(3) Describe what further experiments and modeling are needed to evaluate the use of solenoids versus quads for future WDM experiments

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Art Molvik & HCX and NDCX Groups

the Heavy-Ion Fusion Science Virtual National Laboratory
(HIFS-VNL)

February 22, 2007

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UCRL-PRES-228122

HIFS e-cloud effort

HCX Experiment

Art Molvik
Michel Kireeff Covo
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Peter Seidl

NDCX Experiment

Peter Seidl
Joshua Coleman
Prabir Roy
Frank Bieniosek
Art Molvik

Simulation

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Bill Sharp
Ron Cohen
Alex Friedman
Dave Grote
Steve Lund
Adam Sefkow
Dale Welch

Quads VS solenoids – two issues

(1) Maximum ion-beam current, and the associated emittance – in solenoids and quadrupole magnets

(2) Degradation of (1) by electron and gas cloud effects and their mitigation.

Maximum ion-beam current, and the associated emittance – in solenoids and quadrupole magnets

- **Electrostatic quads:** Lionel Prost – thesis, and Phys. Rev. Special Topics - Accelerators and Beams (PRSTAB) 8, 020101 (2005) – Applications at low energy
- **Magnetic quads:** Line charge increases with beam velocity
- **Solenoids:** Highest line charge at low energies – would like to observe details of Brillouin flow.

Beam current and envelope agree with envelope codes in each case: implies good agreement between experiment and theory.

Theory: E. P. Lee, R. J. Briggs, “The solenoidal transport option: IFE drivers, near term research facilities, and beam dynamics,” Report LBNL 40774, Sept. 1997; some of this in NIMA **415,** 218 (1998).

Degradation of (1) by electron (and gas) cloud effects

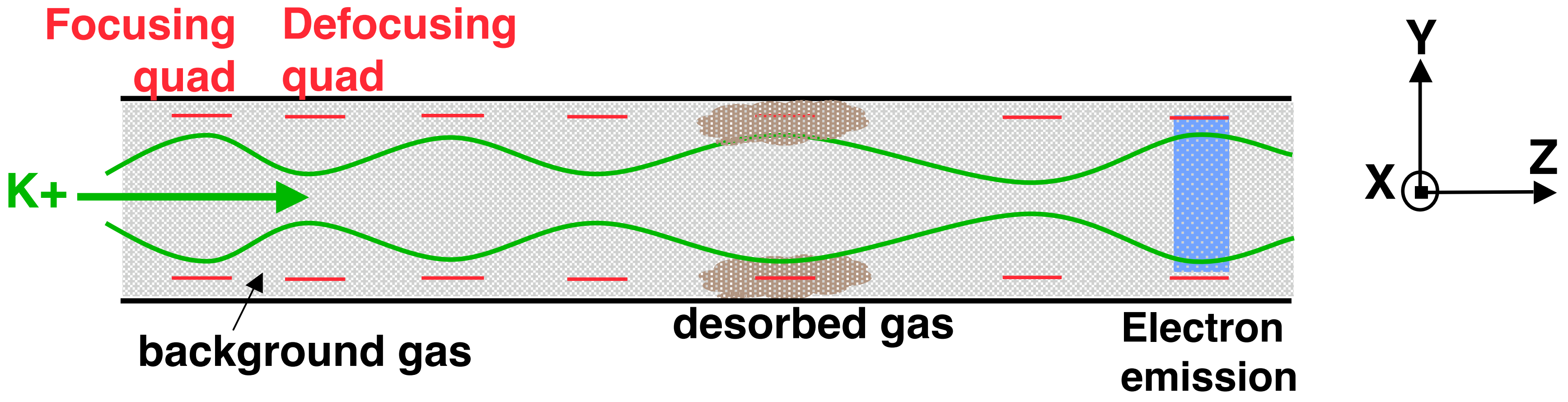
- **Electrostatic quads:** Clears e-clouds, ok if e- sources small
- **Magnetic quads:**
  - See effects at high e- line charge
  - Can measure e- line charge [PRL **97**, 054801 (2006)]
  - Validate simulations – determine experimental thresholds for allowable electron charge from each type of e- source: ionization, beam-tube & end-wall emission.
- **Solenoids:**
  - See effects at high e- line charge
  - Need to measure e- line charge
  - Validate simulations – determine thresholds for allowable electron charge from each type of source: ionization, beam-tube & end-wall.

Backup slides

New accelerators for WDM and HIF must push performance to cost ratio, and guarantee successful operation

- Electron and gas physics likely to determine operating limits, e.g.:
  - Maximum beam current
  - Compactness - how close can beam tube approach beam?
  - Electron-ion instabilities (as seen in PSR)
- Devise mitigation techniques to increase limits
  - Clearing electrodes remove electrons
  - Roughened walls reduce electron and gas generation
  - Materials or coatings reduce electron and gas generation
  - Halo scraping by apertures reduces electron and gas generation

Control of accelerator beam-surface interactions is as important as control of MFE plasma-surface interactions



Charged particle beams transport efficiently with ‘strong focusing’, alternating gradient magnetic quadrupoles

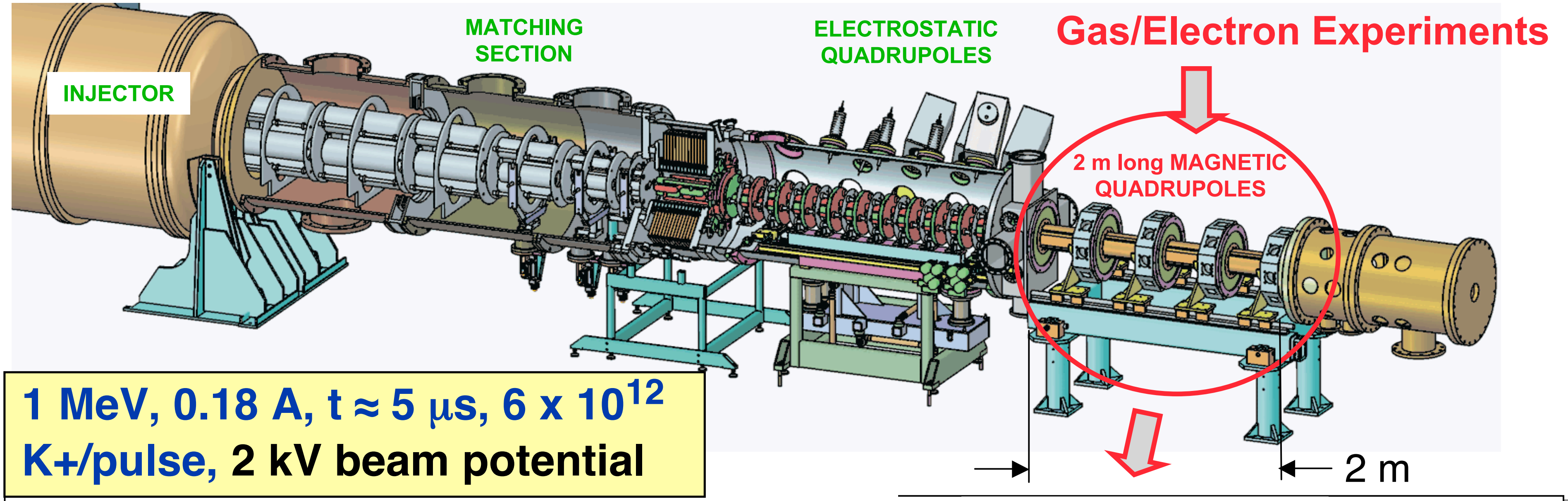
Primary:

- **Ionization of background or desorbed gas**
- **Ion-induced gas & electron emission from**
  - **expelled ions hitting vacuum wall**
  - **beam halo scraping**

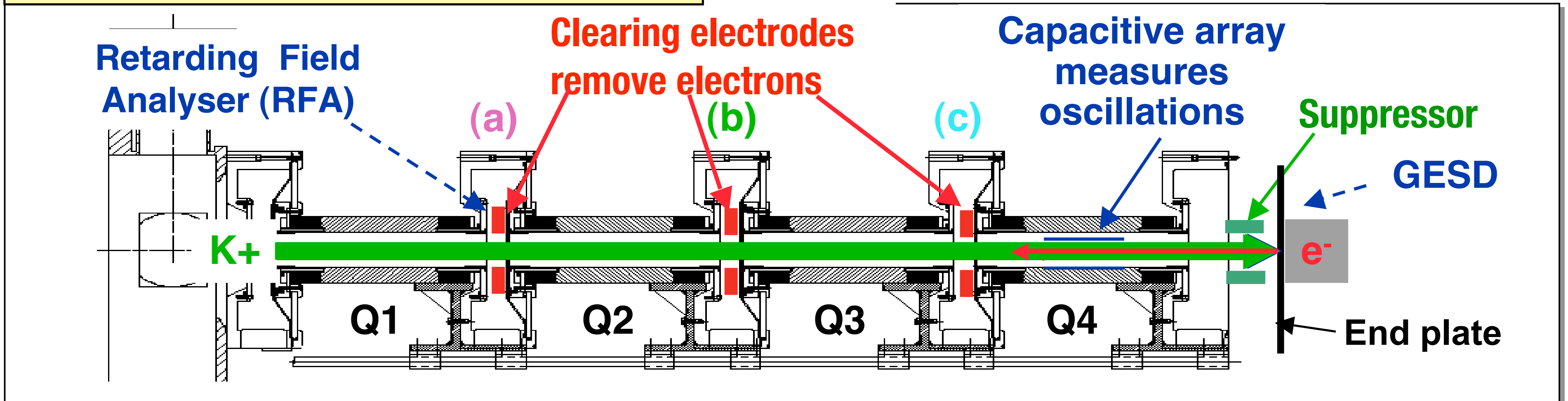
Secondary:

- **secondary emission from electron-wall collisions**

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



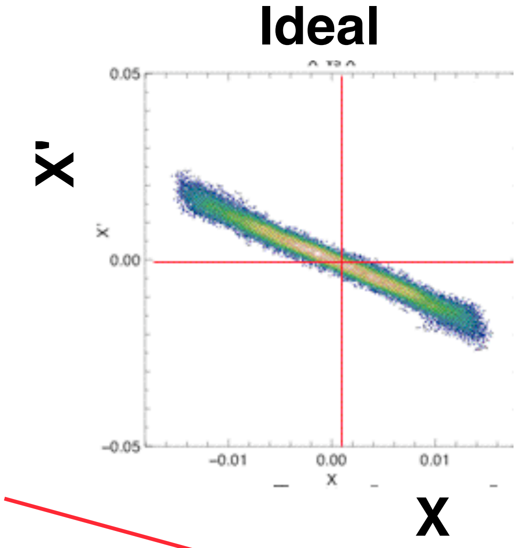
1 MeV, 0.18 A, t ≈ 5 μs, 6 x 10^{12} K+/pulse, 2 kV beam potential



