Collimation issues

Outline

1. **Single collimator on Neutralized Drift Compression Experiment (NDCX) and on High Current Experiment (HCX) at LBNL: partially successful.**
2. **Issues: intercept core – not just halo, beam scattering, gas desorption, electron emission, impedance, image charges, some halo ions within core**

Art Molvik

for the

Heavy Ion Fusion Science Virtual National Laboratory

SLAC BDS Meeting

June 12, 2007

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UCRL-PRES-231652

HIFS collimation builds out of e-cloud effort

HIFS-VNL

Experiment

Art Molvik
Michel Kireeff Covo
Frank Bieniosek
Joshua Coleman
Christian Leister
Prabir Roy
Peter Seidl

Simulation

Jean-Luc Vay
Ron Cohen
Alex Friedman
Dave Grote
Steve Lund
Bill Sharp

Consultants

Miguel Furman, Christine Celata (LBNL-Center for Beam Physics)

Irv Haber (U. Maryland)

R. Davidson, L. Grisham, I. Kaganovich, H. Qin, A. Sefkow, E. Startsev, et al (PPPL)

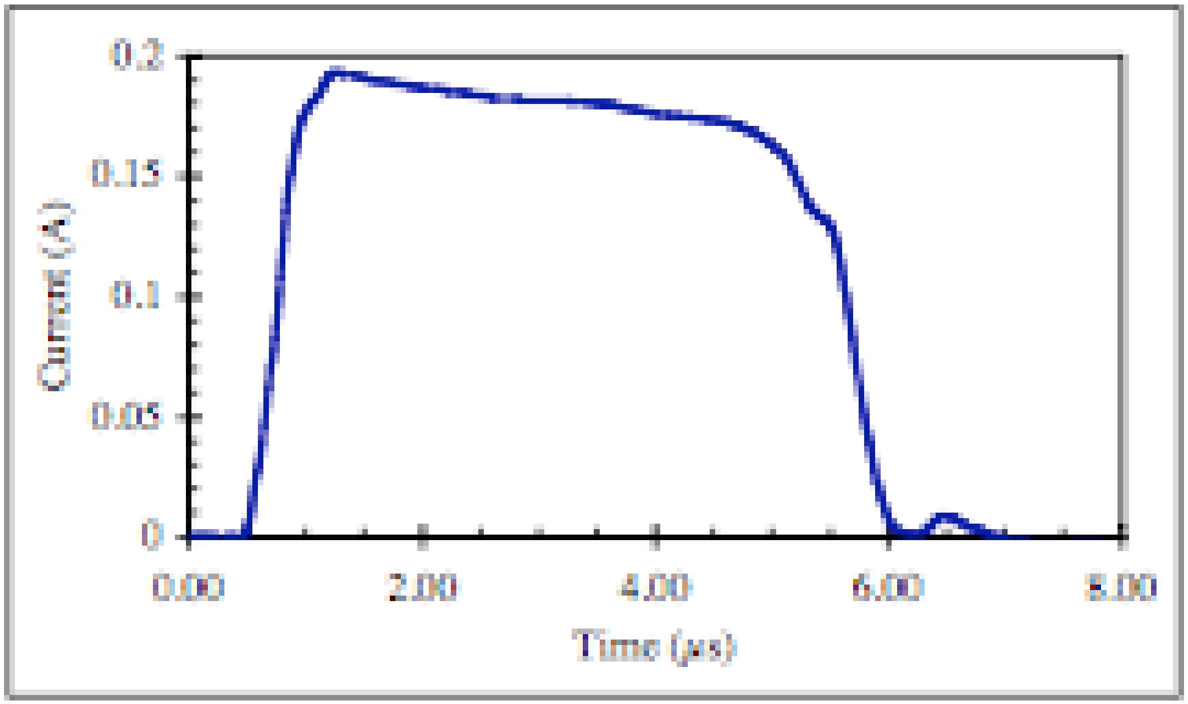
Peter Stoltz, Seth Veizer (Tech-X Corp.)

John Verboncoeur (UC-Berkeley)

We use long beam pulses with a ~4 μs "flattop"

Bunch train multipactor absent – we measure "seed-electrons" that lead to e-clouds in rf accelerators.

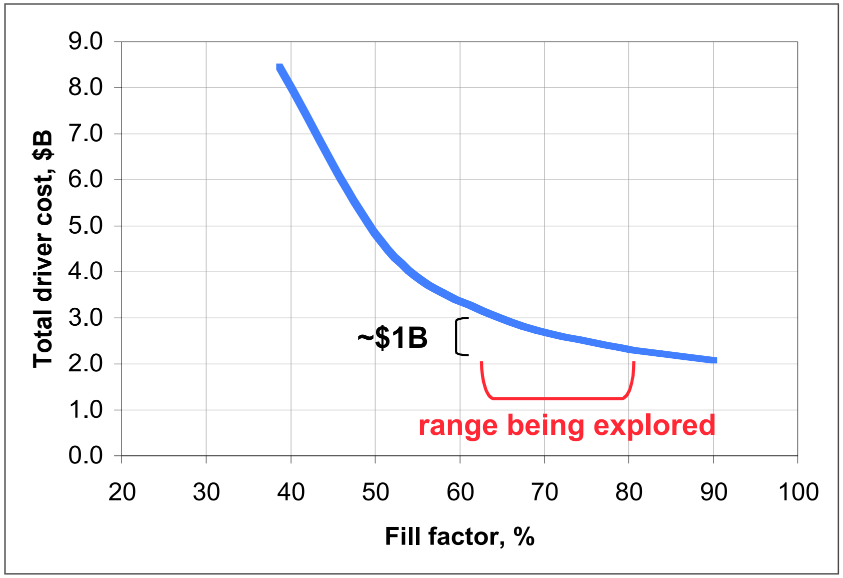
- Seeds from ion-induced wall emission, ionization of gas
- Seeds can be copious



We need large beam diameter in heavy-ion inertial fusion energy

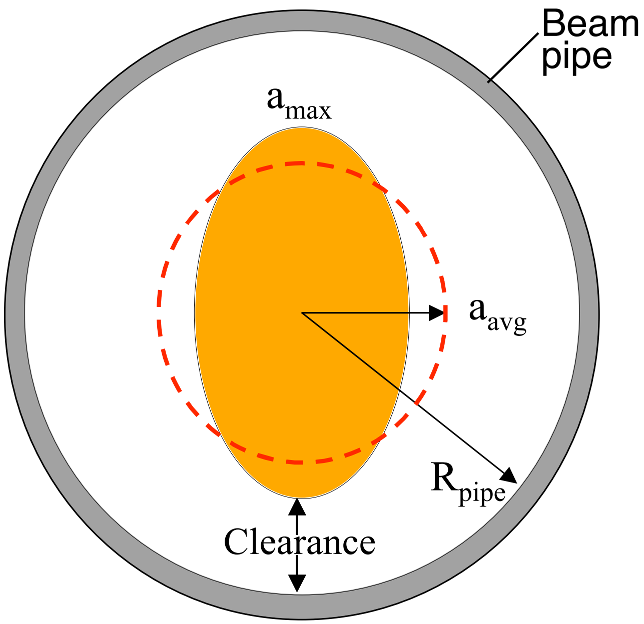
- **Power plant cost decreases with increasing fill factor**

IBEAM results[1]:



(fixed number of beams, initial pulse length, and quadrupole field strength)

