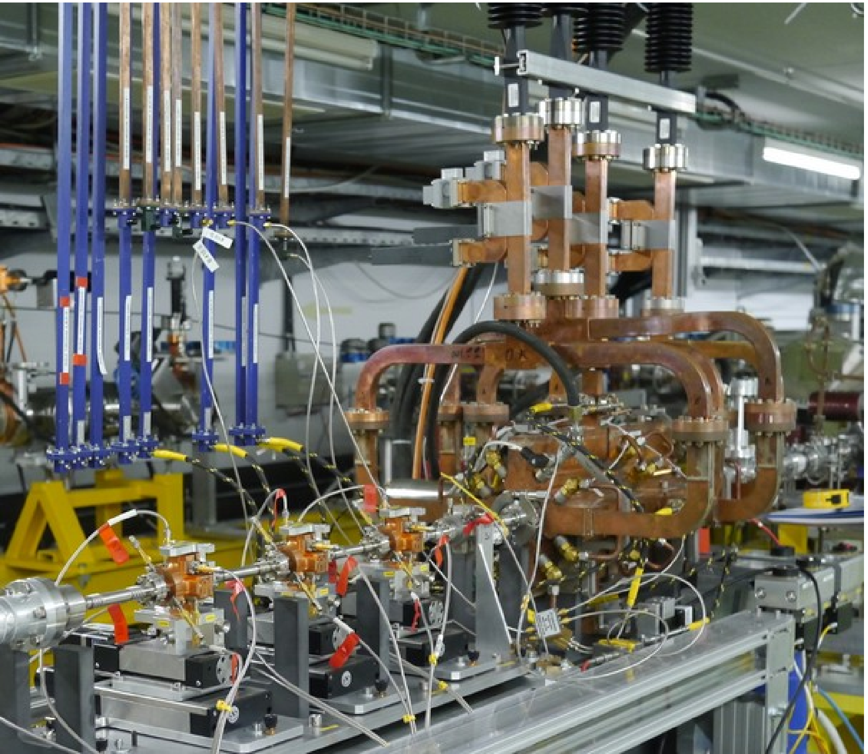
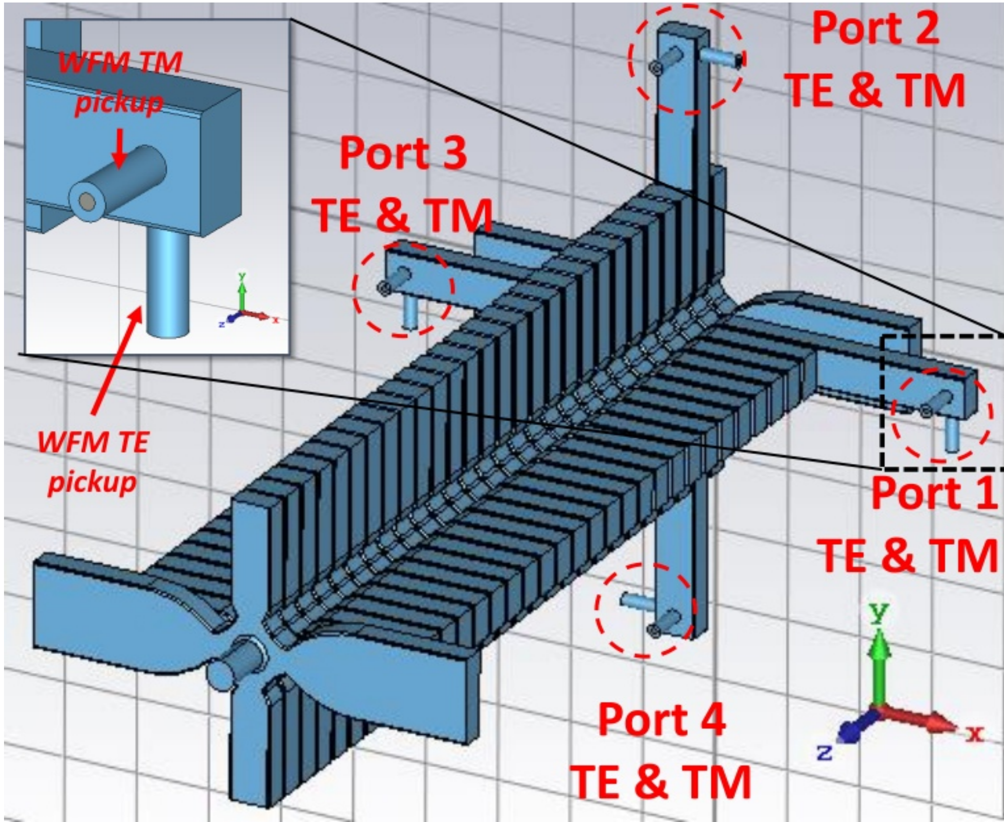
Wake Field Monitor characterization in CLEAR

K. Sjobak, H. Bursali, A. Gilardi

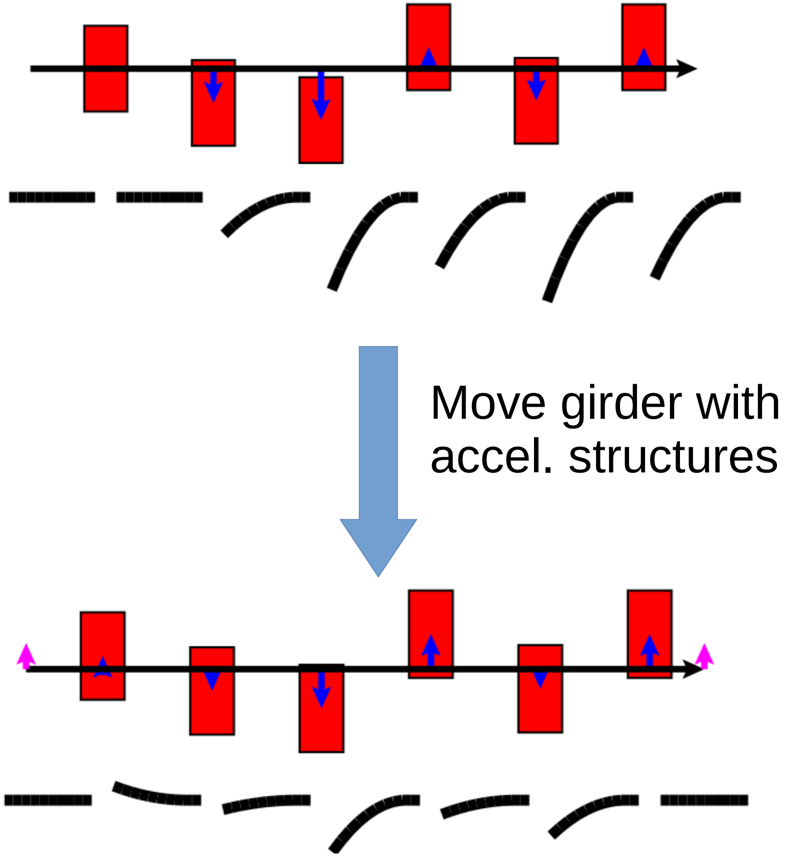
Extended CASC, 07/03/2023





Purpose of CLIC WFMs

- Align accelerating wrt. beam
  => Reduce wake field kick
- For CLIC luminosity target:
  Need alignment better than 3.5 µm
- Wake Field Monitors (WFM) provides
  local relative position measurement
- Must show that this is feasible
  and develop hardware and algorithms
  - Demonstration in CLEAR



Data presented in this presentation

- Based on a paper in preparation
- Expecting to submit to PRAB in 2023
  - Will post preprint to arXiv
- Please do not reuse plots etc. without asking

CLIC Wake Field Monitors as a detuned Cavity Beam Position Monitor: Explanation of center offset between channels

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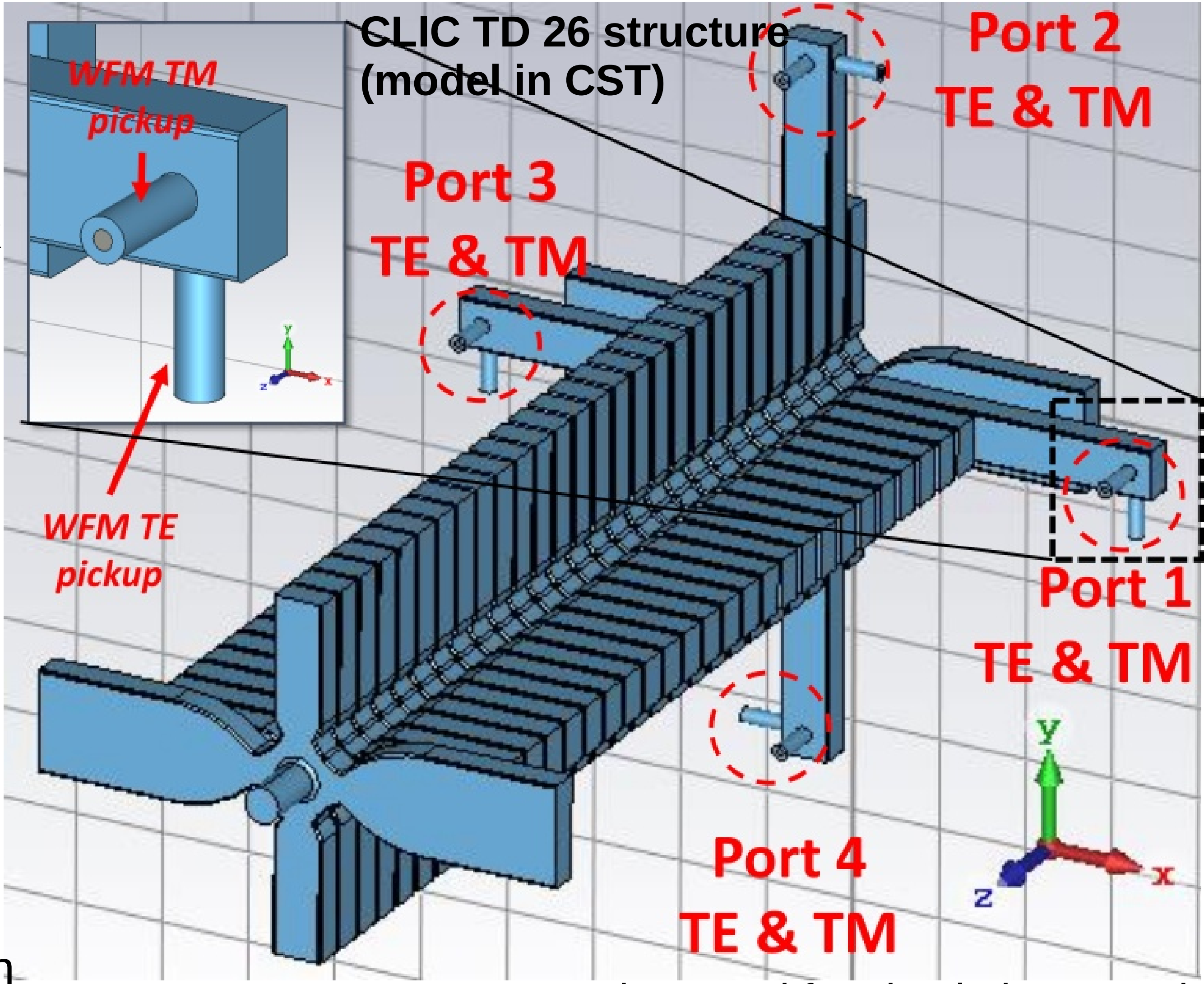
(Dated: March 5, 2023)

The Wake Field Monitor (WFM) system installed on the CLIC prototype accelerating structure in CERN Linear Accelerator for Research (CLEAR) has two channels for each horizontal/vertical plane, operating at different frequencies. When moving the beam relative to the aperture of the structure, a disagreement is observed between the center position of the structure as measured with the two channels in each plane. This is potentially a major issue for the planned use of WFMs in the Compact Linear Collider (CLIC), which will be used to measure the center offset between the accelerating structures and the beam. Through a mixture of simulations and measurements, we have discovered a potential mechanism for this, which is discussed along with implications for improving position resolution near the structure center, and the possibility determination of the sign of the beam offset.

Wake field monitors

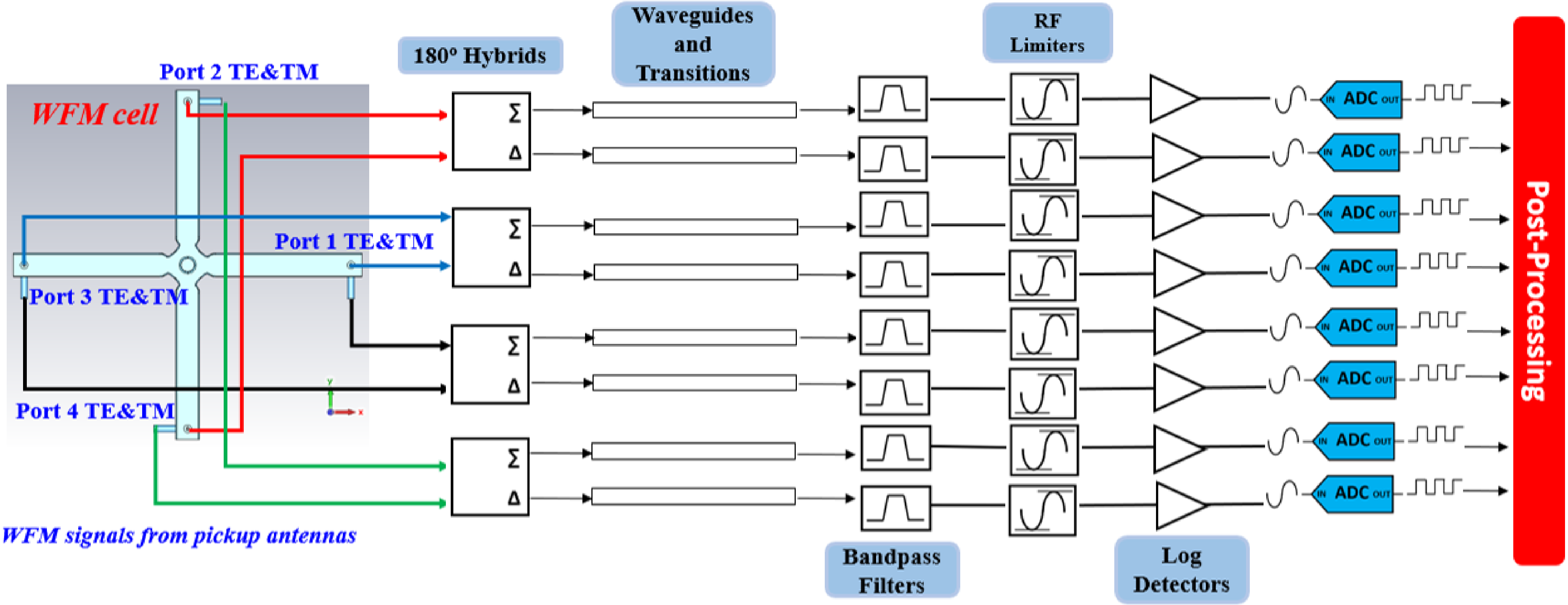
- Experimental setup in CLEAR uses a set of 8 antennas on one structure
  - 2 channels per plane
  - 2 antennas per channel
- Signals from each channel is combined to Σ & Δ signals
- Acquisition using log(power) detectors
- Expect to measure position using Δ or Σ signal depending on mode and antenna location



