# Physics of Ultra-low emittance Beams

David L. Rubin

*April 11, 2012*

# ILC damping ring

Damping ring required to:

- Reduce emittance from $\varepsilon_h = \varepsilon_v = 1$ mm-mrad
  to $\varepsilon_h = 0.5 \times 10^{-3}$ mm-mrad, $\varepsilon_v \Rightarrow 2 \times 10^{-6}$ mm-mrad
- Deliver 2100 of these cold bunches/linac pulse
  (every 200 ms)
- $2 \times 10^{10}$ positrons/bunch

=> Trains of closely spaced bunches (3-6 ns)
and high average current (~0.5 - 1 A) and high
charge density

# ILC damping ring

Damping ring required to:

- Reduce emittance from $\varepsilon_h = \varepsilon_v = 10^{-6}$ m-rad
  to $\varepsilon_h = 0.5 \times 10^{-9}$ m-rad, $\varepsilon_v \Rightarrow 2 \times 10^{-12}$ m-rad
- Deliver 2100 of these cold bunches/linac pulse
  (every 200 ms)
- $2 \times 10^{10}$ positrons/bunch

=> Trains of closely spaced bunches (3-6 ns)
and high average current (~0.5 - 1 A)
and high charge density

Anticipated that intensity (bunch current, total current, emittance) will be limited by

- Electron cloud effects
- Emittance diluting misalignments and optical errors

## 2006 – ILC Damping Rings Task Force
## identified outstanding technical issues requiring further R&D

- Determination of ecloud instability thresholds
- Development of electron cloud suppression techniques
- Modeling tools for computing electron cloud effects for extrapolation to damping ring machine parameters
- Demonstration of 2pm-rad vertical emittance for positrons or at least at strategy for getting there
- Lattice design consistent with beam specifications

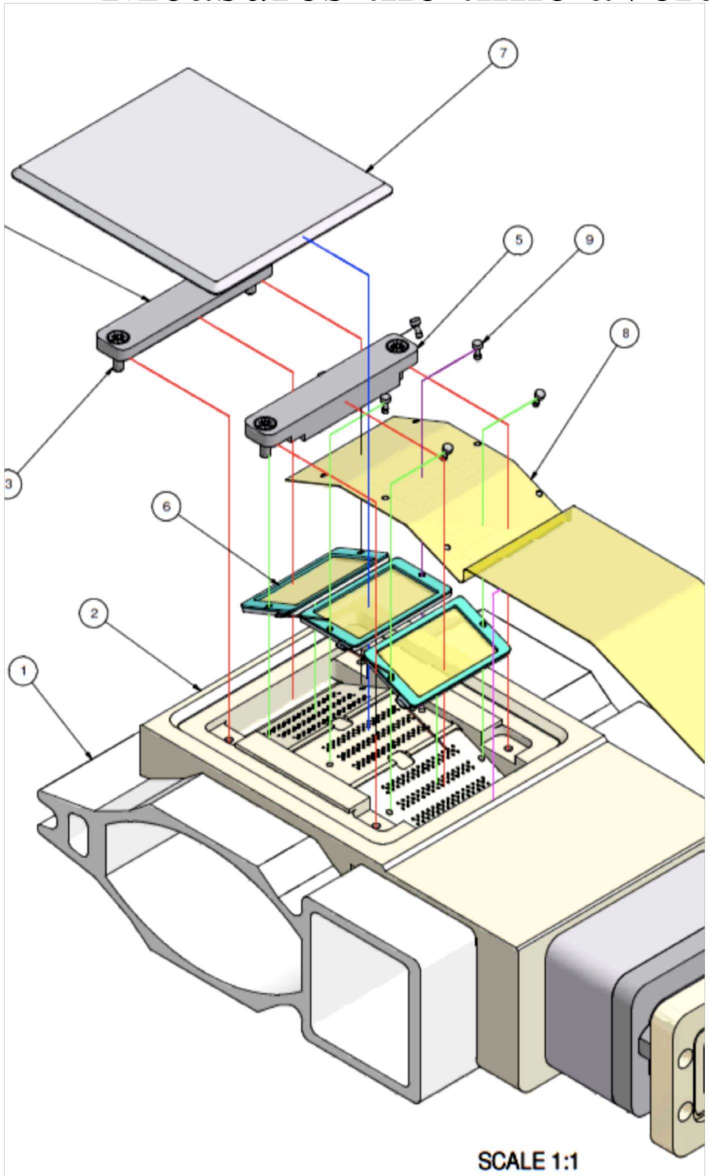
CesrTA was conceived as a laboratory to address these questions

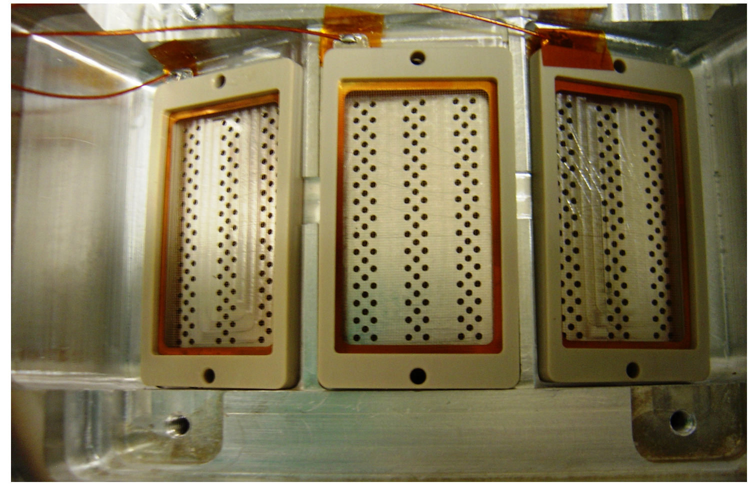
# CesrTA Instrumentation

- Retarding field analyzers - time averaged local electron cloud density and energy spectrum and spatial distribution
- Shielded pickups - growth and decay of the cloud
- Bunch by bunch/turn by turn beam position monitors
  - Bunch dependent tune shift generated by the electron cloud
  - Beam based measurements of emittance diluting optical errors
- Xray beam size monitor - vertical emittance 2-40 pm-rad in a single pass of a single bunch
- Visible light interferometer – bunch width and energy spread for IBS
- Streak camera - for bunch length
- Electron cloud mitigations – suppression of the cloud

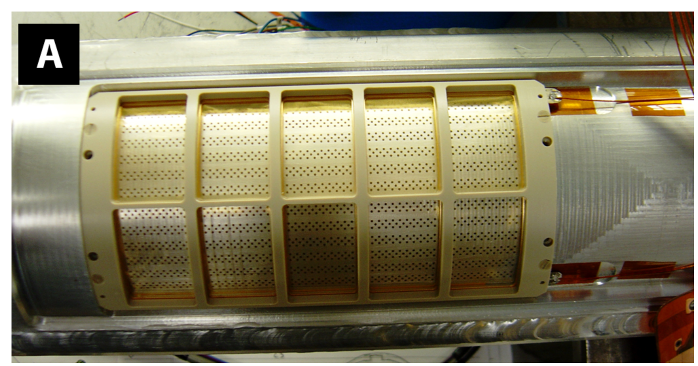
# Retarding Field Analyzer

## Measures the time average cloud density and energy spectrum



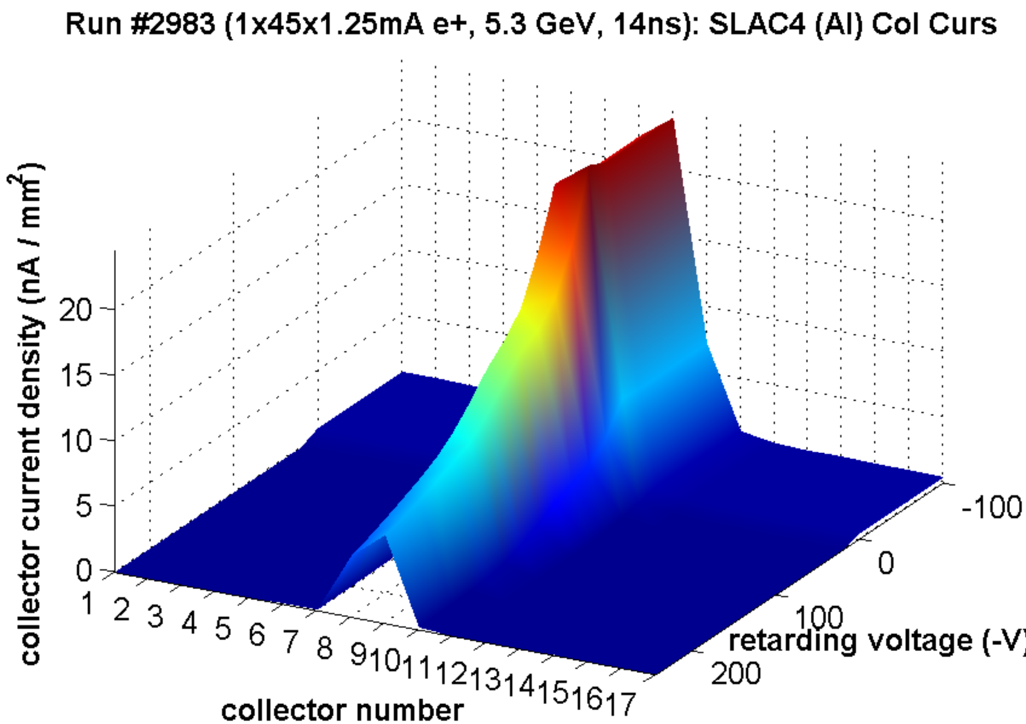
View of from outside vacuum chamber of dipole style RFA with 9 independent collectors. The fine mesh wire grid is in place (but transparent)




Quadrupole RFA

# Electron cloud - RFA

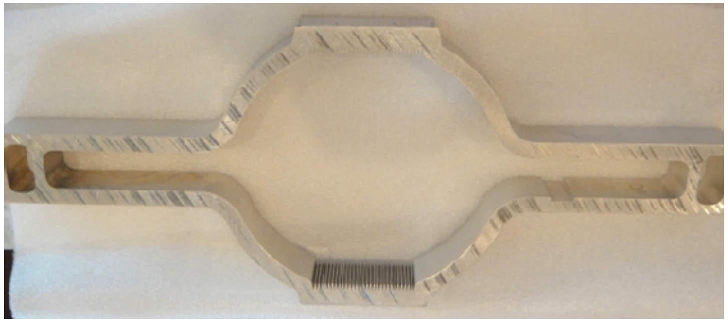
## Dipole RFA data with characteristic central peak