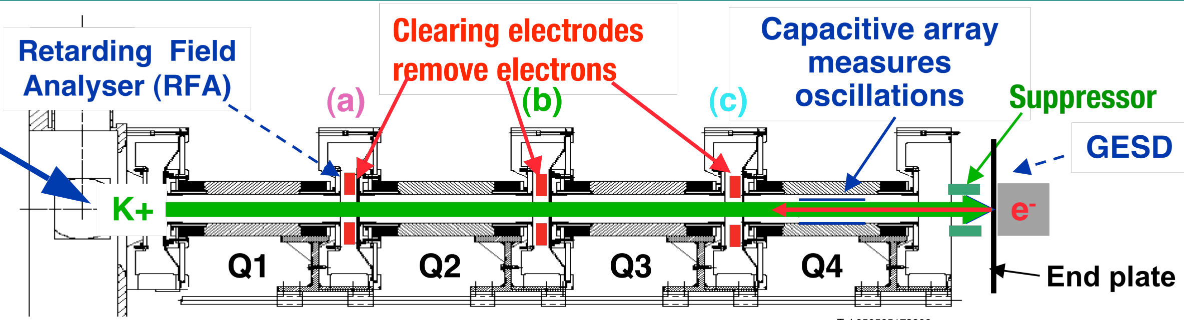
Fill factor = a_{max}/R_{pipe}

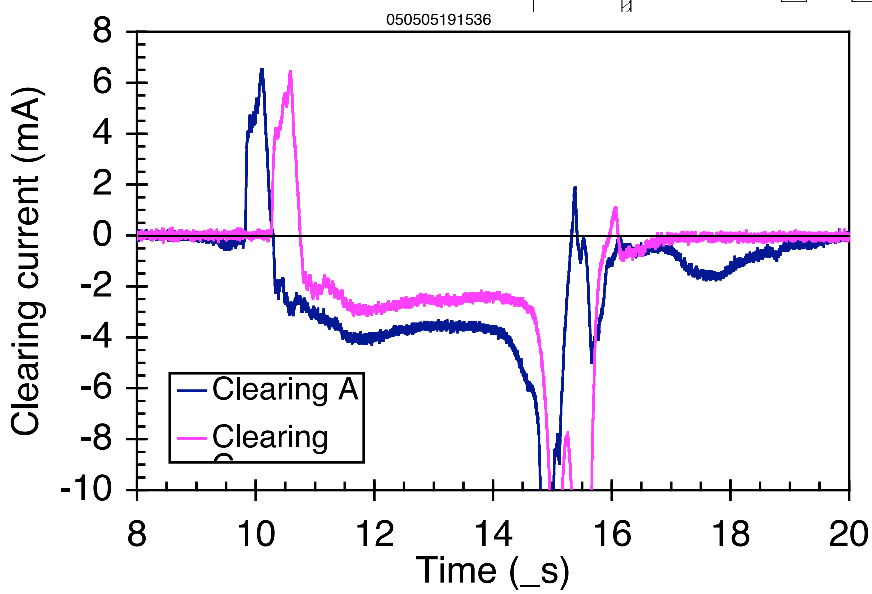


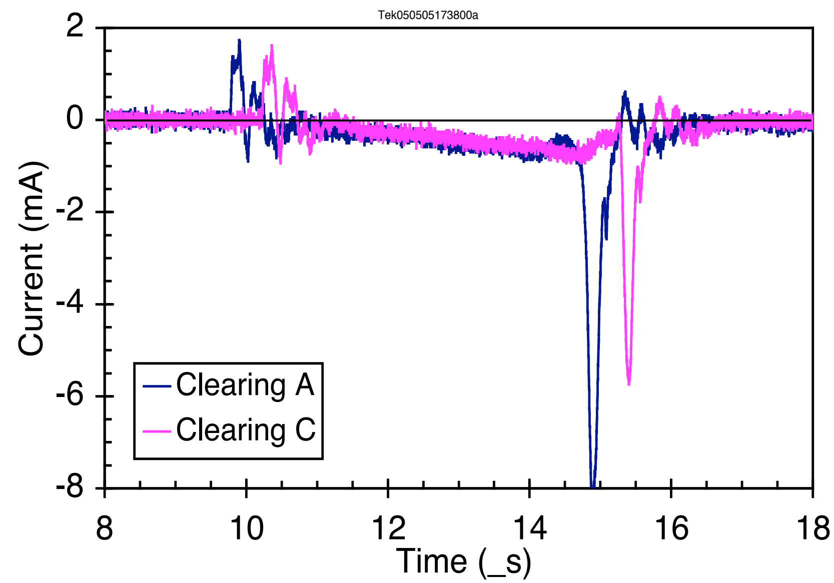
- **Electron and gas emission are likely to limit fill factor.**
- **E-cloud may also limit beam current or spot size for WDM. With short pulses, gas desorption is unlikely to be a significant issue.**

Aperture reduces beam and loss to beam tubes, but loss grows in time (High Current Experiment – HCX)

+4kV aperture passes 1/7 of 1 MeV K+ beam.
Beam pot~2kV



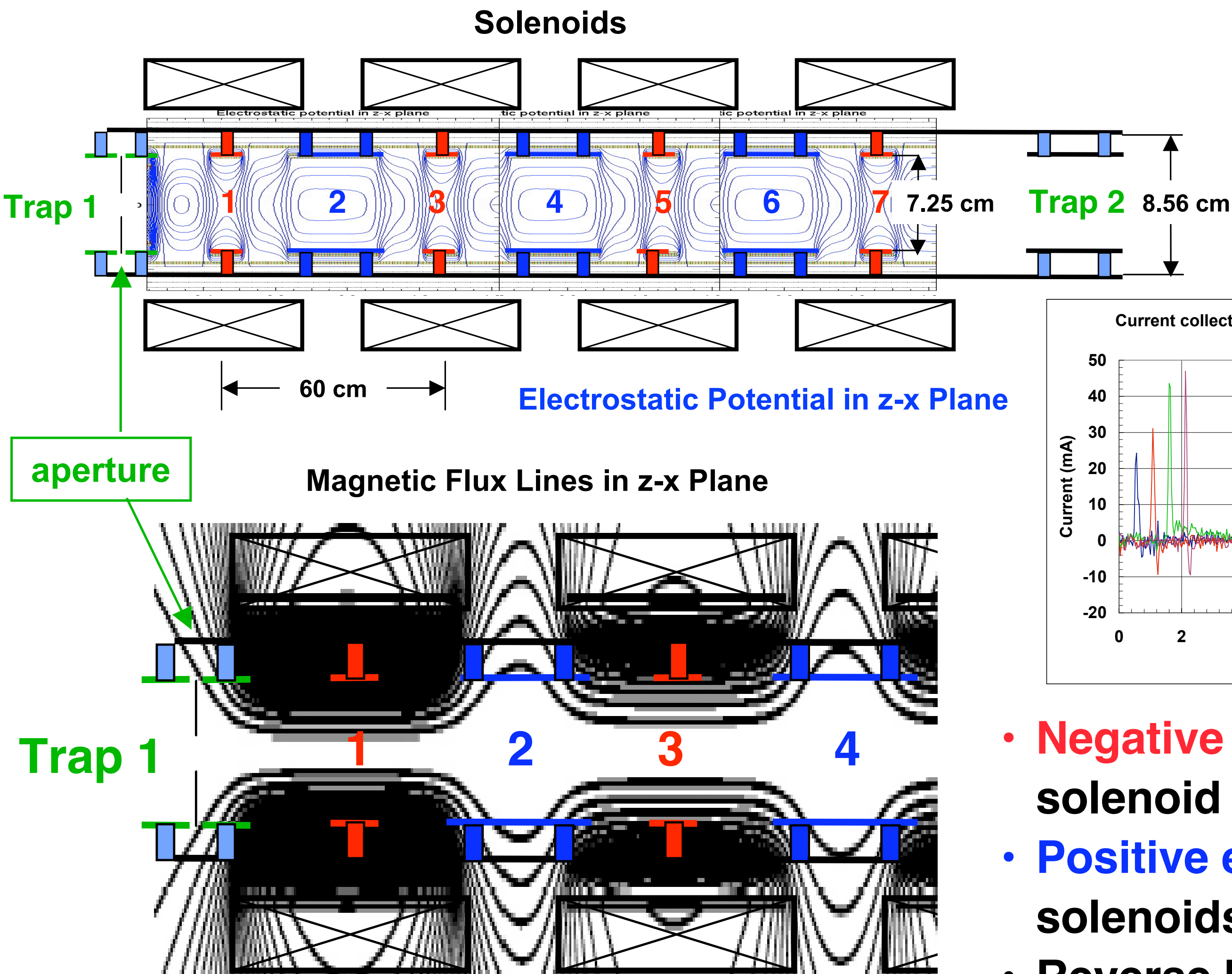




Beam loss generates electrons that are measured by clearing electrodes

Beam loss smaller with apertured beam, but growth in time suggests electron or gas accumulation.

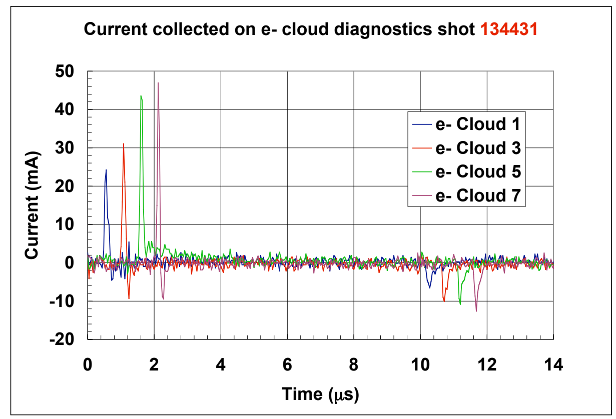
NDCX solenoids use in-bore electrodes to measure and control electron clouds



Radial Beam Potential

$$\psi = \int \vec{D} \cdot d\vec{a}$$

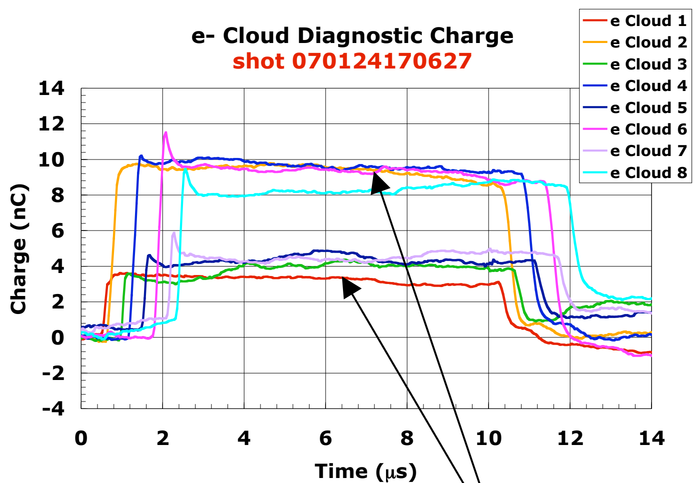
$$\Rightarrow \Delta V = \frac{\lambda}{2\pi\epsilon_o} \ln\left(\frac{r_{beam}}{r}\right)$$



