Recent Advances in Measurement and Modeling of Electron Cloud Buildup at CESR and Predictions for CHESS-U (Part 2)

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CLASSE Seminar

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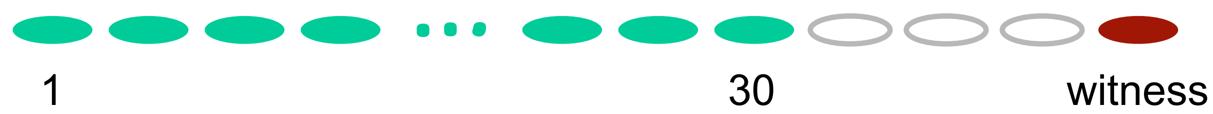
Overview

- (Part 1: Simulations of synchrotron-radiation-induced electron production in the CESR vacuum chamber wall)
- Part 2: Measurements and model validation of electron-cloud-induced betatron tune shifts in the CESRTA, CHESS and CHESS-U transition lattices and predictions for CHESS-U operation
  - Emittance growth measurements
  - Improved betatron tune shift measurements
  - Fitting e-cloud model parameters to tune shift measurements in CESRTA and CHESS conditions
  - CHESS-U transition lattice tune shifts & predictions for CHESS-U
  - Emittance growth simulations

Measurements

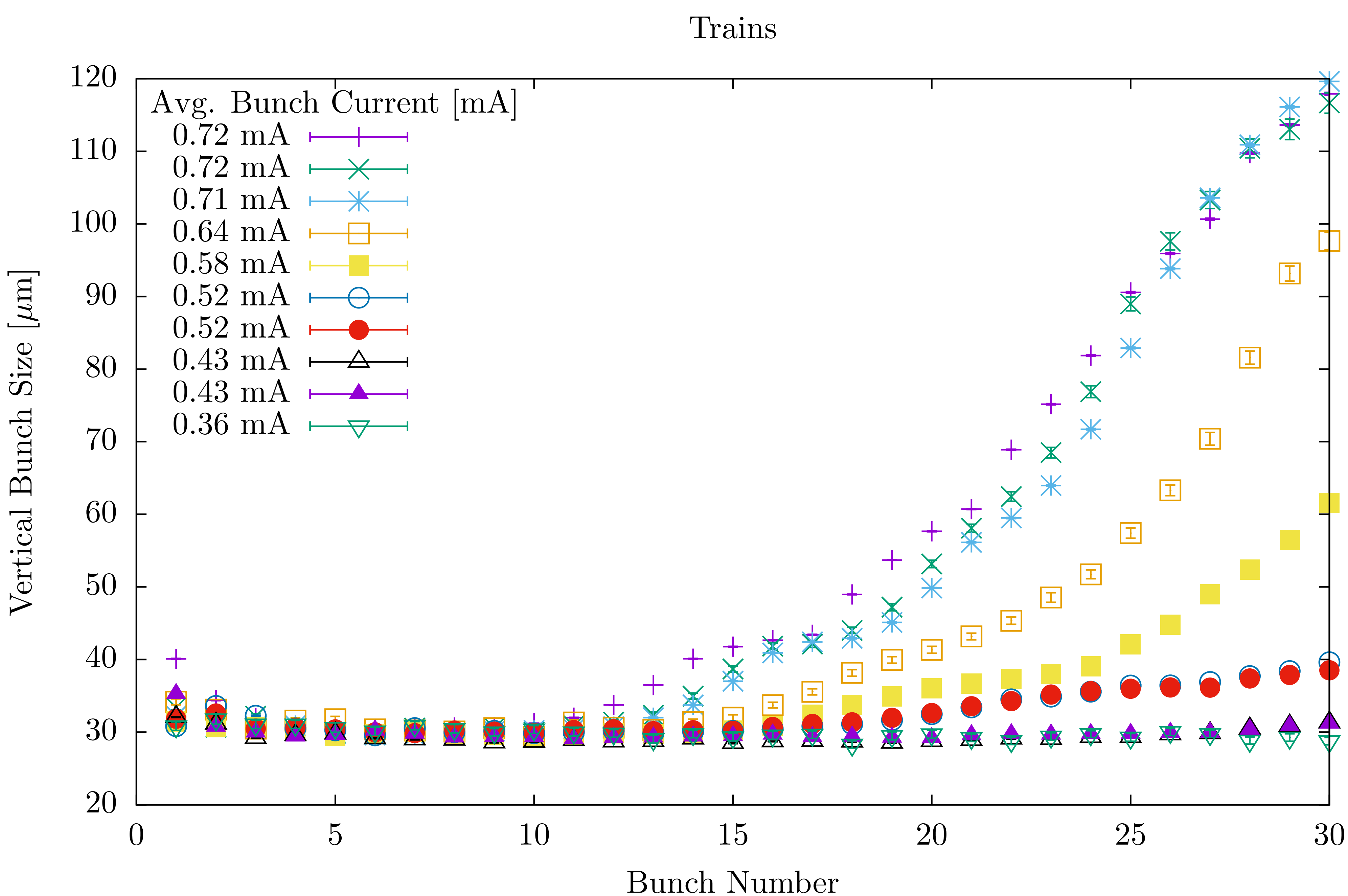
- Beam:
  - 2.1 GeV positrons or electrons (5.3 GeV for additional tune shifts)
    - ★ Horizontal emittance: 3.2 nm, fractional energy spread: 8×10^{-4}, bunch length: 9 mm
  - 30 bunch train, 0.4 mA/b and 0.7 mA/b, 14 ns spacing (2-6 mA/b at 5.3 GeV)
    - ★ (0.64×10^{10} and 1.12×10^{10} bunch populations)
  - 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

