Emittance Dilution In Electron/Positron Damping Rings

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Outline

- CESR Test Accelerator
- Single Particle Emittance
- Current dependent effects
  - Intra-beam scattering
  - Emittance growth from transverse wakefields
  - Electron cloud induced emittance growth
- Summary/Conclusions

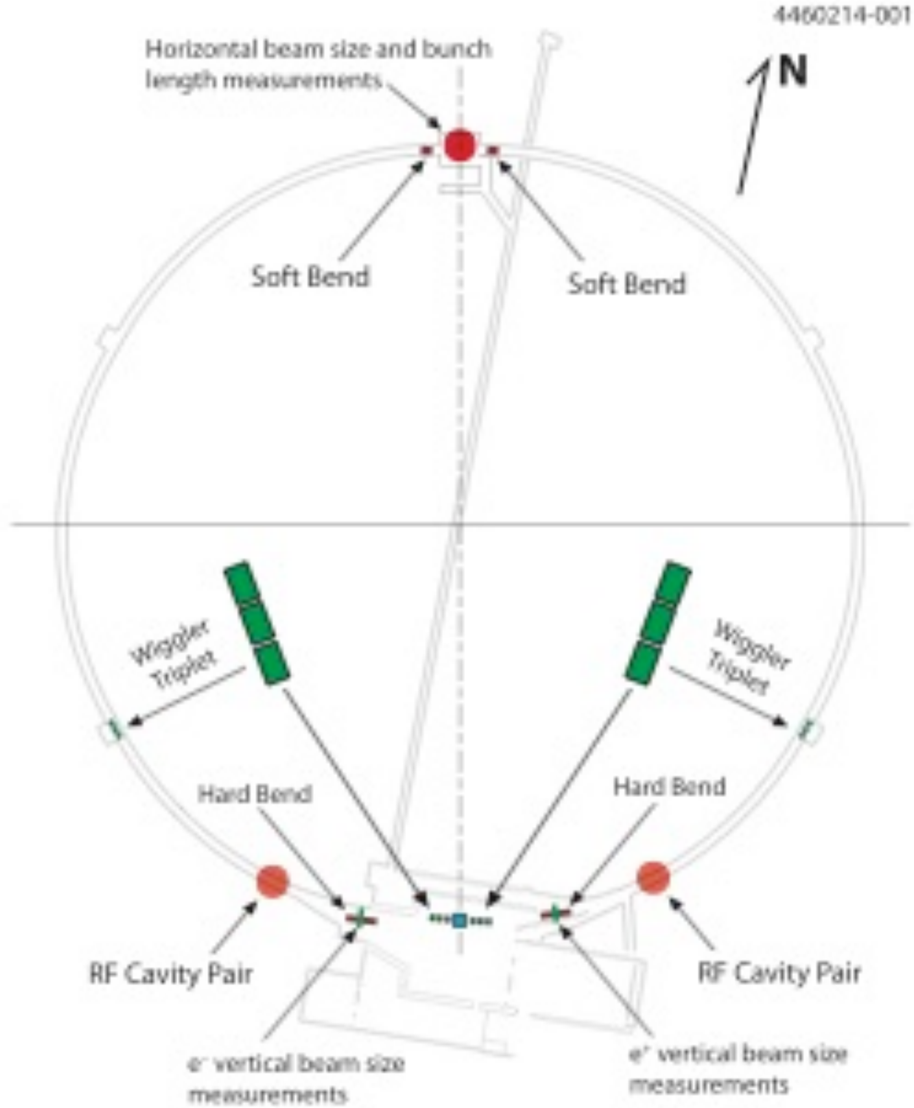
Cornell Electron/Positron Storage Ring (CESR)

768 m circumference
Energy reach: 1.8 GeV < E < 6 GeV

CESR operates at

5.3 GeV for CHESS
(Cornell High Energy Synchrotron Source)
Horizontal emittance $\varepsilon_x \sim$ 100 nm

2.1 GeV as CesrTA
(CESR Test Accelerator)
Horizontal emittance $\varepsilon_x \sim$ 2.5 nm



Storage Ring - CESR

Manipulate/control beams

~ 300 magnets
- Dipoles - Steer
- Quadrupoles - Focus
- Sextupoles -Compensate energy spread
- Skew quadrupoles - Compensate coupling
- Wigglers - Vary radiation damping
- Pulsed magnets – drive oscillations

4 SRF Accelerating cavities – focusing and vary bunch length

Monitor beam environment

- Retarding field analyzers, shielded pickups, resonant microwave detection > electron cloud
- Residual gas analyzers
- Pressure gauges
- Thermometry

Control System

Monitor beams

- 100 Beam position montors
- X-ray and visible synchrotron light beam size monitors
- Tune tracker
- Current monitors
- Bunch length measurement
- Spectral measurement

Modeling codes

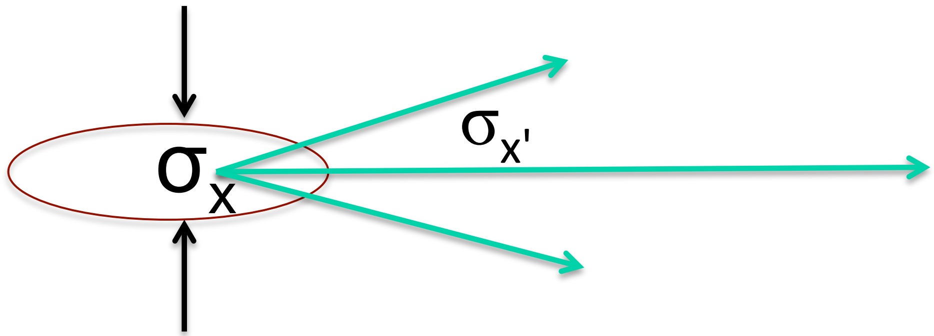
- Lattice design and correction
- Orbit,coupling,beta – closed bumps
- Tracking simulations

CESR, reconfigured as CesrTA is a laboratory for investigating the physics of low emittance charged particle beams

- Intra-beam scattering
- Fast ion effect
- Single particle emittance
- Emittance tuning
- Wakefields and impedances
- Particle beam optics
- Electron cloud growth and mitigation
- Electron cloud beam dynamics

Emittance

Emittance $\varepsilon_x \sim \sigma_x \sigma_{x'}$ (product of size and divergence)



$$\epsilon = \sqrt{\langle x^2 \rangle \langle {p_x}^2 \rangle + \langle x p_x \rangle^2}$$

Two broad categories of effects contribute to emittance of a stored electron (or positron beam)

- Single particle effects – volume of a single particle in phase space on multiple turns
- Collective effects – that depend on the number and density of particles in a bunch.

Single Particle Emittance

In the rest frame of a bunch - $\langle \vec{p} \rangle = 0$

- Kinetic energy of the particles corresponds to a temperature, and we can assign an equivalent temperature to motion in each of x,y and z
- Hot bunches are injected into a damping ring, and cold bunches extracted
- i.e. - ILC damping ring reduces emittance of positron bunch by 6 orders of magnitude at a repetition rate of 5 Hz

Phase space coordinates are mapped through a single turn

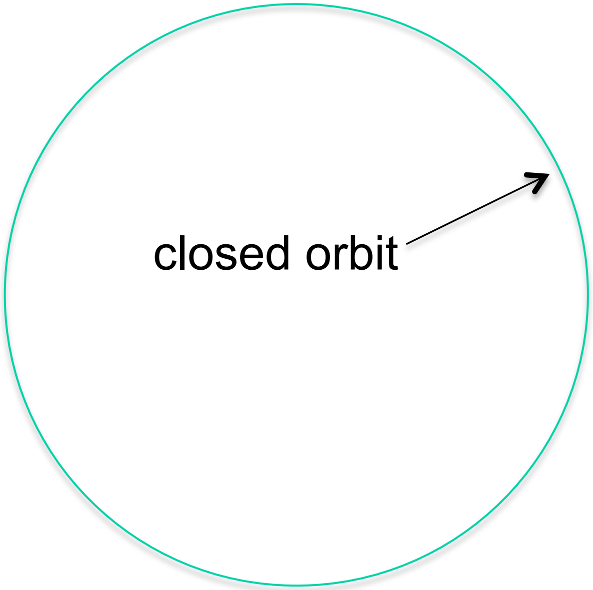
$$\begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix}_{start} \quad \text{Full Turn}(\rightarrow) \begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix}_{end}$$

For particles with coordinates on the closed orbit

$$\begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix}_{start} = \begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix}_{end}$$

Closed orbit

Simple closed orbit in uniform vertical B-field



If the initial coordinates are displaced from the closed orbit the trajectory will oscillate about it.

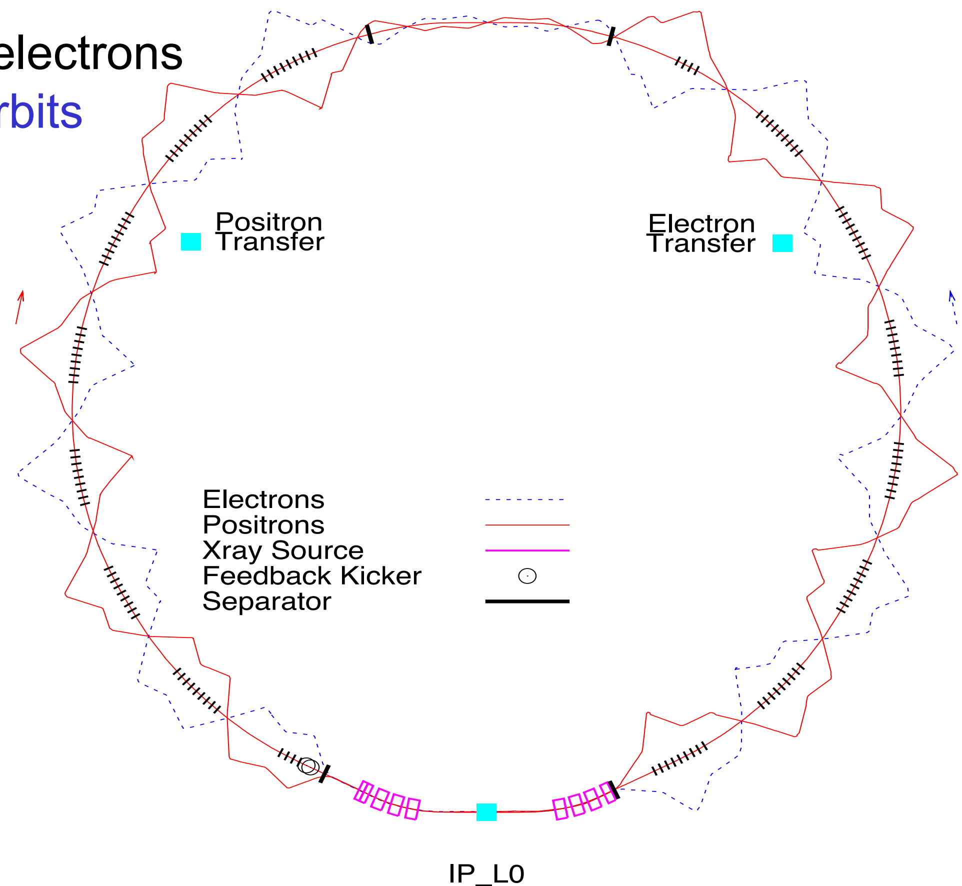
$$x(s) = a\sqrt{\beta(s)}\cos(\phi(s) - \phi_0) \qquad \phi(s = C) = 2\pi Q$$

The area in phase space mapped out in subsequent turns is the single particle emittance

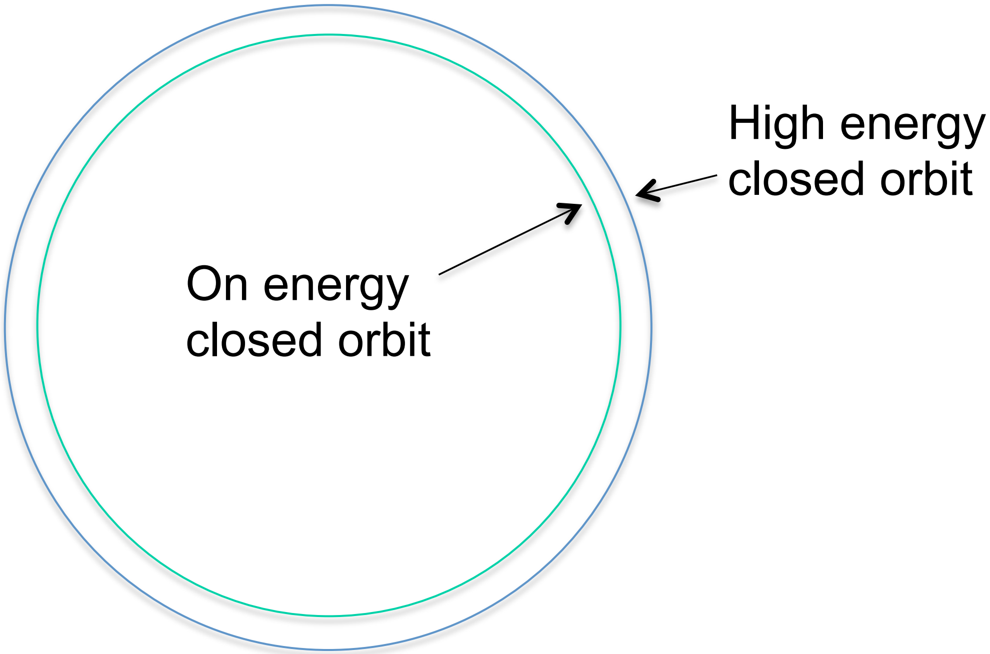
The closed orbit is generally not a simple circle

Two beam operation for CHESS

Electrostatic separators differentially kick electrons and positrons generating distinct closed orbits



The closed orbit depends on the energy

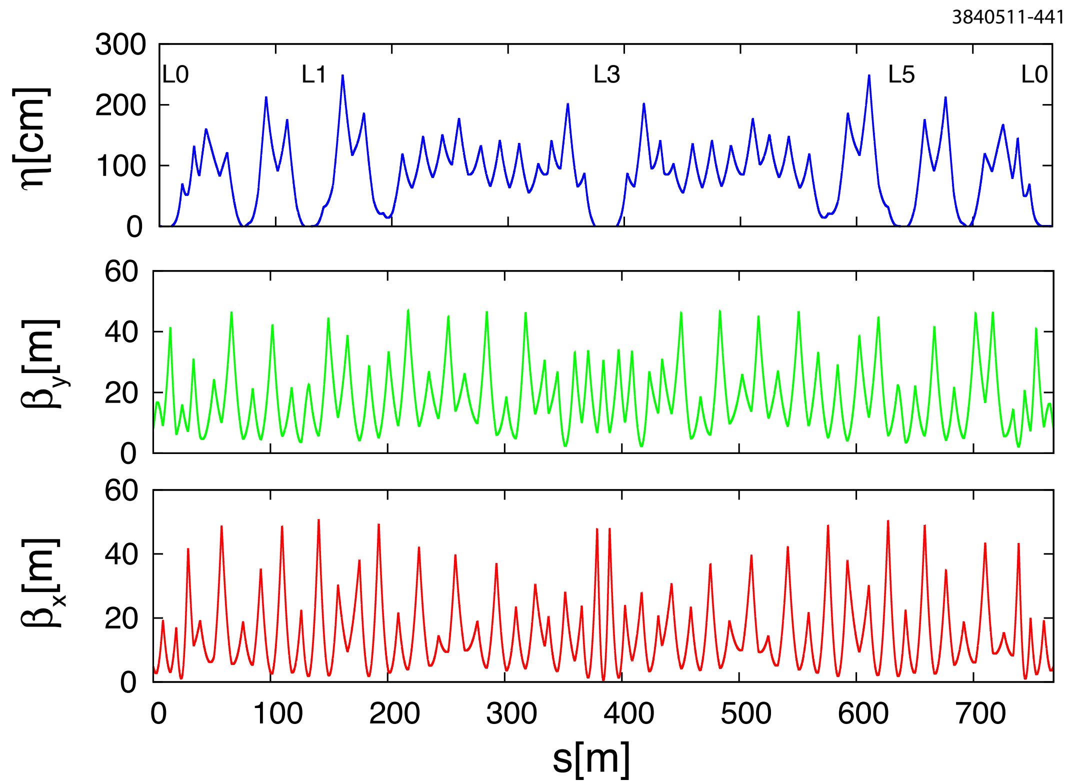


Dispersion

$$\vec{\eta} = \frac{d\vec{x}}{d\delta}$$

Dispersion

The form of the dispersion $\eta(s)$ is determined by the bending field and the quadrupole focusing



Dispersion in CesrTA optics

Radiation excitation

In the absence of any disturbance, a particle on the closed orbit will remain there and the single particle emittance is zero.

