Electron Cloud Diagnostics

Michel Kireeff Covo

LBNL

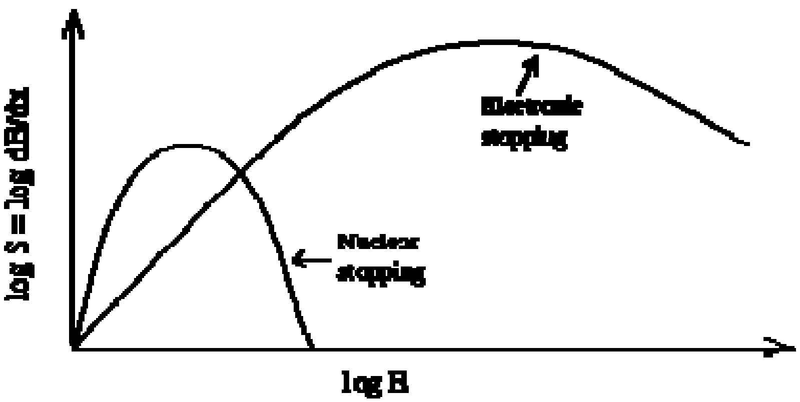
April 03, 2009
First DITANET School on Beam Diagnostics
Royal Holloway, University of London

Electron Cloud Diagnostics

Outline

1. E-cloud issues and tools
2. Diagnostics
   a. Gas-Electron Source
   b. Retarding Field Analyzer
      i. Electron Mode
      ii. Ion Mode
      iii. Electron Cloud Density
      iv. Total Cross Sections
   c. Shielded Capacitive Electrode
   d. Microwave Dispersion Technique
3. Conclusions

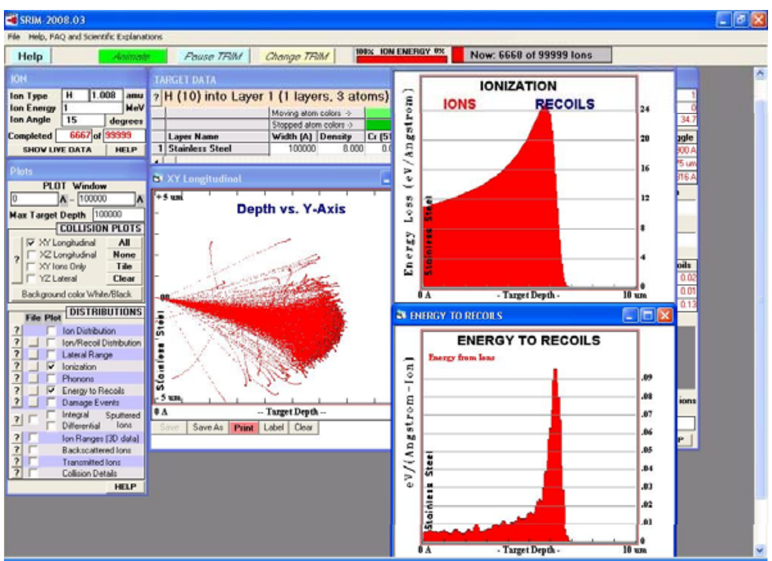
Stopping Power



$$S_{total} = S_{electronic} + S_{nuclear} = dE/dx$$

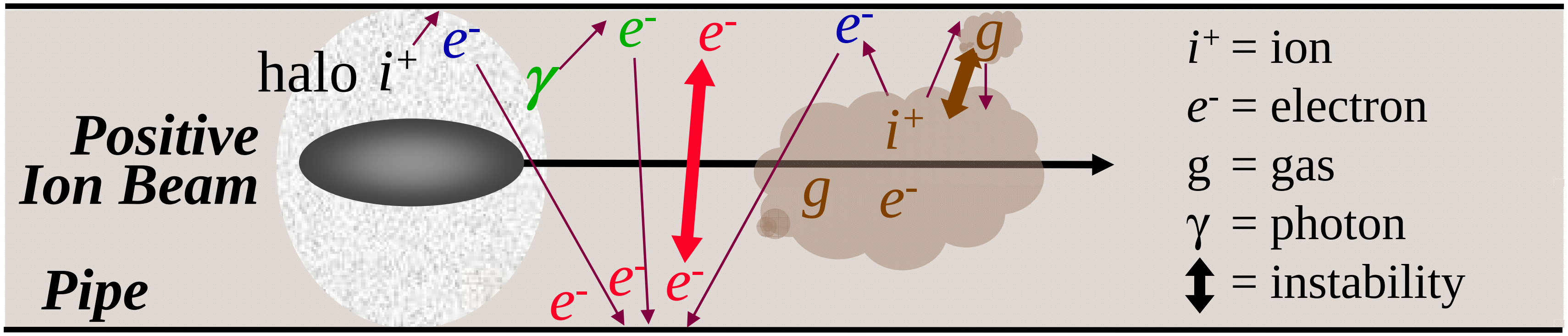
due to the inelastic collisions between bound electrons in the medium and the ion moving through it.

due to elastic collisions between the ion and atoms in the medium



James F. Ziegler, http://www.srim.org/

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 clouds are an issue in major HEP accelerators and potentially in WDM and HIF accelerators

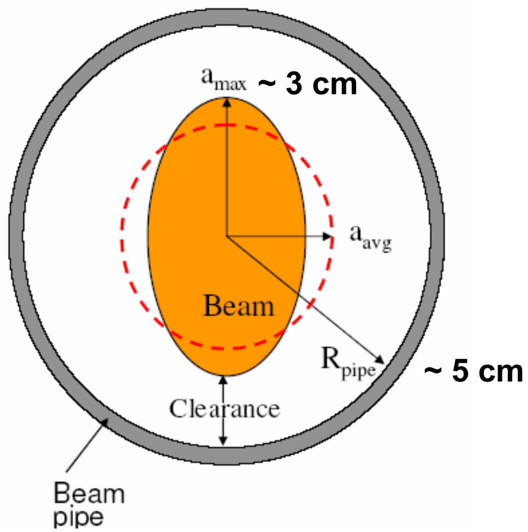
- **Electron Cloud Effects (ECE) were observed in the:**
  - **Proton Storage Rings at BINP,**
  - **Intersecting Storage Rings at CERN,**
  - **Proton Storage Ring at LANL,**
  - **Relativistic Heavy Ion Collider at BNL,**
  - **Positron Ring at KEKB, etc.**
- **ECE can potentially limit the performance of the:**
  - **International Linear Collider,**
  - **Large Hadron Collider (LHC) at CERN,**
  - **WDM and HIF accelerators.**

Understanding and mitigation of electron clouds will increase the performance of present and future accelerators

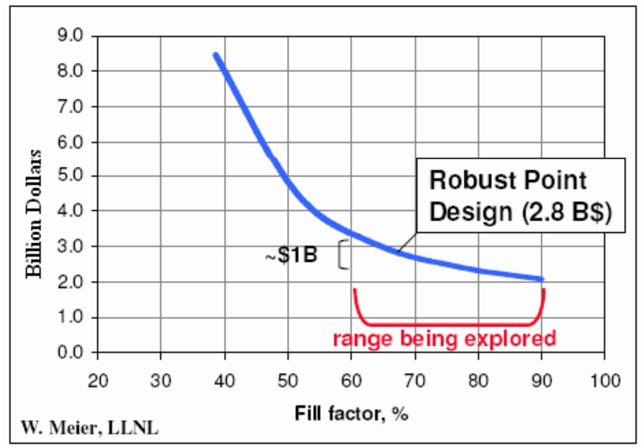
High-Current Experiment (HCX) facility beam features

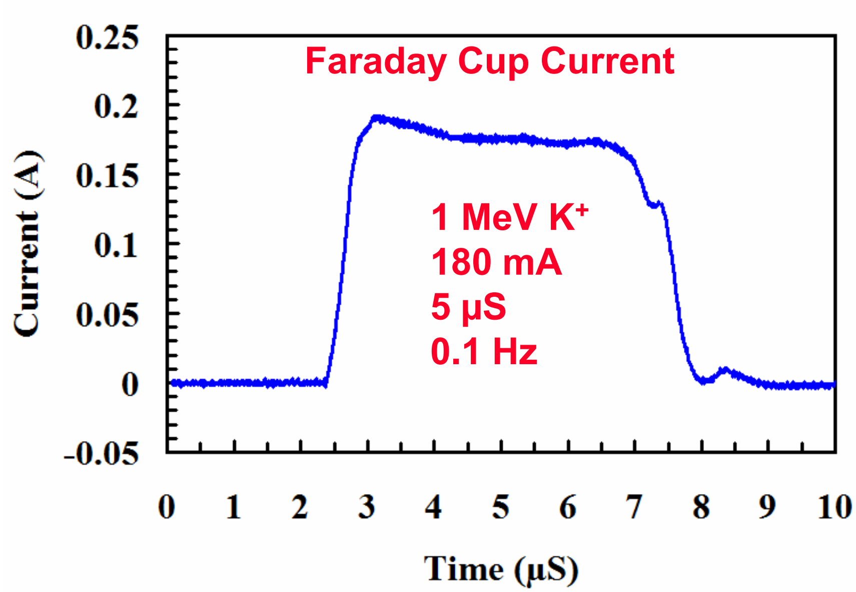
Fill Factor $= \frac{a_{max}}{R_{pipe}}$

Fill Factor = 60%



IBEAM results:



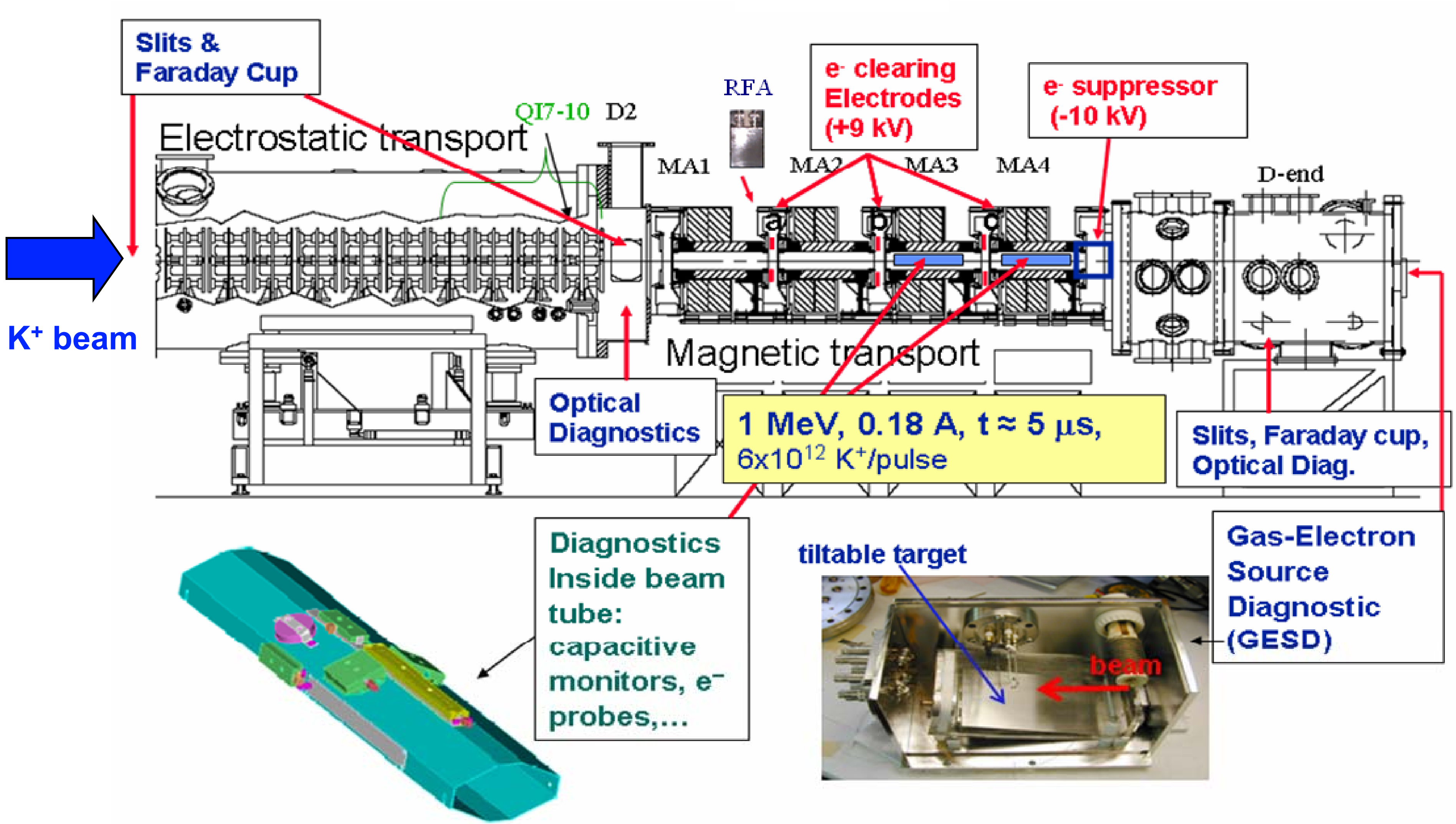


Characteristics:

- **Do not have synchrotron radiation and electron multipacting (time between bunches is too long), but**
- **Have long bunch duration with large beam interaction with background gas and walls**

