Beam Position Monitors

for the

CLIC Drive Beam

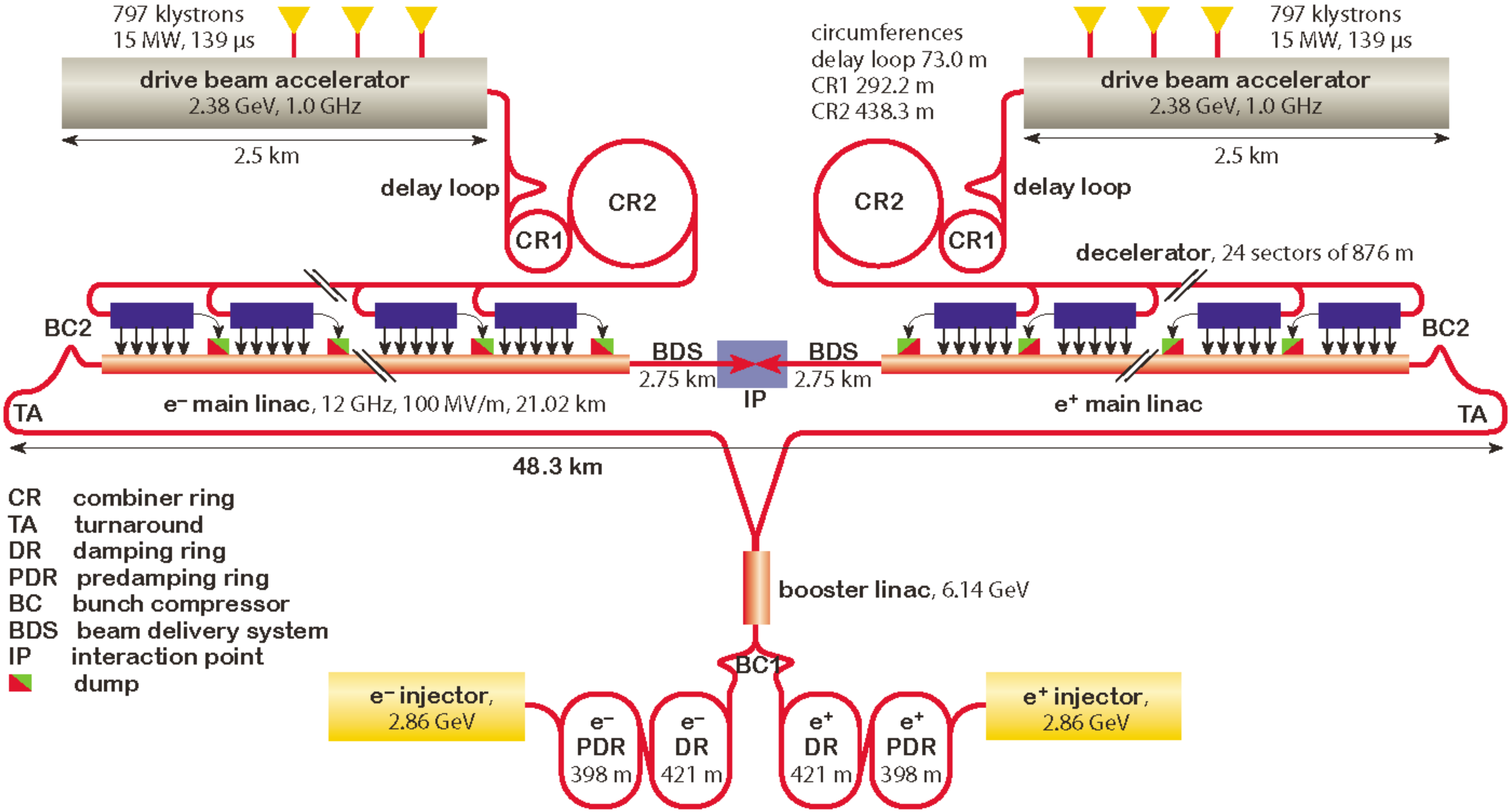
Steve Smith
SLAC National Accelerator Lab

BPM Workshop
CERN
16 January 2012

CLIC

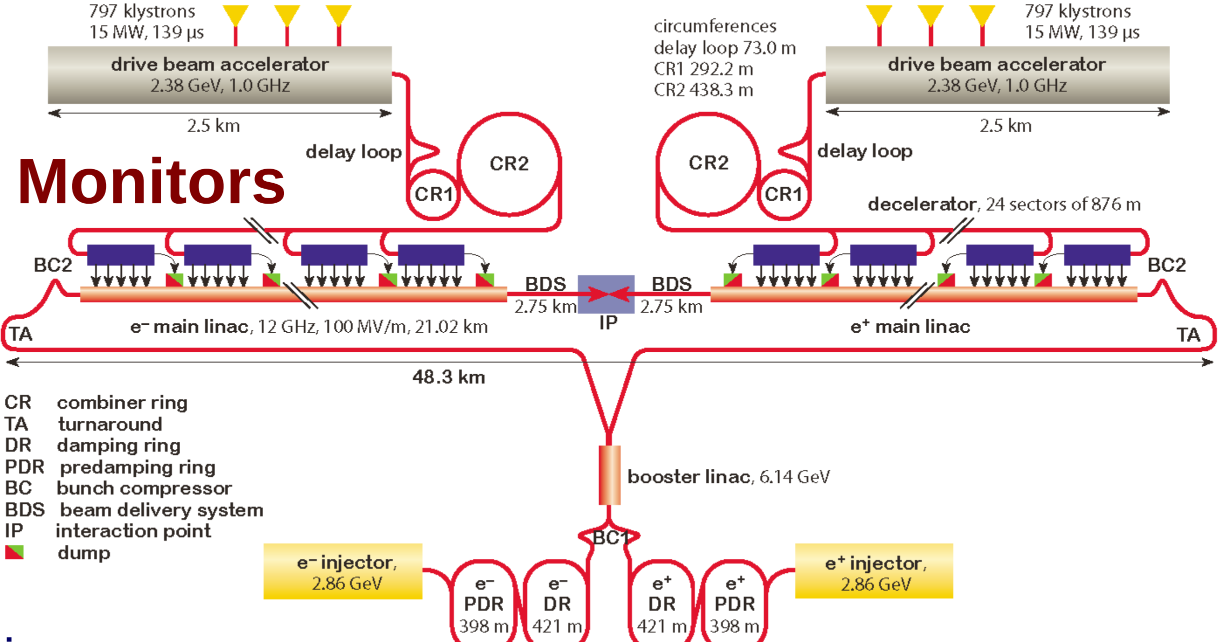
- Linear Collider
- Two-Beam acceleration
- Accelerate Drive beam
  - high current (100Amp)
  - low energy (1GeV)
  - long pulse (140 microsec)

- Extract RF from drive beam
- Transfer to luminosity beam
  - Lower current (1 A)
  - High energy (1.5 TeV)
  - Short pulse (150 ns)

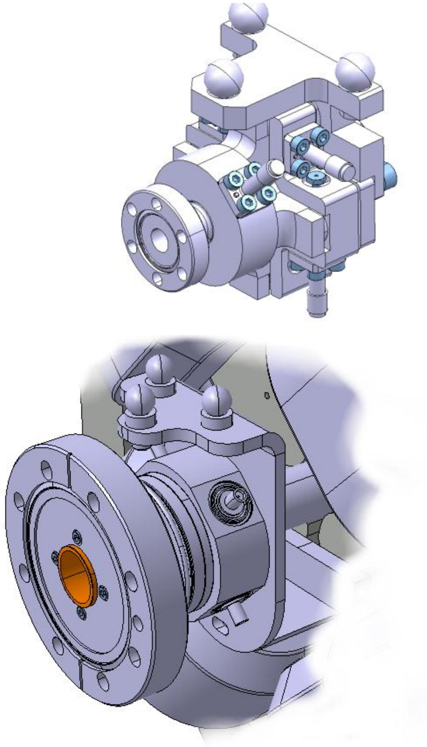


CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
🟥	dump

Beam Position Monitors



- **Main Beam**
  - Quantity ~7500
    - Including:
    - 4196 Main beam linac
      - 50 nm resolution
    - 1200 in Damping & Pre-Damping Ring
- **Drive Beam**
  - Quantity ~45000
    - 660 in drive beam linacs
    - 2792 in transfer lines and turnarounds
    - 41000 in drive beam decelerators **!**



CLIC Drive Beam Decelerator BPMs

- **Requirements**
  - Transverse resolution < 2 microns
  - Temporal resolution < 10 ns
    - ➔ Bandwidth > 20 MHz
  - Accuracy < 20 microns
  - Wakefields must be low

