# The Challenges of Ultra-low Emittance Damping Rings

David Rubin

September 6,2011

IPAC2011 – San Sebastian, Spain

- Requirements
- Lattice
- Emittance Dilution
- Emittance Tuning
  - Instrumentation
  - Algorithms
  - Results
- Collective Effects
  - Electron Cloud
  - Ions
  - Intra-beam scattering
- Conclusion

# Requirements

- Accept hot bunches of positrons $\varepsilon \sim 4.5 \times 10^{-6}$ m-rad
- Deliver ultra-low emittance $\varepsilon_x \sim 0.5$nm-rad and $\varepsilon_y \sim 2$pm-rad positrons in trains of 1300 bunches at a repetition rate of 5 Hz
- Cool them and kick them out to the linac 200ms later, having reduced that emittance by > 4 orders of magnitude with nearly 100% transfer efficiency as the average beam power is > 200kW.

  (*Meanwhile, ~2MW is being radiated away as synchrotron radiation)*
- The 1300 bunch train consists of many smaller trains with gaps for ions to clear in the electron ring and the electron cloud to clear in the positron ring.
- The bunches are plucked one at a time in a 3MHz burst.
- For every low emittance bunch that is extracted into a transfer line, a hot bunch is accepted from the source.

# Requirements

- Meanwhile the 2MW of synchrotron radiation photons strikes the walls of the vacuum chamber, emitting photo electrons
- The electrons are accelerated by the positron beam across the chamber and into the walls again where secondaries are emitted.
- The accumulating cloud of electrons is trapped in the potential well of the positron beam.
- The electron cloud
  – focuses the positrons, shifting tunes
  – Couples motion of the leading to the trailing bunches and
  – And the head of the bunch to the tail
  – Destabilizing the train and diluting the emittance.

# Lattice

- The compression of the train is limited in the end by
  - Our ability to extract cold and inject hot bunches without disturbing the other bunches in the circulating trains
  - The total current in the ring, likely limited by instabilities or emittance dilution
- We consider the ILC baseline as a point of reference, nominally 3.2 km, with 1300 bunches and 6.2ns spacing within the mini-trains

# Optics

- Positrons emerging from converter have large emittance, 9mm-mrad equivalent.
- But we require equilibrium horizontal emittance of 0.5 nm-rad.
- Typically a low emittance optics is strong focusing, with a large natural chromaticity, strong sextupoles and small dynamic aperture.
- Usually this is not a problem as the emittance, and therefore the required acceptance shrinks along with the dynamic aperture.
- Acceptance required for the DR does not shrink along with the dynamic aperture.
- Acceptance is determined by phase space volume of the incoming beam.
- The other requirement is that the beam emittance approach its equilibrium value in 200ms, necessarily about 8 damping times => $\tau_x \approx$ 24ms.
- Relatively large circumference, the necessity for expansive dynamic aperture, short damping time (~ 2000 turns), and low equilibrium emittance

- => Use wigglers to augment the radiation damping
  - – little impact on dynamic aperture.

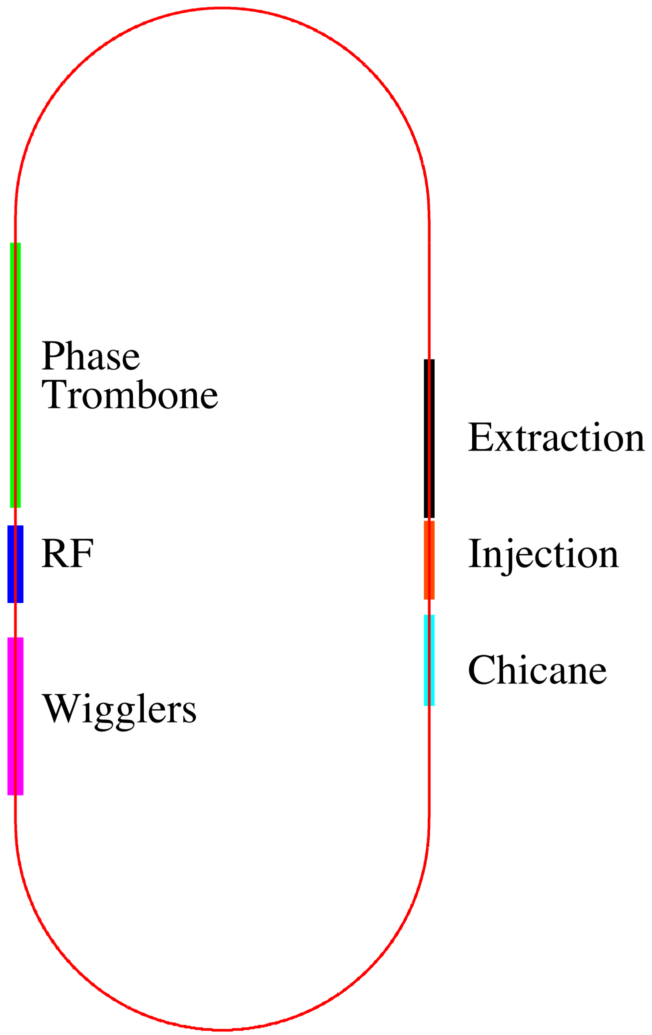
# Layout

- Periodicity
  - A high degree of symmetry enhances dynamic aperture, as it reduces the number of systematic resonances.
  - But not so convenient for facilities.
- Racetrack puts all of the cryogenics for RF and wigglers in a single straight
- Injection and extraction in another so that transfer lines can share a tunnel.
- Conventional facilities dictate a racetrack, and in the baseline design the circumference is evenly divided between straight and arc.
- There is zero dispersion in the straights so they generate nothing but chromaticity, that is left to the arc sextupoles to correct.

# Parameters

- Another consideration is the momentum compaction
  - Small enough to ensure that 6mm bunch length can be achieved with reasonable RF voltage
  - Large enough for reasonable threshold for single bunch instabilities.

# Damping Ring Layout




| Parameter | Value |
|---|---|
| Circumference[km] | 3.242 |
| Energy[GeV] | 5 |
| $T_x$[ms] | 24 |
| Wiggler length [m] | 104 |
| $B_{wiggler}$[T] | 1.5 |
| RF[MHz] | 650 |
| RF[MV] | 14 |
| ΔE/turn[MeV] | 4.5 |
| $\Upsilon\varepsilon_x$ [μm] | 5.4 |
| I[A] | 0.4 |
| $\sigma_{z[}$ [mm] | 6 |
| $\sigma_\delta$ [%] | 0.11 |
| $\alpha_p$ | $3.3 \times 10^{-4}$ |

# Wigglers

- Wigglers decrease damping time from 135ms to 24ms
- Decrease emittance from $2.5 \times 10^{-9}$ to $5.2 \times 10^{-10}$
  - Effective as they do significant damping but relatively little excitation
- Increase synchrotron radiated power from 320kW to nearly 2MW

# Vertical emittance

- Due almost exclusively to misalignments and field errors
- In perfectly aligned machine vertical emittance is more than an order of magnitude smaller than 2pm target.
- Vertically offset quadrupoles and rolled dipoles generate vertical kicks and vertical dispersion and emittance
- Tilted quadrupoles and offset sextupoles couple horizontal dispersion into vertical
- Survey and alignment – what would it take?

| | |
|---|---|
| Quadrupole vertical offset[μm] | 30 |
| Quadrupole tilt [μm] | 30 |
| Dipole roll [μm] | 30 |
| Sextupole vertical offset [μm] | 30 |
| Wiggler tilt [μm] | 30 |

$\Rightarrow$ 50% seeds, $\varepsilon_x$> 4pm-rad (95% < 14pm-rad)

Need to do much better

# Emittance tuning

- Measure and correct
  - Given enough correctors (steerings and skew quads everywhere) and quality measurements, emittance diluting errors can be corrected
  - If we measure the dispersion with enough precision, and fit a machine model using all of those correctors, load into the machine, done
- Machine physicists at light sources have been very successful cleaning up lattice errors and achieving very low emittance, indeed in some cases exceeding the ILC damping ring spec.
- In a damping ring this will have to be done routinely and necessarily with some efficiency

- ATF and CesrTA have developed tuning procedures.
  - Tested on the respective machines and evaluated in simulation
  - We can predict with some confidence extrapolation to 3.2km and 2pm
- To achieve and maintain very low emittance
  - Periodic survey and alignment of guide field magnets
  - Precision beam position monitors and beam based calibration of position monitor offsets, tilts, button gains so that sources of emittance dilution can be identified
  - Algorithms for compensating the misalignments with corrector magnets.

# ATF Damping Ring

| Parameter | |
|---|---|
| Circumference[m] | 138.6 |
| Energy[GeV] | 1.3 |
| Lattice type | FOBO (18 cells /arc) |
| Symmetry | Racetrack |
| Horizontal steerings | 48 |
| Vertical steerings | 50 |
| Skew quadrupoles | 68 |
| Horizontal emittance[nm] | 1.1 |
| Beam detectors | 96 |
| BPM diff resolution[μm] | <1 |

# ATF low emittance tuning

- Measure and correct closed orbit distortion with all steerings
- Measure orbit and dispersion. Simultaneously correct a weighted average of dispersion and orbit errors using vertical steerings
  - Dispersion is the difference of orbits with 1% energy differential

  *Few pm-rad vertical emittance requires residual vertical dispersion < 5mm, corresponds to orbit difference of 50μm (insensitive to BPM offsets)*
- Measure coupling and minimize with skew quads.
  - Coupling is defined as the change in vertical orbit due to the effect of two nondegenerate horizontal steerings.

# ATF Low Emittance Tuning

Effectiveness depends on the BPM offset error and BPM resolution. Calibration of BPM offsets is essential.

With 20μm BPM resolution and no BPM alignment
    5.8mm residual dispersion and measure >10pm vertical emittance with laser wire

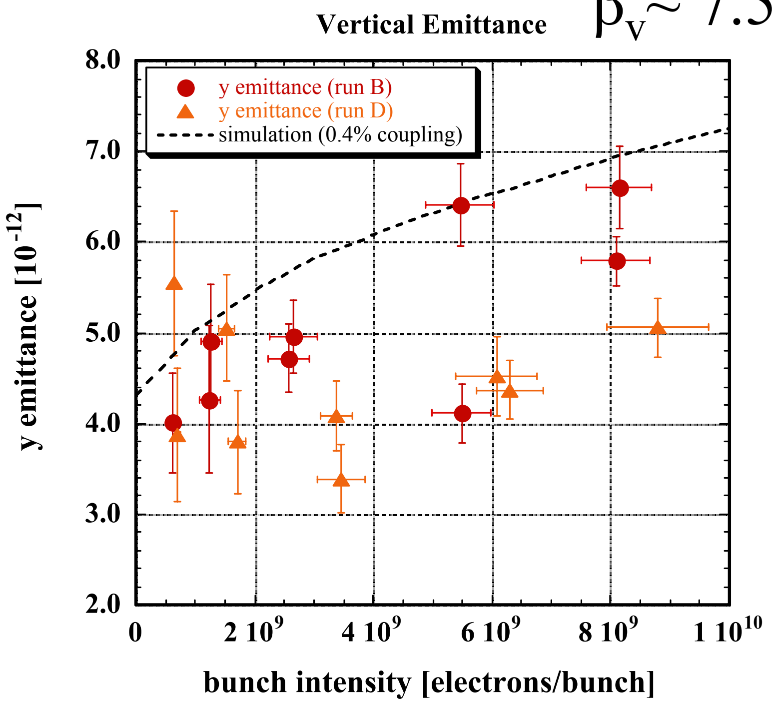
With improved beam position monitors, 5μm resolution and BPM alignment
    1.7mm residual dispersion and 3.5-5pm emittance with laser wire.

Consistent with simulations which furthermore indicates that with $\sigma_{BPM} < 1\mu m$, will reach $\varepsilon_y < 2pm$

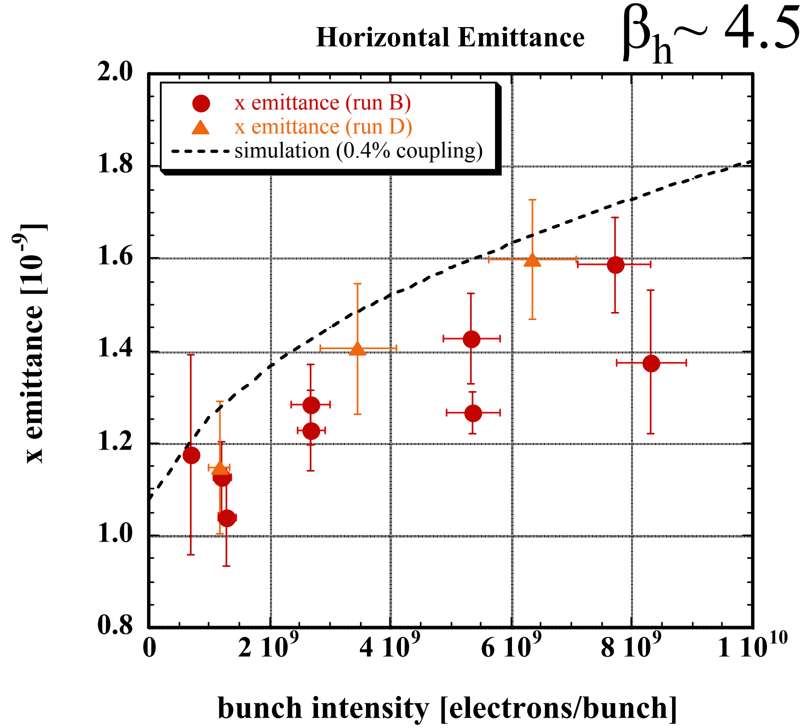
# ATF emittance tuning

## Laser wire measurement of emittance after tuning

$\beta_v \sim 7.5\text{m}$




$\beta_h \sim 4.5\text{m}$



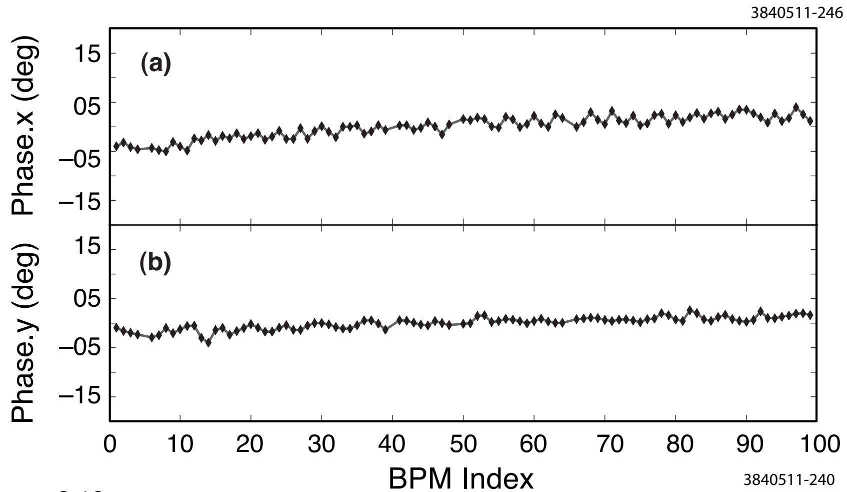

Some evidence for IBS emittance growth

| Parameter | |
|---|---|
| Circumference[m] | 768.4 |
| Energy[GeV] | 2.1 (1.8-5.3) |
| Lattice type | FODO |
| Symmetry | ≈ mirror |
| Horizontal steerings | 55 |
| Vertical steerings | 58 |
| Skew quadrupoles | 25 |
| Horizontal emittance[nm] | 2.6 |
| Damping wigglers [m] | 19 (90% of synchrotron radiation) |
| Wiggler $B_{max}$ [T] | 1.9 |
| Beam detectors | 100 |
| BPM diff resolution[μm] | 10 |

