Quantitative experiments with electrons in a positively charged beam

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For the Heavy-Ion Fusion Science Virtual National Laboratory

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30 years of Heavy Ion Inertial Fusion

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LBNL & LLNL

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HIFS 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

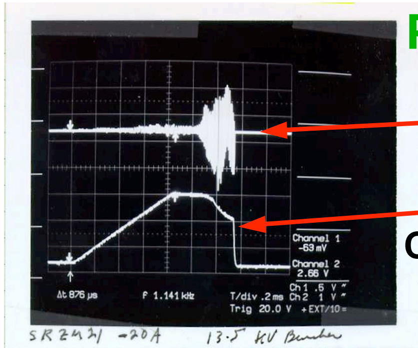
Consultants
- Miguel Furman (LBNL-Center for Beam Physics)
- Irv Haber (U. Maryland)
- R. Davidson, I. Kaganovich, H. Qin, A. Sefkow, E. Startsev, et al (PPPL)
- Peter Stoltz, Seth Veizer (Tech-X Corp.)
- John Verboncoeur (UC-Berkeley)

Outline

1. Introduction and tools
2. Beam-surface interactions
3. Absolute measurements of gas and electrons
4. Plasma oscillations

Electron clouds impact beams of positively-charged particles

PSR e-cloud effect



BPM

Beam Current

Electrons from:
- ionization of gas
- Beam tube
- end wall emission

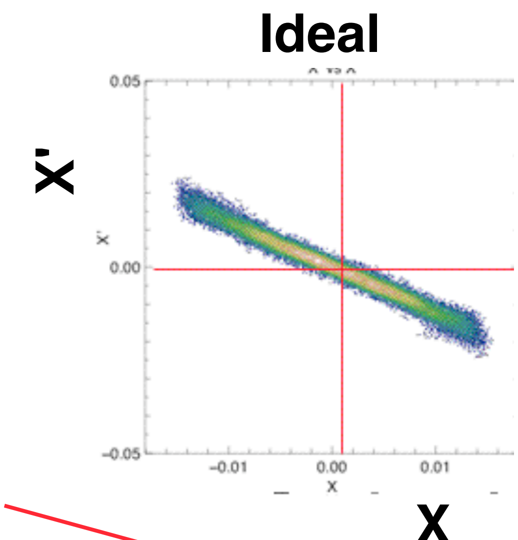
- Electron clouds can severely limit the performance of
  - present colliders and accelerators (PEP-II, KEKB, SNS)
  - next generation (LHC, GSI-FAIR , ILC)
  - warm-dense matter (WDM) heavy-ion accelerators
  - heavy-ion inertial fusion (HIF) accelerators

HIF beam edge (halo) scraping will generate gas and electrons, which limit beam current.

Need to mitigate halo, electrons, and gas.

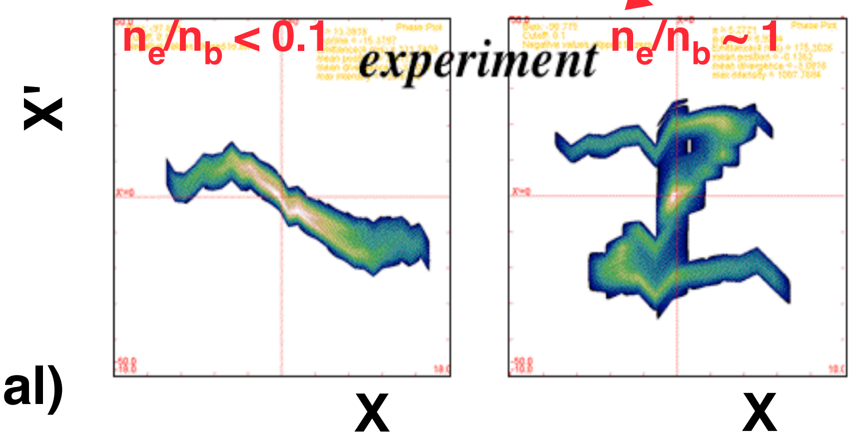
Heavy-ion beams can be degraded by electron clouds

- **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.**

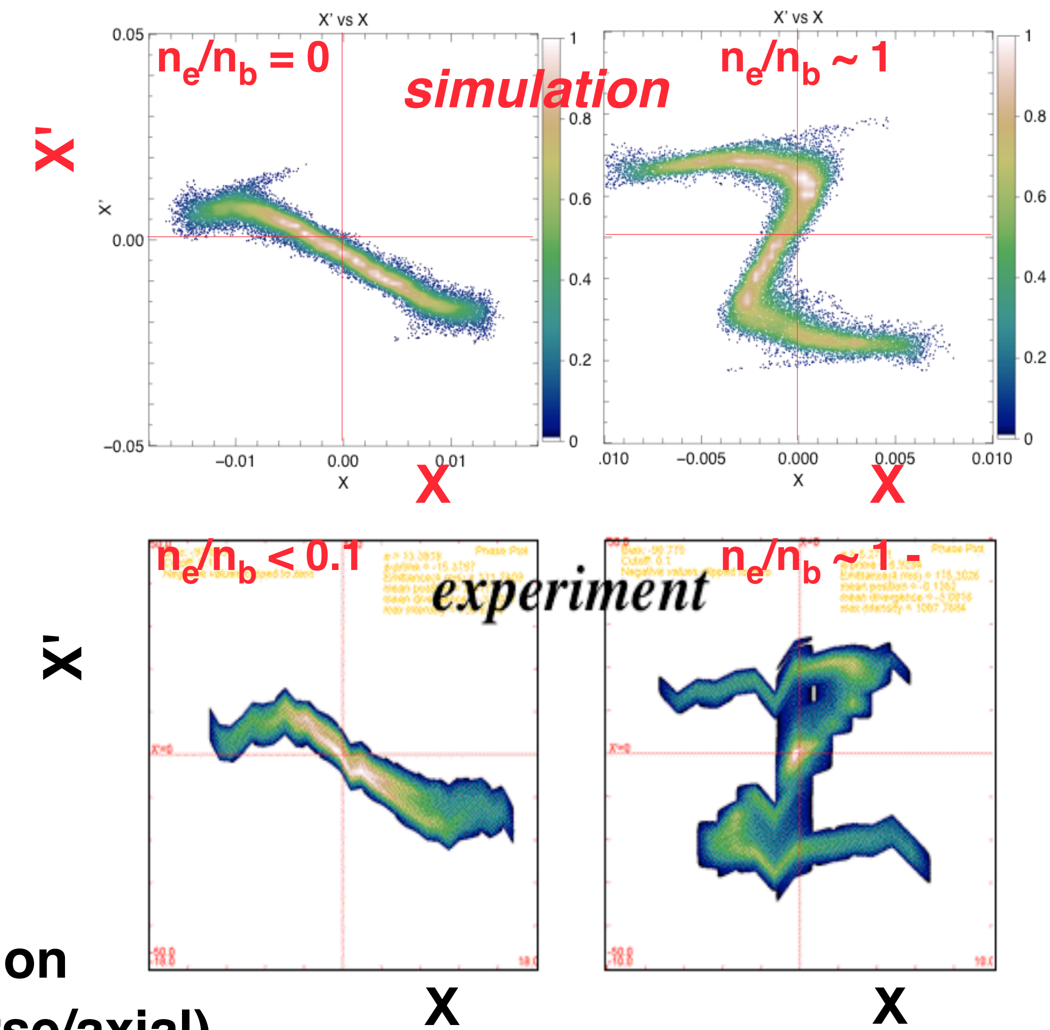


x = horizontal location of ion

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

Heavy-ion beams can be degraded by electron clouds –2

- We look at extreme cases to validate models



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

x = horizontal location of ion

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

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

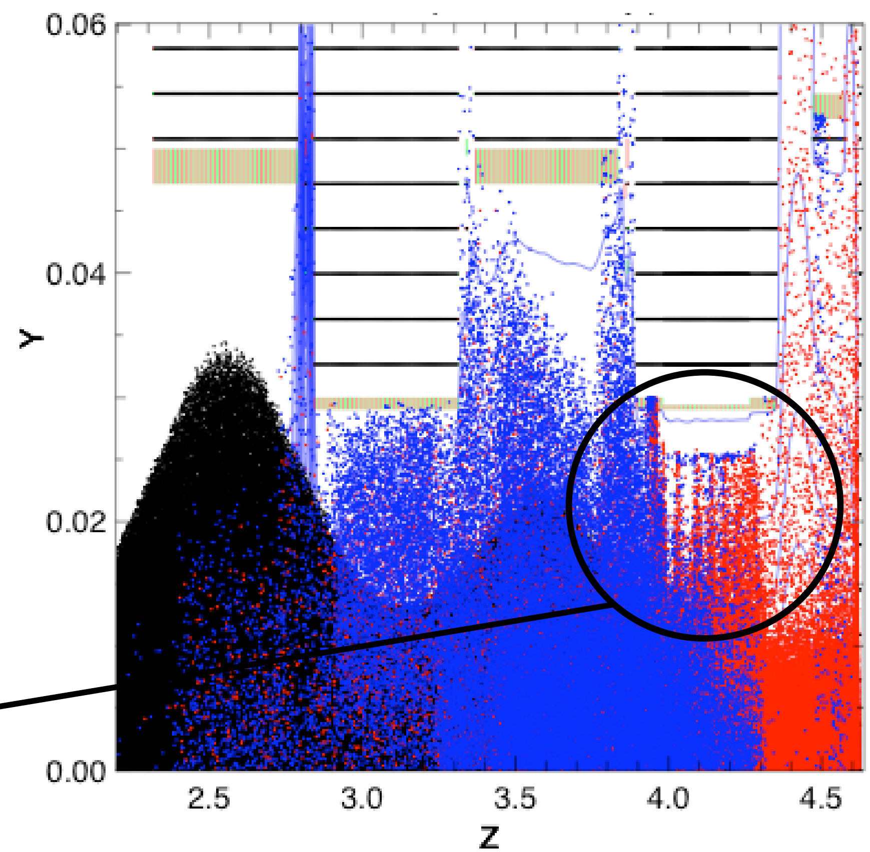
We perform 3-D self-consistent simulations with the WARP-POSINST code

