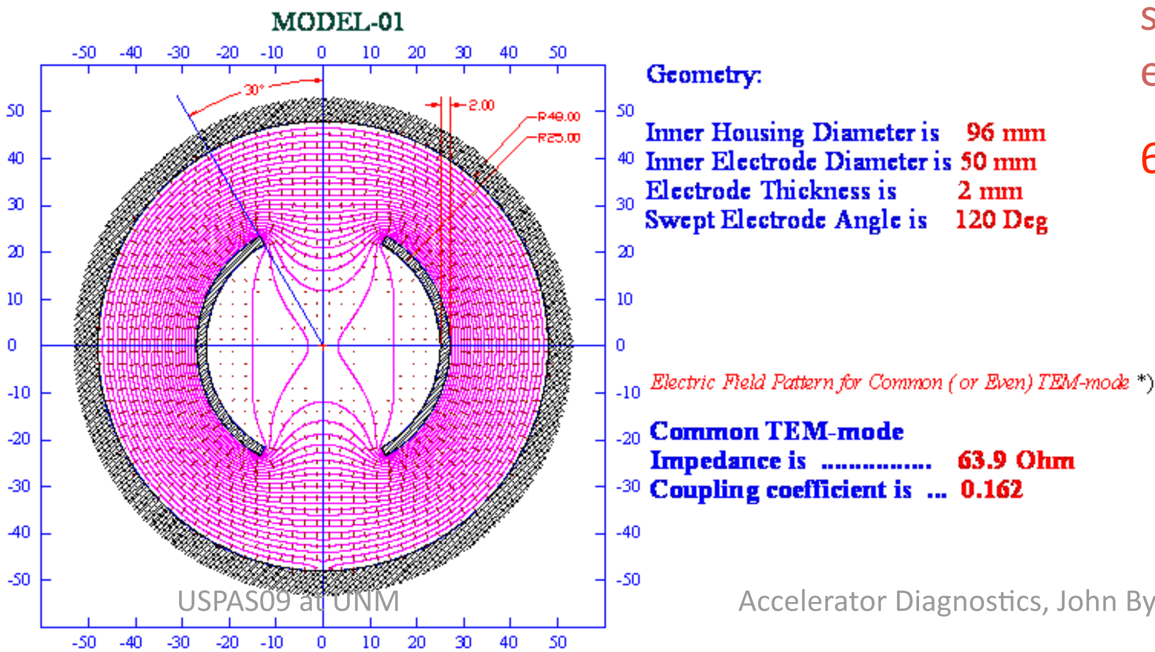


Fields in Kicker Strip Line Structure



A pulser produces a transverse kick. The difference (or odd) TEM mode is excited.

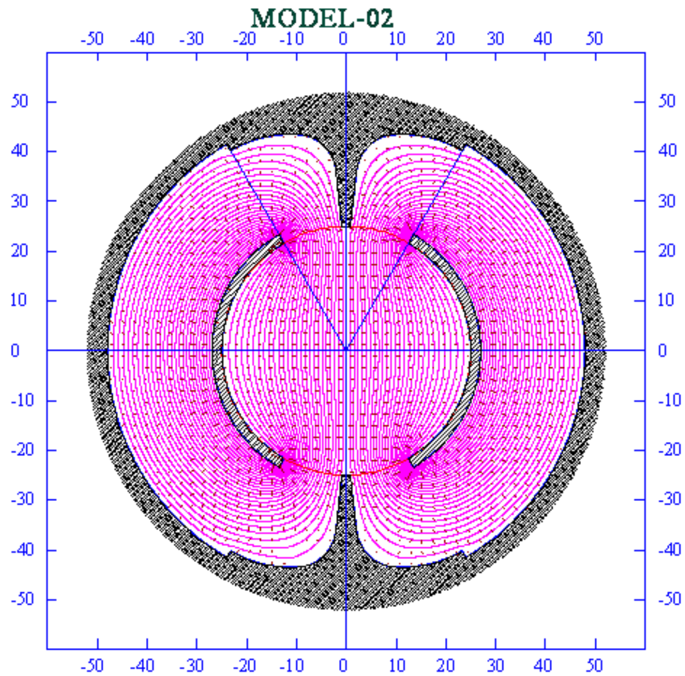
49.5 Ohm



When the bunch passes a kicker structure it induces an effectively even (or sum) TEM-mode.

