Review of electron cloud at CESRTA and future machines for bright beams

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Beam Dynamics meets Vacuum, Collimations, and Surfaces

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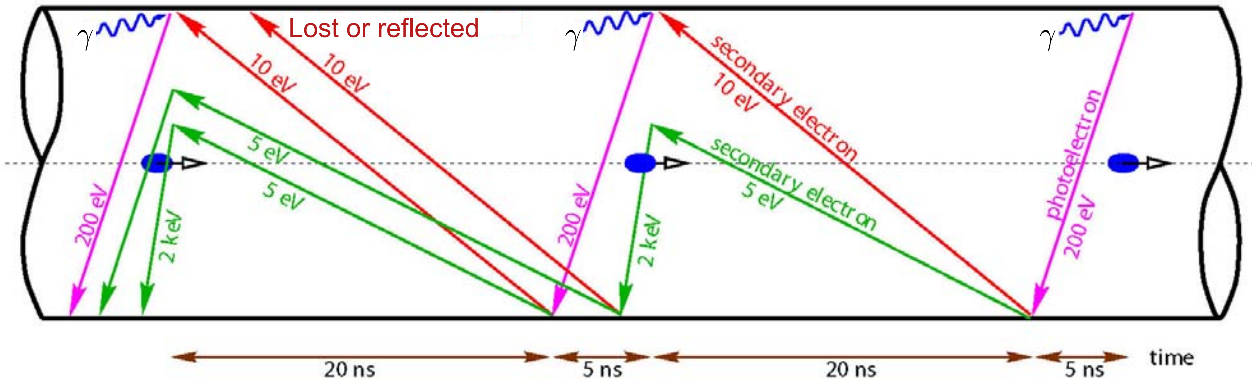
Overview

- Electron cloud (EC) can cause instabilities and emittance growth, and can be a limiting factor in accelerator performance
- EC has been studied at CESRTA (the Cornell Electron-Positron Storage Ring Test Accelerator) since 2008
  - Local and ring-wide EC measurements
  - EC mitigation techniques
- Emittance growth from EC not well understood until now

⇒ We have developed an incoherent model which predicts emittance growth from EC

- This talk will compare simulations to measurements for tune shifts and equilibrium beam size

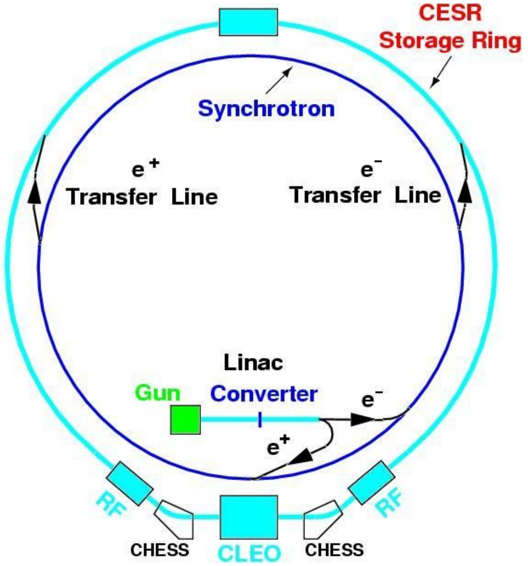
Electron Cloud



F. Ruggiero

- 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



- The vacuum system was modified to include various EC diagnostics
  - EC Experimental Regions & special vacuum chambers
  - RFAs (Retarding Field Analyzers)
  - SPUs (Shielded Pickups)
  - Microwave resonance EC detectors (TE Wave)
  - In-situ SEY station
- The beam instrumentation was also upgraded
  - Bunch-by-bunch, turn-by-turn beam position monitors
  - Bunch-by-bunch, turn-by-turn X-ray beam size monitor

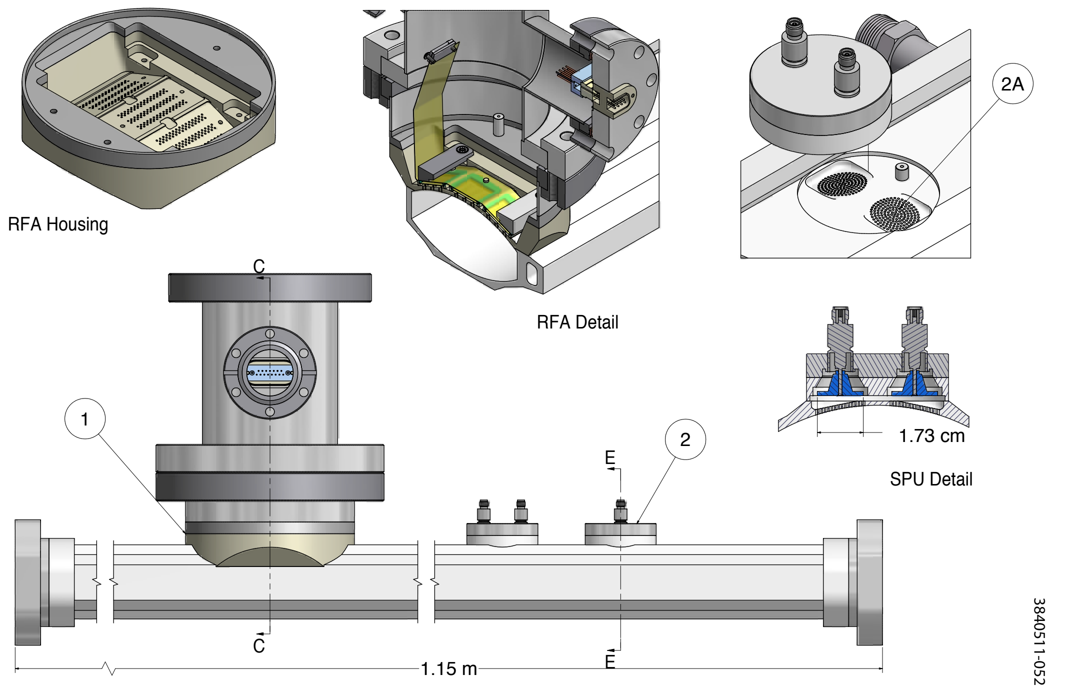


Figure 2.13: Q15 EC Test Chamber, equipped with a RFA (1) and 4 SPUs (2)

Local EC measurements

- Local EC measurements from RFAs and SPUs provide
  - A way of measuring the effect of various EC suppression techniques:
    - ★ Low emission coatings
      - TiN, amorphous carbon, diamond-like carbon
    - ★ Grooves in chambers
    - ★ Solenoid windings
    - ★ Clearing electrodes
  - A way of calibrating simulation parameters
    - ★ Primary and secondary emission parameters

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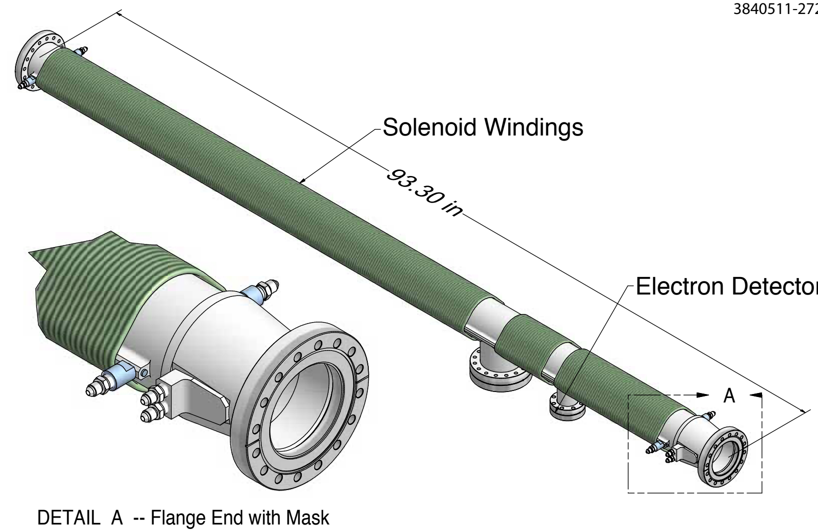

Figure 2.24: PEP-II EC vacuum chambers tested in the L3 experimental region.