Electrons emit photons due to synchrotron radiation with some probability distribution depending on energy and local B-field.

Photons are emitted very nearly tangent to particle trajectory

$$\vec{p}_\gamma \approx \vec{p}_e$$

To first order, only the energy of the electron is changed. The electron is abruptly displaced from the appropriate closed orbit by

$$\Delta\vec{x} = \frac{\delta E}{E}\vec{\eta}$$

The electron begins to oscillate about its new closed orbit

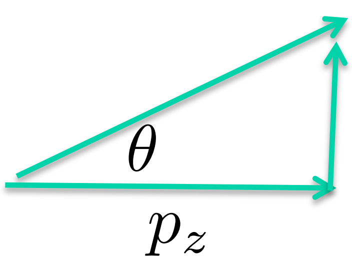
CESR parameters

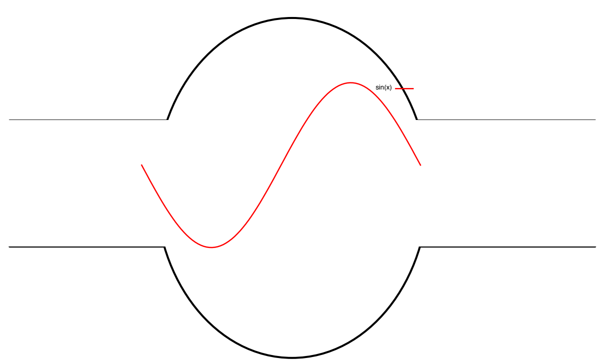
5.3 GeV Beam energy

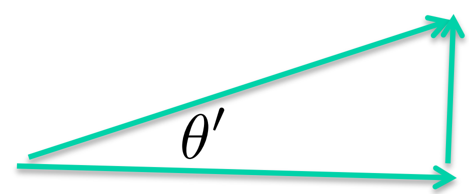
~ 800 photons are emitted/electron/turn
corresponding to ~1 MeV

Energy is restored by RF cavities

$$p_z = p_z + q\langle V_z \rangle$$







$$\theta' = \theta(1 - \frac{\Delta p_z}{p_z})$$

Equilibrium

The radiation damping time corresponds to the number of turns to radiate all of the energy – CESR at 5.3 GeV => 5300 turns (~15 ms)

Equilibrium of radiation excitation due to photon emission and radiation damping which depends on the average energy loss per turn => emittance

Equilibrium horizontal emittance depends on

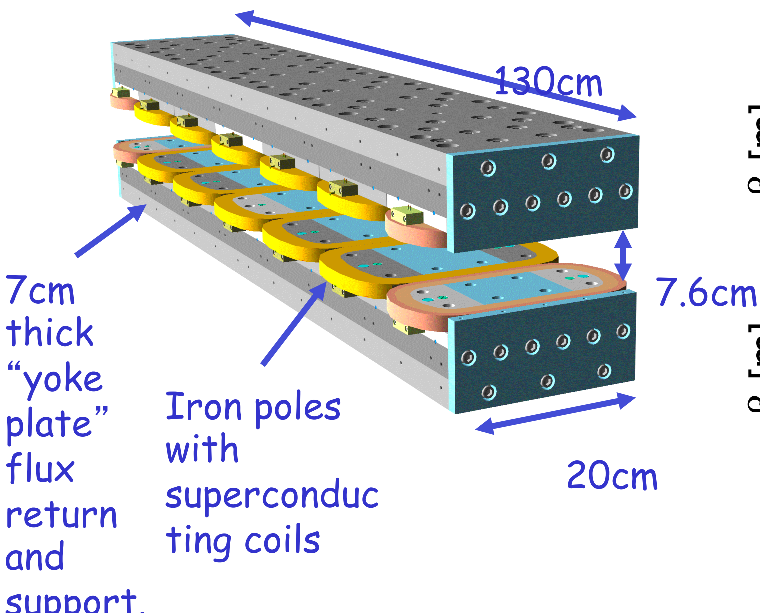
- Beam energy (number and energy of radiated photons ~ γ^2)
- Dispersion function
- Energy loss/turn

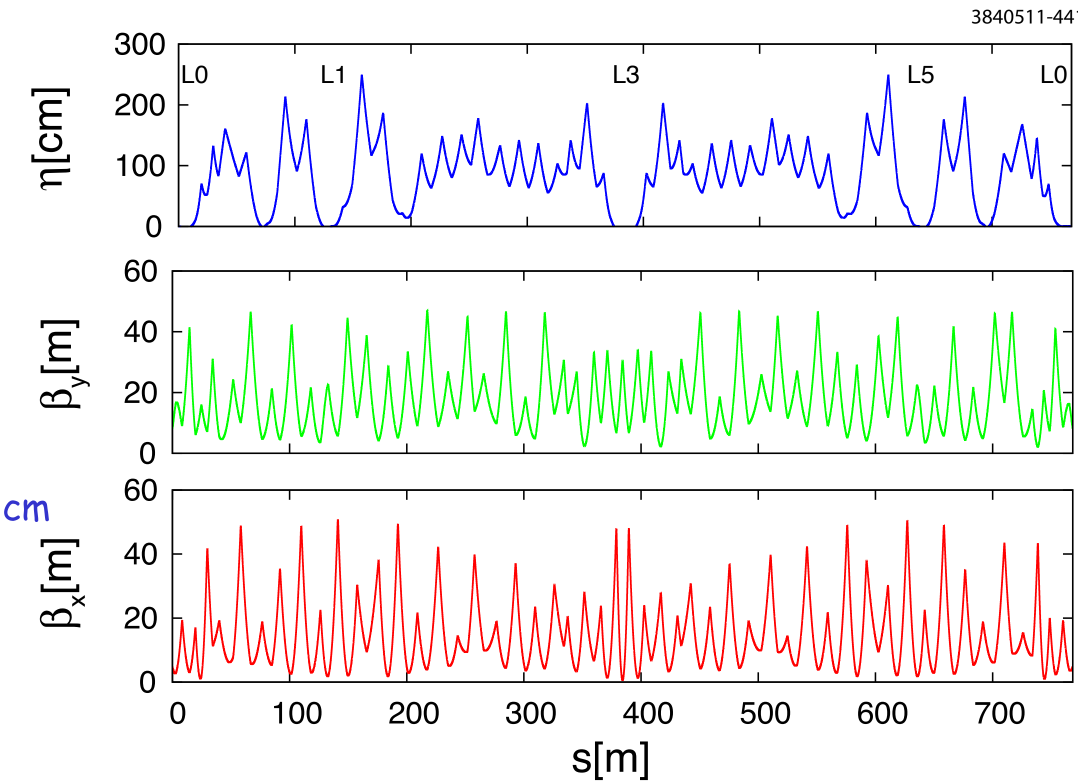
CesrTA Low Emittance Optics

CesrTA – 2.1 GeV

Superconducting wigglers in zero dispersion straight increase radiation damping (X10) without adding to radiation excitation

$\varepsilon_x \sim$ 2.5 nm



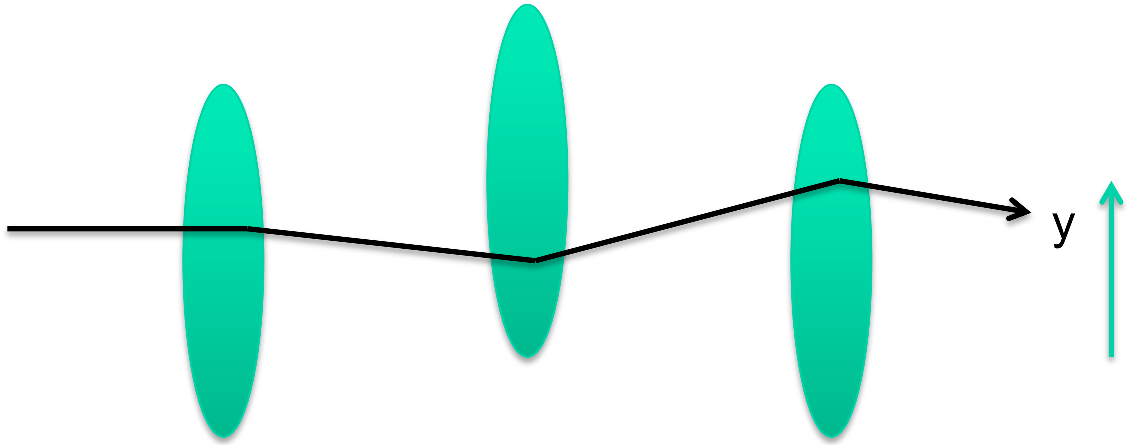


Vertical emittance

In the horizontal plane, dispersion cannot be avoided. The particles have to go around in a circle.

But not so the vertical.

- In a planar ring with magnets perfectly aligned, there are no vertical dipole kicks
- The vertical component of the closed orbit is independent of energy.
- Radiation of straight ahead photons contributes nothing to the emittance.
- Single particle vertical emittance is typically dominated by misalignments



Quantum Limit

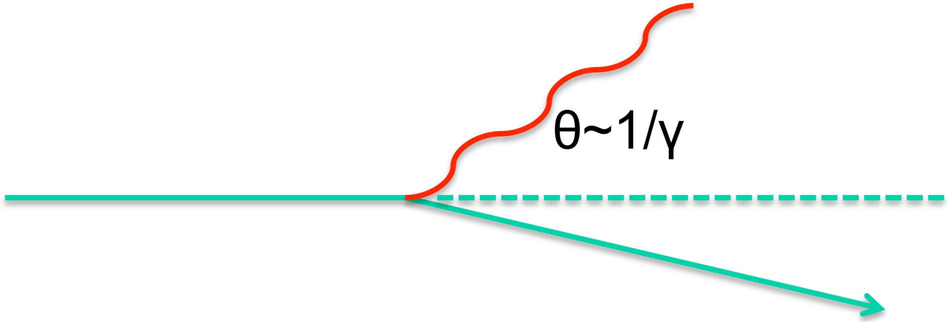
Photon emission is not precisely straight ahead

The small but nonzero transverse momentum of the photon recoils off of the particle.

The theoretical minimum vertical emittance, the quantum limit, obtains when the vertical dispersion vanishes.

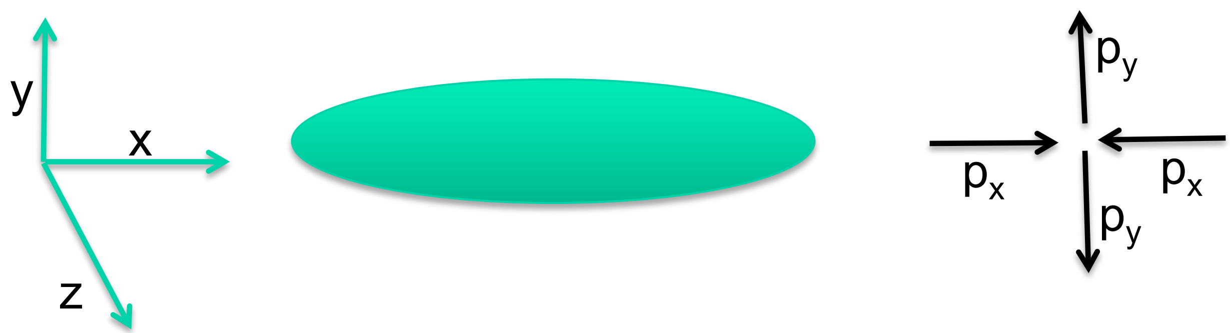
In a couple of storage rings (considerably smaller than CESR), vertical emittance approaching the quantum limit has been achieved.

In CesrTA, $\varepsilon_y \sim$ 10 – 15 pm (< 1% ε_x)
The quantum limited vertical emittance < 0.1 pm



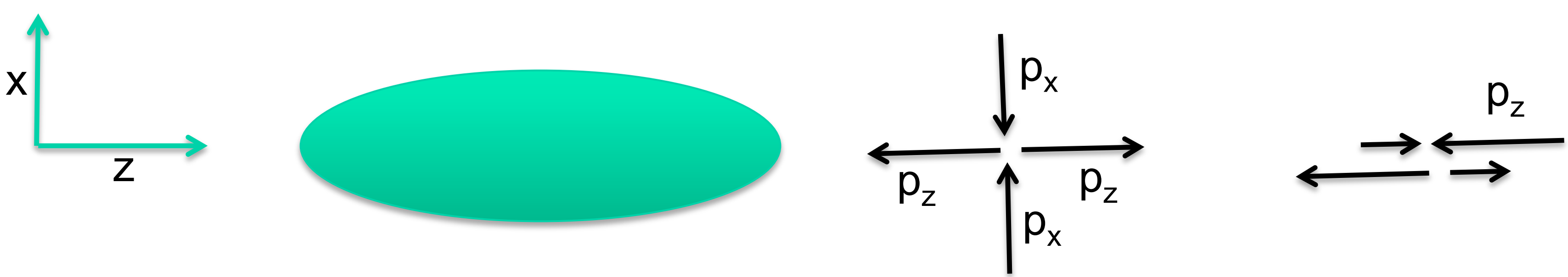
Intra-beam scattering (*Mike Ehrlichman*)

Beam moving in z direction



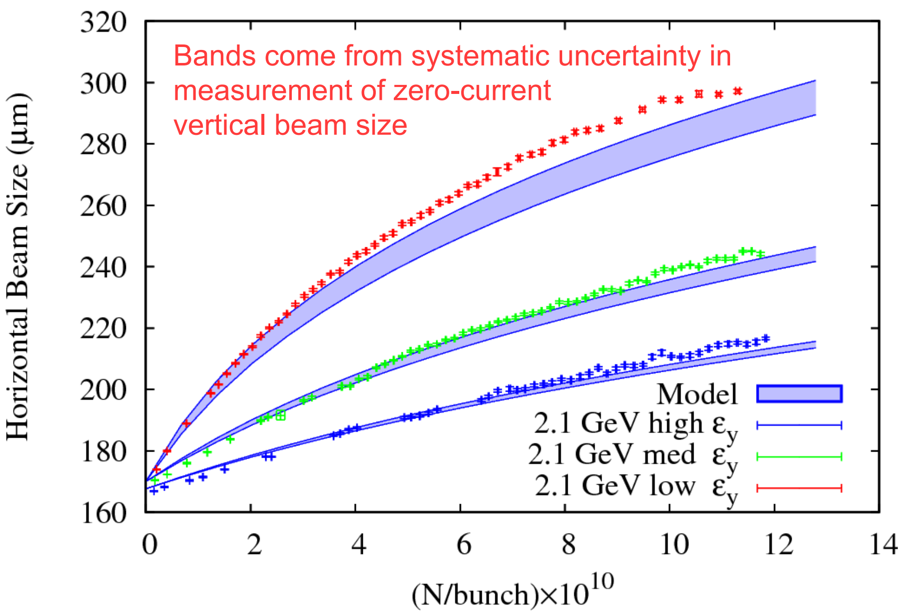
Intra-beam scattering can transfer horizontal momentum into vertical

