Studies of Electron Cloud Growth and Mitigation at CESR-TA

J. Calvey

for the CESR-TA Collaboration

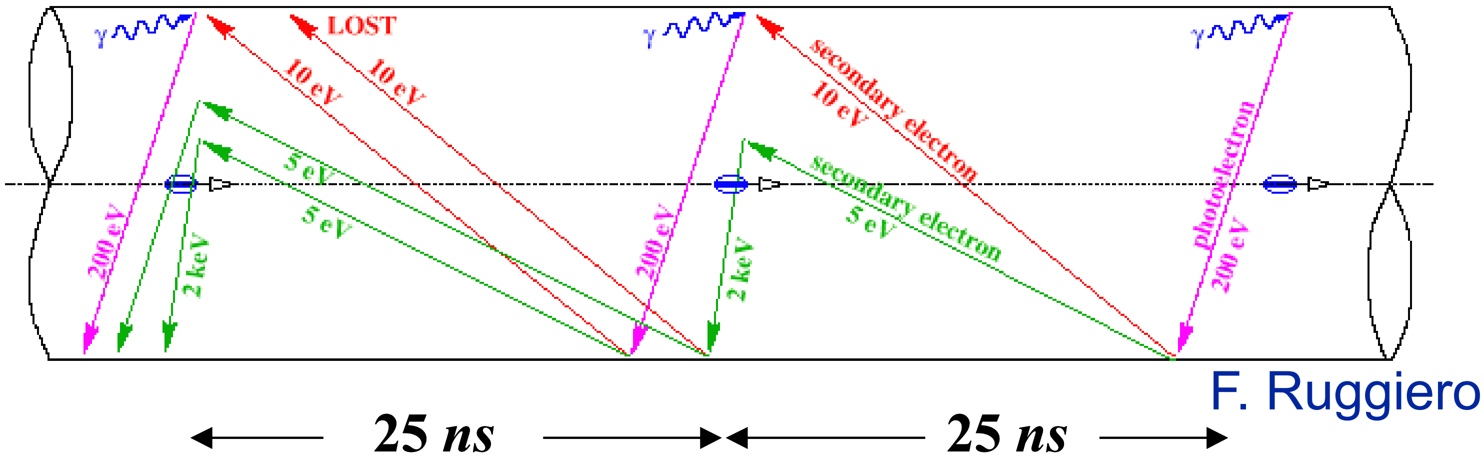
Outline

- Overview electron cloud
  - Buildup physics
  - Problems caused by EC
  - Mitigation
  - History
  - Simulations
- The CESR-TA program
  - Overview
  - EC buildup studies
- Retarding Field Analyzers
  - Measurements
  - Simulations

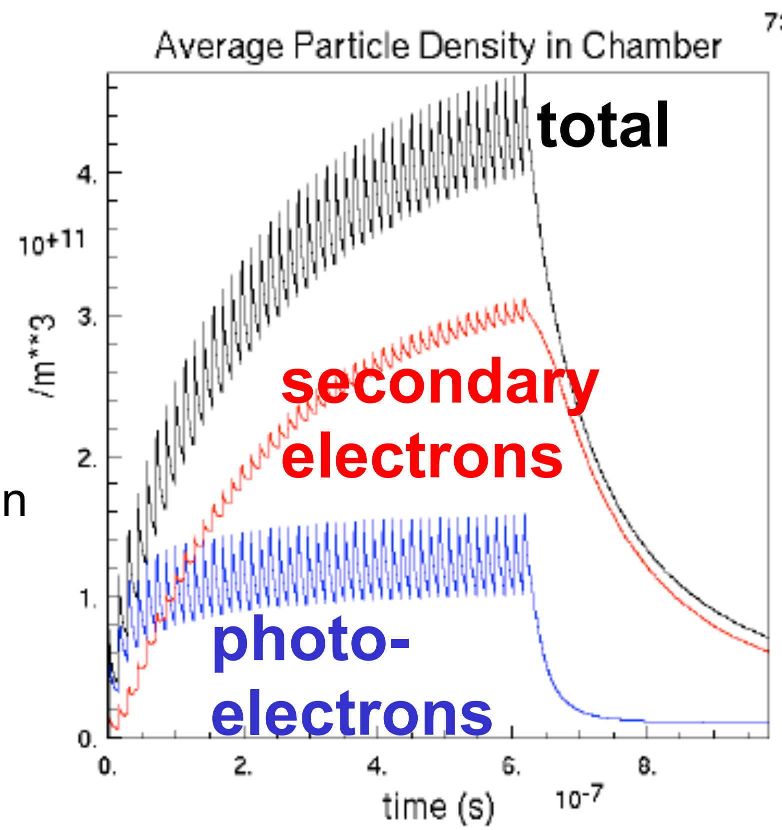
The Basics

- What is CESR-TA?
  - An R&D program at Cornell, tasked with investigating issues related to the ILC damping ring. It has three main areas of research:
  - Low emittance tuning
    - Typical vertical emittance: ~10 pm
  - **Studies of electron cloud growth and mitigation**
  - Studies of electron cloud induced emittance growth and instabilities
- What is electron cloud?
  - Large quantity of low energy electrons hanging around inside vacuum chamber
    - Typical density ~ 10^{11} - 10^{12} e- / m^3
    - Typical energy ~< 200 eV
  - Generated by photoelectrons produced by synchrotron radiation, ionization of residual gas, or particle loss
  - Additional electrons from secondary emission
  - Variety of negative effects
    - Emittance growth
    - Beam instabilities
    - Beam loss
  - These effects are especially strong for positively charged beams

Cloud Buildup



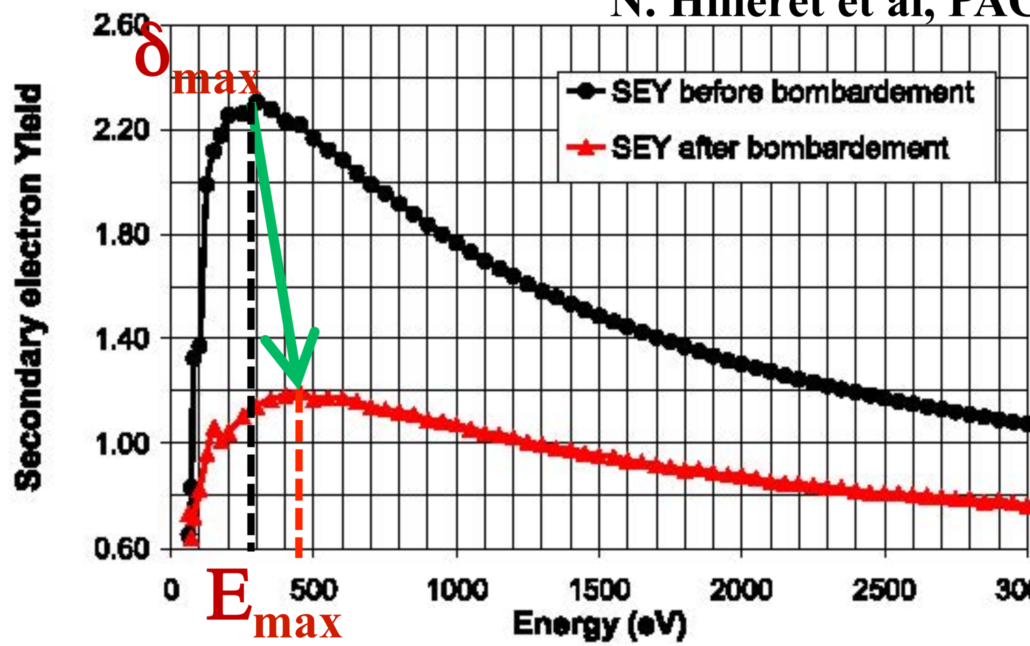
- Beam emits synchrotron radiation
  - Provides source of photo-electrons
- Photoelectrons yield secondary electrons
  - --Typically low energy
- Electrons gain energy from beam kicks
- If average secondary electron yield (SEY) > 1, exponential buildup can result
  - Though cloud density is limited by self-repulsion
- Cloud decays within ~few hundred ns after bunch train



Secondary Electron Yield

- Generation of secondaries is determined by the secondary emission yield (SEY) function $\delta(E)$:
  - Characterized by peak value δ_{max} at $E = E_{max}$
  - Low energy yield $\delta(0)$: determines survival time of cloud during train gap
  - Typically, δ_{max}~1–3, and E_{max}~200-400 eV, $\delta(0)$ ~ .5
  - Yield is also higher for grazing incidence
- Many materials "condition" with electron cloud bombardment
  - Results in lower δ_{max}, higher E_{max}

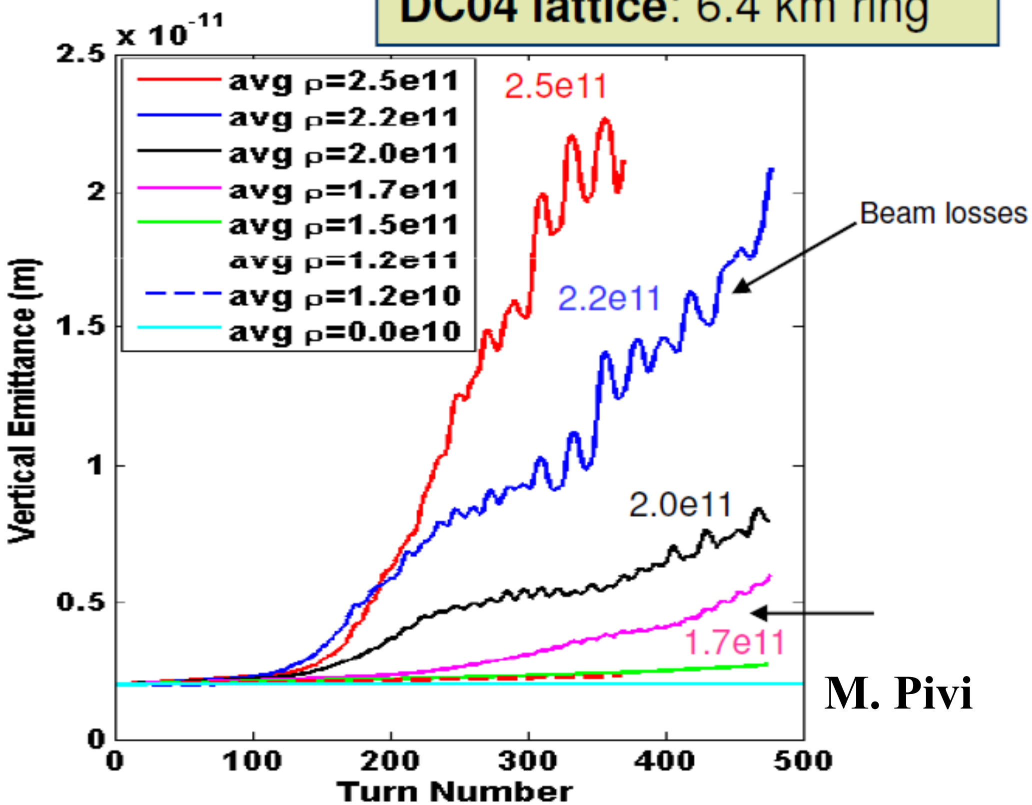
N. Hilleret et al, PAC99



Consequences

- Coherent tune shifts
- Multi-bunch instability
  - Cloud couples motion of successive bunches
- Single bunch instability
  - e.g. Head-tail
  - Happens above “threshold” cloud density
- Emittance growth
  - Below threshold
- Gas desorption
- Excessive energy deposition on the chamber walls
  - important for superconducting machines, eg. LHC
- Particle losses, interference with diagnostics,…

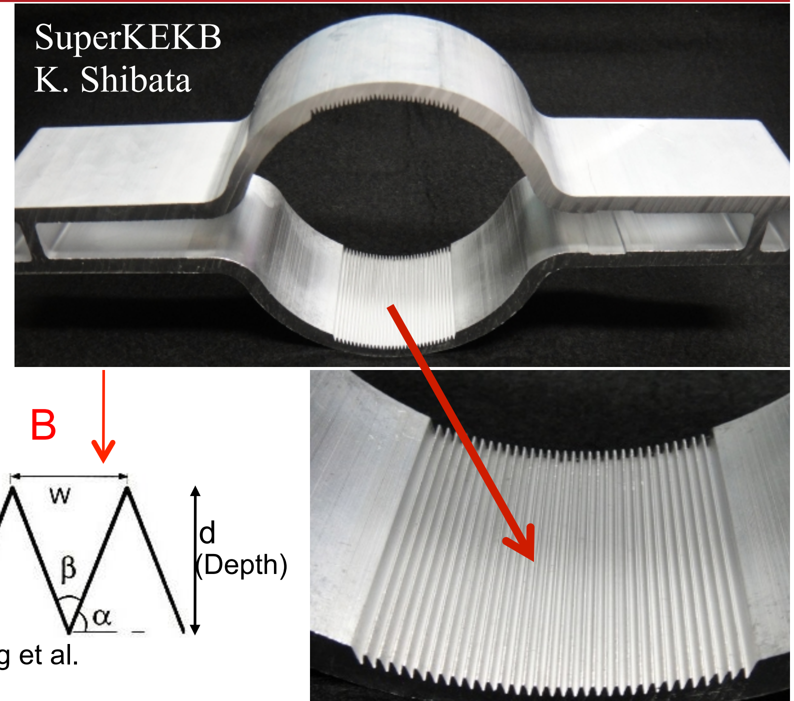
DC04 lattice: 6.4 km ring

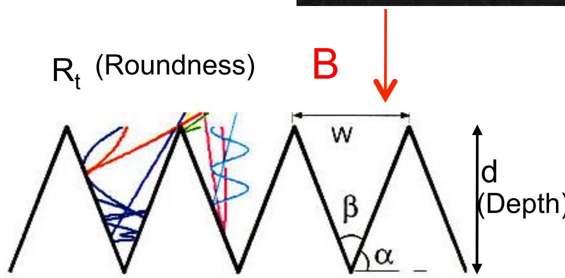


M. Pivi

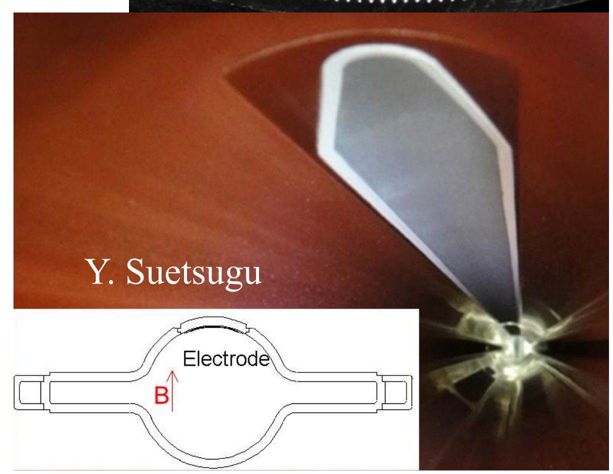
Controlling the ECE

- Antechamber or transverse grooves
  - Reduce effective photon flux
  - Antechamber used at KEK and PEP-II
  - Transverse grooves in LHC beam screen
- Longitudinal grooves
  - suppress effective SEY in dipole field
- Low-SEY coatings
  - TiN (PEP-II, SNS)
  - TiZrV (RHIC and LHC)
    - Also provides pumping
    - Requires activation
  - Amorphous carbon coating
  - Diamond-like carbon
- Clearing electrodes (~400V)
  - push electrons out of the way
- Solenoidal B-fields (~20 G)
  - confines electrons near the chamber, away from the beam
  - Used in drift sections of KEKB and PEP-II
- Conditioning
  - SEY naturally decreases as a result of EC bombardment
- Tailor the bunch fill pattern
  - add strategic gaps in the train
- Use feedback systems to actively counteract instabilities that arise





by L. Wang et al.



Abridged History of EC

- Early observations (60's – 80's): two-stream instabilities in proton storage rings
  - BINP, ISR, Bevatron, PSR (LANL)
- 1995: Coupled bunch instability at KEK Photon Factory that behaved differently for electron and positron beams
  - sensitive to bunch spacing, but not "clearing gap"
  - determined to be caused by photoelectrons
- PEP-II and KEKB limited by EC
  - Needed mitigations to achieve luminosity goals
  - Used antechambers, TiN coating, solenoids
- RHIC: fast vacuum pressure rise instability
  - Solved by TiZrV coating
- PSR: high-current instability, beam loss
  - Coated SNS vacuum chamber with TiN
- Dedicated experiments
  - APS, PEP-II, KEKB, Main Injector, CESR
- LHC: currently limits 25 ns operation
- Concern for future machines
  - LHC upgrade, ILC DR's, MI upgrade,…

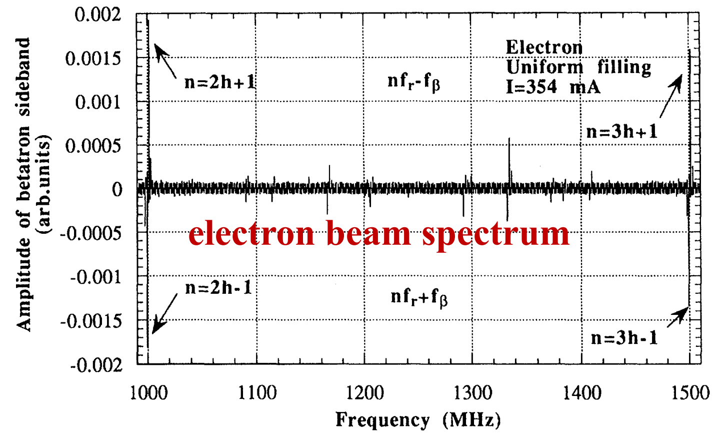


FIG. 1. Distribution of the betatron sidebands observed during electron multibunch operation with uniform filling.

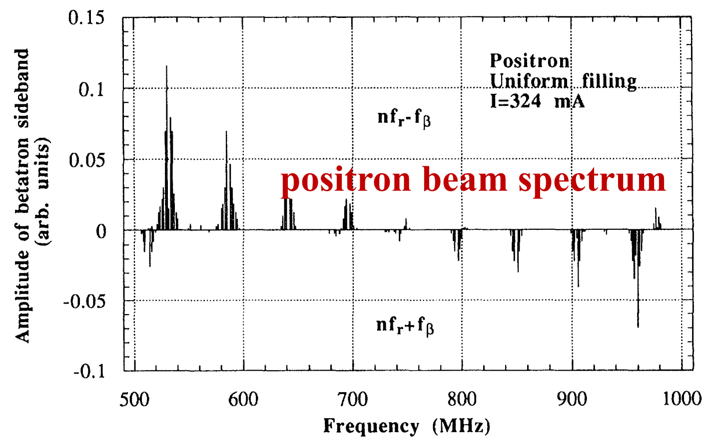


FIG. 2. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling.