# 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)

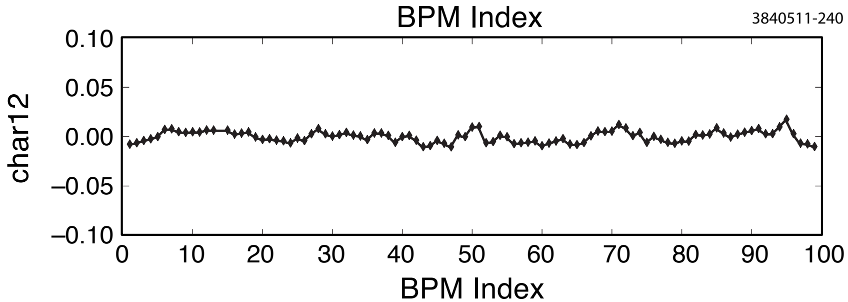
Betatron phase advance




horizontal

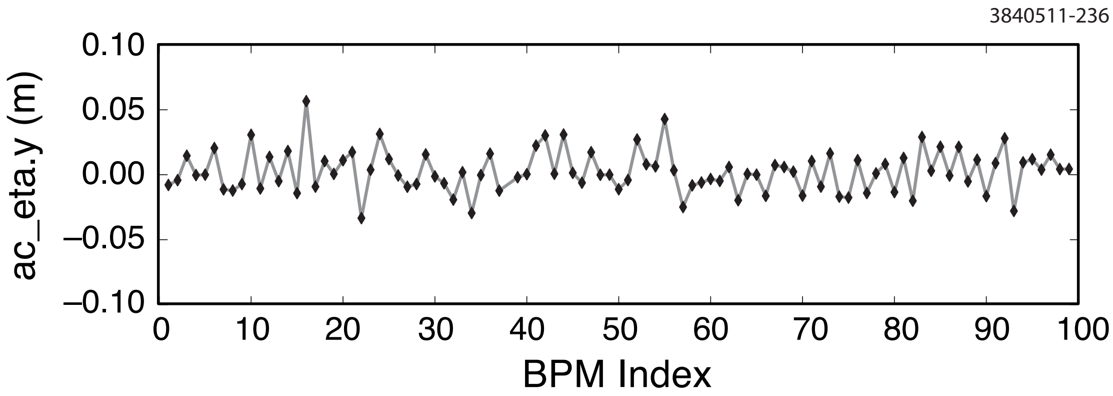
vertical

coupling



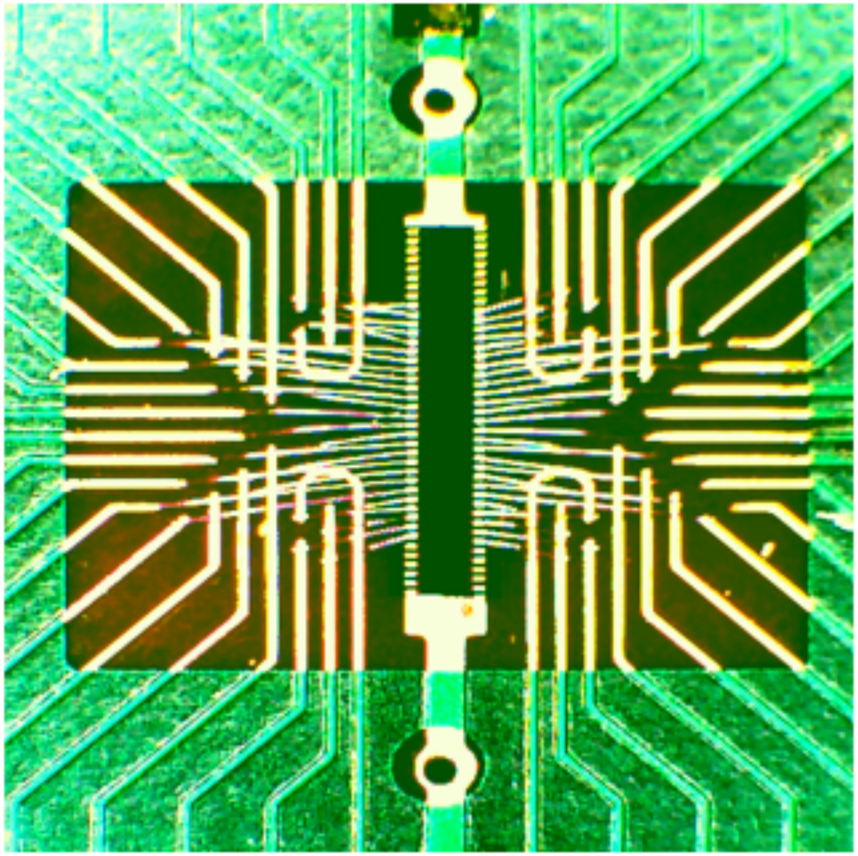
# CesrTA low emittance tuning

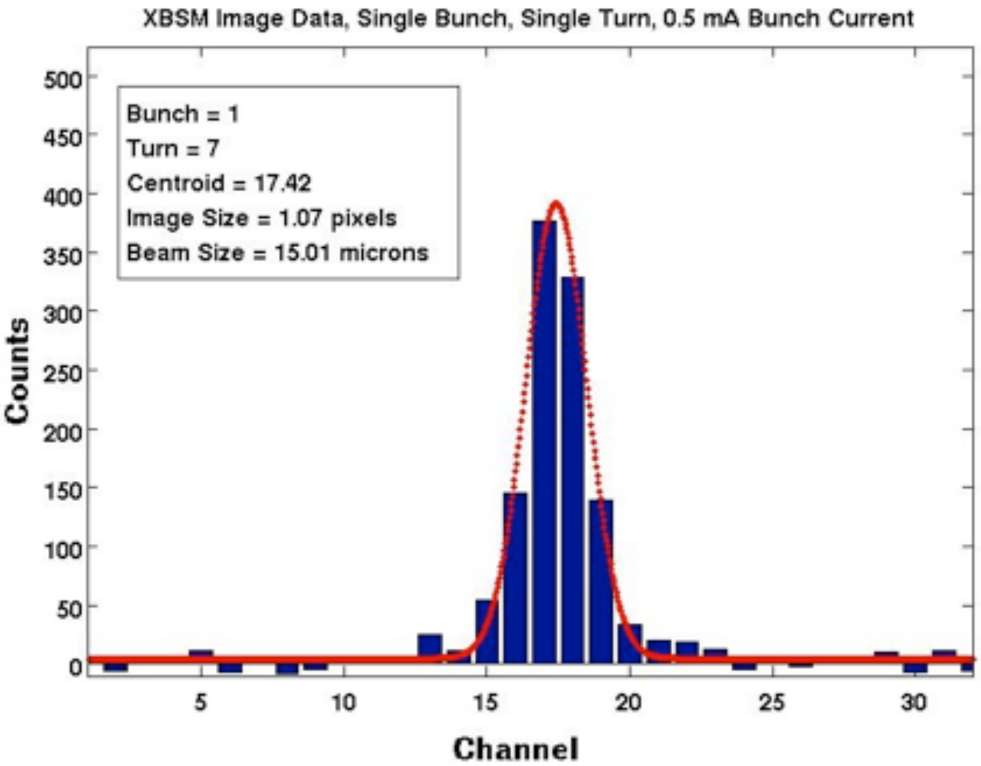
- Re-measure closed orbit, phase and coupling, and dispersion. Simultaneously minimize a weighted sum of orbit, dispersion, and coupling using vertical steerings and skew quads.
  - Dispersion is determined by driving the beam at the synchrotron tune and measuring transverse amplitudes and phases at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




Typically then measure < 10pm with xray beam size monitor

# Xray beam size monitor





# Low emittance tuning - modeling

- Introduce misalignments

| Element | Misalignment |
|---|---|
| Quadrupole vertical offset [μm] | 250 |
| Quadrupole tilt [μrad] | 300 |
| Dipole roll [μrad] | 300 |
| Sextupole vertical offset [μm] | 250 |
| Wiggler tilt [μrad] | 200 |

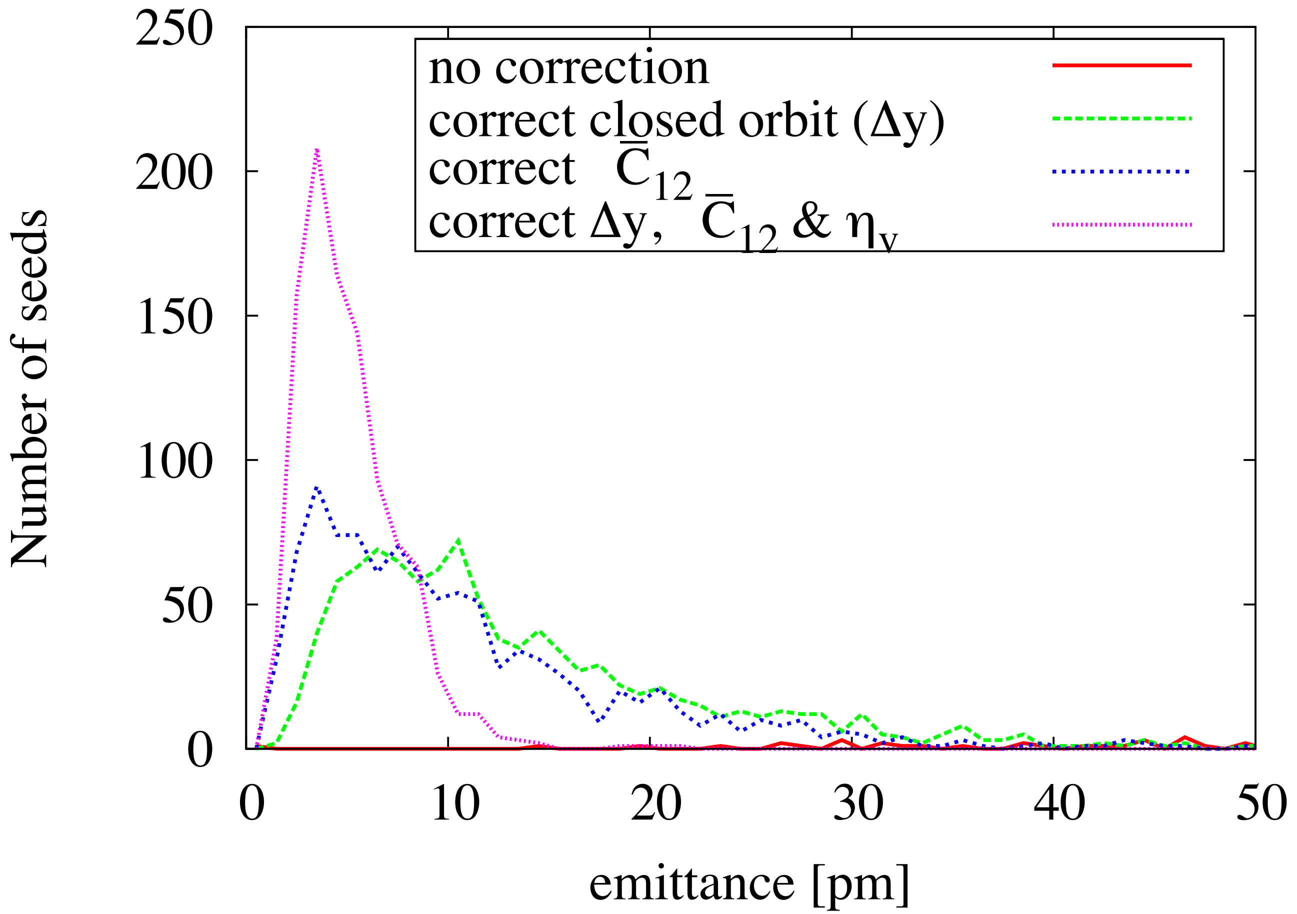
- BPM parameters

| BPM precision | |
|---|---|
| Absolute [μm] | 200 |
| Differential [μm] | 10 |
| Tilt [mrad] | 22 |

# Emittance Tuning Simulation

- Create 1000 models
- Apply tuning procedure

Emittance distribution after each step



# Low Emittance Tuning

The same simulation predicts 95% seeds are tuned to <2pm if BPM

- Offsets < 100μm
- Button to button gain variation < 1%
- Differential resolution < 4 μm  (1 μm for ATF lattice)
- BPM tilt < 10mrad

- We have beam based techniques for calibrating gain variation based on turn by turn position data
- Determining tilt from coupling measurements
- We are exploring a tuning scheme that depends on measurements of the normal modes of the dispersion rather than the horizontal and vertical and that is inherently insensitive to BPM button gain variations and BPM tilts.

# Low Emittance Tuning

Successful low emittance tuning is all about the beam position monitors

Ideally the BPMs have bandwidth to measure individual bunches
- so that a witness bunch can be used to monitor orbit,$\beta$, coupling and $\eta$

*Note that for both ATF and CesrTA the number and placement of correctors is more than adequate.*

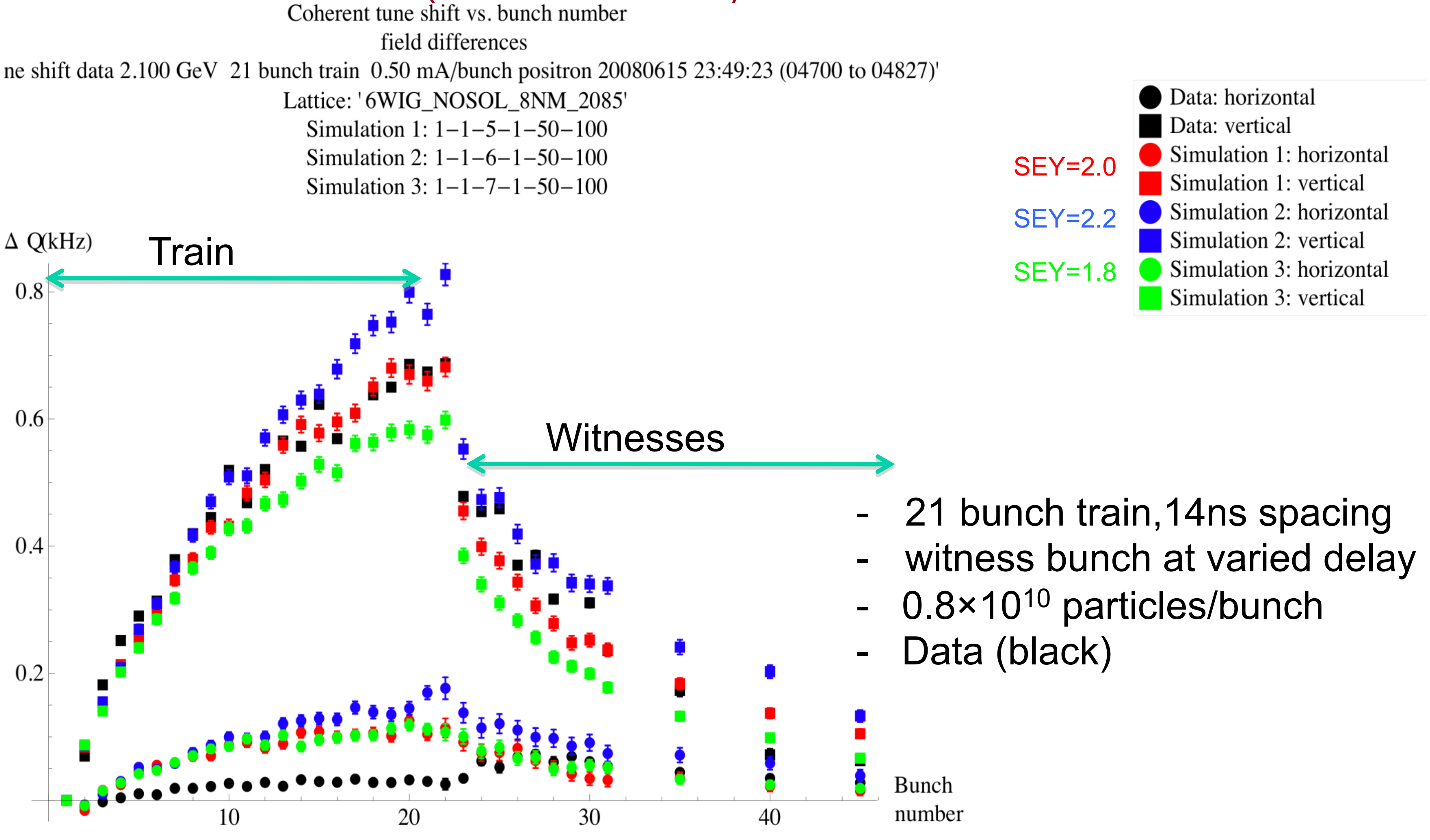
# Electron cloud effects

- Bunch dependent coherent tune shift
  - measure of local cloud density
- Cloud evolution depends on:

  Peak SEY
  Photon reflectivity
  Quantum efficiency
  Rediffused yield
  Elastic yield
  Peak secondary energy

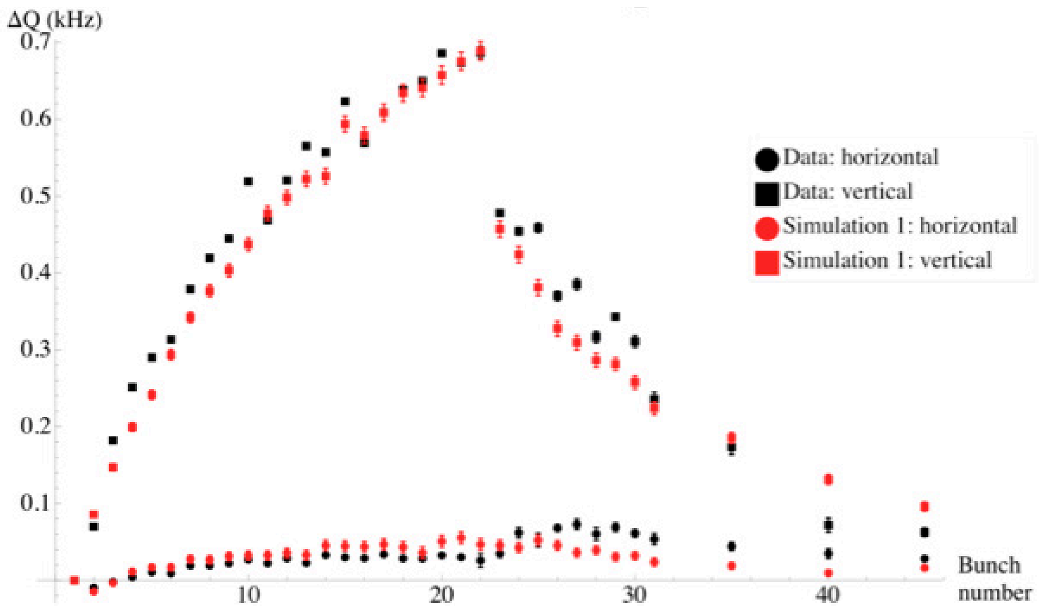
Fit model of cloud development to measurements of bunch by bunch tune shift to determine parameters