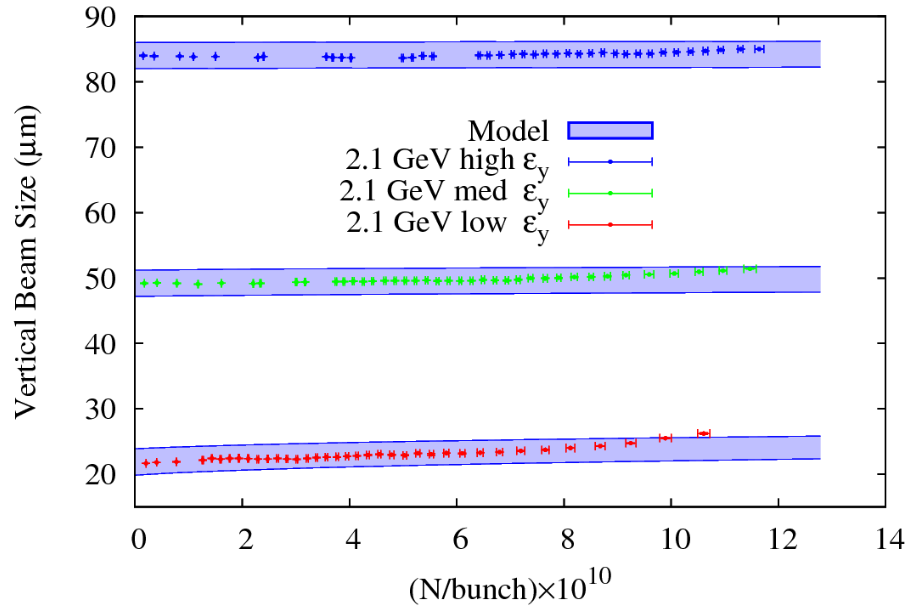
Horizontal into longitudinal



Exchange z momenta

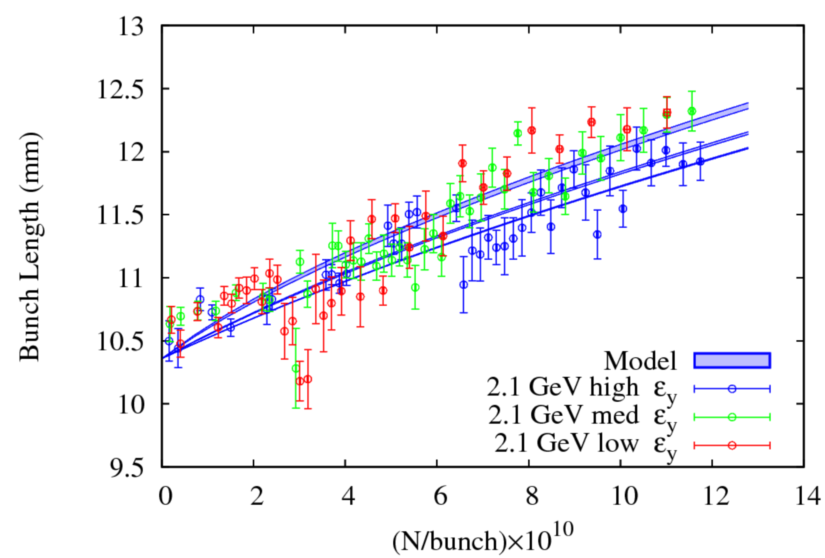
IBS - 2.1 GeV



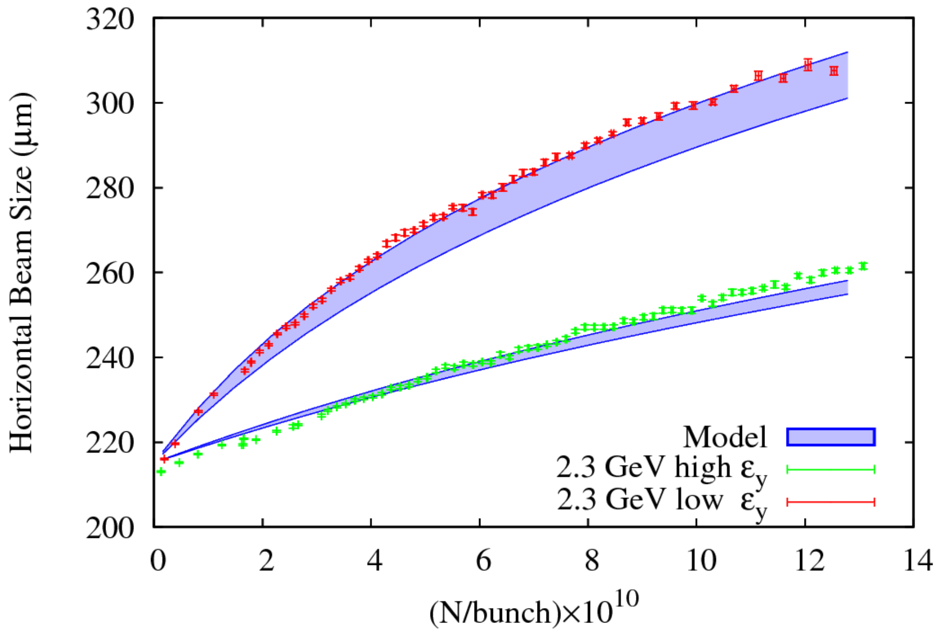


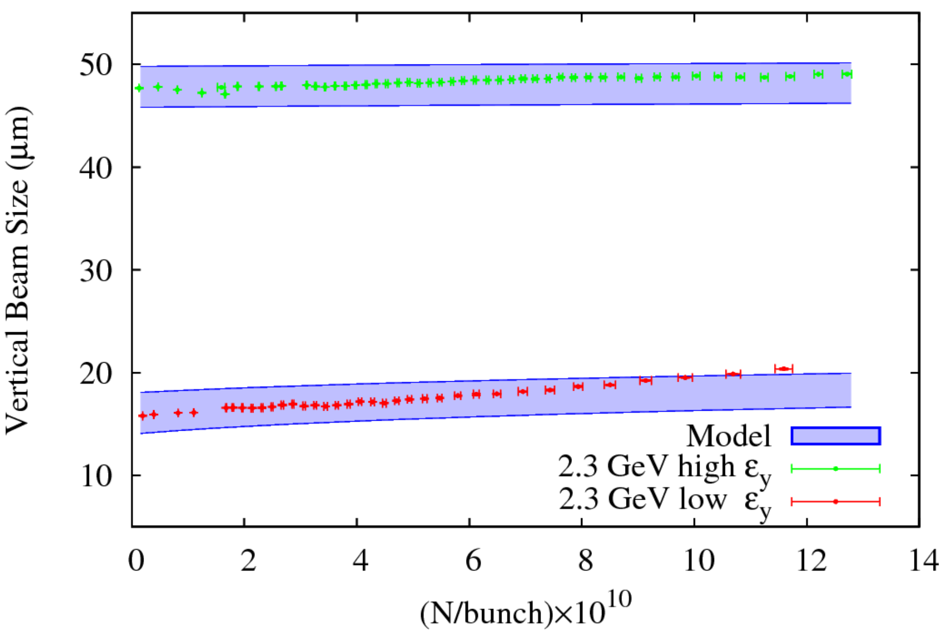
	Zero Current		High Current (data)
Run ID	ε_{y0} (pm)	ε_{x0} (nm)	ε_x (7.5 10^{10} part) (nm)
Low ε_{y0}	9.6 – 13.9	3.6	7.25
Med ε_{y0}	54.2 – 63.8	3.6	6.55
High ε_{y0}	163.6 – 179.9	3.5	5.18

$^*7.5 \times 10^{10}$ part. ≈ 12 nC ≈ 5 mA



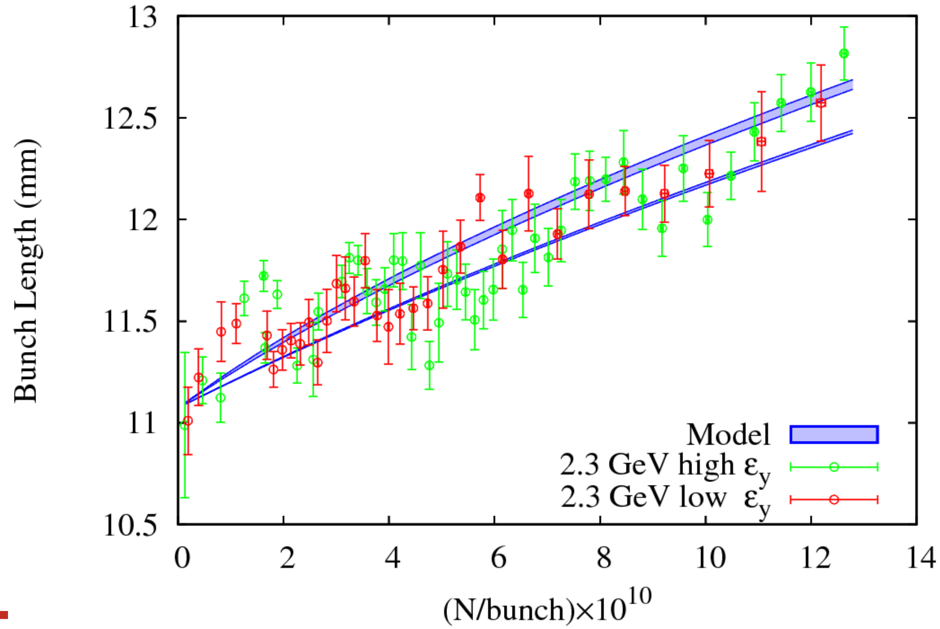
2.3 GeV Results (V15)





	Input Parameters		Result at high current
Run ID	ε_{y0} (pm)	ε_{x0} (nm)	ε_x (7.5 10^{10}) (nm)
Low ε_{y0}	4.9 – 8.1	5.7	10.4
High ε_{y0}	52.3 – 61.8	5.7	7.62

$^*7.5 \times 10^{10}$ part. ≈ 12 nC ≈ 5 mA

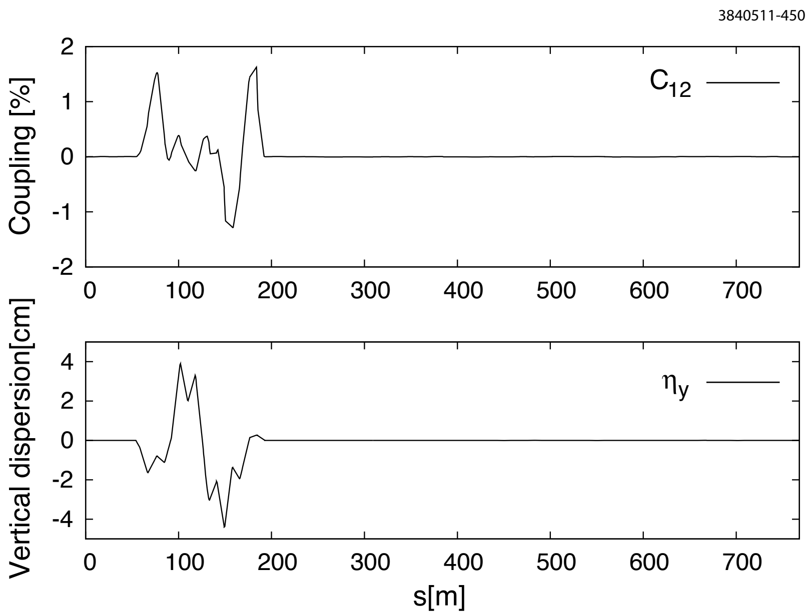


Intra-Beam Scattering

- The direct transfer of momentum from horizontal to vertical by IBS is small
- Dominant contribution to IBS emittance growth is due to exchange of longitudinal momentum coupled with dispersion
- IBS effects are most evident in the horizontal dimension
- And small in the vertical since

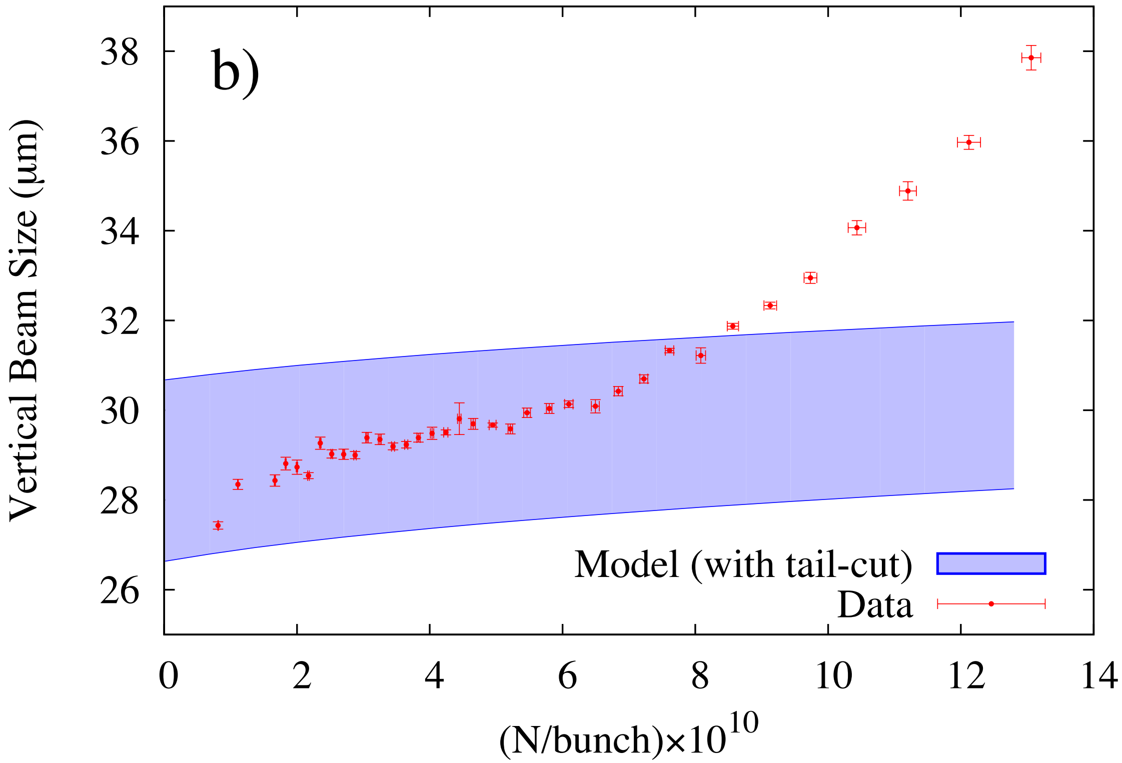
$$\eta_v \ll \eta_h$$

- The amount of the blow-up can be controlled by varying the vertical emittance, and thus the particle density.



Closed vertical dispersion/coupling bump through wigglers generate vertical emittance without introducing global coupling

Wakefield induced emittance growth

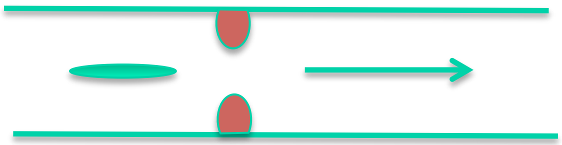


Puzzle

- Abrupt change in slope of vertical beam vs current at ~6 X10^{10} particles
- Observed to depend on synchrotron tune and vertical betatron tune
- The phenomenon is not intra-beam scattering (positive curvature)
- Observed with both electron and positron beams

Transverse Wakefields

(*Jeremy Perrin, Stephen Poprocki*)



$$\vec{W}_{ba}(\mathbf{r}_a, \mathbf{r}_b, \tau) = \frac{1}{q_a q_b} \int_{-\infty}^{\infty} \vec{F}(\mathbf{r}_a, \mathbf{r}_b, t_a, \tau)\ dt_a$$

- Two particles, drive (a) and witness (b), travel through some vacuum chamber geometry.
- Wake is time-integrated force on witness particle
- Longitudinal and transverse components
- Depends on τ, the delay of the witness relative to the drive
- Depends on transverse displacement of drive and witness particle

Wakefields

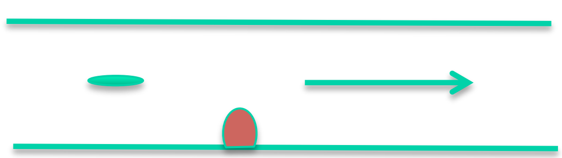
Expand vertical wake about the transverse coordinates

$$W^y_{ba}(\mathbf{r}_a, \mathbf{r}_b, \tau) = W^y_{ba}(0, 0, \tau) + \mathbf{r}_a \cdot \left.\frac{\partial W^y_{ab}}{\partial \mathbf{r}_a}\right|_{0,0,\tau} + \mathbf{r}_b \cdot \left.\frac{\partial W^y_{ab}}{\partial \mathbf{r}_b}\right|_{0,0,\tau} + \ldots$$

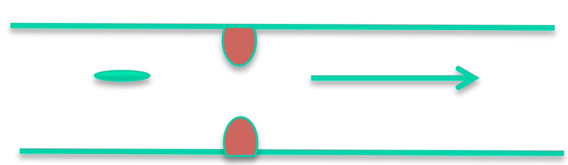
Vertical Monopole Wake

Vertical Dipole and Quadrupole Wakes
(Cause tune shifts, etc.)