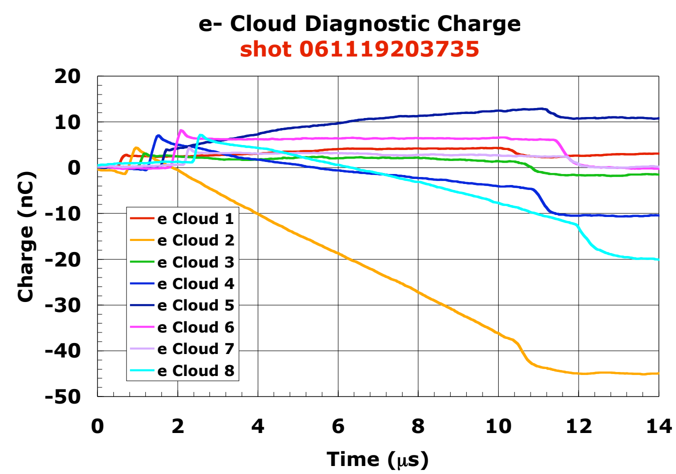
- **Negative electrode inside solenoid will suppress e⁻.**
- **Positive electrode between solenoids will collect e⁻.**
- **Reverse bias to emit and trap e⁻.**

Collected charge on e-cloud electrodes is reduced by removing the beam aperture

4-STX 43-mA Beam



4-STX Apertured 26-mA Beam



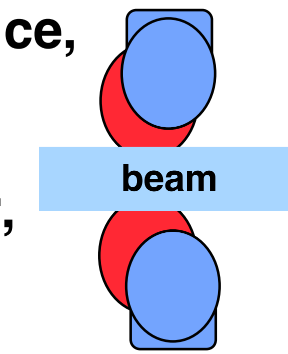
Collected capacitive charge proportional to electrode length

Magnetically connected to aperture

	43-mA beam	26-mA beam
Diagnostic	**Charge (nC)**	**Charge (nC)**
e Cloud 1	-0.51	1.39
e Cloud 2	-1.06	-41.08
e Cloud 3	0.35	-1.70
e Cloud 4	-0.94	-11.24
e Cloud 5	-0.06	9.00
e Cloud 6	-2.22	-1.50
e Cloud 7	-0.85	-1.37
e Cloud 8	-0.35	-18.69
Total Charge (nC)	6.33	85.97

Collimation – issues

- Collimator scrapes configuration space – multiple collimators needed to reduce halo
- Electron emission – minimized by biasing aperture +, or installing negative suppressor electrodes on either side (but they may emit)
- Gas desorption & ionization by beam – bake, material choice, coating, shape to direct gas to nearby pump, …
- Beam particles scattered by aperture – "knife edge" better, but avoid breakdown



- Image charges deflect beam particles – "knife edge" better
- Impedance increased by smaller radius – our large beams minimize this issue, so we can concentrate on others
- Engineering issues – cooling, radiation & activation (absent in our experiments, so reduced costs)

Published work (mostly gas & e-cloud, relevant to collimation)

- **Scaling of electron emission** with electronic component of ion energy loss in matter measured and modeled [Kireeff Covo, et al., PRSTAB 9, 063201 (2006)].
- **Scaling of gas desorption** with electronic component of ion energy loss in matter measured [Molvik, et al., PRL 98, 064801, (2007)].
- **Velocity distribution of desorbed gas** measured [Bieniosek, et al., submitted to PRSTAB, 2007].
- **Cross sections for ionization of gas** by beam ion impact measured and calculated [Kireeff Covo, et al., to be submitted to PRSTAB (2007)].
- **Effectiveness of clearing electrodes** for removing e- demonstrated [Molvik, et al., ECloud04 (2004); Molvik, et al., NIMA 577, 45 (2007)].
- **e-cloud densities** measured [Kireeff Covo, et al., PRL 97, 054801 (2006)].
- **Oscillation involving bunching of electrons** in a quad. magnet observed and simulated [R. Cohen, POP 12, 056708 (2005), Agreement on freq., wavelength, and amplitude of oscillations [Molvik, et al., POP 14, 056701 (2007)].
- **Optical slit scanner** diagnostics developed –quantitative, yield extra dimension of data beyond 2-slit scanners [Bieniosek, et al., NIMA 544, 268 (2005)].

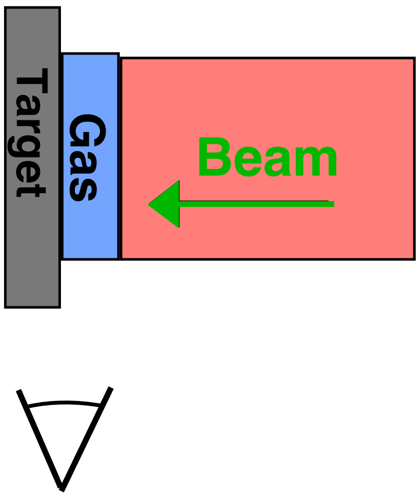
Beam collimation proposal in preparation – for HEP - Advanced Technology R&D

- **Addresses community needs & endorsed by HIFS-VNL-PAC, e.g.**
  - LHC baseline collimation limits performance
  - ILC needs to block halo & synchrotron rad. from interaction region
  - HIF needs beams to ‘fill’ beam tube without beam loss
- **Builds on recent capabilities developed in HIFS-VNL**
  - 3-D self-consistent simulations for beam, electron, & gas
  - Diagnostics for gas & e-cloud density, sources and sinks
  - Diagnostics for beam effects – optical slit scans and profilometry
  - HCX facility can be dedicated to this research
- **Coordinated experimental & simulation program (~$500k/yr for 3 year)**
  - Demonstrate inexpensive halo diag. with 10^4 - 10^5 dynamic range.
  - Develop validated halo model
  - Optimize & understand collimator/halo scraper design with validated simulation.

Backup

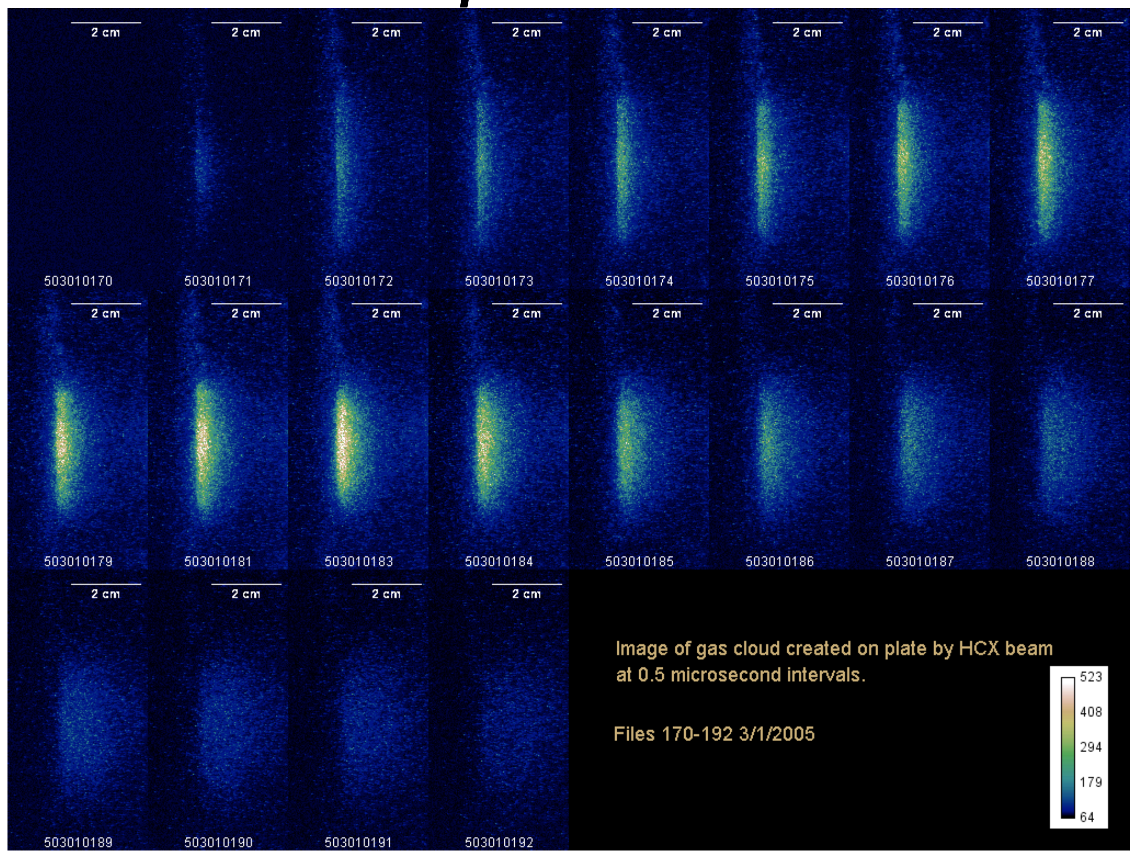
We measure velocity distribution of desorbed gas

Observation: desorbed gas in beam emits light



View expanding gas cloud from side – $f(v_0)$ normal to target [with gated camera]