Particle-in-cell (PIC) code that self-consistently handles

- beam dynamics
- electrons (POSINST)
- gas

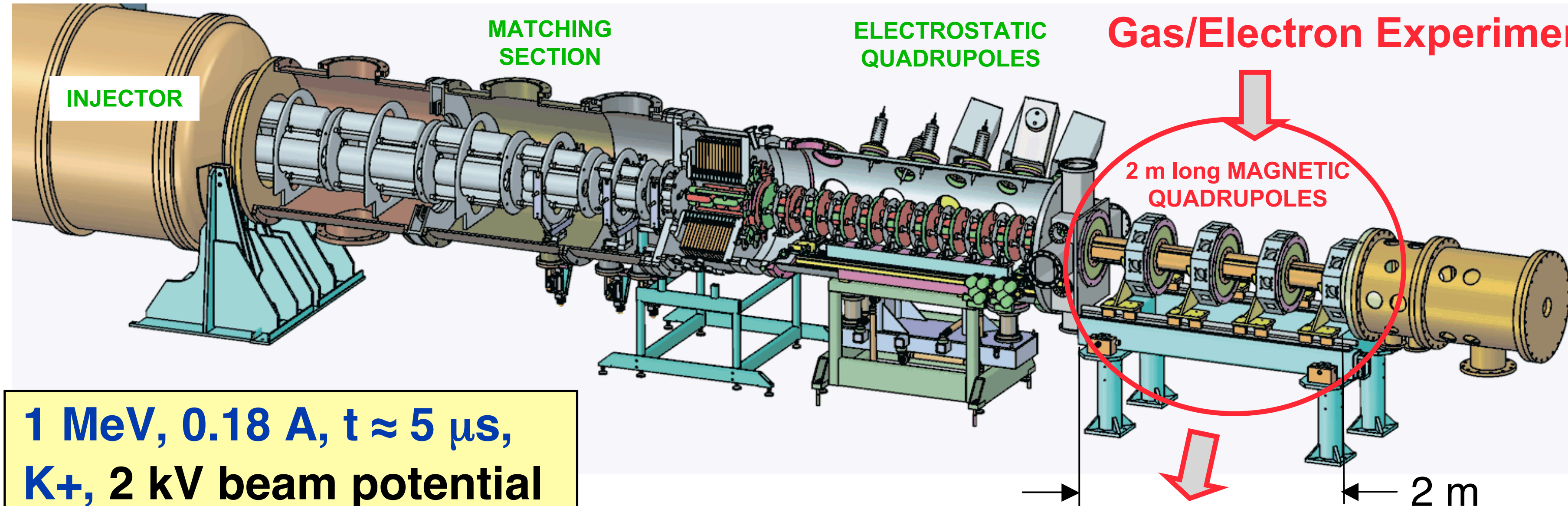
Gas & e- sources, transport, and interactions

For $n_e \sim n_{beam}$ – Oscillations

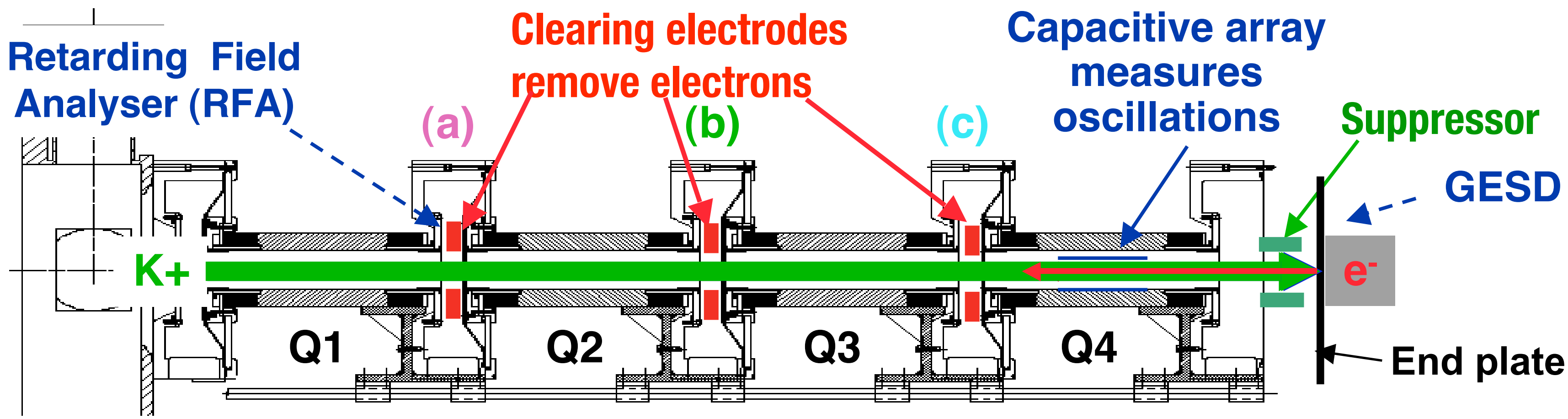


Ref: Ron Cohen, Phys. Plasmas (2005).

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



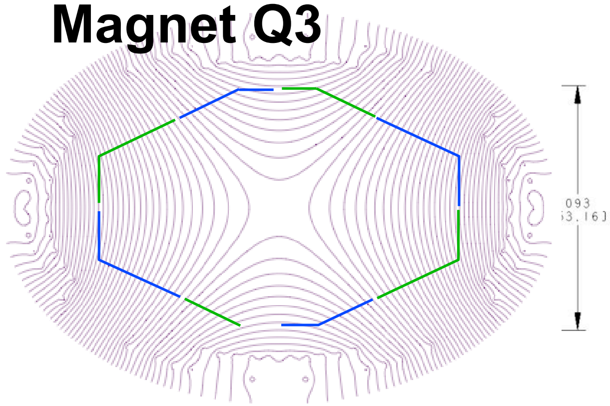
1 MeV, 0.18 A, t ≈ 5 μs, K+, 2 kV beam potential



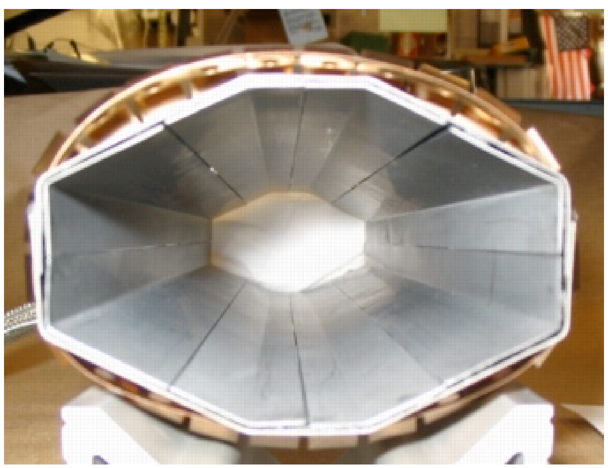
Quadrupole magnets Q1 - Q4 for beam transport

