Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

Electron Cloud Instabilities at CesrTA

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for the CesrTA Collaboration

LCWS13

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- EC Dynamics Instrumentation

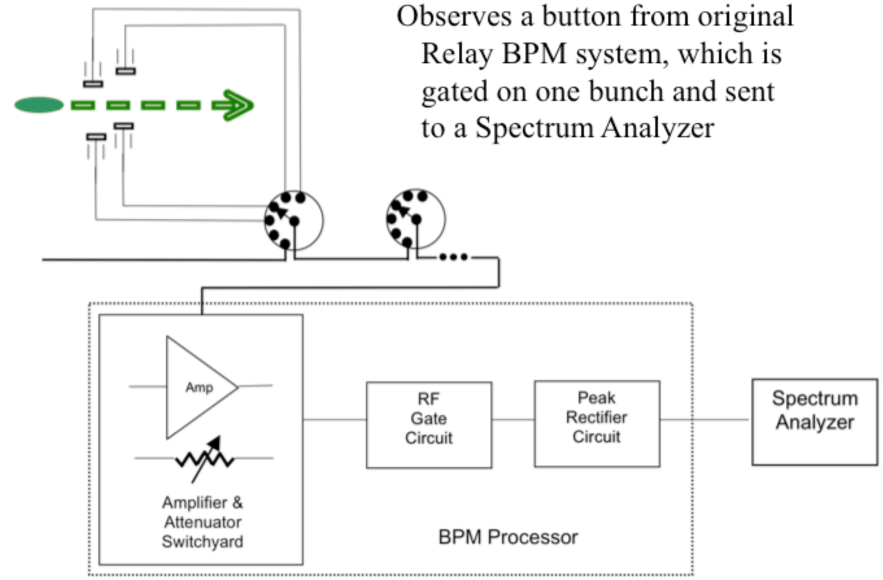
Two Sets of Experiments

A. Effects Visible with Trains Having Different Spacings for the Bunches

B. Investigation of the Vertical Enlargement of the First Bunch in the Train

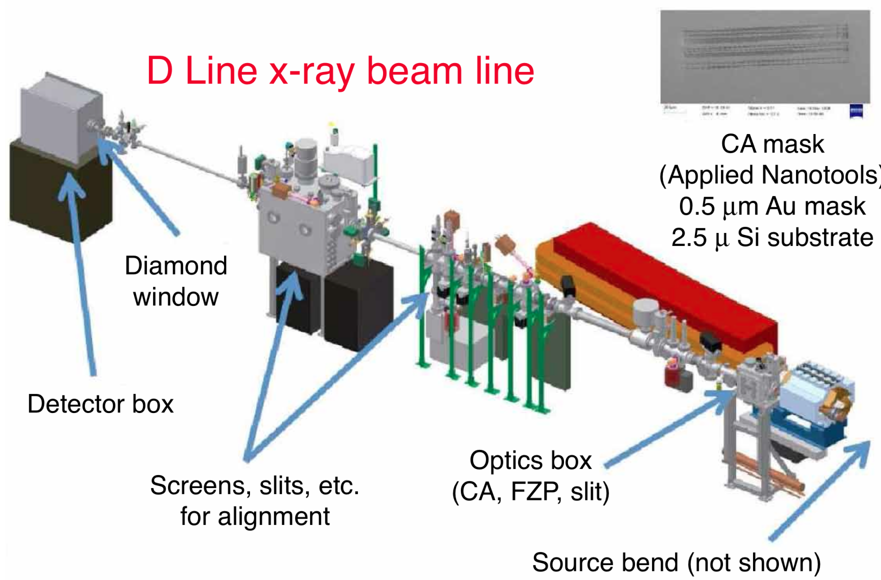
Instrumentation at CESRTA

- Position spectrum of individual bunches within train
  - Single button of a BPM
  - Gate the signal to accept only 1 bunch
  - Send to spectrum analyzer & detect:
    - H & V dipole (m=0) betatron modes at frequencies F_h and F_v
    - Vert head-tail (m=±1) lines at $F_v \pm F_s$
    - Horz head-tail modes (m=±1) lines at $F_h \pm F_s$



(F_s is the synchrotron tune)

- X-ray beam size monitors (xBSMs) for e+/e- beams
  - Linear, Vert 32-pixel arrays: bunch-by-bunch & turn-by-turn
  - Removes dipole motion before fitting vertical beam size σ_V of each bunch.



A. Trains with Different Bunch Spacings

- Experimental Goals
  - Measure the coherent mode growth rates for the most unstable bunches in the train
    - For vertical Dipole modes
    - For vertical Head-tail modes
    - Measured by comparing the peak coherent oscillation amplitudes vs. Vertical Chromaticity
  - Measure with different bunch spacings
  - Calibrate coherent damping rates vs. Vertical Chromaticity

Conditions & Analysis of e+ Stability Data

- Conditions
  - 30 Bunch Positron Trains
  - Bunch Spacings: 4, 8, 12, 14, 16, 20, 24, 28, 36, 42 and 56 nsec
  - Bunch current (nominal) I_b = 0.75 mA   (1.2×10^{10})
- Analysis utilizes
  1) Xquneing-to-Chromaticity calibration data (MGB)
  2) Drive-damp measurements for Vert m=0, ±1 modes for a single bunch ==> fitted damping rate:

$$\alpha = \left(\frac{d^2\alpha}{dI_b \; dQ'} \right) Q' \, I_b + \alpha_{SR}$$

where α_{SR} = SR damping rate, & Q' = chromaticity

  3) Spectral amplitudes for Vert m=0, ±1 modes for each bunch (RLH)

Items 1) & 2)

- Xquneing-to-Chromaticity calibration data

  from control settings vs. chromaticity measurements

$$\begin{pmatrix} Q'_V \\ Q'_H \end{pmatrix} = \begin{pmatrix} 0.00933 & 0.00 \\ -0.0003 & 0.00745 \end{pmatrix} \begin{pmatrix} XQ1 \\ XQ2 \end{pmatrix}$$

- Drive-damp measurements for Vert m=0, ±1 modes for 1 bunch

$$\alpha_V = -\left\{\left(-3\ \sec^{-1} mA^{-1} Q'_V\right)\left(\frac{I_b}{1\ mA}\right) + 110 \sec^{-1}\right\}$$

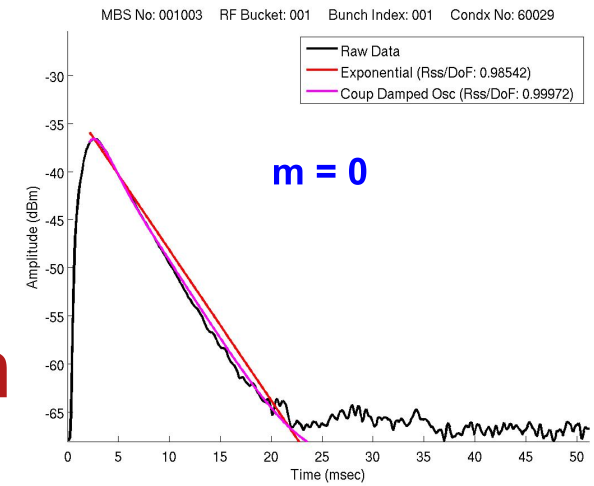
V dipole (m = 0) mode

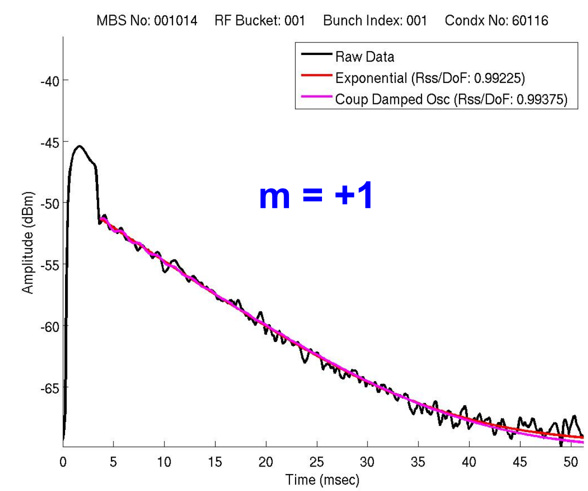
$$\alpha_V = -\left\{\left(21\ \sec^{-1} mA^{-1} Q'_V\right)\left(\frac{I_b}{1\ mA}\right) + 4 \sec^{-1}\right\}$$

V dipole (m = −1) mode

$$\alpha_V = -\left\{\left(17\ \sec^{-1} mA^{-1} Q'_V\right)\left(\frac{I_b}{1\ mA}\right) + 33 \sec^{-1}\right\}$$

V dipole (m = +1) mode





- Instrumentation & Results
  - Gated BPM signal routed to spectrum analyzer
  - Spectrum contains
    - Horizontal and vertical dipole (D) (m=0) betatron modes at frequencies Fh and Fv
    - Vertical head-tail (HT) (m=±1) lines at Fv±Fs
      (Fs is the synchrotron tune)
    - Horizontal HT lines (ocassionally.)
  - Over some range of vertical chromaticity settings
    - Amplitudes of the D and HT lines will decrease as the chromaticity increases.
    - By interpolating within sets of measurements at different chromaticities we arrive at the same spectral D and HT mode amplitudes for the most unstable bunches.

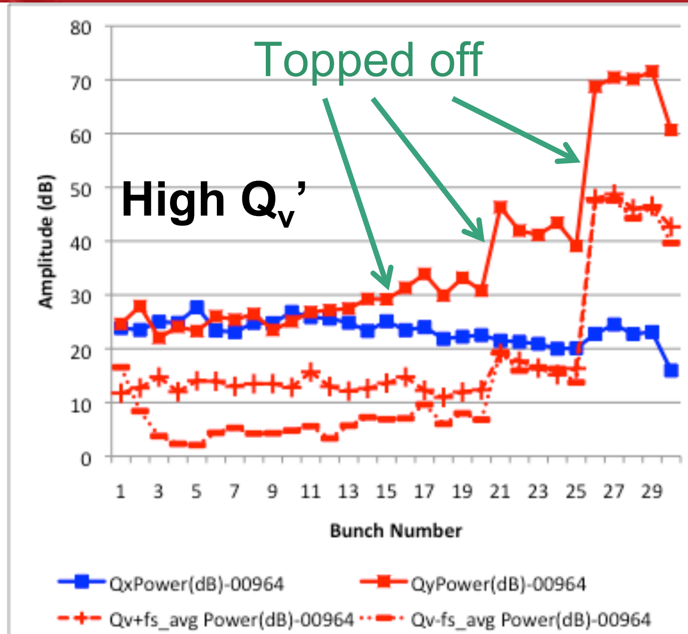
Experimental Procedures

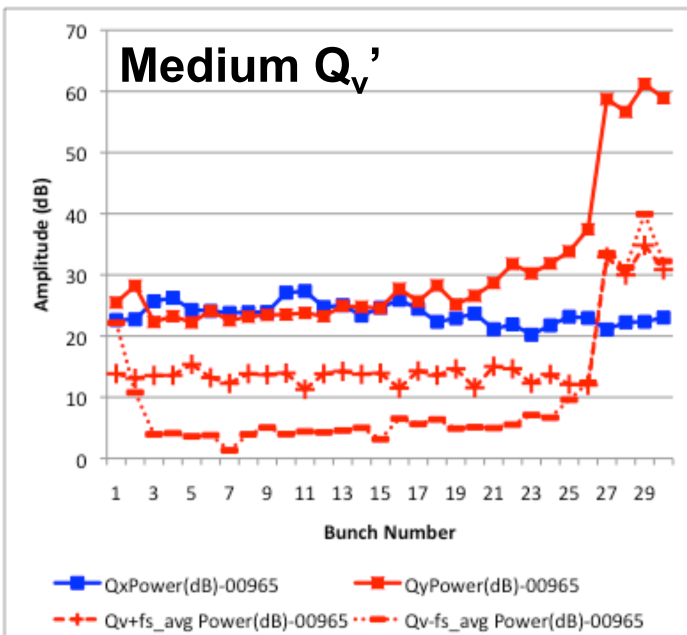
- Select a spacing of bunches
  - Fill 30 bunches to 0.75 mA ($1.2x10^{10}$ particles.)
  - Vary chromaticity while observing amplitude of at least one of the HT modes for bunch 25 to determine a reasonable range for the chromaticity settings.
- For each chromaticity & bunch spacing
  - Set the chromaticity within this range.
  - Top-off beam and take
    - Spectra for five of the bunches (one at a time)
    - Turn-by-turn vertical beam size data for each bunch
  - Iterate last step until all bunches are measured