0.5 μs intervals

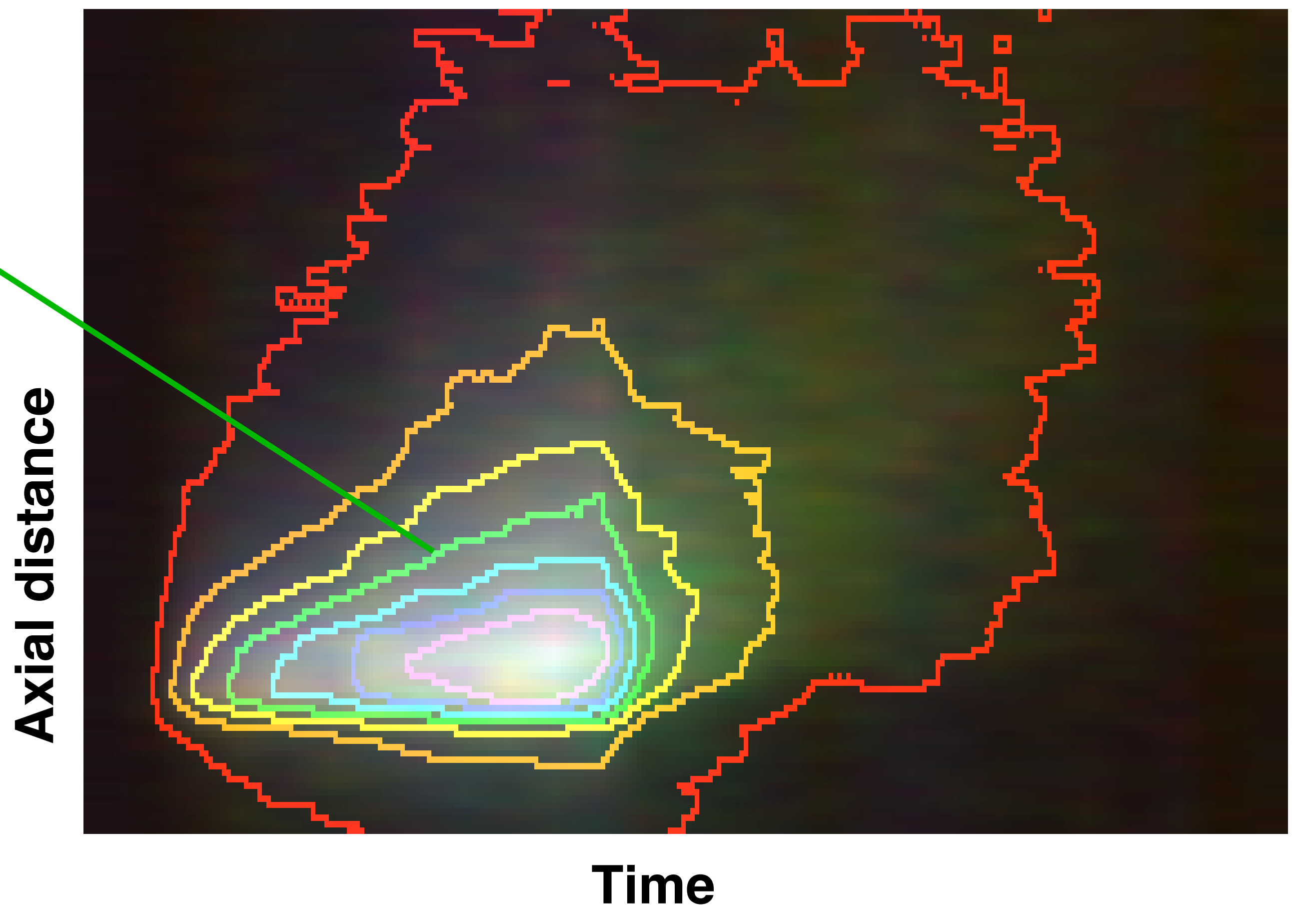


F. Bieniosek

Line integral of images indicates an expansion velocity of up to a few mm/μs

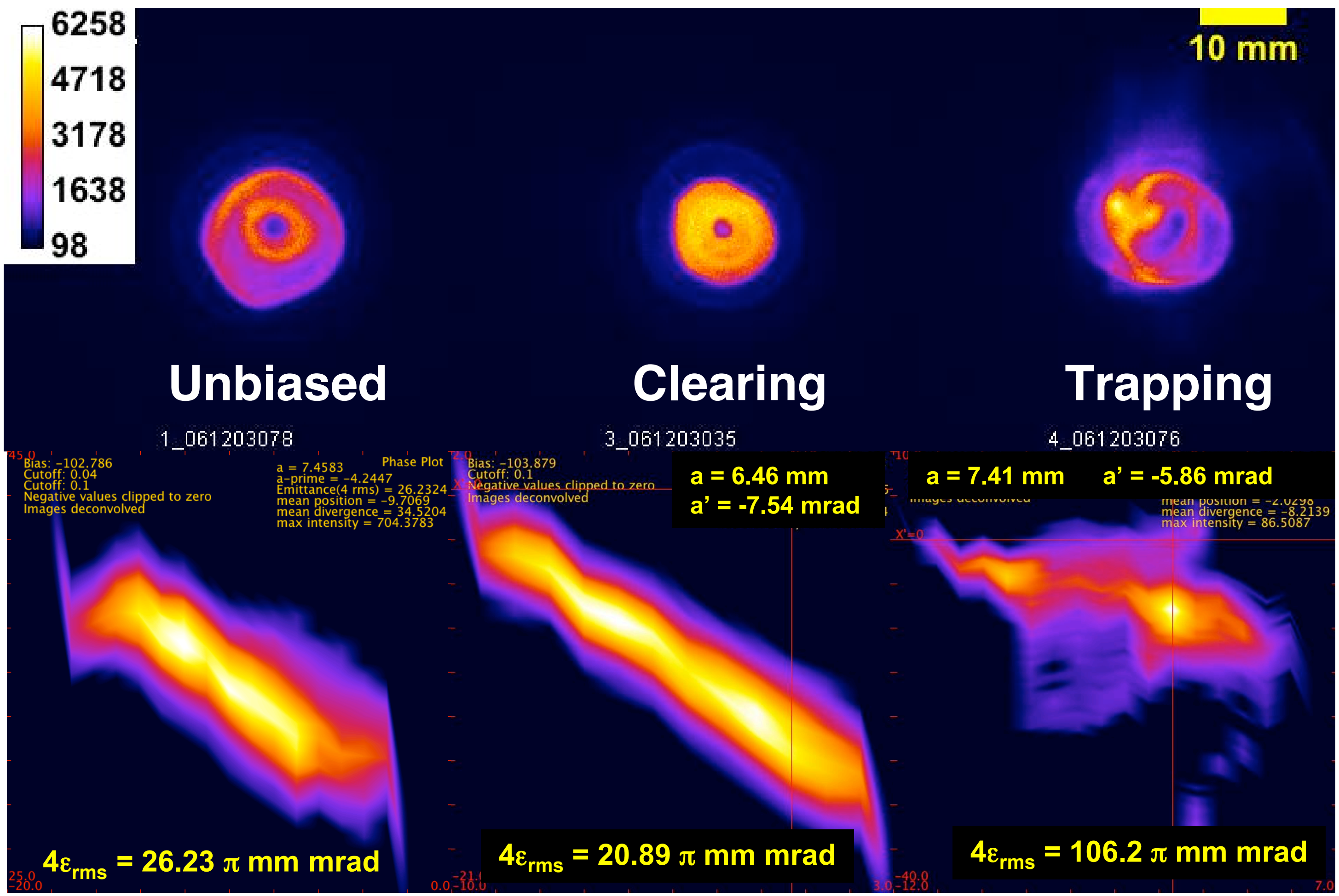
Estimated velocity:
Slope ~1 mm/μs

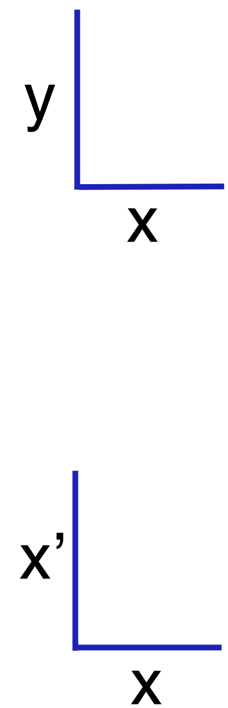
Corresponds to room temperature H_2, consistent with residual gas measurements



E-cloud electrodes have clear effect on apertured beam quality (26 mA ⇒ λ_b = 21 nC/m)

