Experimental Studies of Electrons in a Heavy-Ion Beam*

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With contributions from

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OUTLINE

- Introduction to Electron Cloud Effects (ECE) in HIF
- Measurements of gas desorption & electron emission
- New tools to measure e^- and gas in quad magnets

Related Papers

Ron Cohen, "Simulating electron cloud effects in HIF" Th.I-03

Larry Grisham, "Exper. eval. of neg. ion source for HIF Driver" Th.I-04

Frank Bieniosek, "Exper. study of space-charge waves…" Th.P-21

Peter Seidl, "Magnetic field measurements of quads in HCX" Th.P-22

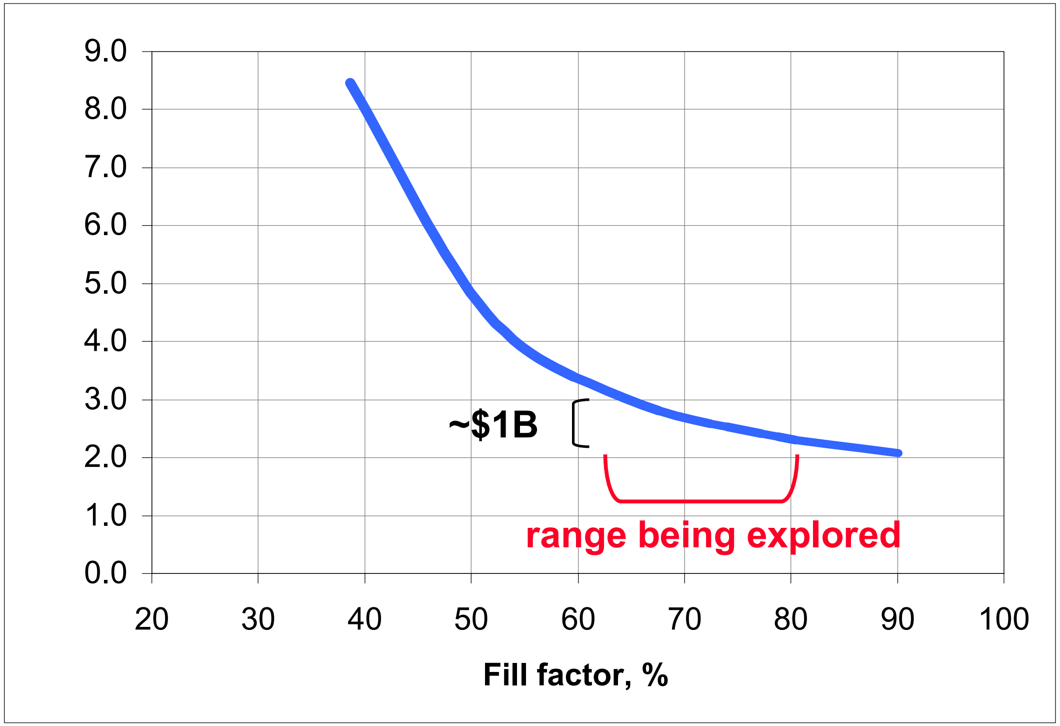
Peter Stoltz, "e^- effects due to grazing coll. … heavy ions and walls" Th.P-25