## Peak SEY Scan
## Coherent Tune Shifts (1 kHz ~ 0.0025), vs. Bunch Number




- 21 bunch train, 14ns spacing
- witness bunch at varied delay
- $0.8 \times 10^{10}$ particles/bunch
- Data (black)

# Tune shift modeled with synrad3d

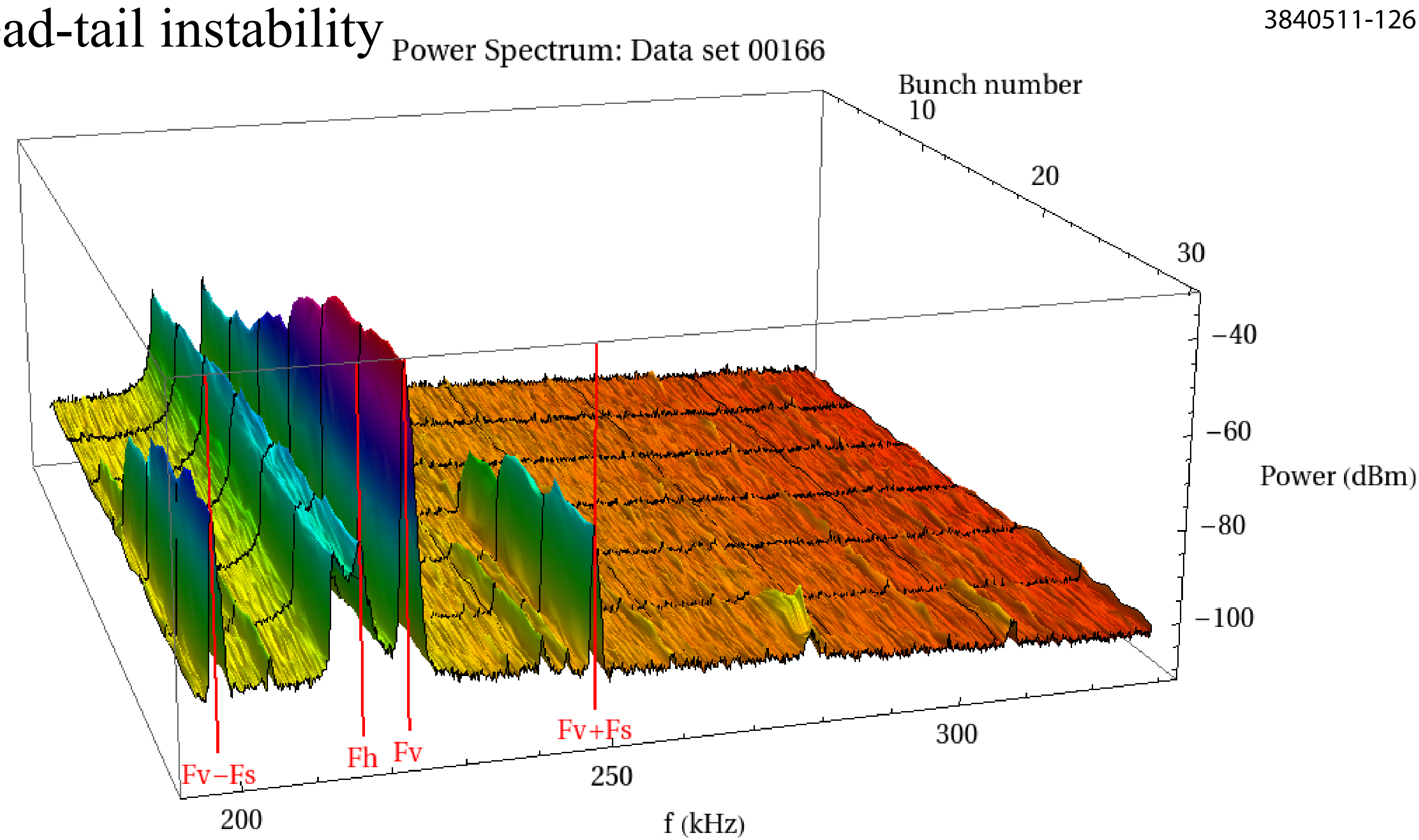



Better fit to horizontal tune shift

*Improved model of radiation distribution*

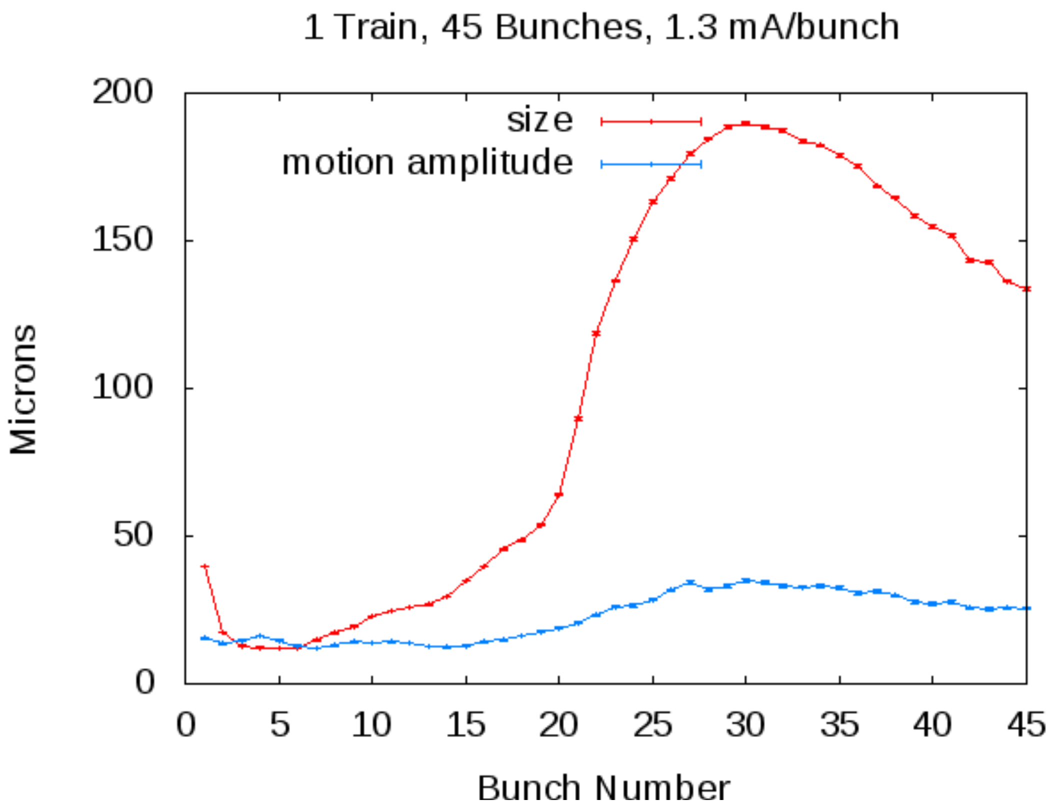
# Electron cloud effects

## Head-tail instability




Self excited power spectrum in each bunch of a 30 bunch train

# Emittance dilution

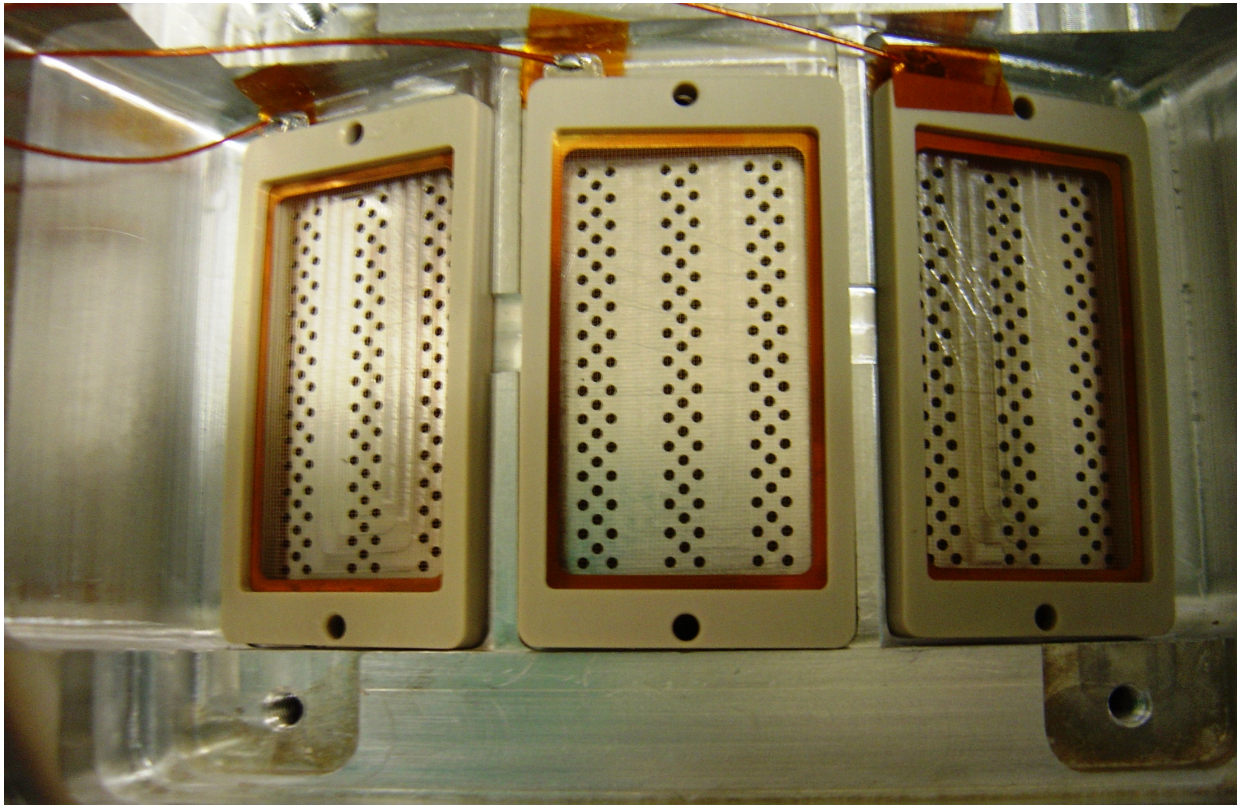



Minimum vertical emittance ~ 20pm

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

# Retarding Field Analyzer

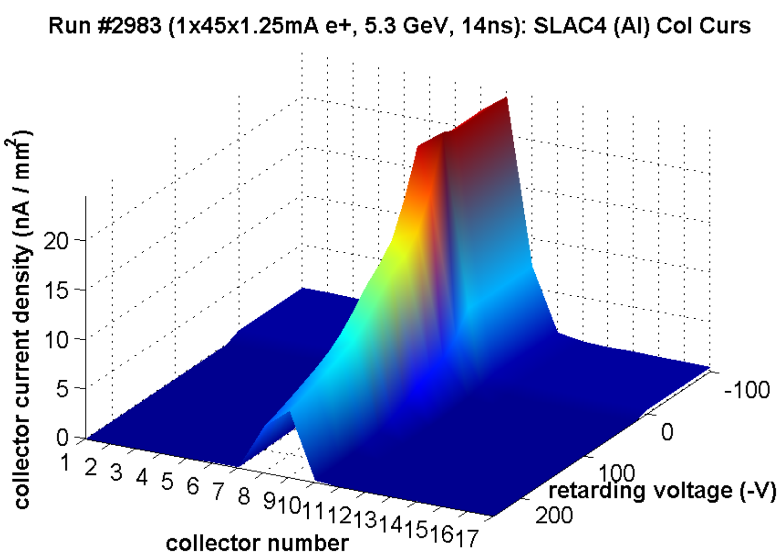
Measures the time average cloud density and energy spectrum



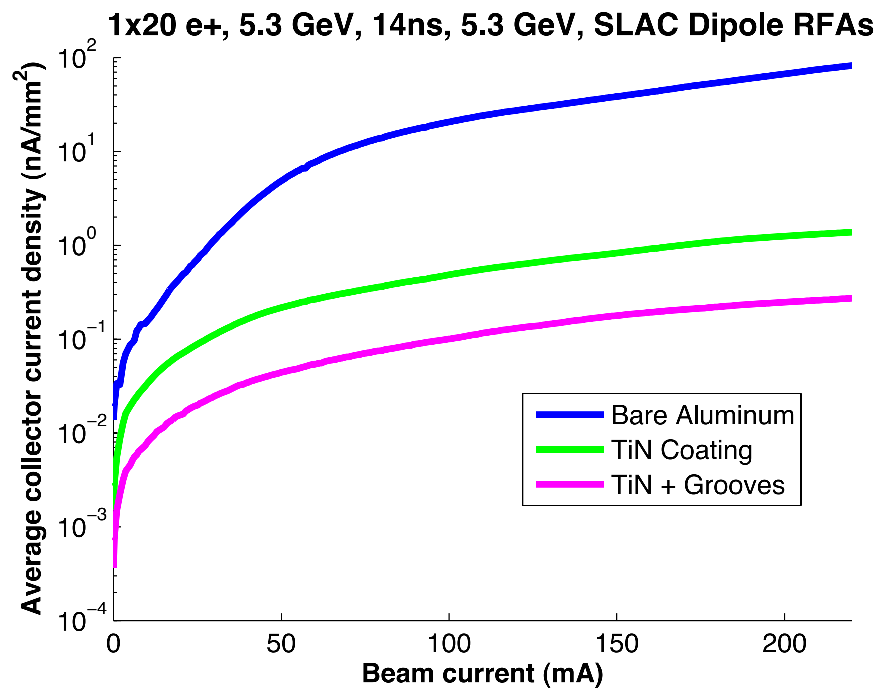
View of from outside vacuum chamber of diple style RFA with 9 independent collectors. The fine mesh wire grid is in place (but transparent)