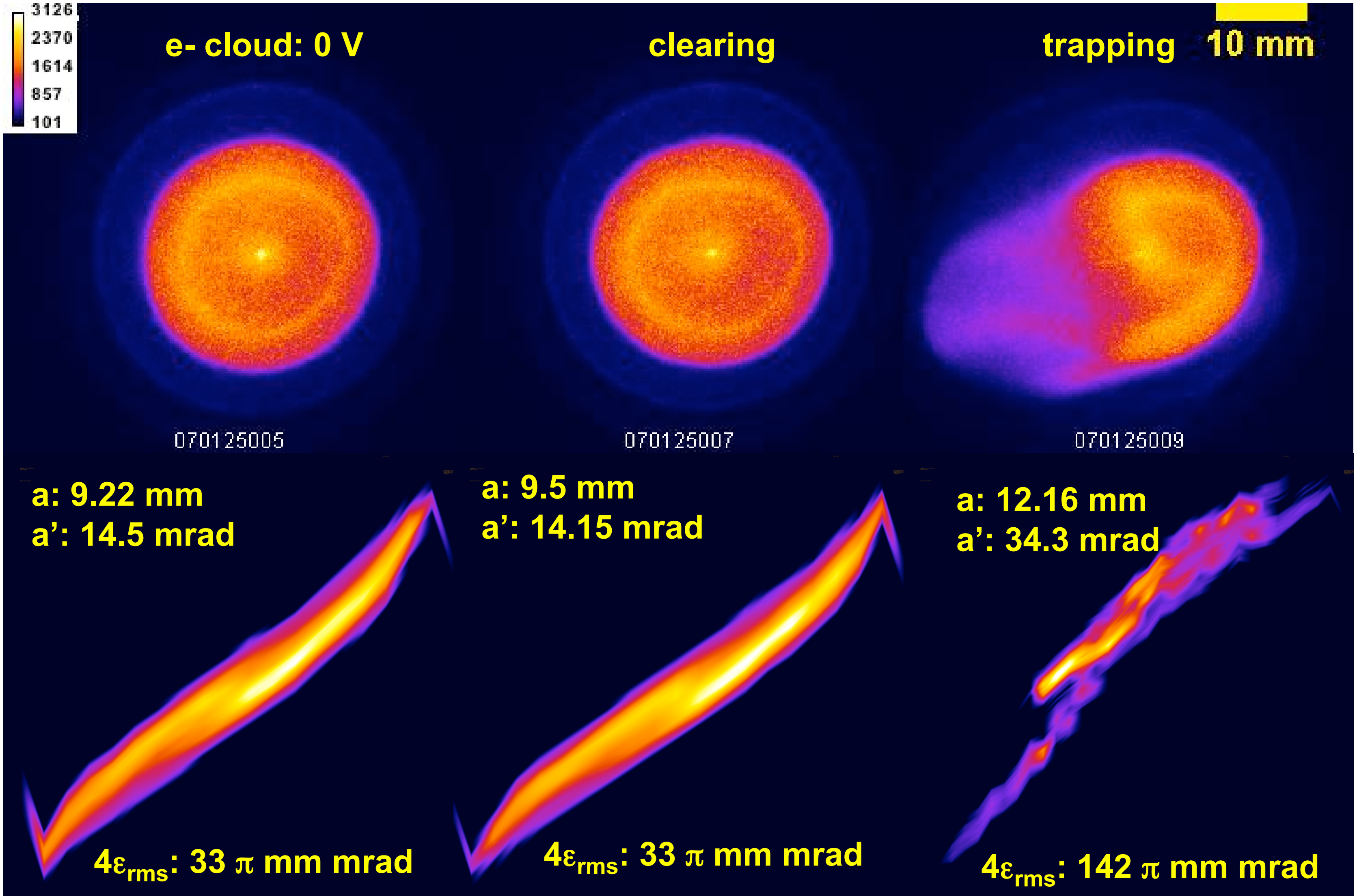
$\lambda_e / \lambda_b \sim 0.005$ $\lambda_e / \lambda_b \sim 1$





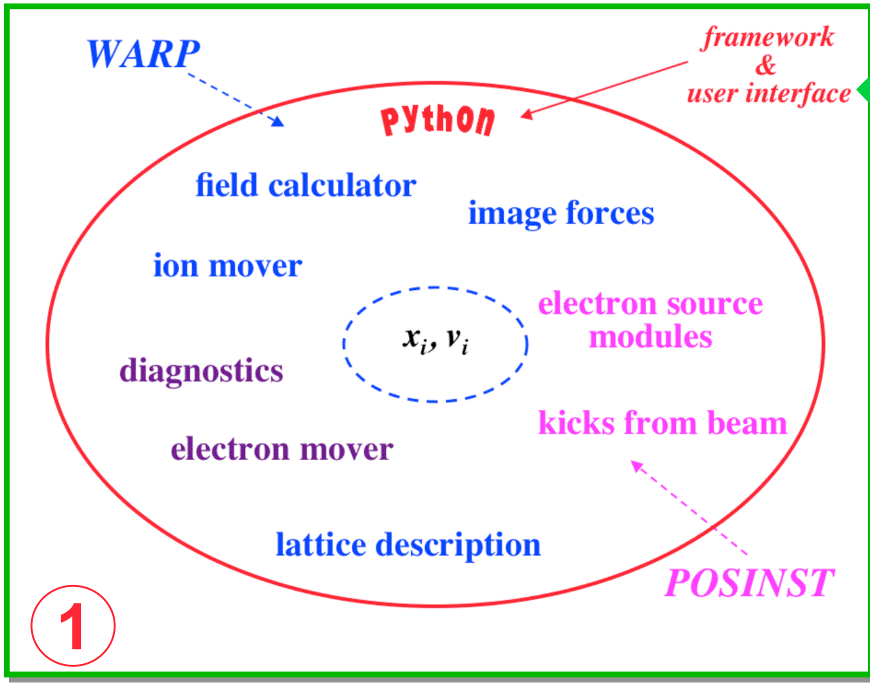
J. Coleman, et al., in preparation for submittal to PRSTAB

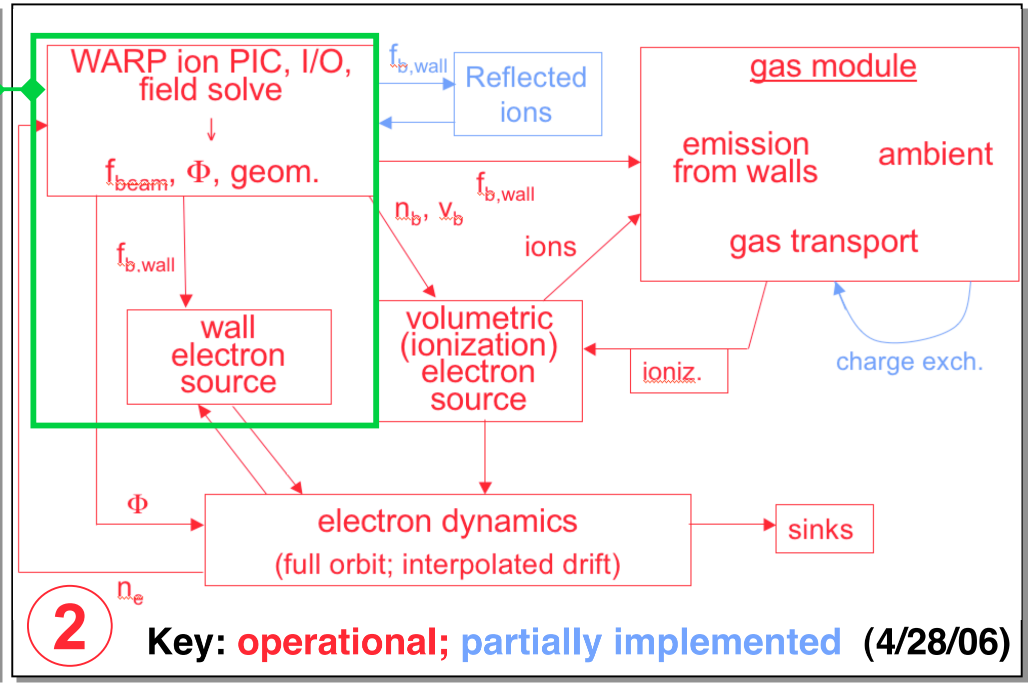
Clearing/diag electrodes may not be needed for unapertured beam (43mA)



WARP-POSINST code – self-consistent 3-D & fast

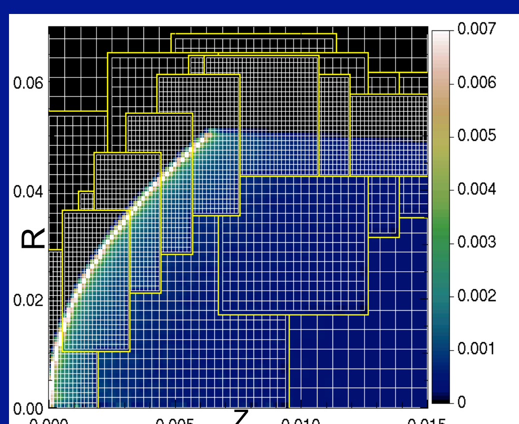
merge of WARP & POSINST + new e⁻/gas modules