Shmuel Eylon, "Electron effects in NTX." Th.P-26

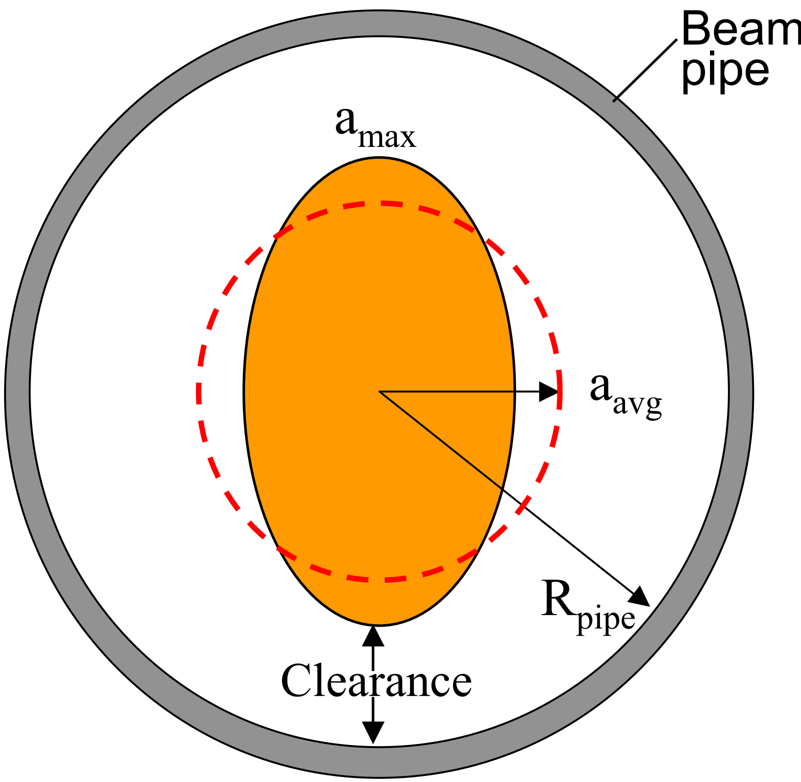
+ numerous neutralized drift compression and final focus papers

System studies show that driver cost reduced at high fill factor – What will limit the fill factor?

IBEAM results[1]:



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

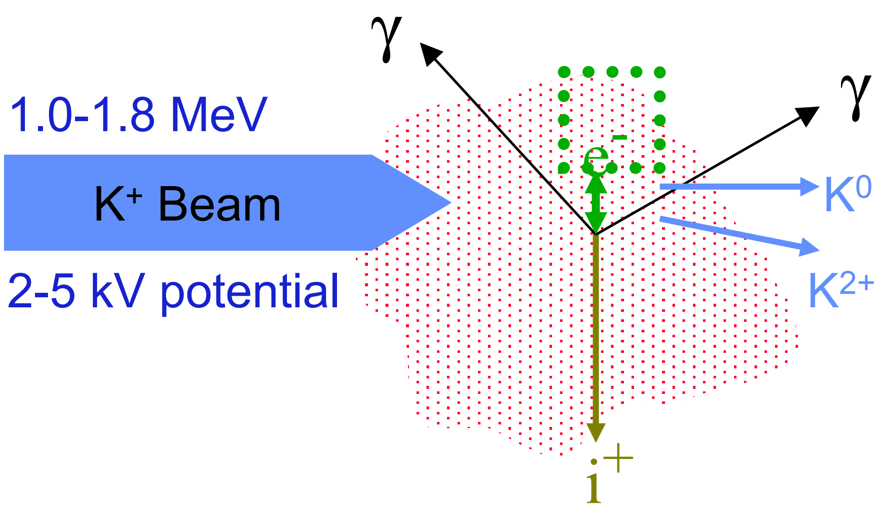


(fixed number of beams, initial pulse length, and quadrupole field strength)

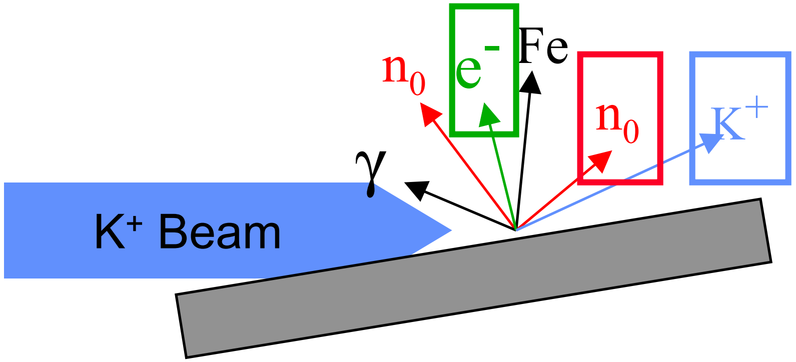
1. Wayne Meier, private communication.