Electron Clouds are an issue

HCX dedicated to studies of gas and electron effects

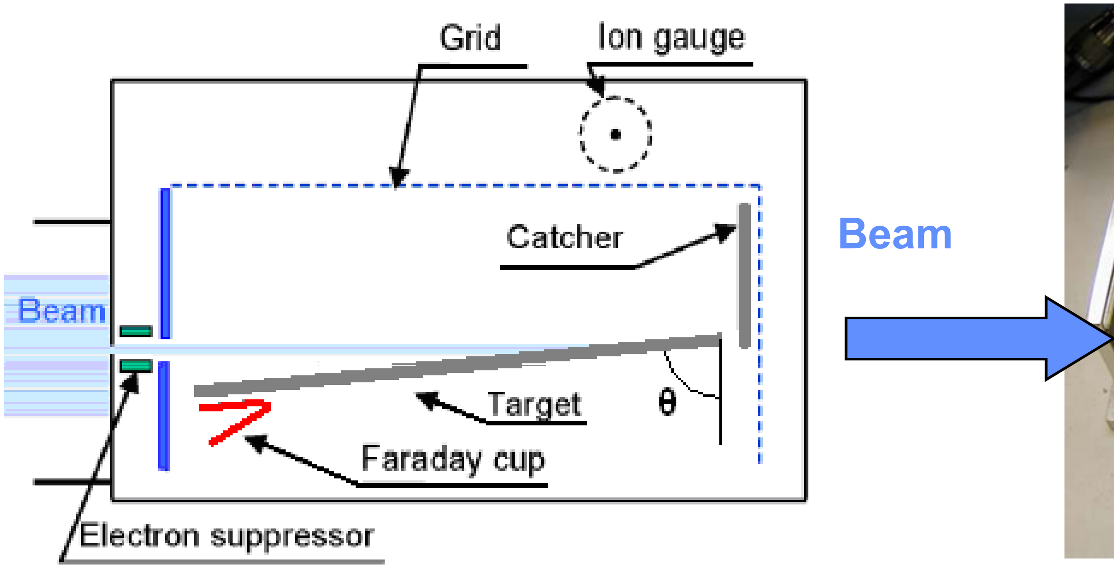


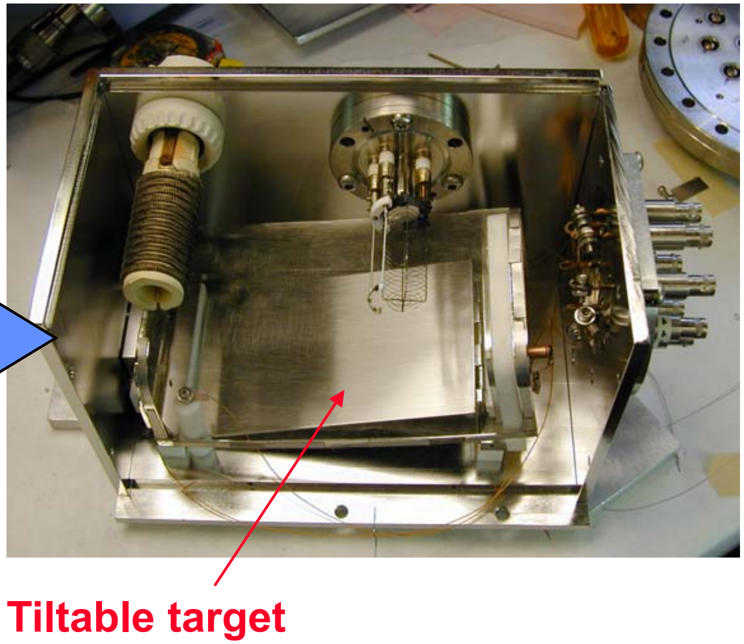
Outline

1. E-cloud issues and tools
2. Diagnostics
    a. Gas-Electron Source
    b. Retarding Field Analyzer
        i. Electron Mode
        ii. Ion Mode
        iii. Electron Cloud Density
        iv. Total Cross Sections
    c. Shielded Capacitive Electrode
    d. Microwave Dispersion Technique
3. Conclusions

Ion-induced gas desorption yield and electron yield* measurements

- **Gas-Electron Source Diagnostic (GESD) measures ion-induced desorption yield and electron yield near grazing incidence.**

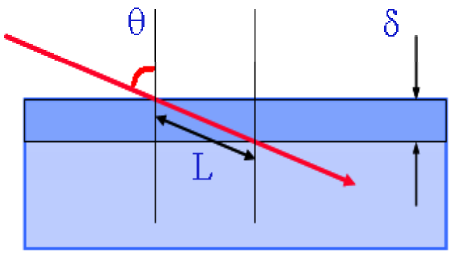




*** A. W. Molvik, Phys. Rev. ST Accel. Beams 7, 093202 (2004).**

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

Simple theory of electron emission



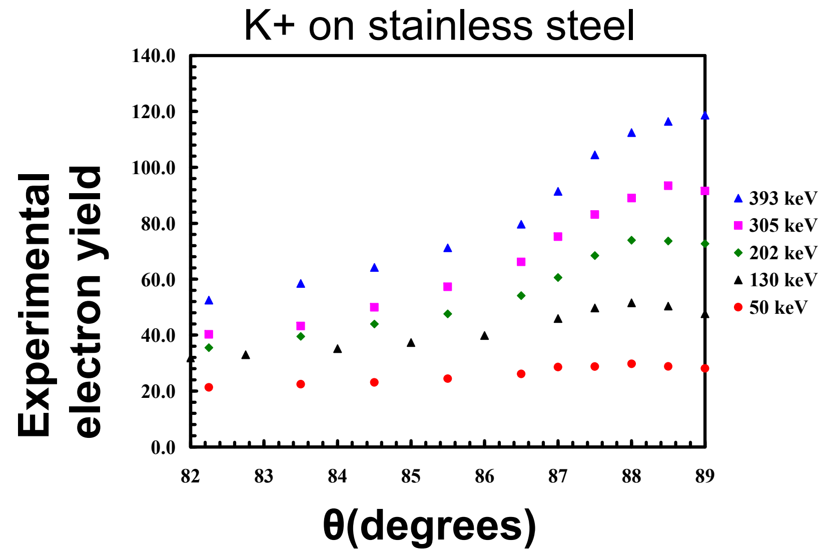
$L = \delta / \cos(\theta)$

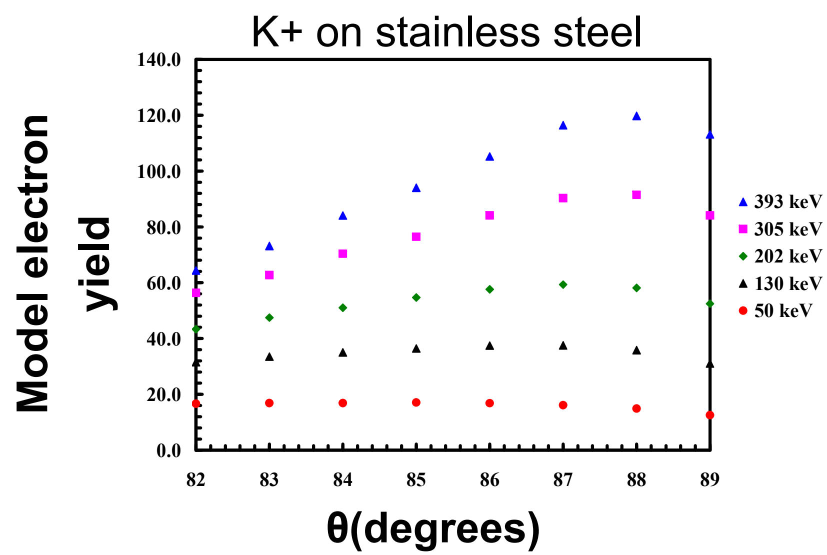
where:
δ - electron escape layer
θ- angle to the surface normal
L= δ /cos(θ) - ion path length

- **A model was developed, using TRIM code, for ion-induced electron yield**

$$\gamma_e = C\frac{P}{J}\left[\frac{\delta}{\cos(\theta)}\left(\frac{dE}{dx}\right)_e\right] = C\frac{P}{J}\sum_{x=0}^{\delta} E_{TRIM}(x)$$

where:
C is a constant to account for variations of the ion species,
P is the fraction of electrons moving towards the surface,
J is the average energy to generate an electron,
$E_{TRIM}(x)$ is the electronic dE/dx data provided by TRIM code as a function of target depth x,and
δ is the depth of the electron escape layer.

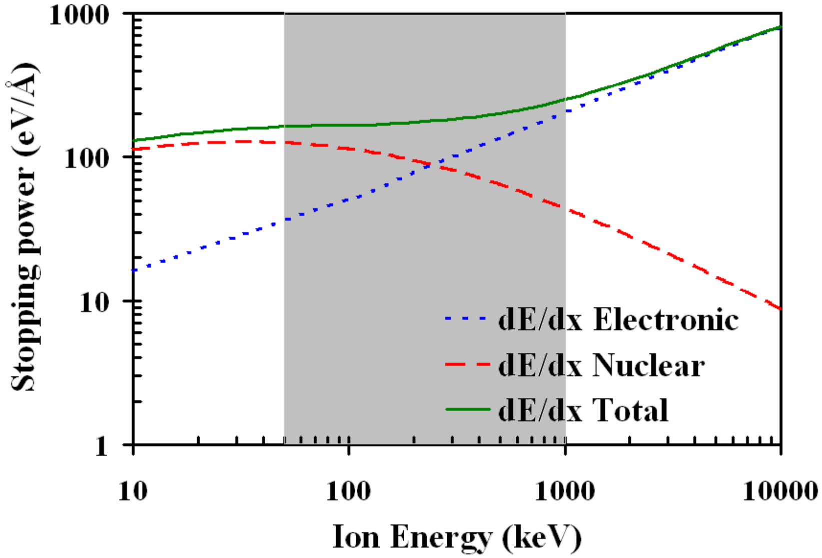




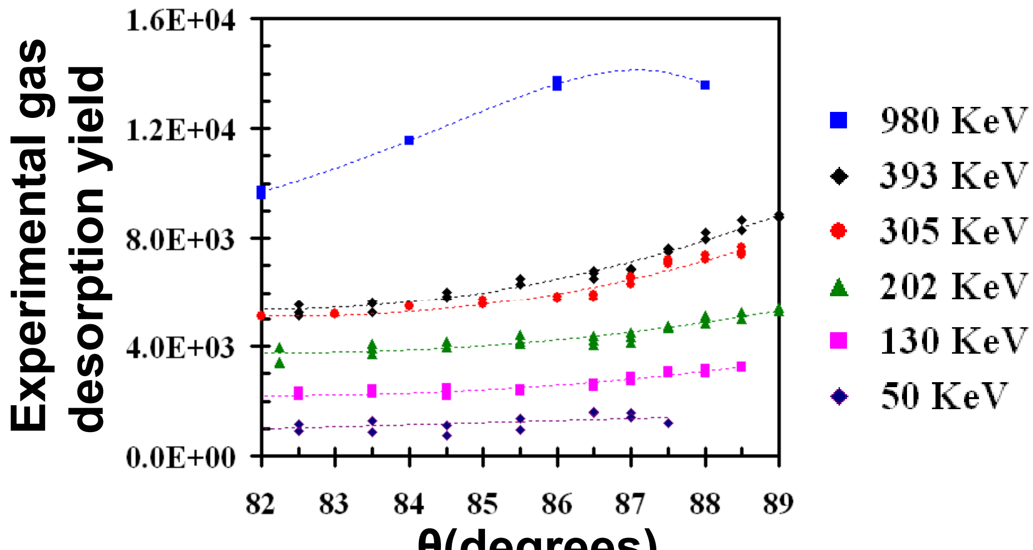
***M. Kireeff Covo et al., PRSTAB 9, 063201 (2006).**

Experimental gas desorption yield measurements at Ion Source Test Stand (STS-500) and HCX facilities*

Electronic versus nuclear stopping power



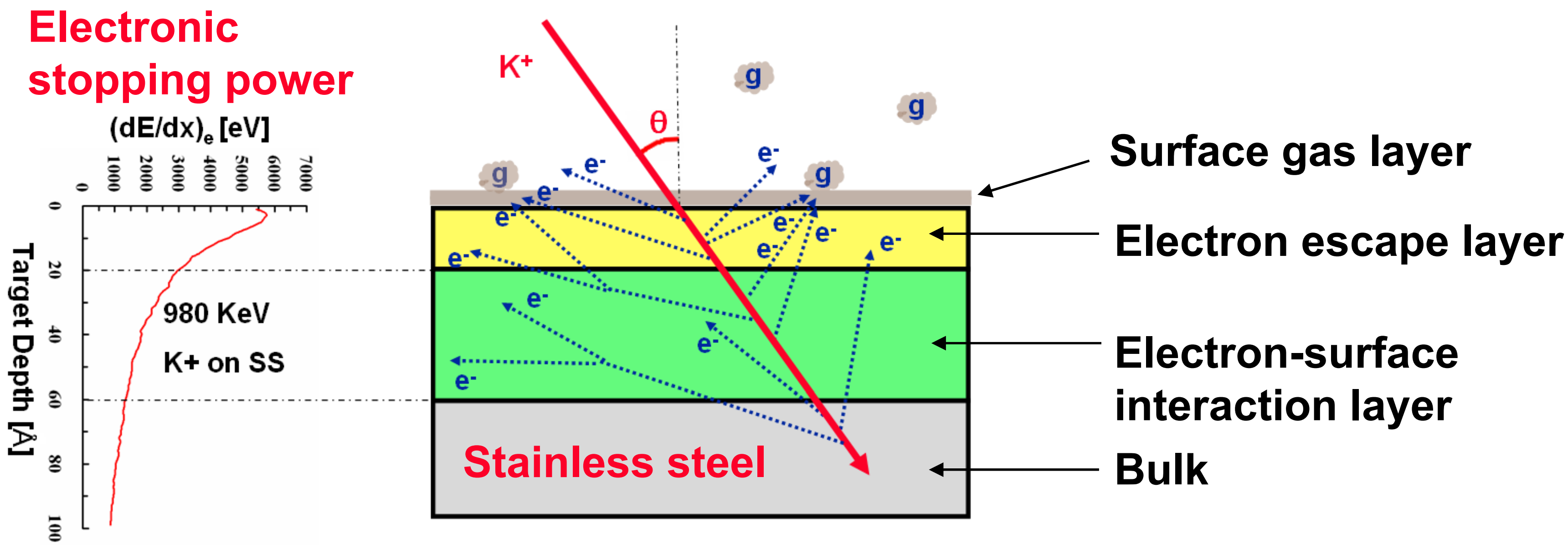
K+ on stainless steel

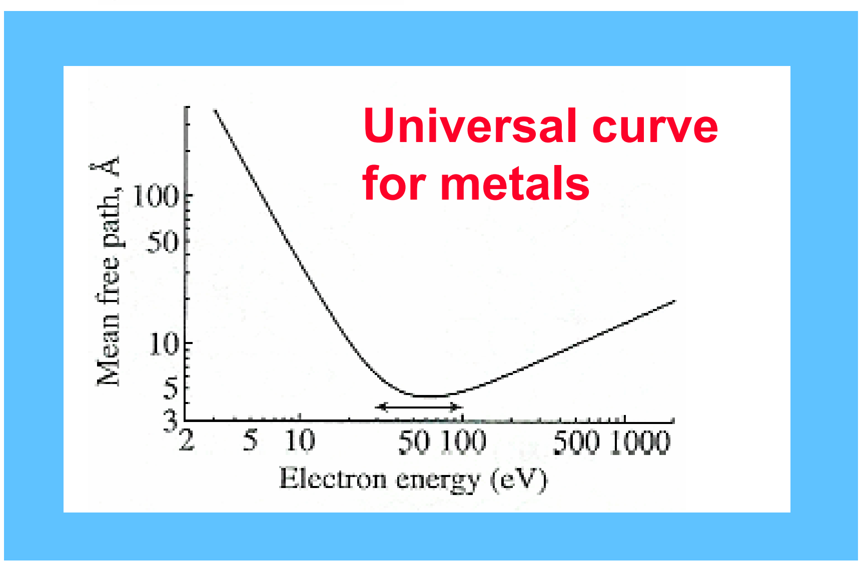


* A. W. Molvik et al., PRL 98, 064801 (2007)

- The stopping power predominance switched from nuclear to electronic in the energy range of measurements. For the same angle, the desorption yield increases with the ion energy in the same way of the electronic stopping power component, showing that this component is a probable mechanism for gas desorption.
- The gas desorption yield exhibits weak angular dependence, which decreases even more with the ion energy reduction.