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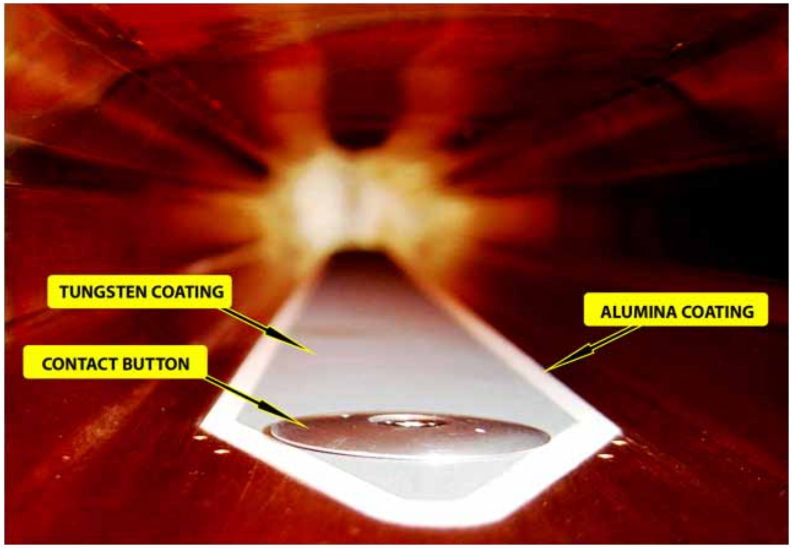


Figure 2.59: Photo of electrode connection button on the bottom of the SCW beam pip

EC model calibration

- EC model calibrated and validated on a wide range of local and ring-wide measurements
- Has been used to help design future accelerators
  - ILC
  - CHESS-U
  - SuperKEKB

Ring-wide

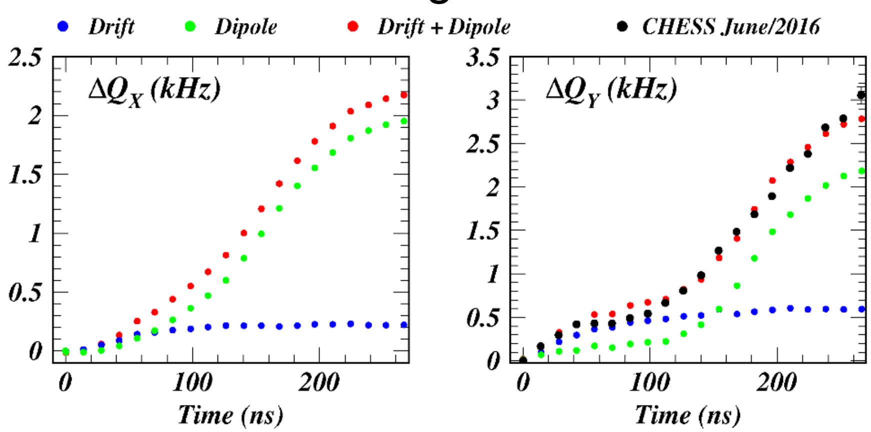
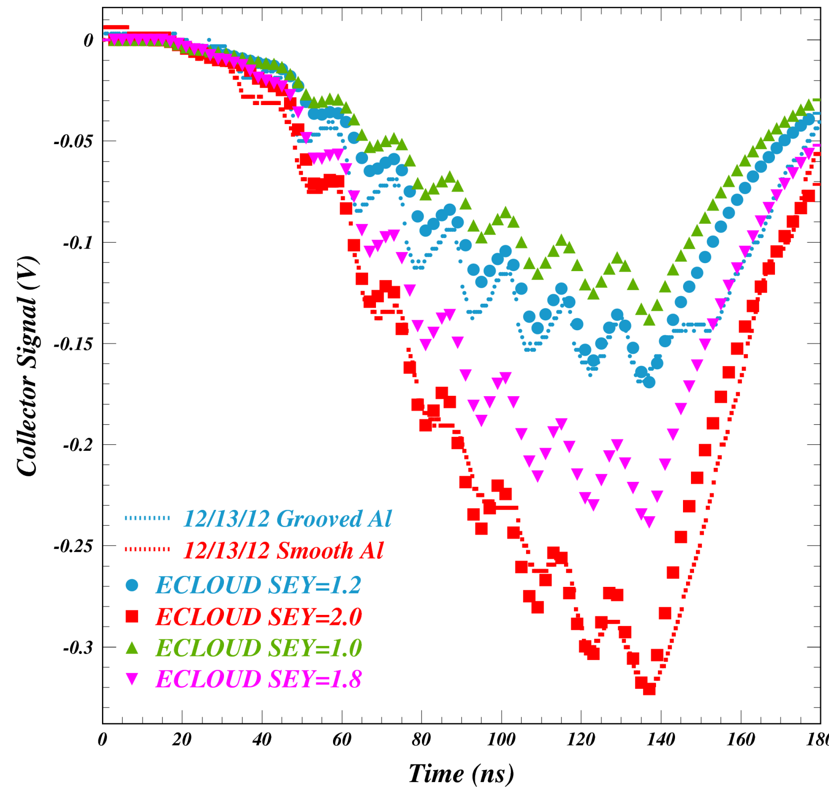


Figure 2: Modeled and measured (black points) tune shifts for a 20-bunch train of 5.3 GeV positrons with population 3.2×10^{10} e^+ (2 mA/b)

Local



Time resolved RFA measurements in grooved and smooth Al chambers compared to simulations varying the peak SEY

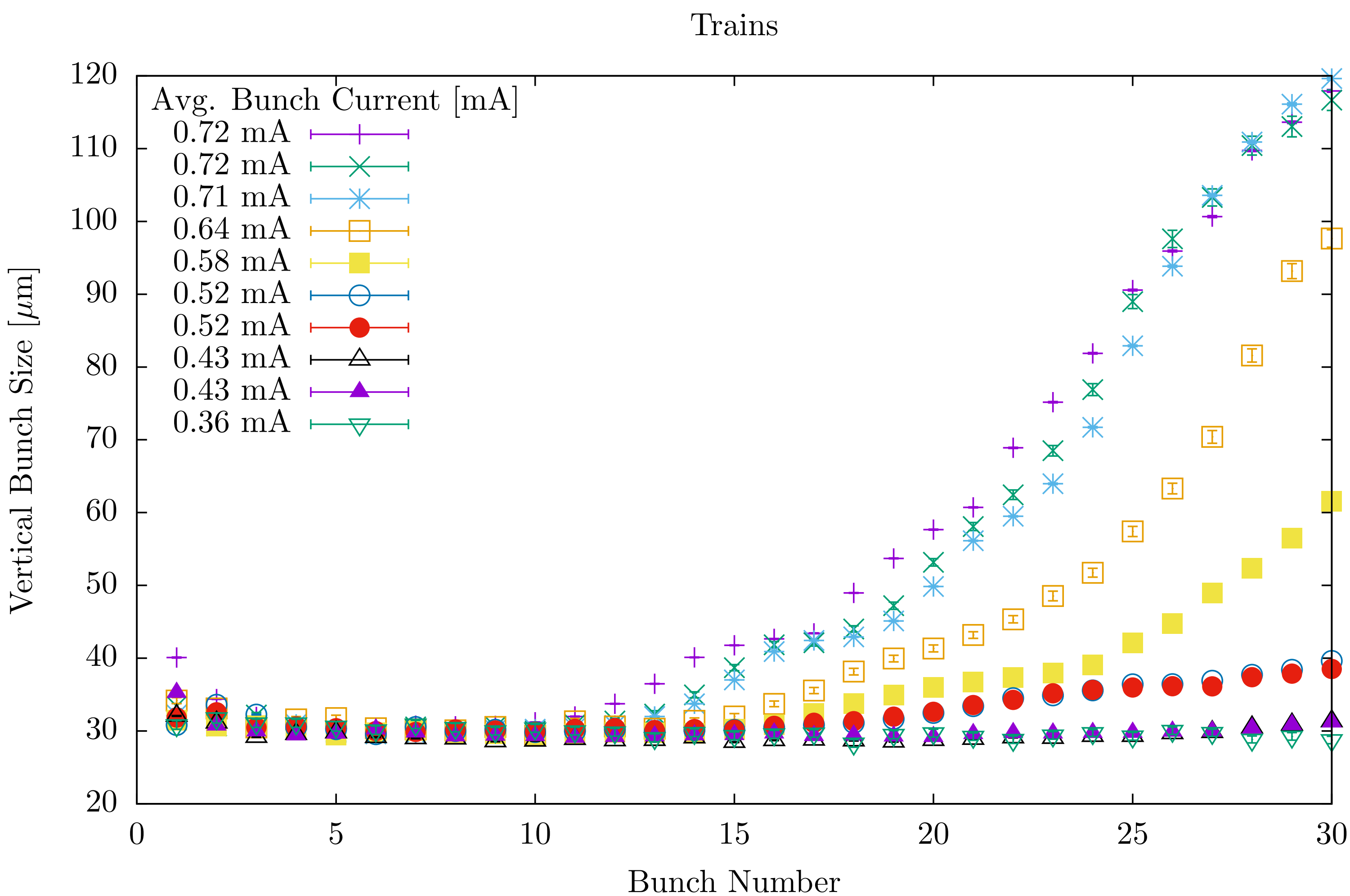
An incoherent model for emittance growth from EC

Measurements

- Beam:
  - 2.1 GeV positrons or electrons
    - ★ 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
    - ★ Bunch-by-bunch
  - 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

