# Low emittance instrumentation at CESR-TA

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# Outline

- Description of CESR and CesrTA program
- X-ray beam size monitor (xBSM)
  - Vertical beam size measurement
  - Turn-by-turn bunch-by-bunch
- Visible-light beam size monitor (vBSM)
  - Horizontal and vertical beam size measurements
  - Average over many turns
- CESR beam position monitor (CBPM)
  - Turn-by-turn bunch-by-bunch
  - Low emittance tuning and diagnostics
- Conclusion

# Cornell Electron-positron Storage Ring

## CESR-TA program

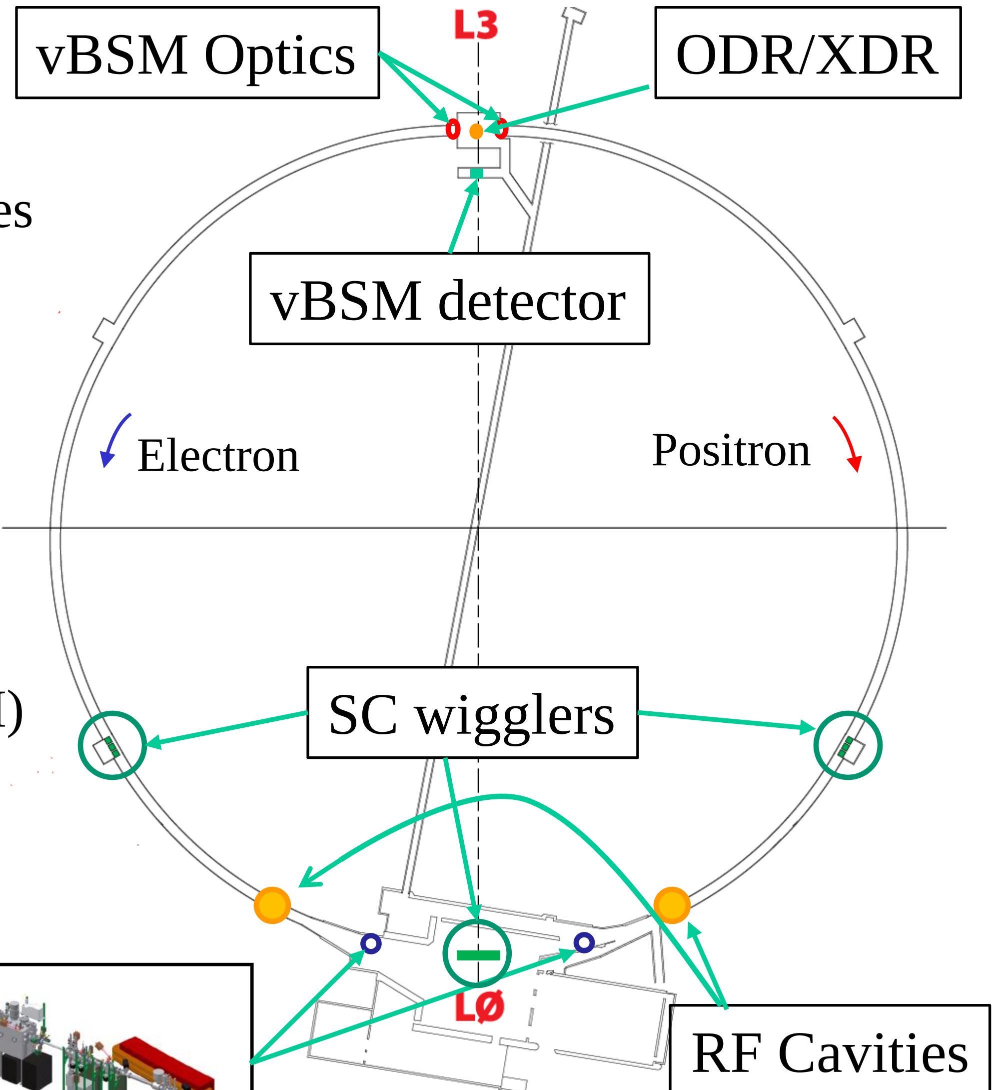
- 768 m ring
- Twelve 1.9 T damping wigglers
- 100 Independently powered quadrupoles
- 1.8 to 5.3 GeV
- $\varepsilon_x$=3 nm rad, $\varepsilon_y$= ~10 pm rad

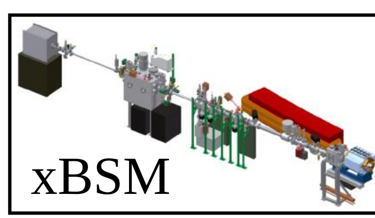
## Emittance measurement tools

- X-ray beam size monitor (xBSM)
  - Measure vertical beam size
  - Bunch-by-bunch turn-by-turn
- Visible-light beam size monitor (vBSM)
  - Measure horizontal beam size with interferometry