Electronic gas desorption model





Enthalpy of hydrogen adsorption (H=U+PV) on:

Nickel ~ 0.99 eV/molecule
Copper ~ 0.44 eV/molecule
Molybdenum ~ 1.17 eV/molecule

∴ A high flux of low energy electrons can interact with the surface by electron-phonon coupling and can desorb gas

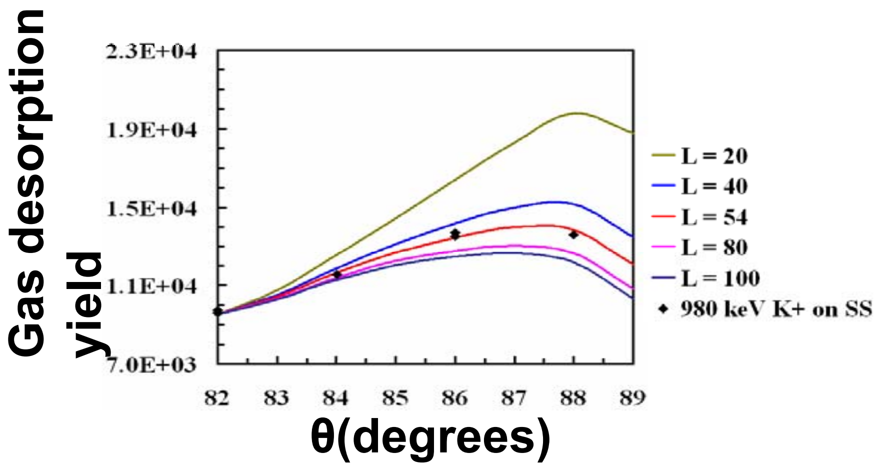
Electronic gas desorption mechanism

- **Three steps mechanism:**
  1. **Excitation of the electron,**
  2. **Transport to the surface, and**
  3. **Interaction with the surface gas layer.**

$$\gamma_0 = \gamma_e \cdot \sigma \cdot n \cdot l =$$

$$C \cdot \frac{P}{J} \cdot \sigma \cdot n \cdot l \cdot \sum_{x=0}^{\delta} \left\{ E_{TRIM}(x) \cdot e^{\left(\frac{-x}{L}\right)} \right\}$$

Normalizing and fitting to the 980 KeV K+ experimental data



∴ **Mean attenuation length (*L*) is 54 Å**

Factor *K* is 0.22 eV^{-1}

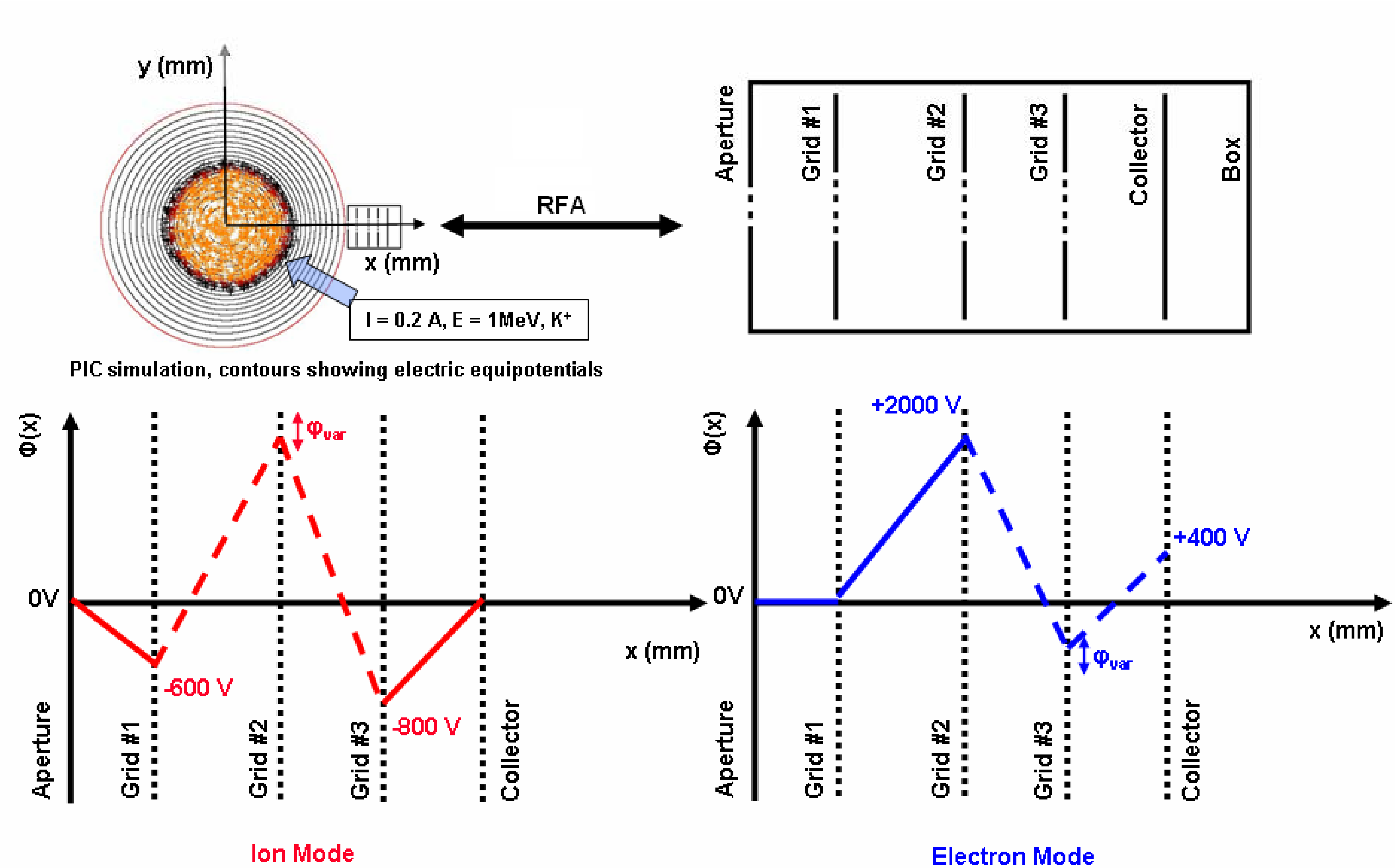
- **Low energetic electrons that interact with the surface gas layer have a mean attenuation length of 54 Å (it is almost 3 times the thickness of the electron escape layer ~ 20 Å).**

- **Factor *K* shows that each 4.54 eV of energy transported by electrons to the surface desorbs one molecule of gas.**

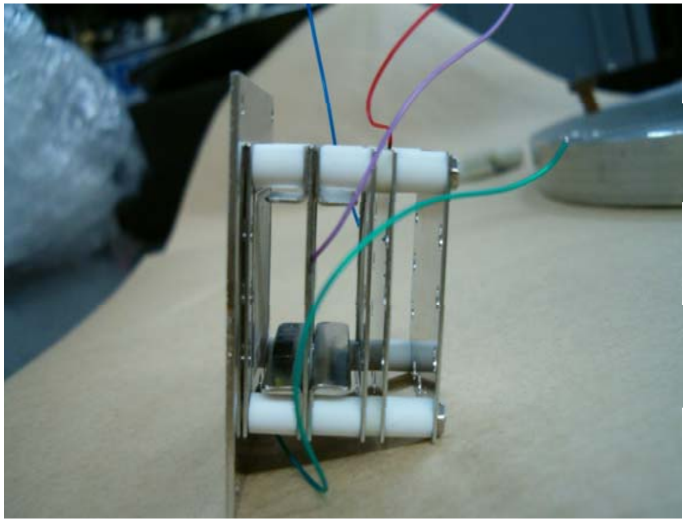
Outline

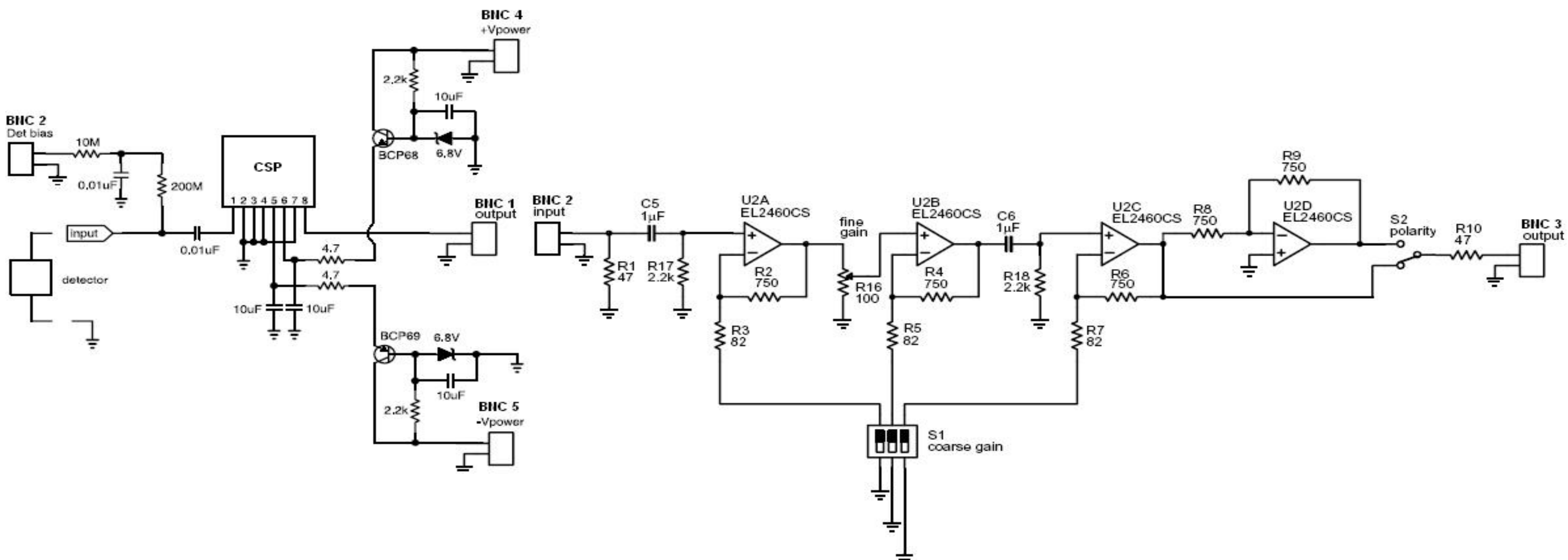
1. E-cloud issues and tools
2. Diagnostics
    a. Gas-Electron Source
    b. Retarding Field Analyzer
        i. Electron Mode
        ii. Ion Mode
        iii. Electron Cloud Density
        iv. Total Cross Sections
    c. Shielded Capacitive Electrode
    d. Microwave Dispersion Technique
3. Conclusions

Retarding Field Analyzer (RFA) design



RFA assembly and electronics

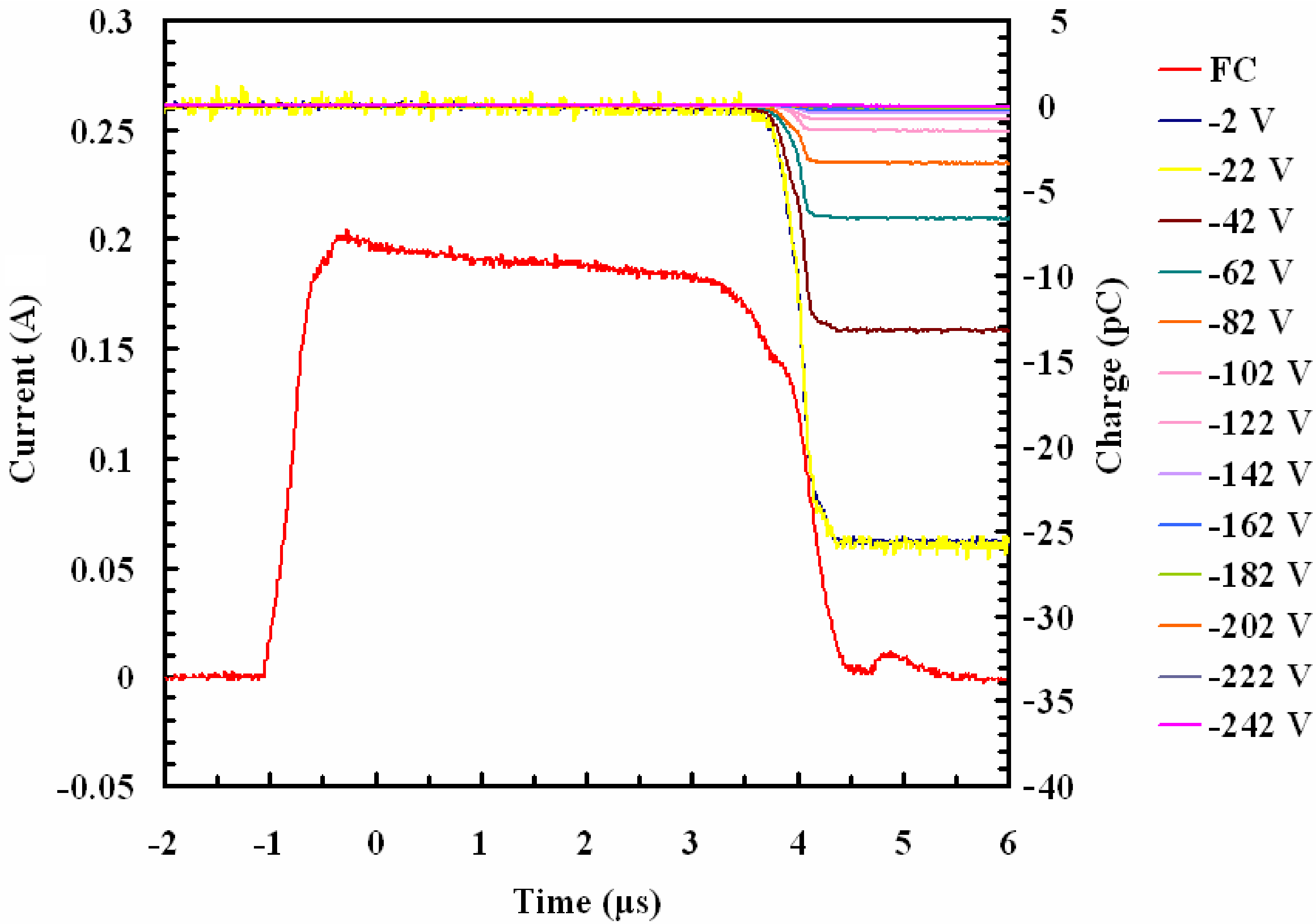




Outline

1. E-cloud issues and tools
2. Diagnostics
    a. Gas-Electron Source
    b. Retarding Field Analyzer
        i. Electron Mode
        ii. Ion Mode
        iii. Electron Cloud Density
        iv. Total Cross Sections
    c. Shielded Capacitive Electrode
    d. Microwave Dispersion Technique
3. Conclusions

