Experimental Studies of Electron and Gas Sources in a Heavy-Ion Beam*

A.W. Molvik[1,2]

With contributions from

F.M. Bieniosek[1,3], J.J. Barnard[1,2], D.A. Calahan[2], R.H. Cohen[1,2], A. Friedman[1,2], M. Kireeff Covo[1,2], J.W. Kwan[1,3], W.R. Meier[2], L. Prost[1.3], A. Sakumi[4], P.A. Seidl[1,3], G. Westenskow[1,2], S.S. Yu[1,3],

[1] HIF-VNL, [2] LLNL, [3] LBNL, [4]CERN

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OUTLINE

- **Introduction to Heavy Ion Fusion (HIF)**
- **Measurements of gas desorption & electron emission**
- **Measurements of electrons in quadrupole magnets**

Related Papers

Jean-Luc Vay, "Status report on the merging of ECE code POSINST with 3-D accelerator PIC code WARP" Tuesday, pm

Ron Cohen, "Simulations of e-cloud for Heavy-Ion Fusion" Wed. am

Peter Stoltz, "The CMEE Lib. for numerical modeling ECE" Wed. am

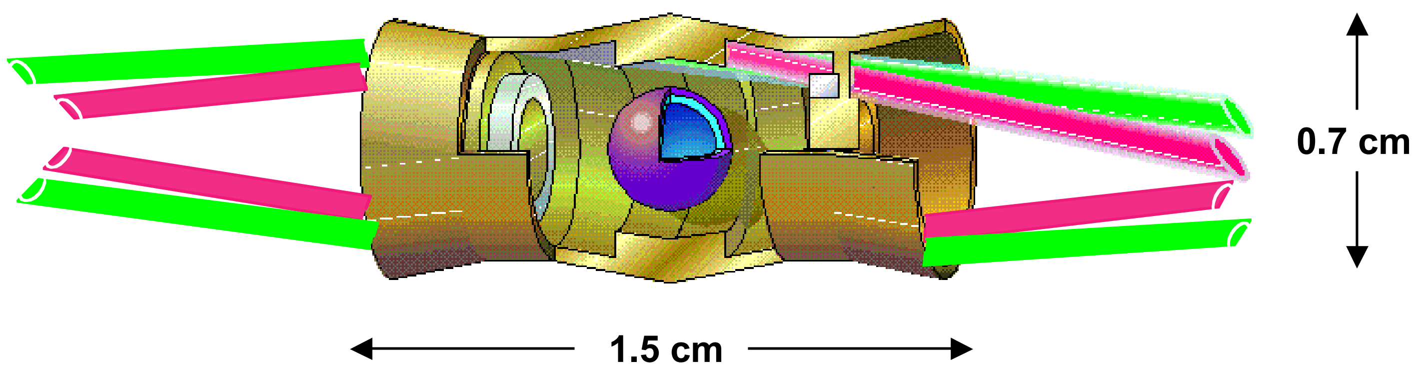
Hong Qin, "Delta-f simulations of Electron 2-stream Instab." Wed. am

Target Requirements establish accelerator requirements for power plant driver

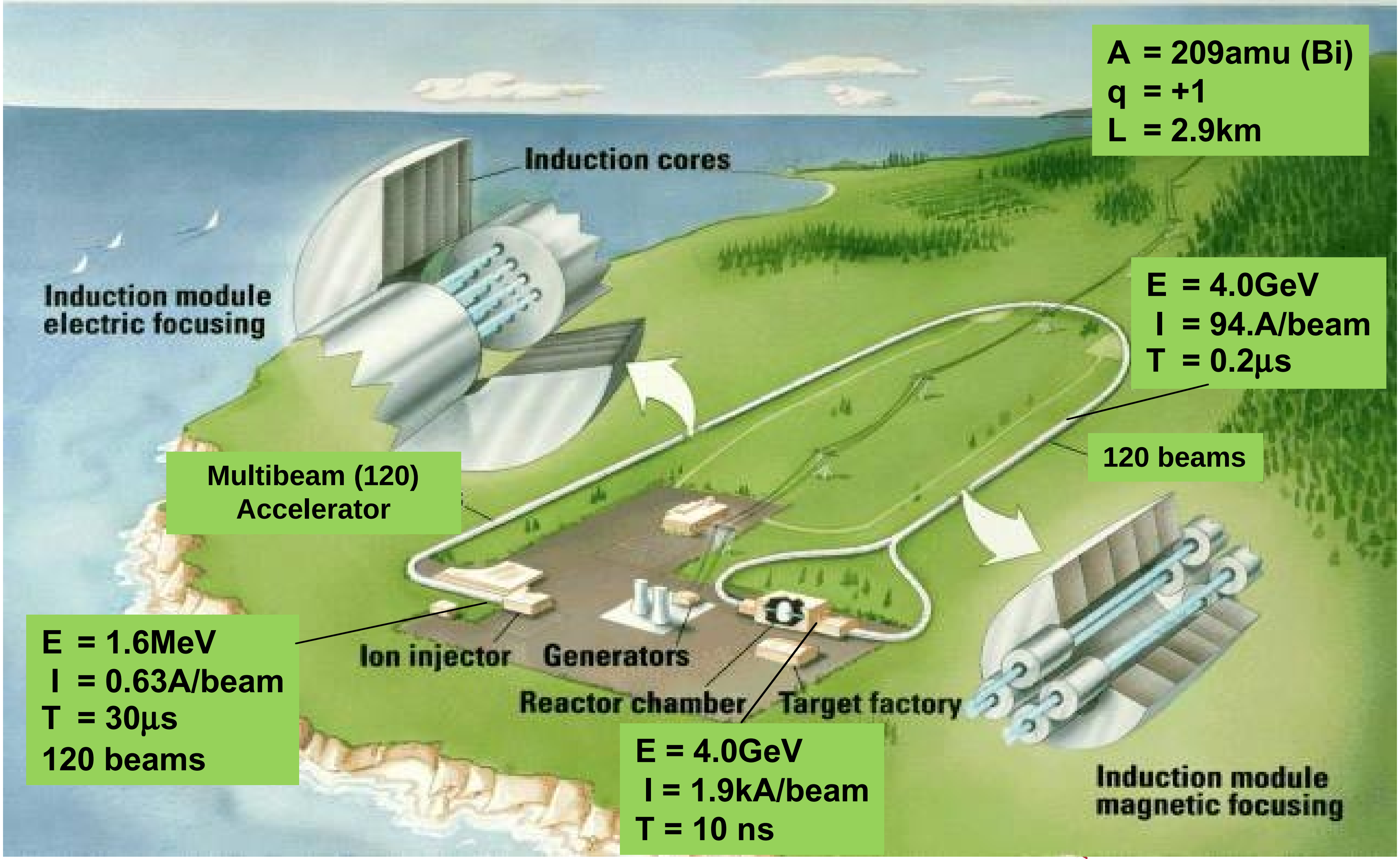
3 - 7 MJ x ~ 10 ns $\Rightarrow$ ***~ 500 Terawatts***

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

Beam charge (3-7 MJ/1-4 GeV) $\Rightarrow$ **few mCoul**



HIF Power Plant Driver – Many high-current beams needed to deliver several Mjoules to target with GeV ions