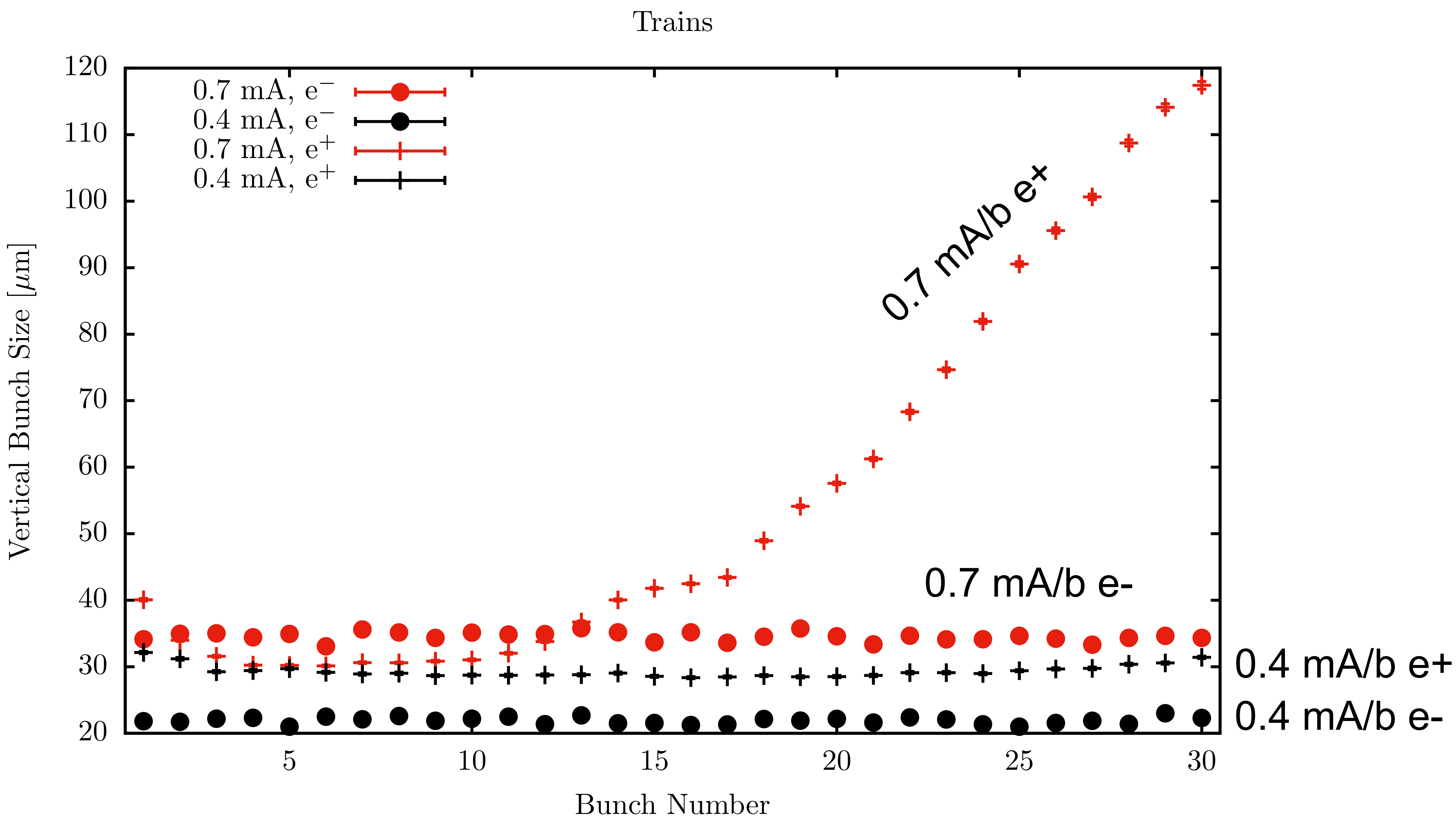
Beam size

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



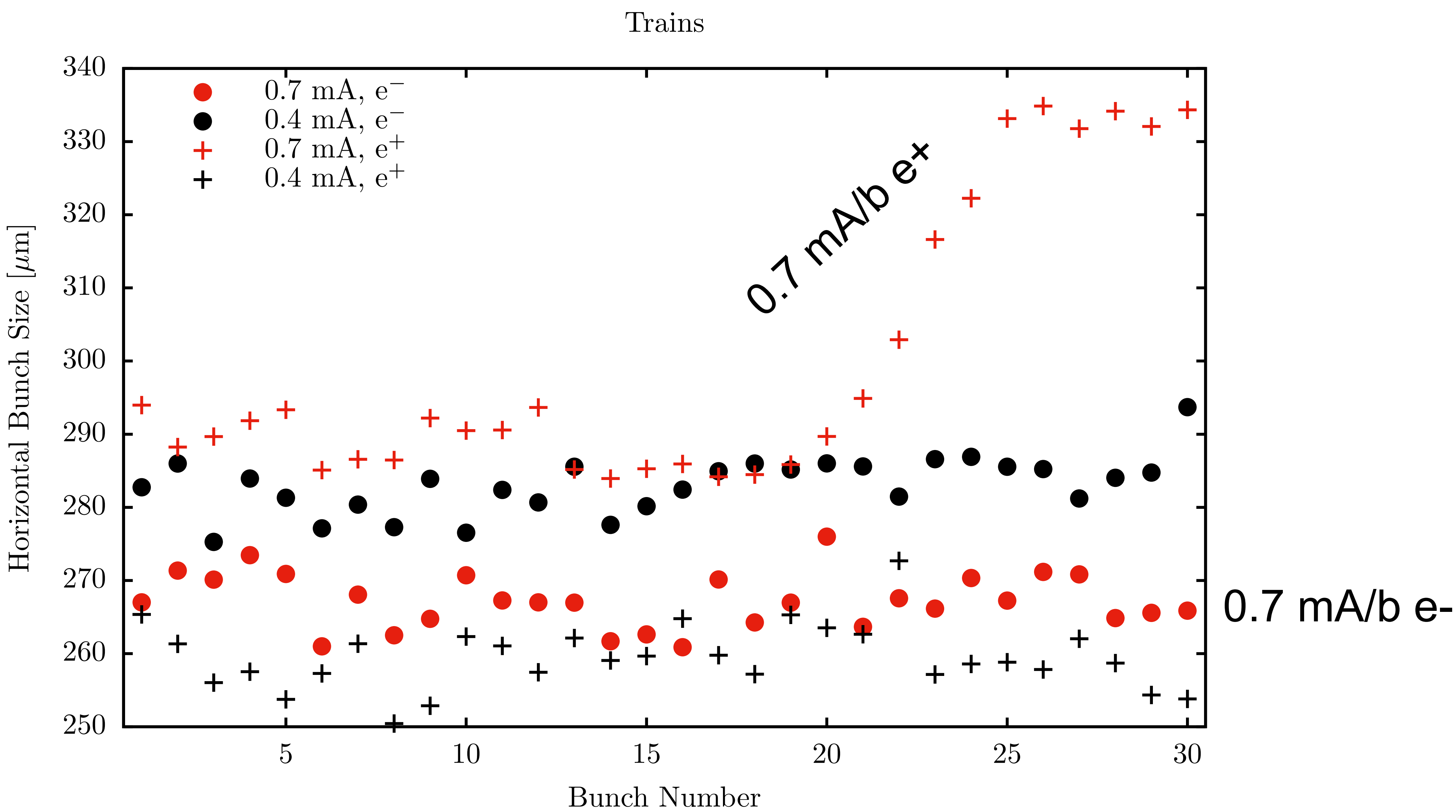
Beam size

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



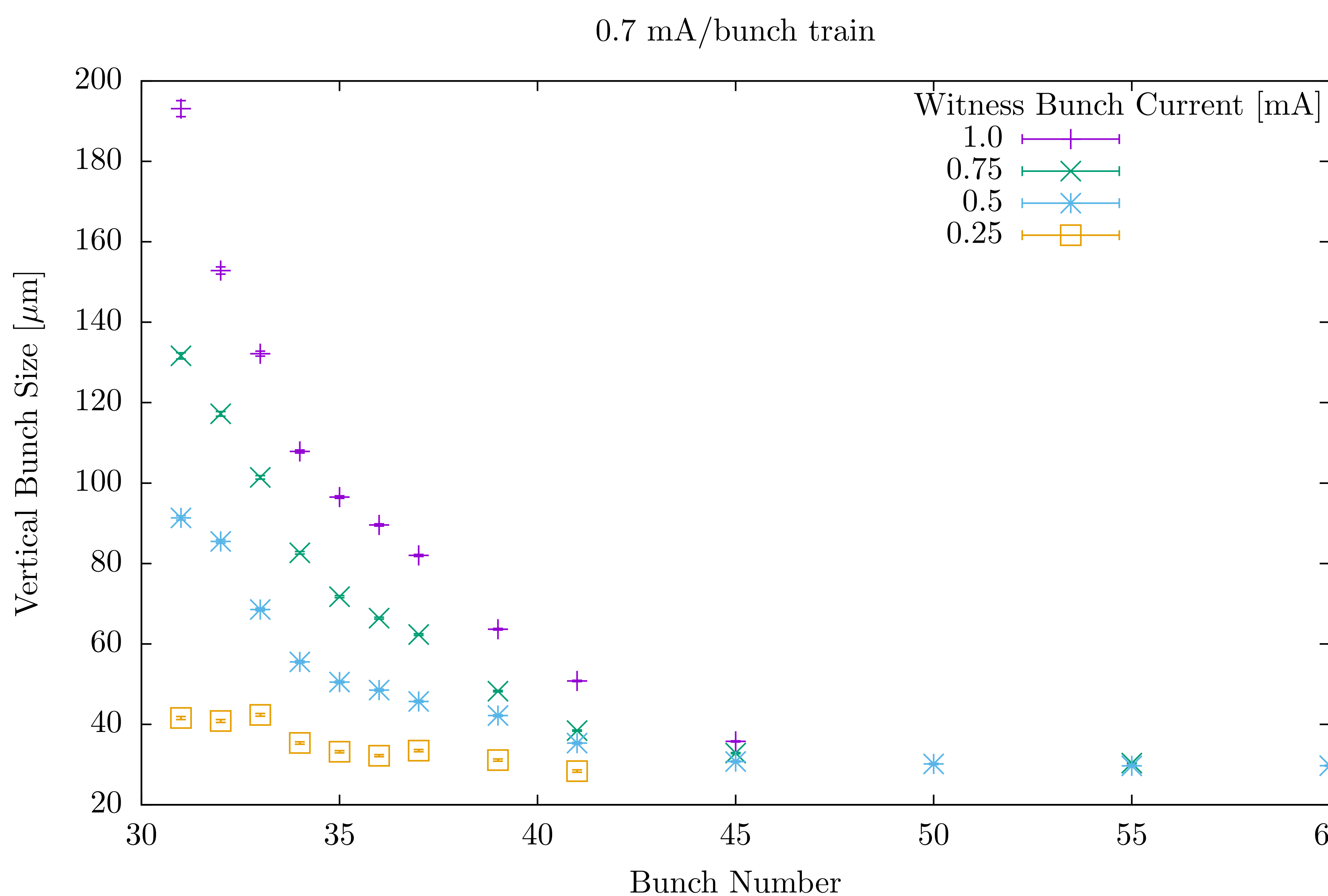
Horizontal beam size

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



Witness bunch beam size

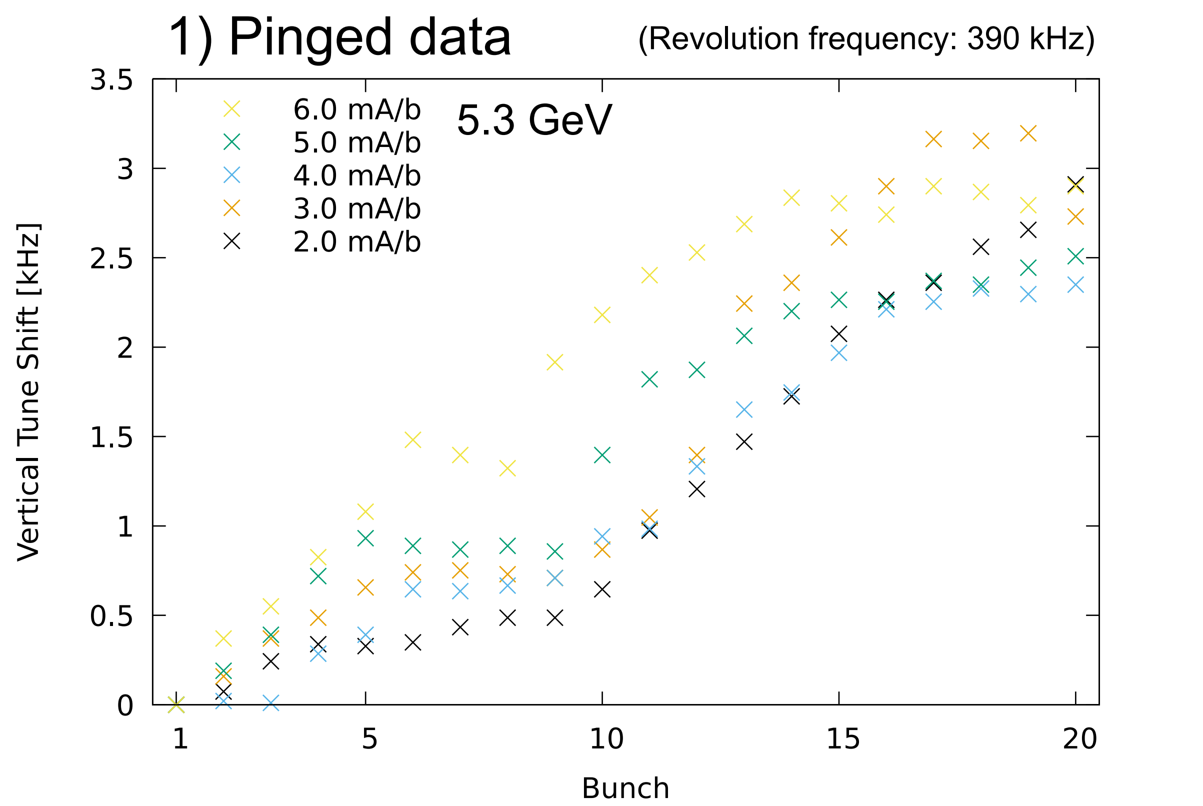
- One witness bunch to a 30 bunch 0.7 mA/b e+ train
  - Start with witness at bunch #60, vary current, eject bunch, move to #55…
  - For a given witness bunch #, the cloud it sees is the same
    - ★ Emittance growth strongly depends on current (pinch effect)

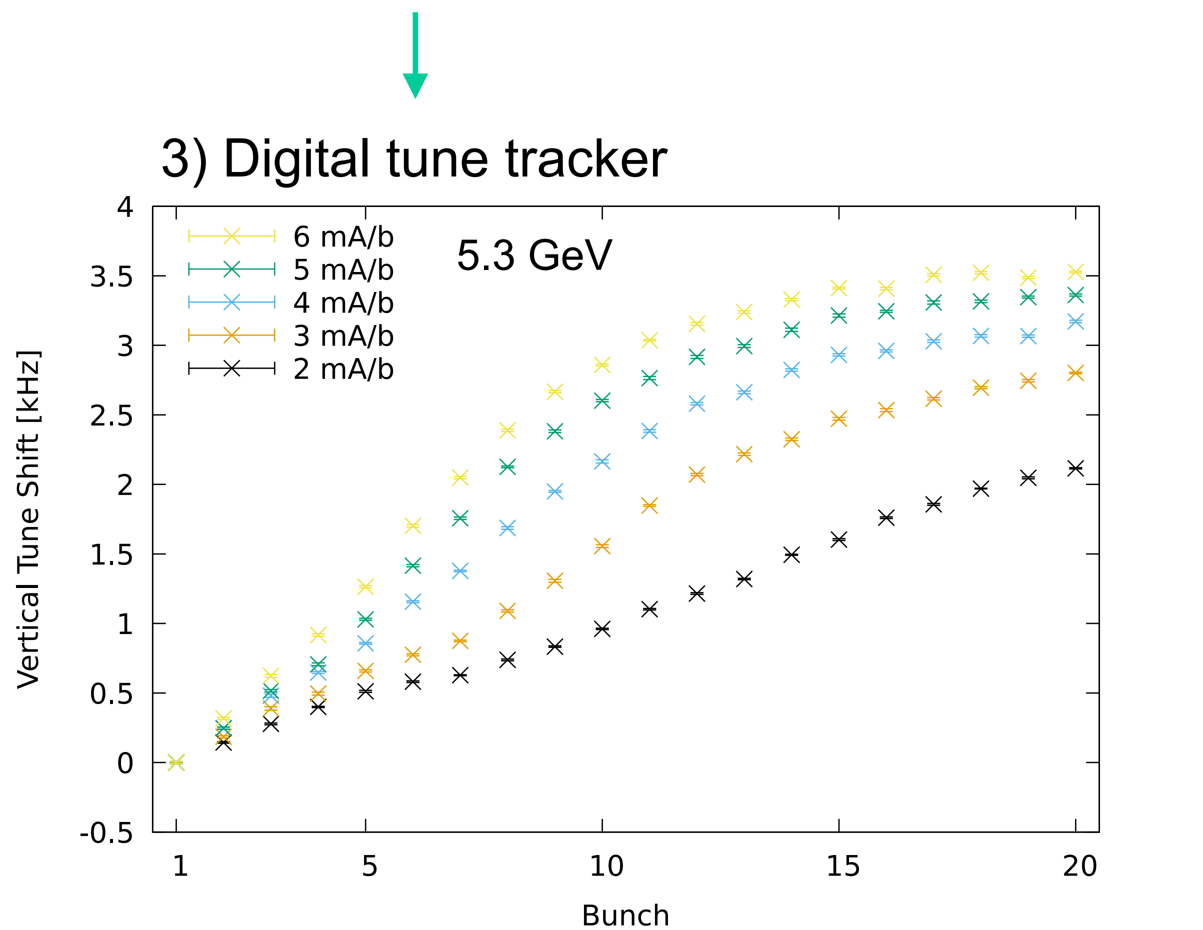


Tune shift measurements

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

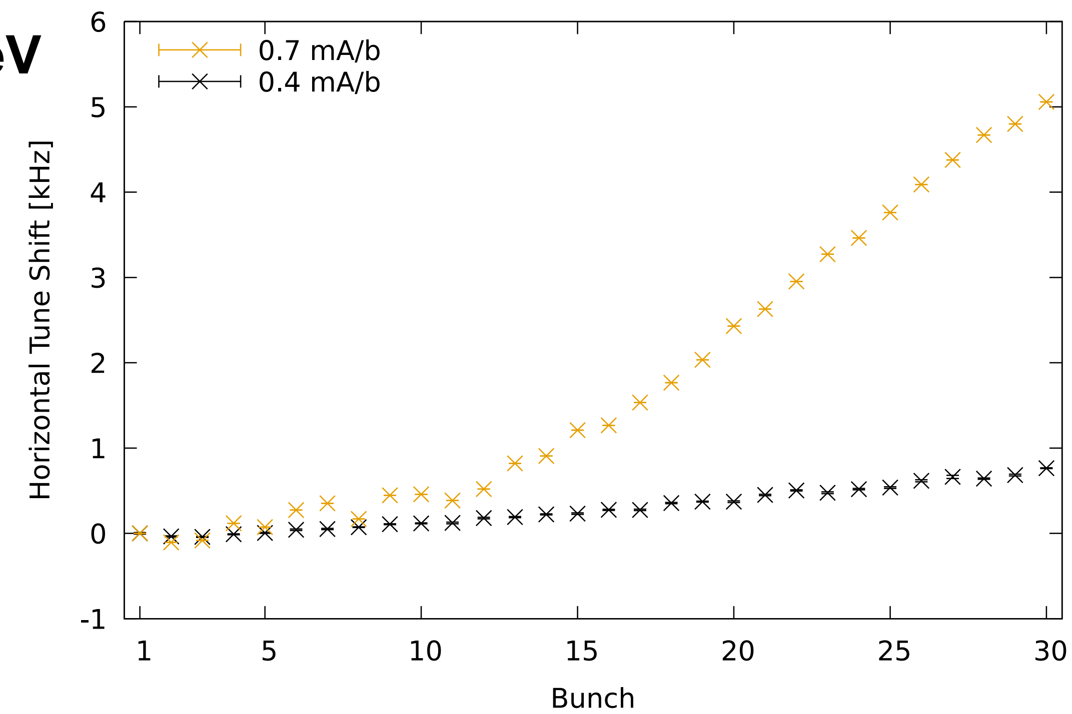


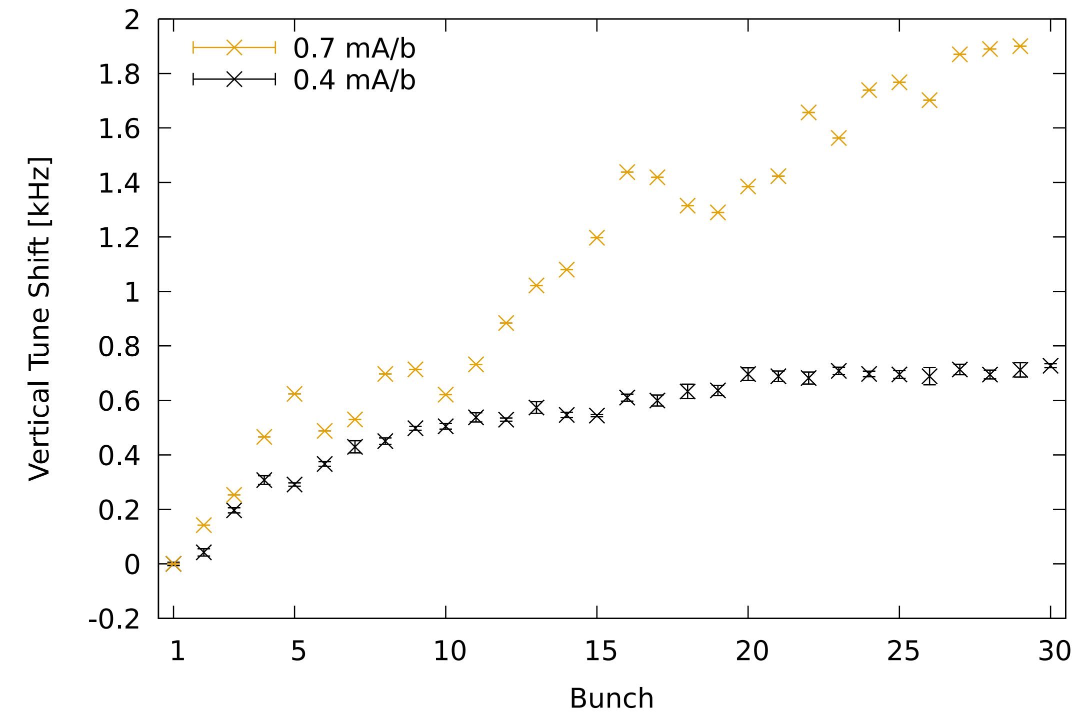


Tune shift measurements

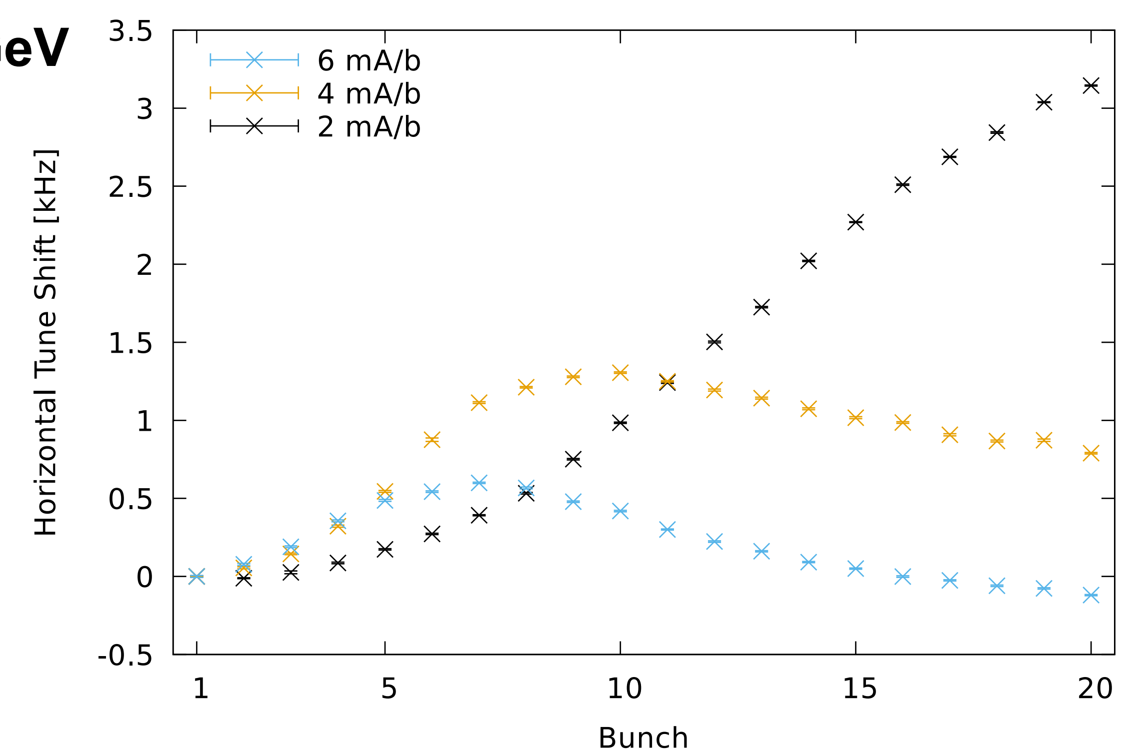
- Tune shifts measured at different energies and a wide range of currents
- World-wide unique data set