+ Adaptive Mesh Refinement

concentrates resolution only where it is needed

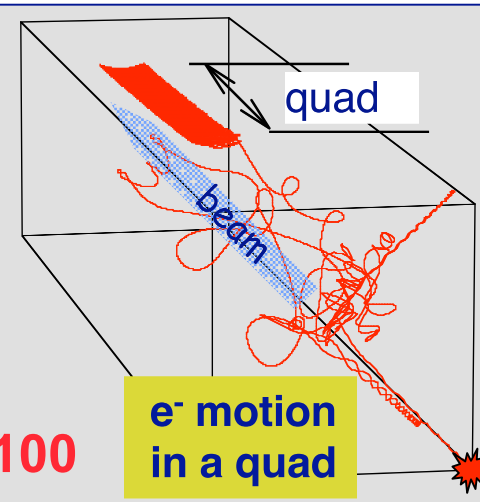


Speed-up

3 x10-10^4

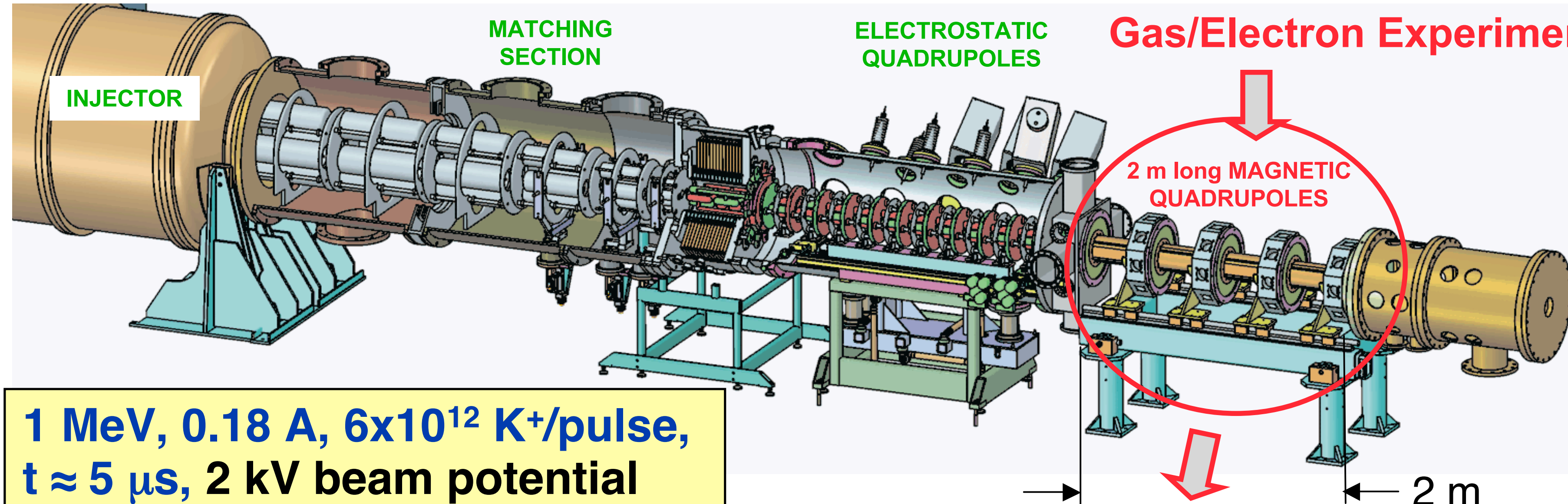
+ New e⁻ mover

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

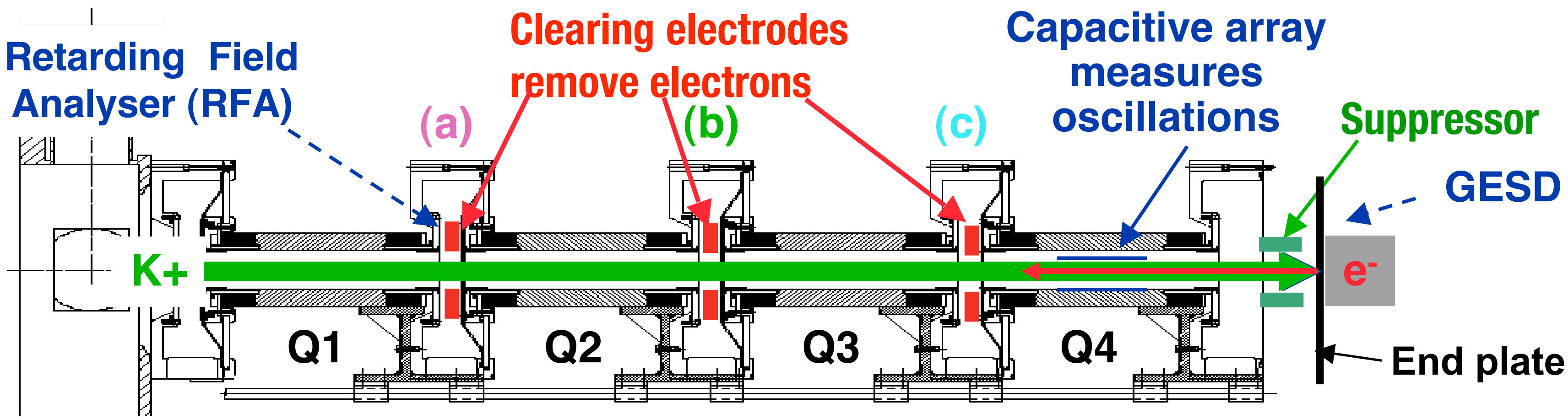


4 Speed-up x10-100

The High Current Experiment (HCX) is a small, flexible heavy-ion accelerator (at LBNL)



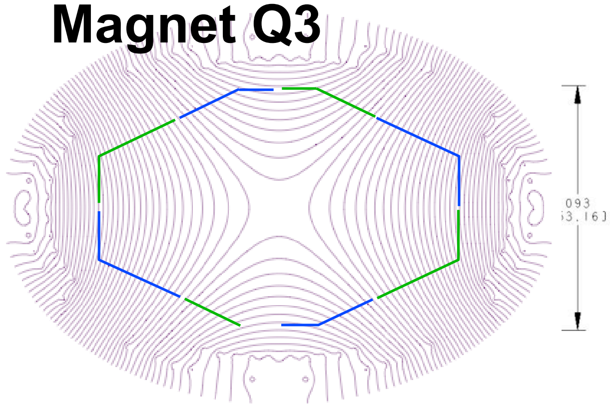
1 MeV, 0.18 A, 6x10^{12} K$^+$/pulse, t ≈ 5 μs, 2 kV beam potential



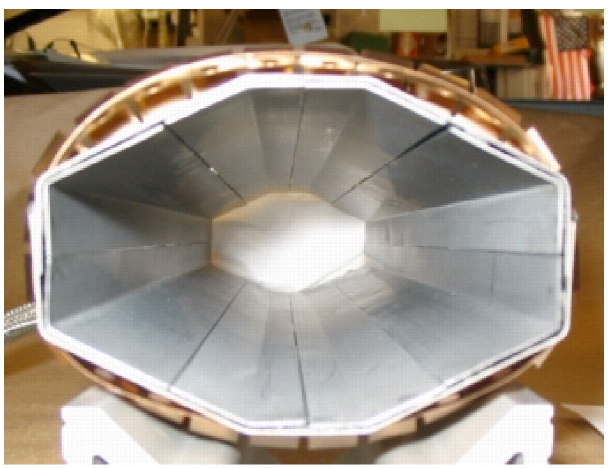
Quadrupole magnets Q1 - Q4 for beam transport

Diagnostics within magnetic quadrupole bores on HCX

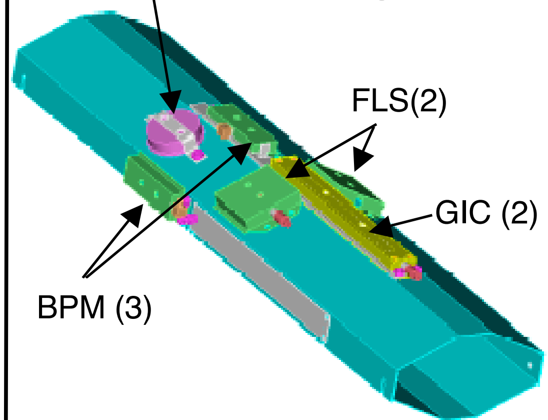
Magnet Q3

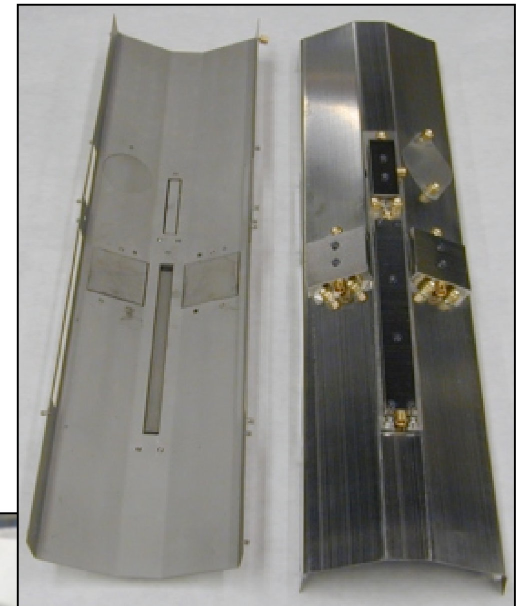


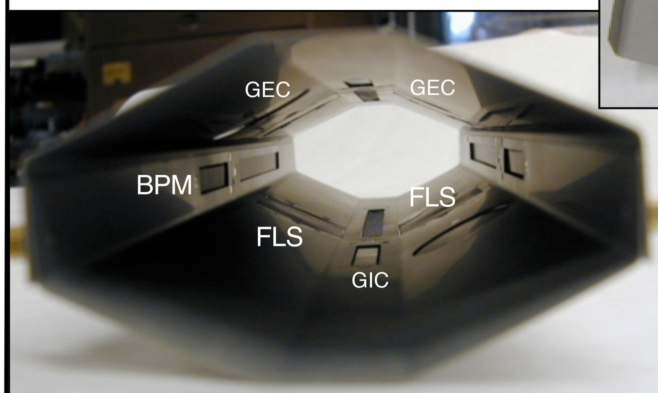
FLL: 8-biased electrodes at ends of field lines: measure capacitive signal + electrons from wall