Quadrupole magnets Q1 - Q4 for beam transport

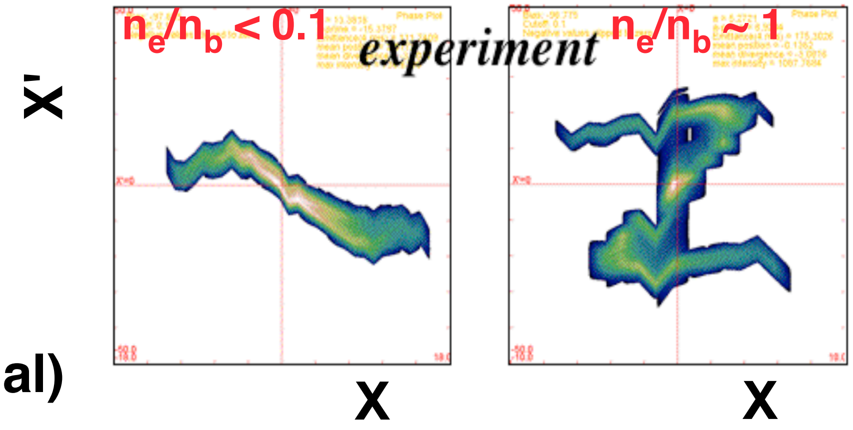
Heavy-ion beams in HCX can be degraded by e-clouds

- **Compact phase-space essential to a small focal spot**
- **Ideal beam has minimum phase space**



Artificially high electron density to exaggerate electron effects

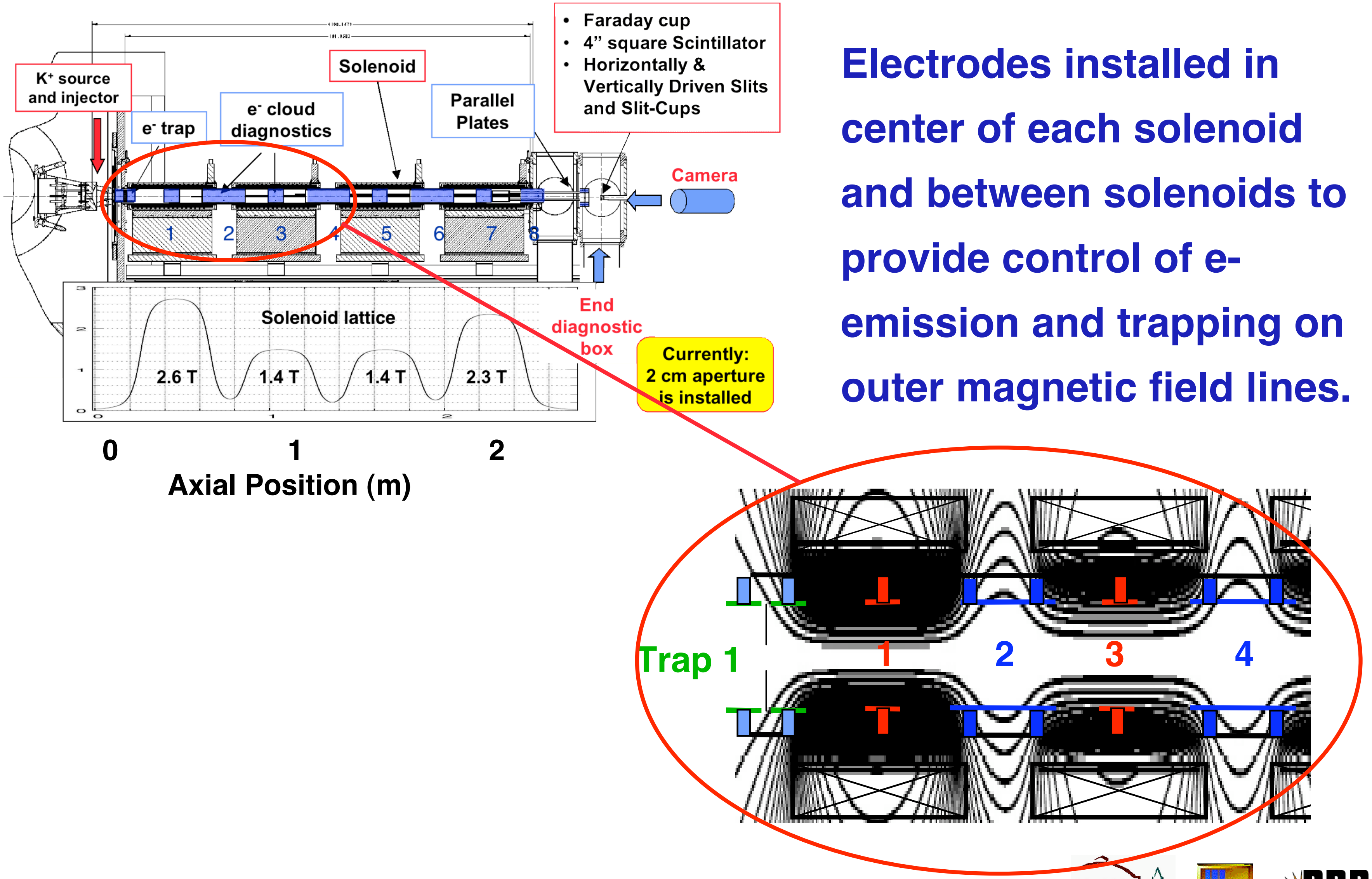
- **Electrons can distort phase space, greatly increasing area of focal spot.**



x = horizontal location of ion

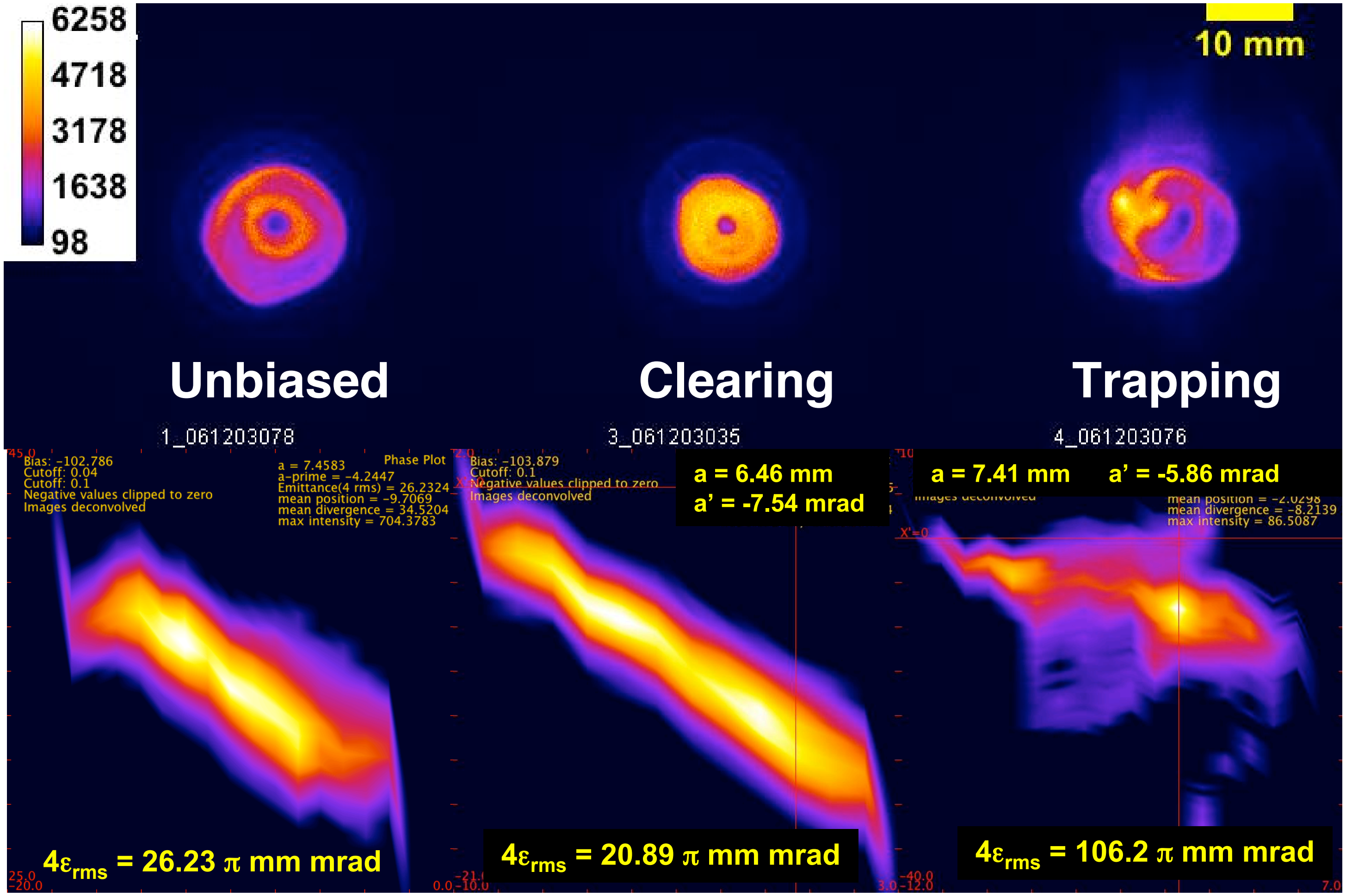
x' = dx/dz of ion (transverse/axial)

We have begun experiments studying e-clouds in NDCX with solenoid magnets



Electrodes installed in center of each solenoid and between solenoids to provide control of e-emission and trapping on outer magnetic field lines.