63.9 Ohm

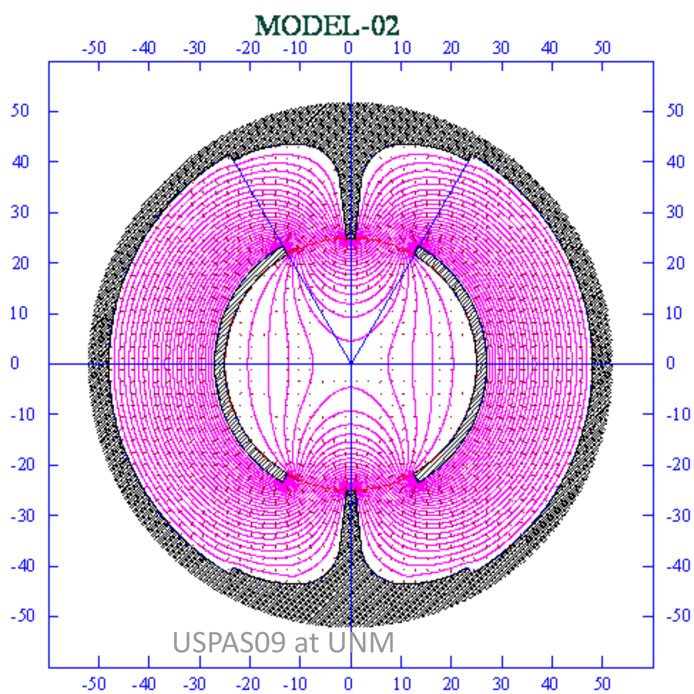
The field patterns for modes are dissimilar. As a result the impedances are different.



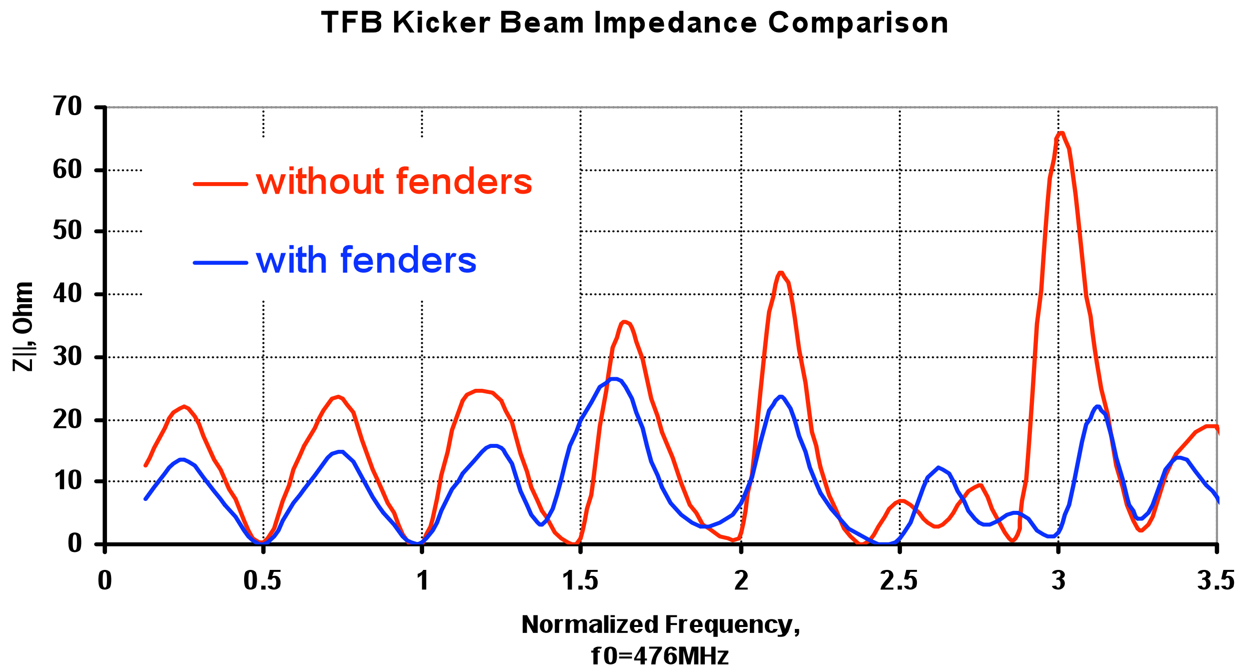
Matching of beam induced fields to 50 ohm ports

Odd TEM-mode, Z=49 Ohm

Matching both impedances is possible by the introduction of the ground fenders.



