Experiments and simulations with clearing electrodes

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Outline

1. E-cloud tools – available for ILC R&D
2. Clearing electrode experiments
3. Clearing electrode simulations
4. Summary

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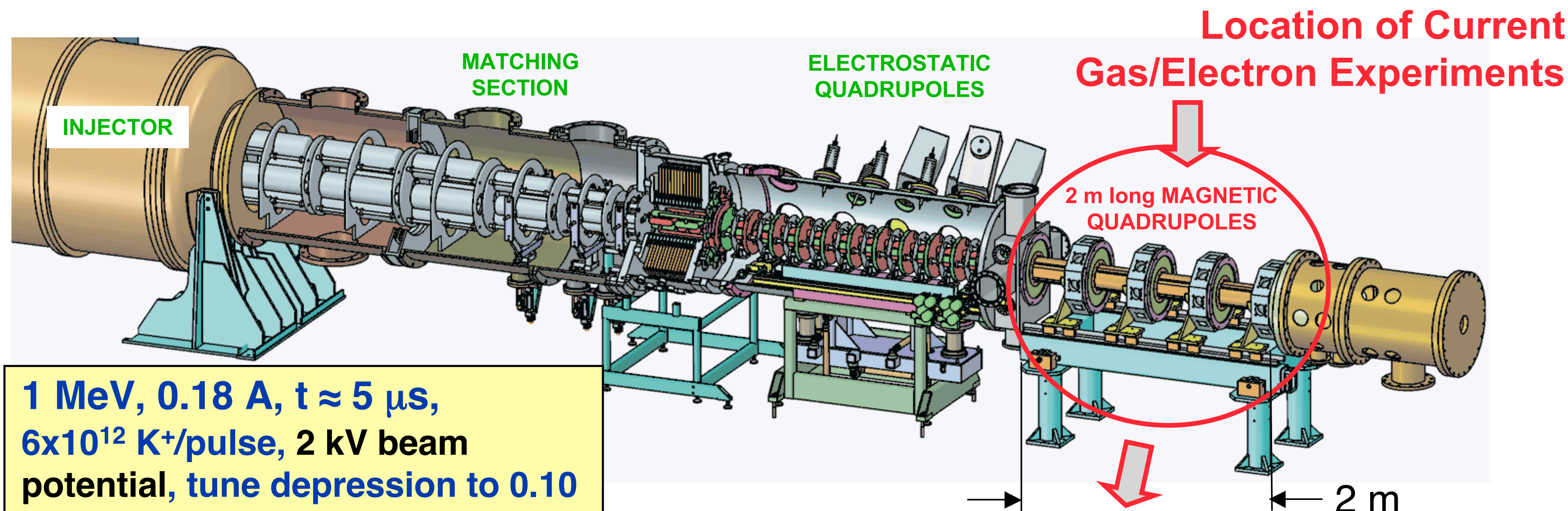
HIFS-VNL has unique tools to study ECE

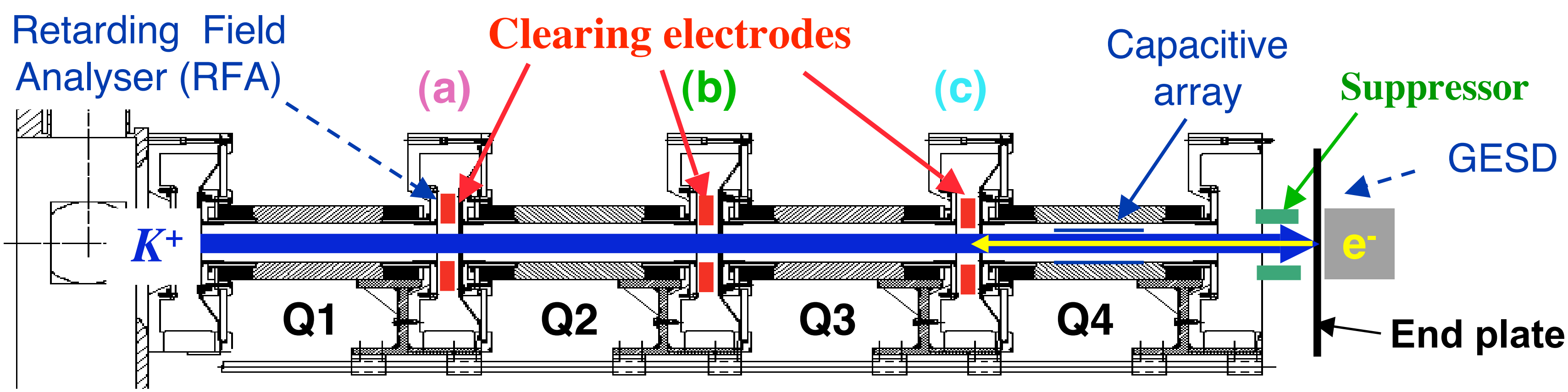
Who we are – The Heavy Ion (Inertial) Fusion Science Virtual National Laboratory (HIFS-VNL) has participants from LLNL, LBNL, and PPPL.

- **WARP/POSINST code goes beyond previous state-of-the-art (Celata)**
  - **Parallel 3-D PIC-adaptive-mesh-refinement code with accelerator lattice follows beam self-consistently with gas/electrons generation and evolution**
- **HCX experiment addresses ECE fundamentals relevant to HEP (as well as WDM and HIF)**
  - **trapping potential ~2kV (~20% of ILC bunch potential) with highly instrumented section dedicated to e-cloud studies**
- **Combination of models and experiment unique in the world**
  - **unmatched benchmarking capability provides credibility**
    - **'Benchmarking' can include: a.** *Code debug*
    - **b. validation against analytic theory**
    - **c. Comparison against codes**
    - **d. Verification against experiments**
  - **enabled us to attract work on LHC, FNAL-Booster, and ILC (2007)**

HCX is available for gas/electron effects studies (at LBNL)

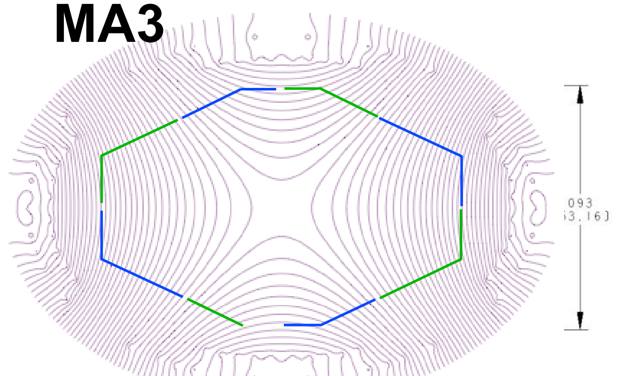


1 MeV, 0.18 A, t ≈ 5 μs,
6×10^{12} K^+/pulse, 2 kV beam potential, tune depression to 0.10

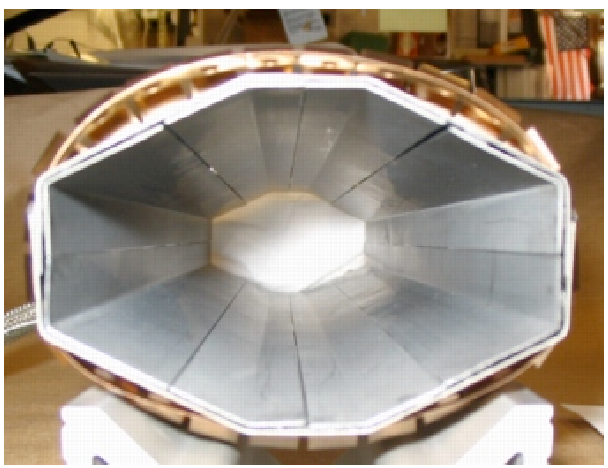


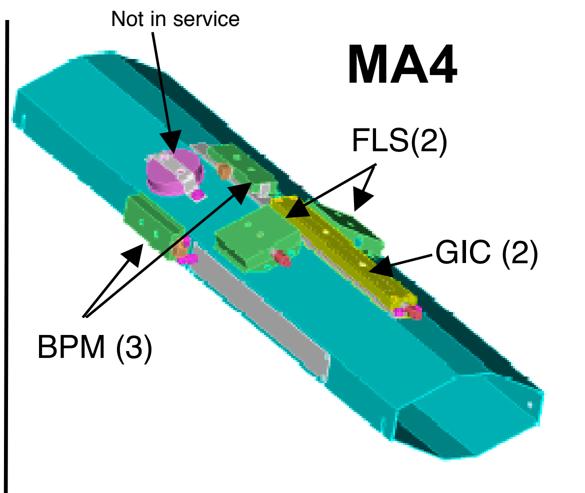
Short experiment => need to deliberately amplify electron effects:
let beam hit end-plate to generate copious electrons which propagate upstream.

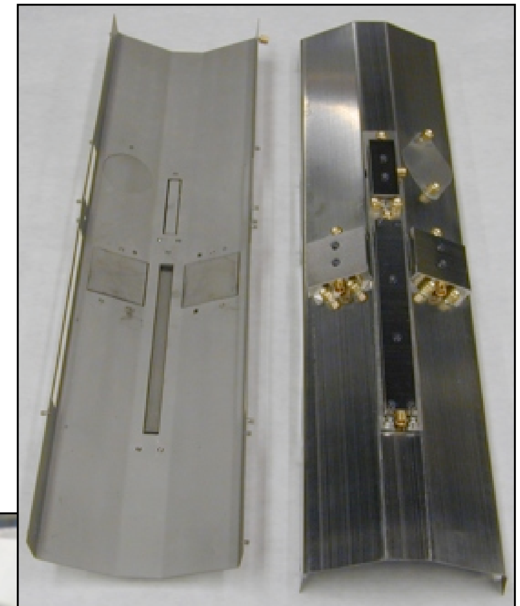
Diagnostics in two magnetic quadrupole bores, & what they measure.