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

Beam on gas, I_b



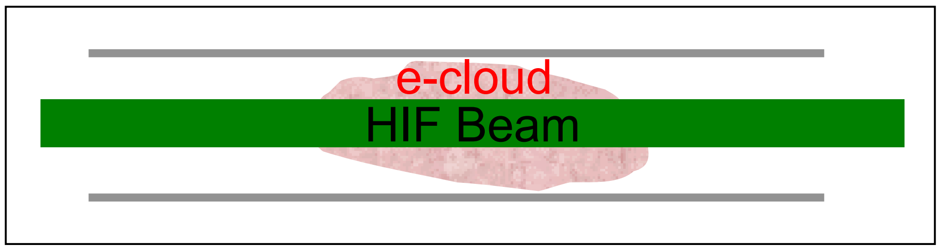
Beam loss to walls, I_{bw}



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

Electron Cloud Effects (ECE) and Pressure Rise may limit fill factor

ECEs are of concern with beams of positively charged particles that electrostatically confine/heat electrons – can limit performance

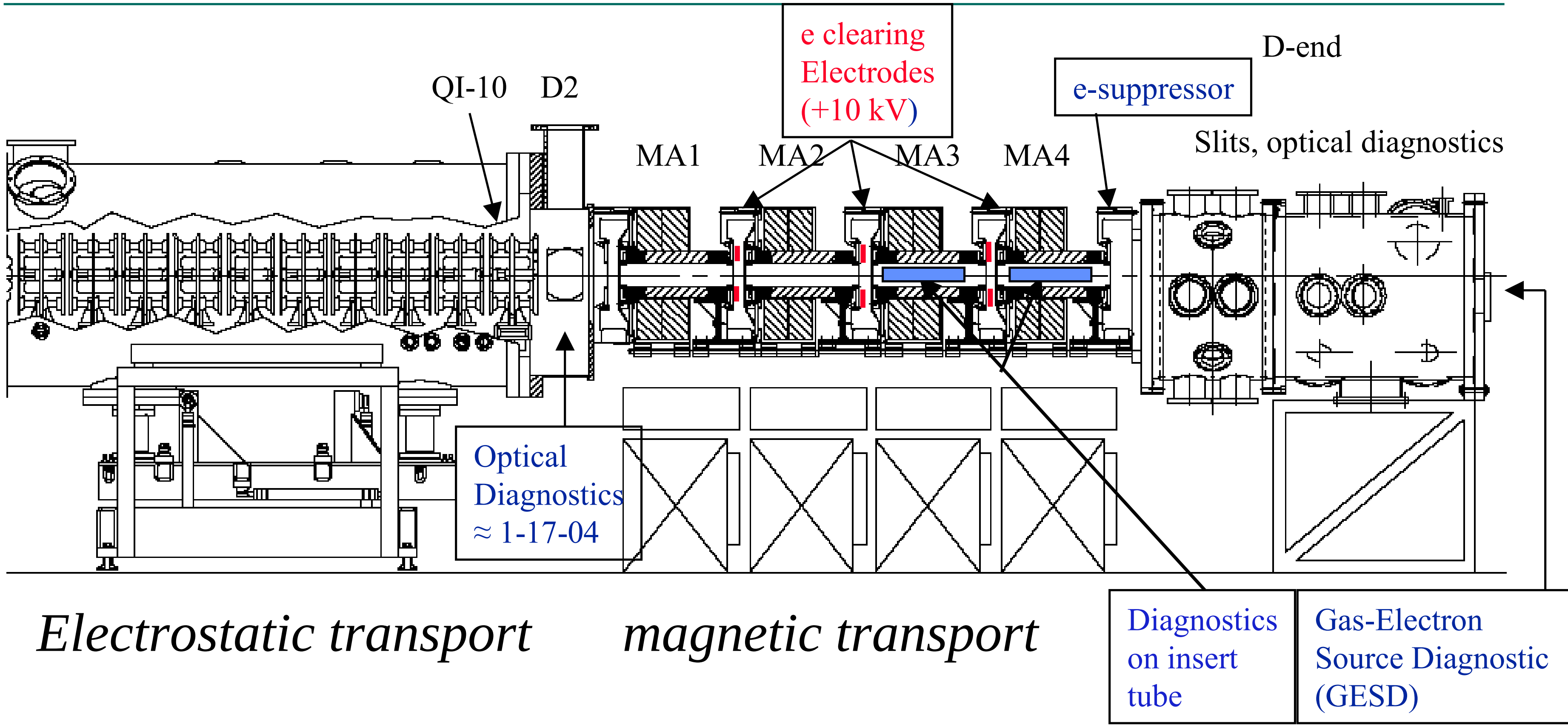


HIF has:

- Economic mandate to maximally fill beam pipe ⇒ ions scrape wall
- Linac with high line charge (Beam potential ϕ_b > 1 kV can trap e^-)
- Induction accelerator characteristics

  - Beam-induced electrons from wall not necessarily trapped, except during rising ϕ_b.
  - Electrons from gas, ionized by beam, are born deeply trapped
  - Acceleration gap detraps electrons: kinetic energy >> ϕ_b .