Beam induced even TEM-mode, Z=55 Ohm



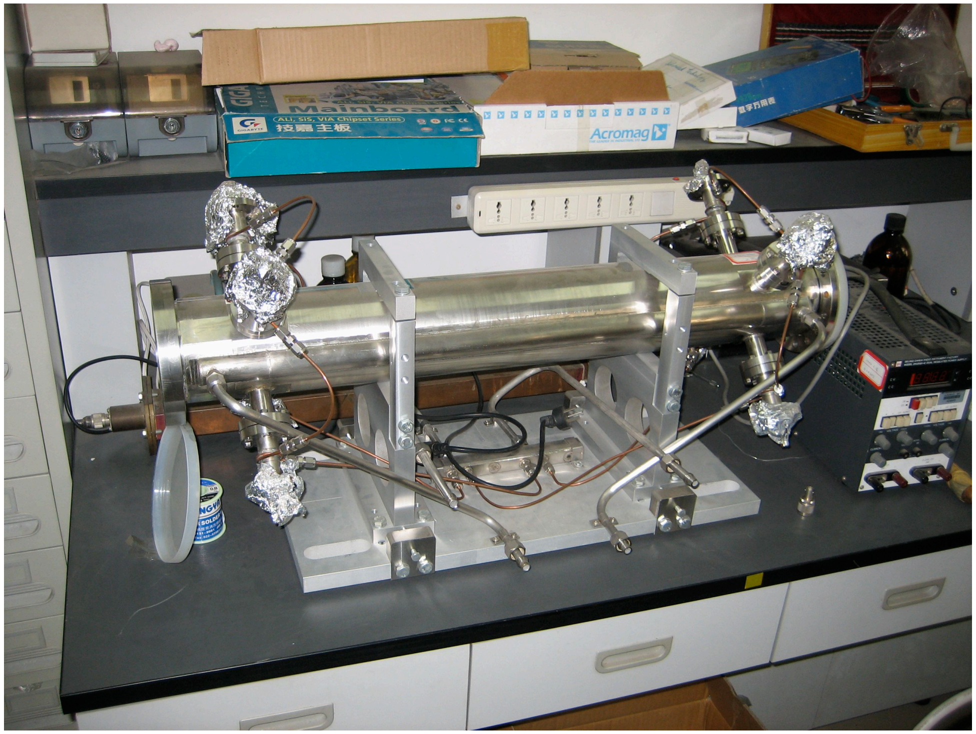
The difference in the field pattern produced by drive amplifier and induced beam wave can be reduced by the ground fenders.

Matching both even and odd impedances results in a reduction of the residual energy in the kicker structure allowing operation in multi bunch mode with a narrow distance between bunches.

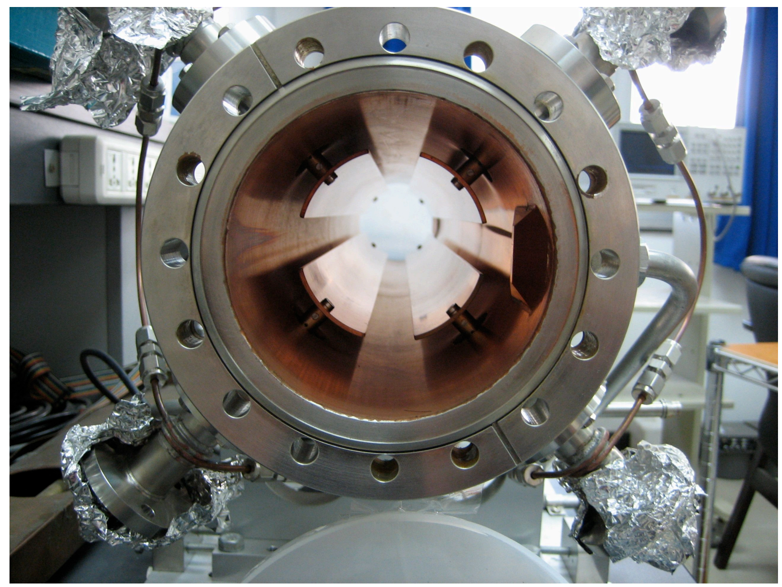
The kicker ends extract energy from the longitudinal momentum of the bunch train. The extracted energy can be reduced by optimization of the kicker end geometry.

Together these measures reduce the impedance of the kicker presented to the beam over a wide frequency range, thus reducing heating and effect on beam motion.

Example: BEPC-II Transverse Feedback Kicker



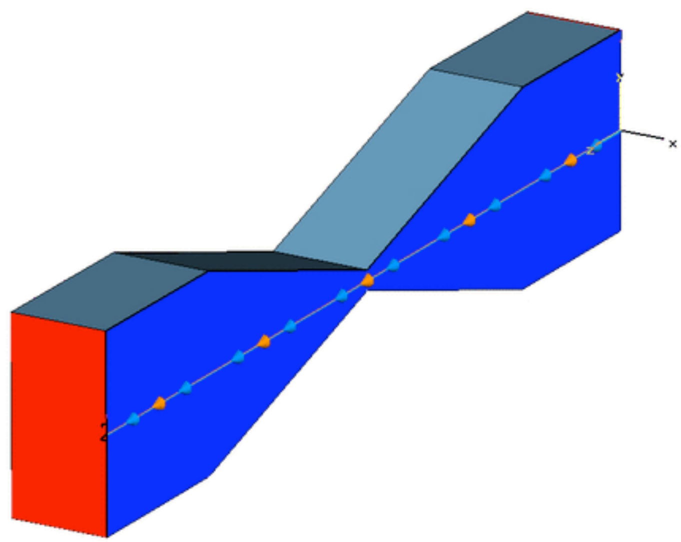
Often, horizontal and vertical electrodes are combined in the same tank.