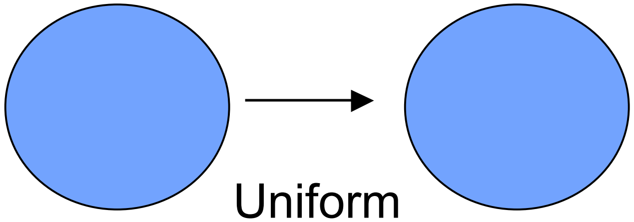
E-cloud electrode bias affects apertured beam quality



x = horizontal location of ion

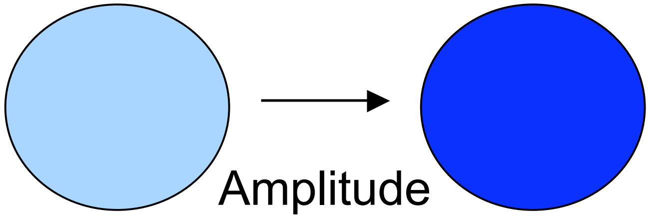
x' = dx/dz of ion (transverse/axial)

Types of specified electron cloud perturbations simulated through 200 quads



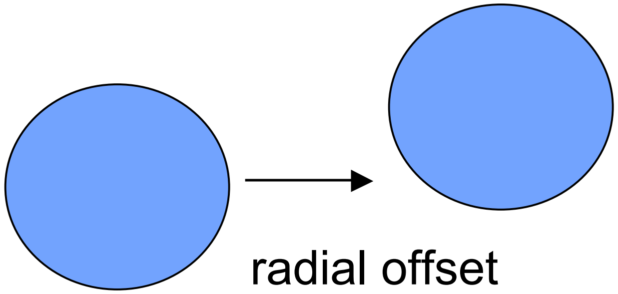
Uniform

(almost no effect)

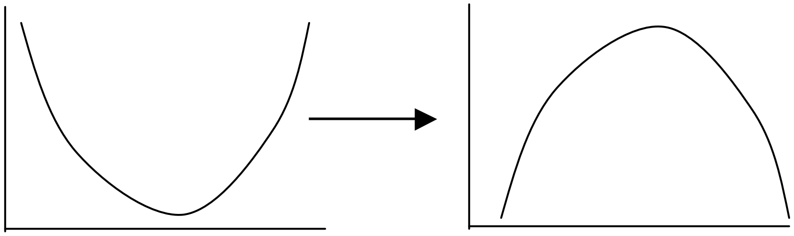


Amplitude

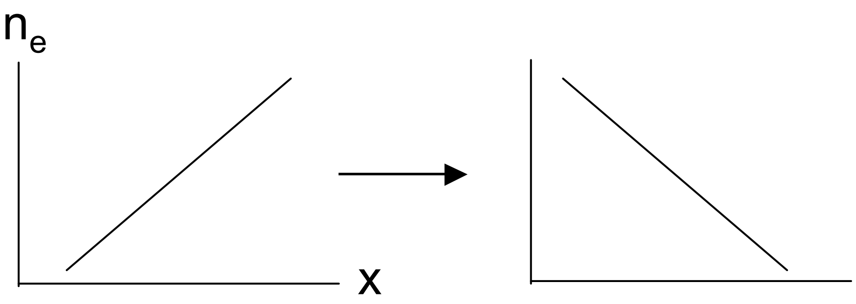
(biggest effect)