# Electron cloud - RFA

Dipole RFA data with characteristic central peak

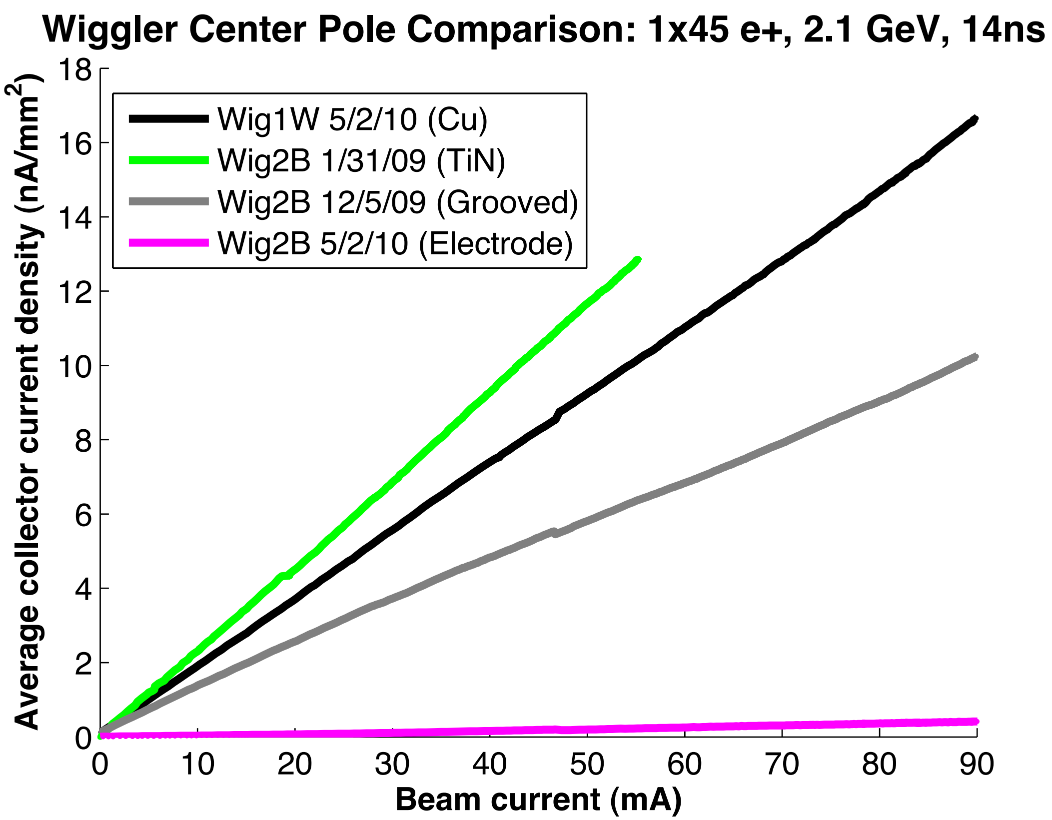



Aluminum chamber
45 bunches, 1.25mA/bunch
14ns spacing
5.3GeV



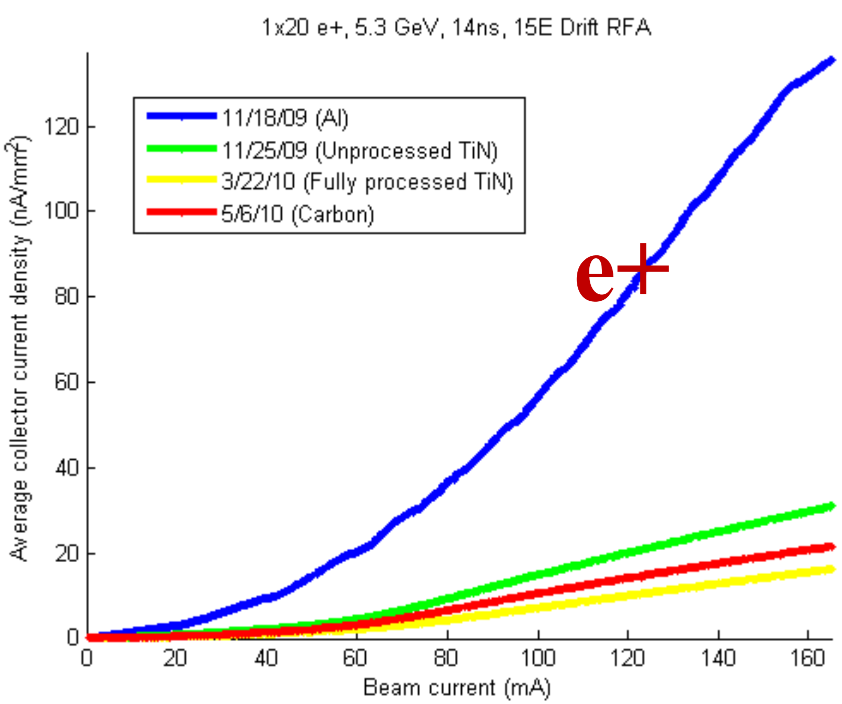

Mitigation in a dipole field

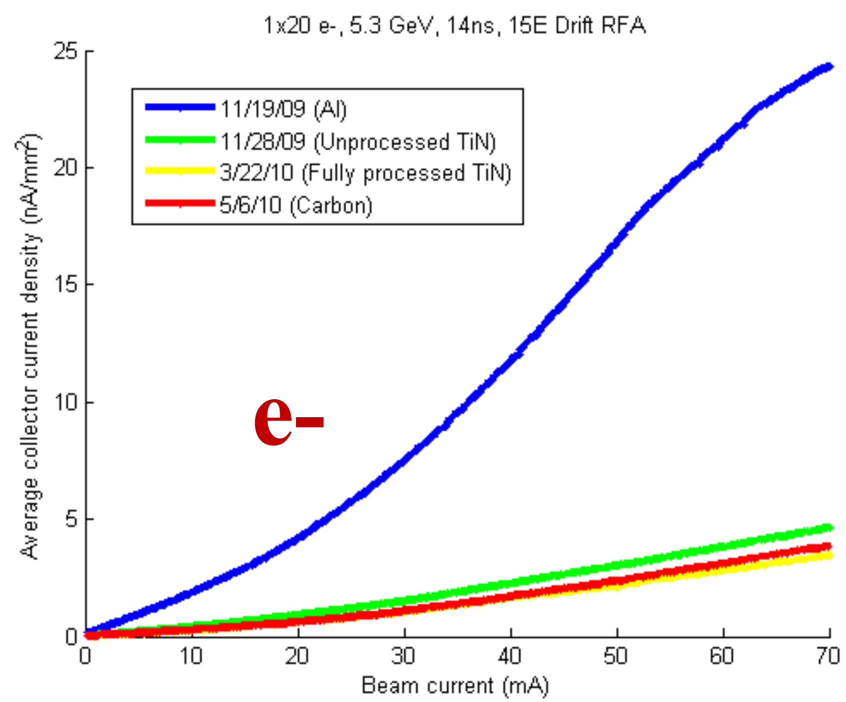
# Electron cloud mitigations in damping wiggler



# Electron cloud - RFA

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



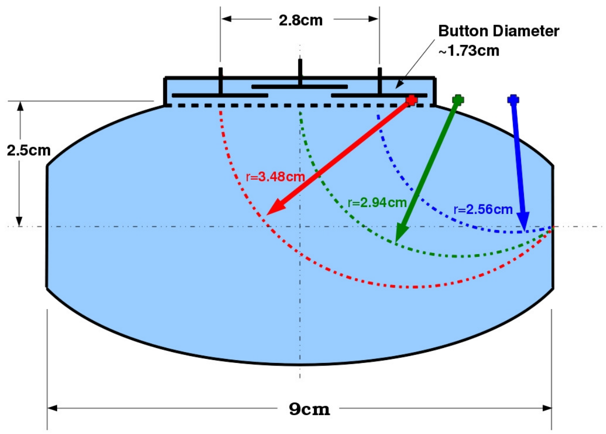



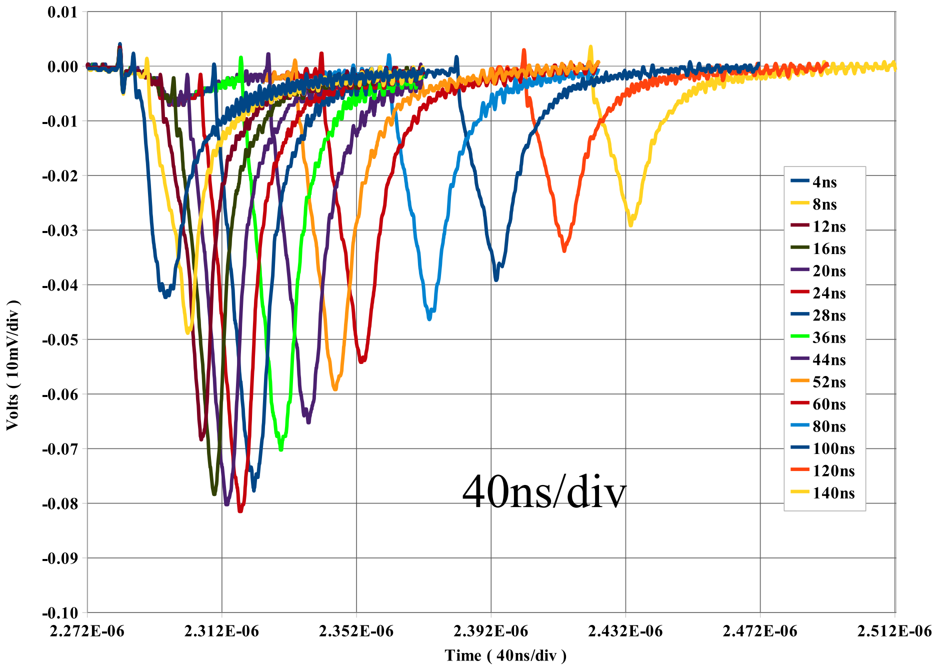
# Surface Characterization & Mitigation Tests

| | 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 |

# Time Resolved Measurements

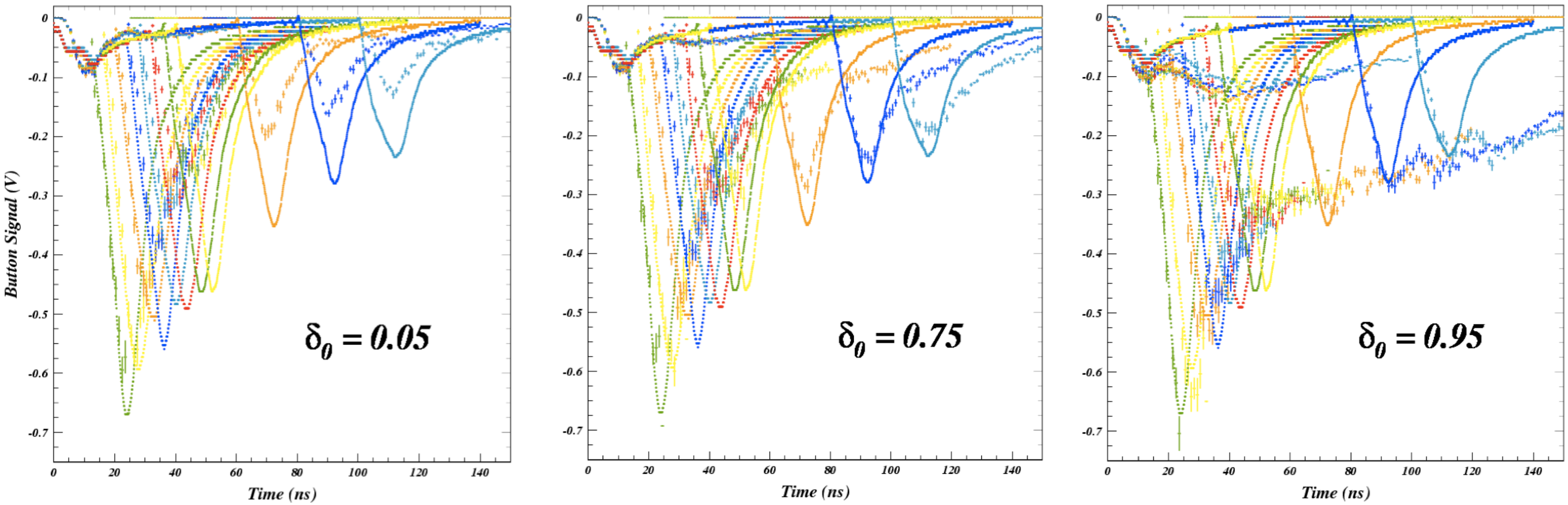
## Shielded pickup




- Overlay of 15 two bunch measurements each with different 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

# Shielded pickup- elastic yield

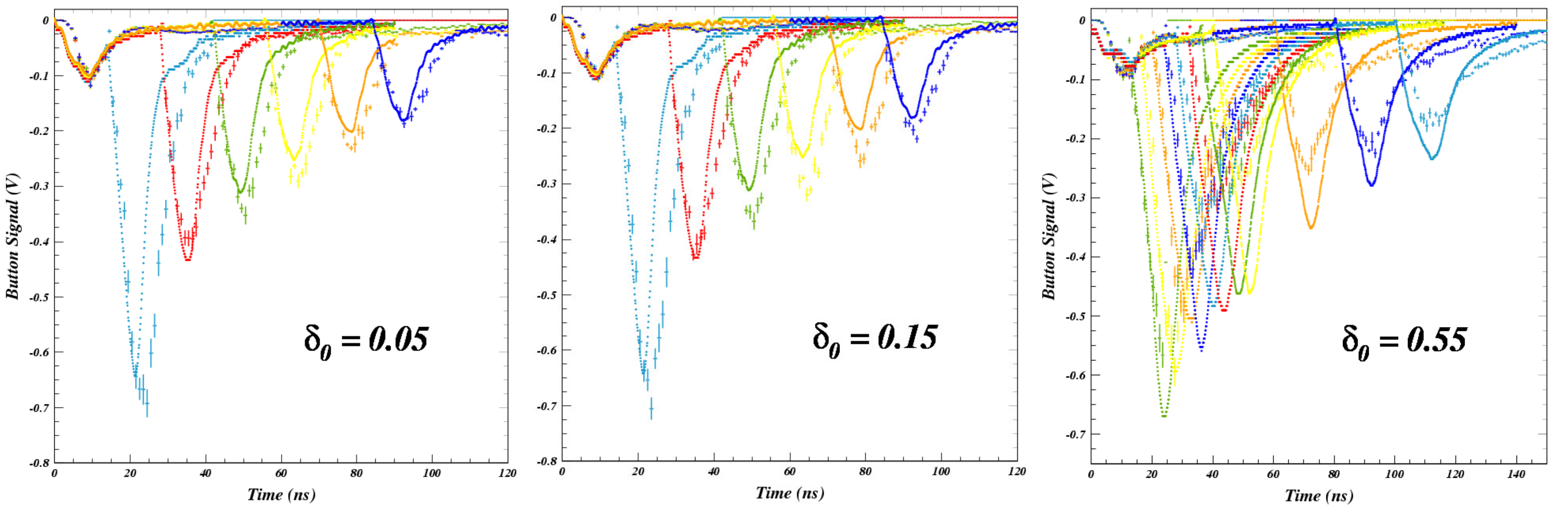



## Uncoated aluminum chamber.

Eleven two-bunch scope traces are superposed with witness bunch delayed from 12 to 100ns. The magnitudes of the modeled signals at large witness bunch delay clearly show the dependence on the elastic yield parameter $\delta_0$ as it is varied from 0.05 to 0.95.

Best fit to the measured signals is given by a value of $\delta_0$ =0.75

# Shielded pickup – elastic yield

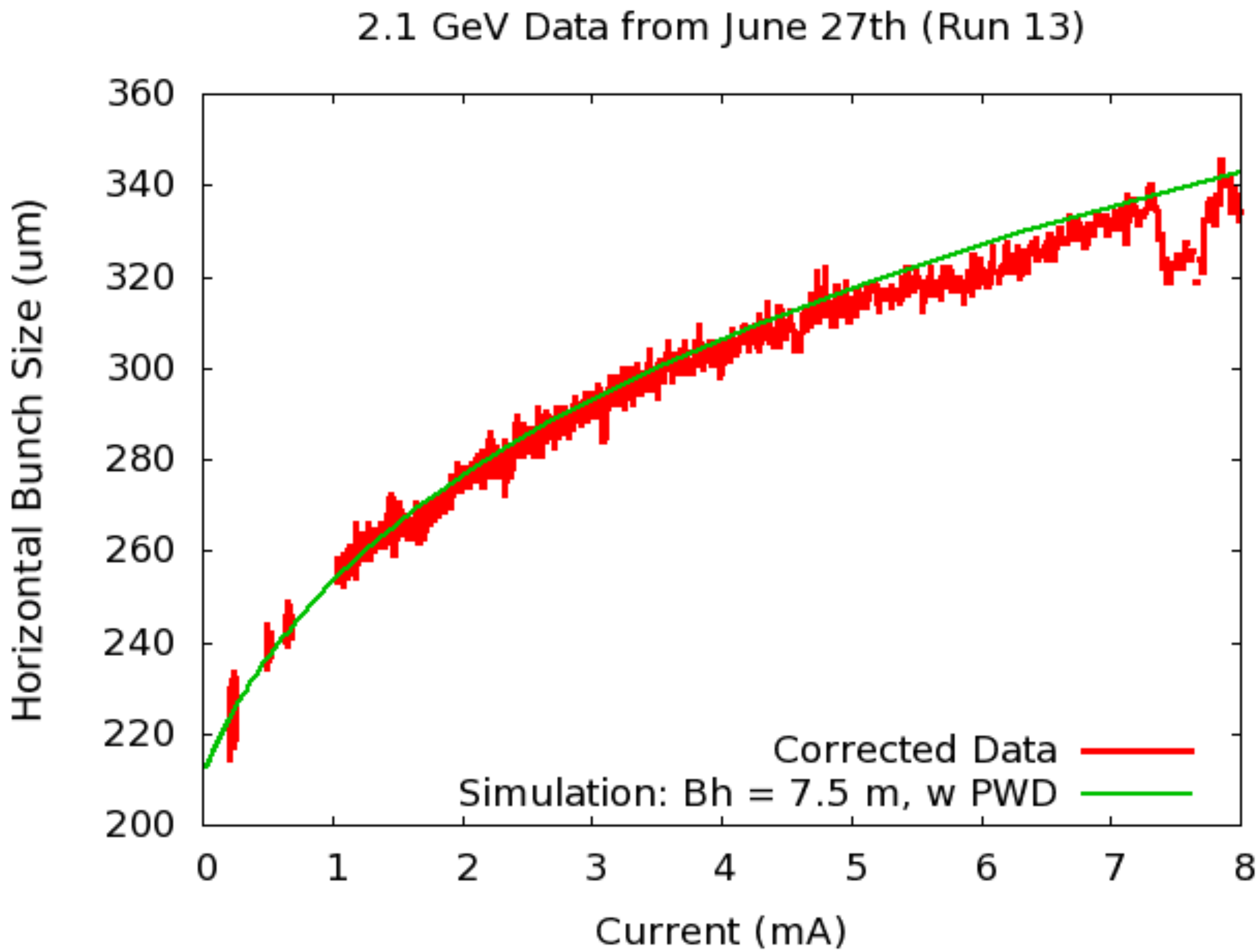



## Titanium-nitride-coated aluminum chamber

- Witness bunch delay ranges from 14 to 84ns
- Best fit for elastic yield parameter is $\delta_0 = 0.05$