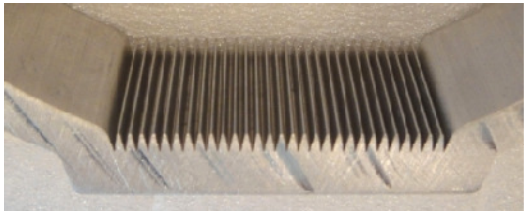



Aluminum chamber
45 bunches, 1.25mA/bunch
14ns spacing,  5.3GeV

# Electron cloud mitigations

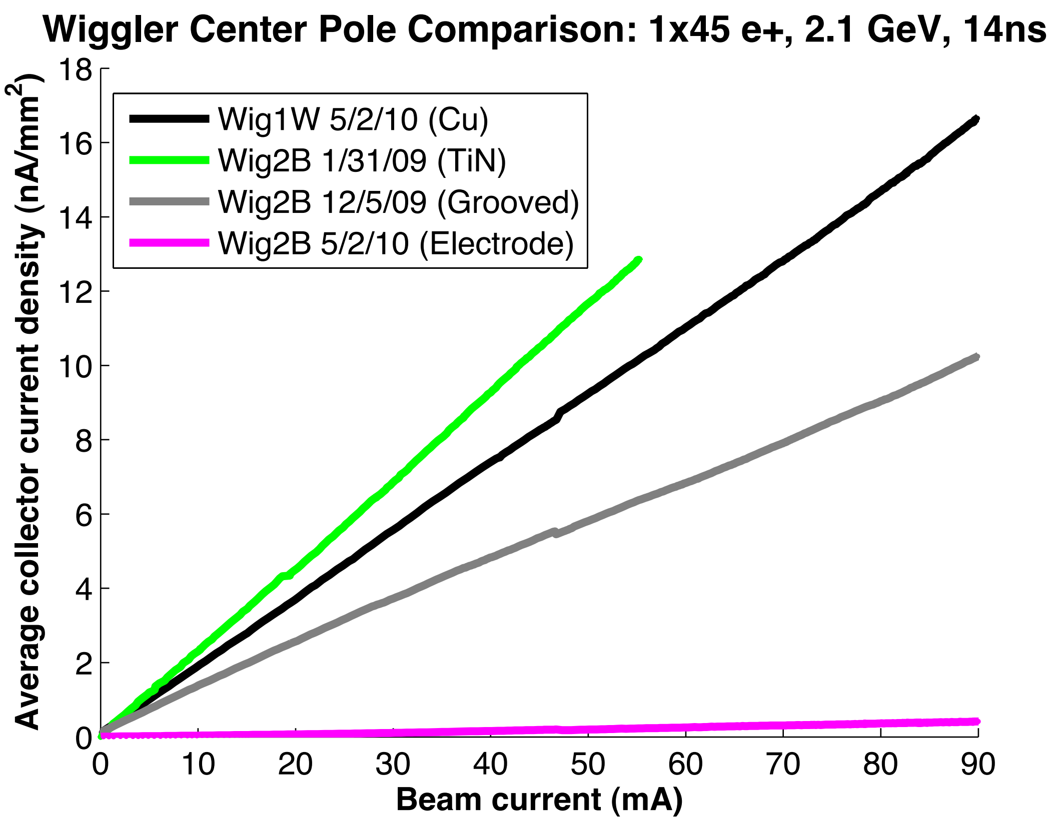
Dipole chamber with antechamber and grooves





Wiggler chamber with clearing electrode

# Electron cloud mitigations in damping wiggler



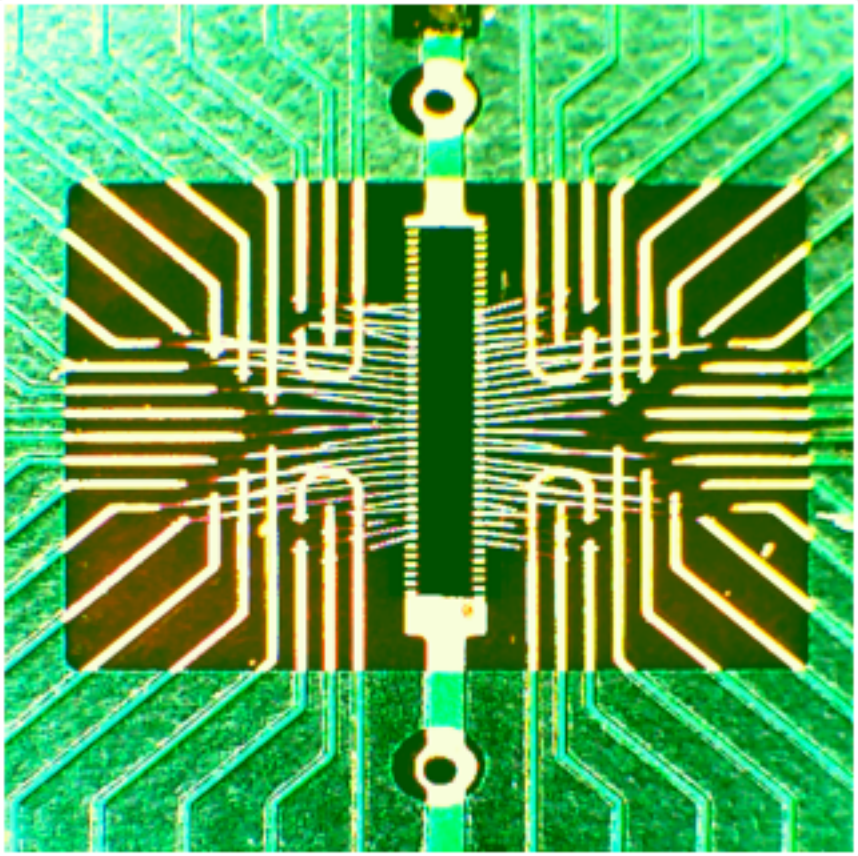

*Joe Calvey (grad student)*

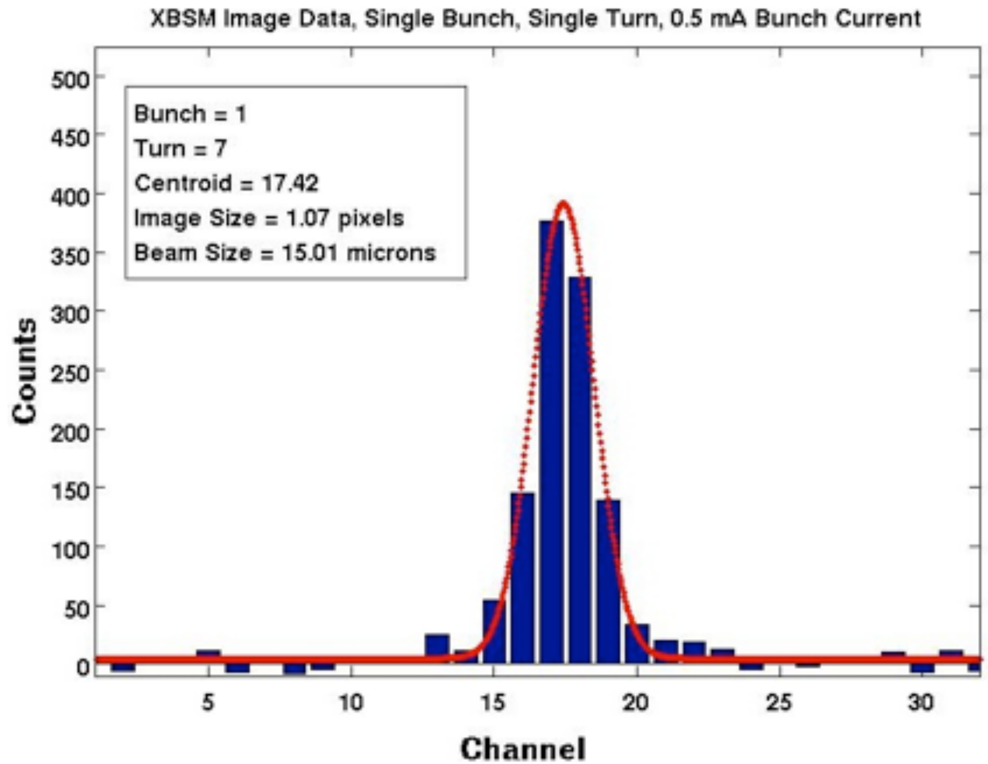
# Electron cloud induced emittance growth

- What is the effect of the electron cloud ?
- What is the threshold for beam blowup ?
- What is the tolerable cloud density ?