Magnet Q4







Capacitive and grid-shielded electrodes

Electronic gas desorption scales with $(dE/dx)^2$, like electronic sputtering

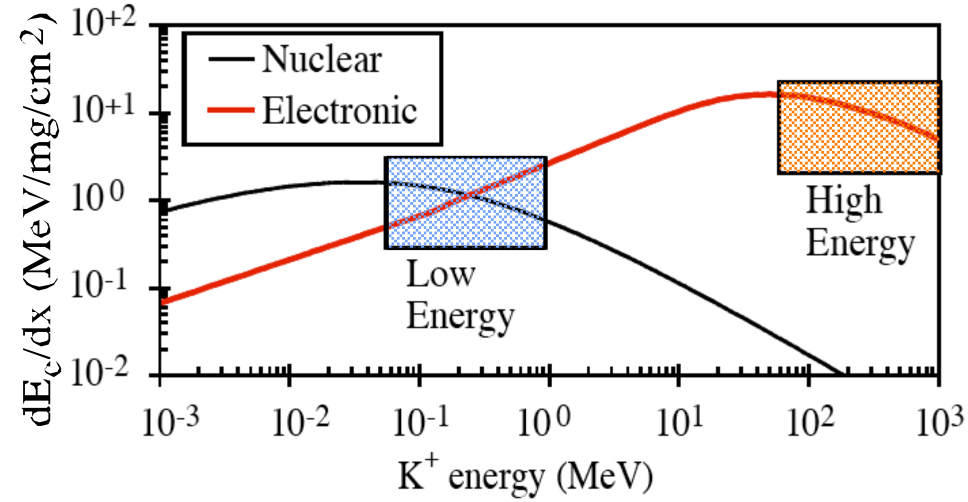
- Conventional sputtering driven by large-angle nuclear scattering

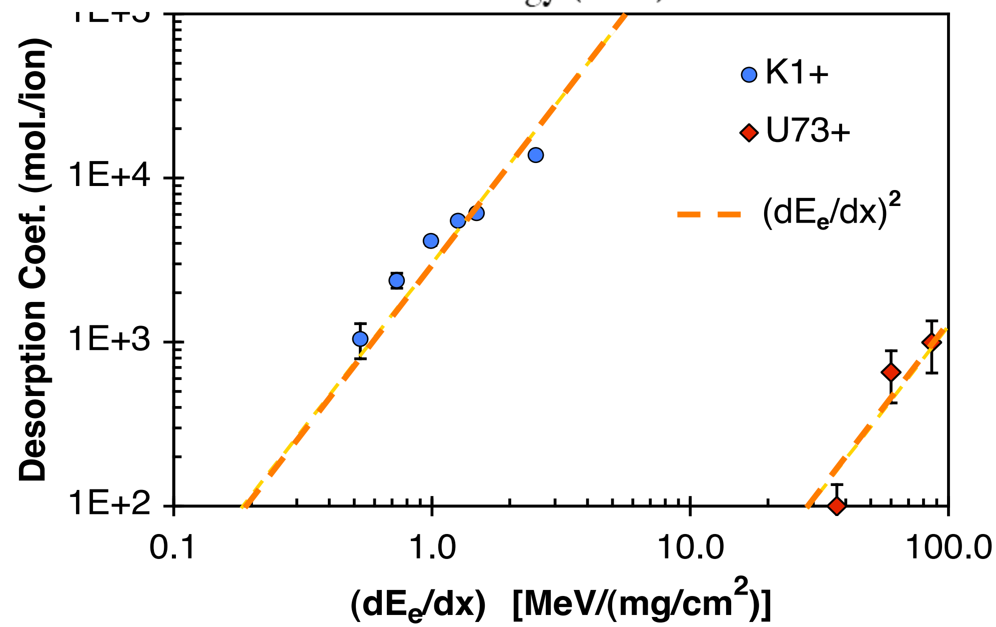
Electronic sputtering more copious.

- Well known for ions onto thick insulating layers,
- Scales with $(dE_e/dx)^n$ where $1 \le n \le 3$.

Electronic desorption, $n \approx 2$.

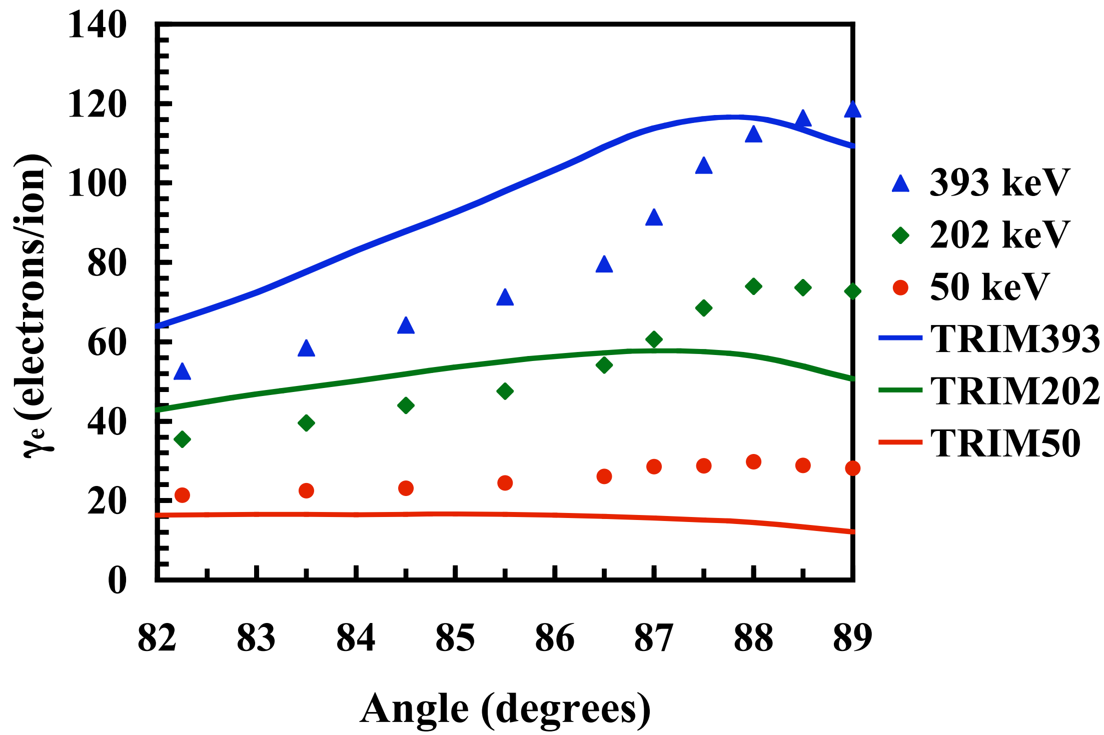
A. Molvik, H. Kollmus, E. Mahner, et al., PRL 98, 064801 (2007).





Developed model for ion-induced electron yield scaling with beam energy and angle of incidence*

- Model electron yield (electrons/ion) versus
  - ion energy
  - angle of incidence
- Reasonable agreement with our measurements
- Not 1/cosθ at these lower ion energies



Modified Sternglass model**
evaluated with TRIM code

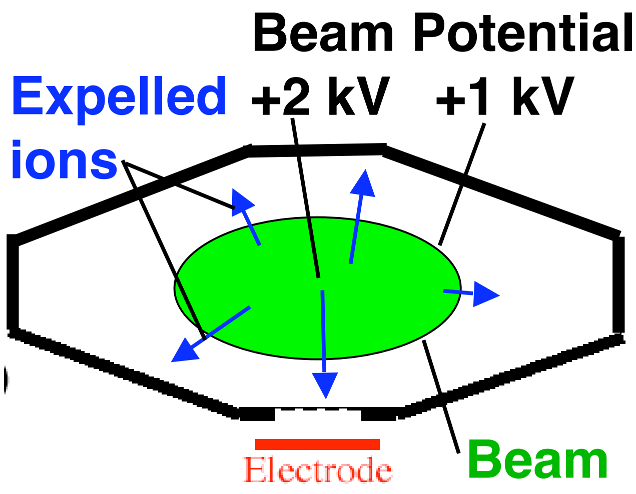
$$\gamma_e \propto \frac{\delta}{\cos(\theta)}\left(\frac{dE}{dx}\right)_e$$

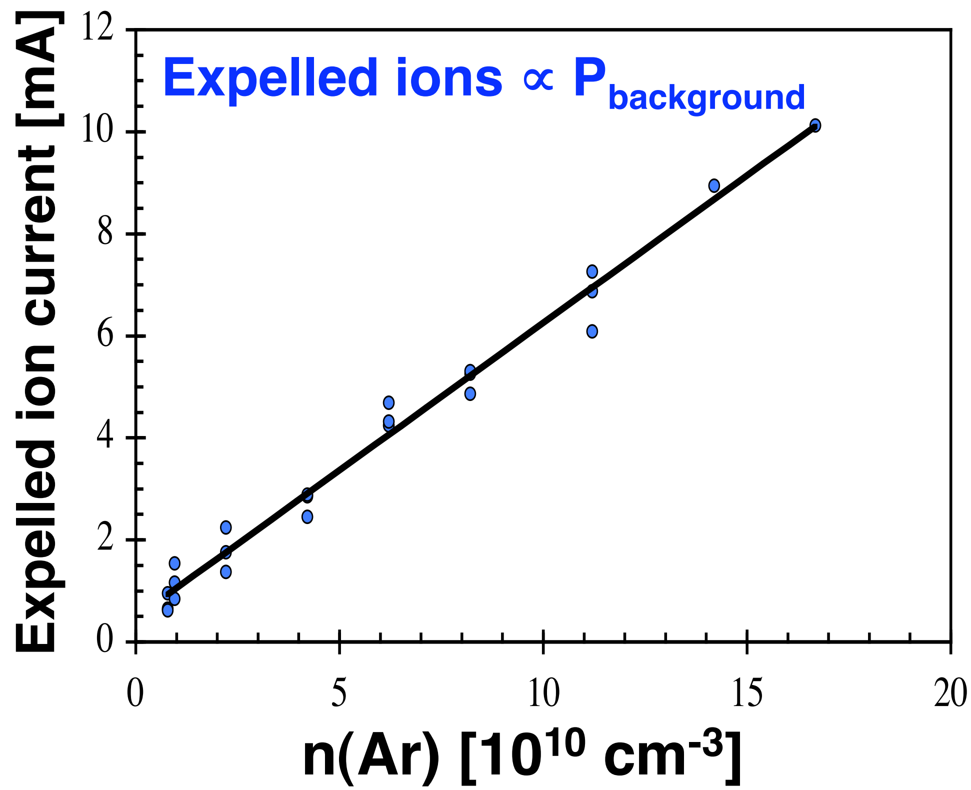
* Michel Kireeff Covo, PRSTAB 9, 063201 (2006).

