CLIC Drive Beam
Beam Position Monitors

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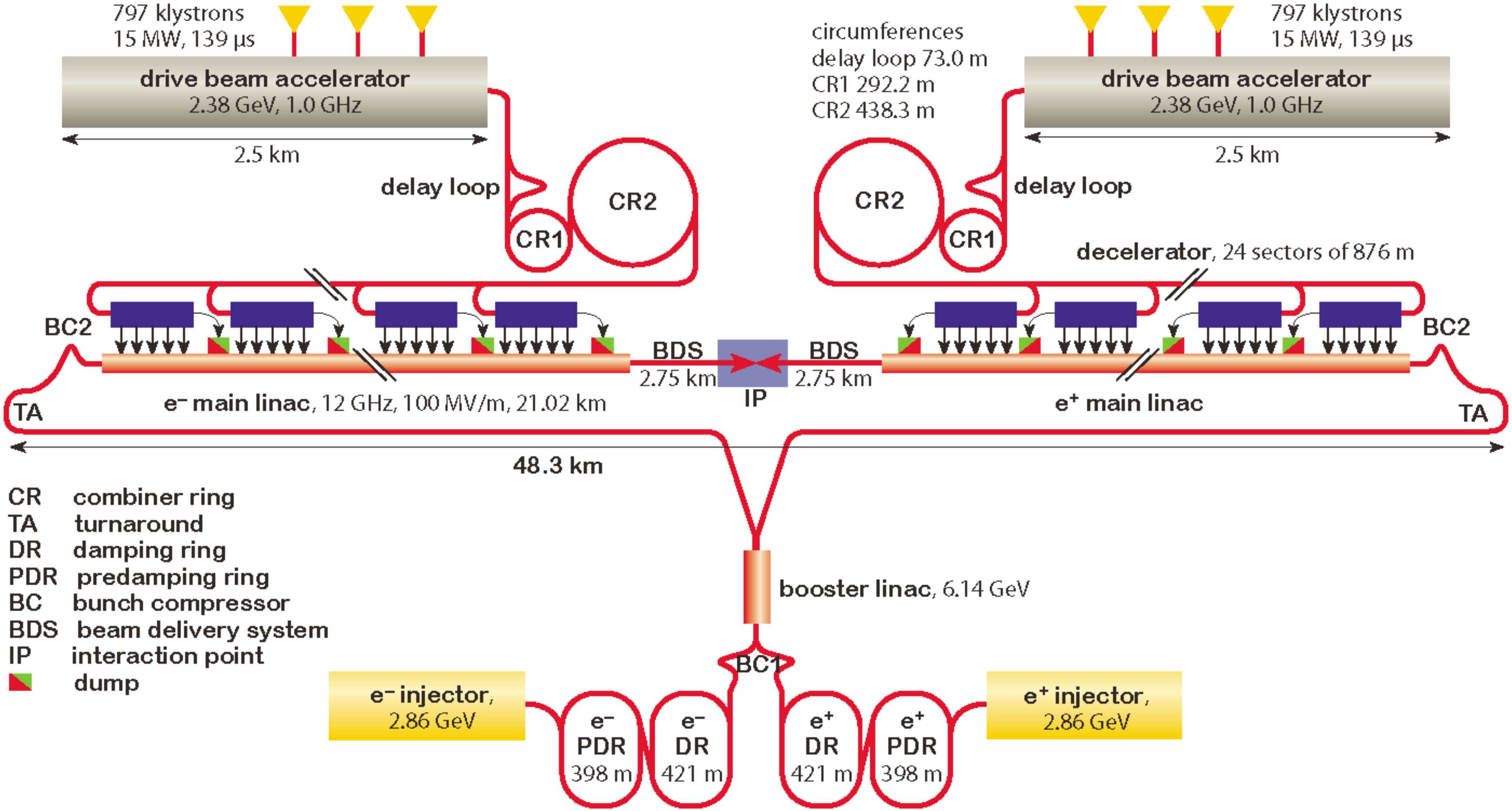
CLIC Accelerator Complex

- RF (klystron) power goes into drive beam efficiently:
  - high current, long pulse, low energy, 500 MHz
- Compress drive beam to high current, high frequency
- Transfer energy to main beam