DWG shortened for simulation speed

Electronics and data acquisition

- Combined signals brought up to gallery & filtered with band-pass filter
- Power measured with log-detectors & output voltage digitized and post-processed to find position



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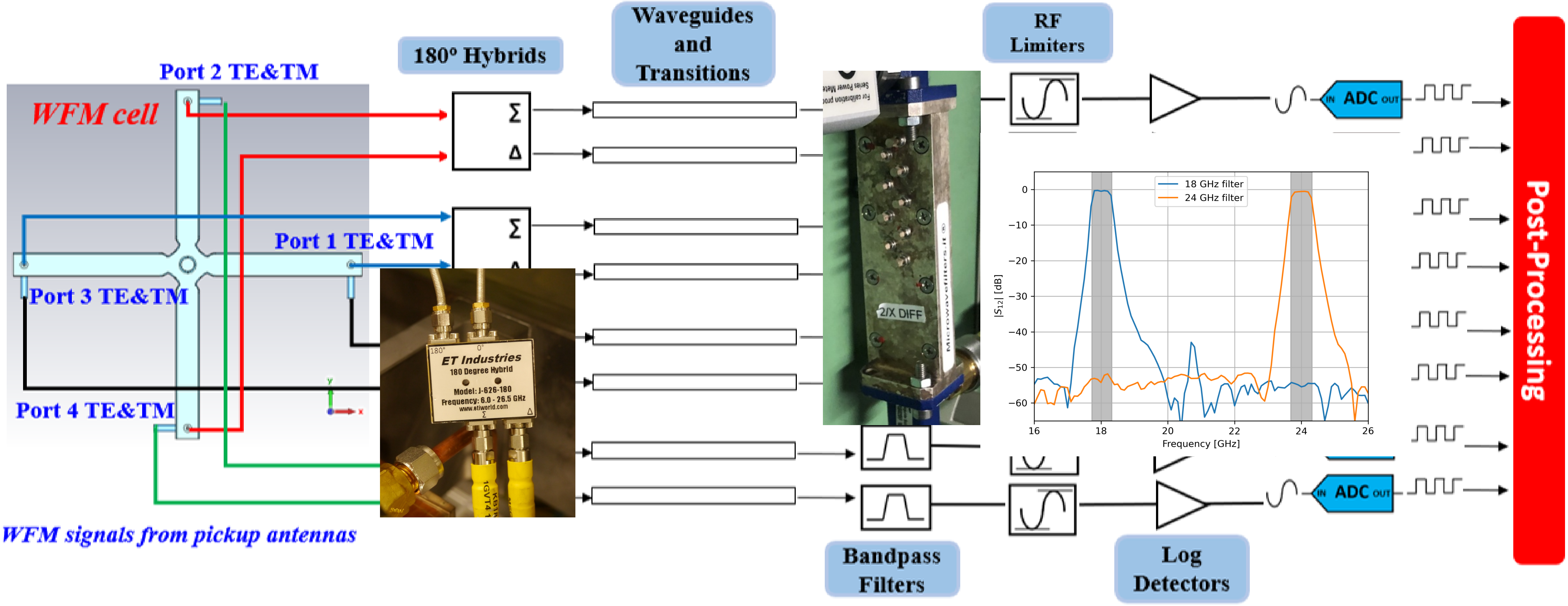
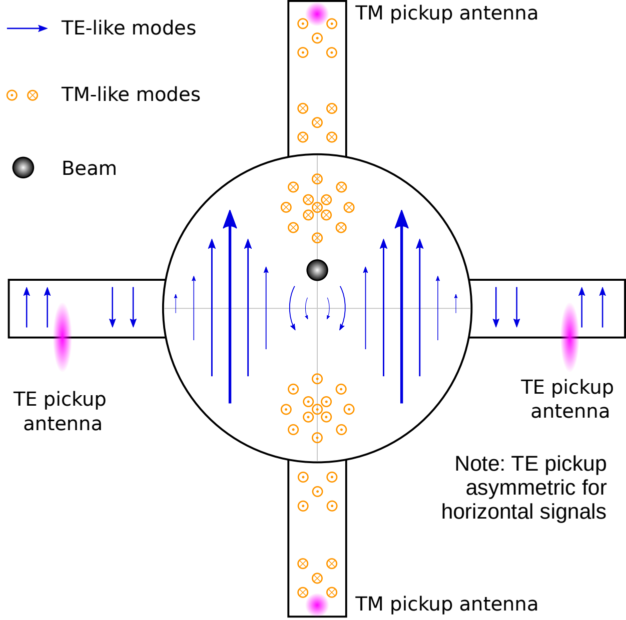
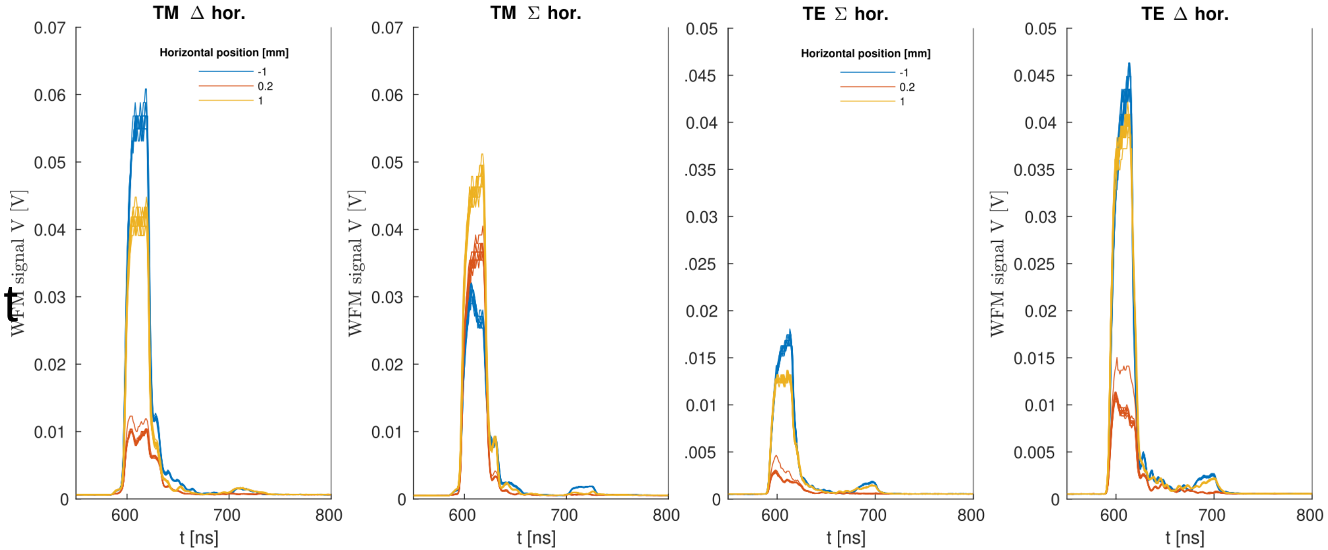


Signals and principle of signal generation

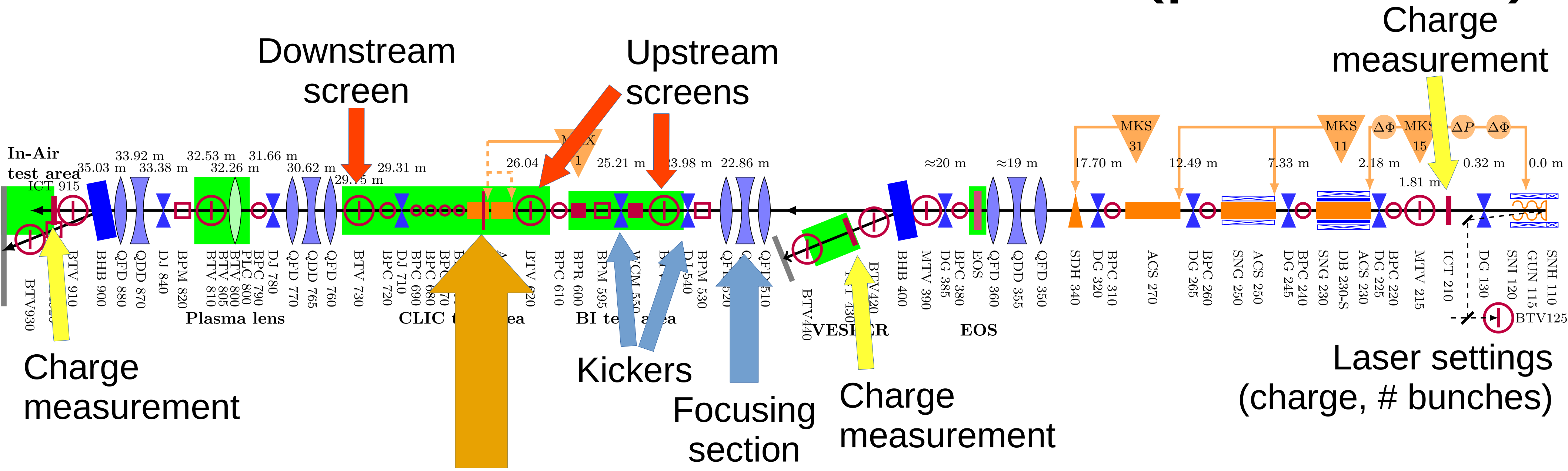
- Expected signal generation mechanism
  - Off-center beam excites TM- and TE-like dipole modes
  - These excitations are picked up by antennas
  - DWG filter out accelerating mode



- Hybrid + antennas select dipole mode
- Amplitude of detected signals proportional to beam offset from structure center & current
- Some cross between Σ/Δ expected if signal phase to hybrid not equal



Installation in CLEAR tunnel (pre 2022)



CLIC acc. Structure
w/ WFMs
on x/y mover with encoder

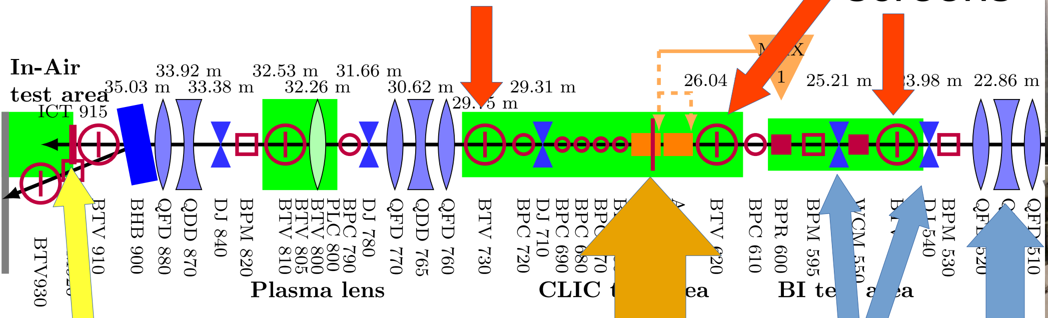
Also:
Radiation monitors (3),
Inductive BPM sum (soon),
RF deflector

- Need to use a wide variety of available instruments and devices
- Strict demands for beam properties
  - Both control and measurement