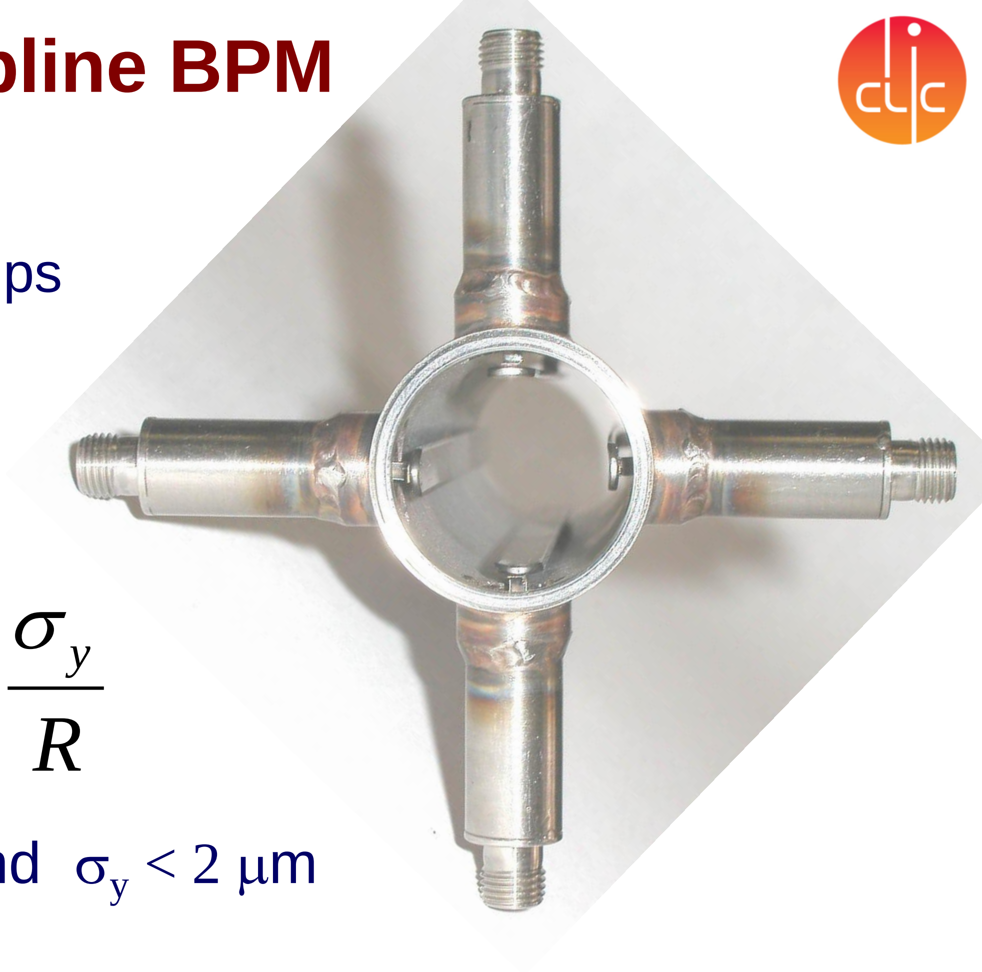
- **Considered Pickups:**
  - Resonant cavities
  - Striplines
  - Buttons

Drive Beam Decelerator BPM Challenges

- Bunch frequency in beam: 12 GHz
  - Lowest frequency intentionally present in beam spectrum
  - It is above waveguide propagation cutoff
    - TE_{11} ~ 7.6 GHz for 23 mm aperture
  - There are **non-local** beam signals above waveguide cutoff.

- Example of non-local signal:
  - Structure purpose is to generate 130 MW @ 12 GHz in nearby Power Extraction Structures (PETS)
    - Leakage to BPM?
  - Also transverse modes induced by
    - Aperture asymmetries
    - beam offsets

Generic Stripline BPM



- Algorithm:
  - Measure amplitudes on 4 strips

$$Y = \frac{R}{2} \cdot \frac{V_U - V_D}{V_U + V_D}$$

- Resolution: $$\frac{\sigma_V}{V_{peak}} = 2\sqrt{2} \cdot \frac{\sigma_y}{R}$$

Given: R = 11.5 mm and $\sigma_y < 2\ \mu$m

Requires σ_V/V_{peak} = 1/6000 ➔ 12 effective bits

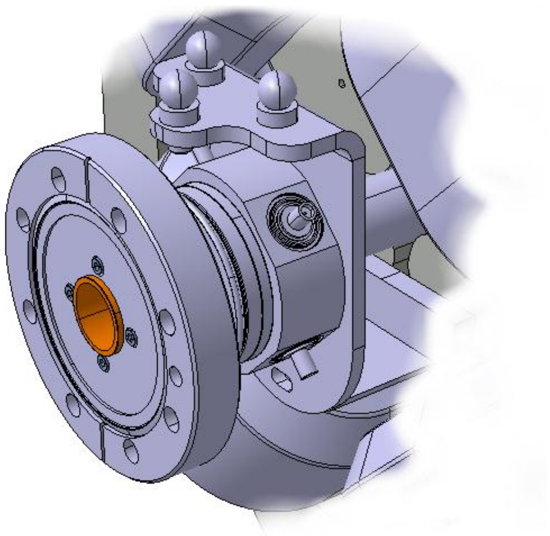
- Small difference in big numbers
- **Calibration is crucial!**

Choose Operating Frequency

- Operate at sub-harmonic of bunch spacing ?
  - Example: F_{BPM} = 2 GHz
    - Signal is sufficient
    - Especially at harmonics of drive beam linac RF
    - Could use
      - buttons
      - compact striplines
    - But there exist confounding signals
      Transverse errors at frequency of bunch combination ! ! !
- OR process at baseband ?
  - Bandwidth ~ 4 - 40 MHz
  - traditional
  - resolution is adequate
  - Check temporal resolution
  - Requires striplines to get adequate S/N at low frequencies
    (< 10 MHz)

OK✓

Decelerator Stripline BPM

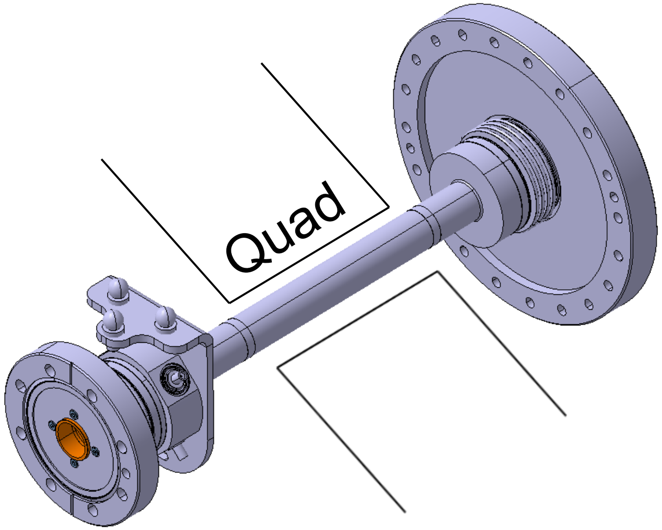


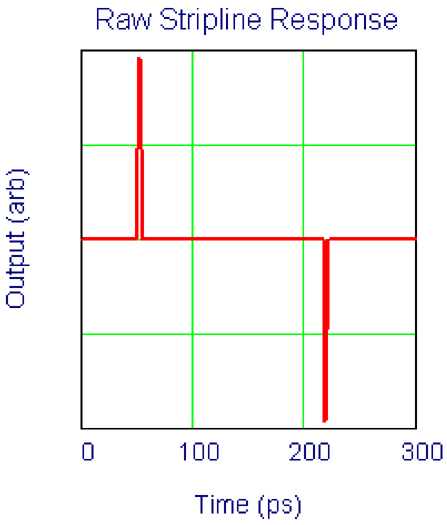
Diameter: 23 mm

Stripline length: 25 mm

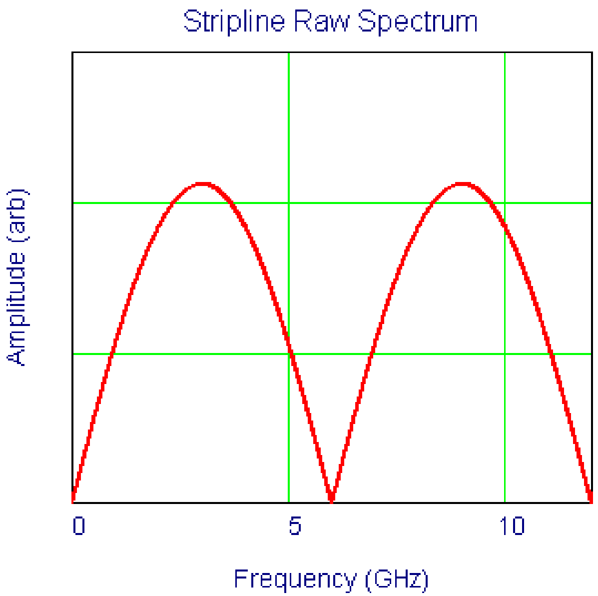
Width: 12.5% of circumference (per strip)

Impedance: 50 Ohm





Response Peak at 3.0 GHz, null at 12 GHz



Signal Processing Scheme

- Lowpass filter to ~ 40 MHz
- Digitize with fast ADC
    - 160 Msample/sec
- 16 bits, 12 effective bits
- Assume noise figure ≤10 dB

