Measurements and simulations of electron-cloud-induced tune shifts and emittance growth at CesrTA

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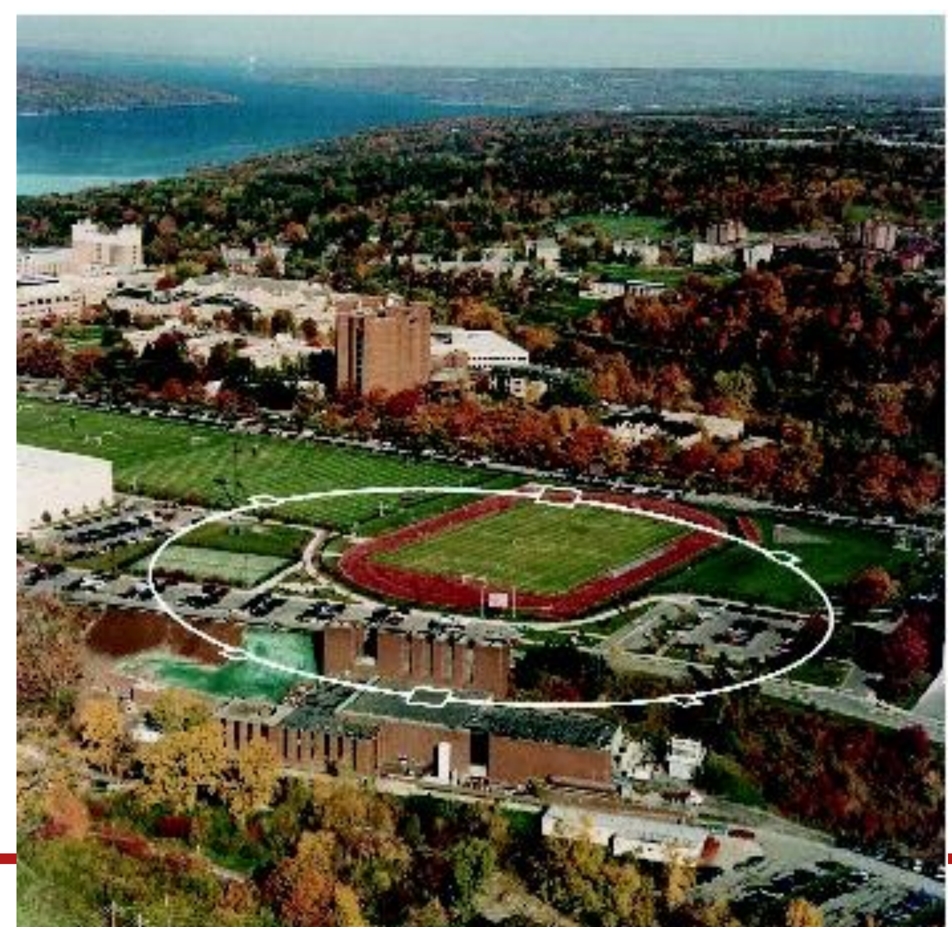


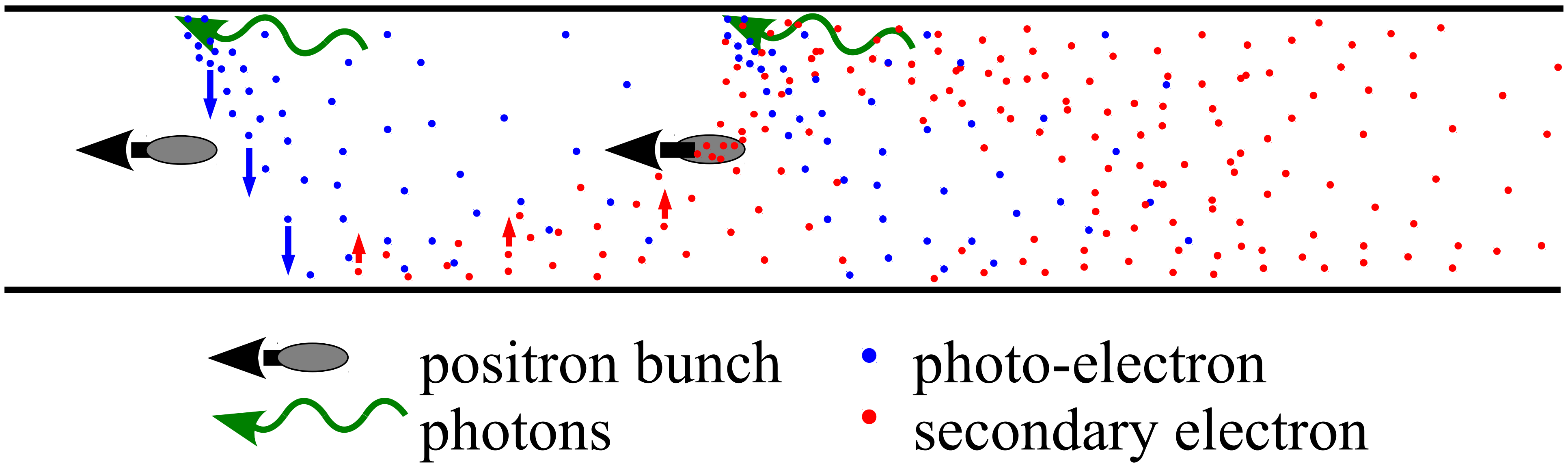
Review

- Electron Cloud (EC) can cause instabilities and emittance growth, and can be a limiting factor in accelerator performance
- An increase in vertical beam size due to electron cloud has been seen in many e+ rings:
  - PEPII, KEKB, DAPHNE, CESR
- EC has been studied at CESRTA (Cornell Electron-Positron Storage Ring Test Accelerator) since 2008
  - Local and ring-wide EC measurements
  - EC mitigation techniques
  - Inform ILC damping ring design
- Emittance growth has been measured along trains of positron bunches, and compared to simulations

Overview

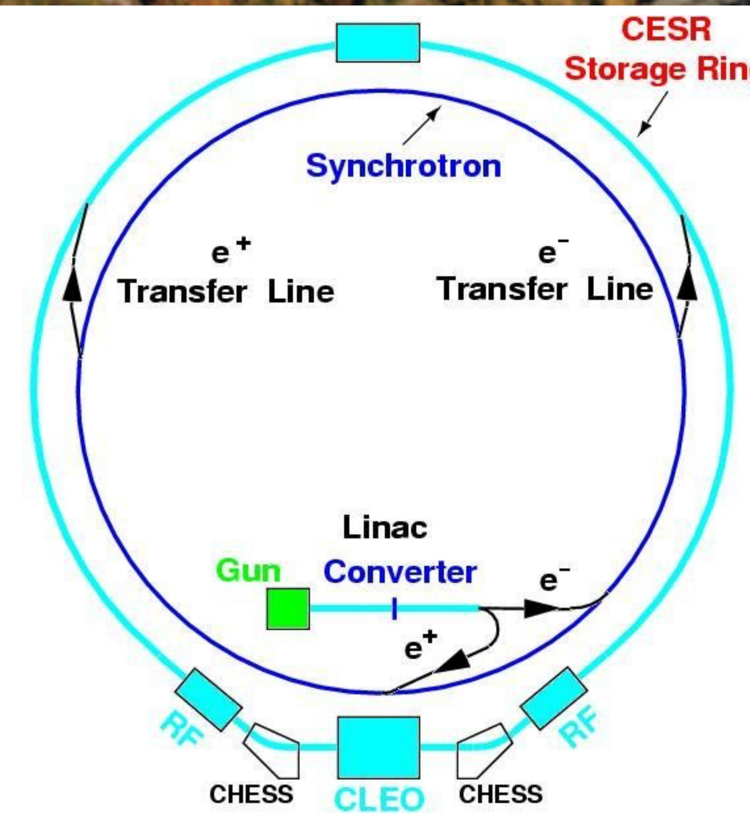
- This talk will present our measurements, describe the simulations, and compare results
- Focus on recent developments:
  - Improved tune shift measurements
  - Fitting e-cloud model to tune shift measurements at various bunch currents & beam energies
  - → Improved modeling of photons from synchrotron radiation & generation of primary electrons
    - ★ (Jim Crittenden's talk Wednesday morning)
  - Effect on emittance growth simulations
- These improvements greatly enhance the predictive power of the model
  - Can be applied to any storage ring given a lattice and vacuum chamber information

Electron Cloud



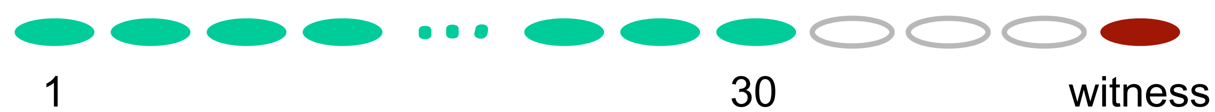
- Buildup of electrons hitting the vacuum chamber wall and generating secondary electrons
- Main source: photoelectrons from synchrotron radiation
  - Also beam-gas ionization or stray protons hitting the wall
- Bunches accelerate the electrons as they pass
- Positron bunches pull the cloud towards it ("pinch effect")
- EC builds up along a train of bunches

- CESR (Cornell Electron-Positron Storage Ring)
  - 768 m in circumference
- Starting in 2008, CESR was reconfigured into a low emittance damping ring as a Test Accelerator (CESRTA) for the ILC Damping Ring specifically, and future high intensity, ultra low emittance storage rings in general
- The goal was to:
  - Characterize the build-up of EC in each of the key magnetic field regions
  - Study the most effective methods of suppressing EC in each region
- Electron and positron beams
- 1.8 – 6 GeV
- Flexible bunch patterns
- 12 Superconducting wigglers at low energy (2 GeV)
  - Generate 90% of the synchrotron radiation



Measurements

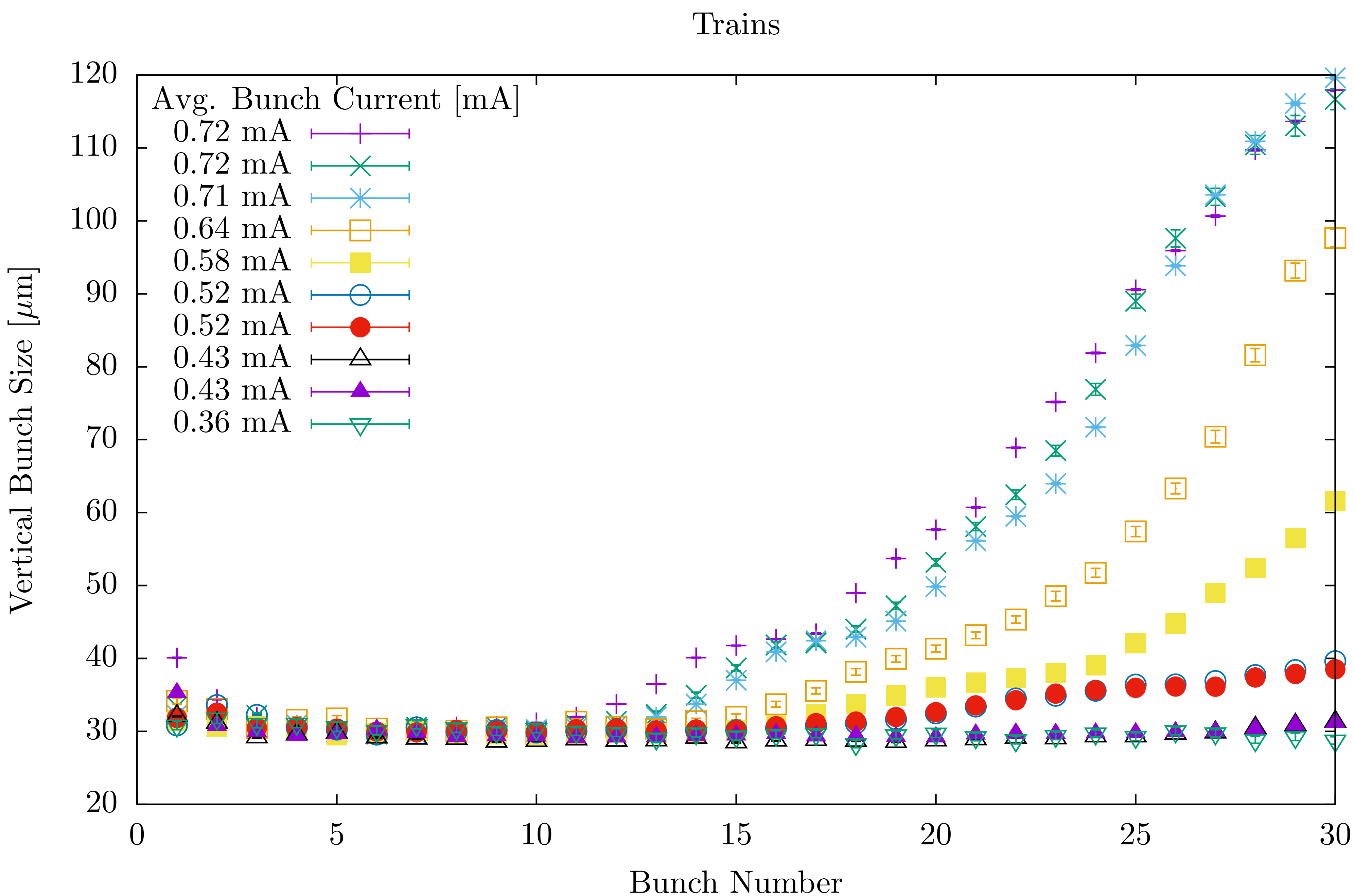
- Beam:
  - 2.1 GeV positrons or electrons (5.3 GeV for additional tune shifts)
    - ★ Horizontal emittance: 3.2 nm, fractional energy spread: 8×10^{-4}, bunch length: 9 mm
  - 30 bunch train, 0.4 mA/b and 0.7 mA/b, 14 ns spacing
    - ★ (0.64×10^{10} and 1.12×10^{10} bunch populations)
  - 1 witness bunch, 0.25 to 1.0 mA, bunch positions 31 to 60



    - ★ Witness bunch position probes cloud as it decays
    - ★ Witness bunch current controls strength of **pinch effect** (cloud pulled in to e+ bunch)
- Measure:
  - Betatron tunes: using digital tune tracker
    - ★ Drive an individual bunch via a gated kicker that is phase locked to the betatron tune
  - Vertical bunch size: from X-ray beam size monitor
    - ★ Bunch-by-bunch, turn-by-turn
  - Horizontal bunch size: from visible light gated camera
    - ★ Bunch-by-bunch, single-shot
- Bunch-by-bunch feedback on to minimize centroid motion
  - Disabled for a single bunch when measuring its tunes