Installation in CLEA

Downstream screen

Upstream screens

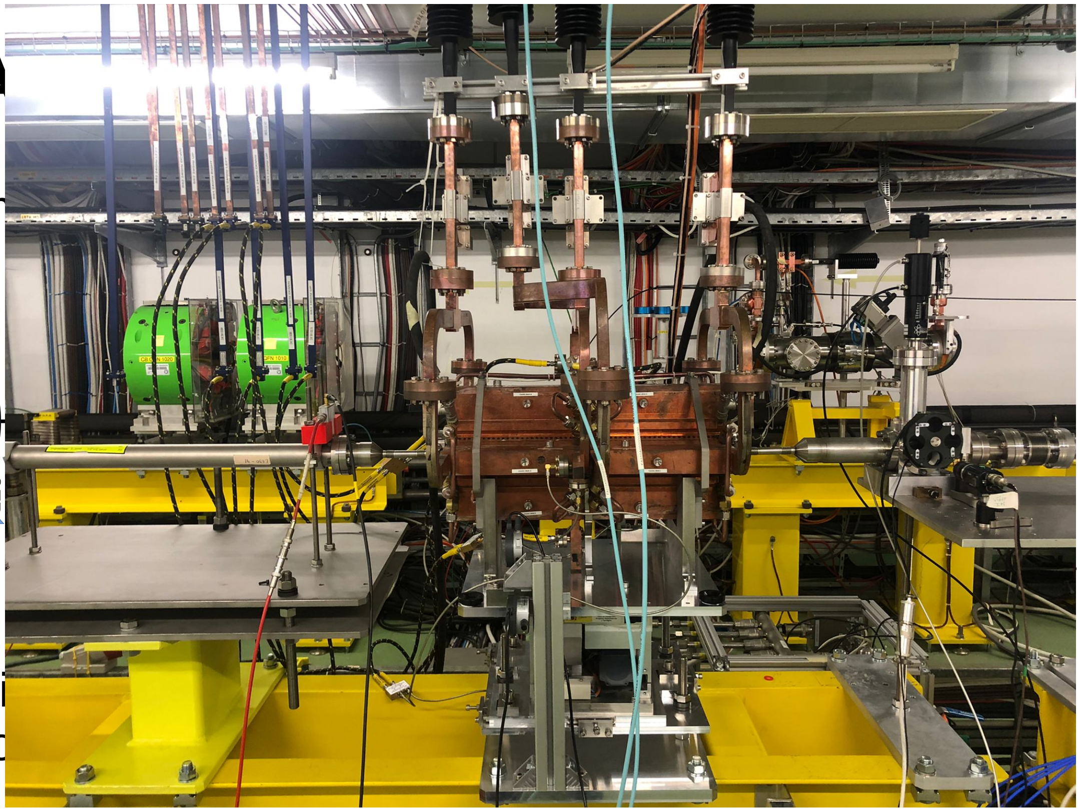


Charge measurement

CLIC acc. Structure w/ WFMs on x/y mover with encoder

Kickers

Focusi sectio



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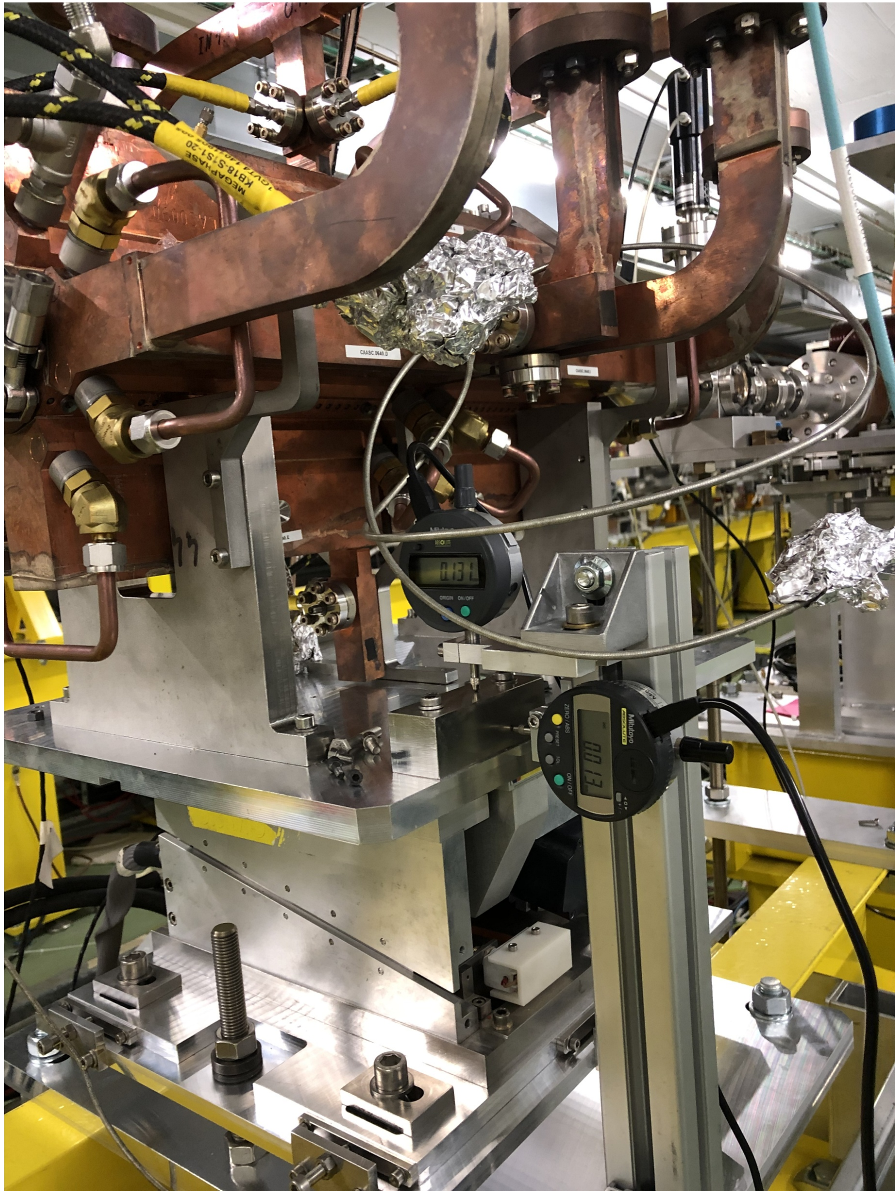
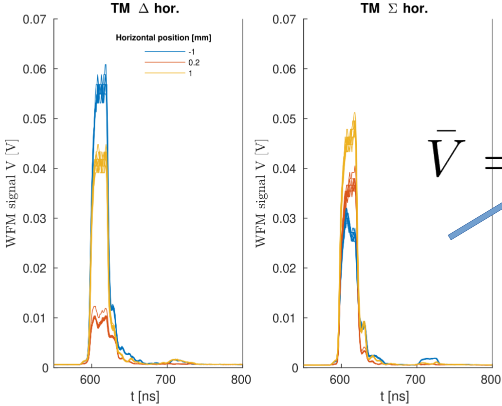
Structure transverse mover with position encoder

- New mover was installed during winter shutdown 2020/2021
  - “Quadrupole mover”, same type as used for Plasma Lens
  - Replacing “whole girder” mover: Less flexible but easier to operate
- Arduino + Mitutoyo gauges with online readout system for true position

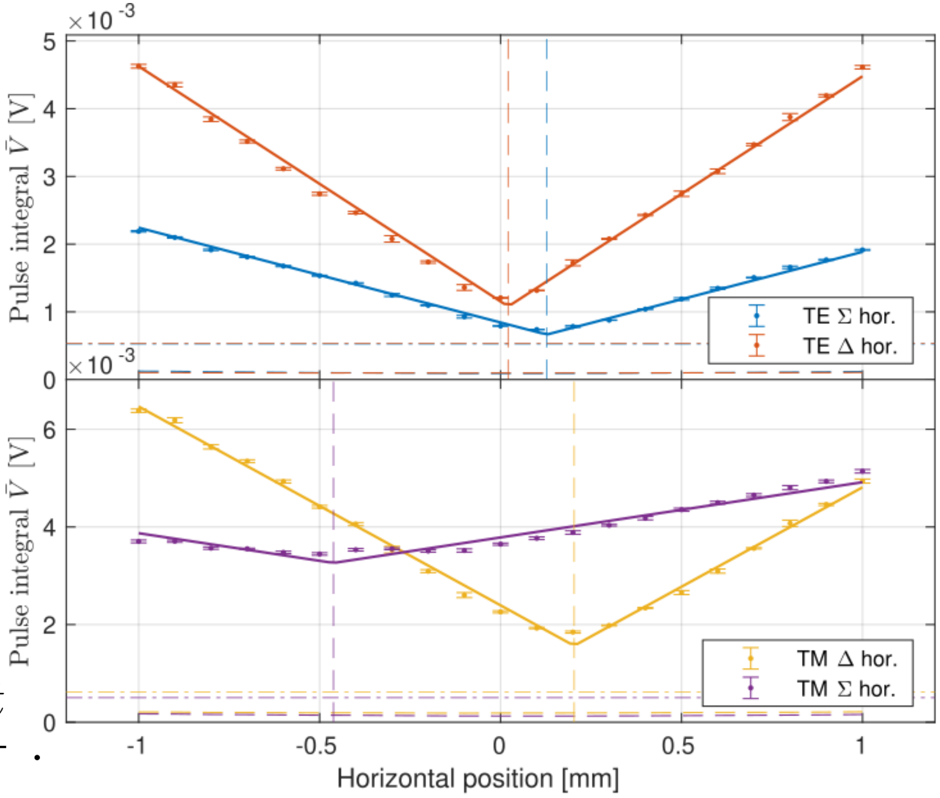


Amplitude from position

- Comparing TE and TM, do not find same center!
- Even Σ/Δ of same signal is disagreeing
- What is the reason for this?
- Which one is true?

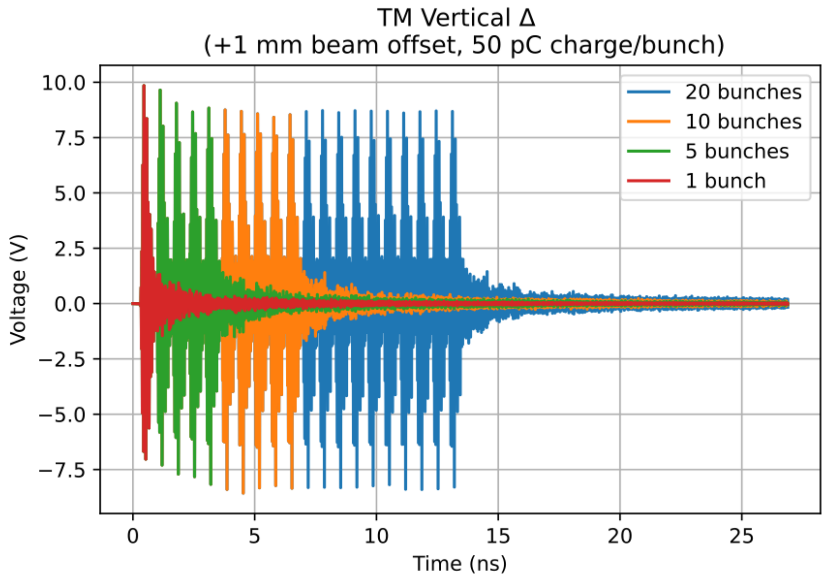


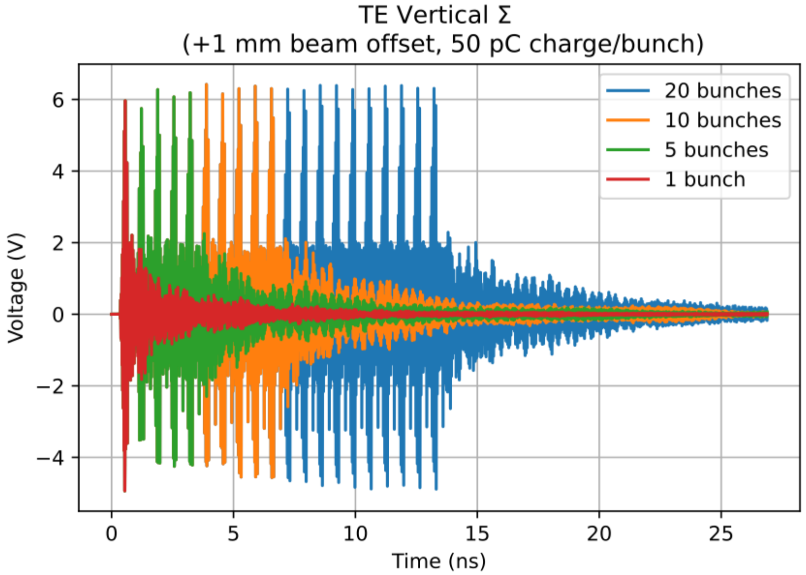
$$\bar{V} = \frac{\int_{t_1}^{t_2} V(t)\,\mathrm{d}t}{t_2 - t_1}.$$



Simulated signals

- With CST, simulate wakefield and antenna voltages
- Make bunch trains, Σ & Δ signals, and frequency filtering in Python external post-processing
- Reproduce “V-plots” from perfectly combined signals
  - Notice a 65 μm offset of vertical TE signals
  - Explained by antenna positioning (a)symmetry





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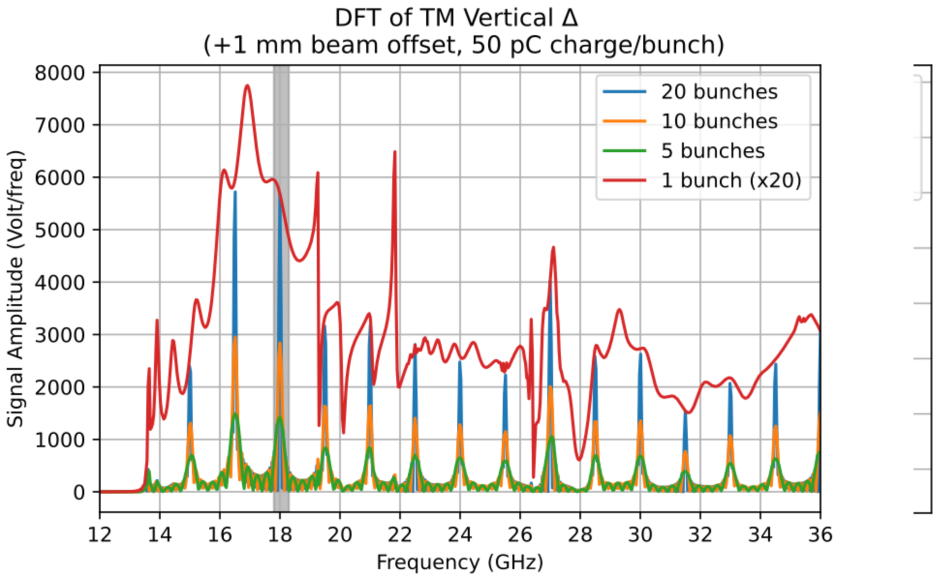