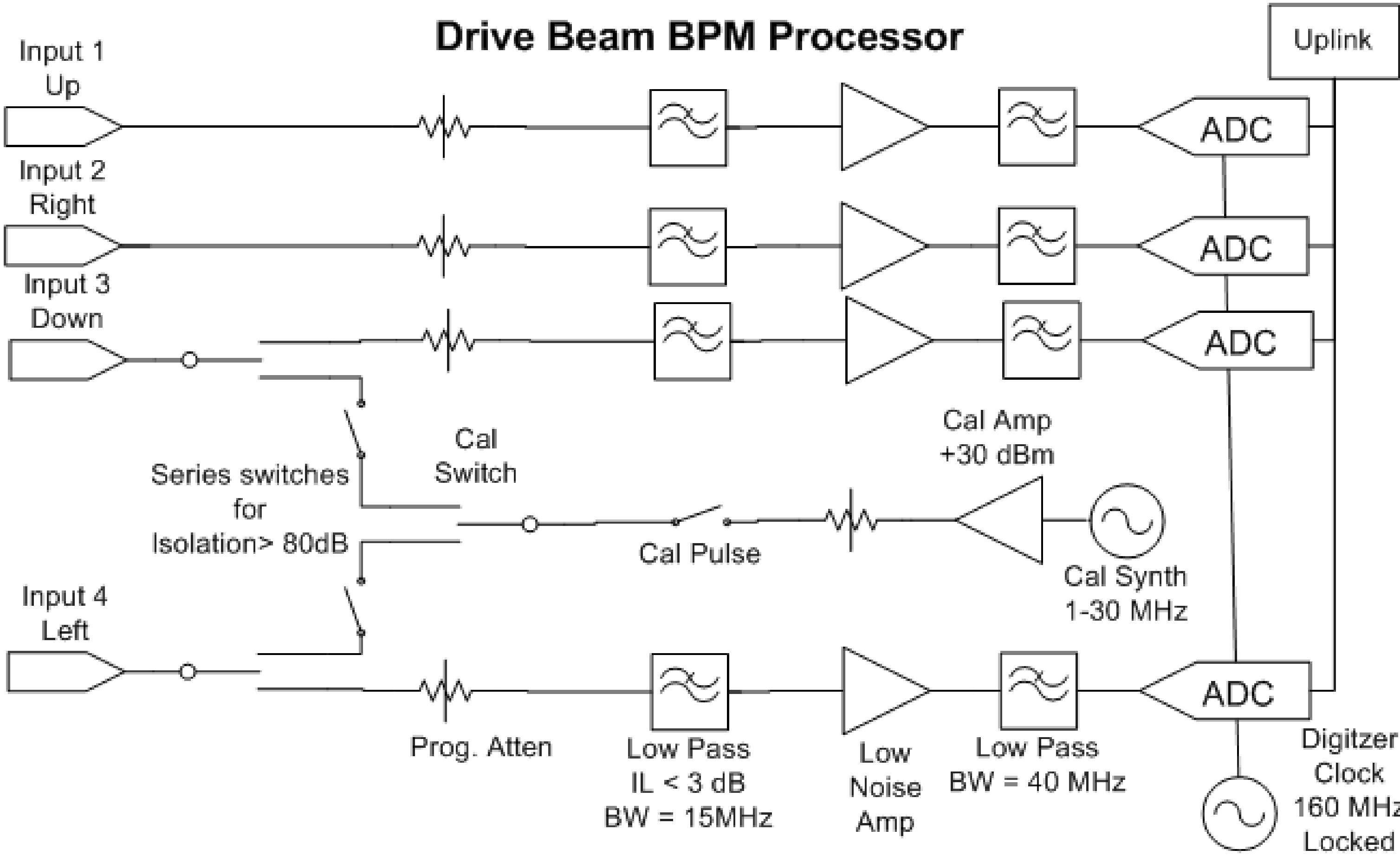
- For nominal single bunch charge 8.3 nC
    - Single bunch resolution $\sigma_y < 1\ \mu m$

Including

Cable & filter losses

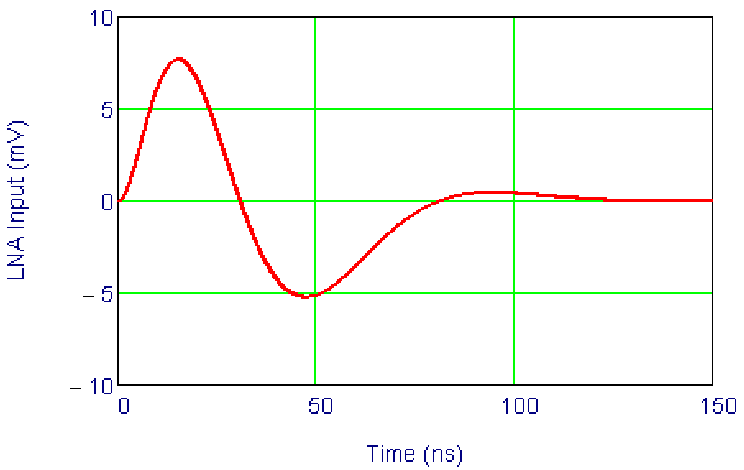
amplifier noise figure

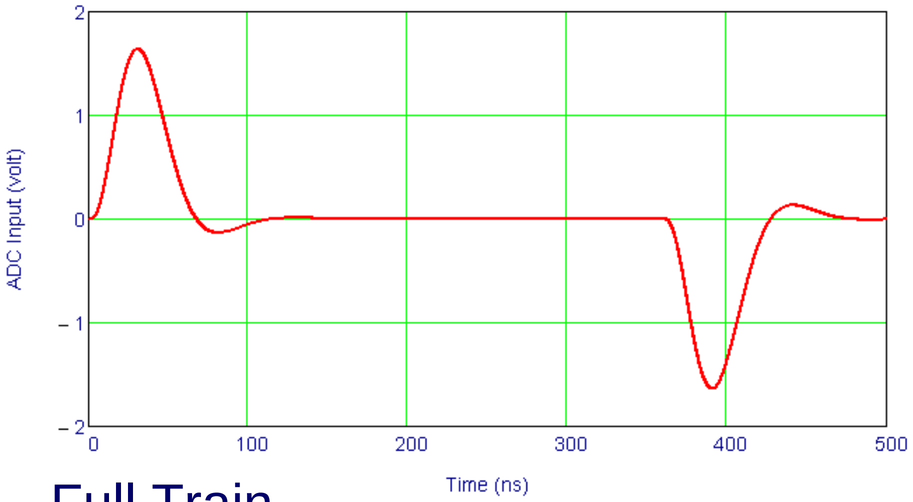
ADC noise



Single Bunch and Train Transient Repsonse

- What about the turn-on / turn-off transients of the nominal fill pattern?
- Provides good position measurement for head/tail of train
  - Example: NLCTA
    - ~100 ns X-band pulse
      - BPM measured head & tail position with 5 - 50 MHz bandwidth
- **CLIC Decelerator BPM:**



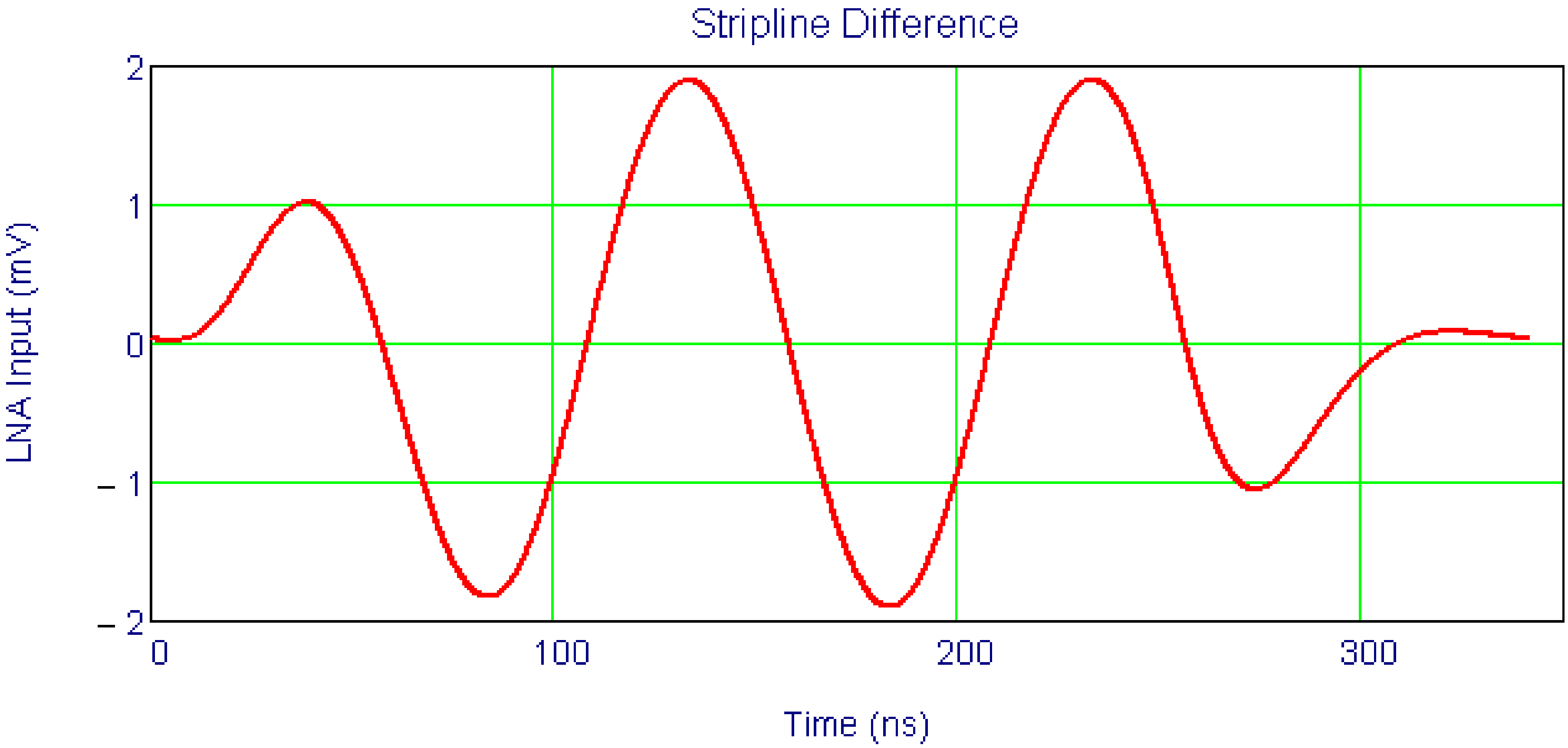


- Single Bunch	Full Train
- Q=8.3 nC	I = 100 Amp
- $\sigma_y \sim 2\ \mu$m	$\sigma_y < 1\ \mu$m (train of at least 4 bunches)