Transverse monopole wakes only occur in the absence of top-down symmetry



Or if the beam is displaced in a symmetric structure

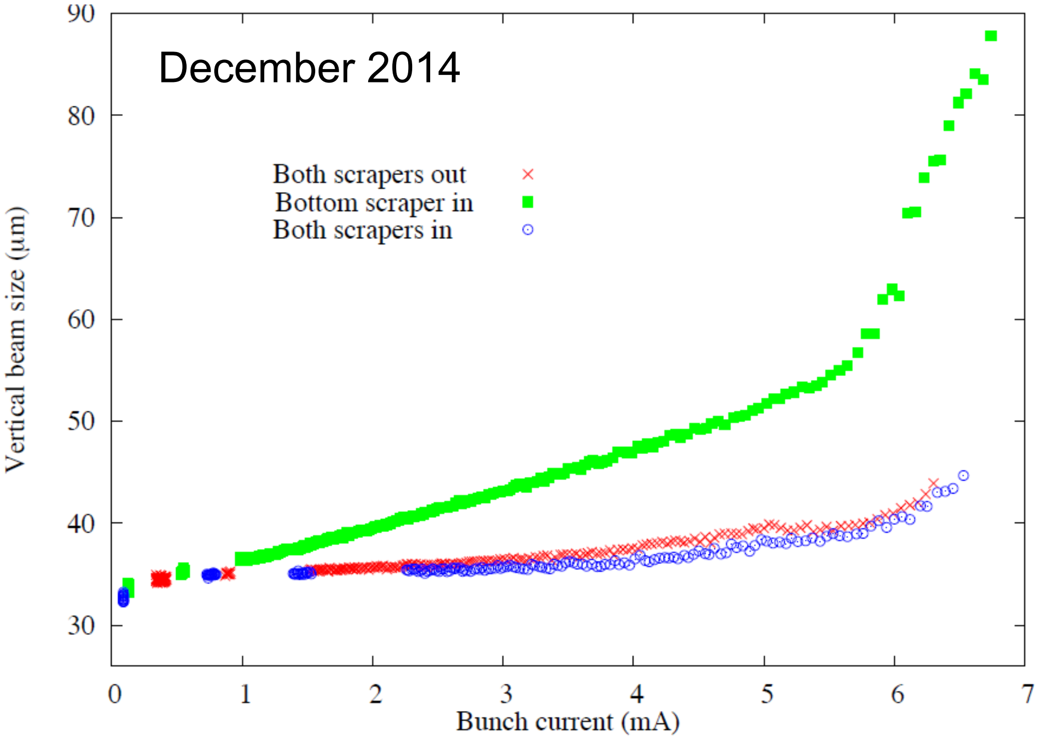


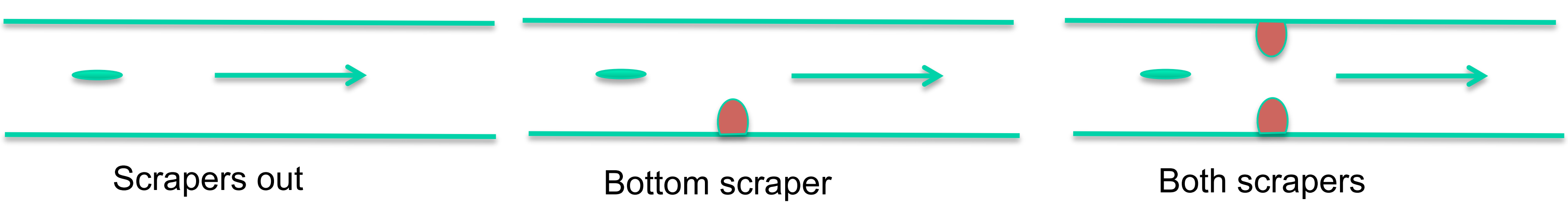
Asymmetric Wake

Scrapers can be inserted to within 3.5 mm of chamber axis

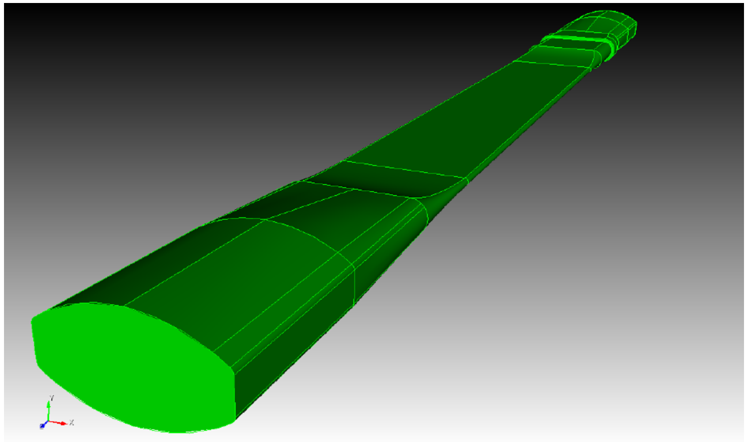
With both scrapers inserted we observe current dependent tune shift, but no blow up.

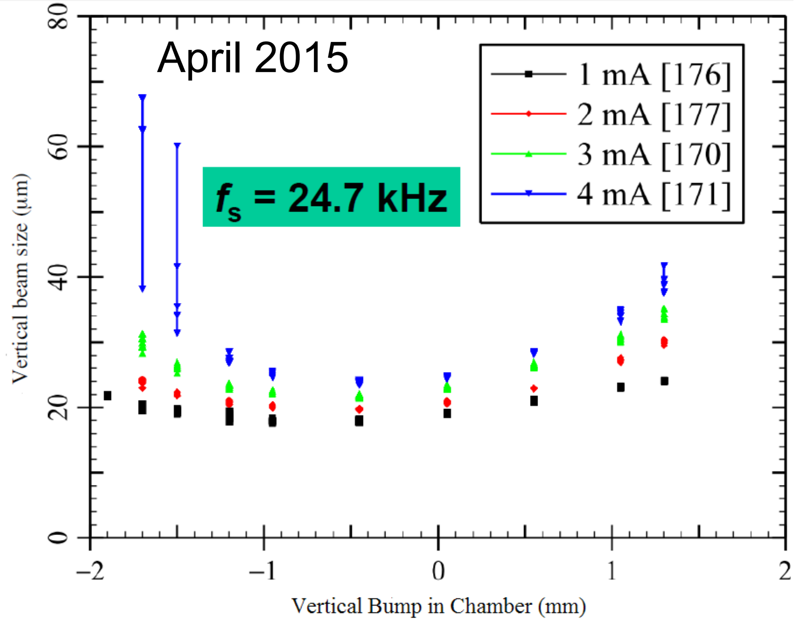
A single scraper causes significant increase in vertical beam size





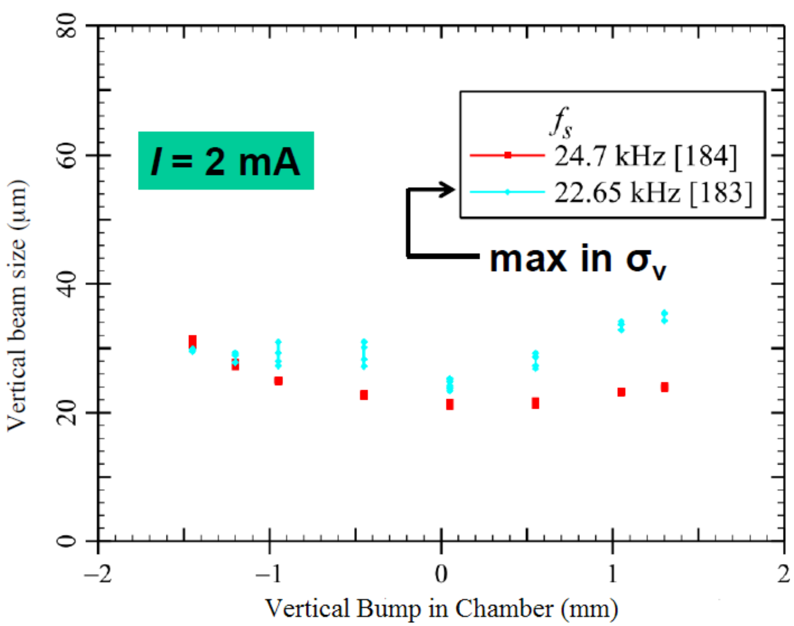
Off Center beam





Measure current dependence of vertical size as a function of displacement in a narrow gap (undulator) chamber (4.5 mm aperture)

Displacement generates an effective monopole wake



Resonance $f_y - nf_s = 0$

f_s = 22.65 kHz

Simulation of Wakefield Effect

Plan A

- Compute single particle wake (already difficult)
- Track a distribution of macro-particles
- Each particle generates a wake that kicks all of the trailing macro-particles

Statistical noise dominates effect we are looking for unless the number of macro-particles is impractically large

Simulation of Wakefield Effect

Plan B

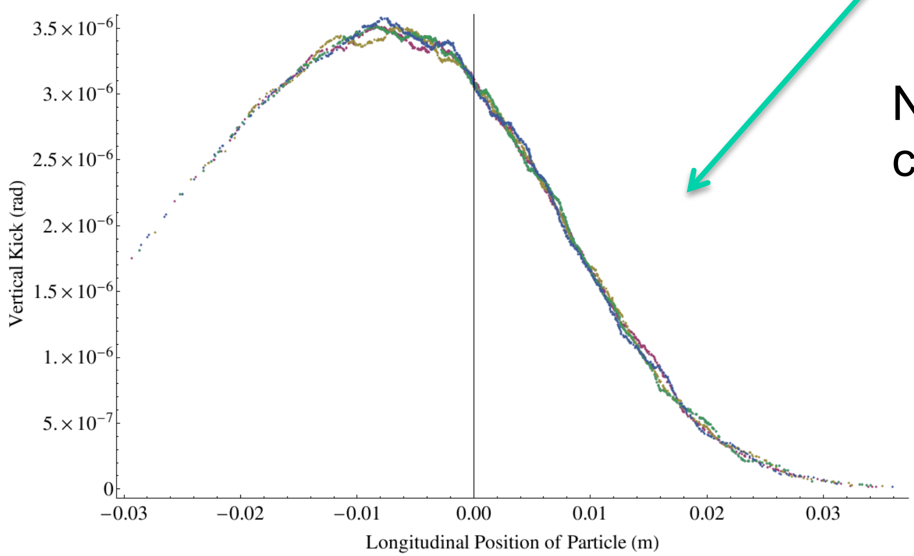
Note that transverse monopole wakes depend only on longitudinal structure of bunch, but do not *influence* longitudinal structure of bunch.

$$W^{y}_{ba}(0, 0, \tau)$$

Therefore, the longitudinal dependence of the wake kick will not vary turn-to-turn.

- Represent the wake as a single element that applies vertical kick with longitudinal (temporal) dependence

$$\begin{pmatrix} x \\ p_x \\ y \\ p_y \\ z \\ \delta \end{pmatrix}$$



Narrow gap chamber wake

Simulation of Wakefield Effect

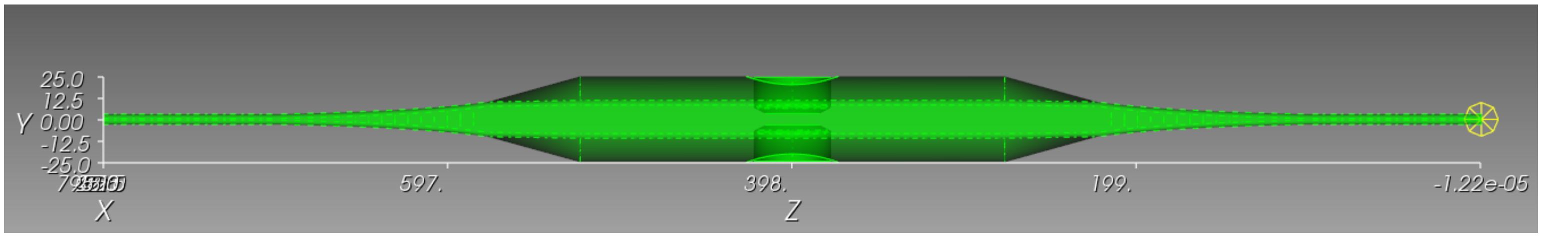
Simulations failed to reproduce the observed emittance growth

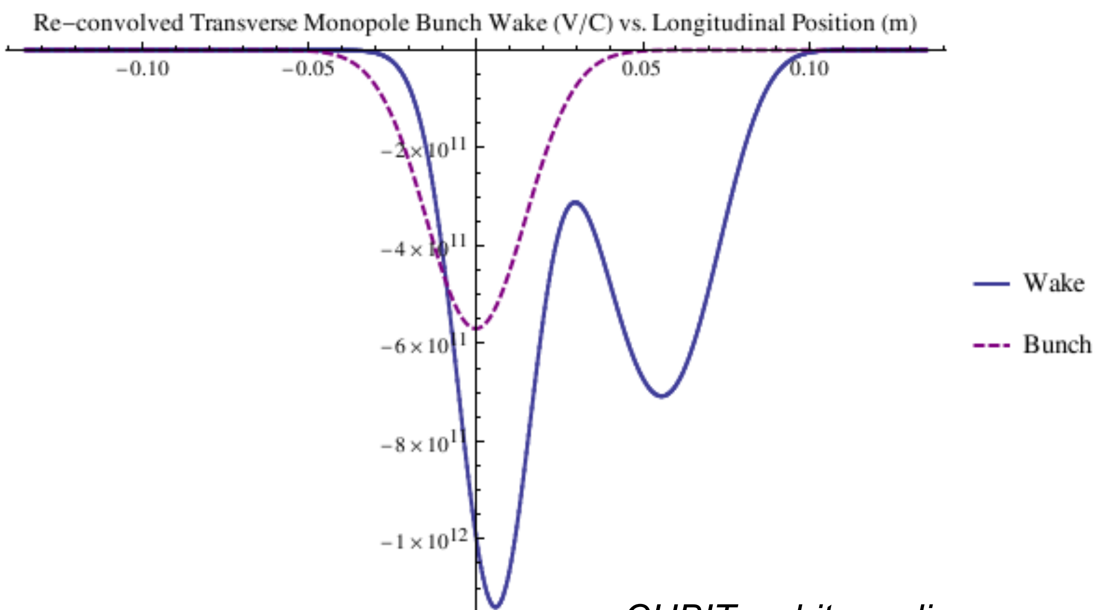
The wake couples longitudinal motion to vertical

Perhaps the effect of the wake is to *tilt* the beam about a horizontal axis increasing the effective (observed) *vertical* size