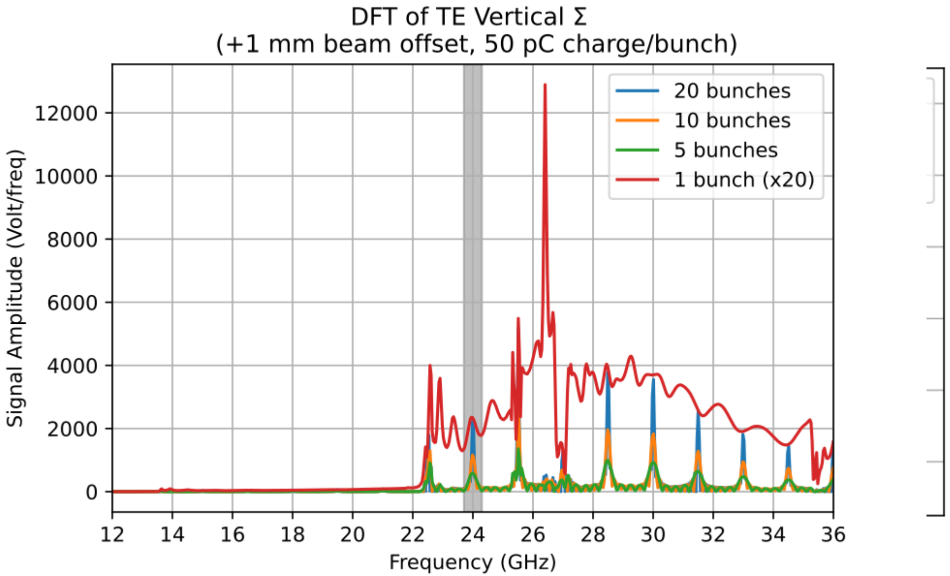

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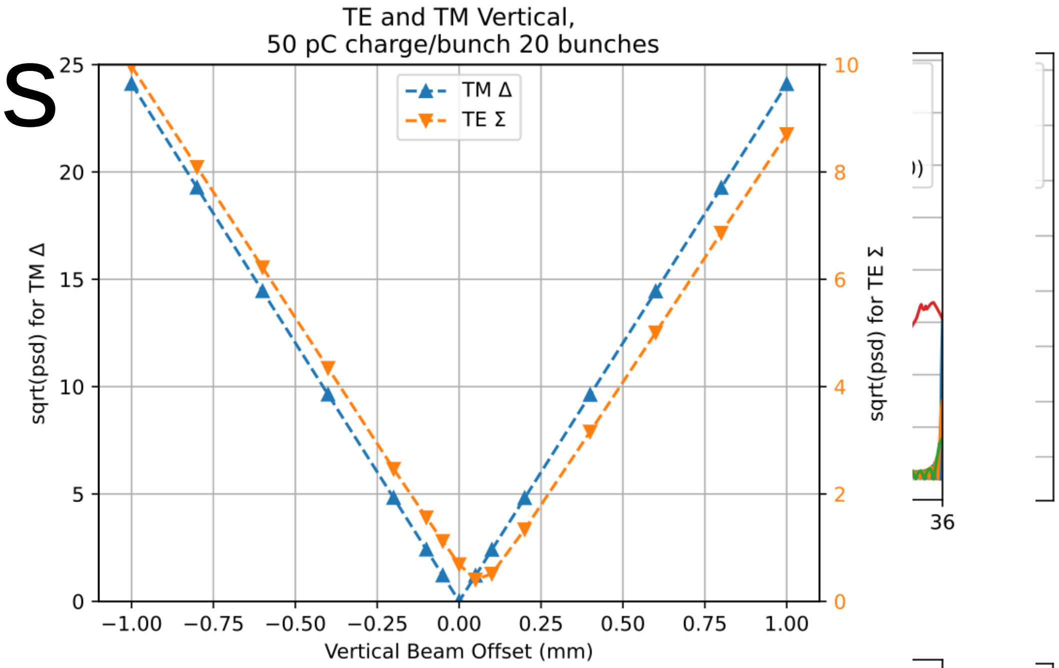
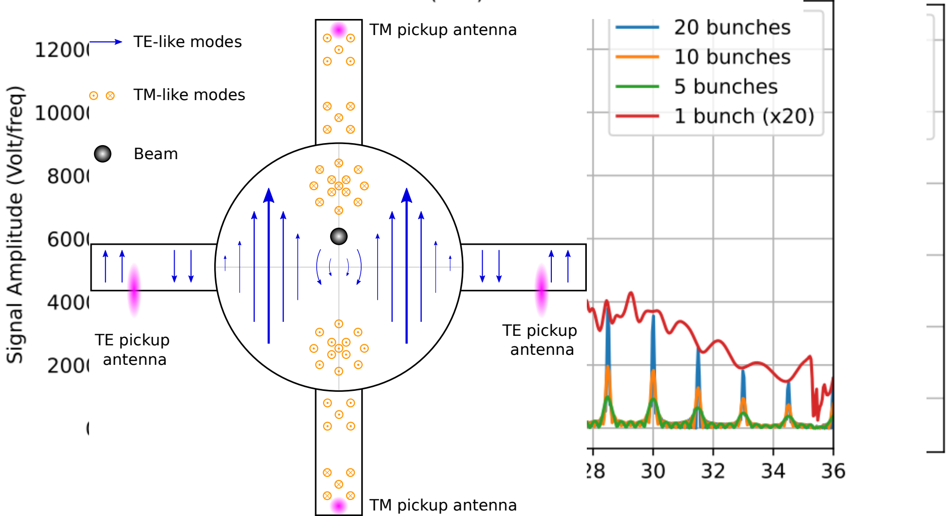
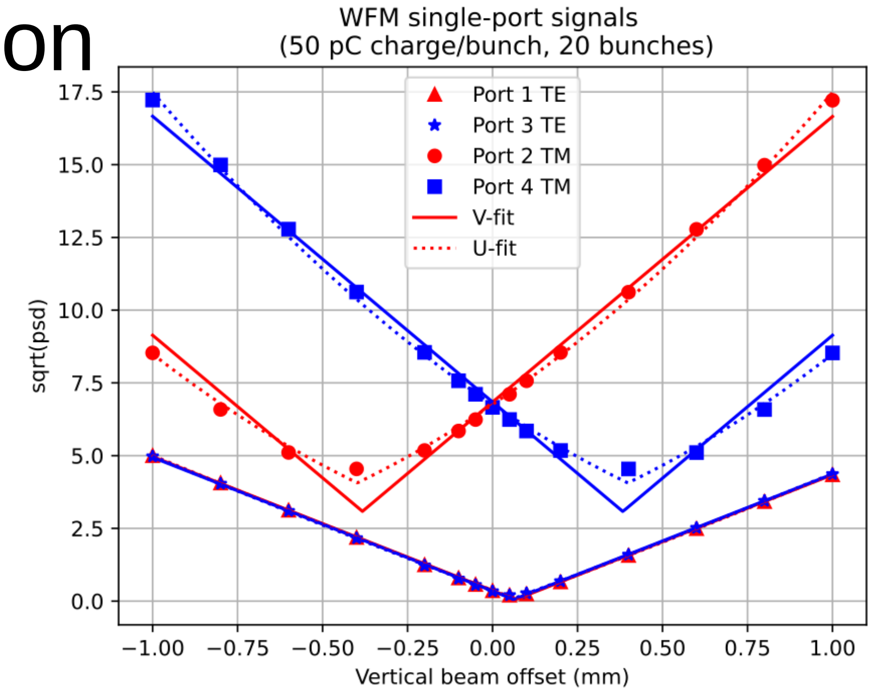


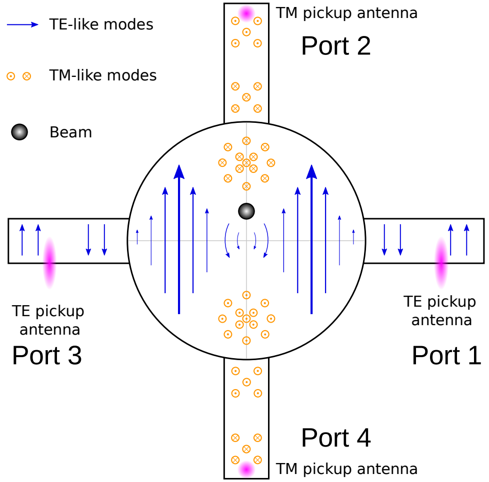


Single antenna signals: Simulation

- For TM:
  - Voltage increase as beam approaches antenna
  - Soft minimum at y = ±400 µm
- For TE:
  - Antennas have identical center
  - Beam-antenna distance independent of vertical position
  - If moving port 3 to top of DWG, the single-antenna center swaps sign

    → Then combined signal is centered





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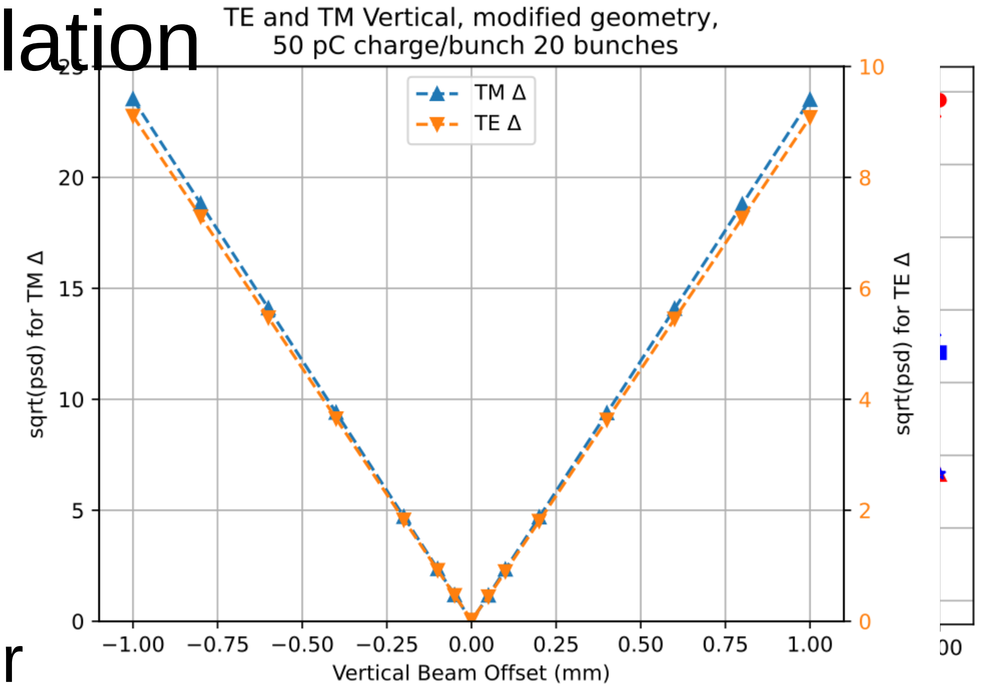

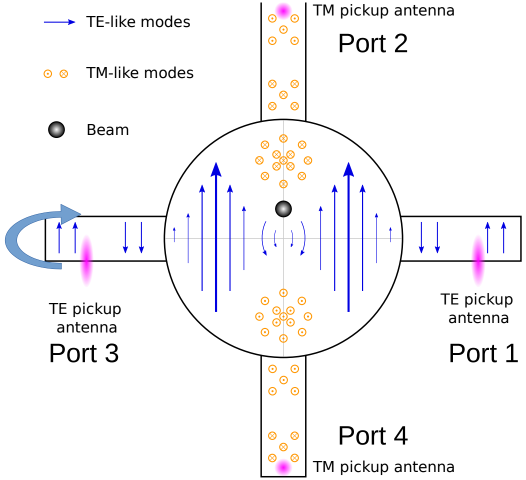

Imperfect connection to hybrid

- Signals will not enter hybrid with exactly same phase and amplitude
  - Cabling and connectors are not perfect
- If each antenna produces a (complex) voltage where *x* is the beam position and *c* is the position of the minimum…

$$\tilde{V}(x,t) = A\exp(\mathbf{i}\omega t)(x-c)$$

- … and the combined signals from the hybrid is on on the form

$$\tilde{V}_\Sigma = D_L e^{\mathbf{i}\theta_L}\tilde{V}_L(x,t) + D_R e^{\mathbf{i}\theta_R}\tilde{V}_R(x,t)$$
$$\tilde{V}_\Delta = D_L e^{\mathbf{i}\theta_L}\tilde{V}_L(x,t) - D_R e^{\mathbf{i}\theta_R}\tilde{V}_R(x,t)$$

  where *D* and *θ* represents the attenuation and phase shift of each arm

- Then with $c_L = -c_R = c'$ (and $A_L = A_R = 1$) this gives:

$$\tilde{V}_\Sigma = \exp(\mathbf{i}\omega t)\left[(D_L e^{\mathbf{i}\theta_L} + D_R e^{\mathbf{i}\theta_L})x - (D_L e^{\mathbf{i}\theta_R} - D_R e^{\mathbf{i}\theta_R})c'\right]$$
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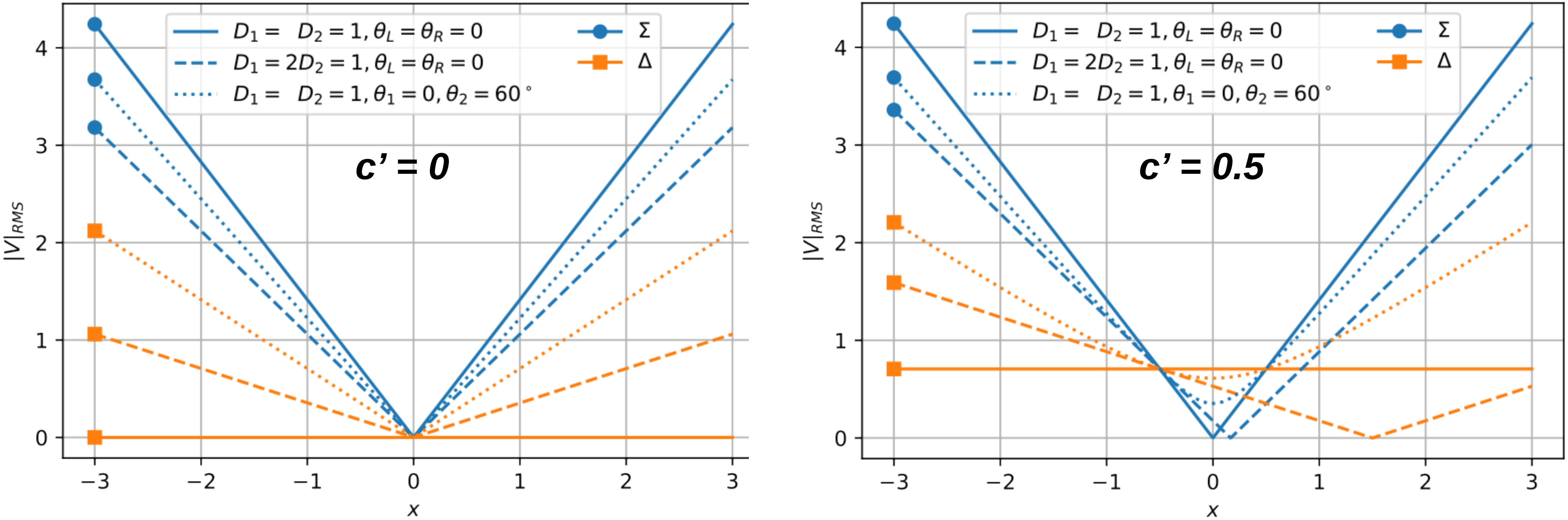
  - With $c' \neq 0$ and $D_L \neq D_R$, **minimum is not at $x = 0$**, and it gets “softer”