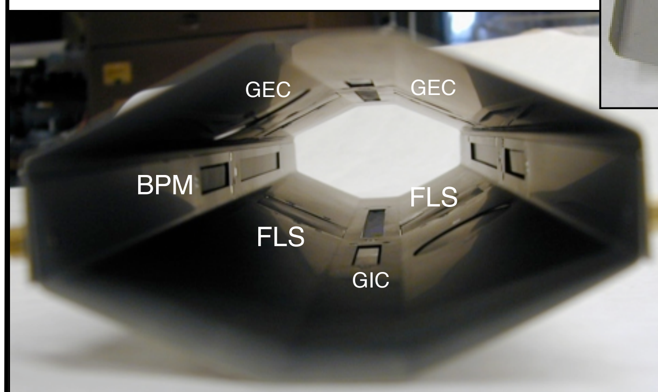


8 “paired” Long flush collectors (FLL): measures capacitive signal + collected or emitted electrons from halo scraping in each quadrant.









3 capacitive probes (BPM); beam capacitive pickup $((n_b - n_e)/ n_b)$.

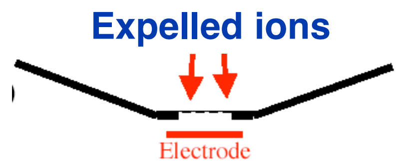
2 Short flush collector (FLS); similar to FLL, electrons from wall.

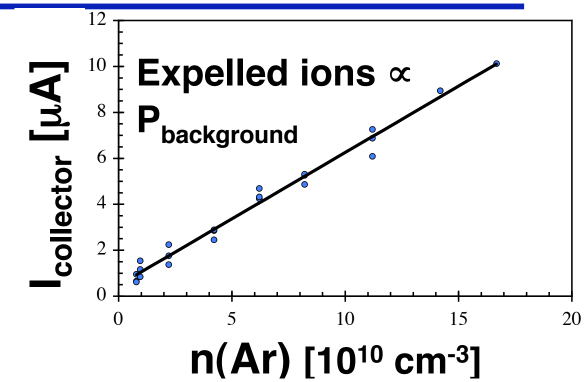
2 Gridded e^- collector (GEC); expelled e^- after passage of beam

2 Gridded ion collector (GIC): ionized gas expelled from beam

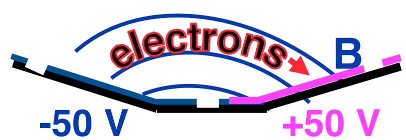
Diagnostics developed to measure all sources and some sinks of electrons

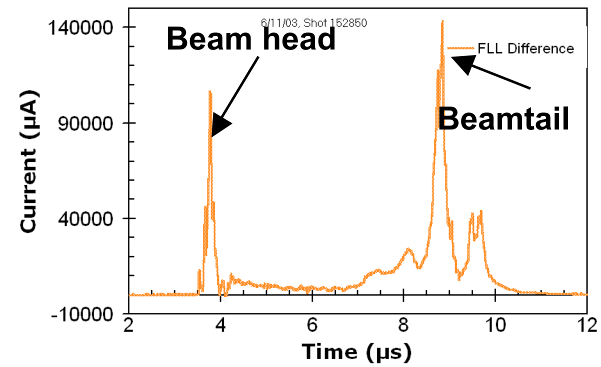
1. Ionization of gas by beam



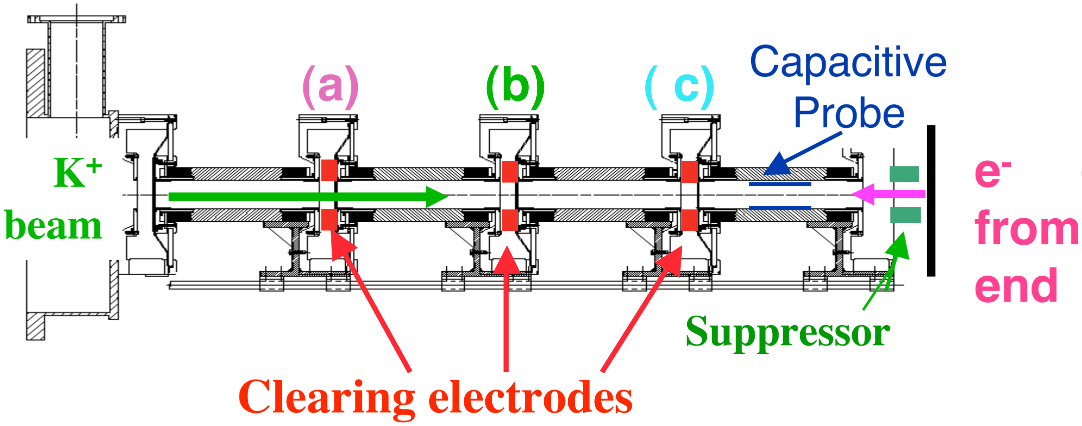


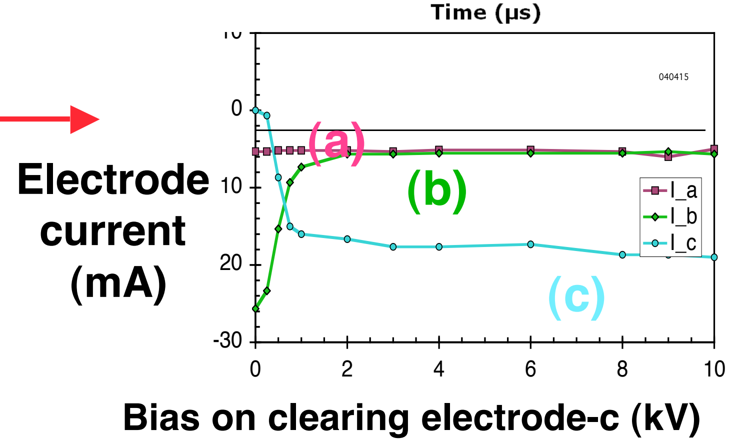
2. Electron emission from wall





3. Axial current of electrons from end





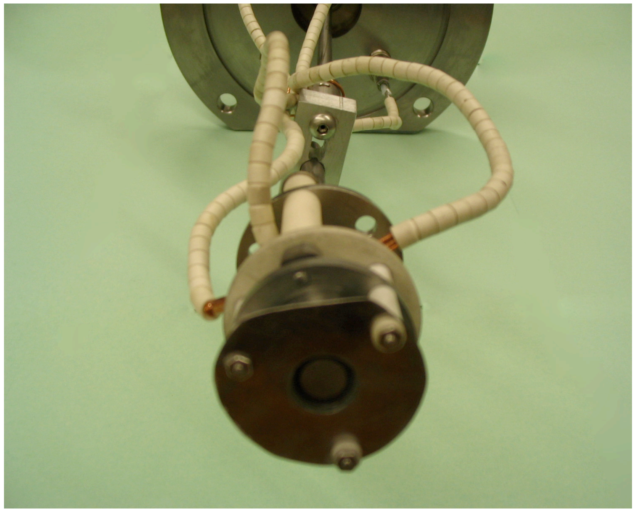
Point source of electrons to simulate synchrotron radiation photoelectrons

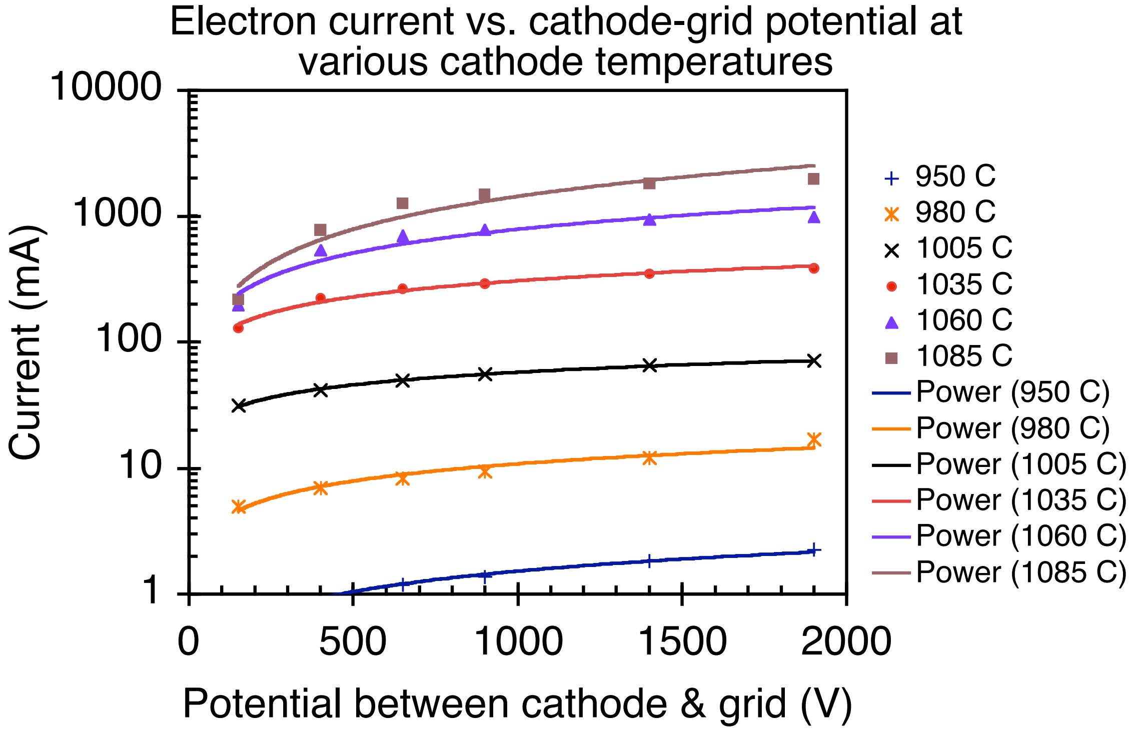
Electron gun enables quantitatively controlled injection of electrons

Electron gun operates over range

~10 eV to 2000 eV (cathode & grid indep.)