To answer these questions we need a measure of vertical emittance

# Xray beam size monitor





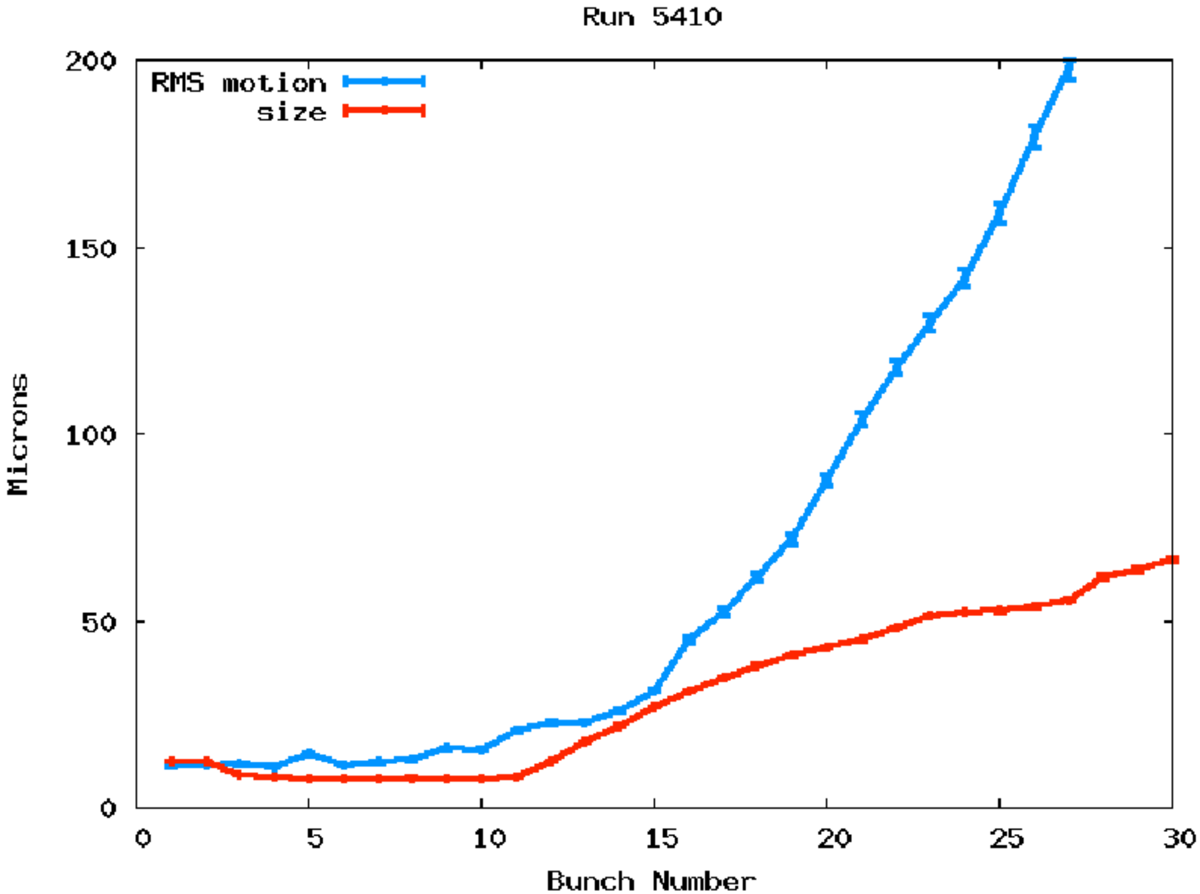

Single pass pin hole image
$\sigma \sim 20\mu m$

32 channel photodiode array
50µm pitch

*W. Hopkins, N. Eggert- grad students*

# Electron cloud effects

Bunch by bunch and turn by turn vertical emittance is measured with xray beam size monitor



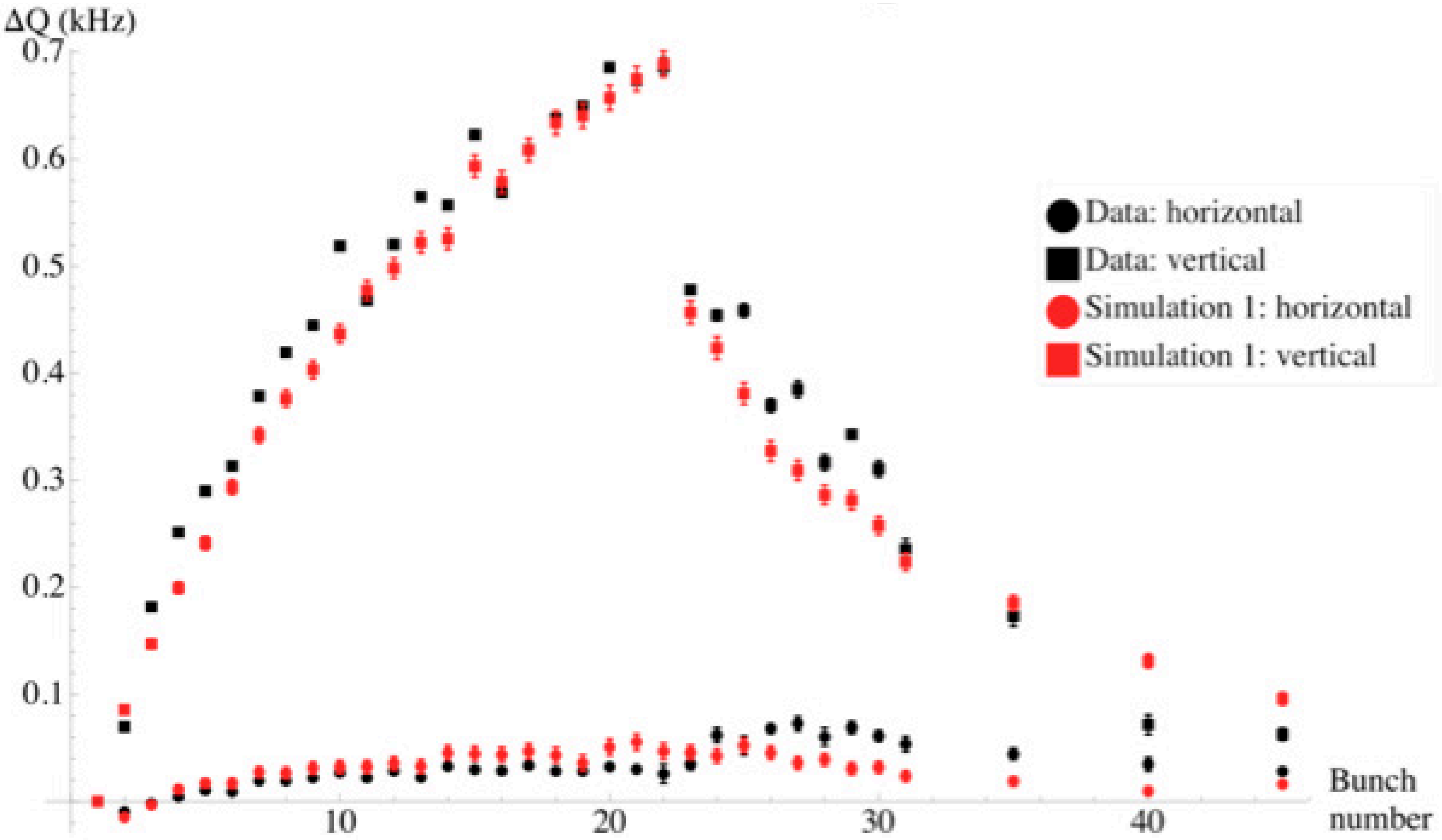

Emittance dilution begins in bunch 12

To determine the threshold for emittance growth we need to measure the cloud density vs bunch

Positron bunches passing through a cloud
electrons experience a focusing force, that shifts their tune

The tune shift is proportional to the cloud density

# Bunch Dependent Tune Shift




Vertical and horizontal tune shift vs bunch number

22 bunches/train - 14ns spacing

$\Delta Q \sim$ cloud density

# Model predicts density

Tune shift measures cloud density versus function of bunch number

Yielding the threshold for emittance growth

Measured suppression of mitigations and knowledge of threshold for emttance growth, combined with model for growth of the cloud

=> specifications for design of damping ring

# Emittance tuning

The very low equilibrium vertical emittance of the ILC damping ring ~2pm-rad - requires

- exquisite alignment of the guide field magnets and
- techniques for identifying and correcting residual emittance diluting errors

# Emittance tuning

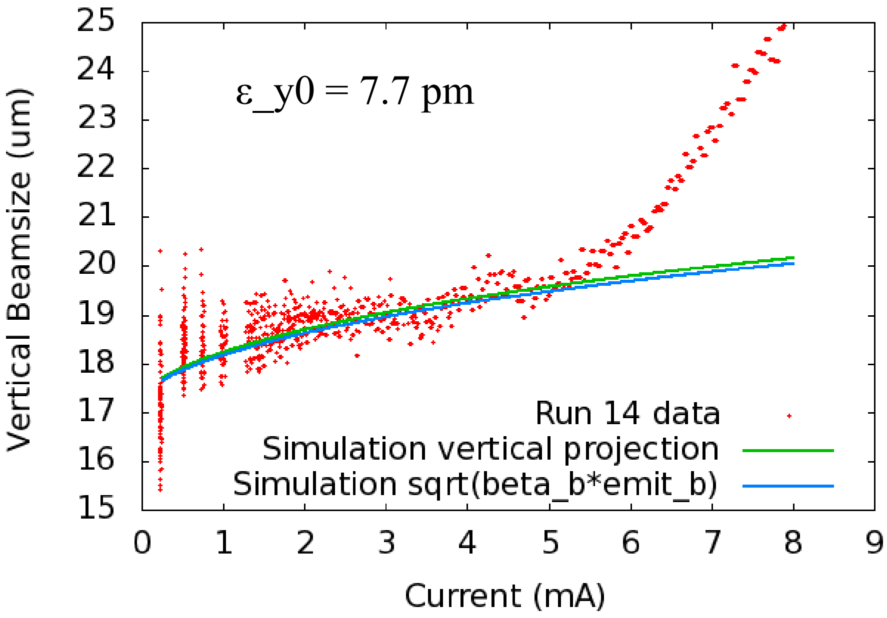
To determine threshold for emittance dilution in a train of bunches
=> Necessary to achieve low vertical emittance in a single bunch

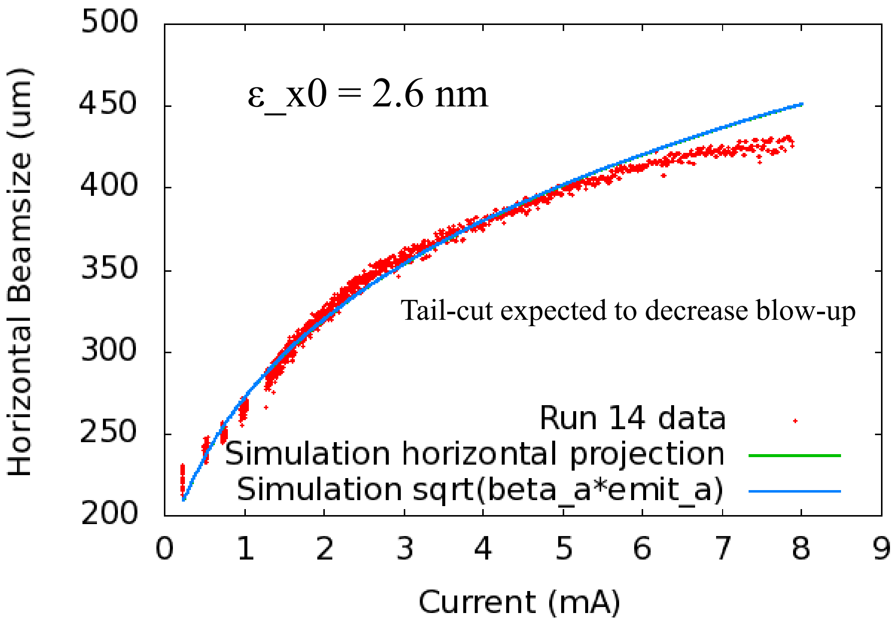
Single particle vertical emittance is due to magnet misalignments & field errors that generate residual coupling and dispersion