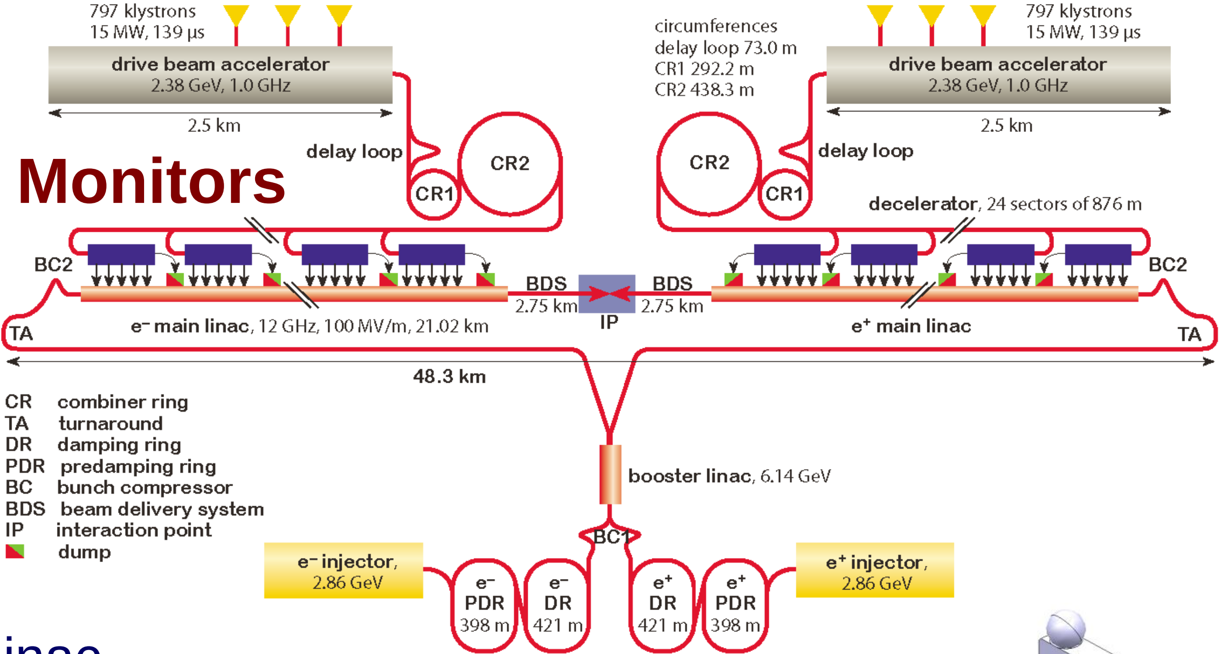


CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
🟥	dump

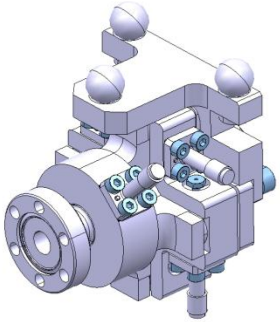
CLIC Acceleration Scheme

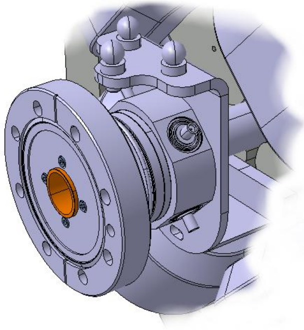
- Drive beam linac:
  - high current (4 Amp),
  - long pulse (140 µs),
  - low energy (2.38 GeV)
  - modest RF frequency (500 MHz)
- Compress train length in Delay Loop, Combiner Rings
  - multiply bunch frequency by 24
  - From 500 MHz to 12 GHz
- Split each drive beam into 24 sub-trains
  - 240 ns each
- Decelerate drive beam / accelerate main beam
  - 24 decelerators segments per main beam linac
  - 800 m each
  - 12 GHz
  - 100 Amp
  - 90% energy extraction

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

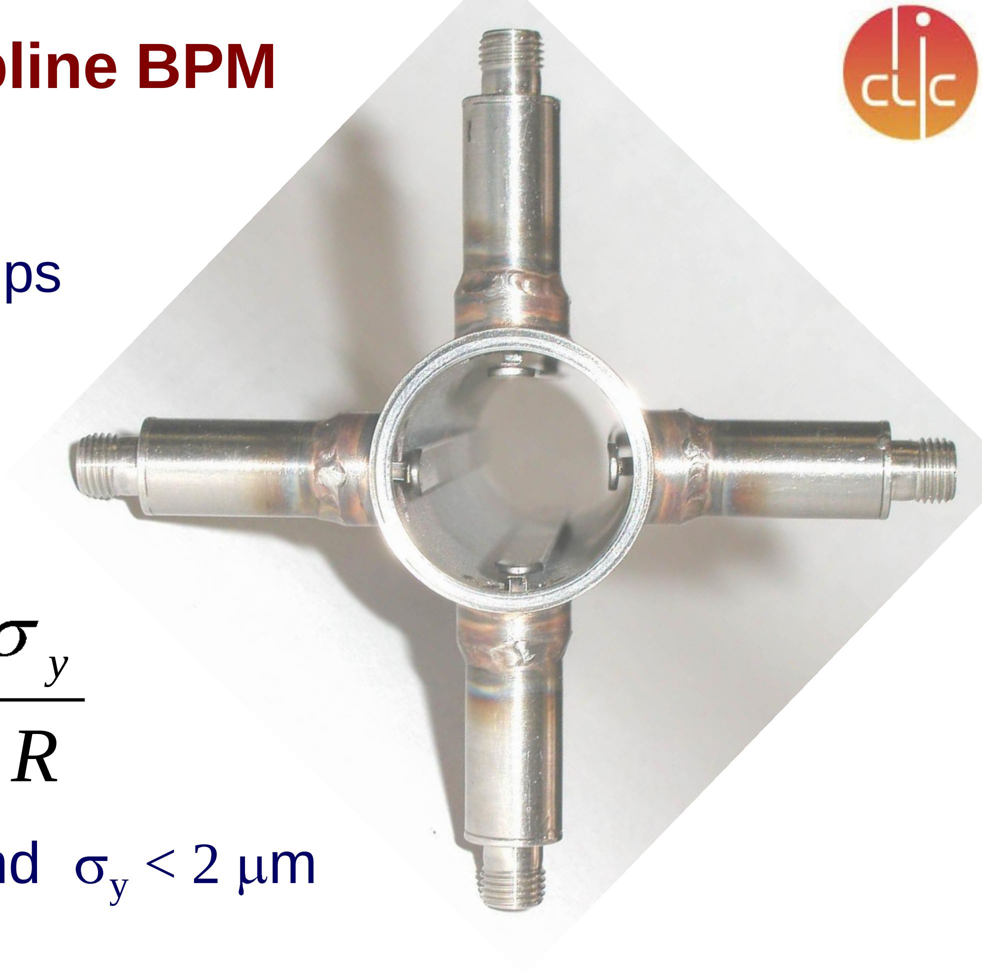
Drive Beam Decelerator BPM Challenges

- Bunch frequency in beam: 12 GHz
  - Lowest frequency intentionally in beam spectrum
  - It is above waveguide propagation cutoff
    - TE_{11} ~ 7.6 GHz for 23 mm aperture
  - There may be **non-local** beam signals above waveguide cutoff.
- 130 MW @ 12 GHz Intentionally propagating in nearby Power Extraction Structures (PETS)
- Consider resonant BPM operating at 12 GHz:
  - Plenty of signal
  - But sensitive to waveguide mode propagating in beampipe
  - Would need to kill tails of 12 GHz modes very cleanly

Operating Frequency

- Study operation 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
- Baseband
  - Bandwidth ~ 4 - 40 MHz
  - traditional
  - resolution is adequate
  - Check temporal resolution
  - Requires striplines to get adequate S/N at low frequencies (< 10 MHz)

Generic Stripline BPM



- Algorithm:
  - Measure amplitudes on 4 strips

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

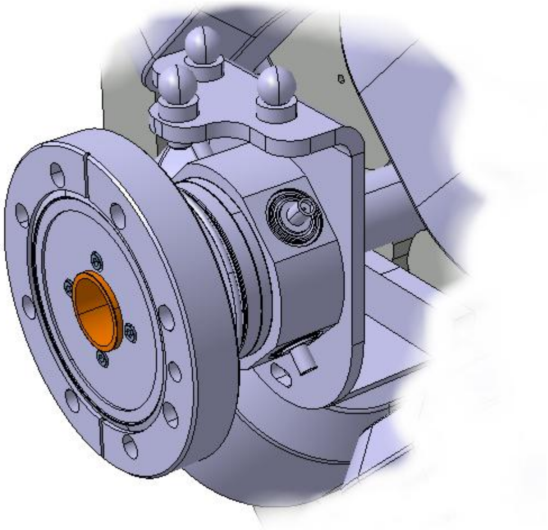
- Resolution: $$\frac{\sigma_V}{V} = 2\sqrt{2} \cdot \frac{\sigma_y}{R}$$