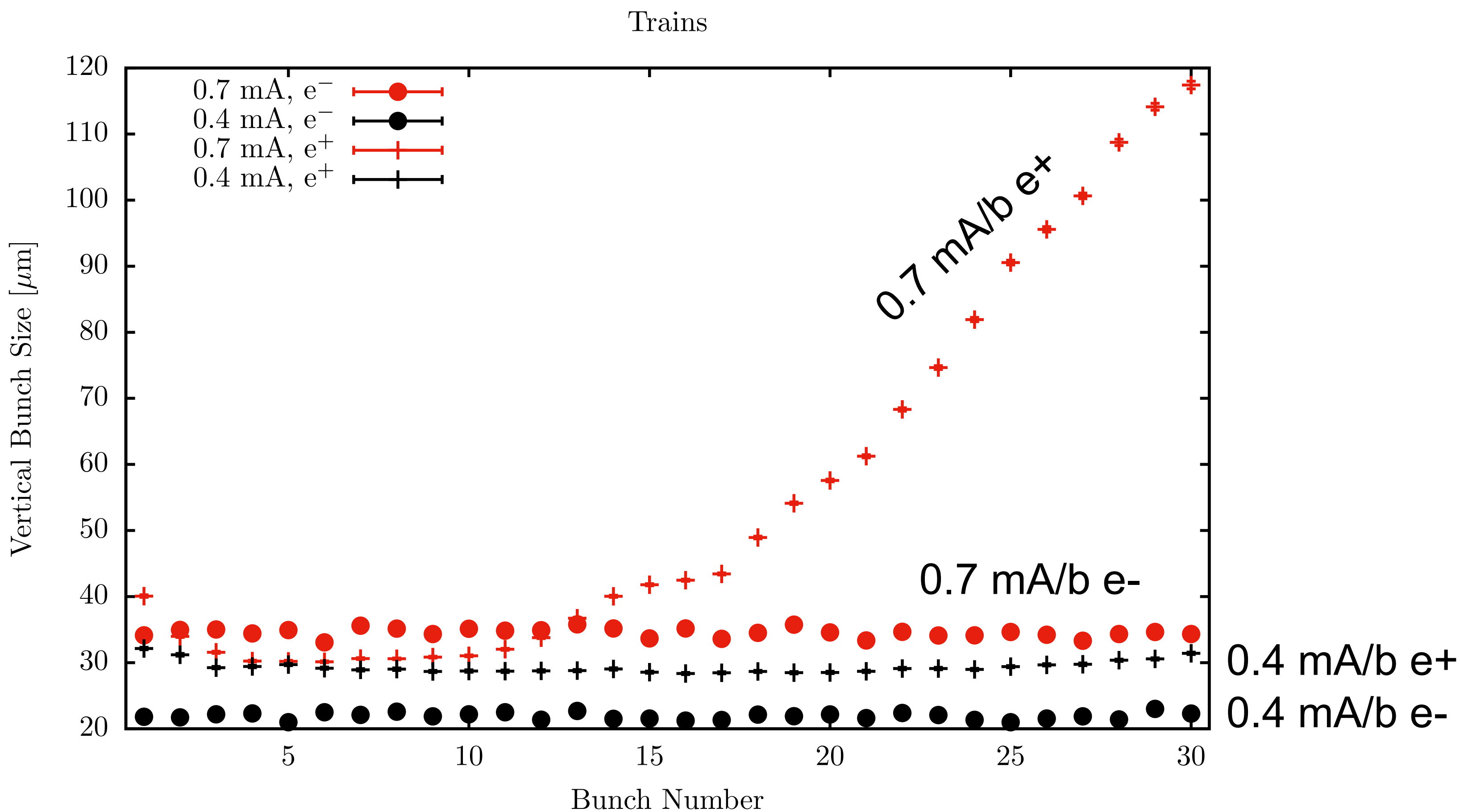
Beam size

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



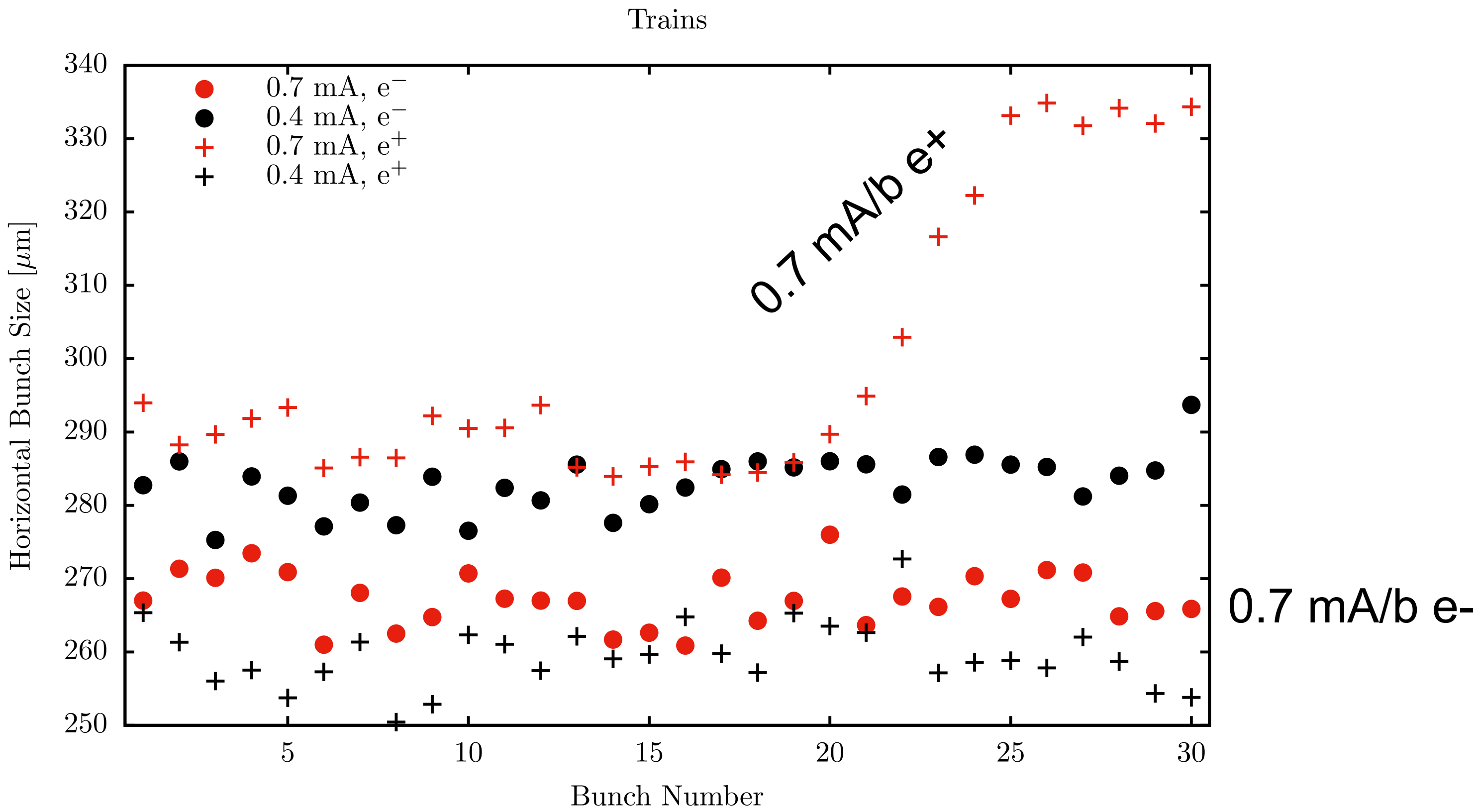
Beam size

- Trains of e- bunches do not blow-up
  - Emittance growth is due to EC



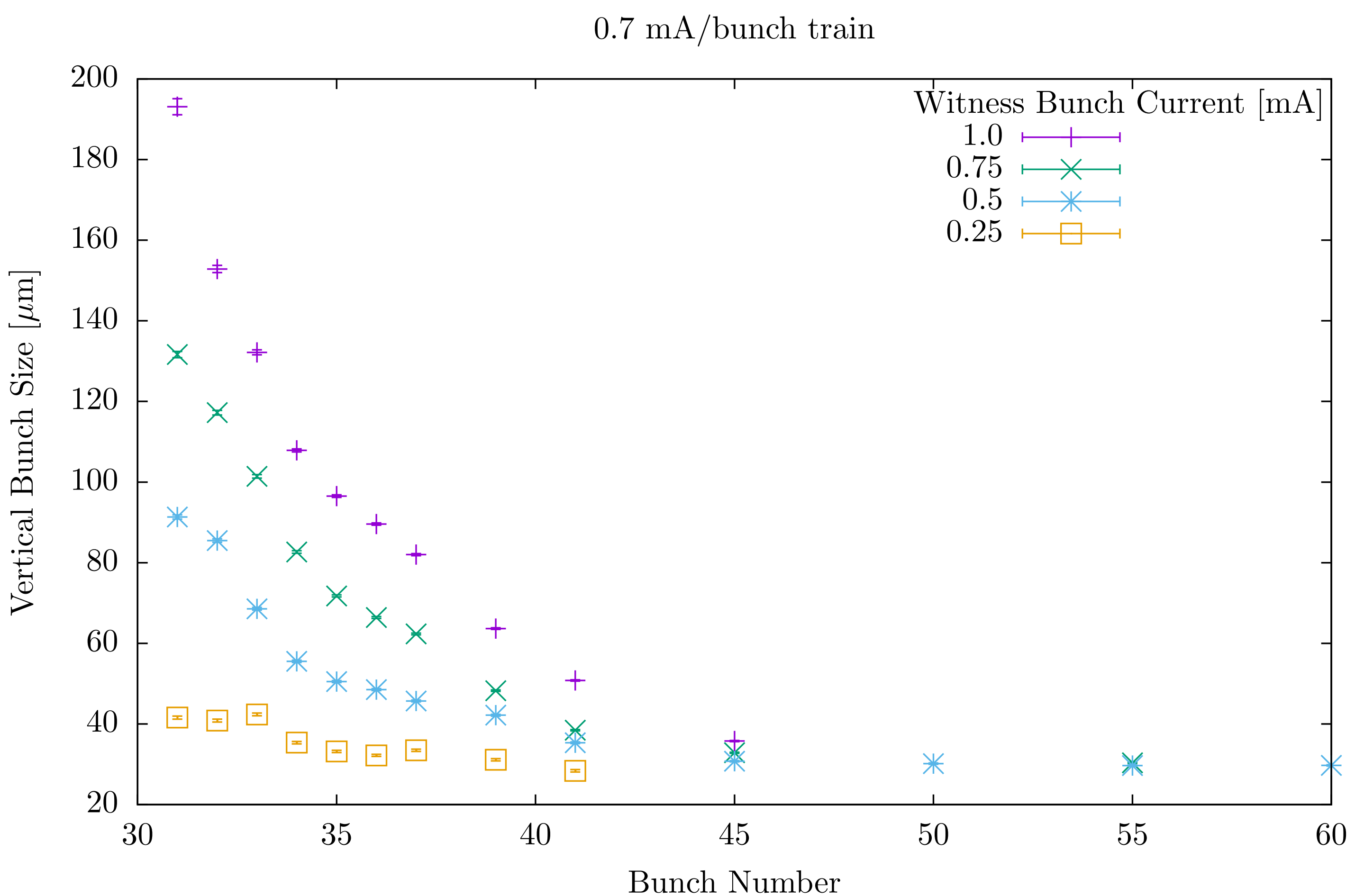
Horizontal beam size

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