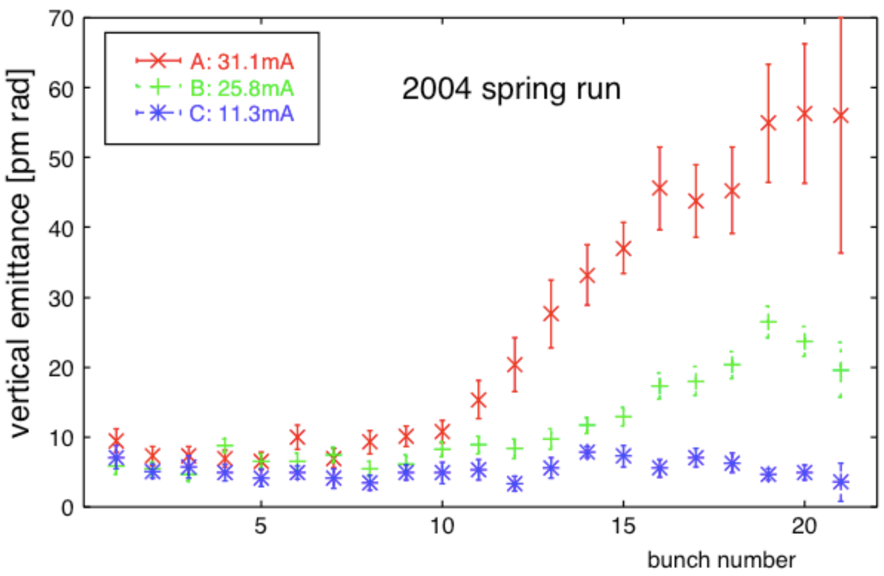
# CesrTA IBS

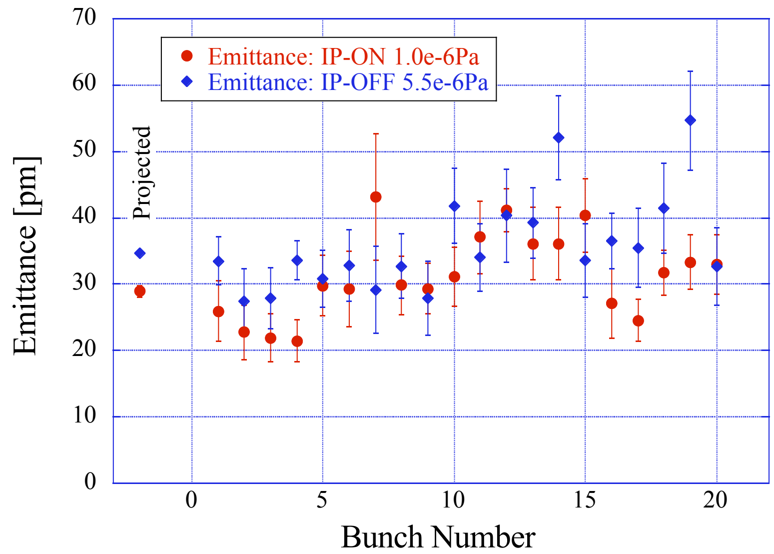
- Horizontal beam size measured with interferometer
- Calculation assumes 9pm-rad zero current vertical emittance and 80% from dispersion



# ATF - Fast Ion Instability

Vacuum spoiled by turning off pumps
Vertical emittance measured with laser wire




Single bunch emittance ~10pm

Single bunch emittance 20pm

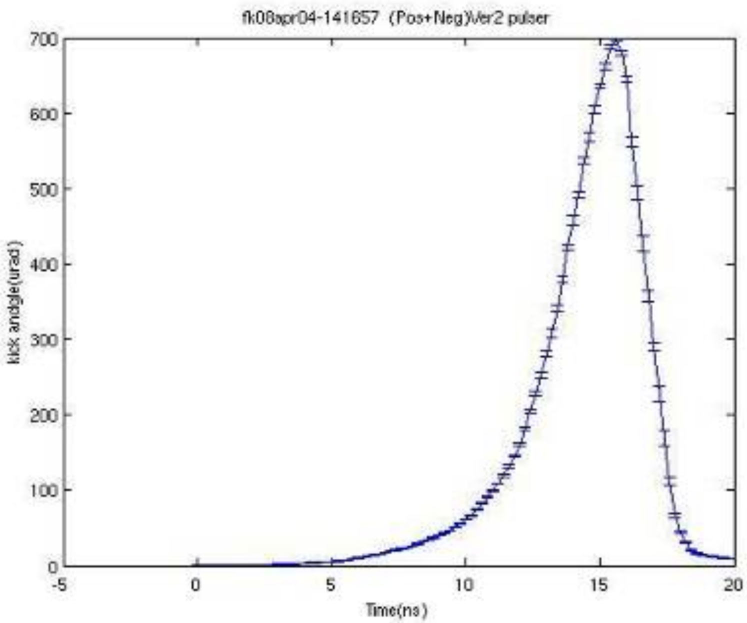
Threshold depends on pressure and vertical emittance

# ATF - Fast Extraction Kicker

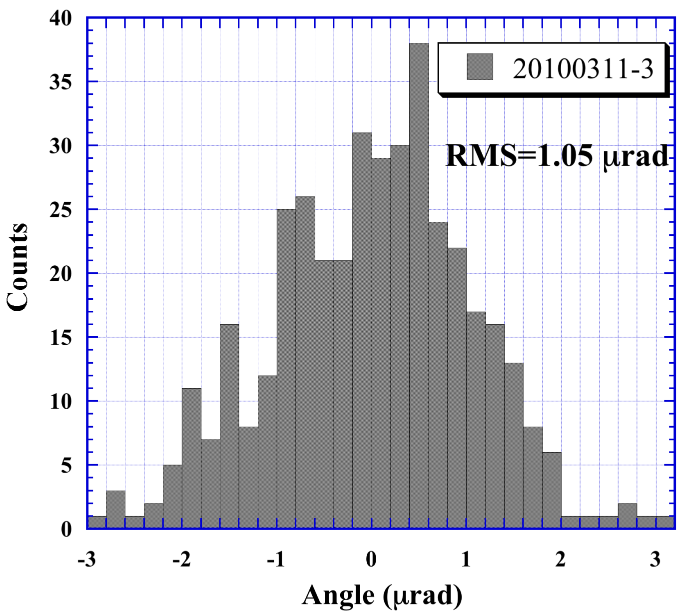
Extraction kicker pulse measured with timing scan

0.44mrad kick with 30cm strip line at ±10 kV

Fast Ionization Dynistor (FID) pulser




Distribution of measured kick angle. $\Delta\theta/\theta \sim 0.035\%$



# The End

Many thanks to all of the many collaborators of the ATF and CesrTA projects who have contributed so much to our understanding of damping ring phenomena.

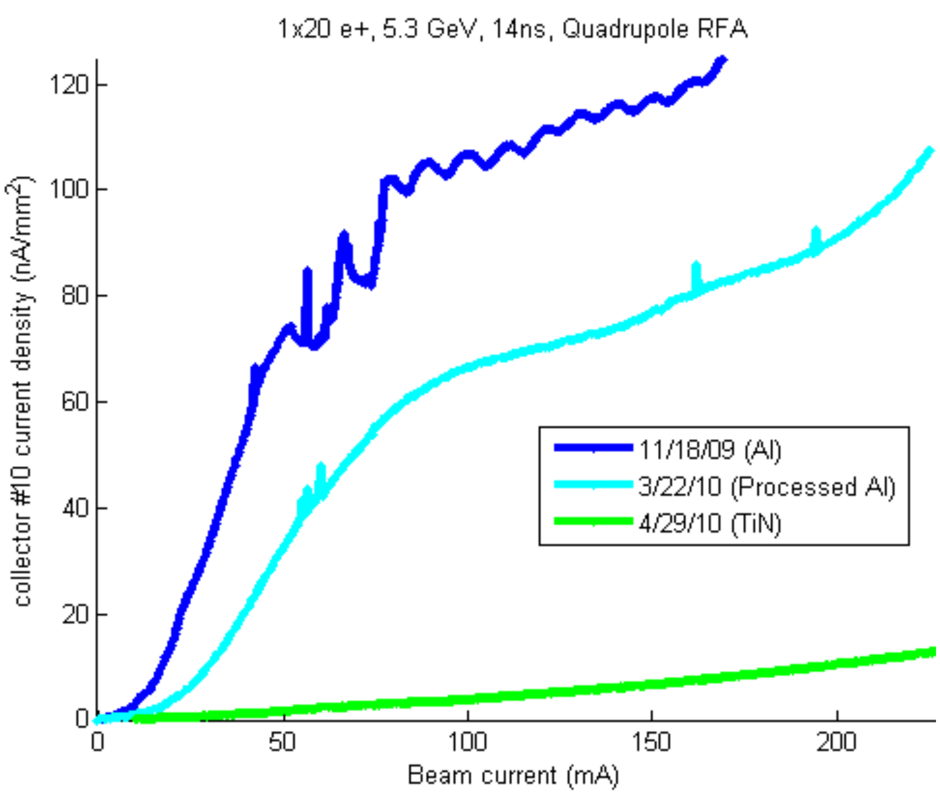
MOOCA03 - Susanna Guiducci: Damping rings design
MOPS083 - Joe Calvey: Electron Cloud Mitigation Studies at CesrTA
MOPS084 - Mike Billing: Electron Cloud Dynamics Measurements at CESR-TA
MOPS088 - Kiran Sonnad: Simulation of Electron Cloud Beam Dynamics for CesrTA
TUPC024 – M.Palmer: Review of the CESR Test Accelerator Program and Future Plans
TUPC030 - Mauro Pivi: Mitigations of the Electron Cloud Instability in the ILC
TUPC052 - Andy Wolski: Normal Mode BPM Calibration for Ultralow-Emittance Tuning
TUPC170 - John Sikora: TE Wave Measurements of Electron Cloud Densities at CesrTA
WEPC135 – J. Crittenden: Modeling Time-resolved Measurements of E-Cloud Buildup at CESRTA
WEYB01 – John Flanagan: Diagnostics for Ultra-Low Emittance Beams

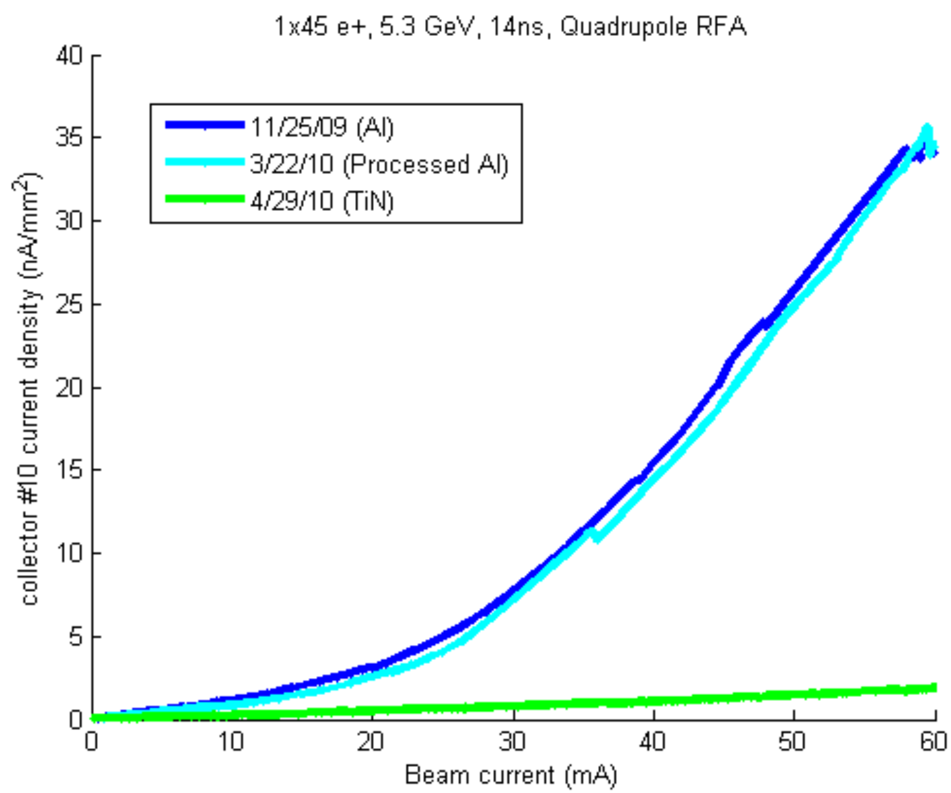
- Extra slides

# Quadrupole Measurements

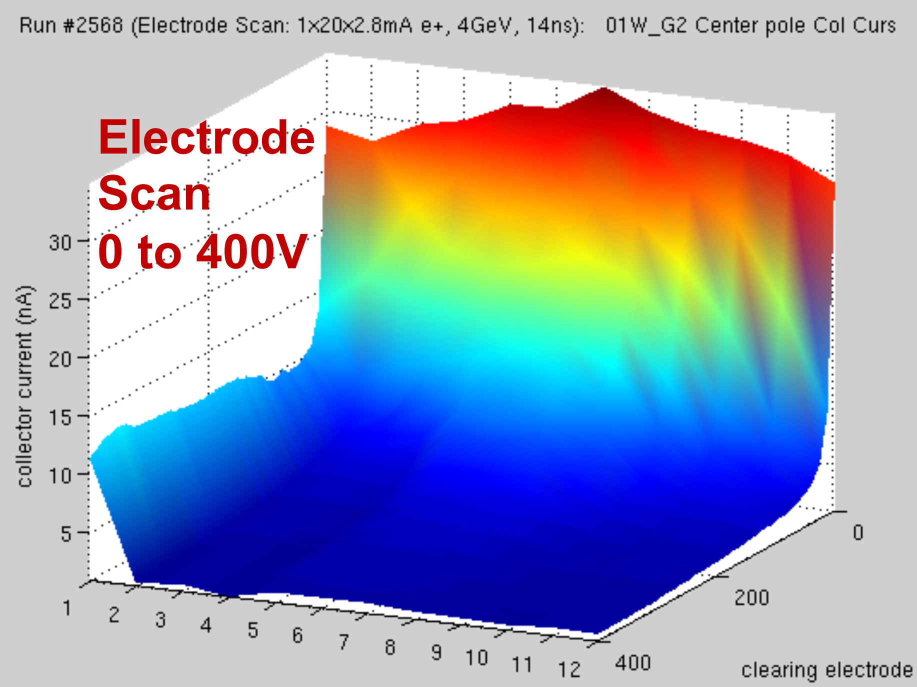
- Left: 20 bunch train e+
- Right: 45 bunch train e+ ⇨ Clear improvement with TiN
- Currents higher than expected from “single turn” simulations
  - Turn-to-turn cloud buildup
  - Issue also being studied in wigglers

**TUPD023**
**TUPEC077**

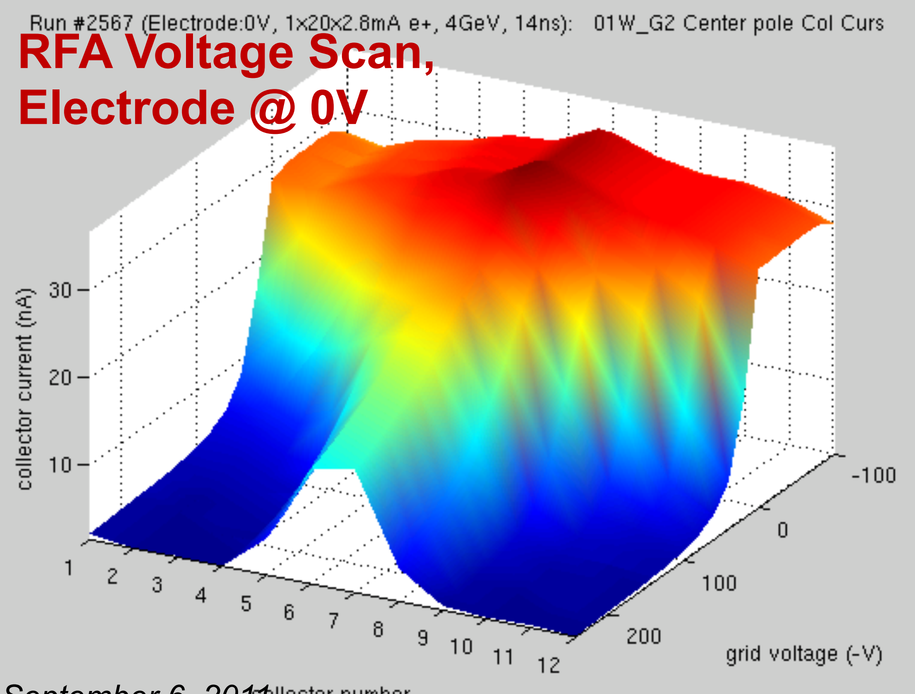


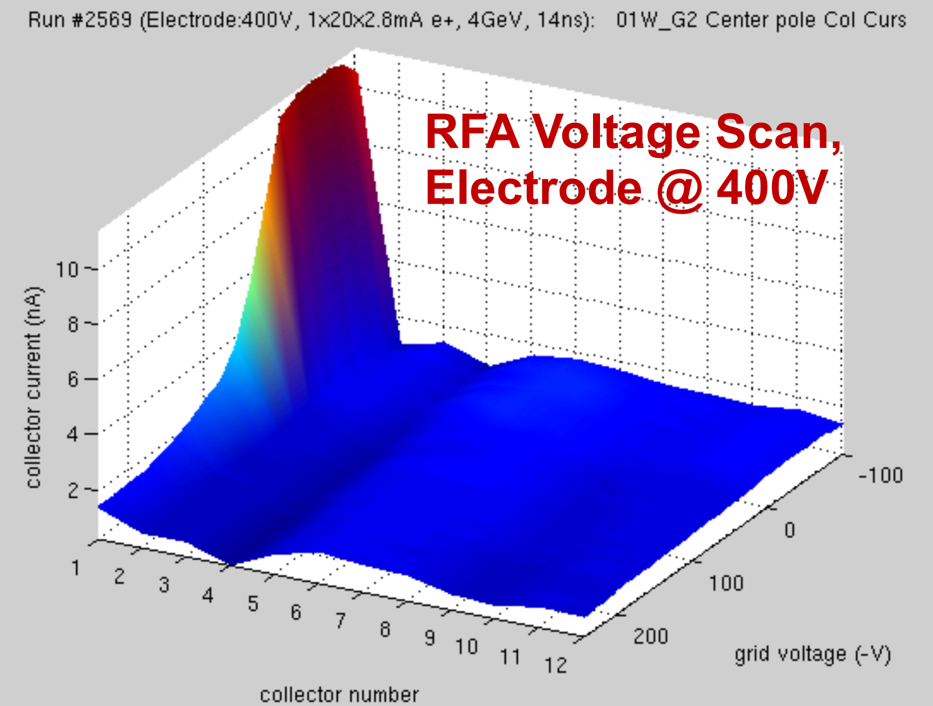



# Wiggler Clearing Electrode



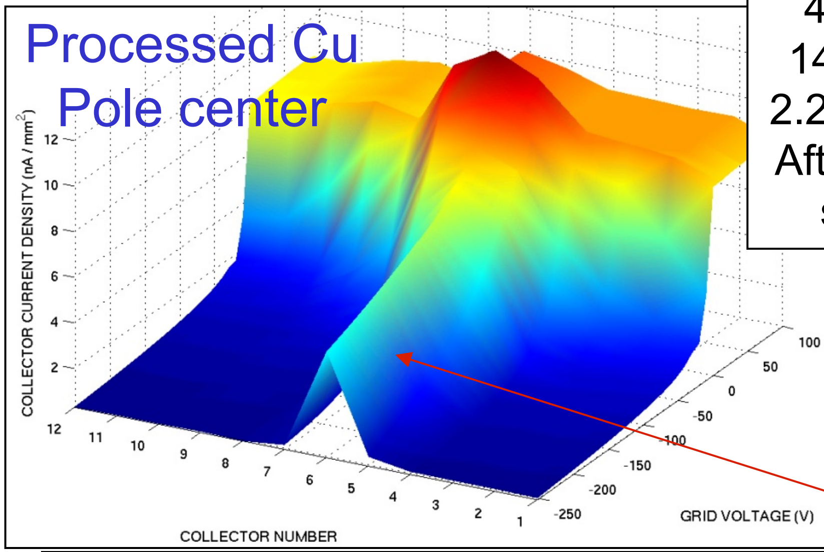

- 20 bunch train, 2.8 mA/bunch
  - 14ns bunch spacing
  - $E_{beam}$ = 4 GeV with wigglers ON
- Effective cloud suppression
  - Less effective for collector 1 which is not fully covered by electrode