<1 mA to 1000 mA





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1. E-cloud tools – available for ILC R&D
2. Clearing electrode experiments
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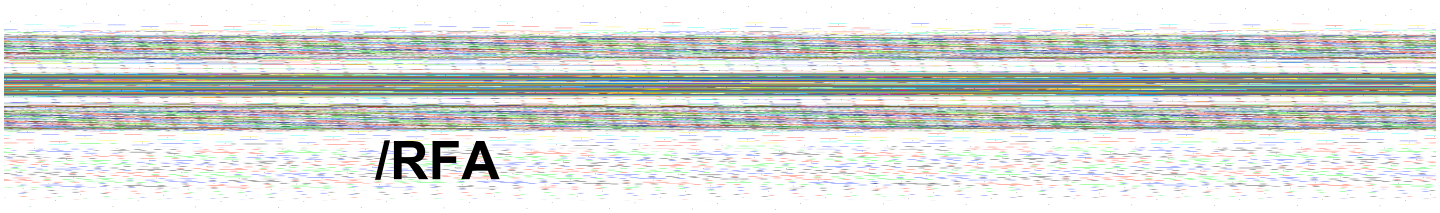
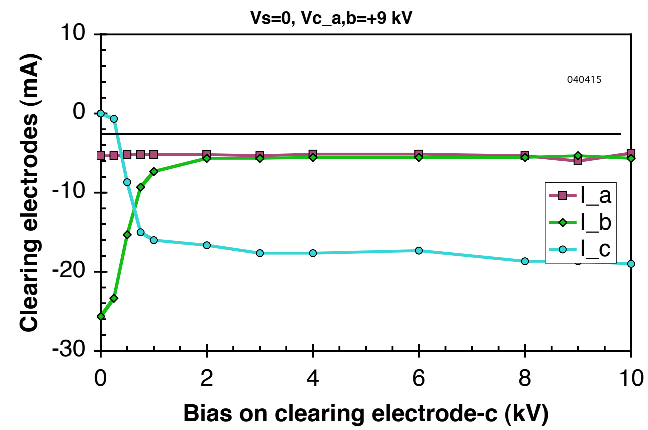
4. Summary

Clearing electrode removes all electrons from a drift region

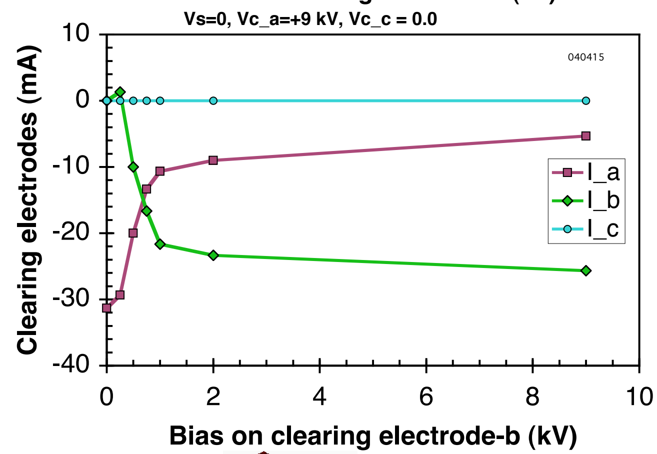


Suppressor bias = 0 V, electrons can leak back into quads along beam.

- **Clearing electrode ring (C) – blocks electrons from (B) when biased more negatively than -3 kV**



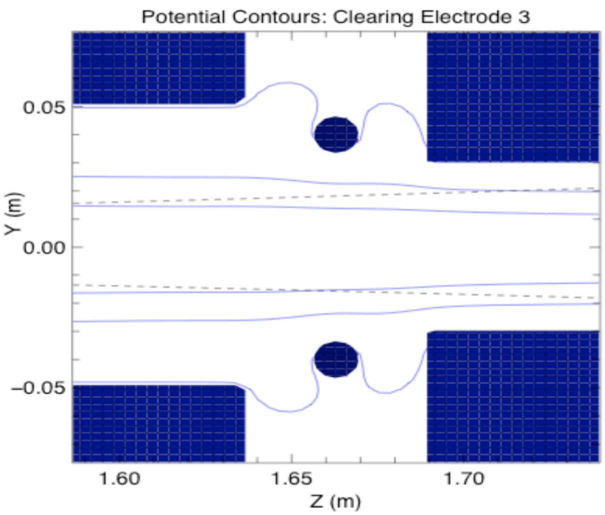
- **Clearing electrode ring (B) [with V_c= 0] blocks electrons from (A) when biased more negatively than -3 kV**



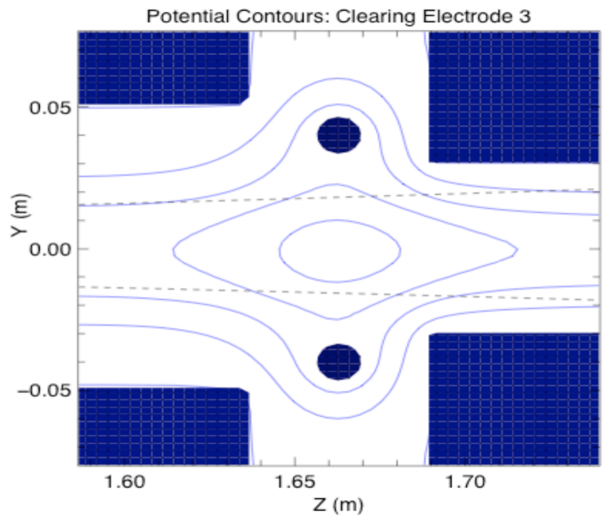
Clearing electrode fields, above 2 kV bias, dominate over beam space-charge field

Beam space-charge potential $\phi_b = +2$ kV

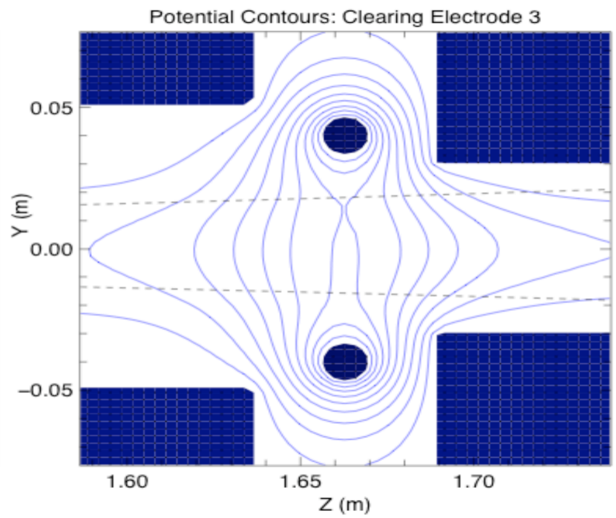
$V_c = 0$ kV
$\phi_b = +2$ kV



$V_c = +2$ kV
$\phi_b = +2$ kV



$V_c = +10$ kV
$\phi_b = +2$ kV



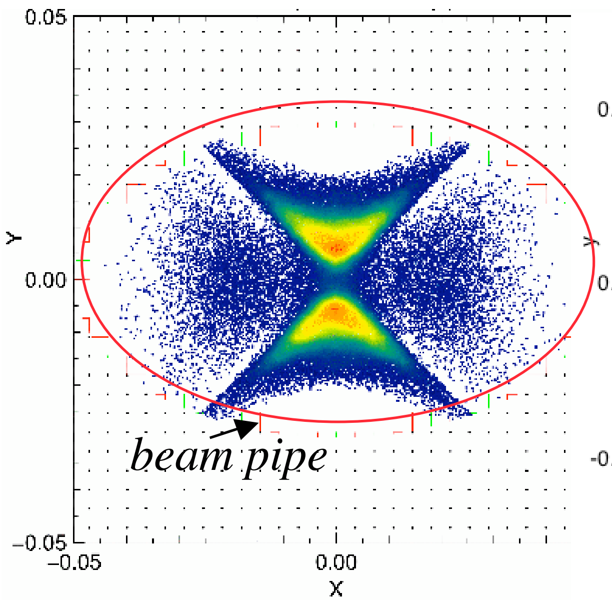
For ILC, probably sufficient for clearing field to dominate over beam space charge averaged over a few bunches (easier), or remove electrons in period between bunches (harder).