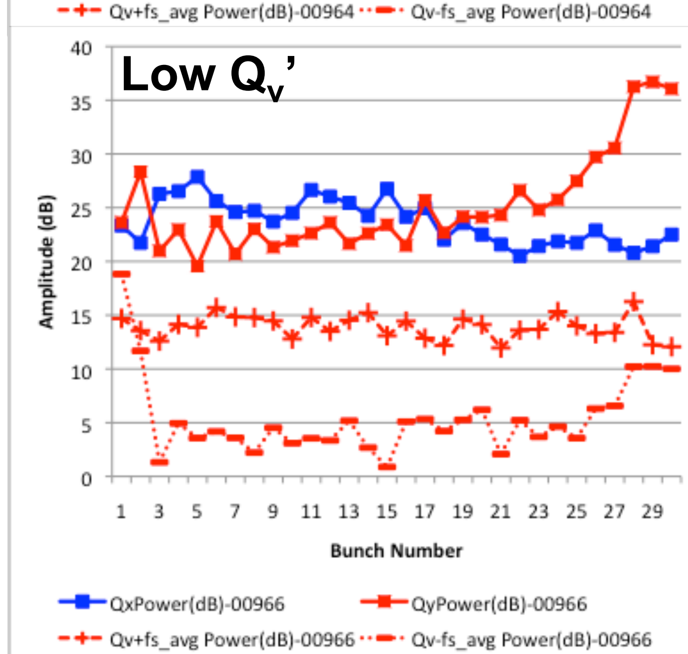
3) Analysis of Bunch-by-bunch Spectra

1. Fit spectral peaks in dB to gaussians for each Q_v'

Plots of spectral amplitudes vs. bunch number for 8 nsec spacing (N.b. bunch 1 blow up)







Analysis of Bunch-by-bunch Spectra

2. Determine "Typical" Max Coherent Oscillation Amplitude (m=0, ±1) for each XQ1 & Spacing:

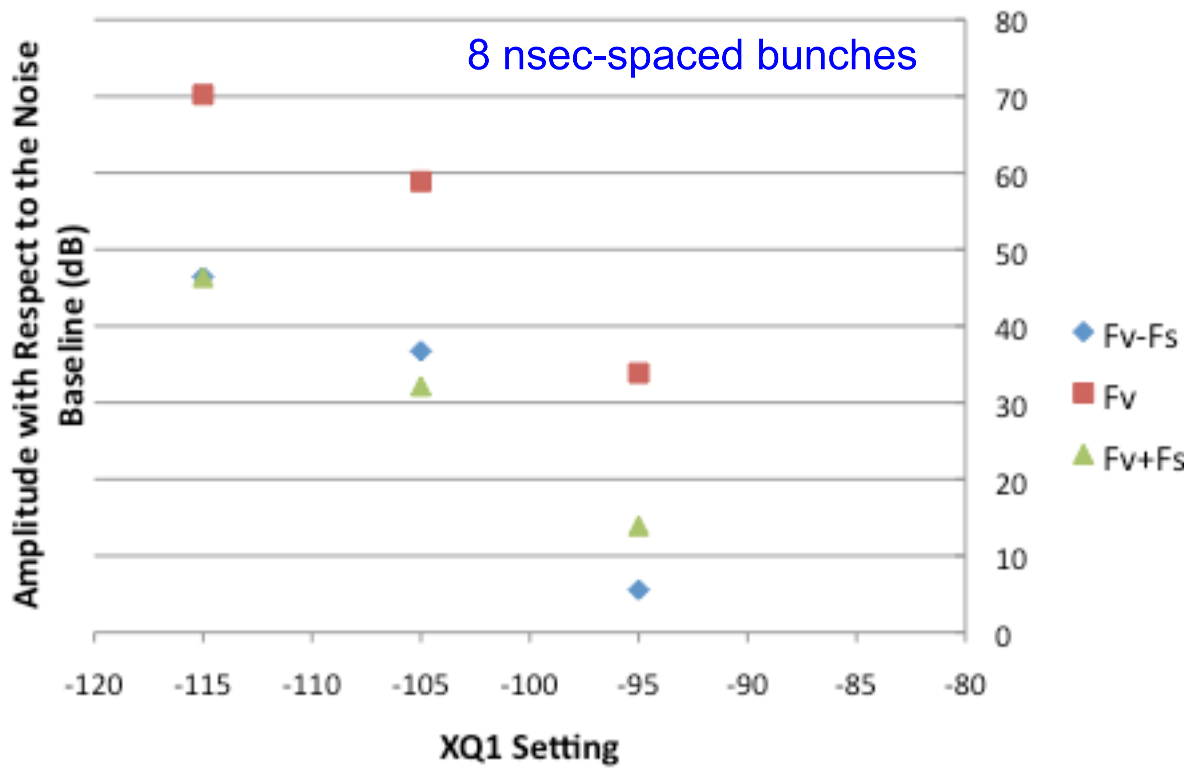
   Average amplitude for all bunches with amplitudes within NN dB of max amplitude (e.g. 5 dB).

3. Fit the 3 points (dB, XQ1) to line

   (for quadratic fit of the data – can give unreasonable fits)

4. Select a Reference Amplitude for each mode (m=0,±1)

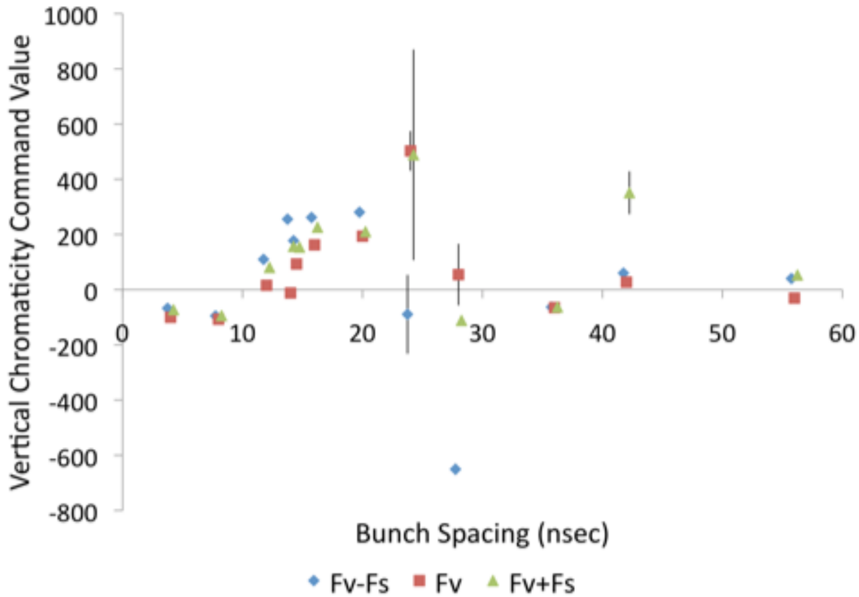
   Interpolate (usually) to find XQ1 value to match



Analysis of Bunch-by-bunch Spectra

5. Vary the range of amplitudes used for finding the Average Unstable Amplitude – Don't assume we know correct value for NN dB
   - Step the value of ΔA = NN dB in 0.5 dB steps
   - Span the range of 2 dB ≤ NN ≤ 6 dB
   - Fit Amplitude (dB) vs Chromaticity command for each step
   - Find Chromaticity command for Reference Level in each step

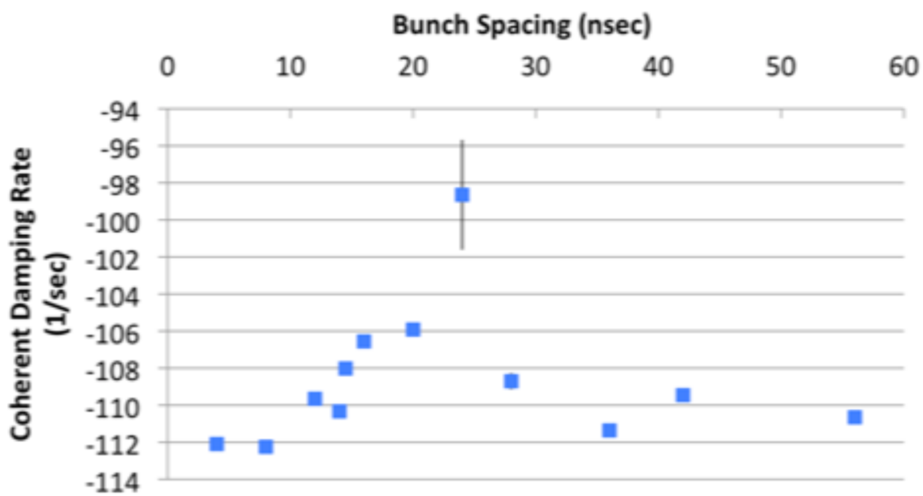
6. Compute from each set: Chromaticity Command
   - For each Coherent Mode and each Bunch Spacing
   - Average Chromaticity Command & Standard Deviation



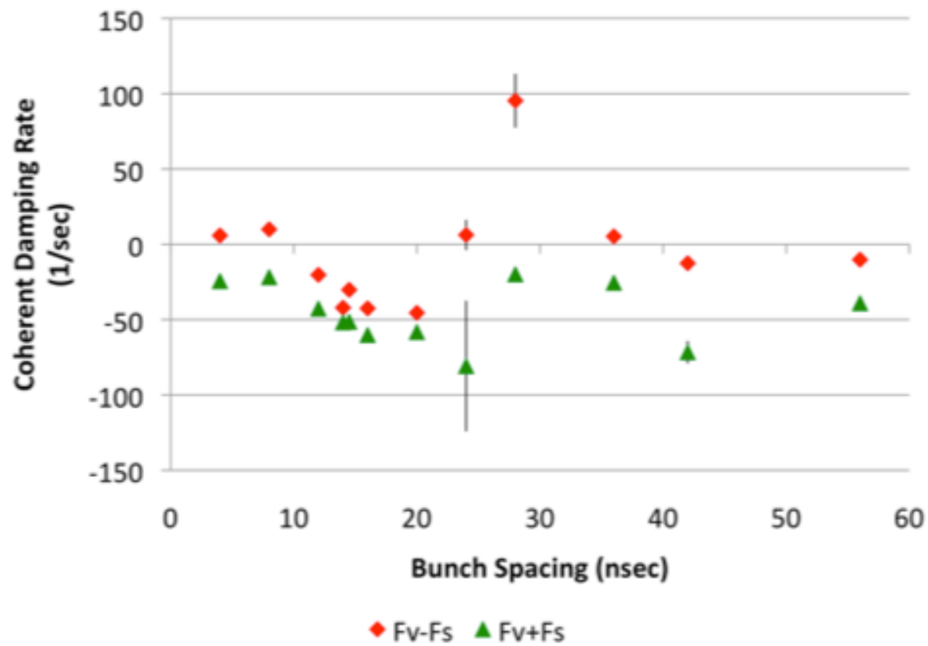
Plots of α vs. Bunch Spacing

- Transform XQ1 to Damping Rate, α, & plot results

Dipole Mode



Head-Tail Modes



Radiation damping for Vertical Dipole Mode (m=0) is $-17.7\ sec^{-1}$

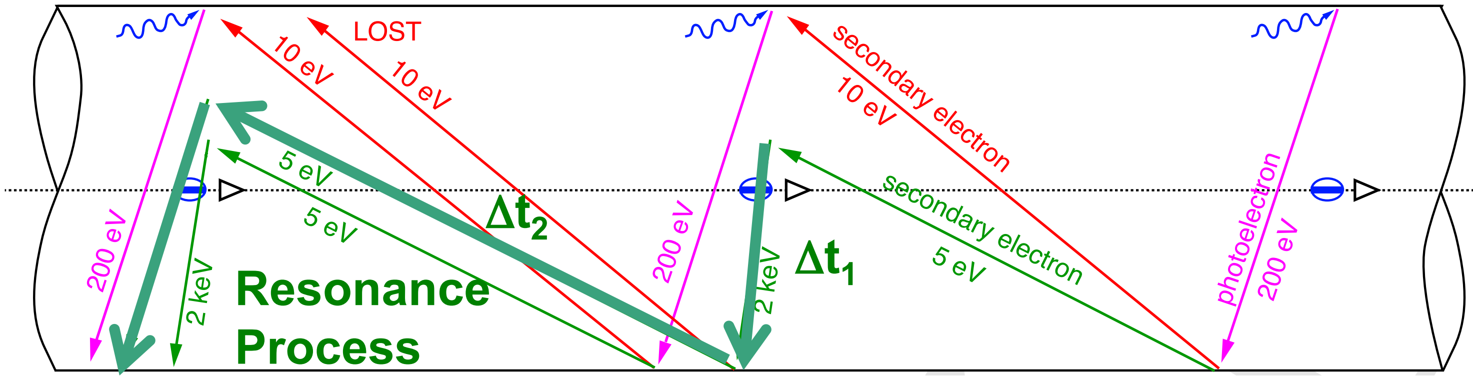
- Conclusions: Trend for Coherent motion with Increase in Bunch Spacing:
  1) Dipole mode essentially constant
  2) HT modes less stable (40-50 sec^{-1}) centered around 16-20 nsec-spacing