## Research program

- Electron cloud studies
- Fast ion instability
- Intrabeam scattering

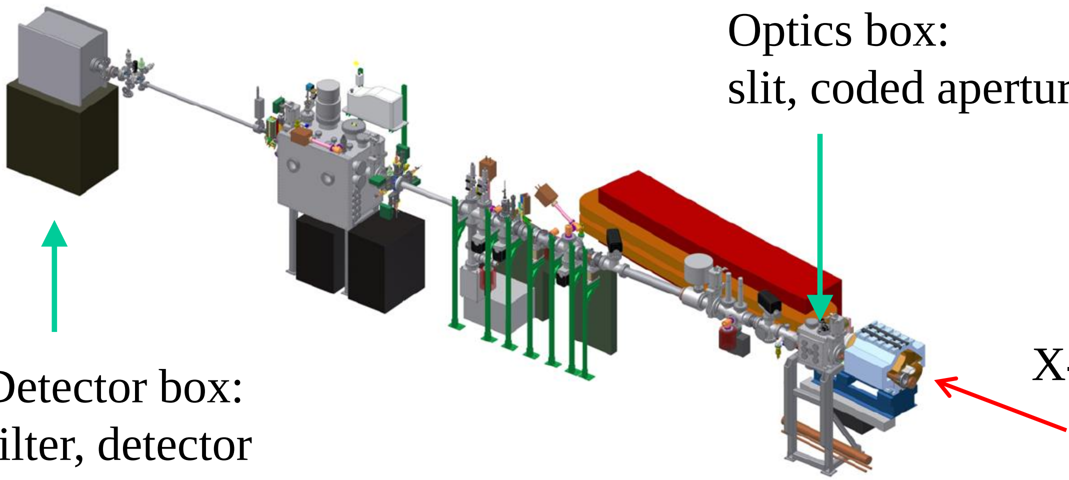


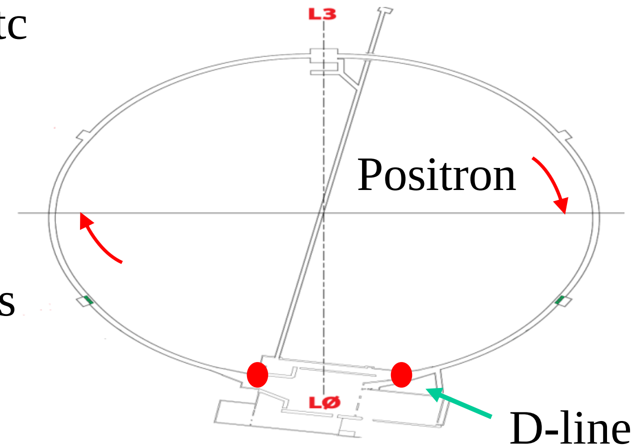
# xBSM layout

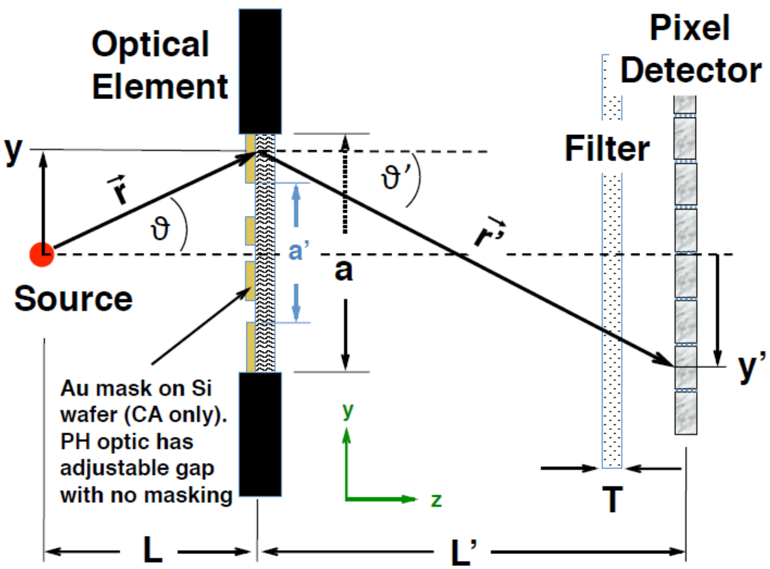
Optics box:
slit, coded aperture, etc

Detector box:
filter, detector



X-rays



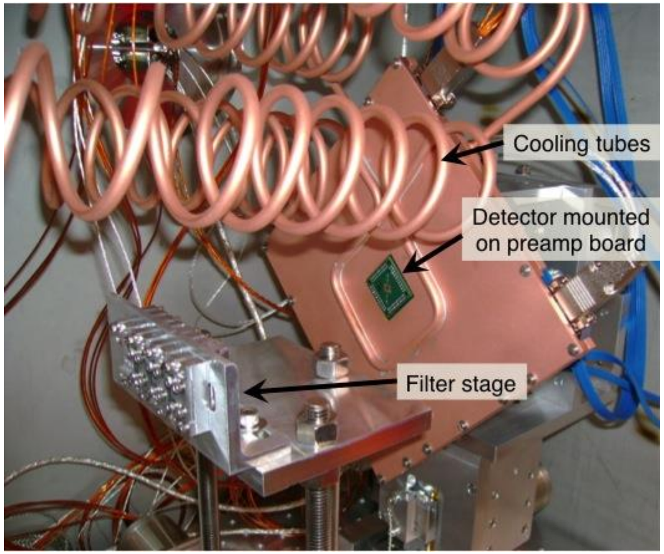




4.48 m    10.01 m

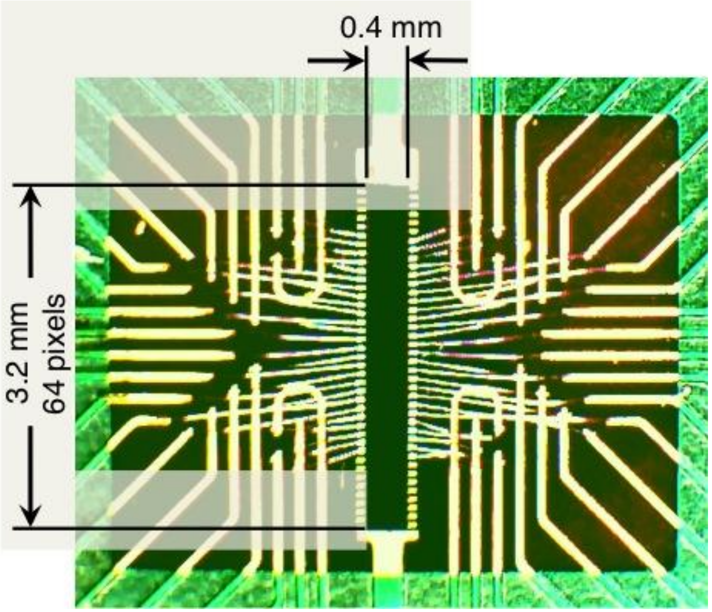
- Synchrotron radiation from a hard bend, $\varepsilon_c$=0.6 keV @ 2.1 GeV
- Windowless x-ray path
- Magnification ~ 2.23,
- Different optical elements
- Motorized stages
- Filters: Diamond, Molybdenum, Aluminum

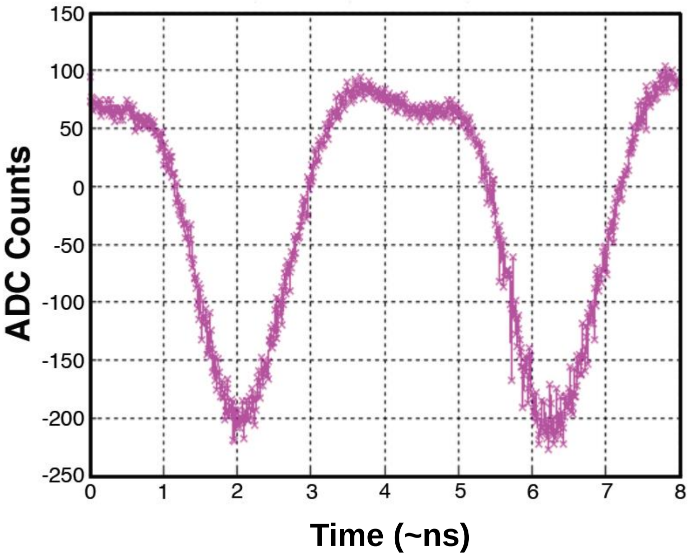
*J.P. Alexander, et al, NIMA 748 (2014) 96*

# xBSM detector




- Linear array of InGaAs diodes
- Pitch = 50 μm, width = 400 μm
- Center 32 pixels for single-shot
- Top 8 pixels for single-diode mode
- Bottom 4 pixels for ground lines
- Mounted on precision stages.
- Water cooled
- Fast response

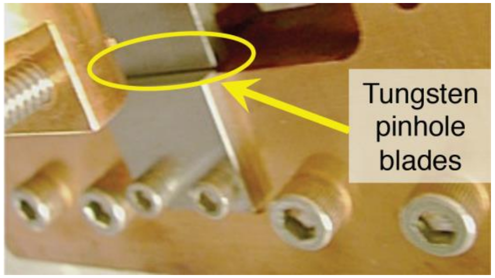


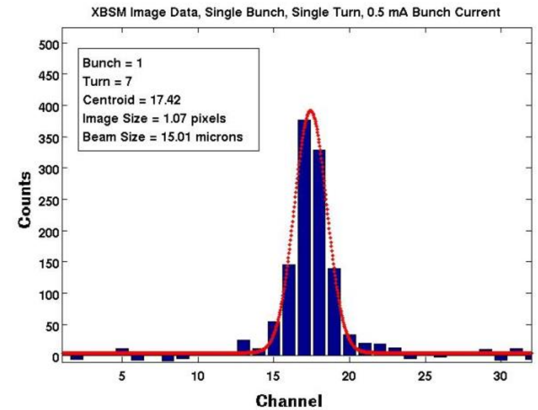

***J.P. Alexander, et al, NIMA 748 (2014) 96***

# xBSM optical elements

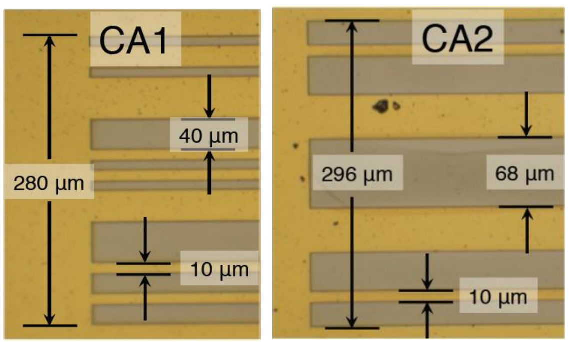
## Pinhole



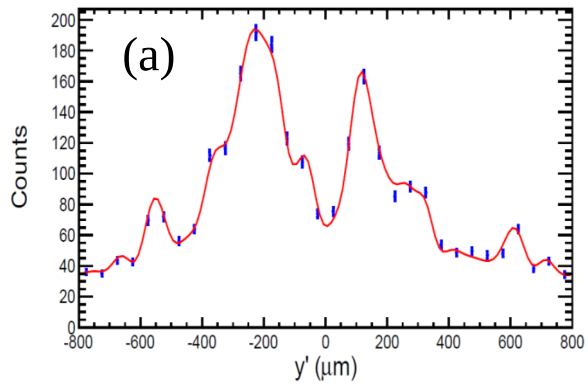

- Two tungsten blades 2.5 m thick
- Adjustable gap 0~ 200 μm
- Pinhole camera principle
- Typical opening ~ 50 μm @ 2.1 GeV




## Coded aperture

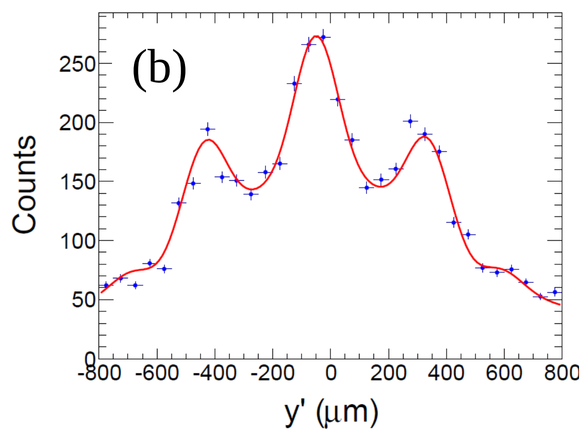


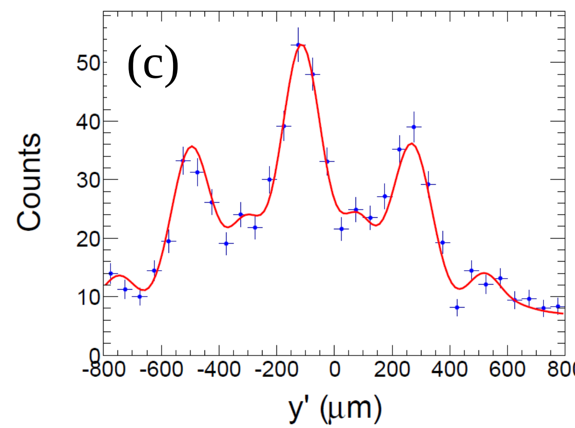

- Au mask on Si substrate
- Thickness: Au ~ 0.62 μm, Si ~ 2.5 μm
- Width: 1.2 mm
- Better sensitivity than PH at small beam size