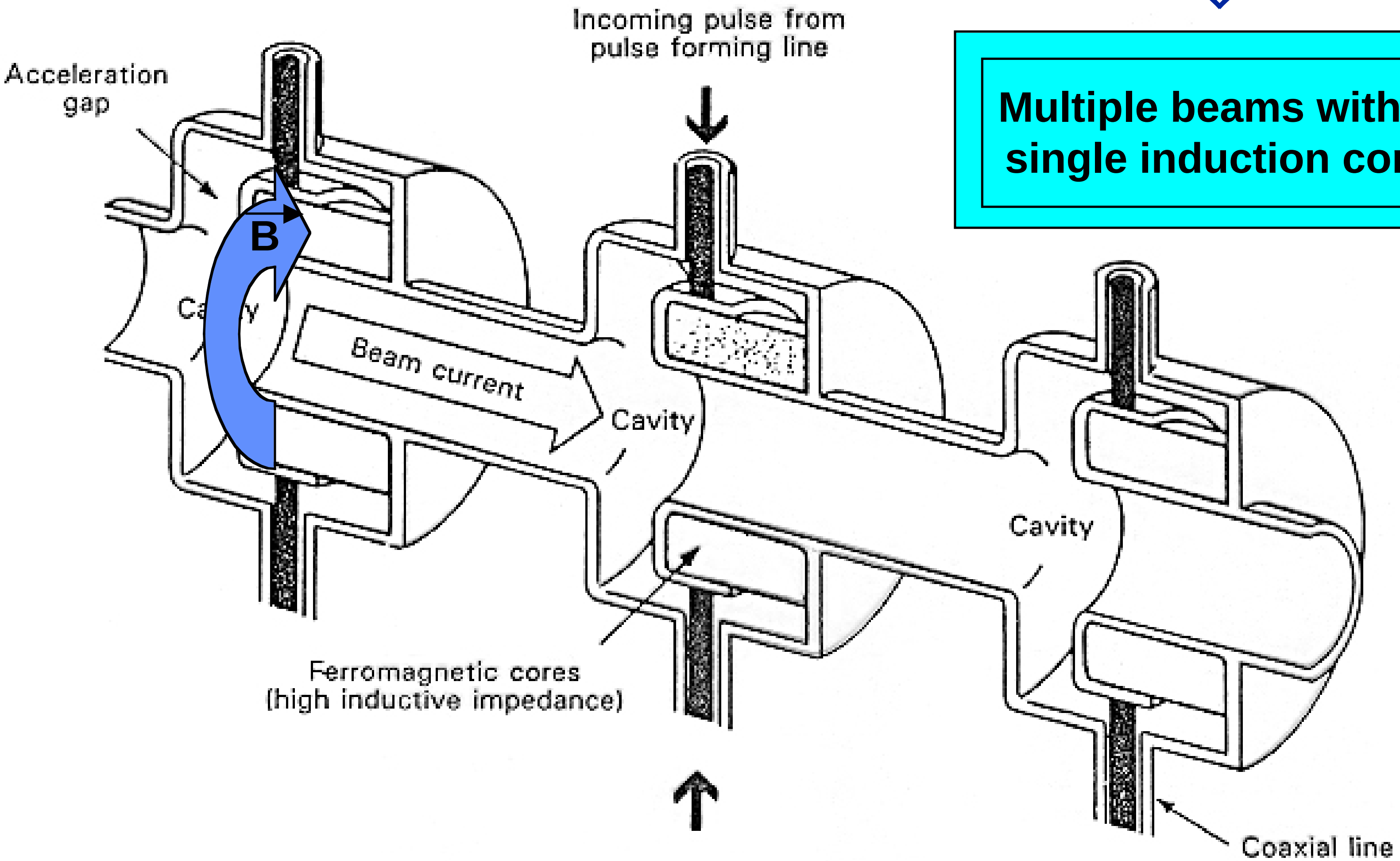


Induction Acceleration can achieve 20-50% efficiency

Efficiency increases as current increases

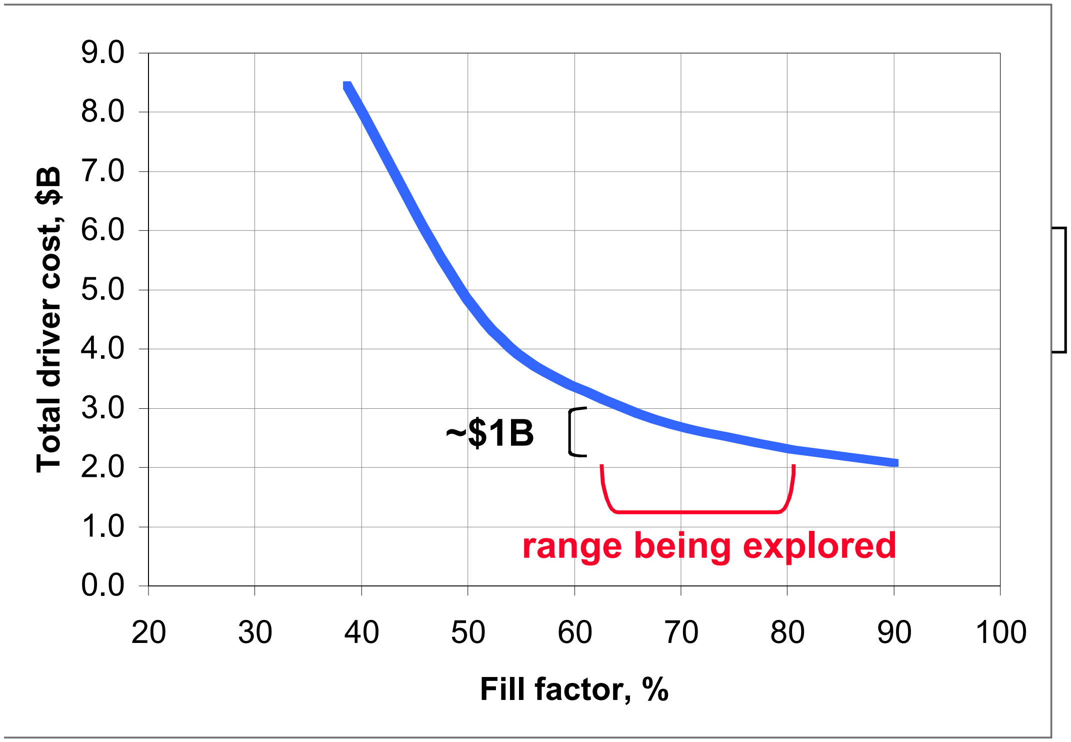
⇓

Multiple beams within single induction core

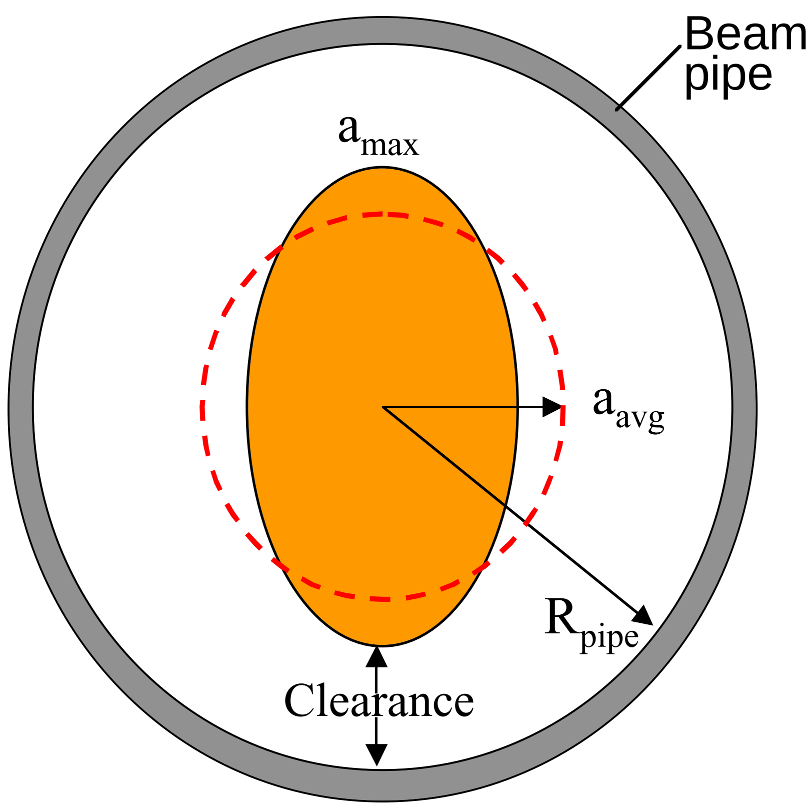


System studies show that driver cost reduced at high fill factor [fill factor may be limited by ECE or desorption]

IBEAM results:



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



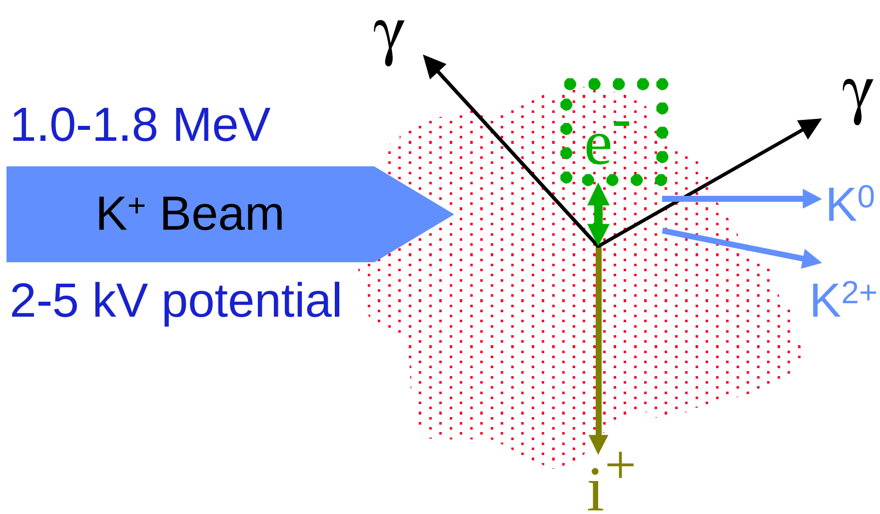
(fixed number of beams, initial pulse length, and quadrupole field strength)

HIF-ECE distinguishing features

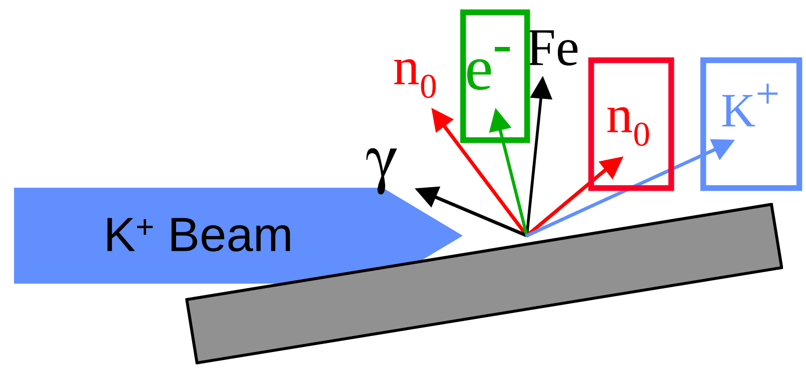
- Economic mandate to **maximally fill beam pipe - ions scrape wall**
- Linac with **high line charge density** (Beam potential ϕ_b > 1 kV)
- Induction accelerator characteristics 0.2-30 μs
  - If beam head scrapes: gas desorbed ($\Gamma_0 \sim 10^3 - 10^4$) and secondary e^- ($\Gamma_e \sim 100$) trapped by rising ϕ_b. **Control of beam head is essential.**
  - If beam flattop scrapes: gas desorbed, SEY not necessarily trapped.
  - If desorbed gas reaches beam: e^- from ionized gas are deeply trapped by ϕ_b, cold ions expelled. **This is expected to be main e^- source in HIF, especially near injection energies (10-100 keV/amu) where atomic cross sections peak ($\sim 10^{-15}$ cm^2).**
  - Electrons are trapped for time to drift through 1 magnet, then expelled.
- Beam-induced multipactor not present
- Trailing-edge multipactor not an issue (≥0.2 s between pulses).