EC Simulations

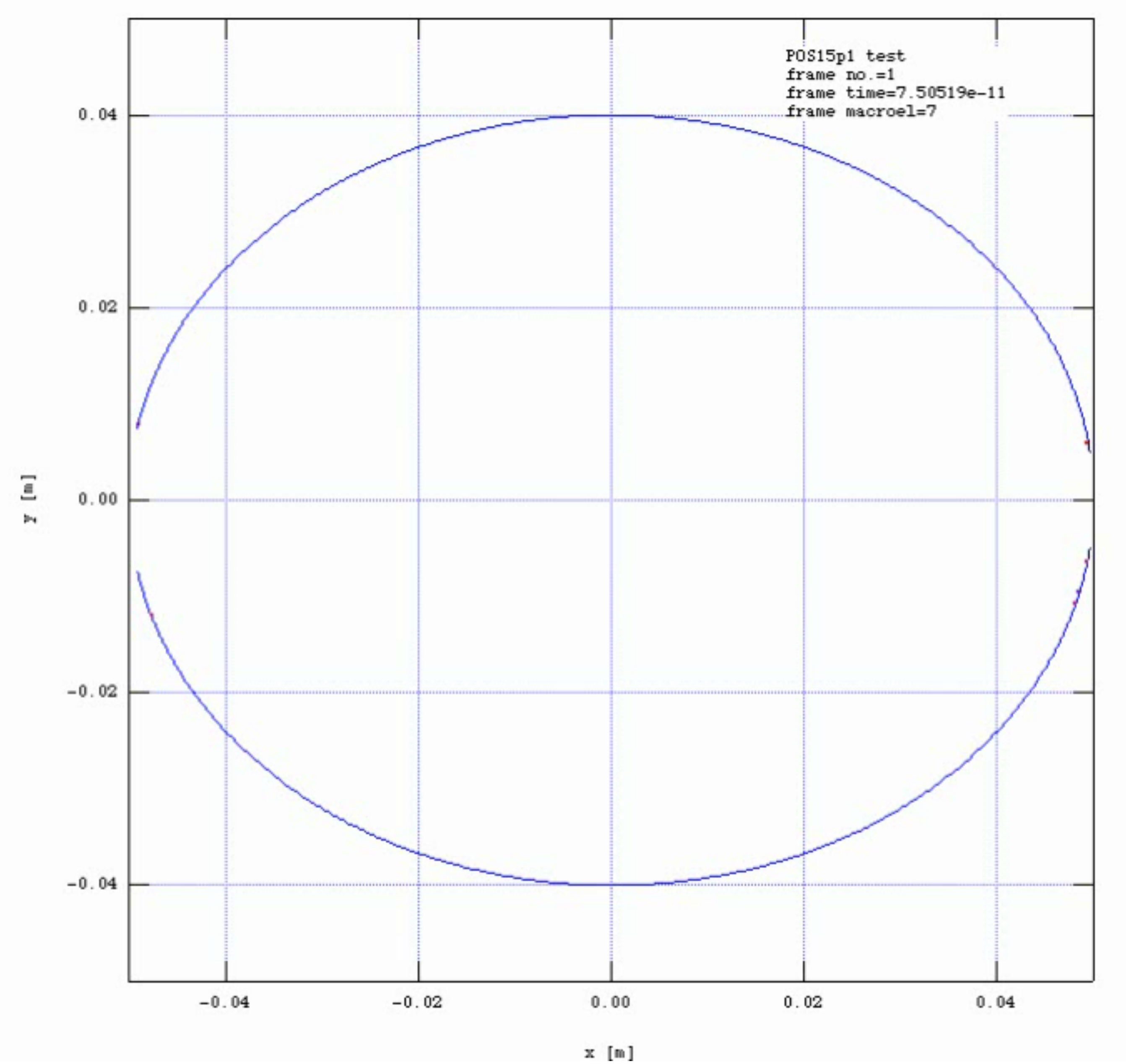
- Cloud buildup simulations shown in this talk were done with POSINST.
  - M. Furman & M. Pivi, PRSTAB/v5/i12/e124404
- Features include:
  - Electrons are dynamical, represented by macroparticles
  - Beam is not dynamical, represented by a prescribed function of time and space
  - A simulated photoelectron is generated on the chamber surface and “tracked” (F=ma) under the action of the beam
    - Secondary electrons can be generated via probabilistic process
  - Space charge and surface charge also included
  - Electron motion is fully 3D, but space charge only 2D
    - Effectively assumes periodic boundary conditions
  - Well travelled
    - Used at LBL, ANL, SLAC, LANL…

Model Inputs

- Vacuum chamber size and shape
  - Rectangular or elliptical
- Local magnetic field
  - Field free, dipole, solenoid, quadrupole
- Local photon flux and azimuthal distribution
- Photoemission parameters
  - Quantum efficiency
  - Photoelectron energy and angular distribution
- Secondary emission parameters
  - SEY vs incident energy and angle $\delta(E,\theta)$
    - ~20 parameters in POSINST!
  - Secondary electron energy and angular distribution
- Beam parameters
  - Proton, electron, or positron beam
  - Beam energy
  - Bunch current
  - Train length, bunch spacing, etc

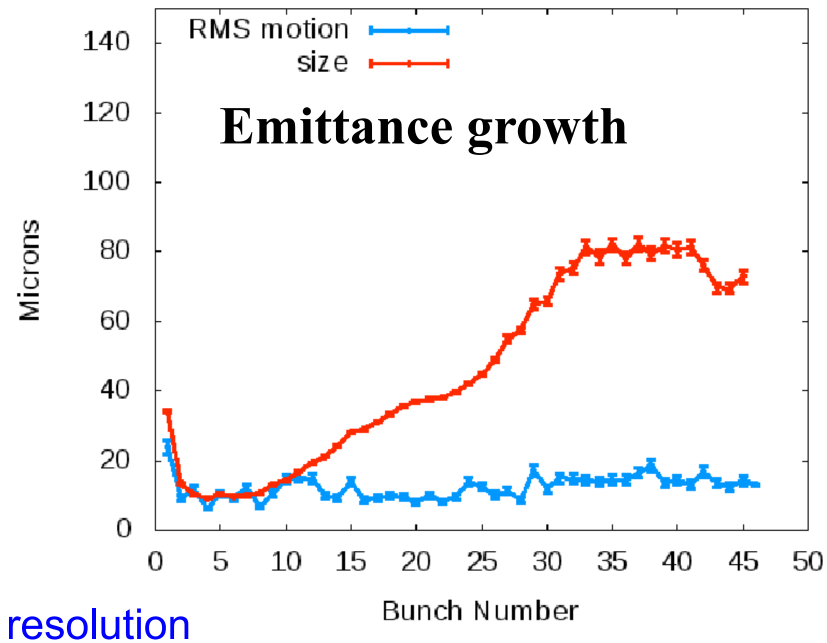
Example Buildup Movie (M. Furman)

- Field free
- e+ beam
- 10 bunches



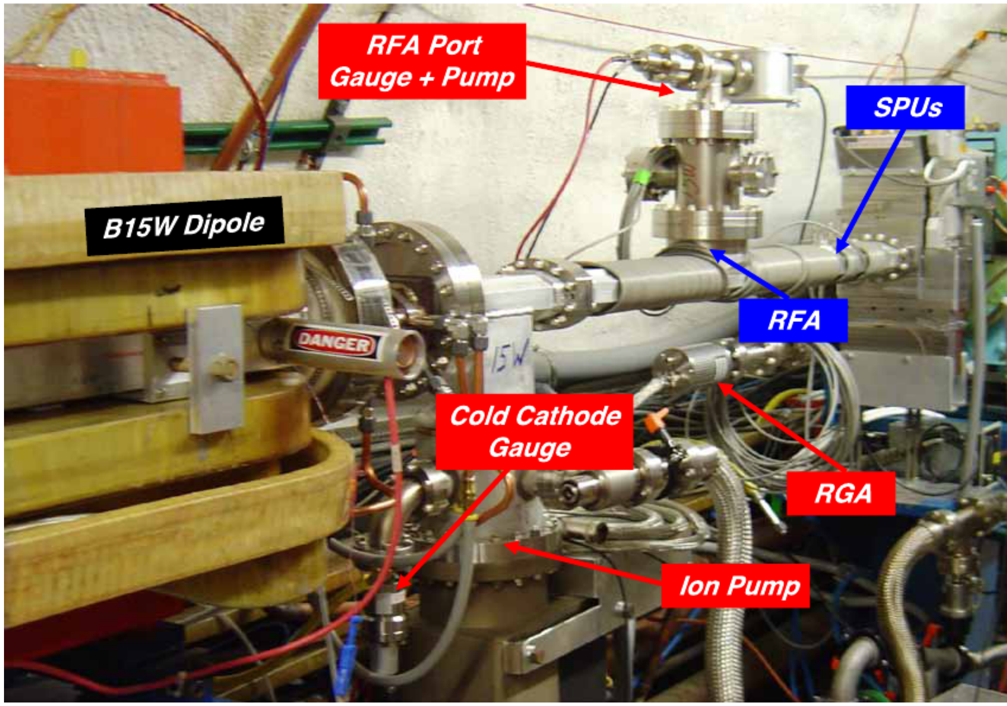
Electron Cloud Studies at CESR-TA

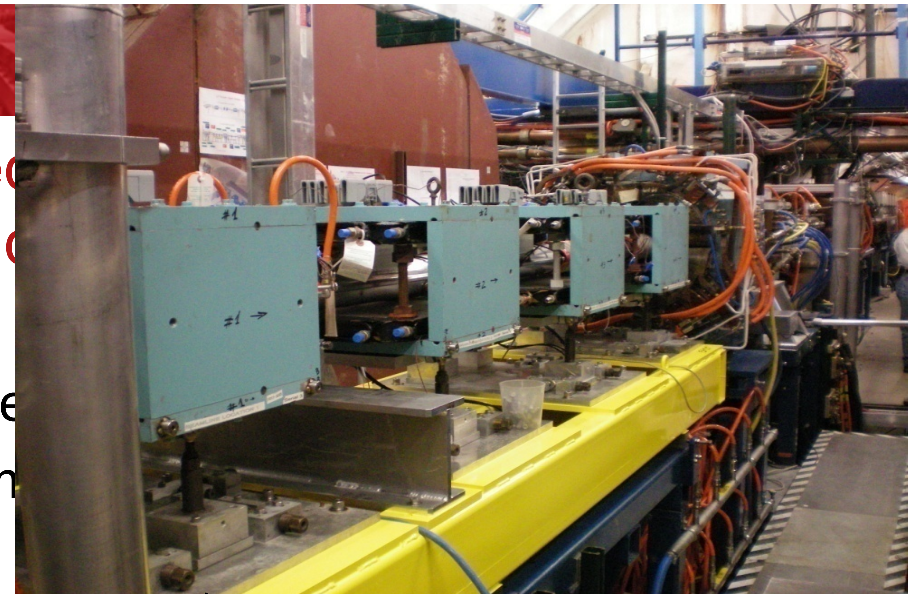
- Global electron cloud signatures
  - Emittance growth
  - Coherent tune shifts
  - Head-tail instability
- Local electron cloud detectors
  - **Retarding field analyzers**
    - **Measure electron cloud wall flux, with transverse and energy resolution**
  - Shielded pickup
    - Measure electron cloud wall flux, with time resolution
  - Microwave transmission
    - Measure electron cloud density
    - Difficult to interpret
- CESR is well suited to accelerator physics studies
  - Similar in size and energy to ILC damping ring
  - Very flexible (see table)



CESR Parameters

Parameter	Value(s)	Units
Circumference	768	m
Revolution Period	2.56	μs
Harmonic number	1281	-
RMS Horizontal Emittance	2.6 - 133	nm
RMS Vertical Emittance	.02 - 1.3	nm
Number of bunches	9, 20, 30, 45	-
Bunch current	.75, 1.25, 2.8, 5, 10	mA[a]
Bunch spacing	4, 14, 280	ns
Beam species	e^+, e^-	-
Beam energy	2.1, 4, 5.3	GeV