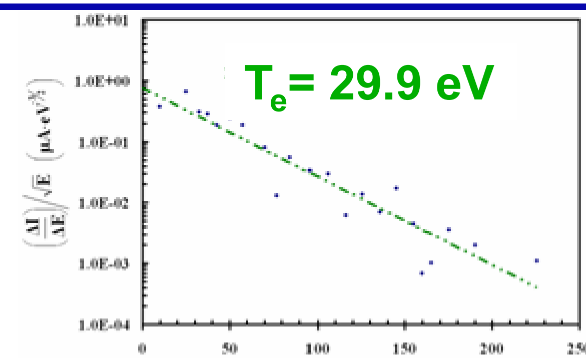
Expelled electron charge at the end of the beam



Ion-induced electron energy distribution is Maxwellian

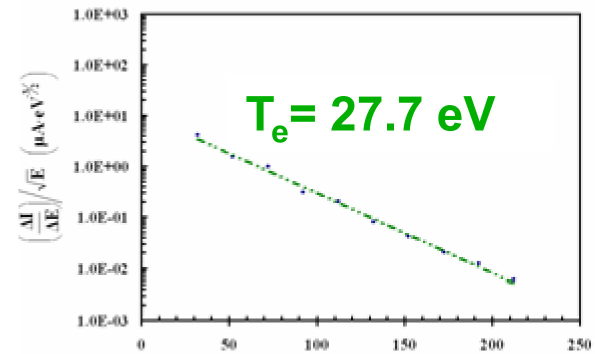
• **Method 1: Gas electron source diagnostic**

The grid surrounding the target was used to filter ion-induced electron energy from K^+ ion impact on the stainless steel target



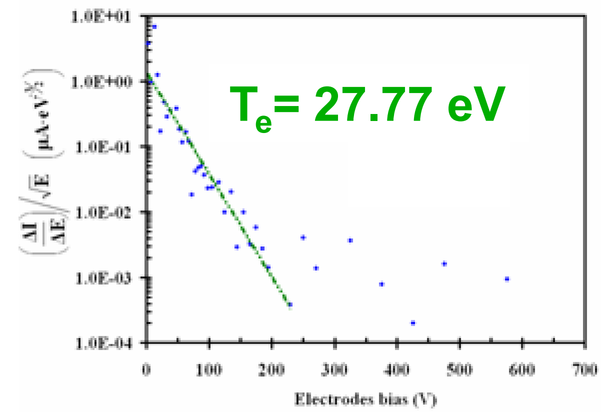
• **Method 2: RFA diagnostic**

The retarding grid of a RFA was used to measure the energy distribution of electrons produced and/or expelled at the end of the beam



• **Method 3: Clearing Electrode diagnostic**

An external C-shaped clearing electrode positively biased was used to suppress electrons from entering a RFA, working as an energy filter

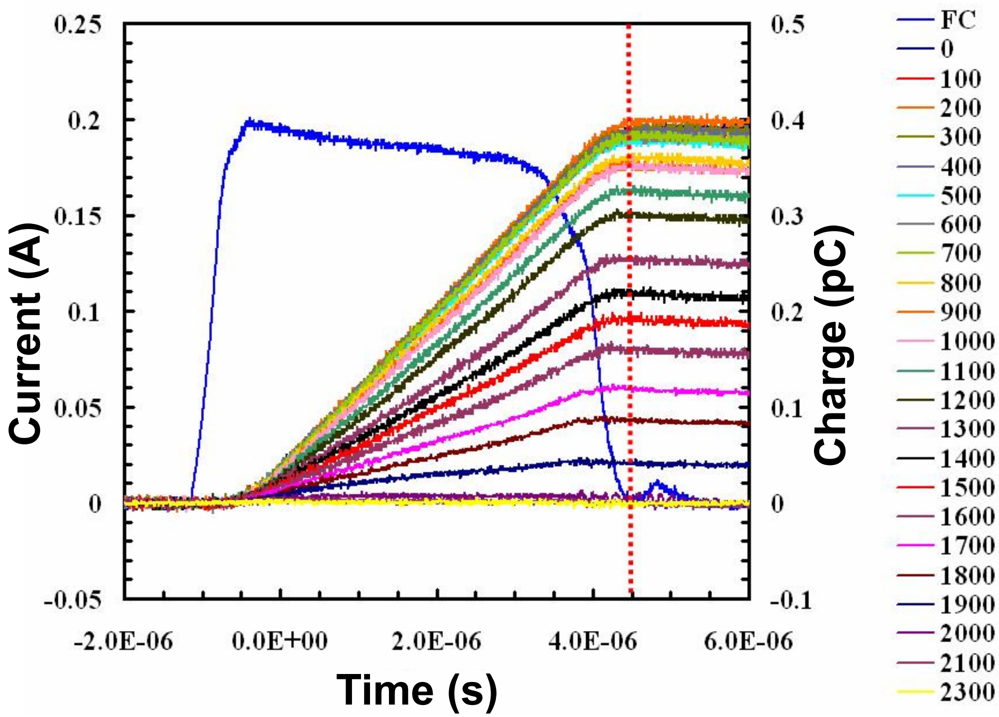


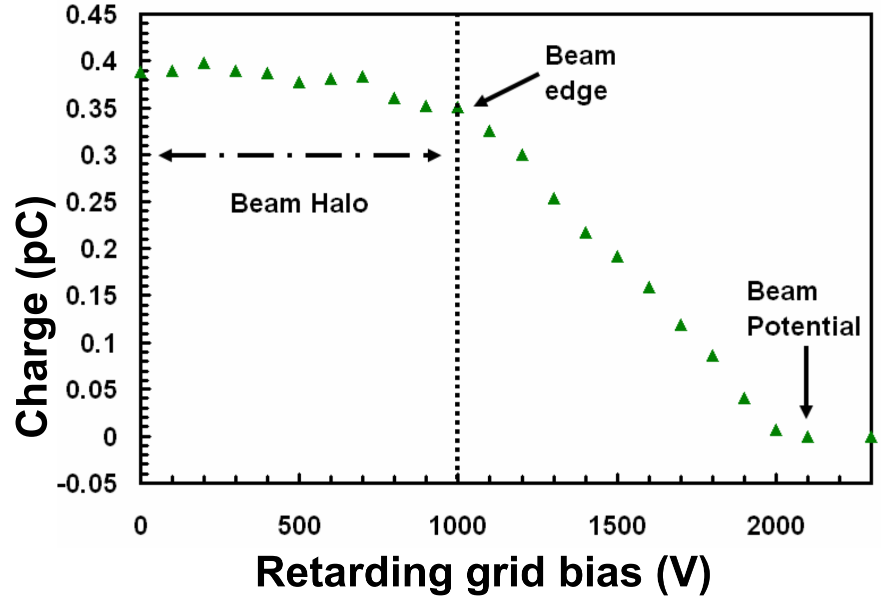
Outline

1. E-cloud issues and tools
2. Diagnostics
    a. Gas-Electron Source
    b. Retarding Field Analyzer
        i. Electron Mode
        ii. Ion Mode
        iii. Electron Cloud Density
        iv. Total Cross Sections
    c. Shielded Capacitive Electrode
    d. Microwave Dispersion Technique
3. Conclusions

RFA measures energy distribution of expelled ions*

- **Potential of beam edge is ~1000 V, and beam axis is ~ 2100 V**



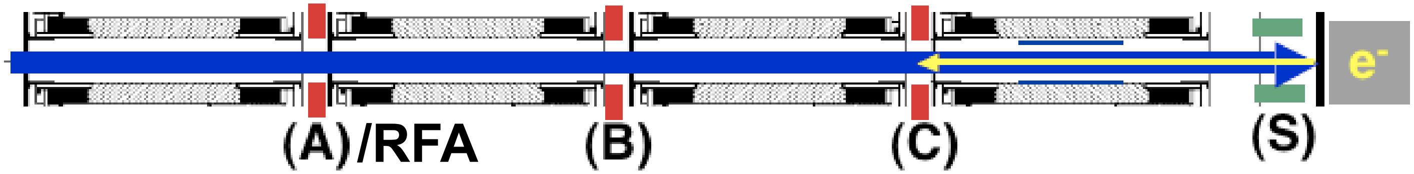


* M. Kireeff Covo et al., Nucl. Instr. and Meth. A 577 (2007) 139.

Outline

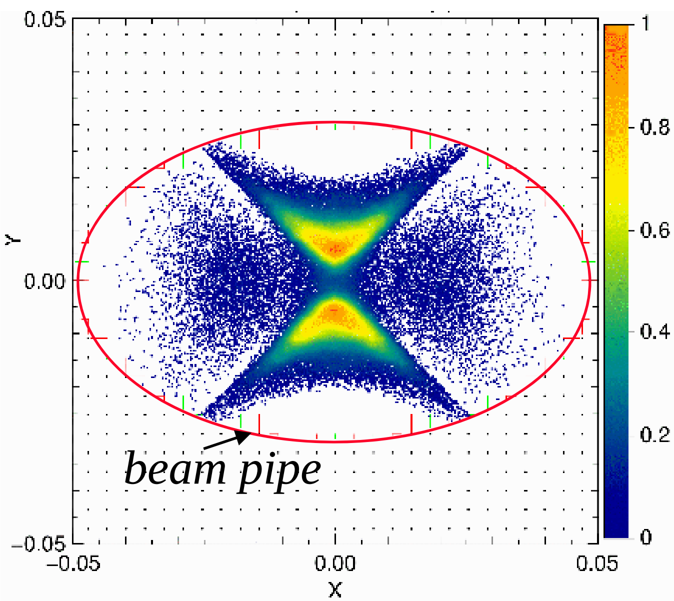
1. E-cloud issues and tools
2. Diagnostics
   a. Gas-Electron Source
   b. Retarding Field Analyzer
      i. Electron Mode
      ii. Ion Mode
      iii. Electron Cloud Density
      iv. Total Cross Sections
   c. Shielded Capacitive Electrode
   d. Microwave Dispersion Technique
3. Conclusions

Transverse electron density distributions inside the magnetic quadrupoles of HCX (simulated using WARP)*