Conclusions from Bunch Spacing Studies

- Dipole Mode Damping Rates
  - Deviation is small (approximately 6 sec^{-1} or less than 50% of the radiation damping rate) & in the direction to slightly increase the damping of the dipole coherent motion for bunch spacings between 8 and 28 ns
- H-T Modes Damping Rates
  - For bunch spacings between 8 and 28 ns
    - Deviation from constant damping rate is much more pronounced yielding between 40 and 50 sec^{-1} of growth rate between 8 and 28 ns bunch spacings.
    - Since the larger amplitudes typically occur for the later bunches, this implies that the HT modes are less stable for the later bunches within trains at these spacings

Possible Mechanism

- Multipacting Resonance in the Dipoles



– EC accelerated by bunch: Δt_1 is quite short

– SEY gives low energy e-, which drift back to beam: Δt_2 is approx. 60 nsec

  - If bunches are spaced at approx. 30 nsec, then every second bunch could resonantly enhance the EC produced

B. Enlargement of Lead Bunch in Trains

- Experimental Goals
  - Explore Conditions when **Vertical Size** of the lead bunch is increased – Three sets of experiments:
    1. Vary spacing between Bunches
    2. Bunch Trailing the train
    3. Precursor bunch in front of the train
    4. Different train Lengths at fixed train Current

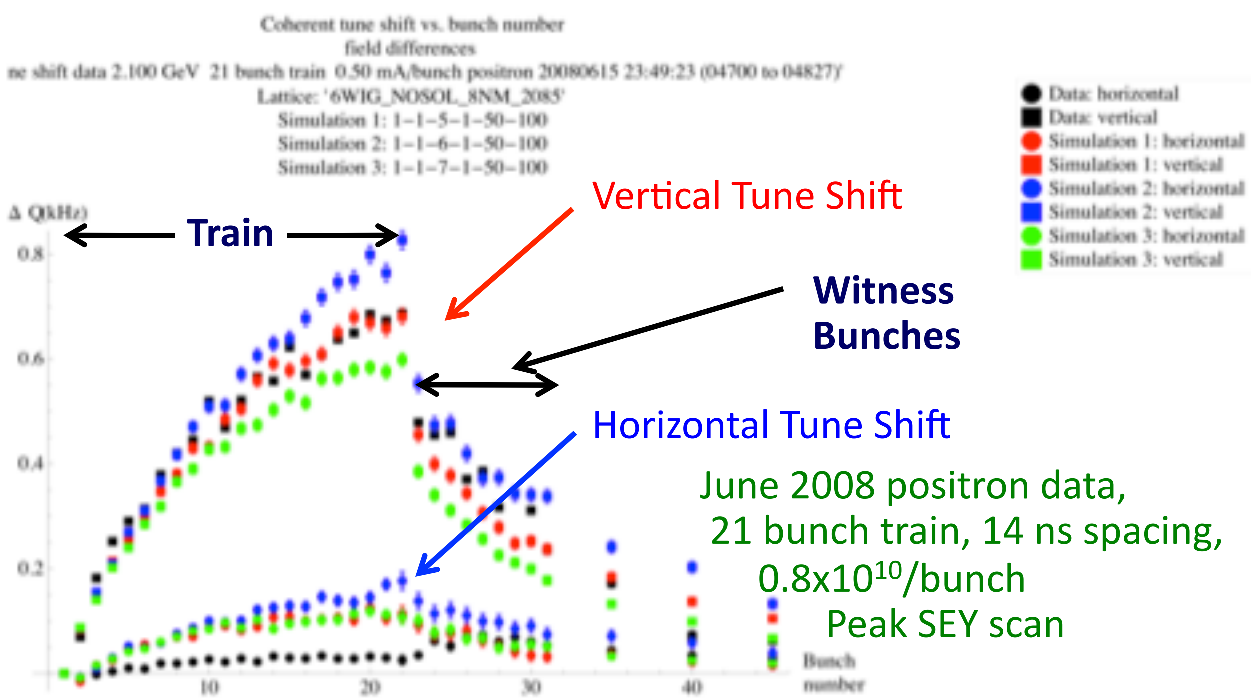
Recap of Early Observations

- CESR Conditions
  - 2.1 GeV
  - Trains containing 30 or 45 bunches
  - 3.6×10^{11} positrons or electrons in the train
  - Bunch-spacings: 4 or 14 ns

Earlier Observations

– EC in positron trains causes

- Growth of coherent oscillations along the train
- Enlargement of vertical beam size in later bunches in trains
- Tune shift from the EC grows in magnitude along the train and then falls ~200 ns after the end of the train
- Tune shift indicates EC similarly grows and then dissipates as the train passed
- EC buildup in Al vacuum chamber in dipoles
  – agrees with POSINST simulations



- Observations
  - Surprising Phenomenon
    - Observed for positrons and **not** for electrons
    - For the **First Bunch & possibly the Second Bunch in the Train**: Enlargement of its vertical beam size and presence of the (m=-1) coherent head-tail mode.
    - 2 μs gap between the last bunch in the train & first bunch
      - Unlikely dipoles or drifts are trapping the EC for 2 μs in CESR.
      - RFA measurements and POSINST simulations hint at 2 possibilities: Trapped EC in quadrupole and wiggler magnets
    - A "precursor" bunch of same charge as other bunches within train and placed 162 ns before train will completely counteract vertical blowup of first bunch(es).

Earlier Observations

- Observations
  - **Summarizing:** These observations caused us to consider the source of the first bunch blowup for Positrons and NOT Electrons
    - Long-lived EC effect
    - Rather than effects such as
      - Impedance/wake-fields
      - Beam loading
      - Malfunction of the bunch-by-bunch beam-stabilizing feedback systems

Beam Configuration for **Present** Observations

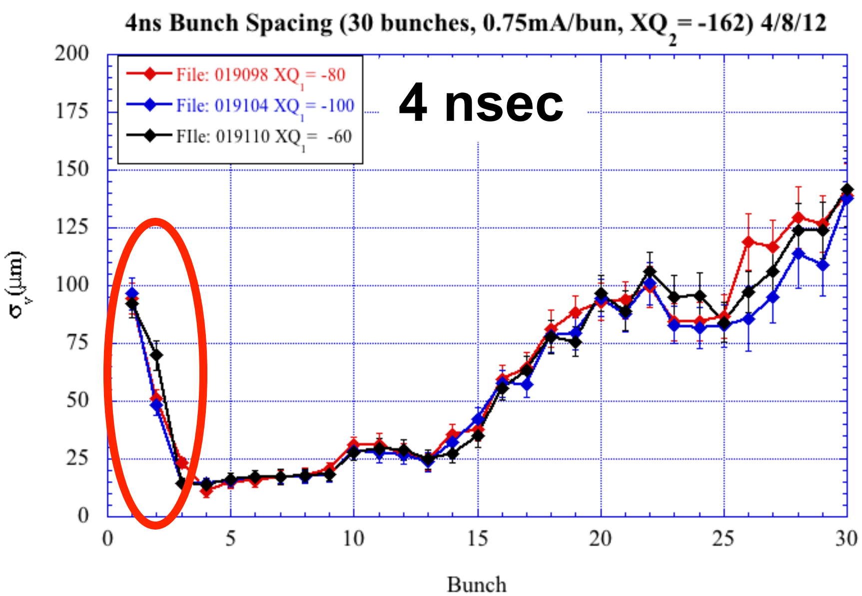
- Typical CESR parameters
  - 2.1 GeV
  - 30 bunches each of 1.2×10^{10} particles
  - Vary following parameters
    - V chromaticity
    - Spacing between bunches

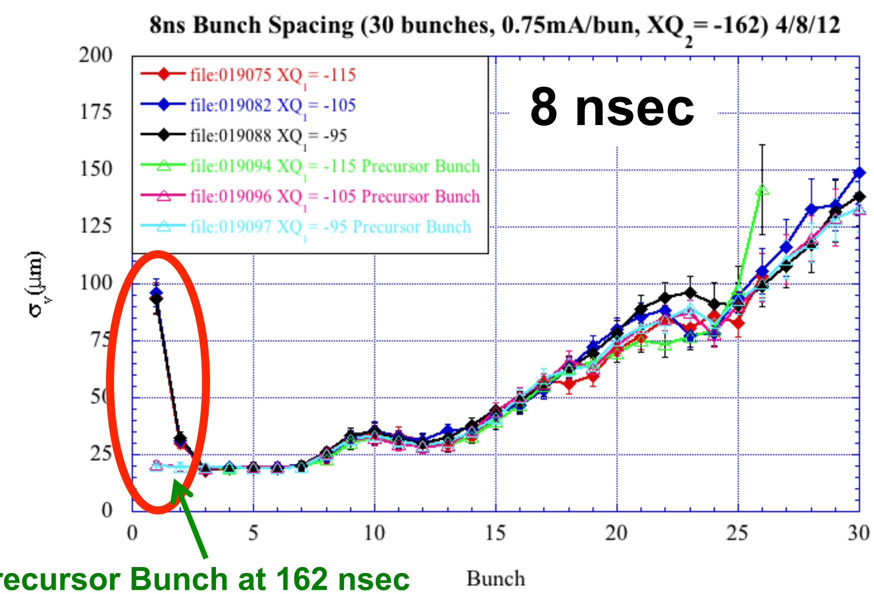
Measurement Plans

- For these experiments
  - Focus on σ_v of first bunch
  - Performed different sets of measurements:
    1. Different spacing of bunches
       - 4, 8, 12, 14, 16, 20, 24, 28, 36, 42 and 56 nsec
    2. Add **precursor** or **trailing** bunch: only took BPM spectra for the first 5 bunches in the train & added bunch
       - 4 nsec-spaced bunches
       - 8 nsec-spaced bunches
       - 12 nsec-spaced bunches
    3. Increased the number of bunches within the train, while holding the total beam current constant.