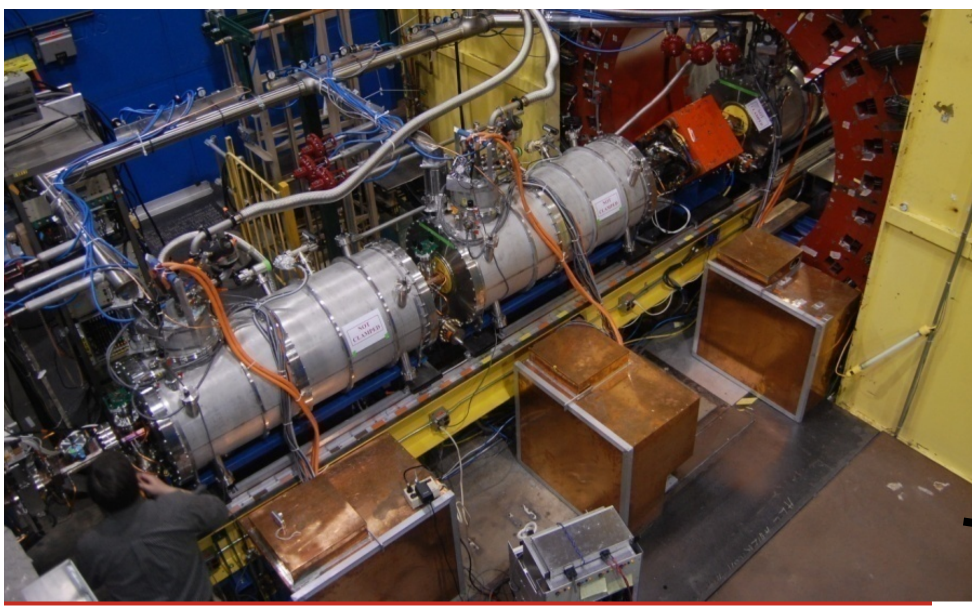


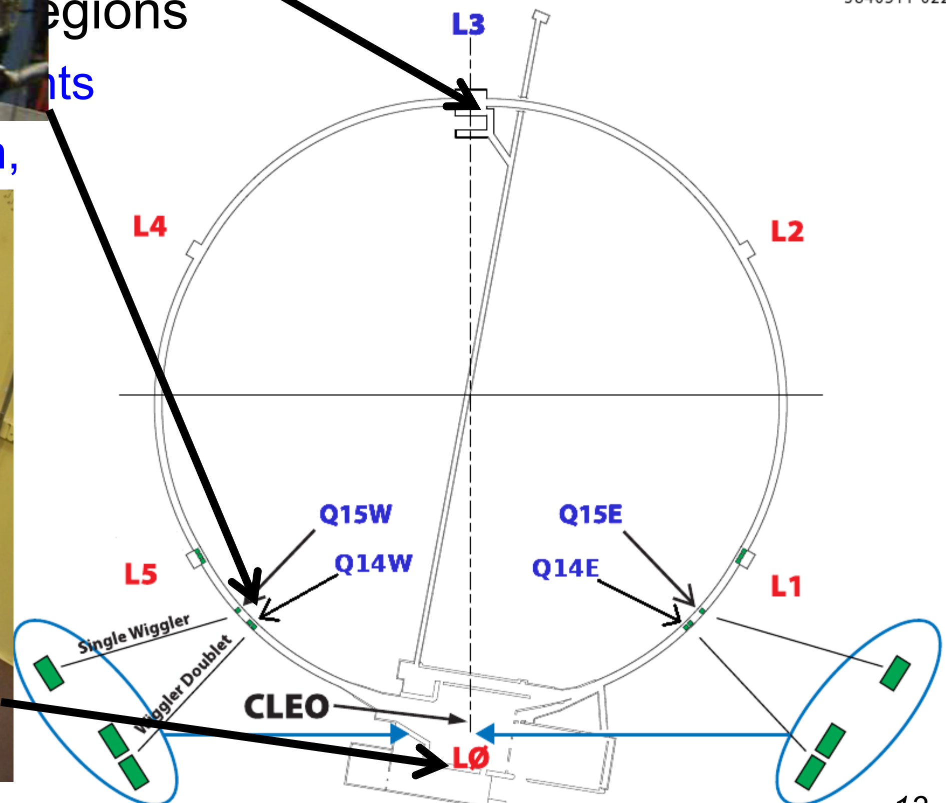


egions

nts

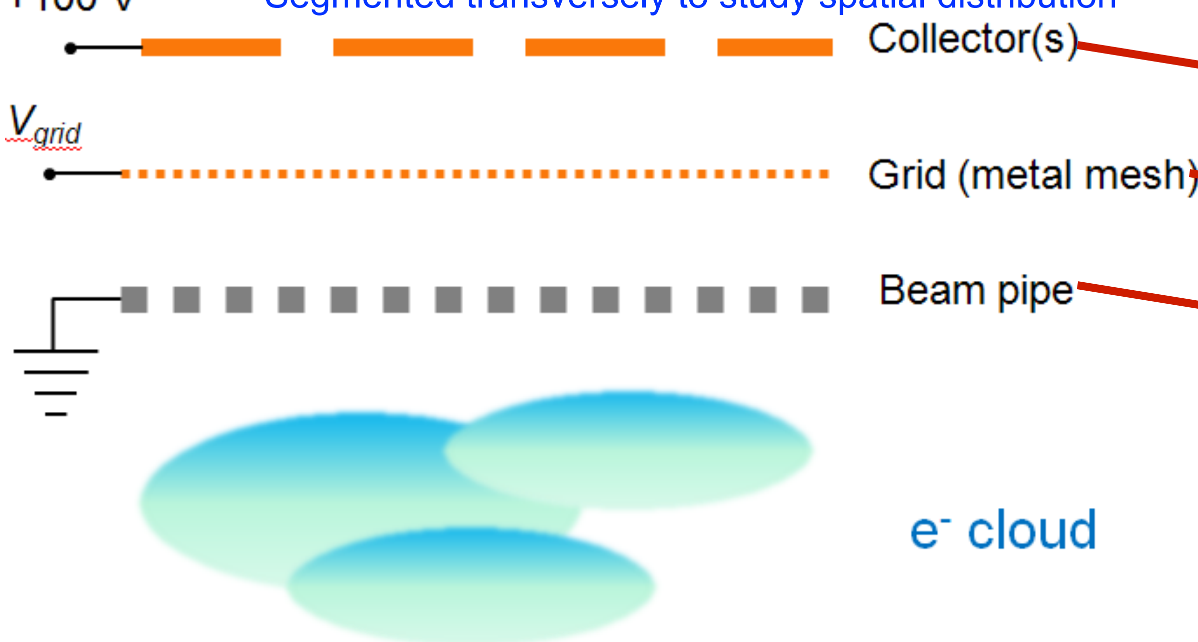
- L3: chicane dipoles, NEG section,

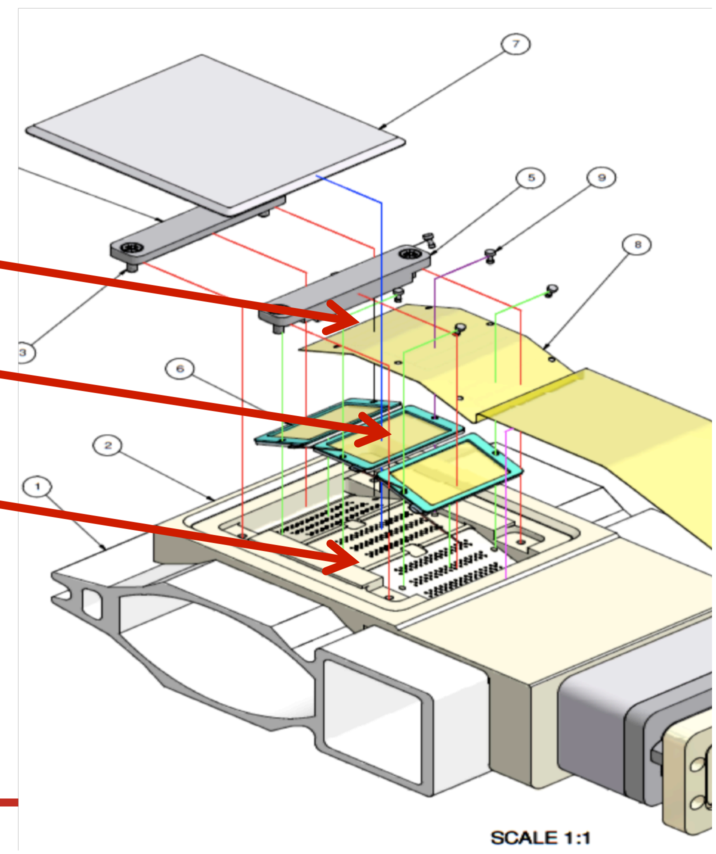




Retarding Field Analyzers

- A method to measure the local electron cloud wall flux, and infer the cloud density, energy, and transverse distribution.
- They consist of:
  - Holes drilled in vacuum chamber wall
    - Allow electrons to enter device
  - Retarding grid
    - Reject electrons with $E < V_{grid}$
    - Scan retarding voltage -> integrated energy spectrum
    - Additional grounded grids optional
  - One or more collectors
    - Segmented transversely to study spatial distribution

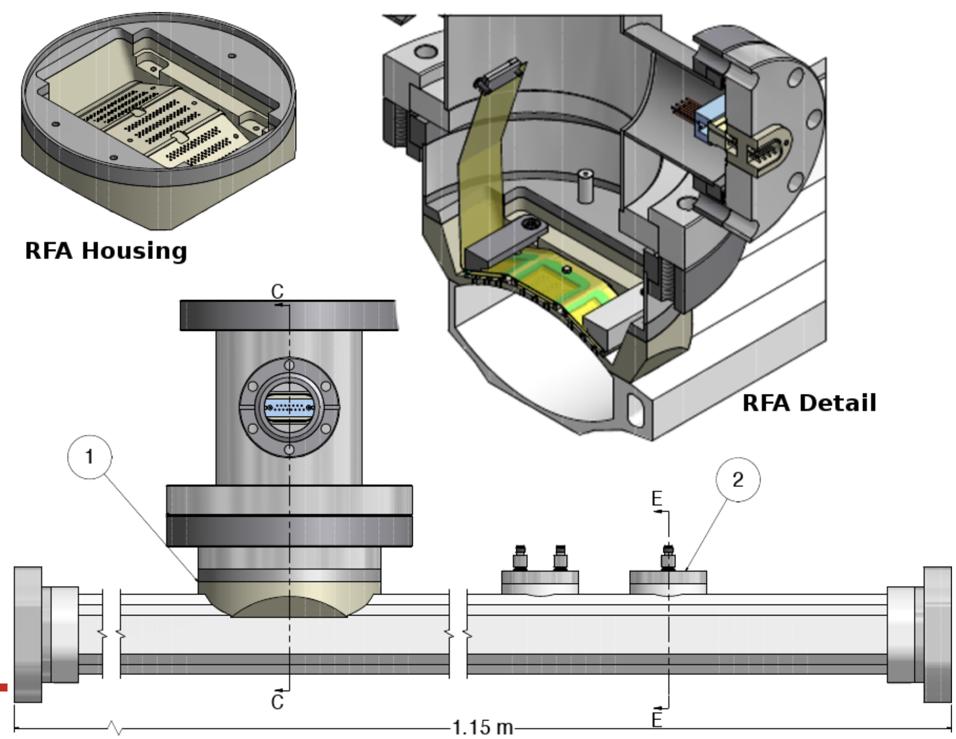




CESR-TA RFA Program

- Unique features
  - Many RFAs (~30) deployed in a single ring
  - RFAs in different environments: drift (field free), dipole, quadrupole, wiggler
  - Designs for insertion in confined spaces
  - Dedicated RFA measurements
    - Under different beam conditions
    - In vacuum chambers with different mitigations
    - Over time, to observe beam conditioning
    - In combination with other EC diagnostics
  - Main operating modes:
    - Voltage scans
    - Current scans
  - Large data set, 4+ years of measurements
  - Proportionally large simulation program
- Collaborators: APS, SLAC, KEK, CERN, LBL

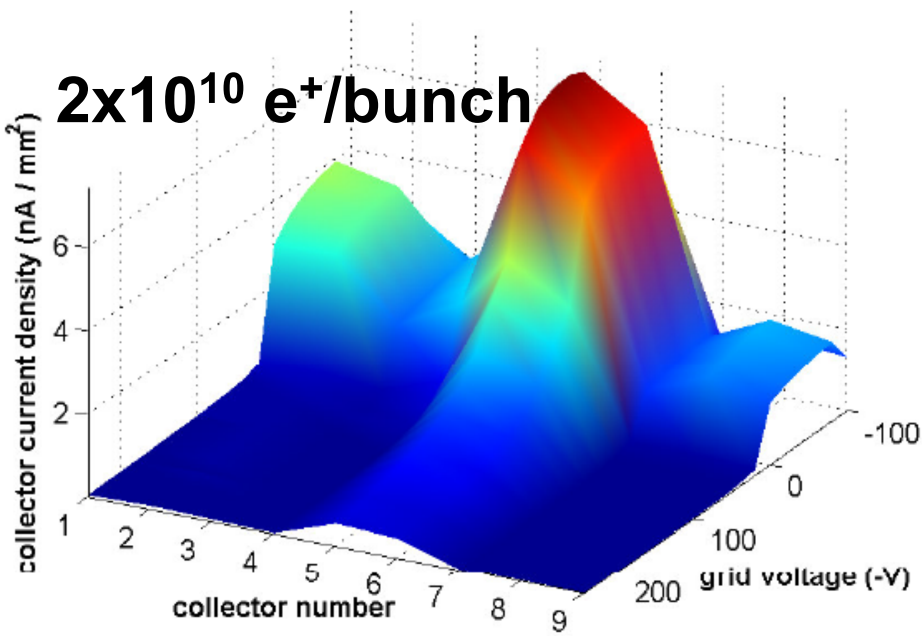
RFA Installation in Q15W



RFA Measurements

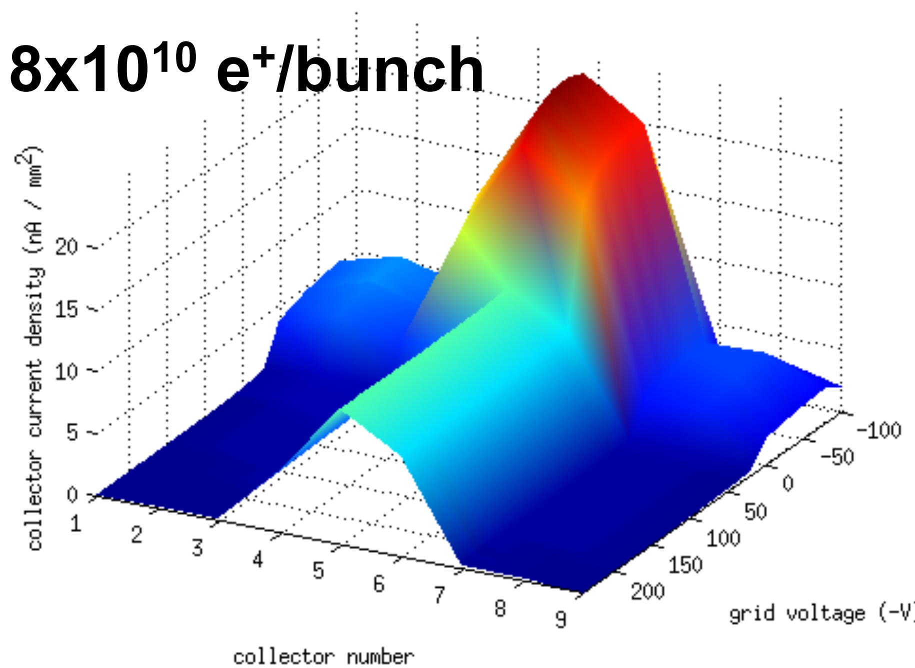
- Plot shows voltage scan done with Q15W drift RFA
  - Shows collector signal vs retarding voltage (~integral of energy) and collector number (~transverse position)
    - left: 45 bunches, 14ns spacing, 2x10^10 positrons/bunch
    - right: 20 bunches, 14ns spacing, 1.6x10^11 positrons/bunch
  - Broad signal across collectors, peaked at center (beam location)
  - High flux of low-energy electrons
  - High beam current example shows more signal, especially at high voltage, central collectors

$2x10^{10}$ e^+/bunch



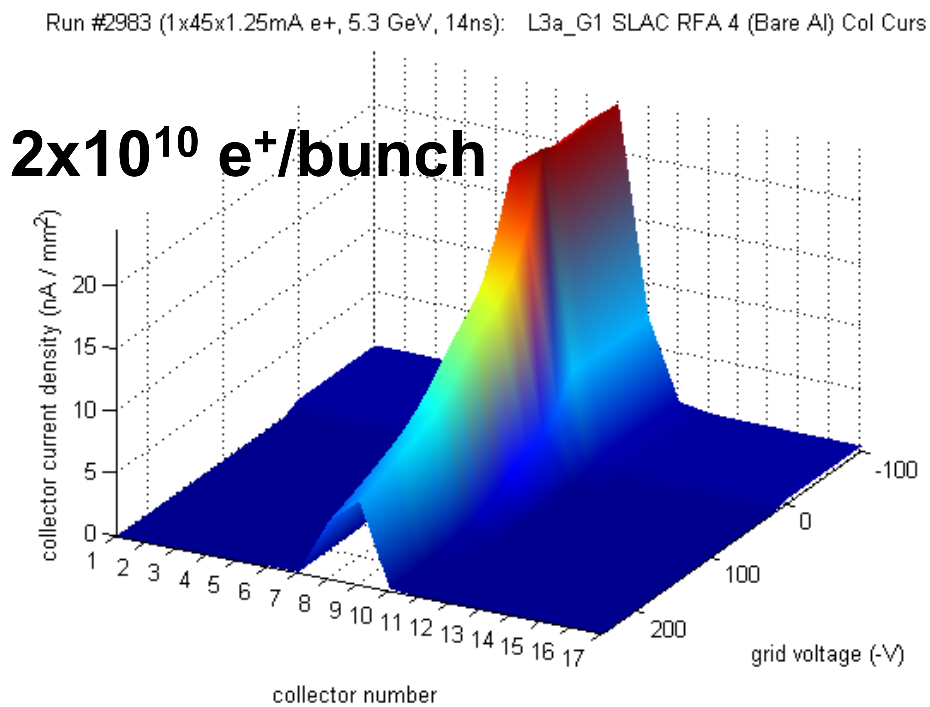
D15W_RFA1_CVC2_aC-Al, Run2993 (1x20x10mA e+, 14ns, 5.3GeV)

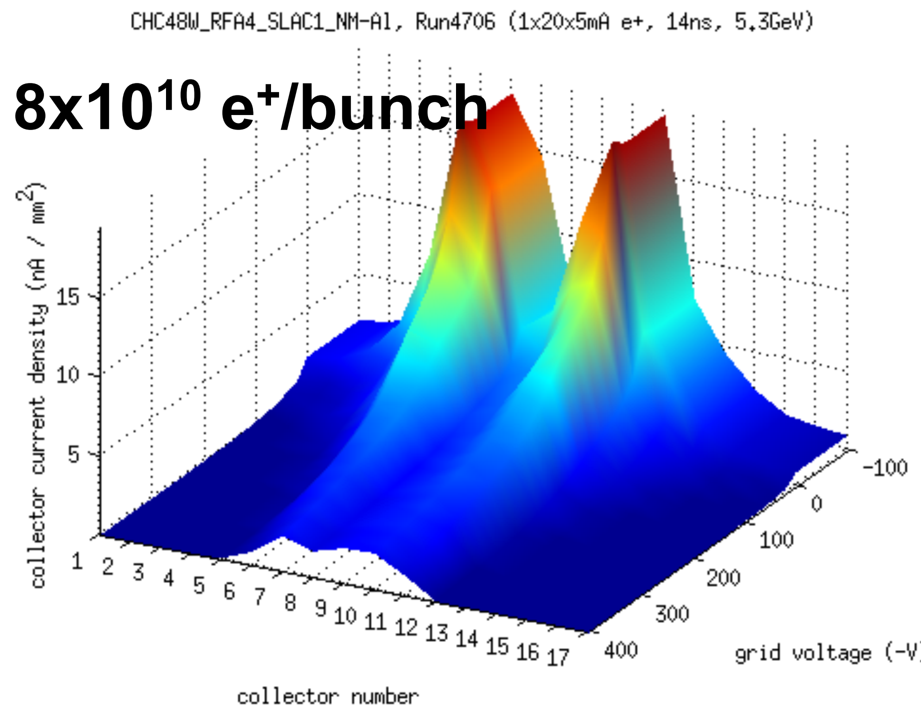
$8x10^{10}$ e^+/bunch



RFA Measurements: Dipoles

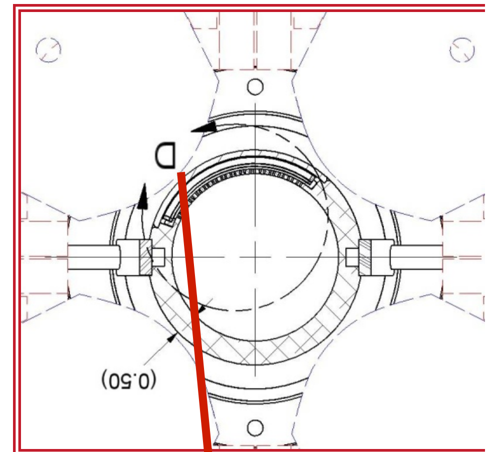
- Dipole measurements done chicane of four dipoles built at SLAC
  - Field is variable, 810 Gauss in plots
- Dipole field pins cloud electrons into mostly vertical trajectories
- Low current (left): electrons aligned with beam have the most energy -> highest SEY -> most secondaries -> highest RFA signal
- High current (right): central electrons have E > Emax, central peak bifurcates

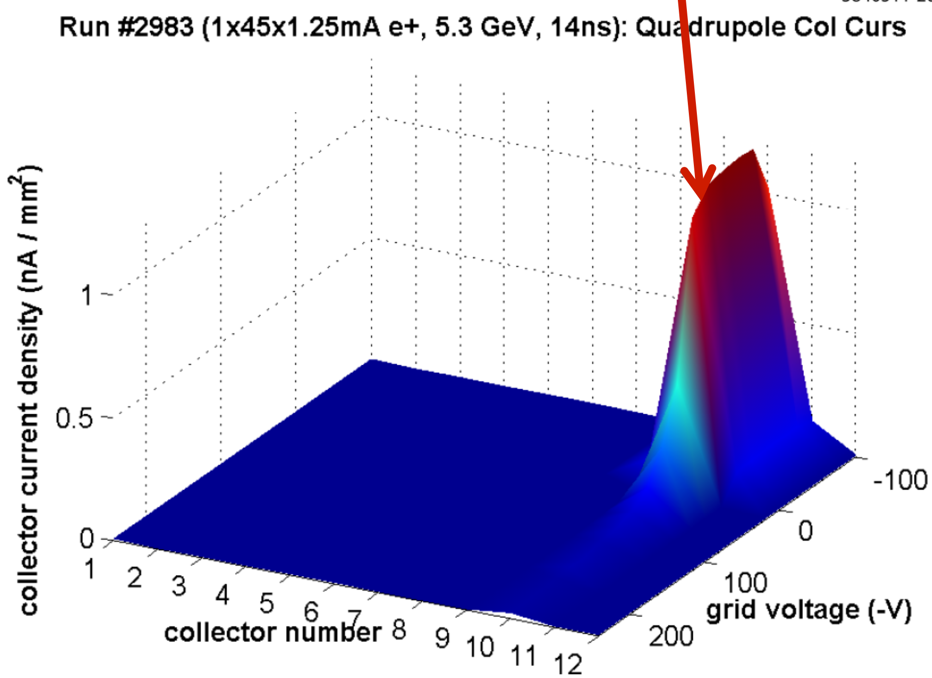


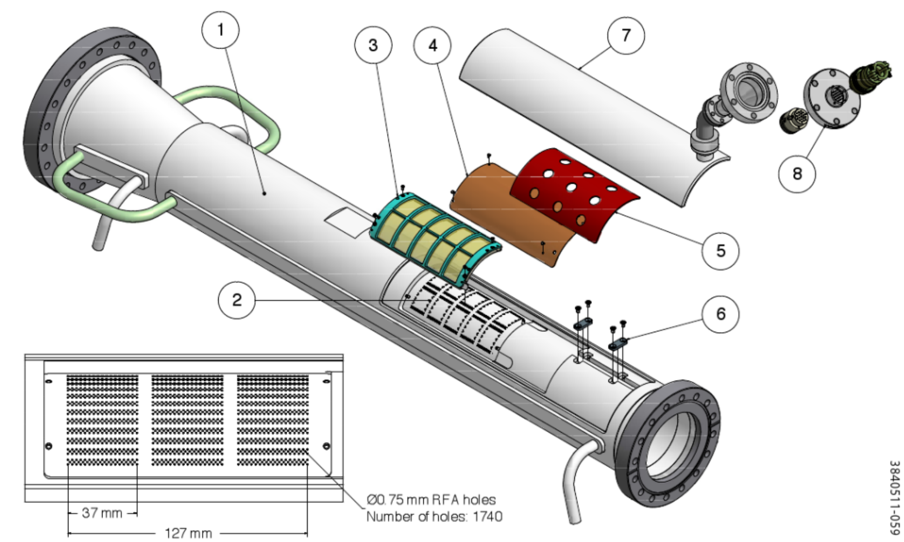


RFA Measurements: Quadrupoles

- Detector wraps azimuthally around chamber
- Quadrupole guides electrons along field lines
- We observe sharp peak in a single collector aligned with quad pole tip
- Electrons can remain trapped long after the bunch has passed