Imperfect connection to hybrid



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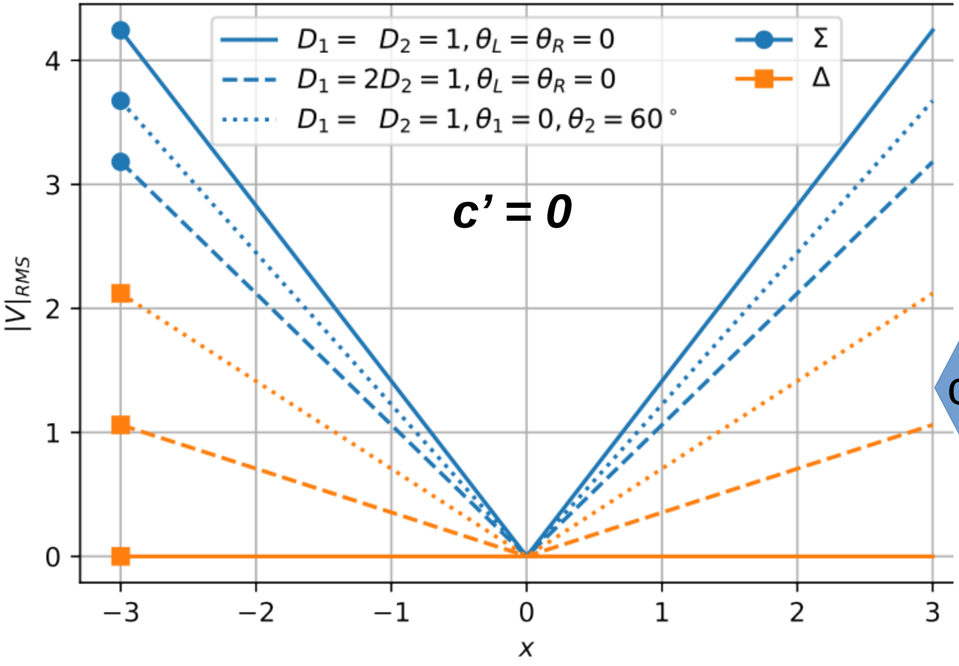
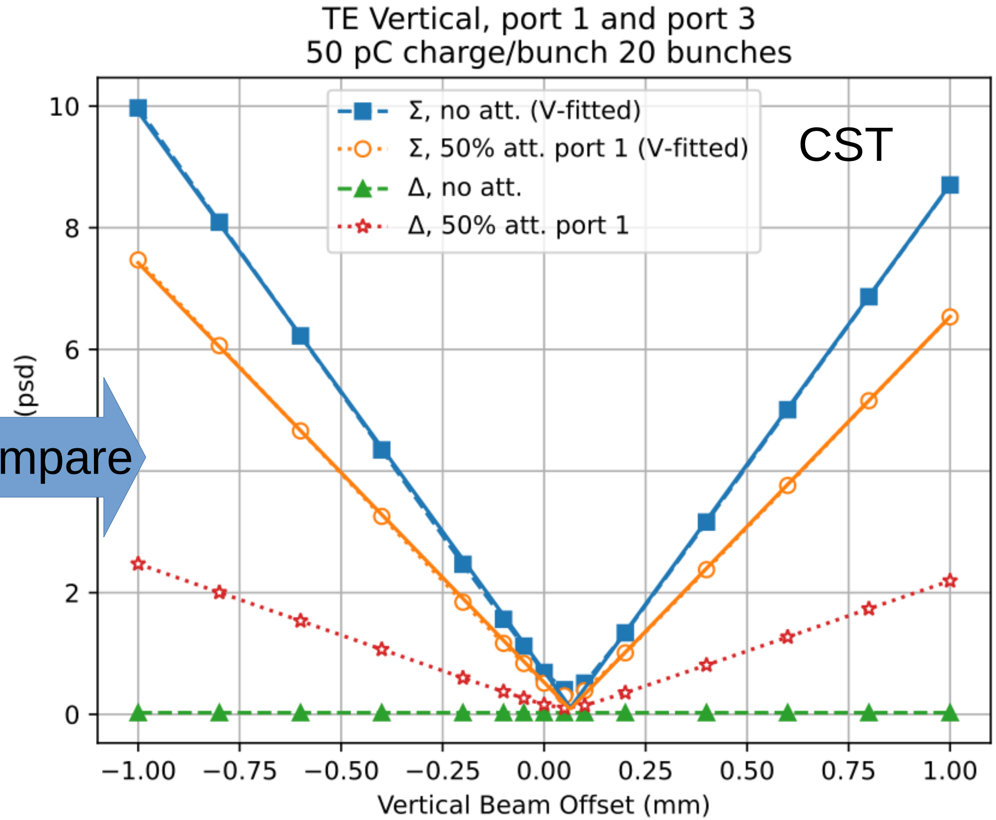


compare



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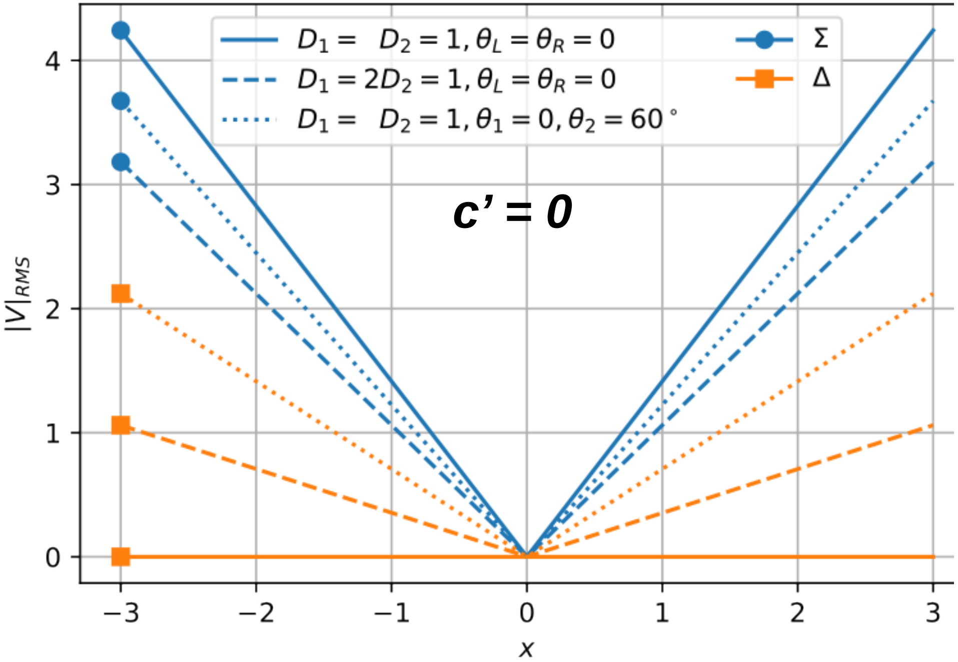

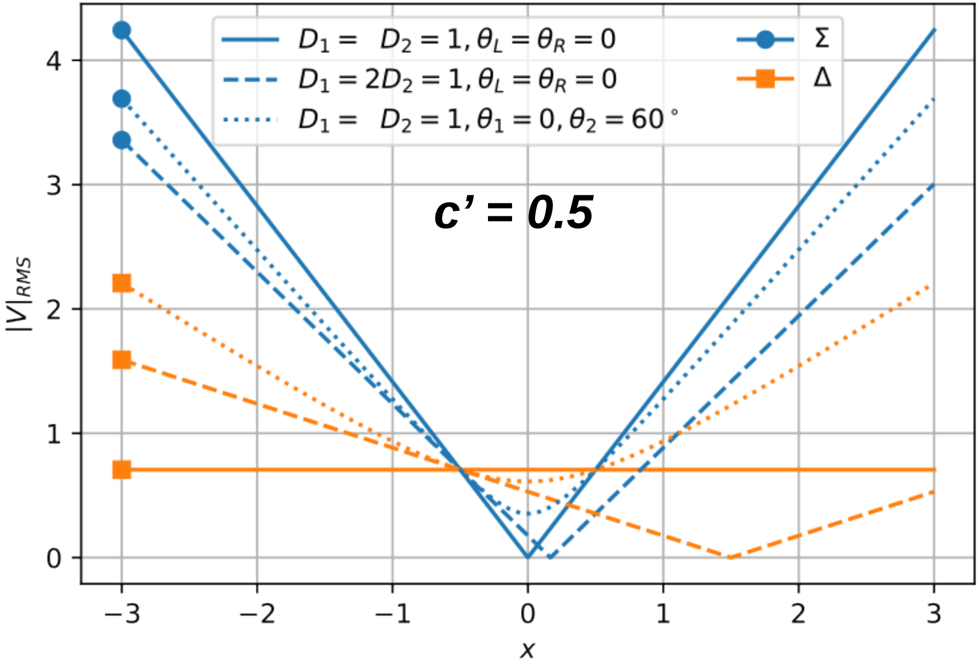

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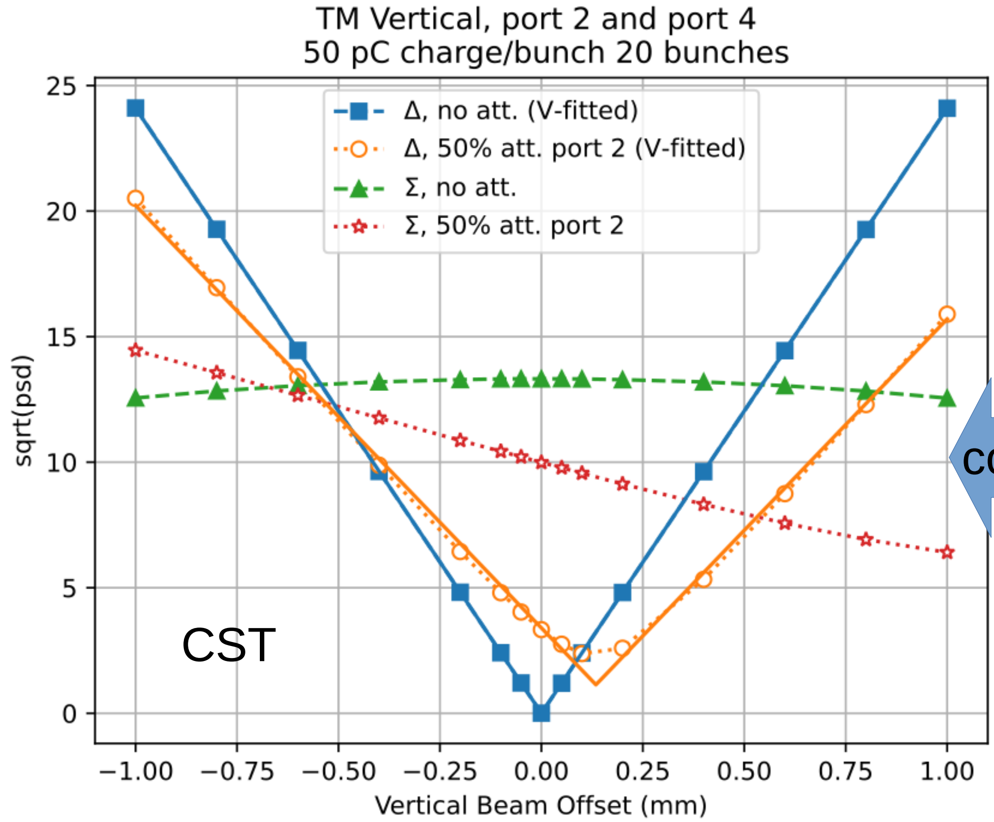

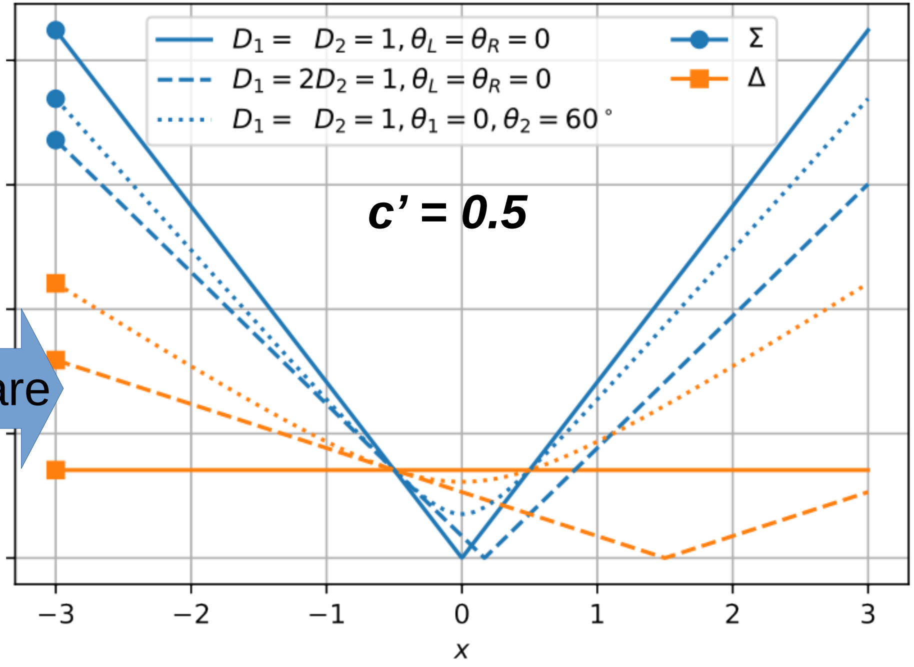

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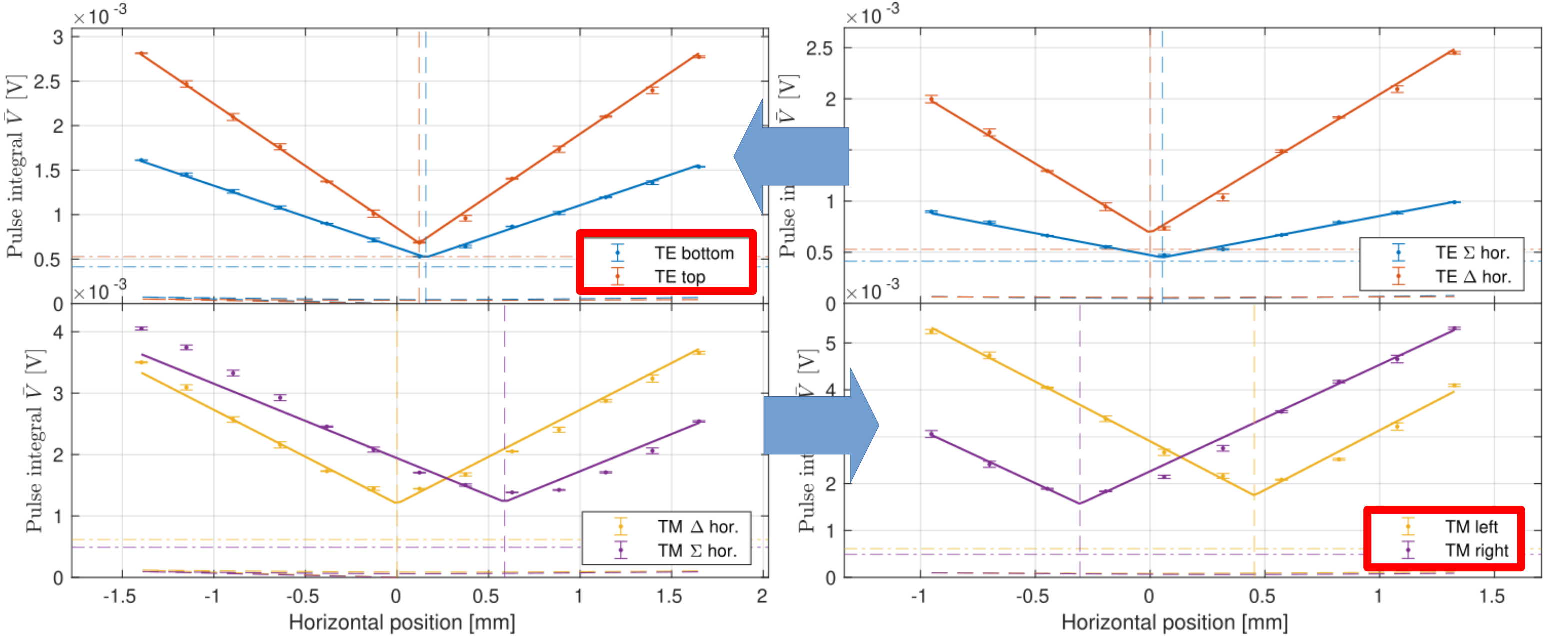
– With *c'≠0* and $D_L \neq D_R$, **minimum is not at *x = 0***, and it gets “softer”