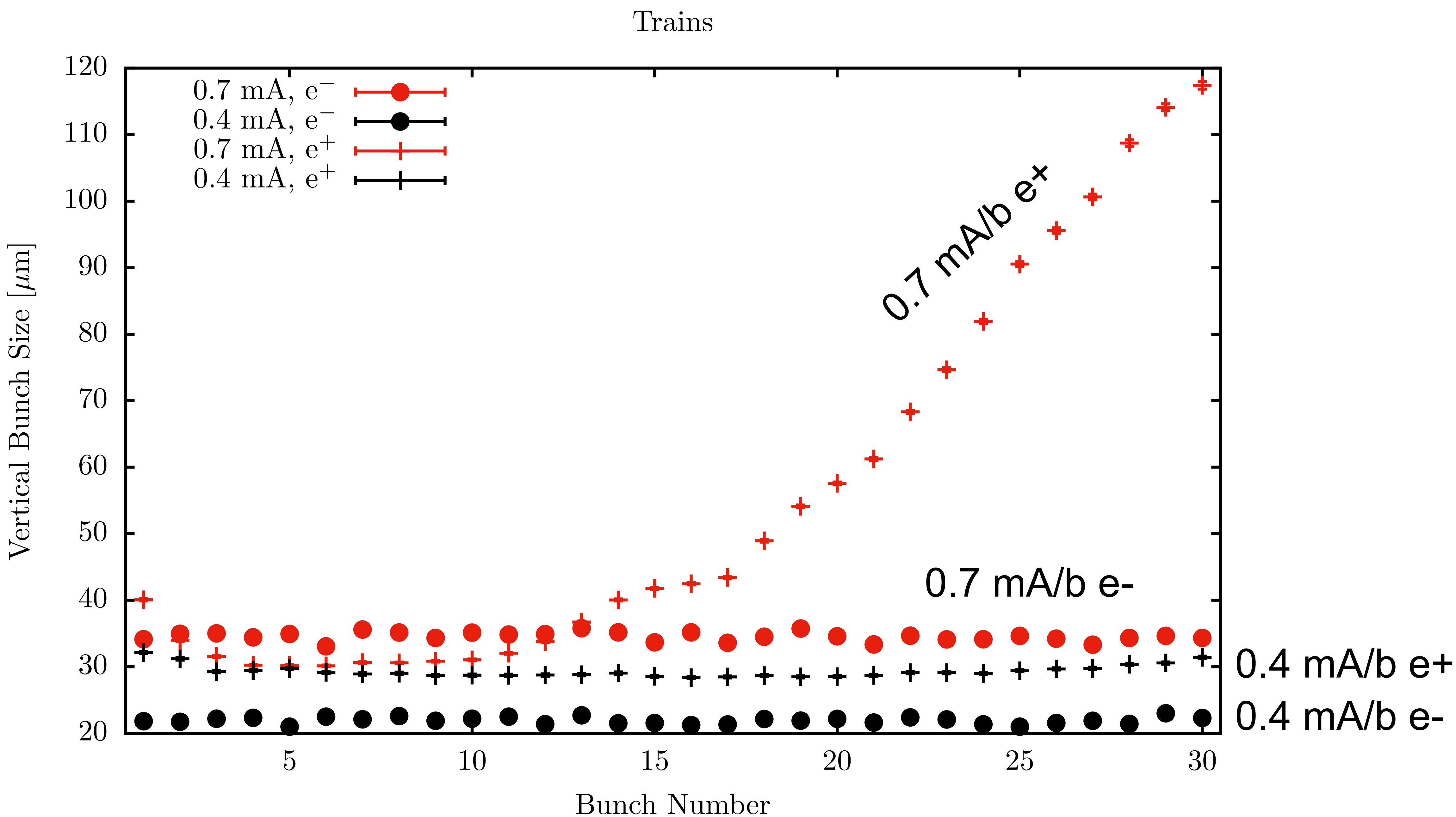
Beam size

- Vertical emittance growth along a train of positron bunches above a threshold current of 0.5 mA/b



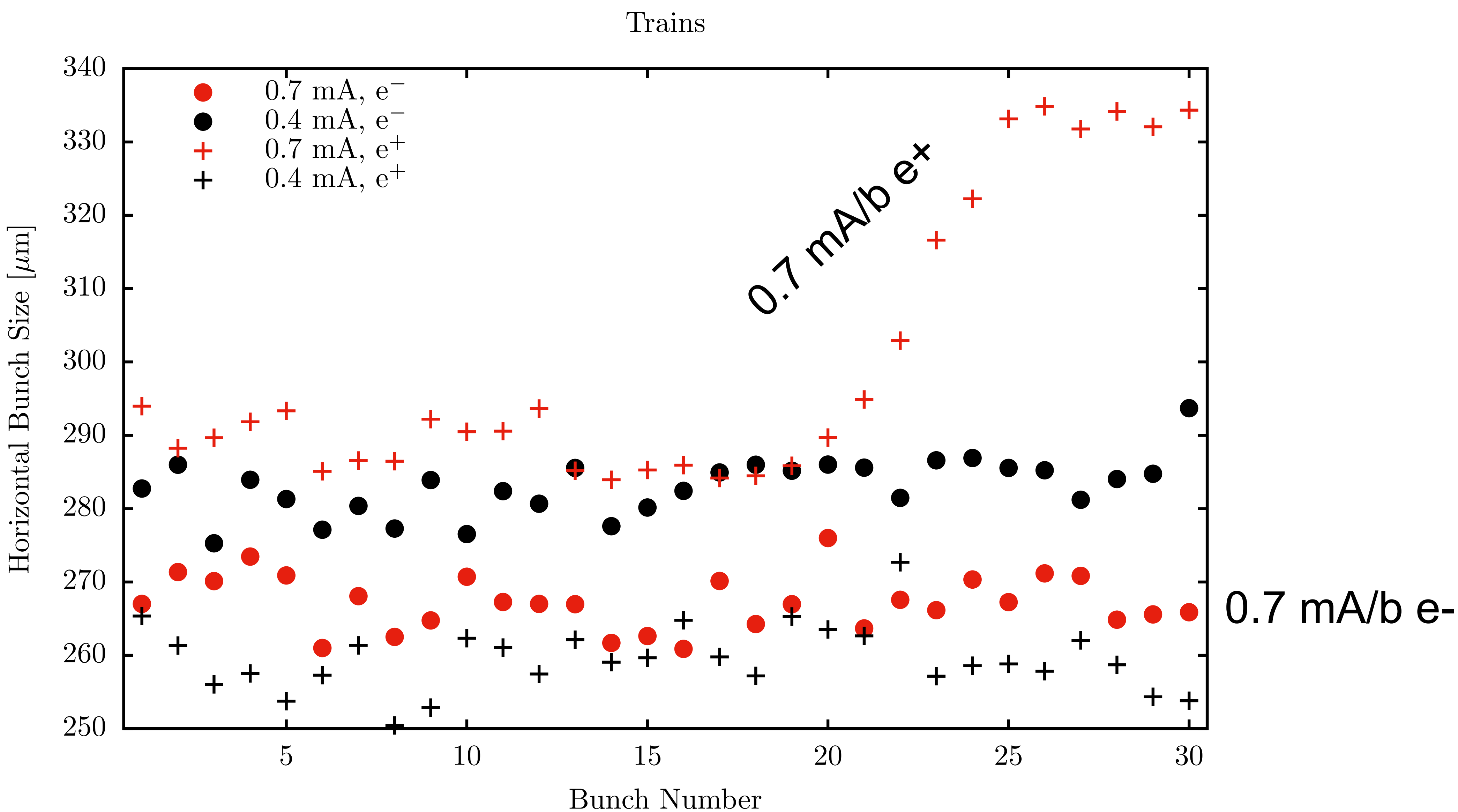
Beam size

- Trains of e- bunches do not blow-up
  - Indicates e+ emittance growth is due to EC, not another effect



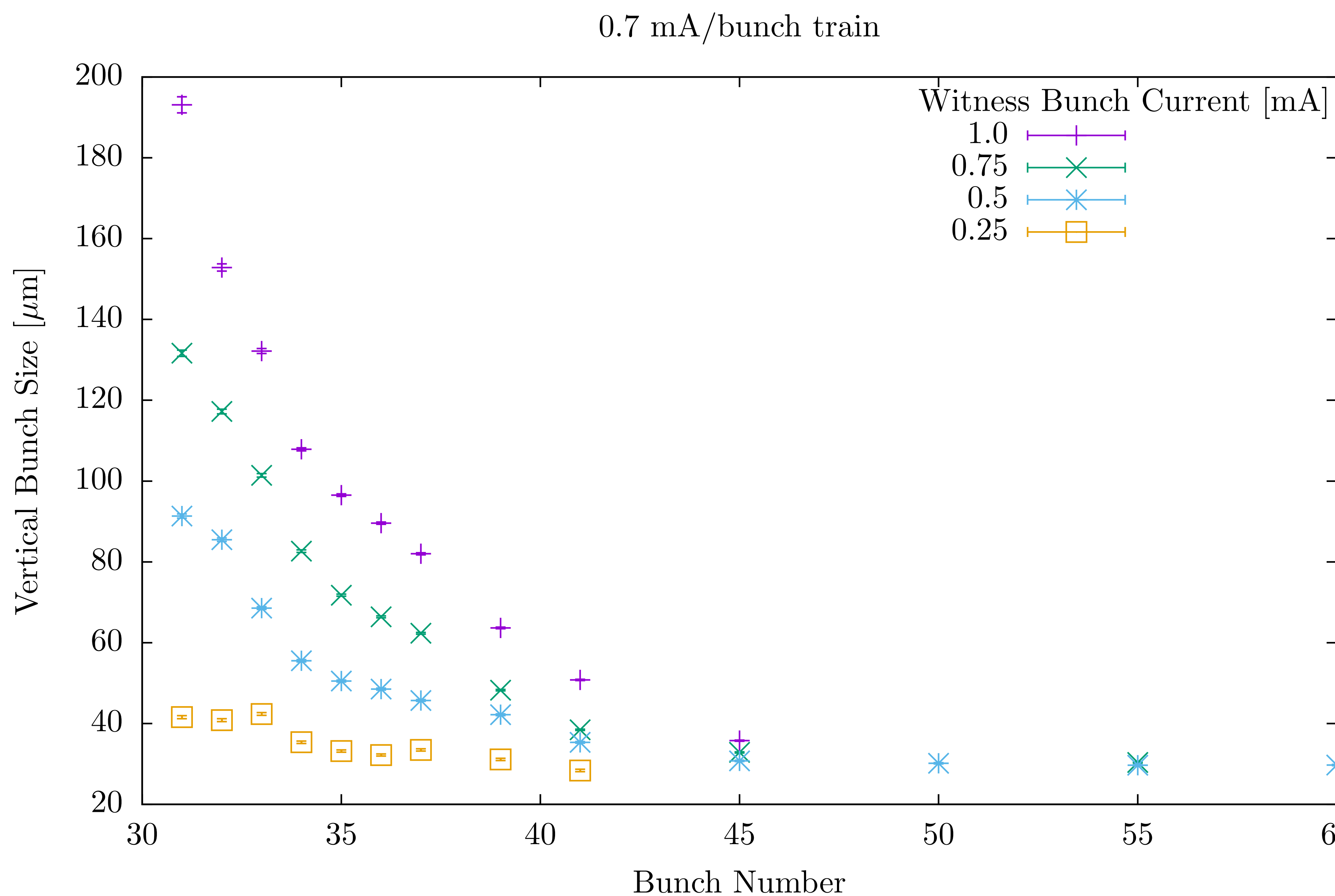
Horizontal beam size

- Horizontal beam size also blows-up in 0.7 mA/b e+ train



Witness bunch beam size

- One witness bunch to a 30 bunch 0.7 mA/b e+ train
  - Start with witness at bunch #60, vary current, eject bunch, move to #55…
  - For a given witness bunch #, the cloud it sees is the same
    - ★ Emittance growth strongly depends on current (pinch effect)