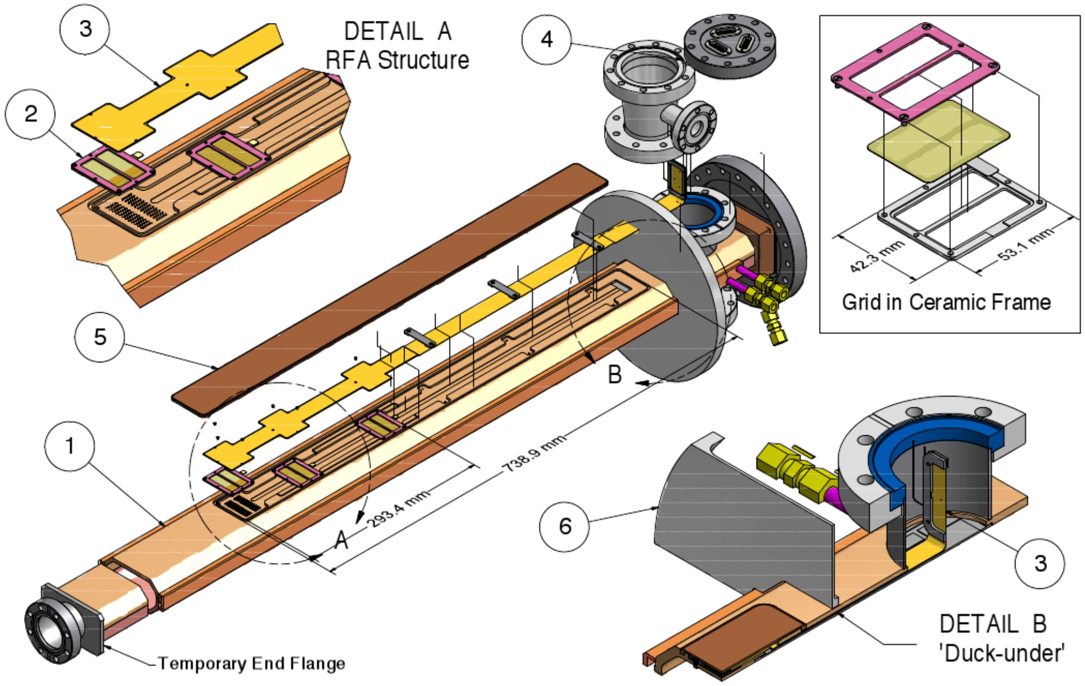


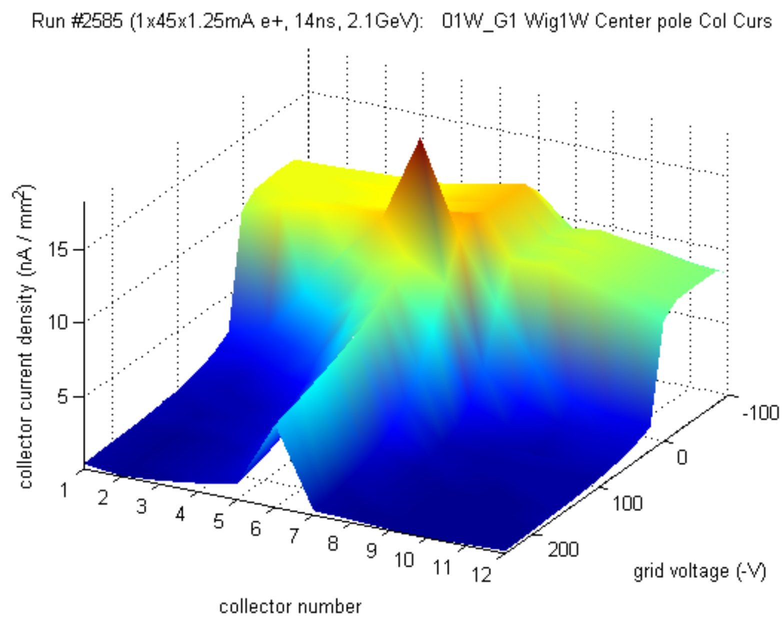


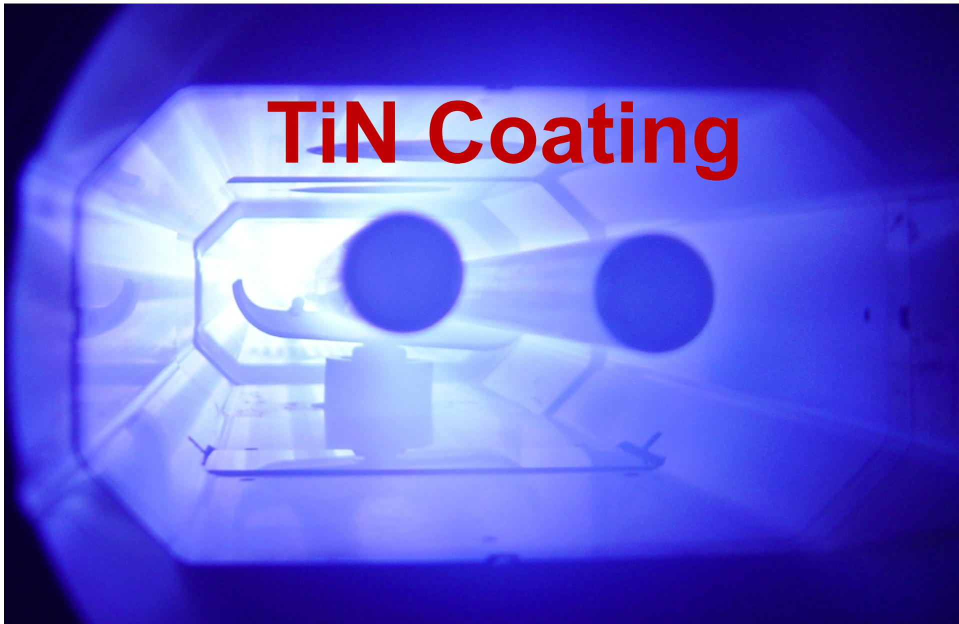


RFA Measurements: Wigglers

- L0 straight contains six superconducting wigglers, three with RFAs
- RFAs in wiggler pole center, between poles, and intermediate region
  - Shown: pole center
- Signal is fairly broad, though peaked in the center at high energy
- Spike at low (but nonzero) retarding voltage, due to interaction between RFA and cloud
  - Resonance between bunch spacing and retarding voltage







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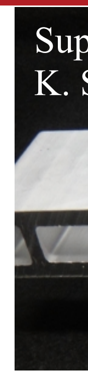

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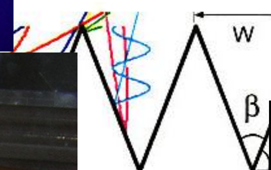
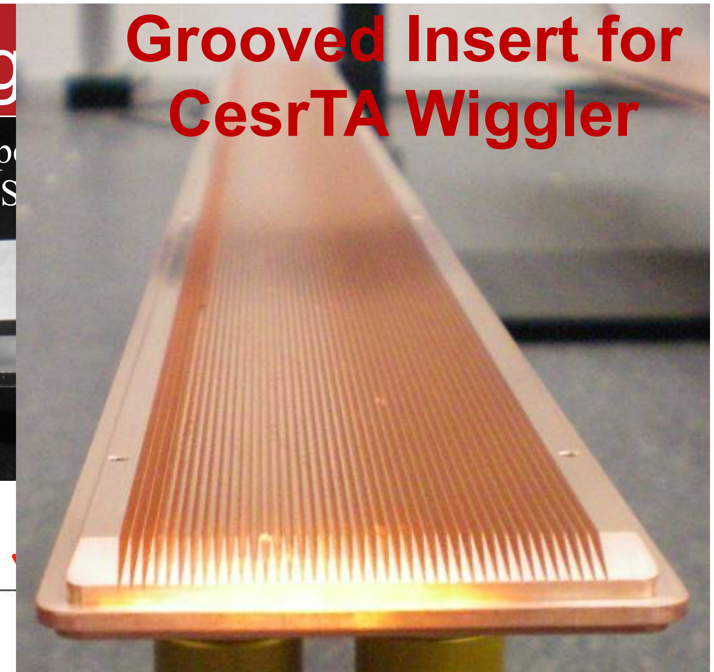
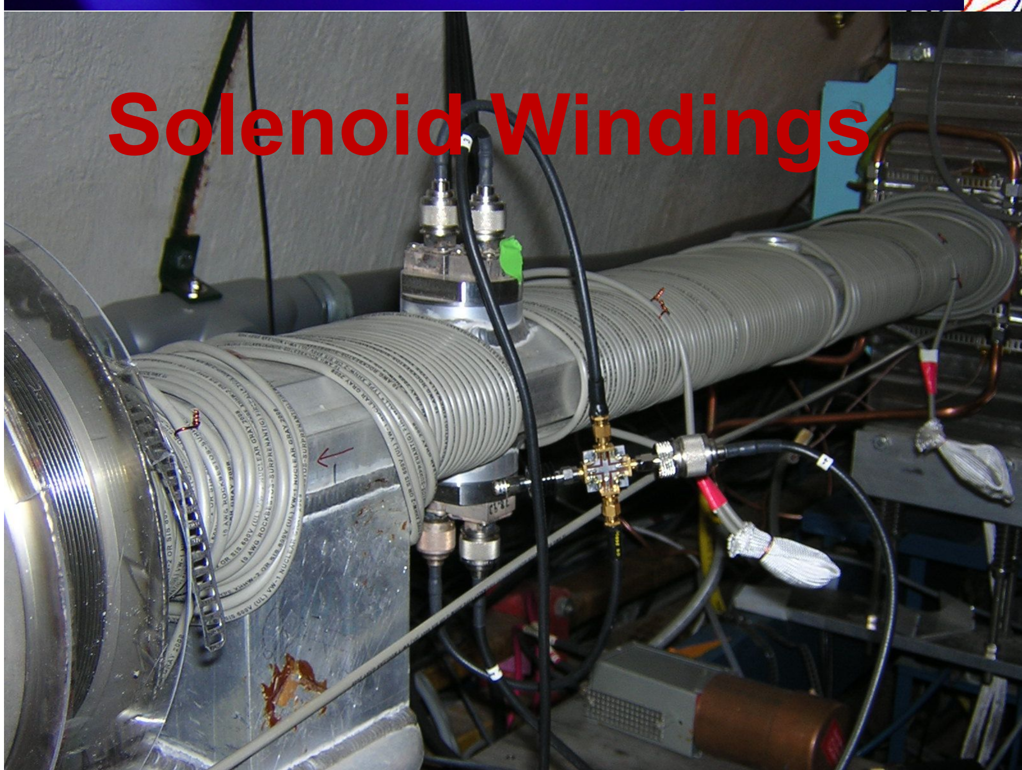


L. Wang et al.





EP-II

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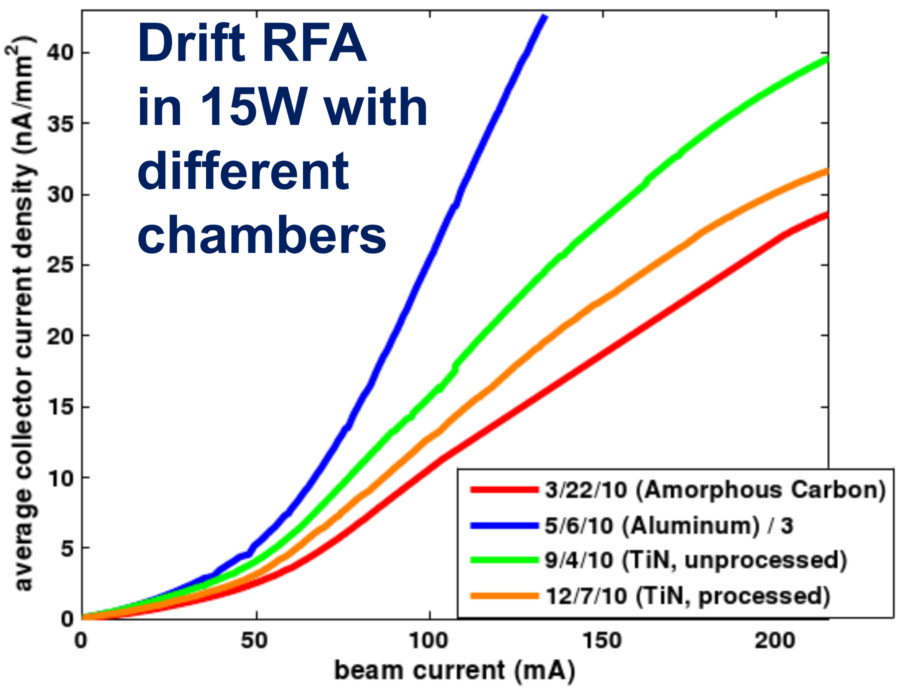
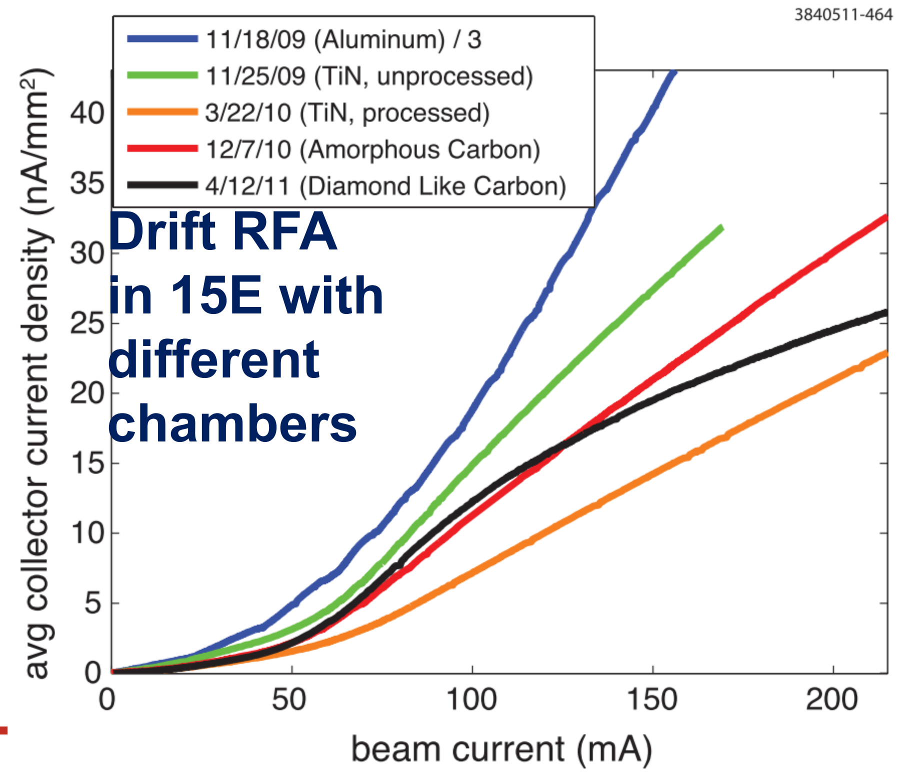
Drift Mitigations

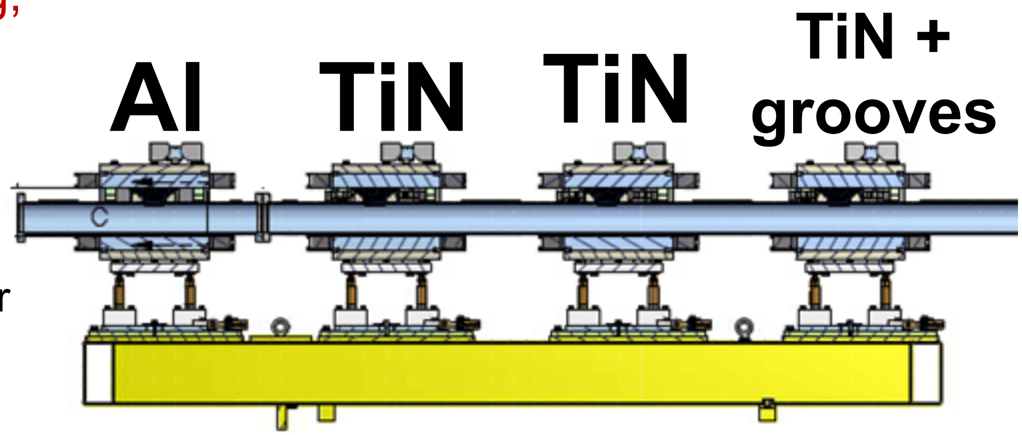
- Cycling different chambers at the same location in CESR allows for direct comparison of their effectiveness
- Plots show average collector signal vs beam current @ 15E/W locations
  - 20 bunches of positrons, 14ns spacing, 5.3GeV
- Tested chambers: Al (blue) TiN (green), Amorphous C (red), Diamond-like C (black)
  - TiN shows significant conditioning (orange)
- All coated chambers show significant improvement relative to aluminum
- Amorphous carbon wins in one case, processed TiN in the other
  - DLC may be superior at very high current