Trapping depth of electrons depends upon their source, in a quadrupole magnet (without multipactor)

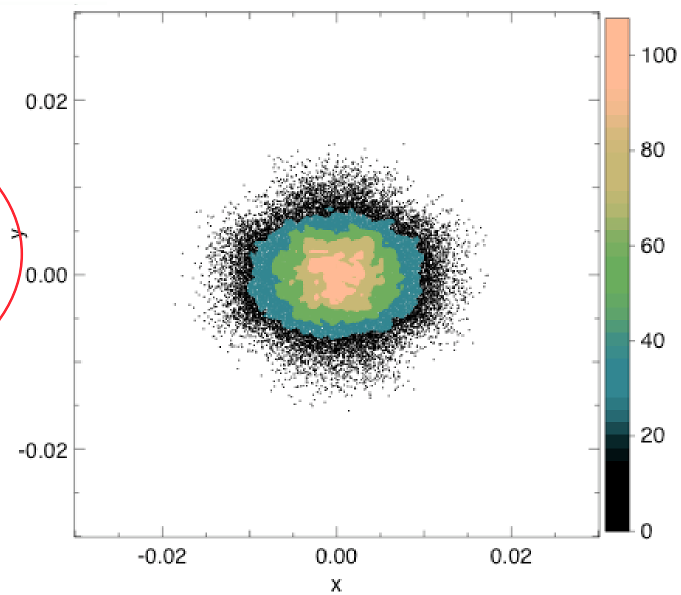
E-cloud in a quadrupole magnet

[Electron mover also speeds simulation in wiggler fields]

Electrons ejected from end wall

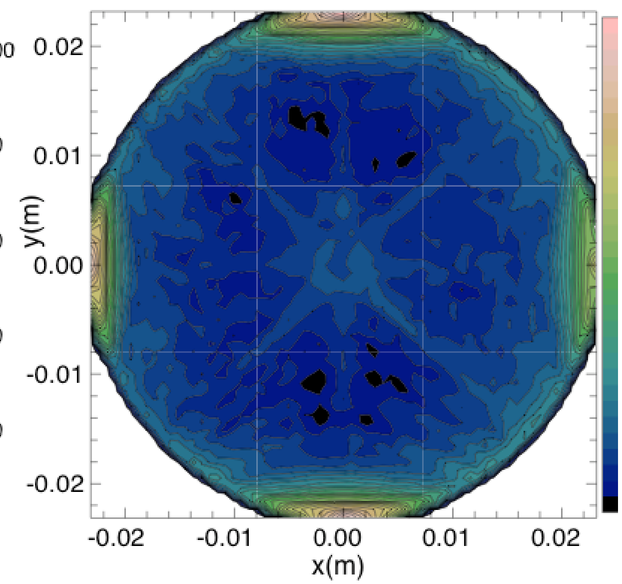


Electrons from ionization of gas



Deeply trapped electrons

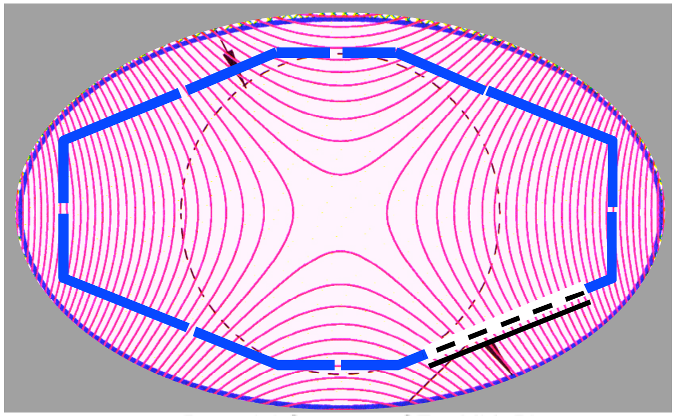
Electrons desorbed from beam pipe in quad upon ion impact



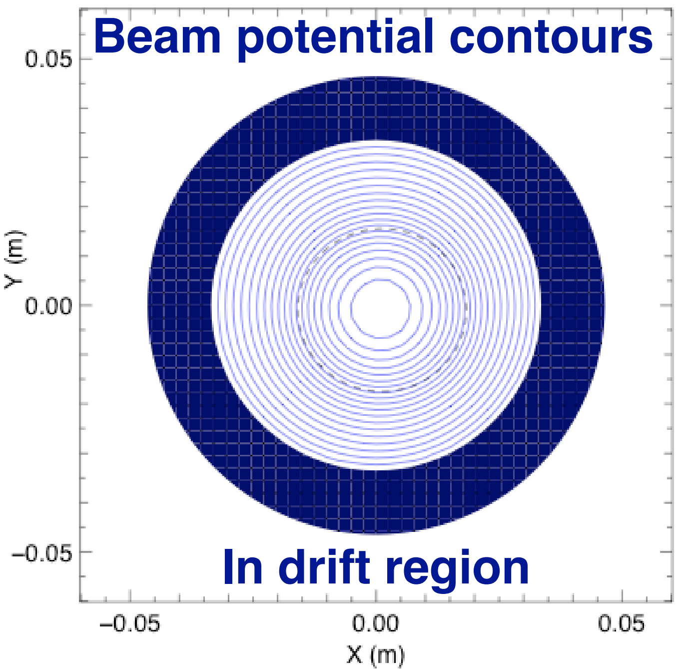
Weakly trapped electrons

Gridded Electron Collectors (GEC) current measures electron depth of trapping

GEC collects e- along B-field lines, detrapped at end of pulse



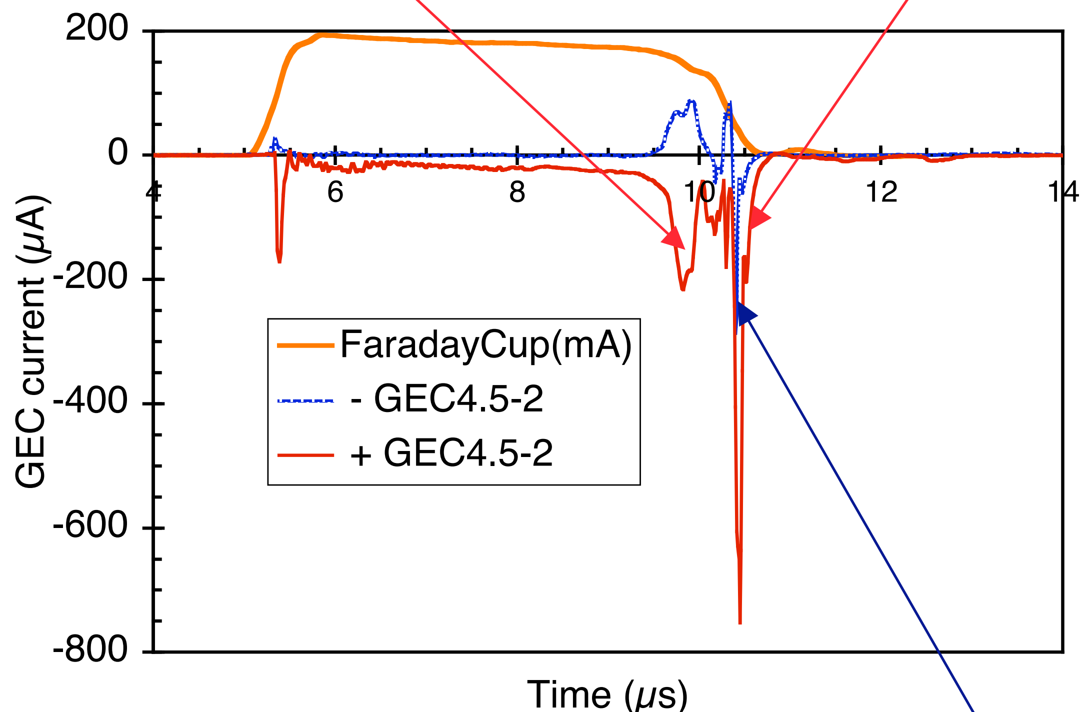
Potential Contours: CE 3 Mid–Plane



HCX current flattops for ~4 μs (like super-bunch)