Single bunch, single turn
(a) CA1 @ 2.1 GeV
(b) CA2, I=4.6 mA @ 1.8 GeV
(c) CA2, I=0.8 mA @ 1.8 GeV

y' is the detector plane



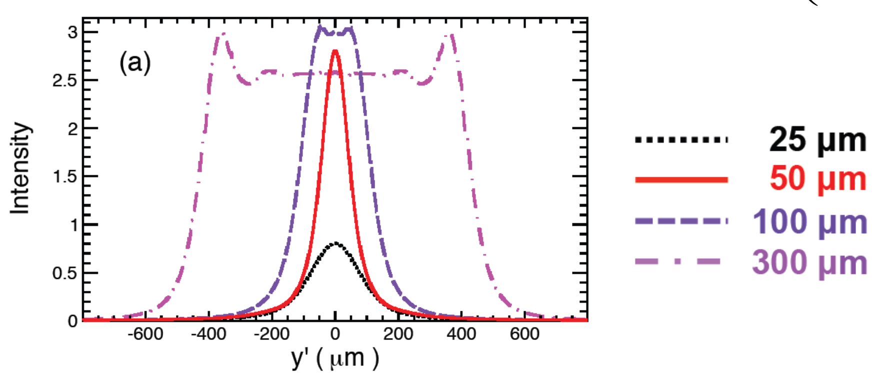
# xBSM data analysis

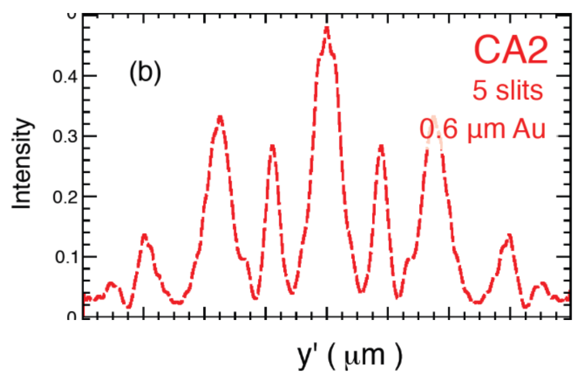
- Find point response function $G(y', y_b)$
  - Find amplitude $E_{img}(y', y_b, \varepsilon)$ with Fresnel diffraction approximation
  - Find spectral responses of detector $S_d(\varepsilon)$ and transmitting materials $S_f(\varepsilon)$

$$G(y', y_b) \propto \int_0^{+\infty} S_d(\varepsilon) S_f(\varepsilon) \left| E_{img}(y', y_b, \varepsilon) \right|^2 d\varepsilon$$

- Create fitting template using fitting function $H(y';A_b,\sigma_b,y_b,d)$
  - Fitting parameters: beam intensity ($A_b$), vertical beam size ($\sigma_b$), the beam offset from the center ($y_b$), the detector offset from the center ($d$)
  - Fitting software: Matlab and CERN *ROOT* package

$$H(y';A_b,\sigma_b,y_b,d) \propto A_b \int_{-\infty}^{+\infty} \exp[-\frac{1}{2}\left(\frac{y'-\eta}{M\sigma_b}\right)^2] \times G(y'-My_b-d-\eta, y_b+\eta/M) d\eta$$



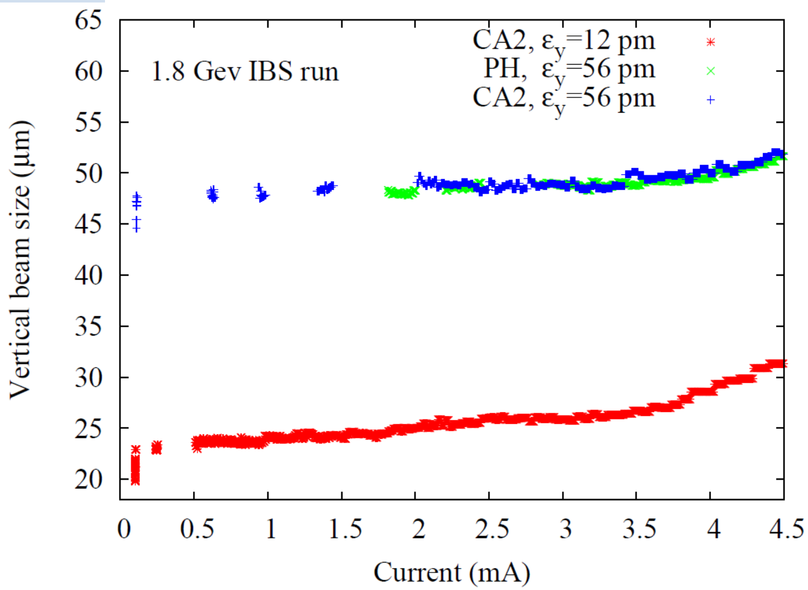




***J.P. Alexander, et al, NIMA 748 (2014) 96***

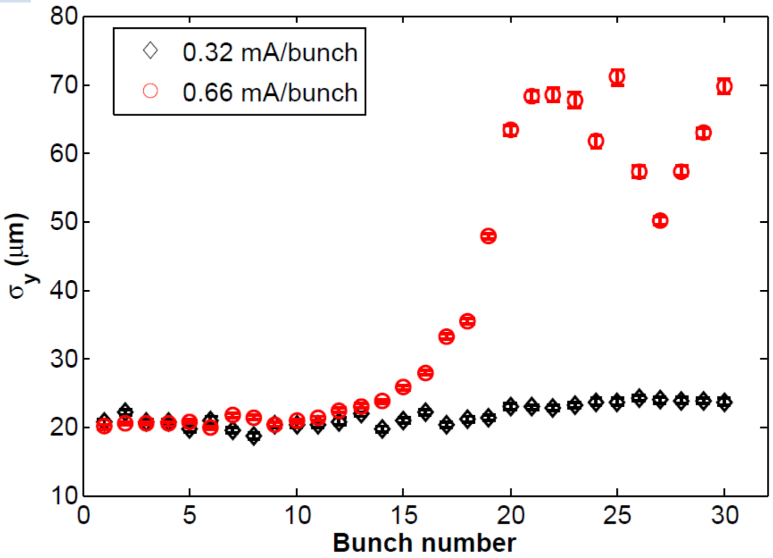
# xBSM summary

- The device can measure vertical beam sizes of 10−100 μm on a turn-by-turn bunch-by-bunch basis at 1.8−4.0 GeV.
- Systematic precision of ~ 1 μm is achieved for a beam size of 12 μm at 2 GeV.
- Application: low emittance tuning, electron cloud, IBS, FII