-

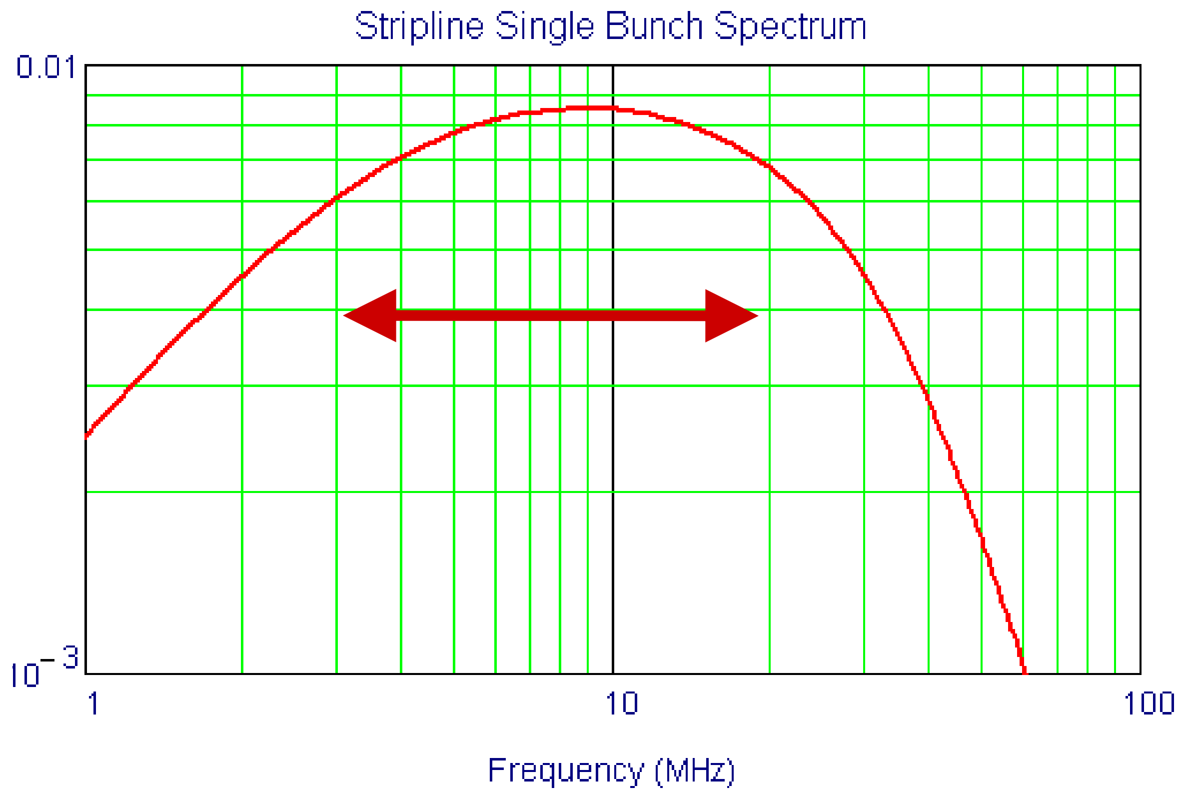
Temporal Response within Train

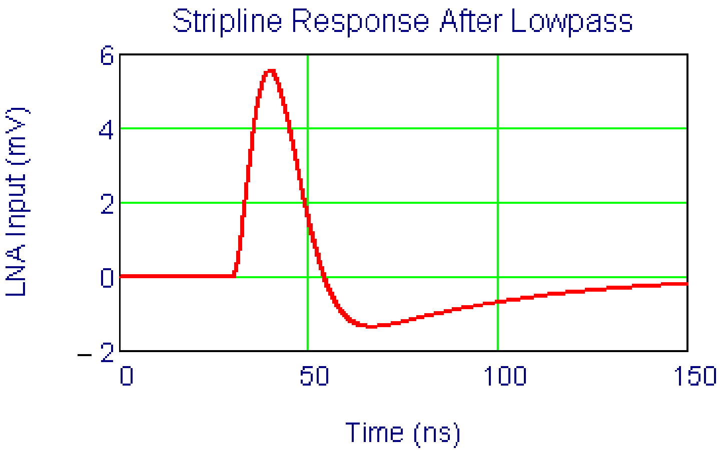
- Simulate 10 MHz transverse oscillation at 2 micron amplitude
- Up-Down stripline difference signal
- $S/N_{thermal}$ is huge
- BUT the ADC noise limit: ~ 2 μm/$\sqrt{N_{sample}}$



Craft Bandwidth

- Maintain adequate S/N across required spectrum
- In presence of linearly rising signal vs. frequency
- Aim for roughly flat S/N vs. frequency from few MHz to 20 MHz
- Choose two single-pole low-pass filters plus one 2nd order lowpass
- Look at spectrum while manually tweaking poles.
  - Example:
  - F_1 = 4 MHz
  - F_2 = 20 MHz
  - F_3 = 35 MHz





Origin of Position Signal

- Convolute pickup source term
  - for up/down electrodes
  - to first order in position y

$$q_{\pm}(t) = I(t)\cdot\left(1 \pm \frac{2y(t)}{R}\right)$$

- With stripline response function
  - where Z is impedance and
  - l is the length of strip

$$R(t) = \frac{Z}{2}\cdot\frac{\phi}{2\pi}\cdot\left(\delta(t) - \delta(t - \frac{2L}{c})\right)$$

- At low frequency << *c/2L* ~ 6GHz
  - Looks like derivative:

$$V_{\pm}(t) = \frac{Z}{2}\cdot\frac{\phi}{2\pi}\cdot\frac{2L}{c}\frac{d}{dt}\left(Q(t)\left(1 \pm \frac{2y(t)}{R}\right)\right)$$

Up-Down Difference:

$$V_{+}(t) - V_{-} = \frac{Z}{2}\frac{\phi}{2\pi}\frac{2L}{c}\frac{2}{R}\left(y(t)\frac{dQ(t)}{dt} + Q(t)\frac{dy(t)}{dt}\right)$$

  - 1st term: $Y \times dQ/dt$
  - 2nd term: $dY/dt \times Q$

- Signal is nice, but is a product of functions of time, and their derivatives. Can predict waveform from y(t) and Q(t)
- But how about inverse?

Nonlinear ! ➔ Inconvenient !

Position & Charge

- Back up one step:
- At low frequency << *c/2L* ~ 6GHz
  - Looks like derivative:
  - Take sum and difference:

$$V_{\pm}(t) = \frac{Z}{2}\cdot\frac{\phi}{2\pi}\cdot\frac{2L}{c}\frac{d}{dt}\left(Q(t)\left(1\pm\frac{2y(t)}{R}\right)\right)$$

Sum

&

Difference

$$\Sigma \equiv V_{+}(t) - V_{-} = \frac{Z}{2}\frac{\phi}{2\pi}\frac{2L}{c}2\frac{dQ(t)}{dt}$$

$$\Delta \equiv V_{+}(t) - V_{-} = \frac{Z}{2}\frac{\phi}{2\pi}\frac{2L}{c}\frac{2Q(t)}{R}\frac{dy(t)}{dt}$$

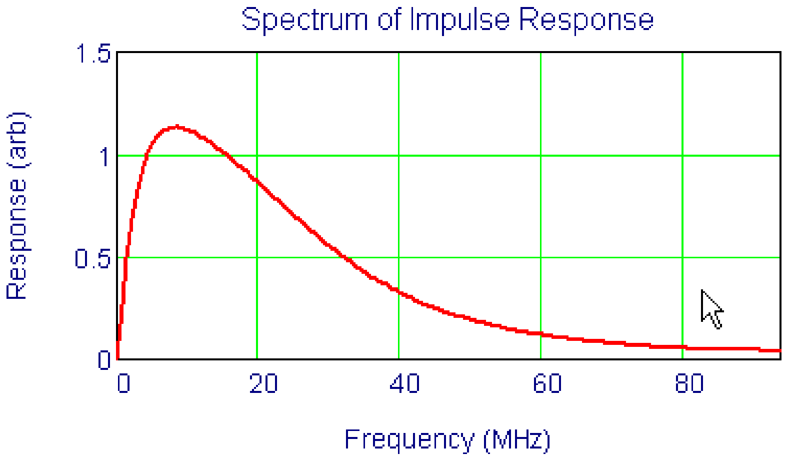
- The expression for Σ is *linear* in $Q(t)$
- Can estimate from digitized waveforms with standard tools
  - Deconvolution
- If we know response function
- Measure impulse response function with a single bunch
  - or a few bunches
    - e.g. < few ns of bunch train
- Then having solved for $Q(t)$
- insert $Q(t)$ in expression for Δ and solve for $y(t)$