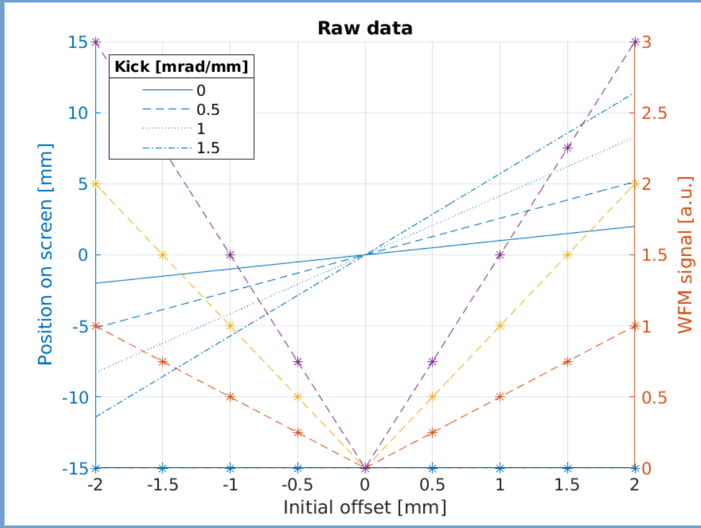
Single antenna signals from experiment

- Bypassed alternatingly TM- or TE hybrids
- Needed to take access to switch – beam center not the same.
  - Plots centered on expected “reference” un-bypassed channel (TMΔ and TEΔ)
  - The *x = 0* in the plots is effectively arbitrary,
    but we only want to compare TE/TM within same scan
- When bypassing:
  - TM splits apart to ±400µm
  - TE signals stay together
- Agrees with simulation

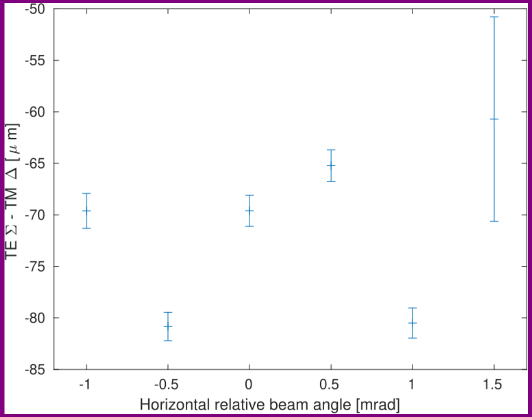


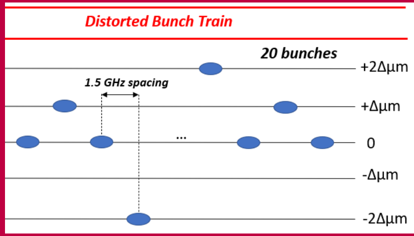
Other measurements

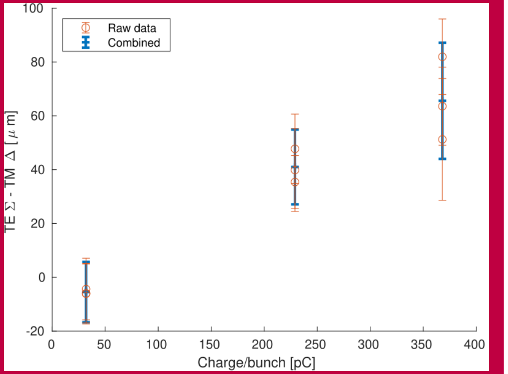
- Wake Field kick should give an absolute position reference to structure center
  - Scan beam position for many charges
  - Technically very difficult to do at CLEAR due to BPM system performance



- We did not see any effect of beam angle on WFM minima positions







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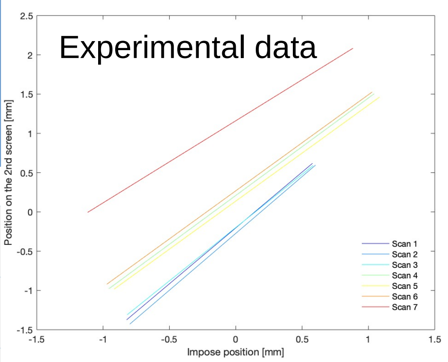

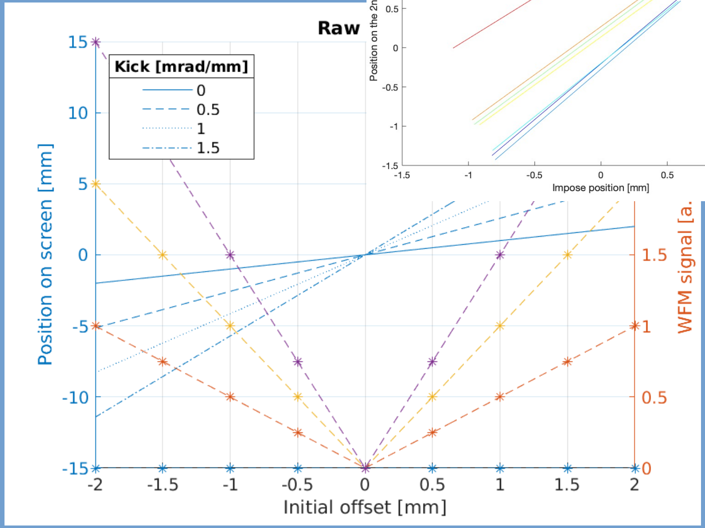

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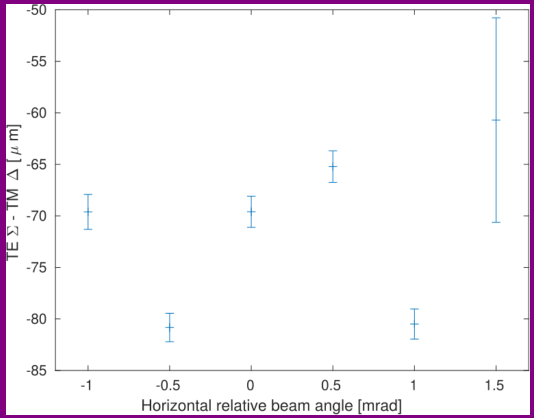

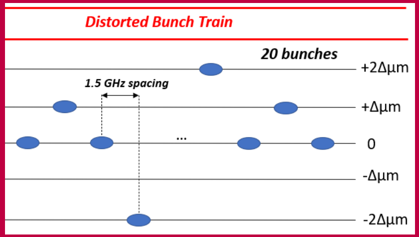

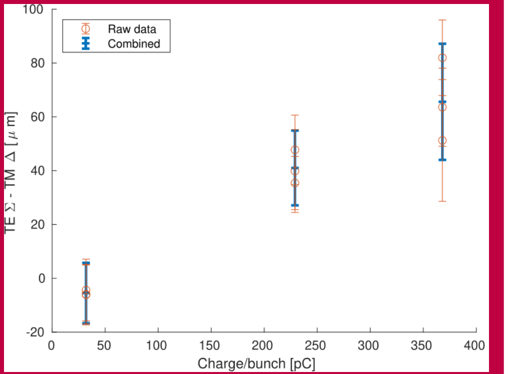

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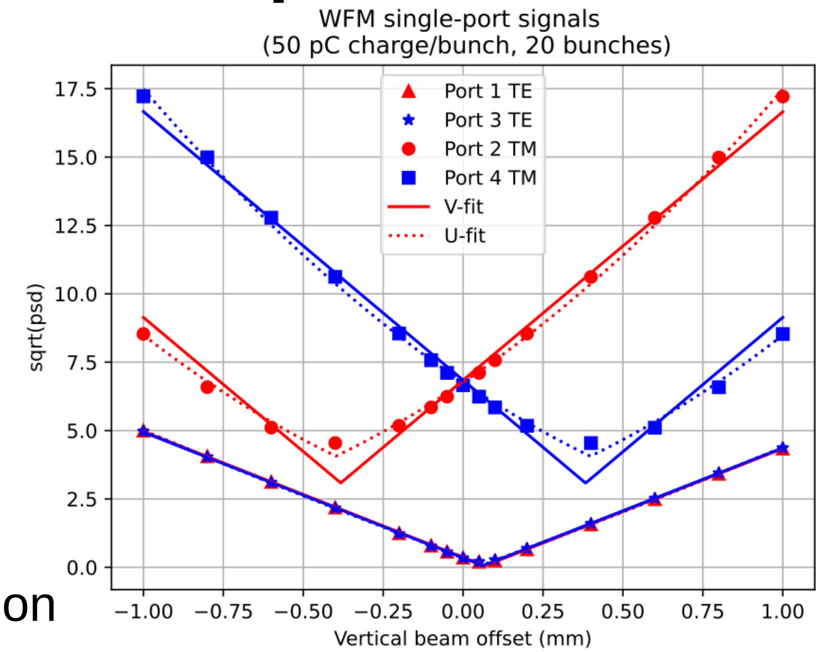
Conclusions from WFM signal split

- Hypothesis of $c_L \neq c_R$ seems well supported,
  explains difference in minima positions
  - Fundamental effect of structure design,
    unrelated to manufacturing etc.
- Hard to “get away from” the effect, requires $D_L = D_R$ everywhere in CLIC
  - Per-structure calibration seems unwieldly
- Soft-bottom of signal “V”s near center
  => Reduced resolution where we really need it
- TE less affected, but higher frequency and lower signal amplitudes

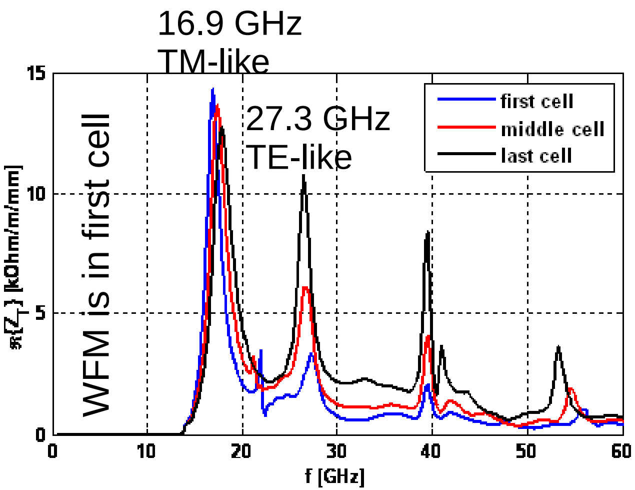
Opportunity in signal “split”?



- Problems with signal-combination system:
  - The combined system cannot tell the sign of the displacement
  - Combined center is difficult to determine
  - Bottom of V is “soft”
- Proposal:
  - Acquire power from both TM antennas separately
  - Use combined information to determine beam position
  - Measures sign of beam displacement – can tell left from right
  - Need to calibrate sensitivity, not offset.
    Requires sweeping a beam with known charge and bunch length over structure
  - Antennas are not “soft” in the same location
  - **BUT:** Requires 2x filters, log-detectors, and fast DAC channels.
    Must process nonlinear output to determine beam position in one structure

BACKUP

Signal generation in acc. structure



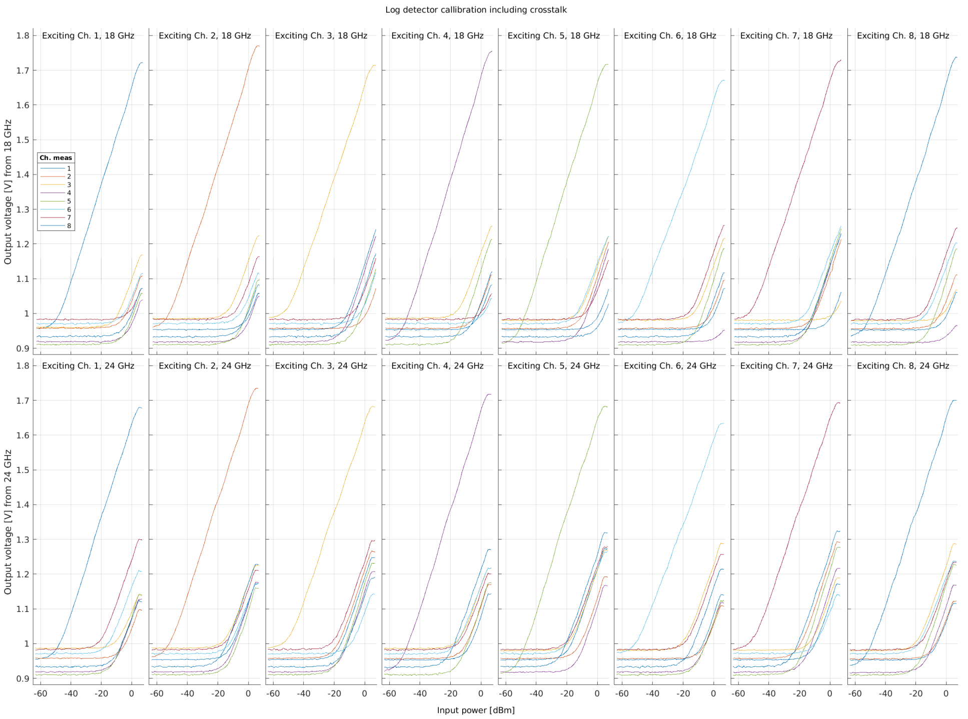
- Each bunch excites multiple modes
  - These then ring down quickly (Q ~ 10 due to damping)
  - Antennas pickup the field
- Can describe signal as sum of signals from each mode, generated by each bunch (or slice of a bunch):

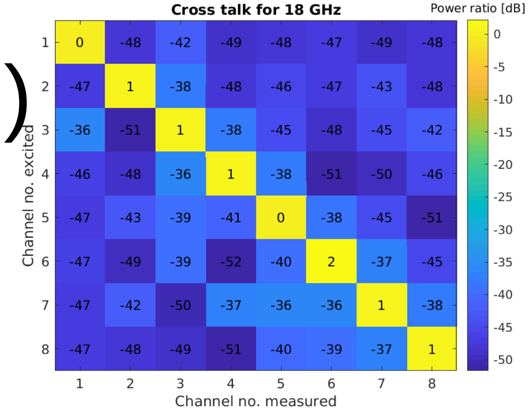
$$V(t)=\sum_{modes\, i}\Re\left[\sum_{bunches\, j} Q_j * A_i \exp\left(\boldsymbol{i}\, 2\pi f_i (t-t_j)-\frac{2\pi f_i (t-t_j)}{2Q_j}\right)\right]$$

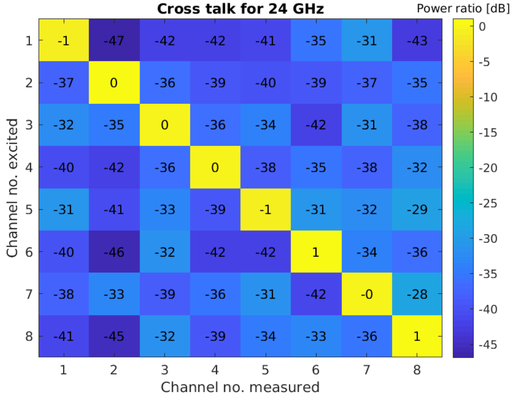
- In CLEAR, bunches arrive at 1/(1.5 GHz) intervals