Beam hitting gas or walls creates electrons and gas — these can multiply

Beam on gas, I_b

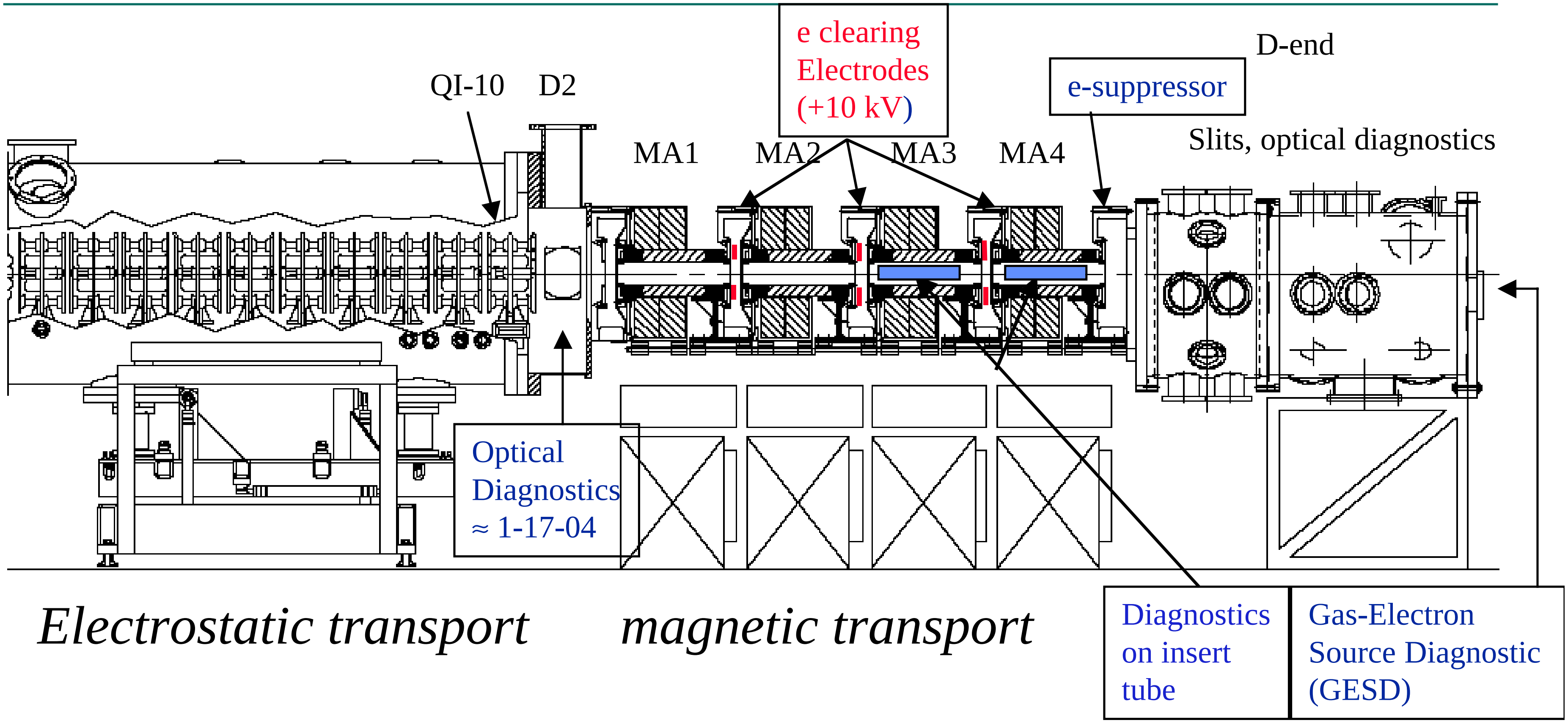


Beam loss to walls, I_{bw}



These interaction products create rich opportunities for diagnostics along with problems for diagnostics and beams

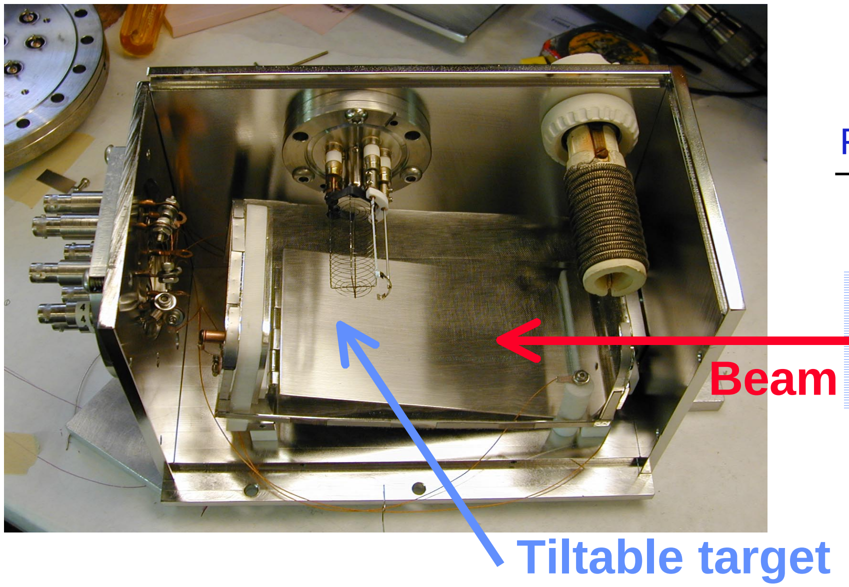
HCX layout for ECE studies in magnetic quads

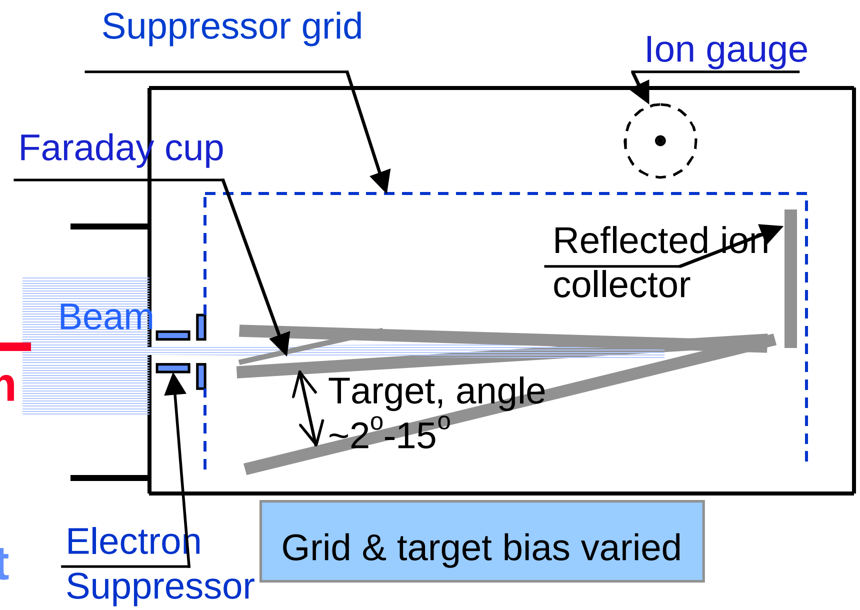


- ECE experiments began with diagnostics mounted on insert tubes within magnetic quads MA3 & MA4.
- Later experiments removed insert tubes, added electron-suppressor after MA4 and clearing electrodes between magnets.

Measure electron emission Γ_e and gas desorption Γ_0 from 1 MeV K^+ beam impact on target

Gas, electron source diagnostic (**GESD**)



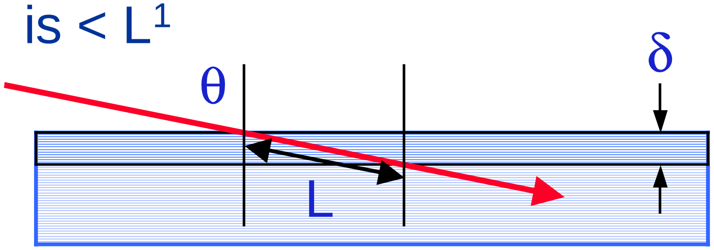


- Measure coefficient of electron Γ_e and gas emission Γ_0 per incident K^+ ion.
- Calibrates beam loss from electron currents to flush wall electrodes.
- Evaluate mitigation techniques: baking, cleaning, surface treatment…
- Measuring scaling of Γ_0 with ion energy – test electronic sputtering model