Scraper Wake Element

Consider the scraper wake
Compute the wake due to the asymmetric scraper

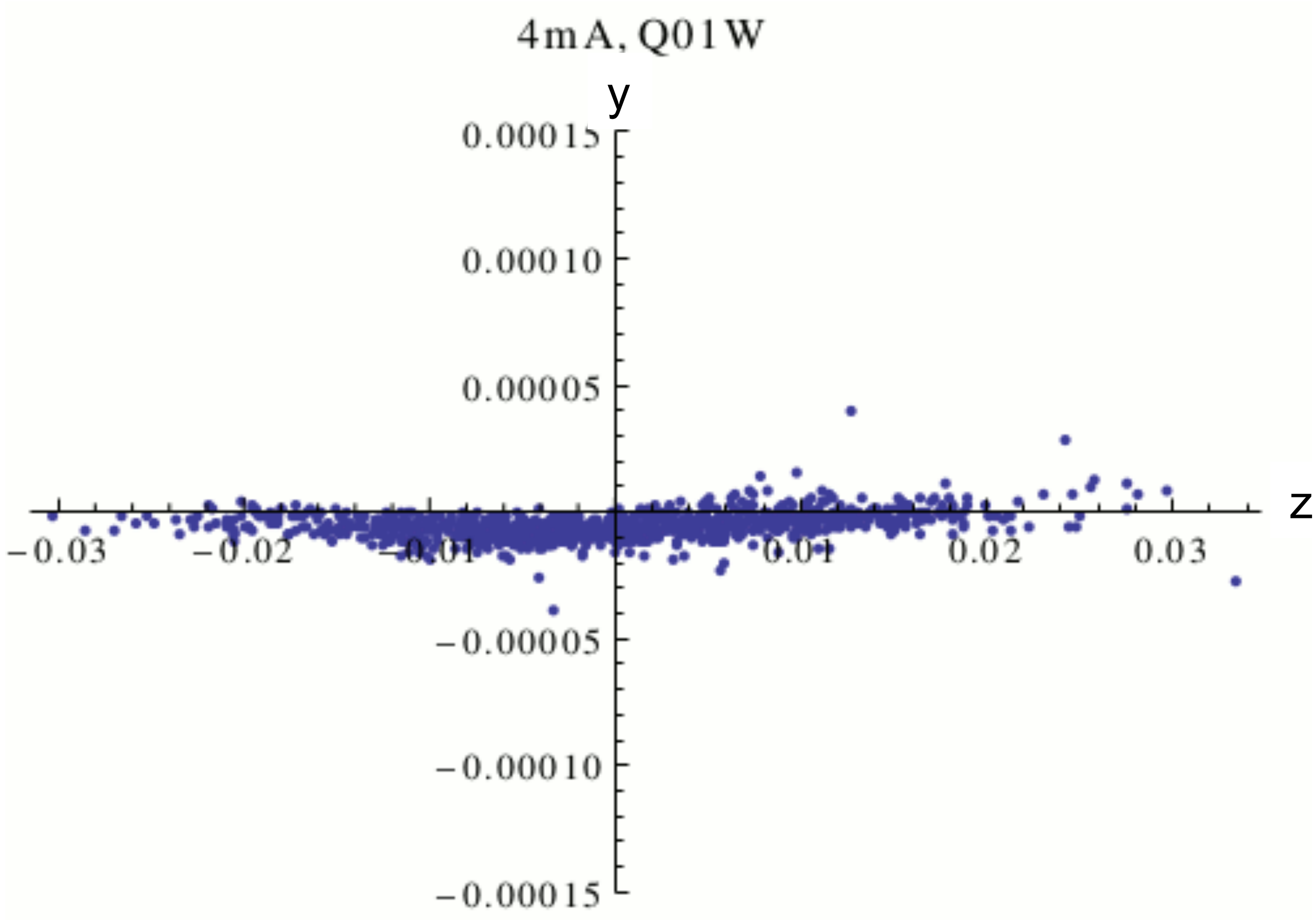




CUBIT: cubit.sandia.gov
T3P: confluence.slac.stanford.edu/display/AdvComp

Wake Induced Crabbing

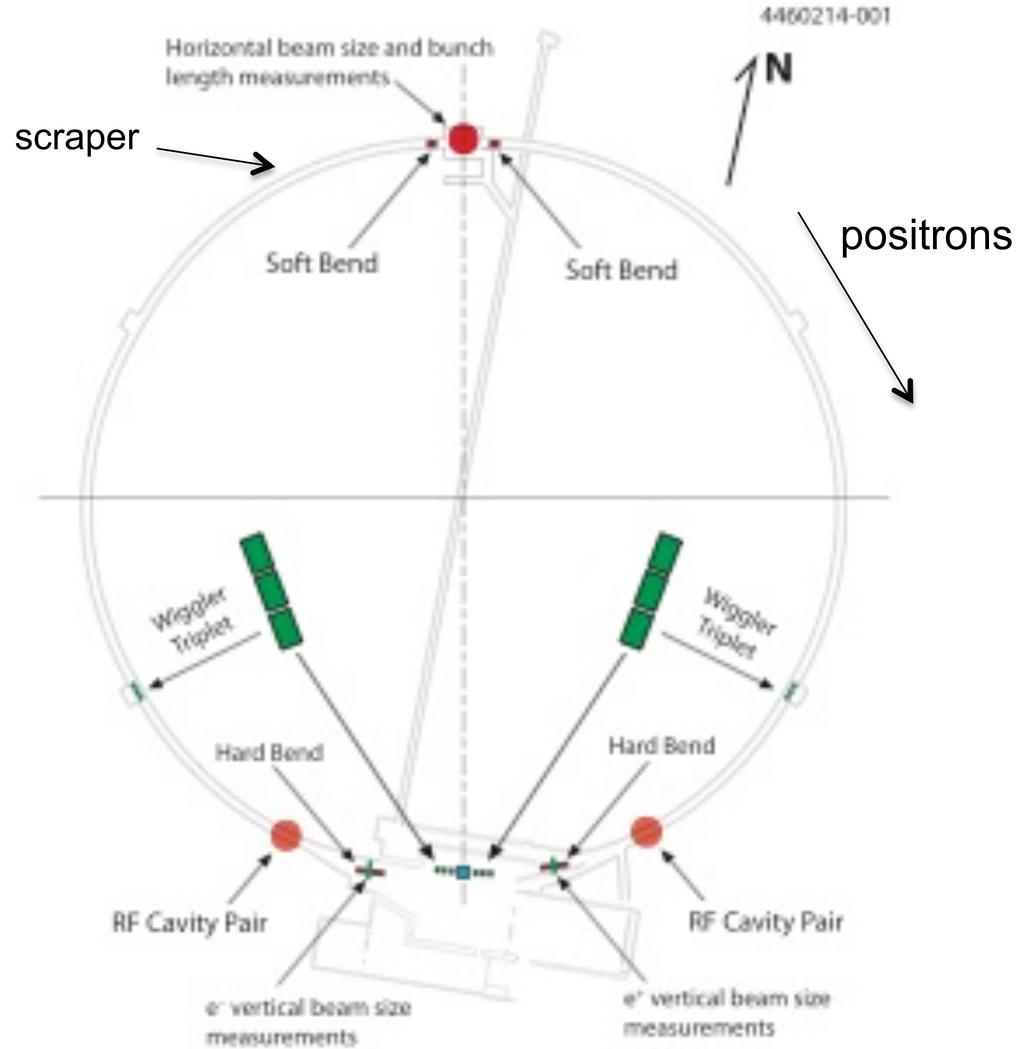
Tilt depends on the observation point



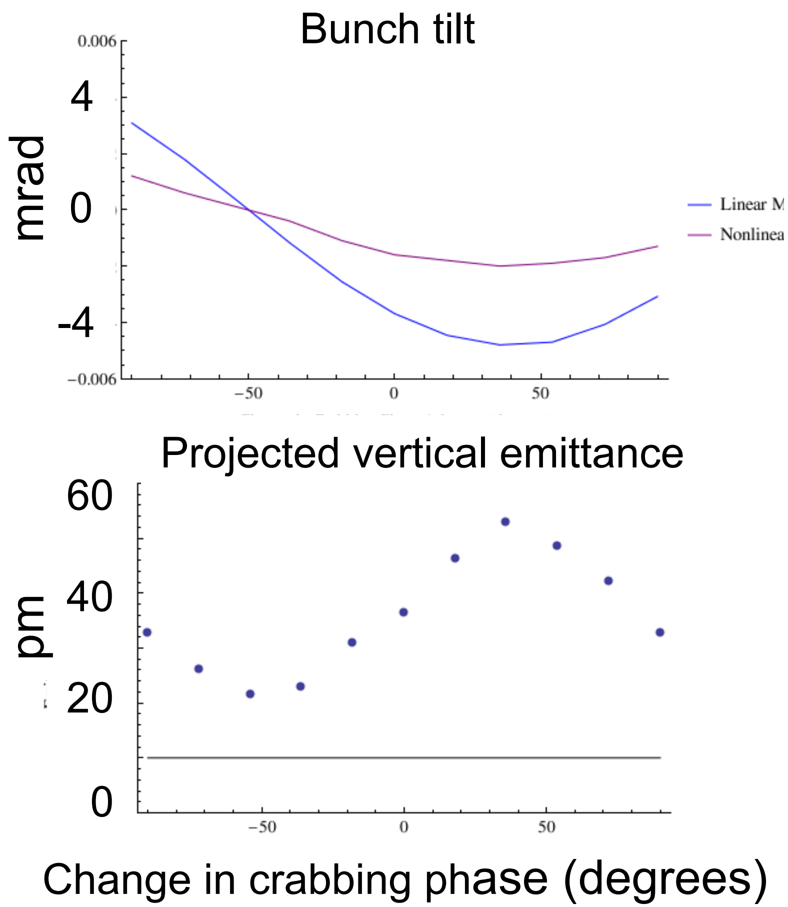
$$\theta_{tilt} \sim \theta_0 \sin(\phi_v(s) - \phi_z(s))$$

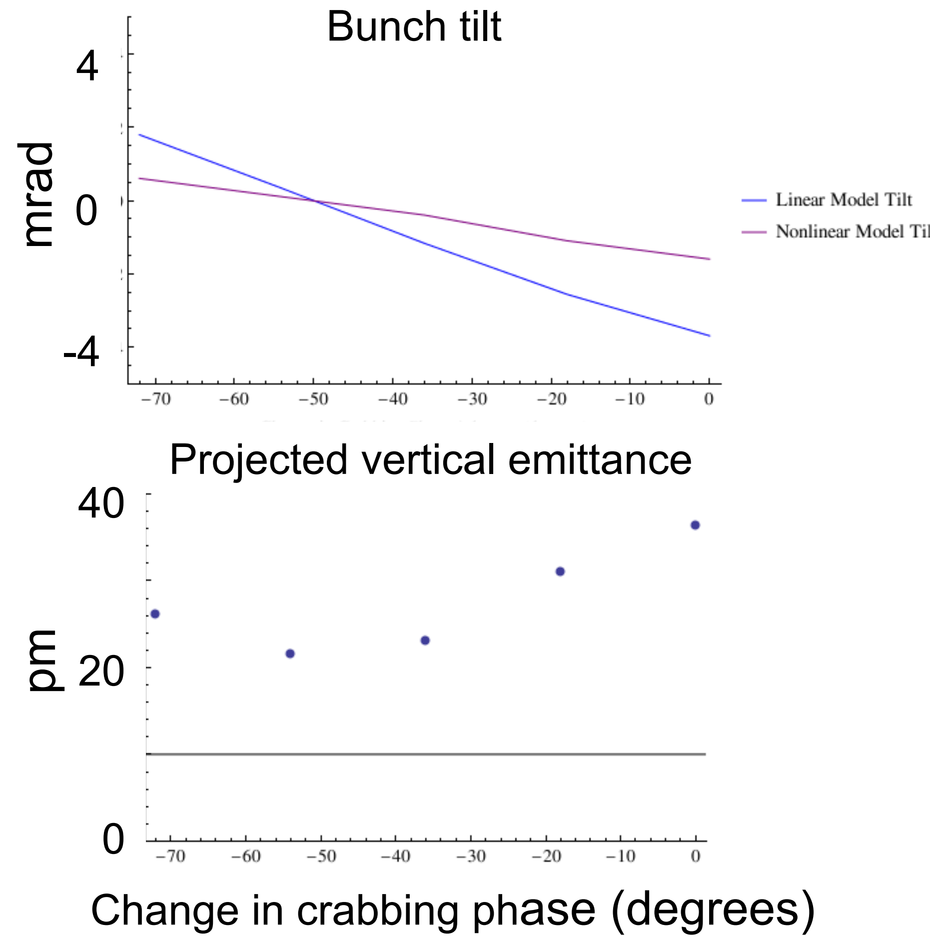
Measurement of Tilt

Vary vertical phase advance from source of tilt (scraper) to beam size monitor to determine if observed increase is due to a tilt or emittance growth



Create multiple lattice configurations

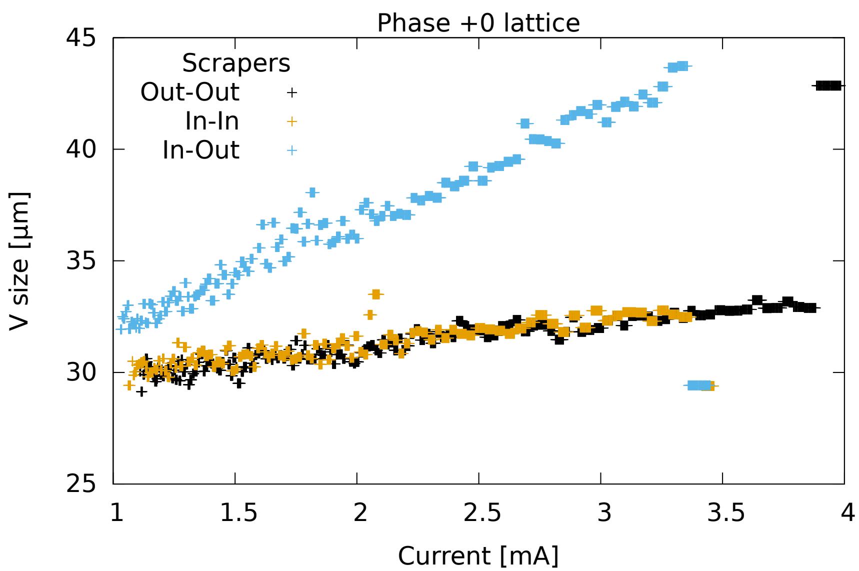


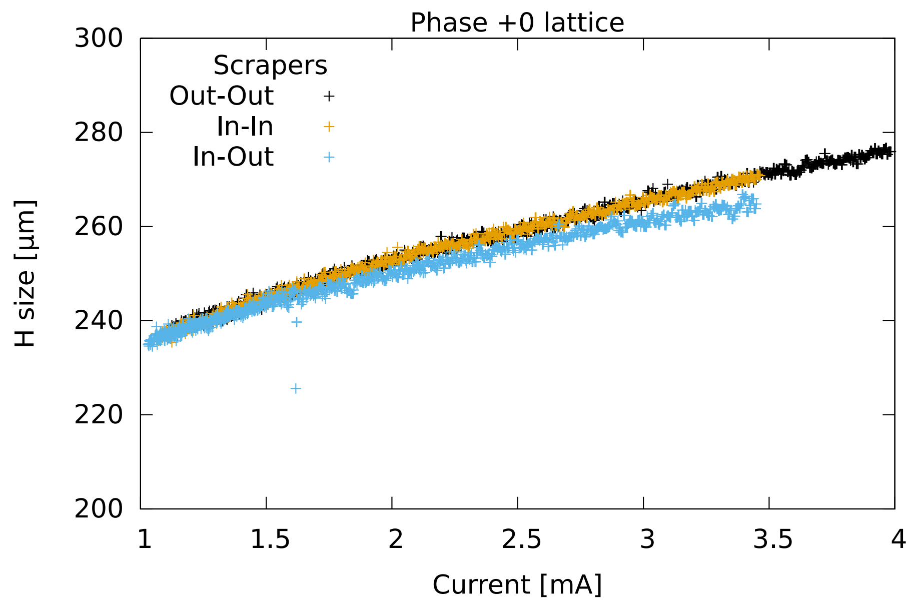


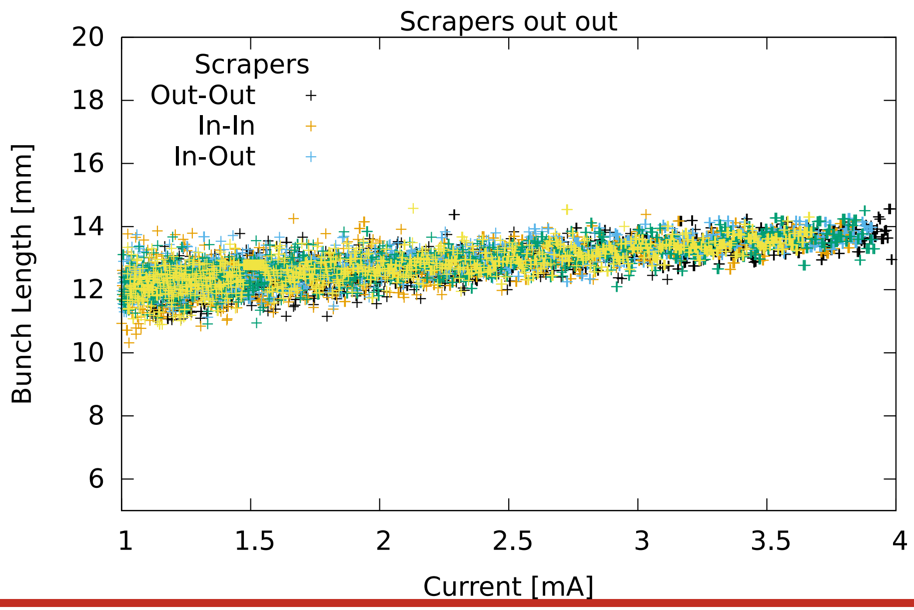
Each of 12 lattices has same global tune but with varying vertical phase from scraper to beam size monitor

These are the 5 that we tested

Baseline Lattice







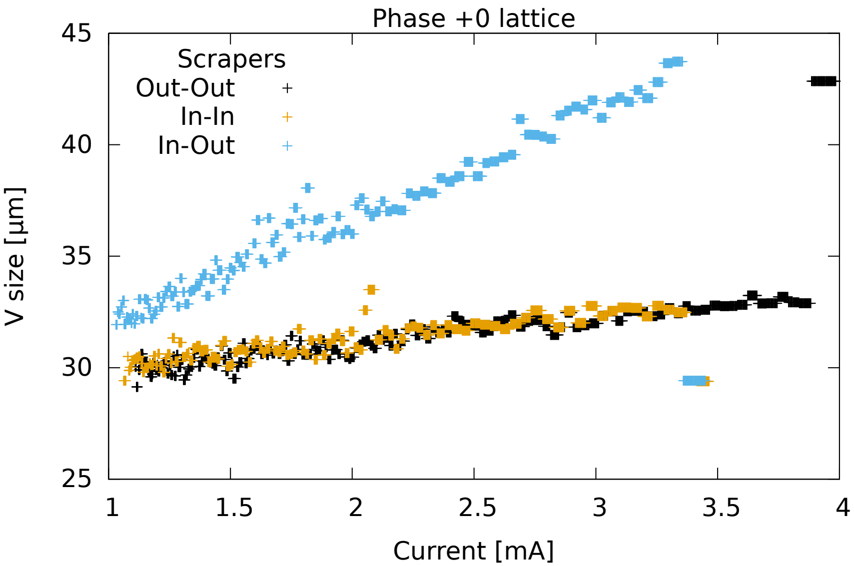
Bunch height, width and length vs current

- Scrapers inserted symmetrically
- Scrapers withdrawn symetrically
- One in and one out