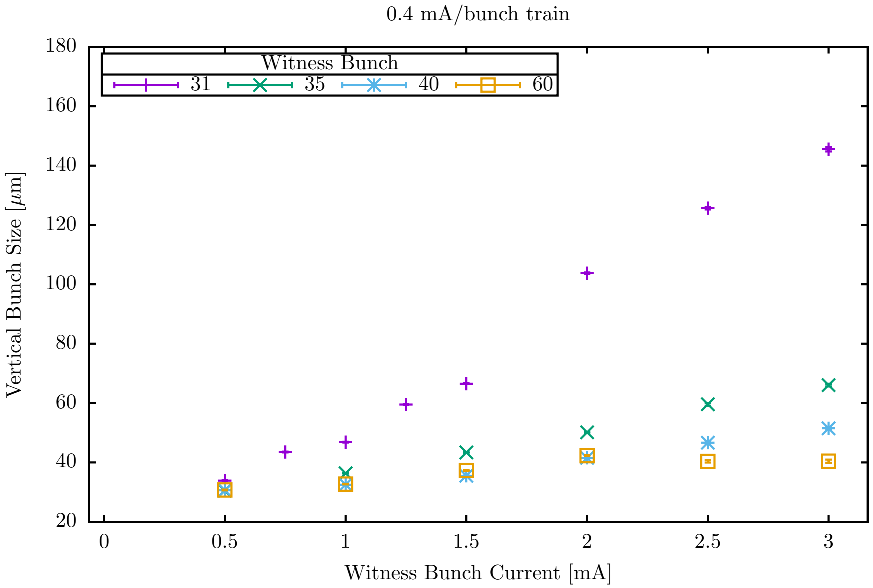
Witness bunch

- 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
    - ★ Strong dependence of emittance growth on current (pinch effect)

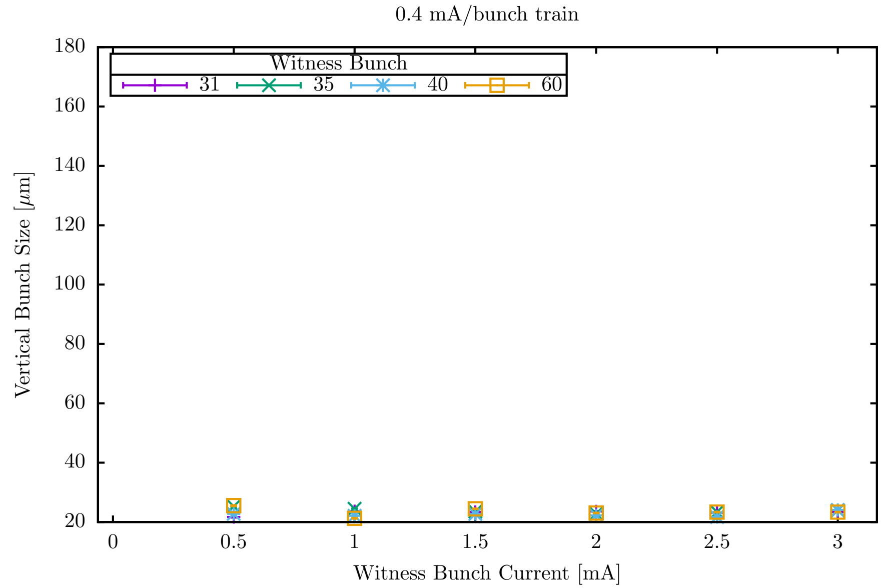


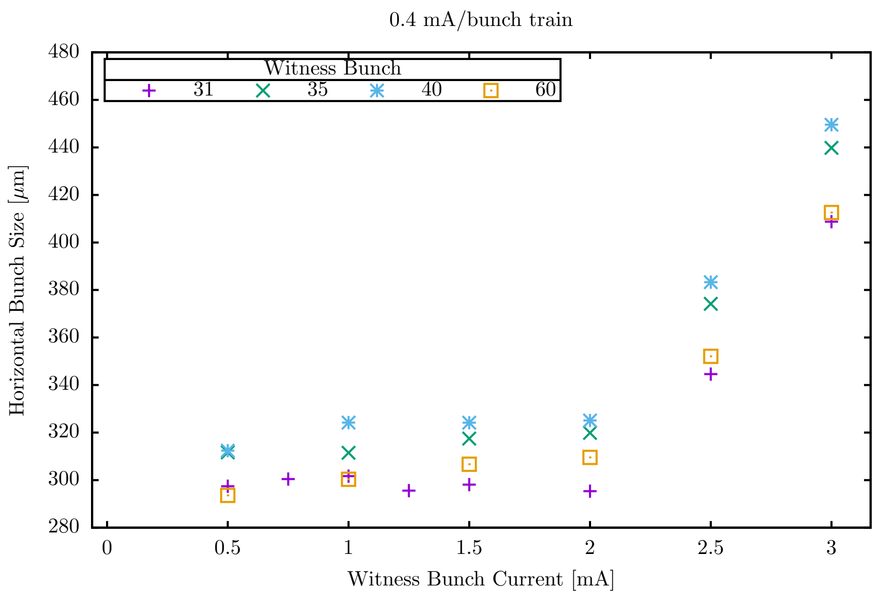
Witness bunch to a 0.4 mA/b train (below threshold)