Diagnostics within magnetic quadrupole bores

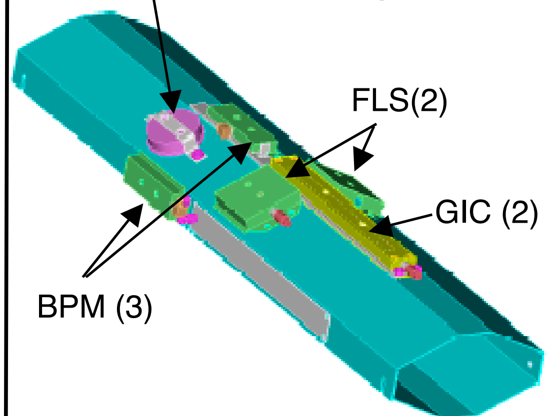
Magnet Q3

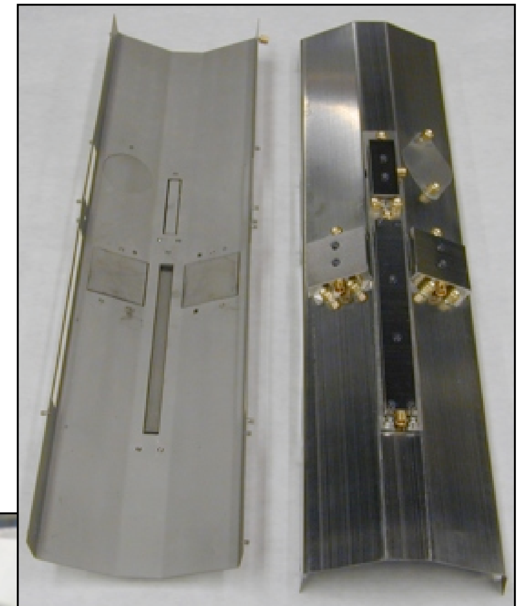


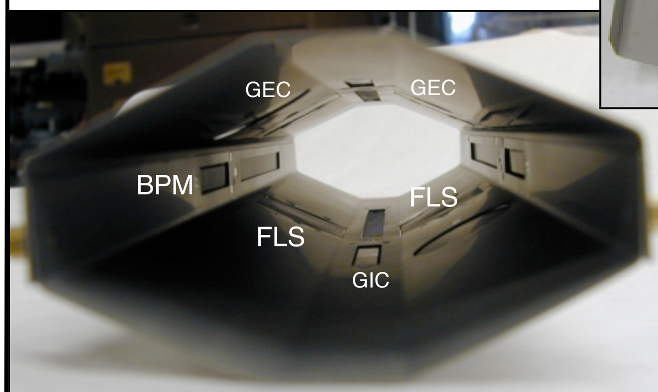
FLL: 8-biased electrodes at ends of field lines: measure capacitive signal + electrons from wall



Magnet Q4







Capacitive and grid-shielded electrodes

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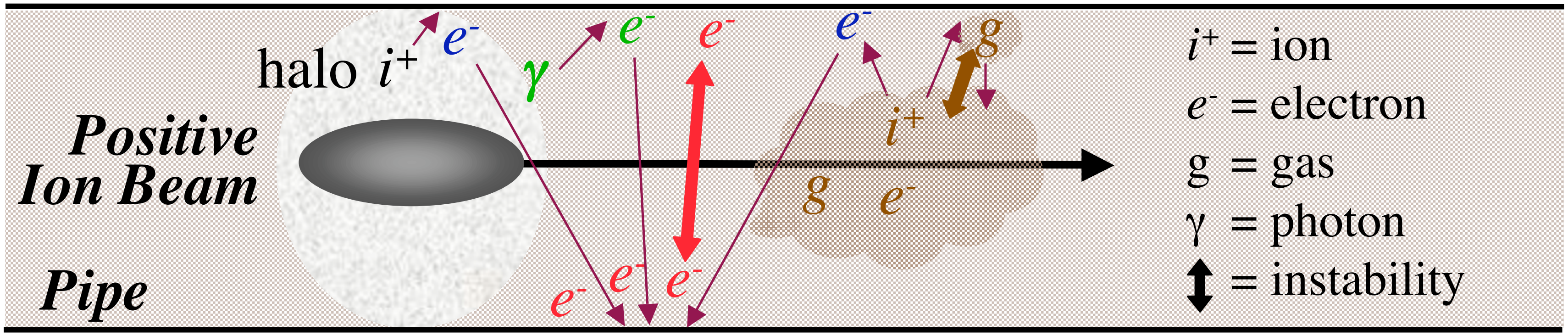
Sources of electron and gas clouds



Primary:

- Ionization of
  - background gas
  - desorbed gas
- ion induced emission from
  - expelled ions hitting vacuum wall
  - beam halo scraping
- photo-emission from synchrotron radiation (HEP)

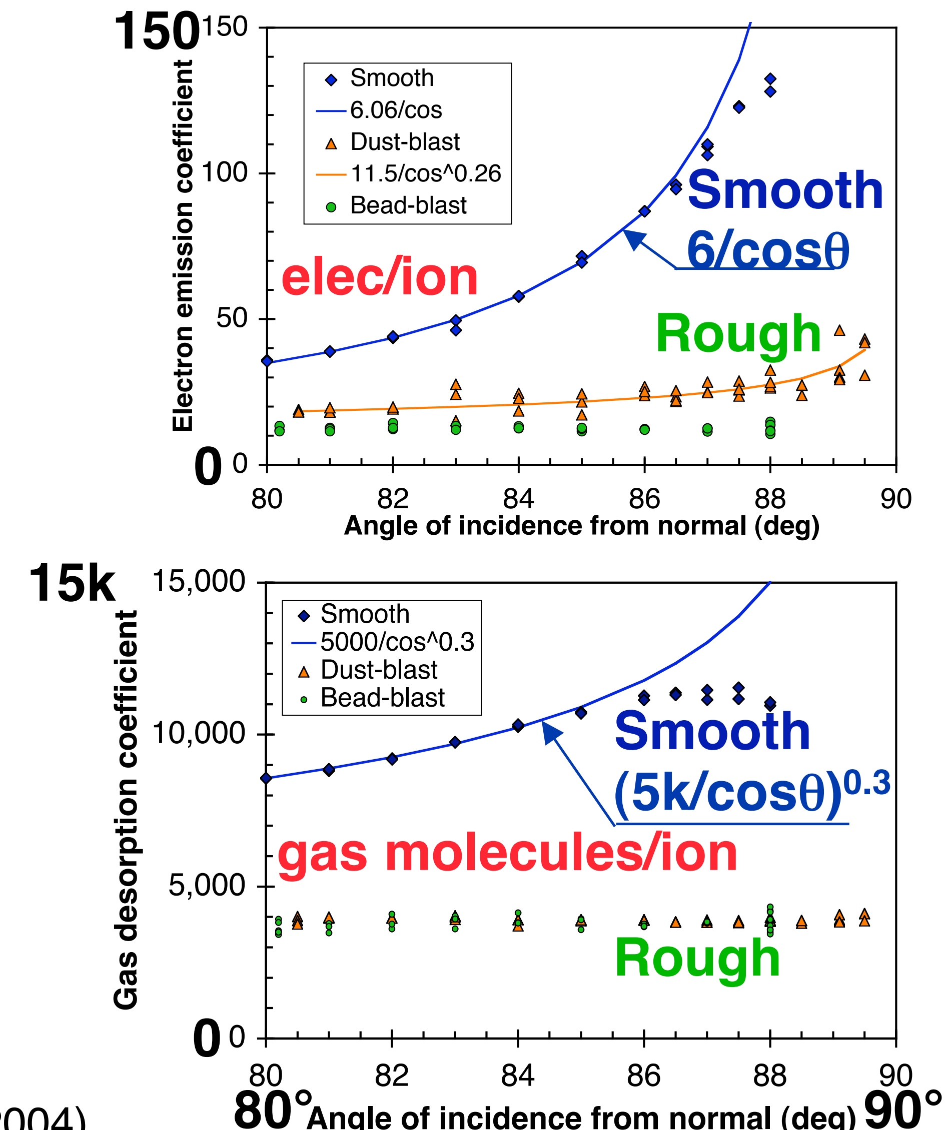
Secondary:

- secondary emission from electron-wall collisions

Electron emission & gas desorption vs angle of incidence measured and mitigated (1 MeV K+)

Mitigation – Roughened target surface eliminates grazing collisions to reduce emission

- glass-bead blast ●
- alumina dust-blast ▲



A. W. Molvik, et al., PRST-AB 7, 093202 (2004).

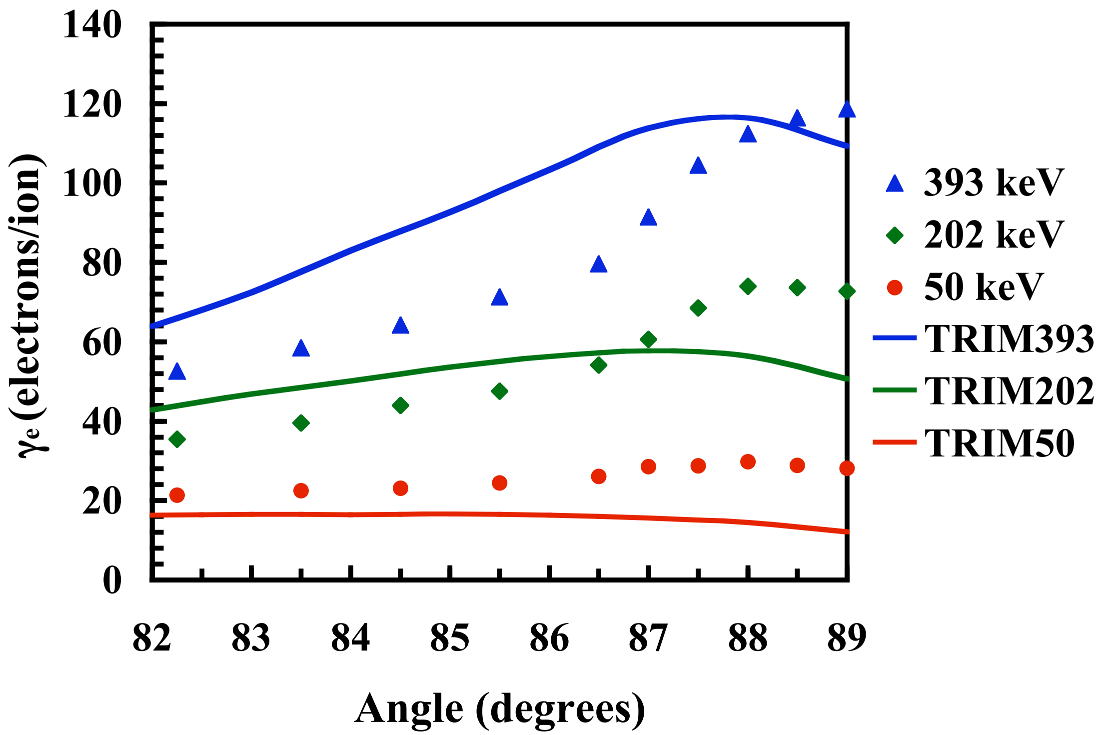
Developed model for ion-induced electron yield scaling with beam energy and angle of incidence*

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).