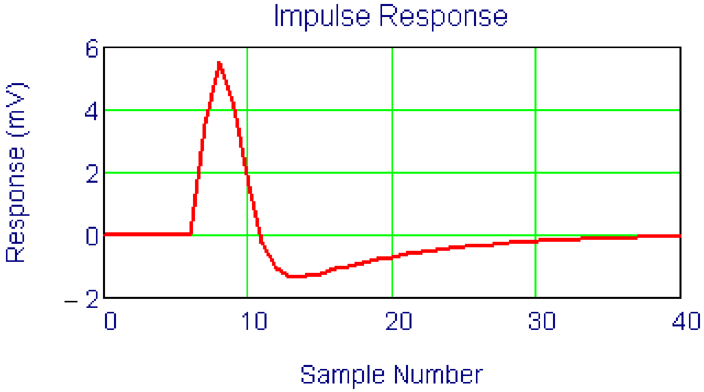
Assumptions

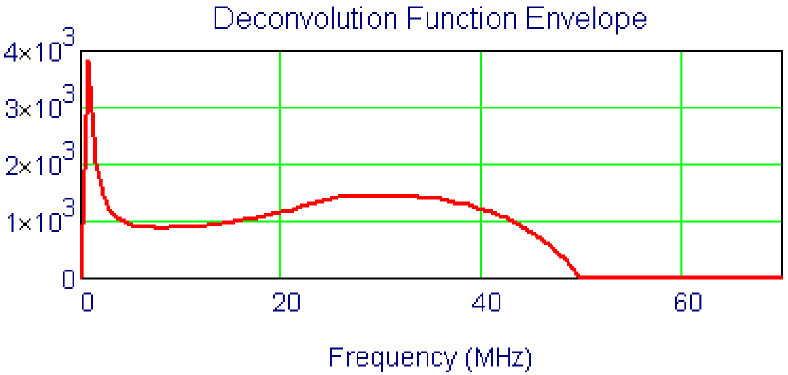
- ADC
  - Sampling rate = 200 MHz
  - S/N = 77 dB_{FS}
  - Record length = 256 samples
- Assume excellent linearity
  - ADC has excellent linearity
  - Don’t mess up linearity in the amplifiers!
    - Specify high IP_3 for good linearity
- $Z_{even} = Z_{odd}$
  - Even / odd mode impedances are equal
    - probably not important assumption
    - the difference can be estimated in 2D EM solver
    - To be investigated

Algorithm

- Define frequency range of interest
  - 0.5 MHz < f < 40 MHz
- Acquire single bunch data
  - Invert single bunch spectrum
  - Roll off < 0.5 MHz and > 40 MHz
  - (maintaining phase info)



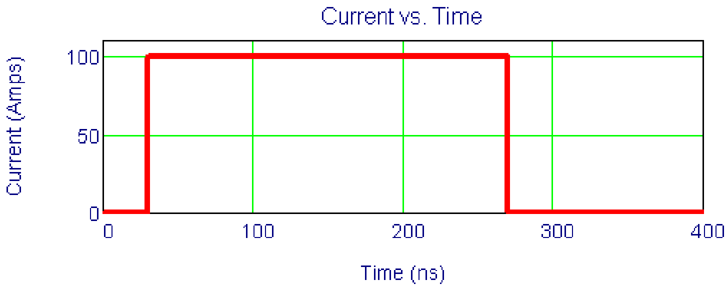


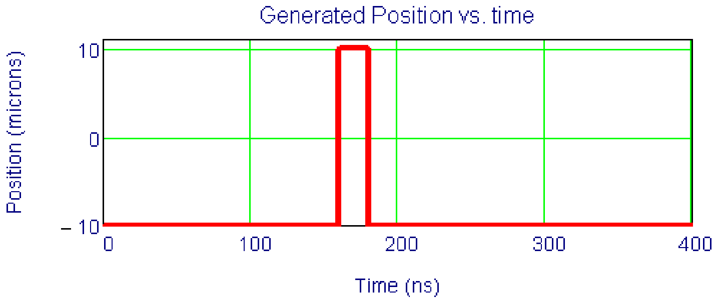


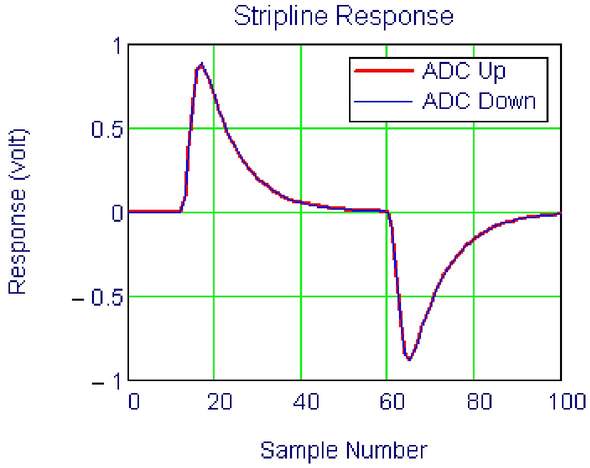
- Acquire bunch train data
  - Form Δ & Σ
  - Deconvolute with impulse response from single bunch acquisition
    - Divide Fourier Transform of data by (weighted) FT of single bunch

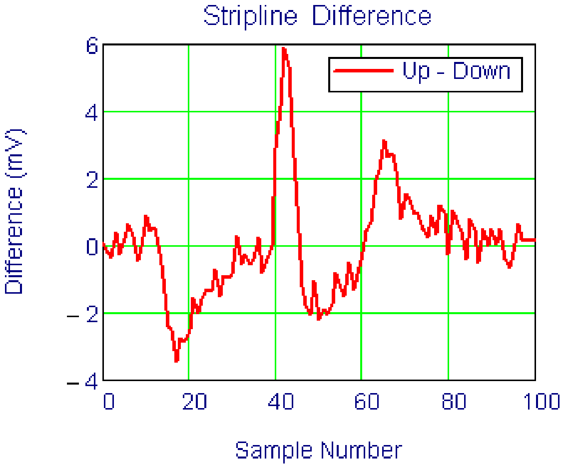
Example

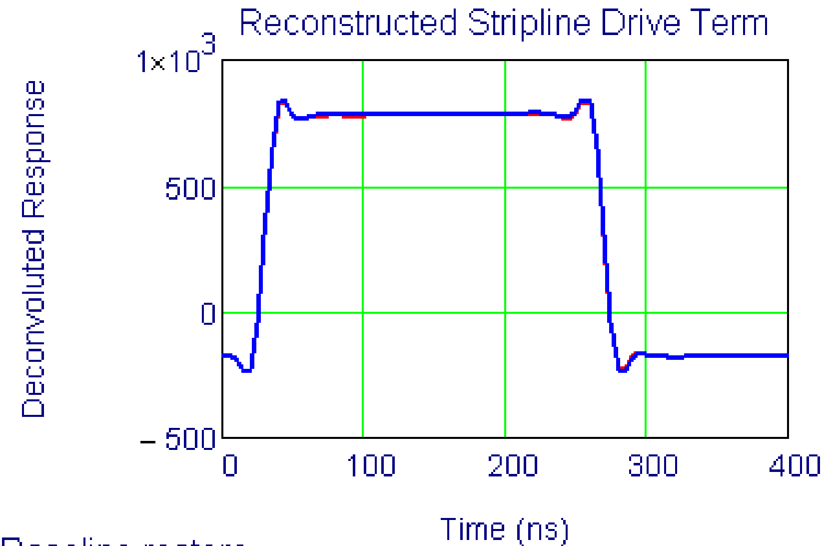
- Simulate Bunch train with position variation
- Simulate response
- Form Δ and Σ (difference & sum)
- Deconvolute
- Compare to generated y(t)