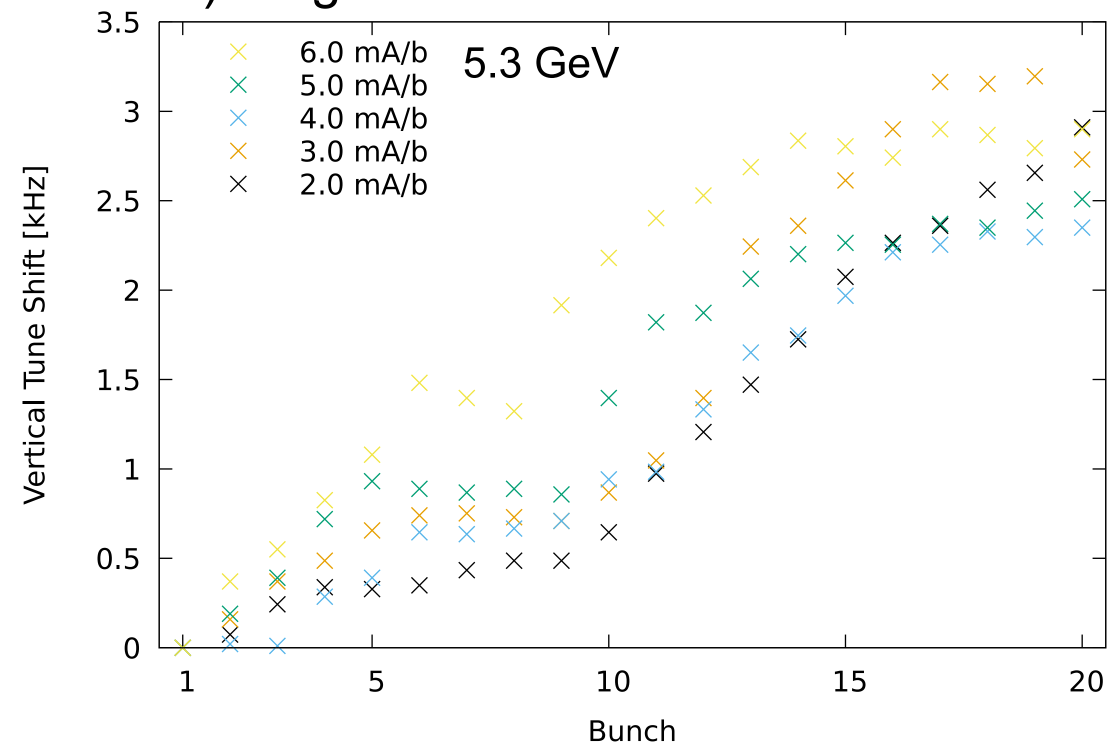


Tune shift measurements

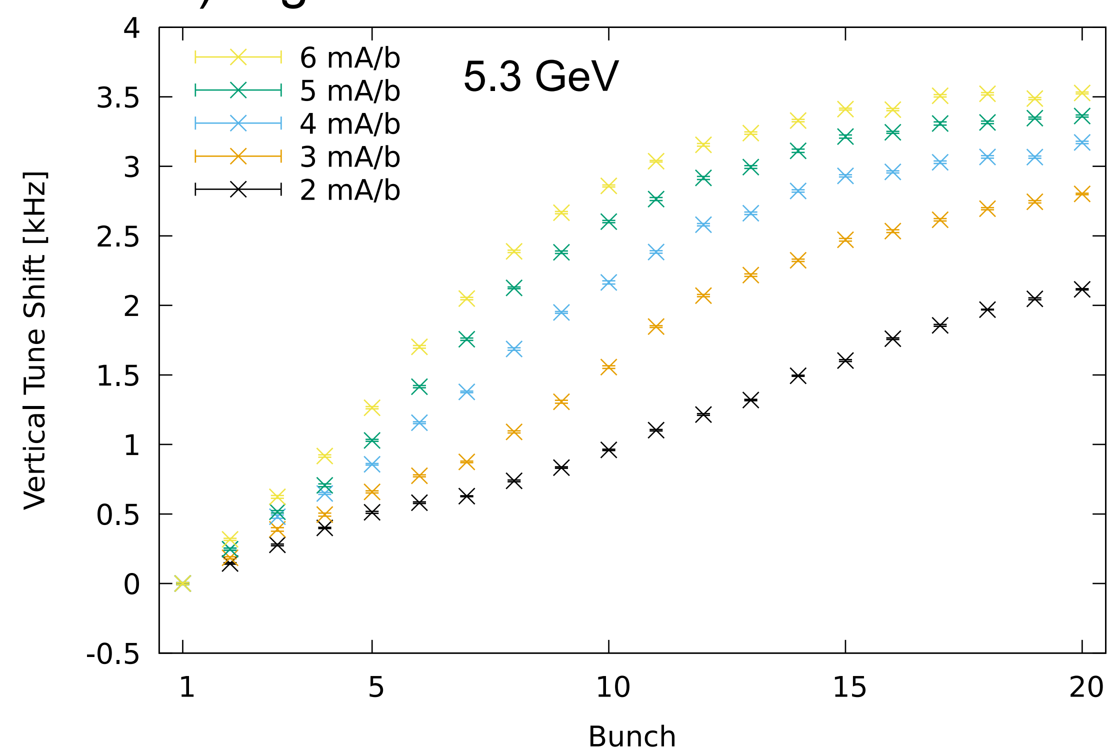
Tune shifts can be measured various ways:

1. “Pinging”: Coherently kicking entire train once, measuring bunch-by-bunch, turn-by-turn positions, and peak-fitting the FFTs
   - ★ Fast measurement (whole train at once)
   - ★ Multiple peaks from coupled-bunch motion contaminate signal
   - ★ Unable to measure horizontal tune shifts from dipoles (vertical stripe of cloud moves with train)
2. “Single bunch”: Feedback on all bunches except one. FFT its turn-by-turn position data
   - ★ Cleaner signal if kicking the single bunch with gated kicker
   - ★ Measures horizontal tune shift
3. “Digital tune tracker”: Enhancement on above technique, driving the bunch transversely in a phase lock loop with a beam position monitor
   - ★ Best method; used here

1) Pinged data (Revolution frequency: 390 kHz)



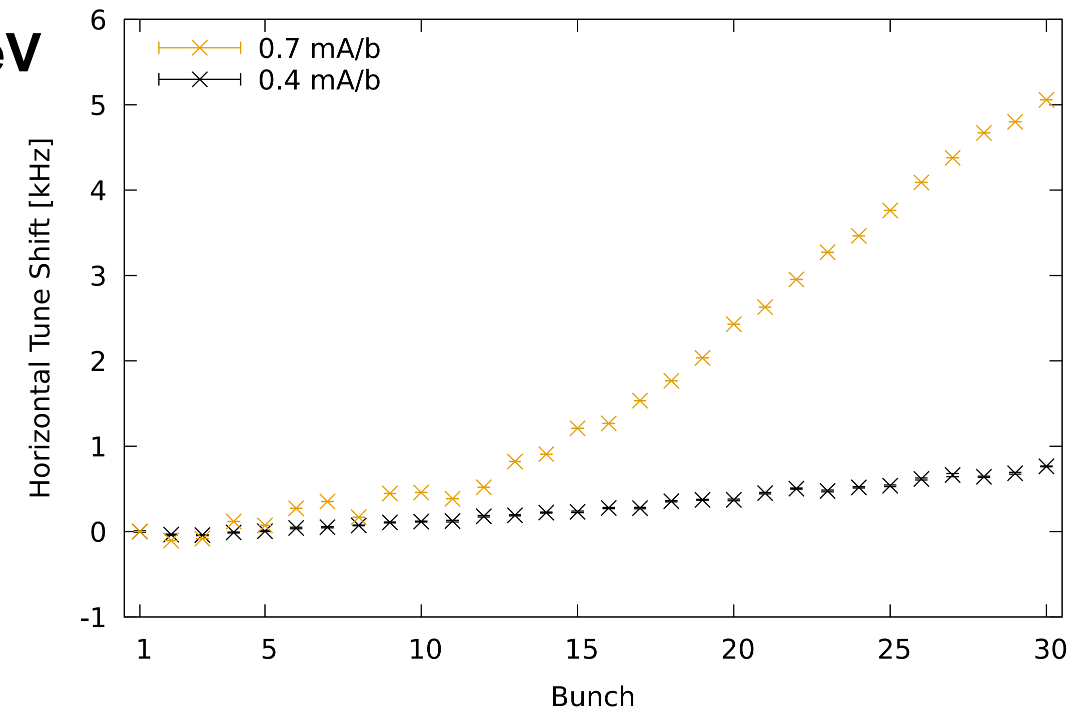
3) Digital tune tracker

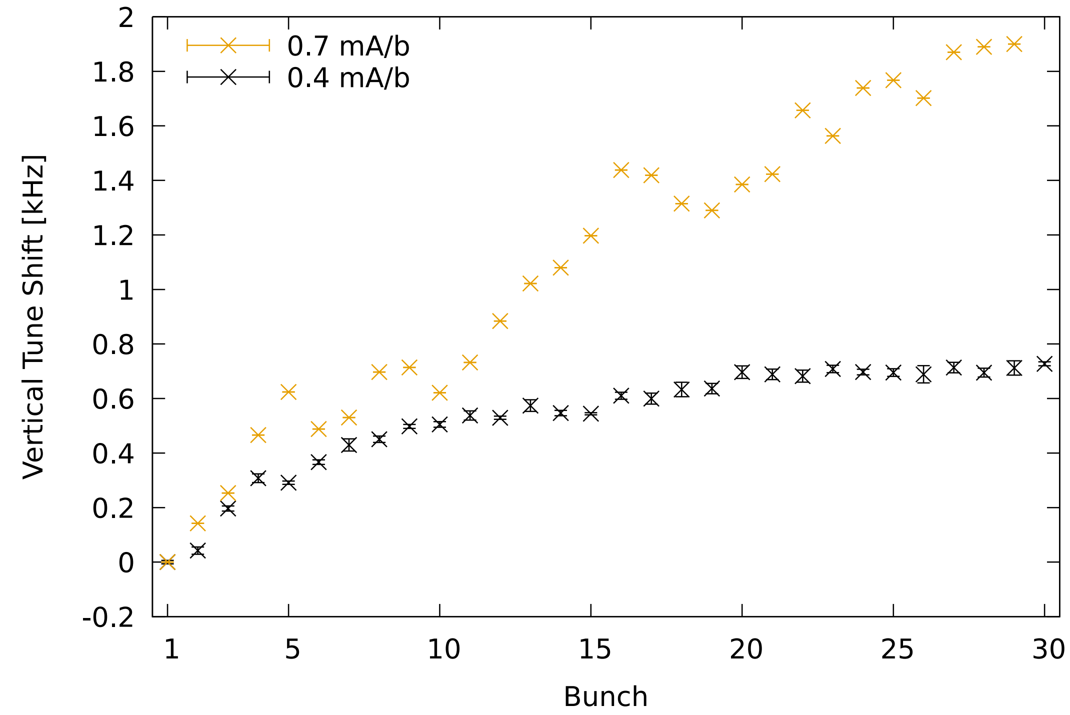


Tune shift measurements

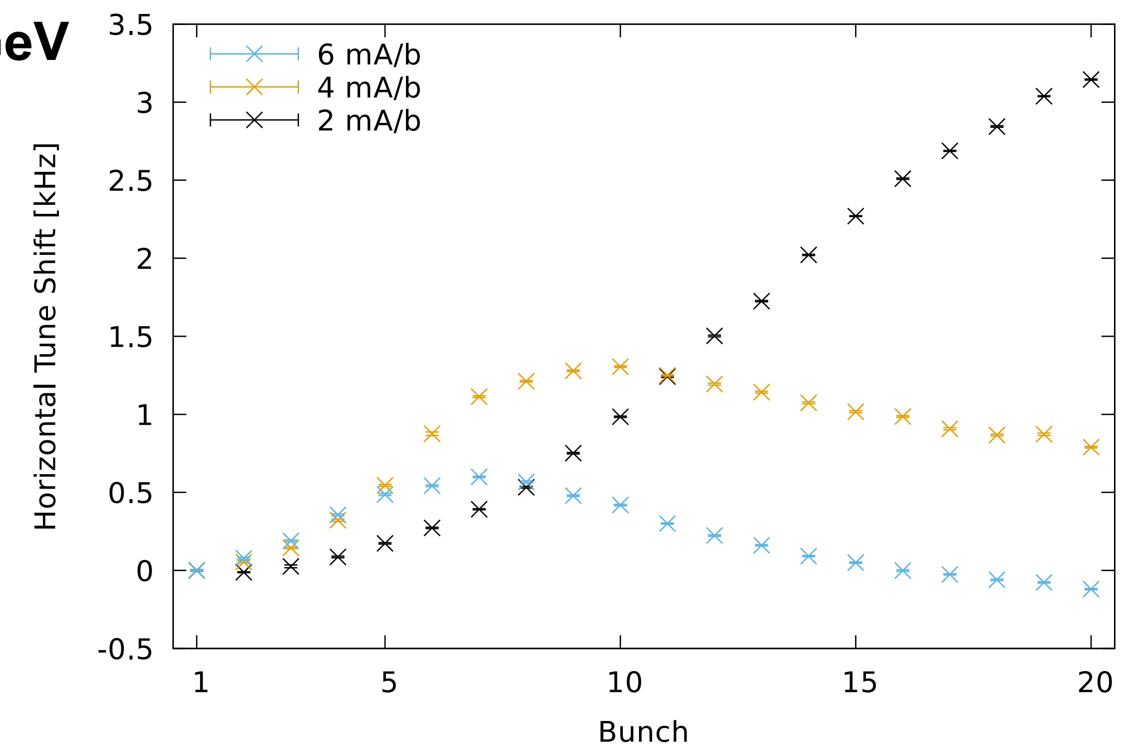
- Tune shifts measured at 2.1 and 5.3 GeV at various currents:

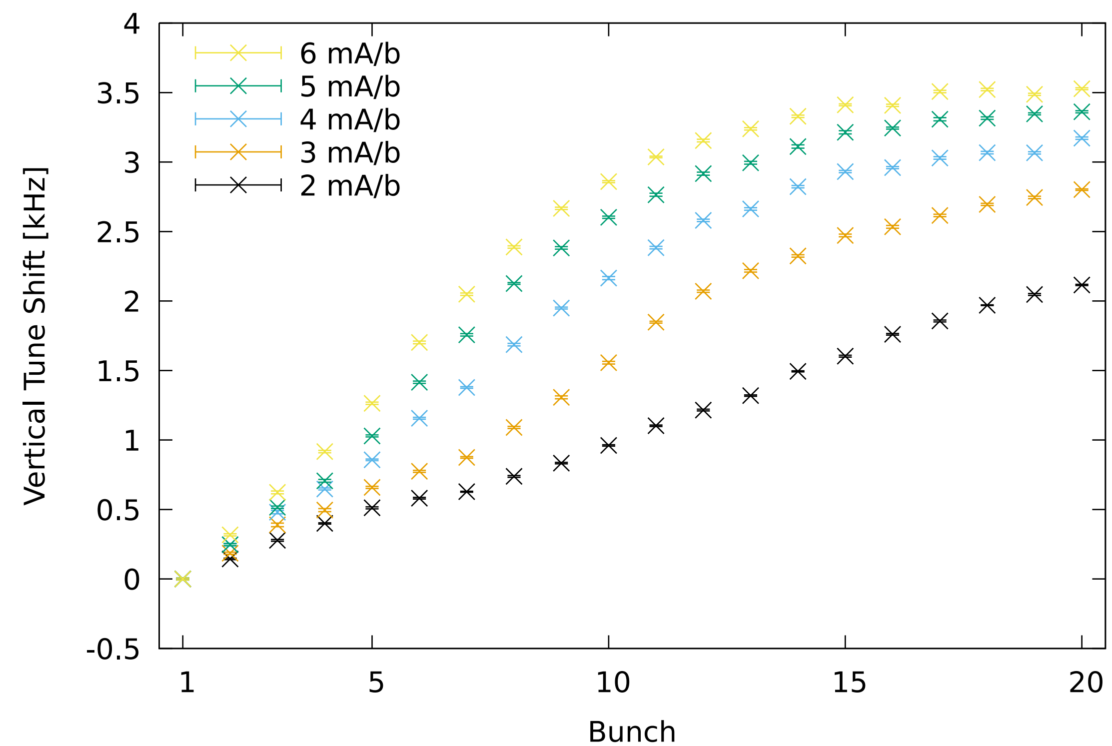
2.1 GeV





5.3 GeV





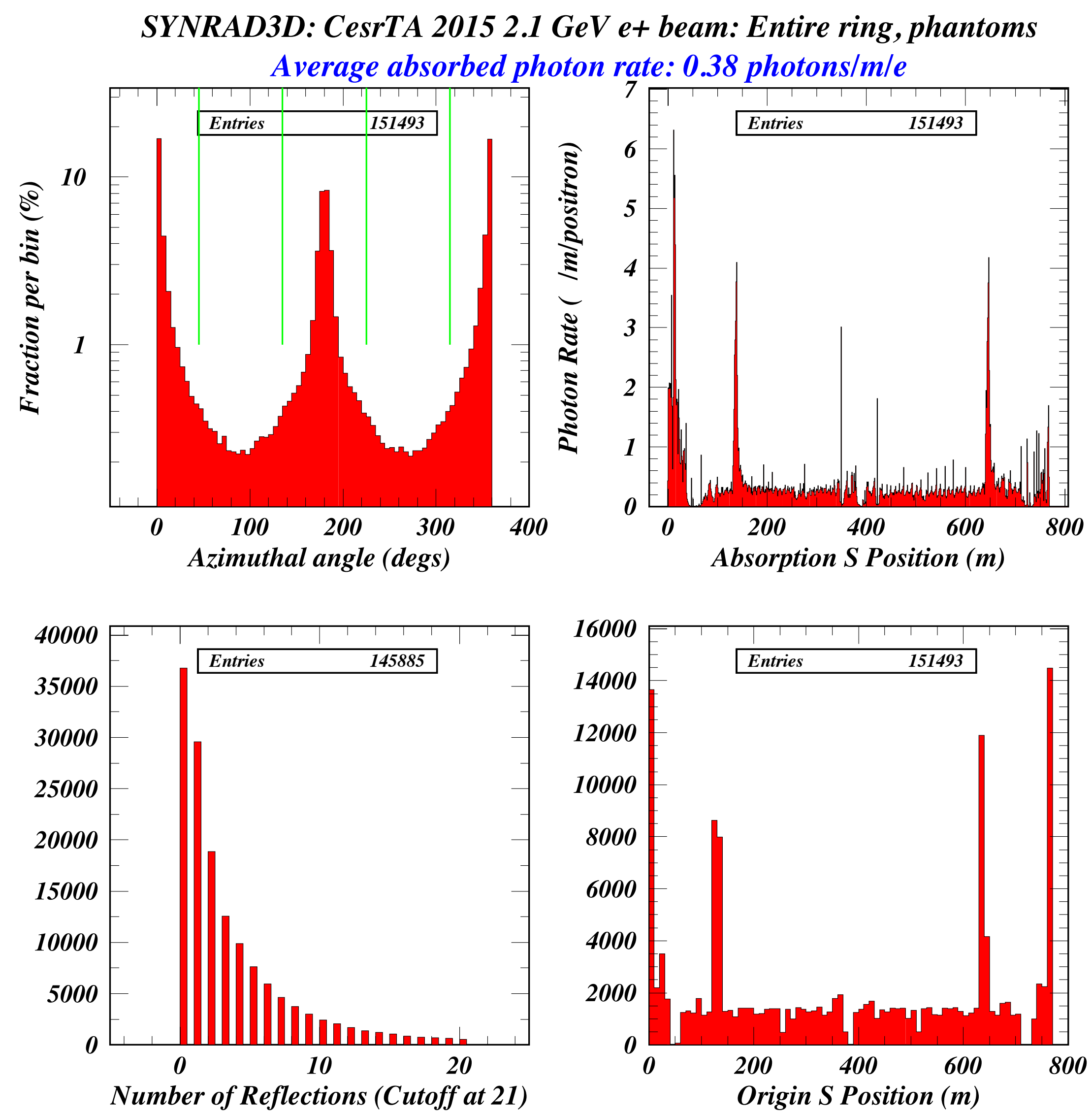
Simulations

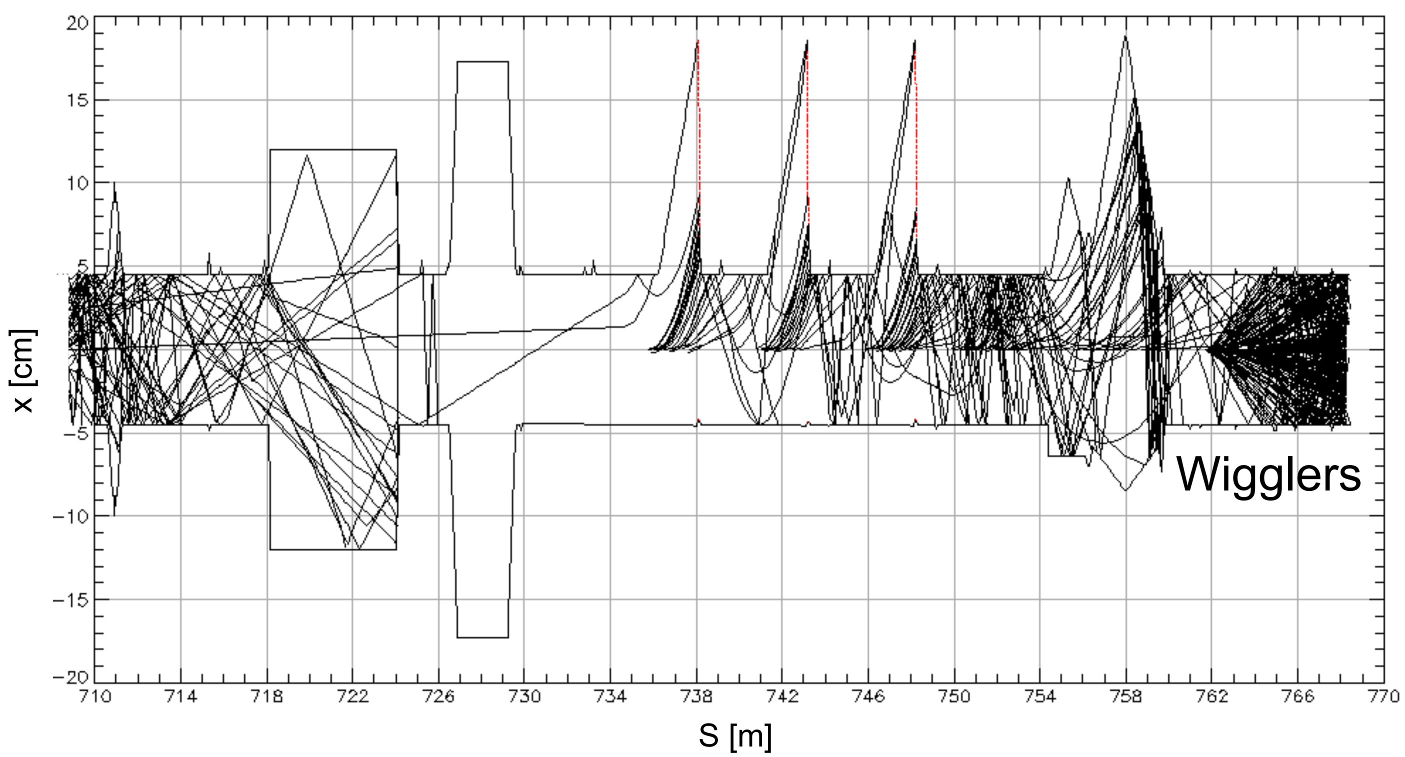
- Simulations involve four codes which feed into each other
  1. Tracking photons from synchrotron radiation (Synrad3D)
     - ➔ Information on photons absorbed in vacuum chamber
  2. Photo-electron production (Geant4)
     - ➔ Quantum efficiencies
     - ➔ Photo-electron energies
  3. Electron cloud buildup (ECLOUD)
     - ➔ Space-charge electric field maps
  4. Tracking of beam through the lattice with EC elements (Bmad)
     - ➔ Betatron tunes
     - ➔ Equilibrium beam size

- The separation of steps 3 and 4 makes this a “weak strong” simulation
  – More on this later

1) Photon tracking

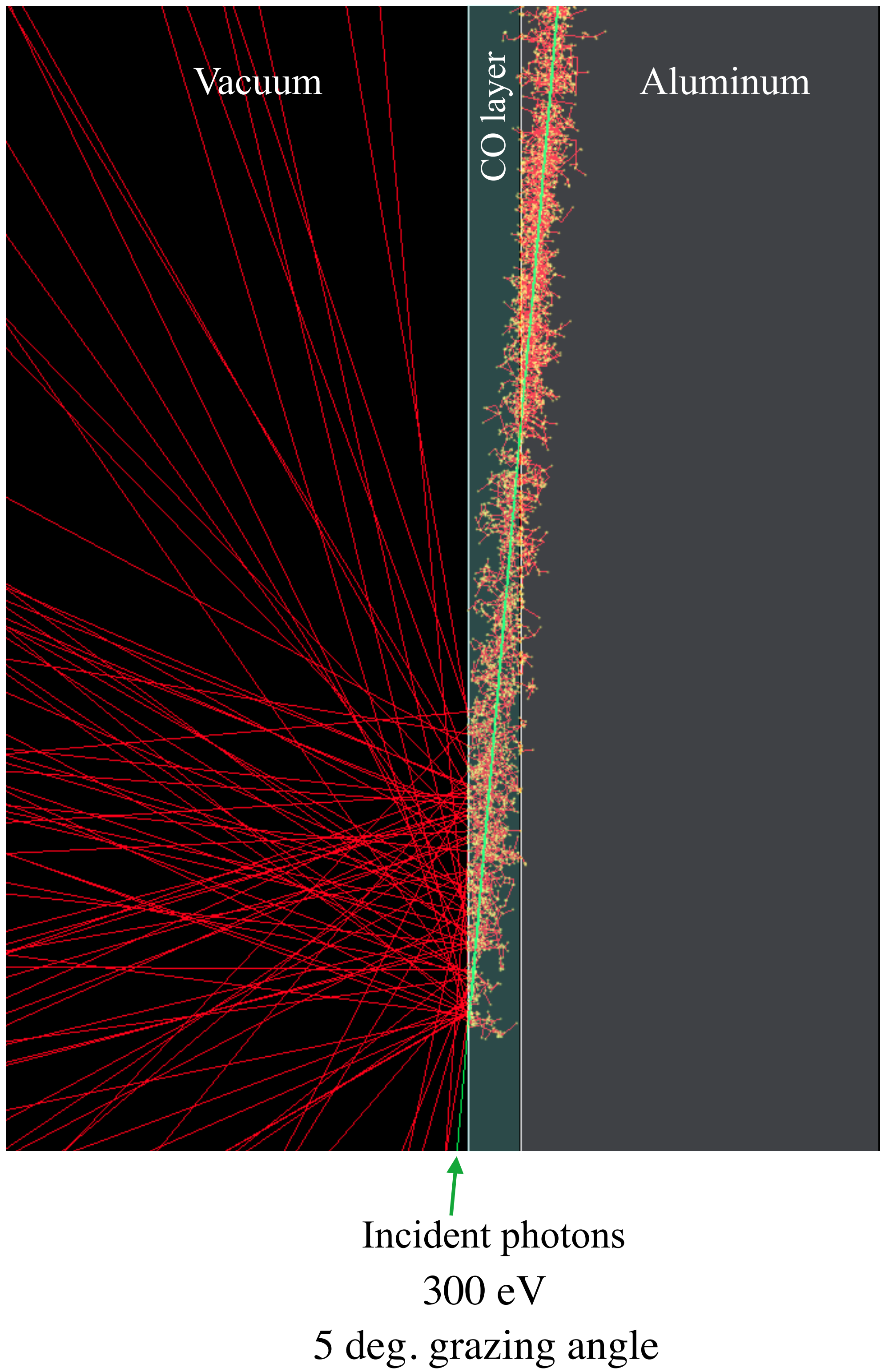
- Synrad3D
  - Simulates photons from synchrotron radiation
  - Tracks photons through vacuum chamber including specular & diffuse reflections
  - Input: lattice, 3D vacuum chamber profile, material
  - Output: information on absorbed photons:
    - ★ Azimuthal angle
    - ★ Energy
    - ★ Grazing angle with vacuum chamber wall





2) Photo-electron production

- Geant4
  - Input: Absorbed photons
    - ★ Azimuthal angle
    - ★ Energy
    - ★ Grazing angle with vacuum chamber wall
  - Simulates electron production from photo-electric and Auger effects
  - Vacuum chamber material (Aluminum) and surface layer (5 nm carbon-monoxide)
  - Output:
    - ★ Quantum efficiency vs azimuthal angle
    - ★ Photo-electron energy distributions
  - QE depends on photon energy & grazing angle which vary azimuthally
  - Improvement on ECLOUD model
  - Big improvement to predictive ability

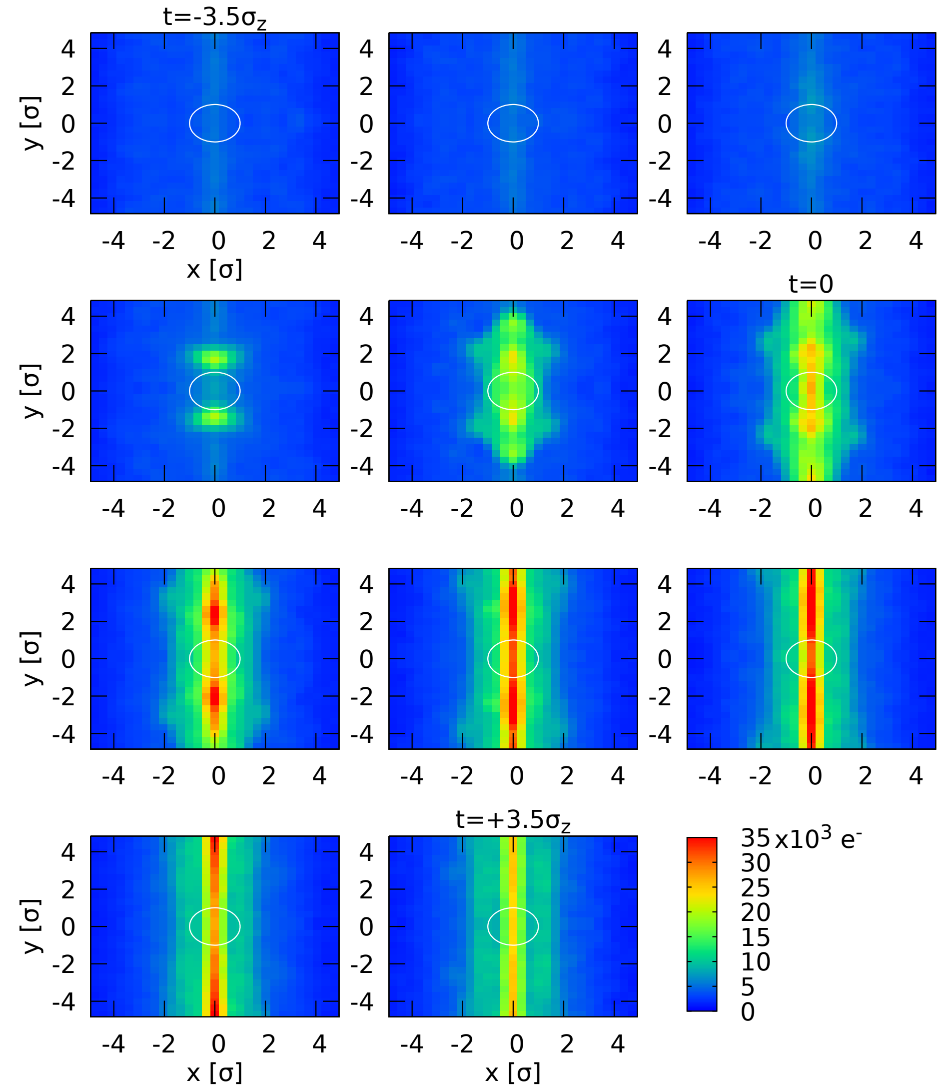


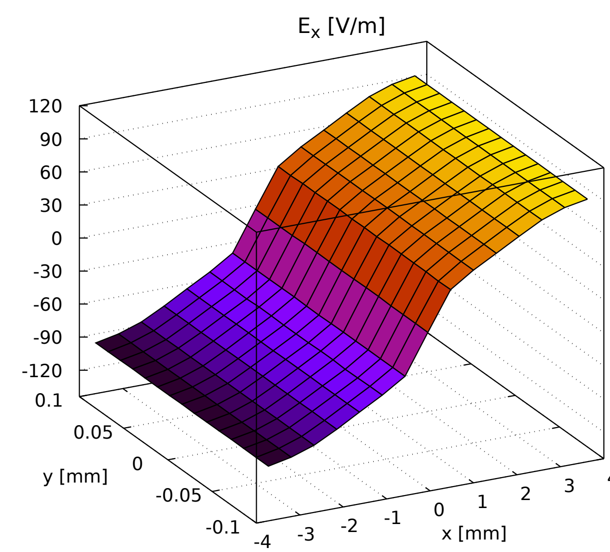
★ See Jim Crittenden's talk Wednesday morning