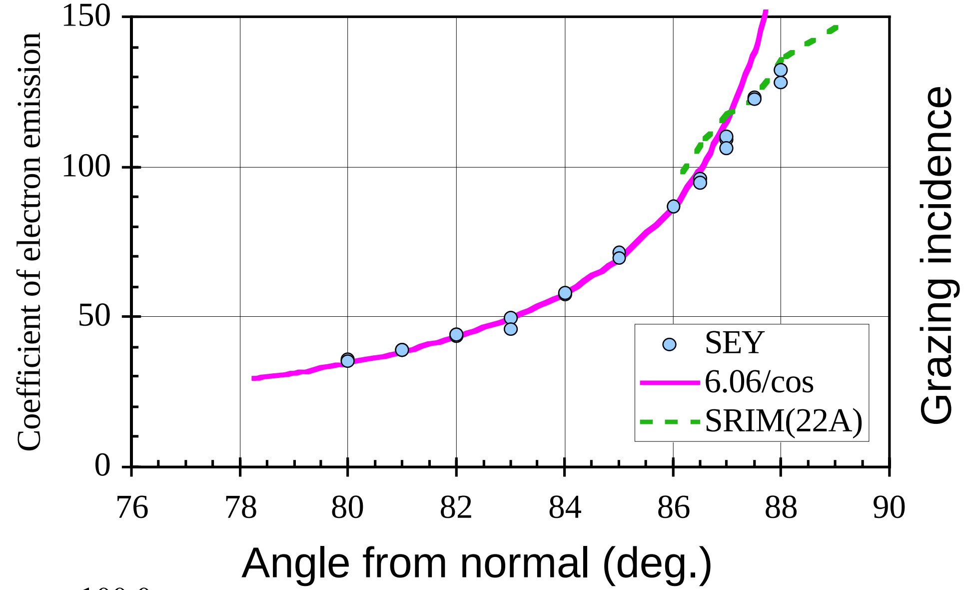
GESD secondary electron yield (SEY) varies with $\cos(\theta)^{-1}$, secondary energy T_e = 30 eV

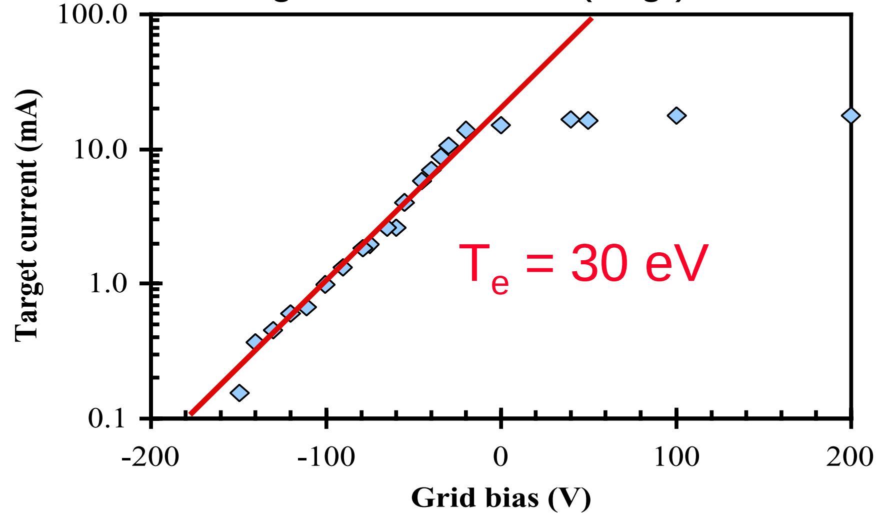
- Simple model gives $\cos(\theta)^{-1}$
  - Delta electrons pulled from material by beam ions (dE/dx)
  - Electrons from depth > δ (δ~ few nm) cannot leave surface
  - Ion path length in depth δ is L.

    $L = \delta / \cos(\theta)$
- Results depart from this near grazing incidence where the distance for nuclear scattering is < L[1]



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

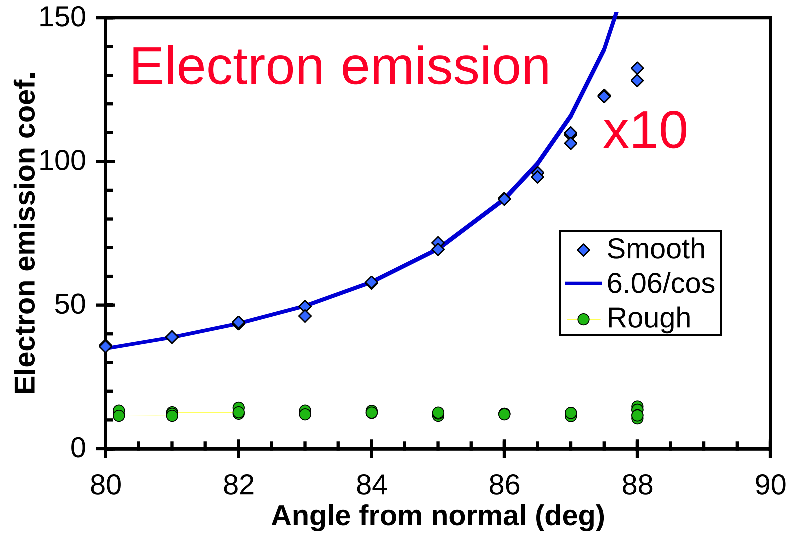


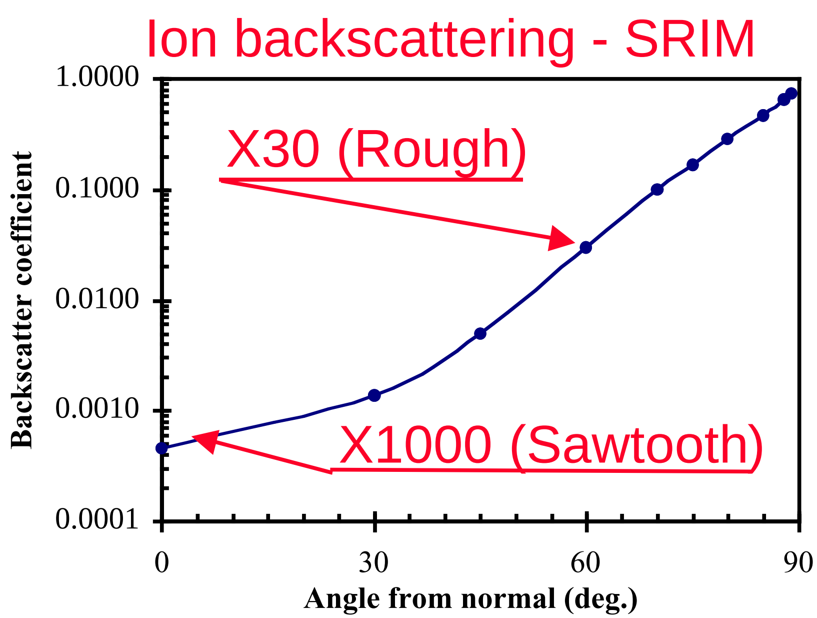


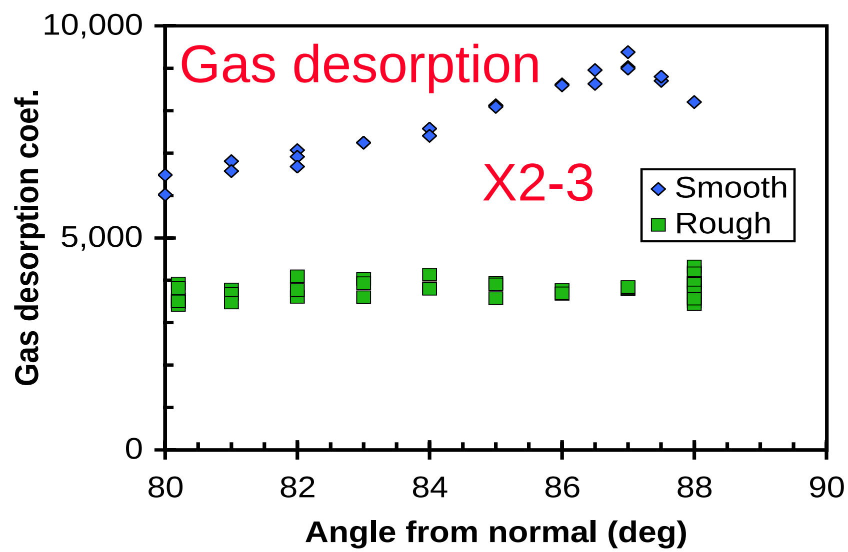
1. P. Thieberger,A. L. Hanson, D. B. Steski, et al., Phys. Rev. A 61, 42901 (2000).

Rough surface mitigates ion-induced electron emission, gas desorption, and ion scattering

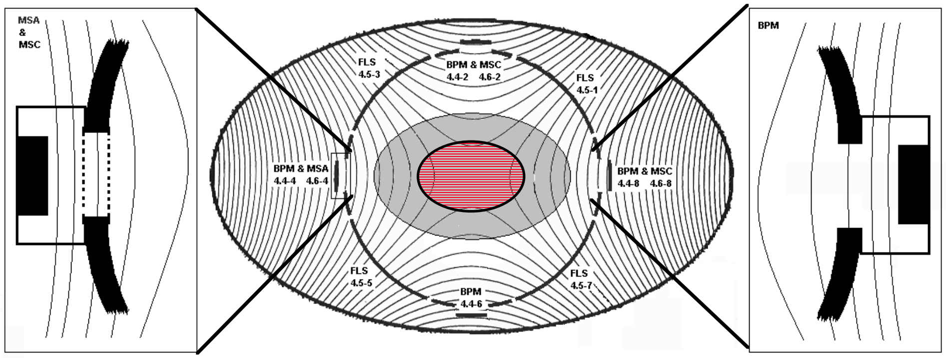
- Surface roughened by glass-bead blasting (Inexpensive, but can warp surface)
- Angle of incidence: grazing ⇒ ~60º [from 1/cos emission]
- Sawtooth surface (CERN-SPS) more effective, but more expensive.