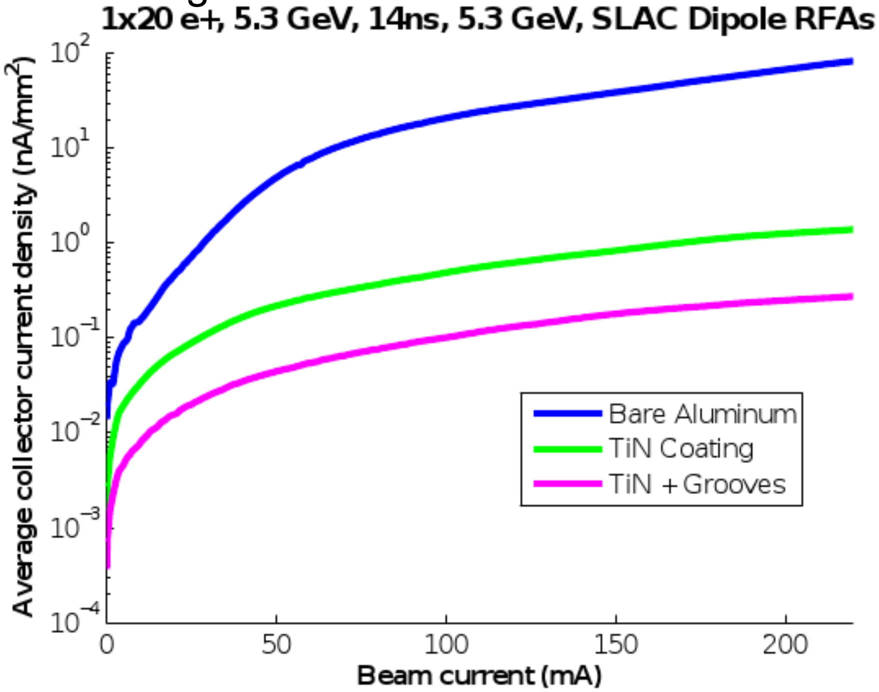


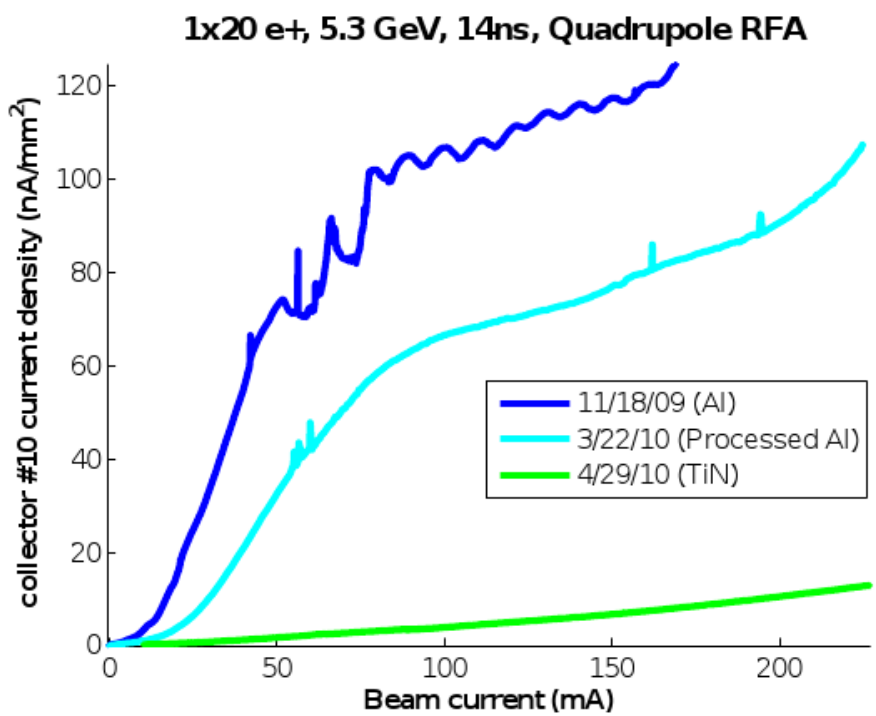


Dipole/Quad Mitigation

- 20 bunches of positrons, 14ns spacing, 5.3GeV
- Left: SLAC chicane RFAs
  - Each chicane dipole has different mitigation
  - Coating good, grooves + coating better
  - Note log scale
- Right: quadrupole
  - TiN coated chamber shows much less signal

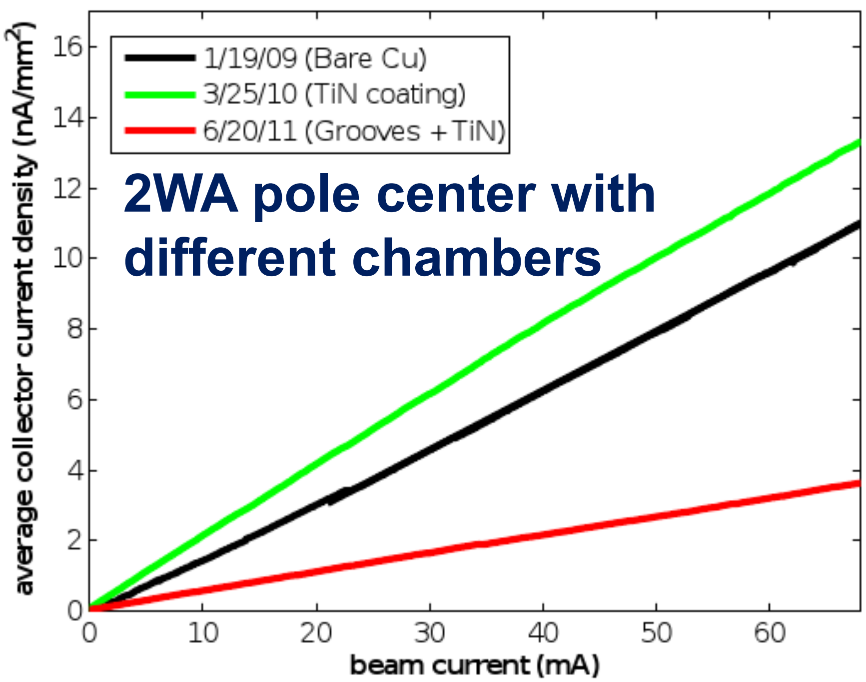


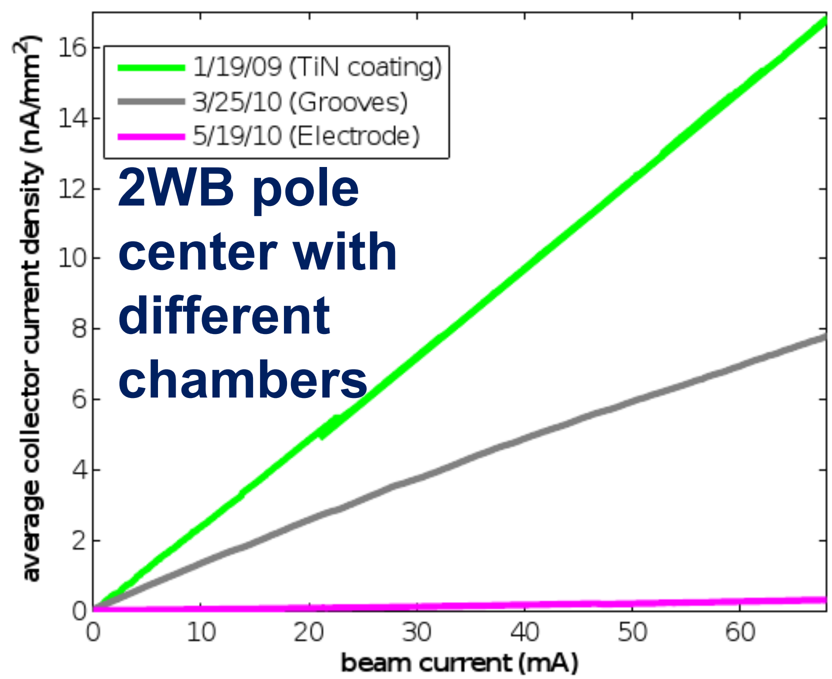




Wiggler Mitigations

- Wiggler mitigations cycled through the same two locations in L0
  - Mitigations tested: Cu (black), grooves (grey), TiN coating (green), grooves + coating (red), clearing electrode (magenta)
- Left and right plots: two different locations in L0 straight
  - 45 bunches e+, 14ns spacing, 2.1GeV
  - TiN installed in both, seems relatively ineffective
  - Grooves good, coated grooves better
  - Electrode is clear winner





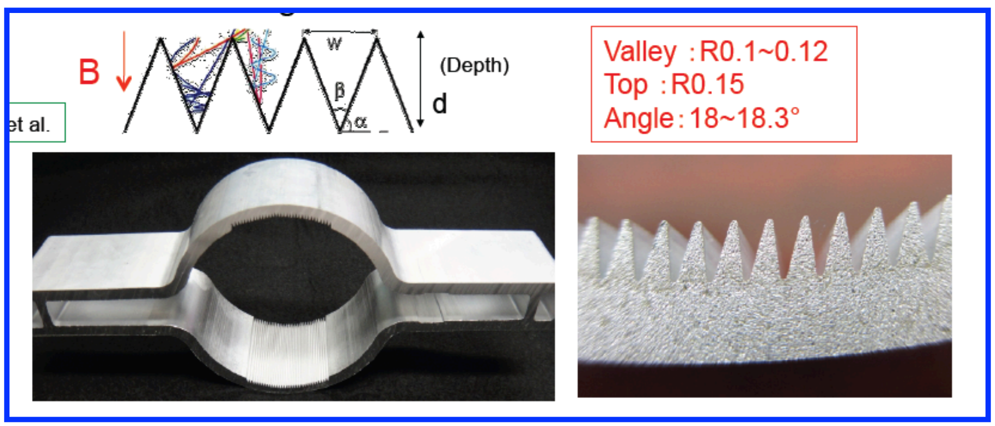
ILC Baseline Mitigation Plan (G. Dugan)

Mitigation Evaluation conducted at satellite meeting of ECLOUD`10 (October 13, 2010, Cornell University)

EC Working Group Baseline Mitigation Recommendation

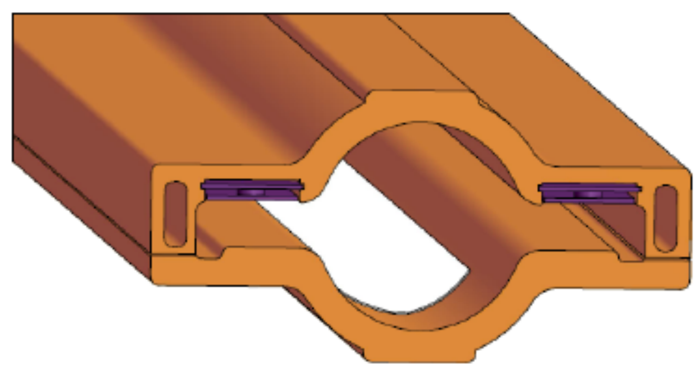
	Drift*	Dipole	Wiggler	Quadrupole*
Baseline Mitigation	TiN Coating+ Solenoid Windings	Grooves with TiN coating	Clearing Electrodes	TiN Coating

SuperKEKB Dipole Chamber Extrusion



Y. Suetsugu

DR Wiggler chamber concept with thermal spray clearing electrode – 1 VC for each wiggler pair.



Conway/Li

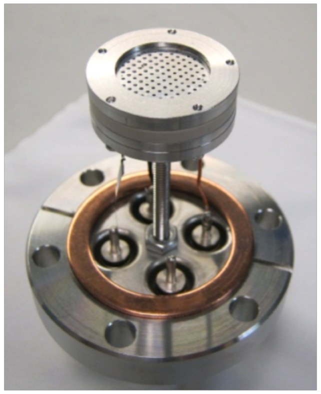
RFA Simulations

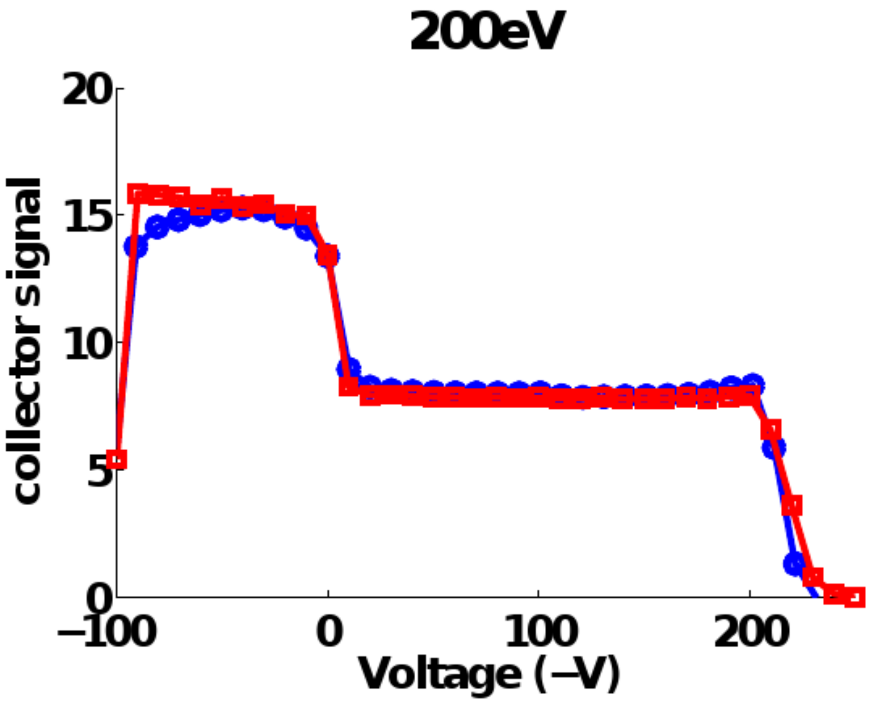
- Goal: obtain simulated RFA signals via specially modified cloud buildup code, adjust simulations to match data
  - Provide constraints on the surface parameters of the instrumented chambers
  - Understand cloud dynamics on a more fundamental level
  - Validate primary and secondary emission models
- Requires cloud simulation program (e.g. POSINST)
- Also need a model of the RFA itself
  - Method 1: Analytical model
    - Special function in POSINST, called when particle collides in RFA region
    - Maps incident particle position, energy, and angle into collector signals
    - Binned by energy and transverse position
    - Charge that goes into RFA is removed from macroparticle
    - Simulated "voltage scan" automatically produced by POSINST
  - Method 2: full particle tracking model
    - Track electron in RFA, using native POSINST routines
    - More self-consistent, can model effects of the RFA on the development of the cloud
    - Need to do a separate simulation for each retarding voltage
    - Needed for wigglers, possibly for dipoles

Drift RFA Model

- RFA model used in “analytical” method features:
  - Model of secondary electron production in beam pipe holes, and grid
    - Results in enhancement of signal at low/positive voltage
  - Realistic fields
    - Results in non-ideal energy cutoff
  - Cross checked with bench measurements done with a test RFA and electron gun
- Plot compares measurement (blue) to model (red)
  - Agreement is excellent

RFA used for bench measurements





Field Free RFA Simulations

- Using the "analytical" method, a large quantity of data can be simultaneously fit, using a chi squared minimization procedure
- Basic method:
  - Choose several different voltage scans, done under a wide variety of beam conditions
  - Choose a few (~3), simulation parameters which have significant and independent effects on the simulations
    - Typically δ_{max}, $\delta(0)$, quantum efficiency
  - Find parameter values which minimize difference between data and simulation
- Features:
  - Photon flux and azimuthal distribution determined by a 3 dimensional simulation of photon production and reflection (SYNRAD3D)
    - Includes diffuse scattering and a realistic model of the CESR vacuum chamber geometry
  - SEY parameters taken from in-situ measurements done at CESR
  - Cross check RFA model with bench measurements
  - Errors on parameters derived from covariance matrix of fits

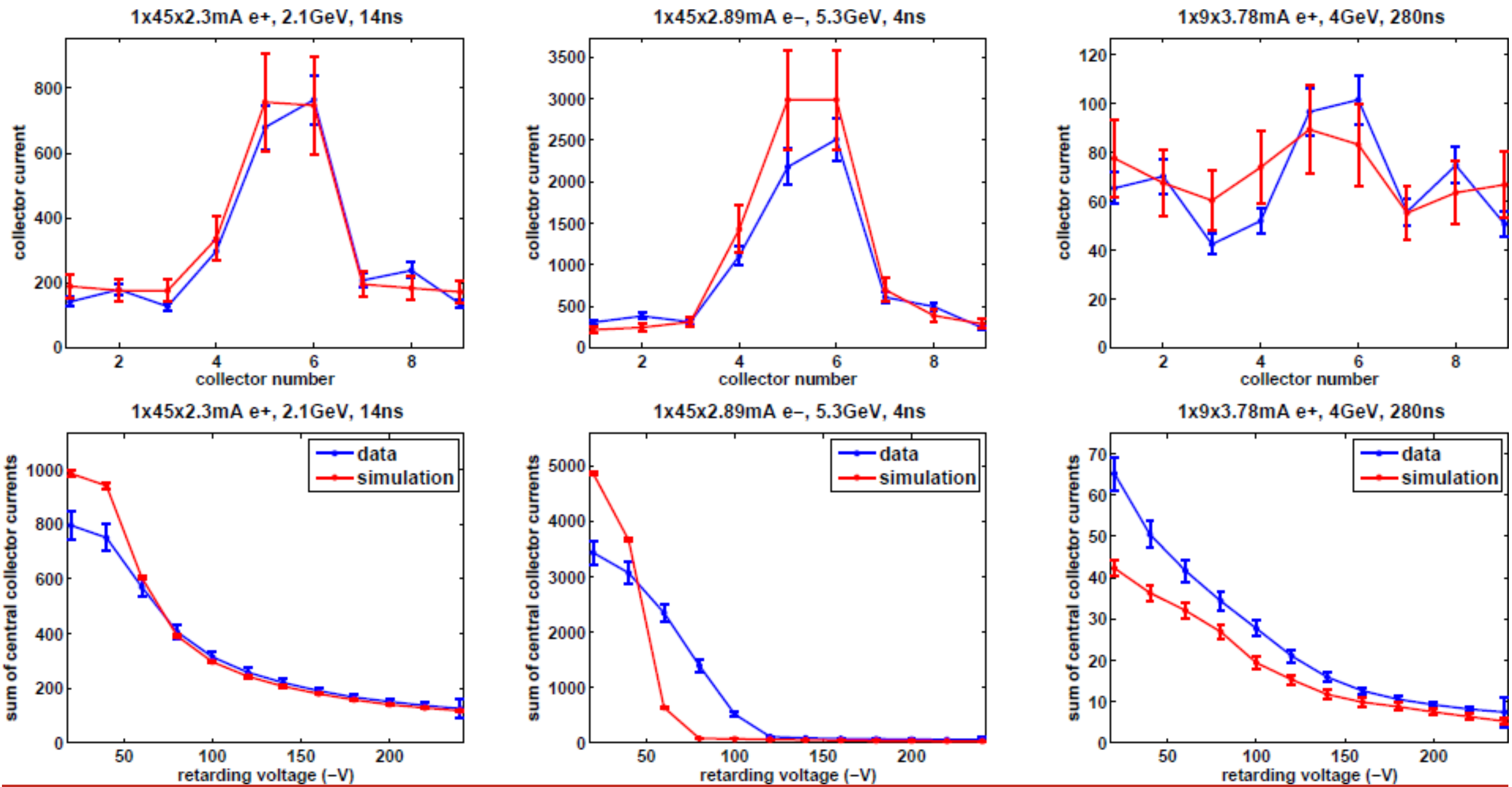
Quantitative Analysis: Example

- Beam conditions used for one round of fitting, and EC model parameters which are sensitive to conditions are shown
  - Peak SEY determined by data with moderately high current, short spacing (where typical cloud electron has E ≈ 300 eV)
  - Low energy yield determined by high bunch spacing data
  - Quantum efficiency determined by low current data