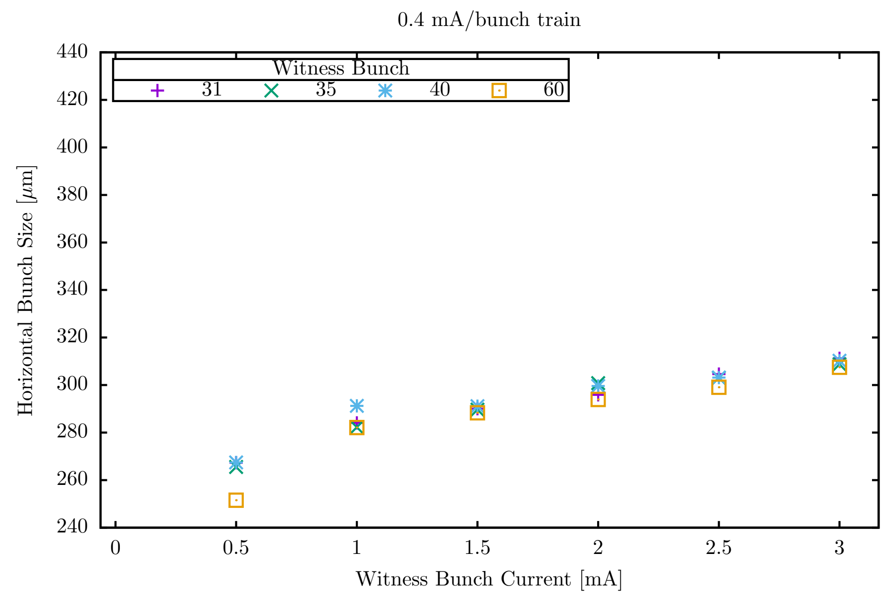
e+



e-







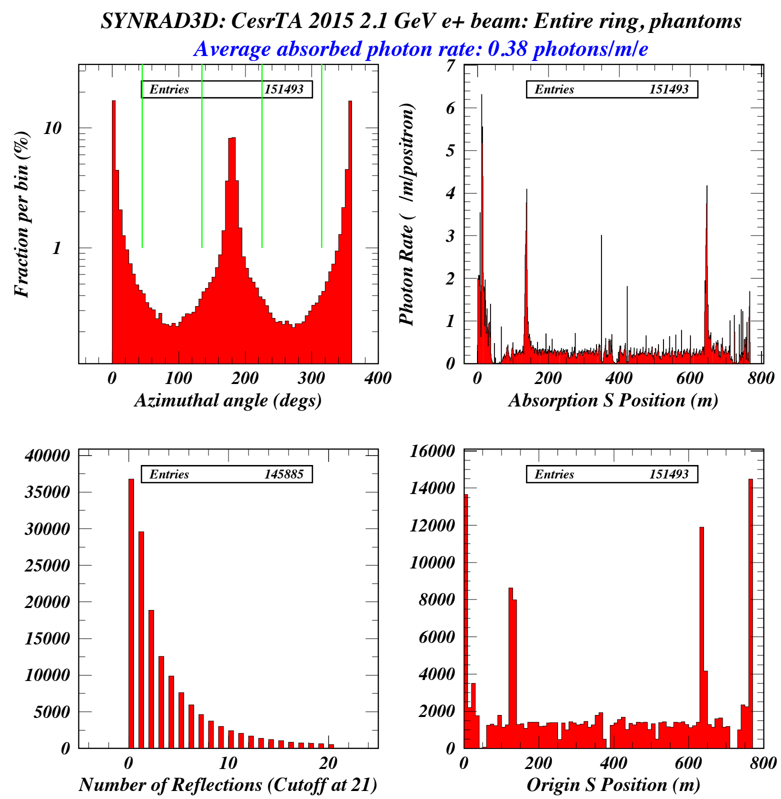
Simulations

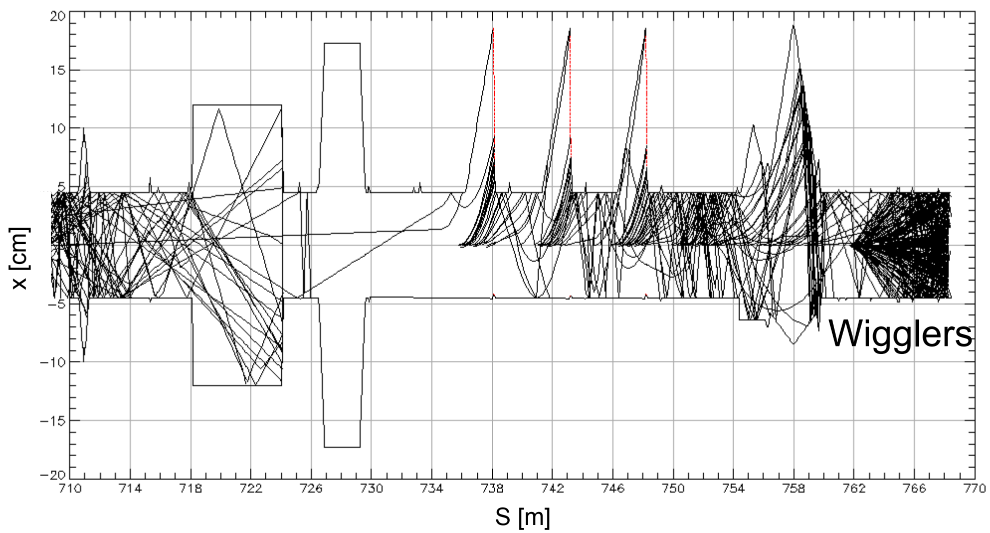
- Simulations involve three codes which feed into each other
  - Synchrotron radiation
    - → Photo-electron production rate along the wall
  - Electron cloud buildup
    - → Electric field maps
  - Tracking of beam through the lattice with EC elements
    - → Betatron tunes
    - → Beam size

Synchrotron radiation simulation

- Benchmark EC simulations at CesrTA have used a 2D analytic calculation for the photon absorption rate along the walls in a lattice
  - Current results use this method

- We are currently incorporating a 3D Monte Carlo simulation including reflections (specular & diffuse)

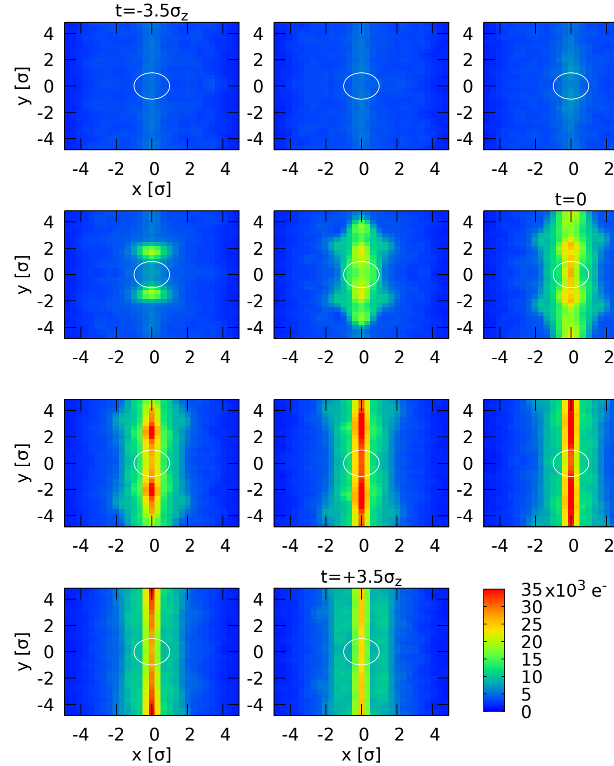


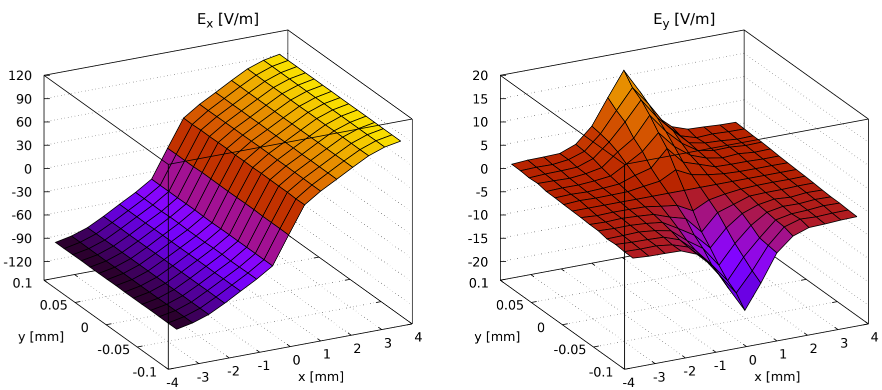


EC buildup simulation

- 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 electric field maps from the EC for 11 time slices during a single bunch passage, in ±5σ of the transverse beam size
  - $\Delta t = 20$ ps
- Only ~0.1% of electrons are within this beam region
  - Necessary to average over many ECLOUD simulations