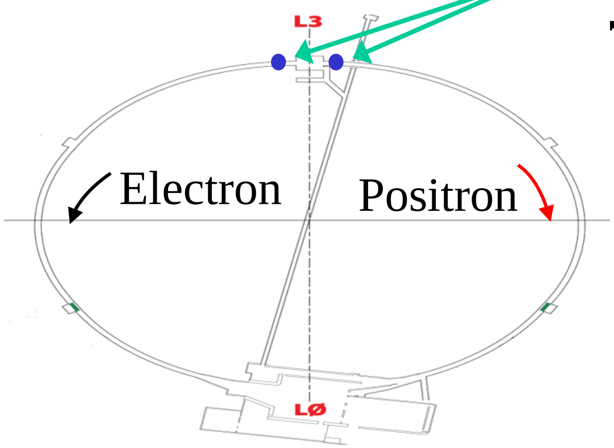
IBS Single bunch electron @ 1.8 Gev

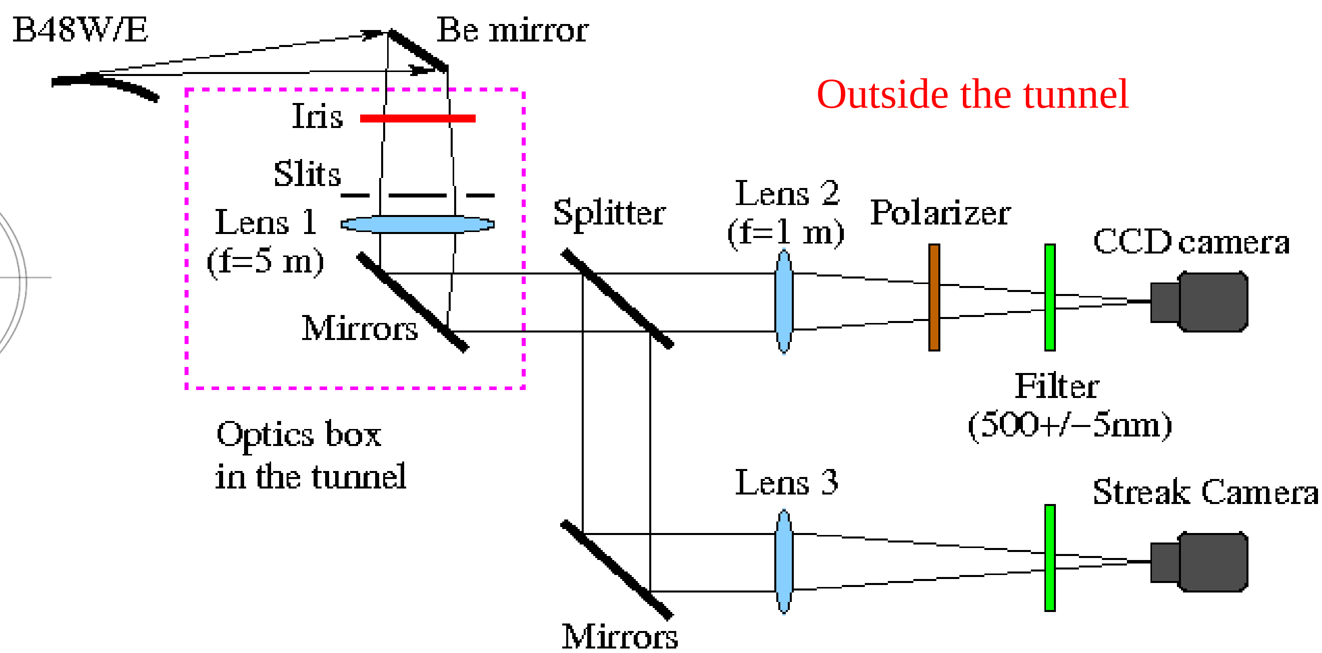



FII 30 bunches electron @ 2.1 Gev

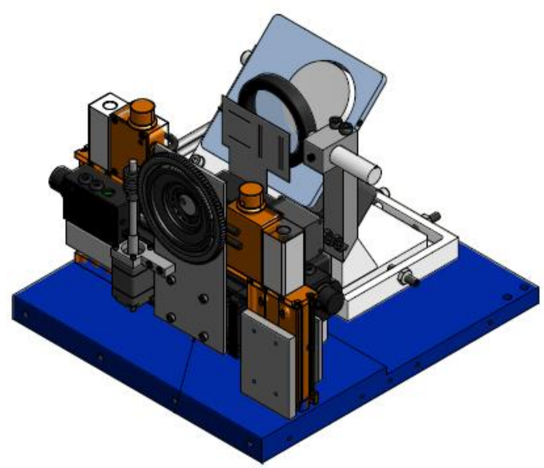


# Visible-light beam size monitor (vBSM)




- Be mirror: 16x12 mm$^2$ (HxV)
- Adjustable iris: 3.0 - 25 mm
- Replaceable sets of double slits
  Horizontal D=2.0, 2.5, 3.0 mm
  Vertical D=5, 8, 10 mm
- Slits on rotation stage
- Motorized stages to control the positions of iris and slit sets



***S.T. Wang et al. NIMA 703 (2013) 80-90***

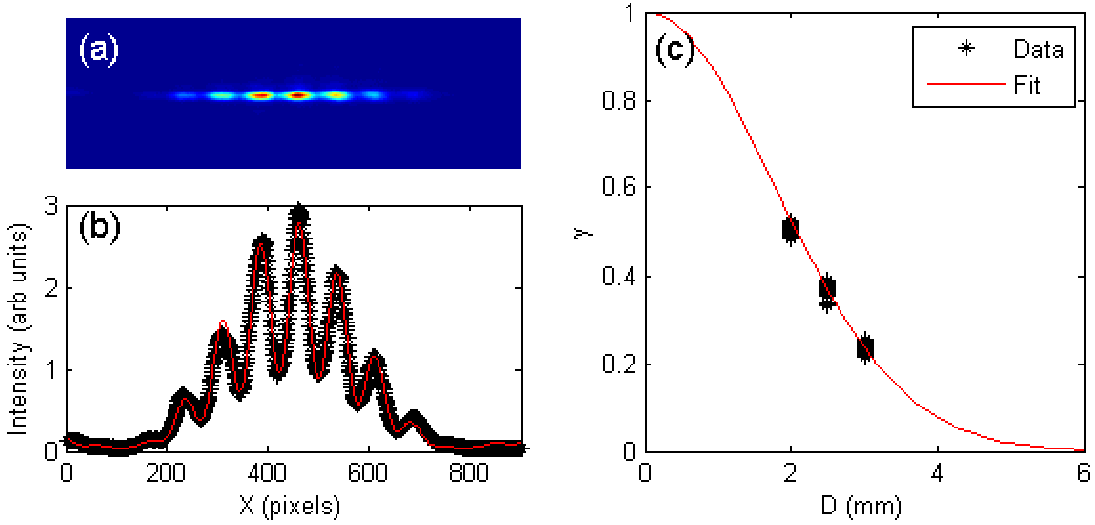
Can measure horizontal, vertical, and longitudinal beam sizes simultaneously.

H: imaging, interferometer
V: interferometer, π-polarization
L: streak camera

Complementary tool to xBSM

# vBSM horizontal beam size

Direct imaging is good to measure larger beam sizes $\sigma_x > 500$ μm.
Interferometer is used to measure $\sigma_x \sim 50$-500 μm with a precision of 5 μm.




(a) A typical CCD image
2.1 GeV, 1.5 mA, $D$=2.5 mm
(b) Extracted fringe pattern and fit
$\sigma_x$=275±4 μm
(c) Visibility vs slit separation $D$
$\sigma_x$=272±1 μm

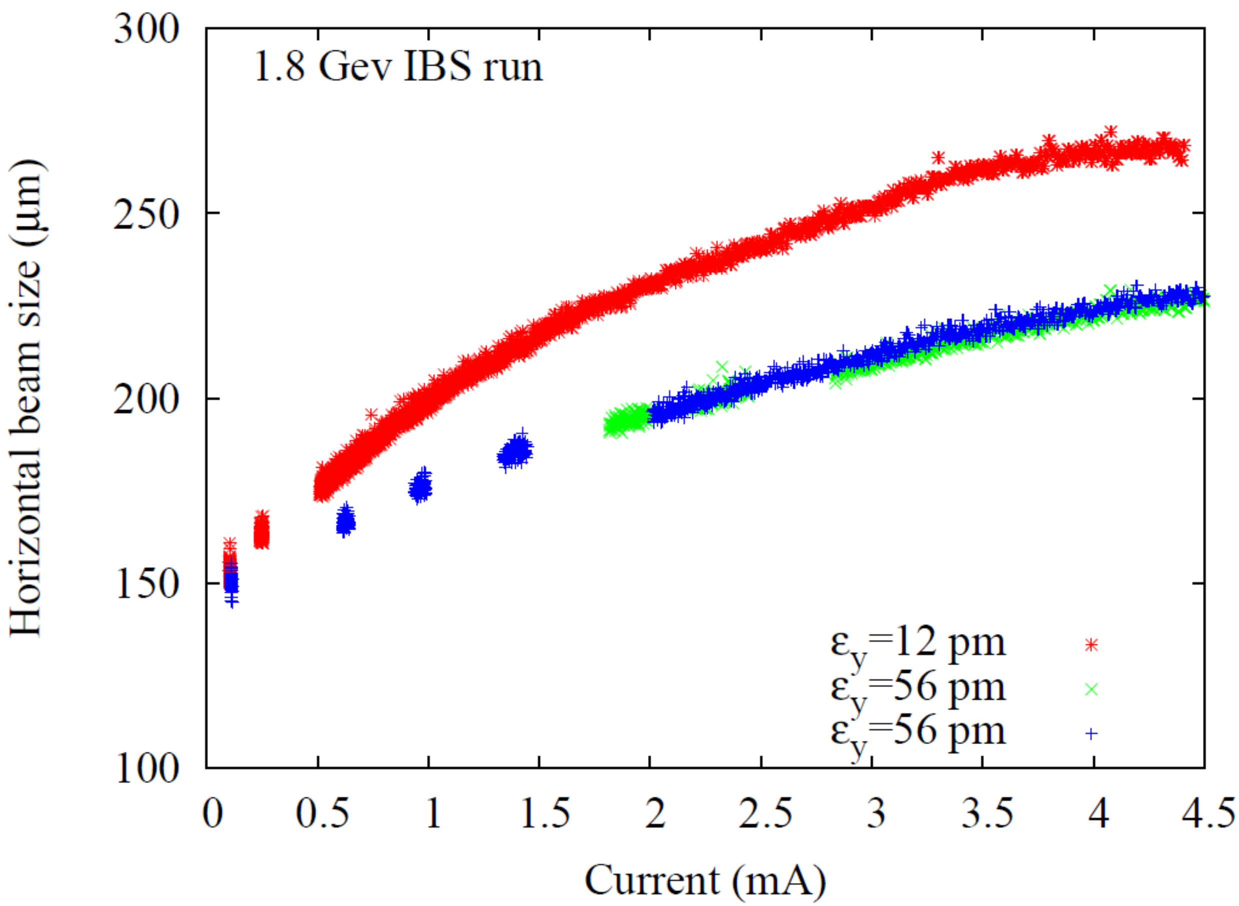
$$\sigma_x = \frac{\lambda L}{\pi D}\sqrt{\frac{1}{2}\ln\frac{1}{\gamma}}$$

- The systematic error due to the depth of field should be corrected for $\sigma_x$.
- The integration time of CCD camera is usually 1-100 ms (400-40000 turns).
- CCD camera cannot avoid the systematic error due to beam motion and vibration.
- However, the error due to beam motion is < 1 % in the horizontal plane.