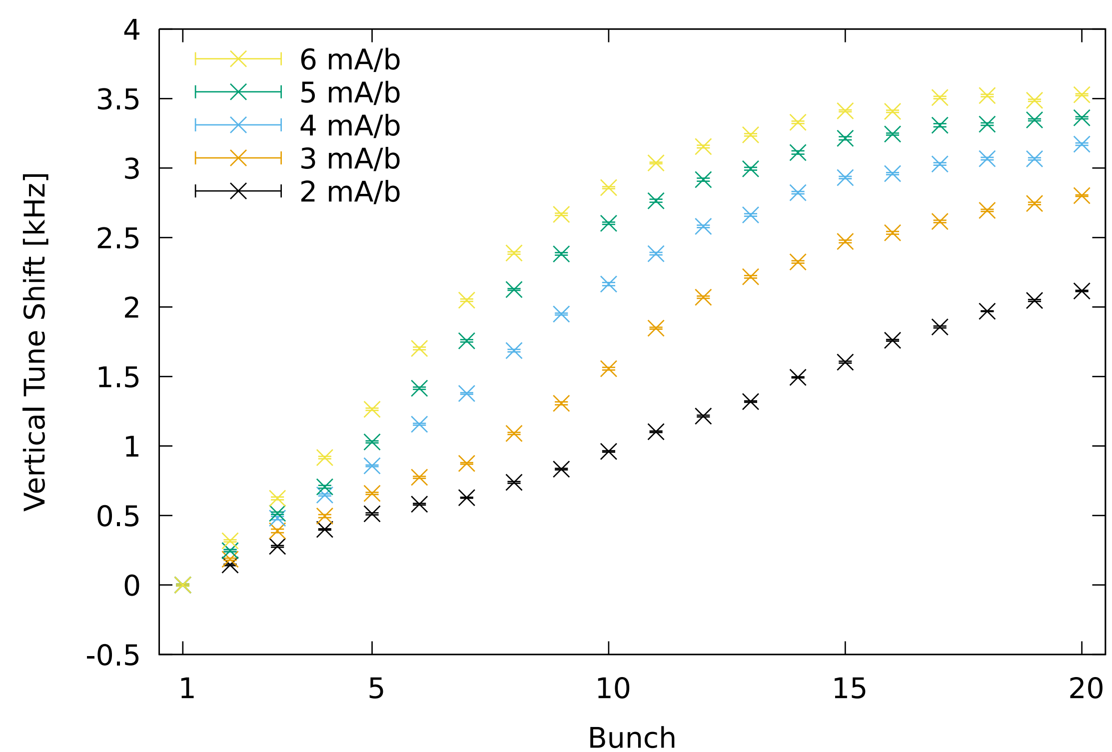
2.1 GeV





5.3 GeV





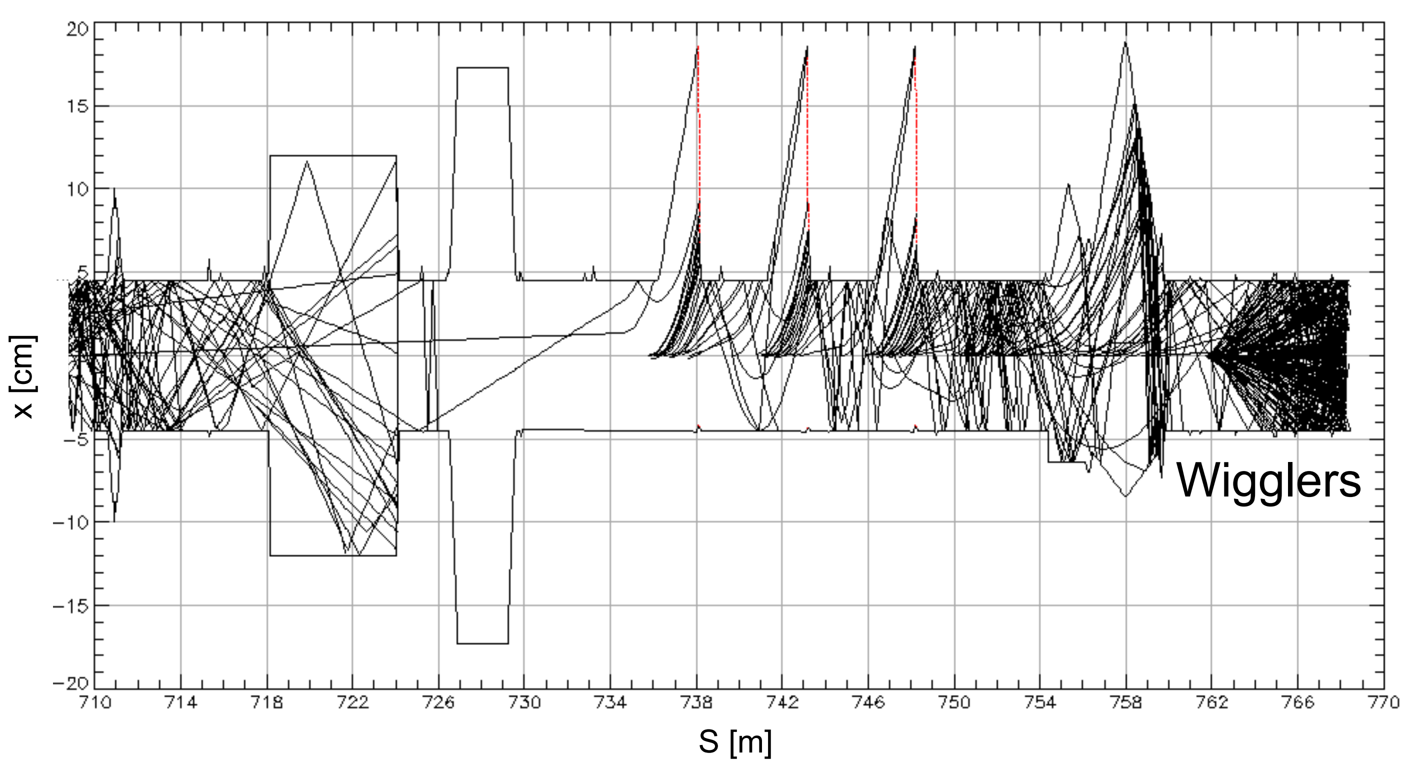
Simulations

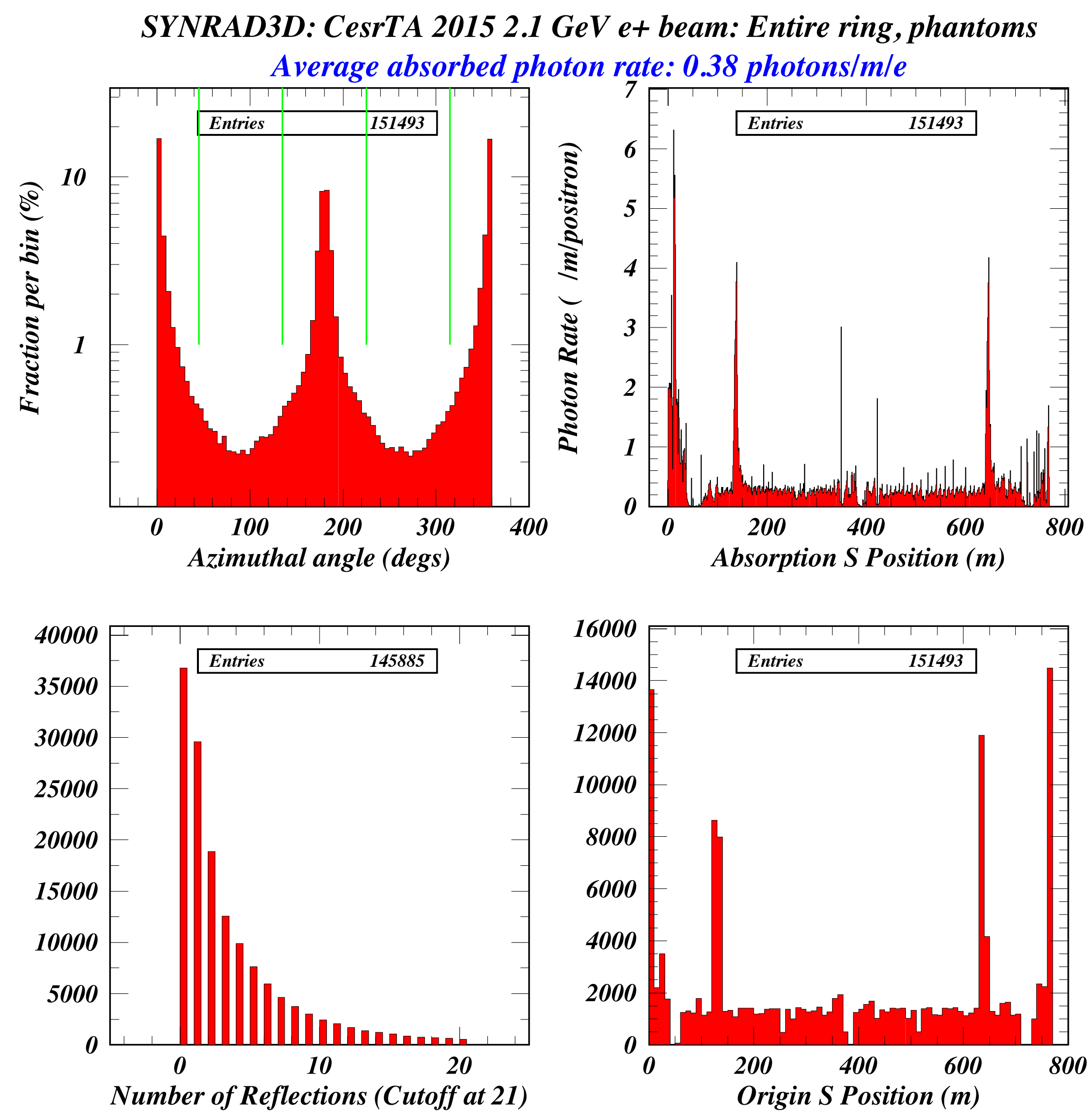
- Simulations involve four codes which feed into each other

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
   - ➔ Betatron tunes
4. Tracking of beam through the lattice with EC elements (Bmad)
   - ➔ Equilibrium beam size

1) Photon tracking

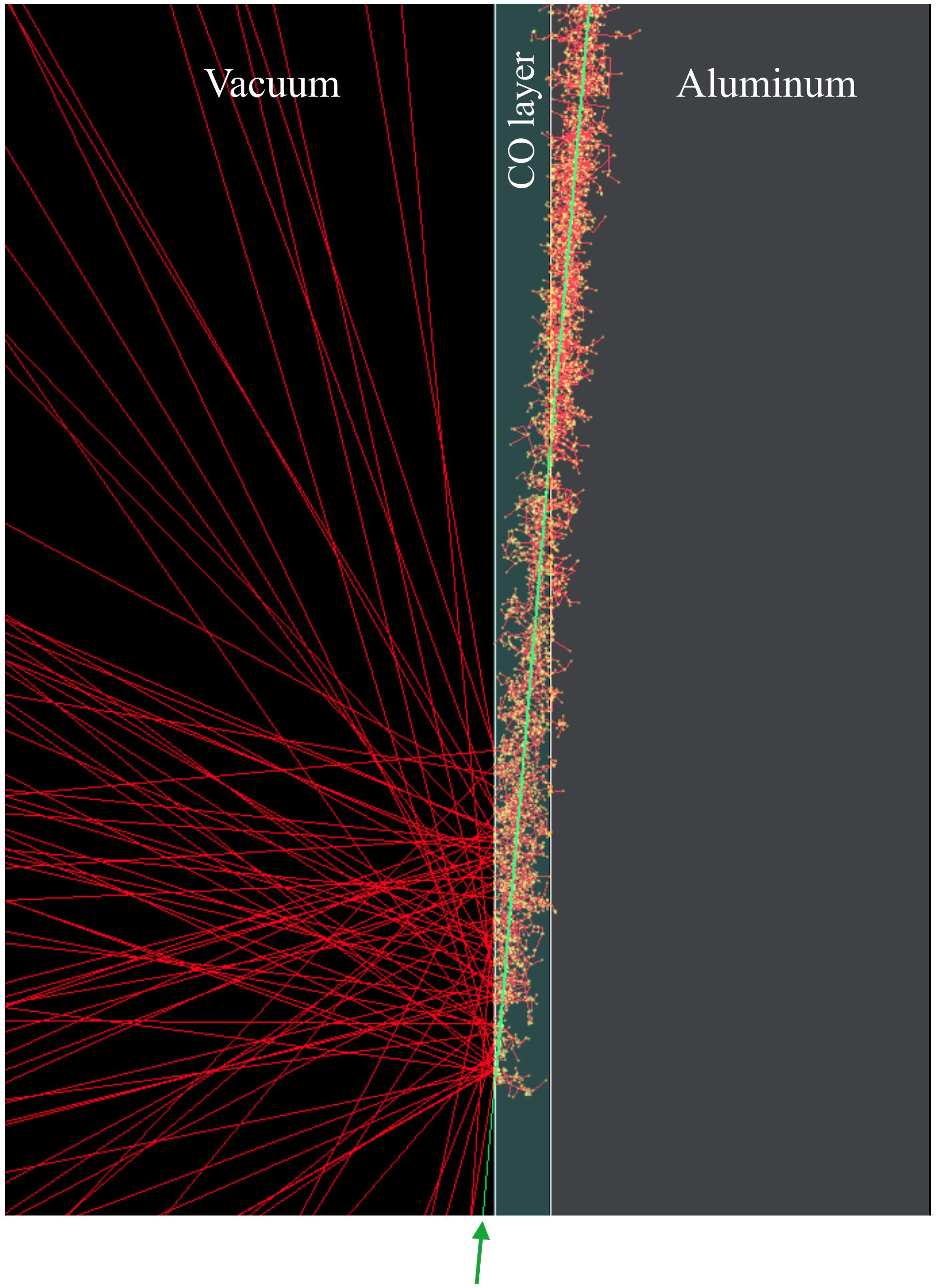
- Synrad3D
  - Simulates photons from synchrotron radiation
  - Tracks photons through vacuum chamber including specular & diffuse reflections
  - Input: lattice, 3D vacuum chamber profile, material
  - Output: information on absorbed photons:
    - ★ Azimuthal angle
    - ★ Energy
    - ★ Grazing angle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