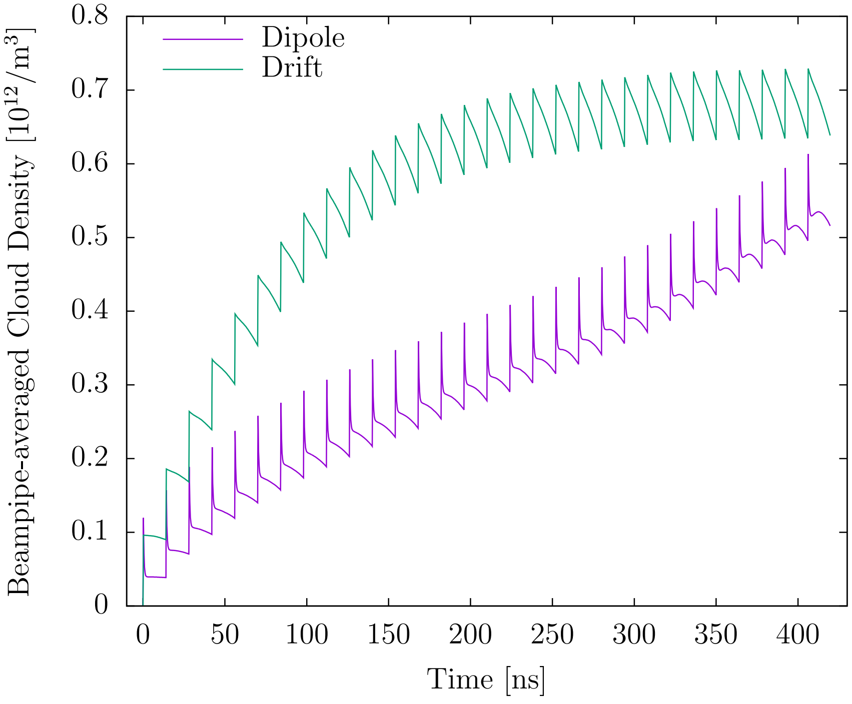
Transverse EC charge distributions in an 800 G dipole for bunch 30 of a 0.7 mA/b positron train

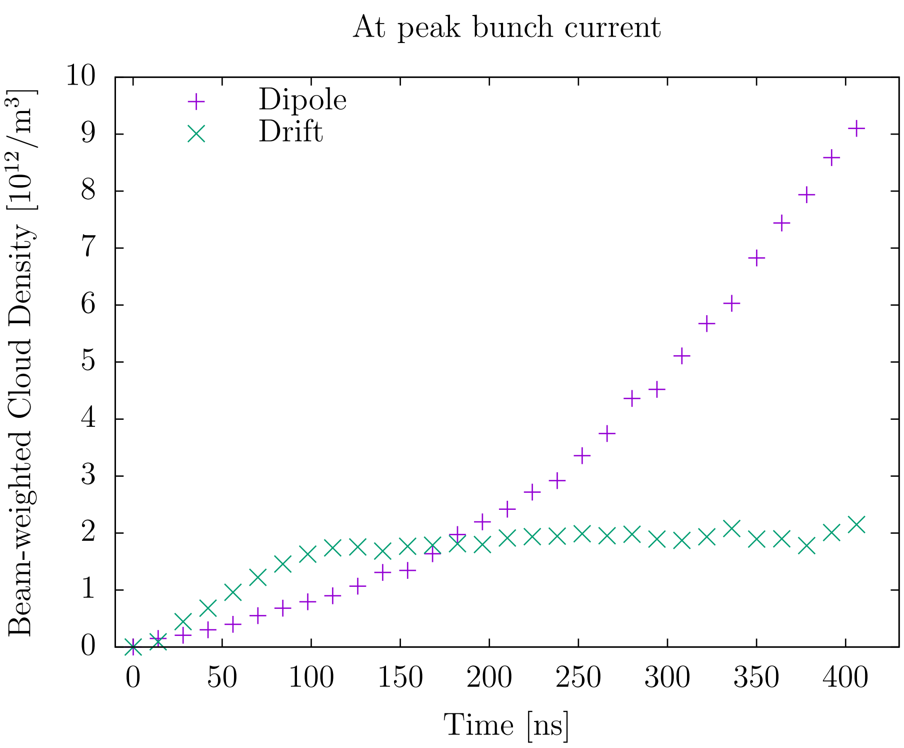




EC densities

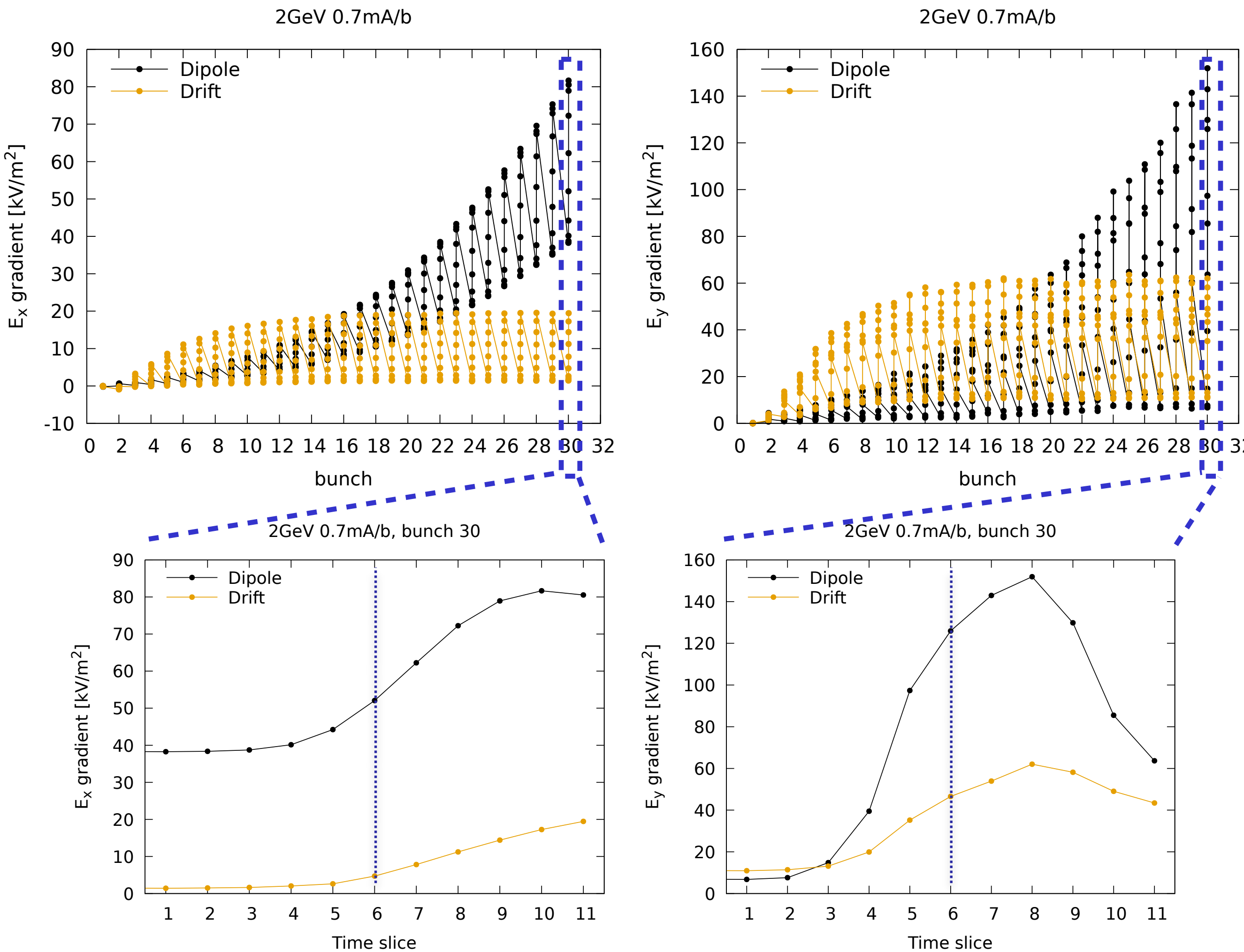
- EC density calculated during buildup simulation in dipoles and drifts for a train of bunches
- Beampipe-averaged density larger for drifts
- Bunch-charge-weighted density larger for dipoles later in the train
  - EC pinned to the vertical magnetic field lines in the dipoles