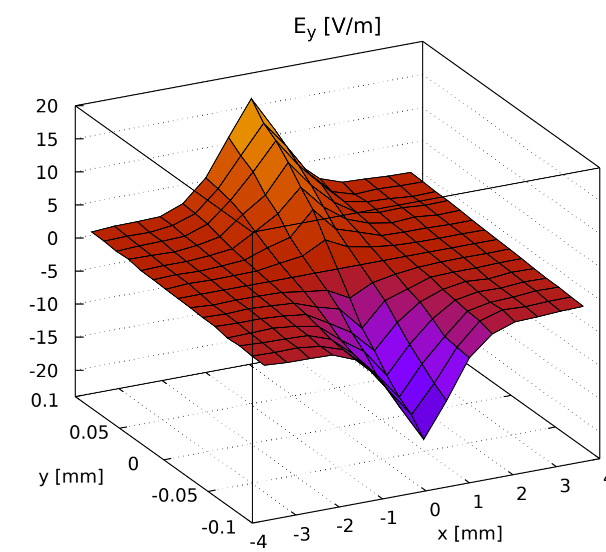
3) EC buildup simulation

- Start with EC buildup simulations with ECLOUD in both dipole and field-free regions
- Use element-type ring-averaged beam sizes
  - Dipole: 730 x 20 um
  - Drift: 830 x 20 um
    - ★ The large horizontal size is dominated by dispersion
- Obtain space-charge electric field maps from the EC for 11 time slices during a single bunch passage, in ±5σ of the transverse beam size
  - Δt = 20 ps
- Only ~0.1% of electrons are within this beam region
  - Necessary to average over many ECLOUD simulations

Transverse EC charge distributions in an 800 G dipole for bunch 30 of a 0.7 mA/b positron train







Calibration of model to tune shift measurements

- ECLOUD simulations depend strongly on vacuum chamber secondary yield (SEY) parameters
- Direct SEY measurements provide a good starting point, but it's hard to accurately determine all the parameters
- Still, the condition in the machine may be different

- To improve agreement between the ECLOUD model and our various measurements:
  - Use a multi-objective optimizer to fit the SEY parameters to tune shift data
  - At each iteration, run ECLOUD simulations in parallel varying each parameter by an adaptive increment
    - ★ Calculate Jacobian & provide to optimizer

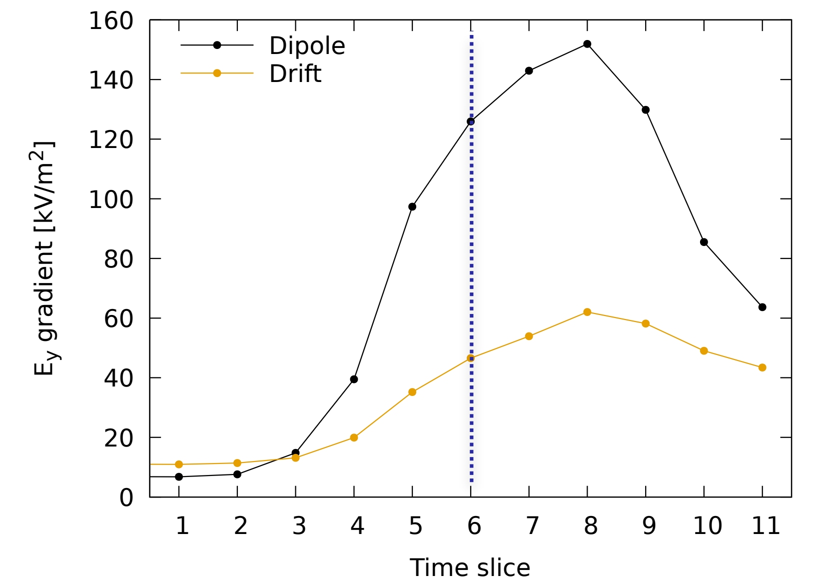
TABLE I. Main parameters of the model.

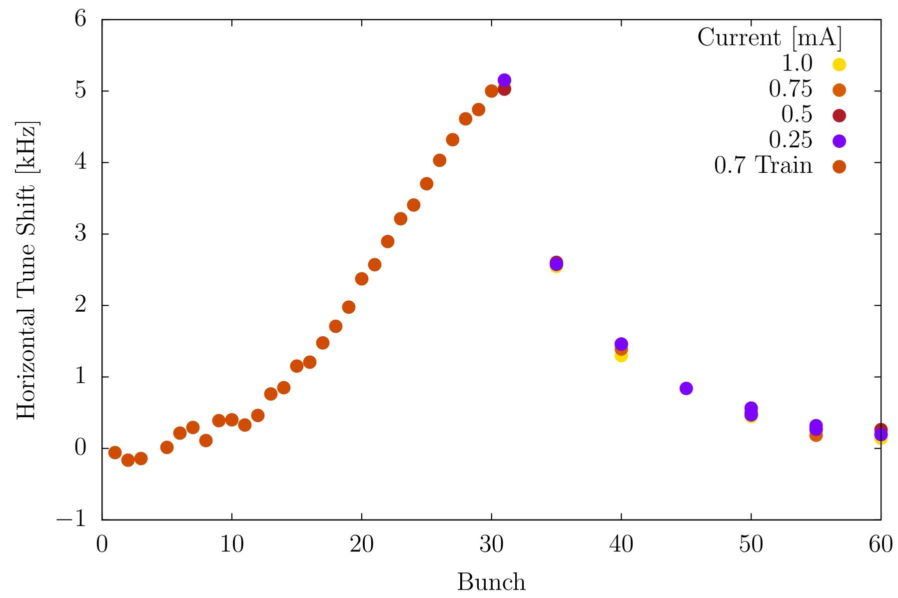
	Copper	Stainless steel
	Emitted angular spectrum (Sec. IIC1)	
α	1	1
	Backscattered electrons (Sec. IIIB)	
$P_{1,e}(\infty)$	0.02	0.07
$\hat{P}_{1,e}$	0.496	0.5
$\hat{E}_e$ (eV)	0	0
W (eV)	60.86	100
p	1	0.9
σ_e (eV)	2	1.9
e_1	0.26	0.26
e_2	2	2
	Rediffused electrons (Sec. IIIC)	
$P_{1,r}(\infty)$	0.2	0.74
E_r (eV)	0.041	40
r	0.104	1
q	0.5	0.4
r_1	0.26	0.26
r_2	2	2
	True-secondary electrons (Sec. IIID)	
$\hat{\delta}_{ts}$	1.8848	1.22
$\hat{E}_{ts}$ (eV)	276.8	310
s	1.54	1.813
t_1	0.66	0.66
t_2	0.8	0.8
t_3	0.7	0.7
t_4	1	1
	Total SEY[a]	
$\hat{E}_t$ (eV)	271	292
$\hat{\delta}_t$	2.1	2.05

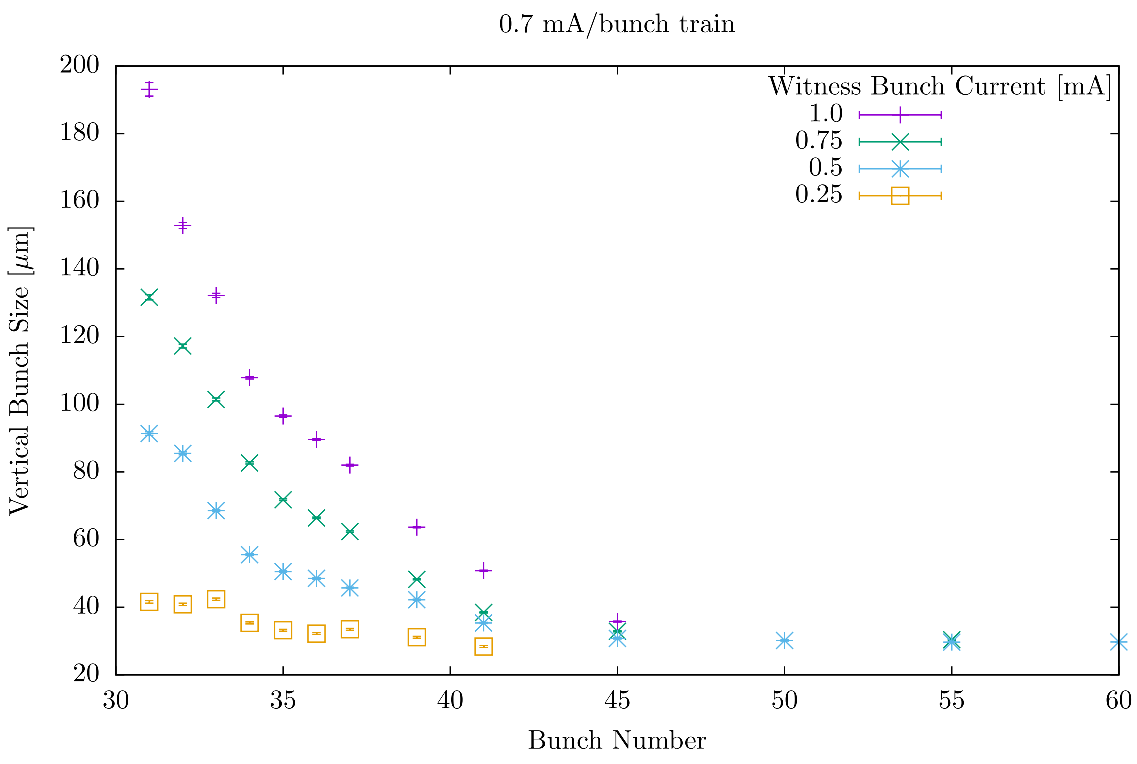
M. Furman & M. Pivi, "Probabilistic Model for the Simulation of Secondary Electron Emission," *Phys. Rev. ST Accel. Beams* **5**, 124404 (Dec. 2002)

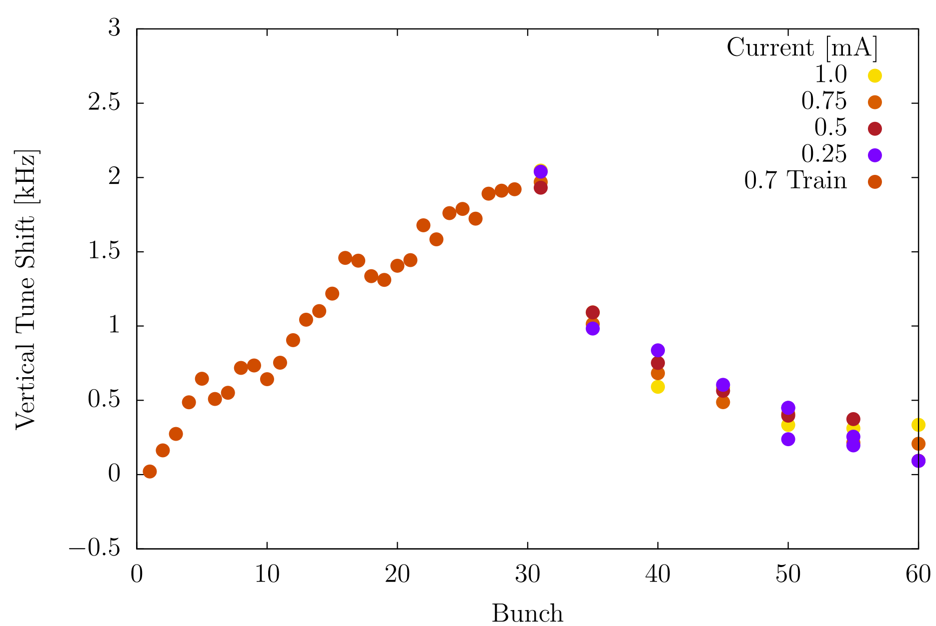
Electric field gradients from cloud space-charge fields

- Tune shifts calculated from the cloud space-charge electric field gradients
- Gradient just before a bunch passage ➔ coherent tune shift
  - Demonstrated in witness bunch tune measurements (left)
- Gradient during pinch ➔ incoherent tune spread, emittance growth
  - Demonstrated in witness bunch size measurements (right)