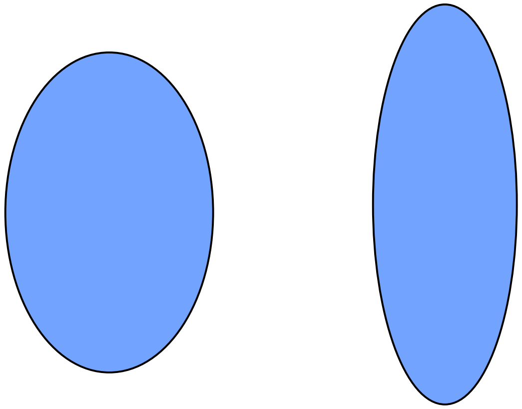
radial offset



radial shape variation



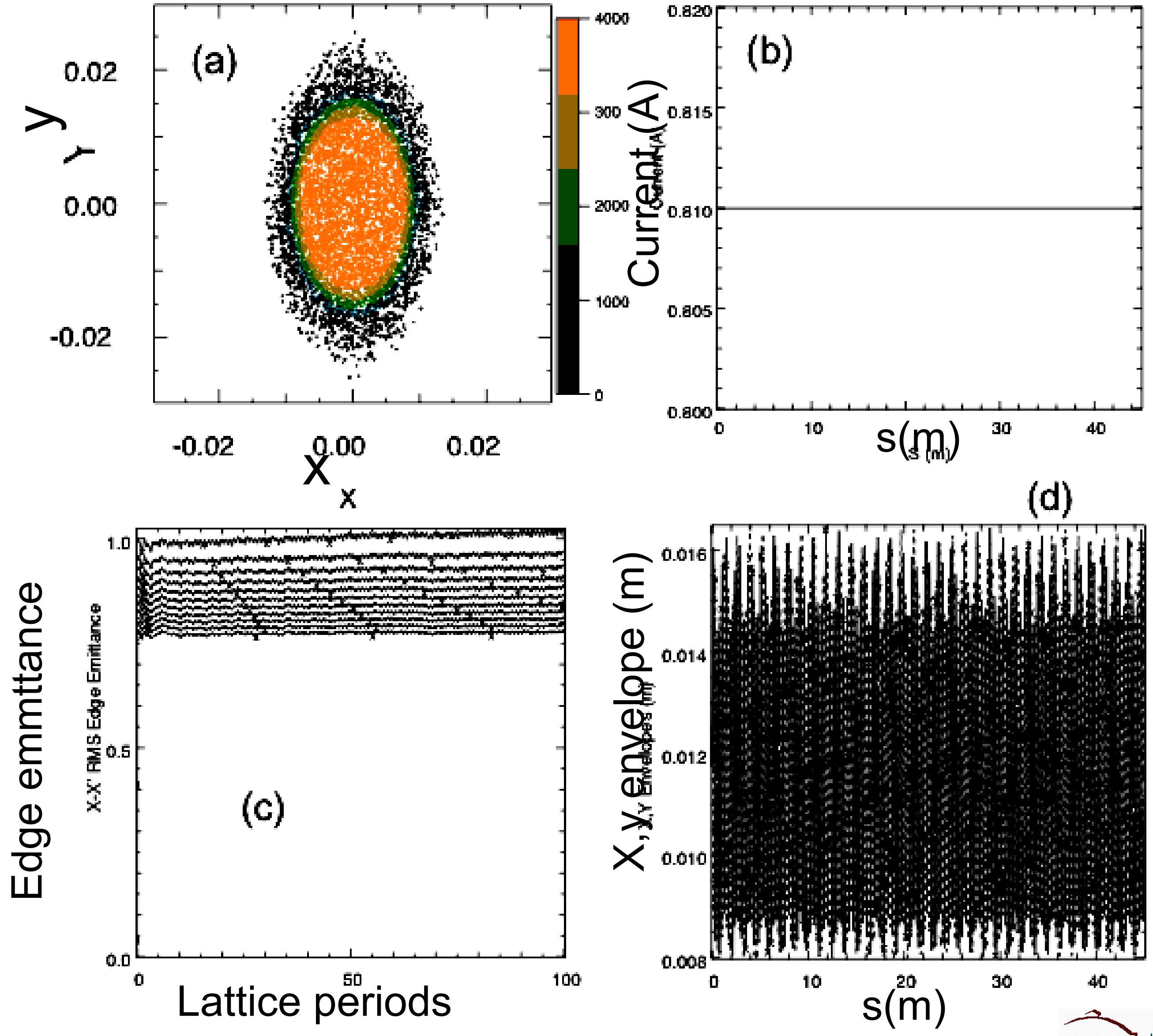
ramp



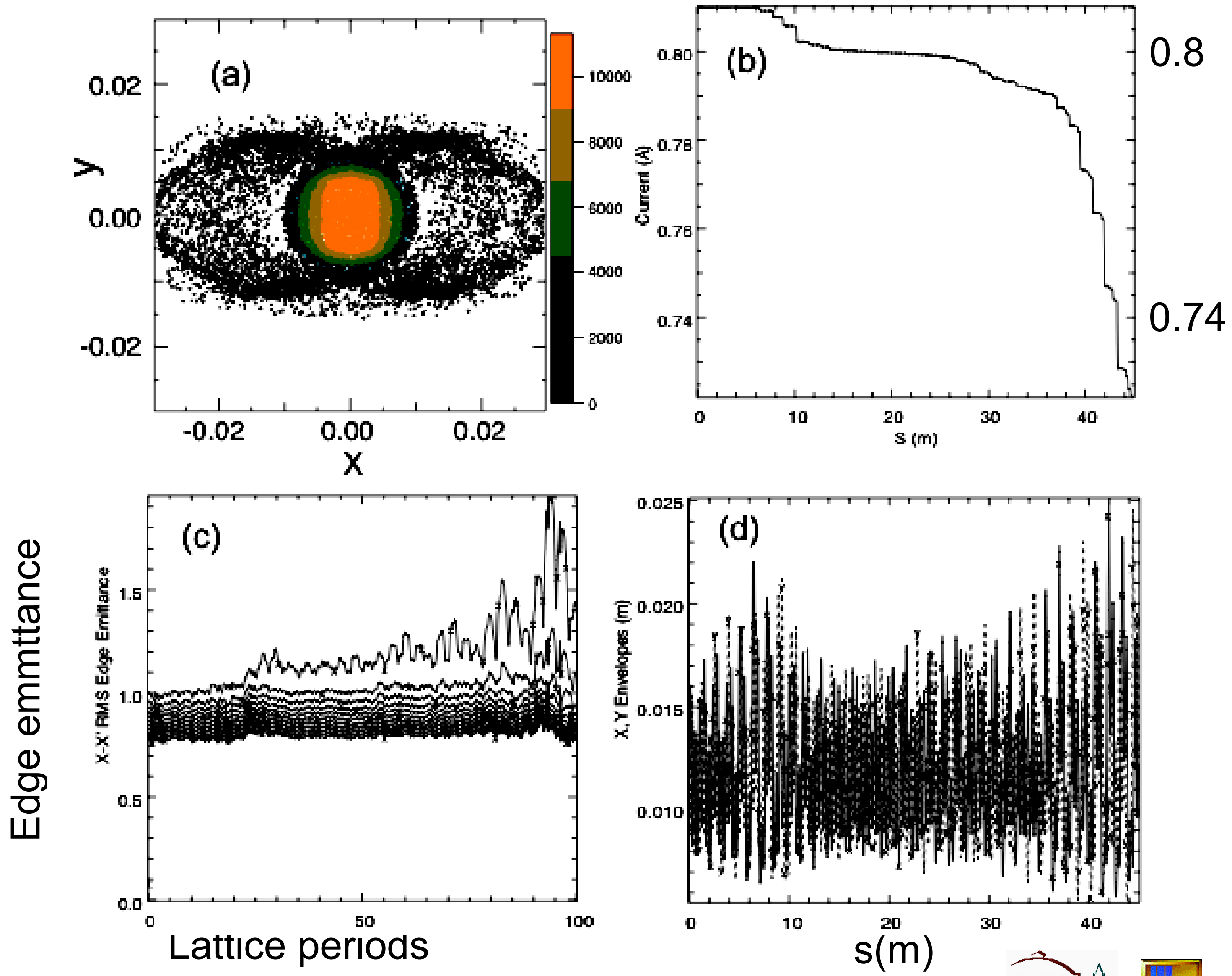
ellipticity

R. Cohen, et al., PRSTAB **7**, 124201 (2004).

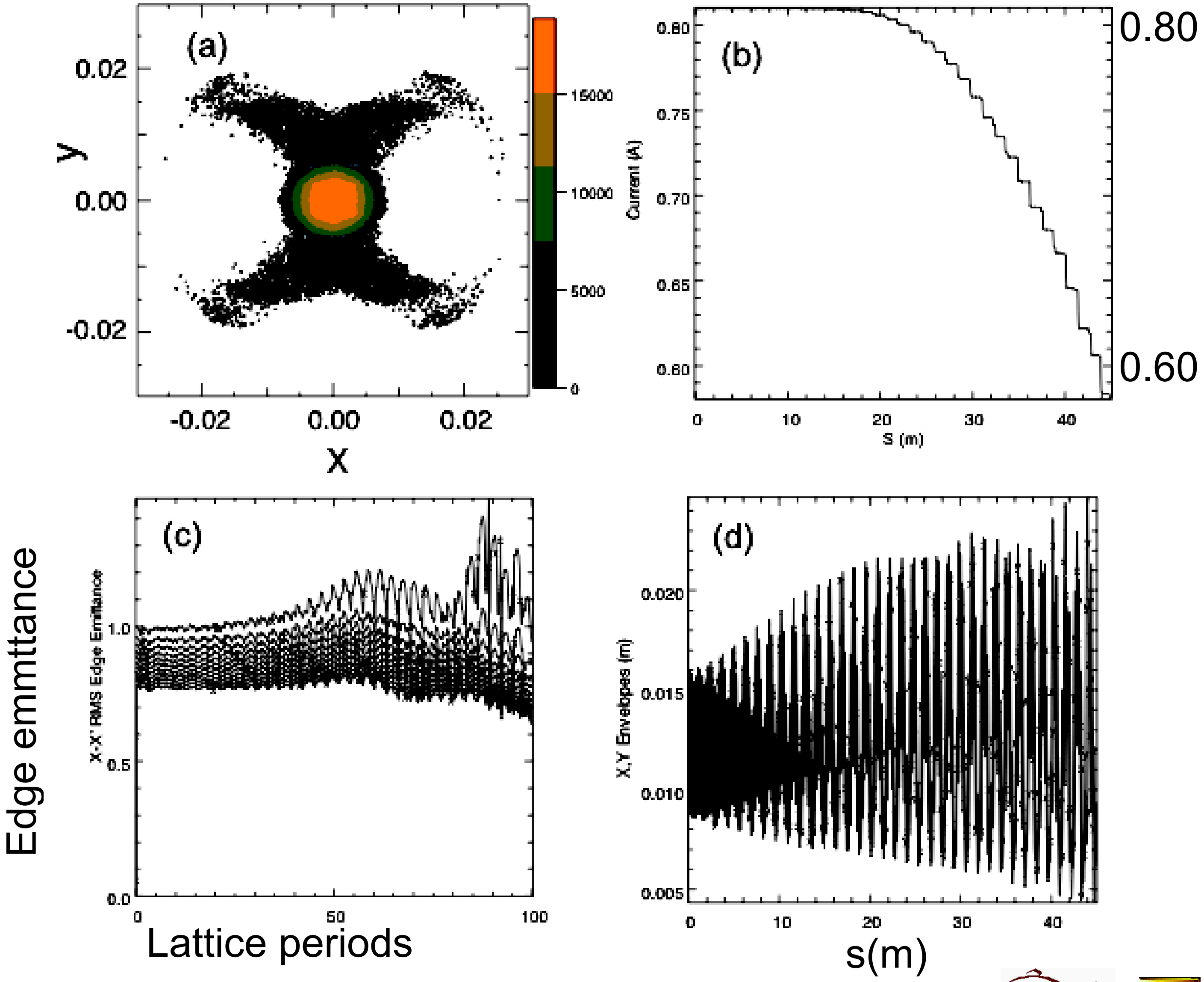
20% constant n_e has little effect



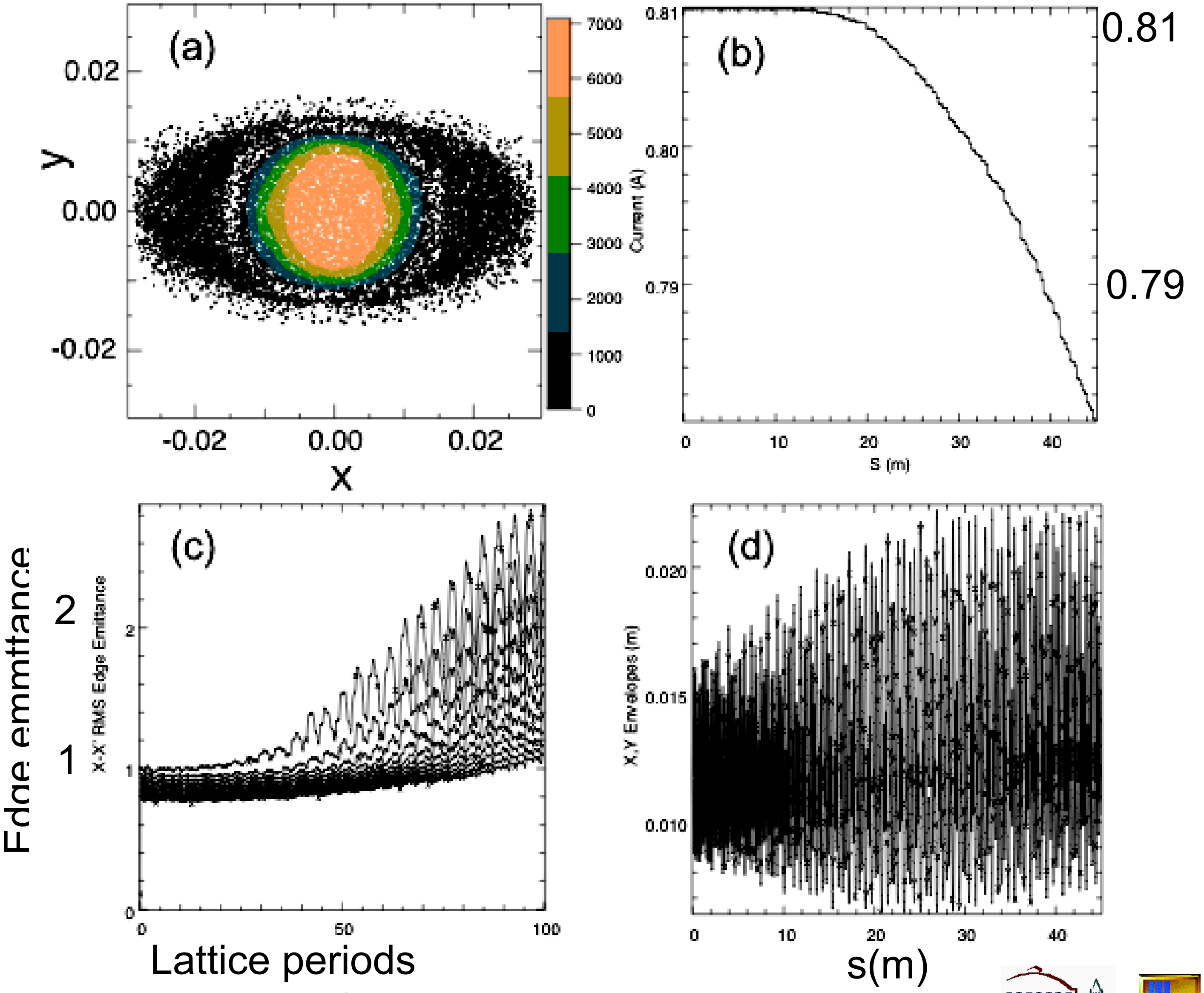
20% mean, 0-40% random n_e produces significant beam loss, envelope growth, halo



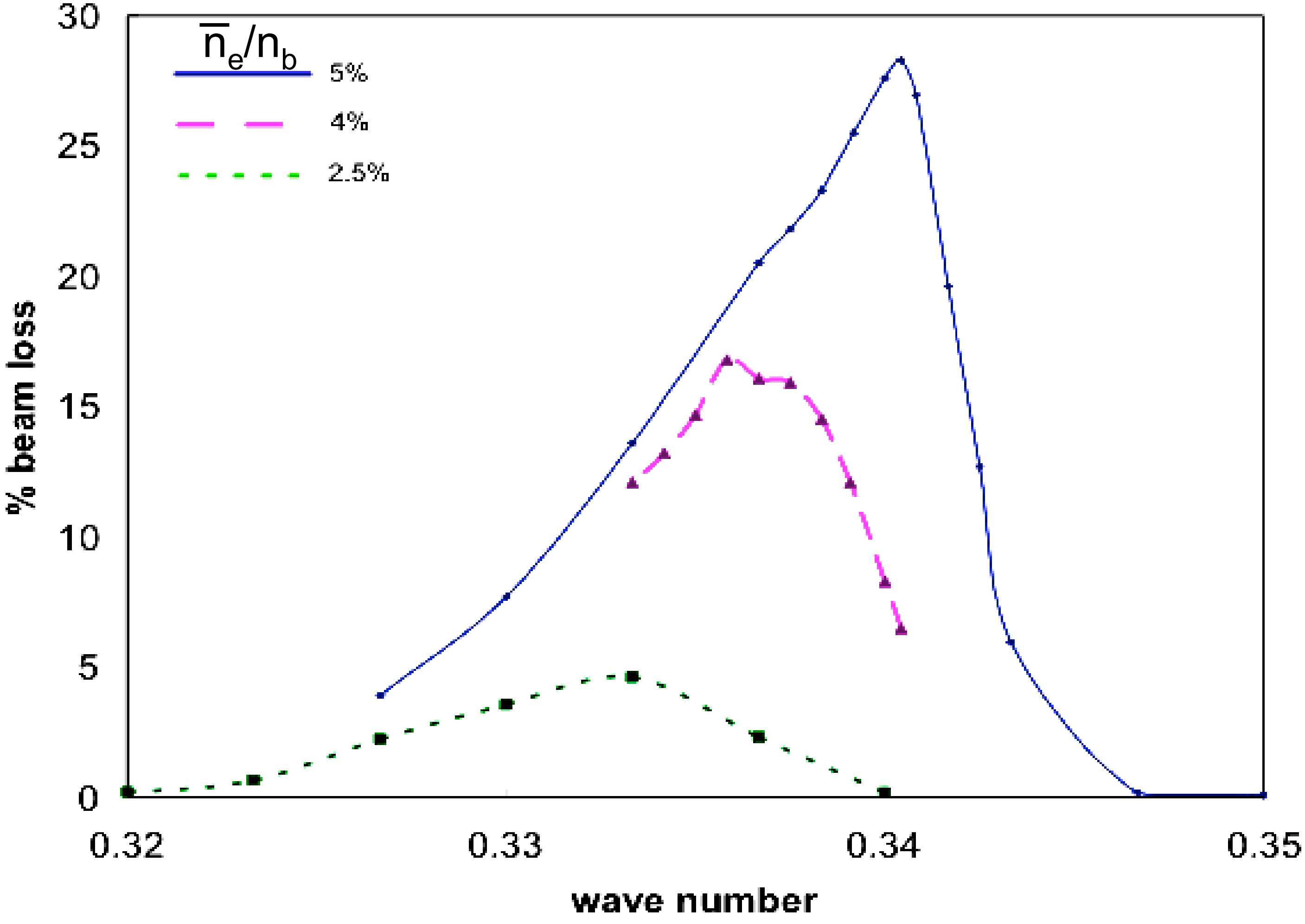
RESONANT perturbations are more damaging: 0-10% sinusoidally varying n_e resonant with breathing mode