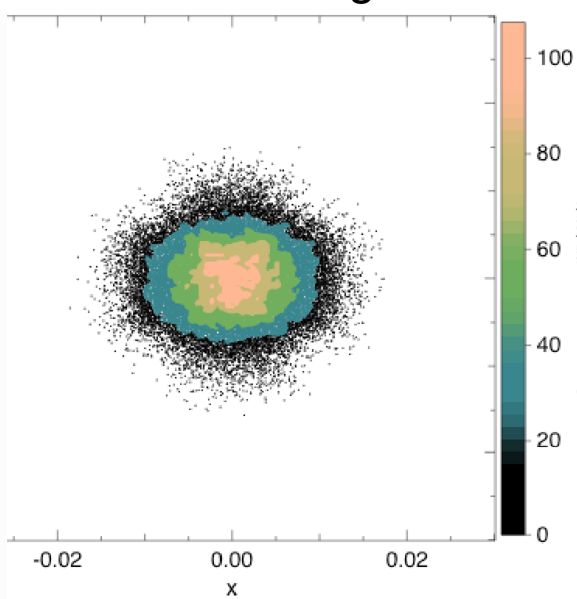


E-cloud in a Quadrupole

Electrons ejected from end wall

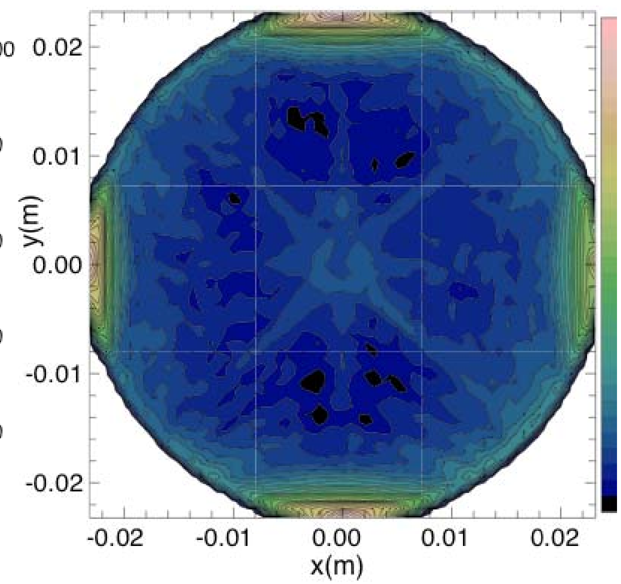


Electrons from ionization of gas



Deeply trapped electrons

Electrons desorbed from beam pipe in quad upon ion impact

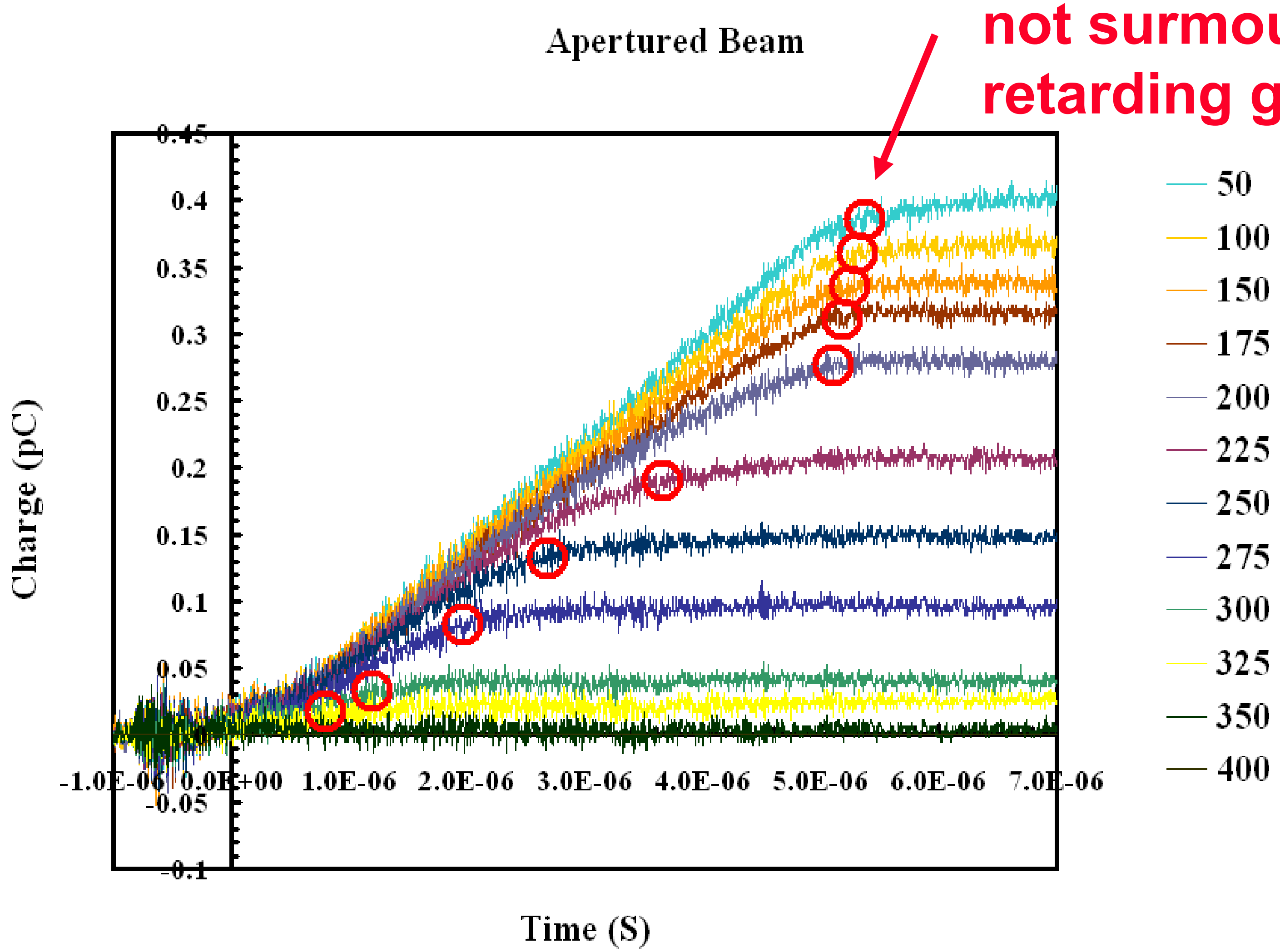


Weakly trapped electrons

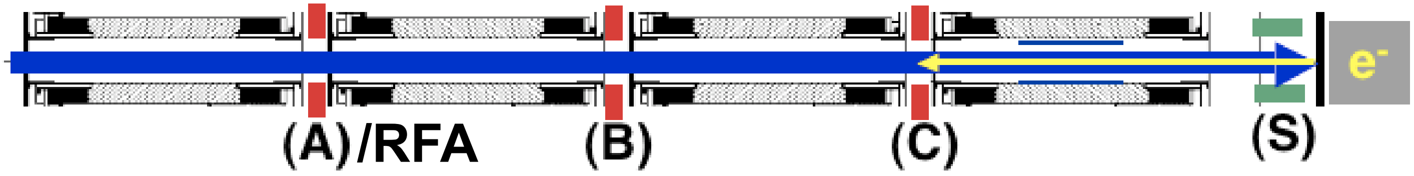
*** R. H. Cohen et al., PRSTAB 7, 124201 (2004).**

Illustrative "beam potential versus time" raw data

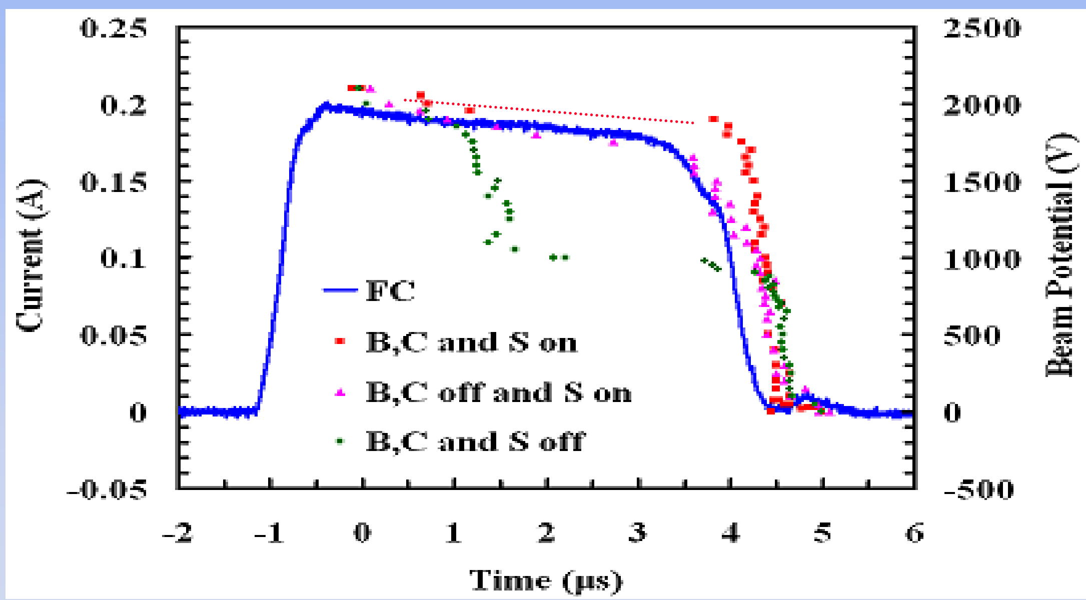
Ion energy does not surmount the retarding grid bias



A first time-dependent measurement of absolute electron cloud density* (I)



Retarding field analyzer (RFA) measures beam potential on axis



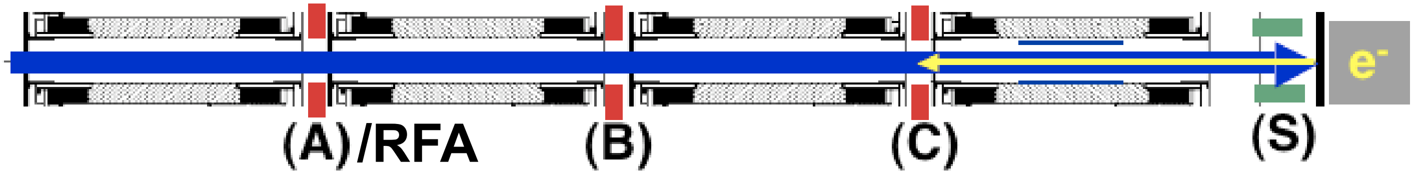
P_b = initial beam potential

$P_e = P_b$ – depressed beam potential

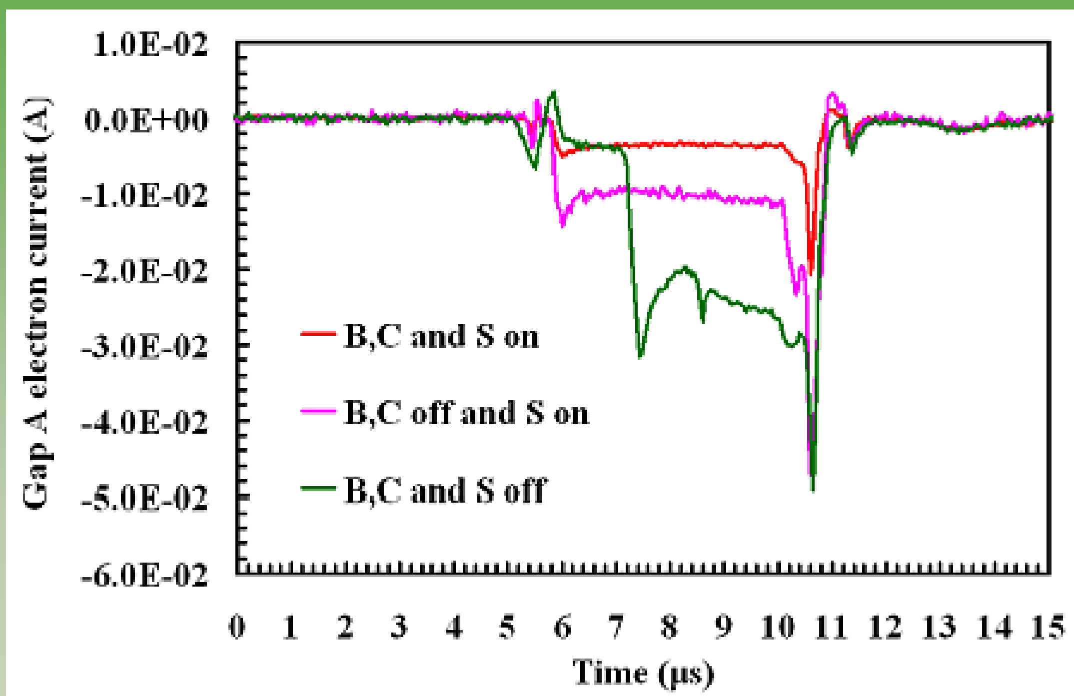
Neutralization = $\frac{P_e}{P_b} * 1.64$ + initial neutralization

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

A first time-dependent measurement of absolute electron cloud density* (II)



Clearing electrode measures electron current



$$\lambda_e = \frac{I_e}{V_d}$$

$$\text{Neutralization} = \frac{\lambda_e}{\lambda_b}$$

where:

I_e – electron current

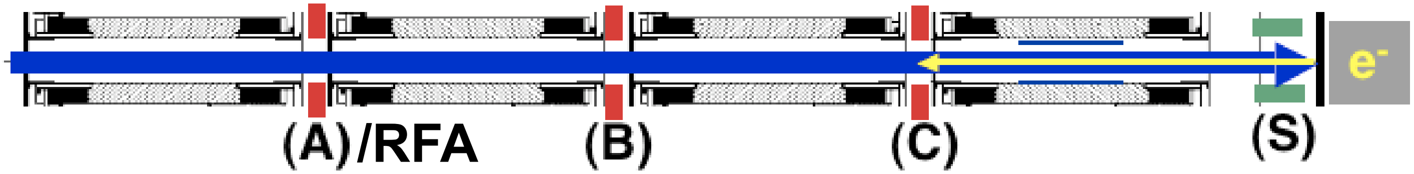
V_d – electron drift velocity

λ_e – electron line charge density

λ_b – beam line charge density

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

A first time-dependent measurement of absolute electron cloud density* (III)



Comparison of the Beam Neutralization 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%

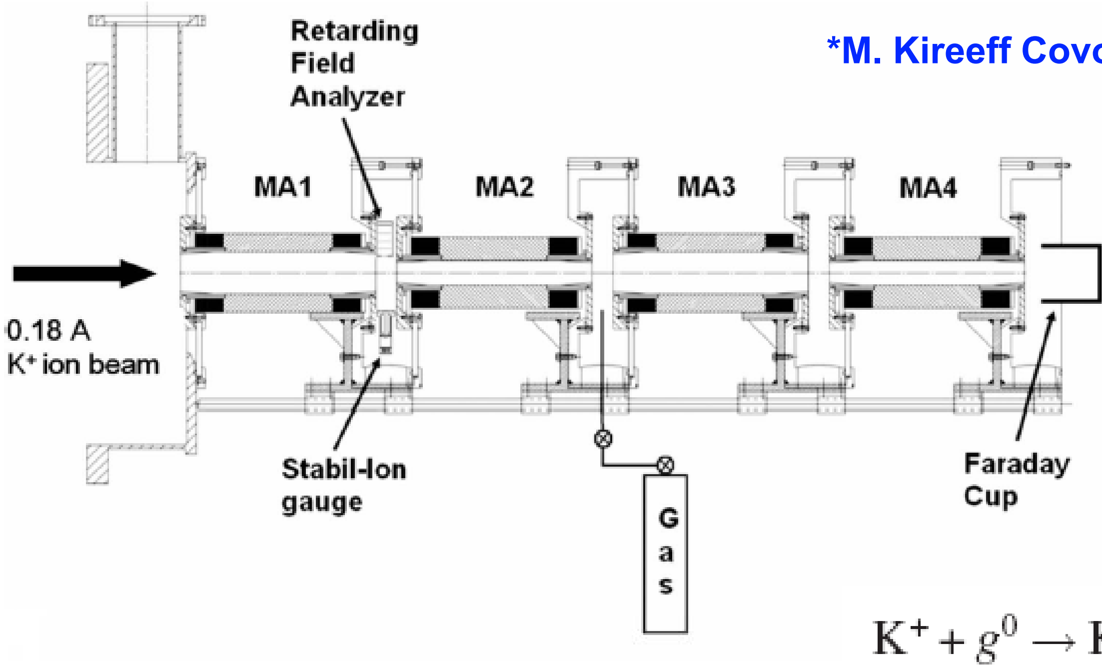
*M. Kireeff Covo et al., Phys. Rev. Lett. 97, 054801 (2006).

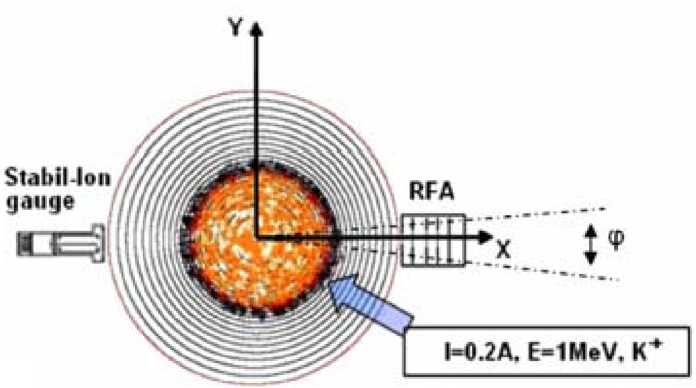
Outline

1. E-cloud issues and tools
2. Diagnostics
    a. Gas-Electron Source
    b. Retarding Field Analyzer
        i. Electron Mode
        ii. Ion Mode
        iii. Electron Cloud Density
        iv. Total Cross Sections
    c. Shielded Capacitive Electrode
    d. Microwave Dispersion Technique
3. Conclusions

RFA measures total cross sections (ionization + charge exchange)*

*M. Kireeff Covo et al., Phys. Rev. A 78, 032709 (2008).