*T. Mitsuhashi, Proc. of the Joint US-CERN-Japan-Russia School on Particle Accelerators, May 1998, 399-427*

# vBSM horizontal beam size

## The horizontal interferometer is successfully used for IBS studies.



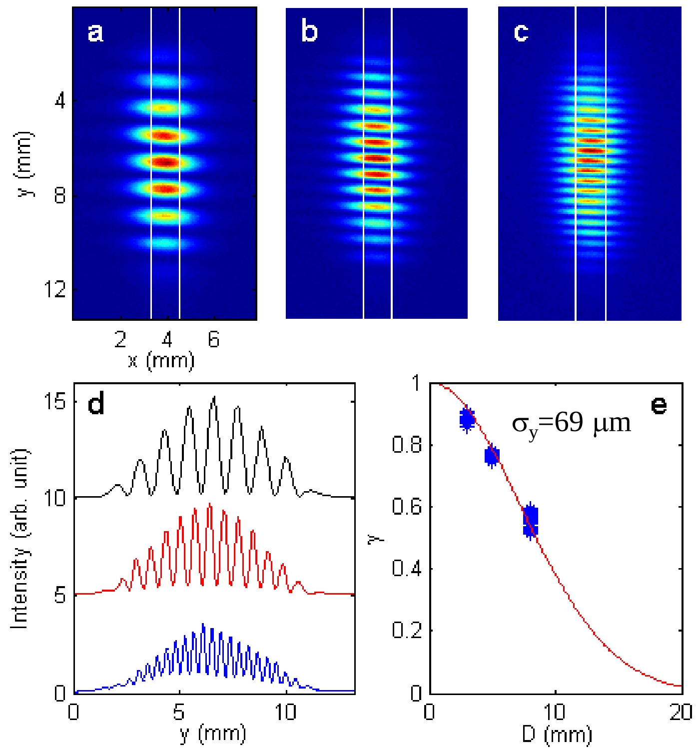

The measured zero current emittance is ~ 2.6 nm, which is consistent with the theoretical value.

***M.P. Ehrlichman et al. PRSTAB 17 (2014) 044002***

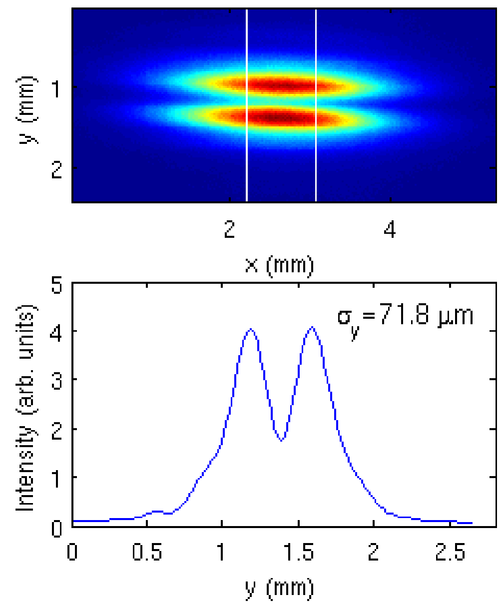
# vBSM vertical beam size

Interferometer is also implemented to measure vertical beam size $\sigma_y$.
Alternatively, $\pi$-polarization method is good for measuring $\sigma_y < 100\ \mu m$.

D=5, 8, 10 mm




$\pi$-polarization




Single bunch 1.0 mA electron @ 5.3 GeV

- Two methods are consistent.
- To measure small $\sigma_y$, need slits with large separation *D* for interferometer.
- Be mirror with large vertical acceptance to eliminate diffraction effect.

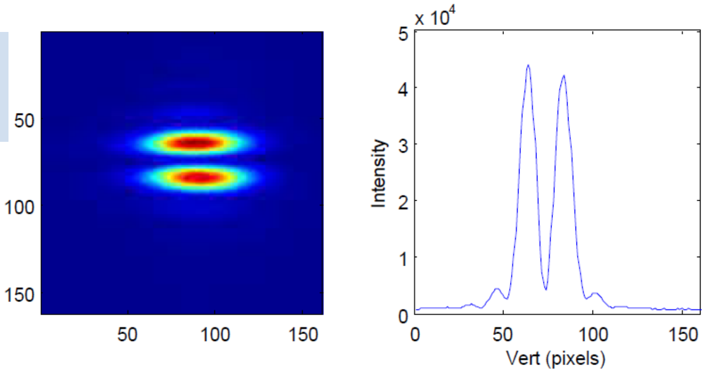
***A. Andersson, et al., NIMA 591 (2008) 437 ;   S.T. Wang et al.  NIMA 703 (2013) 80-90***

# vBSM vertical beam size

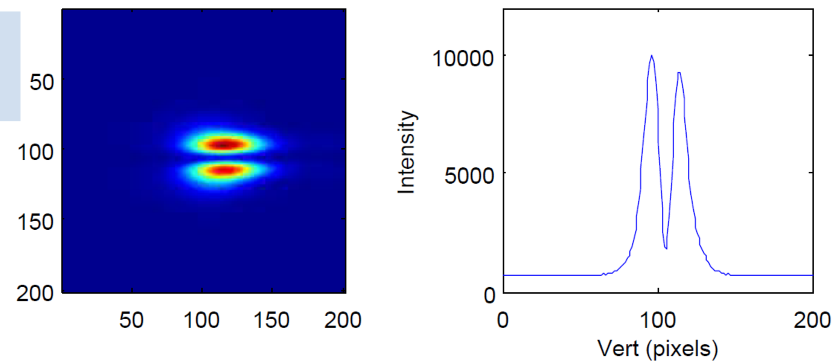
## Be mirror was upgraded to have large vertical acceptance (12 mm -> 25 mm).

- Eliminate the diffraction effect for π-polarization
- Slits with larger separation for interferometer

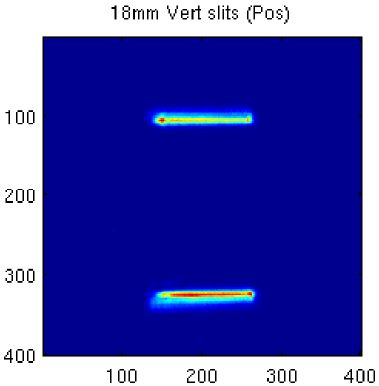
Old mirror

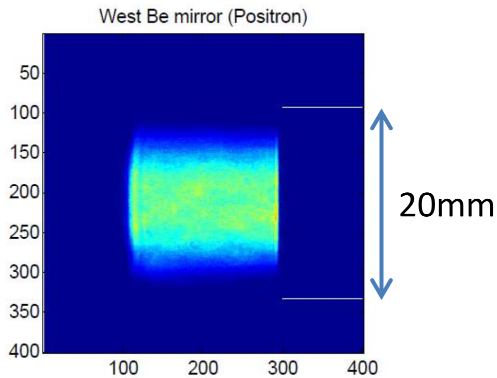


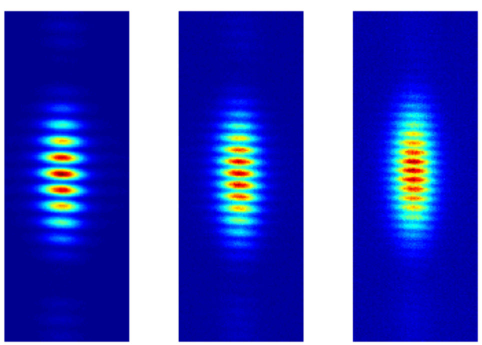

New mirror

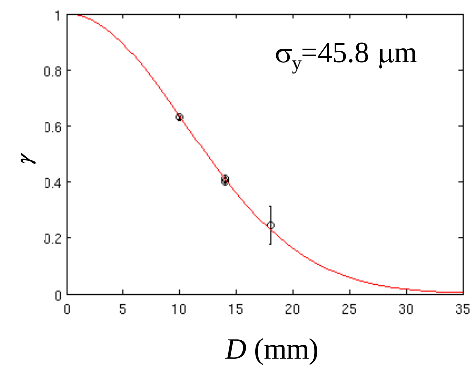



## The slits need to be aligned to get the imbalance factor.
## CCD integration time is longer for slits with larger separation.



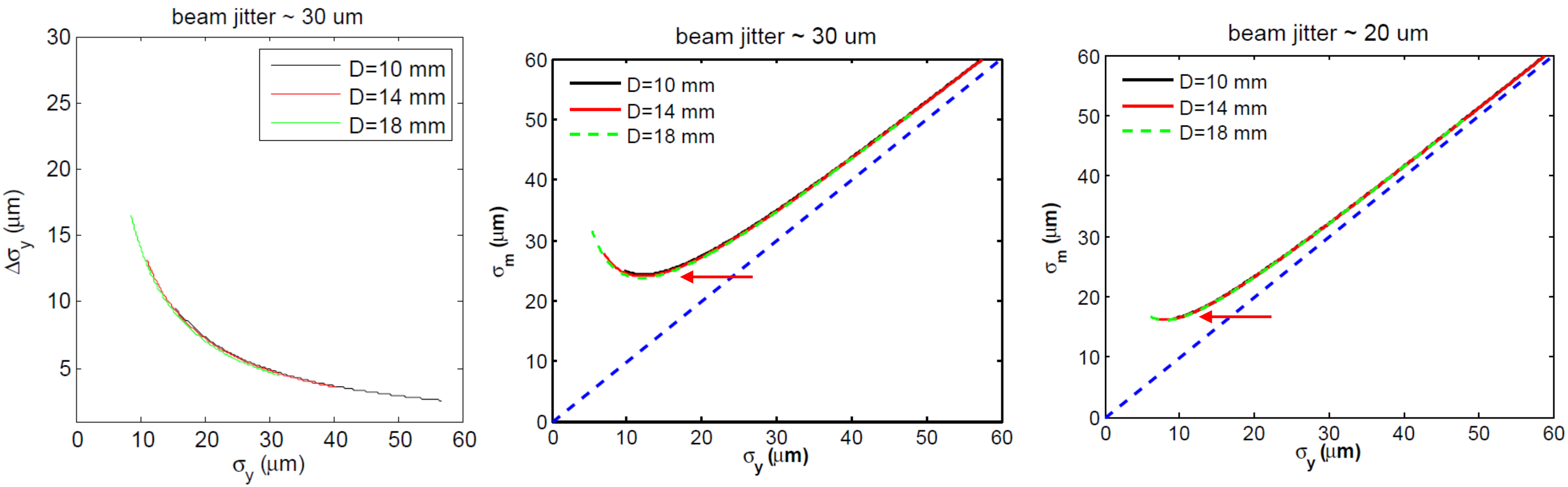




Single bunch 0.6 mA positron @ 2.1 GeV

# Beam jitter effect for interferometer

The beam motion $\Delta y_{beam}$ introduces the phase shift $\Delta\psi$ so as to smear the visibility.