Ellipticity resonant with q-pole oscillation (10% n_e) produces small beam loss but more bulk emittance growth



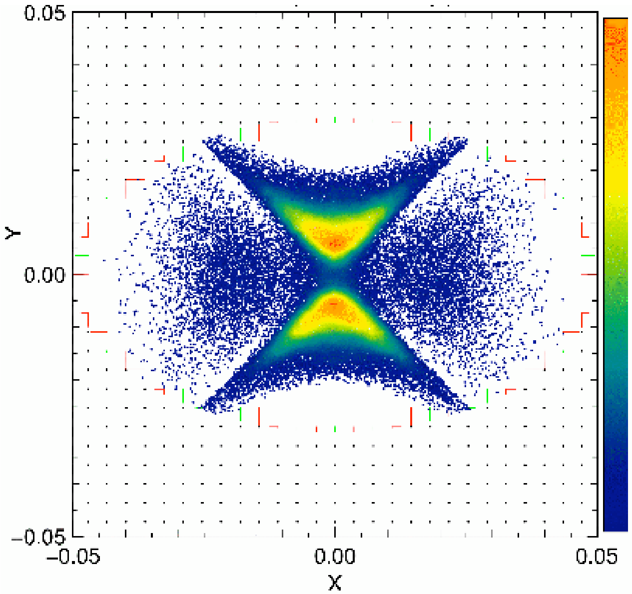
RESONANT perturbations are more damaging: sinusoidally varying n_e resonant with breathing mode (100% modulation)



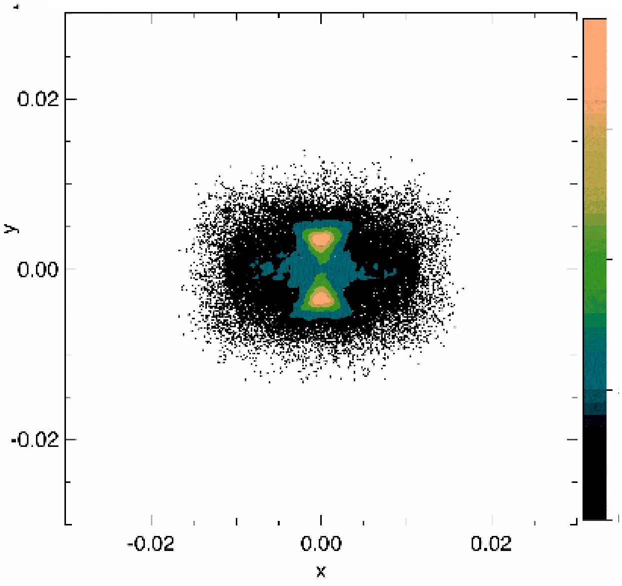
Max $\Delta I \sim (n_e/n_b)^p$, $p \sim 2.3 - 2.6$

Comparing presented distributions, we see that the NATURE of the electron source matters

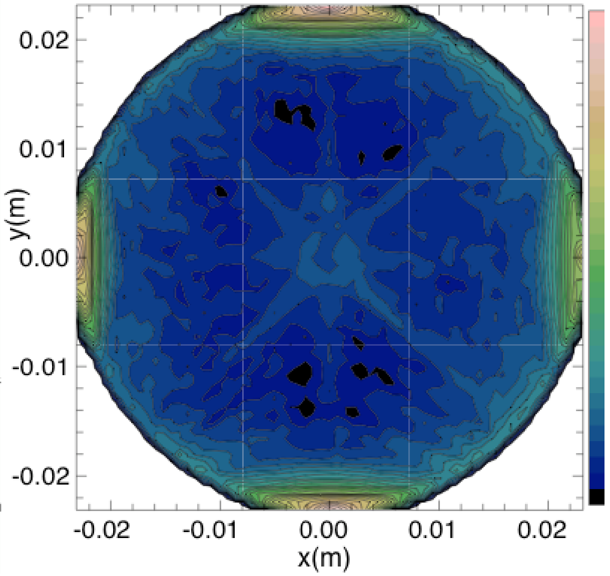
Electrons ejected from end wall



Electrons from ionization of gas

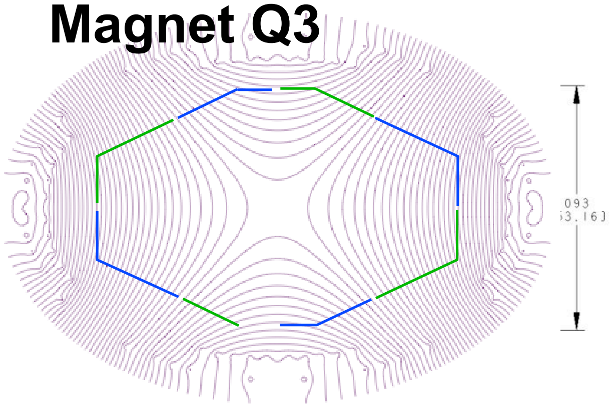


Electrons desorbed from beam pipe in quad upon ion impact

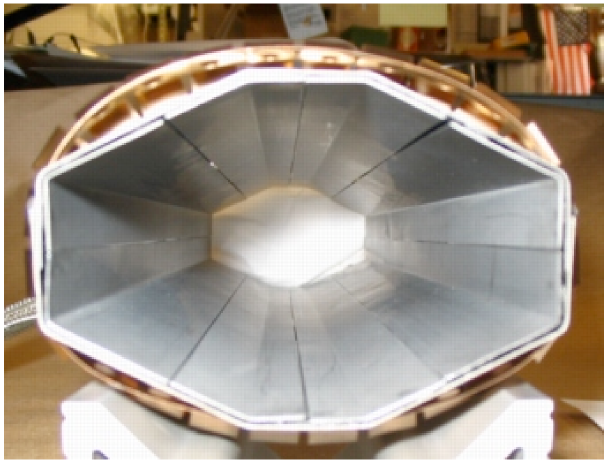


Diagnostics within magnetic quadrupole bores

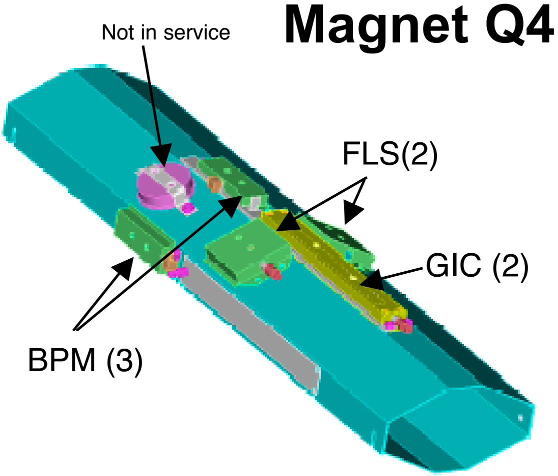
Magnet Q3

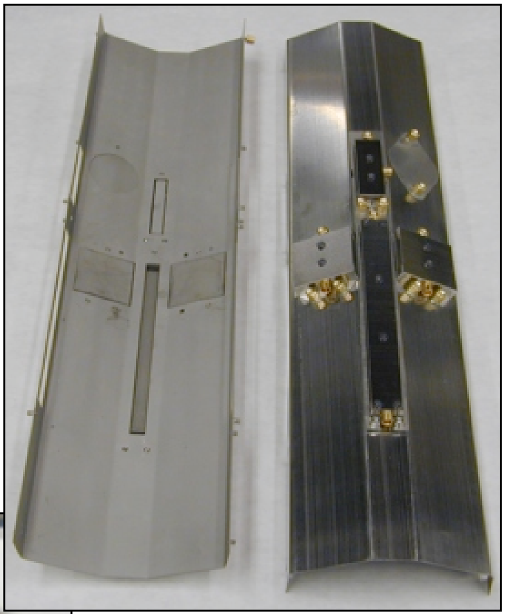


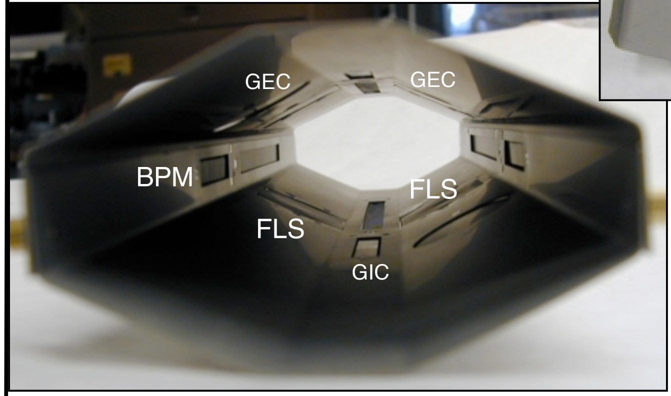
FLL: 8-biased electrodes at ends of field lines: measure capacitive signal + electrons from wall