Basic ingredients to achieve low vertical emittance are
- Good magnet alignment < 100 microns
- Beam based measurements of orbit, lattice functions, transverse coupling, and vertical dispersion (*Jim Shanks – grad student*)
- Corrector magnets (dipole and skew quadrupoles) with sufficient density to compensate errors measured above

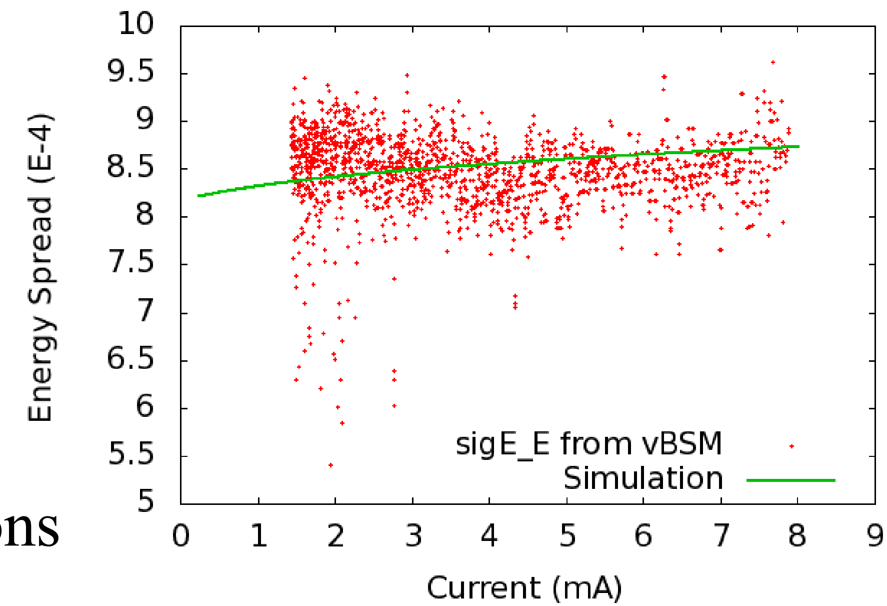
CesrTA low emittance tuning algorithm typically achieves vertical emittance ~ 5-10 pm-rad
- *smallest vertical emittance in a positron beam*

# Intra-beam scattering




At lowest emittance we have sensitivity to emittance blowup due to IBS (*M. Ehrlichman – grad*)

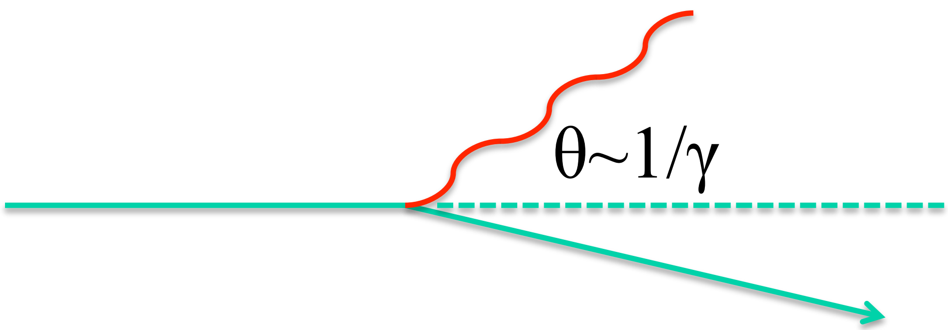



Beam size vs bunch current - electrons

# Quantum limit

- The theoretical minimum vertical emittance (quantum limit) obtains when the magnets are perfectly aligned (or perfectly compensated) so that the residual vertical dispersion vanishes.

Our goal is to reach the quantum limit




In CesrTA quantum limited vertical emittance ~ 20 times smaller than best achieved to date

# Beam physics at the quantum limit

- As we achieve ever smaller emittance, sensitivity to the physics of colder and higher charge density beams is enhanced.
- Electron cloud:
  - The head of a ribbon-like positron bunch pinches the cloud, intensifying the interaction of the cloud with the tail of the bunch – destabilizing the beam
- Intra-beam Scattering:
  - In high intensity bunches, intra-beam scattering will limit vertical emittance
  - As beam size, (equilibrium between IBS and radiation damping), increases with bunch charge.
- Ion instabilities:
  - Interaction of ions with train of intense electron bunches will dilute emittance and generate instabilities

# Beam physics at the quantum limit

Performance of electron positron colliders, damping rings, synchrotron light sources will all be limited

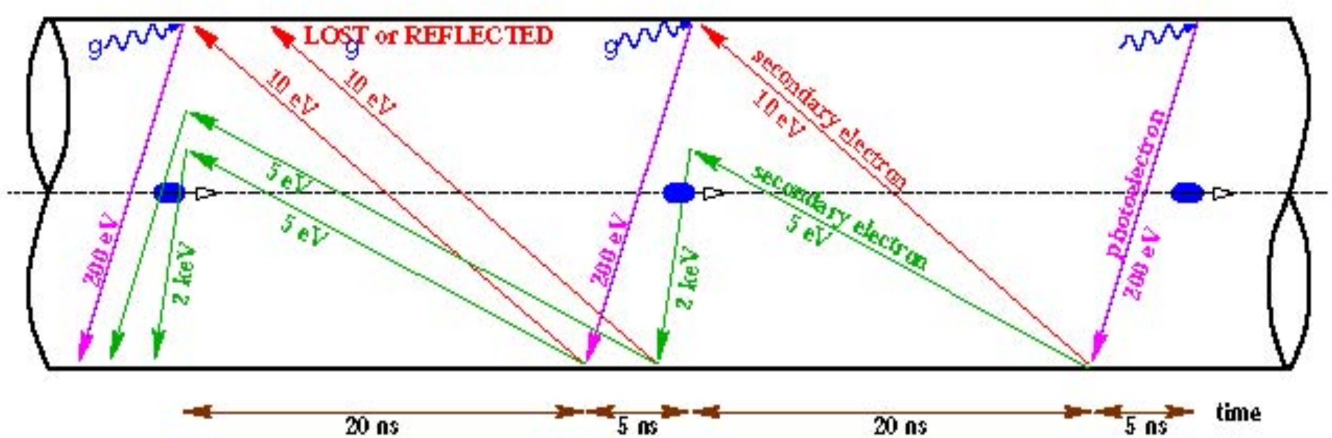
- ability to achieve and maintain low emittance in a single low current bunch
- the collective effects listed above

We aim to explore collective effects at the quantum limit

END

# What is the electron cloud?

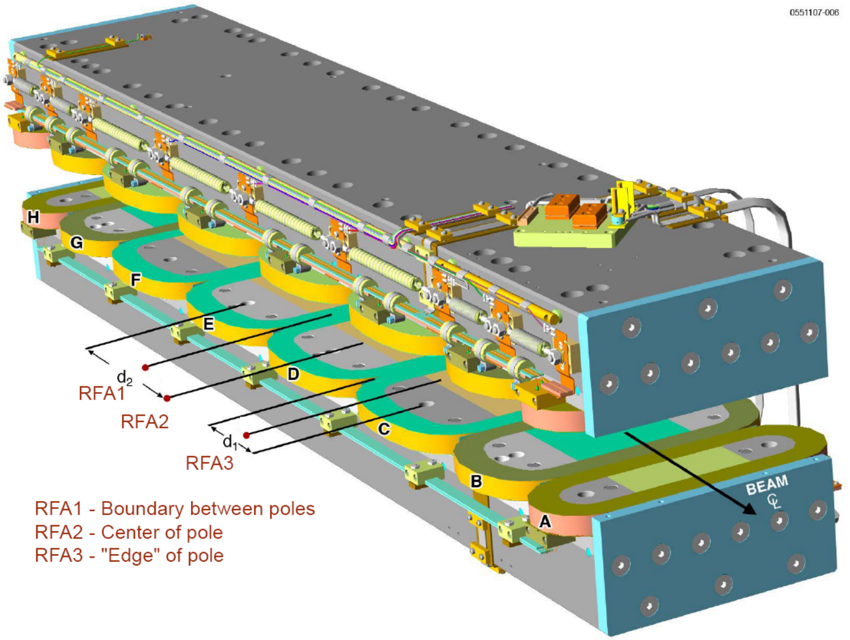
- Synchrotron radiation from the circulating positrons, strikes the walls of the vacuum chamber and photoelectrons are emitted
- Photo electrons traverse the chamber, strike the opposite wall and emit secondary electrons
- Secondary electrons are accelerated by subsequent bunches, hit the wall and emit . . .
- Evolution of the cloud depends on chamber geometry and local magnetic field




schematic of e- cloud build up in the arc beam pipe, due to **photoemission** and **secondary emission**