Beam Impedance

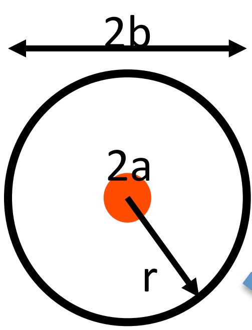
- As a beam passes through a vacuum chamber device, its TEM field can be distorted, resulting in some net longitudinal field on the beam.
- The beam impedance is defined as the ratio of the net beam voltage to the beam current

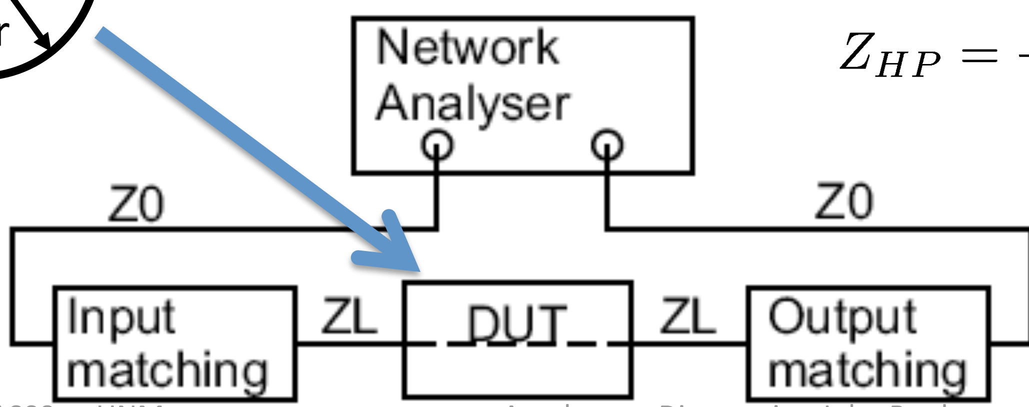
$$Z_{\|}(\omega) = -\frac{1}{q}\int_{-\infty}^{\infty} E_z\left(r=0;\omega\right)\exp\left(j\frac{\omega}{c}z\right)dz \qquad (\Omega)$$



Coaxial Wire Method

- The TEM mode of a coaxial wire approximates the fields of a relativistic beam
- Use a wire stretched thru the device under test (DUT) to measure the beam impedance of that device
  - NWA is used to measure the transmission of the DUT and a reference
  - Characteristic impedance, Z_0, must be matched to the line impedance Z_L=60ln(b/a)

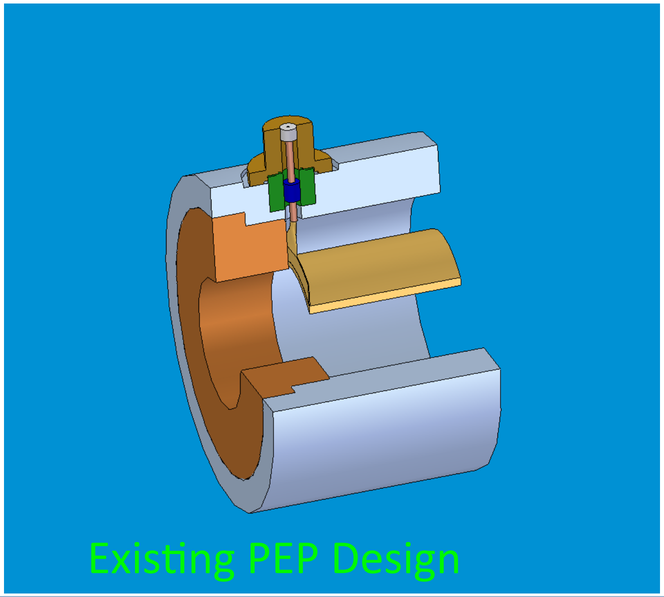




Hahn-Pedersen formula (1978)

$$Z_{HP} = -2Z_c \frac{S_{21}^{DUT} - S_{21}^{REF}}{S_{21}^{DUT}}$$

Broadband Matching by tapering of stripline is one option that will be evaluated.