** E. J. Sternglass, Phys. Rev. 108, 1 (1957).

We measure electron sources – ionization

1. Ionization of gas by beam ($n_e/n_b \leq 3\%$)





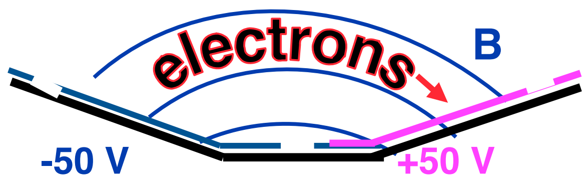
Beam current known; from expelled ion current infer

- Ionization rate
- Also, gas density in beam

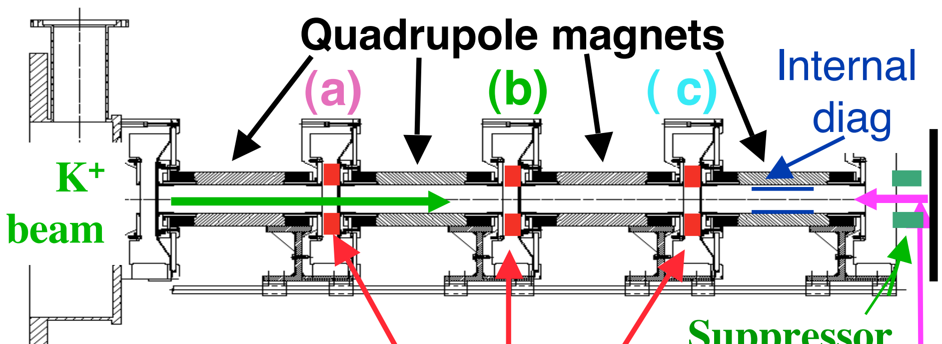
A. Molvik, et al., NIMA 544, 194-201 (2005).

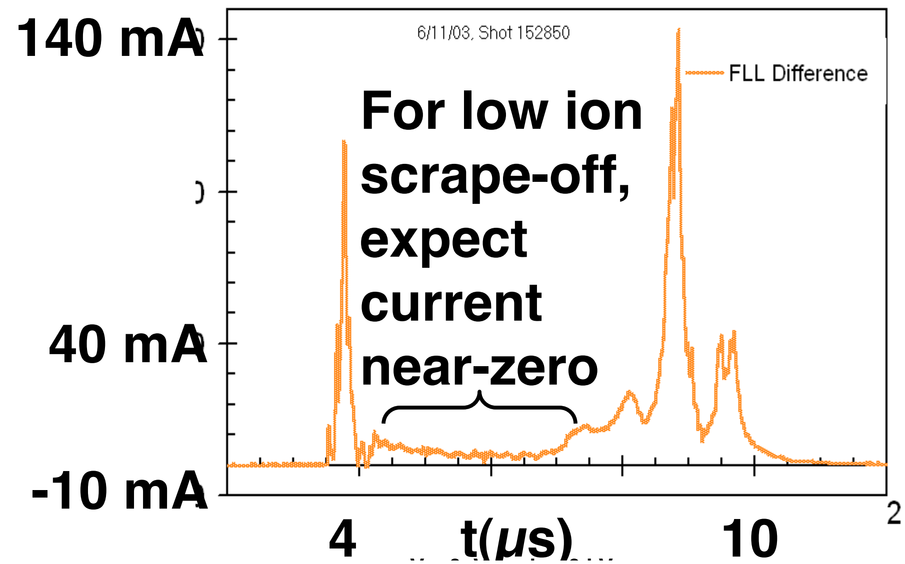
We measure electron sources – walls

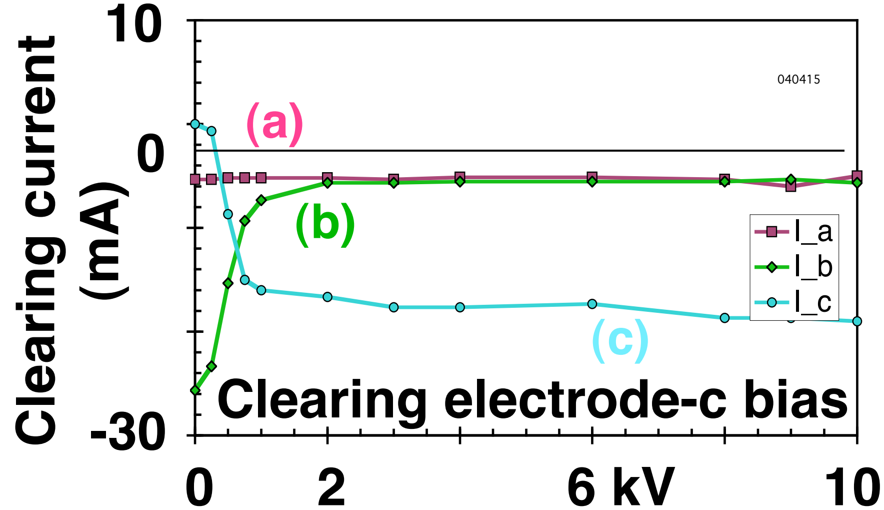
2. Electron emission – beam tube $(n_e/n_b \leq 7\%)$



3. Electron emission – end wall $(n_e/n_b, 0, 100\%)$

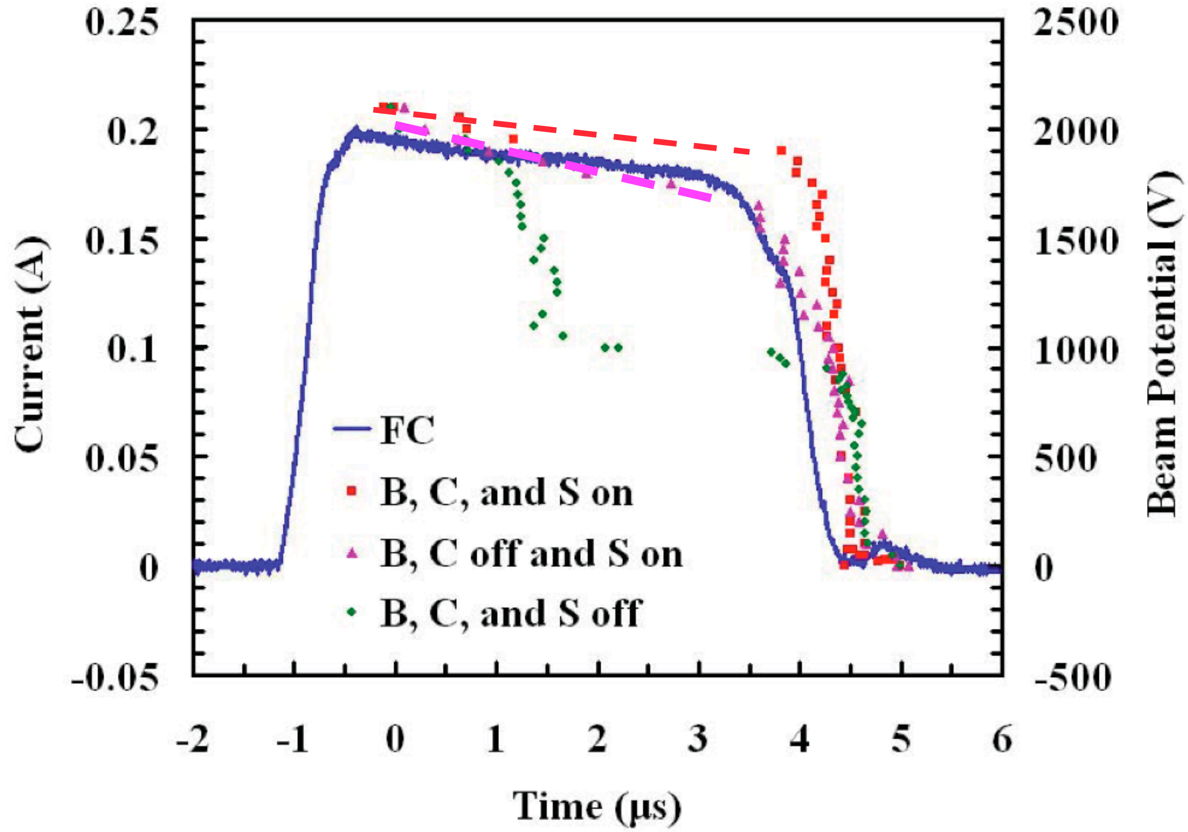






1st measurement of absolute electron cloud density* – used retarding field analyzer (RFA) and clearing electrodes

- RFA measures max. expelled ion energy E_i (scan bias on successive pulses)
- $E_i = \phi_b$, max. beam potential
- ϕ_b depressed by electrons
- Clearing electrode current: infer minimum n_e, and corroborate higher n_e



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. Electr. A	~ 7%	~ 25%	~ 89%
RFA	(~ 7%)	~ 27%	~ 79%

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

Other