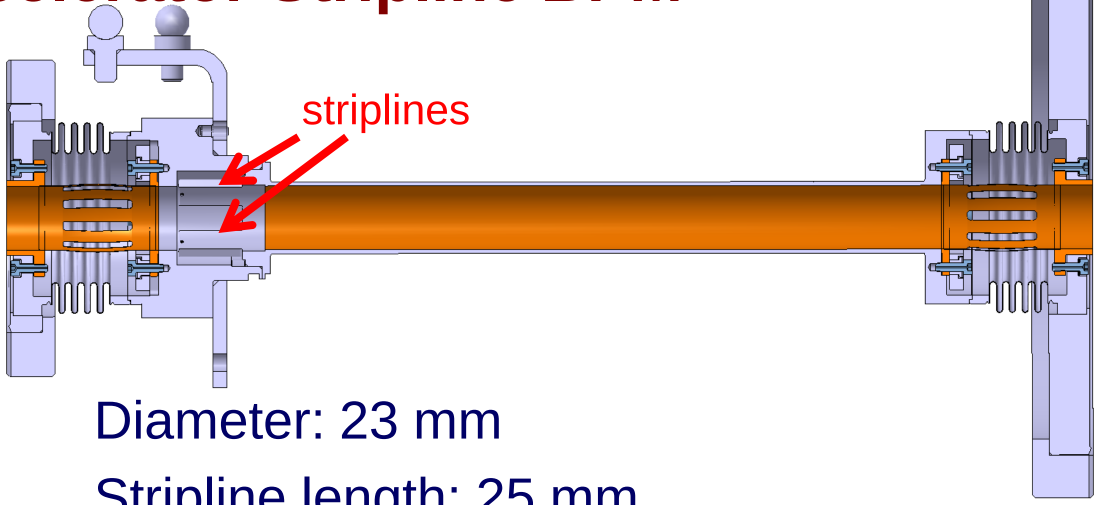
Given: R = 11.5 mm and $\sigma_y < 2\ \mu\text{m}$

Requires $\sigma_V/V_{peak} = 1/6000$ ➔ 12 effective bits

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

Decelerator Stripline BPM



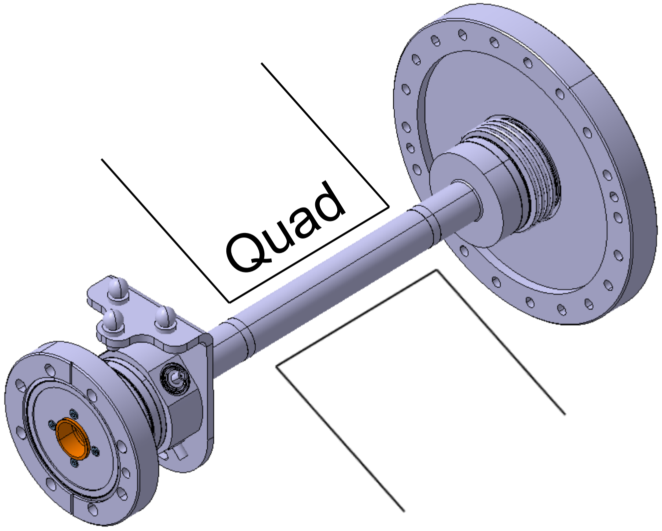


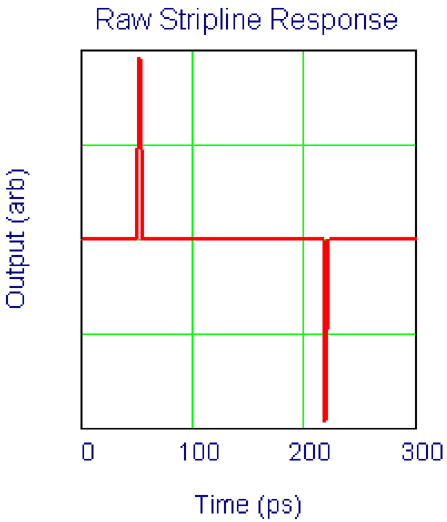
Diameter: 23 mm

Stripline length: 25 mm

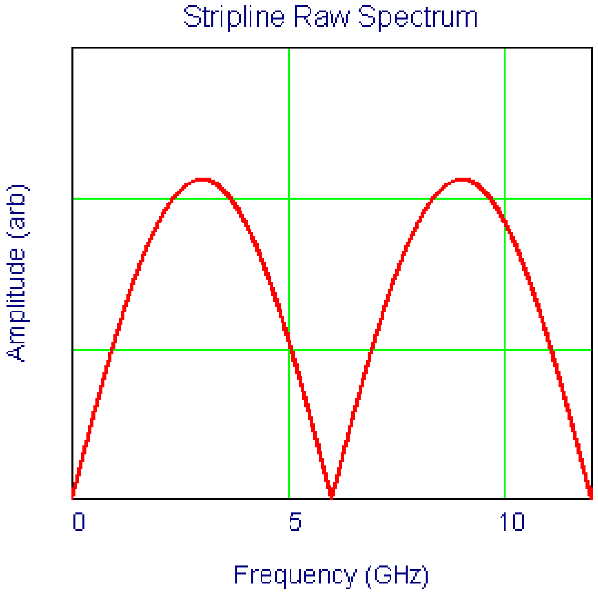
Width: 12.5% of circumference (per strip)

Impedance: 50 Ohm





Response Peak at 3.0 GHz, null at 12 GHz



Signal Processing Scheme

- Lowpass filter to ~ 20 MHz
- Digitize with fast ADC
    - 160 Msample/sec
- 16 bits, 12 effective
- Assume noise figure ≤10 dB