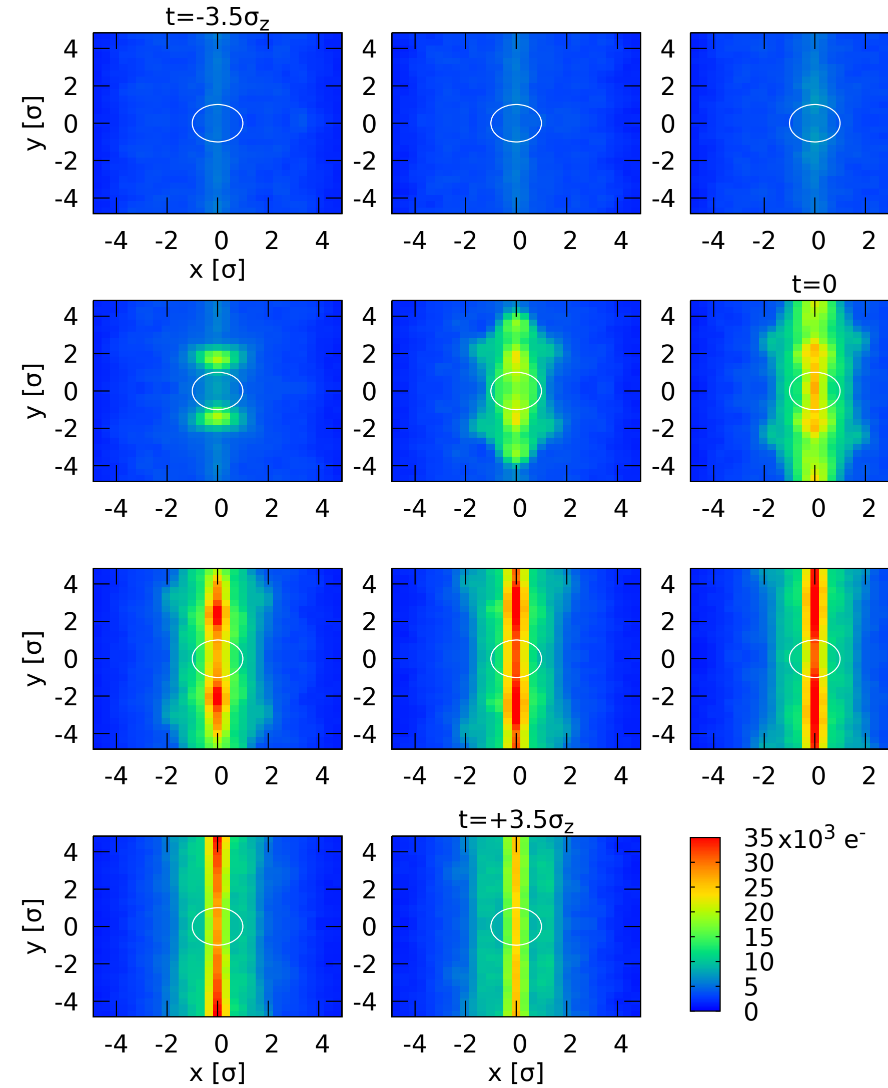
Incident photons
300 eV
5 deg. grazing angle

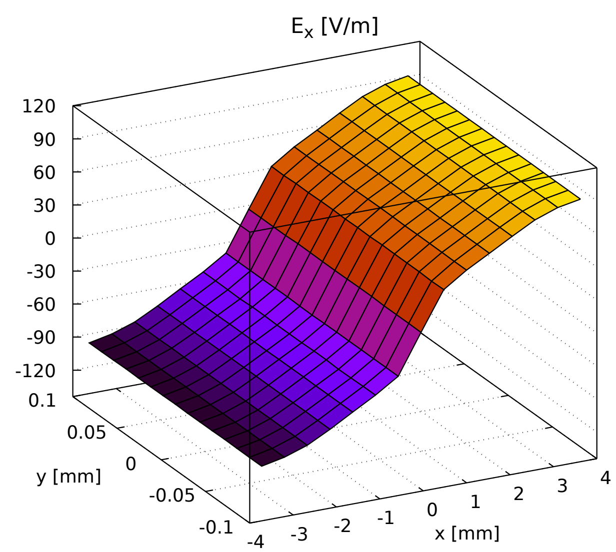
★ Refer to Part 1 for details

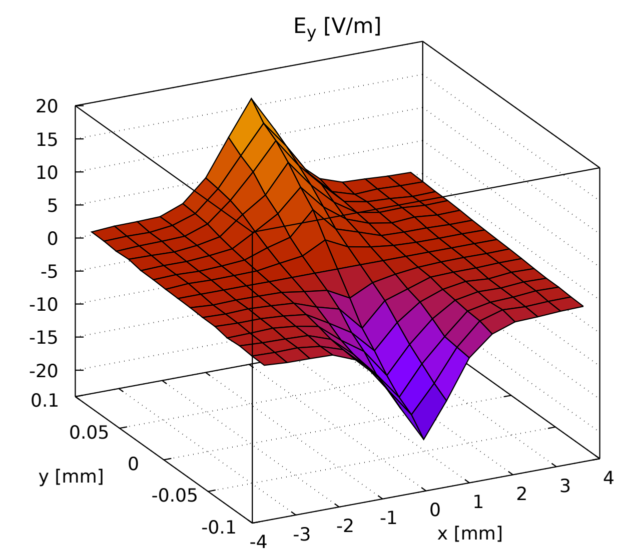
3) EC buildup simulation

- 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

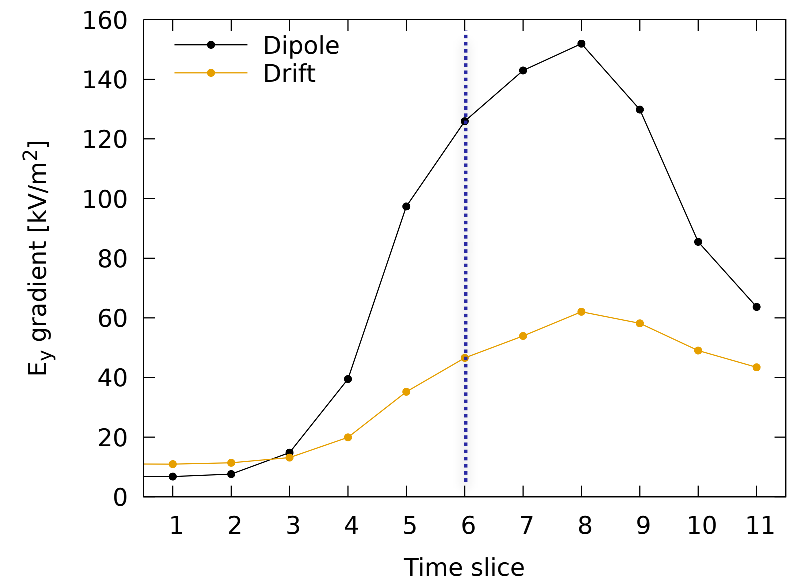


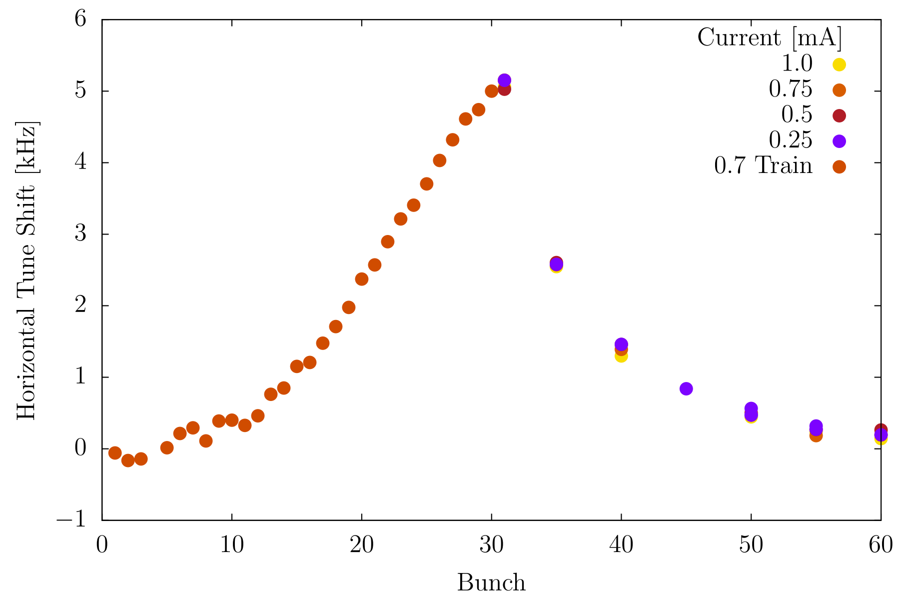


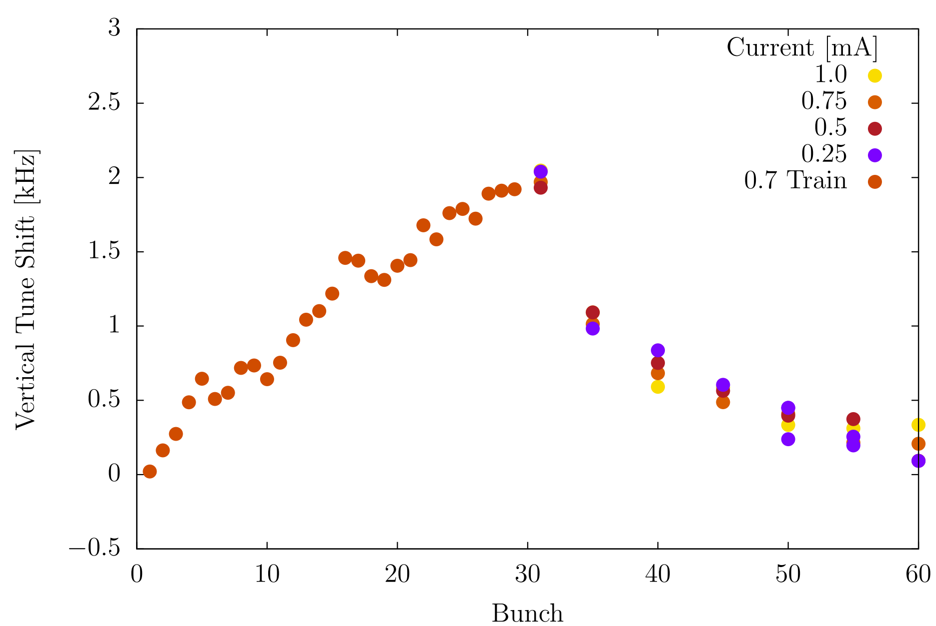


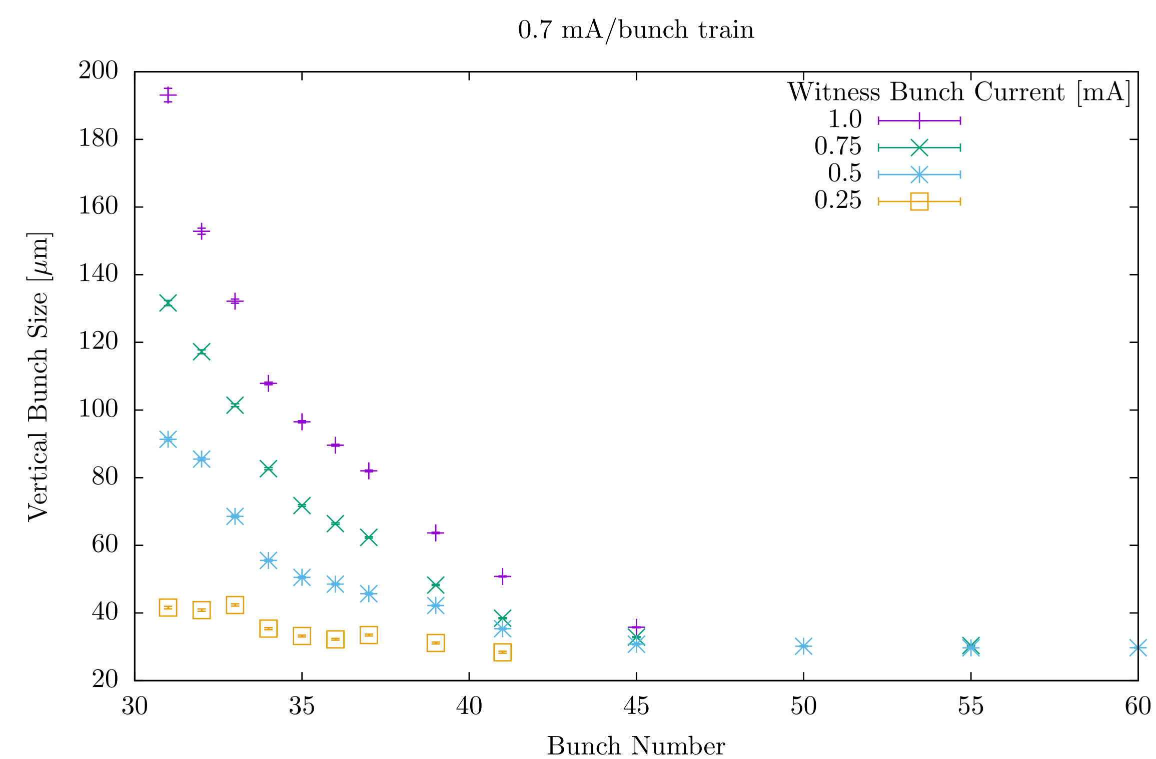
Electric field gradients from cloud space-charge fields

- Tune shifts calculated from electric field gradients (dE_x/dx, dE_y/dy)
- 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)









Calibration of model to tune shift measurements

- ECLOUD simulations depend strongly on vacuum chamber secondary electron 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
- Use results from copper for our aluminum vacuum chamber

- 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

✳ Thanks to Colwyn Gulliford & Adam Bartnik for optimizer framework

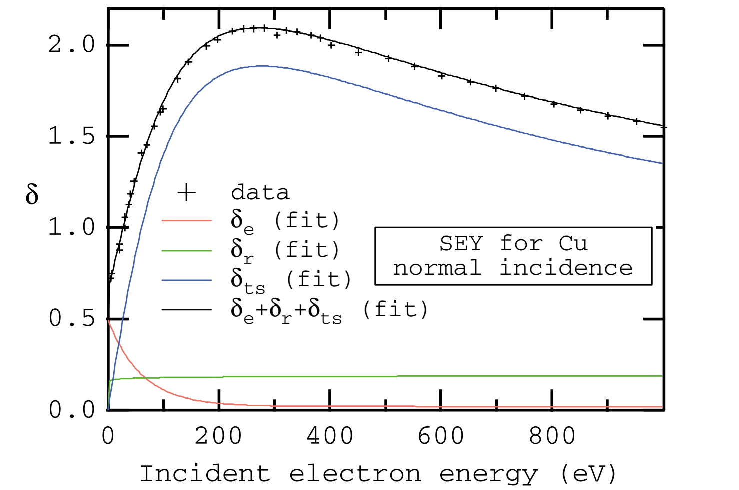


TABLE I. Main parameters of the model.