Log. power detector

- Converts freq. filtered power signal to voltage
  - Calibration needed
  - Fit linear curve P(V)
- Wide dynamic range
- Low cross-talk (~20 dB)
- Based on Analog Devices HMC662LPE

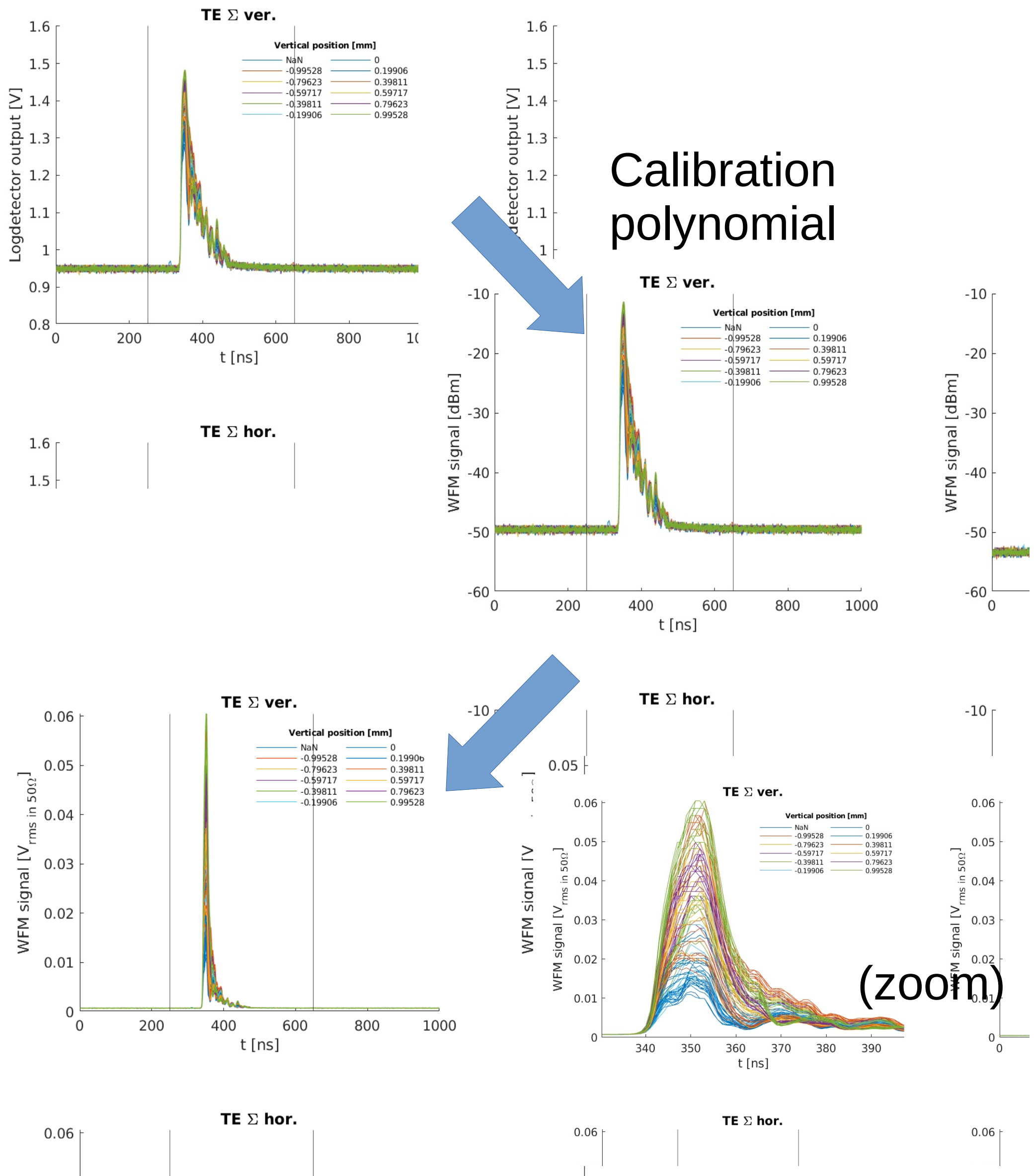


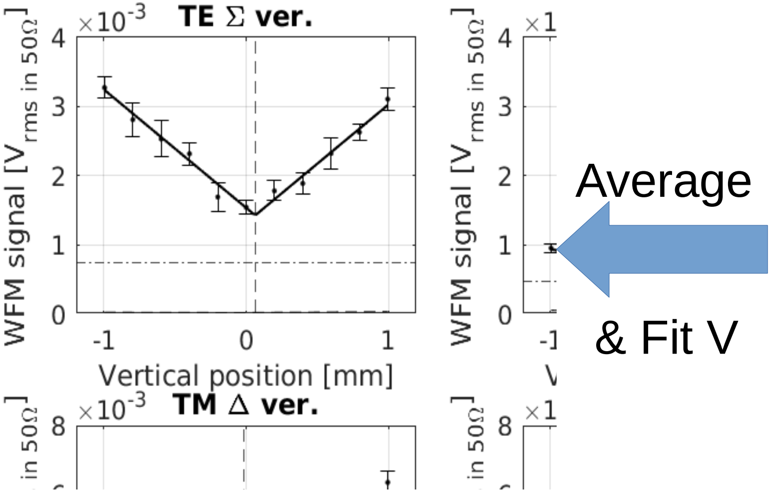




From V_{out} [V] → P(t) [dBm] → V_{in} [V_{rms} (50Ω)]

- Need to turn the V(t) from the log detector into a position signal
- Currently done by averaging in window
- Done separately for each signal
- Need to deal with reflections, varying train lengths, etc.





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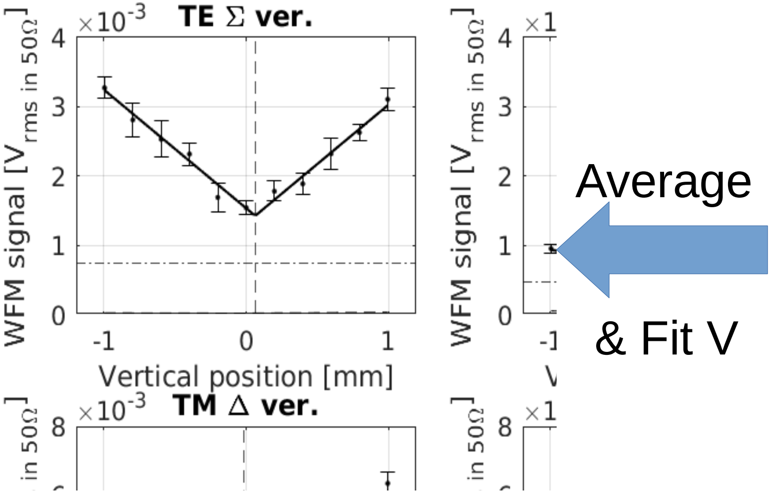
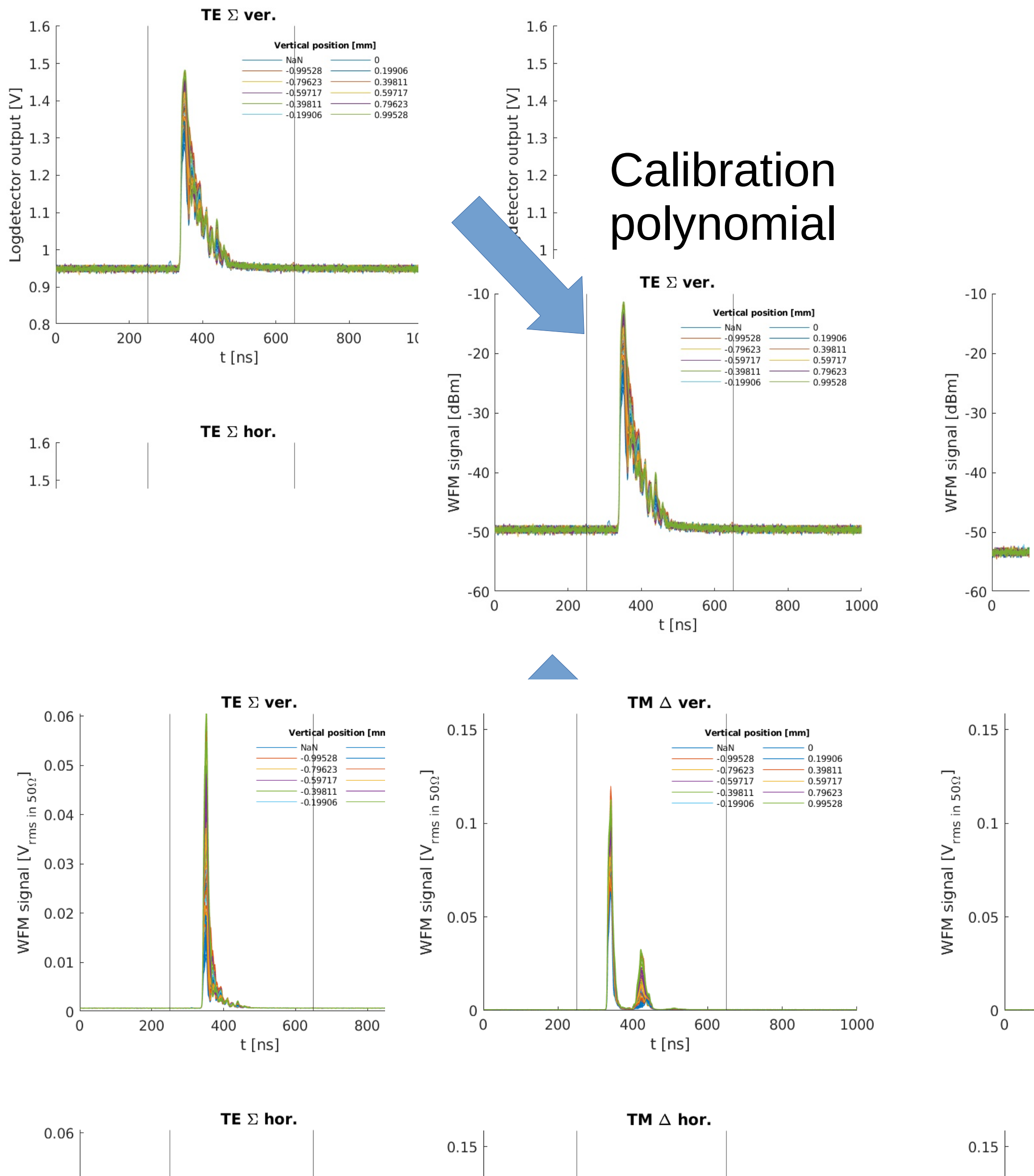
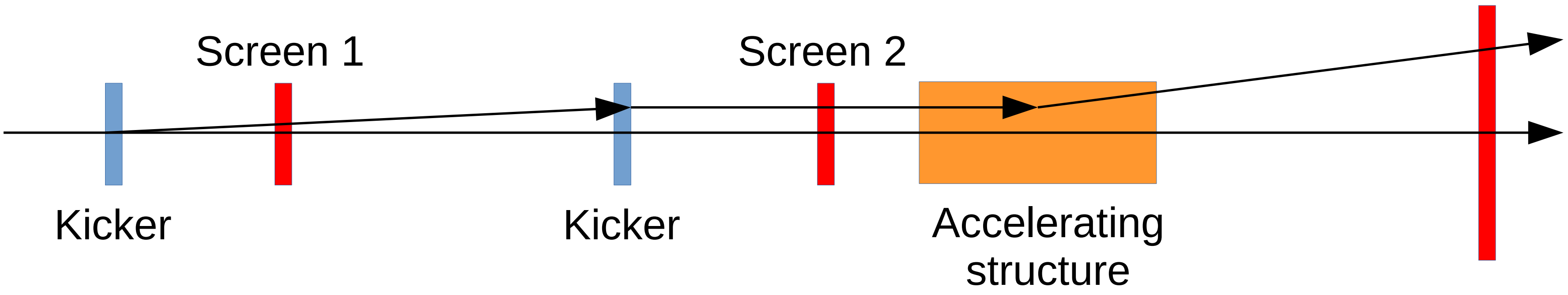




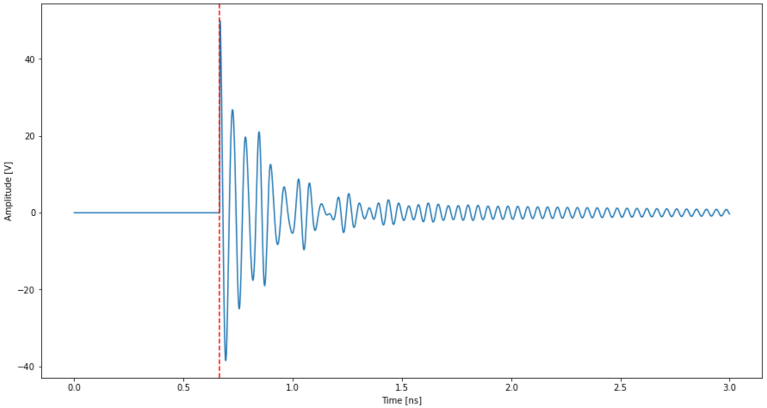
Method: Transverse scan

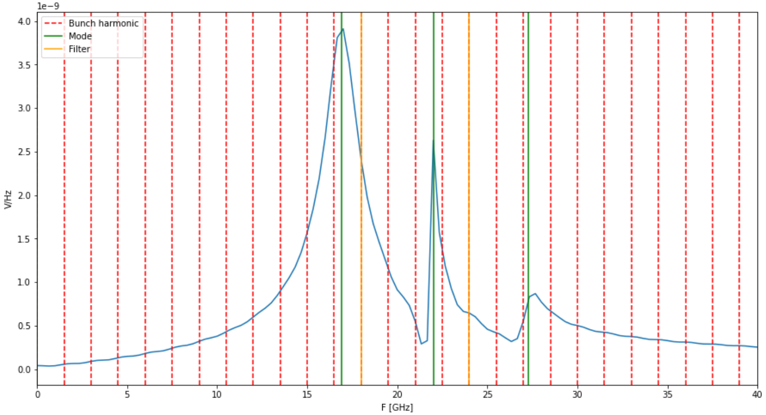


- Scan beam position vs. structure,
  observe WFM signal & kick as function of beam transposition
- While structure is equipped with a mover,
  this has not been reliable to operate
- Rather use the two upstream kickers to transpose the beam
  - Magnet strengths were carefully measured with beam;
    parallelism and calibration confirmed with low-charge beam on screen 2 & 3