Observations 1

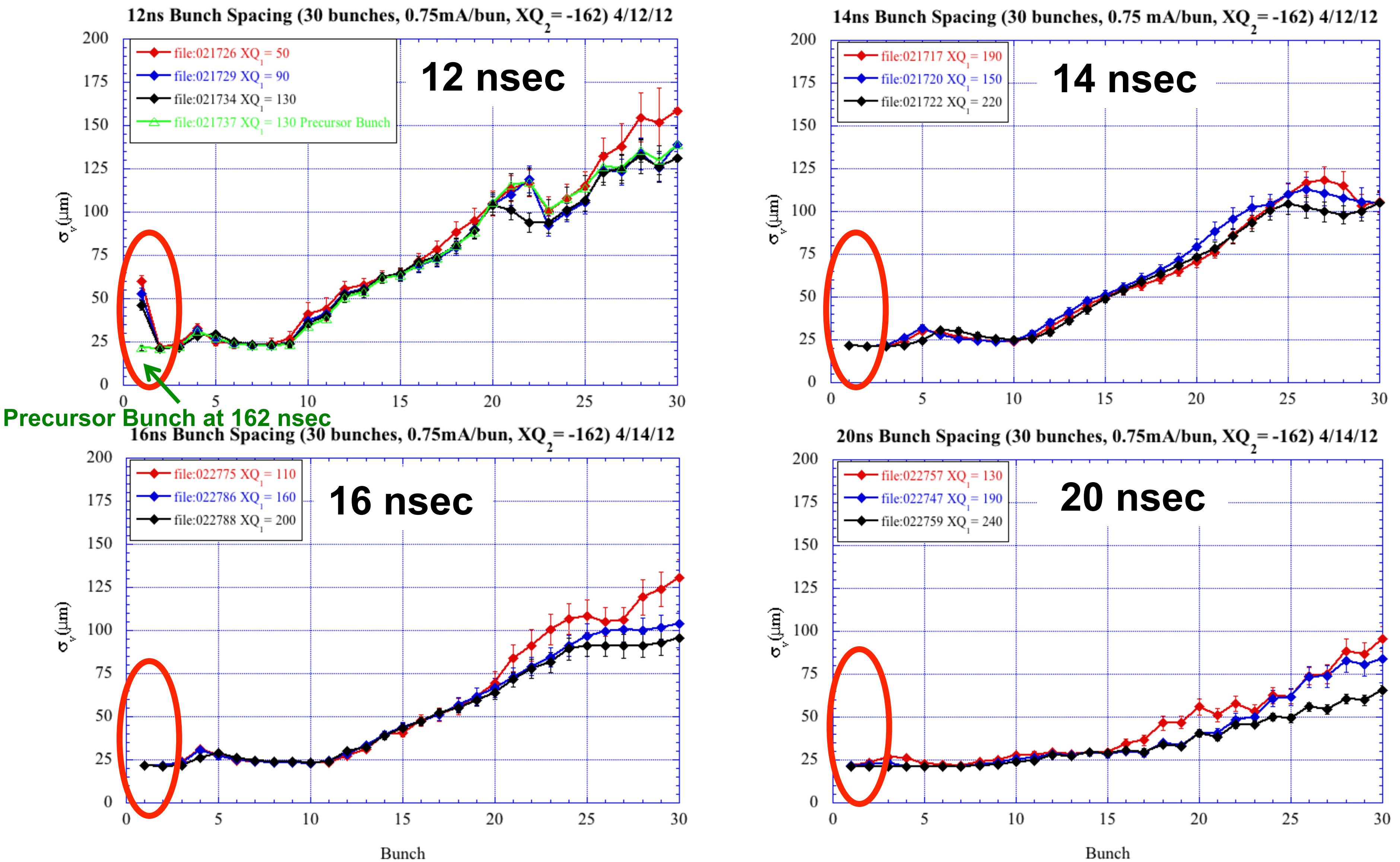
- ***Vary Spacing Between Bunches in the Train***
  - Spacing between bunches: 4, 8, 12, 14, 16, 20, 24 & 28 ns — Vertical Chromaticity: Low / Medium / High
  - Bunch in train: 1.2×10^{10}
  - General Conclusions
    - Enlargement of σ_V of first bunch only occurs for spacings of 4, 8, 12 and under some circumstance 14 ns.





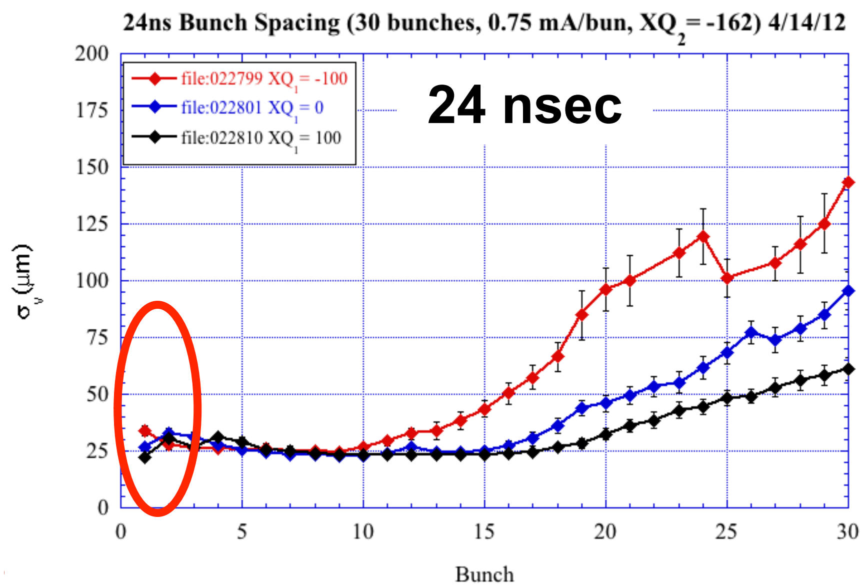
Observations 1

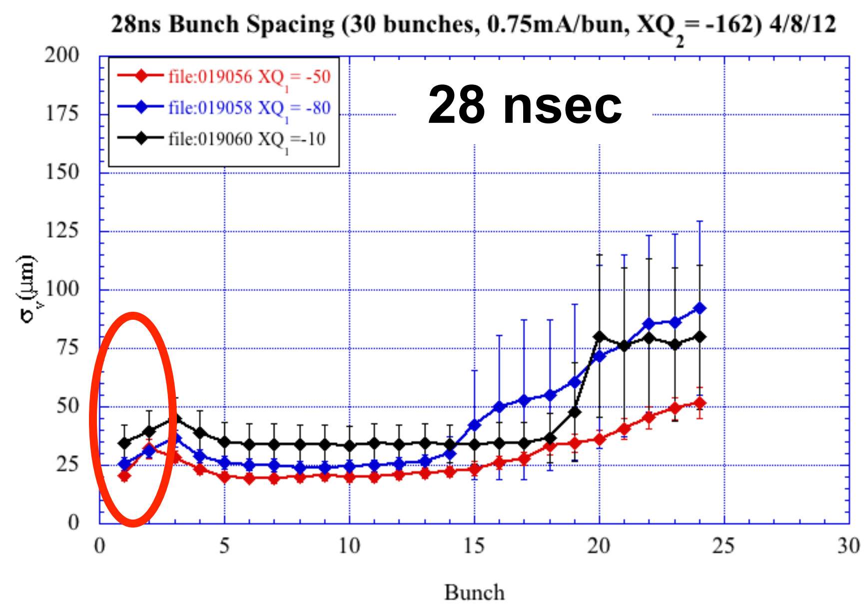
- ***Vary Spacing Between Bunches in the Train***



Observations 1

- ***Vary Spacing Between Bunches in the Train***





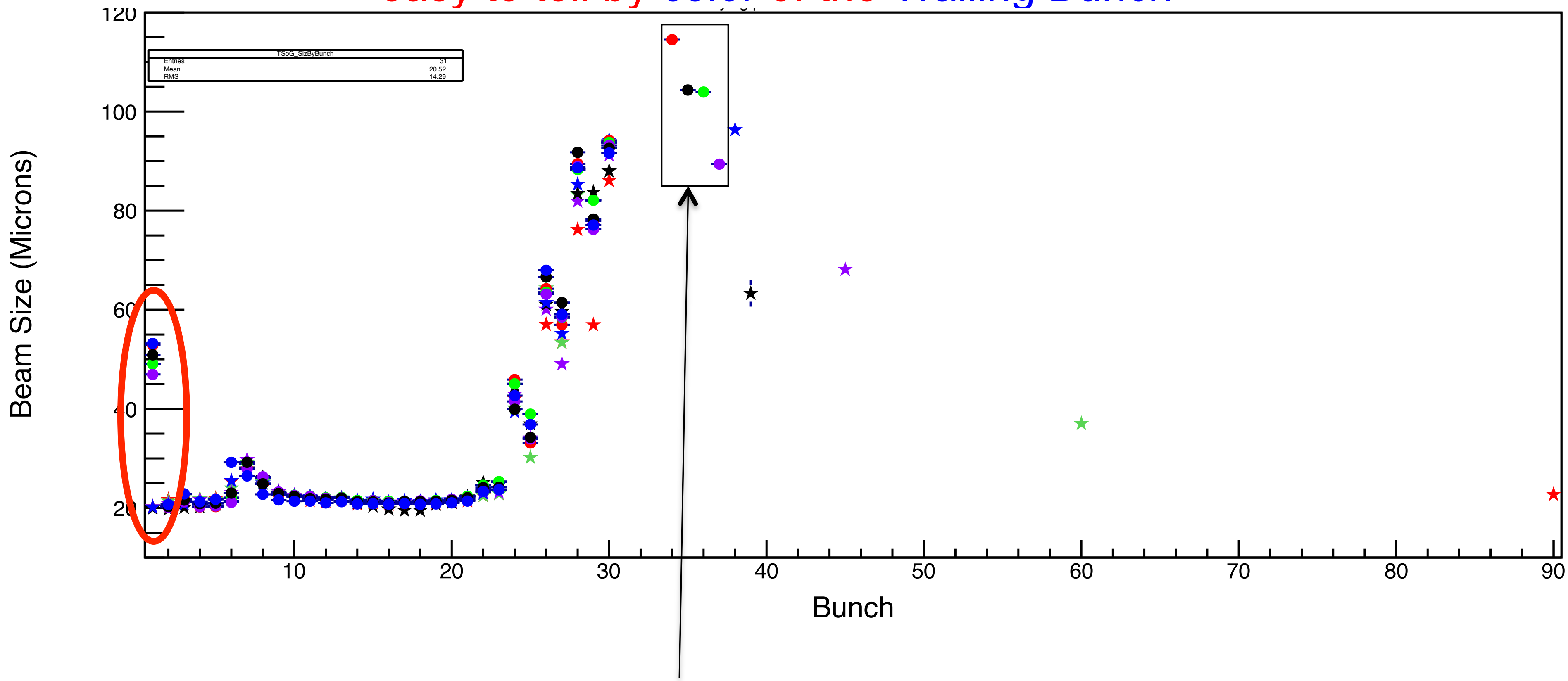
(All above plots are shown for three different value of Vertical Chromaticity)

- ***Studies with Trailing Bunches***
  - 30 bunch-long, 4 ns-spacing of bunches ($1.2\text{x}10^{10}$)
  - Add single trailing bunch delayed from end of train

Delay from End of Train (in nsec)	Number of Particles in Added Bunch	Relative Magnitude of σ_V for First Bunch	Relative Amplitude of Fv-Fs HT Mode for First Bunch	Relative Magnitude of σ_V for Added Bunch
16-28 nsec	$1.2\text{x}10^{10}$	Large	Large	Large
36-240 nsec	$1.2\text{x}10^{10}$	Not Enlarged	Not Enlarged	Less Large to Not Enlarged
Approx. 32 nsec	$1.2\text{x}10^{10}$	Sometimes Large	Sometimes Large	Large
24 nsec	Between $1.6\text{x}10^{10}$ and $2.4\text{x}10^{10}$	Becomes Not Enlarged	Becomes Not Enlarged	Large
40 nsec	Between $8.0\text{x}10^{9}$ and $4.0\text{x}10^{9}$	Becomes Large	Becomes Large	Large

- ***Studies with Trailing Bunches***
  - 4 ns-spaced bunches in train

σ_V for each condition is plotted below with different color – easy to tell by color of the Trailing Bunch

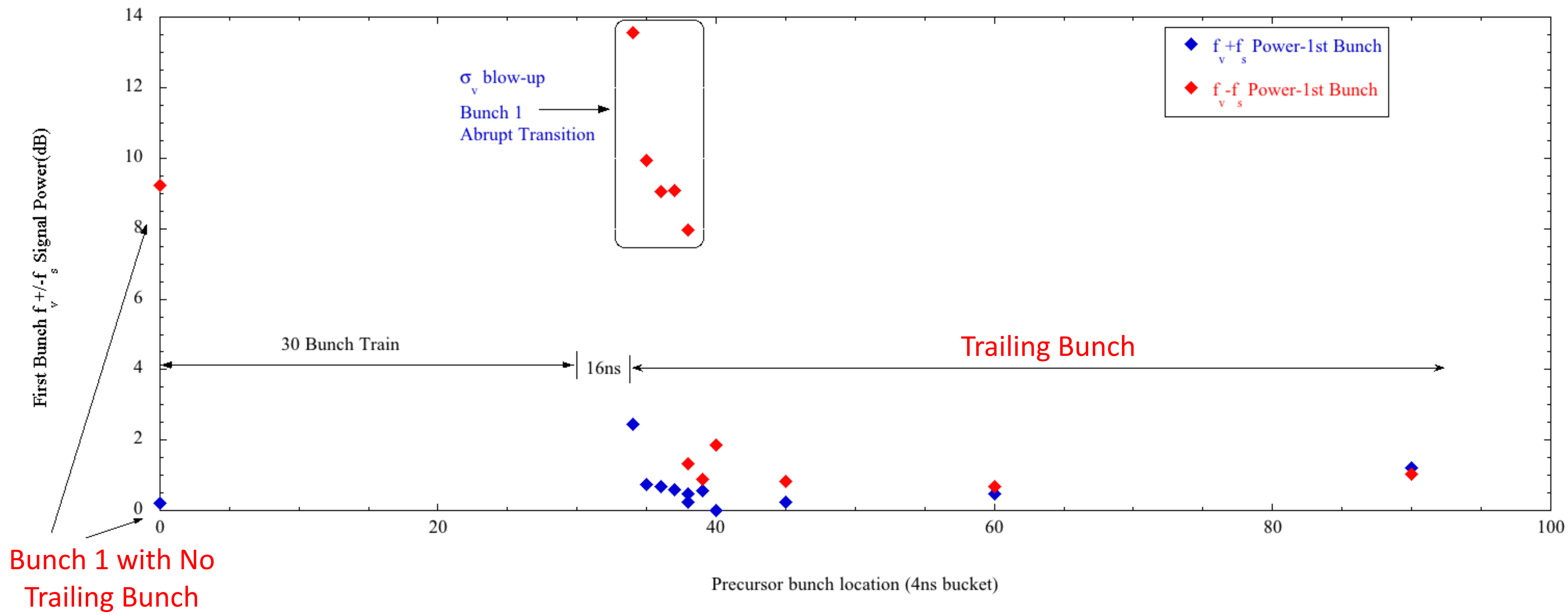


- When Trailing Bunch is 16-28ns behind 30 bunch train, bunch 1 vertical beam size blows-up (dots).