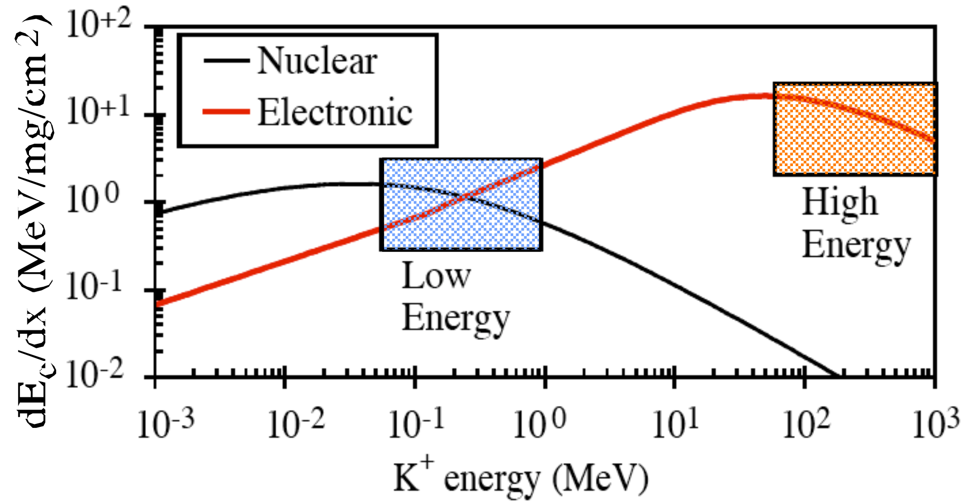
Electronic gas desorption scales with $(dE/dx)^2$, like electronic sputtering

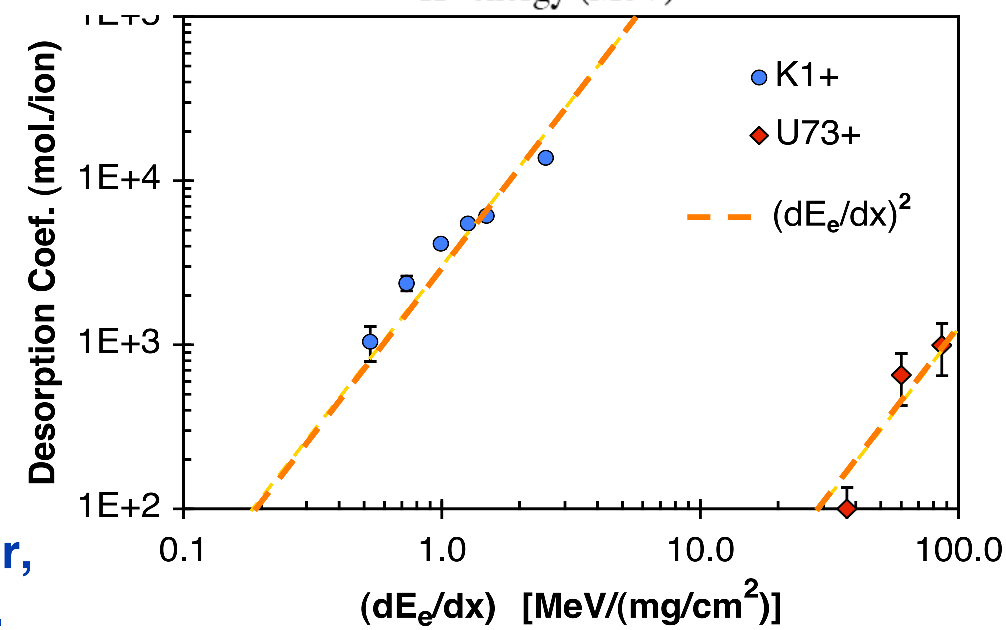
Conventional sputtering driven by large-angle nuclear scattering

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, $n \approx 2$.

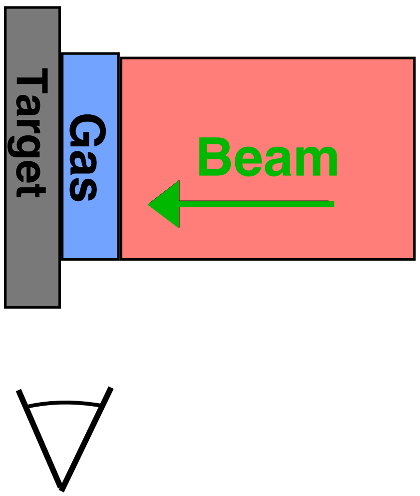




A. W. Molvik, H. Kollmus, E. Mahner, et al., Submitted to Phys. Rev. Lett.

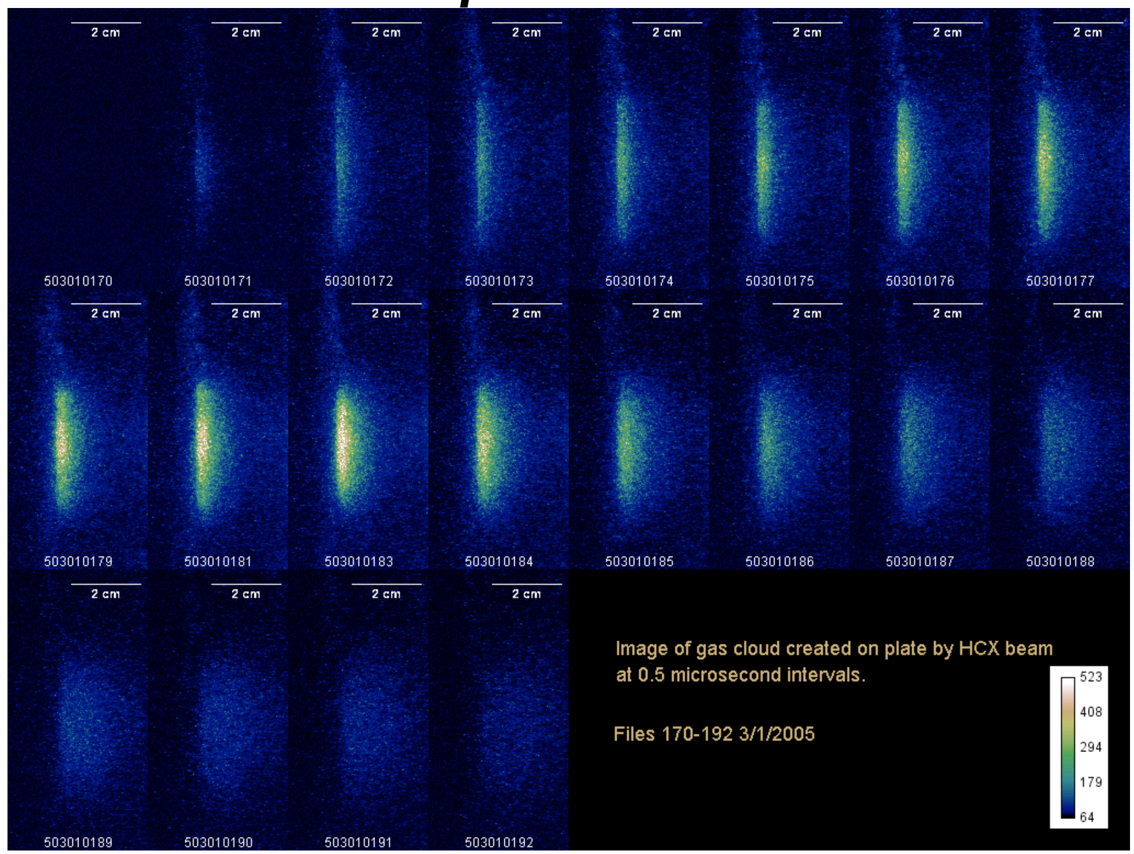
We measure velocity distribution of desorbed gas