Weakly-trapped electrons

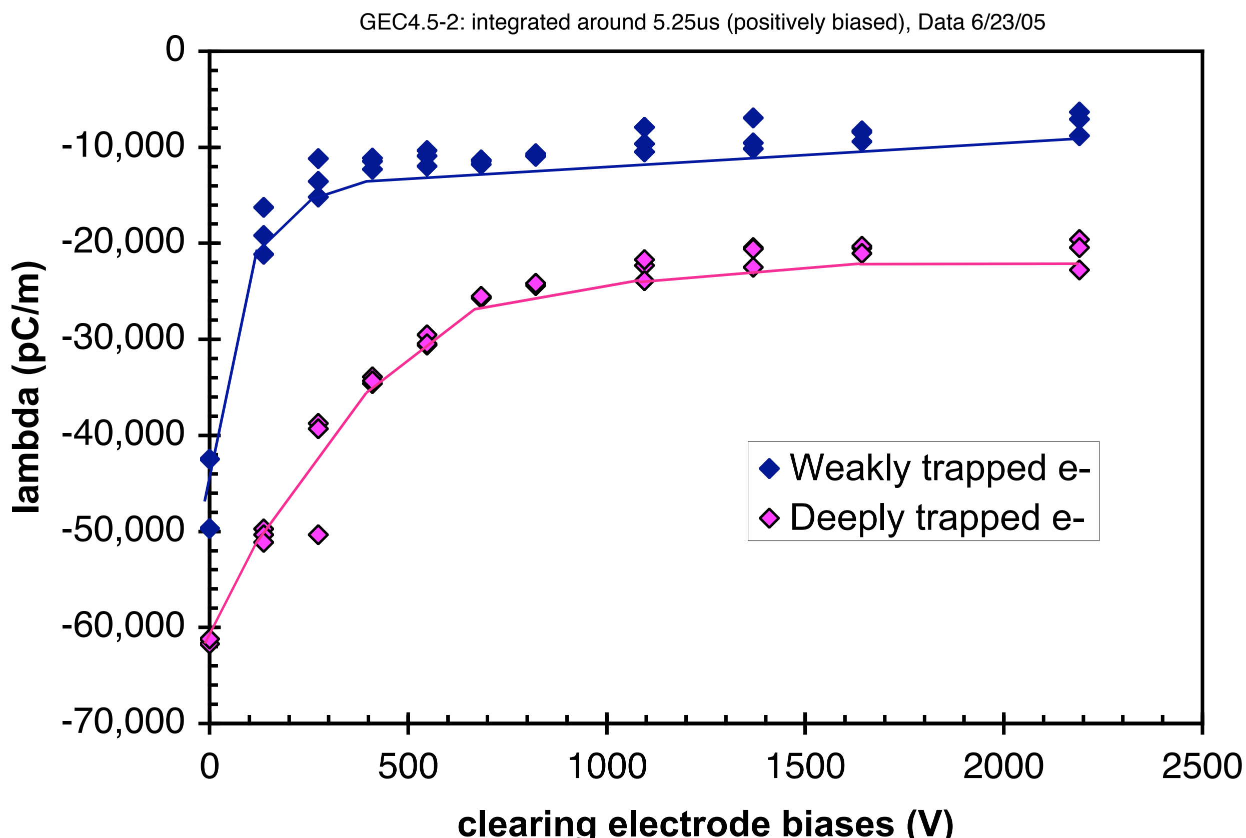
Deeply-trapped electrons



Beam-tail scrapes wall

Weakly trapped electrons cleared with ~300 V bias, whereas deeply trapped require >1000 V

- **Weakly trapped electrons originate on or near a wall (beam tube) – turning points near wall.**
- **Deeply trapped electrons originate from beam impact ionization of gas, or scattering of weakly trapped electrons – turning points within beam.**



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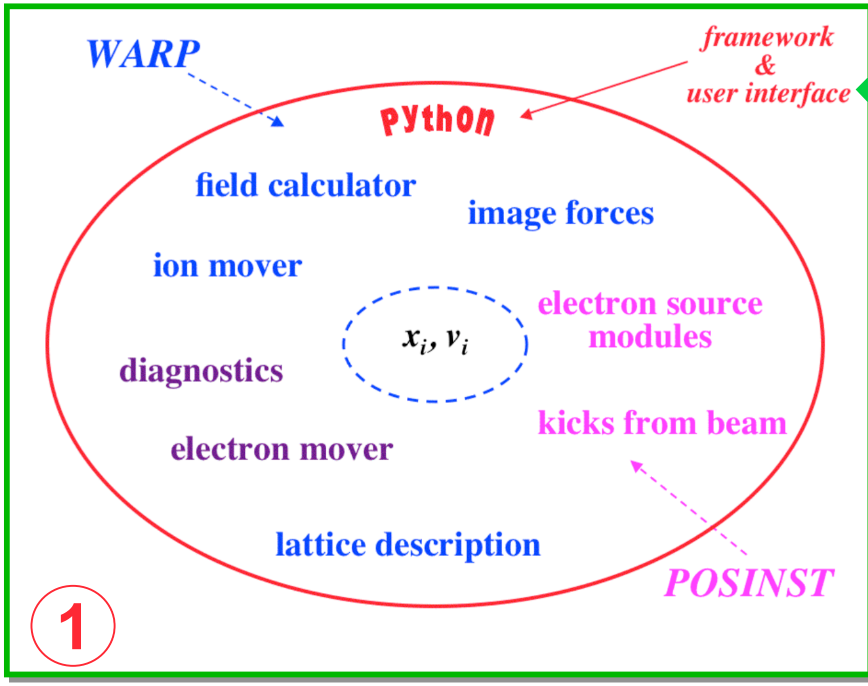
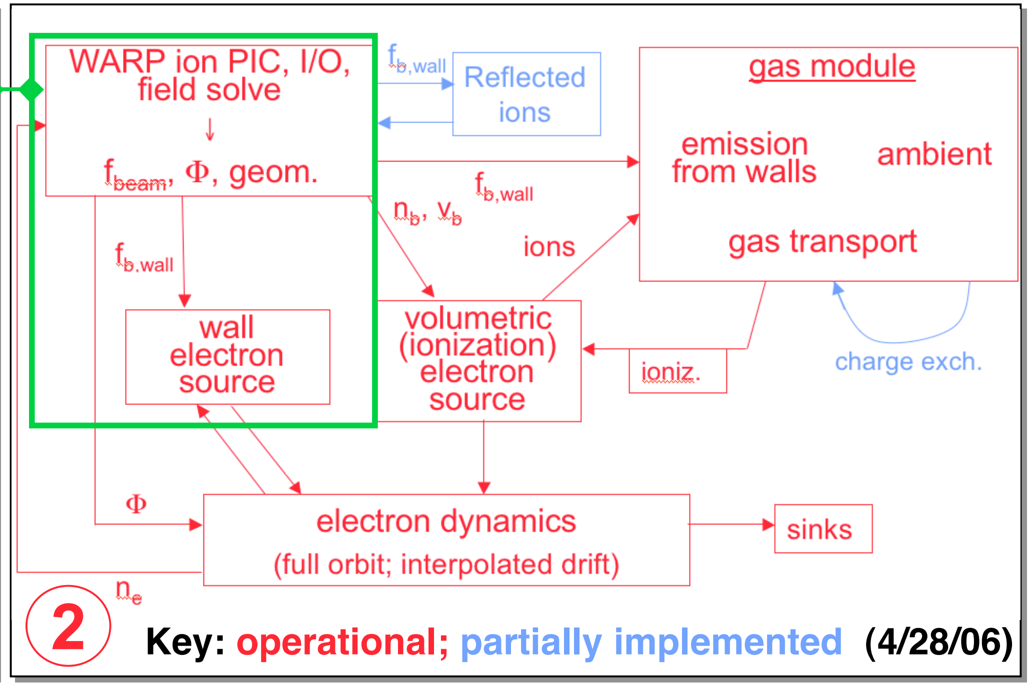
WARP-POSINST code suite is unique in four ways