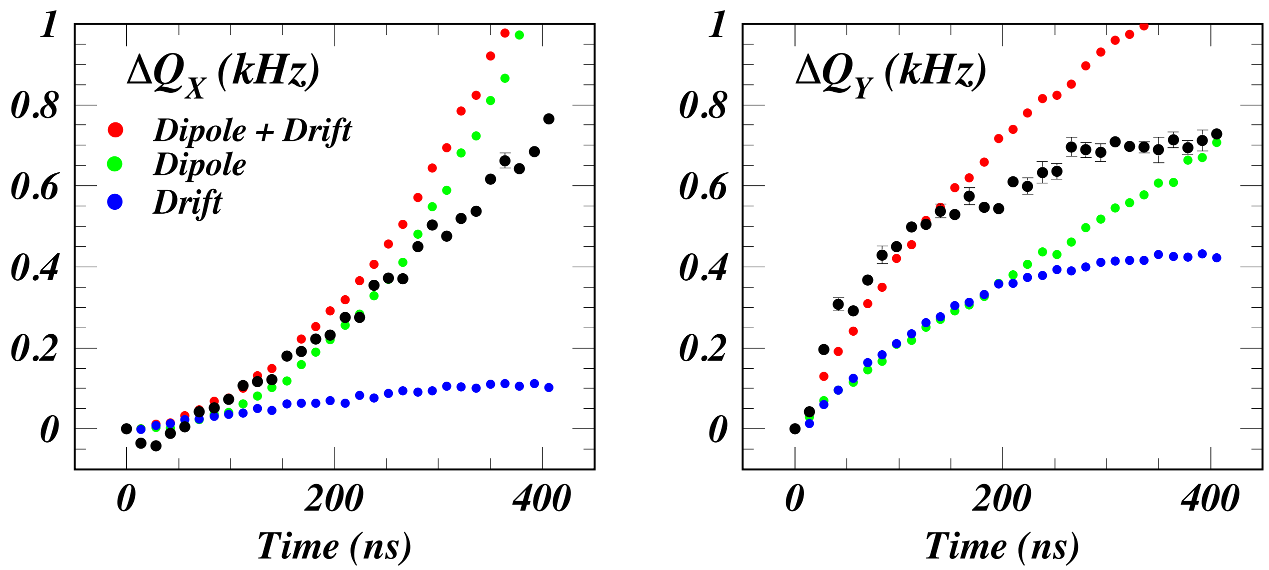
	Copper	Stainless steel
	Emitted angular spectrum (Sec. IIC1)	
α	1	1
	Backscattered electrons (Sec. IIIB)	
$P_{1,e}(\infty)$	0.02	0.07
$\hat{P}_{1,e}$	0.496	0.5
$\hat{E}_e$ (eV)	0	0
W (eV)	60.86	100
p	1	0.9
σ_e (eV)	2	1.9
e_1	0.26	0.26
e_2	2	2
	Rediffused electrons (Sec. IIIC)	
$P_{1,r}(\infty)$	0.2	0.74
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)

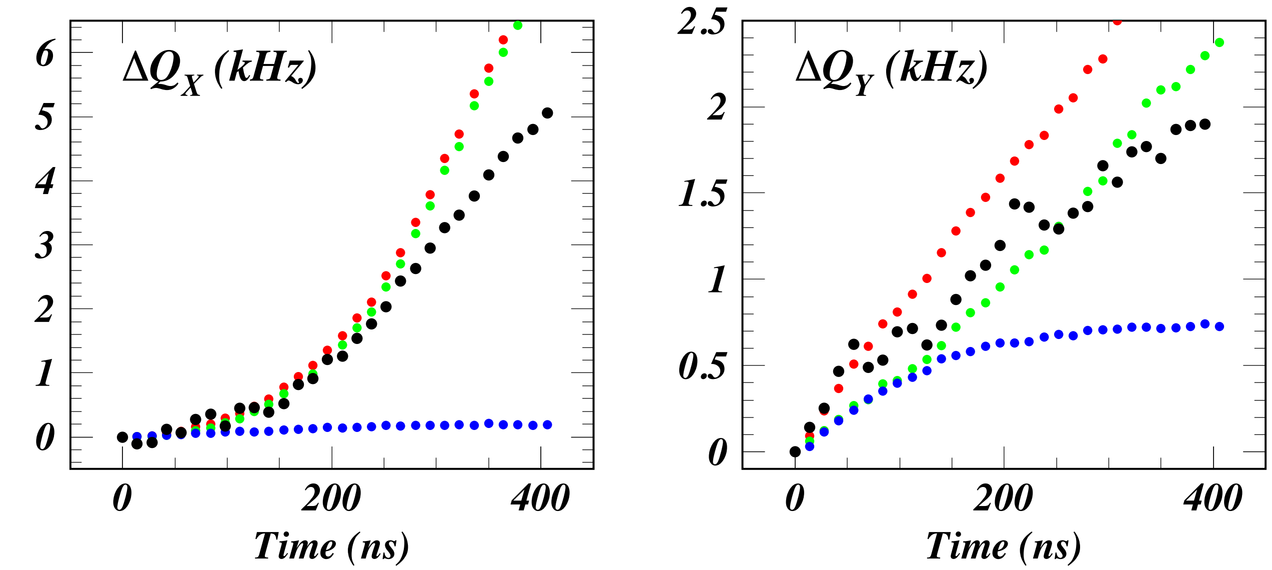
Simulated tune shifts with ***initial SEY parameters***

2.1 GeV (CESRTA)

0.4 mA/b



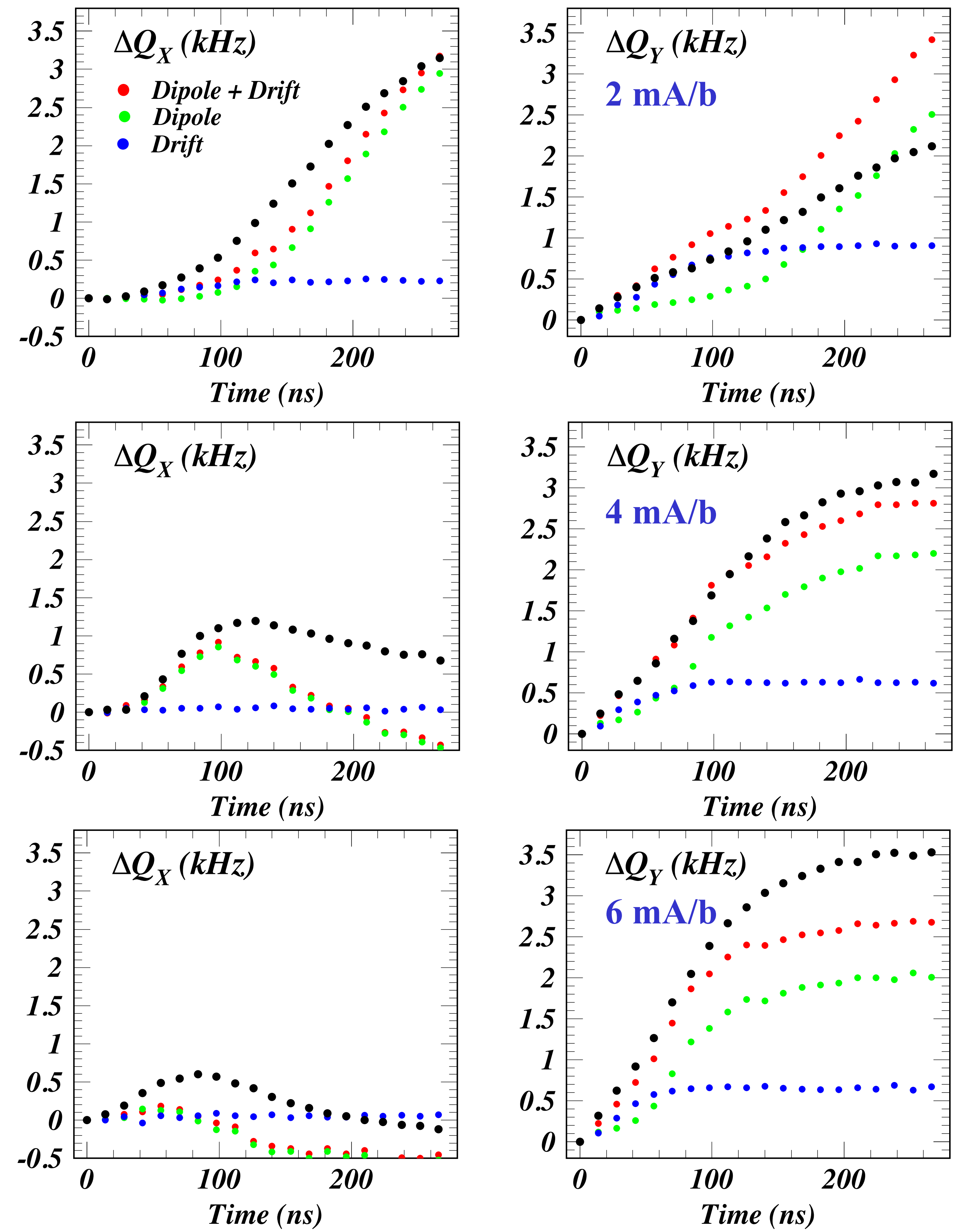
0.7 mA/b



(Revolution frequency: 390 kHz)

- Various discrepancies between model & measurements
- However, just getting this close required a sophisticated model
- Adjusting SEY parameters to better match data is a final calibration

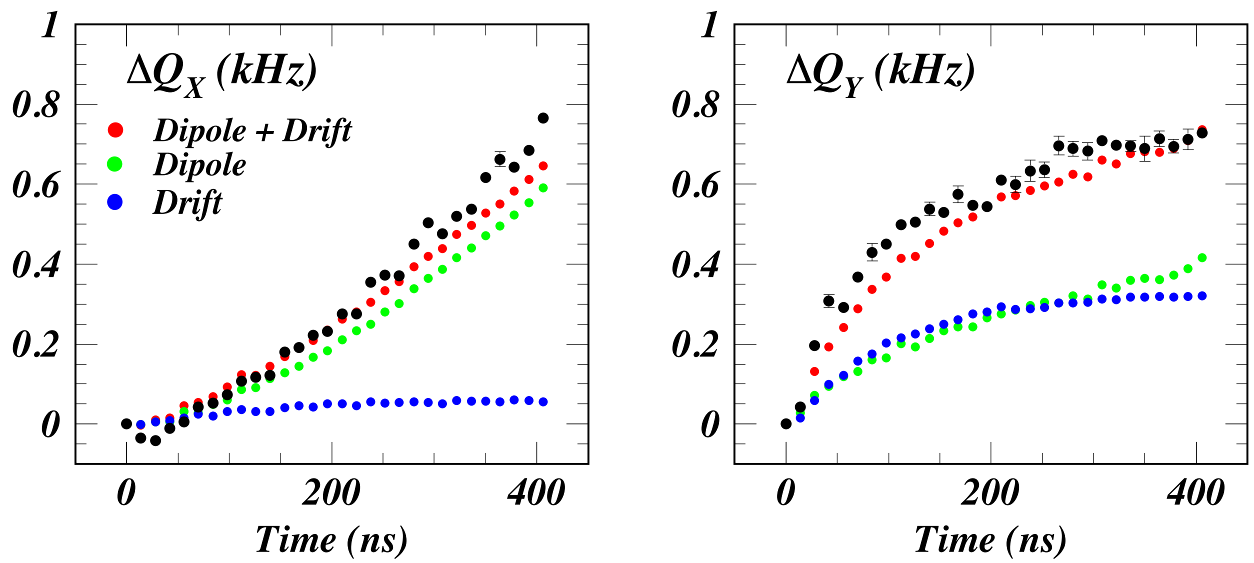
5.3 GeV (CHESS)



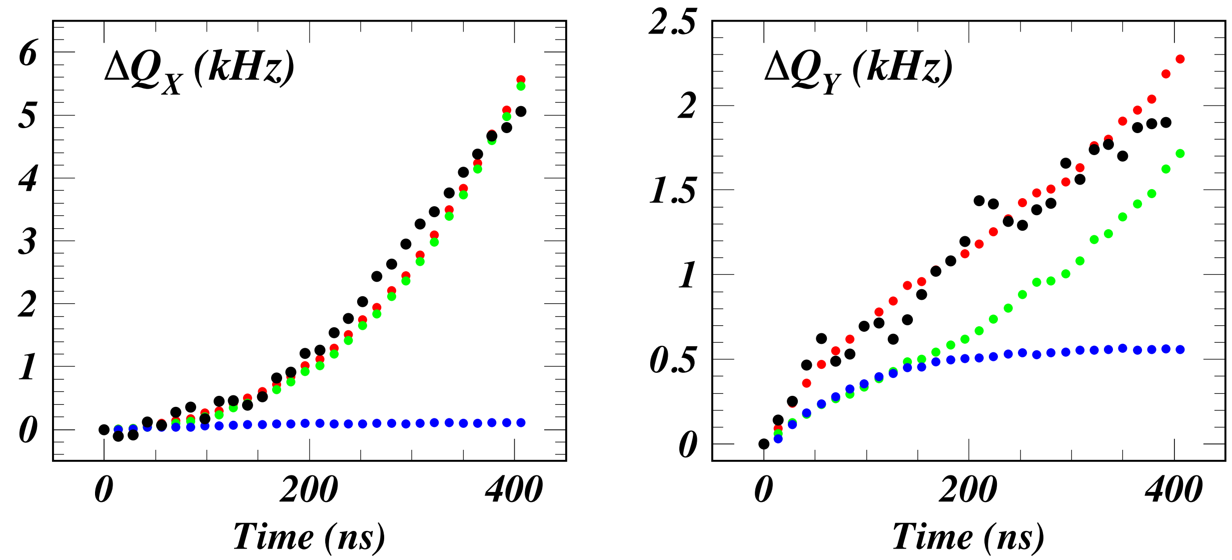
Simulated tune shifts with ***fit SEY parameters***