- ***Studies with Trailing Bunches***
  - 4 ns-spaced bunches in train

Relative Amplitudes of Head-Tail Modes (Fv – Fs) & (Fv + Fs) for **First Bunch** in Train,

Plotted at the Location of the Trailing Bunch



First Bunch has Fv-Fs Head-Tail Coherent Oscillations, which decrease as the delay of Trailing Bunch increases

This correlates with enlargement of σ_V for First Bunch

Observations 2

- ***Studies with Precursor Bunch***
  - 8 ns- or 12 ns-spaced bunches ($1.2x10^{10}$)
  - Add single trailing bunch of $1.2x10^{10}$.
  - Trailing bunch: transition for affecting lead bunch is around 20-24 nsec

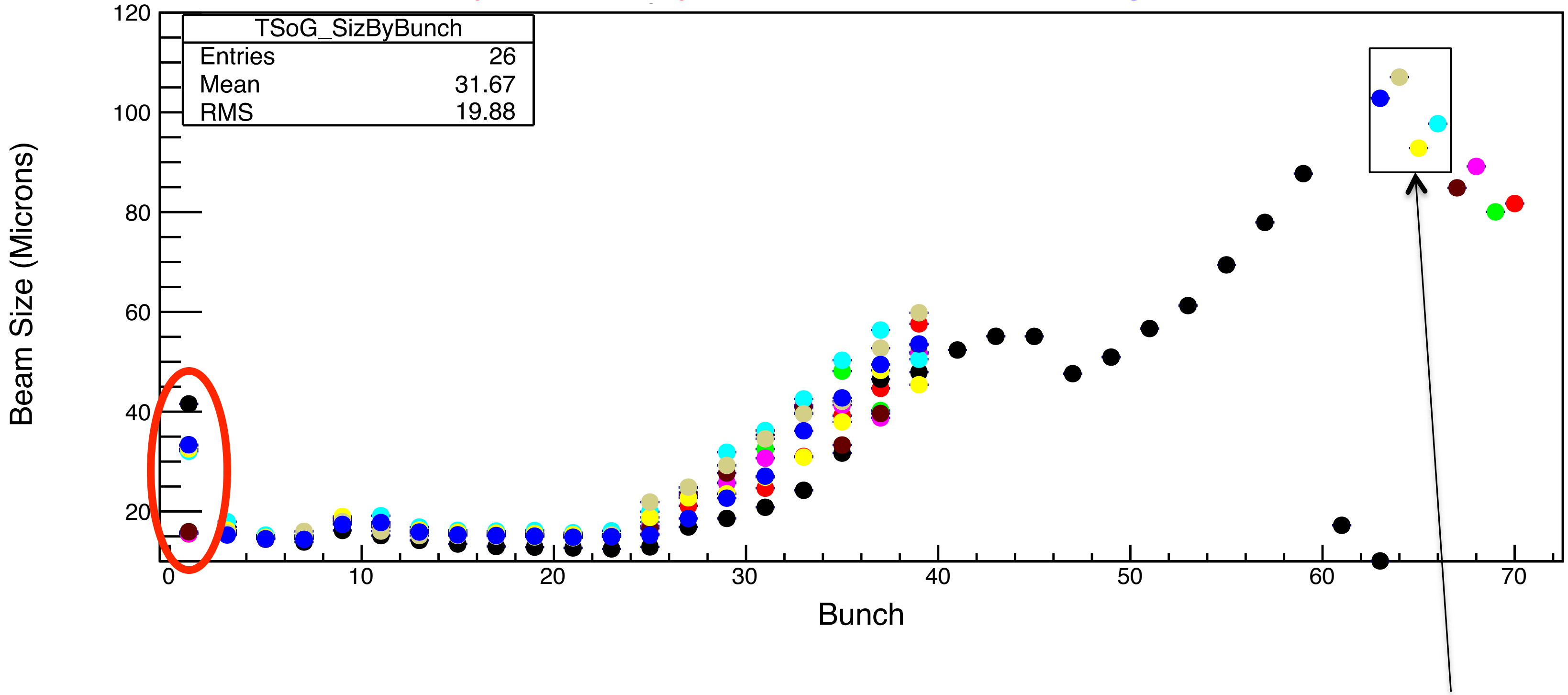
Delay from End of Train (in nsec)	Number of Particles in Added Bunch	Relative Magnitude of σ_V for First Bunch	Relative Amplitude of Fv-Fs HT Mode for First Bunch	Relative Magnitude of σ_V for Added Bunch
8 nsec Spaced Bunches				
12-20 nsec	$1.2x10^{10}$	Large	Less Large	Large
24-36 nsec	$1.2x10^{10}$	Not Enlarged	Not Enlarged	Less Large
12 nsec Spaced Bunches				
12-20 nsec	$1.2x10^{10}$	Less Large	Barely Enlarged	Large
24-28 nsec	$1.2x10^{10}$	Not Enlarged	Not Enlarged	Less Large

• *Studies with Trailing Bunches*

– 8 ns-spaced bunches in train

σ_V for each condition is plotted below with different color

– easy to tell by color of the Trailing Bunch



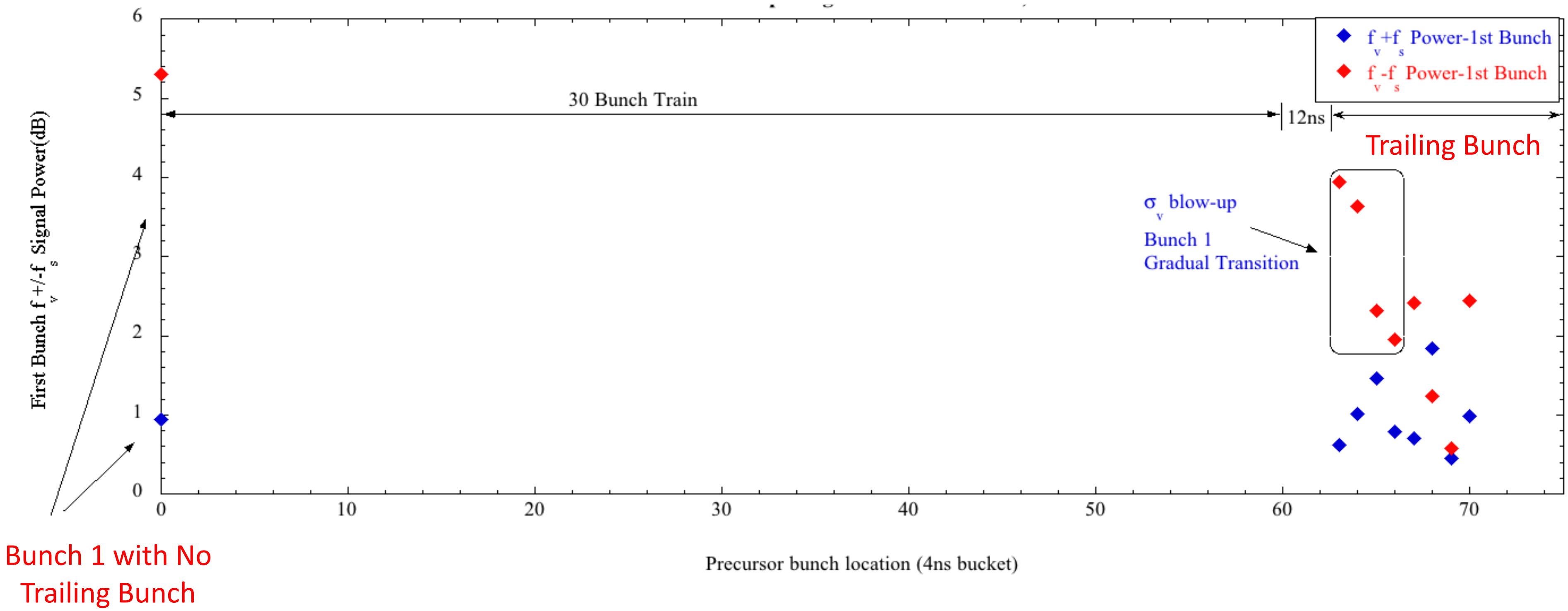
- Vertical beam size blow up for bunch 1 occurs when Trailing Bunch is 12-24ns behind 30 bunch train.
- Bunch 1 vertical beam size decreases as the Trailing Bunch is placed further away from the 30 bunch train. A dramatic transition is made between 24-28ns behind the train.

Observations of Amplitude of Head-Tail Modes

- ***Studies with Trailing Bunches***
  - 8 ns-spaced bunches in train

Relative Amplitudes of Head-Tail Modes (Fv – Fs) & (Fv + Fs) for **First Bunch** in Train,

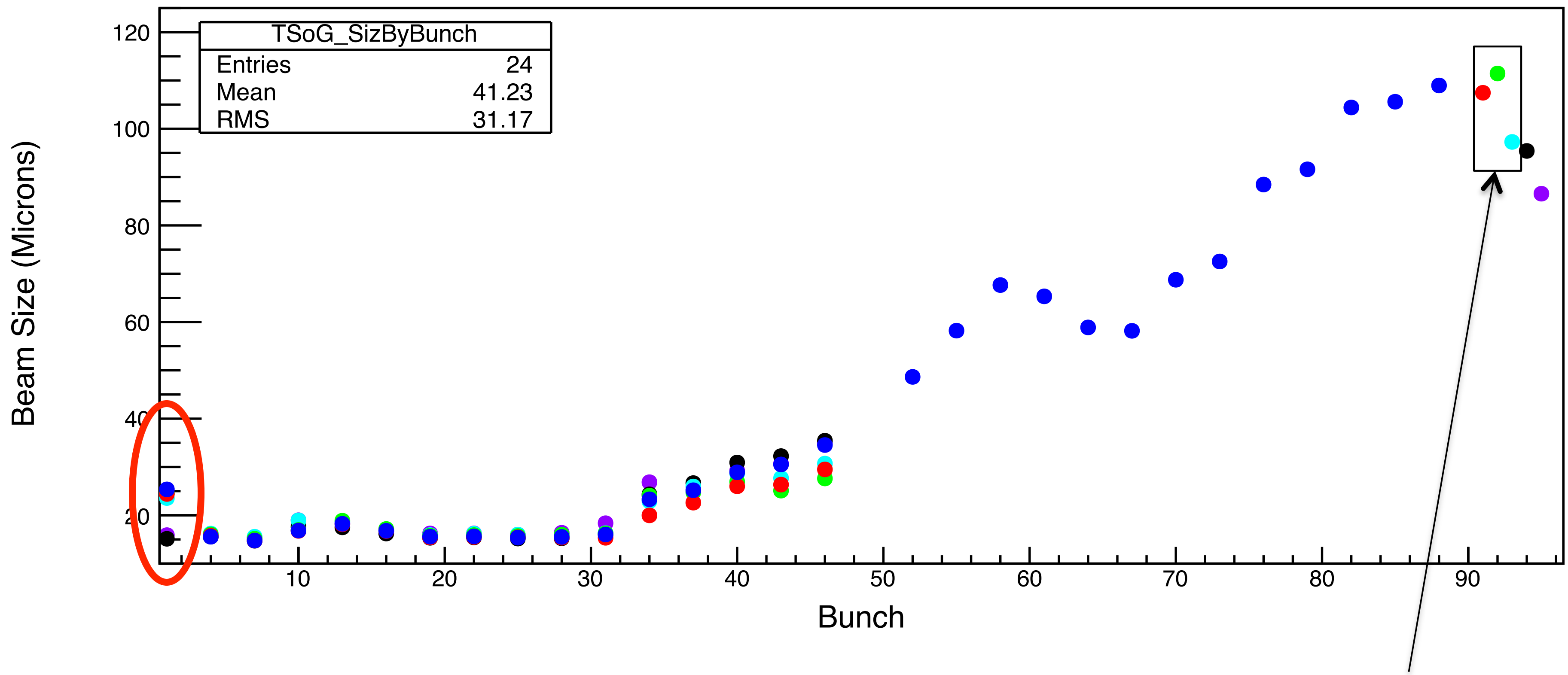
Plotted at the Location of the Trailing Bunch