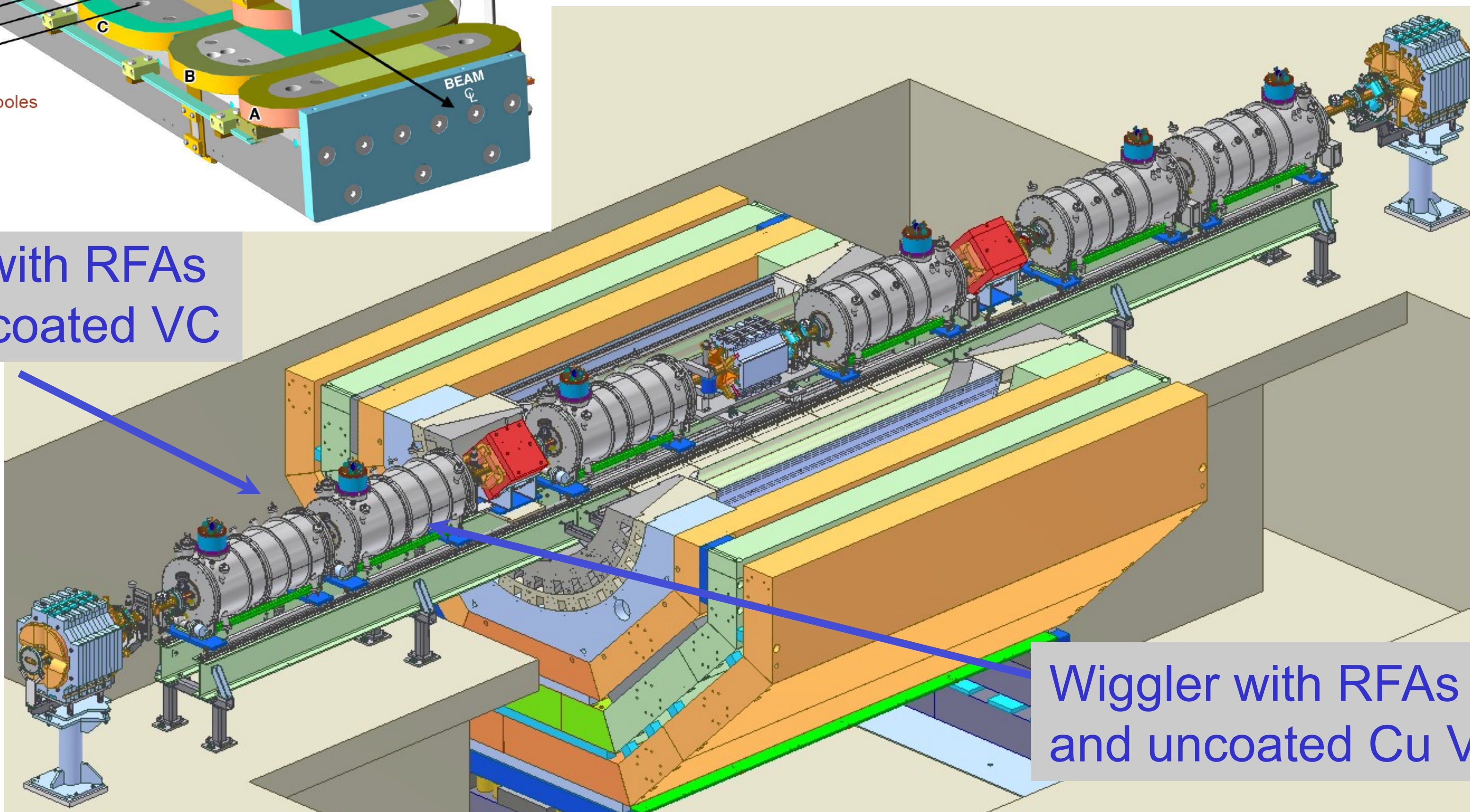
[Courtesy F. Ruggiero]

# Superconducting Damping Wigglers



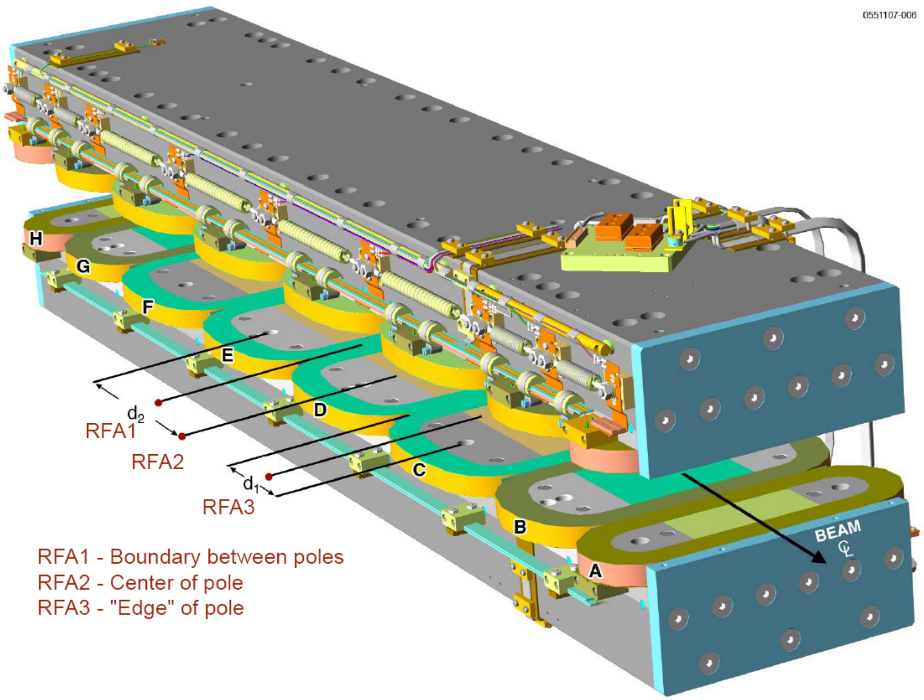

$$B_{peak} = 2.1\ \mathrm{T}$$

Wiggler with RFAs and TiN-coated VC



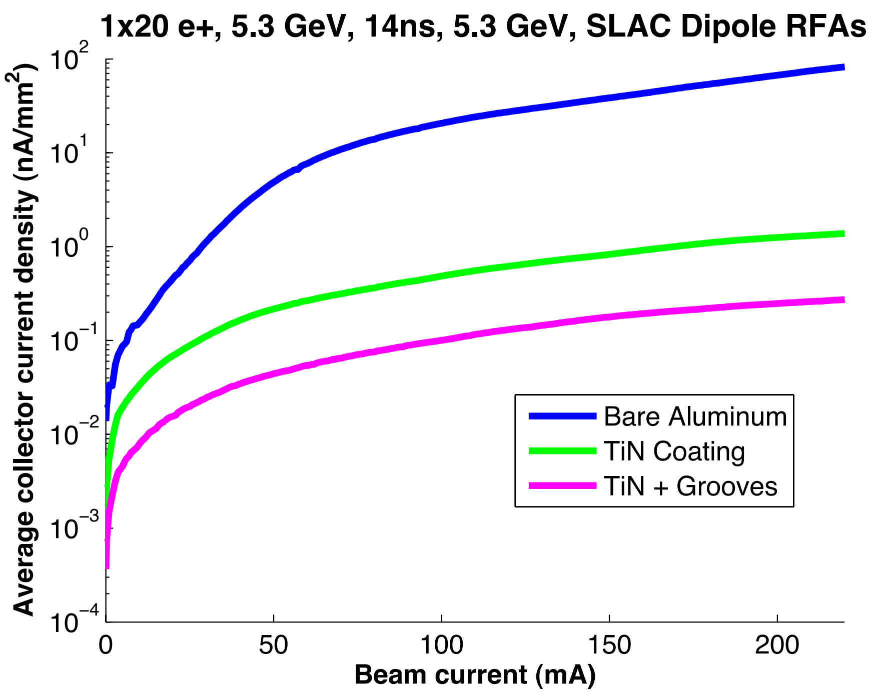
Wiggler with RFAs and uncoated Cu VC

# Retarding Field Analyzer




Wiggler and vacuum chamber with RFAs

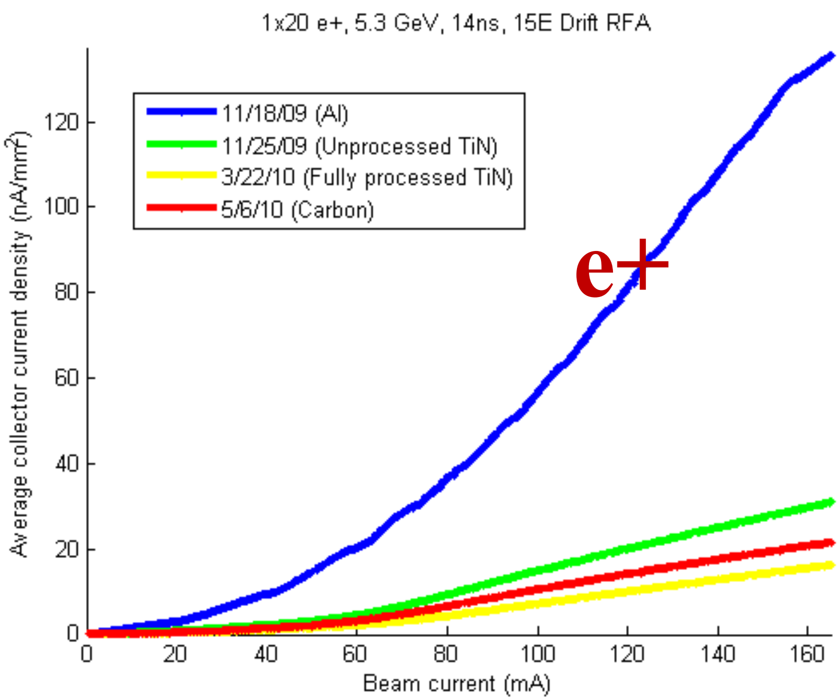
# Electron cloud - RFA

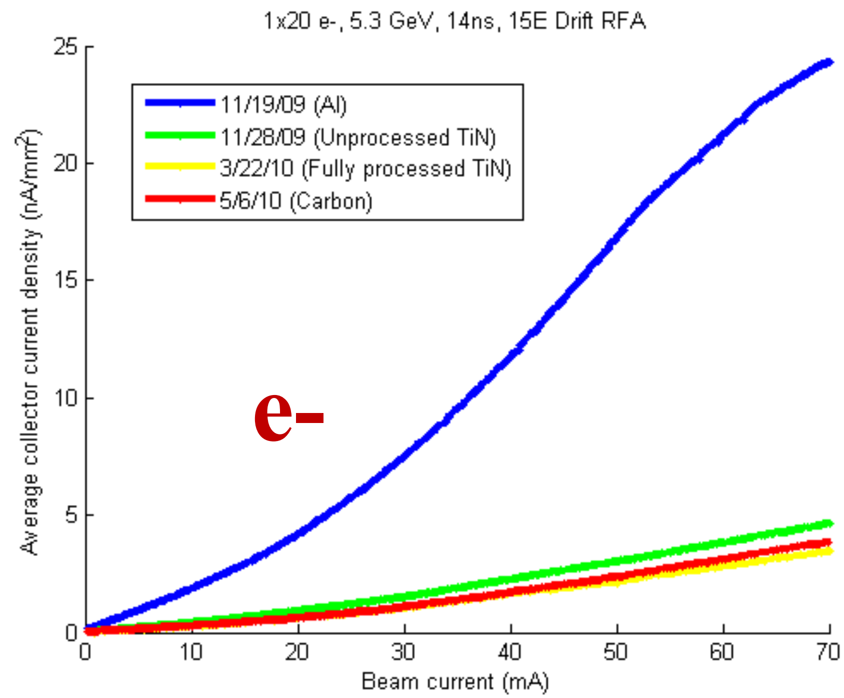



Mitigation in a dipole field

# Electron cloud - RFA

- Mitigation in field free region
  - Electron cloud from positron and electron beams
  - 20 bunches – 14ns spacing – 5.3 GeV