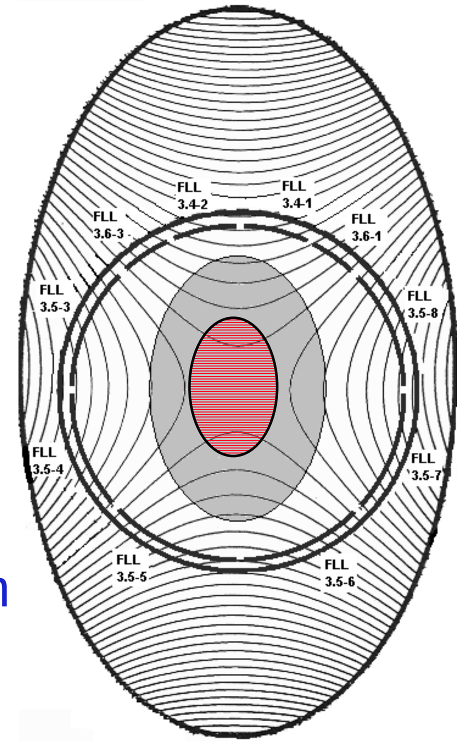






Electron studies in magnetic quads —Initial studies with diagnostics mounted on 5.5 cm diameter tube in quad.





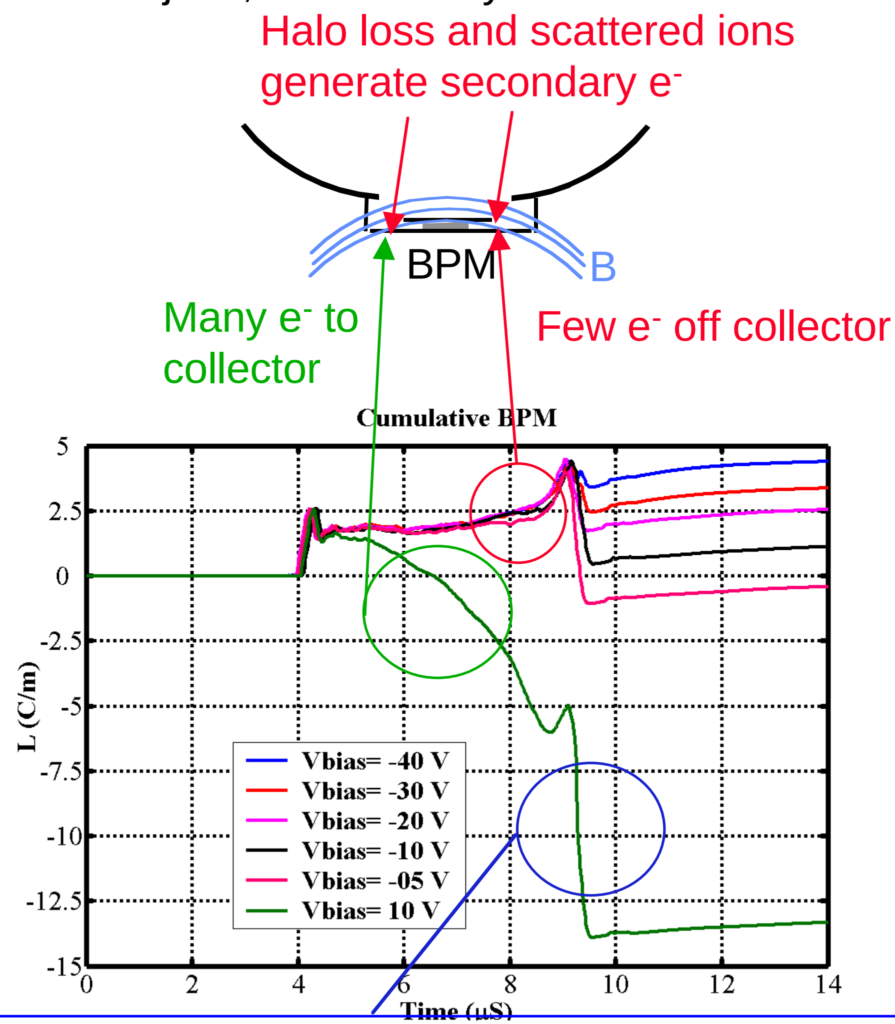
- 180 mA full beam – scraped cylindrical diag. tube
  - Diagnostics difficult to interpret
- 15-25 mA apertured beam, mostly not scraping wall
  - Capacitive probes measure ϕ_b (With apertured beam signals approximate expectations $\Rightarrow n_e \leq n_b$)
  - Flush probes (right) measure secondary electron emission, from which we infer beam loss and gas desorption.

Goal — measure accumulation of electrons and gas

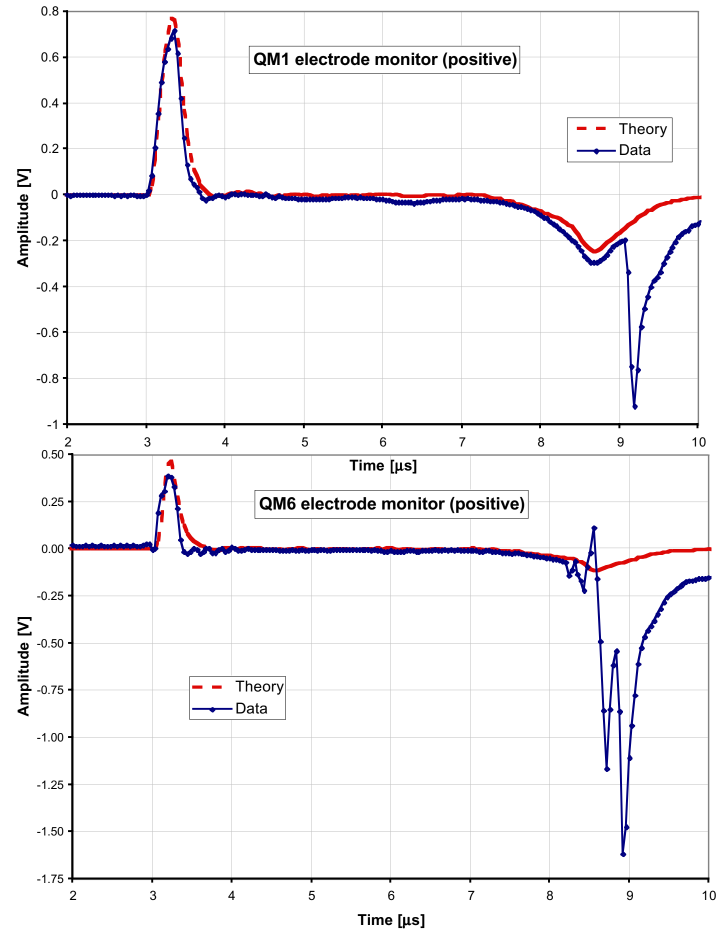
- This may require diagnostics functioning with electrons / gas present.
- Develop mitigation techniques to increase performance.

Puzzle solved: negative spike at end-of-pulse varies with bias on BPM, caused by SEY from beam loss

Joel Fajans, UC Berkeley – not confinement!



ESQ currents (capacitive pickup) match $dI_{Rogowski}/dt$ except for burst at end of pulse [L. Prost, Ph.D thesis]



Loss of 0.6% of beam can produce e- pulse at tail

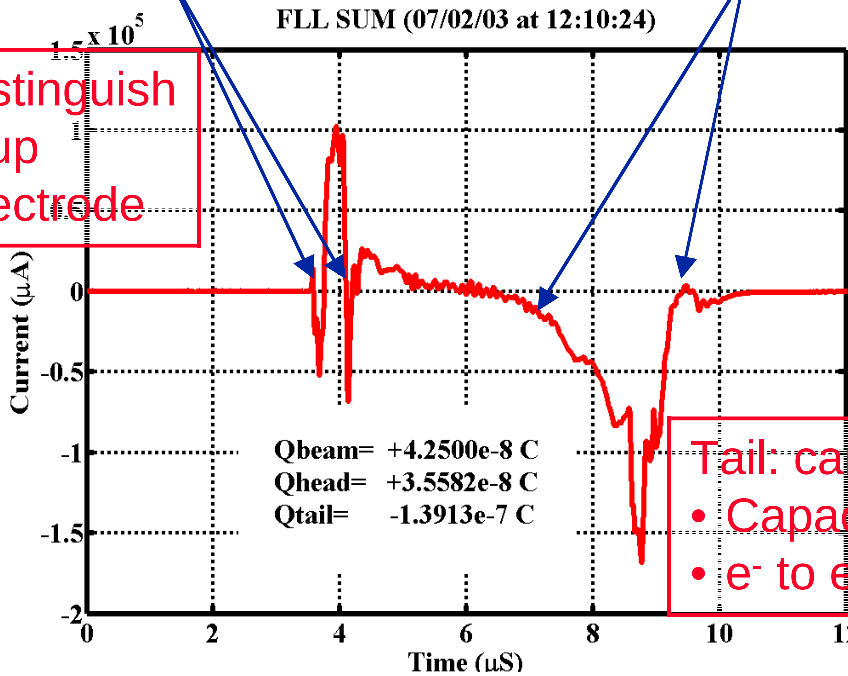
Integrated charge to flush full-length collectors in quad magnets – ok at head, but tail?