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

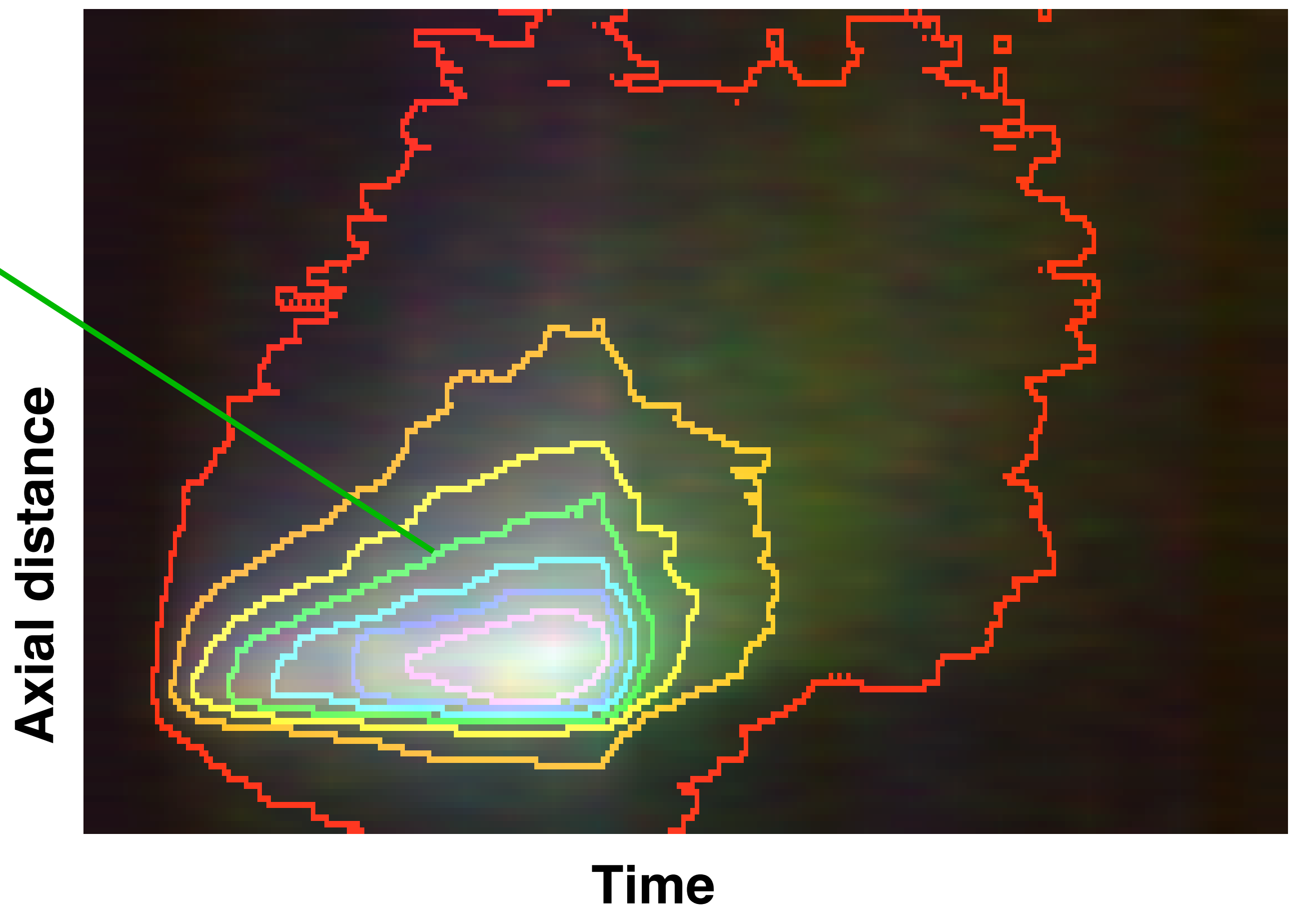


F. Bieniosek

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



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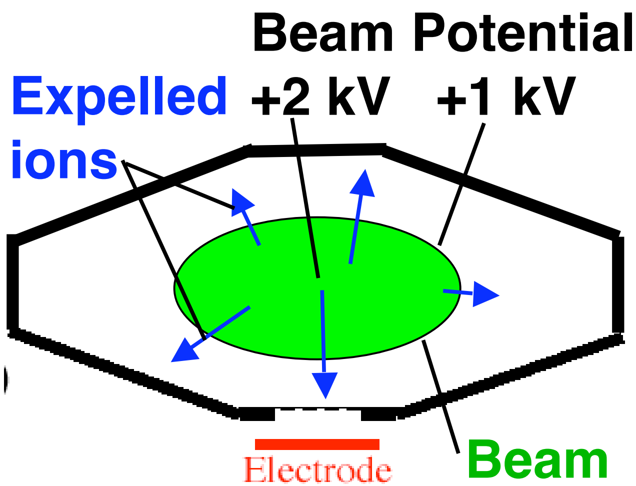
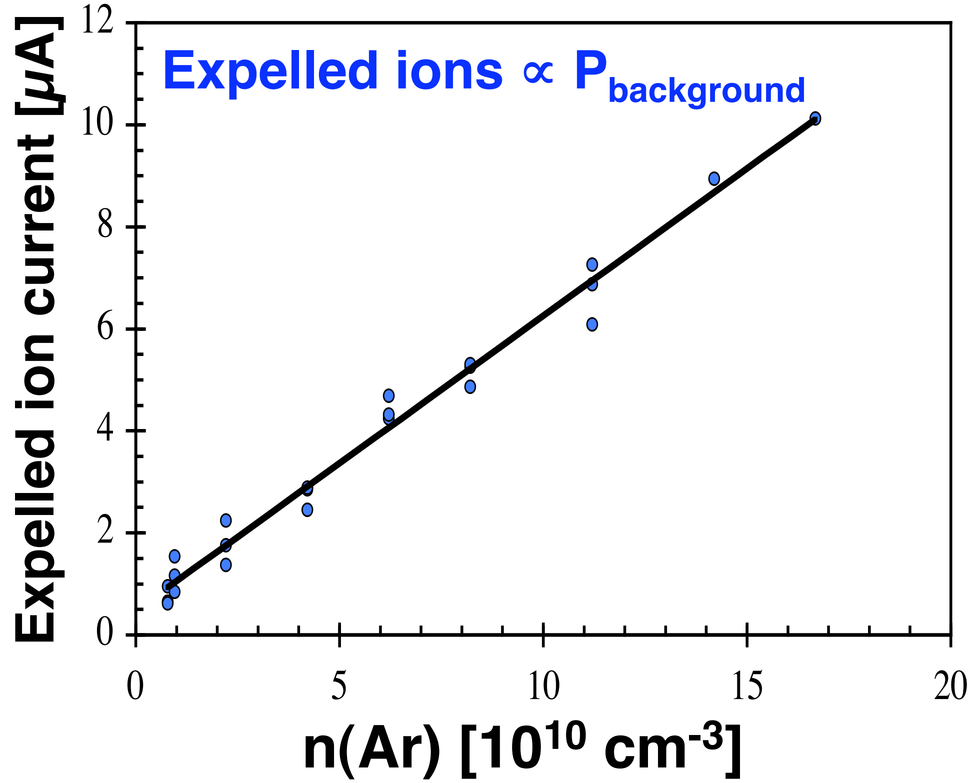
We measure electron sources – ionization

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



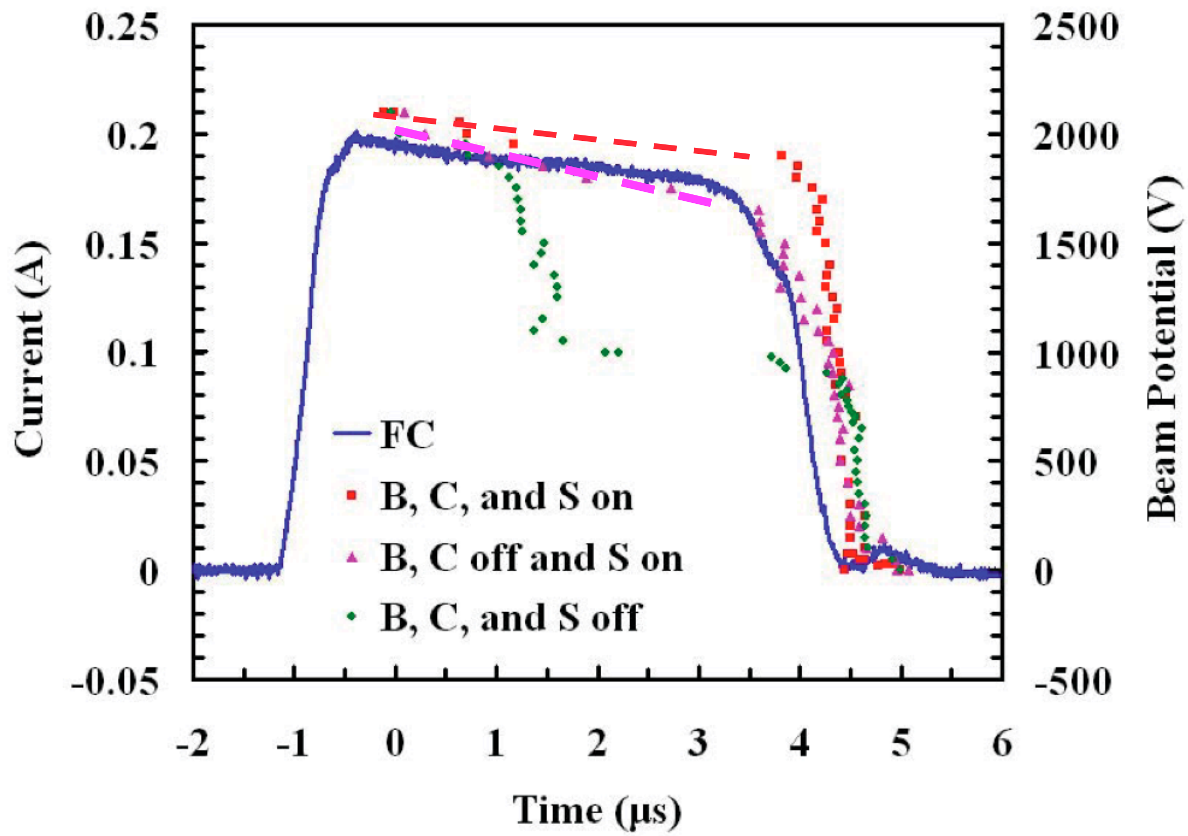


Beam current known; from expelled ion current infer

- **Ionization rate**
- **Also, gas density in beam**

1^{st} 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	C, S on	C off S on	C, S off
Clear. Electr. A	~ 7%	~ 25%	~ 89%
RFA	(~ 7%)	~ 27%	~ 79%