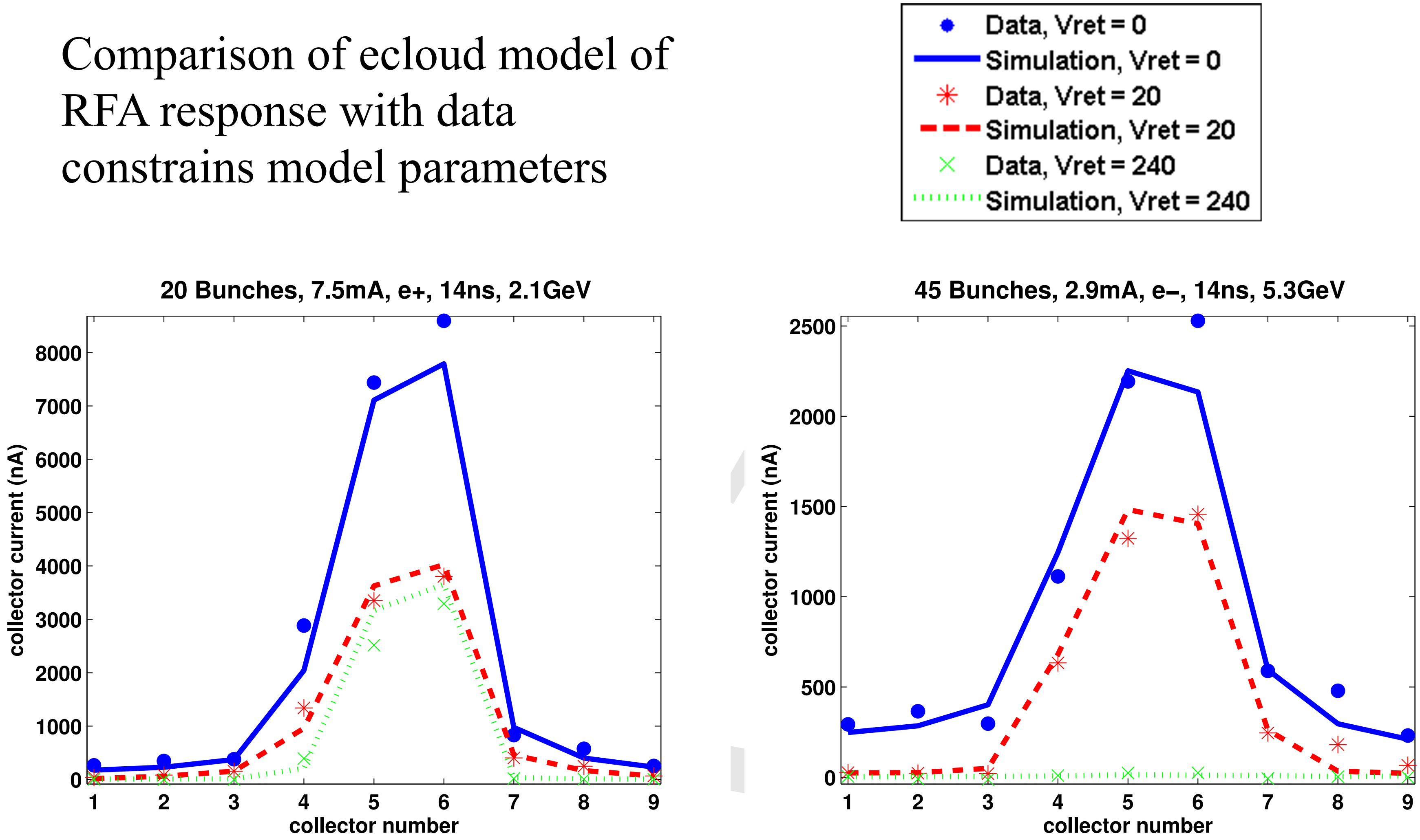



# Surface Characterization & Mitigation Tests

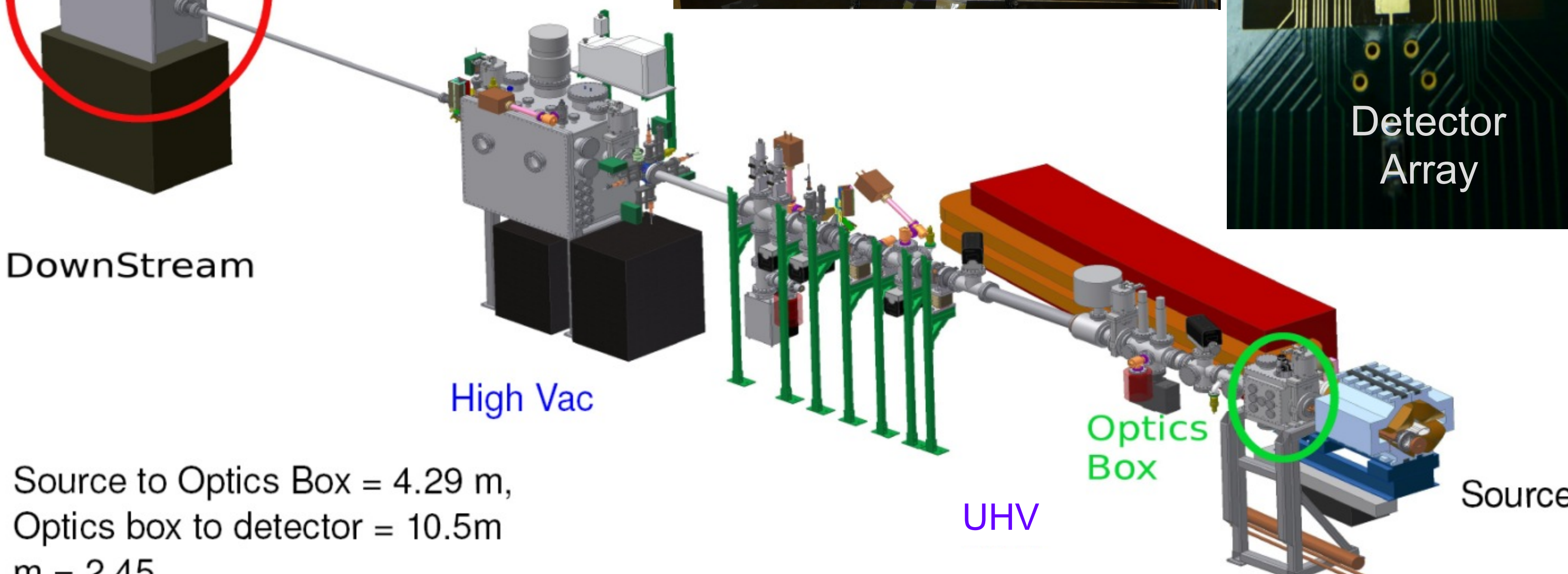
| | Drift | Quad | Dipole | Wiggler | VC Fab |
|---|---|---|---|---|---|
| Al | ✓ | ✓ | ✓ | | CU, SLAC |
| Cu | ✓ | | | ✓ | CU, KEK, LBNL, SLAC |
| TiN on Al | ✓ | ✓ | ✓ | | CU, SLAC |
| TiN on Cu | ✓ | | | ✓ | CU, KEK, LBNL, SLAC |
| Amorphous C on Al | ✓ | | | | CERN, CU |
| Diamond-like C on Al | ✓ | | | | CU,KEK |
| NEG on SS | ✓ | | | | CU |
| Solenoid Windings | ✓ | | | | CU |
| Fins w/TiN on Al | ✓ | | | | SLAC |
| Triangular Grooves on Cu | | | | ✓ | CU, KEK, LBNL, SLAC |
| Triangular Grooves w/TiN on Al | | | ✓ | | CU, SLAC |
| Triangular Grooves w/TiN on Cu | | | | ✓ | CU, KEK, LBNL, SLAC |
| Clearing Electrode | | | | ✓ | CU, KEK, LBNL, SLAC |

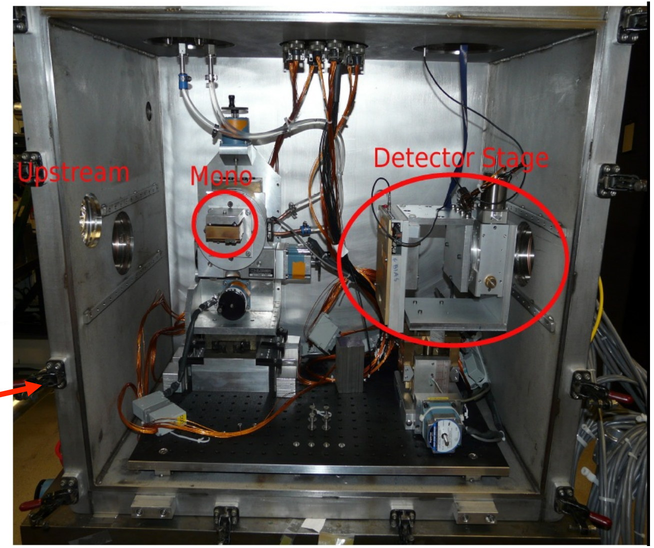
# Electron cloud modeling

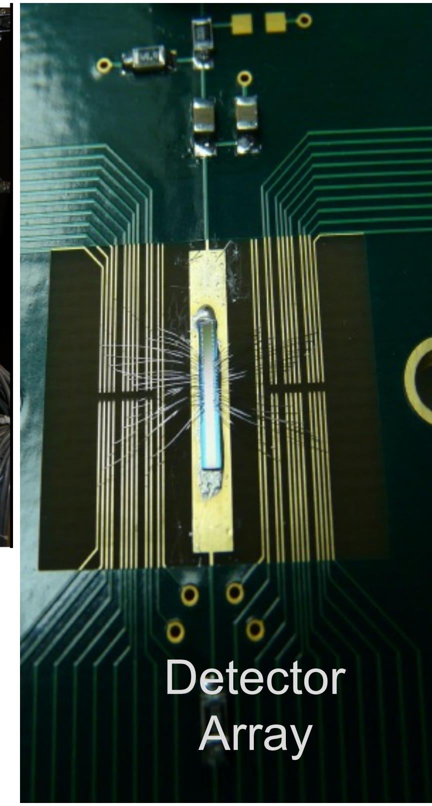
Comparison of ecloud model of RFA response with data constrains model parameters