2.1 GeV (CESRTA)

0.4 mA/b



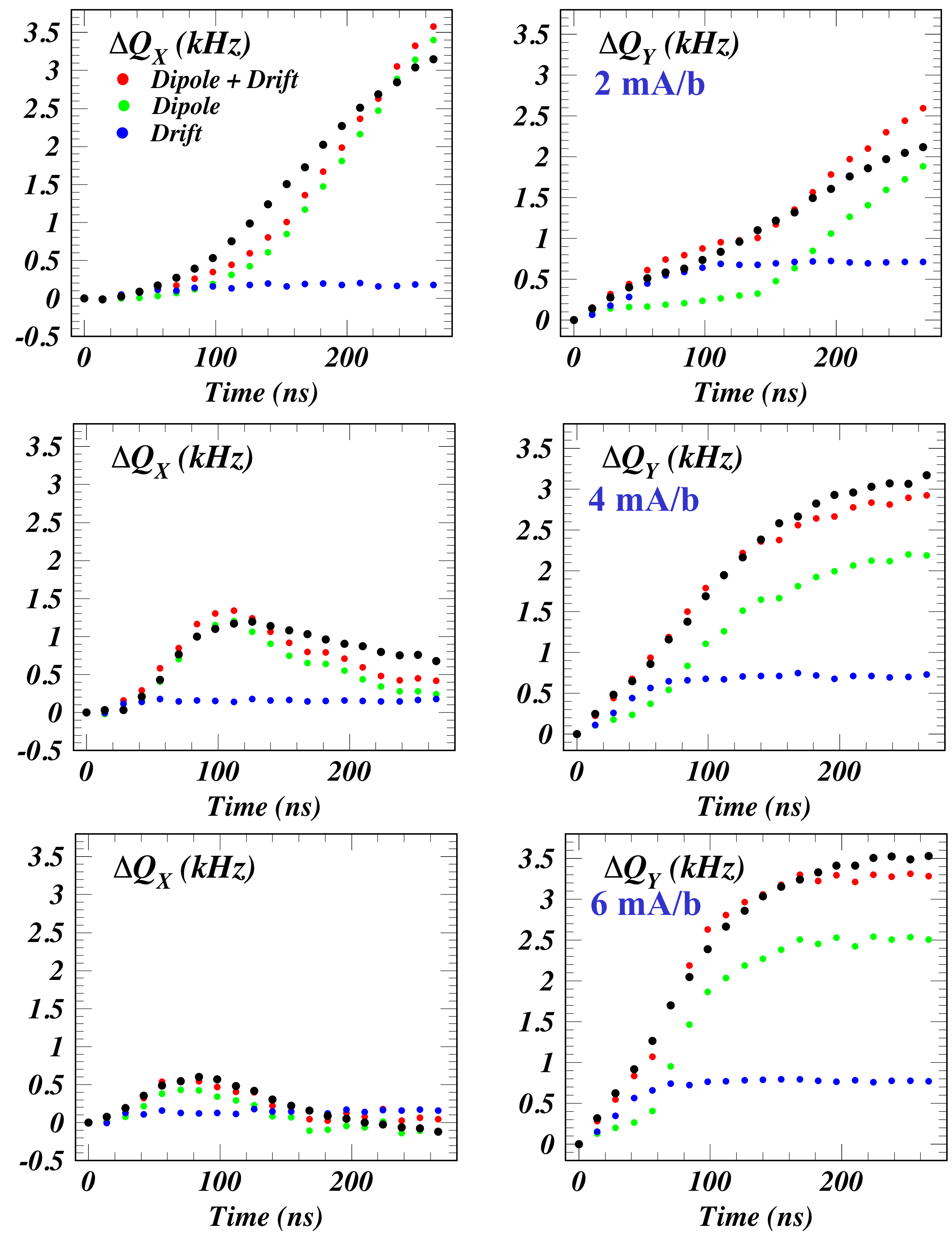
0.7 mA/b



(Revolution frequency: 390 kHz)

- Excellent agreement for a range of currents and beam energies!
- Seeing the different contributions from dipoles & drifts has taught us about cloud dynamics

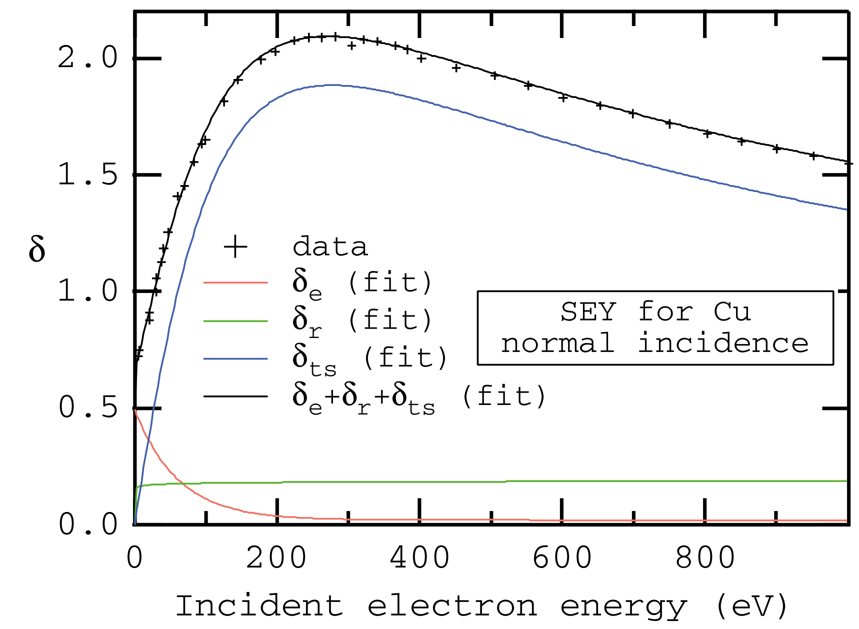
5.3 GeV (CHESS)

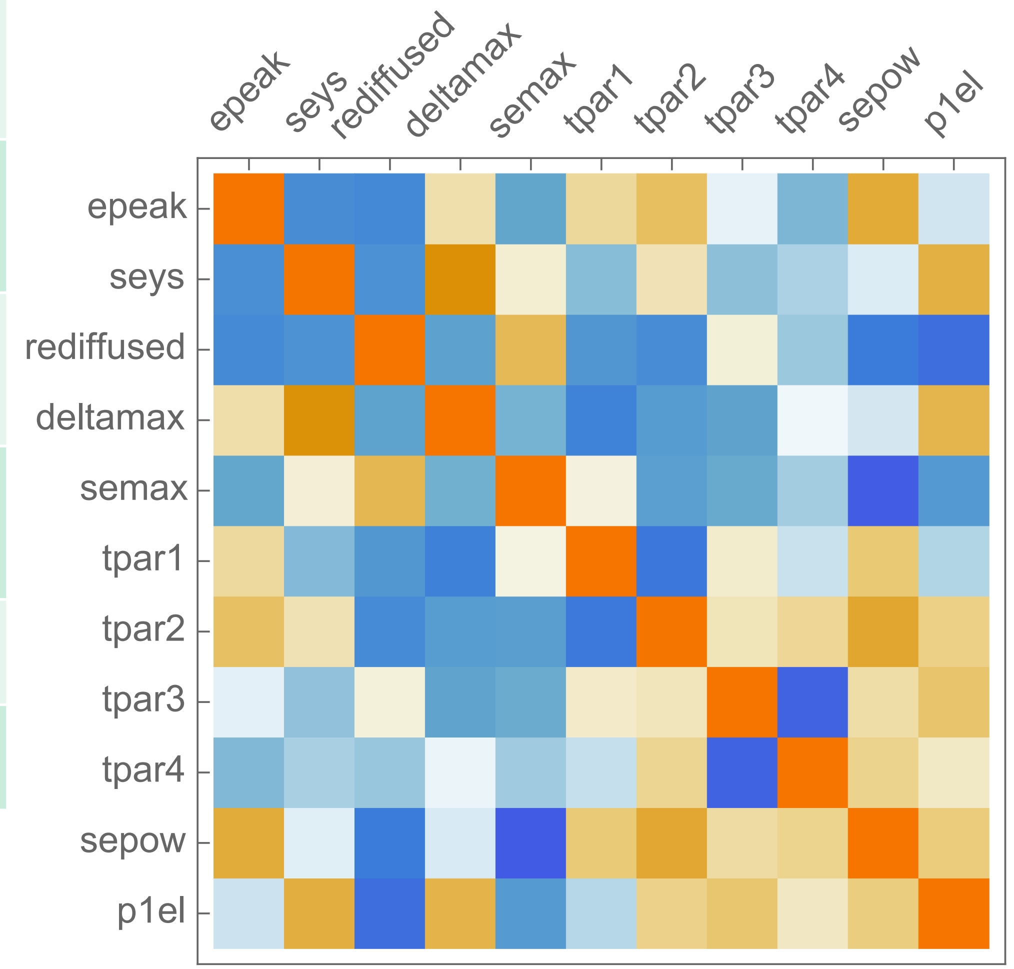


Fit SEY parameters

	Initial	Fit	Uncertainty
epeak Peak energy of true secondary yield	277	260	10
seys True secondary yield 's' parameter	1.54	1.58	0.05
rediffused Rediffused secondary yield	0.2	0.39	0.01
deltamax True secondary yield	1.88	1.53	0.04
semax Energy spread of secondaries	1.8	3.58	0.4
tpar1 Angular dependence of true secondary yield	0.66	0.99	0.2
tpar2 Power of cosine in angular dependence of true secondary yield	0.8	1.5	0.4
tpar3 Angular dependence of peak energy of true secondary yield	0.7	0.77	0.5
tpar4 Power of cosine in angular dependence of peak energy of true secondary yield	1.0	1.16	1
sepow Power of energy of secondaries	1.0	0.84	0.2
p1el Elastic yield at 'zero' energy	0.5	0.07	0.02

- Fit uncertainties come from covariance matrix, estimated from Jacobian
- Does not include correlations (shown in correlation matrix)





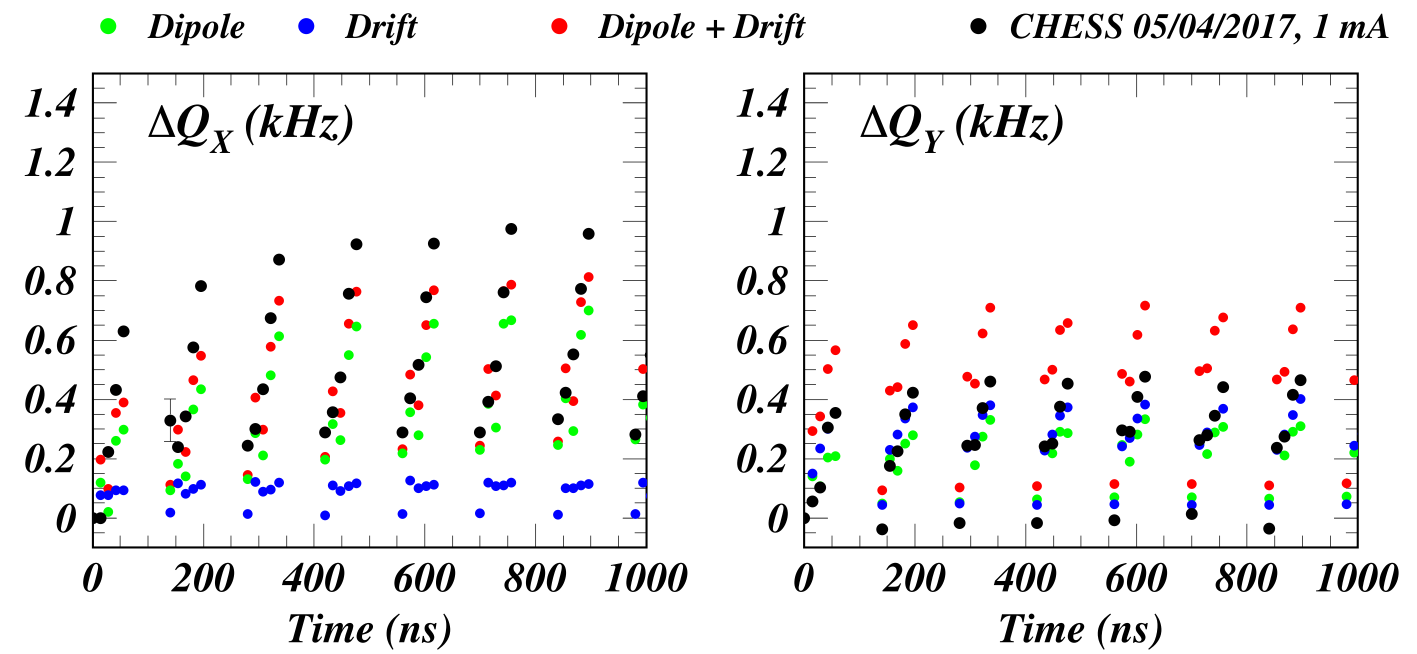
Red is +1
Blue is -1

CHESS-U Transition Lattice

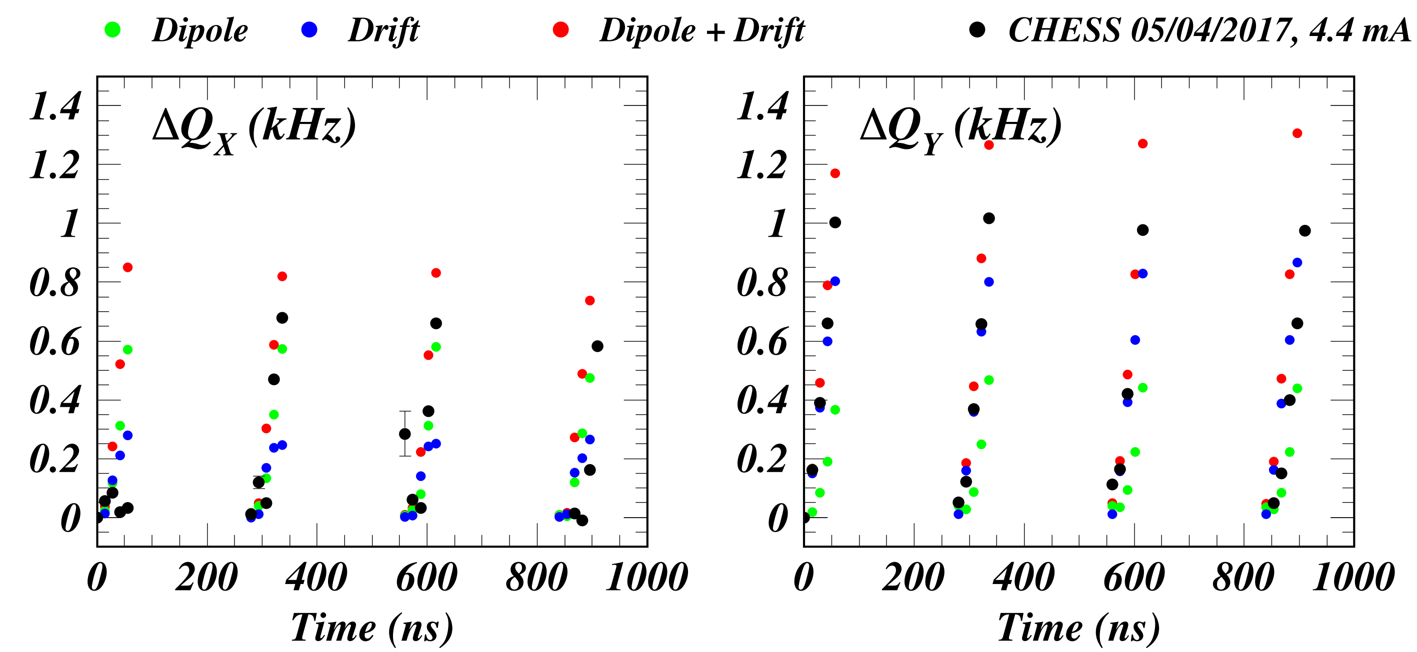
CHESS-U transition and CHESS-U results by summer REU student Keefer Rowan