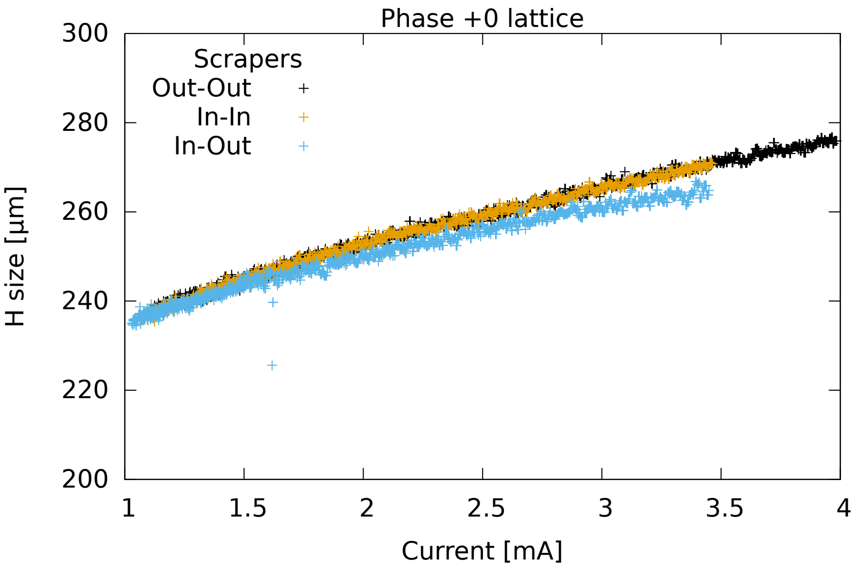
December 2015

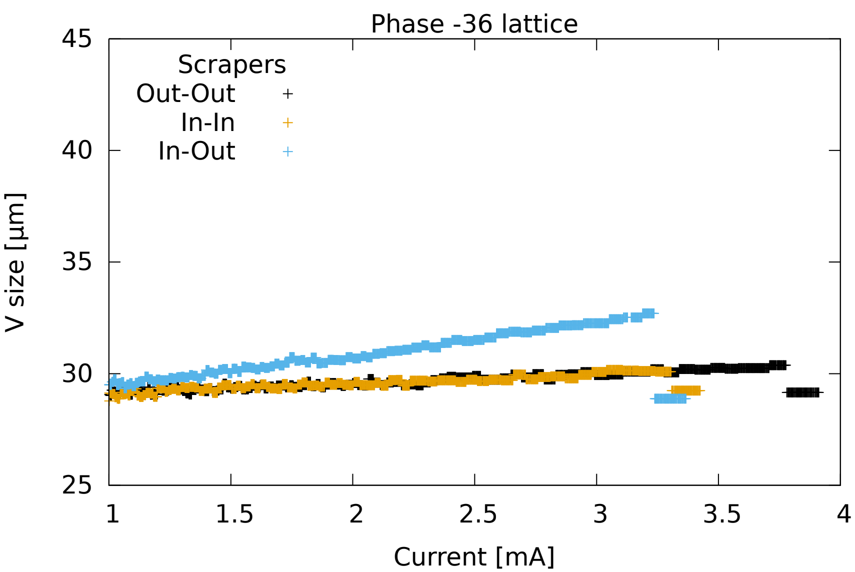
Tilt vs Crabbing Phase – 0& 36 deg

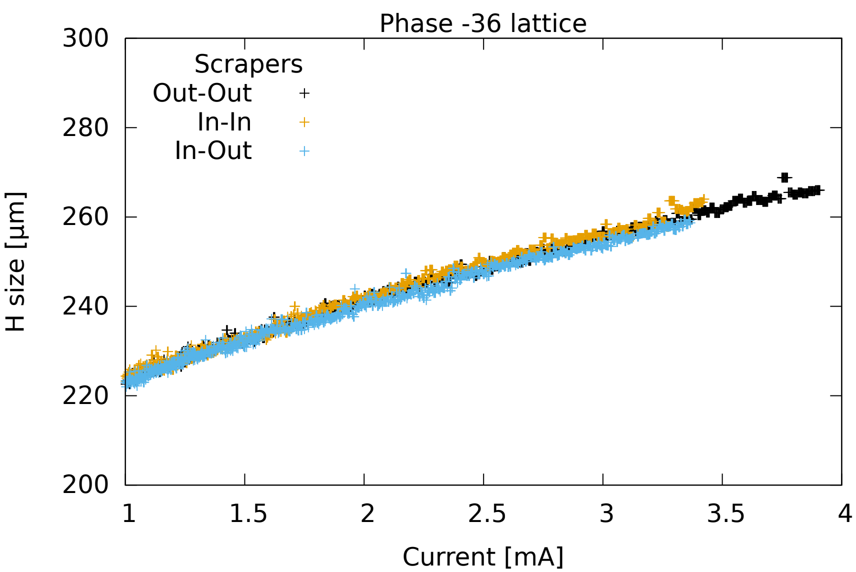
Bunch height vs current



Bunch width vs current

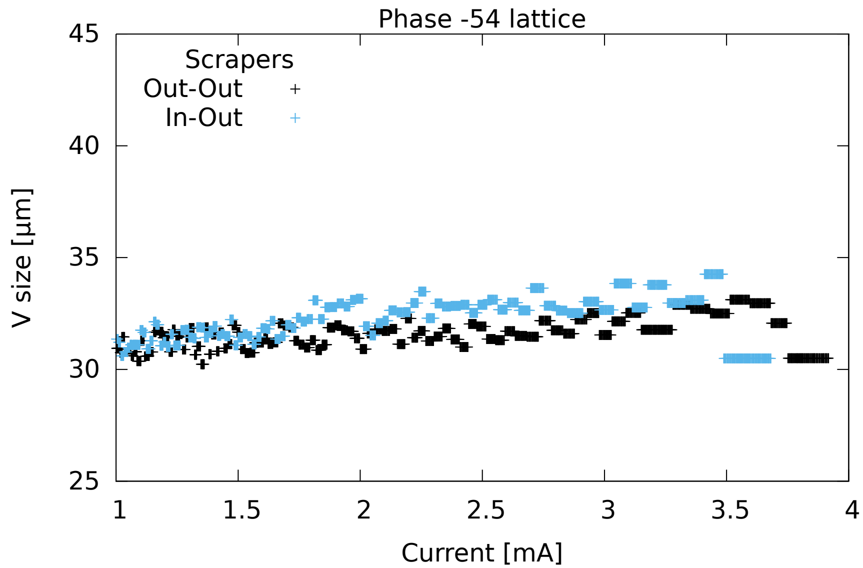


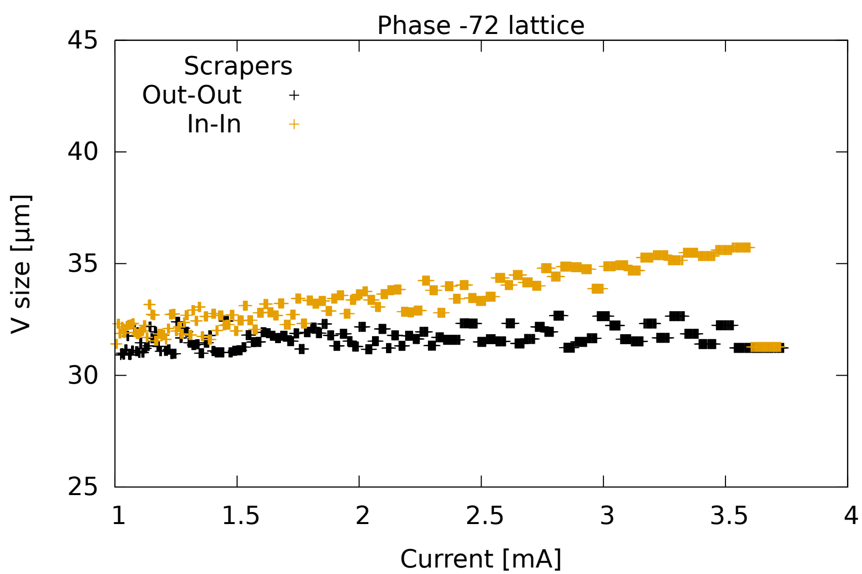




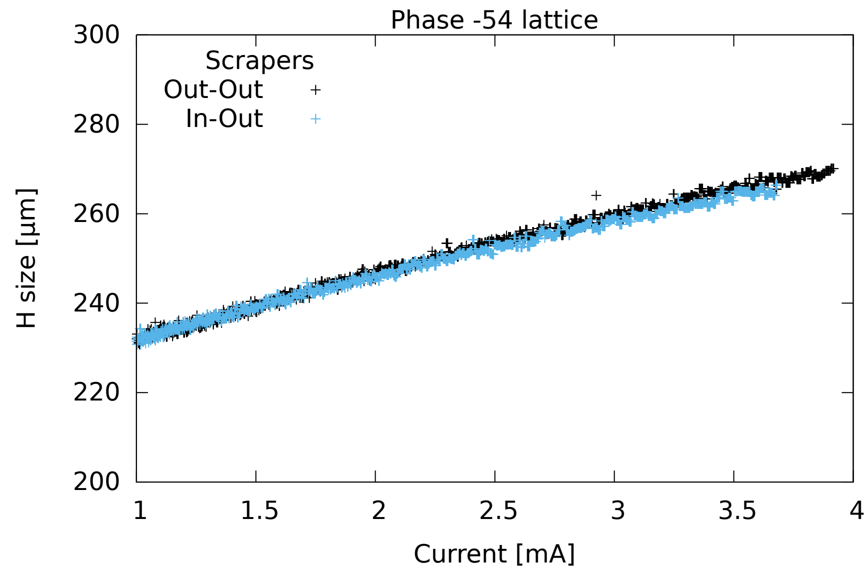
Tilt vs Crabbing Phase, 54&72 deg

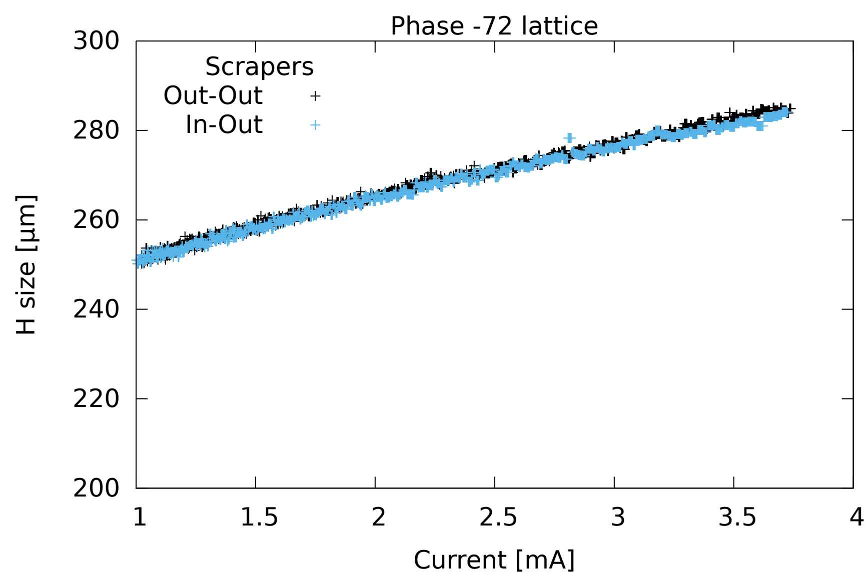
Bunch height vs current





Bunch width vs current





Wake Induced Growth

Monopole wake due to asymmetric structure tilts bunch in y-z plane

Effect of wake on true emittance is small

- Current dependent increase in vertical size is almost entirely compensated by adjusting the crabbing phase
- The current dependent growth in horizontal size is indifferent
- However – the coupling of transverse kick and longitudinal phase space coordinates effectively generates vertical dispersion, same as a vertical bend

Simulations are underway to determine if our model includes the relevant physics and to make more quantitative comparison of theory and measurements

Implications ?

- Vacuum chamber design must preserve top down symmetry
- Misalignment of the beam in small aperture chambers can generate significant growth in vertical beam size

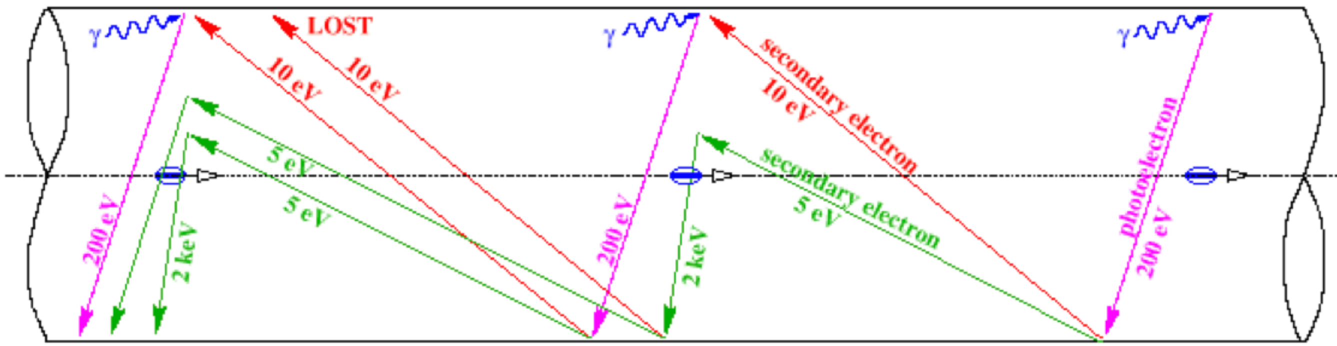
Especially in ultra-low emittance rings with high bunch charge

What about the anomalous emittance growth observed in the IBS measurements?

Electron Cloud

(*Stephen Poprocki, Sumner Hearth, Jim Crittenden*)

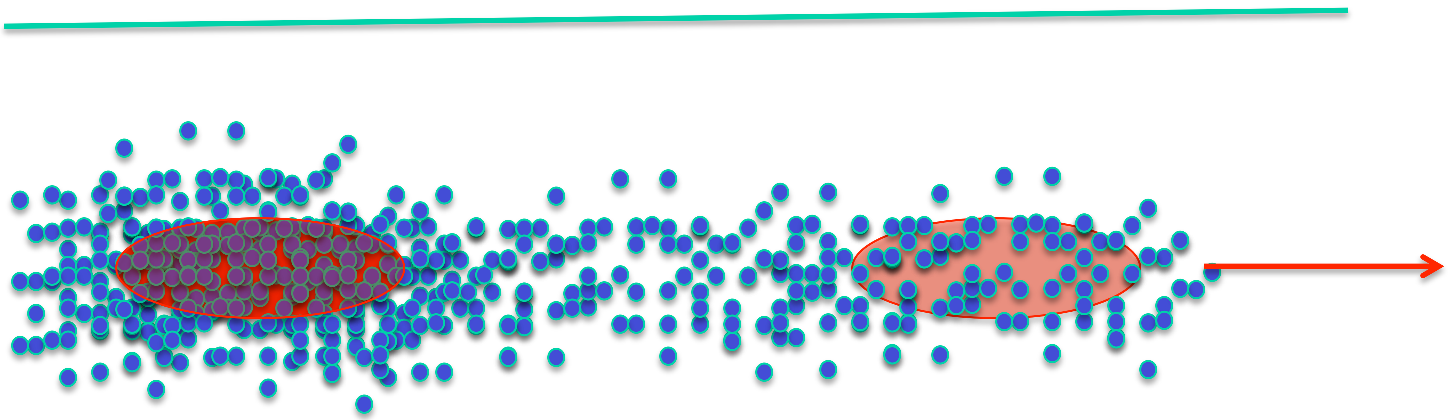
Electron cloud



- Beam emits synchrotron radiation:
  - provides source of photo-electrons
  - other sources: beam-gas ionization, stray protons→wall
- Photo-electrons get rattled around the chamber from multibunch passages
  —especially for intense positively-charged beams (e^+, protons, heavy ions)
- Photoelectrons yield secondary electrons
  - yield is determined by the secondary emission yield (SEY) function $\delta(E)$:
  - characterized by peak value δ_{max}
  - e^- reflectivity $\delta(0)$: determines survival time of e^-
- Typical e^- densities: $n_e=10^{10}$–10^{13} m^{-3} (~a few nC/m)

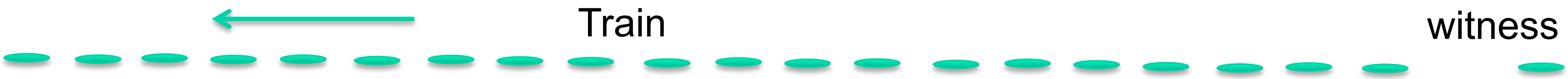
Electron Cloud Focusing

What is the effect of the cloud on the beam ?