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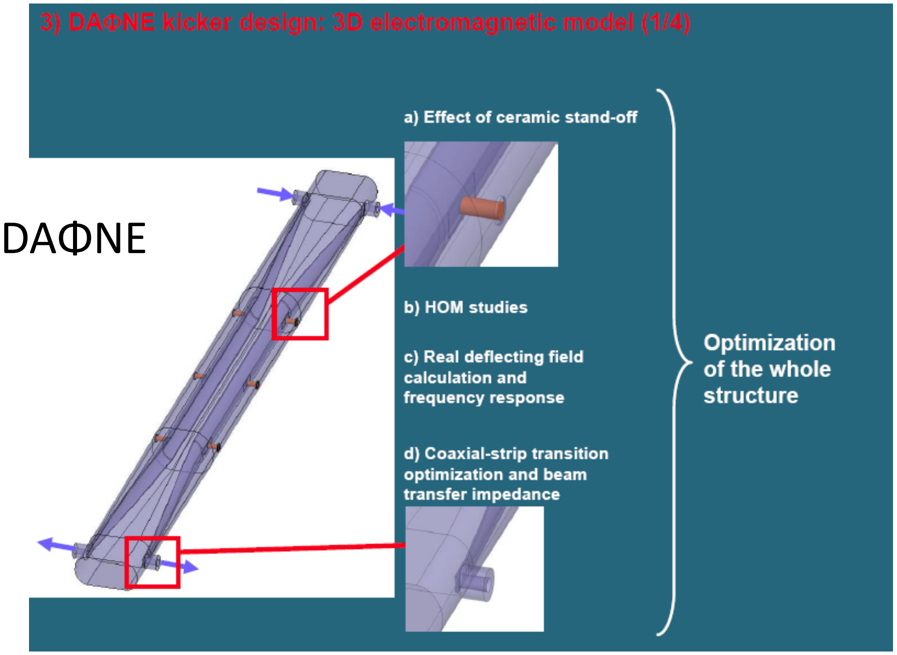
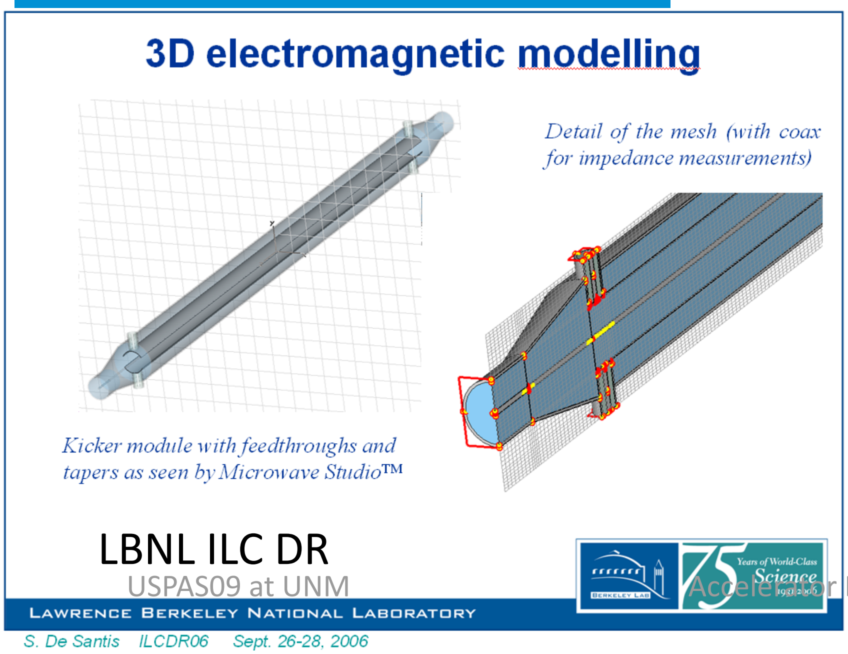
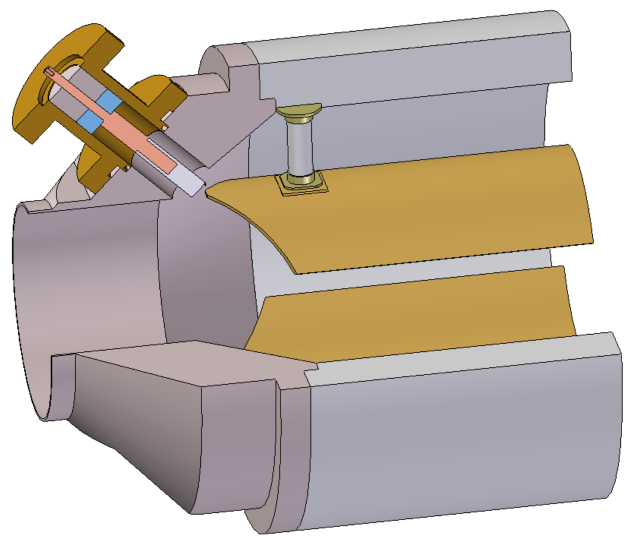