$Q_{beam} \equiv \lambda(\mu Coul/m)\, l$ = Beam charge within magnet of length l

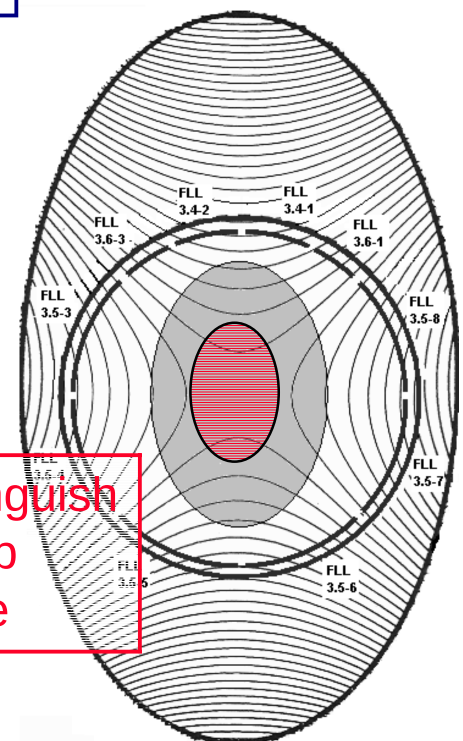
$Q_{head} \approx (0.8\text{-}1.0)\, Q_{Beam}$

$Q_{Tail} \approx 3 \times Q_{Beam}$ – *Why?*

Head: can't distinguish
- Capac. Pickup
- SEY from electrode



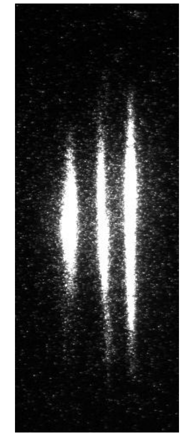
Tail: can't distinguish
- Capac. Pickup
- e^- to electrode

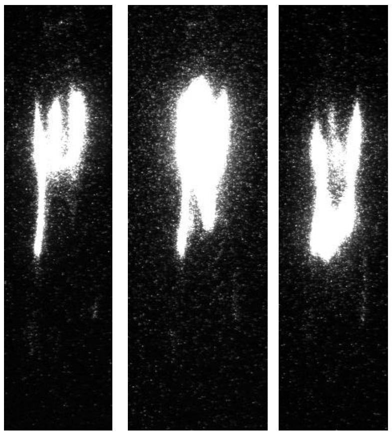


Gradual growth of negative signal: Measured Q can't exceed Q_{beam} unless electrons supplied from outside this beam tube.

Progress towards high quality beam transport – electron effects only part of picture

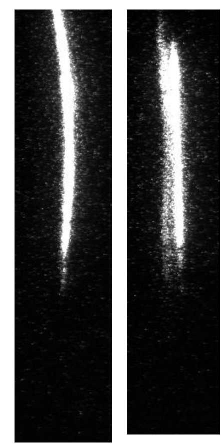
- Beam split into 3, going through a 5.5 cm diam. circular bore (Imaged on scintillator, after beam passes through a slit)





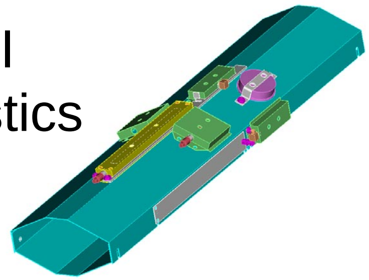
- Slight improvement from opening bore to 6 x 10 cm elliptical bore without suppressor.
- 3-shots shown: still not reproducible.

- Electron suppression added between quad. magnets and scintillator – blocks secondary electrons ⇒ trifurcation an ECE
- Scintillator image of beam through a slit is much cleaner
- Quad magnetic field errors: harmonics ≤1%, ≤1mm, ≤1° (?)
- Simulations predict retuning of electrostatic and magnetic quads will eliminate beam loss.

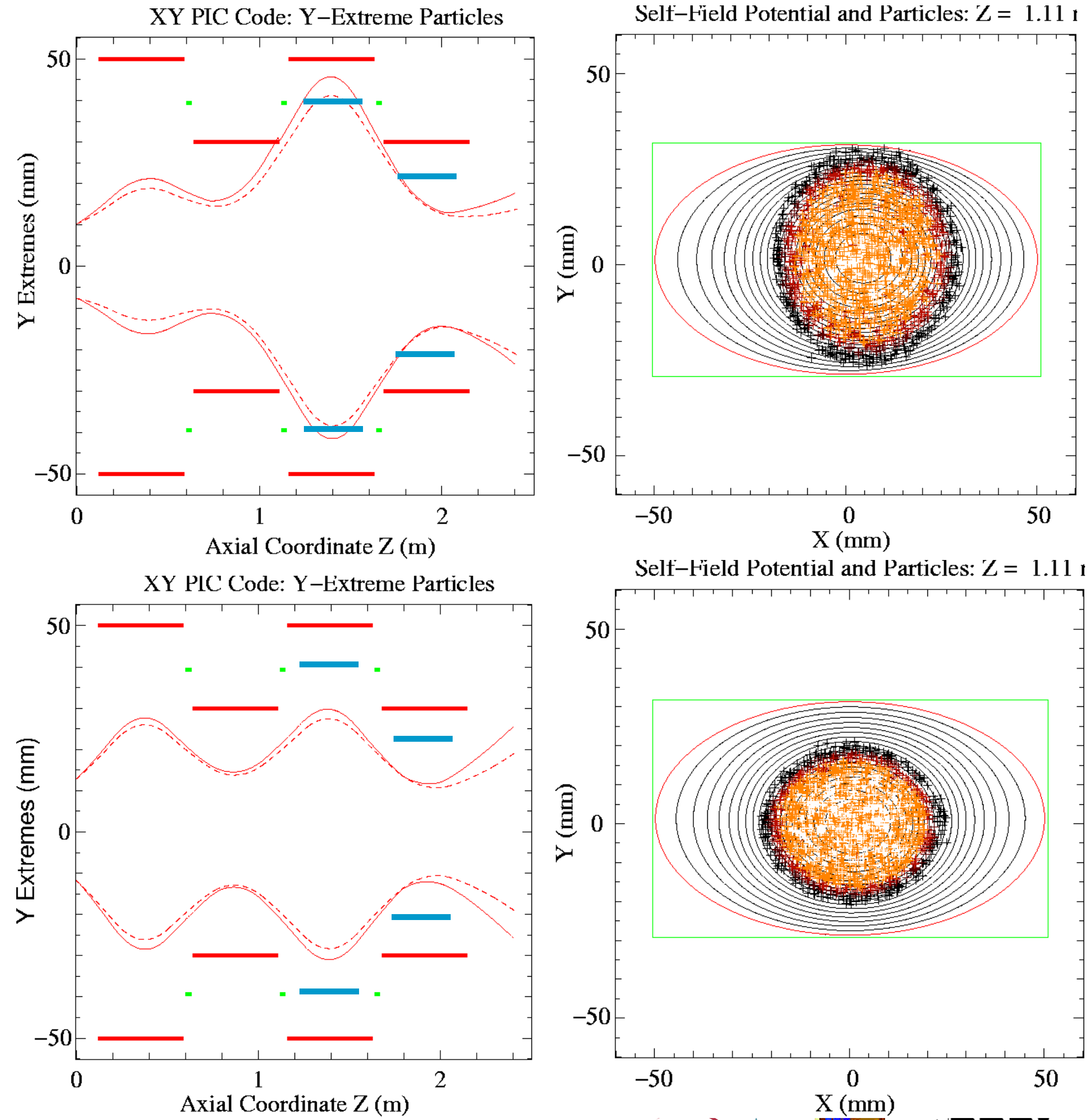


Simulations: centering beam and minimizing envelope changes reduces halo growth*

Phase-II diagnostics



- Elliptical-quad-magnet beam tube ——
- Diagnostic tube-II ——
- Dashed red lines from envelope code, solid from XY PIC Code – PIC shows larger excursions
- Retuning required upstream to match into magnets.

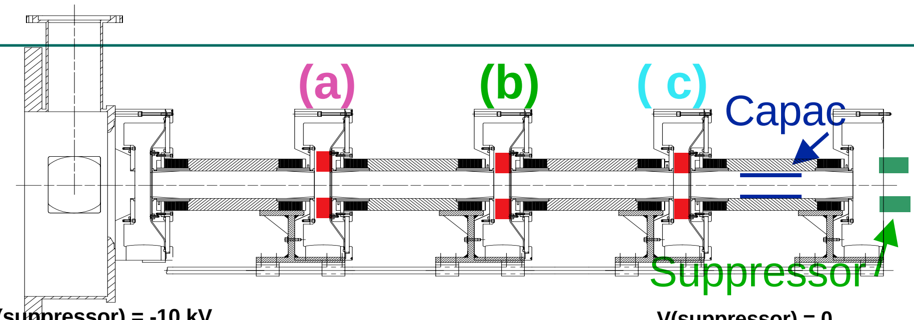


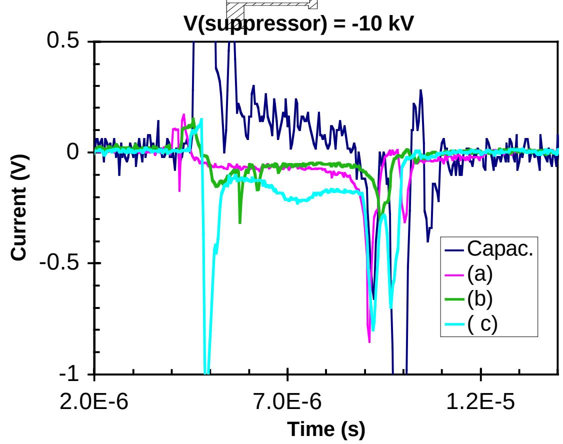
*Steven Lund, private communication 2004.