merge of WARP & POSINST + new e⁻/gas modules



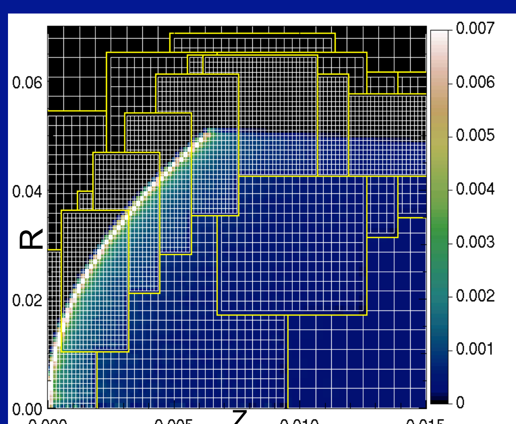


+ Adaptive Mesh Refinement

concentrates resolution only where it is needed

Speed-up

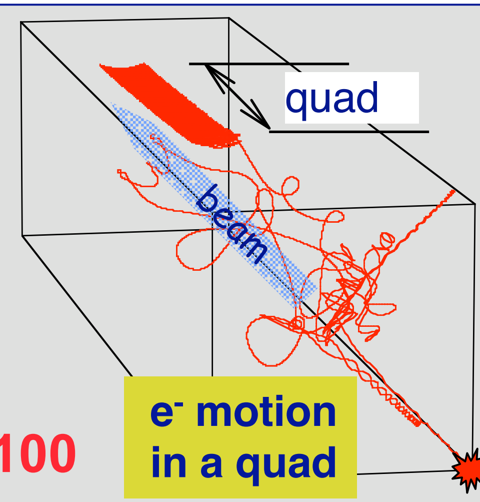
3 **x10-10⁴**



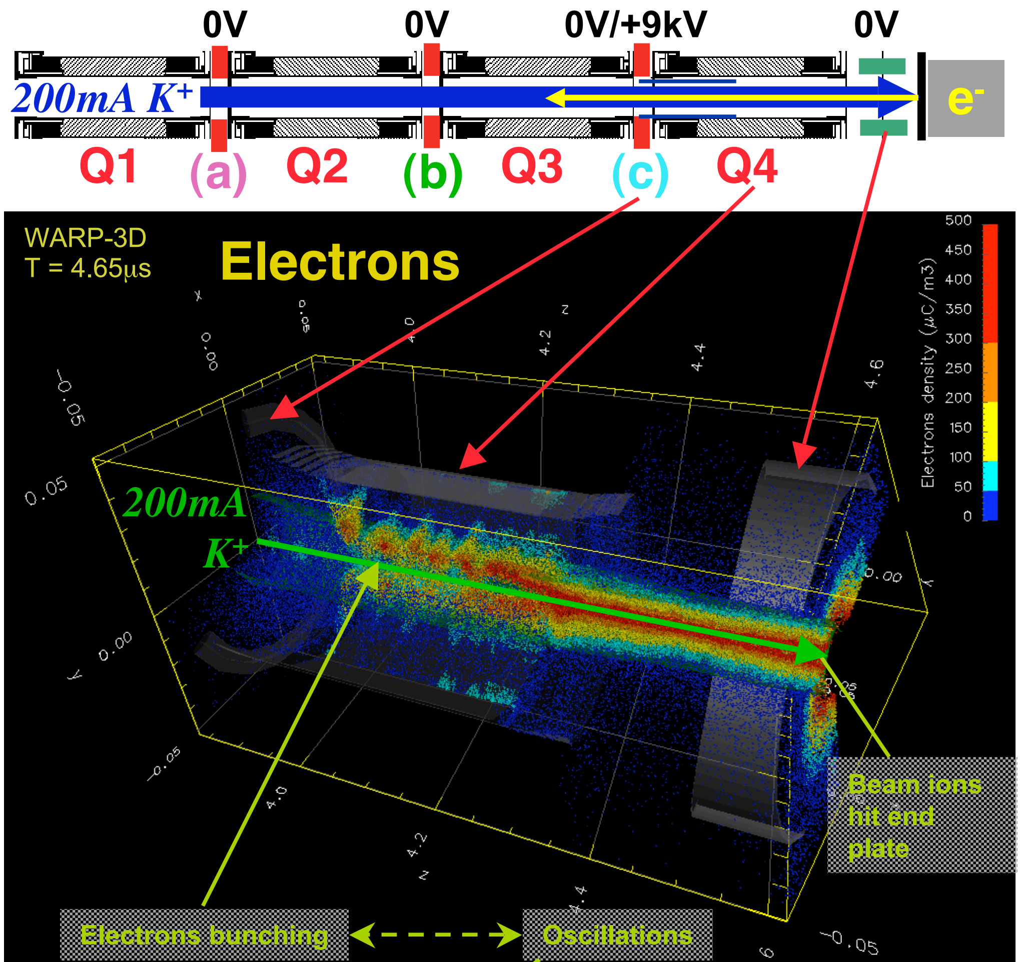
+ New e⁻ mover

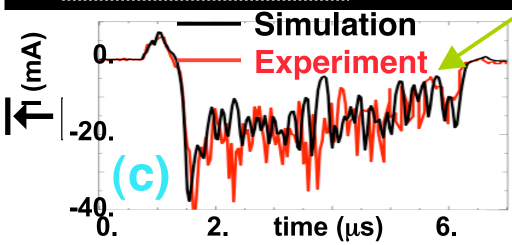
Allows large time step greater than cyclotron period with smooth transition from magnetized to non-magnetized regions

4 **Speed-up x10-100**

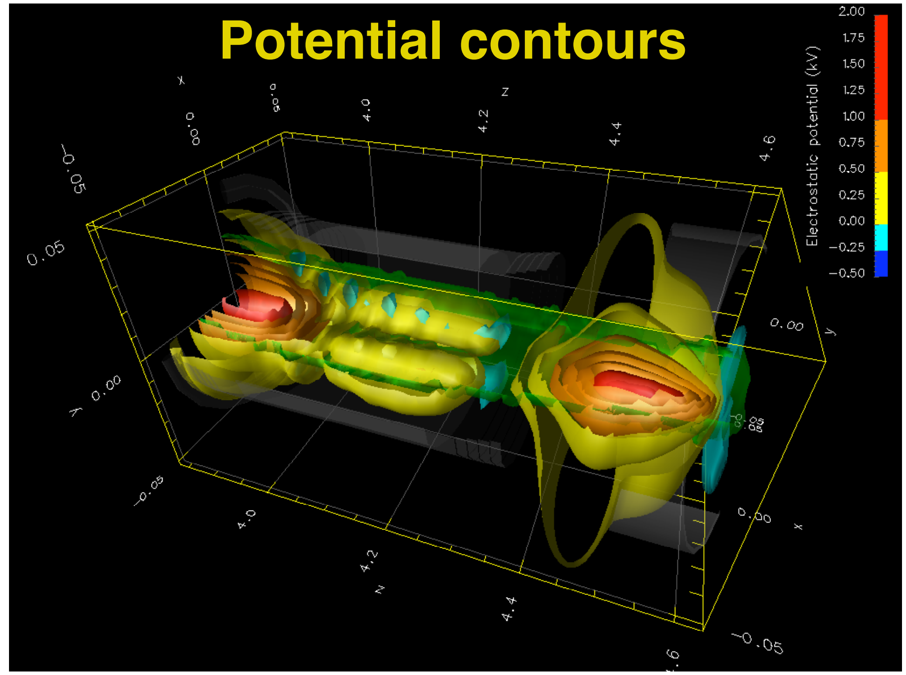


High-density electron oscillation provides benchmark of simulations

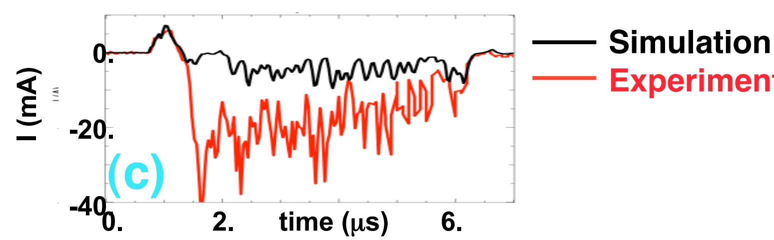




~6 MHz signal in (C) in simulation AND experiment



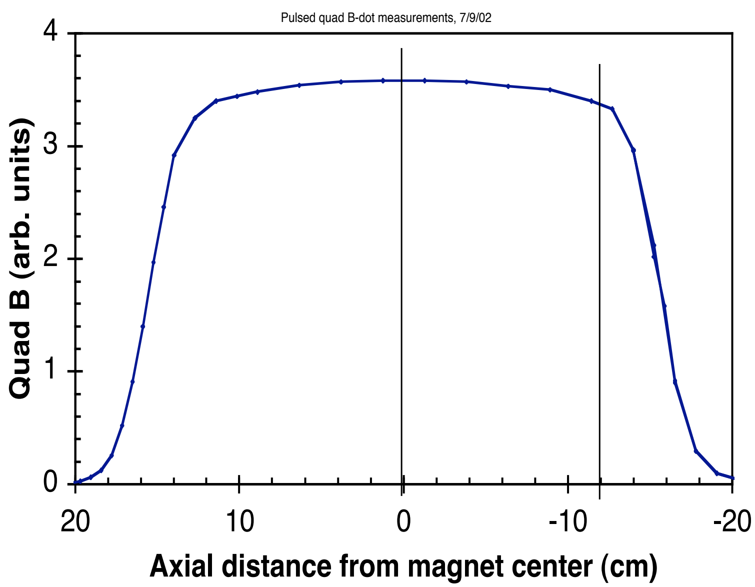
1. Good test of secondary module
   - no secondary electrons:

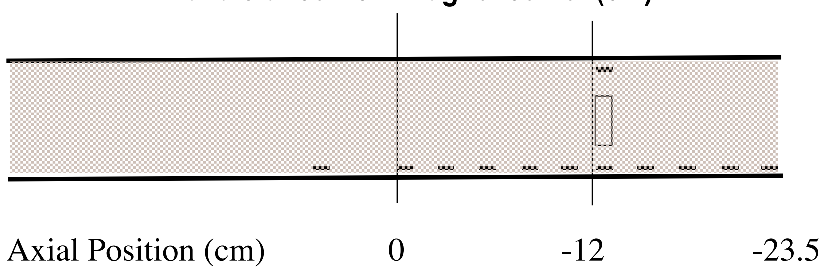


2. run time ~3 days,
   - without new electron mover and MR, run time would be ~1-2 months!

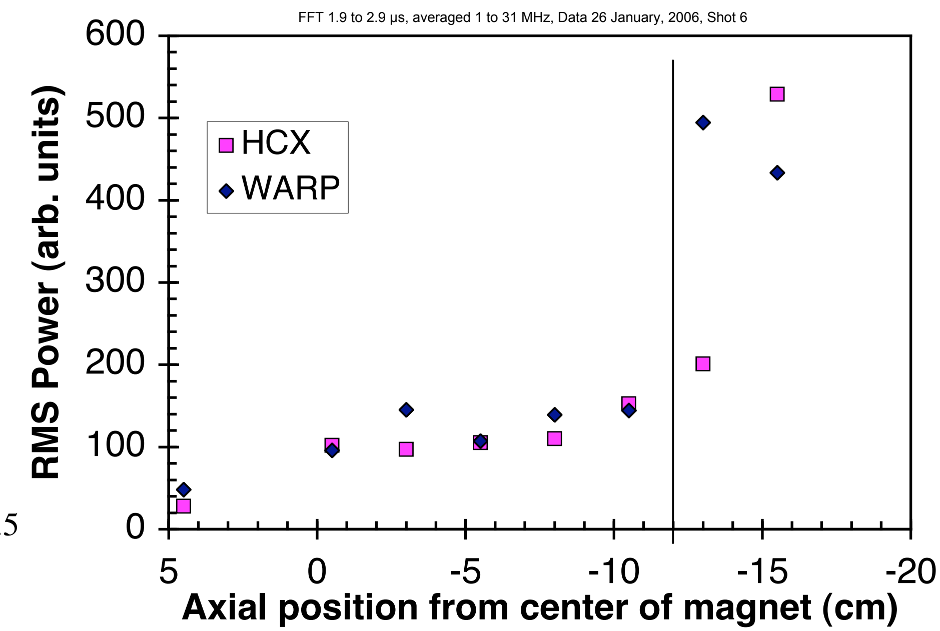
Array of BPMs in Quad 4 verified simulation results

Beam Position Monitor (BPM): electrode capacitively coupled to beam





- **HCX experiment and WARP simulations agree quantitatively on oscillation**
  - **Frequency ~ 6 MHz**
  - **Wavelength ~ 5 cm**
  - **Amplitude – see below**