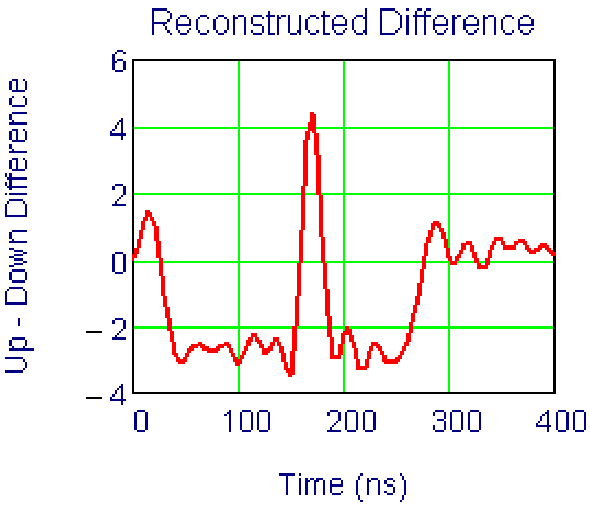

Current vs. Time


Generated Position vs. time


Stripline Response

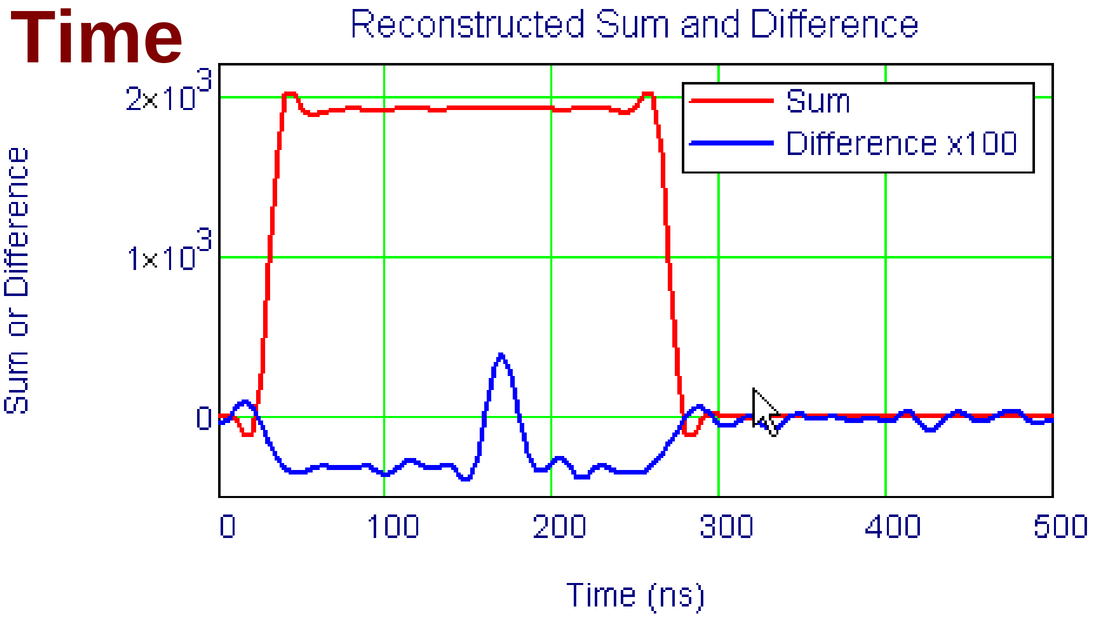

Stripline Difference

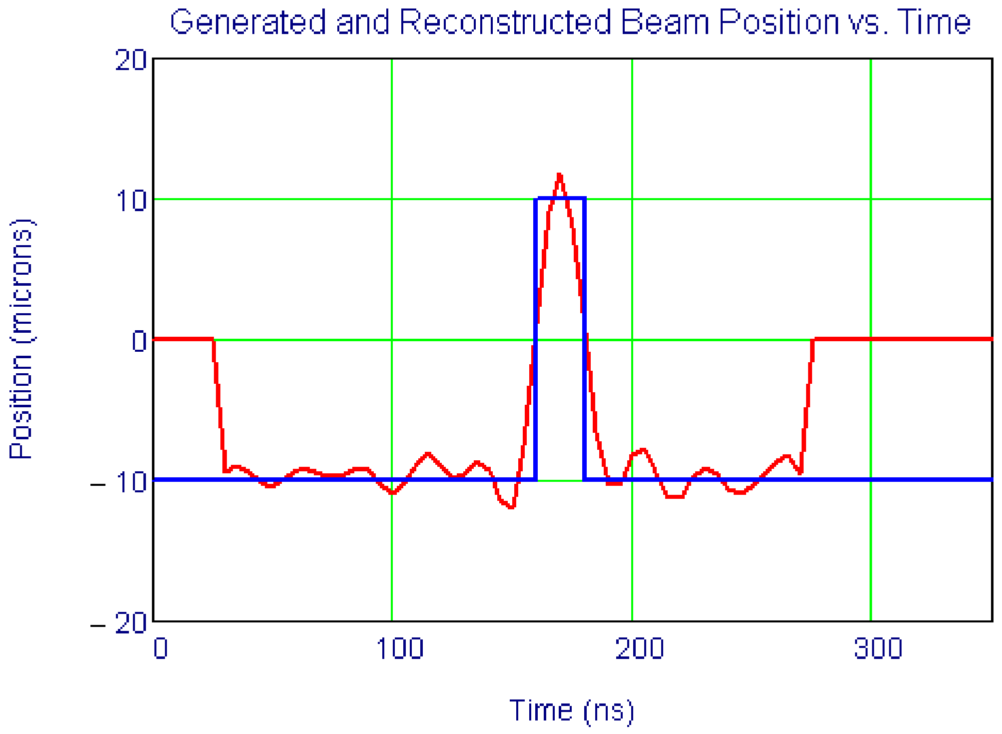

Reconstructed Stripline Drive Term


Reconstructed Difference

Charge & Position vs. Time

- Works quite well
  - On paper
- Must add effects of nonlinearities
- Can deconvolute Q(t) and y(t) from sum and differences of digitized stripline waveforms
- Dynamic range of ADC makes it challenging


Reconstructed Sum and Difference


Generated and Reconstructed Beam Position vs. Time

Summary of Performance

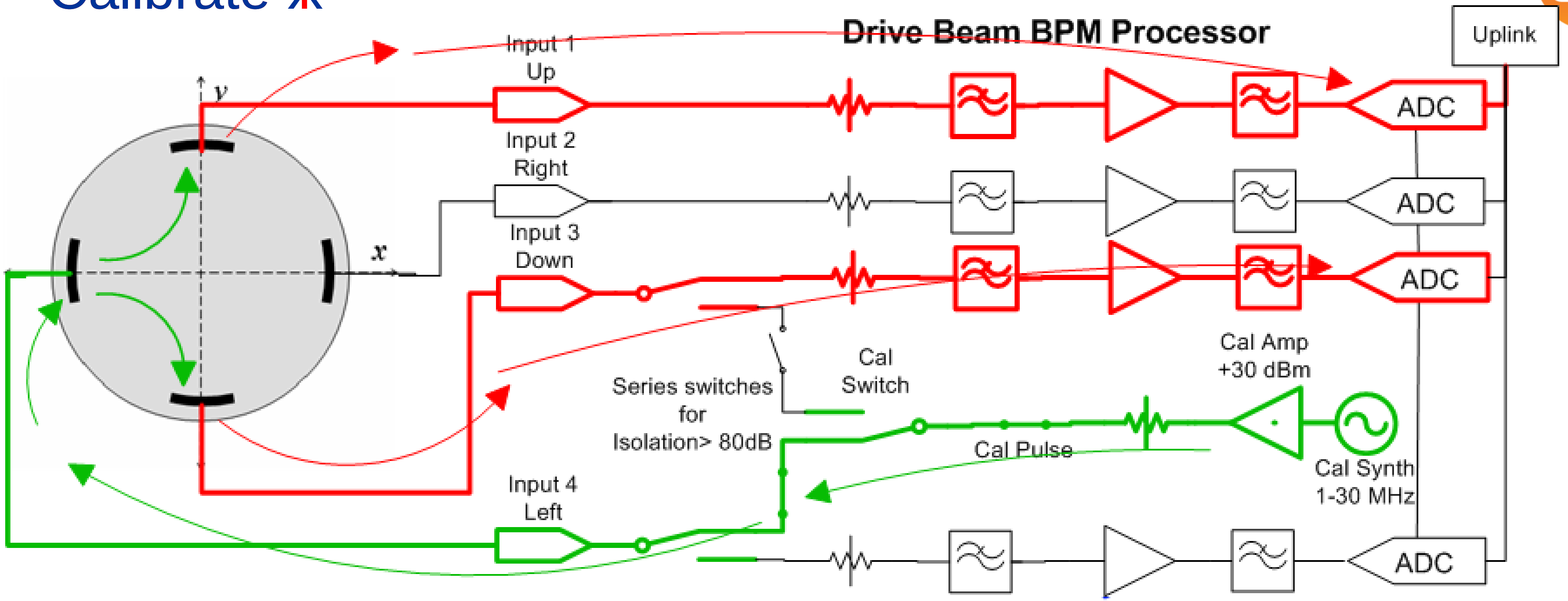
- Single Bunch
  - For nominal bunch charge Q=8.3 nC
  - $\sigma_y \sim 2\ \mu m$
- Train-end transients
  - For current I = 100 Amp

    $\sigma_y < 1\ \mu m$ (train of at least 4 bunches)
  - For full 240 ns train length
    - current I > 1 Amp
    - resolution $\sigma_y < 1\ \mu m$
- Within train
  - For nominal beam current ~ 100 A

    $\sigma_y \sim 2\ \mu m$ for $\delta t > 20$ ns

Calibration

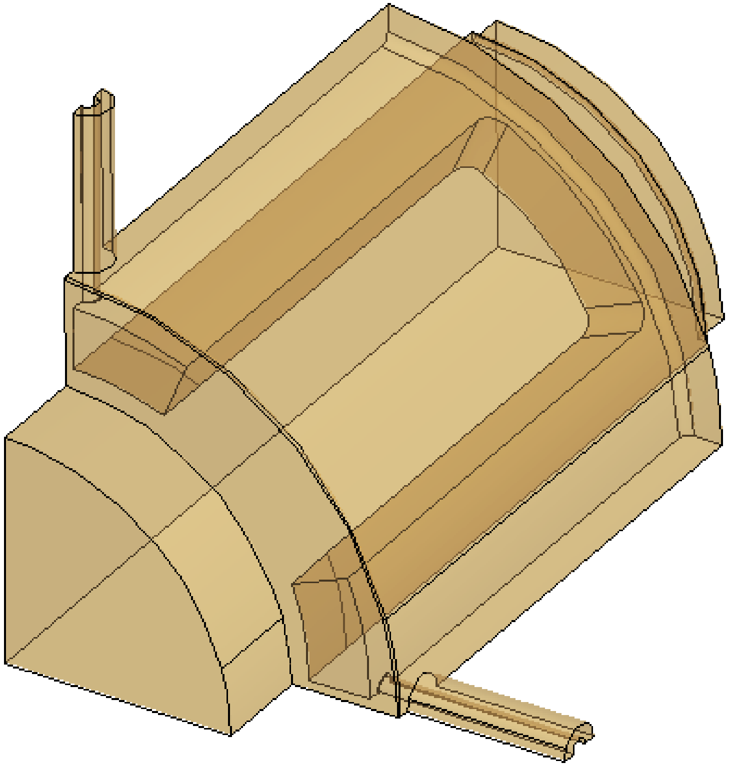
Calibrate ~~X~~

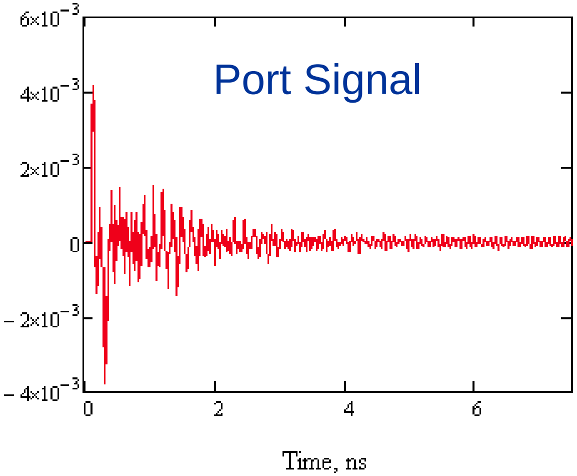


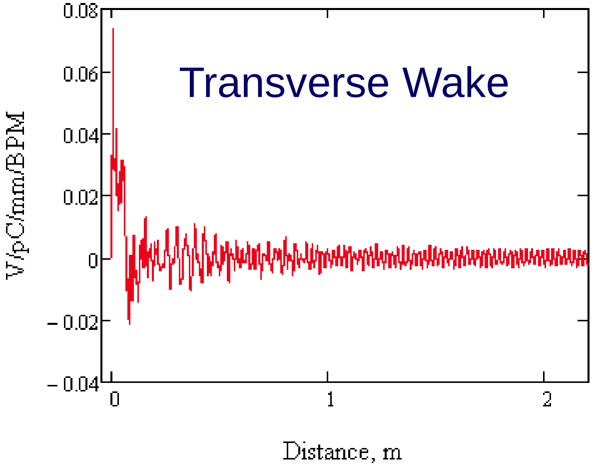
- Transmit calibration from one strip
  - Measure ratio of couplings on adjacent striplines
- Repeat on other axis
- Gain ratio ➔ BPM Offset
- Repeat between accelerator pulses
  - Transparent to operations
- Extremely successful at LCLS (SLAC)