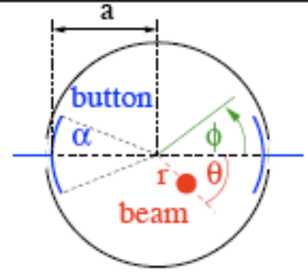




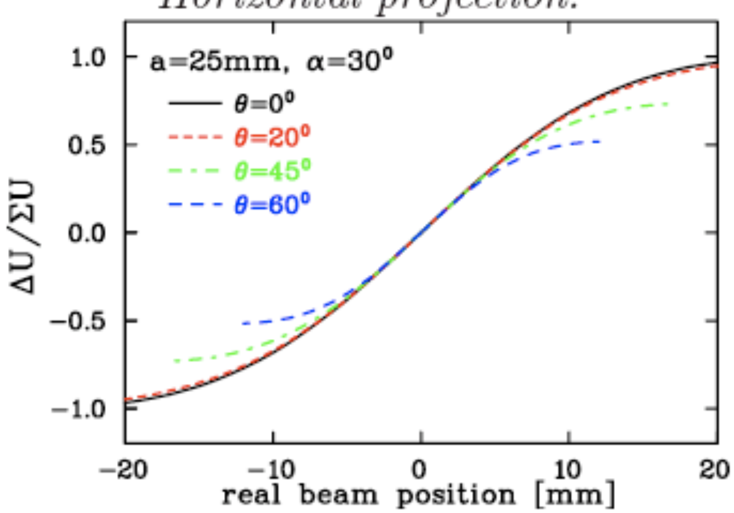
SLAC 2005 Proposed Design

Beam position determination by proximity effect

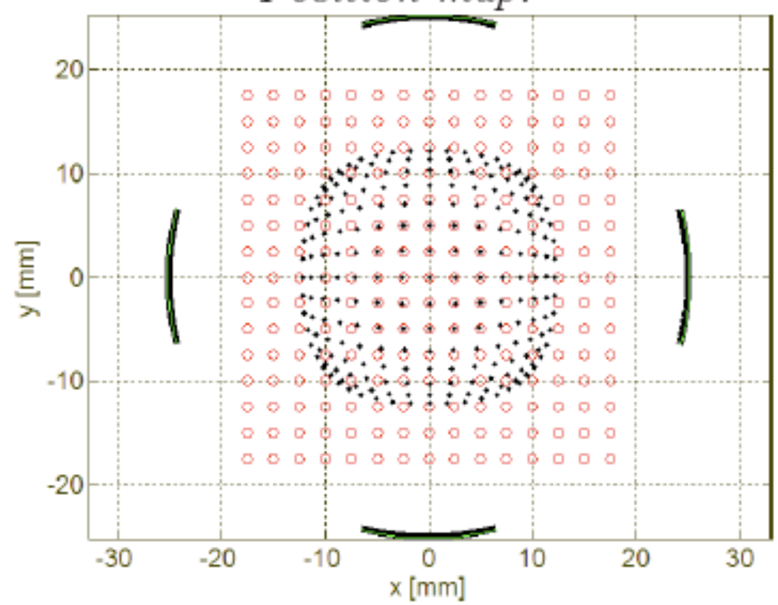
Model calculation within round geometry:



Horizontal projection:



Position map:



Position sensitivity $S_x(x) = \frac{d}{dx}\left(\frac{U_\Delta}{U_\Sigma}\right)$ with the unit [%/mm]

The measurement of U delivers: $x = \frac{1}{S_x} \cdot \frac{U_\Delta}{U_\Sigma}$, here $S = S(x, y)$ i.e. non-linear.