First Bunch has a **Weak** Fv-Fs Head-Tail Coherent Oscillations, which approximately decrease as the delay of Trailing Bunch increases

- ***Studies with Trailing Bunches***
  - 12 ns-spaced bunches in train

σ_V for each condition is plotted below with different color – easy to tell by color of the Trailing Bunch



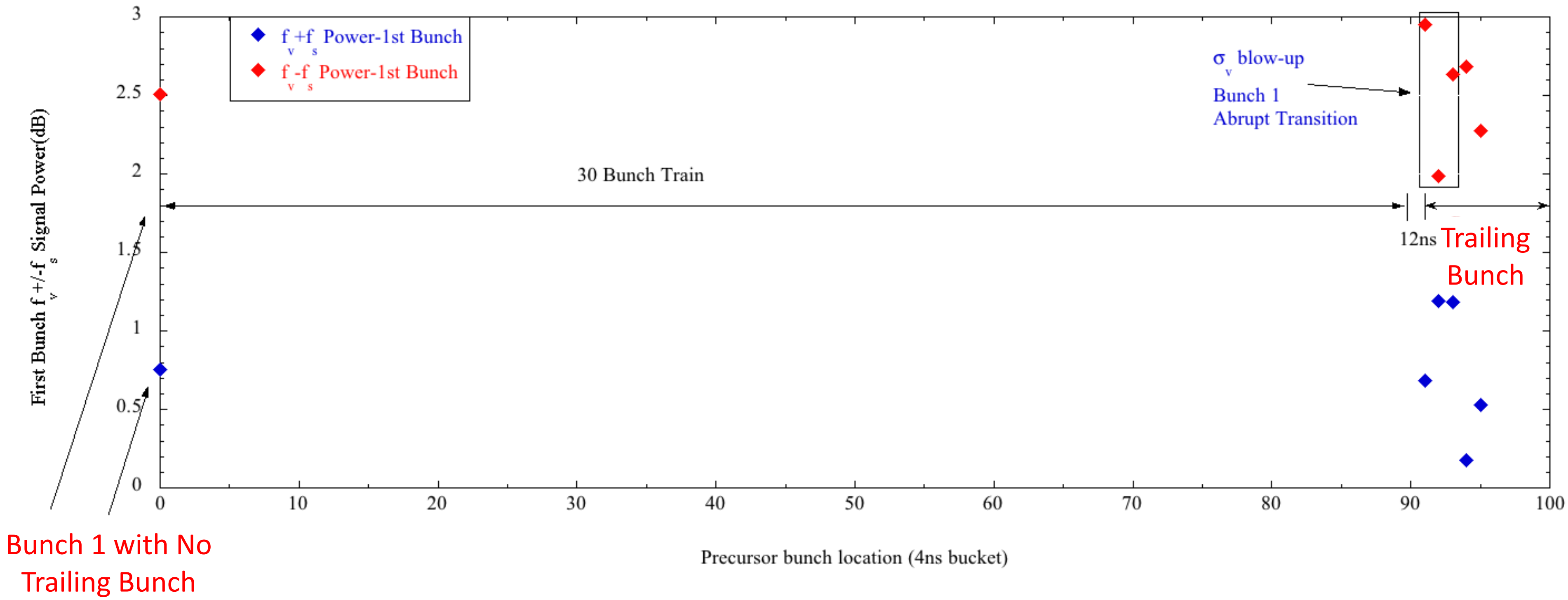
- Vertical beam size blow up for bunch 1 occurs when precursor is is between 12-20ns behind 30 bunch train.

Observations of Amplitude of Head-Tail Modes

- ***Studies with Trailing Bunches***
  - 12 ns-spaced bunches in train

Relative Amplitudes of Head-Tail Modes (Fv – Fs) & (Fv + Fs) for **First Bunch** in Train,

Plotted at the Location of the Trailing Bunch



First Bunch has a **Quite Weak** Fv-Fs Head-Tail Coherent Oscillations, which approximately decrease as the delay of Trailing Bunch increases

Observations 3

- ***Precursor Bunch Studies***
  - 4 ns-spaced bunches in train
  - Add single Precursor bunch at one of three intensities: 4.0×10^{9}, 8.0×10^{9} and 1.2×10^{10}
  - Precursor bunch: precedes the train
    - Train begins at 4 ns bucket number 41 and continues through 70
    - Precursor is placed in buckets from 1 to 40; the values for σ_V are overlaid in different colors depending on the location of the precursor bunch

Conclusions from Observations 3

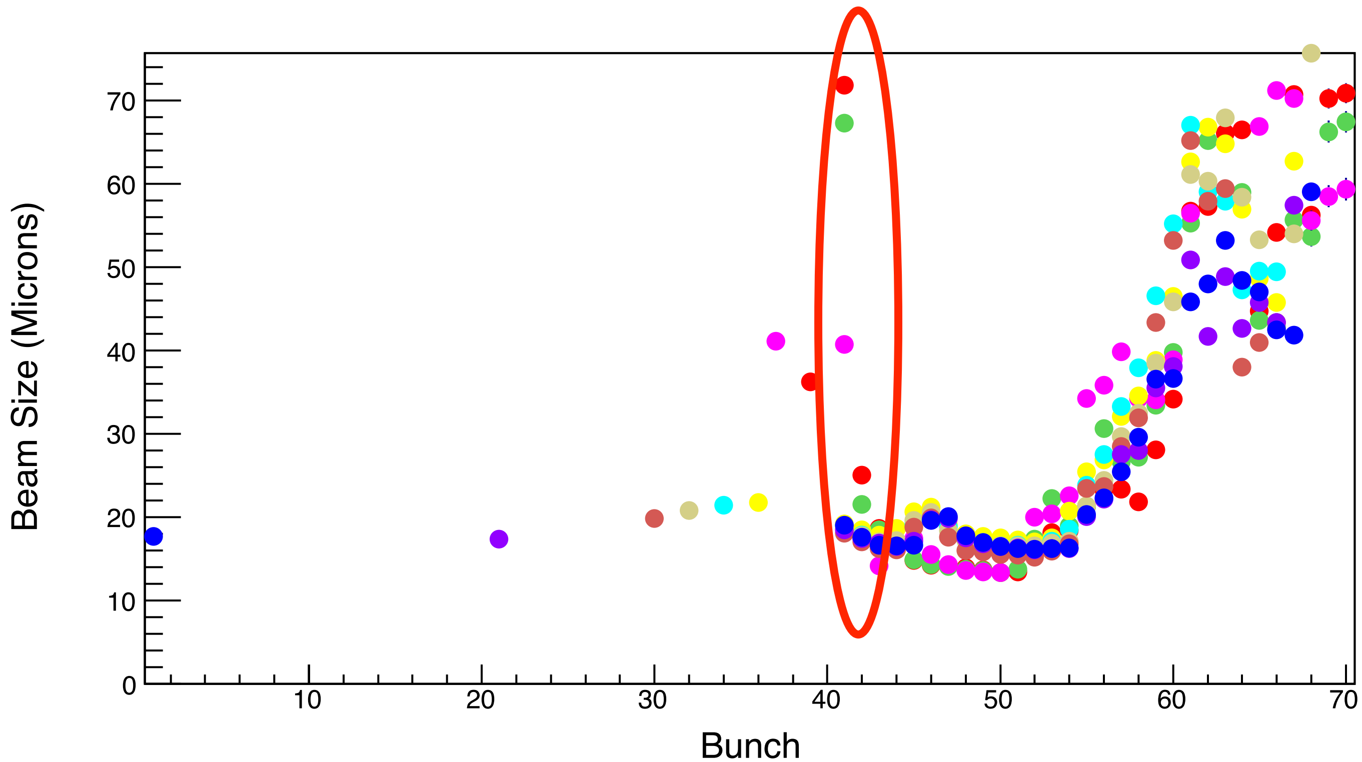
- ***Precursor Bunch Studies***
  - 4 ns-spaced bunches in train
  - Precursor bunch: precedes the train
    - Results for σ_V for 8.0×10^9 & 1.2×10^{10} yielded essentially the same results
    - Precursor bunches ≥ 8.0×10^9 & placed in any preceding 4 ns bucket always reduces blow up of σ_V for first bunch.
    - However, Precursor bunches = 4.0×10^9 particles as moved earlier in 4 ns steps from the front of train, σ_V of **first bunch** is **reduced in magnitude** monotonically over first 16 ns.
    - Enlargement of precursor bunch is reduced as it moves further ahead of train!!

    - ➔ Difficult to argue that the effect we observe is caused by a remnant EC, which enlarges σ_V of the first bunch that passes through it while the EC is dispersed by this bunch's passage.

Observations 3

- ***Studies with Precursor Bunch***
  - 4 ns-spaced bunches in train
  - Add Precursor bunch: 4.0×10^9

σ_V for each condition is plotted below with different color – easy to tell by color of the Trailing Bunch