$$\Delta\psi = \frac{2\pi}{\lambda}\frac{D}{L}\Delta y_{beam} \Rightarrow \quad \bar{\gamma} = \mathrm{sinc}(\Delta\psi)\gamma \quad \Delta\sigma_y = \sigma_m(\bar{\gamma}) - \sigma_y(\gamma) = \frac{\lambda^2 L^2}{4\pi^2 D^2}\frac{1-\mathrm{sinc}(\Delta\psi)}{\sigma_y}$$




- Beam jitter effect becomes more significant when $\sigma_y$ is smaller.
- To find the true $\sigma_y$, need to know the beam jitter $\Delta y_{beam}$ .

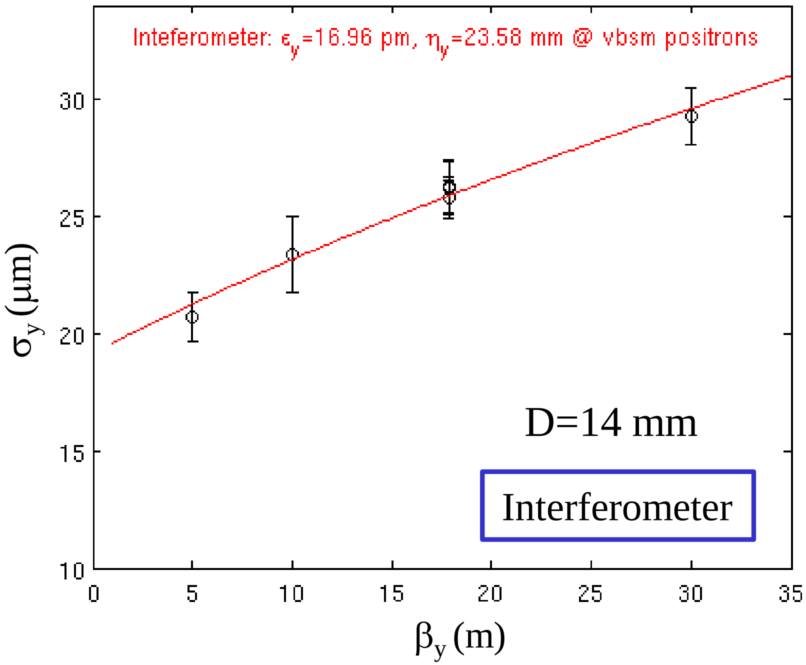
***S.T. Wang et al. NIMA 703 (2013) 80-90***

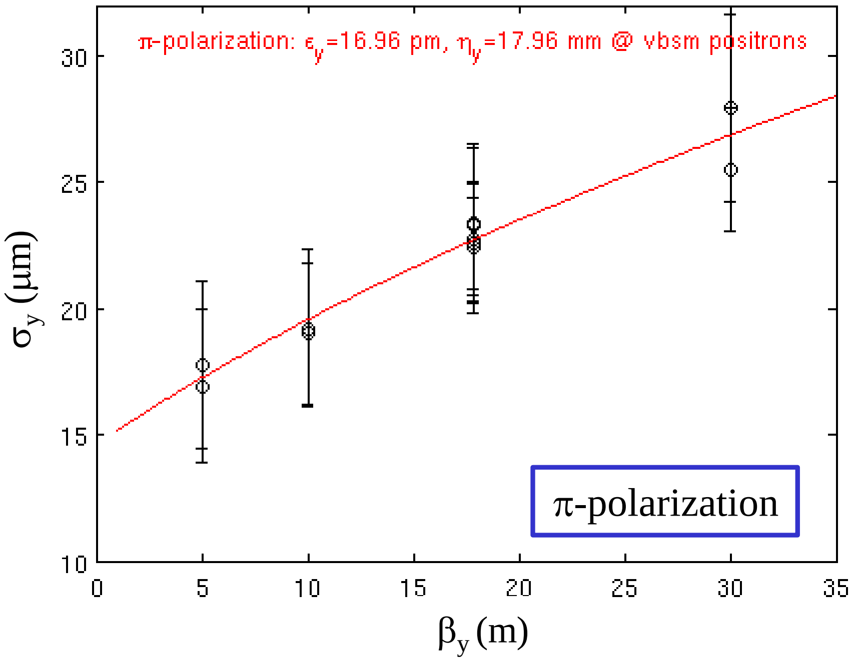
# vBSM beta bump

## Create a closed beta bump at vBSM source point to vary the $\beta_y$

Single electron bunch, 0.8 mA @ E=1.8 GeV

$$\sigma_y = \sqrt{\beta_y \varepsilon_y + \eta_y^2 \delta^2} \qquad \delta = 7.67 \times 10^{-4}$$



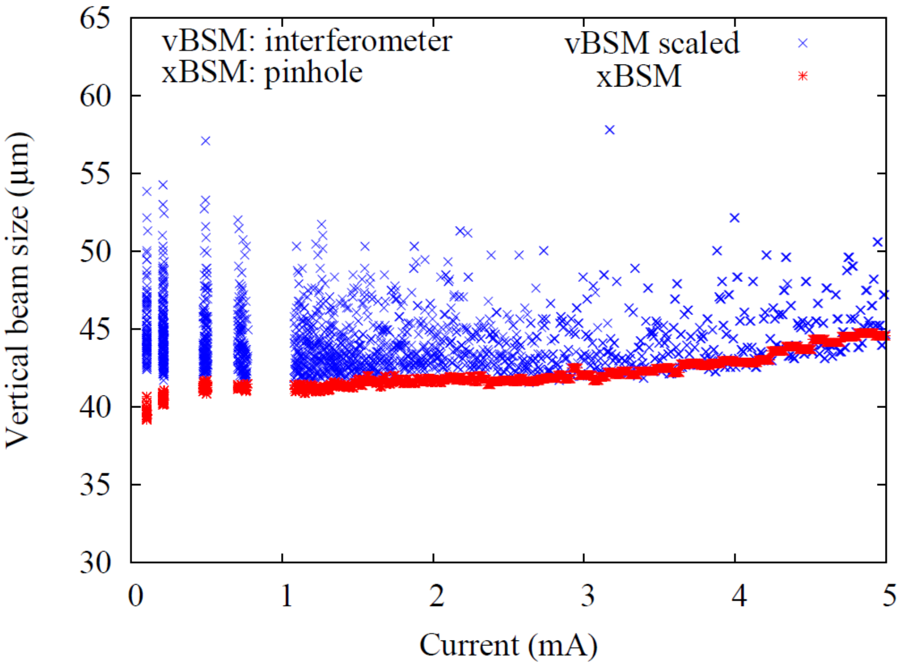




- Interferometer reports larger vertical beam size than π-polarization method.
- Without correction, both methods report similar emittance ~ 17 pm.
- The measured large dispersion may not be real because of the beam motion effect.
- If no dispersion at source point, $\sigma_y$ limited at ~20 μm, implying 20-30 μm beam motion.

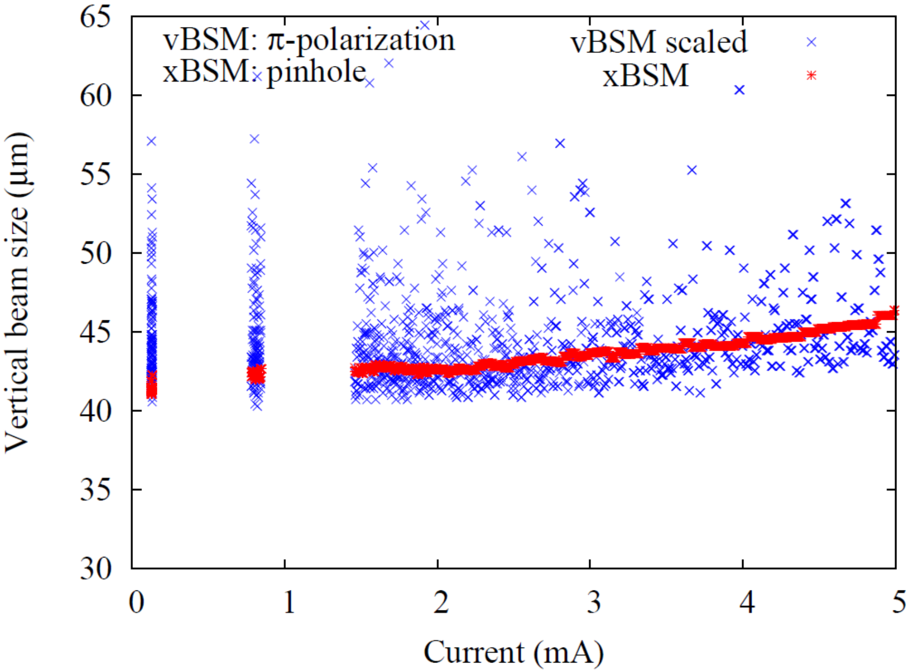
## Compare vBSM with xBSM

Single positron bunch @ 2.1 GeV, $\beta_{y\_xBSM}$ = 40.5 m, $\beta_{y\_vBSM}$ = 20.3 m $\sqrt{\frac{\beta_{y\_xBSM}}{\beta_{y\_vBSM}}} = 1.414$

Interferometer D=14 mm




π-polarization




At large emittance (~ 40 pm), vBSM and xBSM measurements are consistent.