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Summary of capabilities

- **Diagnose e-cloud density, electron sources, emission coefficients, mitigate, measure effects on beam.**
- **Diagnose gas cloud desorption coefficients, velocity.**
- **Model combined gas and electron clouds and validate with experiment.**
- **LLNL & LBNL engineering – variety of accelerator skills including UHV, cooling, rf, working in close collaboration with physicists.**

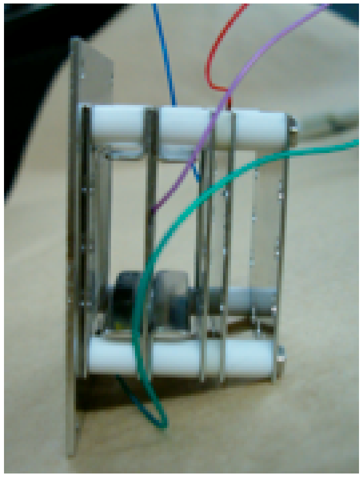
Conclusions

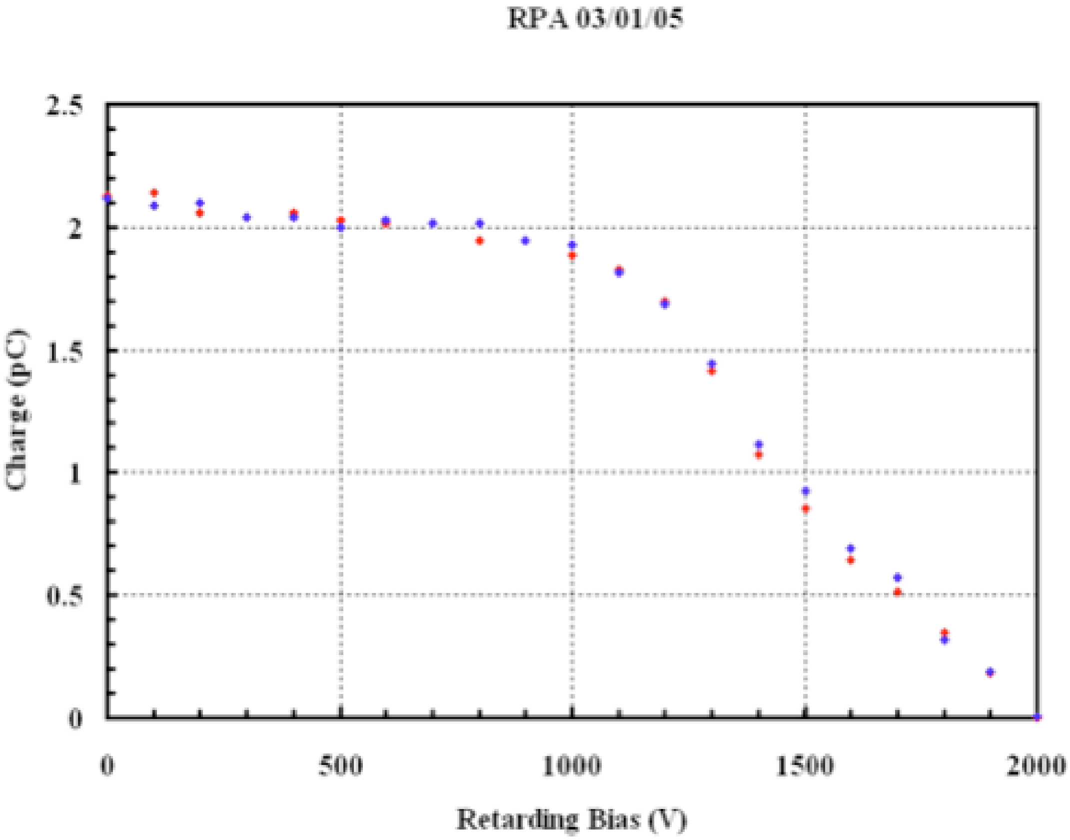
- Clearing electrode rings are effective at removing 'all' electrons from drift region
    - HCX experiment available for testing diagnostics and selected clearing electrode designs, between or in quads.
- Simulations benchmarked against experiment – accurately reproduce many details of experiment
    - Simulations can explore a variety of 3-D clearing electrodes or coatings to mitigate electrons
    - Then, experiment can test selected solutions for effectiveness

Backup slides

Retarding field analyzer (RFA) measures energy distribution of expelled ions

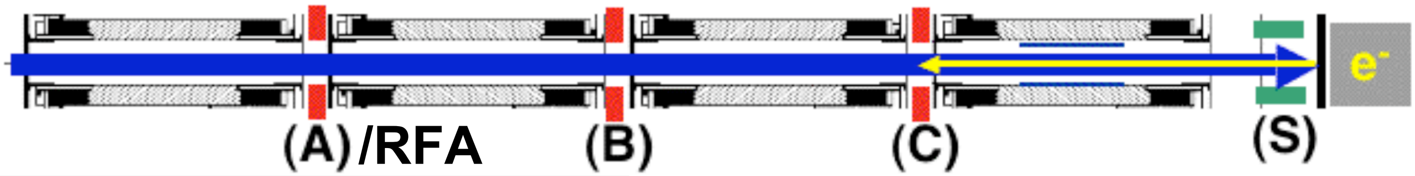
- **RFA an extension of ANL design (Rosenberg and Harkay)**
- **Can measure either ion (shown) or electron distributions**
- **Potential of beam edge ~1000 V, beam axis ~ 2000 V**



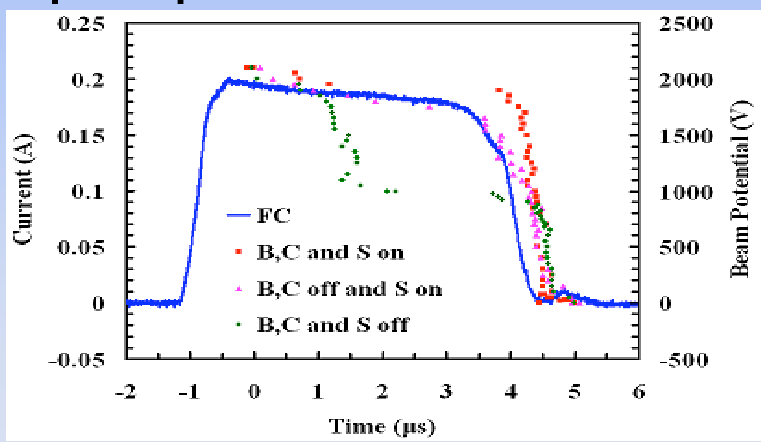


Ref: Michel Kireeff Covo, Physical Review Special Topics – Accelerators and Beams 9, 063201 (2006).

– A first –
time-dependent measurement of absolute electron cloud density*

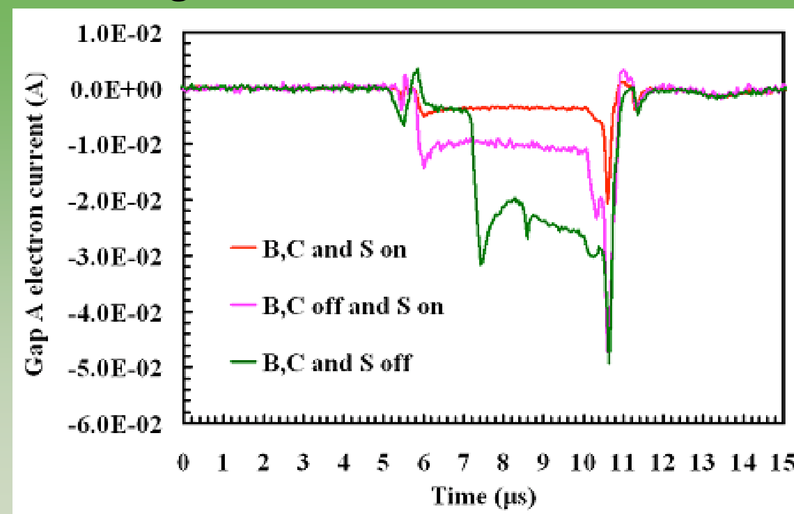


- **Retarding field analyzer (RFA) measures potential on axis = ion-repeller potential**



- **+ beam/e- distr. => $f=N_e/N_{beam}$**

Clearing electrode measures e^- current



+ e^- velocity drift => $f=N_e/N_{beam}$

Absolute electron fraction can be inferred from RFA and clearing electrodes

Beam neutralization	B, C, S on	B, C off S on	B, C, S off
Clear. Electrode A	~ 7%	~ 25%	~ 89%
RFA	(~ 7%)	~ 27%	~ 79%

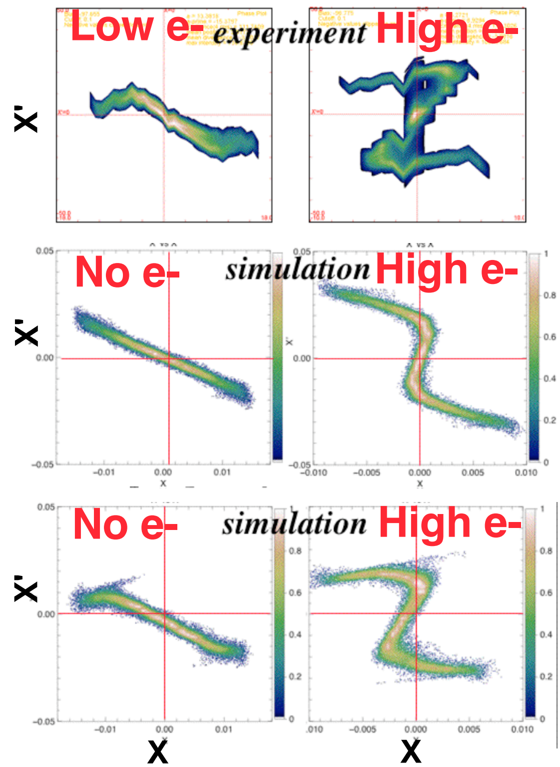
***Michel Kireeff Covo, et al, Phys. Rev. Lett. 97, 054801 (2006).**