# xBSM Optics Line & Detector

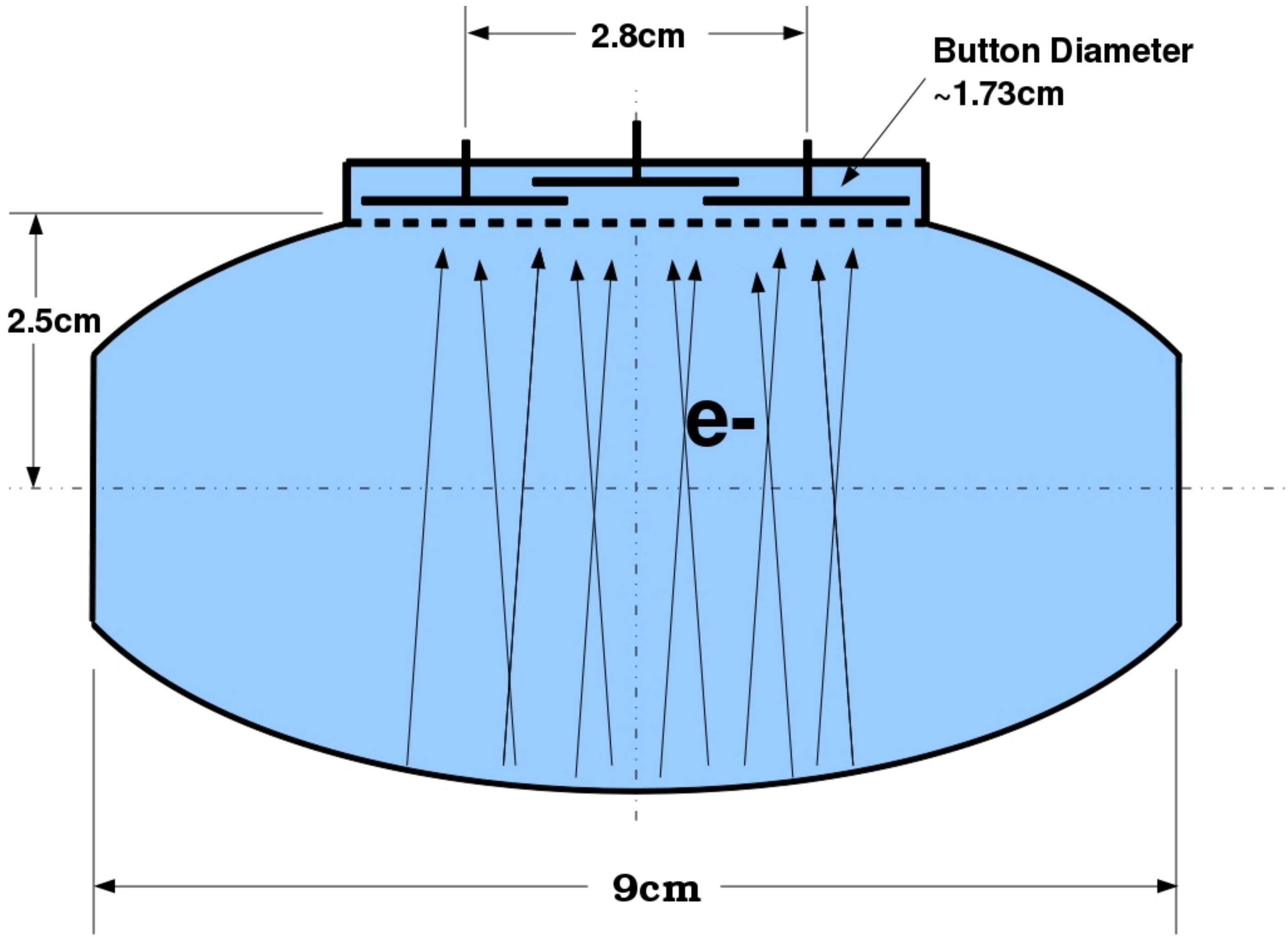


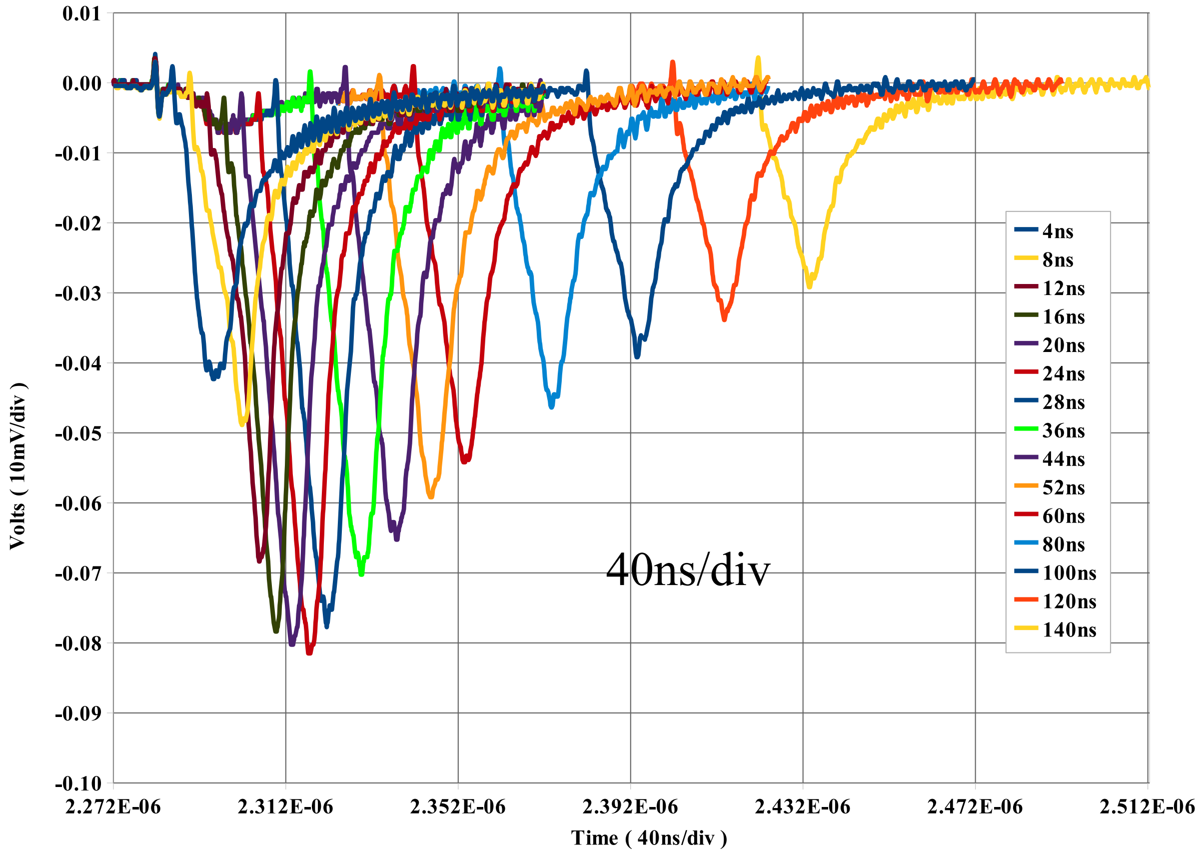

Source to Optics Box = 4.29 m,
Optics box to detector = 10.5m
m = 2.45

# Shielded Pickup




With no magnetic field, electrons come from the floor of the chamber

# Time Resolved Measurements

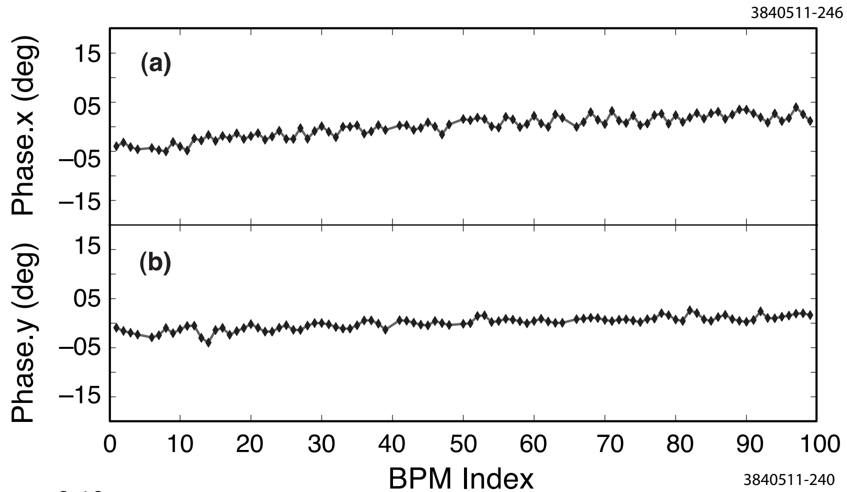



- Overlay of 15 two bunch measurements with varying delay of second bunch
- First bunch initiates cloud
- Second bunch kicks electrons from the bottom of the chamber into the pickup
- Yielding time resolved development and decay of cloud

# CesrTA low emittance tuning

- Measure and correct closed orbit distortion with all steerings
- Measure betatron amplitudes, phase advance and transverse coupling. Use all 100 quadrupoles and 25 skew quads to fit the machine model to the measurement, and load correction
  - (Phase and coupling derives from turn by turn position data of a resonantly excited beam)