Finite-Element Calculation

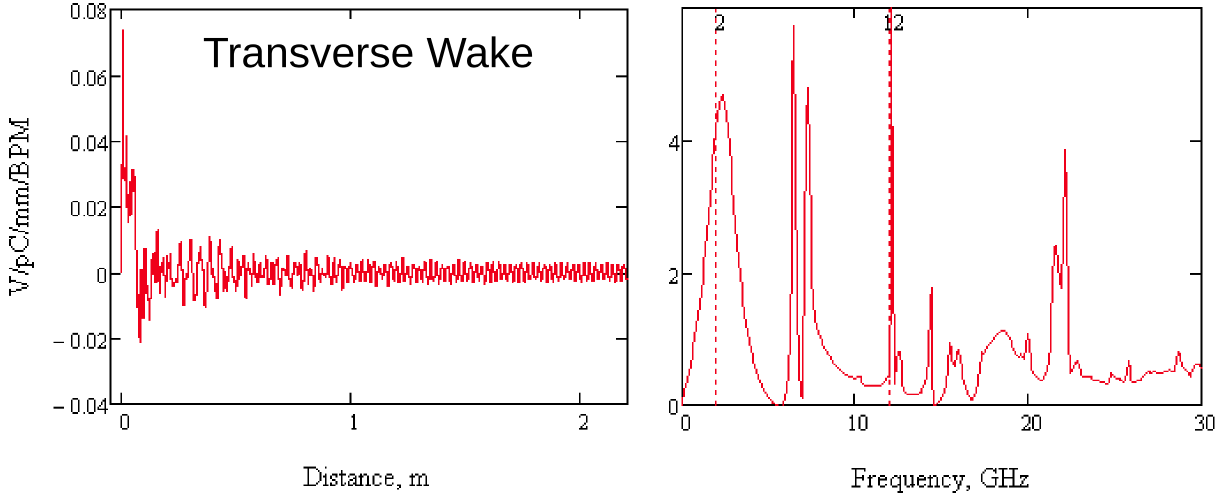
- Characterize beam-BPM interaction
- GDFIDL
  - Thanks to Igor Syratchev
  - Geometry from BPM design files
- Goals:
  - Check calculations where we have analytic approximations
    - Signal
    - Wakes
  - Look for
    - trapped modes
    - Mode purity





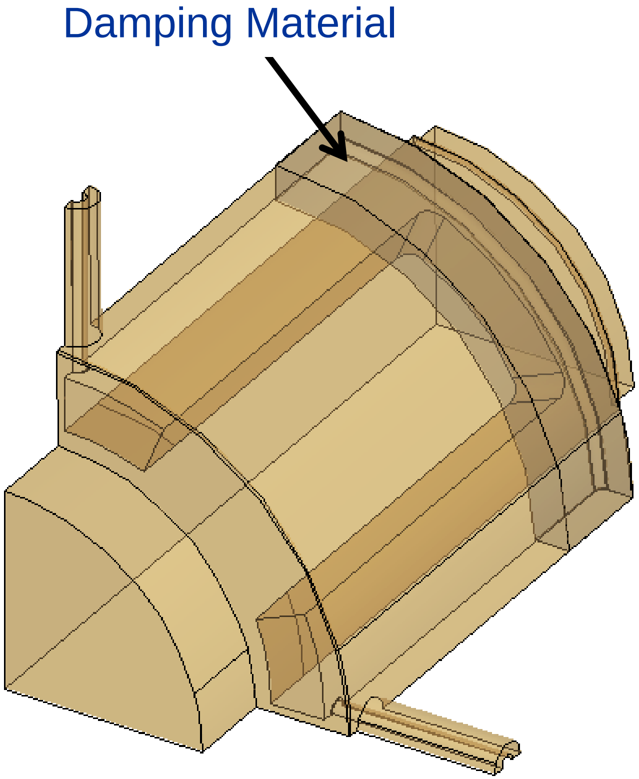


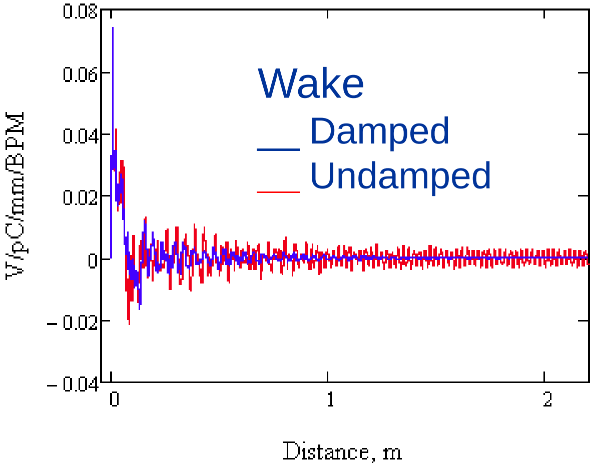
Transverse Wake

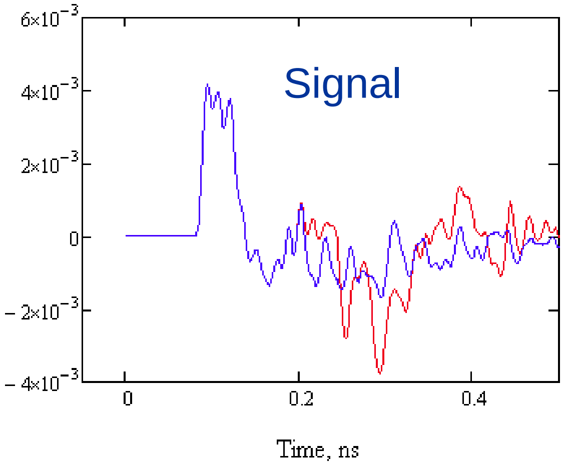


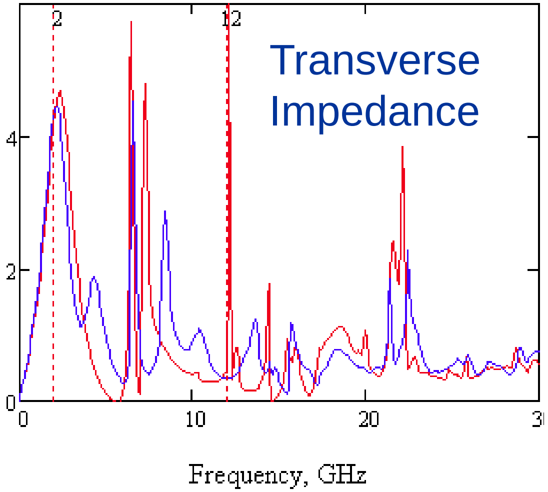
- Find unpleasant trapped mode near 12 GHz (!)
- Add damping material around shorted end of stripline
  - Results:
    - Mode damped
    - Response essentially unchanged at signal frequency

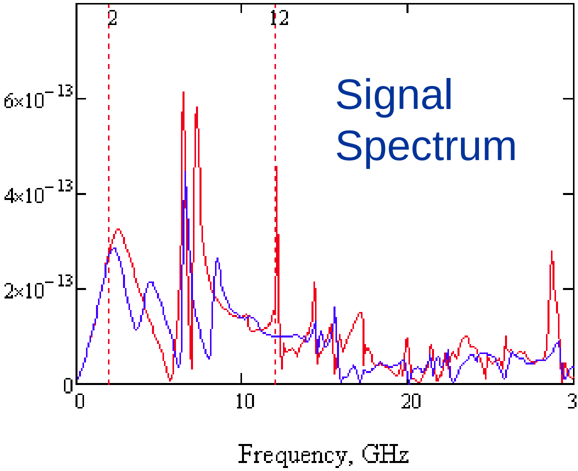
Damped Stripline BPM











- Few mm thick ring of SiC
- Transverse mode fixed
- Signal not affected materially
    - Slight frequency shift

Comparison to GDFIDL

- Compare to analytical calculation of “perfect stripline”
- Find resonant frequencies don’t match
  - GDFIDL ~ 2.3 GHz
  - Analytic model is 3 GHz
  - Is this due to dielectric loading due to absorber material?
- Amplitudes in 100 MHz around 2 GHZ differ by only ~5% (!)
- Energy integrated over 1 bunch:
  - 0.16 fJ GDFIDL
  - 0.15 fJ Mathcad
- Must be some luck here
  - filter functions are different
  - resonance frequencies don’t match
  - Effects of dielectric loading partially cancels
    - Lowers frequency of peak response ➔ raises signal below peak
    - Reduces Z ➔ decreases signal

Sensitivity

- **Ratio of Dipole to Monopole**
    - Δ/Σ ratio
- GDFIDL calculation
    - Signal in 100 MHz bandwidth around 2 GHz
        - Monopole 1.75 mV/pC
        - Dipole 0.25 mV/pC/mm
        - Ratio 0.147/mm