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

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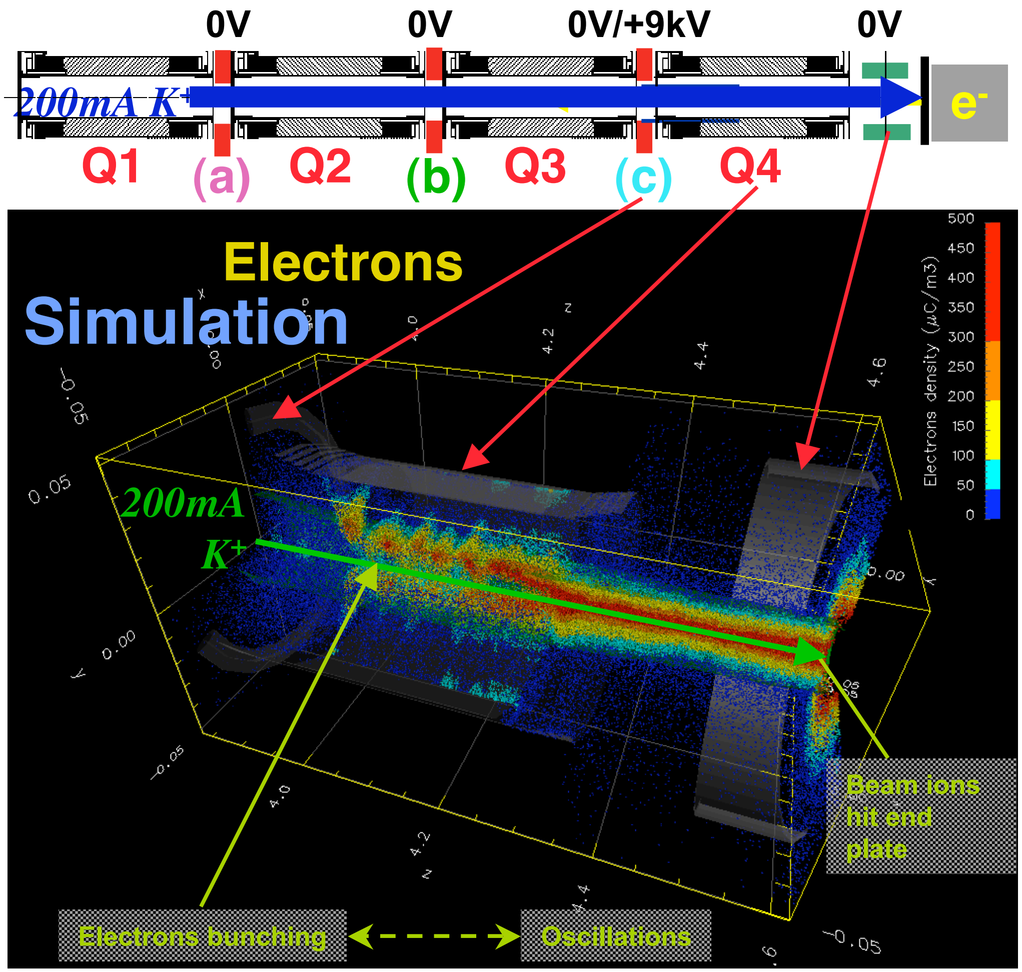
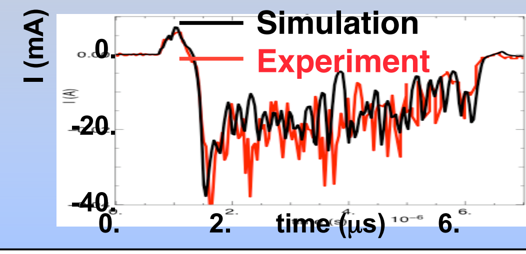
Electron oscillations – simulation & experiment agree

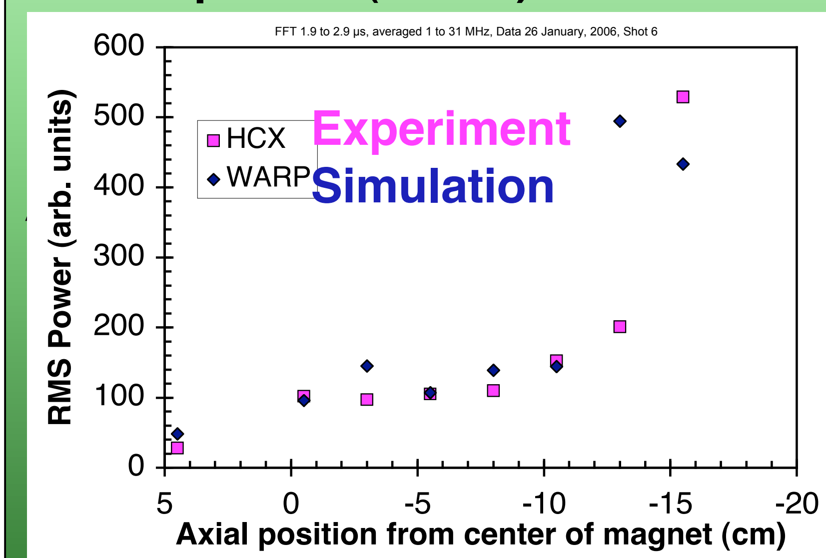


Virtual cathode oscillations and diocotron (Kelvin Helmholtz) are likely suspects; 2-stream eliminated.

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

- **Increased understanding of beam-surface interactions**
  - **Electron emission measured and modeled, $\propto dE_e/dx$**
  - **Discovered gas desorption ~ $(dE_e/dx)^2$**
- **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 as function of time**
- **Electrons bunch, generating oscillations**
  - **Simulation & experiment agree – freq., wavelength, & amplitude**
  - **Experimental validation of simulations provides credibility**

Future – understand & mitigate electron and gas effects – push performance / cost

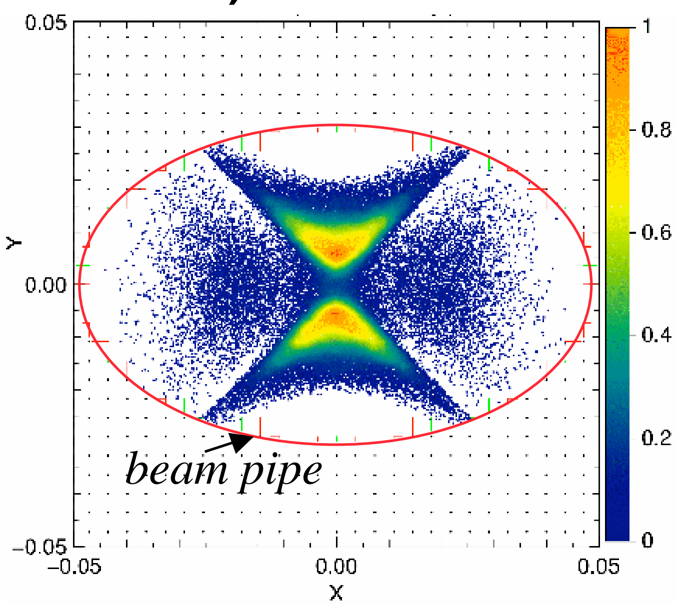
- Quantitative calibration of optical gas desorption diagnostic
  - Measure desorption from non-evaporable getter (NEG)
- Continue work to understand oscillation mechanism, apply e^- gun
- Measure effects on beam vs electron accumulation
- Compare electron effects in solenoids and quadrupoles
- Apply models to high-energy physics accelerators: LHC, ILC, …
- Seek operating mode in existing and future WDM/HIF machines with negligible to tolerable gas and electrons
  - Apertures to scrape halo
  - Extend limits by other mitigation techniques