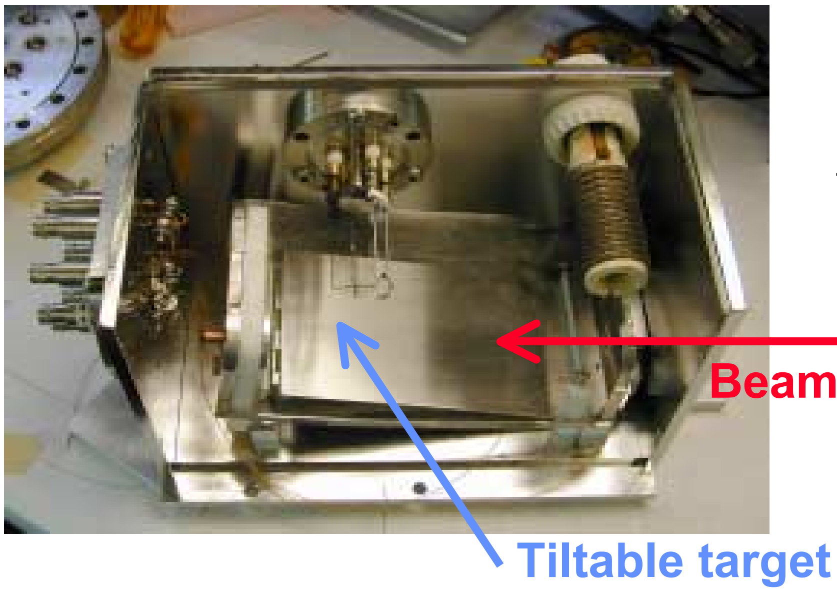
HCX layout for ECE studies in magnetic quads

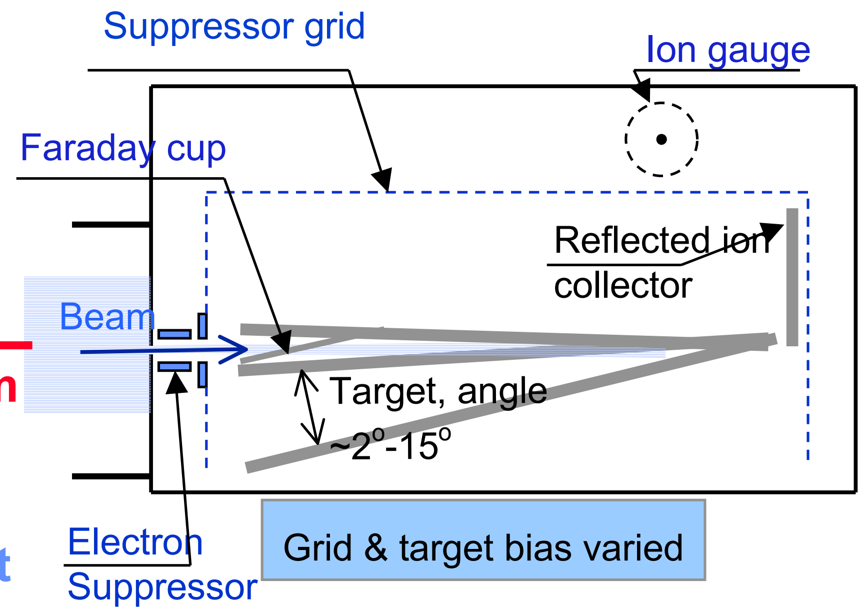


- ECE experiments began with, and has returned to, diagnostics mounted on insert tubes within magnetic quads MA3 & MA4.
- Intermediate experiments added electron-suppressor after MA4 clearing electrodes between magnets, and temporarily removed insert tubes.