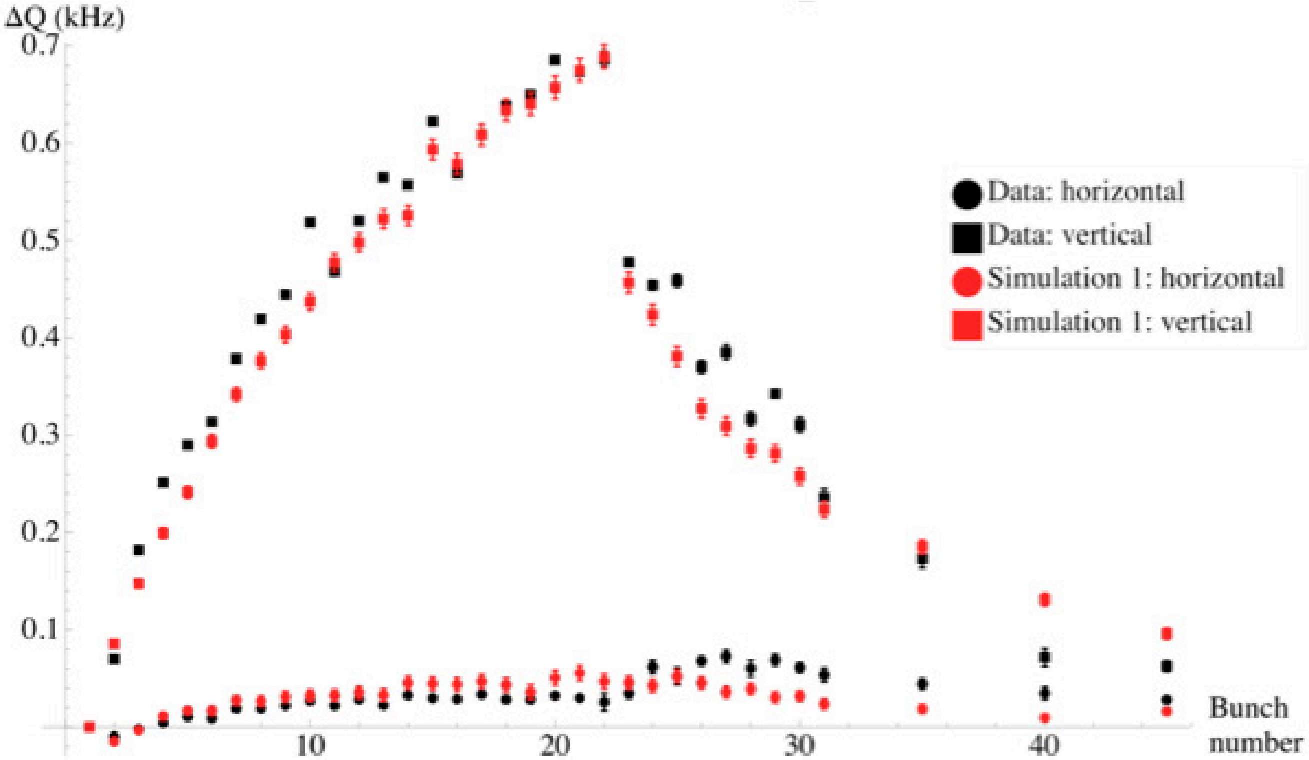


$$\langle \rho_c \rangle = \gamma \frac{\Delta Q_x + \Delta Q_y}{r_e \langle \beta \rangle C}$$

Electron cloud tune shift

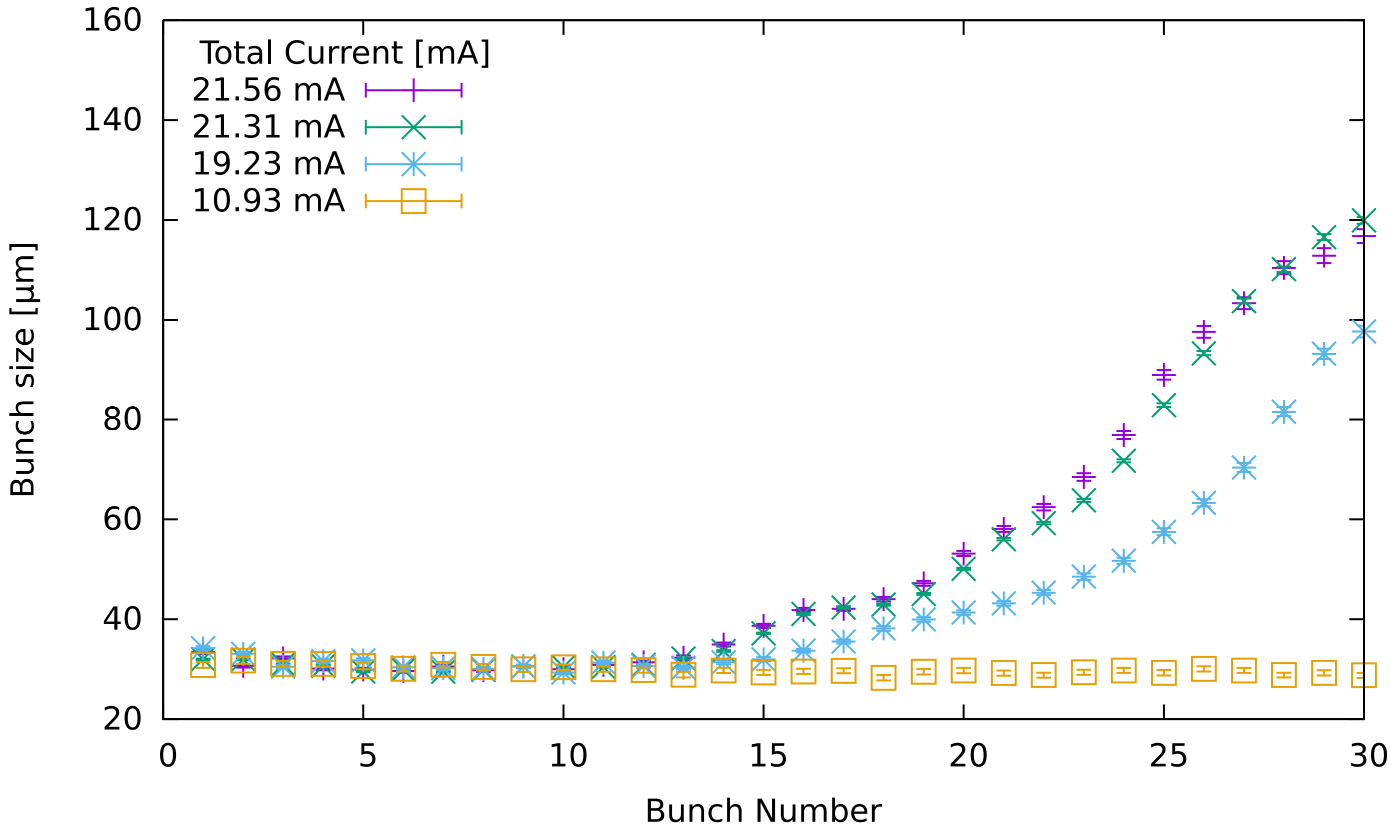


Cloud density increases along a train of bunches
The cloud electrons focus the traversing positron bunch, shifting the tune



The differential focusing (tune shift) is our measure of the increasing cloud density along the train of bunches

Electron cloud emitance growth



Threshold for emittance growth at bunch 13.

Model for emittance growth

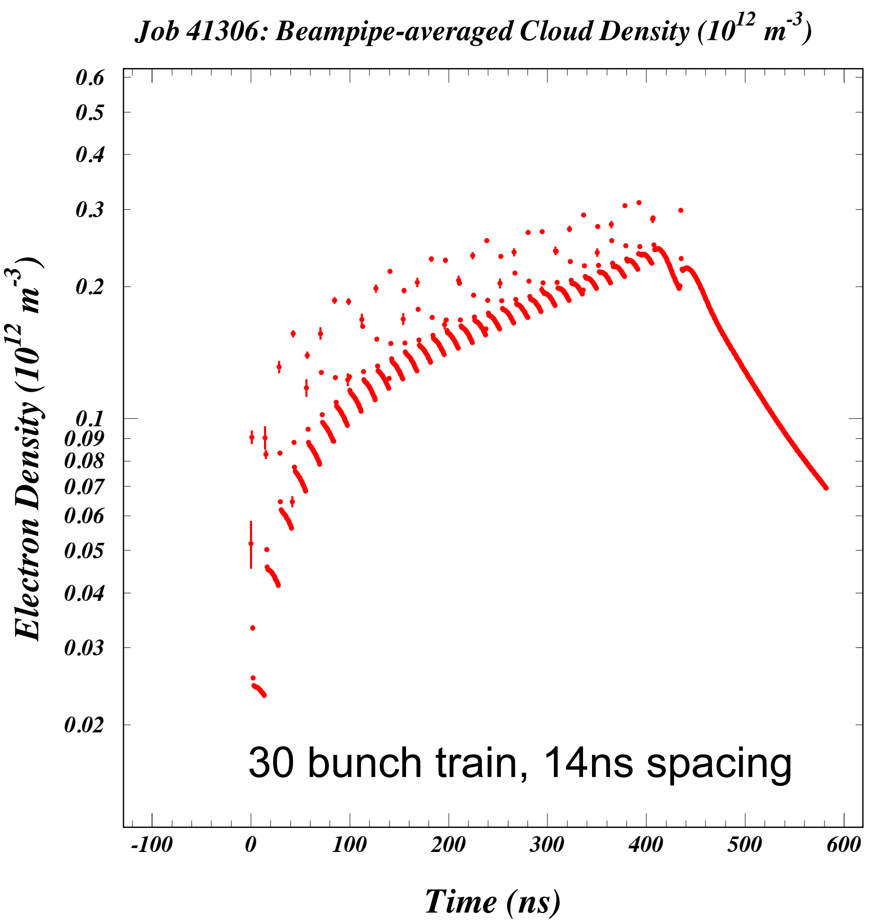
Physics models for electron cloud growth and beam dynamics

- Codes like ECLOUD (Rumolo and Zimmermann) and POSINST (Furman) with SYNRAD3D (Sagan) predict cloud distribution in reasonable agreement with direct measurements (RFA, resonant microwave, shielded pickups) and tune shifts
- Quantitative estimates of emittance growth are more elusive
  - CMAD (Pivi) and PHETS (Ohmi) are strong-strong simulations
  - Both electron cloud and positron bunch are represented as distributions of macro-particles that interact with each other
  - Limited to tracking through hundreds of turns
  - But damping times are 20,000 turns in CesrTA it is impractical to track long enough to equilibrate

Weak Strong Model

The electron cloud is the strong beam

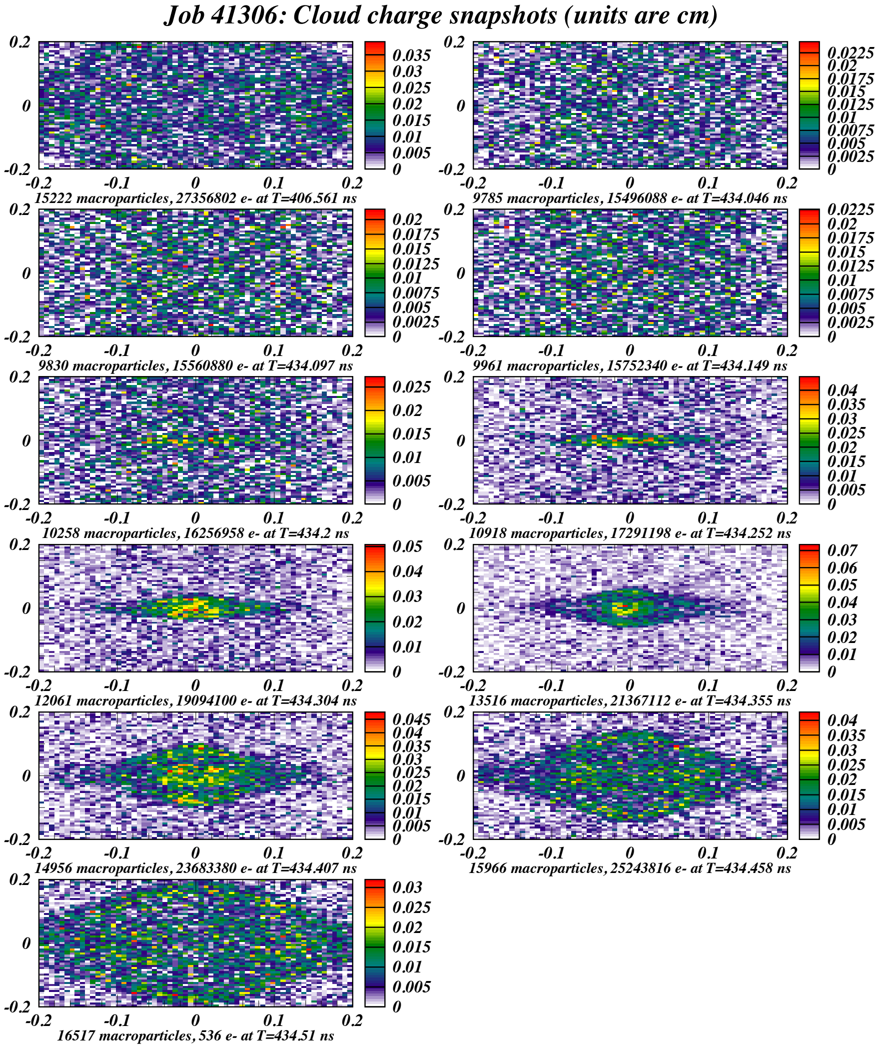
Compute the cloud distribution using cloud growth codes (i.e. ECLOUD)

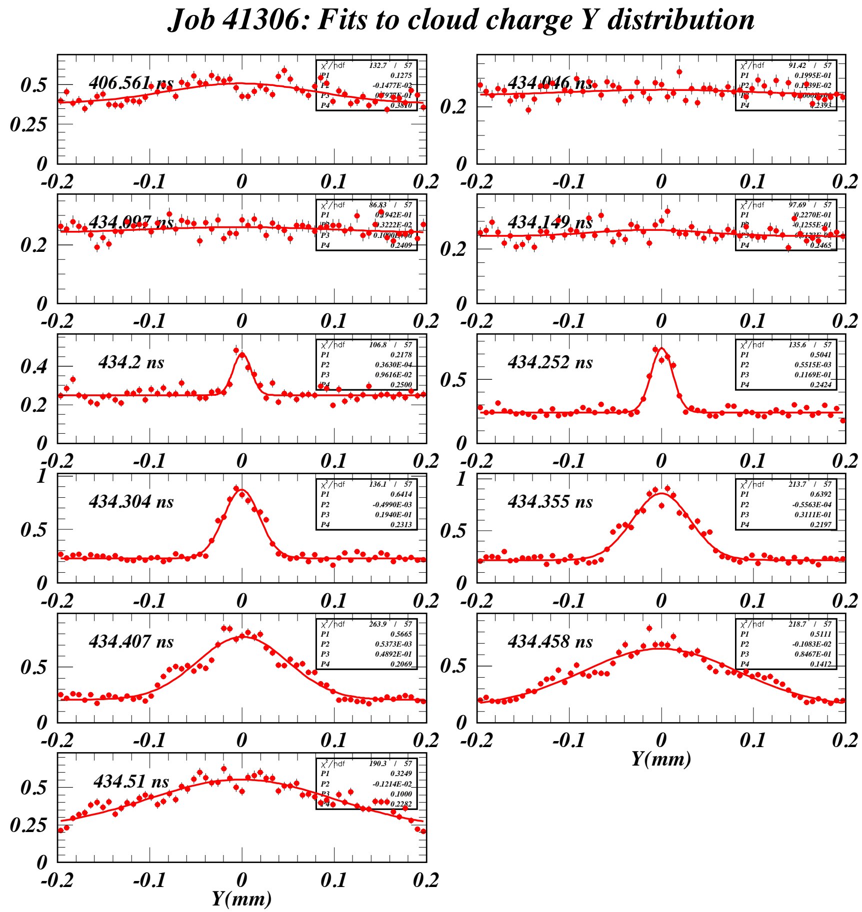


The cloud is pinched by the passing bunch, the density increasing from head to tail

Electron cloud pinch

With ECLOUD we compute electron distribution in 11 time slices that extend the length of the bunch





The distribution is ~ Gaussian with varying width and amplitude

Strong Beam – The Cloud

Model the cloud as *strong beam* with Gaussian charge distribution
The parameters of the Gaussian depend on the longitudinal coordinate

$$\rho(x,y,t) = A_x(t)A_y(t)e^{-\frac{x^2}{\sigma_x(t)^2}-\frac{y^2}{\sigma_y(t)^2}}$$

Compute $A_x(t_i), A_y(t_i), \sigma_x(t_i), \sigma_y(t_i)$ with ECLOUD

Particles at the head of the positron bunch experience a relatively weak kick
Particles near the tail get a much stronger kick

Does this representation of the positron bunch / electron cloud interaction predict emittance growth?