Magnet Q4



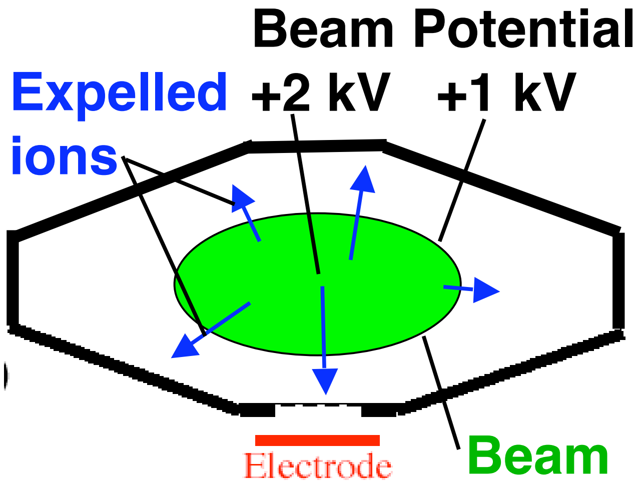


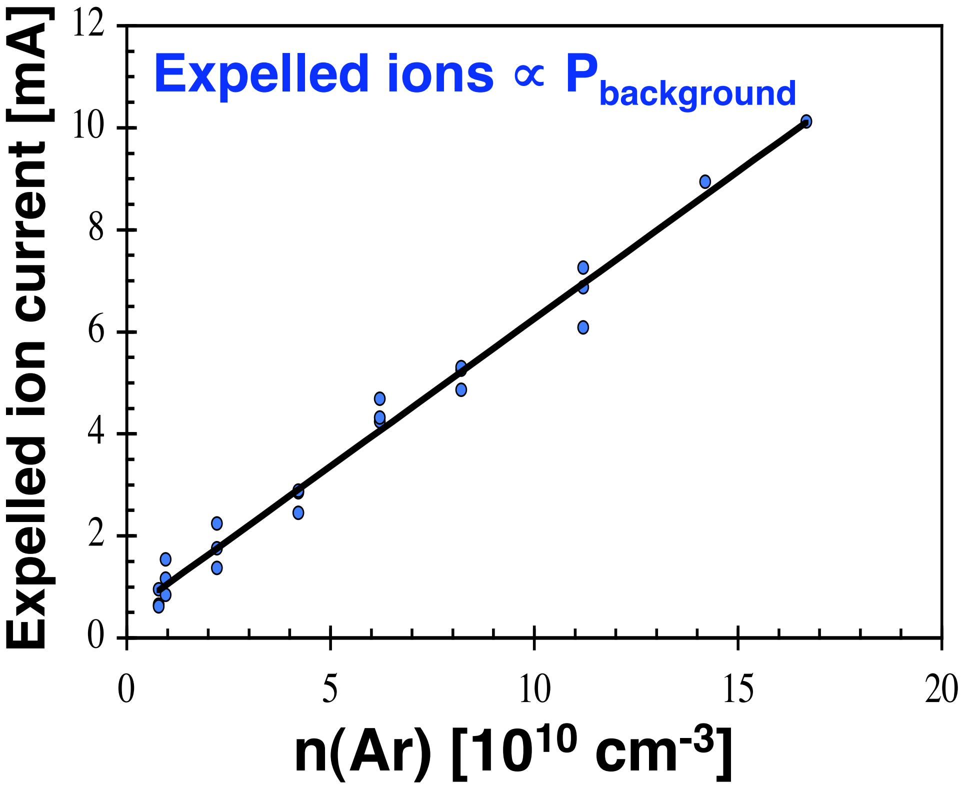


Capacitive and grid-shielded electrodes

We measure electron sources – ionization

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

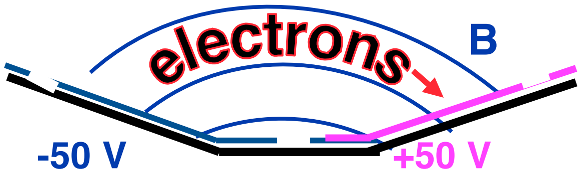


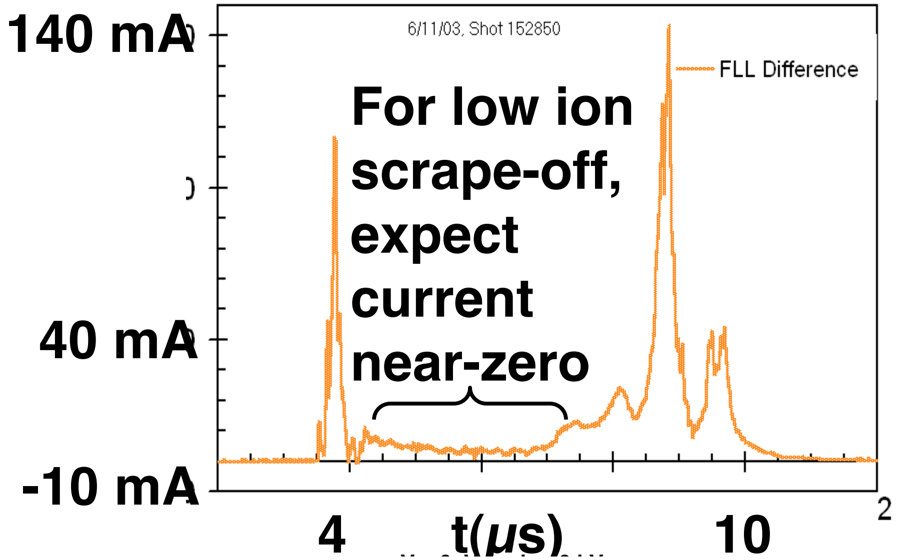


Beam current known; from expelled ion current infer
- Ionization rate
- Also, gas density in beam

We measure electron sources – walls

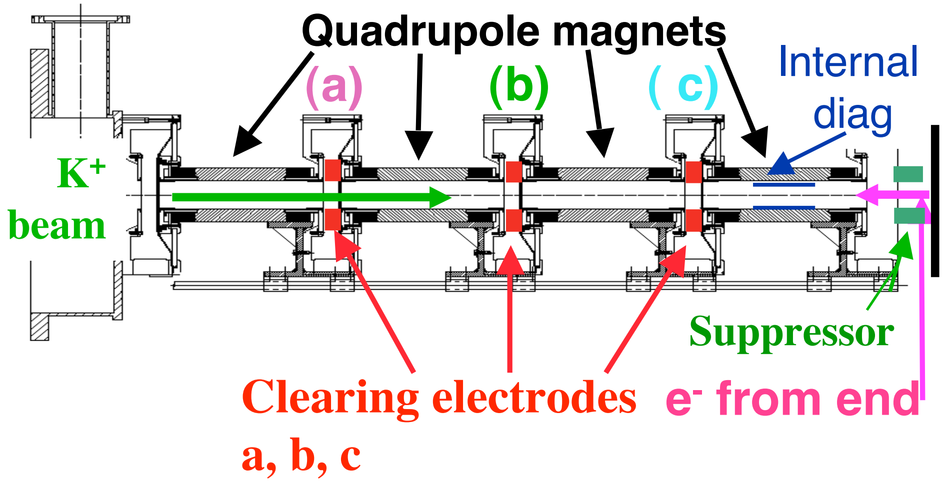
2. **Electron emission – beam tube** ($n_e/n_b \le 7\%$)

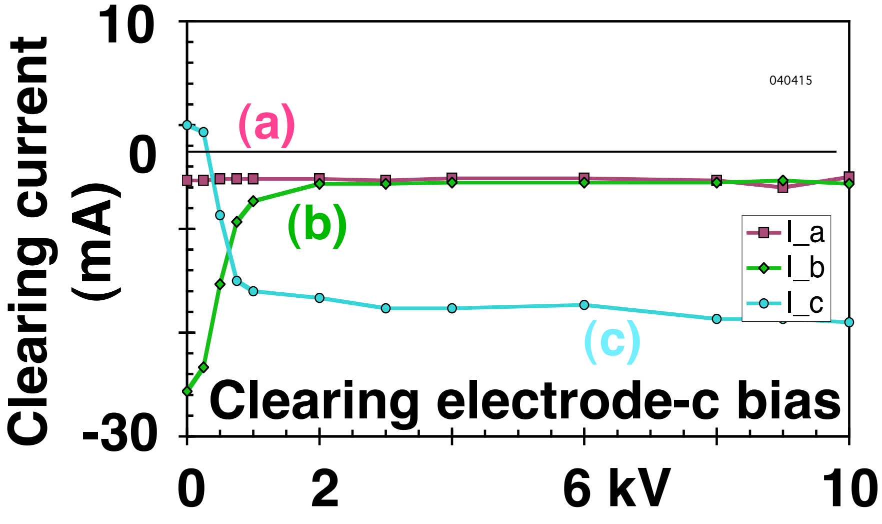




For low ion scrape-off, expect current near-zero

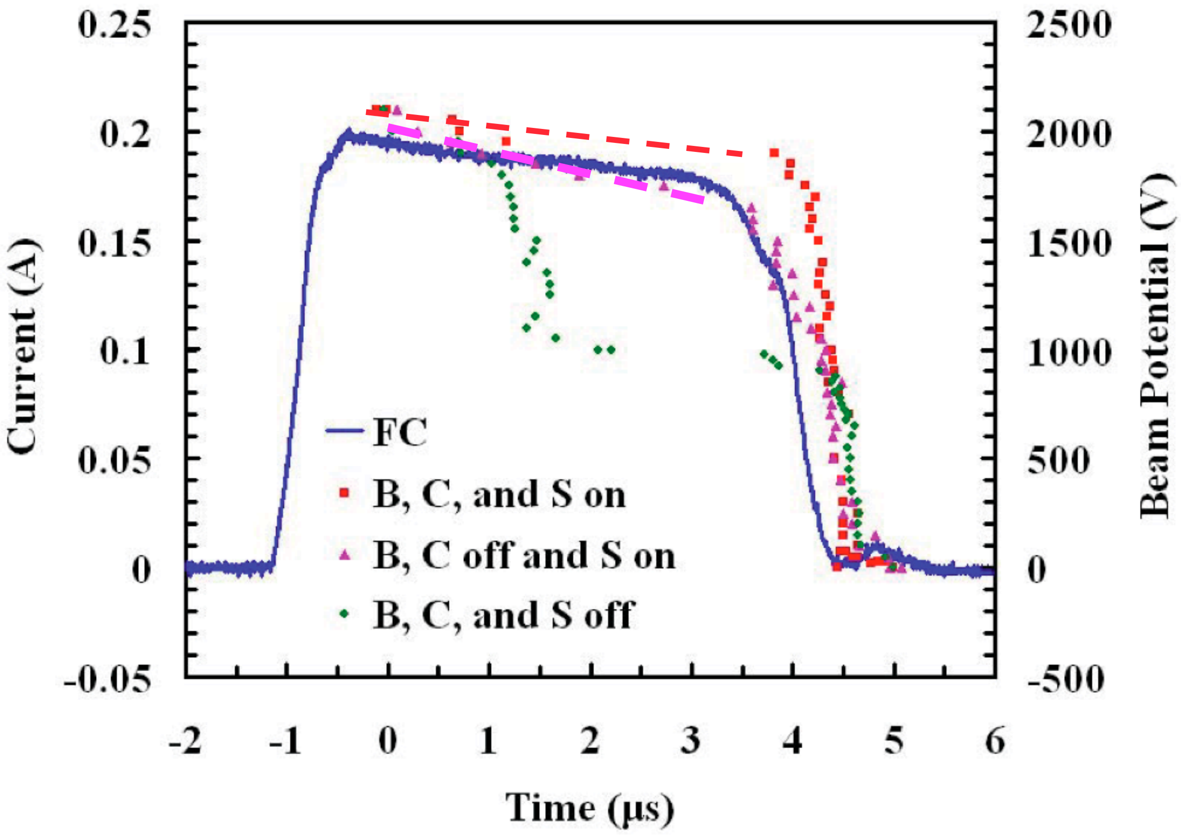
3. **Electron emission – end wall** (n_e/n_b, 0, 100%)





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).