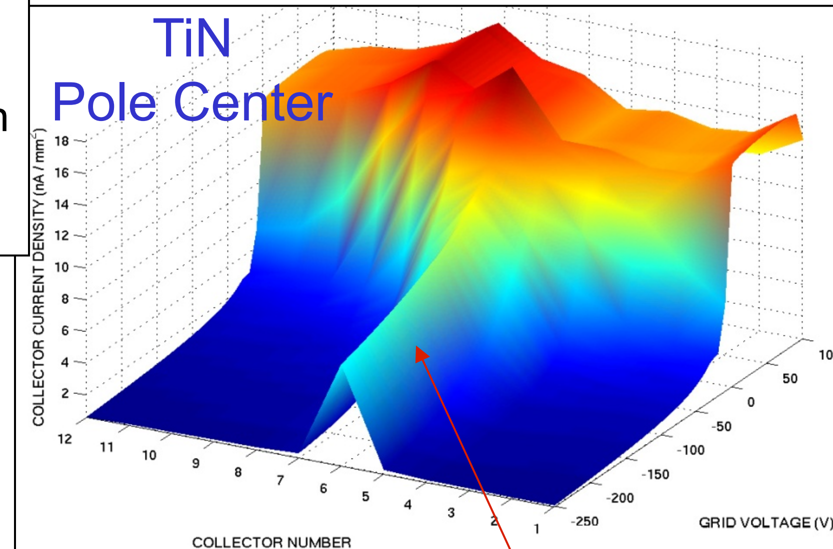


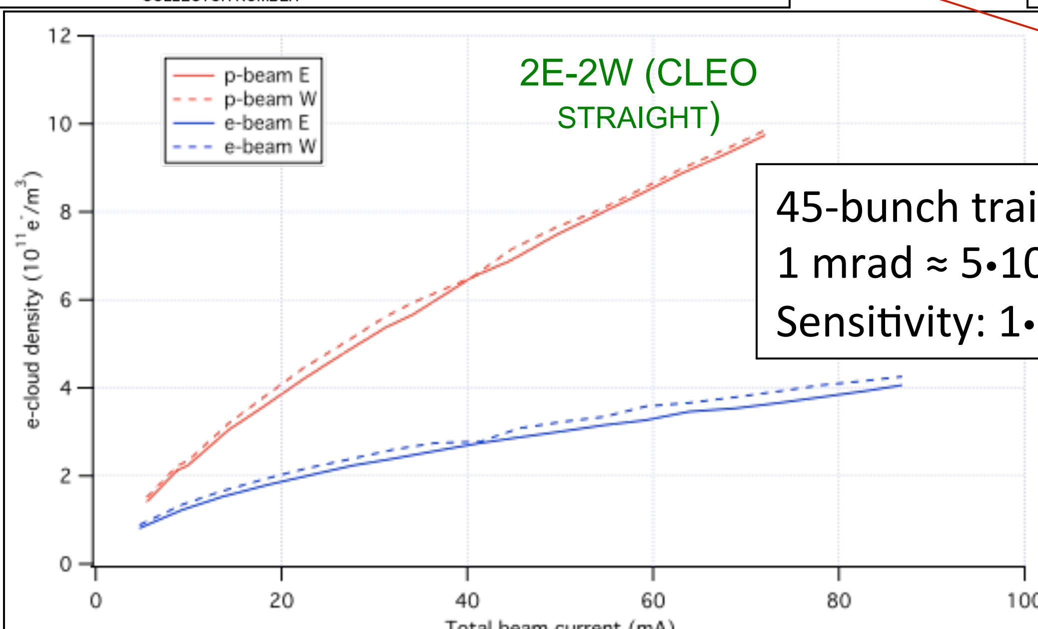



# TE Wave & RFA Measurements in L0

45 bunches
14ns spacing
$2.2\times10^{10}$/bunch
After extended scrubbing



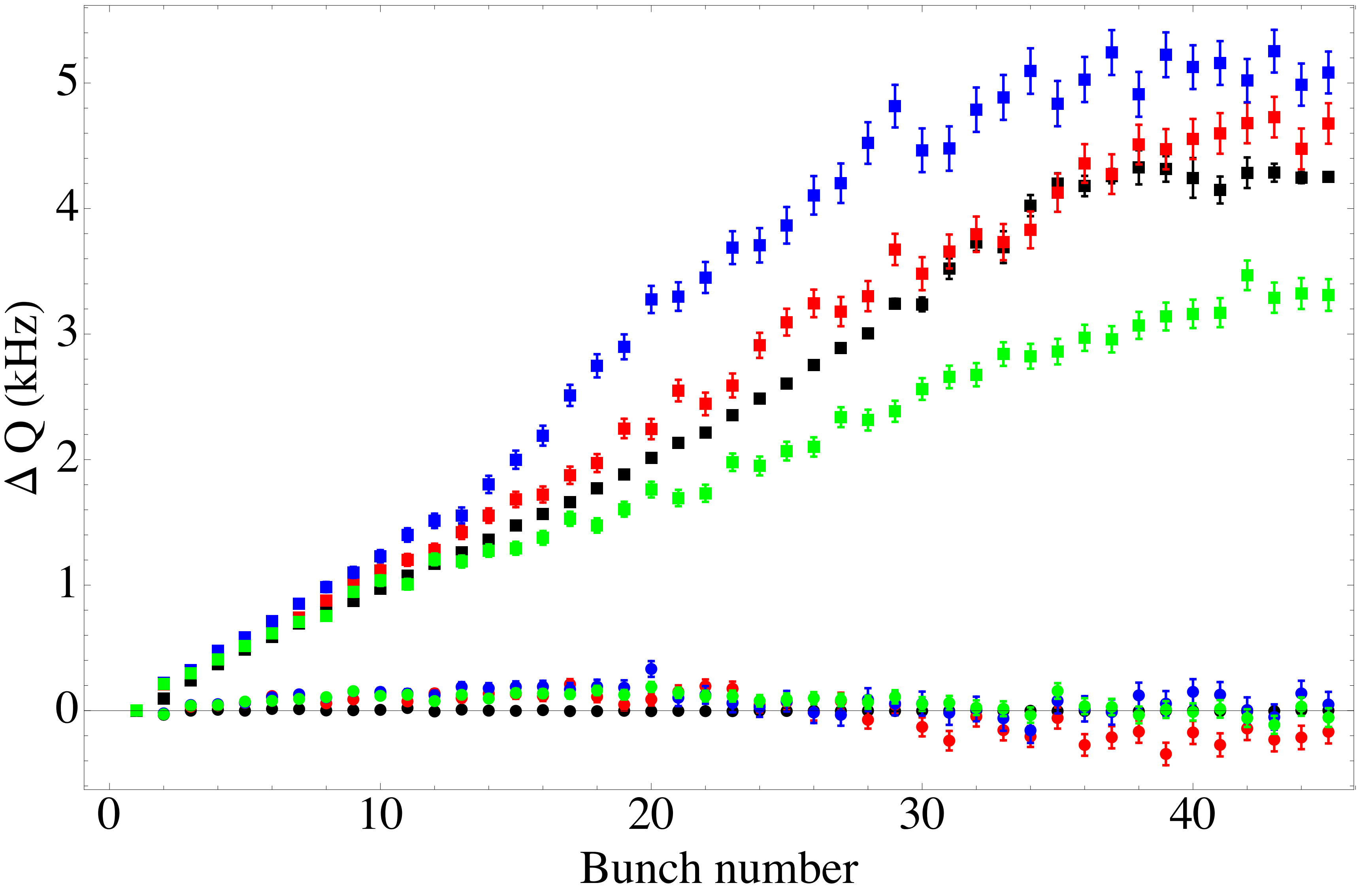



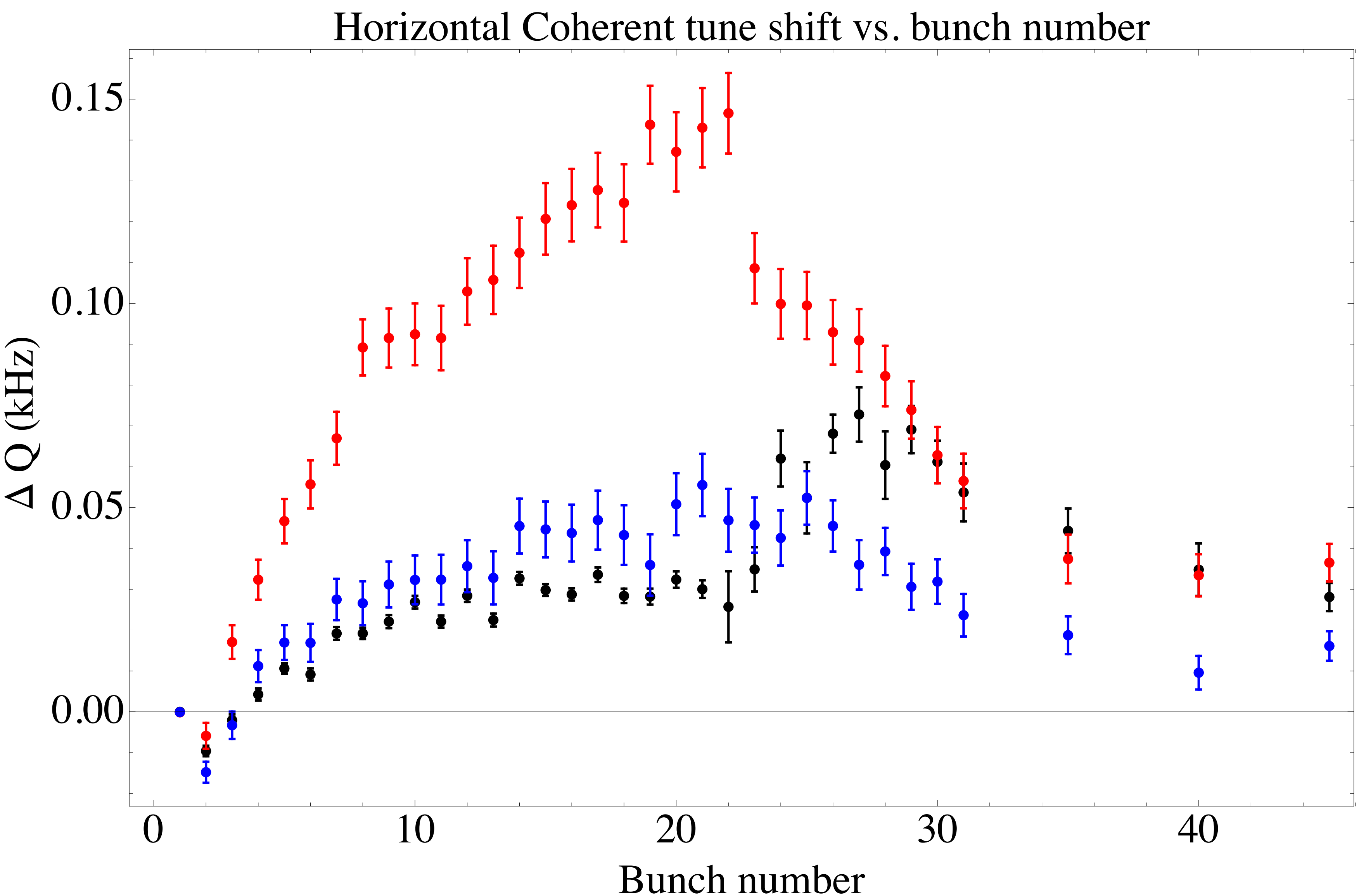

45-bunch train (14 ns)
1 mrad ≈ $5\cdot10^{10}$ e$^-$/m$^3$
Sensitivity: $1\cdot10^{9}$ e$^-$/m$^3$ (SNR)