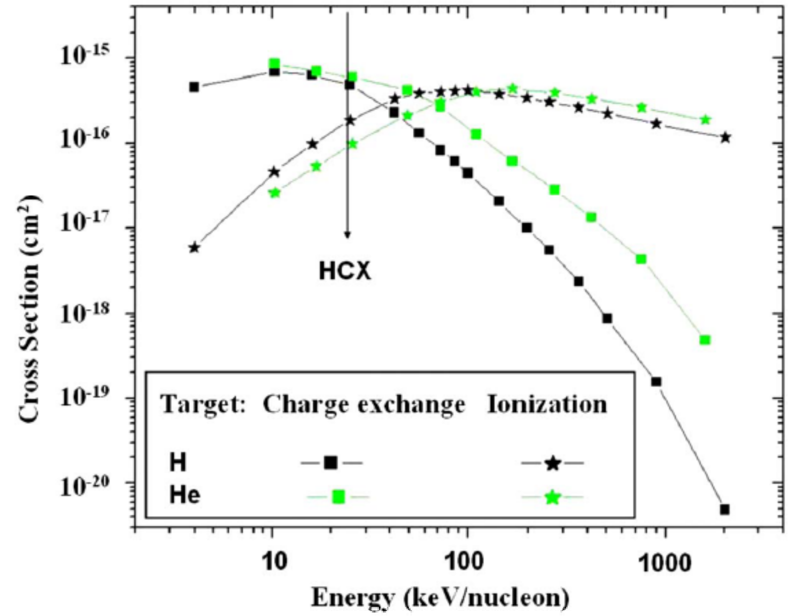
$$K^+ + g^0 \rightarrow K^+ + g^+ + e^- \quad \text{(ionization)}$$

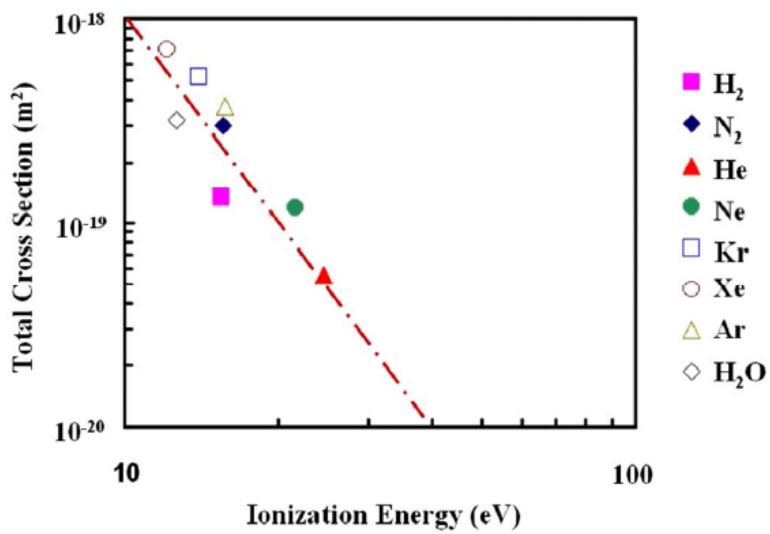
$$K^+ + g^0 \rightarrow K^0 + g^+ \quad \text{(charge exchange)}$$

$$I_{G^+} = I_{K^+} \times P/kT \times \sigma_{Total} \times l \times \varphi/360$$

RFA measures total cross sections (ionization + charge exchange)

Gas	Total cross section (m^2)	Standard deviation (m^2)
H_2	1.35×10^{-19}	1.55×10^{-20}
N_2	2.98×10^{-19}	2.98×10^{-20}
He	5.62×10^{-20}	5.70×10^{-21}
Ne	1.19×10^{-19}	1.01×10^{-20}
Kr	5.20×10^{-19}	6.83×10^{-20}
Xe	7.11×10^{-19}	7.68×10^{-20}
Ar	3.71×10^{-19}	4.38×10^{-20}
H_20	3.17×10^{-19}	4.81×10^{-20}



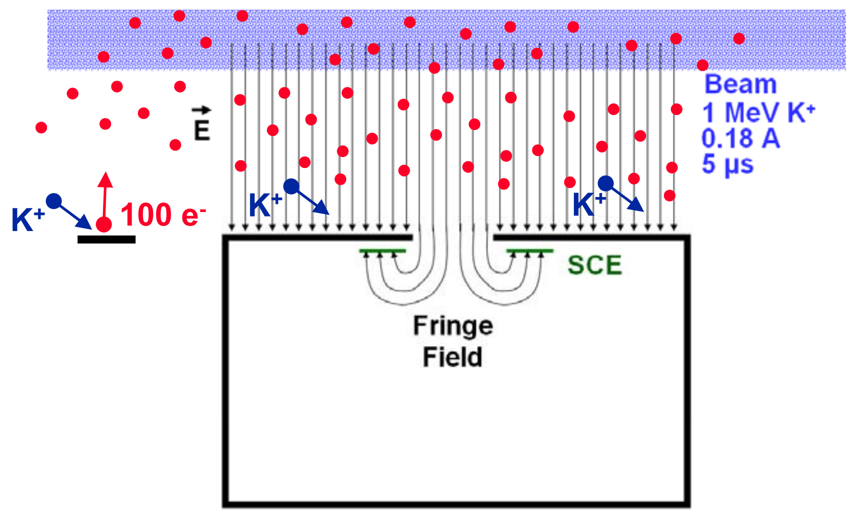


Cross Section	Experiment (m^2)	Slater model (m^2)
H_2	1.35×10^{-19}	0.89×10^{-19}
He	5.62×10^{-20}	5.20×10^{-20}
Ne	1.19×10^{-19}	1.34×10^{-19}

Outline

1. E-cloud issues and tools
2. Diagnostics
    a. Gas-Electron Source
    b. Retarding Field Analyzer
        i. Electron Mode
        ii. Ion Mode
        iii. Electron Cloud Density
        iv. Total Cross Sections
    c. Shielded Capacitive Electrode
    d. Microwave Dispersion Technique
3. Conclusions

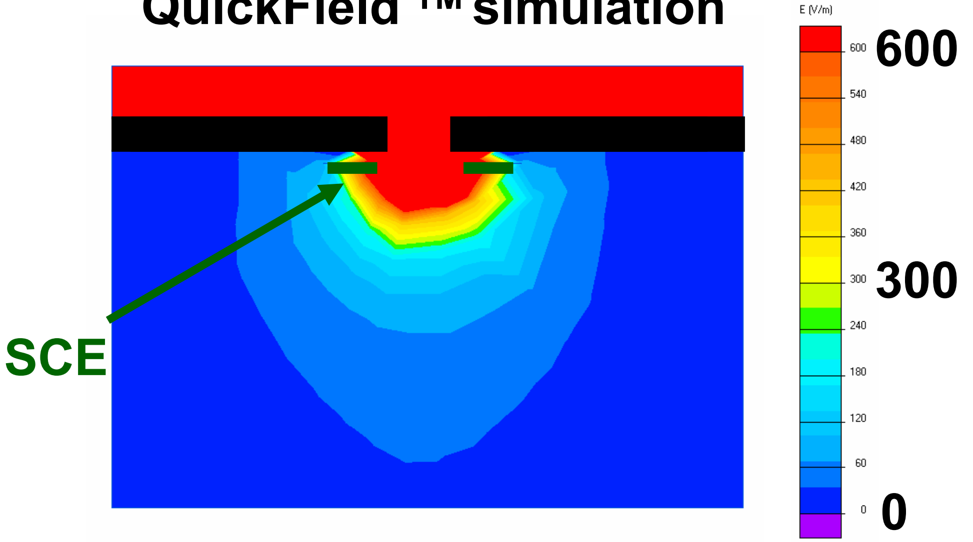
Shielded Capacitive Electrode (SCE)*



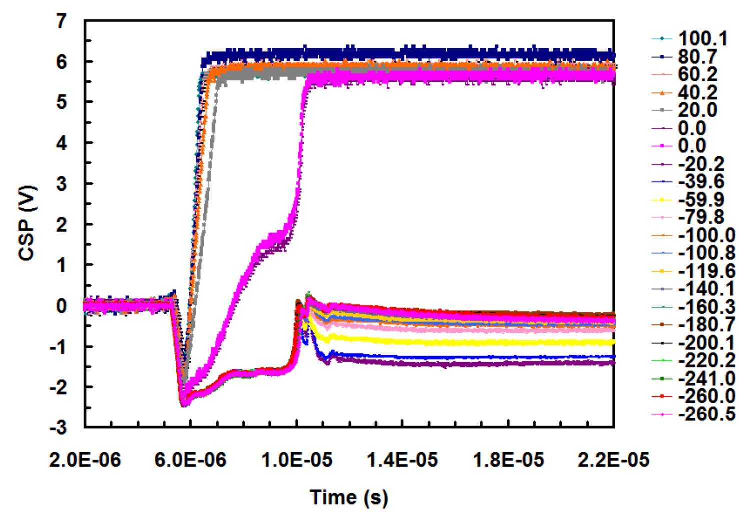
* In Patent process

• The fringe fields reaching the SCE electrode induce an image charge proportional to the net charge (K^+ and e^-) inside the beam pipe.

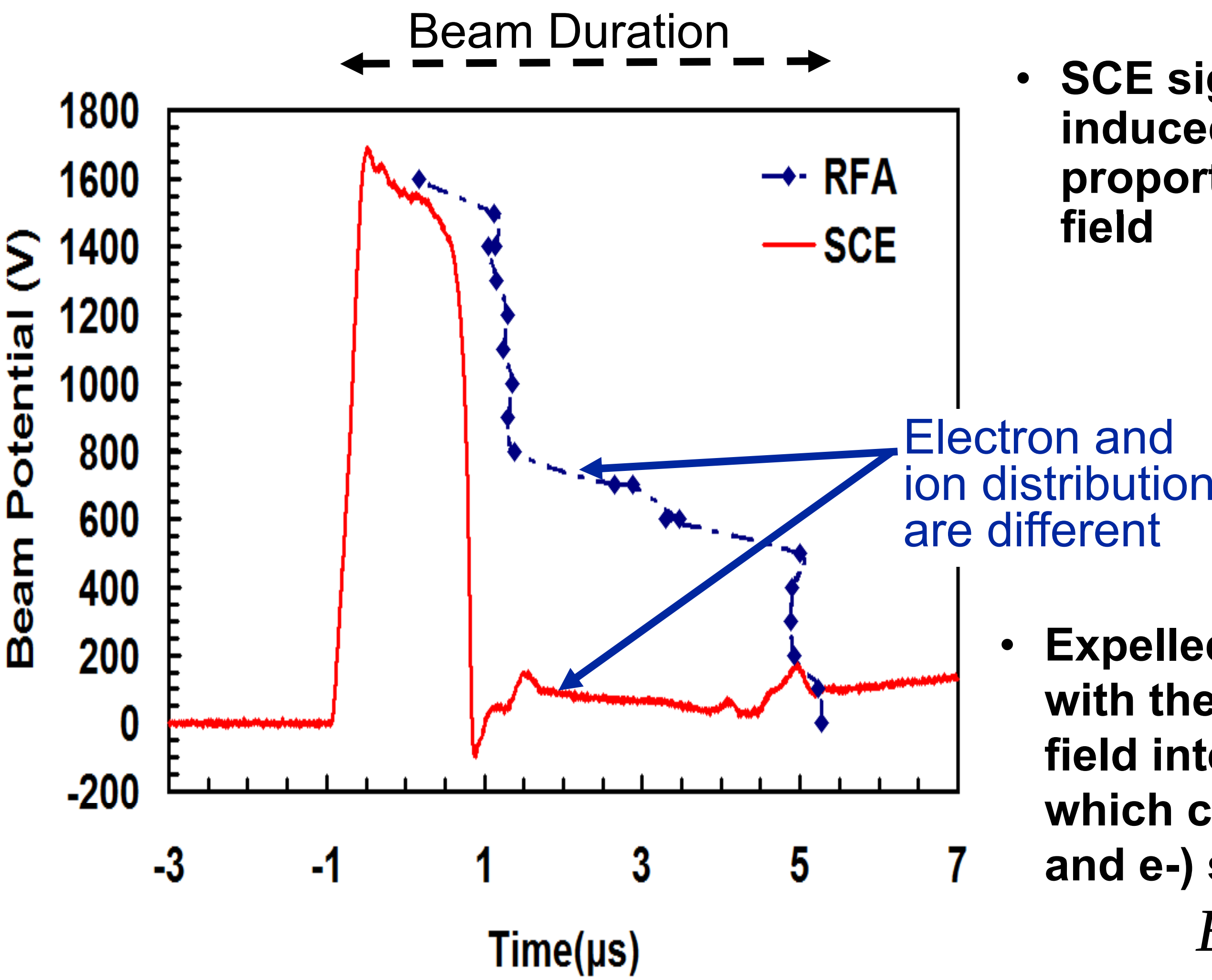
QuickField TM simulation



SCE Bias Scan



Probing the electric field



- **SCE signal gives the charge induced on the electrode, that is proportional to the local electric field**

$$Q_{ind} \propto \vec{E}_{local}$$

- **Expelled ion energy measured with the RFA gives the electric field integral along the ion path, which corresponds to the net (K+ and e-) space-charge potential**

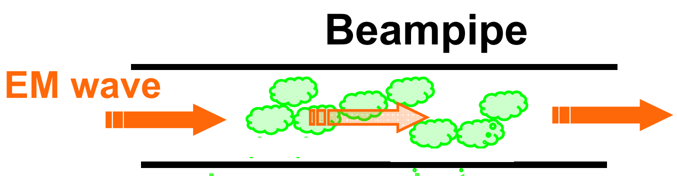
$$E_{ion} = q.V_{net} = q.\int \vec{E}.dl$$

$$V_{net} = \int \vec{E}.dl$$

Outline

1. E-cloud issues and tools
2. Diagnostics
    a. Gas-Electron Source
    b. Retarding Field Analyzer
        i. Electron Mode
        ii. Ion Mode
        iii. Electron Cloud Density
        iv. Total Cross Sections
    c. Shielded Capacitive Electrode
    d. Microwave Dispersion Technique
3. Conclusions