Backup

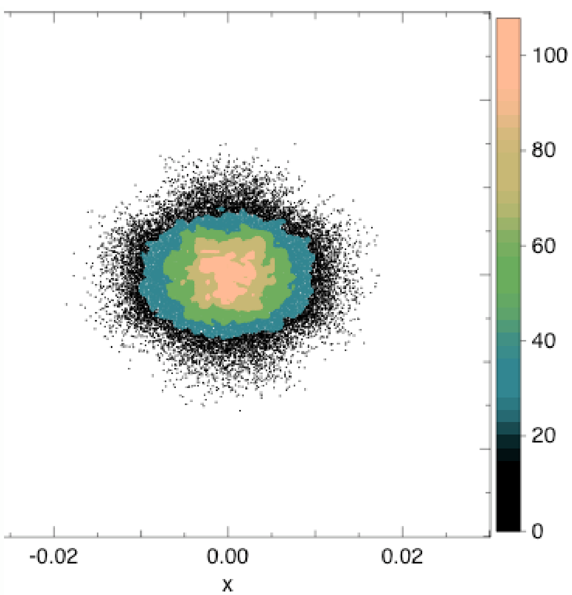
Spatial distribution of electrons in quadrupole magnet varies with the source

Electrons in a quadrupole magnet

Electrons ejected from end wall drift upstream in 2 quadrants (top & bottom)

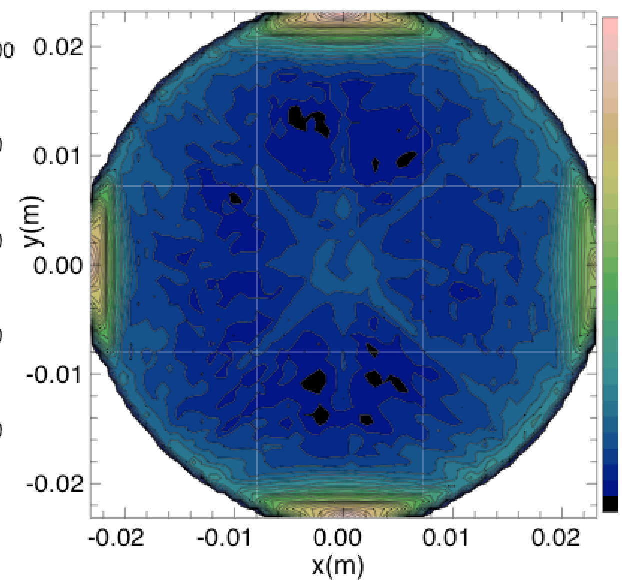


Electrons from ionization of gas map out beam profile



Deeply trapped electrons

Electrons desorbed from beam pipe in quad upon ion impact fill beam tube

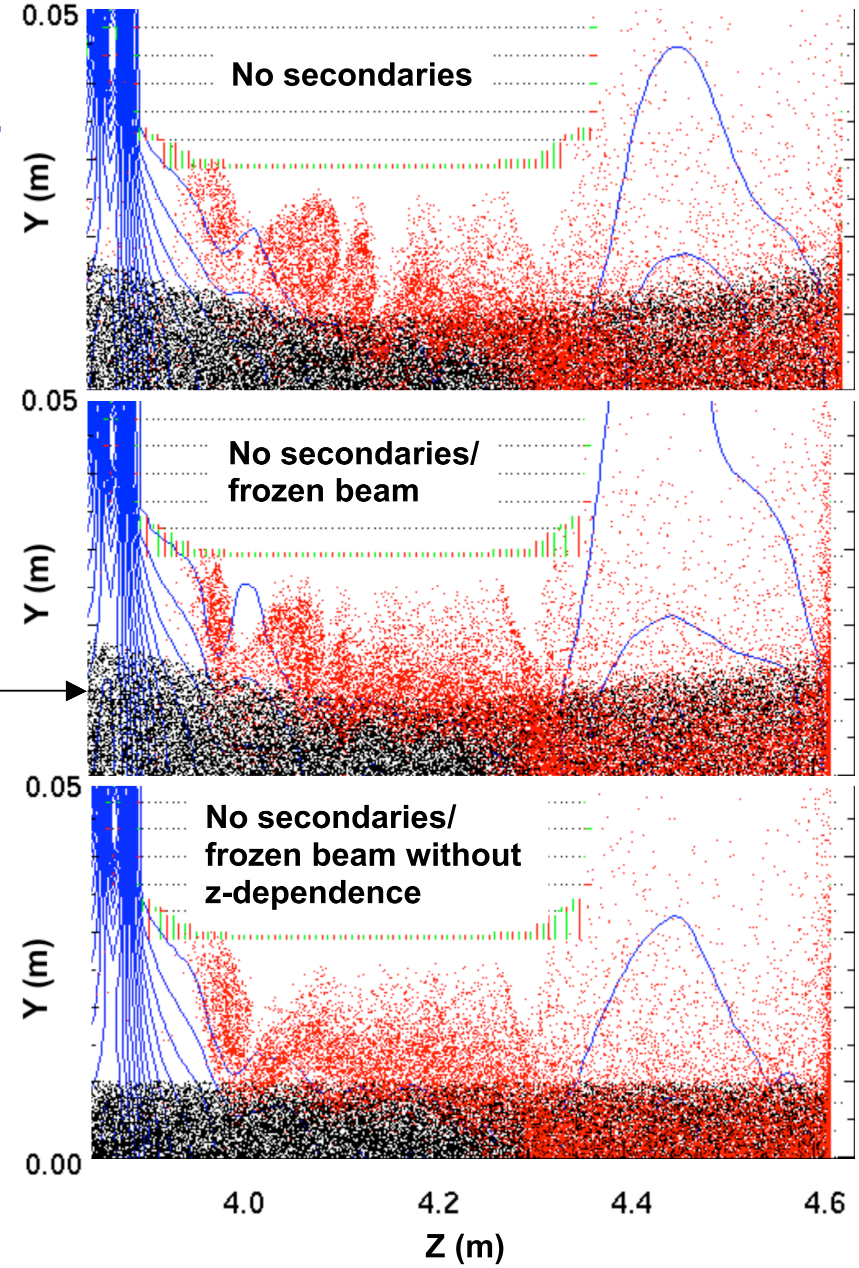


Weakly trapped electrons

Quest - nature of oscillations?

Progressively remove possible mechanisms in simulations

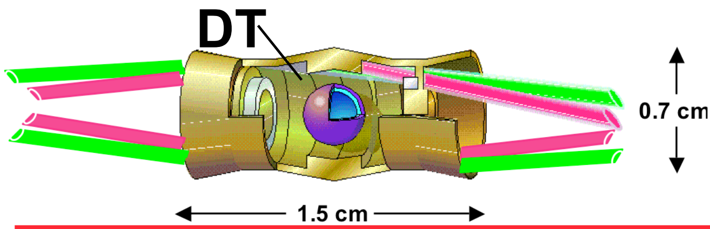
Not ion-electron two stream



Other mechanisms:

- Virtual cathode oscillations near end wall and at quad. end
- Kelvin Helmholtz / diocotron (plausible, shear in drift velocities)

Heavy Ion Inertial Fusion or "HIF" goal is to develop beams to ignite an inertial fusion target



Target Requirements:

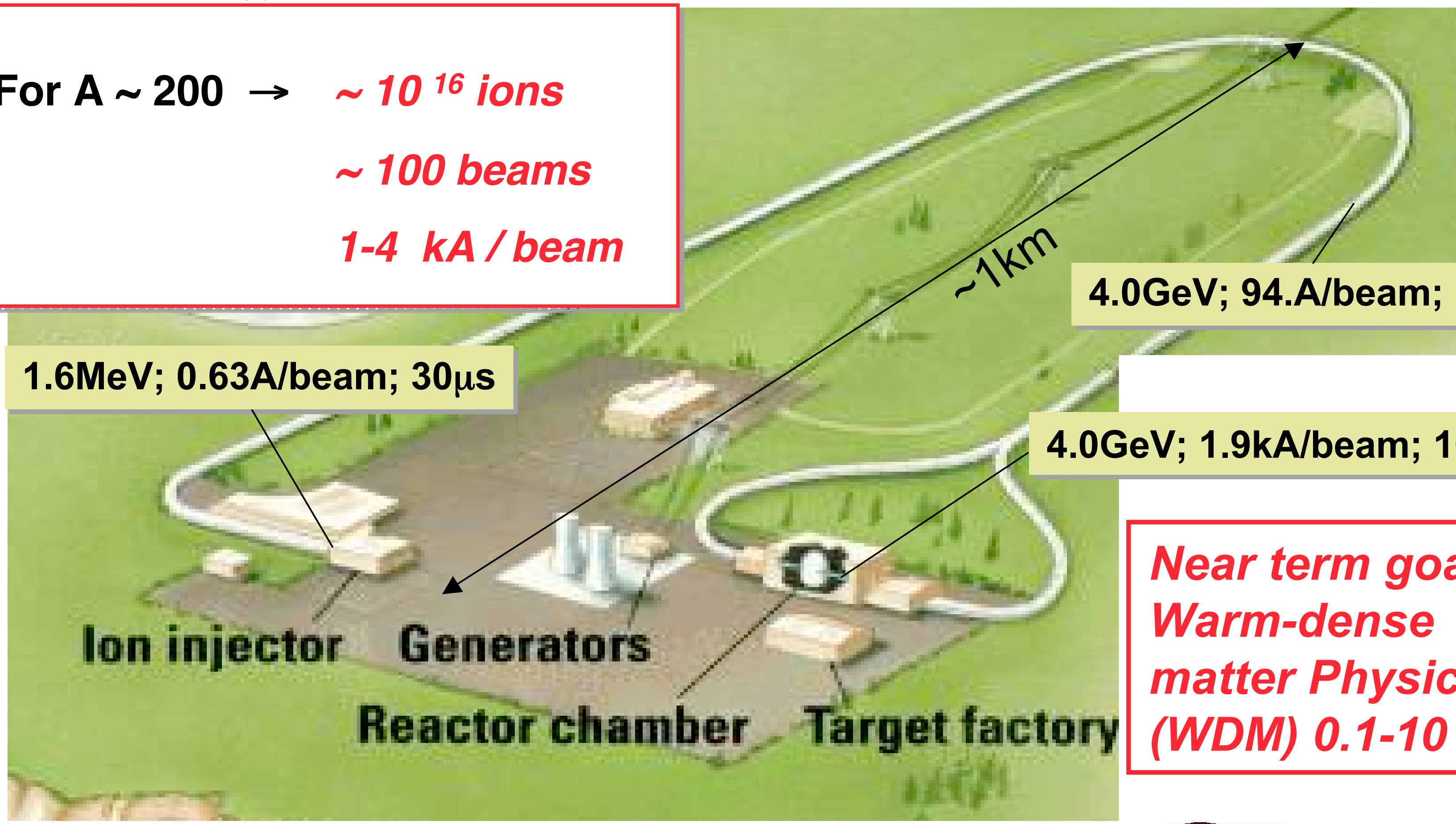
3 - 7 MJ x ~ 10 ns

Ion Range: 0.02 - 0.2 g/cm^2 $\Rightarrow$ *1- 10 GeV*

For A ~ 200 → *~ 10^{16} ions*

~ 100 beams

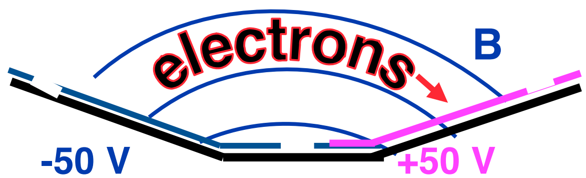
1-4 kA / beam



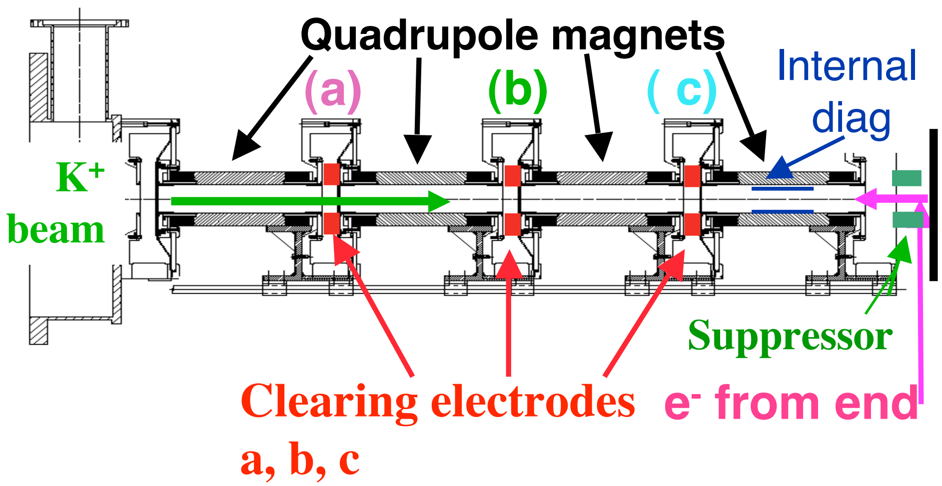
Near term goal: Warm-dense matter Physics (WDM) 0.1-10 eV

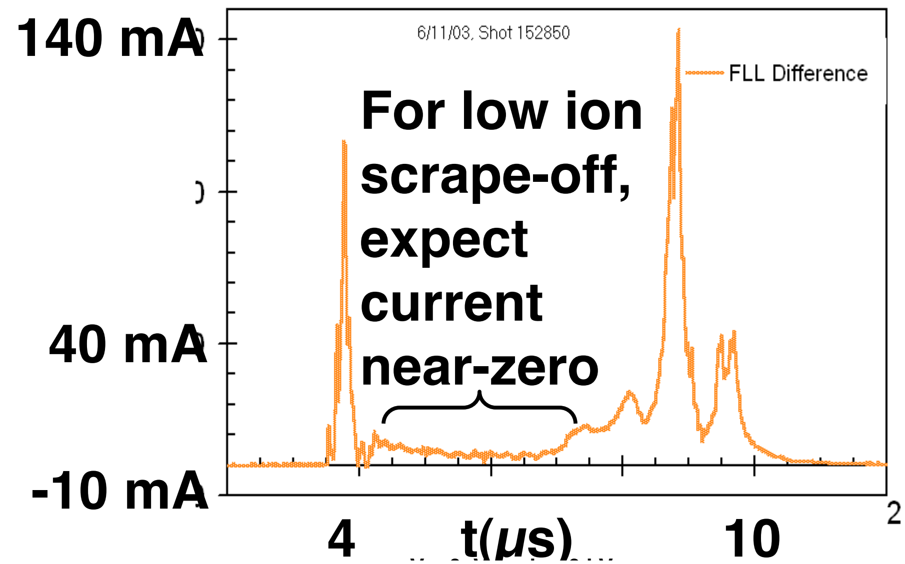
We measure electron sources – walls

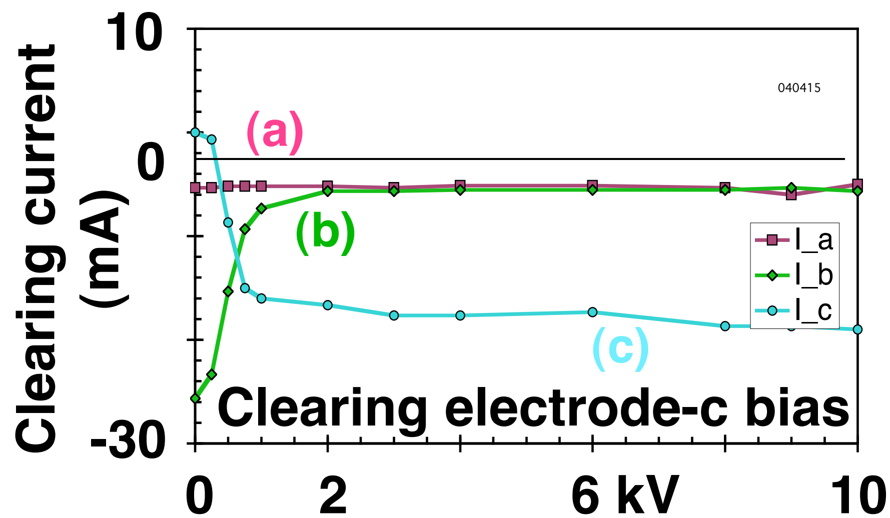
2. **Electron emission – beam tube** ($n_e/n_b \leq 7\%$)



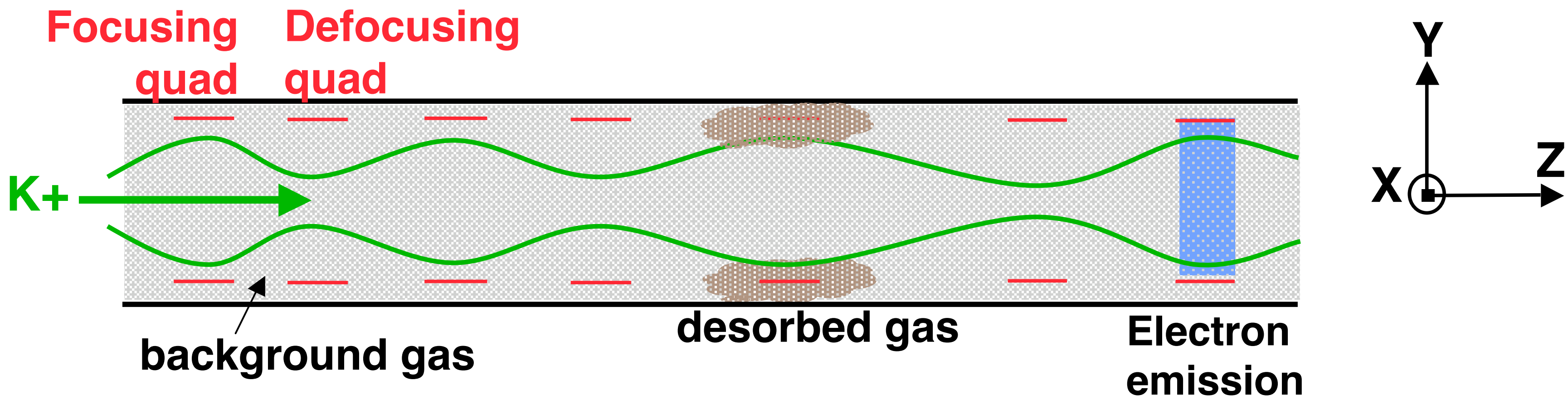
3. **Electron emission – end wall** (n_e/n_b, 0, 100%)







Control of accelerator beam-surface interactions is important



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