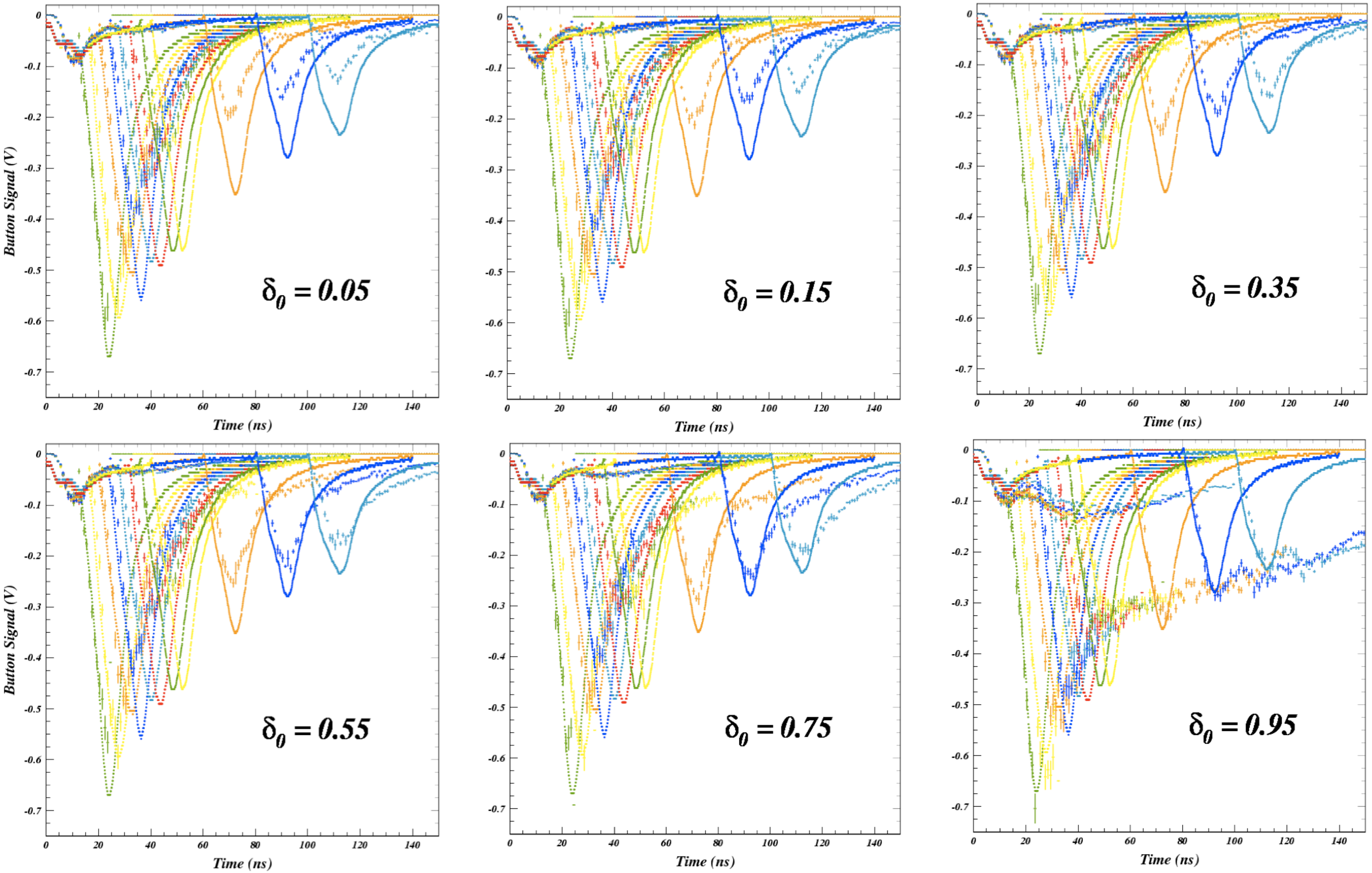
**Similar performance observed**

See this afternoon's posters for a discussion of RFA modeling

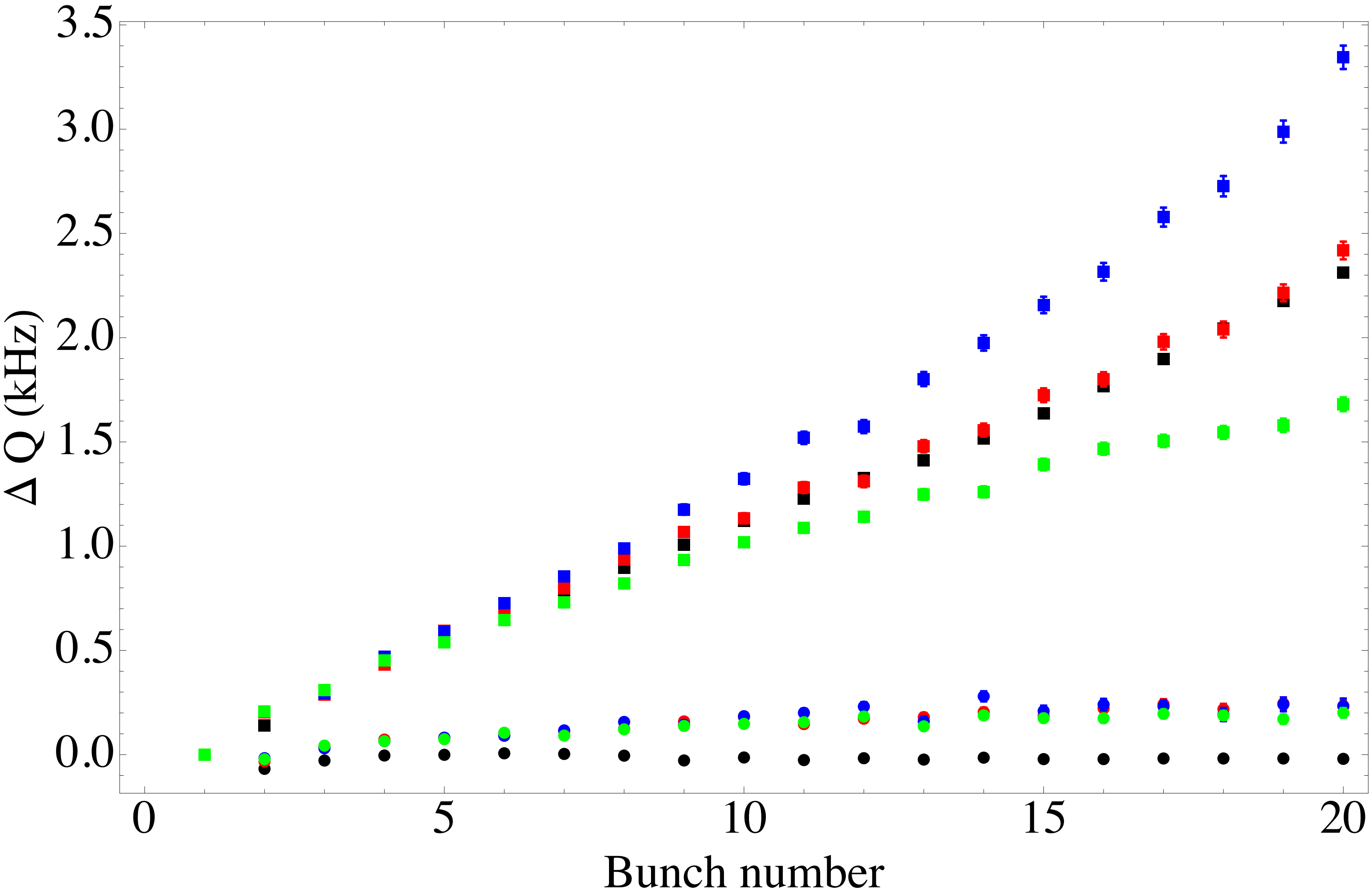
**MOPE088**
**MOPE091**
**TUPD022**
**TUPD023**


5
4
3
2
1
0
Δ Q (kHz)
0
10
20
30
40
Bunch number


Horizontal Coherent tune shift vs. bunch number
0.15
0.10
0.05
0.00
Δ Q (kHz)
0
10
20
30
40
Bunch number

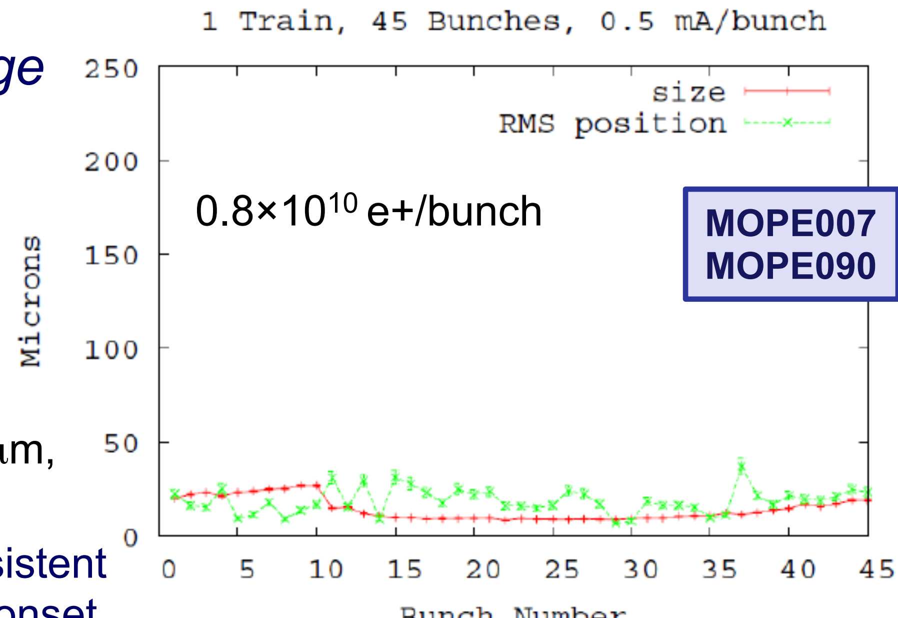

Button Signal (V)
Time (ns)
$\delta_0 = 0.05$
$\delta_0 = 0.15$
$\delta_0 = 0.35$
$\delta_0 = 0.55$
$\delta_0 = 0.75$
$\delta_0 = 0.95$

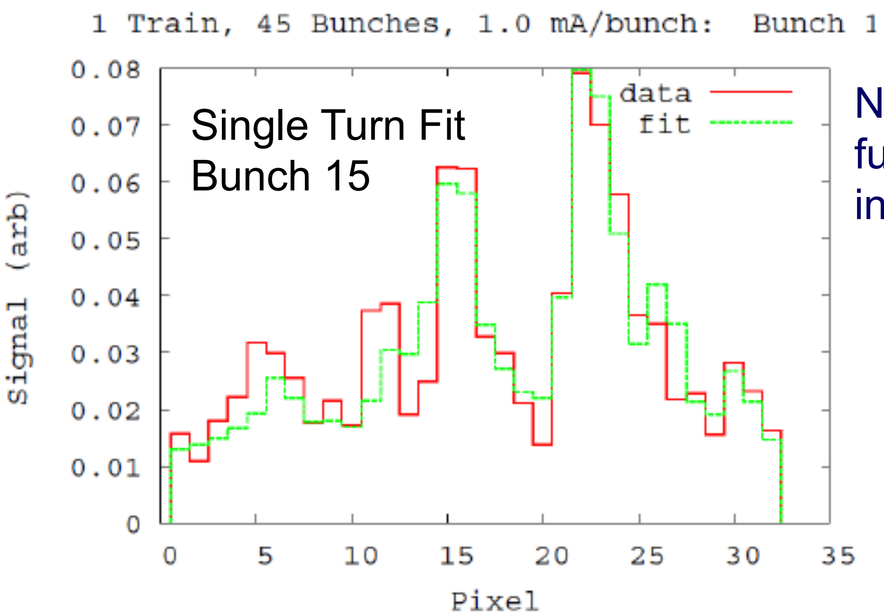
# Coherent tune shift vs. bunch number

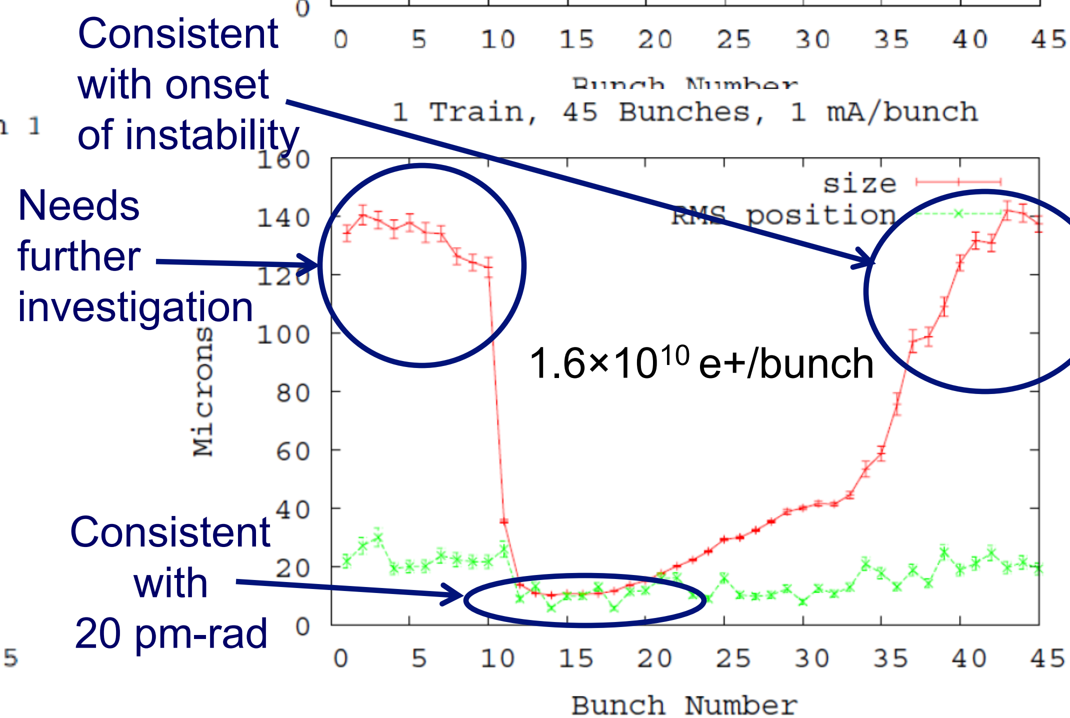


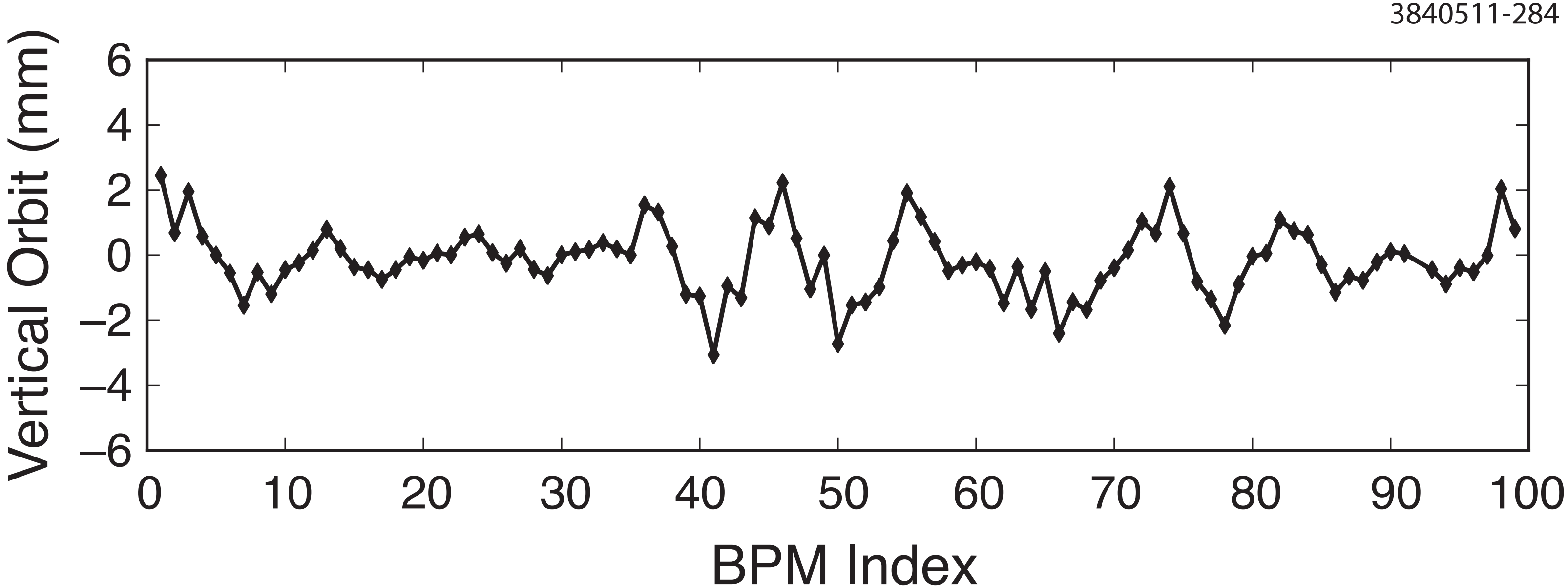
# Beam Size

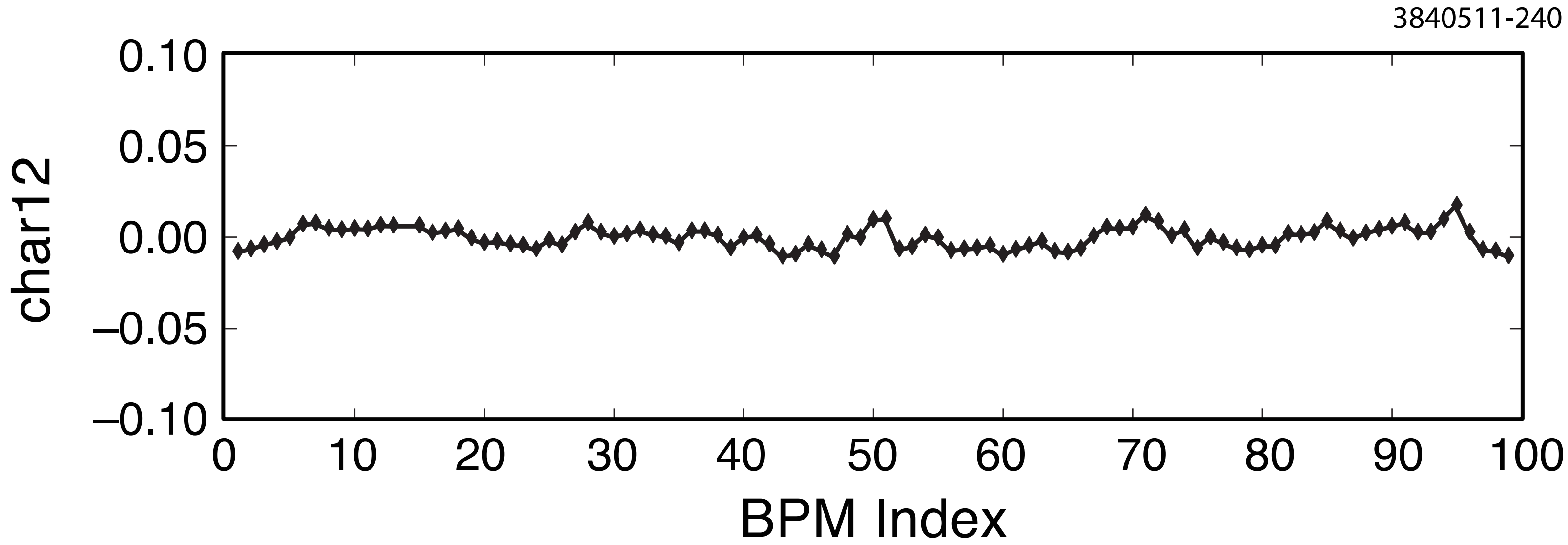
- Measure Bunch-by-Bunch Beam Size
  *Same current scan as on preceding page*
  - Beam size enhanced at head and tail of train
    *Source of blow-up at head requires further investigation (resonance? other?).*
    *Beam lifetimes (Touschek) consistent with center of train having smallest size.*
  - Beam size measured around bunch 15 is consistent with $\varepsilon_y \sim$ 20pm-rad ($\sigma_y$=11.0±0.2 $\mu$m, $\beta_{source}$=5.8m)