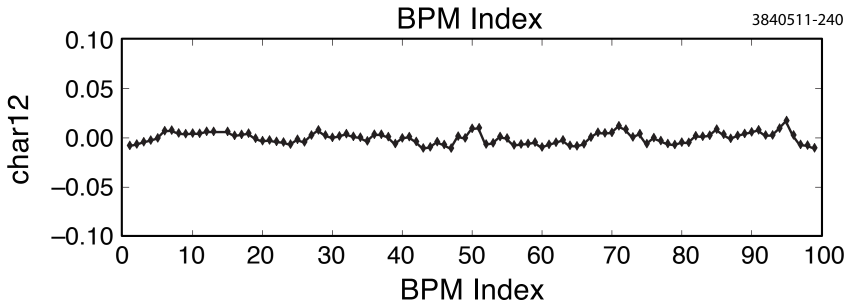
Betatron phase advance




horizontal

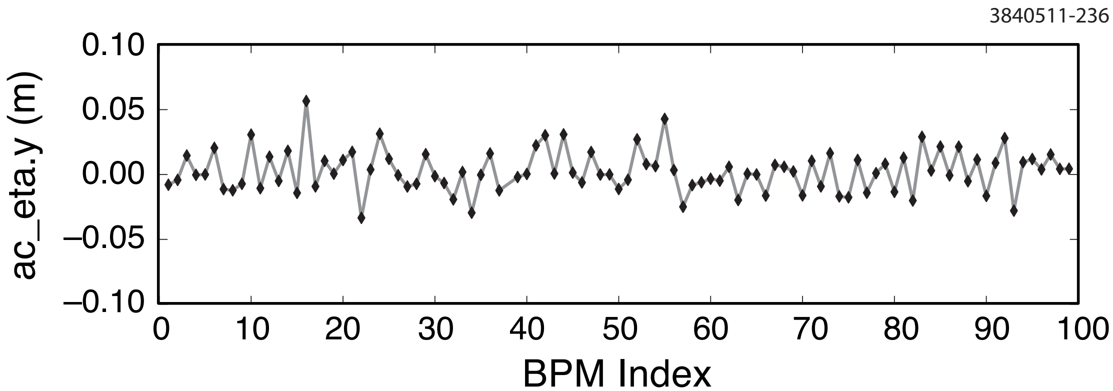
vertical

coupling



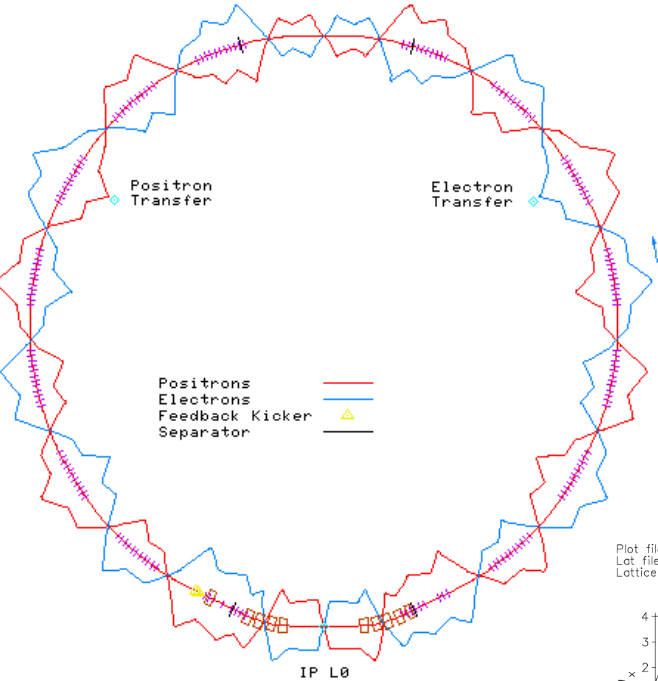
# CesrTA low emittance tuning

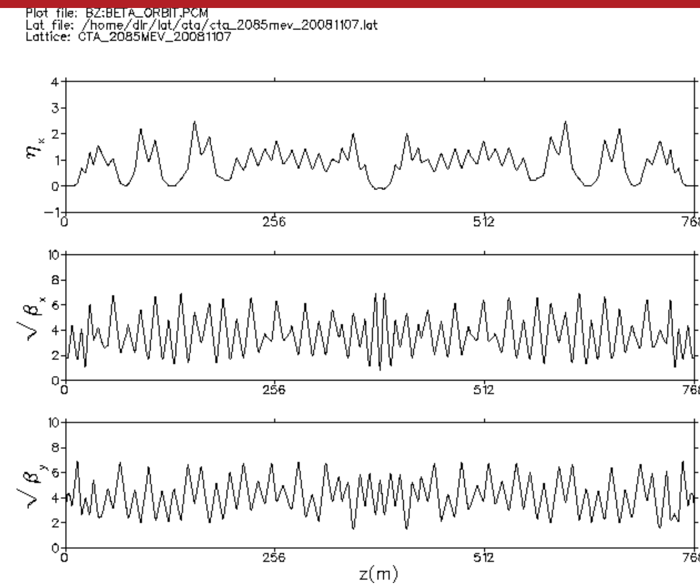
- Re-measure closed orbit, phase and coupling, and dispersion. Simultaneously minimize a weighted sum of orbit, dispersion, and coupling using vertical steerings and skew quads.
  - Dispersion is determined by driving the beam at the synchrotron tune and measuring transverse amplitudes and phases at each BPM



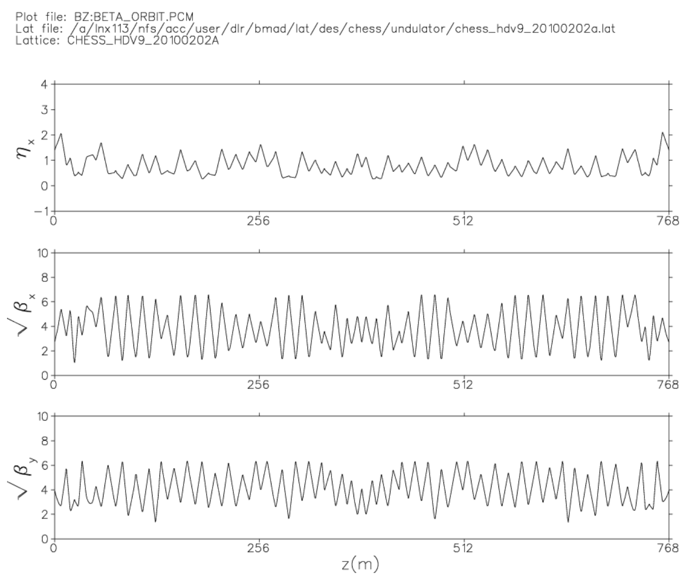

Typically then measure < 10pm with xray beam size monitor

Two beam, multibunch operation for xray science
8 beam lines ($\epsilon_h \sim$ 130 nm-rad at 5.3GeV)



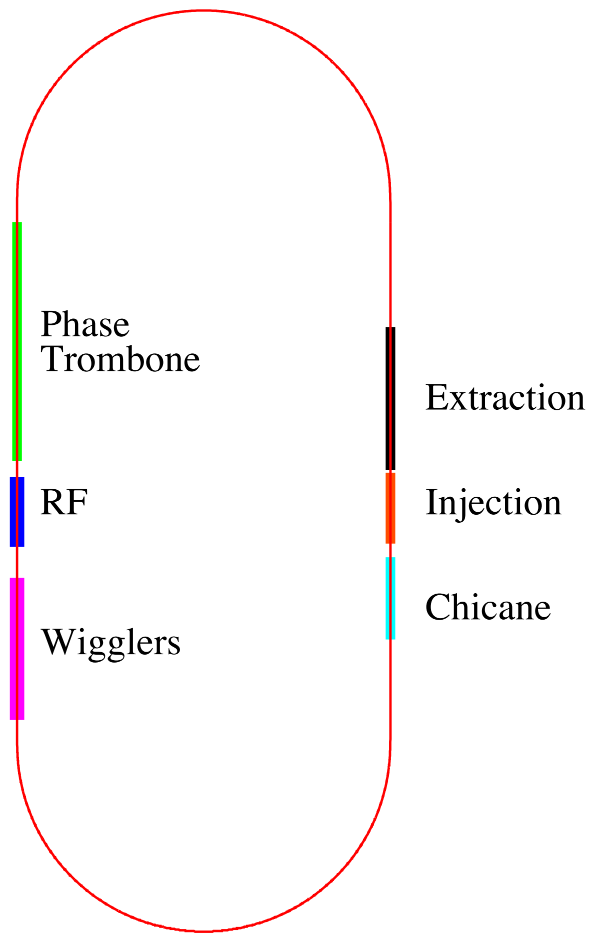



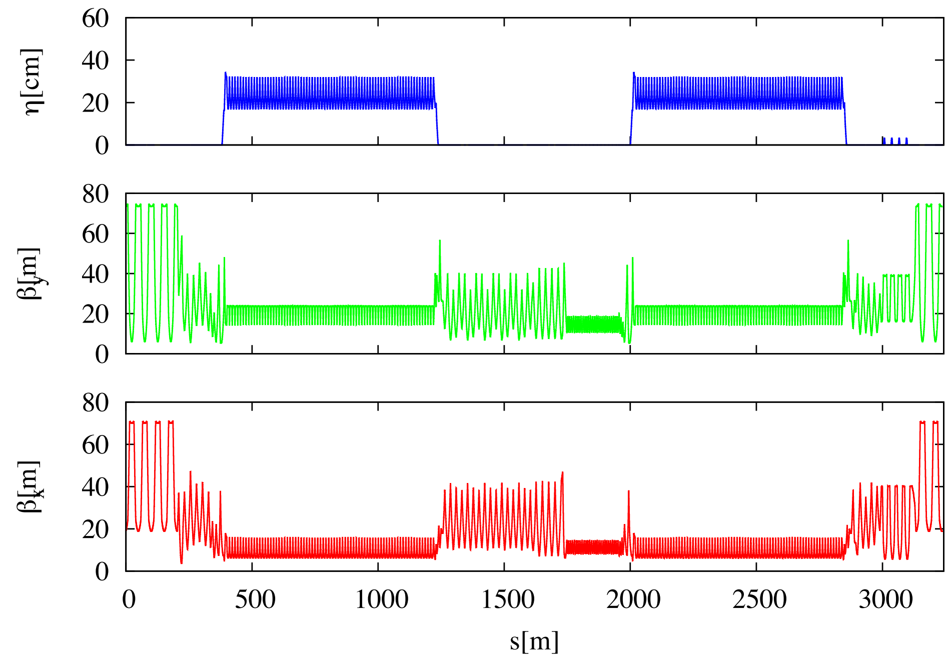

CesrTA wiggler dominated
2 GeV, 2.5 nm-rad




Single beam undulator optics,
($\epsilon_h \sim$ 50 nm-rad at 5.3GeV)
5mm compact undulator

# ILC Damping Ring Lattice




Bending arcs are based on
Ultimate Storage Ring style cells