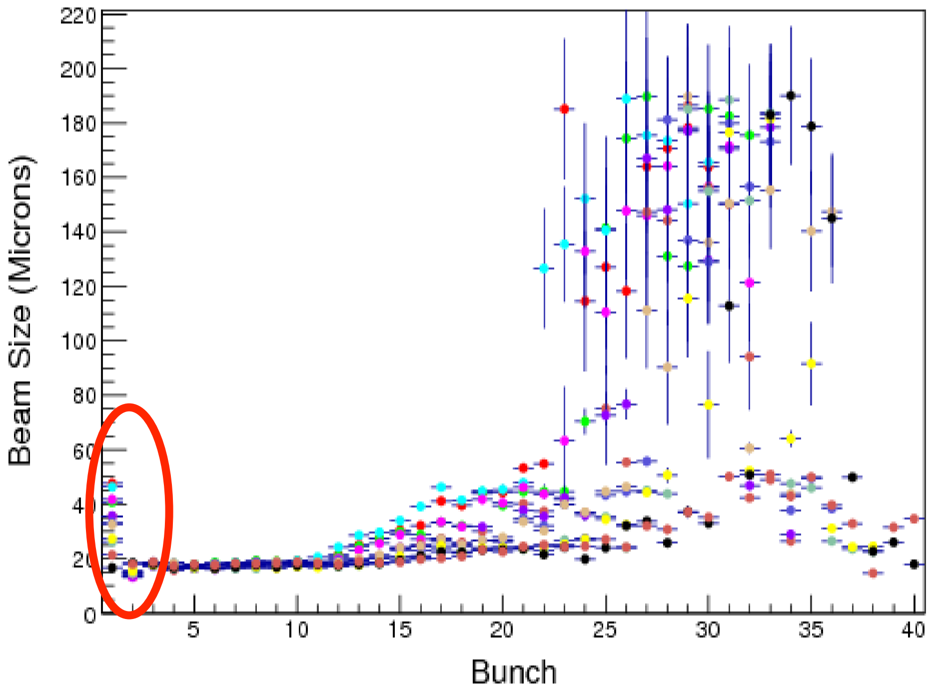
Observations 4

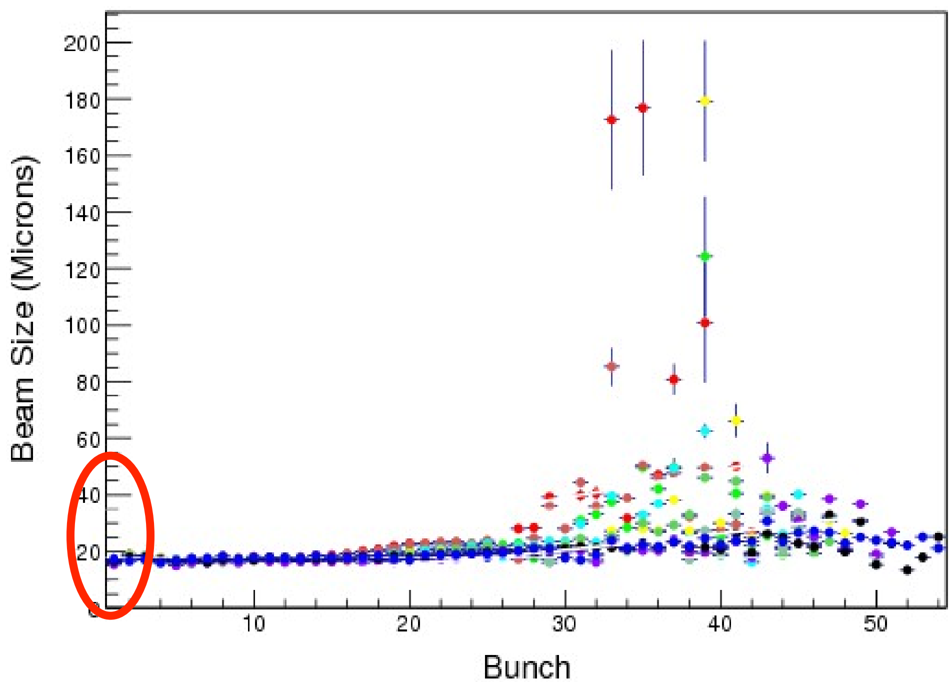
- ***Vary Number of Bunches Within the Train***
  - Total number of particles in the train constant at 30 x (1.2×10^{10})
  - Vary number of 4 ns-spaced bunches in the train between 30 and 60.
  - Results for σ_V: trains between 30 and 60 bunches
    - Large error bars are indicative of large dipole oscillations for those bunches
    - Enlargement of σ_V for the **first bunch decreases** monotonically & disappears for trains longer than 40 bunches.

Observations 4

- ***Vary Number of Bunches Within the Train***
  - Total Charge in the Train: 30 x (1.2x10^{10})

σ_V for each condition is plotted below with different color – easy to tell by color of the Trailing Bunch





Enlargement of first bunch decreases; it is gone for 40 bunch-long trains

Enlargement of later bunches in train decreases as train lengthens

Conclusions

- These experiments were expected to clarify the observations of the enlargement of the lead bunch in a 30 bunch e+ trains.
- Real effect since it is observed with 2 different instruments, BPM & xBSM
- Effect visible for e+ and not e-, it is not likely that this is an impedance/wake-field or beam-loading effect.
- Our measurements have mostly studied e+ trains, perhaps it may be visible with e- also, but in a difference range of parameters.
- Regardless of possible mechanisms, we must conclude that further observations of electron trains under a wider range of parameters should be part of future experimental studies.
- As this is an un-anticpated effect, it may be important to understand its source.

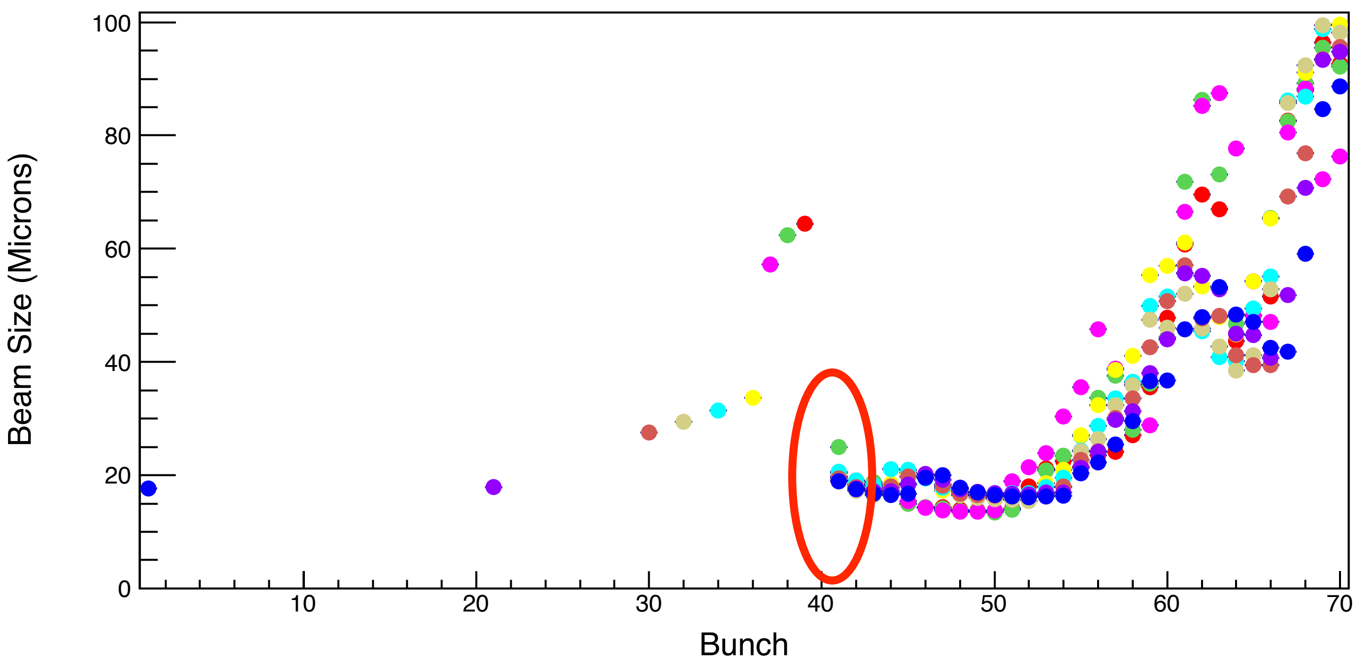
Backup Slides

- ***Additional Experimental Tests***
  - Tested other potential mechanisms, which might enlarge σ_V of first bunch in 30 bunch trains of $1.2x10^{10}$ positrons having 4 ns-spacing per bunch.
    - Turn on/off EC solenoids wound around beam pipes for most the drift length of CESR.
    - Change V & L 4 ns-feedback system gains including off
    - Raise H 4 ns-feedback system gain, but never was off
    - Disconnect 14 ns modulators from amp for the feedback system's stripline kickers
    - Disconnect & terminate drive cable to stripline kickers
    - Disconnect drive to shaker used for F_h/F_v measurements
    - Vary V chromaticity
    - In all cases: No effect on σ_V of first bunch in train

Observations

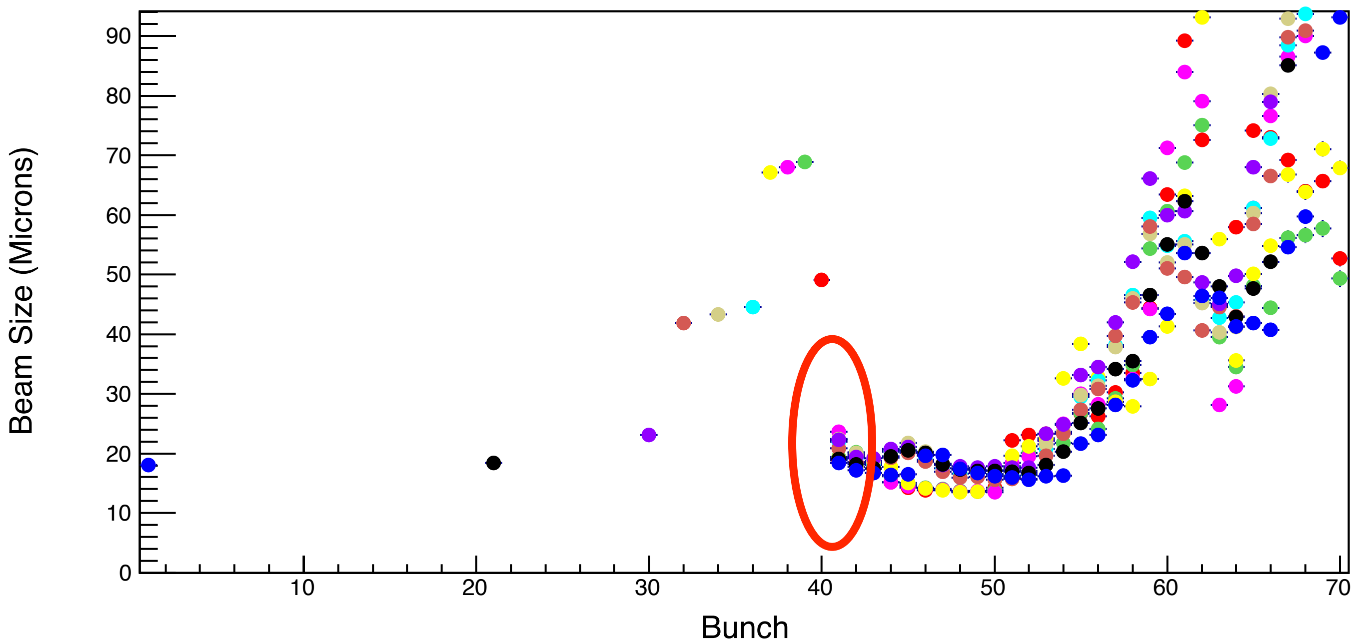
- ***Studies with Precursor Bunch***
  - 4 ns-spaced bunches in train
  - Add Precursor bunch: 8.0×10^9

σ_V for each condition is plotted below with different color – easy to tell by color of the Trailing Bunch



- ***Studies with Precursor Bunch***
  - 4 ns-spaced bunches in train
  - Add Precursor bunch: 1.2×10^{10}

σ_V for each condition is plotted below with different color – easy to tell by color of the Trailing Bunch

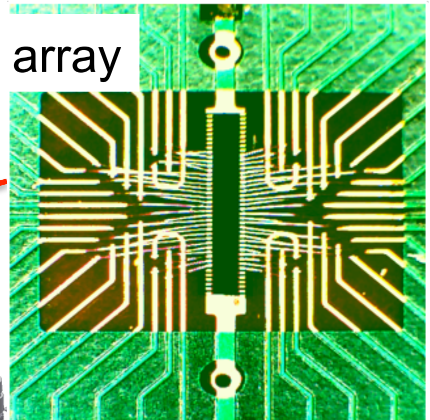


- Instrumentation at CESRTA
  - Position spectrum of individual bunches within train
    - Single button of a BPM
    - Gate the signal to accept only 1 bunch
    - Send to a spectrum analyzer & gives
      - H & V dipole (m=0) betatron modes at frequencies F_h and F_v
      - V head-tail (HT) (m=±1) lines at $F_v \pm F_s$ (F_s is the synchrotron tune)
      - H HT modes (m=±1) lines at $F_h \pm F_s$
  - X-ray beam size monitors (xBSMs) for e+/e- beams
    - Linear, Vert 32 pixel arrays bunch-by-bunch & turn-by-turn
    - Removes dipole motion before the fitting the vertical beam size σ_V of each bunch.