- To gain confidence in this model for *predicting* tune shifts for CHESS-U, compare with measurements of CHESS-U Transition lattice
  - Same optics as CHESS-U except in south arc
- Tune shift measurements were taken for two bunch configurations (14 ns bunch spacing)
  - 18x5 at 1.0 mA/b (90 mA total)
  - 9x5 (every other train) at 4.4 mA/b (200 mA total)
- The 18x5 train was seemingly limited by a horizontal instability, possibly caused by electron cloud
  - Investigation underway

18x5 at 1.0 mA/b



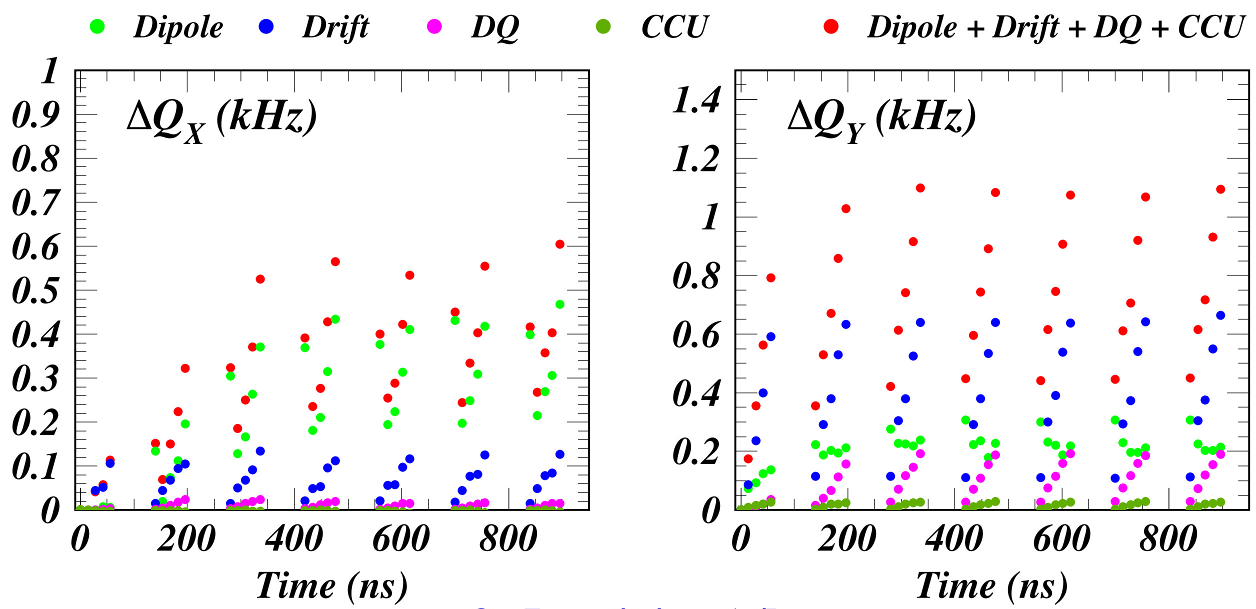
9x5 at 4.4 mA/b



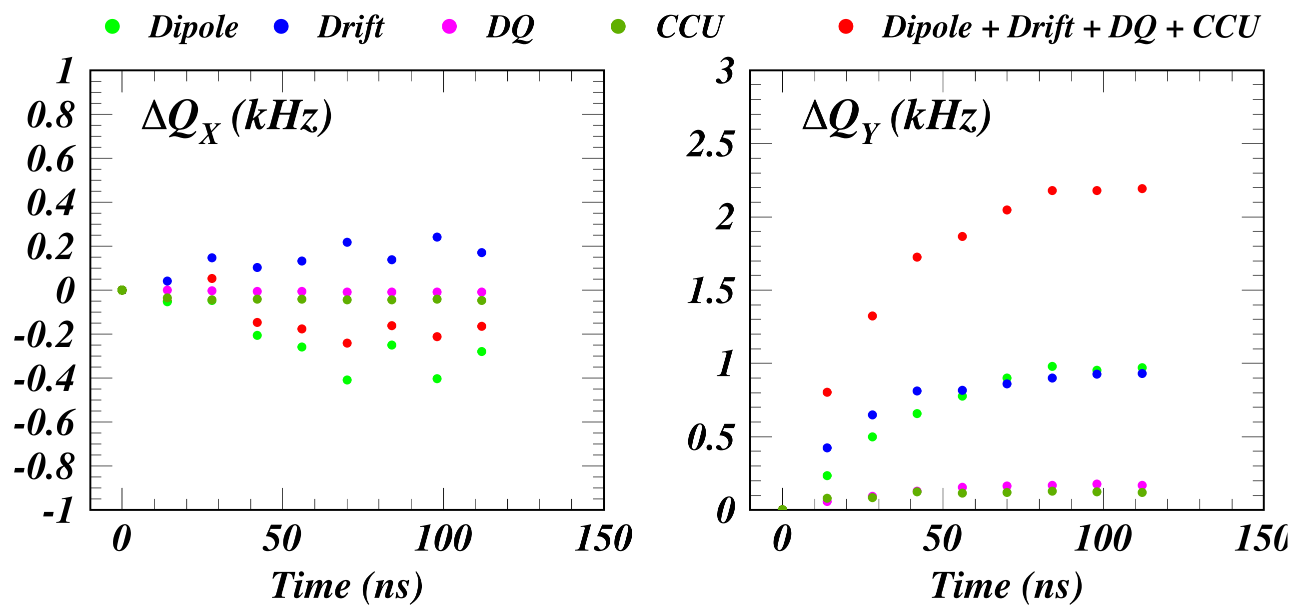
CHESS-U at 6 GeV

- Various bunch configurations, all 200 mA total
- Includes contribution from combined function magnets (DQ) and compact undulators (CCU)
- Tune shifts at 5.3 GeV very similar, about 5-10% lower
- All tune shifts, except for 1x9 with 4ns spacing, are < 2.5 kHz and should not present a problem
  - We had tune shifts up to 3.5 kHz in the 5.3 GeV measurements
  - Tune plane of CHESS-U better than CHESS