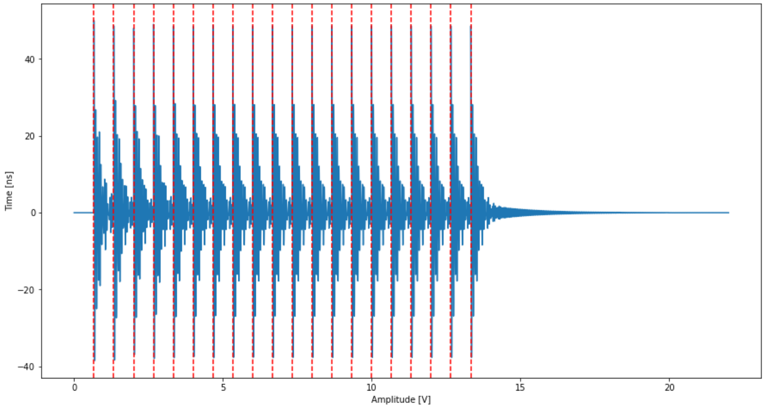
Bunch harmonics toy model

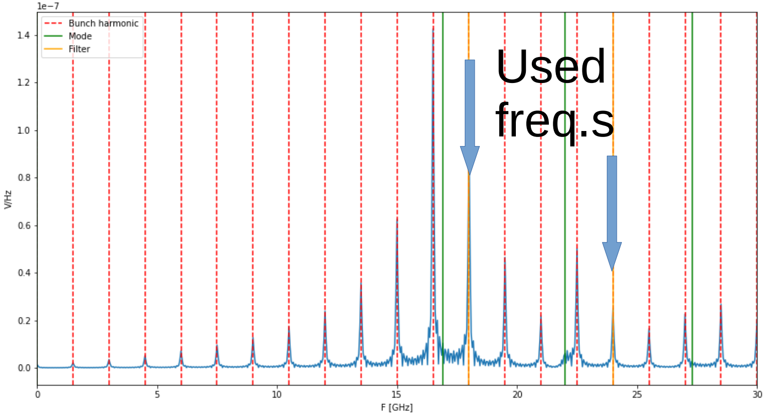
- Single bunch:





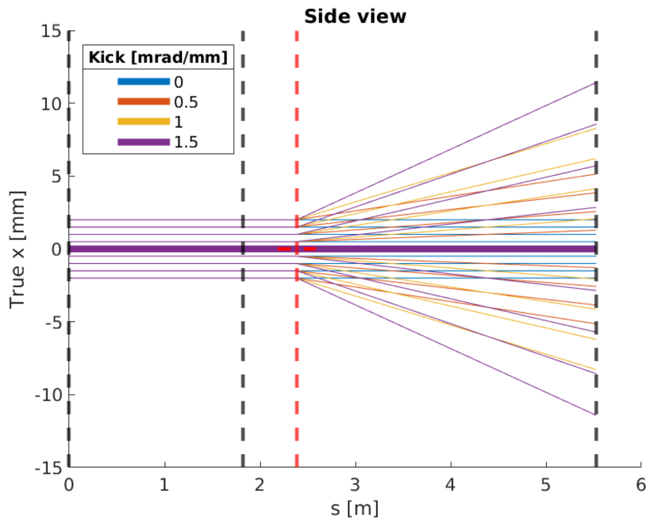
- 20 bunches:



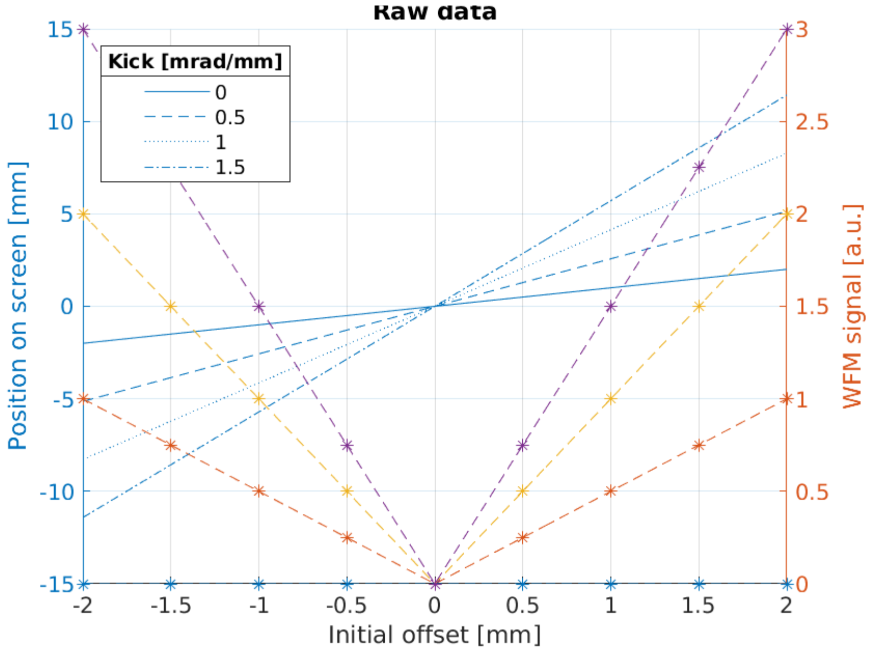


Center comparison between WFM and kicks

- Purpose of WFMs:
  Center the structure to minimize the kick
- Need relationship between WFM center and kick center (same or constant offset?)
- Find this by comparing WFMs and kicks

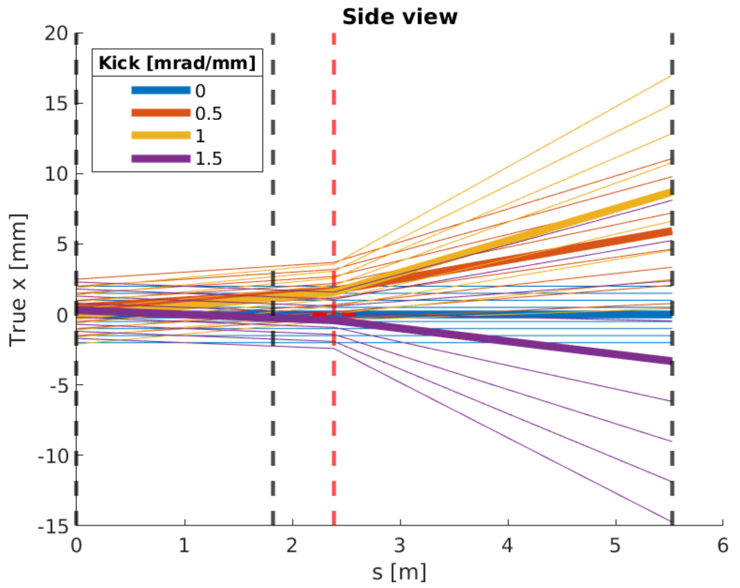


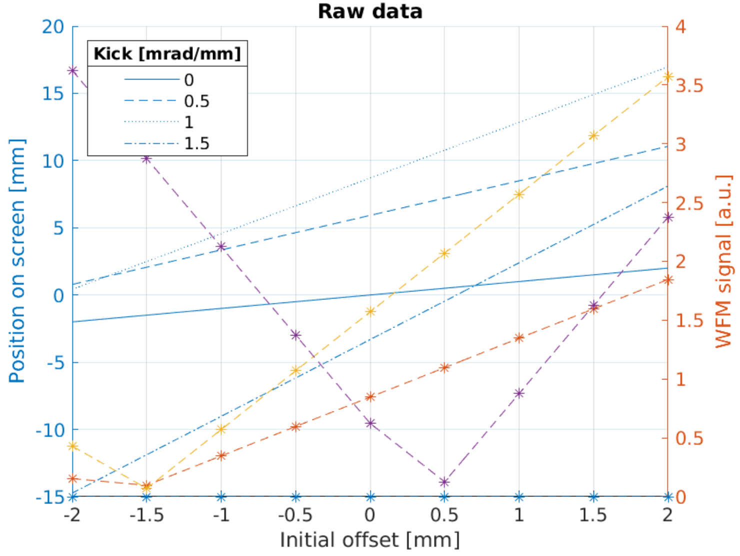
PLOTS:
"IDEAL WORLD" TOY MODEL



Estimation and correction for initial trajectory params

- In reality:
  - Screens are misaligned
  - Initial beam position & angle changes when changing charge
  - Screens have finite resolution
- Need to be able to correct for this
- Found correction scheme that works in simulation:
  - Measure initial beam angle and offset with first 2 screens
  - Correct for shift on last screen and in structure





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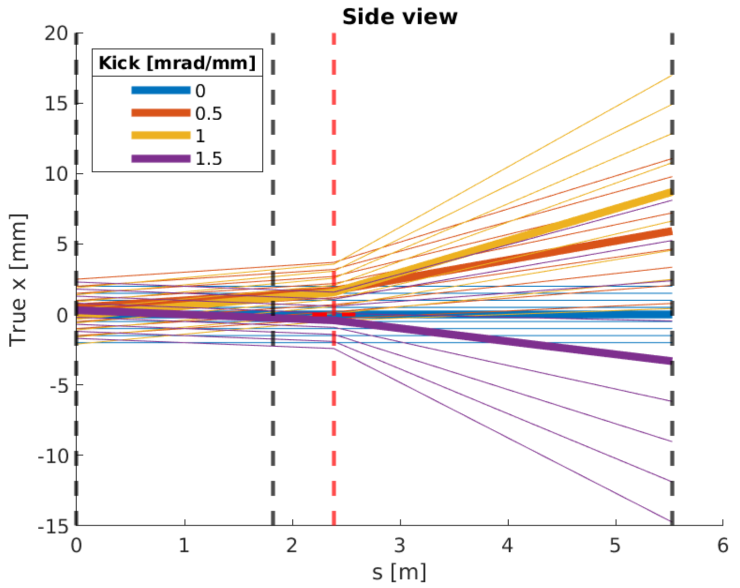
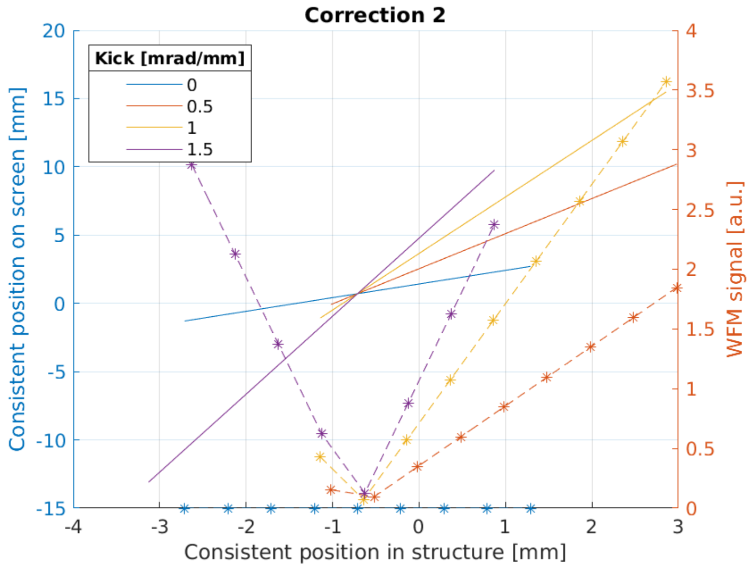
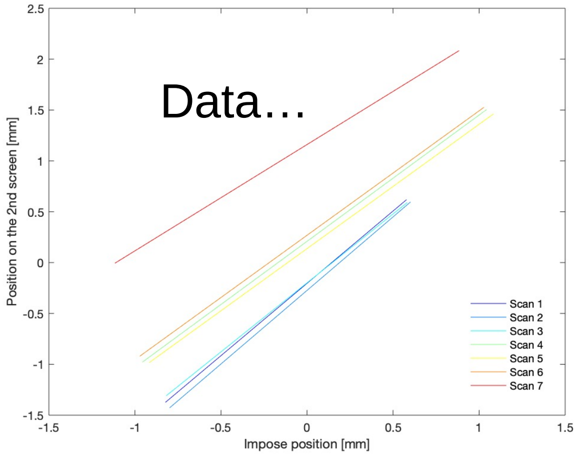
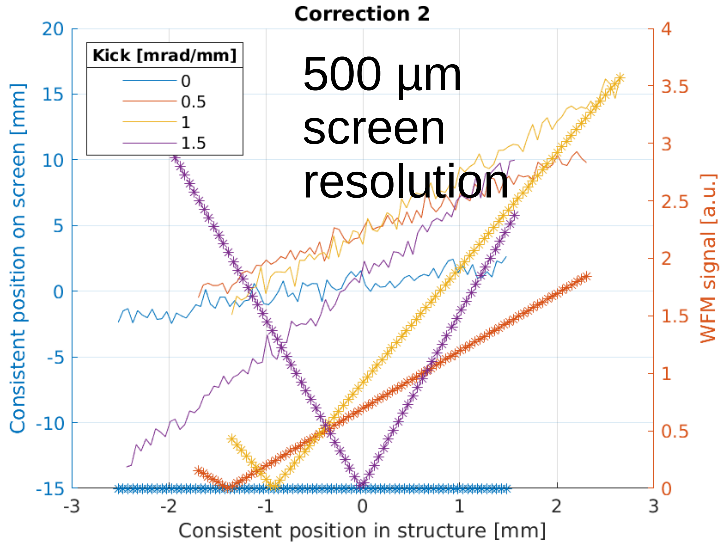


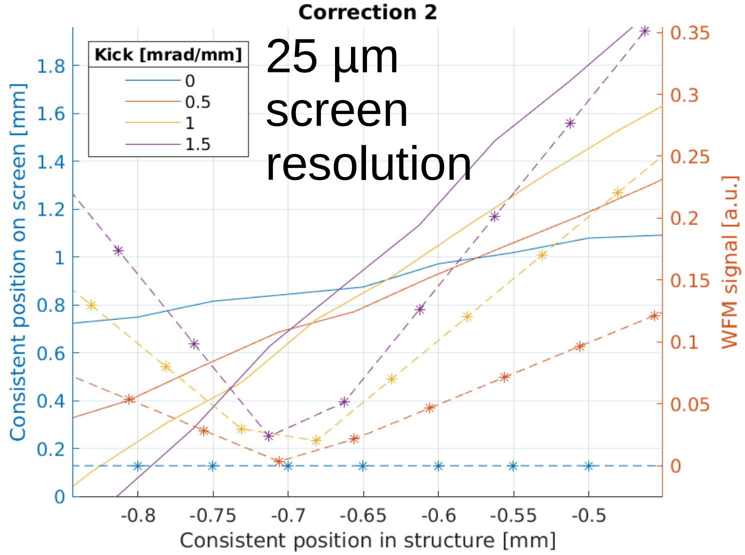


Effect of screen resolution

- Method relies on good estimate of initial trajectory
- This requires good measurements upstream of structure
- Not yet working well







Effect of beam angle

- Can use bump to create an angle on top of displacement
- If center discrepancy caused by frequencies traveling down the structure, would expect to see an effect
- **No effect observed**