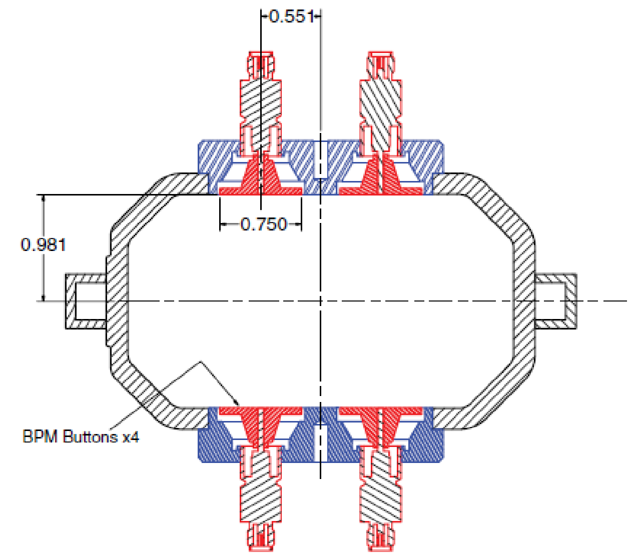
However, vBSM reports larger emittance than xBSM due to beam jitter at low emittance (~10 pm).

# vBSM summary

- Measure horizontal emittance precisely
  - Used for IBS studies
- A complementary tool for vertical emittance
  - Beam jitter correction needed
- A turn-by-turn bunch-by-bunch vBSM is under development.
  - Fast detector e.g. PMT or xBSM detector

# CESR beam position monitor (CBPM)

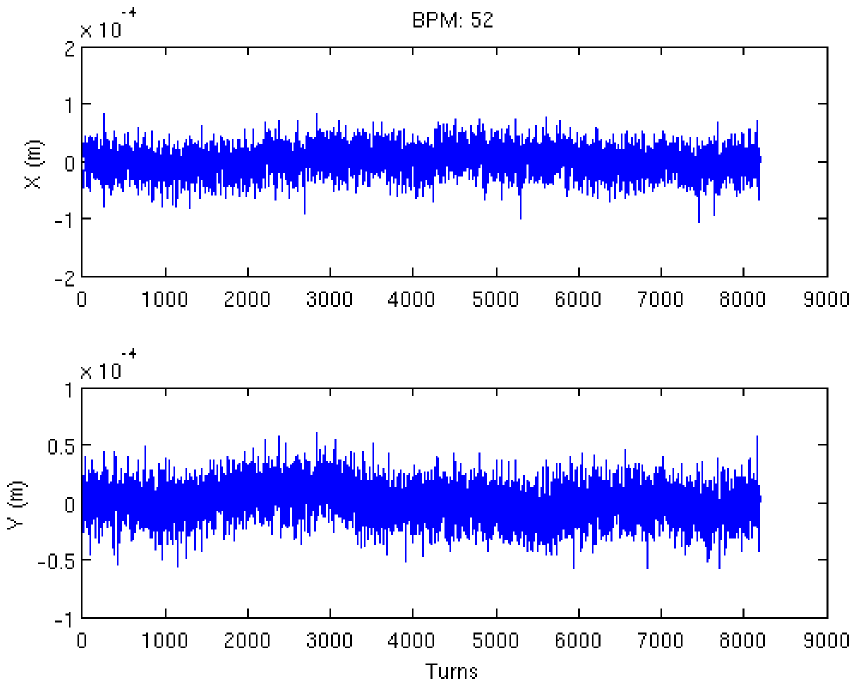
- Fast electronics readout
  - Measure the beam position on a turn-by-turn bunch-by-bunch basis
- 100 CBPMs distributed around the ring
  - Orbit, phase, coupling, dispersion measurements [a]
  - Low emittance tuning [b]
- Calibrations
  - Timing and gain for each button
  - BPM centering and tilt

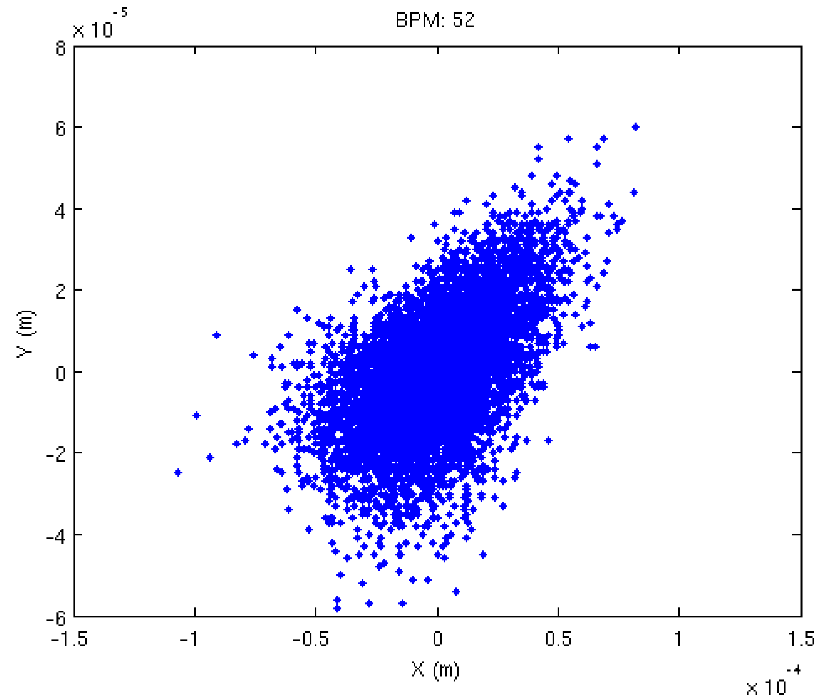



[a] *D. Sagan, et al, PRSTAB 3 (2000) 092801*
[b] *J. Shanks, et al, PRSTAB 17 (2014) 044003*

# CBPM turn-by-turn example

BPM 52, 8192 turns, 0.8 mA electron @ 1.8 GeV



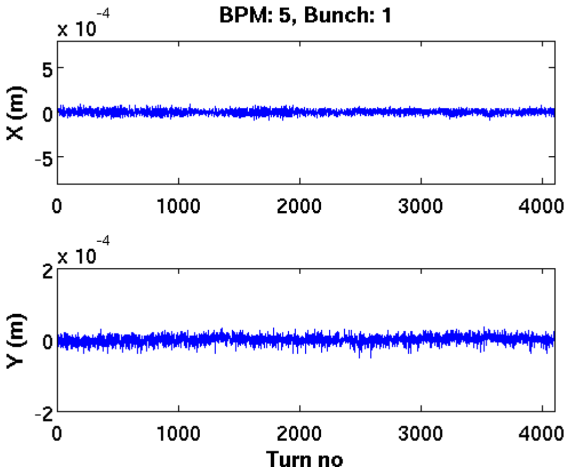



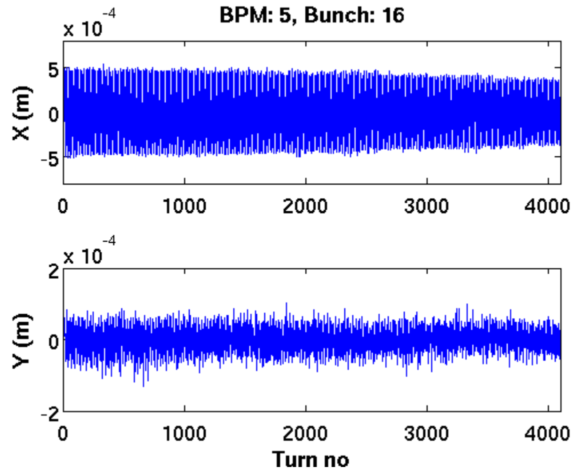

RMS (beam jitter): $\delta_{y\_51}$= 43.1 μm, $\delta_{y\_52}$= 14.5 μm

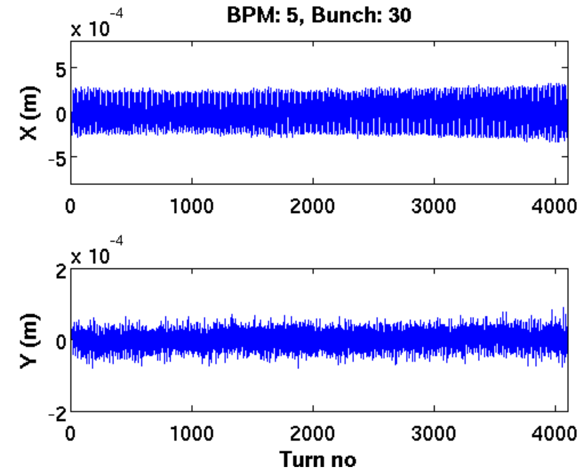
vBSM source point between BPM 51 and 52. The extracted beam jitter at vBSM source point may be ~ 25 μm, consistent with vBSM observation.