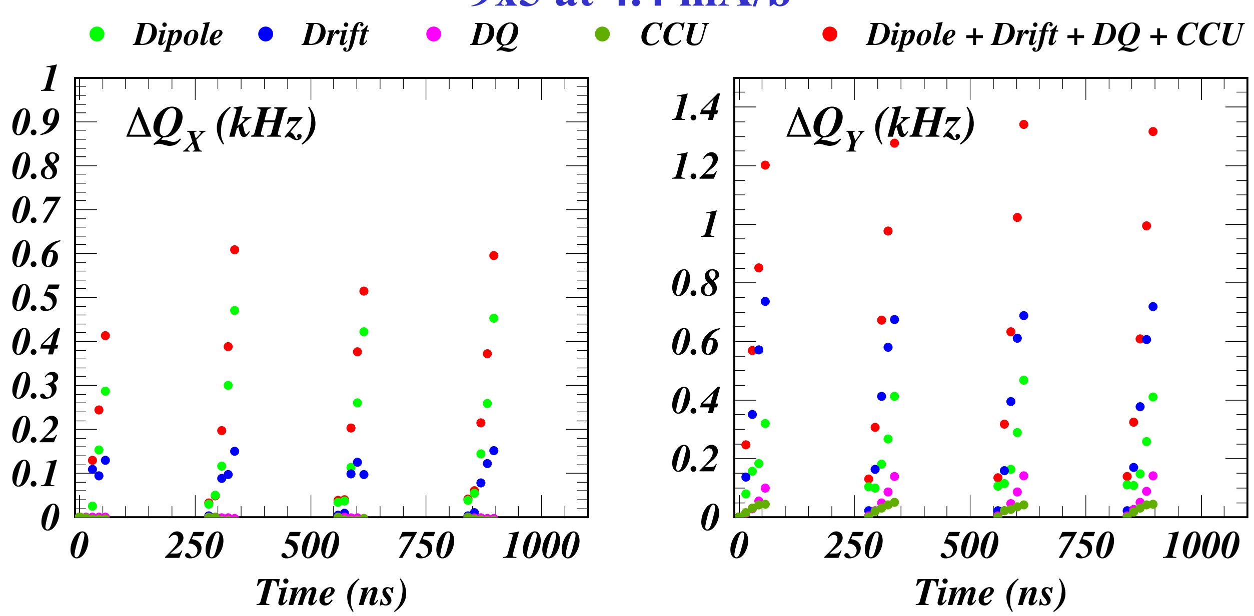
18x5 at 2.2 mA/b



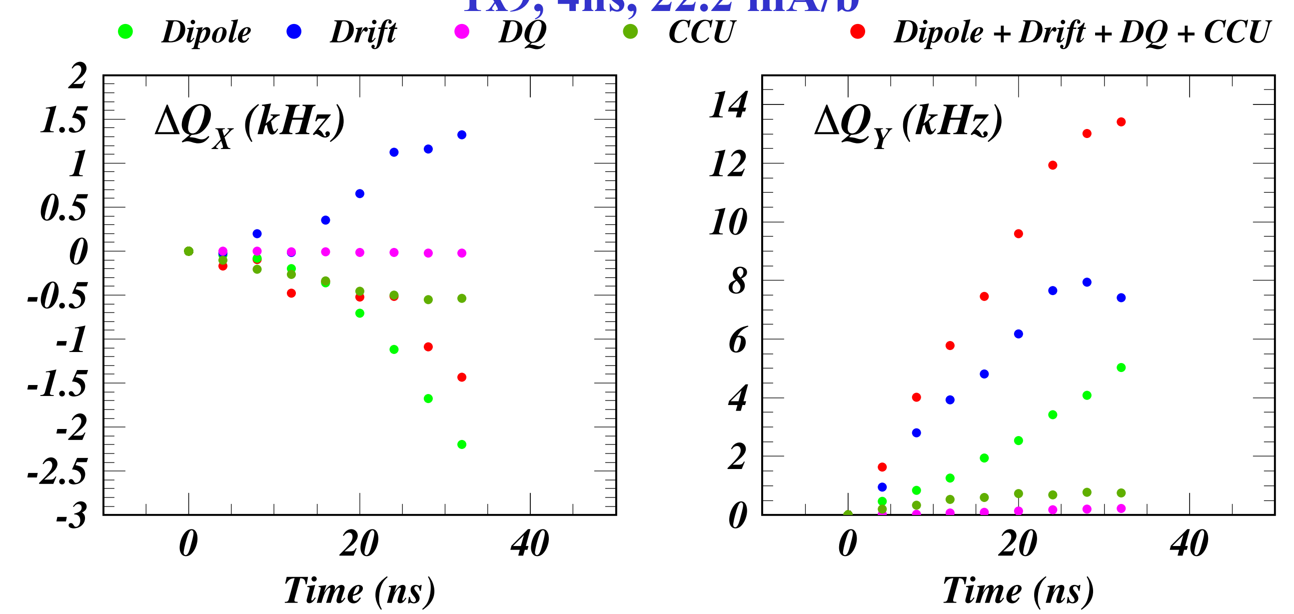
1x9, 14ns, 22.2 mA/b



9x5 at 4.4 mA/b



1x9, 4ns, 22.2 mA/b

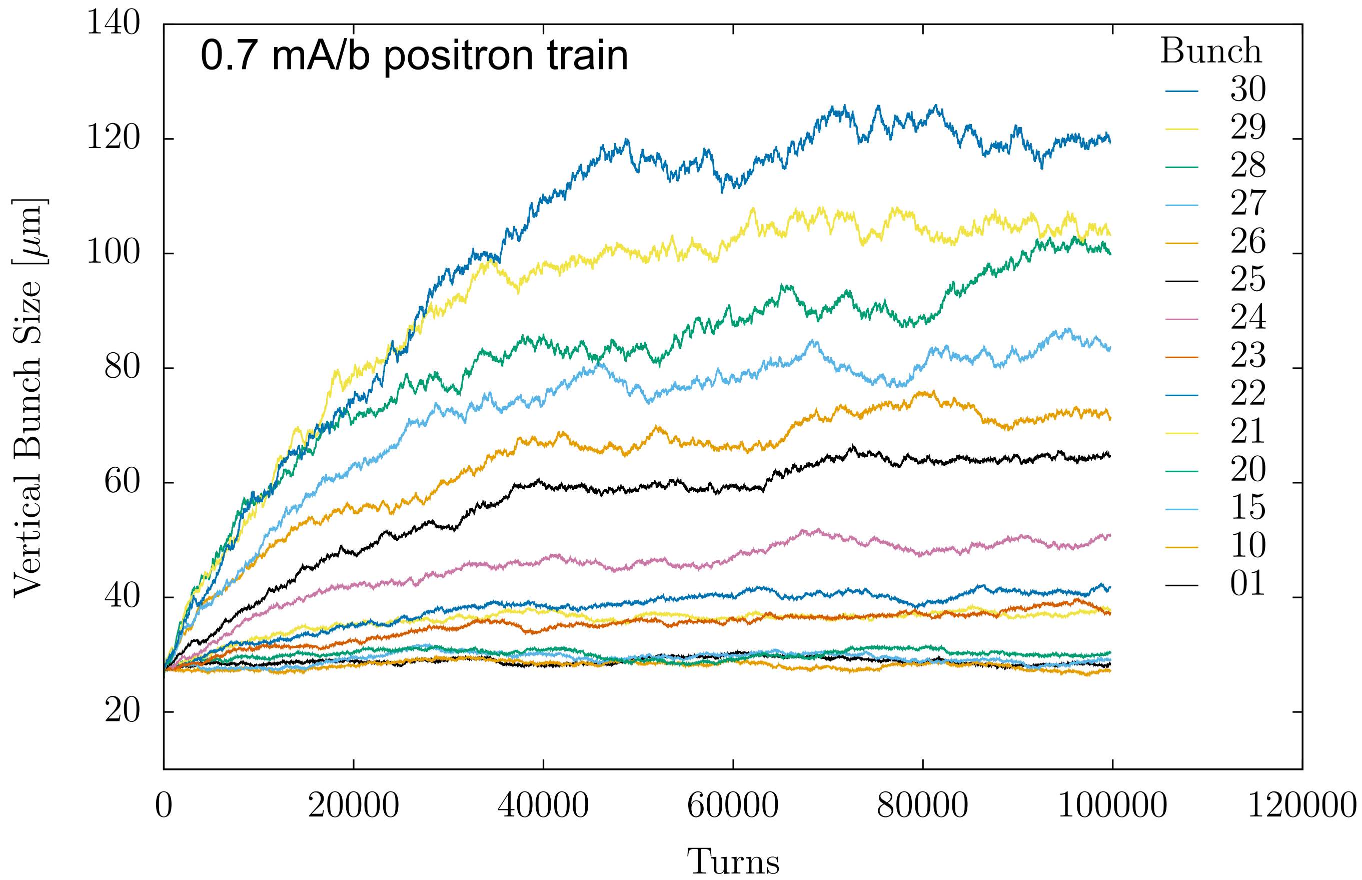


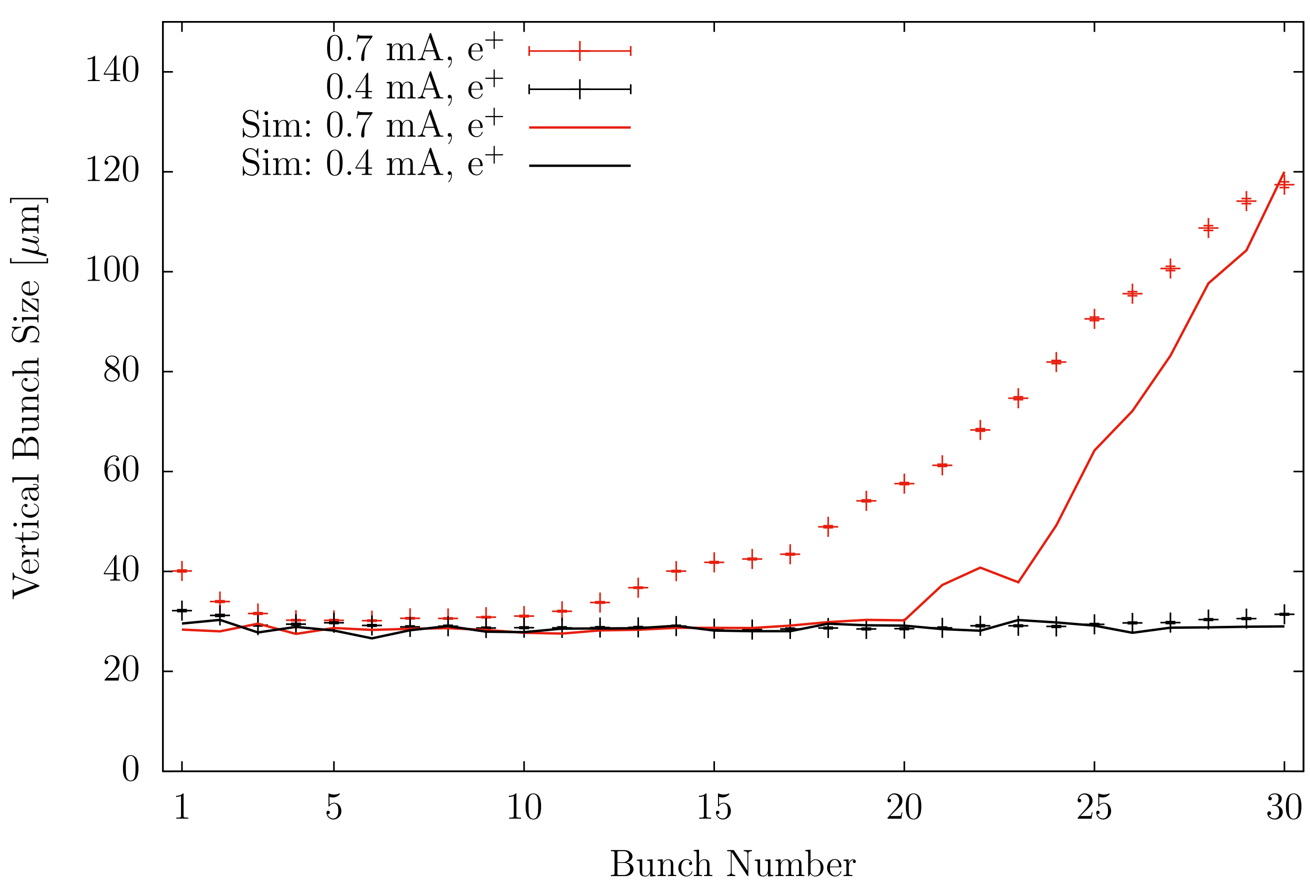
4) Tracking simulations

- 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

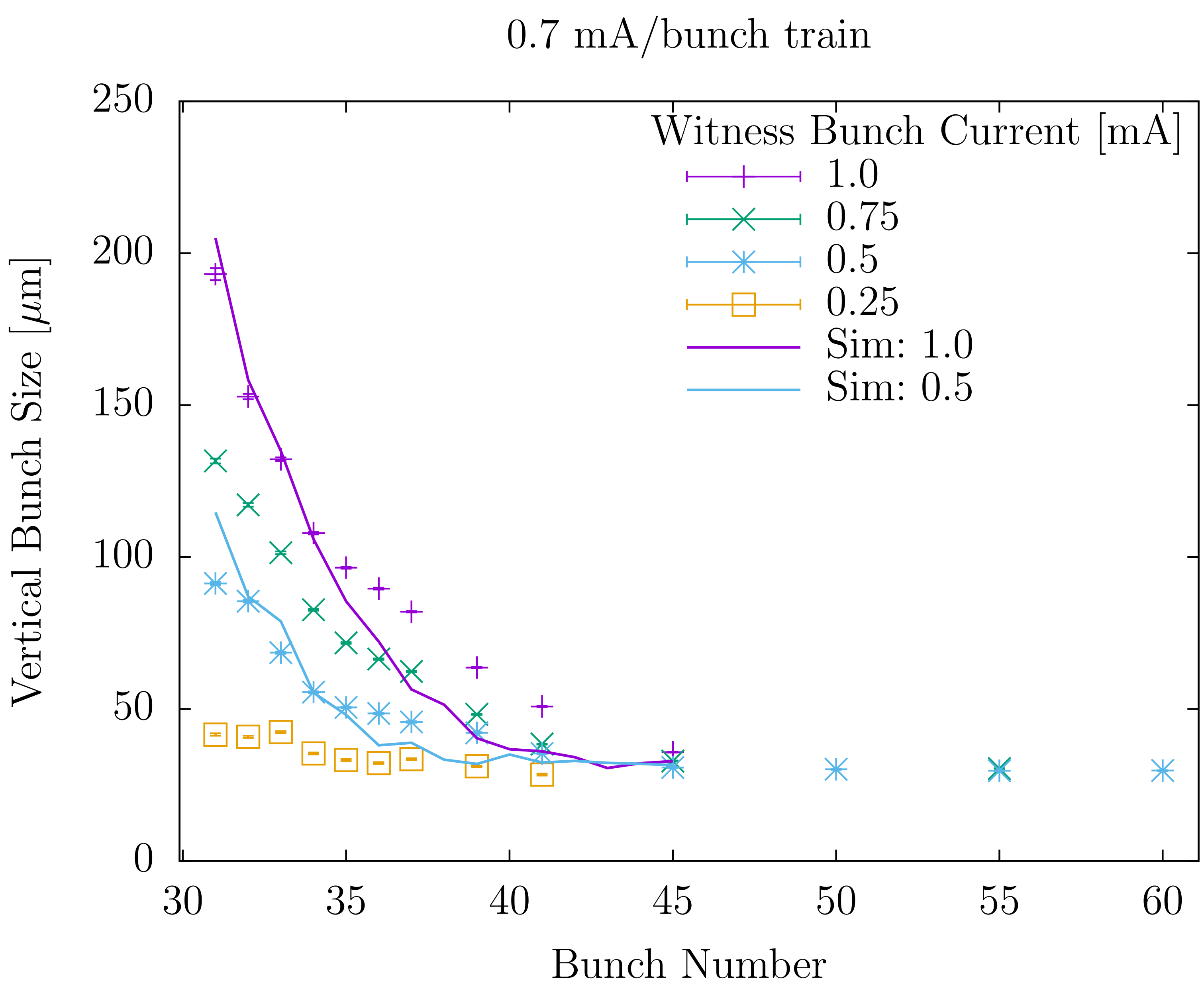
Vertical bunch size growth - train

- Bunch size from simulation is the average over last 20k turns (of 100k)
- See vertical emittance growth in 0.7 mA/b simulations





Vertical bunch size growth - witness bunch



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

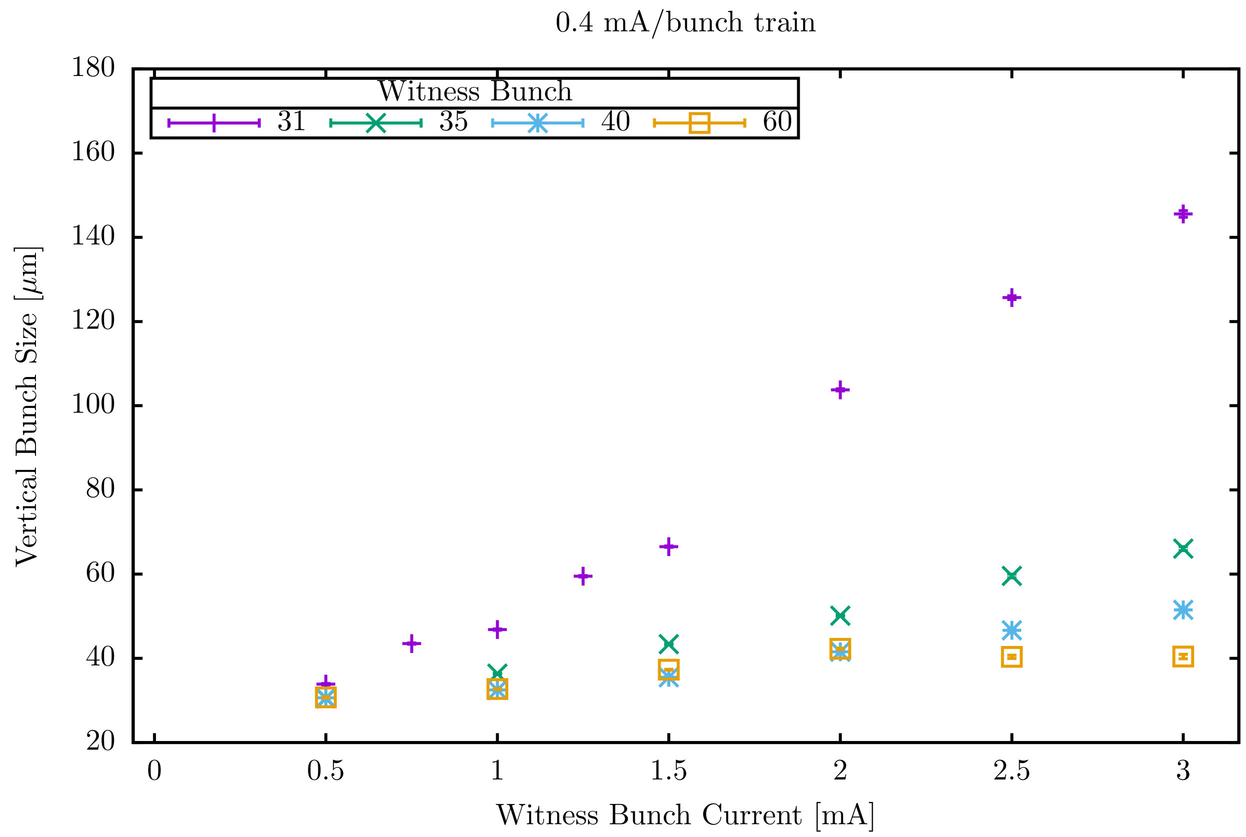
Summary

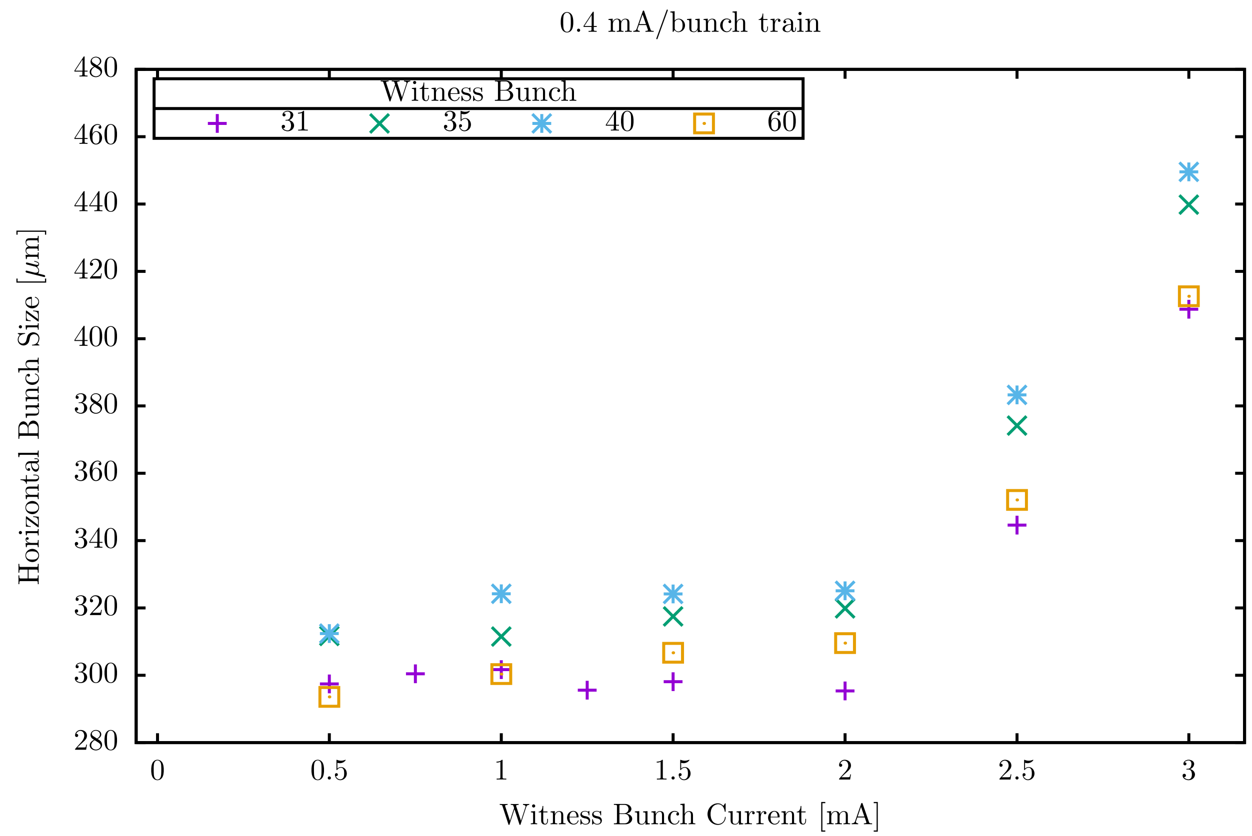
- We have obtained various measurements of tune shifts and emittance growth from electron cloud
- Our e-cloud model has been improved with precise modeling of synchrotron radiation photons & generation of primary electrons
- The model has been validated with improved tune shift measurements for a range of bunch currents at 2.1 and 5.3 GeV
- The validated model was used to predict tune shifts in CHESS-U transition and CHESS-U
  - All tune shifts (except for 1x9 with 4ns spacing) are < 2.5 kHz; should not present a problem
  - Disclaimer: We have not ruled out other possible sources of instabilities from EC:
    - Cloud shape, pinch effect, cloud trapping
    - The simulations can be used to address problems as they arise
- Our model 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:
  - 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-