- **Theory**
    - $y = R/2 * \Delta/\Sigma$
    - ➔ Ratio of dipole/monopole = 2/R = 0.148/mm for R =13.5 mm
        - (R of center of stripline, it's not clear exactly which R to use here)

- Excellent agreement for transverse scale

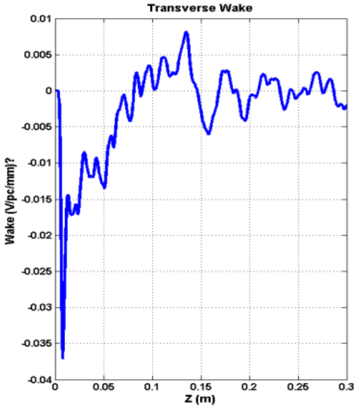
Multibunch Transverse Wake

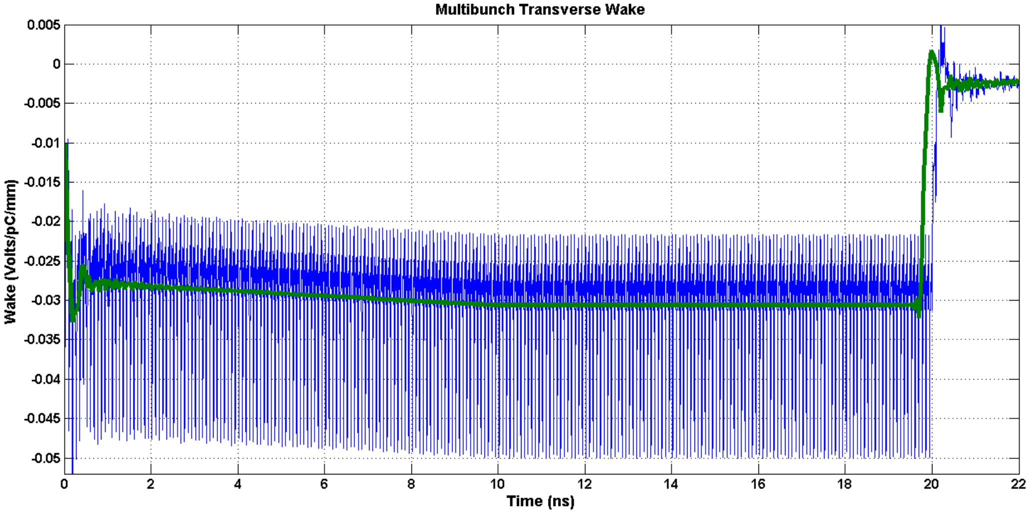
- Calculate transverse wakefield:

Transverse Wake Function of Stripline BPM
K.Y.Ng & Karl Bane
Handbook of Accelerator Physics and Engineering p. 236
(Wake due to signal induced on striplines)
Wake lasts for time 2L/c so integrate over bunches: $N_{bunches} := \frac{2 \cdot L}{c} \cdot Fb$ $\quad N_{bunches} = 2$

$$W_1 := \frac{8 \cdot Z \cdot c}{\pi^2 \cdot R^2} \cdot \sin\left(\frac{\varphi}{2}\right)^2 \cdot N_{bunches} \qquad W_1 = 27 \cdot \frac{mV}{pC \cdot mm}$$

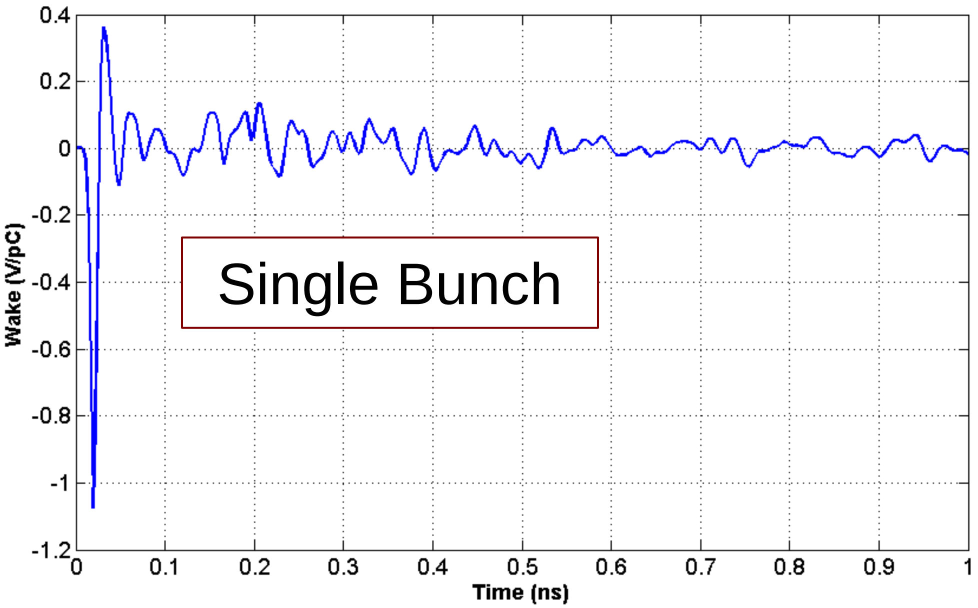
- Compare with GDFIDL:





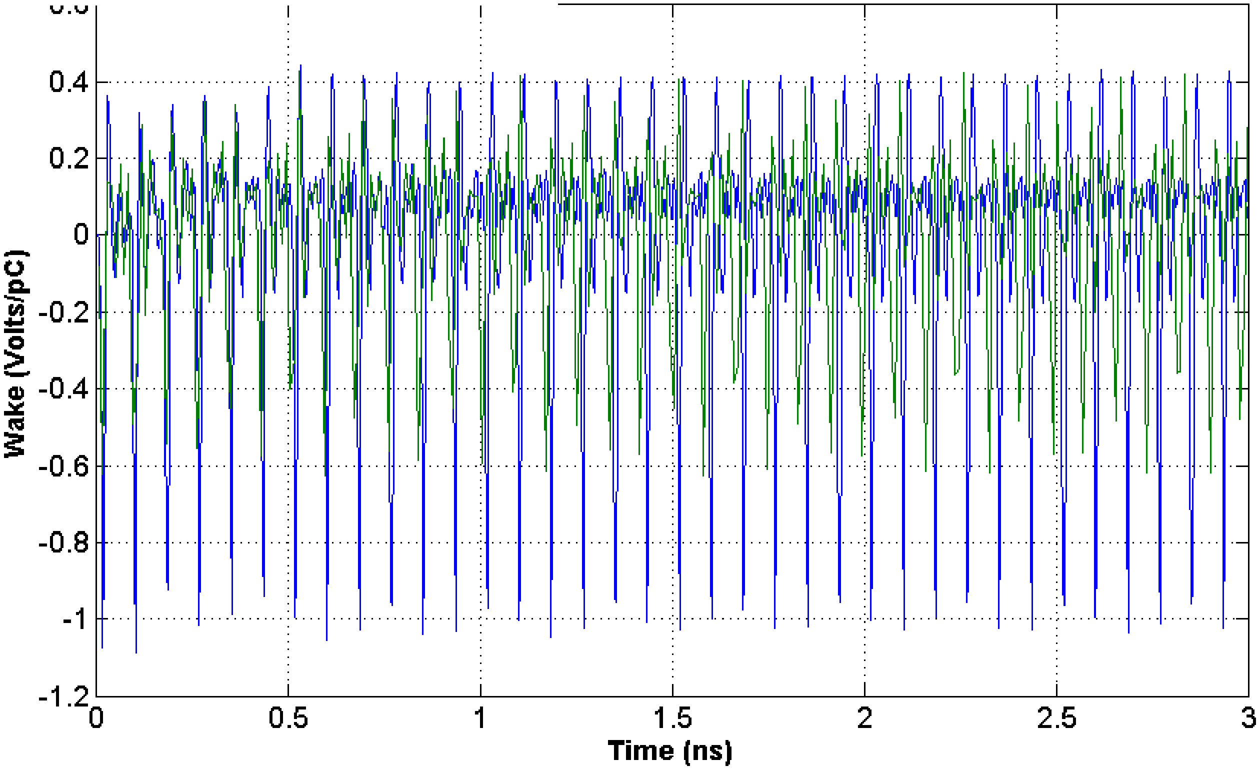
- GDFIDL shows quasi-DC Component: 30.6 mV/pC/mm/BPM
  - Calculate 27 mV/pC/mm/BPM for ideal stripline
  - Excellent agreement
- Components at 12 GHz, 24 GHz, 36 GHz:
- Comparable to features of PETS

Longitudinal Wake
from GDFIDL



Multibunch:

- No coherent buildup
- Peak voltage unchanged
- Multiply by bunch charge in pC to get wake
  - 8.3 nC/bunch



Summary of Comparison to GDFIDL

- GDFIDL and analytic calculation agree very well on characteristics
  - Signals at ports:
    - Monopole
    - Dipole
  - Transverse Wake
  - Disagreement on response null at signal port
    - May need lowpass filter to reduce 12 GHz before cables
- Signal Characteristics Good
- Longitudinal & transverse wakes are OK

Summary

- A conventional stripline BPM should satisfy requirements
  - Processing baseband (4 – 40 MHz) stripline signals
  - Signals are **local**
    (not subject to modes propagating from elsewhere)
  - Calculation agrees with simulation:
    - Wakefields
    - Trapped modes
- Should achieve required resolution
- Calibrate carefully
  - Online
  - transparently
- Should have accuracy of typical BPM of this diameter
- Pay attention to source of BPM signal
  - Need to unfold position signal y(t)
  - Must occasionally measure response function
    - with single bunch or few bunch beam

Conventional, well-established

Novel, untested