Physical Principles



Phase velocity changes in the ec region

The resulting phase shift per unit length is: Proportional to ECD

$$\frac{\Delta\varphi}{L} = \frac{\omega_p^2}{2c(\omega^2 - \omega_c^2)^{1/2}}$$

and the electron density (e^-/m^3) is about:

$$n_e \approx \frac{f_p^2}{80}$$

Formulas valid when B=0

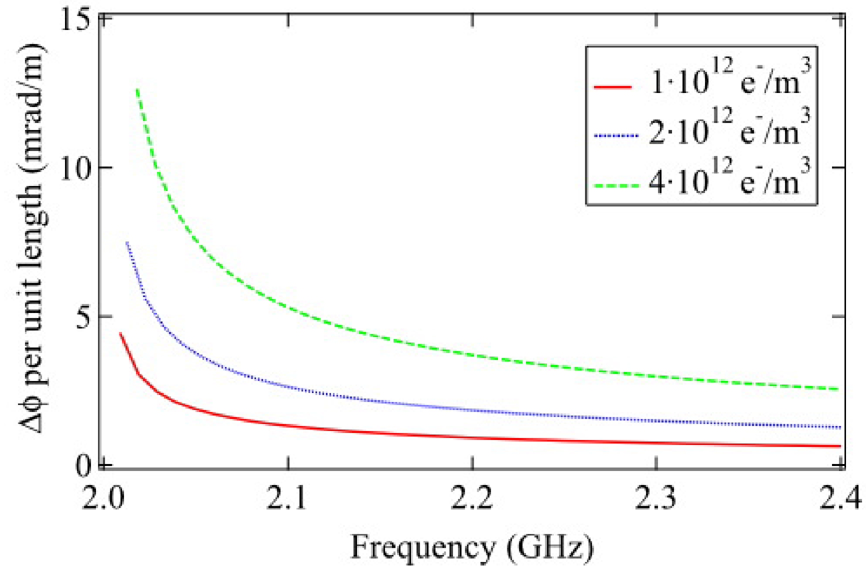
Propagation through the electron plasma introduces additional dispersion:

$$k^2 = \frac{\omega^2 - \omega_c^2 - \omega_p^2}{c^2}$$

Plasma frequency

Standard waveguide dispersion

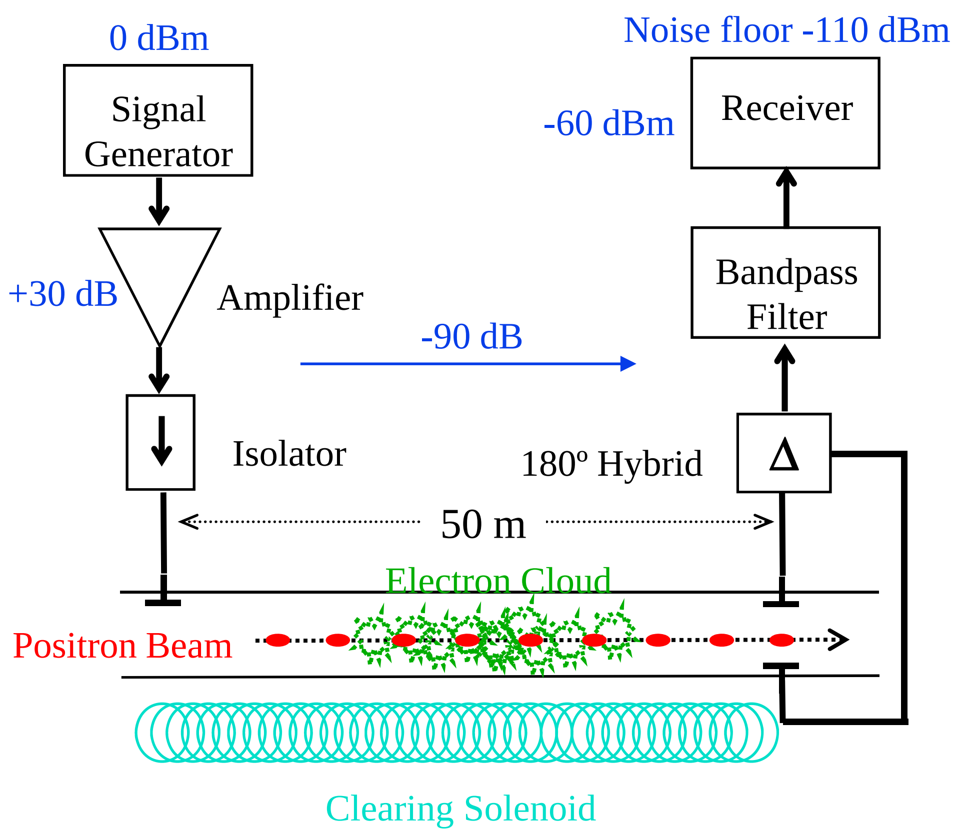
Beampipe cut-off frequency



Frequencies closer to cut-off experience larger phase shifts. Their attenuation is generally larger, though.

Experimental setup on the PEP-II LER*

No installation required: BPM's used to transmit/receive EM wave. Since there are BPM's all around the ring it is possible to measure any section of the pipe.

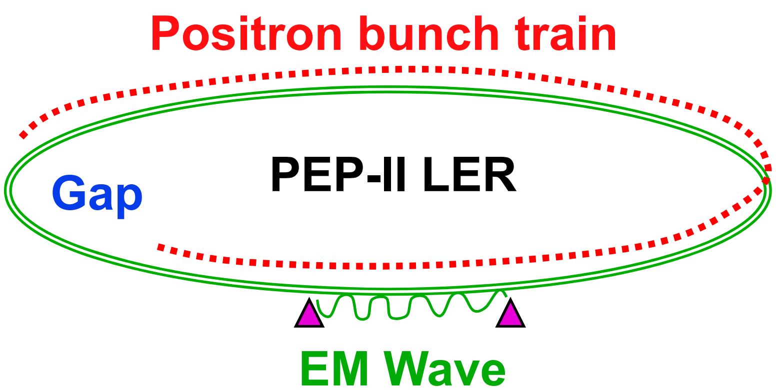


PEP-II LER IR12 Straight

- Clearing solenoids wrapped around the beampipe can generate a magnetic field up to 40 G.
- The hybrid reduces the direct beam signal picked up by the receiver (spectrum analyzer)
- A Bandpass Filter is used to further reduce beam power on the receiver. Total received power < 100 mW.
- The 20 dB isolator protects transmitter and amplifier.
- Transmission attenuation is around 90 dB, with a 50 dB SNR at the receiver.

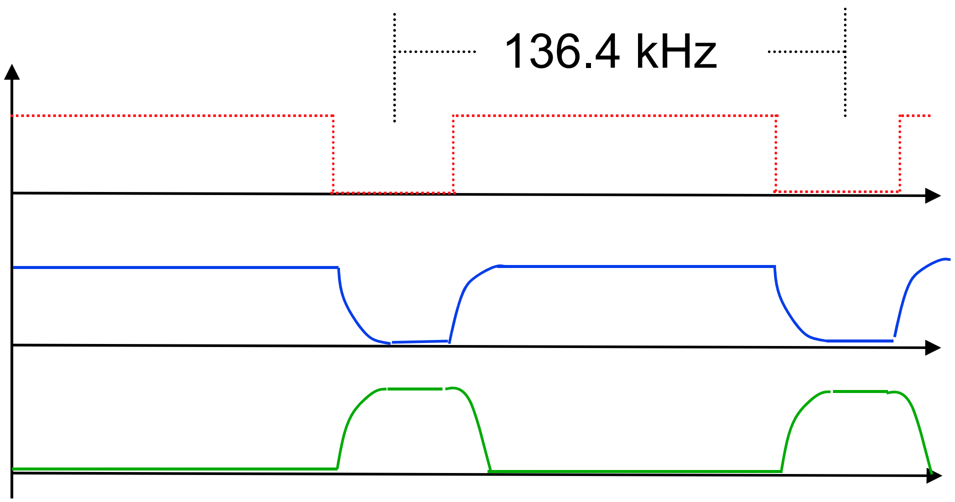
*** S. De Santis et al., PRL 100, 094801 (2008).**

Phase Shift Time Dependence



Gap length ≈ 100 ns
Revolution period ≈ 7.3 μs
Bunch spacing ≈ 4 ns

- The distance between bunches is short compared to the e-cloud rise/decay time
- The gap length is long enough to clear the low-energy electrons



Positron current

E-Cloud Density

Relative phase shift

The phase shift changes at a frequency equal to the (gap) revolution frequency !!!

Phase Modulation – Std. formula

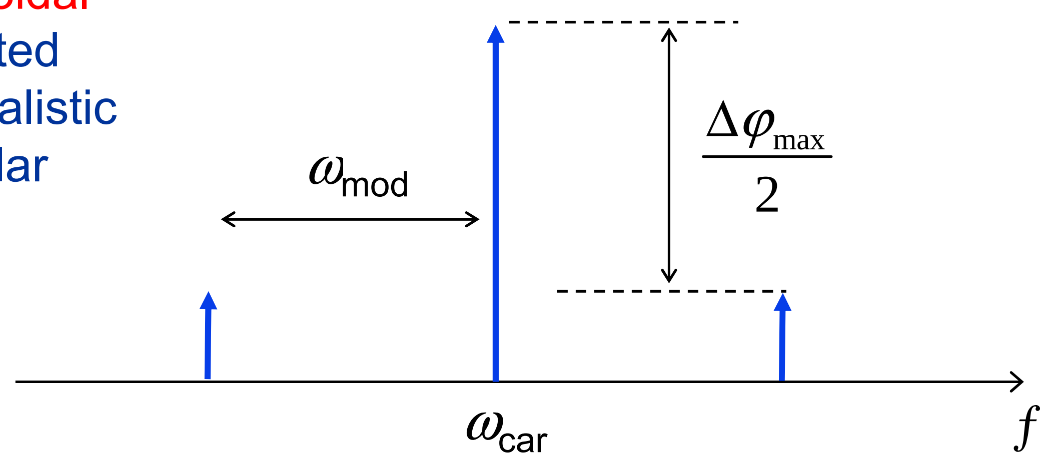
The *periodic clearing of the electron cloud* by the gap, when it passes between our Tx and Rx BPM's *phase modulates the transmitted signal*:

$$s(t) = A\cos[\omega_{car}t + \Delta\varphi(t)]$$

Amplitude modulation ? (Caspers)
At very low modulation depth AM and PM are undistinguishable in standard spectrum analyzers.

β=Δφ/2 is valid only for sinusoidal modulation. We have calculated correction factors for more realistic modulating signals (rectangular wave, sawtooth,…)

If $\Delta\varphi(t) = \Delta\varphi_{\max}\sin(\omega_{\mathrm{mod}}t)$



Outline

1. E-cloud issues and tools
2. Diagnostics
   a. Gas-Electron Source
   b. Retarding Field Analyzer
      i. Electron Mode
      ii. Ion Mode
      iii. Electron Cloud Density
      iv. Total Cross Sections
   c. Shielded Capacitive Electrode
   d. Microwave Dispersion Technique
3. Conclusions

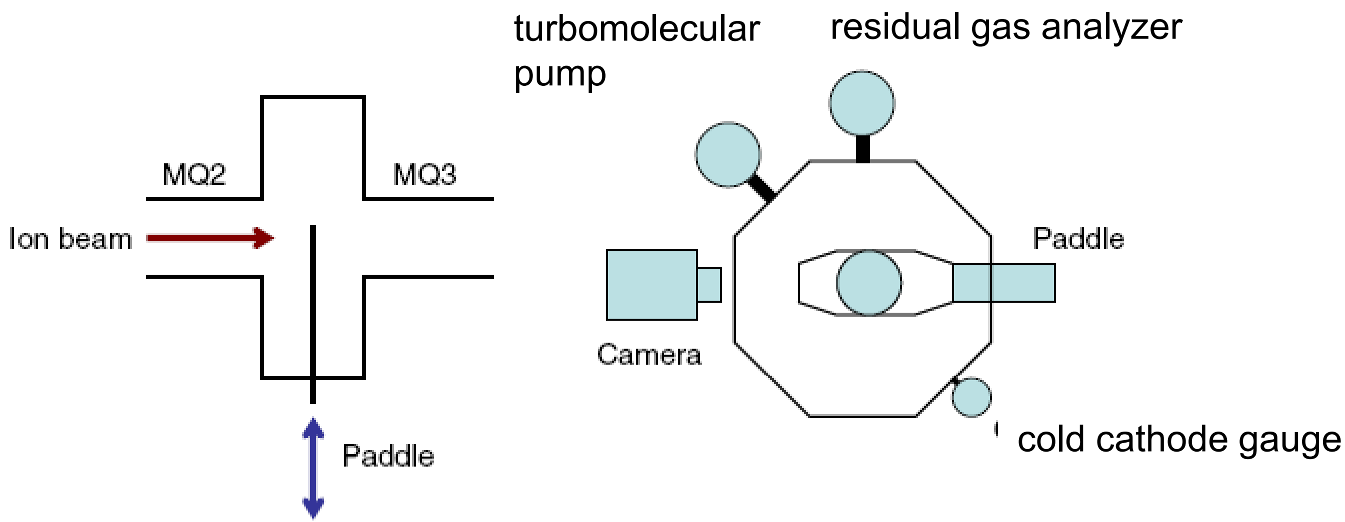
Conclusions

- Electron clouds are ubiquitous in particle accelerators and frequently limit the performance of storage rings. In order to have a better understanding of the phenomena, several diagnostics were designed to quantitatively measure electron and gas sources, transport, electron cloud density and energy distribution.

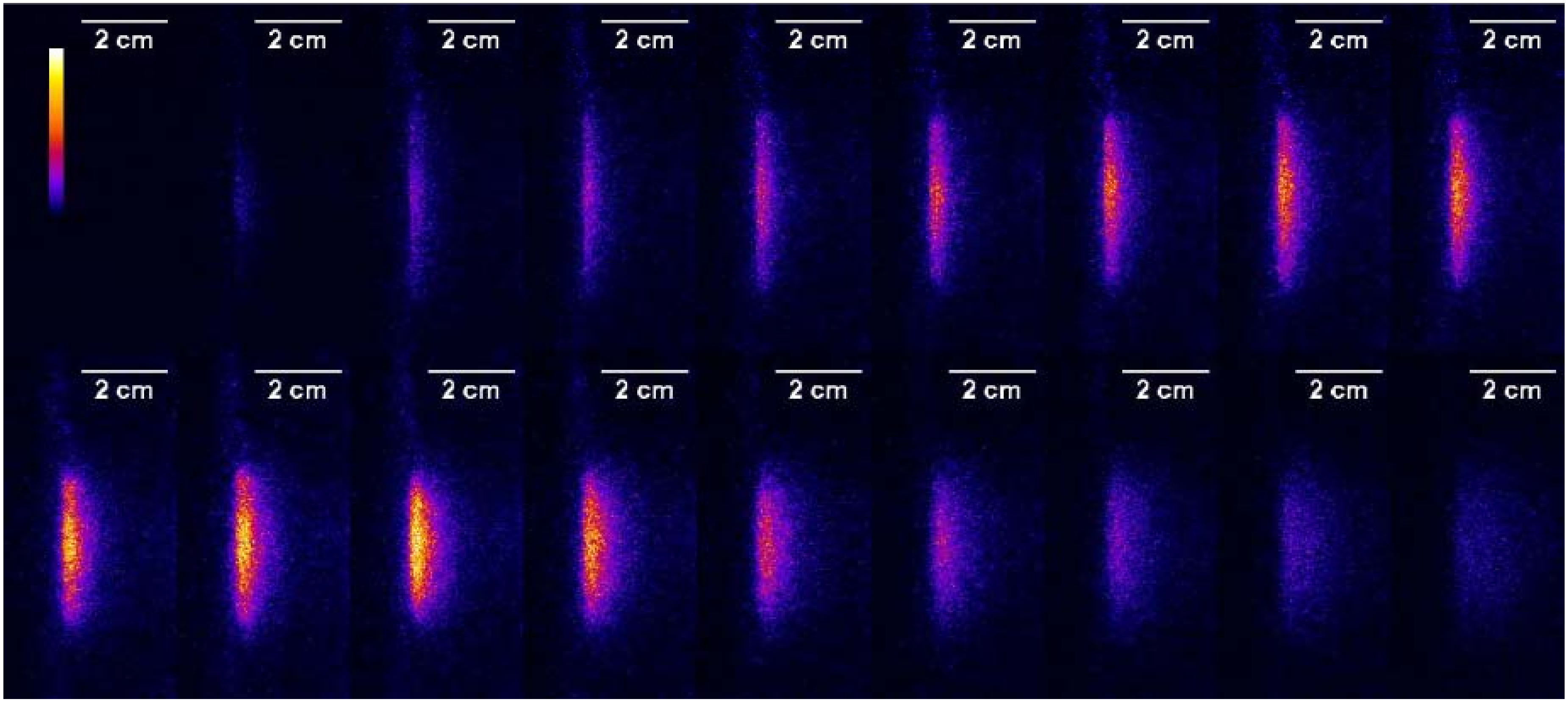
Backup

Experimental setup for imaging ion-induced desorption*

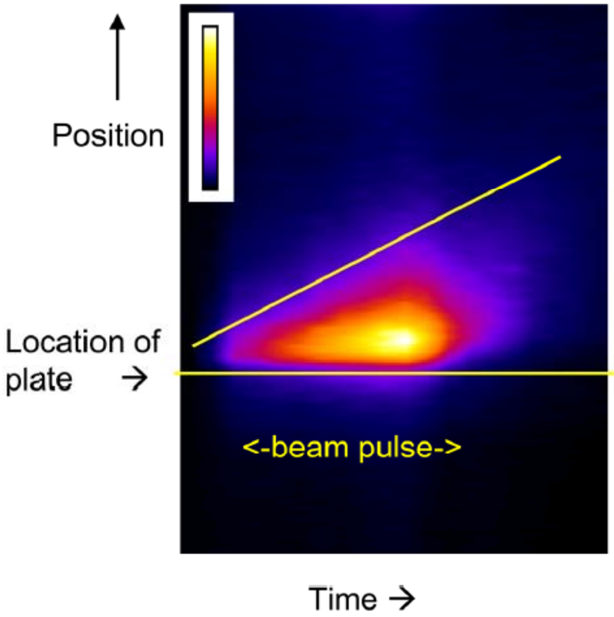
*F.M. Bieniosek et al., Phys. Rev. ST Accel. Beams 10, 093201 (2007).