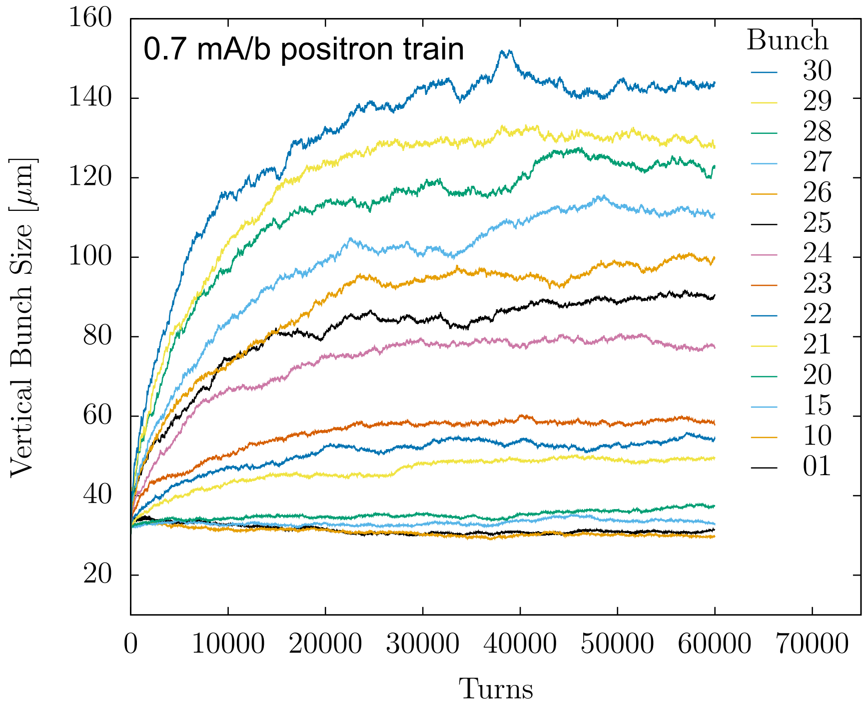
Electric field gradients from cloud space-charge fields

- Tune shifts are proportional to the electric field gradients
- Gradient just before a bunch passage ➔ coherent tune shift
- Gradient during pinch ➔ incoherent tune spread, emittance growth



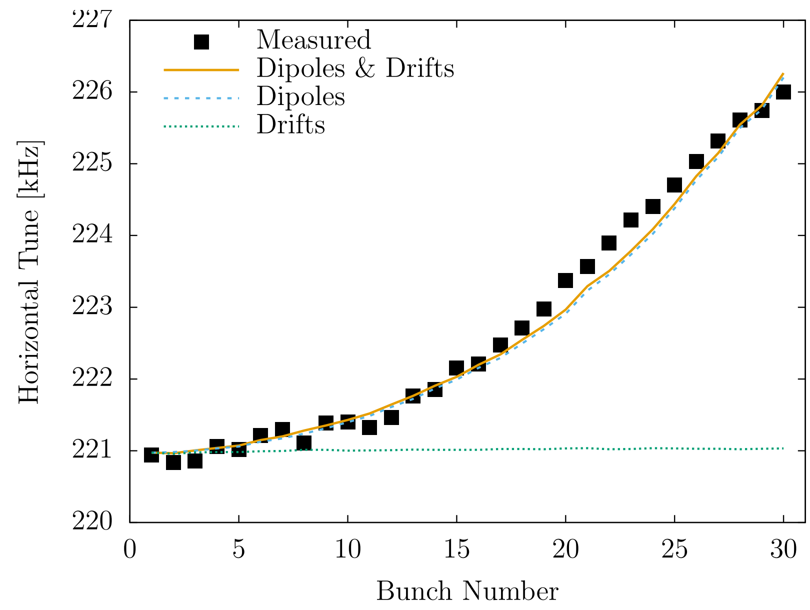
Tracking simulations

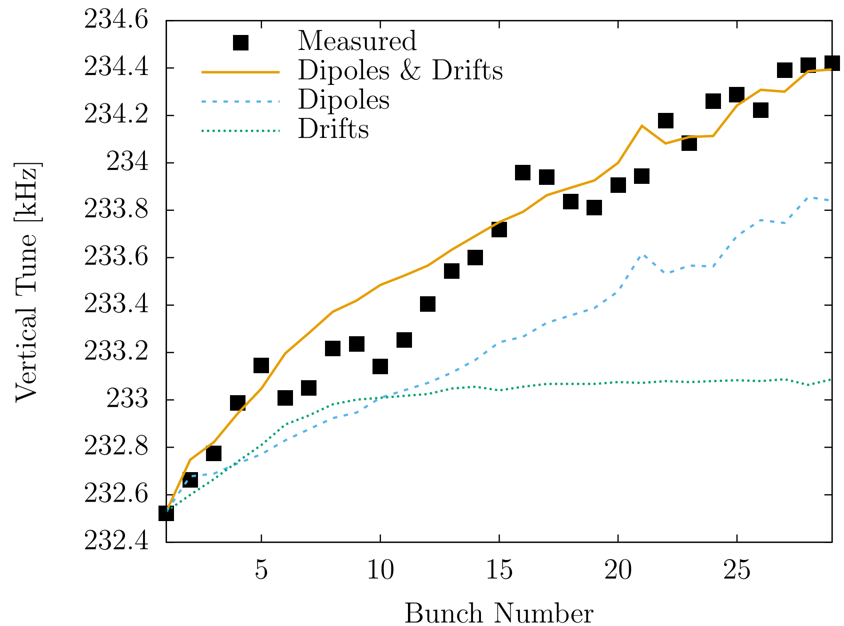
- Use the *time-sliced electric fields* in EC elements at the dipole and drifts
- Track particles in bunch through the full lattice (using Bmad) for multiple damping times, with radiation excitation and damping
- "weak-strong" model: does not take into account effects on the cloud due to changes in the beam
  - Weak: beam; Strong: EC
  - In the 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



Tune shifts - train

- Measurements (points):
  - Feedback is disabled for a single bunch
  - Use digital tune tracker to measure tunes of the bunch
    - ★ Frequency sweep & phase lock
- Simulations (lines):
  - Calculated from 1-turn transfer matrix or FFTs (good agreement)
  - Dipoles (62% of ring) dominate the horizontal tune shift compared to drifts (23%)
  - Drifts do contribute to vertical tune shift

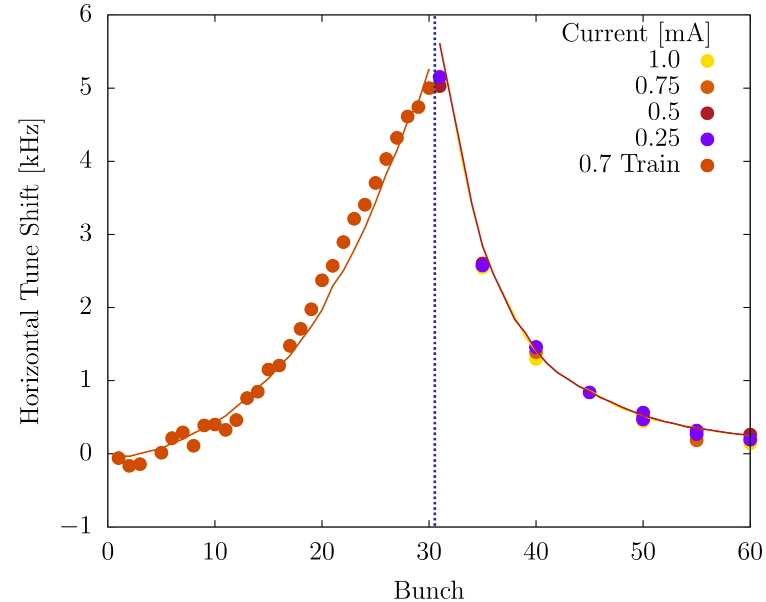


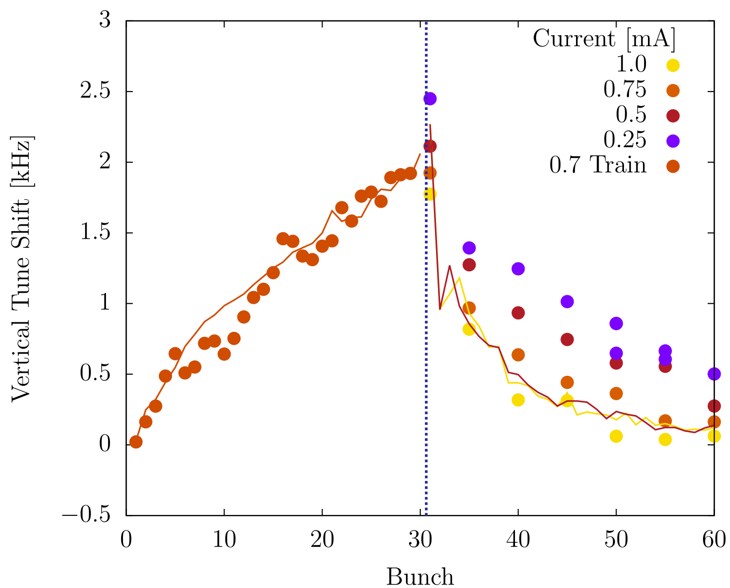


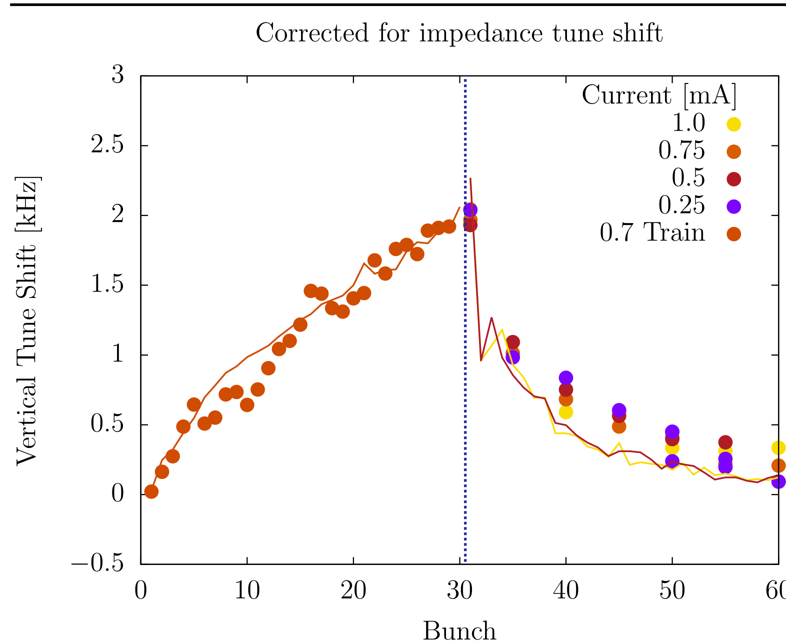
(Revolution frequency: 390 kHz)