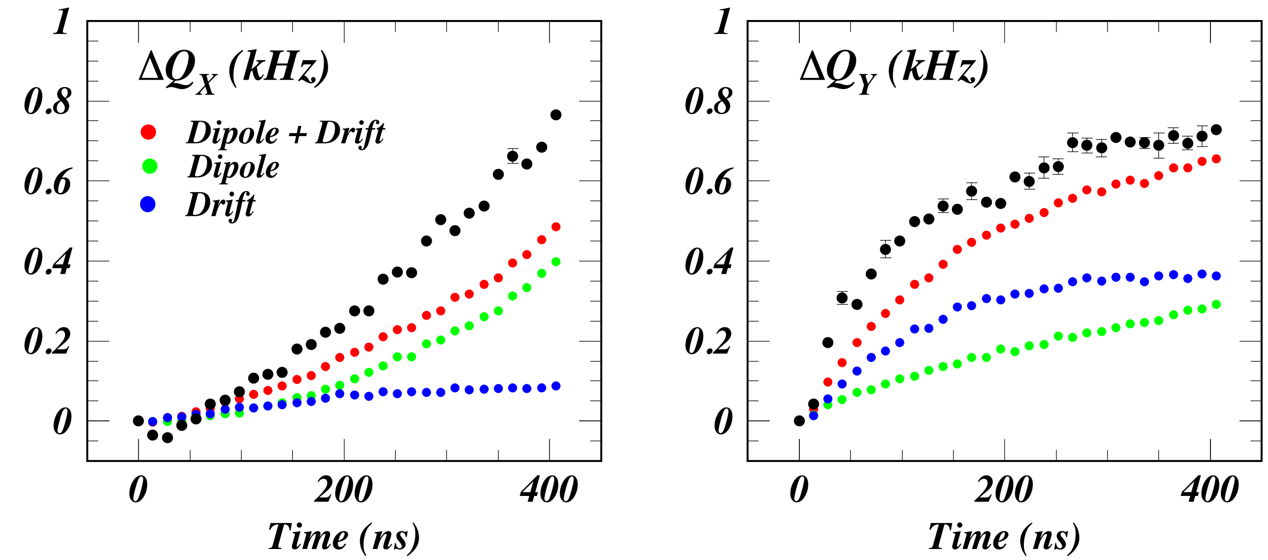




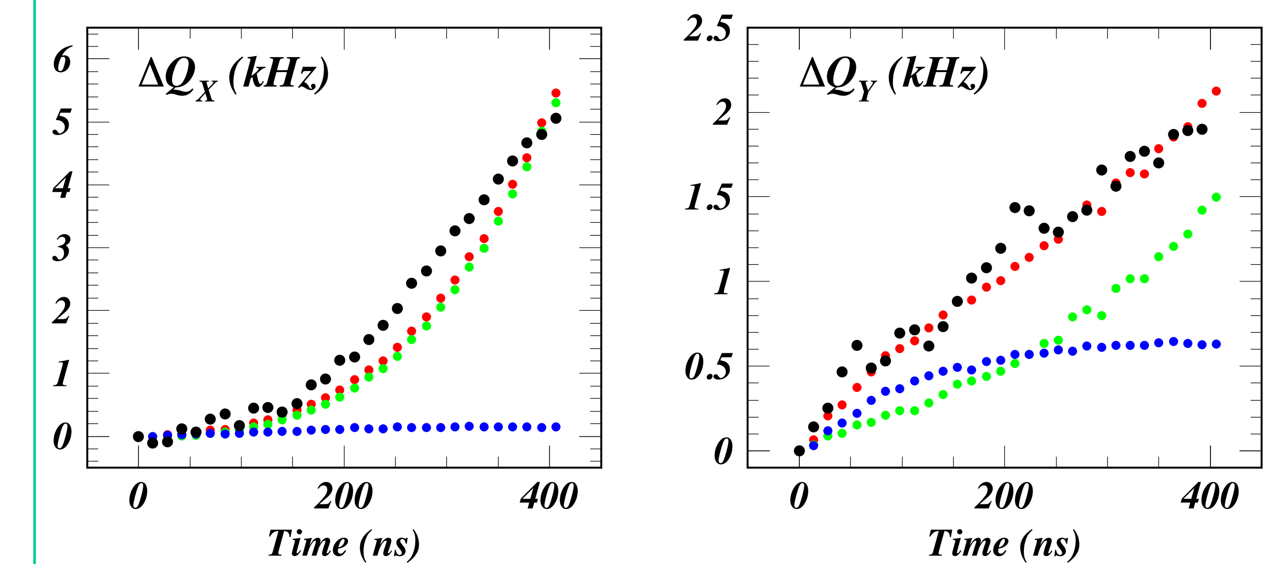
Simulated tune shifts at 2.1 GeV

- Results from fitting ECLOUD model to data
- Simultaneously fit to:
  - 0.7 mA/b at 2.1 GeV
  - 2, 3, and 6 mA/b at 5.3 GeV (next slide)
- Parameters varied include:
  - Peak energy of true secondary yield
  - True secondary yield 's' parameter
  - True secondary yield
  - Rediffused secondary yield
  - Elastic yield at 0 energy
- Same SEY parameters used in simulations at all currents & energies

0.4 mA/b

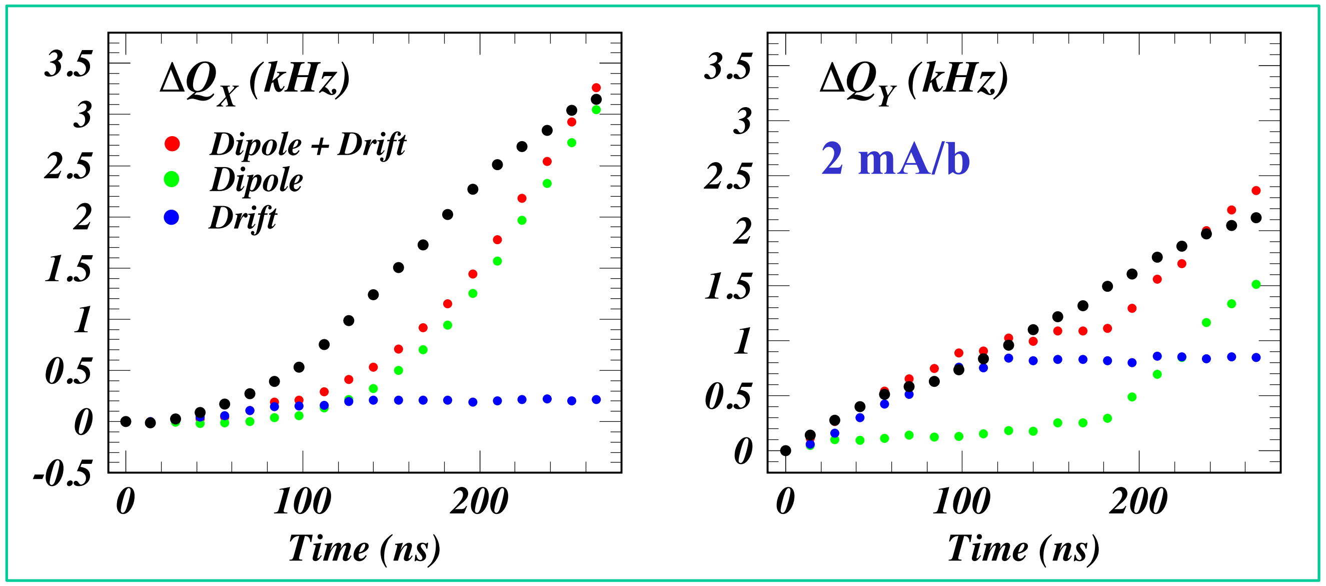


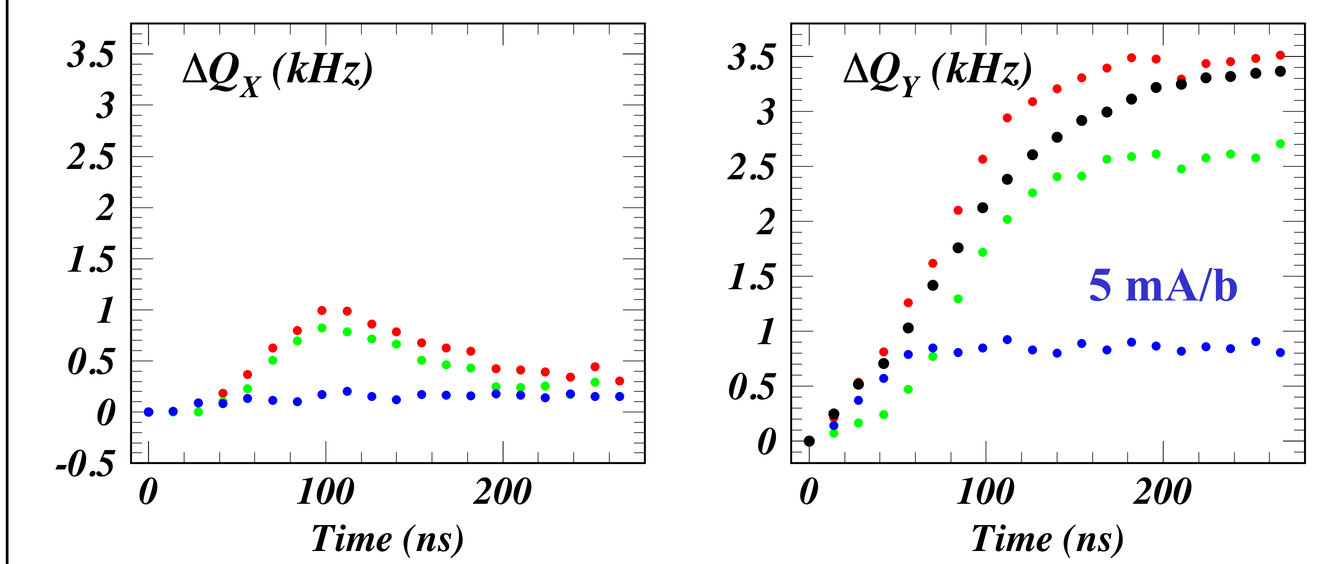
0.7 mA/b

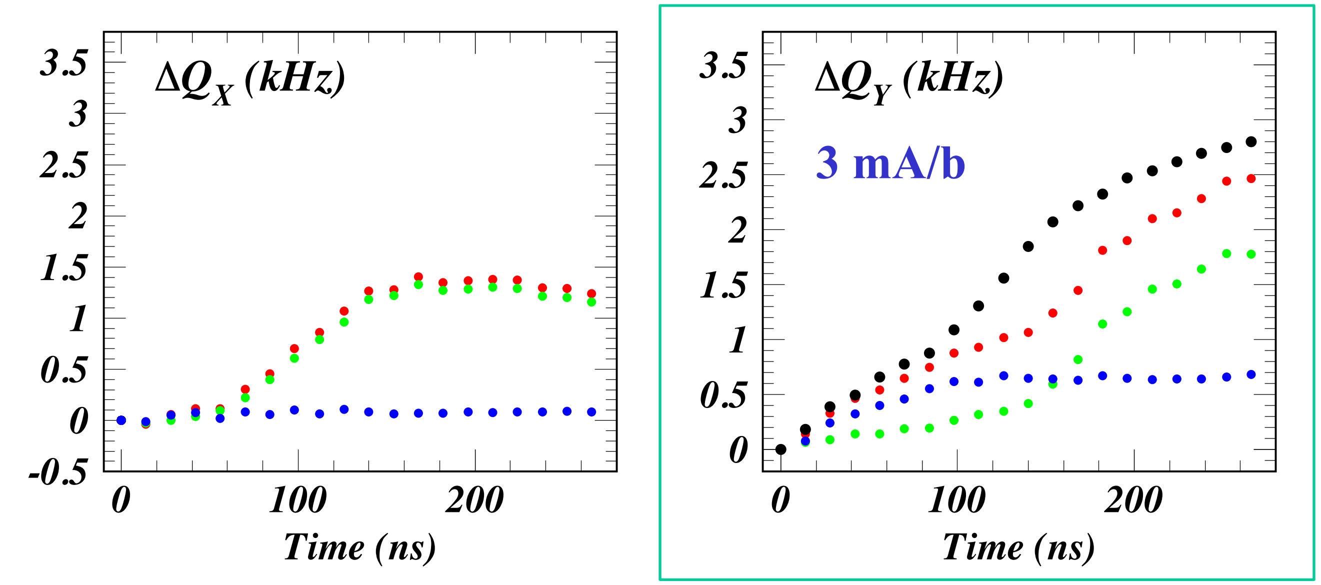


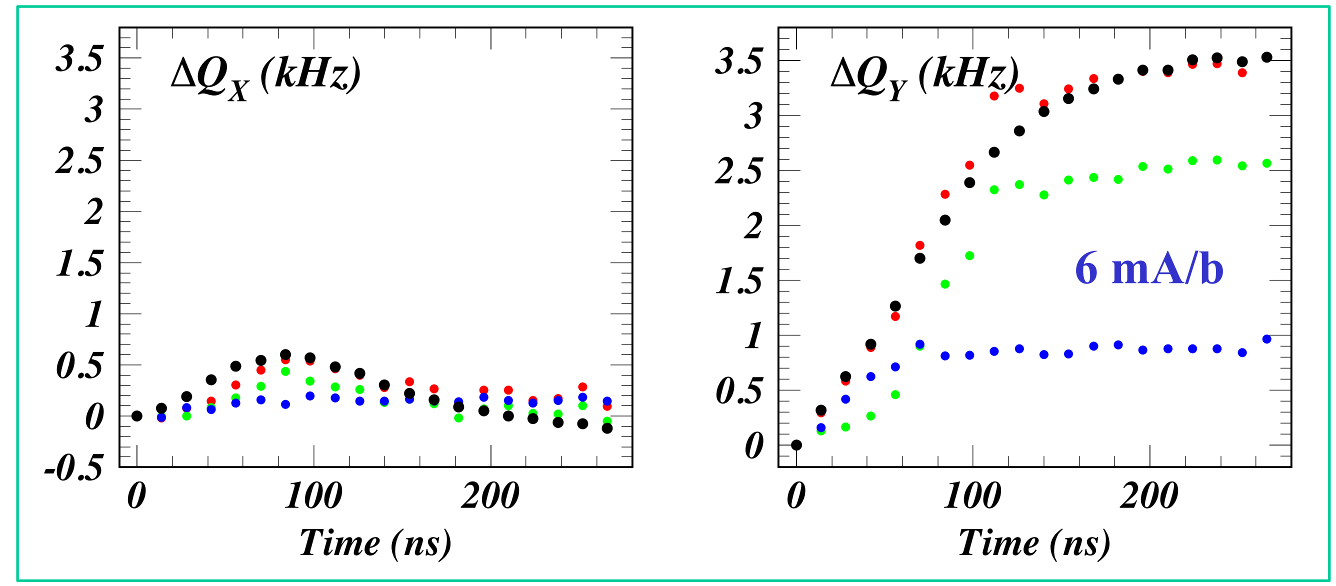
(Revolution frequency: 390 kHz)