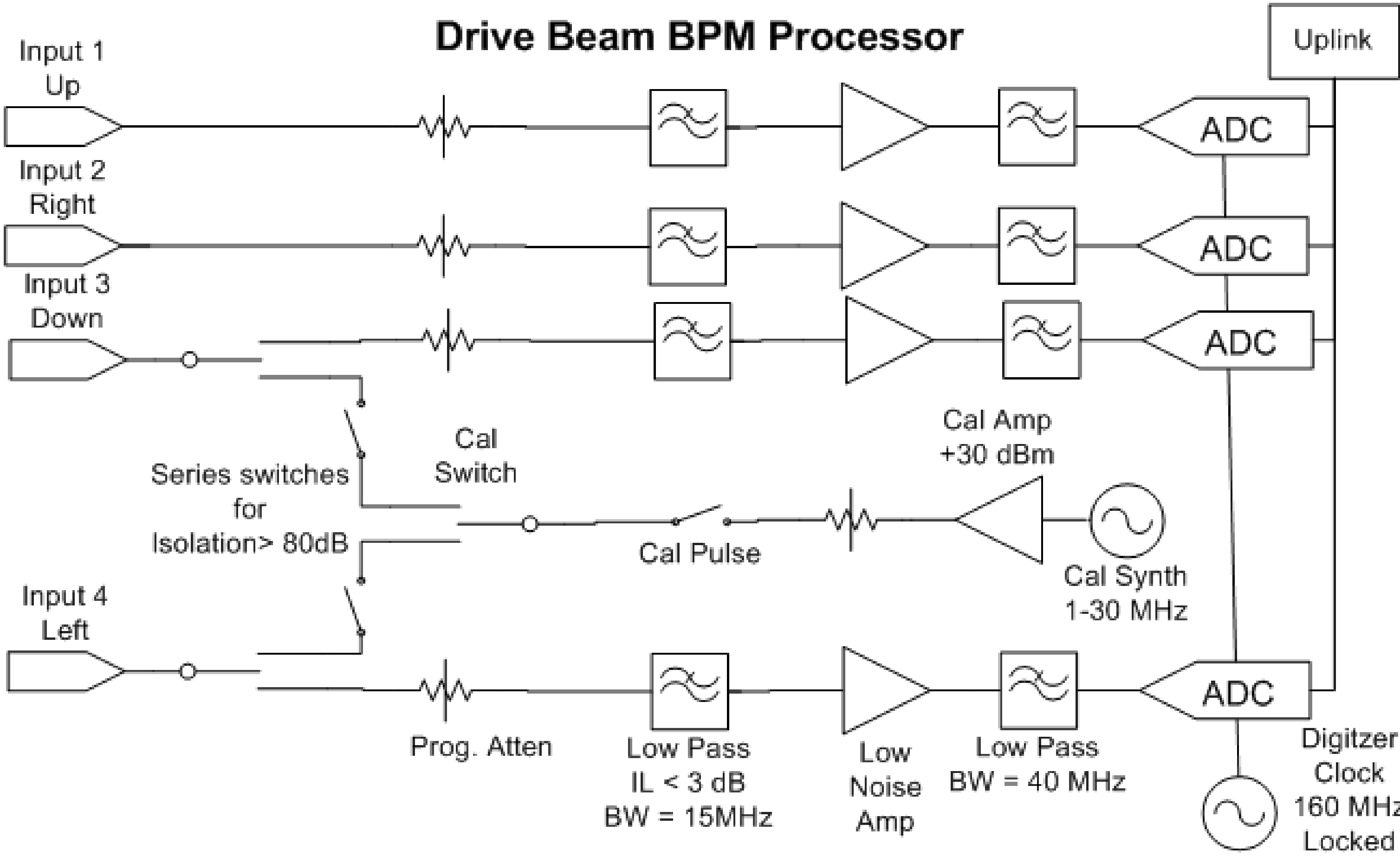
- For nominal single bunch charge 8.3 nC
    - – Single bunch resolution $\sigma_y < 1\ \mu m$

Including

Cable & filter losses

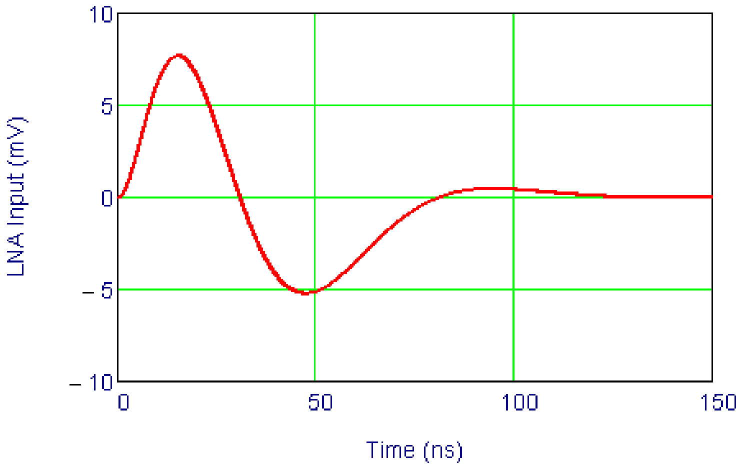
amplifier noise figure

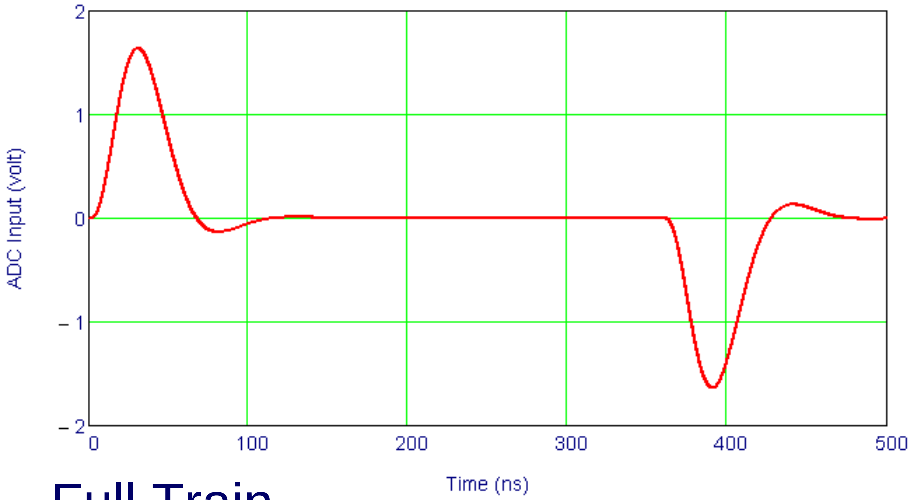
ADC noise



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
- Q=8.3 nC
- $\sigma_y \sim 2\ \mu\mathrm{m}$