Bunches	Bunch current	Bunch Spacing	Beam Energy	Parameter
45 e^-	2.89 mA	4 ns	5.3 GeV	δ_{max}
45 e^+	2.3 mA	14 ns	2.1 GeV	
20 e^+	7.5 mA	14 ns	2.1 GeV	
20 e^-	2.8 mA	14 ns	5.3 GeV	
20 e^+	2.8 mA	4 ns	4 GeV	
9 e^-	3.78 mA	280 ns	2.1 GeV	$\delta(0)$
20 e^+	10.75 mA	14 ns	5.3 GeV	
9 e^+	3.78 mA	280 ns	2.1 GeV	
9 e^+	3.78 mA	280 ns	4 GeV	
9 e^+	4.11 mA	280 ns	5.3 GeV	
45 e^+	0.75 mA	14 ns	5.3 GeV	Q.E.
45 e^-	1.25 mA	4 ns	5.3 GeV	
45 e^+	0.75 mA	14 ns	4 GeV	
45 e^+	0.75 mA	14 ns	2.1 GeV	
45 e^-	2 mA	14 ns	2.1 GeV	

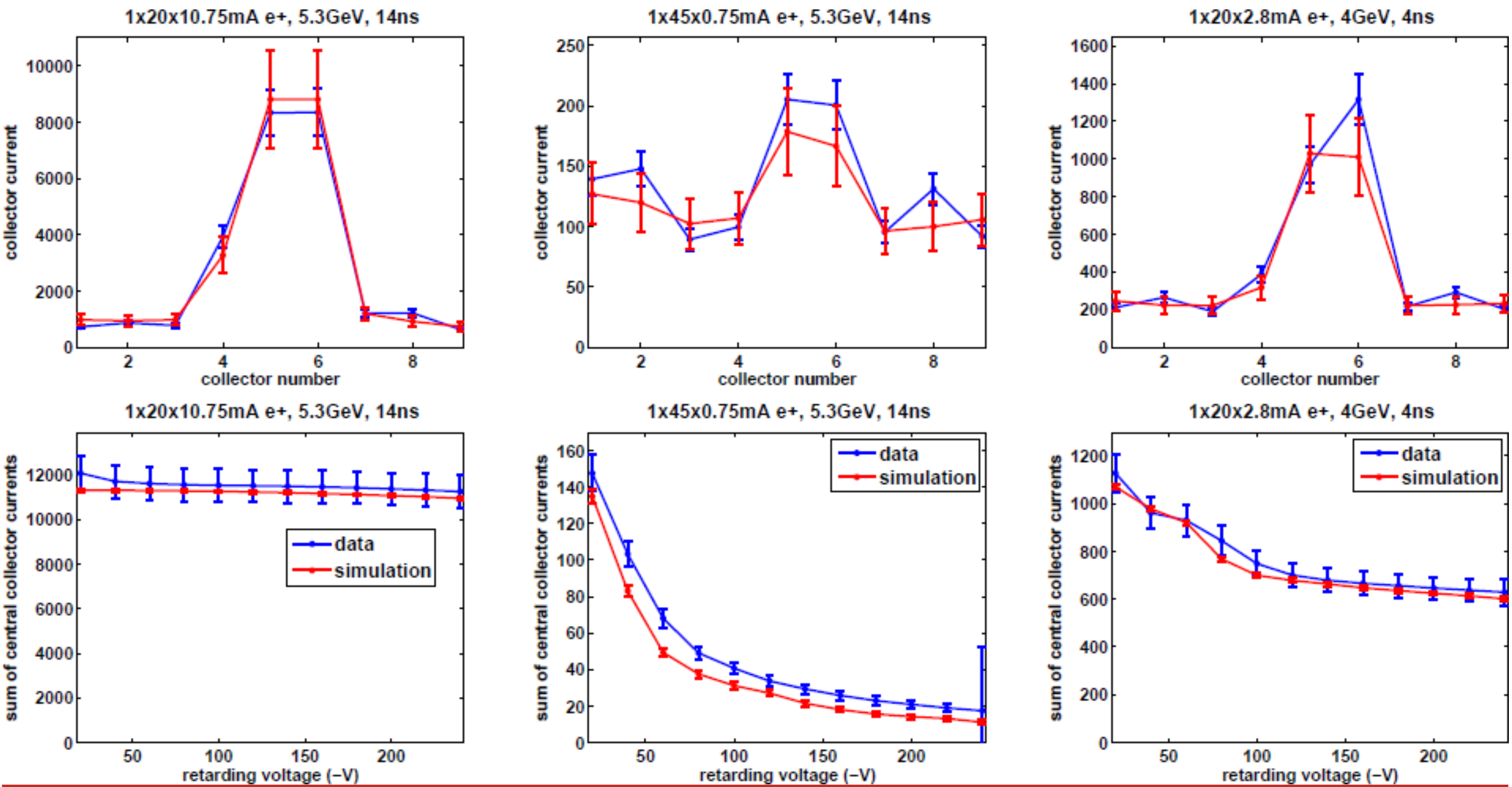
Fit Results I

- Top plots show transverse distribution, bottom plots show retarding voltage scan
  - Data in blue, simulation in red



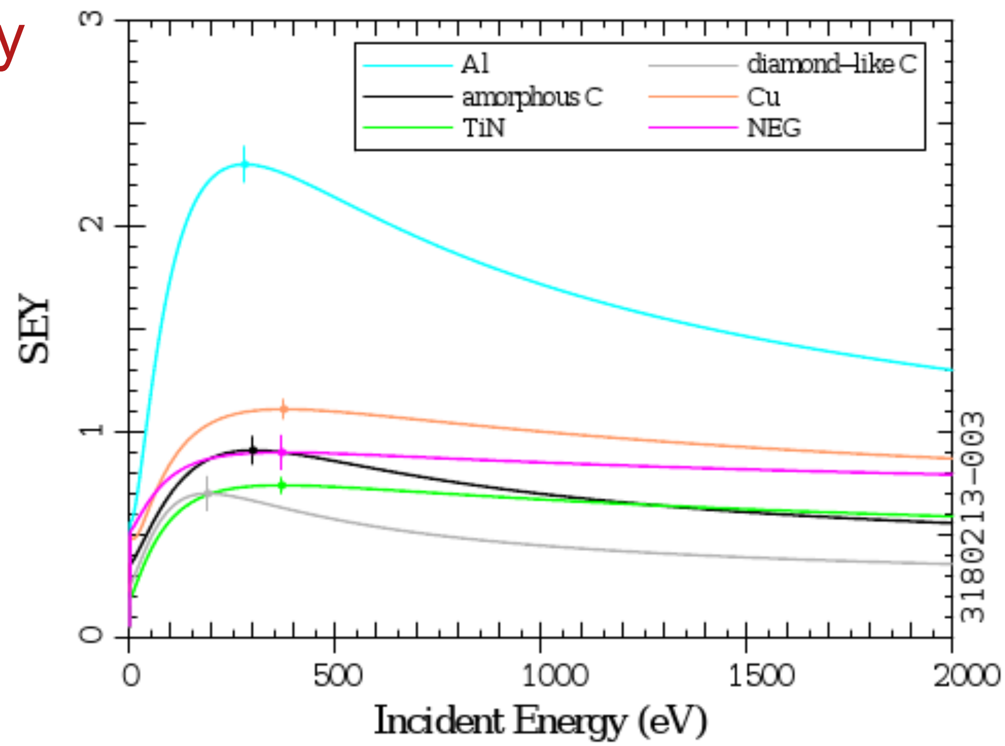
Fit Results II

- Top plots show transverse distribution, bottom plots show retarding voltage scan
  - Data in blue, simulation in red



Best Fit Parameters

- Have obtained best fit primary and secondary emission parameters for all instrumented surfaces
  - Table shows results for Al chamber
  - Plot shows best fit SEY curves
  - TiN and DLC have lowest SEY
    - Some question about effect of charging in DLC
  - aC has lowest quantum efficiency

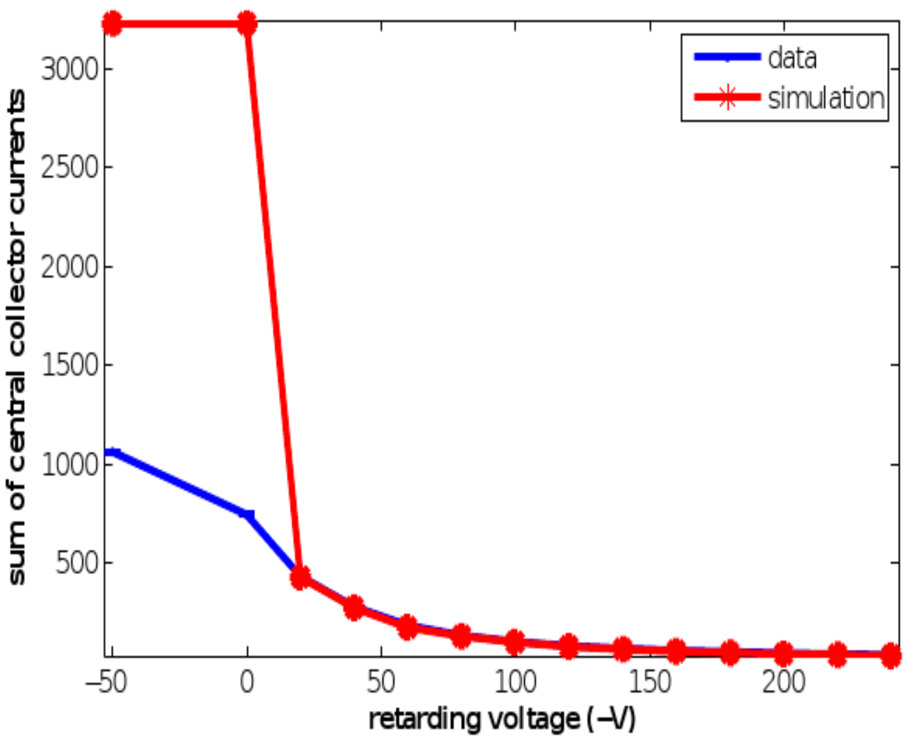


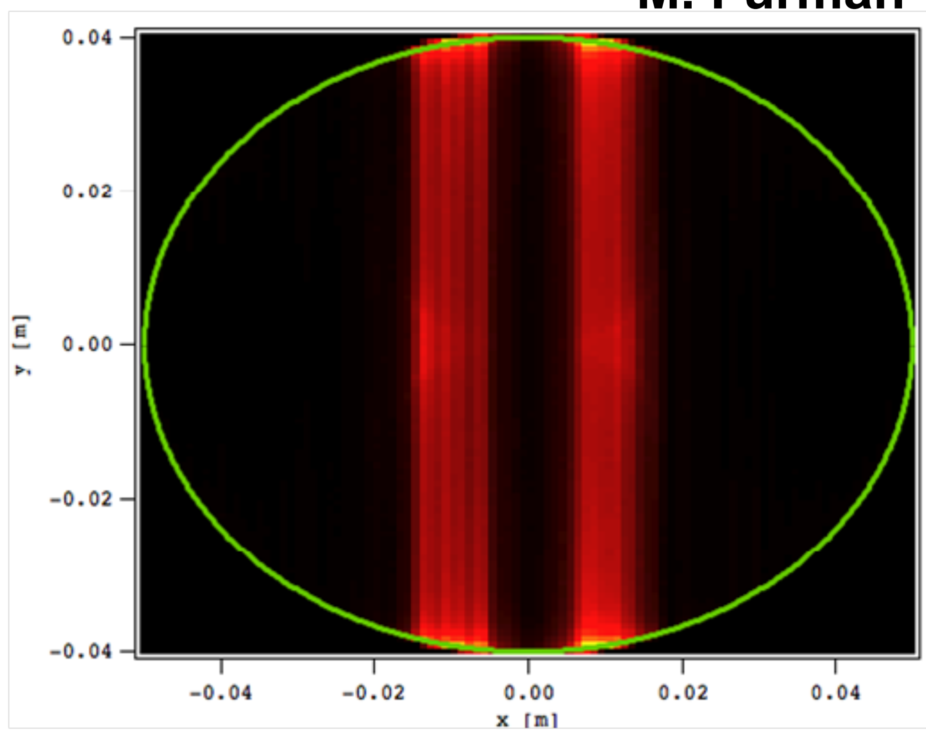
Parameter	Base	Best Fit
True secondary yield (δ_{ts})	1.37	2.08 ± .09
Elastic yield (δ_0)	.5	.36 ± .03
Rediffused yield (δ_{red})	.2	.2
Peak yield energy (E_{ts})	280 eV	280 eV
Quantum efficiency, 5.3 GeV	.1	.11 ± .01
Quantum efficiency, 2.1 GeV	.1	.08 ± .01

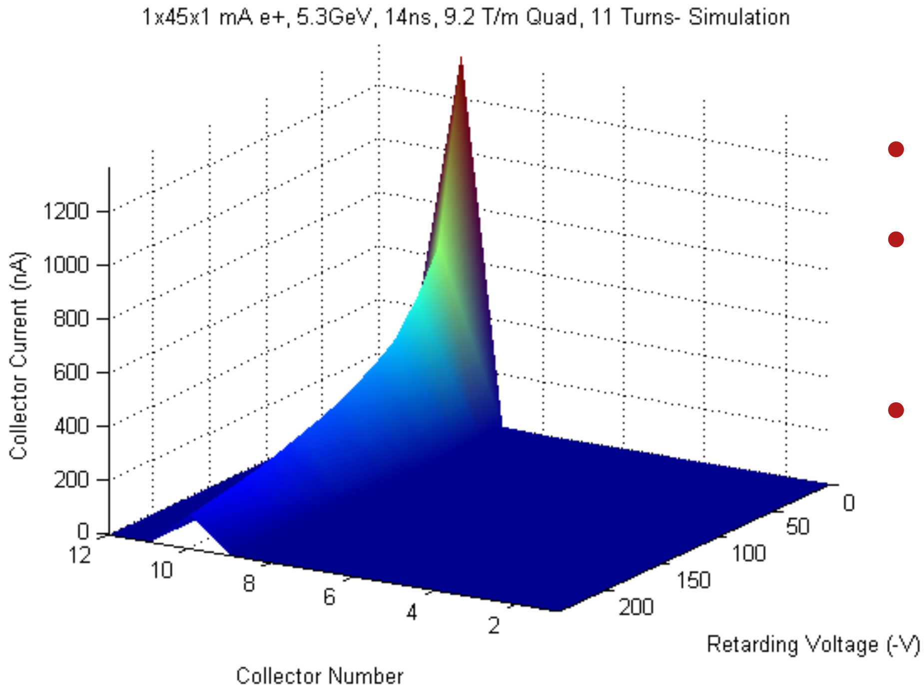
Dipole Simulations

- Different concerns than drift
  - Interaction between cloud and RFA due to approximately one dimensional nature of electron movement
    - RFA depletes the cloud it's measuring!
  - Worse with higher dipole field, lower energy electrons
- Fitting data has proved challenging
- Do observe qualitative phenomena (e.g. bifurcation)

M. Furman

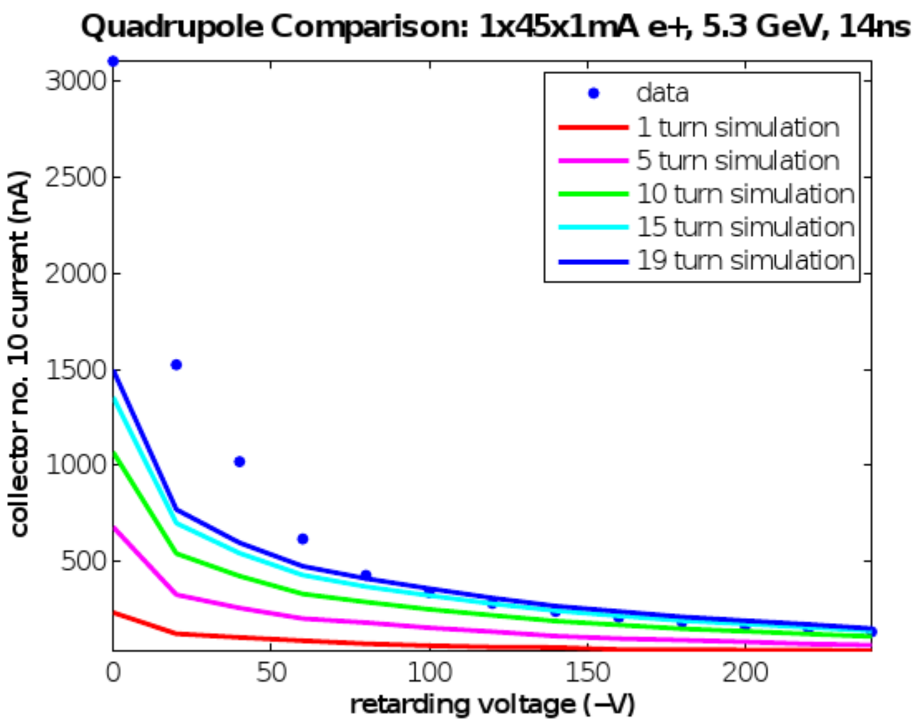




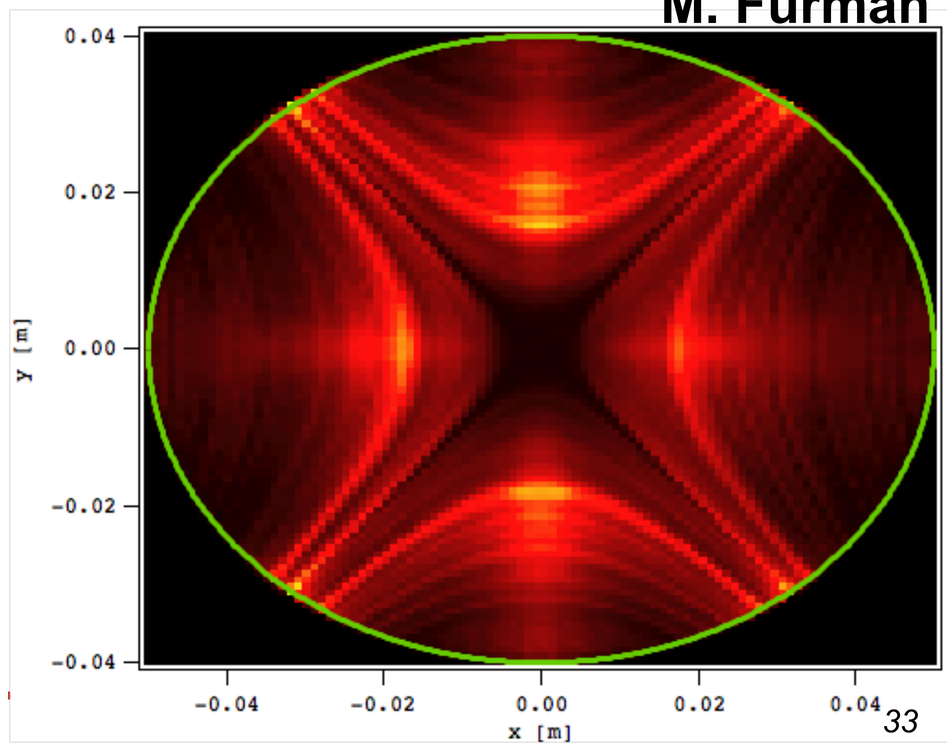


Quadrupole Simulations

- Cloud particles follow field lines
- Also predict most signal will be in collector 10
- Suggest long term trapping of cloud
  - Multi-turn simulation needed to reach equilibrium