Tune shifts - witness bunch

- Simulations shown as lines
- Measurements show no dependence of witness bunch current on tune shift
  - Pinch effect doesn't contribute to coherent tune shift
- Measured vertical tunes at different currents include a machine impedance tune shift
  - 1 kHz/mA from single bunch measurement
  - Subtract out for comparison to simulations

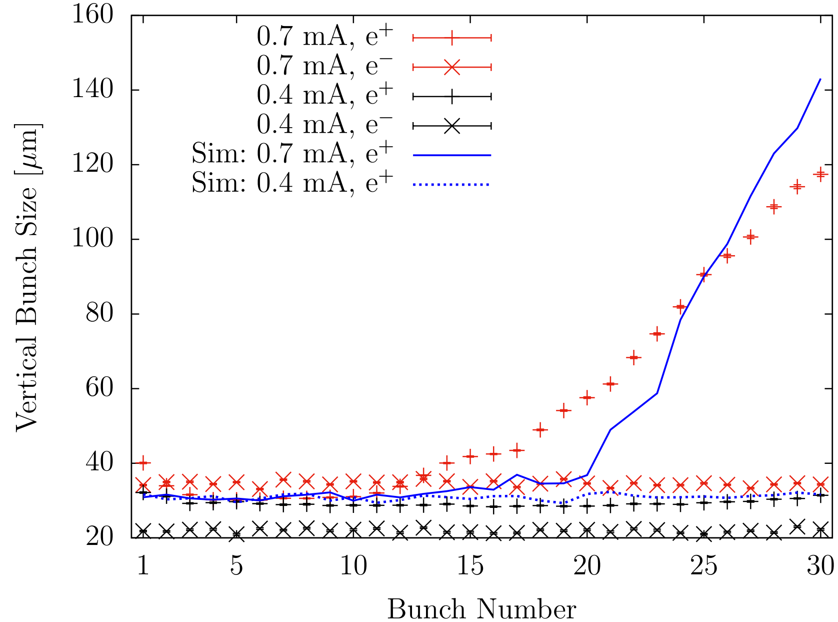


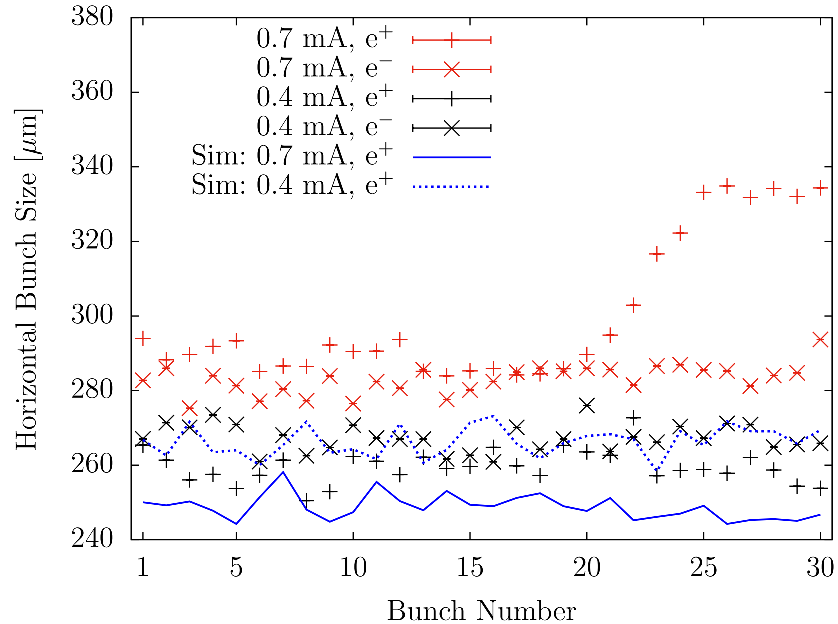




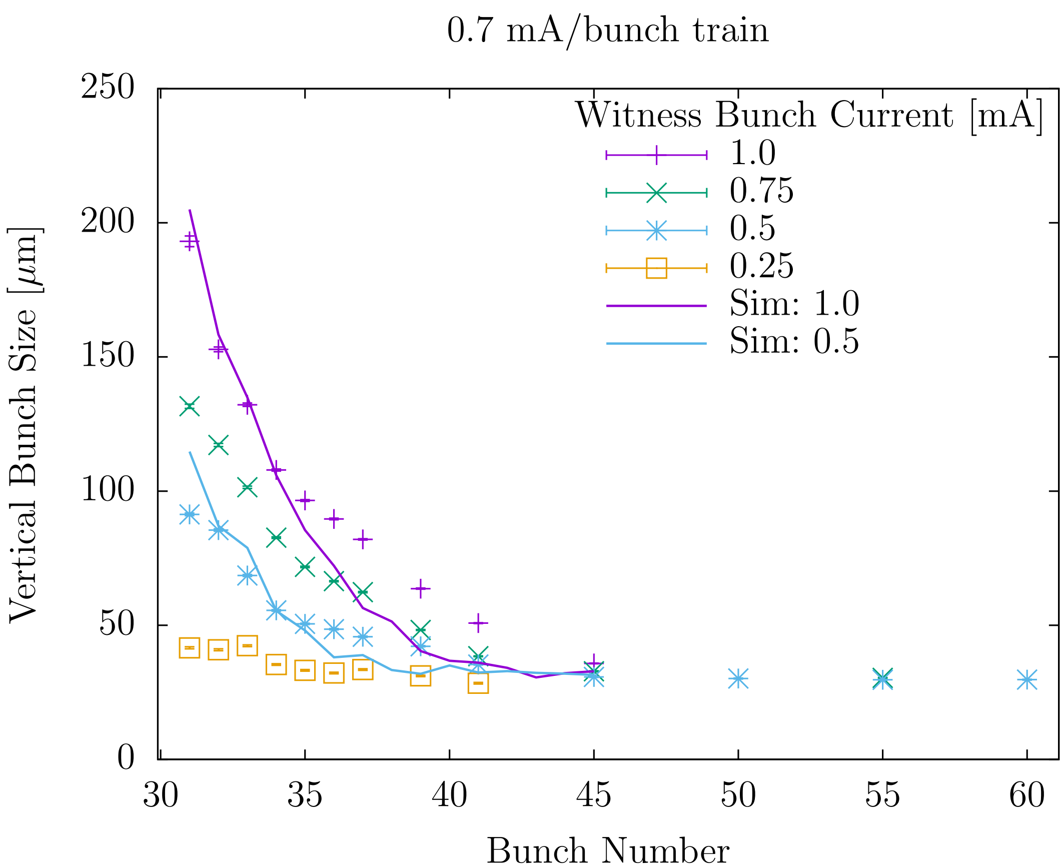
Bunch size growth - train

- Bunch size from simulation is the average over last 10k turns (of 60k)
- See vertical emittance growth in 0.7 mA/b simulations
- Do not see horizontal emittance growth at 0.7 mA/b
  - Do see growth for higher currents
  - ECLOUD simulation used large ring-wide horizontal beam size
    - ★ Pinch effect is stronger with smaller beam sizes
    - ★ May need to use different EC elements based on local horizontal beta





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

- Cornell has made extensive measurements of EC effects since 2008
  - Constrain parameters in EC buildup simulations
- Simulations in good agreement with local (RFA, SPU) and ring-wide (tune shift) measurements

- 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
- We have developed a weak-strong incoherent model which 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:
  - Reconcile data/simulation discrepancies (horizontal emittance growth)
  - Revisit emittance growth predictions in ILC damping ring
  - Use model to understand underlying factors driving emittance growth
    - ★Develop new approaches to mitigating emittance growth from EC

Thank you for your attention