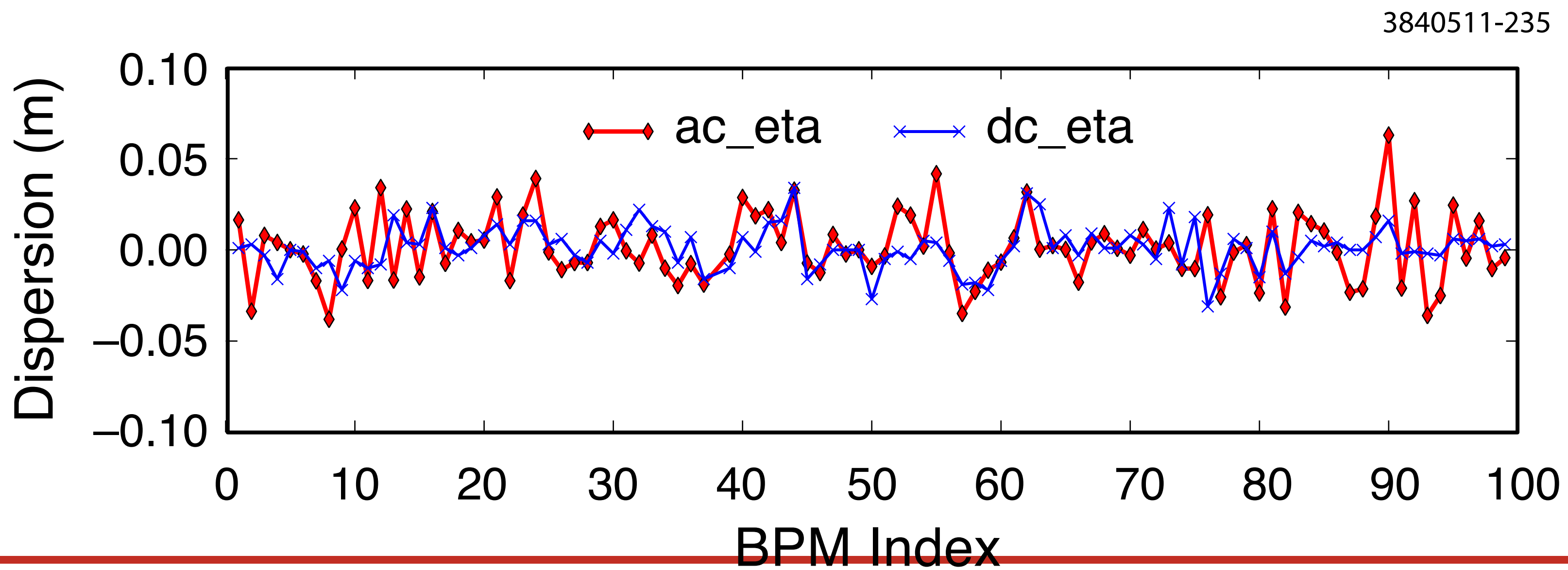


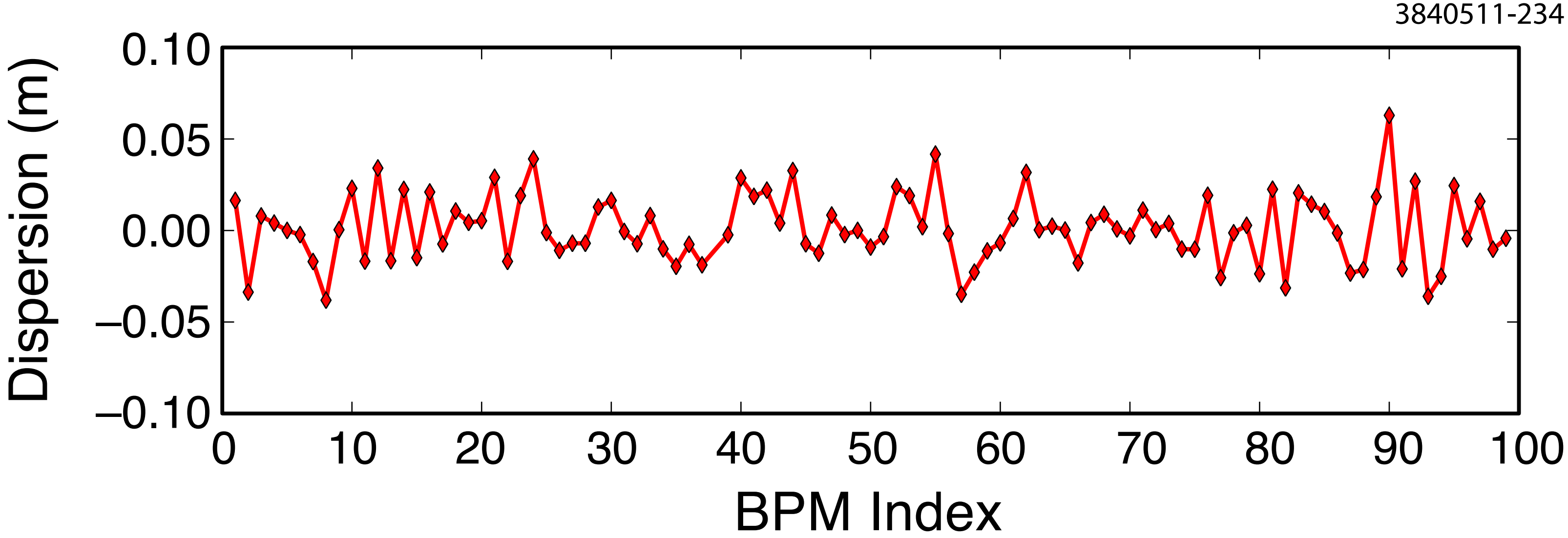



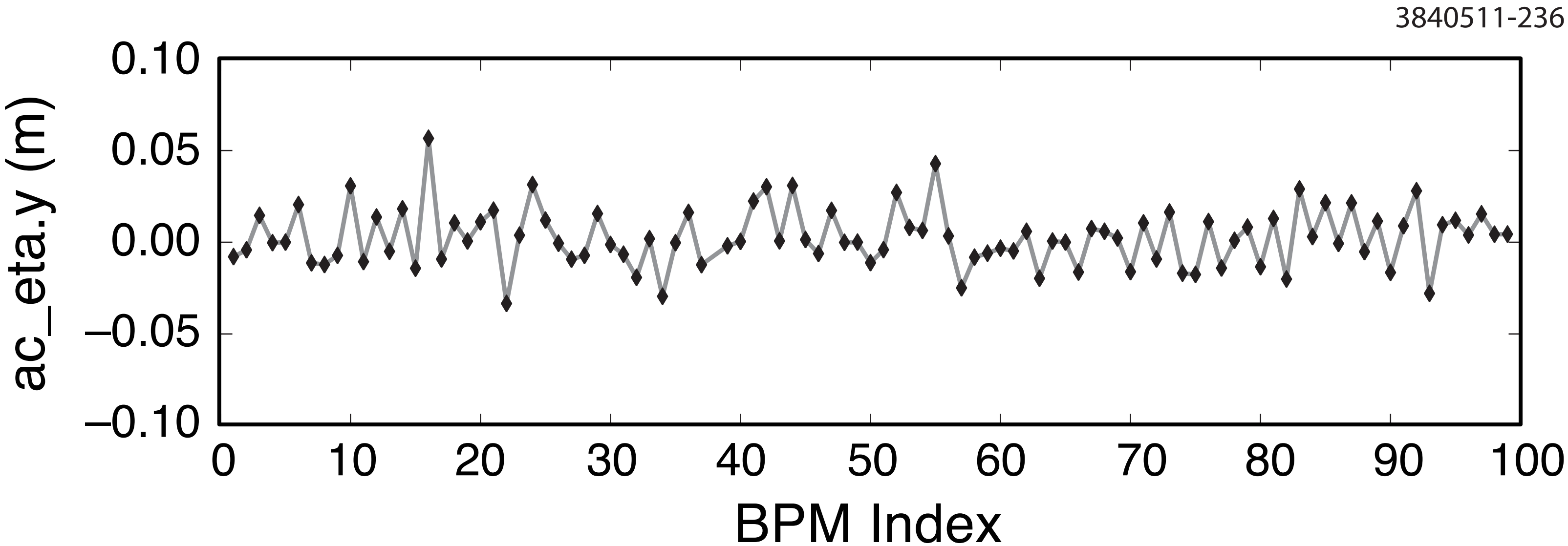




3840511-284
Vertical Orbit (mm)
6
4
2
0
–2
–4
–6
0
10
20
30
40
50
60
70
80
90
100
BPM Index


3840511-240
0.10
0.05
0.00
–0.05
–0.10
char12
0
10
20
30
40
50
60
70
80
90
100
BPM Index


3840511-235
ac_eta
dc_eta
0.10
0.05
0.00
–0.05
–0.10
Dispersion (m)
0
10
20
30
40
50
60
70
80
90
100
BPM Index

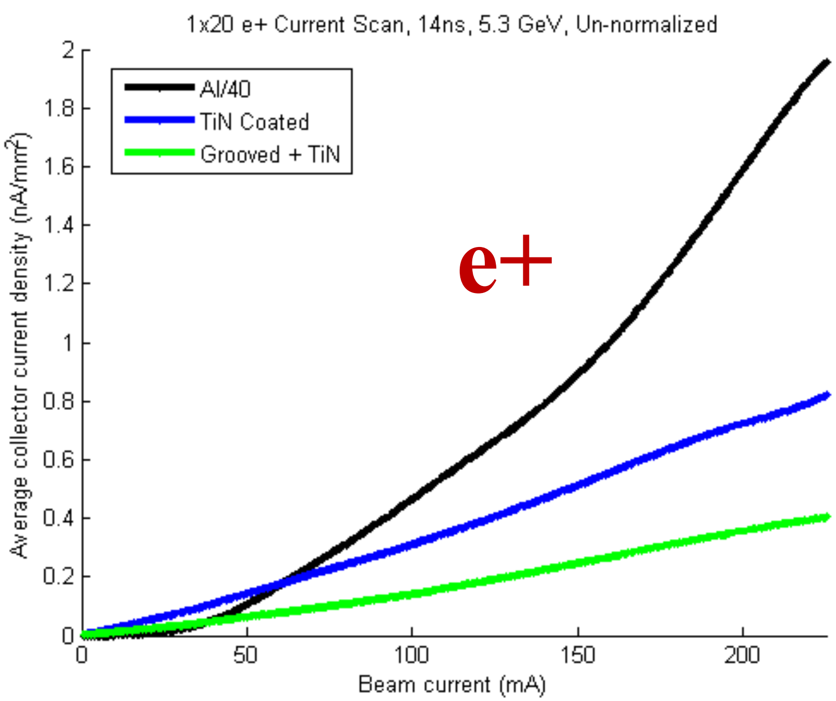

3840511-234
Dispersion (m)
0.10
0.05
0.00
–0.05
–0.10
0
10
20
30
40
50
60
70
80
90
100
BPM Index

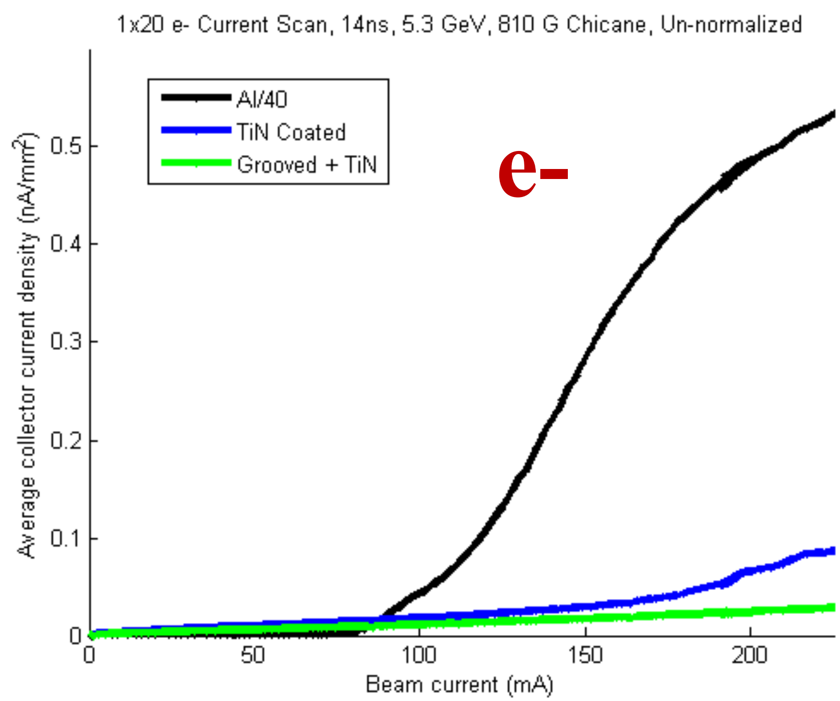

3840511-236
ac_eta.y (m)
0.10
0.05
0.00
–0.05
–0.10
0
10
20
30
40
50
60
70
80
90
100
BPM Index

# Mitigation Performance in Dipoles (e+ & e-)

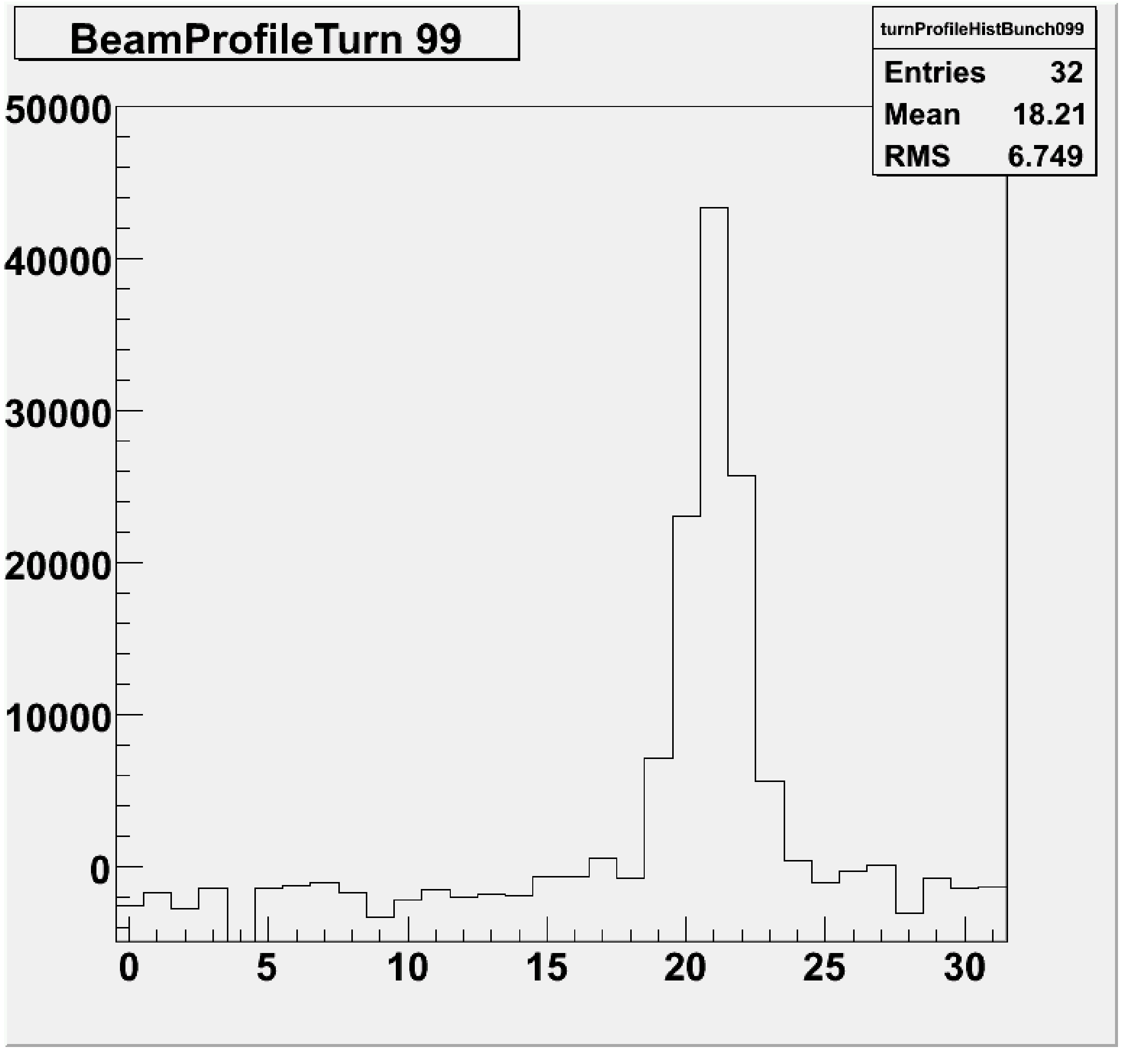
- 1x20 e+, 5.3 GeV, 14ns
  - 810 Gauss dipole field
  - Signals summed over all collectors
  - Al signals ÷40

Longitudinally grooved surfaces offer significant promise for EC mitigation in the dipole regions of the damping rings



3840511-233


BeamProfileTurn 99
turnProfileHistBunch099
Entries 32
Mean 18.21
RMS 6.749
50000
40000
30000
20000
10000
0
0
5
10
15
20
25
30

# Lattice - Energy

- Higher energy
  - Higher threshold for collective effects, intrabeam scattering
  - Emittance of injected beam reduced by adiabatic damping
- Lower energy
  - Lower cost (RF, magnets)
  - Lower equilibrium emittance

Compromise is 5 GeV