# CBPM bunch-by-bunch example

Fast ion studies, 30 electron bunches, 14 ns spacing, 0.66 mA/bunch @ 2.1 GeV, 4096 Turns



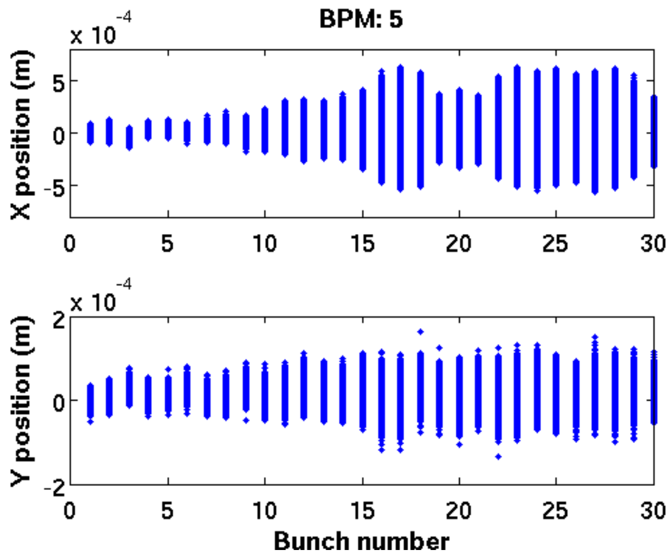



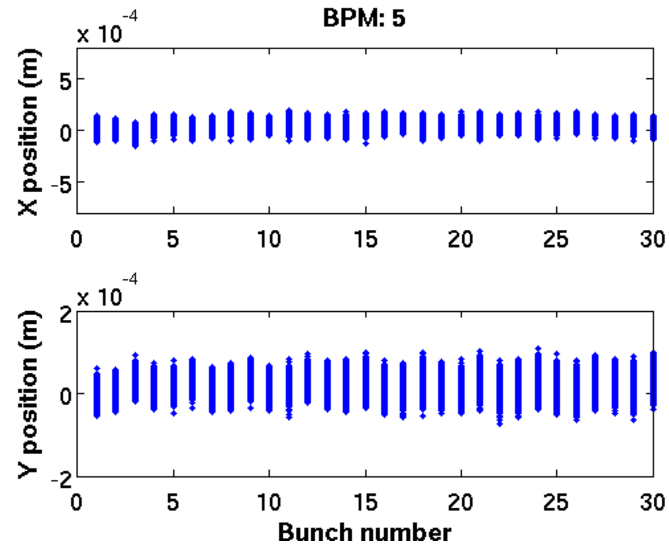




0.66 mA/bunch

0.32 mA/bunch

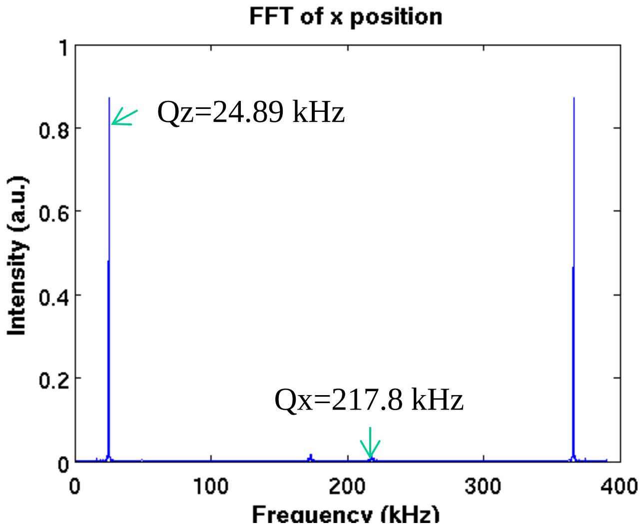
Beam starts to oscillate around bunch 10 at higher bunch current, indicating the instability starts around bunch 10.

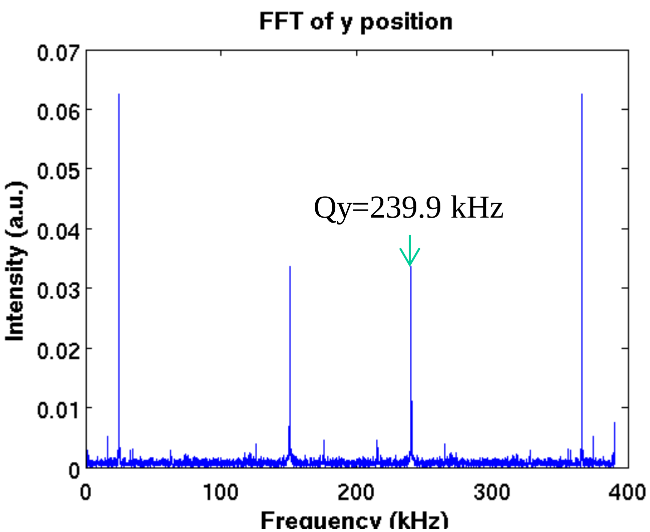


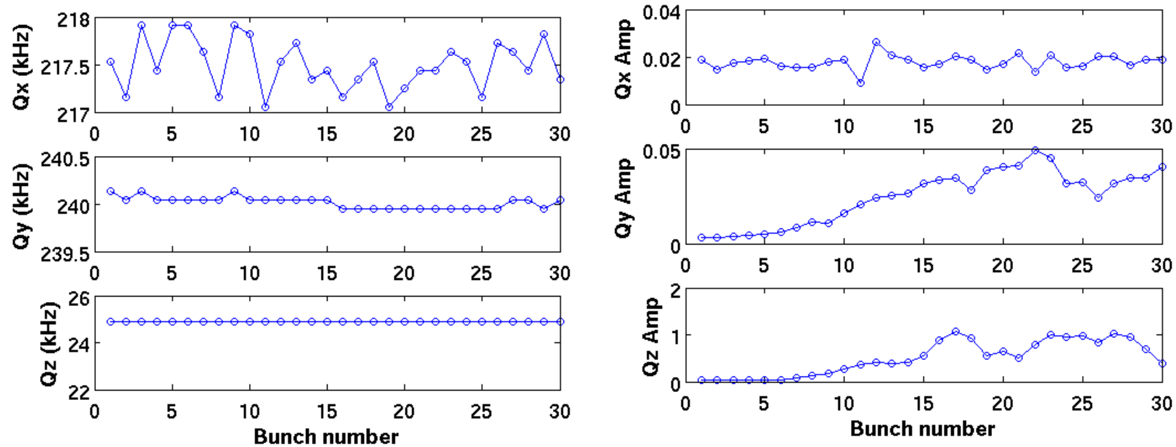
# CBPM bunch-by-bunch example

## BPM 5, bunch 16, 0.66 mA/bunch

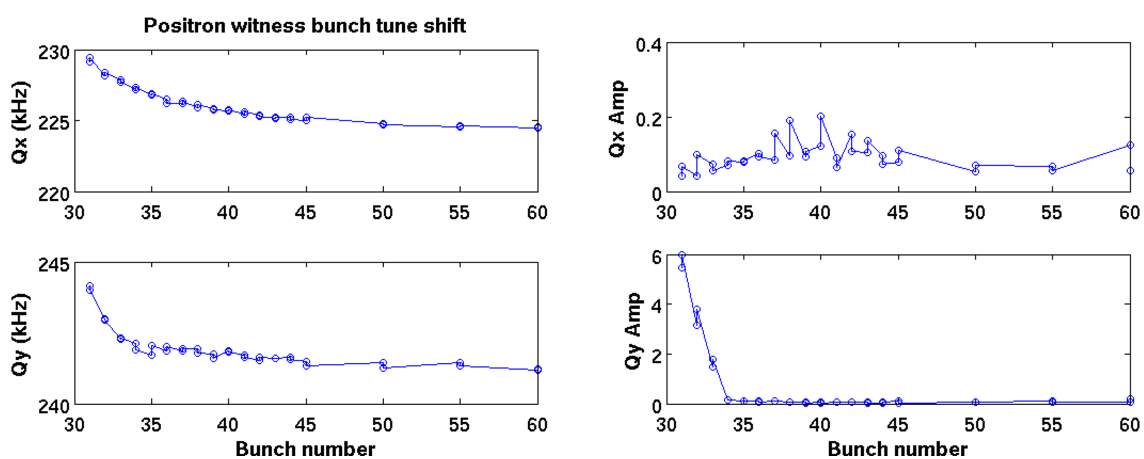



## No tune shift was observed for 30 electron bunches.




## Witness bunch tune shift after 30 positron bunches



# Conclusion

- xBSM
  - Can measure very low vertical emittance
  - Bunch-by-bunch turn-by-turn capability
- vBSM
  - Precise horizontal emittance measurement
  - A complementary tool for vertical emittance
- CBPM
  - Bunch-by-bunch turn-by-turn capability
  - Optics correction: orbit, phase, coupling, dispersion
  - Low emittance tuning and diagnostic tool

# Acknowledgement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