Analysis for position determination: Fourier spectrum

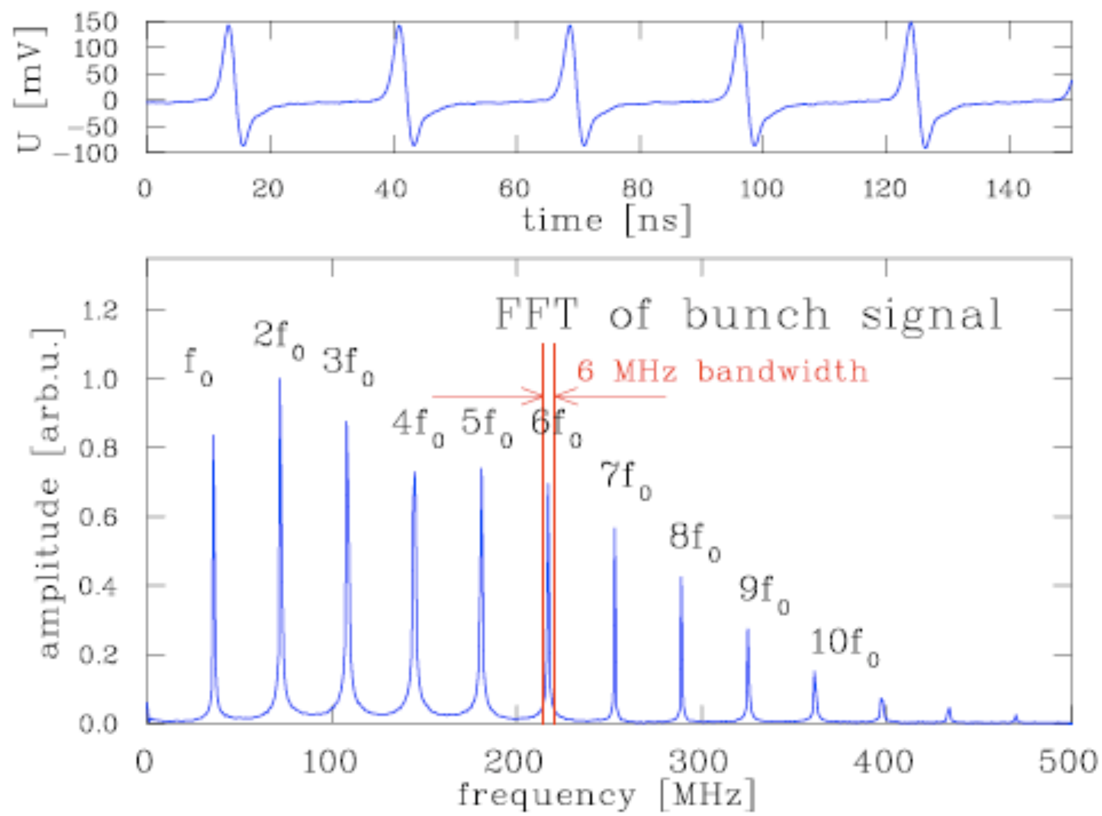
The position determination is done in the 'frequency domain':

- Differentiated or proportional shape is *not* important.
- The Fourier spectrum is important.

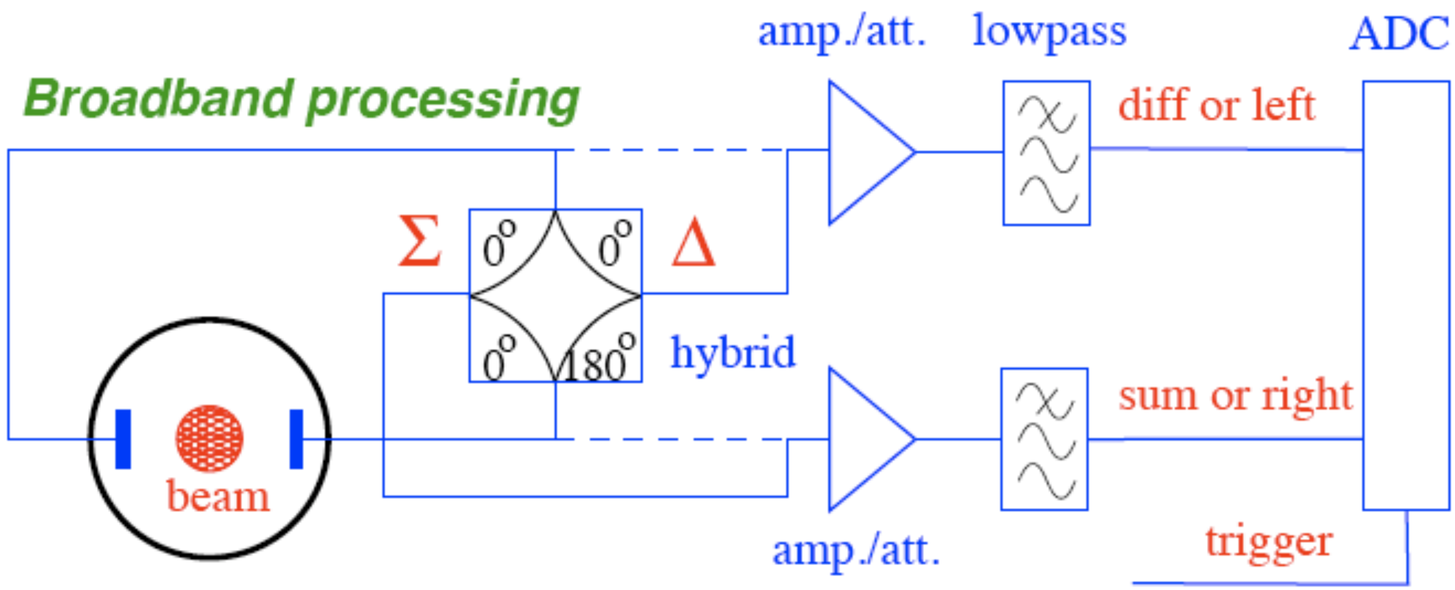
$\Longrightarrow$ Broadband or narrowband processing.

Bunch signal (top) and Fourier spectrum (bottom) at the 36 MHz GSI-LINAC.

Each line is a harmonics of $f_0 = 36$ MHz.