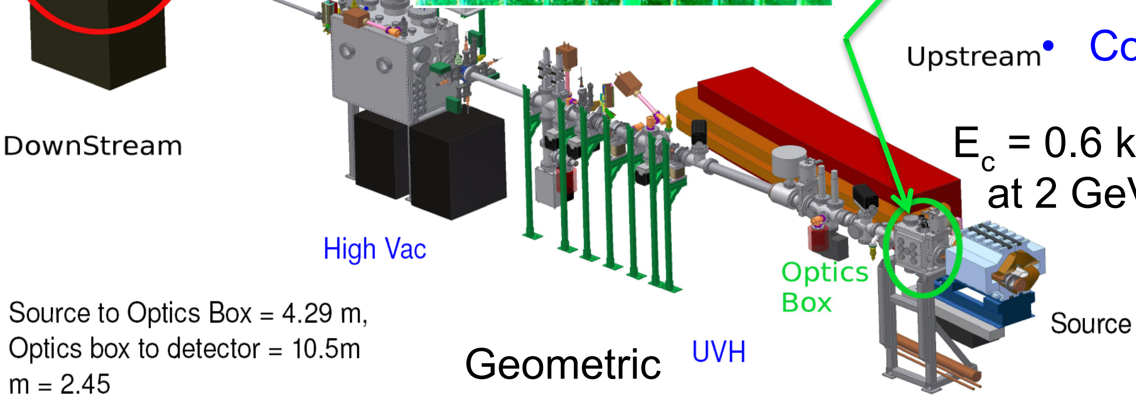
X-ray Vertical Beam Size Monitor

xBSM diode array

50 μm pitch



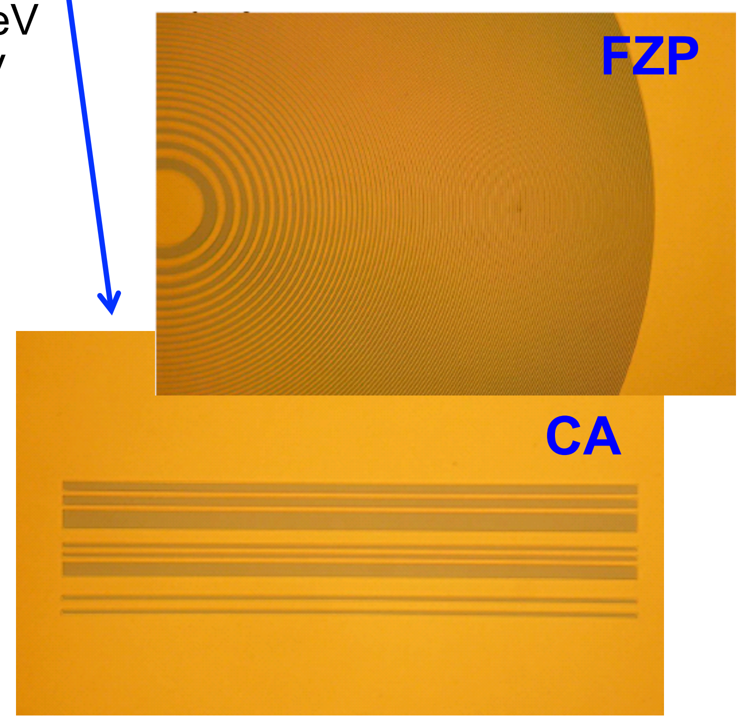
- X-ray Beam Size Monitor (xBSM)
  - Images X-rays from bending magnet
  - Uses 1D 32-chan vertical diode array
  - Has 3 choices for Optics Element
    - Adjustable Slit ("Pinhole" optics)
    - Fresnel Zone Plate (FZP)
    - Coded Aperture (CA)



E_c = 0.6 keV at 2 GeV

Source to Optics Box = 4.29 m,
Optics box to detector = 10.5m
m = 2.45

Geometric Magnification ~2.5

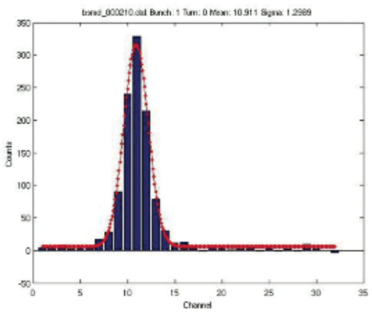


- Functions
  - Capable of measuring TBT bunch size for ≥ 4ns-spaced bunches
  - 40 dB gain adjustment
  - Primary tool for confirming vertical emittance corrections

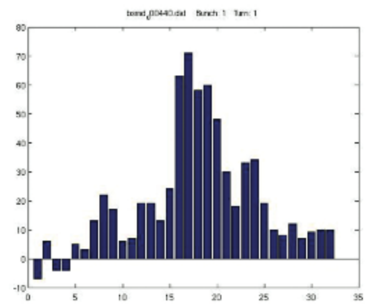
xBSM Measurements

- Observe signal with single bunches with different x-ray optics

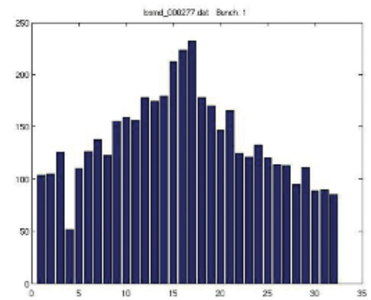
Slit



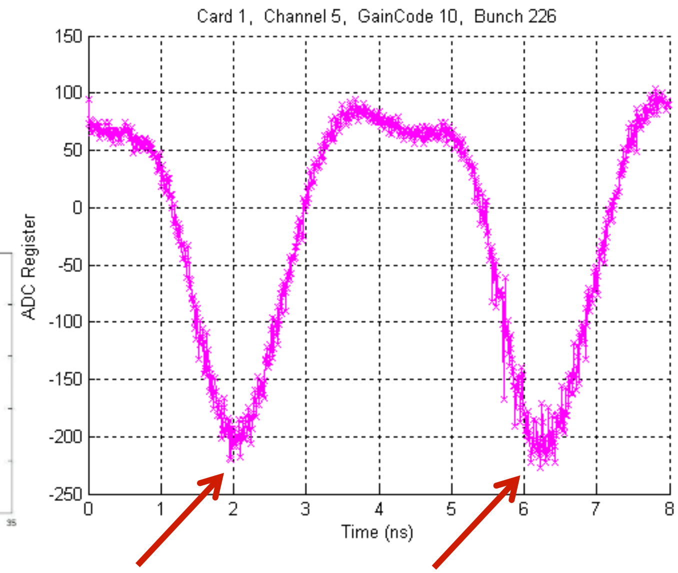
Coded Aperture



Fresnel ZP



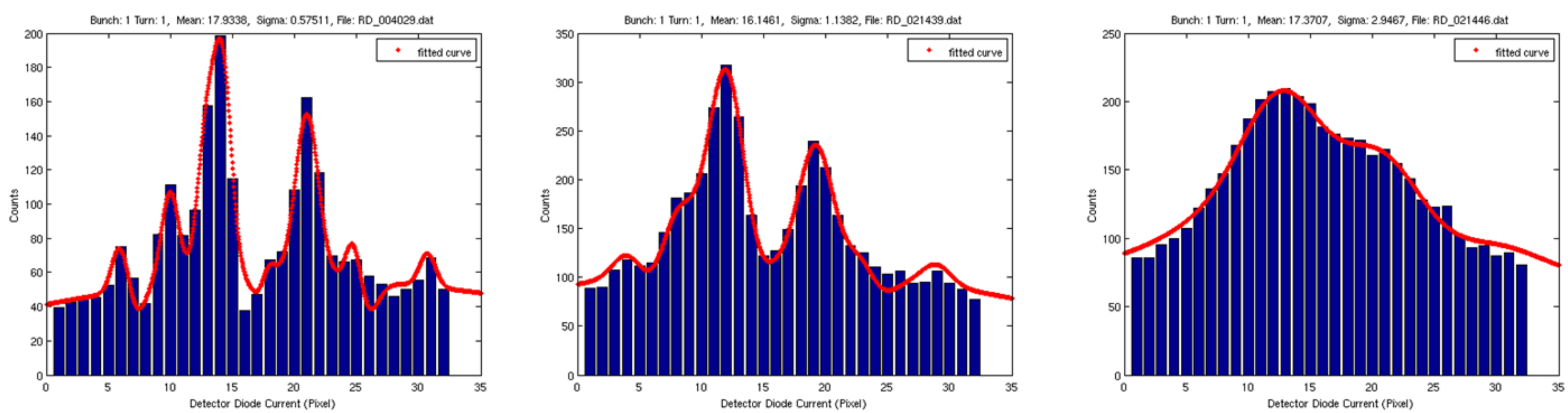
Single Pass-Single Bunch Distributions with Fitting Function



Sample Point Bunch 1

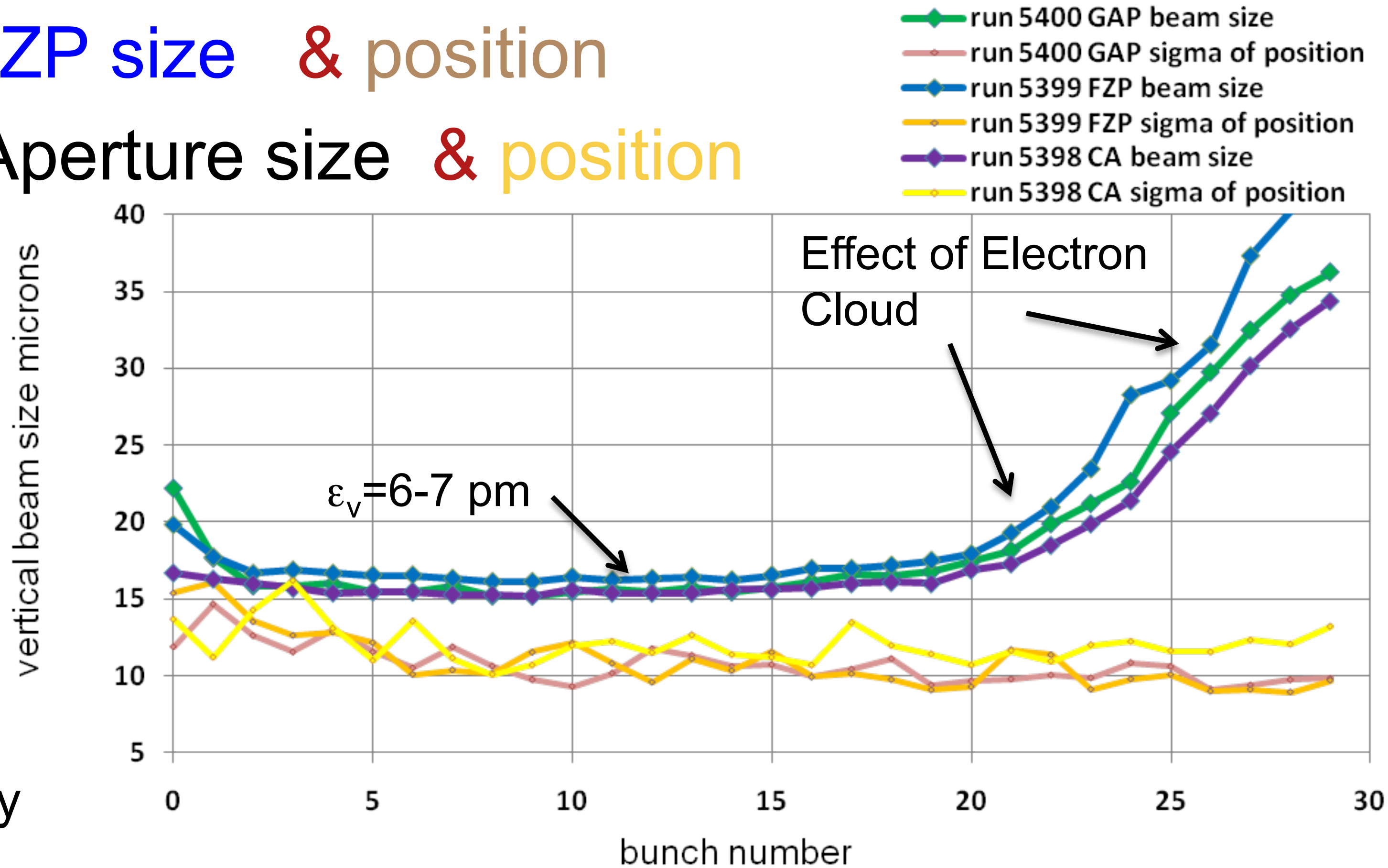
Sample Point Bunch 2

Coded Aperture Fits for Different Beam Sizes



xBSM Measurements

- Systematic studies of multi-bunch performance with different x-ray optics (30 bunch train)
  - Slit (Gap) size & position
  - Fresnel ZP size & position
  - Coded Aperture size & position



Data for each optic taken simultaneously