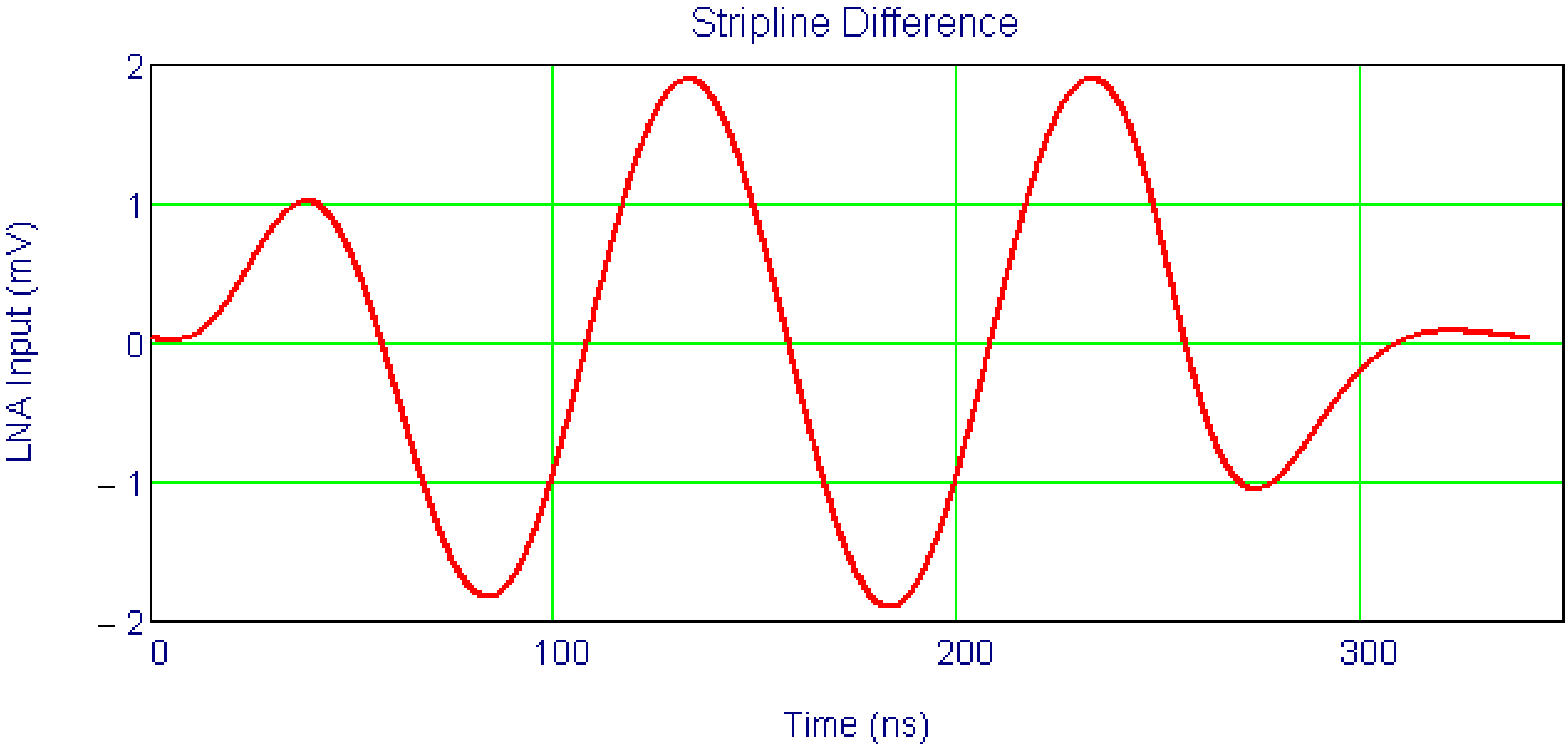
Full Train

I = 100 Amp

$\sigma_y < 1\ \mu\mathrm{m}$ (train of at least 4 bunches)

Temporal Response within Train

- Transverse oscillation at 10 MHz with 2 micron amplitude
- Stripline difference signal Up-Down:
- S/$N_{thermal}$ huge but ADC noise limit: ~ 2 μm/$\sqrt{N_{sample}}$



Where do Position Signals Originate?

- 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

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

Up-Down Difference:

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

- In middle of train we measure position via Q*d/dt(y) signal
  - Difference signal starts/ends in phase w/ position
  - but is in quadrature away from initial/final transient
- In order to reconstruct position vs. time along train
  - must measure response function with single/few bunches

Summary of Performance

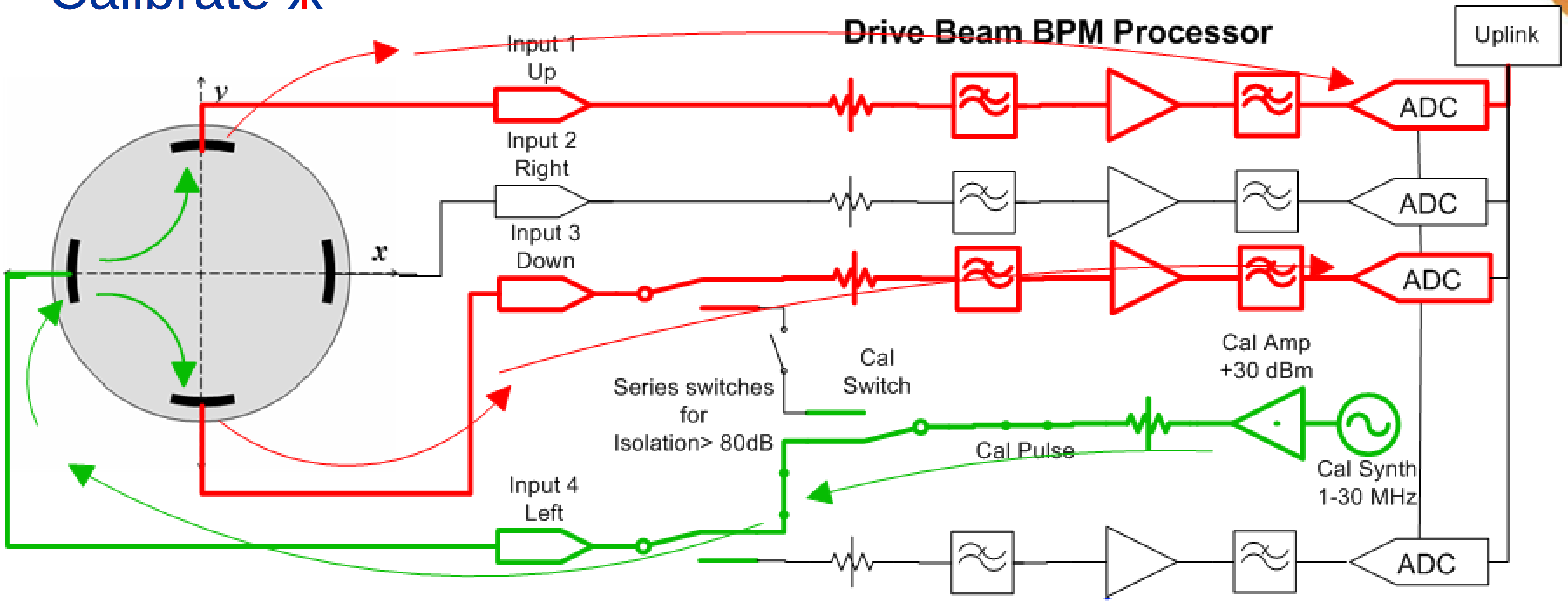
- Single Bunch
  - For nominal bunch charge Q=8.3 nC
  - $\sigma_y \sim 2\ \mu m$
- Train-end transients
  - For current I = 100 Amp