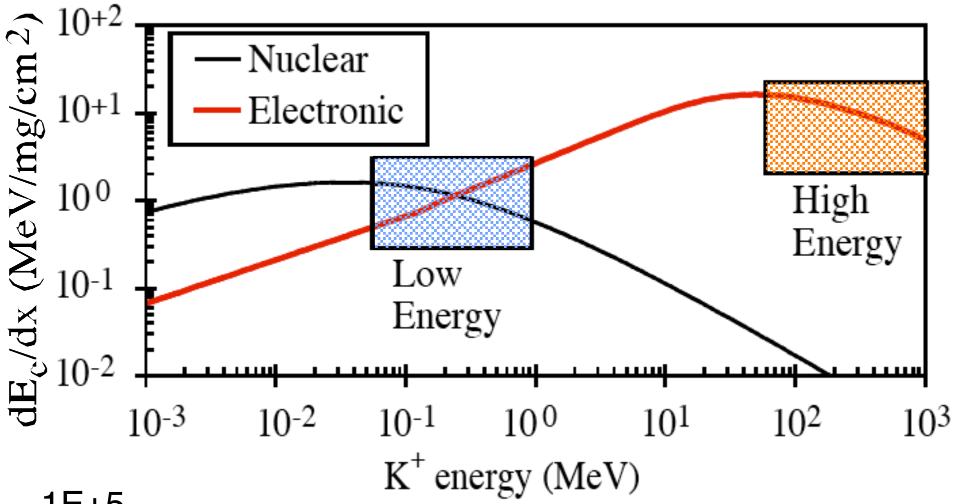
Electronic gas desorption scales with $(dE/dx)^2$, like electronic sputtering

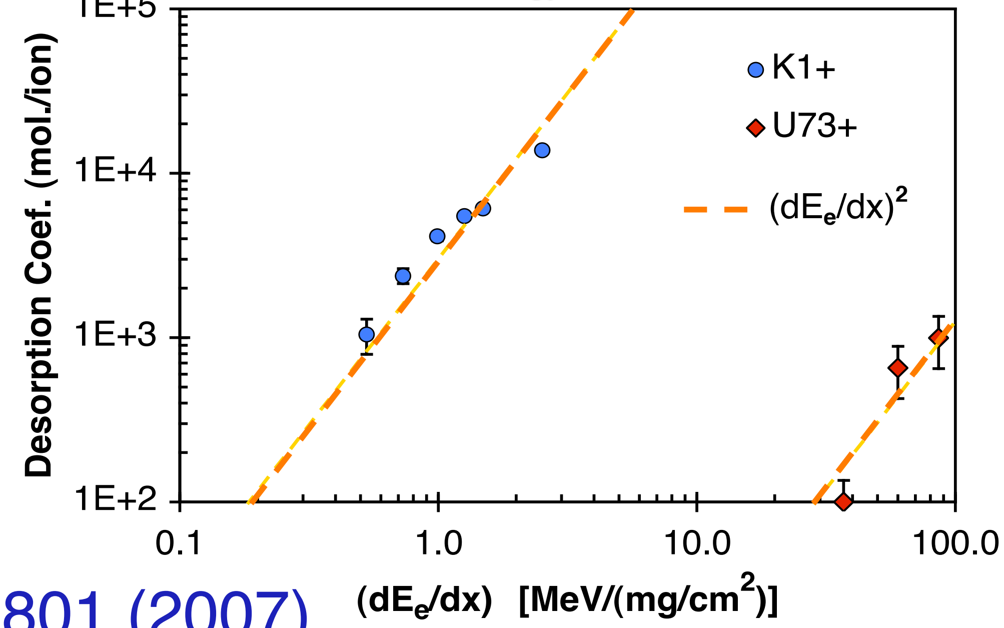
Conventional sputtering driven by large-angle nuclear scattering

Electronic sputtering more copious.

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

Electronic desorption, n ≈ 2.





A. Molvik, et al., PRL 98, 064801 (2007).

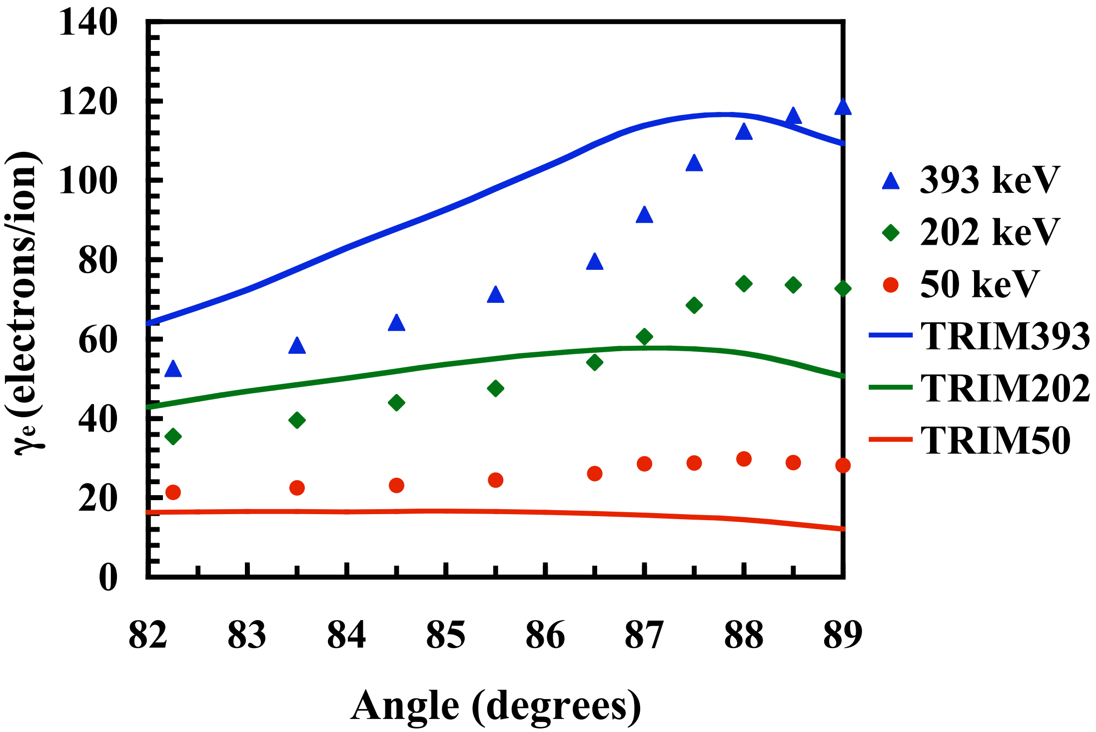
Developed model for ion-induced electron yield scaling with beam energy and angle of incidence*

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

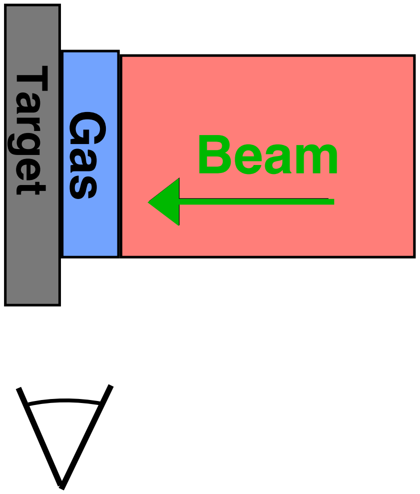
$$\gamma_e \propto \frac{\delta}{\cos(\theta)}\left(\frac{dE}{dx}\right)_e$$

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

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

We measure 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**

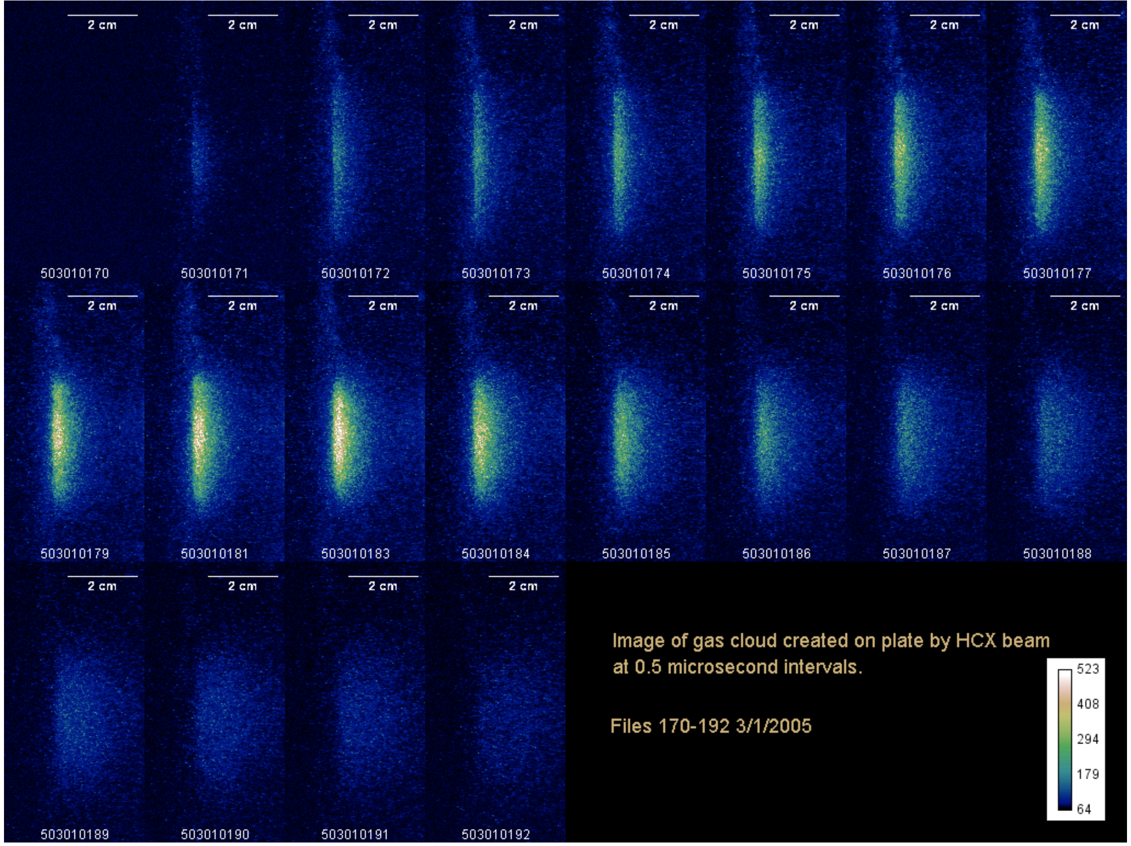


Image of gas cloud created on plate by HCX beam at 0.5 microsecond intervals.