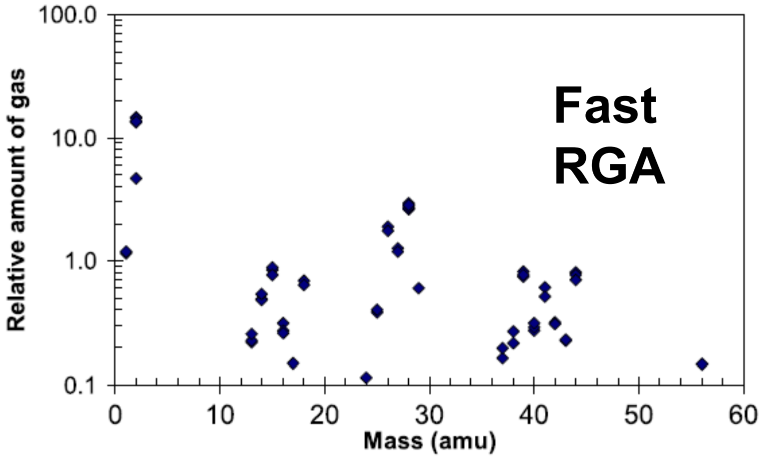
Images of the gas cloud show growth and decay as a function of time.



Line integral of the images



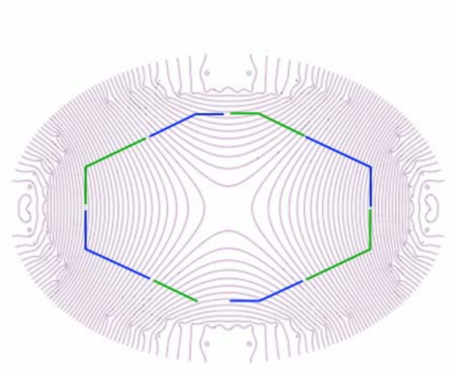
The overall mean gas velocity was 0.5 mm/μs, corresponding to a distribution of H_2 molecules near room temperature.

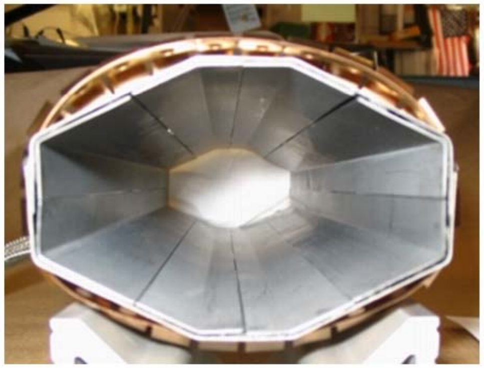


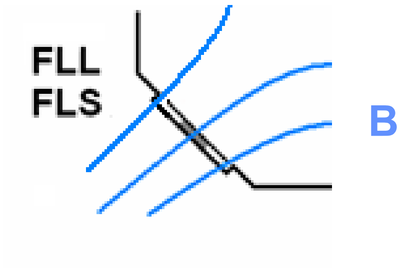
The results indicate that the gas released is dominated by hydrogen (1 or 2 amu). The next largest peak is mass 28 (CO or N_2).

Diagnostics within last two magnetic quadrupole bores

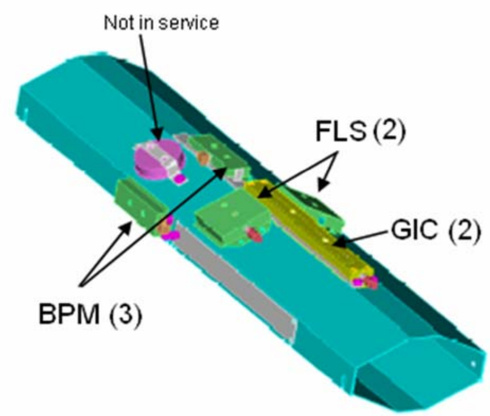
QM3

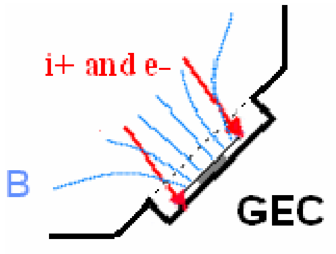


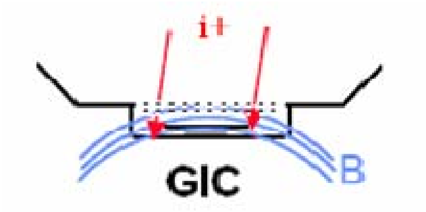




QM4

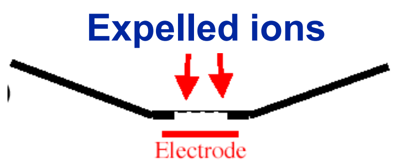


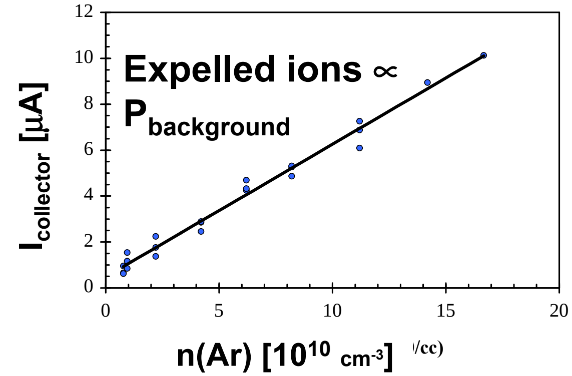




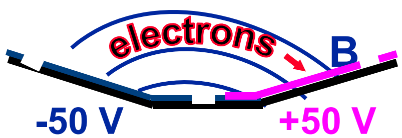
All sources of electrons can be measured*

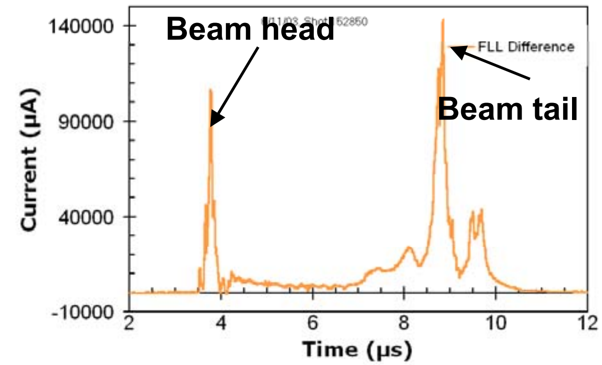
1. **Ionization of gas by beam**



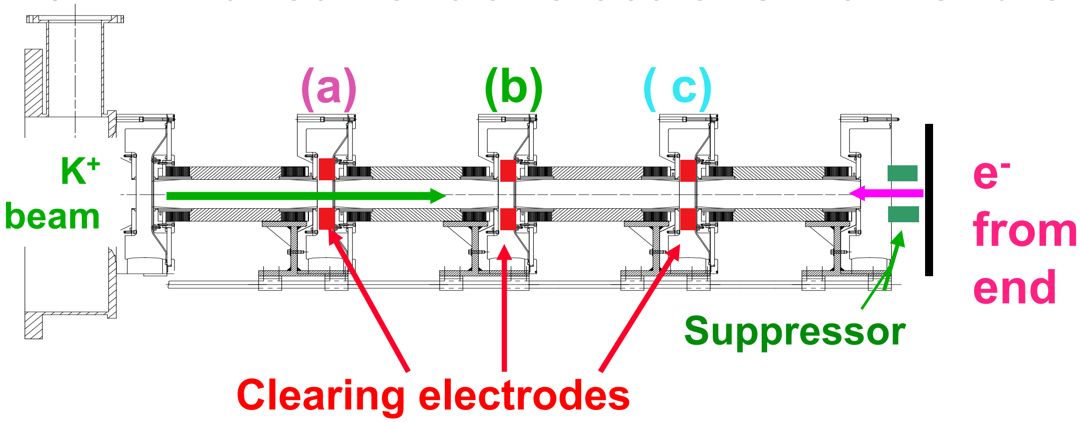


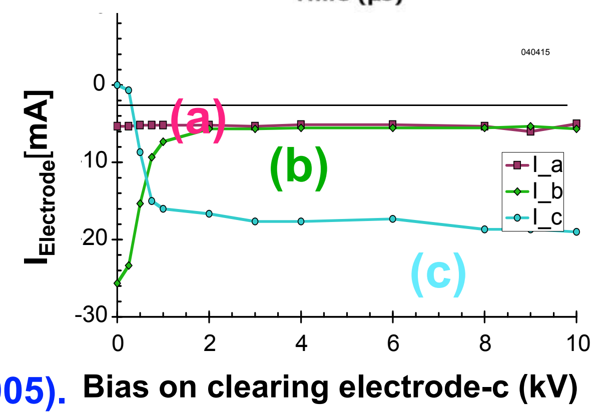
2. **Electron emission from beam tube**





3. **Axial current of electrons from end of linac**

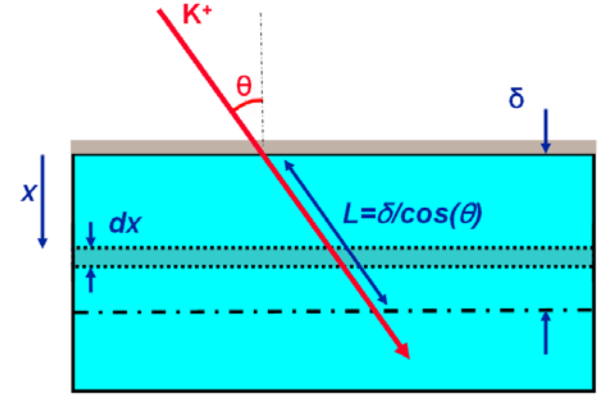




*A.W. Molvik et al., Nucl. Instrum. Methods Phys. Res. A 544,194 (2005).

Electronic gas desorption mechanism (I)

- **Three steps mechanism:**
  1. Excitation of the electron,
  2. Transport to the surface, and
  3. Interaction with the surface gas layer.



Sternglass Theory for electron emission

$$\gamma_e = C\frac{P}{J}\left[\frac{\delta}{\cos(\theta)}\left(\frac{dE}{dx}\right)_e\right] = C\frac{P}{J}\sum_{x=0}^{\delta} E_{TRIM}(x)$$

where:

- *C* is the ion species parameter;
- *P* is the fraction of electrons moving towards the surface;
- *J* is the average energy to generate an electron;
- δ is the layer depth;
- θ is the ion angle from the surface normal; and
- *Etrim(x)* is the total ionization as a function of target depth *x.*

transport issues

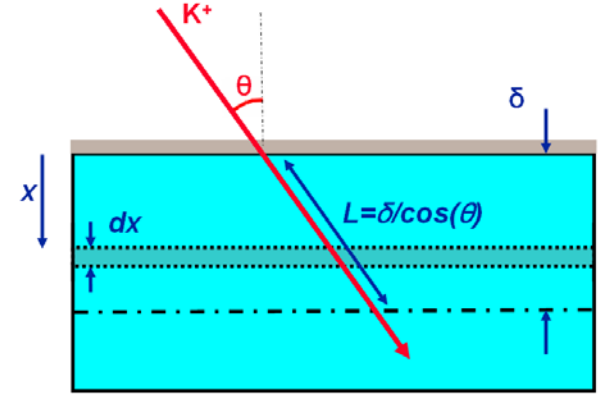
$$\gamma_e = C\frac{P}{J}\sum_{x=0}^{\delta}\left\{E_{TRIM}(x)\cdot e^{\left(\frac{-x}{L}\right)}\right\}$$

where:

- *x* is the distance to the surface; and
- *L* is the mean attenuation length.

Electronic gas desorption mechanism (II)

- **Three steps mechanism:**
  1. **Excitation of the electron,**
  2. **Transport to the surface, and**
  3. **Interaction with the surface gas layer.**



$$\gamma_0 = \gamma_e \cdot \sigma \cdot n \cdot l =$$

$$C \cdot \frac{P}{J} \cdot \sigma \cdot n \cdot l \cdot \sum_{x=0}^{\delta} \left\{ E_{TRIM}(x) \cdot e^{\left(\frac{-x}{L}\right)} \right\}$$

Rewriting

$$\gamma_0 = K \sum_{x=0}^{\delta} \left\{ E_{TRIM}(x) \cdot e^{\left(\frac{-x}{L}\right)} \right\}$$

where:

- γ_o **is the gas desorption yield;**
- γ_e **is the electron yield;**
- σ **is the desorption cross section;**
- ***n*** **is the gas surface layer density; and**
- ***l*** **is the gas surface layer thickness.**

unknowns:

- **Factor *K* ; and**
- **The mean attenuation length - *L*.**