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

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

Calibration

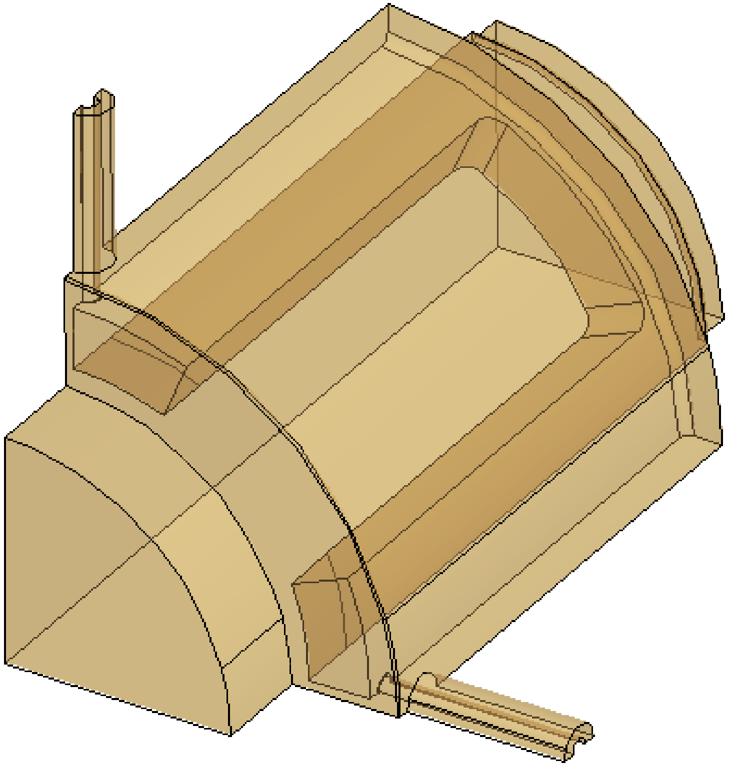
Calibrate X

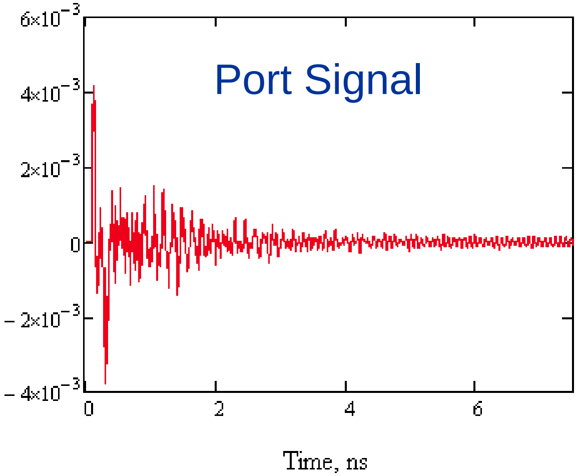


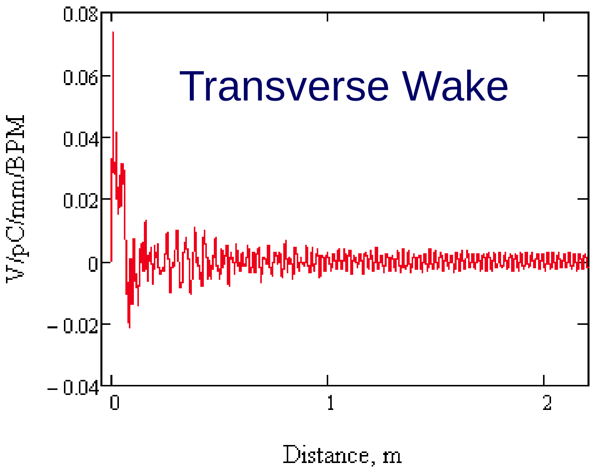
- Transmit calibration from one strip
  - Measure ratio of couplings on adjacent striplines
- Repeat on other axis
- Gain ratio ➔ BPM Offset
- Repeat between accelerator pulses
  - Transparent to operations
- Very successful at LCLS

Finite-Element Calculation

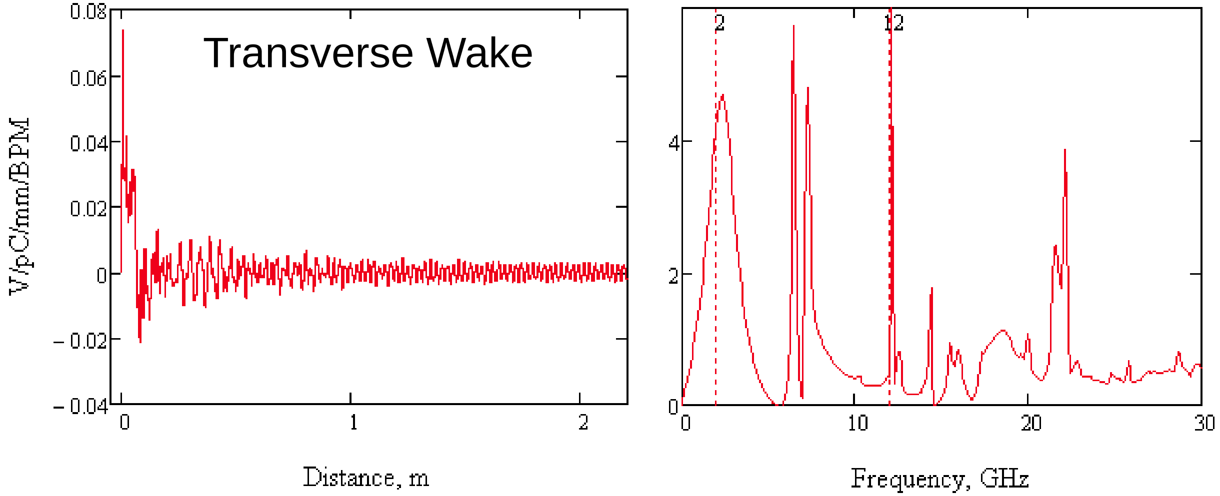
- Characterize beam-BPM interaction
- GDFIDL
  - Thanks to Igor Syratchev
  - Geometry from BPM design files
- Goals:
  - Check calculations where we have analytic approximations
    - Signal
    - Wakes
  - Look for
    - trapped modes
    - Mode purity