Broadband signal processing



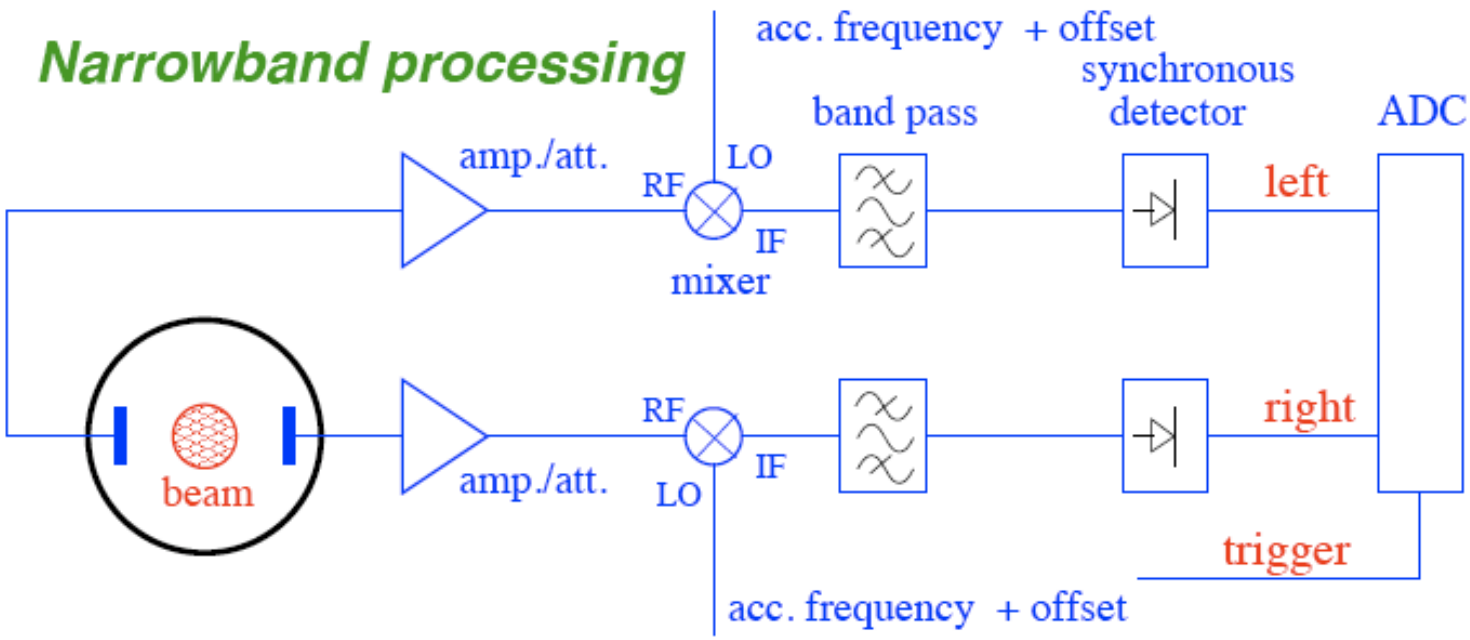
1. Attenuator/amplifier
2. Optional: lowpass filter to suppress alias products
3. ADC: digital calculation of U_Δ/U_Σ

Most frequently used:
Analog sum and differences by hybrid or transfromer + larger amplification of U_Δ.

Advantage: Full information: e.g. for synchrotron turn-by-turn diagnosis possible.

Disadvantage: Resolution down to $\sim 100\ \mu$m, worse than narrowband processing.

Narrowband signal processing



1. attenuator/amplifier
2. mixing with accelerating frequency f_{rf}
3. bandpass filter for one harmonics of the mixed signal (harmonics of 10.7 MHz)
4. rectifier (diode or synchronous detector)
5. ADC: digital calculation of U_Δ/U_Σ

Advantage: Resolution up to 1 μm; about 100 time better than broadband.

Disadvantage: No turn-by-turn diagnosis, due to 'long averaging time'.

Mixer and synchronous detector

Mixer: A passive rf device with

- Input RF (radio frequency): Signal of investigation $A_{RF}(t) = A_{RF}\cos\omega_{RF}t$
- Input LO (local oscillator): Fixed frequency $A_{LO}(t) = A_{LO}\cos\omega_{LO}t$
- Output IF (intermediate frequency):

$$\begin{aligned} A_{IF}(t) &= A_{RF}\cdot A_{LO}\cos\omega_{RF}t\cdot\cos\omega_{LO}t \\ &= \frac{1}{2}A_{RF}\cdot A_{LO}\cos(\omega_{RF}-\omega_{LO})t\cdot\cos(\omega_{RF}+\omega_{LO})t \end{aligned}$$

Multiplication of both input signals, containing the sum and difference frequency.

Synchronous detector: A phase sensitive rectifier