Simulation

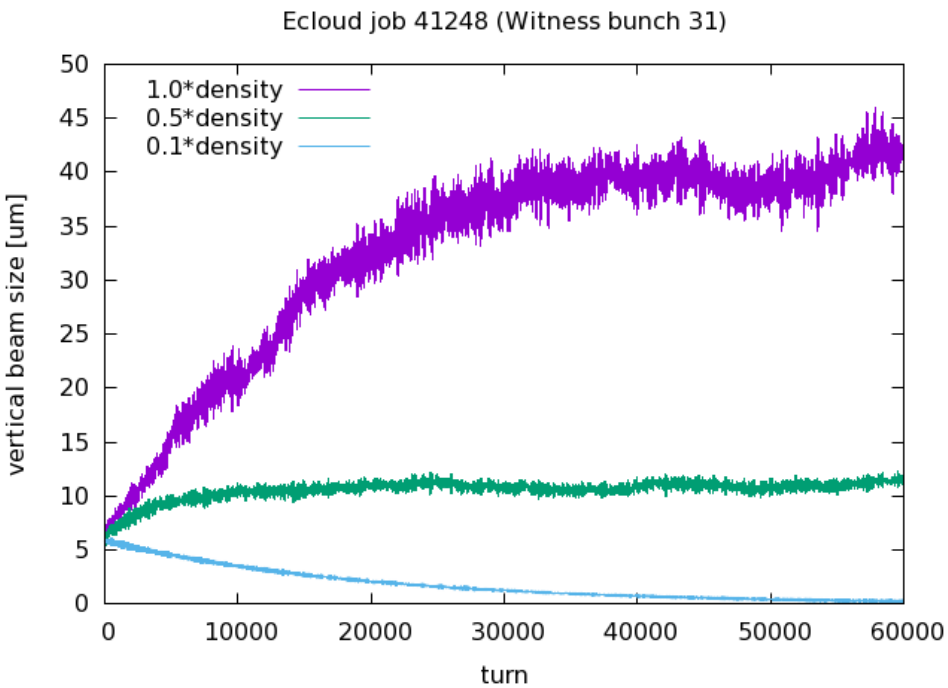
Electron cloud is represented in the tracking code as a time dependent "*beam-beam*" kick
- 11 time slices
- Each slice the kick from a Gaussian charge distribution
- Charge distribution is computed by ECLOUD for a witness bunch in slot 31

An electron cloud "*element*" is place in each dipole in the CesrTA lattice

Positron bunch represented as a distribution of macro-particles

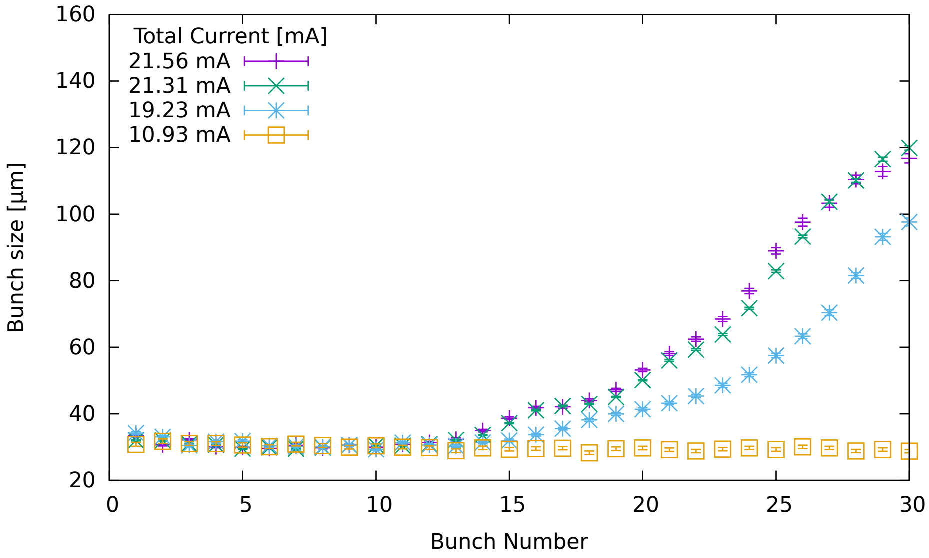
Tracking simulation includes all magnets in the storage ring lattice, (dipoles, quad, sextupoles, wigglers) and radiation excitation and damping

Track positrons for several damping times



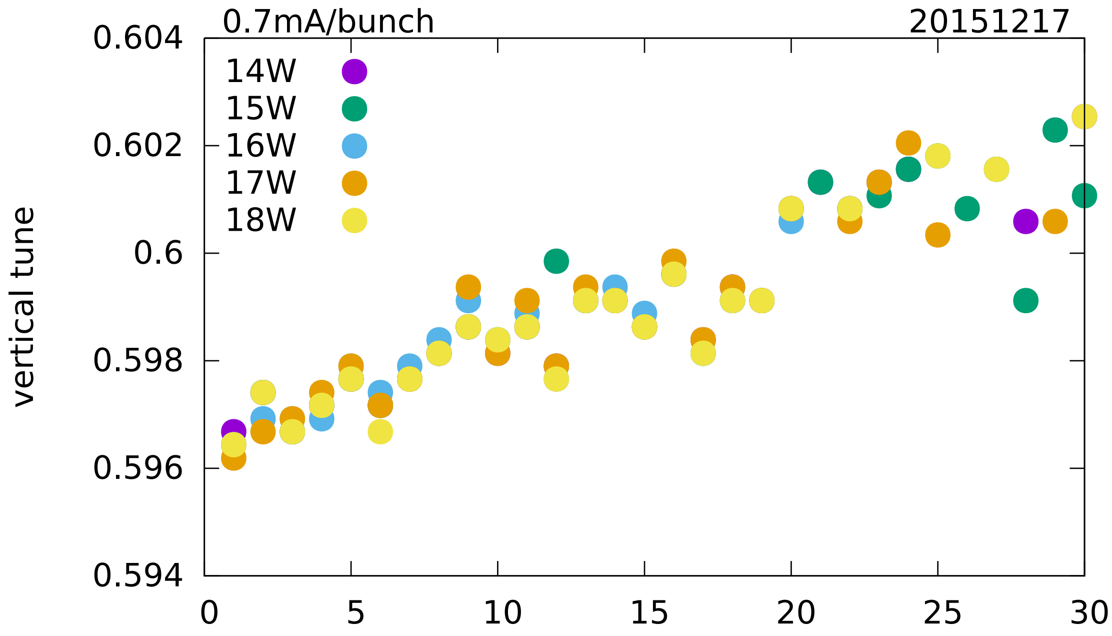
We find
- Significant emittance growth at nominal ecloud charge density
- Cloud density threshold for emittance growth ~ half nominal
- No growth at 10% nominal density

30 Bunch train



Vertical emittance increases with cloud density – with threshold at bunch 13

Tuneshift increases ~ linearly with cloud density

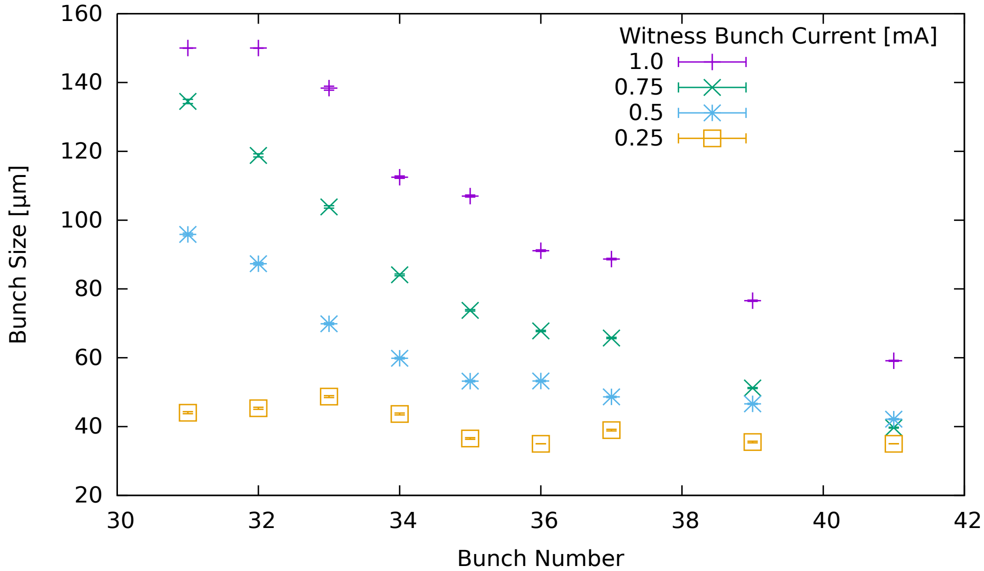


Witness bunch measuements

Generate a cloud with a long train

- Explore dependence on cloud density by varying delay of witness with respect to train
- Measure dependence on bunch charge for fixed density by varying charge in witness bunch

Witness Bunch Measurements



Witness bunches trailing a 30 bunch train (0.7mA/bunch)

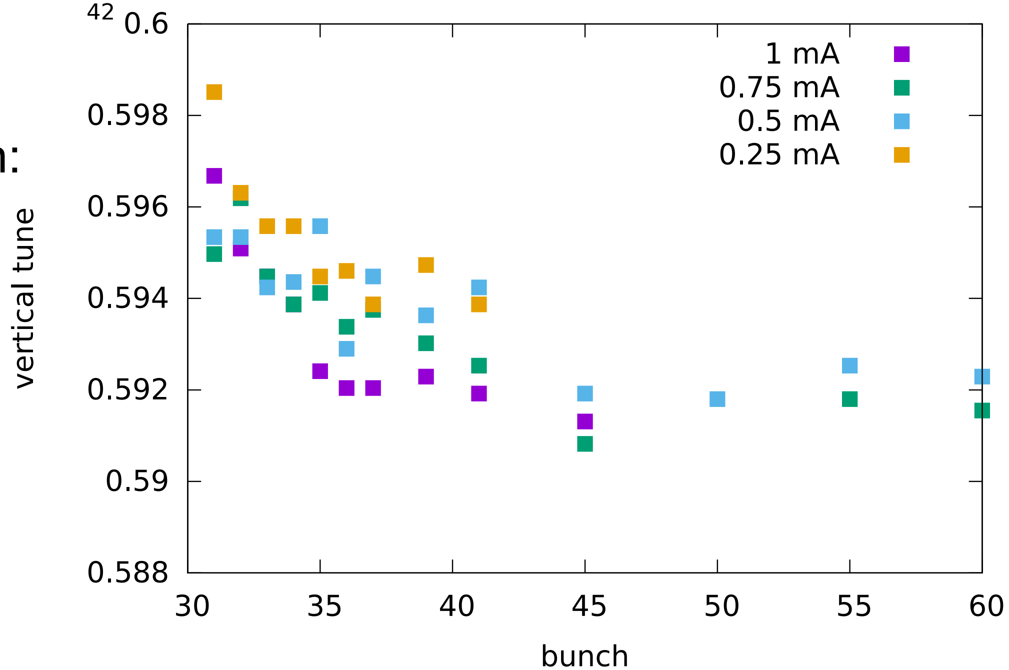
(1mA = 1.6 X 10^{10} positrons)

Vertical emittance growth increases with:

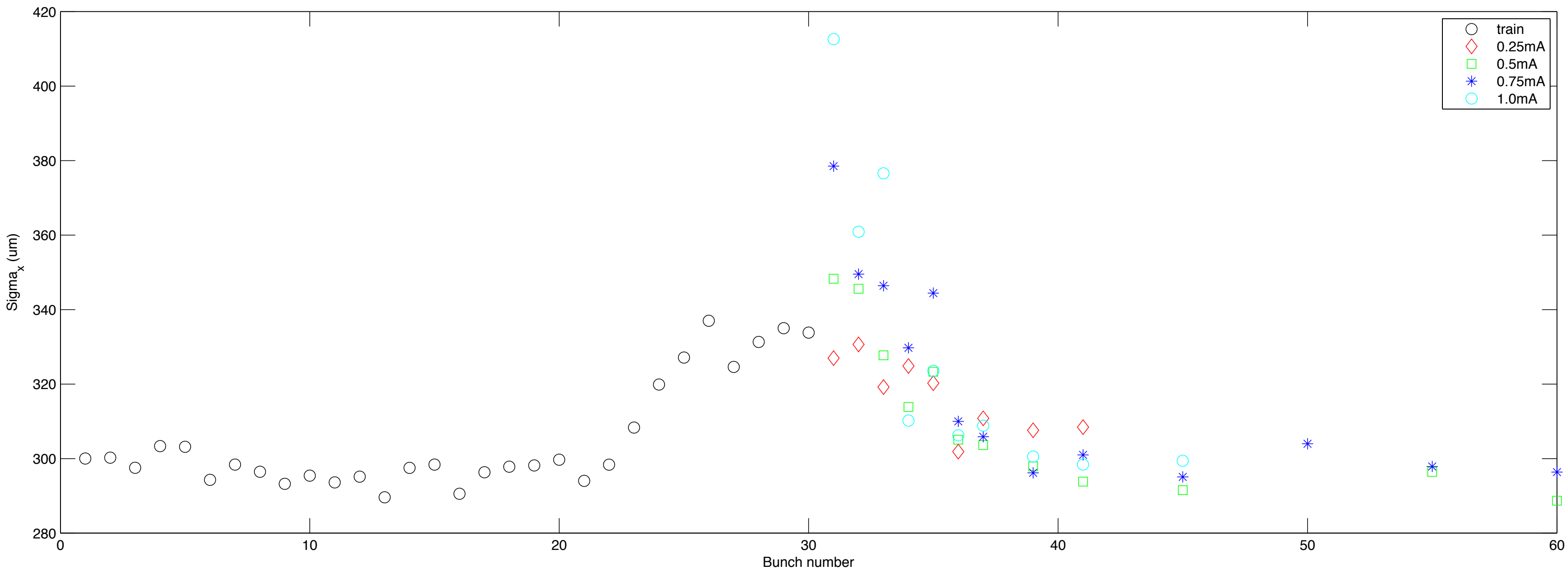
- Density of the cloud (bunch number)
- Witness bunch charge (pinch effect)

Vertical tune shift

- increases with cloud density
- ~ Decreases with pinch

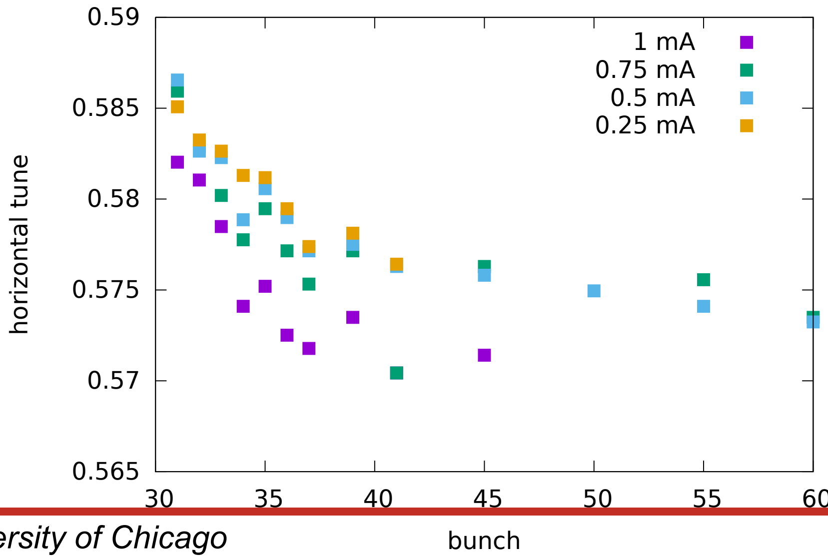


Horizontal emittance growth



Horizontal emittance increases with Cloud density (proximity to train)

Tune shift increases with cloud, Decreases with pinch



Electron Cloud Summary

Goal:
Model that quantitatively predicts vertical and horizontal emittance growth and tune shifts due to the cloud

We measure

$$\Delta Q_x, \Delta Q_y, \epsilon_x, \epsilon_y$$

All three quantities depend on

- average cloud density, which we control via the train length, bunch current and delay of the witness with respect to the train
- pinch, independently controlled via the witness bunch current

The *weak-strong* model has promise.
We plan to further develop the model and compare predictions with measurements

Sources of Emittance Growth Summary

Single particle emittance (well understood)
- Correct or compensate sources of vertical dispersion

Intra-beam scattering (theory and measurements in good agreement)
- Minimize dispersion

Wakefields (developing the fixed wakefield model)
- Symmetrize vacuum chambers
- Minimize transverse impedance of chambers
- Center beam

Electron cloud(developing “weak-strong” model)
- Mitigate cloud growth
- Explore bunch spacing

Speculation

Can we learn to exploit collective effects ?

- Shape the vacuum chamber better focus or stabilize the beam?
- Taylor the electron cloud to compensate intra-beam scattering?

Depends on developing predictive models