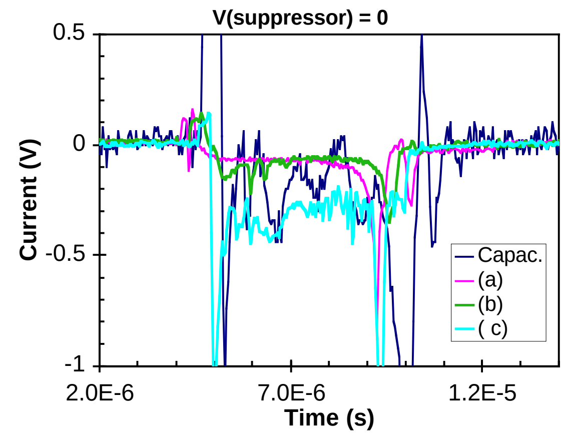
New tools: suppressor ring, clearing electrodes between quads

- Suppressor blocks electrons from quads – improves beam quality
- Clearing electrodes work: upstream indep. of down-stream changes
- Measure drift velocity of e$^-$?

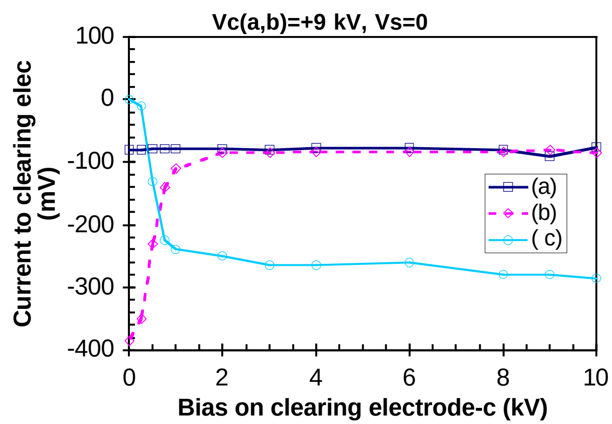
$$\frac{v_e}{v_b} = \frac{2I_e}{I_b} = 0.14$$

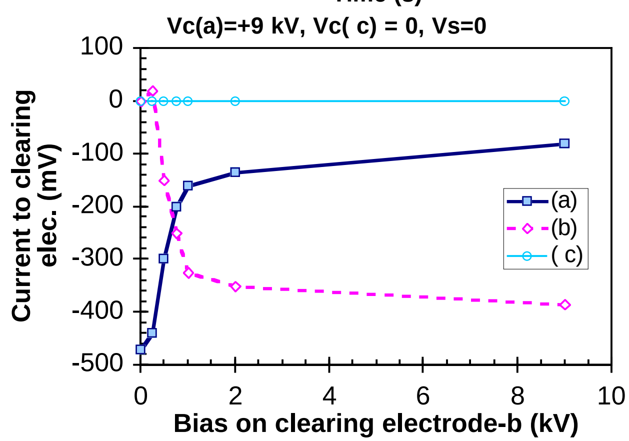






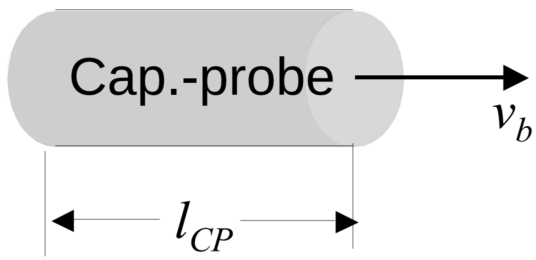
- Capac. electrode: polarity varies with V_s
- Can suppressor reduce e$^-$ to reproducible trickle?





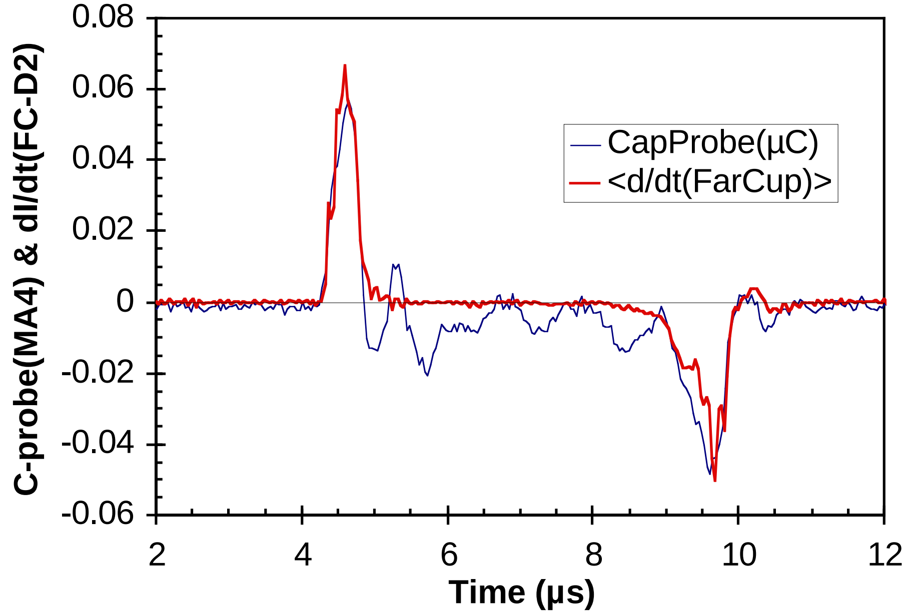
Compare capacitive electrode (MA4) with time-derivative of beam current (Faraday cup)

Head – Consistent with electrons ≤13% of beam charge.



$$\frac{d(I_b)}{dt} = \left(\frac{\Delta I(t+0.12\mu s)}{\Delta t} + \frac{\Delta I(t)}{\Delta t}\right)\frac{l_{CP}}{2v_b}$$

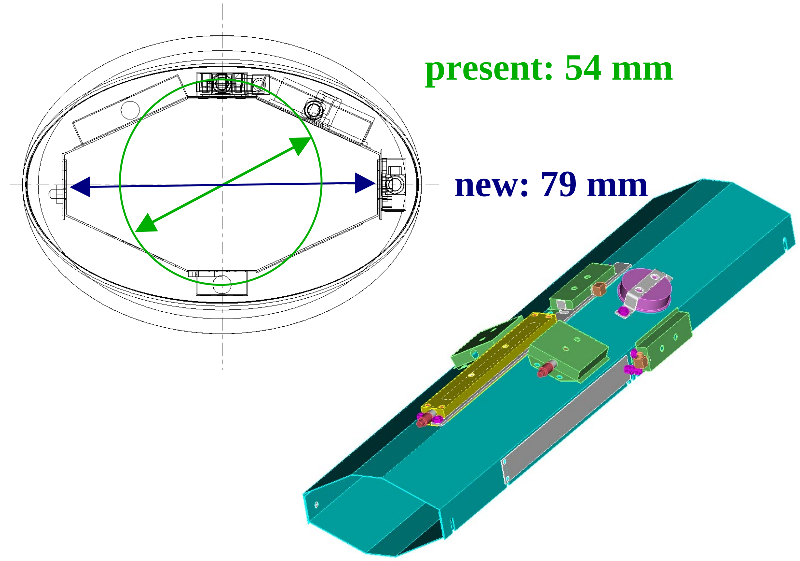
where $l_{CP} \approx 0.12$ s (v_b)



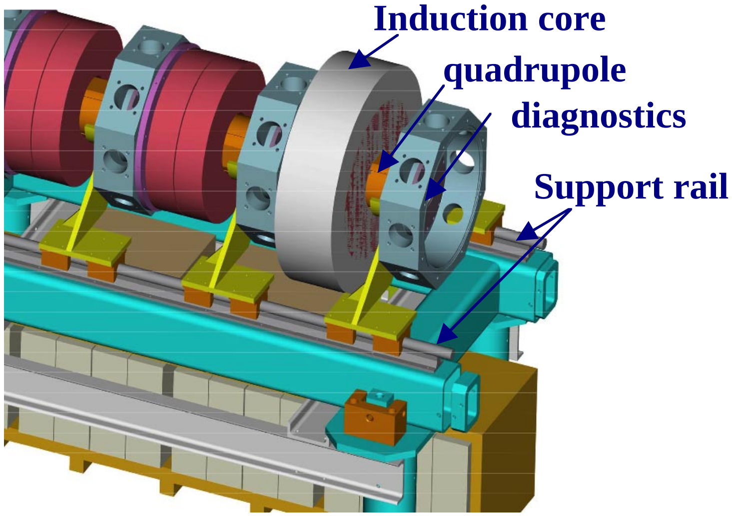
	C-electrode (μCoul)	dI/dt(FC) (μCoul)	Fraction e-
Head	**0.020**	**0.023**	**0.13**
Tail	**-0.033**	**-0.022**	**?**

Near-term upgrades to ECE experiments on HCX

Mid-FY04: New octagonal diagnostic tubes approximate elliptical shape to pass larger beams without scraping walls – study full beam without aperturing.



Later-FY04: Addition of induction cores between magnets: can accelerate electrons in gap to energy $E_e > \phi_b$. They will be lost to wall in upstream magnet.



HIF-ECE Experimental Summary/conclusions

ECE (mostly from desorption) likely to influence allowable fill factor, and therefore cost of HIF Driver for power plant.

- Gas desorption Γ_0 large – testing electronic sputtering model
- Rough surface reduces emission, desorption, & scattering.
- Beam transport through 4 magnetic quads, with high fill factor – ok. Progress in understanding diagnostic signals.
- Simulation plays significant role in improving performance.