Simulations with beam reconstructed from slit scans – improved agreement

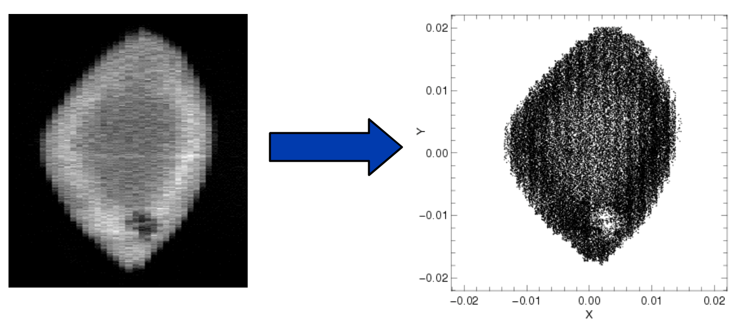
- **Effects of electrons on beam**
  - – **beam loading in simulation now uses reconstructed data from slit-plate measurements**
    - **leads to improved agreement between simulation and experiment**

Semi-gaussian load =>

New load from reconstructed data =>

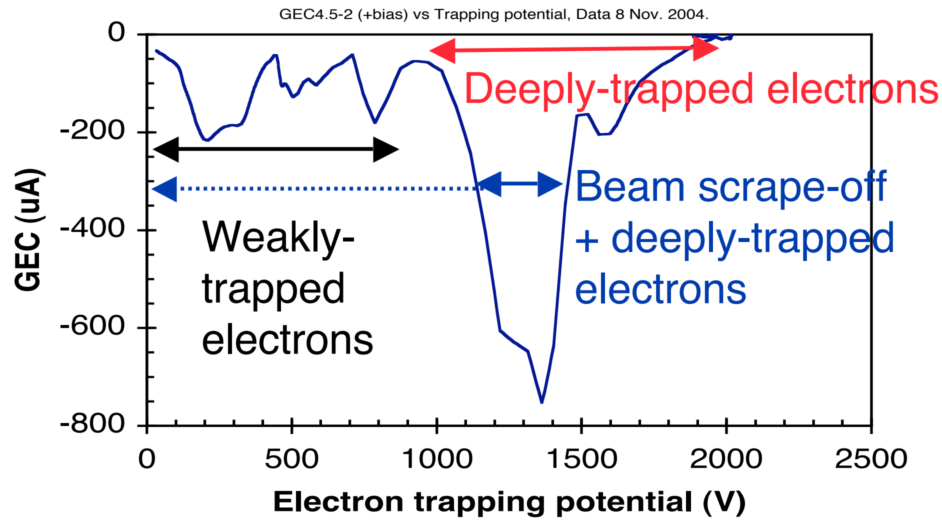


Reconstructed X-Y distribution from slit-plate measurements

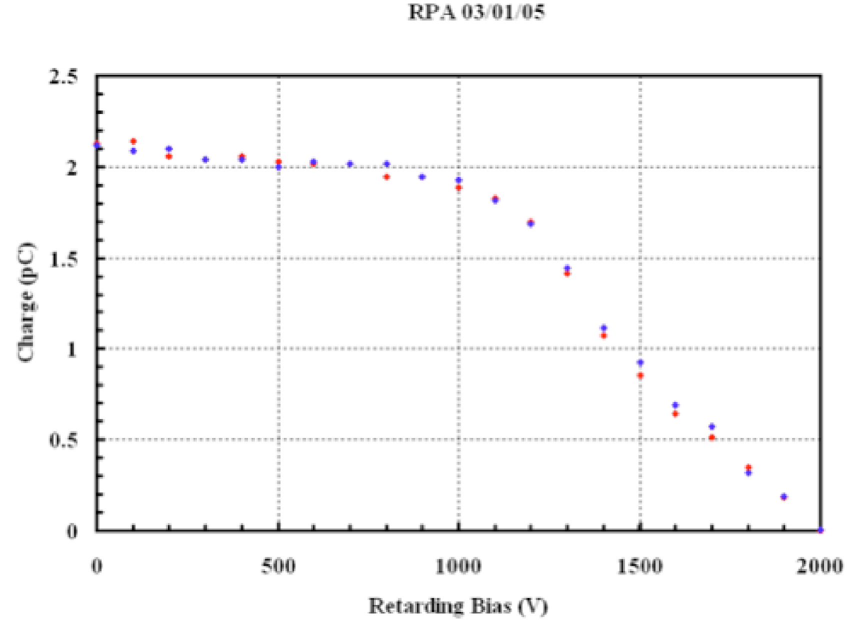


Beam potential when electrons are detrapped can indicate their origin

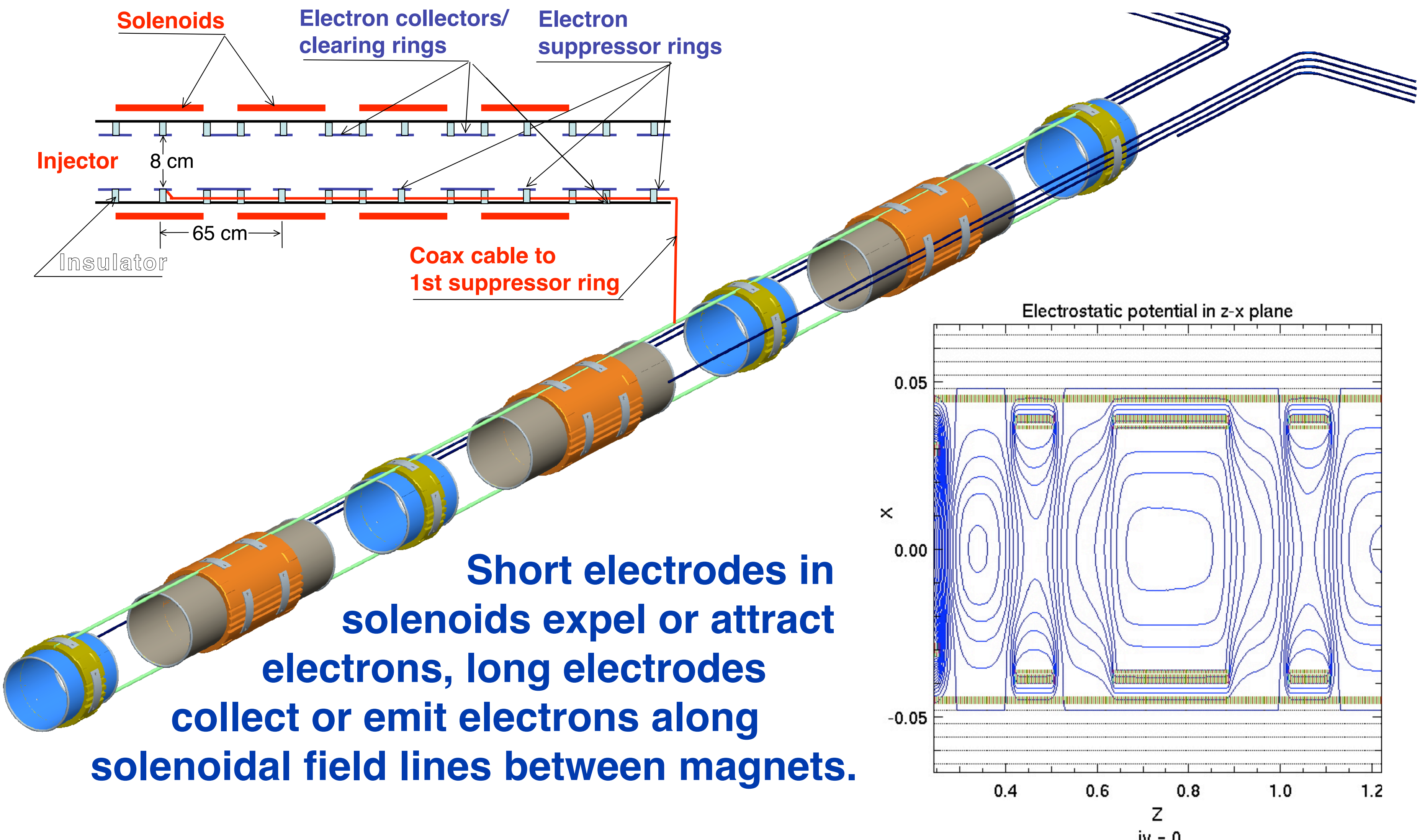
- **Requires electron bounce time (~10 ns) short relative to beam tail decay (~1 *μ*s)**
- **High detrapping energy of electrons ⇒ gas ionization (or scattered e-)**
- **Low detrapping energy ⇒ e- from walls (or near walls).** **Why >400 eV width?**
- **Electrons with $E_t \geq 1500$ eV decrease with volume of e-**



- **Beam potential measured with RPA, from energy of expelled ions (from beam impact on gas) [Michel Kireeff Covo]**



Electron accumulation and effects on beam transport in solenoidal field – initial experiments



Short electrodes in solenoids expel or attract electrons, long electrodes collect or emit electrons along solenoidal field lines between magnets.