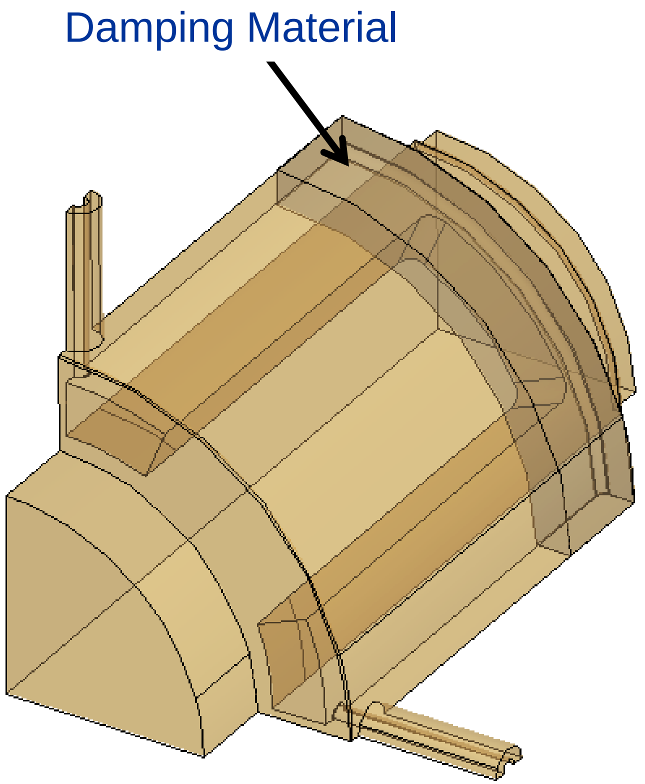


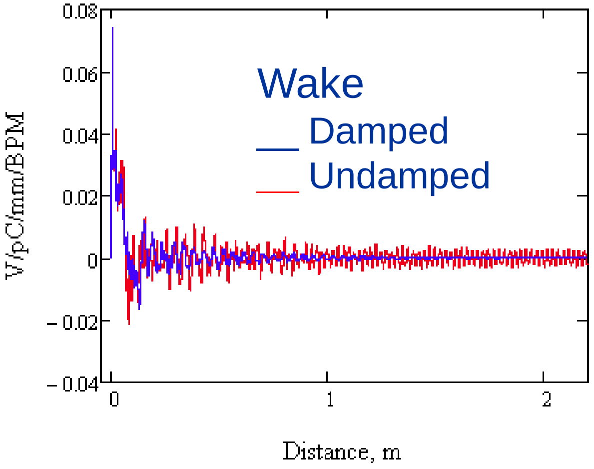
Transverse Wake

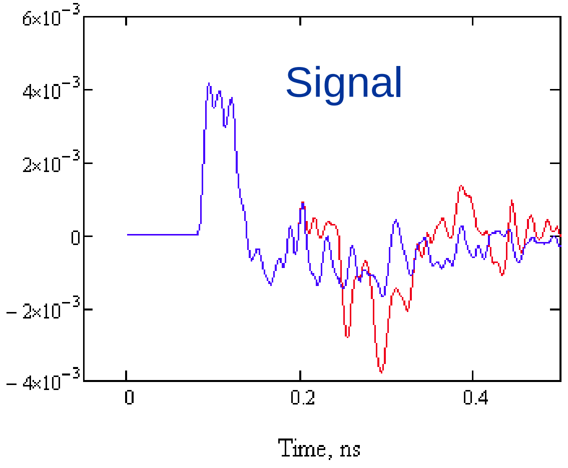


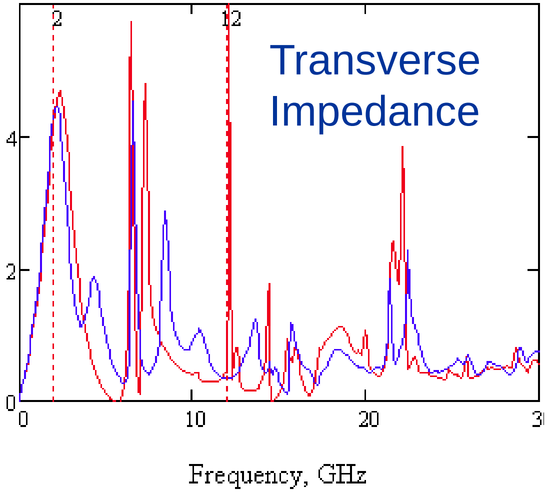
- Find unpleasant trapped mode near 12 GHz (!)
- Add damping material around shorted end of stripline
  - Results:
    - Mode damped
    - Response essentially unchanged at signal frequency

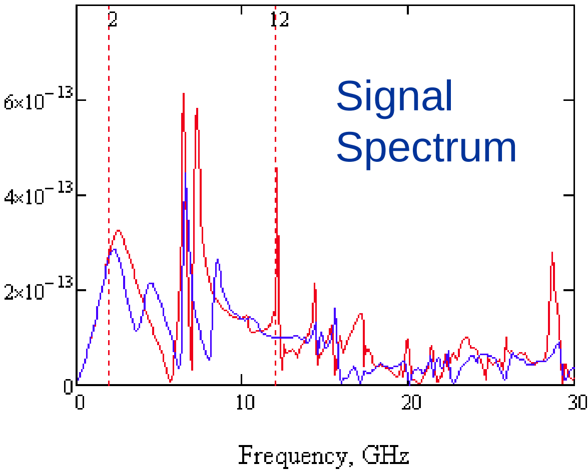
Damped Stripline BPM











- 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
        - Ratio 0.147/mm

- **Theory**
    - y = R/2*Δ/Σ
    - ➔ Ratio of dipole/monople = 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

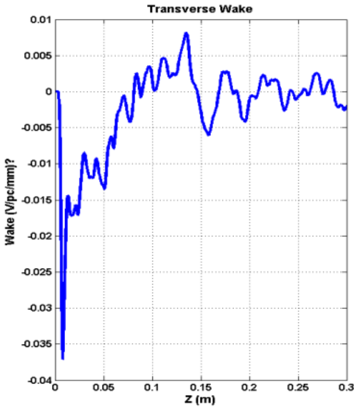
Multibunch Transverse Wake

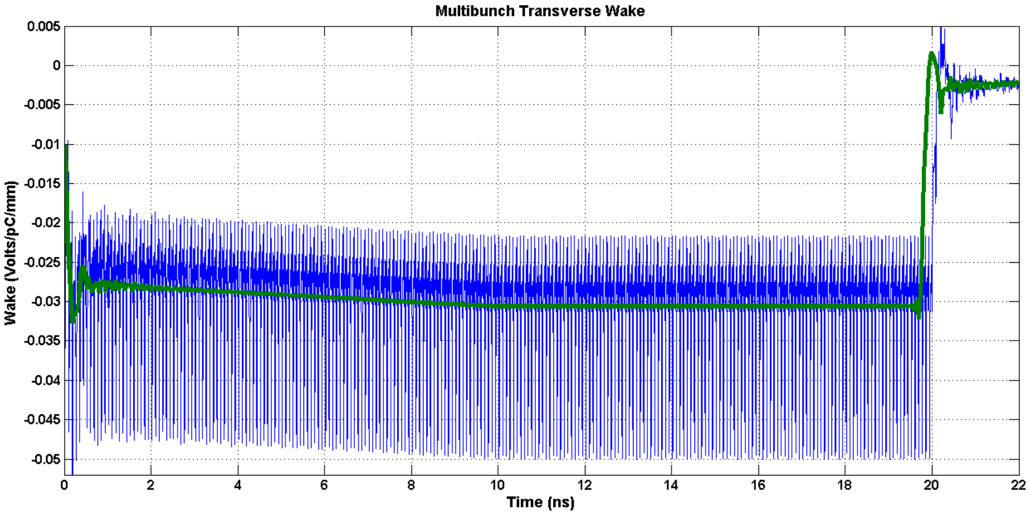
- Calculate transverse wakefield:

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: $N_{bunches} := \frac{2 \cdot L}{c} \cdot Fb$ $\quad N_{bunches} = 2$

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

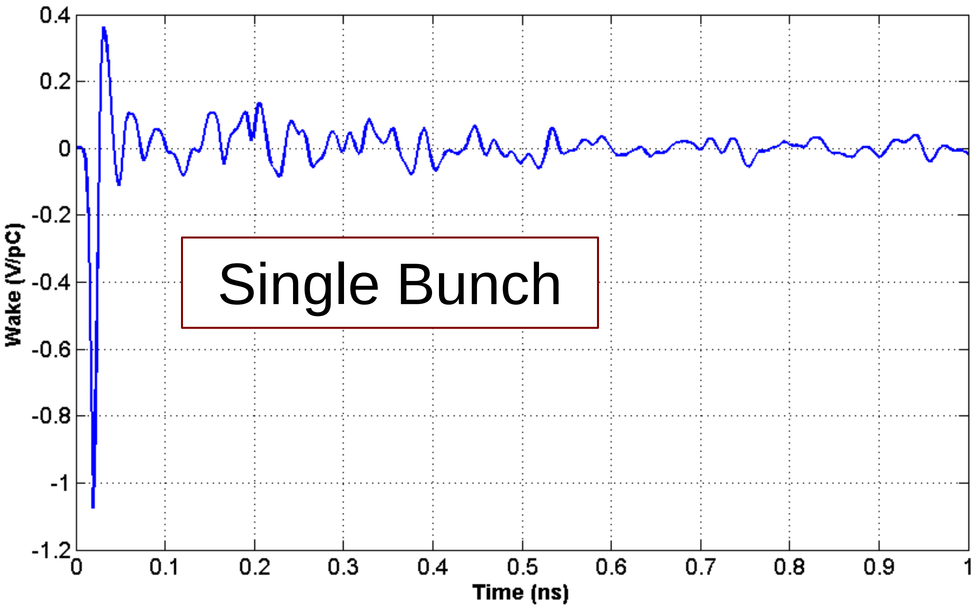
- Compare with GDFIDL:





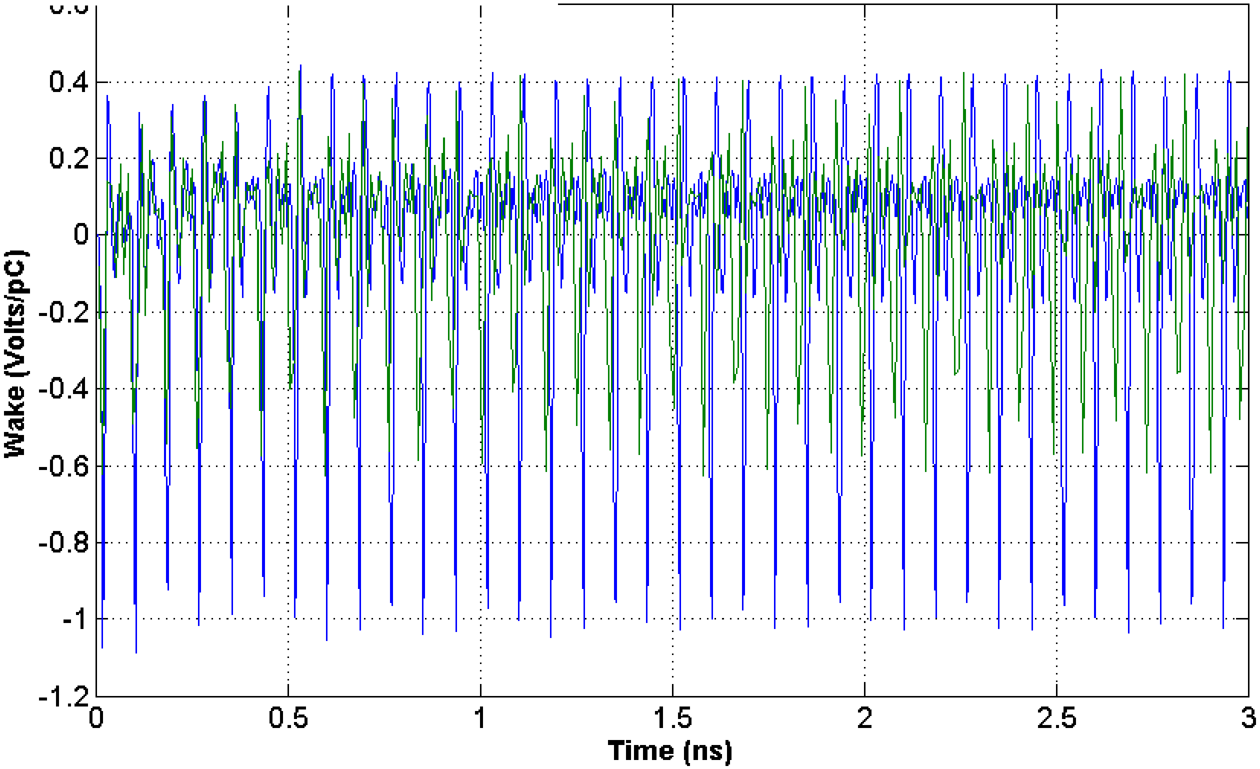
- GDFIDL shows quasi-DC Component: 30.6 mV/pC/mm/BPM
  - Calculate 27 mV/pC/mm/BPM for ideal stripline
  - Excellent agreement
- Components at 12 GHz, 24 GHz, 36 GHz:
- Comparable to features of PETS

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
  - Disagree on response null at signal port
    - May need lowpass filter to reduce 12 GHz before cables
- Signal Characteristics Good
- Longitudinal & transverse wakes Good

Summary

- A conventional stripline BPM should satisfy requirements
  - Processing basband (0 – 40 MHz) stripline signals
  - Signals are **local**
  - Calculation agrees with simulation:
    - Wakefields
    - Trapped modes
- Can 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)
  - Occasionally measure response functions
    - with single/few bunch beam