- Electron suppressor necessary at magnet exit.
- Clearing electrodes remove electrons in drift region.

new tools for ECE in linacs

Backup material

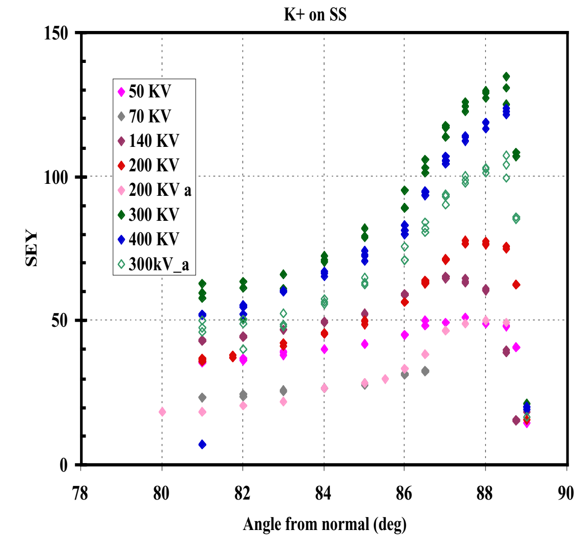
HIF-ECE distinguishing features

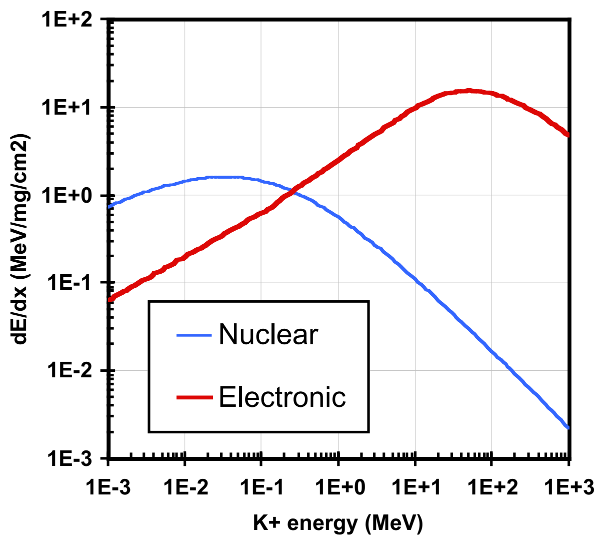
- Economic mandate to **maximally fill beam pipe - ions scrape wall**
- Linac with **high line charge density** (Beam potential ϕ_b > 1 kV)
- Induction accelerator characteristics 0.2-20 µs
  - Long (ish) pulse duration 0.2-20 µs [Time for desorbed gas to reach beam and be ionized? But no beam-induced multipactor]
  - 5 Hz rep. rate [time to pump desorbed gas?]
  - >50% of length at injector occupied by quadrupoles, $v_{e\text{-drft}} < v_{e\text{-thermal}}$
  - Ionized gas e^- are born trapped, e^- from wall may not be trapped
  - Multiple beams and frequent accel gaps [Pump gaps or cold bores?]
  - Large neutral desorption coefficients at pipe wall (Γ_o~10^3 - 10^4)
  - Injection energies near peak atomic cross-sections [10-100 keV/amu]
- Heavy-ions – stripping cross sections $\sigma \propto E^{-0.5}$, $\sigma v \propto E^0$; don't win at high energy like proton accelerator where $\sigma \propto E^{-1}$

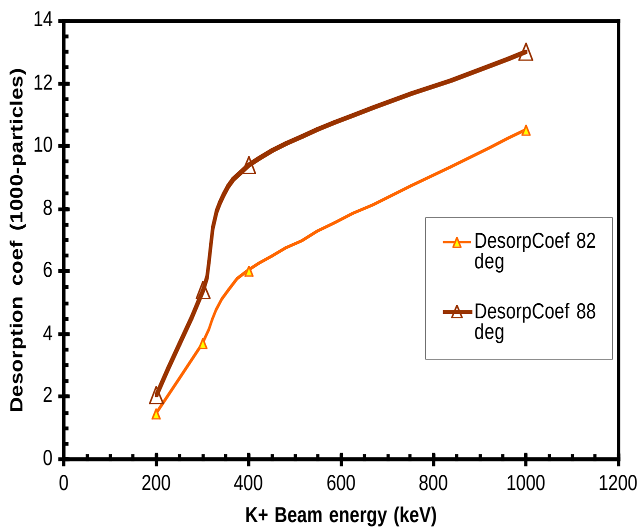
In search of a mechanism for gas desorption

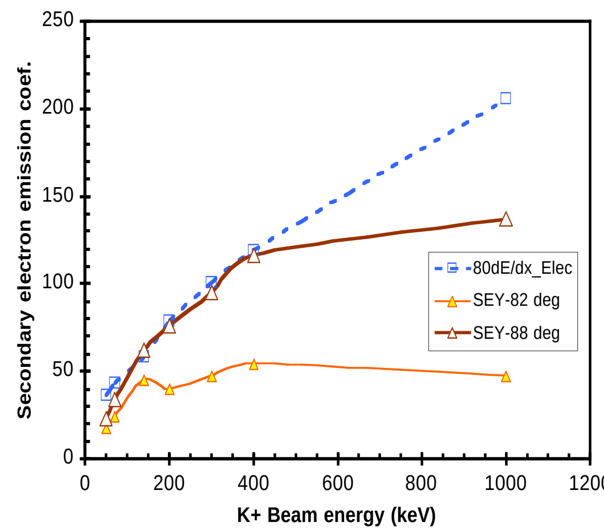
- SEY = secondary emission coef.
- Γ_0 = Gas desorption coef.
- Γ_0 scales with dE/dx(elec) for electronic sputtering
- Improved background subtraction for 300 kV_a

  [Compare open vs. solid green diamonds]
- Experiments and analysis continuing



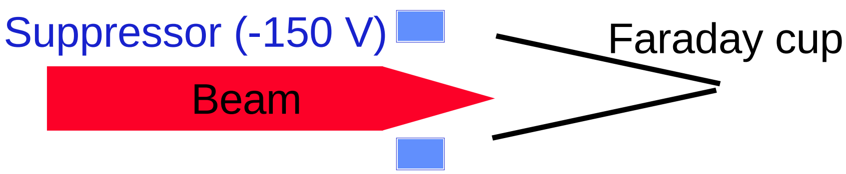


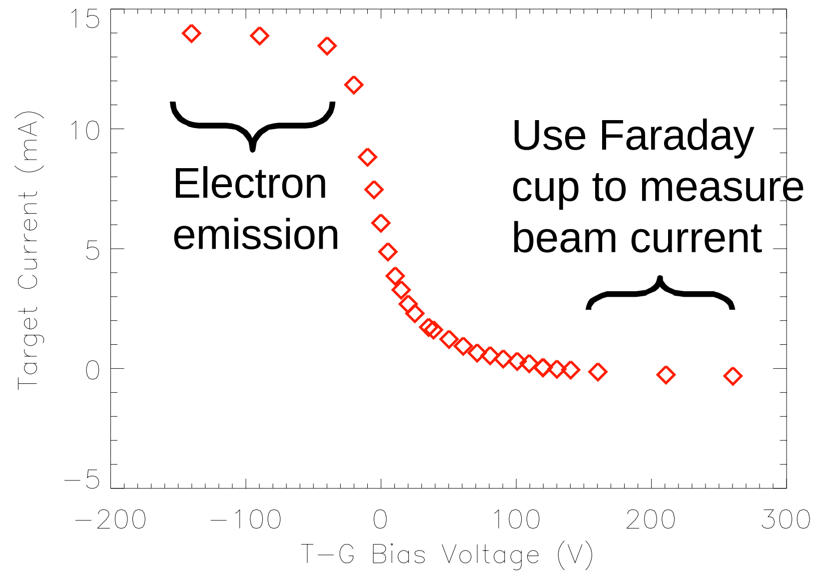


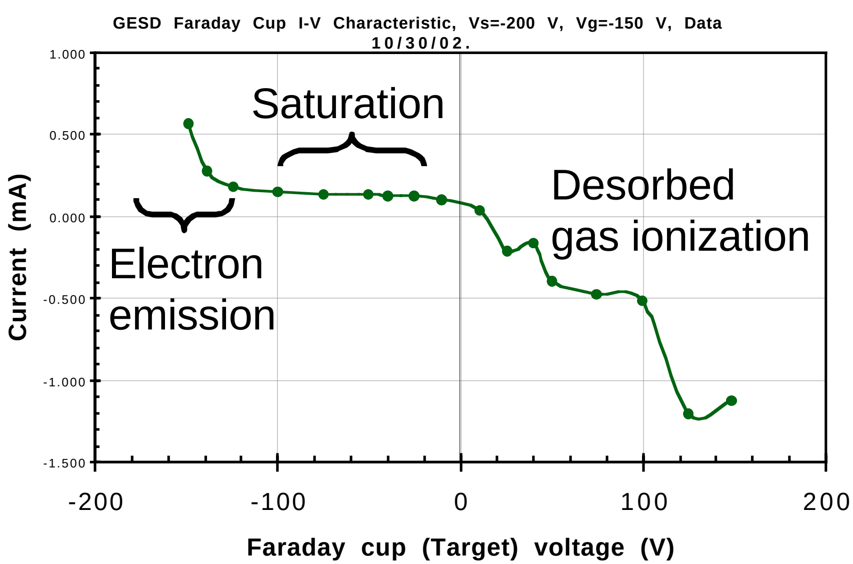


Current-Voltage characteristics of GESD Faraday cup and target, indicate reliable current measurements

- Negative Faraday cup measures beam current into GESD.
- Positive Faraday cup measures electrons from ionization of desorbed gas.







- Saturation of target current indicates reliable measurement of electron emission.
- Electron emission coefficient is ratio of electron emission current to incoming ion-beam current from Faraday cup.