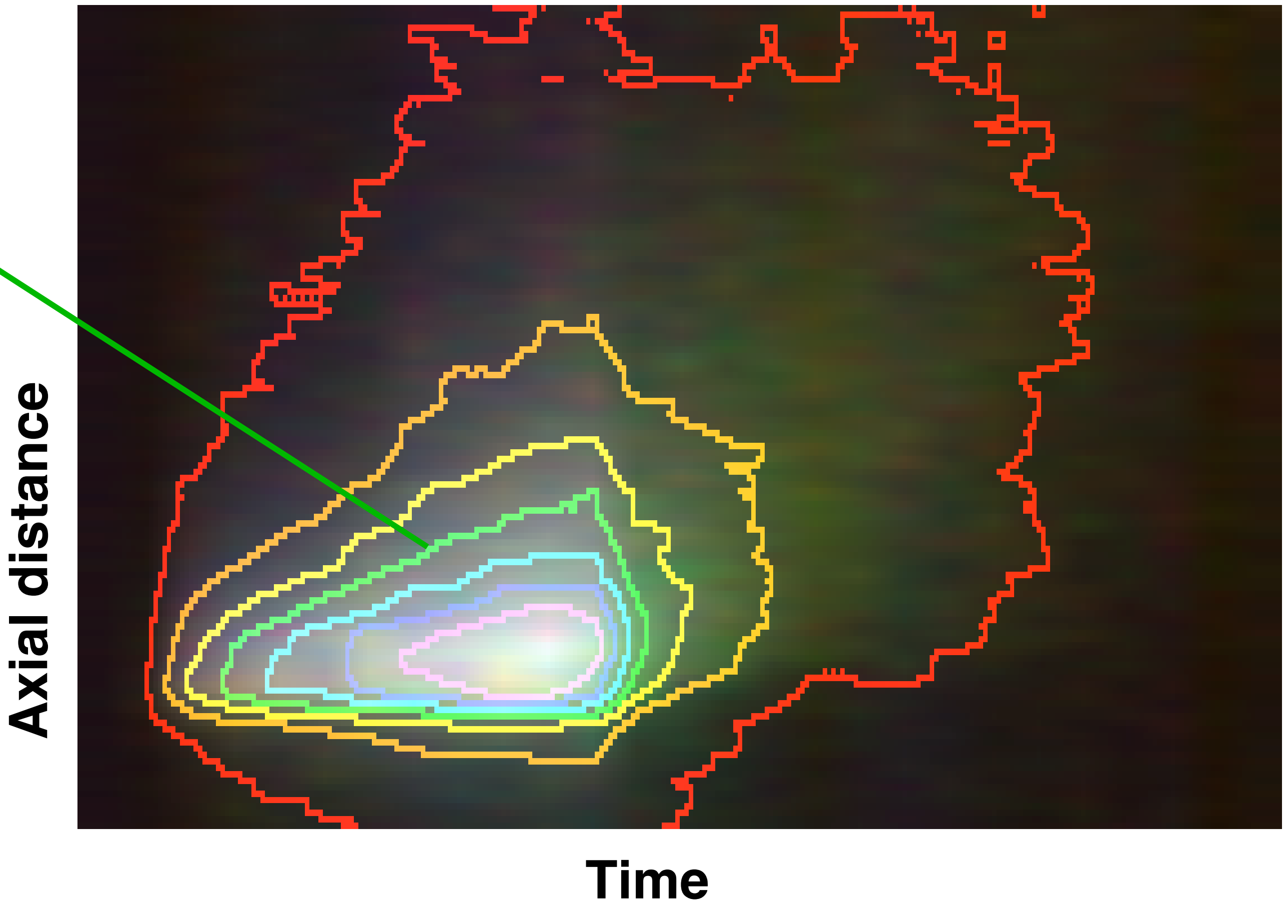
Files 170-192 3/1/2005

Future – absolutely calibrate camera to determine desorption yield, apply technique to non-evaporable getter (NEG)

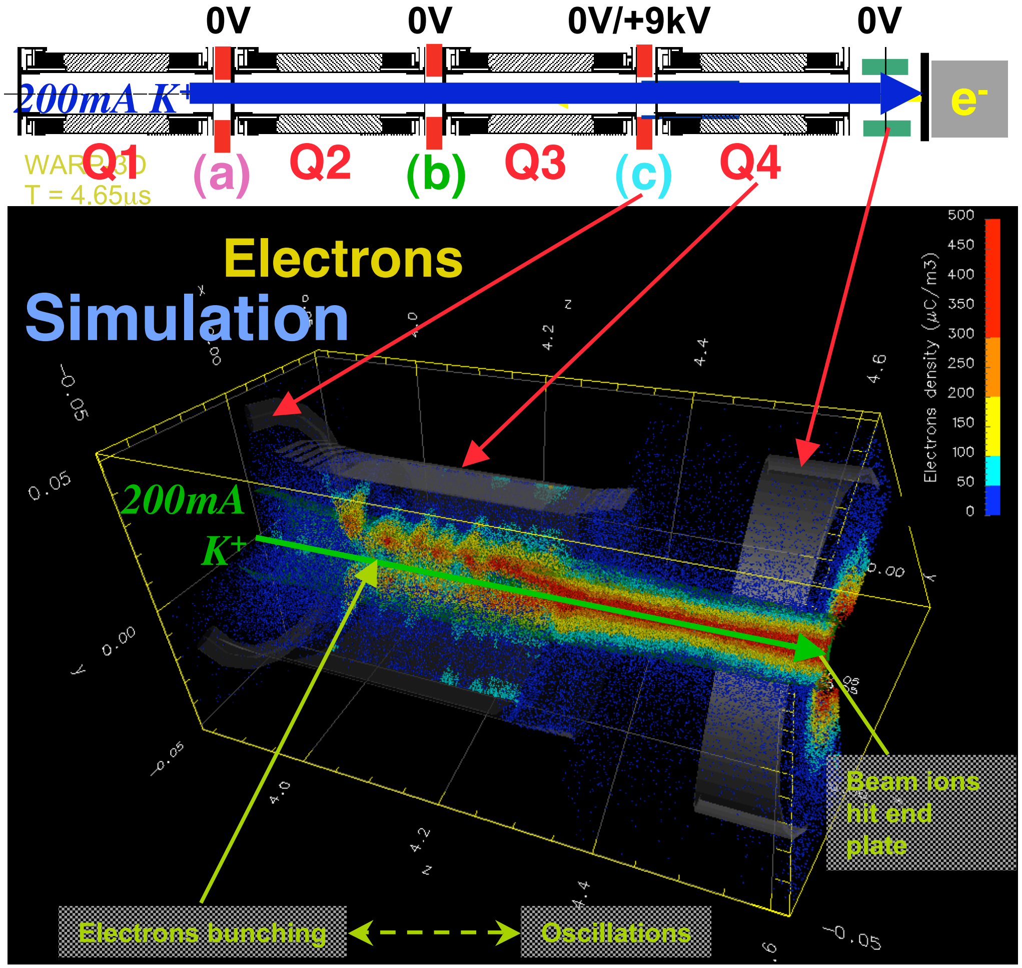
Line integral of images indicates an expansion velocity of up to a few mm/μs

Estimated velocity:
Slope ~1 mm/μs

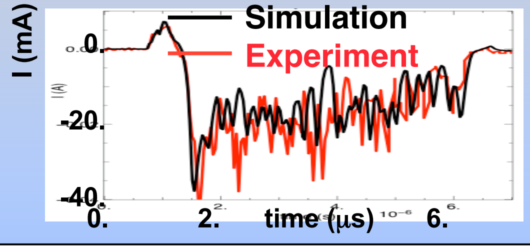
Corresponds to room temperature H_2, consistent with residual gas measurements



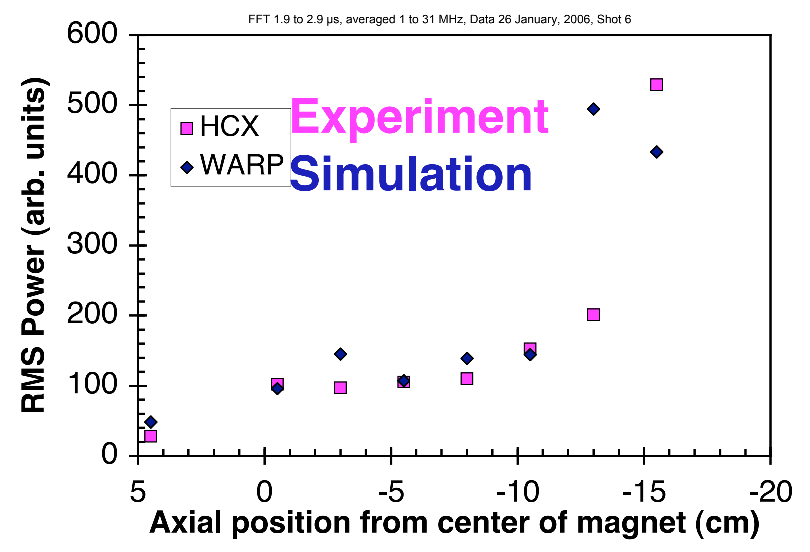
Electron oscillations – experiments validate simulations



Current to clearing electrode (c) agrees in frequency ~ 6 MHz



Currents to capacitive electrode array agree in wavelength ~5 cm, and amplitude (below)



Summary – We have established a sound basis to understand and mitigate electrons and gas in quads & sols

- Increased understanding of beam-surface interactions
  - Electron emission measured and modeled, $\propto dE_e/dx$
  - Discovered gas desorption $\sim (dE_e/dx)^2$
- Specified electron distributions simulated, resonant worst
- Major electron sources measured:
  - Wall emission from beam-scrape-off dominates (~7%) +gas
  - End-wall emission suppressed to ~0% (if not suppr. ~80%)
  - Gas ionization small (~3%)
- Absolute measurement of e- accumulation Vs. time in quads
- Electrons bunch, generating oscillations
  - Simulation & experiment agree – freq., wavelength, & amplitude
  - Experimental validation of simulations provides credibility