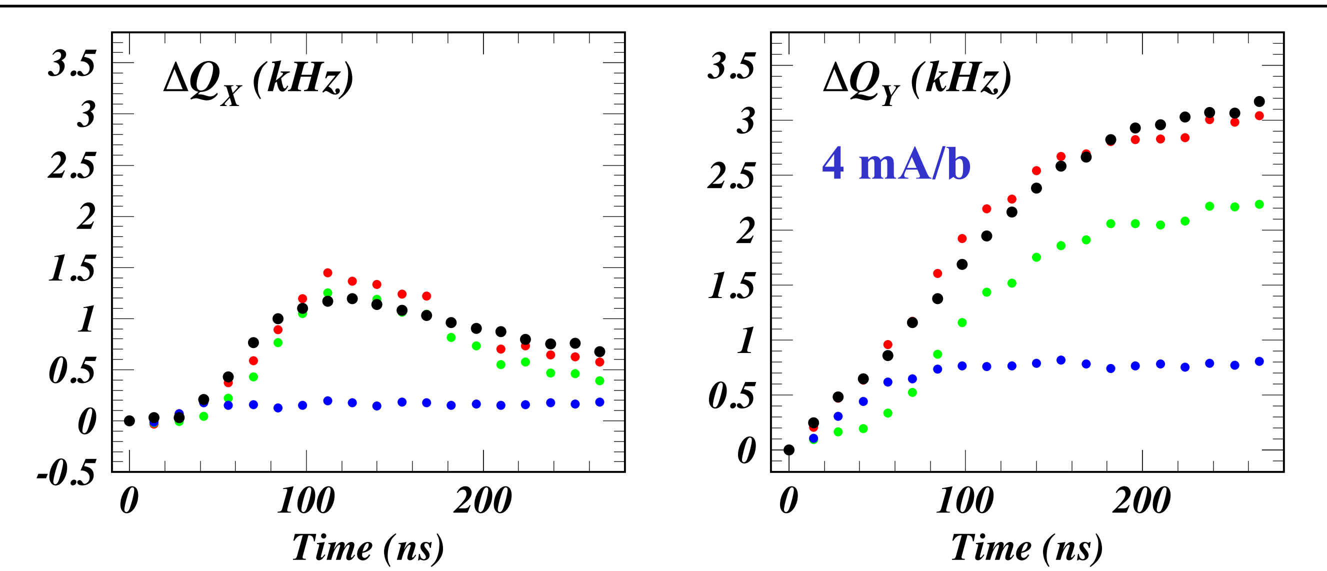
Simulated tune shifts at 5.3 GeV









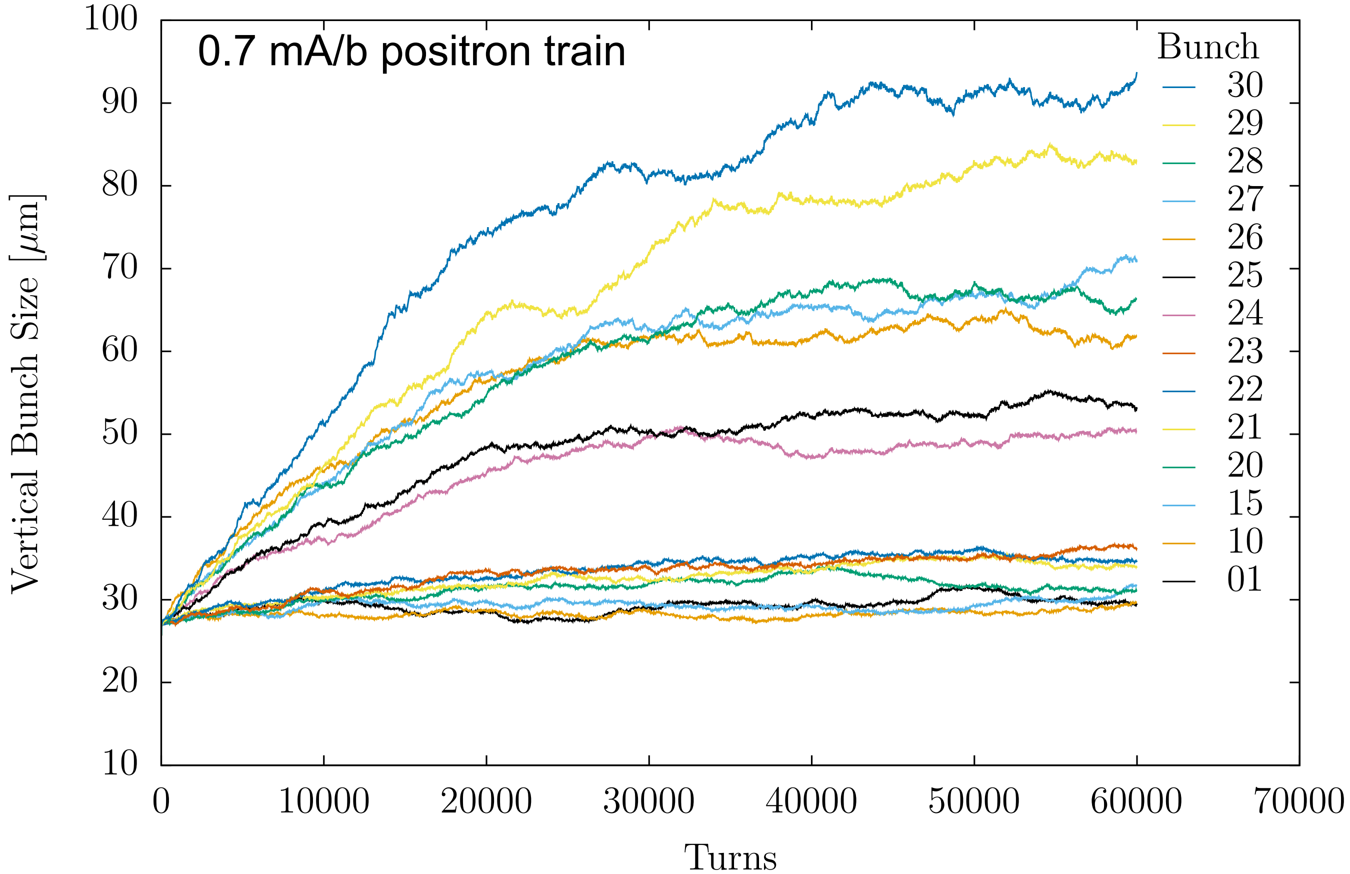


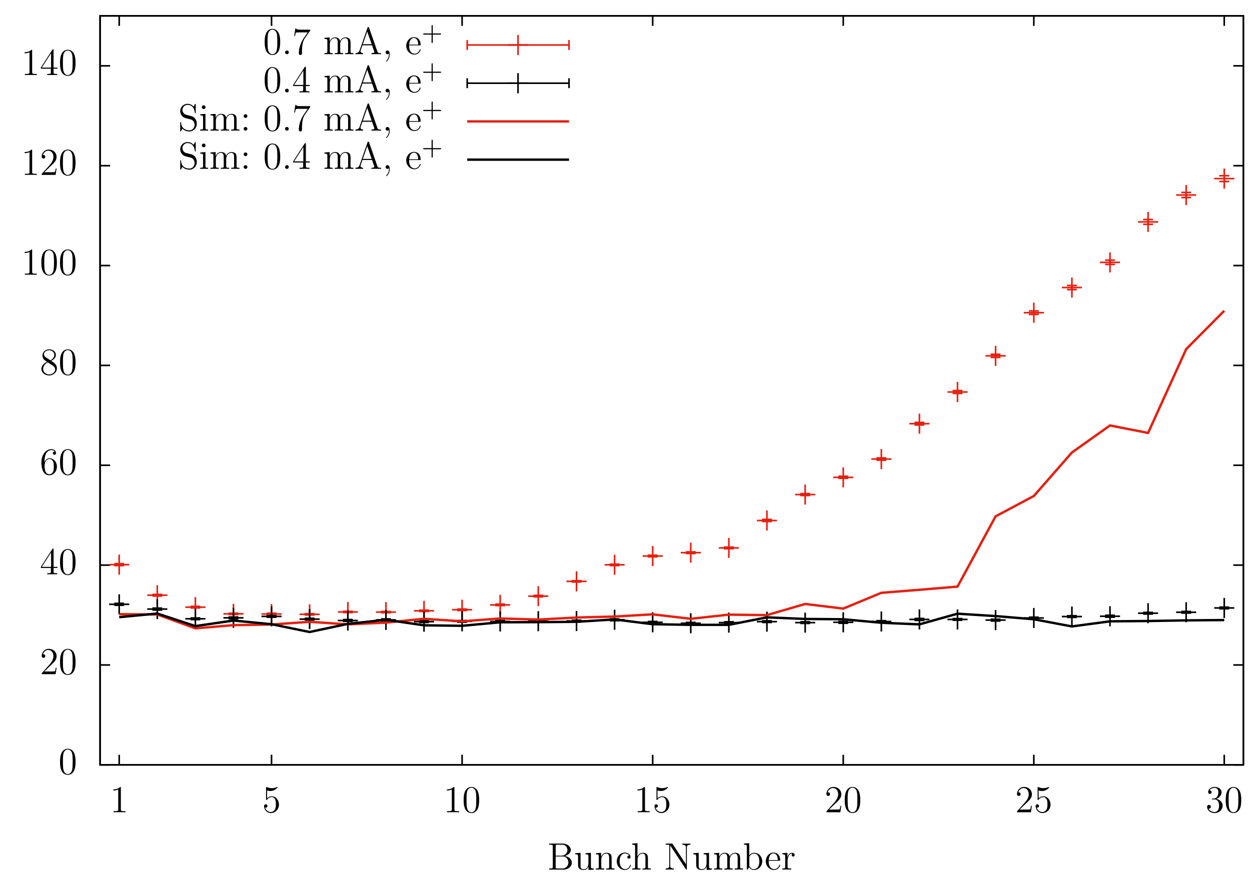
4) Tracking simulations

- Use the *time-sliced electric field maps* in EC elements at the dipole and drifts
- Track particles in bunch through the full lattice (using Bmad) for multiple damping times, with radiation excitation and damping
- "weak-strong" model: does not take into account effects on the cloud due to changes in the beam
  - Tracking: Weak: beam; Strong: EC
  - EC buildup simulations: Weak: EC; Strong: beam
  - Justification: EC buildup simulations are rather insensitive to vertical beam size
- Strong-strong simulations are too computationally intensive to track for enough turns
  - Damping times at CesrTA are ~20,000 turns
  - We want equilibrium beam sizes

Vertical bunch size growth - train

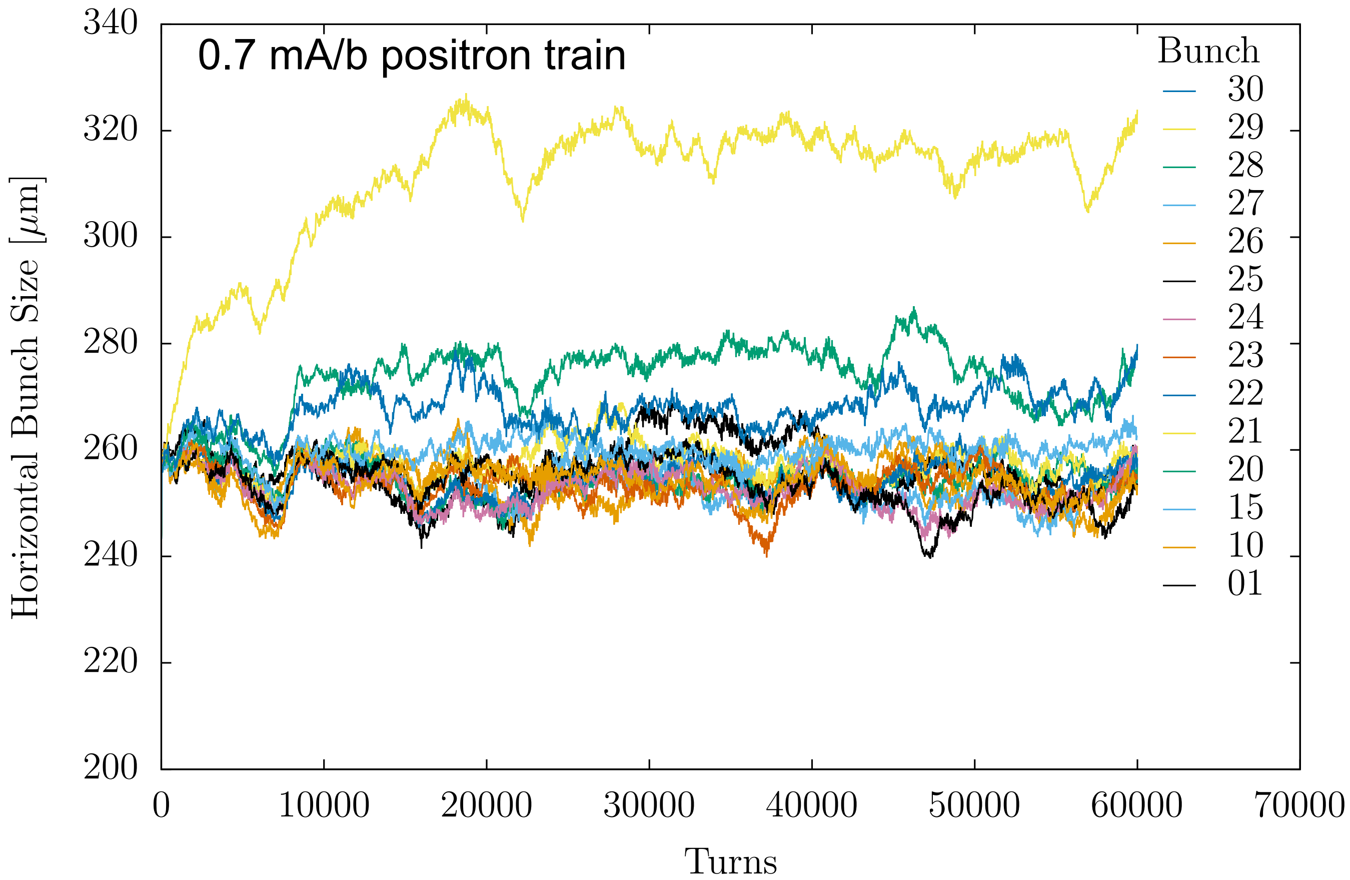
- Bunch size from simulation is the average over last 10k turns (of 60k)
- See vertical emittance growth in 0.7 mA/b simulations