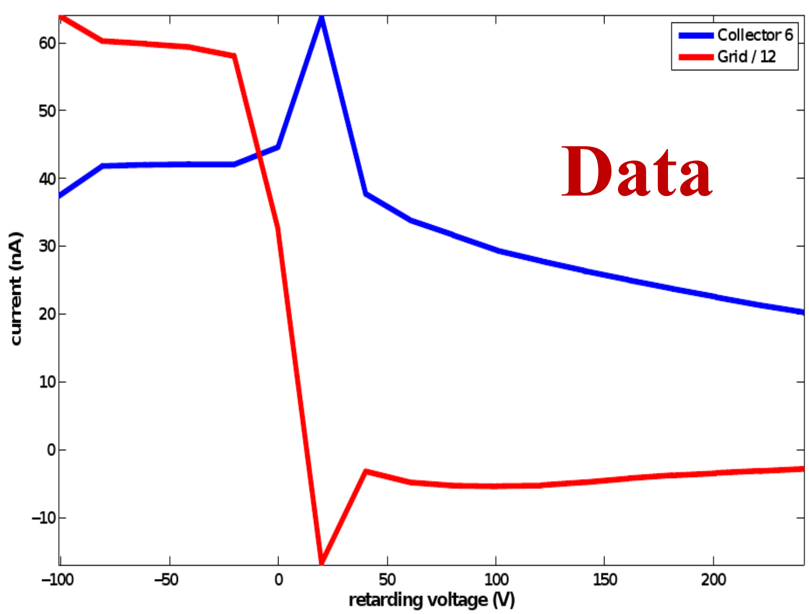


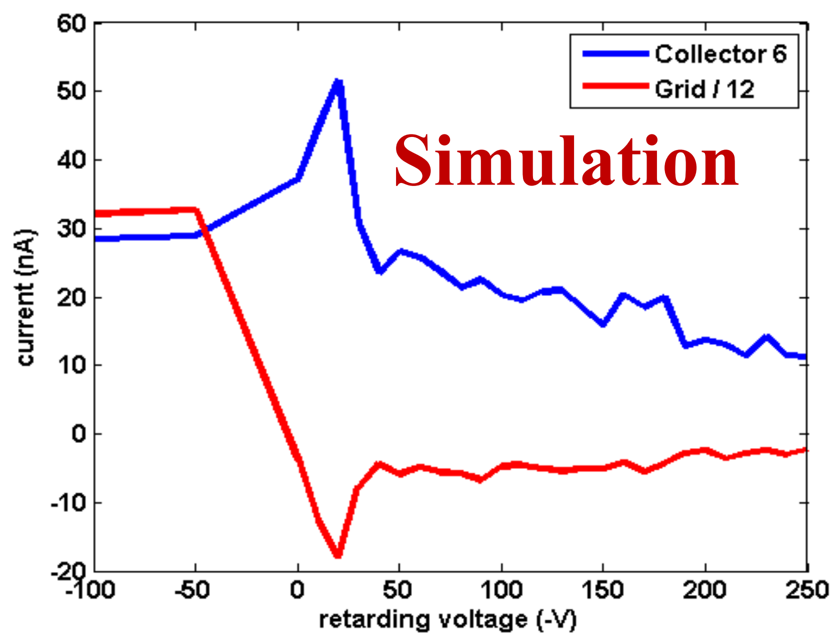
M. Furman



Wiggler Simulations

- In the wiggler data, we observe an anomalous spike in current at low (but nonzero) retarding voltage
  - Due to a resonance between the voltage and bunch spacing
  - Extra signal comes from secondaries produced on the retarding grid
- Need full particle tracking model to observe this in simulation





Conclusions

- Electron cloud is ubiquitous in accelerators
  - Especially with positively charged beams
  - Always bad, often a limiting factor
  - Major issue for next generation machines
- CESR-TA is (among other things) the most extensive investigation of electron cloud in a single machine to date
- Many RFAs have been installed in CESR
  - Drifts, dipoles, quadrupole, wigglers
  - Different mitigations: coatings, grooves, clearing electrode…
    - Coatings effective in drifts, dipoles, and quads
    - Grooves effective in dipoles and wigglers
    - Coating + grooves is better than either individually
    - Wiggler: clearing electrode best option
  - Measurements taken under a wide variety of beam conditions
    - Helps for pinning down different SEY and PEY parameters
  - Interesting phenomena observed
    - Bifurcation in a dipole, long term trapping in quadrupole, RFA interaction with cloud
    - Backup slides: beam-induced multipacting, cyclotron resonances, wiggler field ramp

Conclusions II

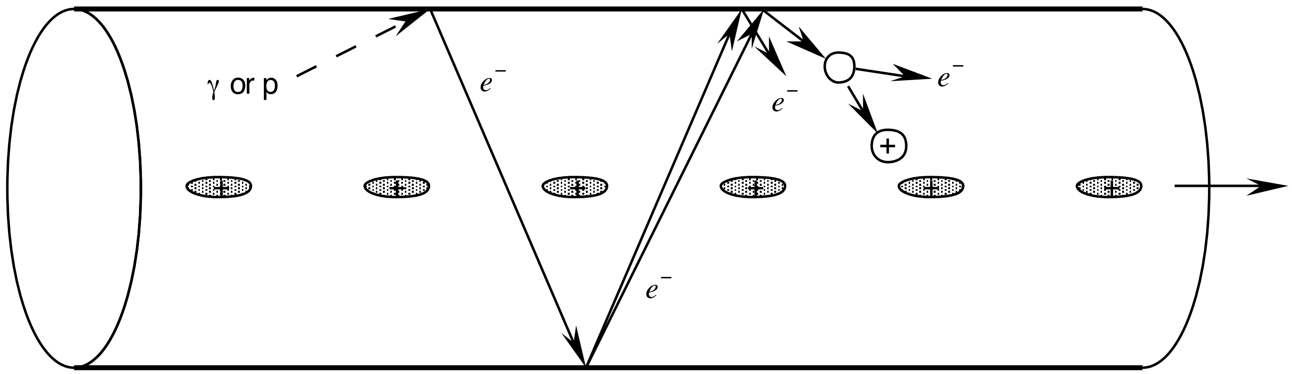
- Quantitative analysis is challenging
  - Requires detailed model of the RFA
    - Drift:
      - After extensive effort, fits to data generally successful across wide variety of beam conditions
      - Result: best fit parameters for different materials
    - Field regions:
      - Qualitative phenomena reproduced
      - Interaction between cloud and RFA significant
      - Fitting is more difficult
- Accomplishments/aspirations:
  - Deeper understanding of the electron cloud
  - Detailed evaluation of different materials/mitigations
  - Validation of buildup codes
  - Input for future machines

Thanks!

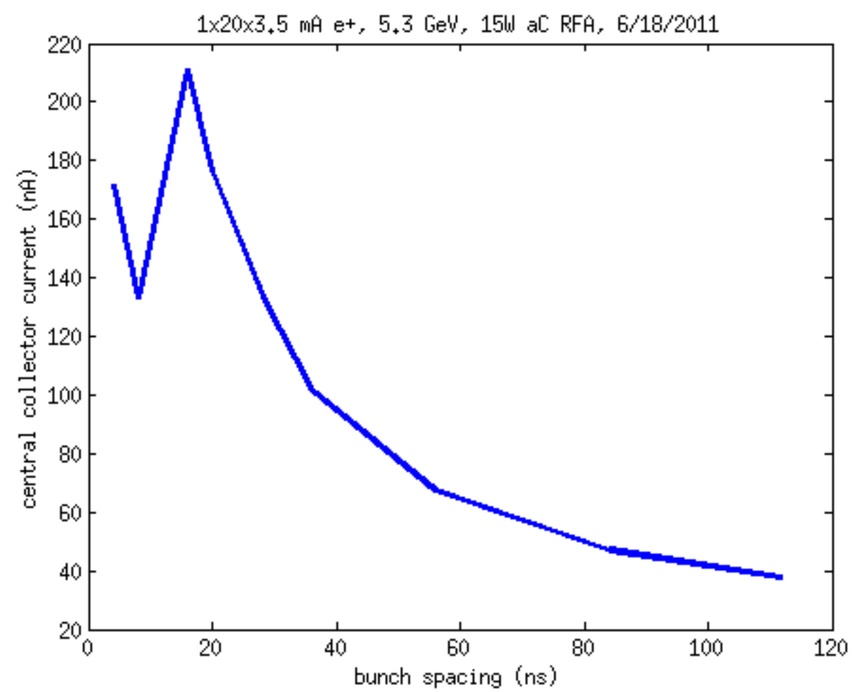
- M. Furman
- G. Dugan, M. Palmer, D. Rubin
- CESR-TA group: L. Bartnik, M.G. Billing, J.V. Conway, J.A. Crittenden, M. Forster, S. Greenwald, W. Hartung, Y. Li, X. Liu, J. Livezey, J. Makita, R.E. Meller, S. Roy, S. Santos, R.M. Schwartz, J. Sikora, and C.R. Strohman
- Collaborators:
  - LBL: C.M. Celata, M. Venturini
  - SLAC: M. Pivi, L. Wang
  - APS: K. Harkay
  - CERN: S. Calatroni, G. Rumolo
  - KEK: K. Kanazawa, S. Kato, Y. Suetsugu
- **You, for your attention**

Backup Slides

Beam-induced multipacting (BIM)

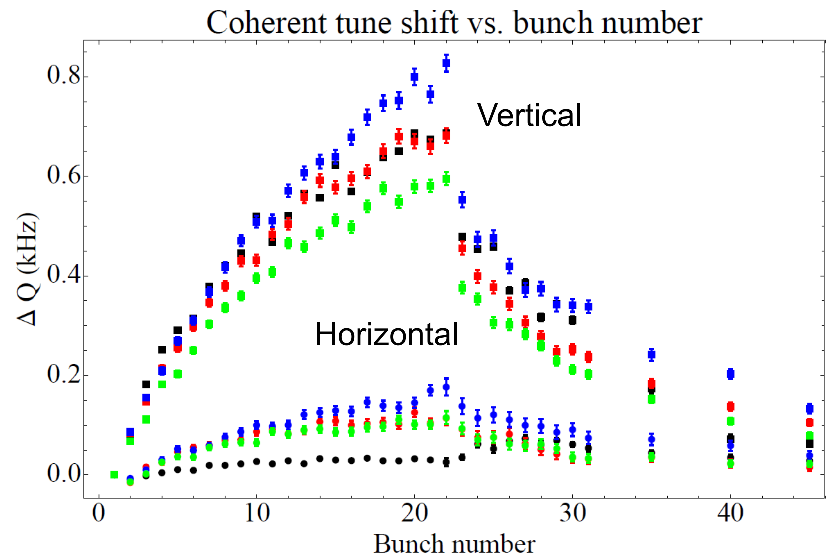


- Low energy electrons near chamber wall kicked by positron beam, given energy E
- Reach opposite wall in time Δt, generate secondaries determined by $\delta(E)$
- Resonant buildup if Δt = bunch spacing and $\delta(E) > 1$
- Has been observed in RFA data



Coherent tune measurements (G. Dugan)

- A large variety of bunch-by-bunch coherent tune measurements have been made, using one or more gated BPM's, in which a whole train of bunches is coherently excited, or in which individual bunches are excited.
- These data cover a wide range of beam and machine conditions.
- The change in tune along the train due to the buildup of the electron cloud has been compared with predictions based on the electron cloud simulation codes (POSINST and ECLOUD).
- Quite good agreement has been found between the measurements and the computed tune shifts. The details have been reported in previous papers and conferences.
- The agreement constrains many of the model parameters used in the buildup codes and gives confidence that the codes do in fact predict accurately the average density of the electron cloud measured in CesrTA.

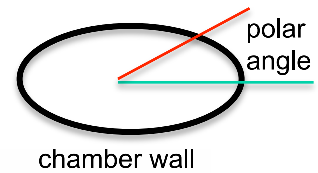


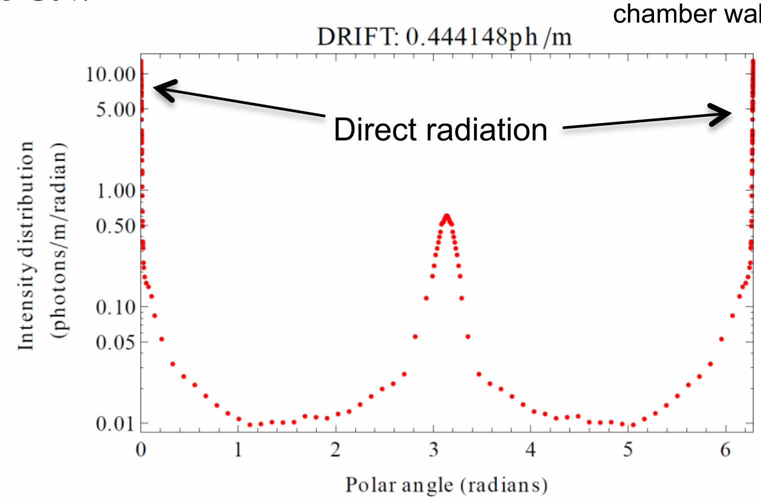
2.1 GeV positrons, 0.5 mA/bunch
Black: data
Blue, red, green: from POSINST simulations, varying total SEY by +/-10%

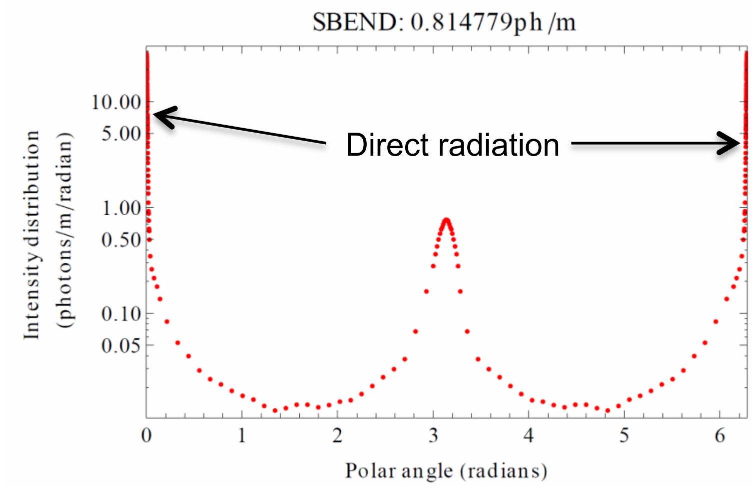
Photon reflectivity simulations (G. Dugan)

- Since synchrotron radiation photons generate the photoelectrons which seed the cloud, the model predictions depend sensitively on the details of the radiation environment in the vacuum chamber. To better characterize this environment, a new simulation program, SYNRAD3D, has been developed.
- This program predicts the distribution and energy of absorbed synchrotron radiation photons around the ring, including specular and diffuse scattering in three dimensions, for a realistic vacuum chamber geometry.
- The output from this program can be used as input to the cloud buildup codes, thereby eliminating the need for any additional free parameters to model the scattered photons.

SYNRAD3D predictions for distributions of absorbed photons on the CesrTA vacuum chamber wall for drift and dipole regions, at 5.3 GeV.