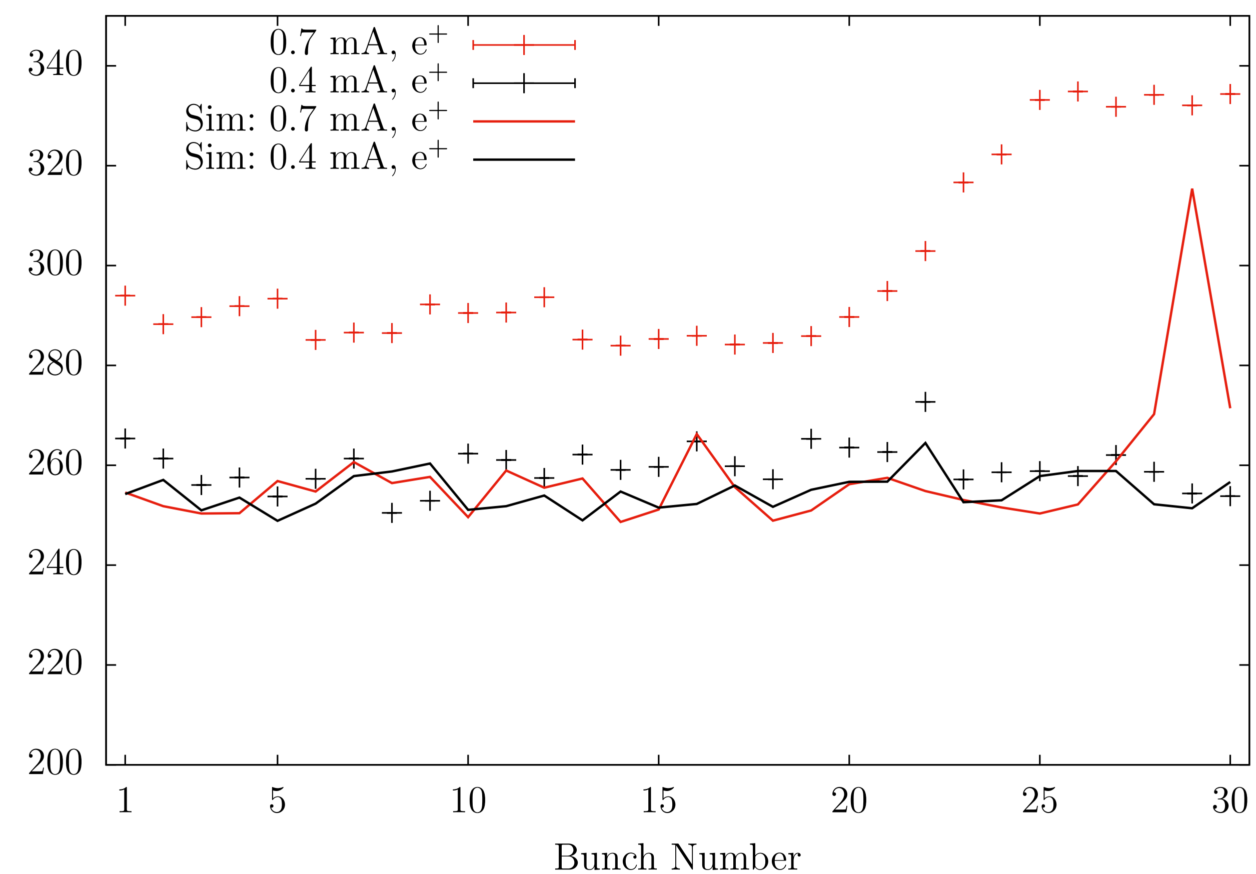




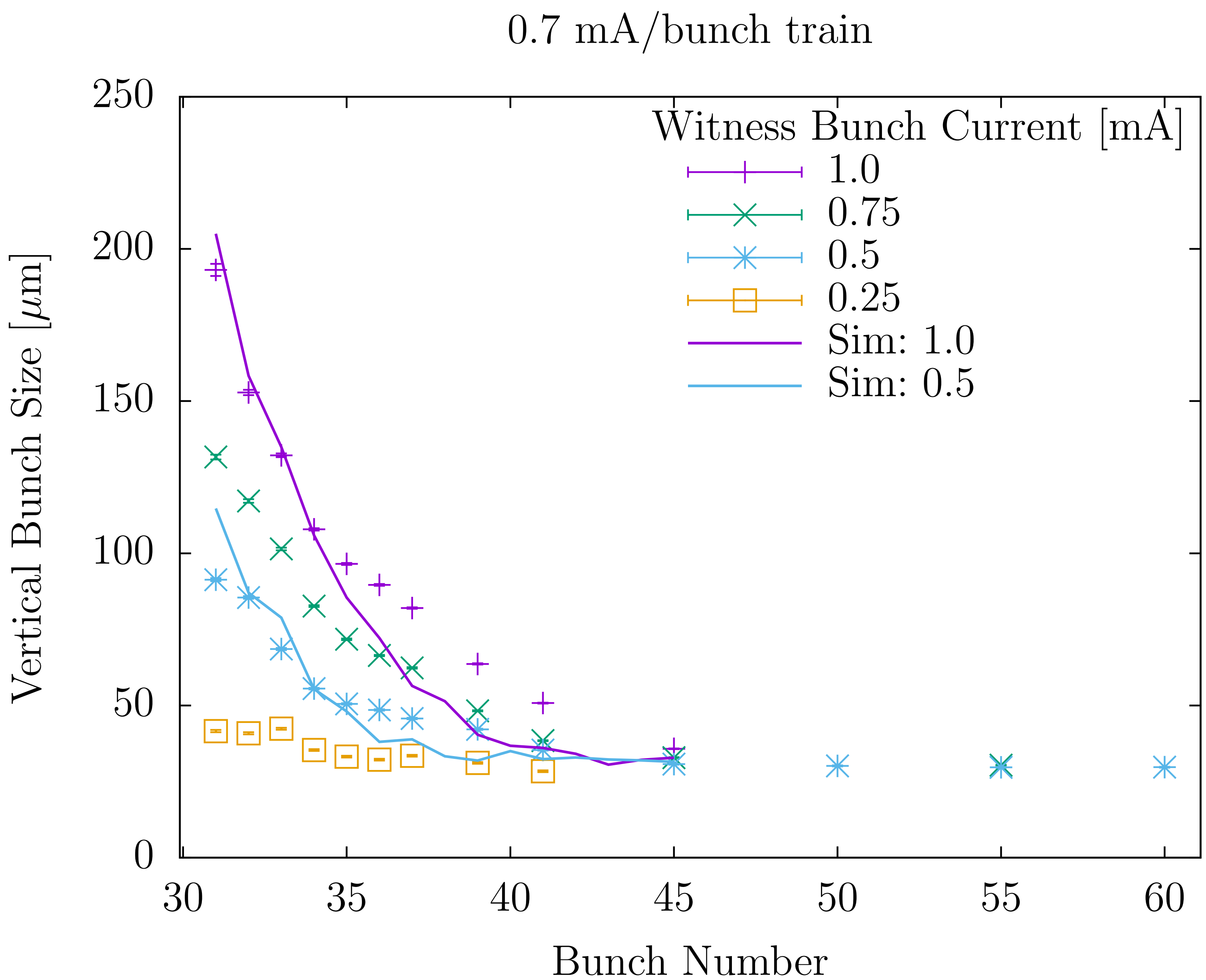
Horizontal bunch size growth - train

- See some horizontal emittance growth in 0.7 mA/b simulations compared to 0.4 mA/b but needs investigation





Vertical bunch size growth - witness bunch



- More emittance growth with:
  - shorter distances from train (more cloud)
  - *higher witness bunch current (more pinch)*
- Simulations show similar behavior

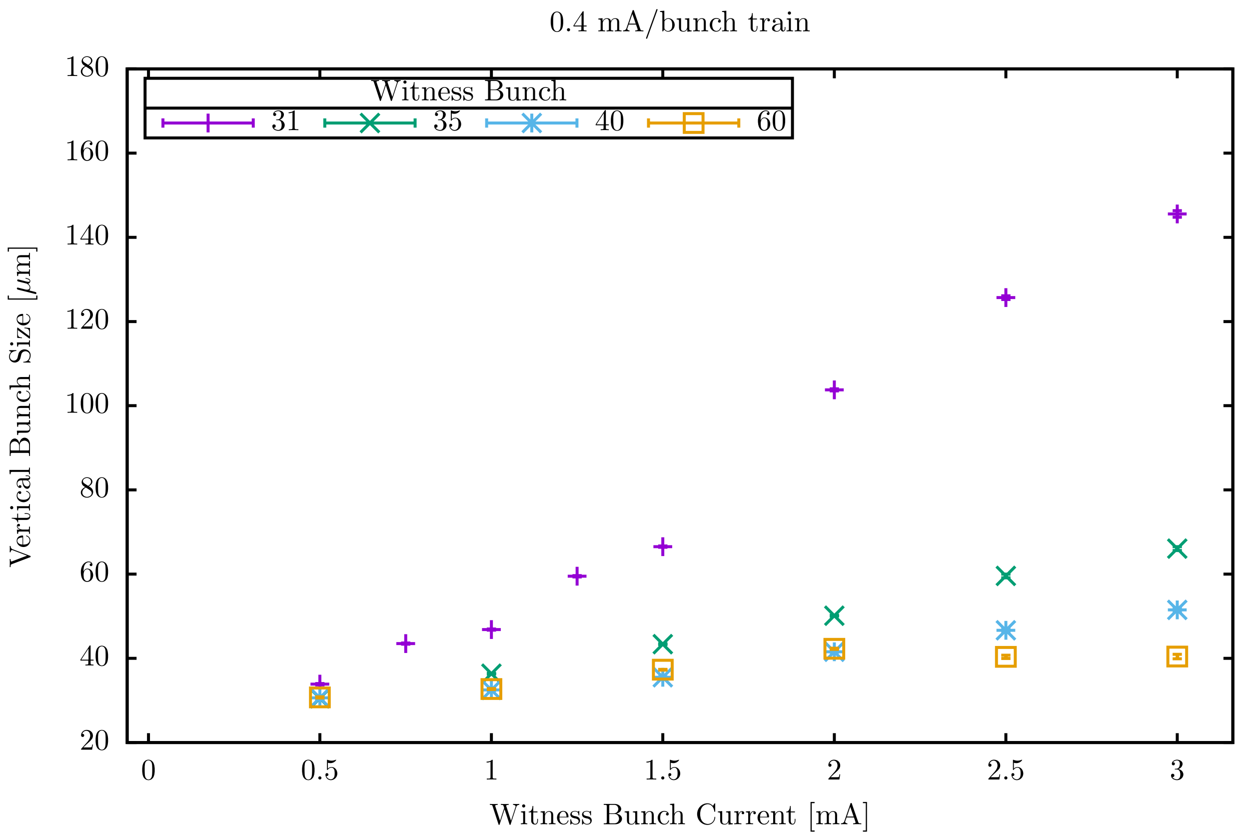
Summary

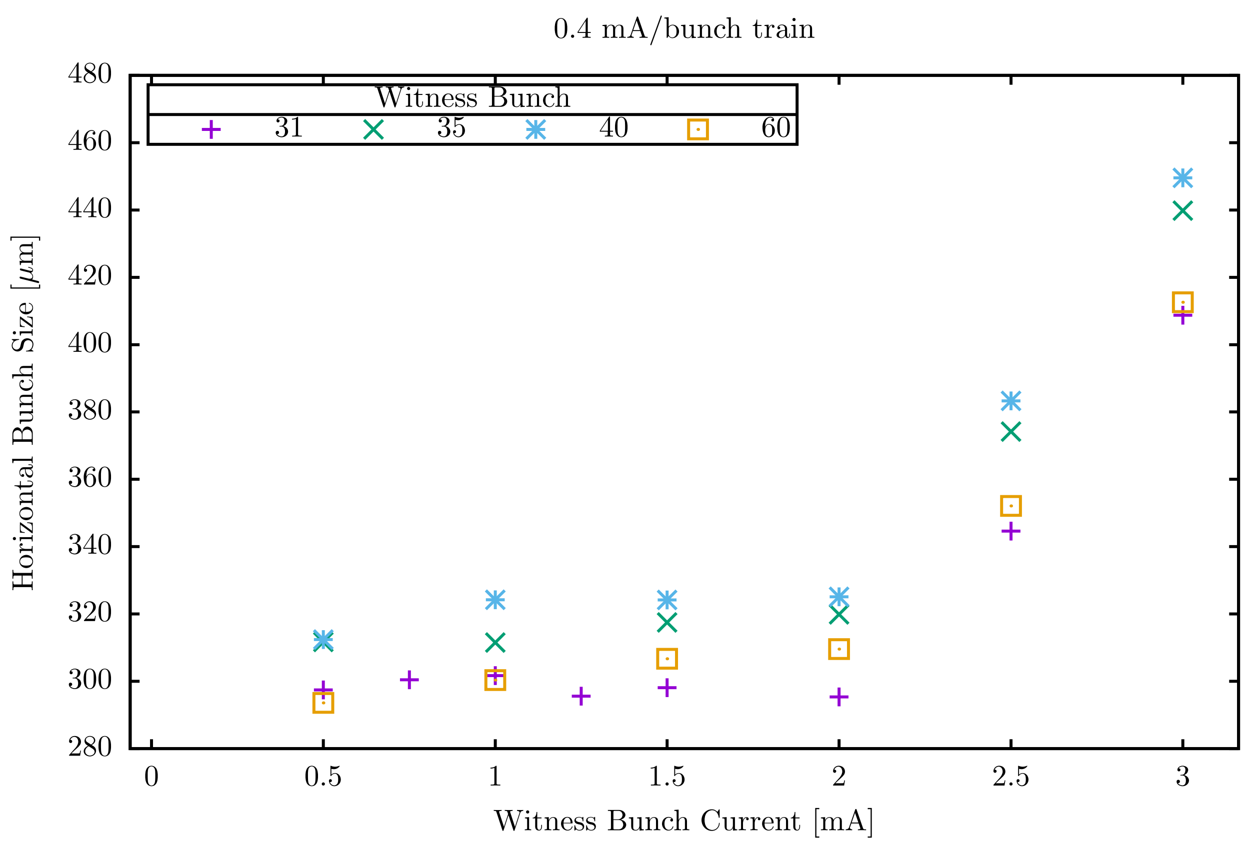
- We have obtained various measurements of tune shifts and emittance growth from electron clouds
- Our e-cloud model has been improved with precise modeling of synchrotron radiation photons & generation of primary electrons
- The model has been validated with improved tune shift measurements for a range of bunch currents at 2.1 and 5.3 GeV
- A witness bunch at a range of currents gives a direct measurement of the pinch effect
  - Vertical emittance growth scales with pinch
  - Coherent tune shift does not
- Our weak-strong incoherent model is consistent with this data
- The simulations can uncover the largest contributions to tune shifts and emittance growth
  - EC mitigation methods can be targeted to these regions and tested in simulation
- Future work:
  - Further investigate horizontal emittance growth in simulation
  - Use model to predict EC effects at future accelerators
  - Use model to understand underlying factors driving emittance growth
    - ★ New approaches to mitigating emittance growth from EC

Thank you for your attention

Witness bunch to a 0.4 mA/b train (below threshold)

e+





e-