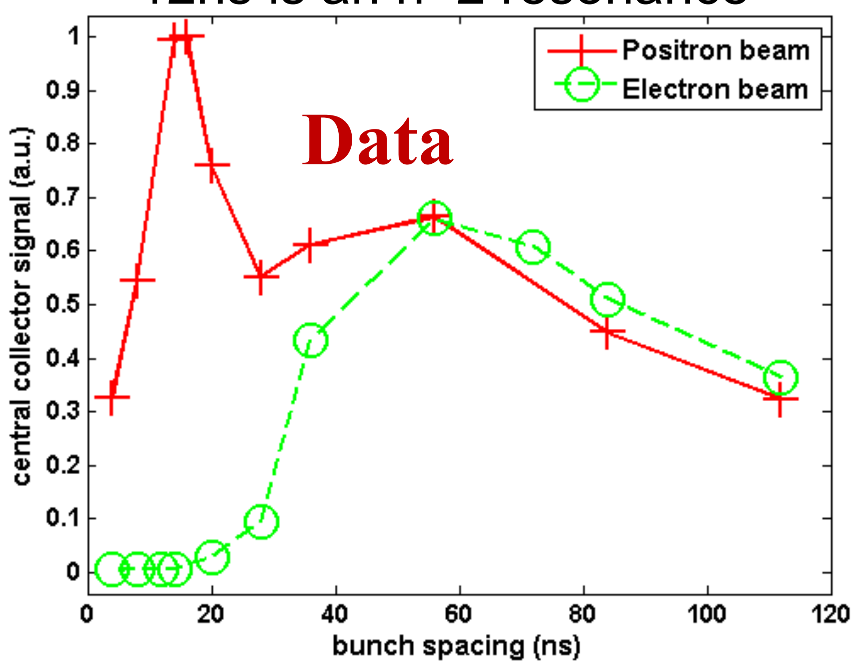


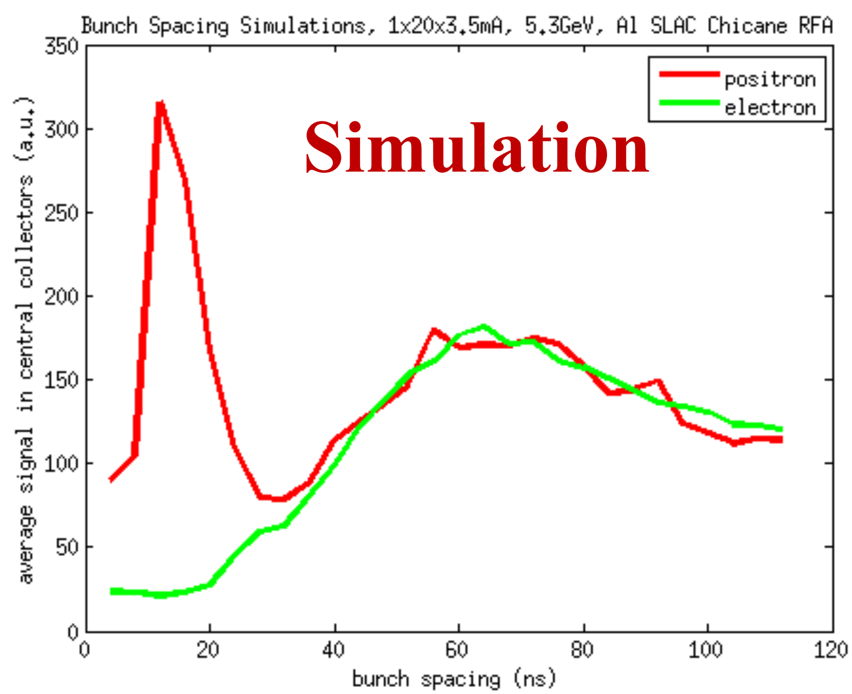




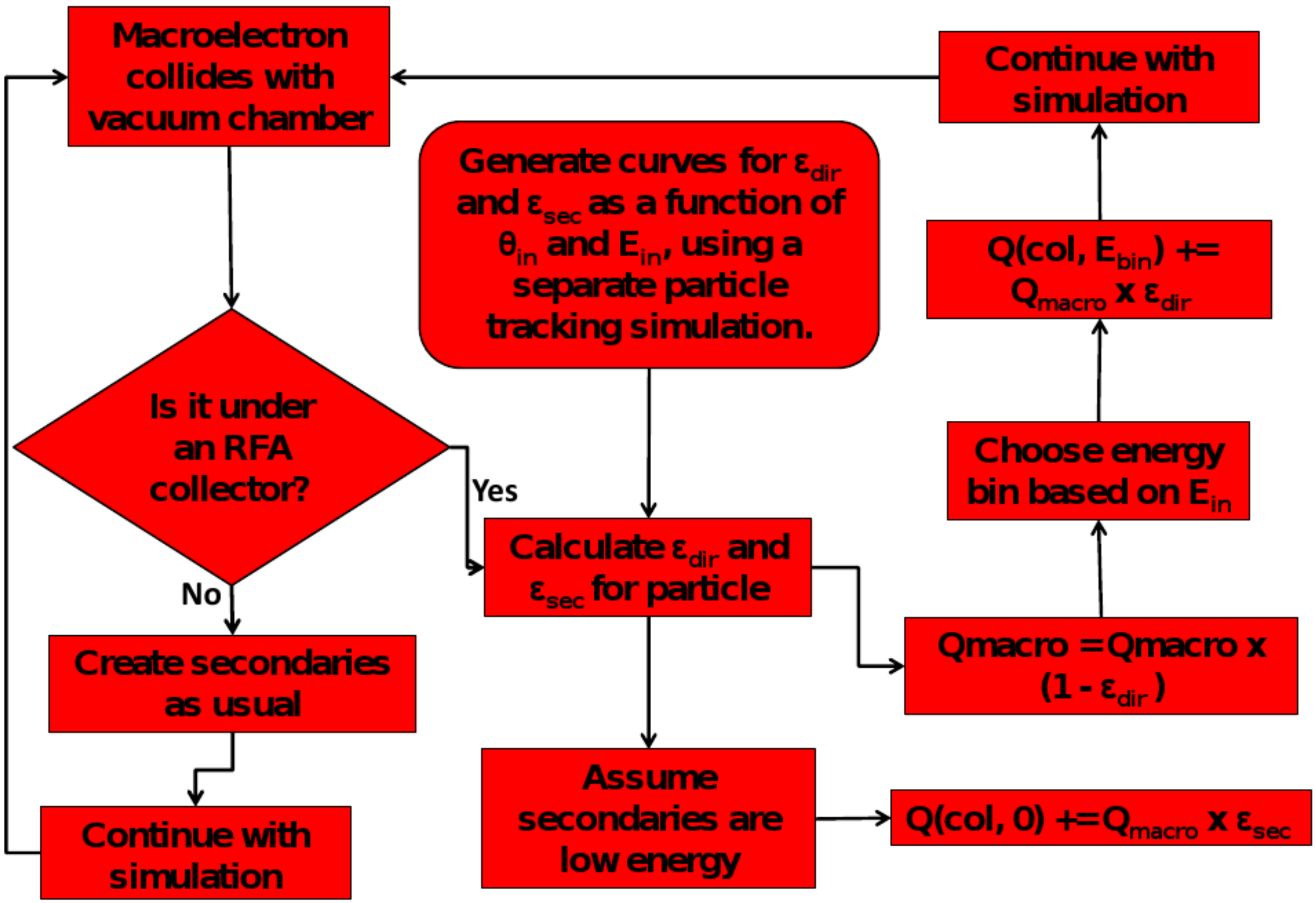
Multipacting Simulations

- Looking at data taken vs bunch spacing, 1x20x3.5mA, 5.3GeV
  - Aluminum SLAC chicane RFA
- Both data and simulation show:
  - strong peak at ~12ns in positron data
  - Broader peak at ~60ns in both electron and positron data
- Theory:
  - 60ns is time for secondary electron to drift into the center of the chamber
  - 12ns is an n=2 resonance



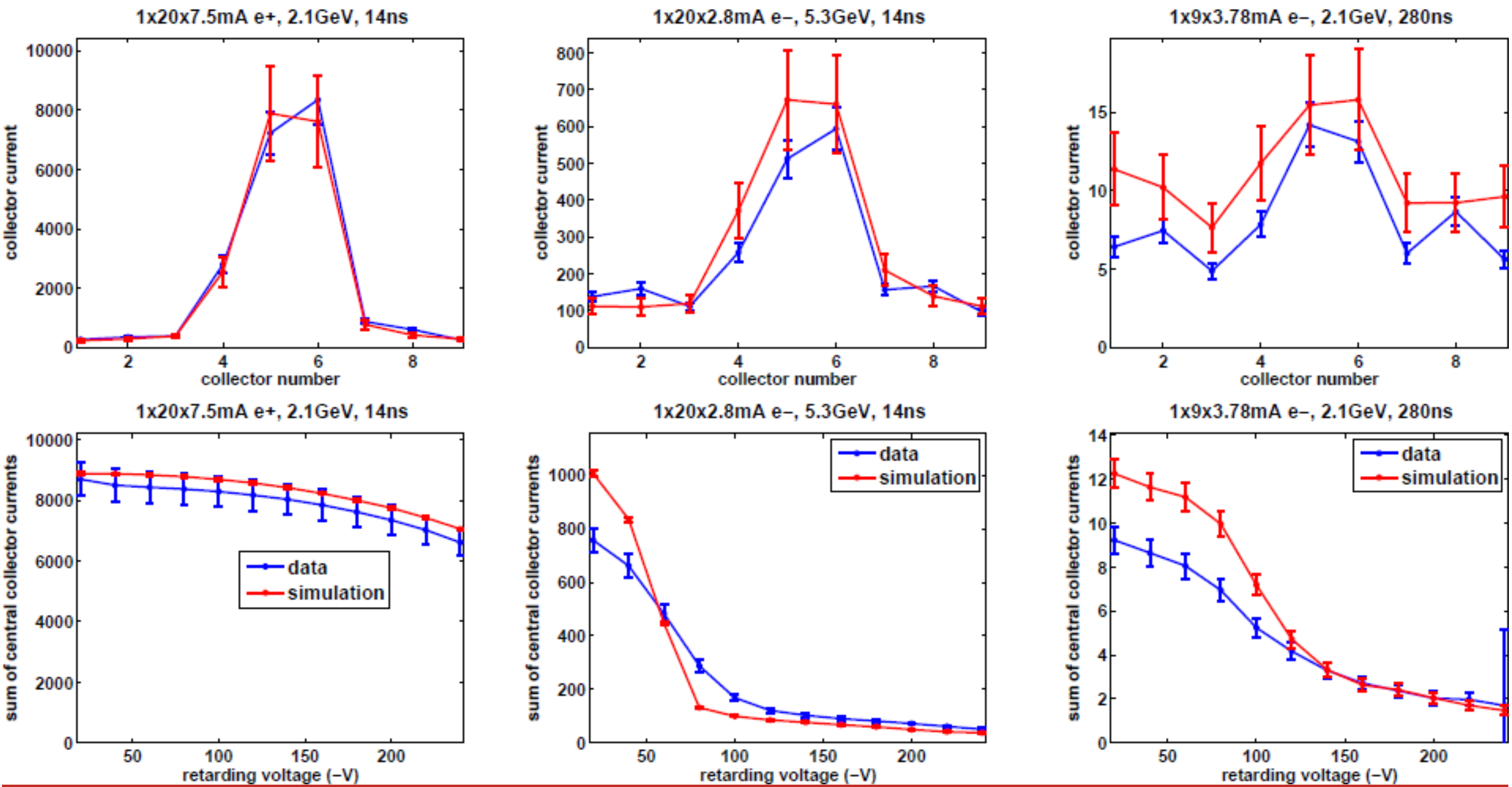


Analytical RFA Model



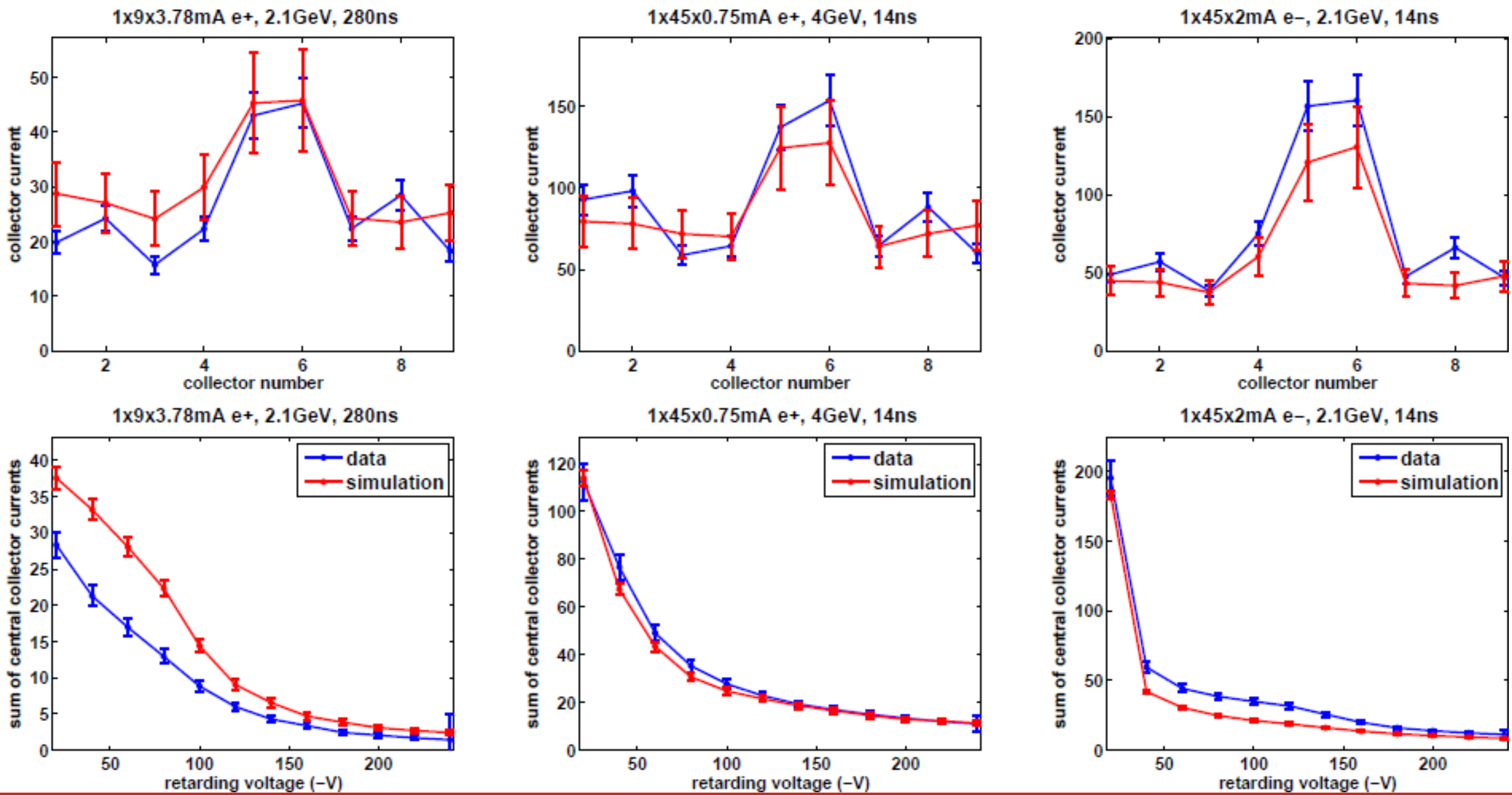
Fit Results III

- Top plots show transverse distribution, bottom plots show retarding voltage scan



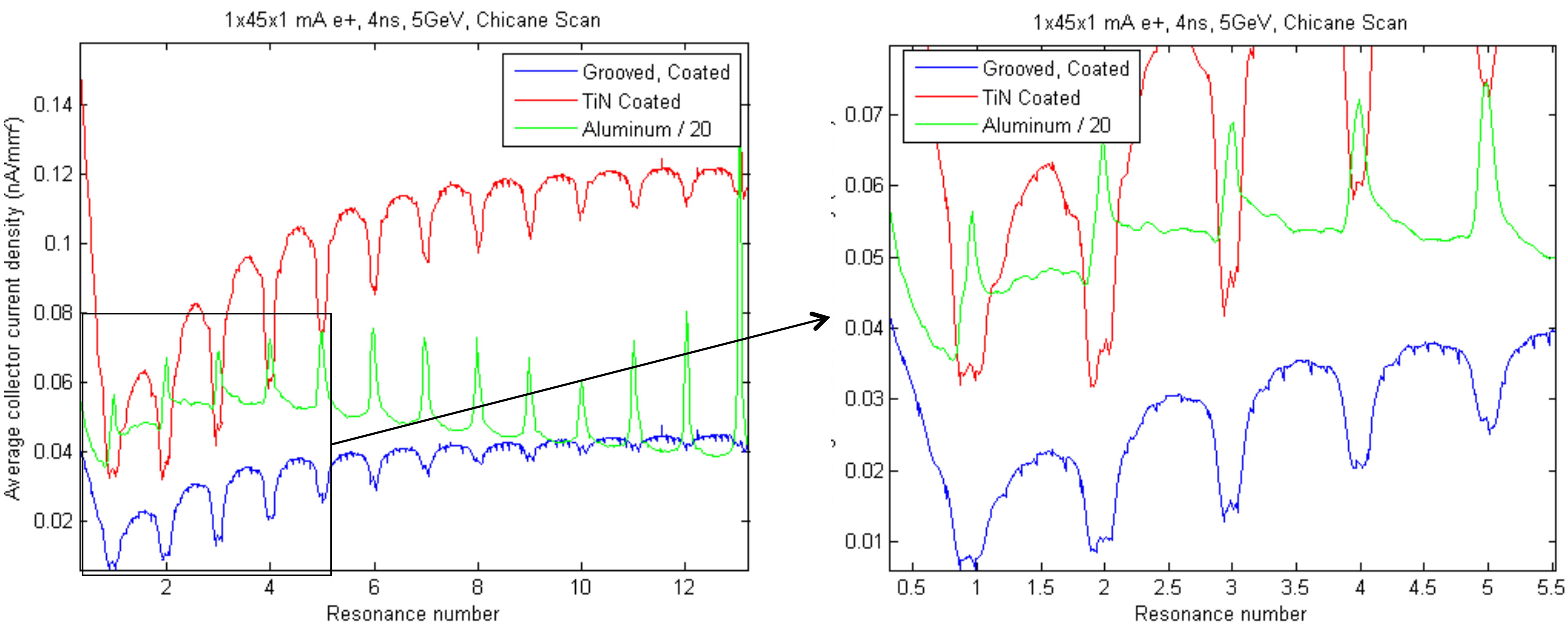
Fit Results IV

- Top plots show transverse distribution, bottom plots show retarding voltage scan



Chicane Field Scan

- 1x45x1 mA, 4ns, 5GeV, positrons
- Plots show sum of all collectors in each RFA
  - Note that Aluminum RFA signal is divided by 20
  - In terms of absolute current, Al >> TiN > Grooved + TiN
- On resonance, there are peaks in the Al chamber and dips in the TiN and grooved chambers
  - Both dips and peaks are exactly on resonance



Wiggler Ramp

- Data taken during wiggler ramp on 12/18/2010
  - Plots show signal in RFA and TEW detectors as a function of wiggler field
    - RFAs = solid lines, Resonant TEW = dotted lines, Transmission TEW = dashed lines
    - Red = further downstream, violet = further upstream
    - All signals normalized to 1 at peak wiggler field
  - Further downstream detectors turn on first
    - TEW 2W-2W ~= TEW 0W-2W ~= RFA 2WB < RFA 2WA < RFA 1W ~= TEW 0W-0W < TEW 0W-2E
    - RFA and TEW turn on points are roughly consistent