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

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



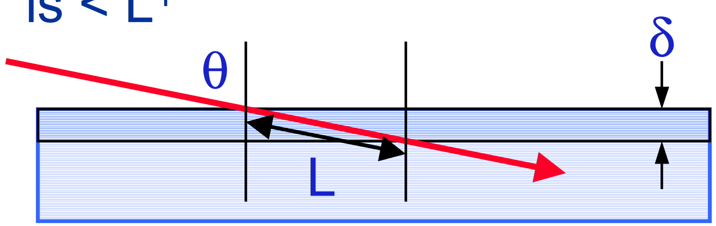


- Measure coefficient of electron Γ_e and gas emission Γ_0 per incident K^+ ion.
- Calibrates beam loss from electron currents to flush wall electrodes.
- Evaluate mitigation techniques: baking, cleaning, surface treatment…
- Measuring scaling of Γ_0 with ion energy – test electronic sputtering model

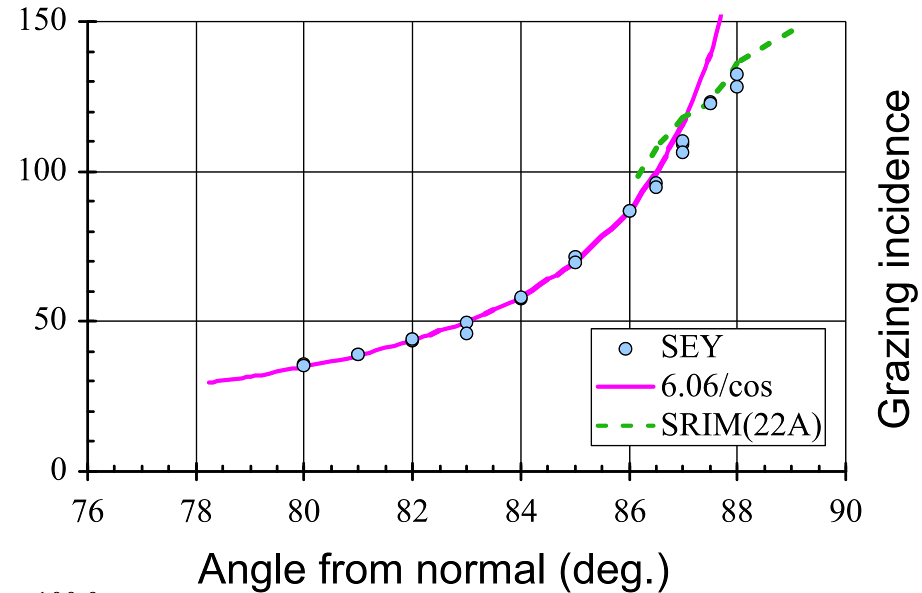
GESD secondary electron yield (SEY) varies with $\cos(\theta)^{-1}$, secondary energy T_e = 30 eV

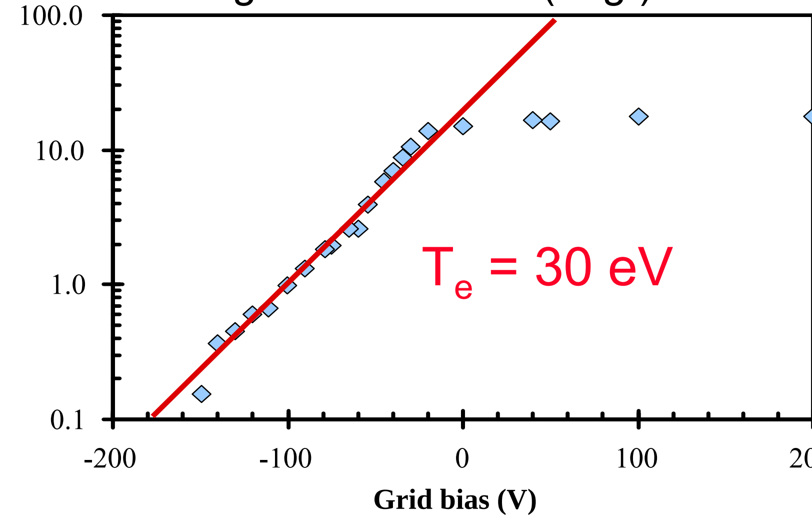
- Simple model gives $\cos(\theta)^{-1}$
  - Delta electrons pulled from material by beam ions (dE/dx)
  - Electrons from depth > δ (δ~ few nm) cannot leave surface
  - Ion path length in depth δ is L.

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



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

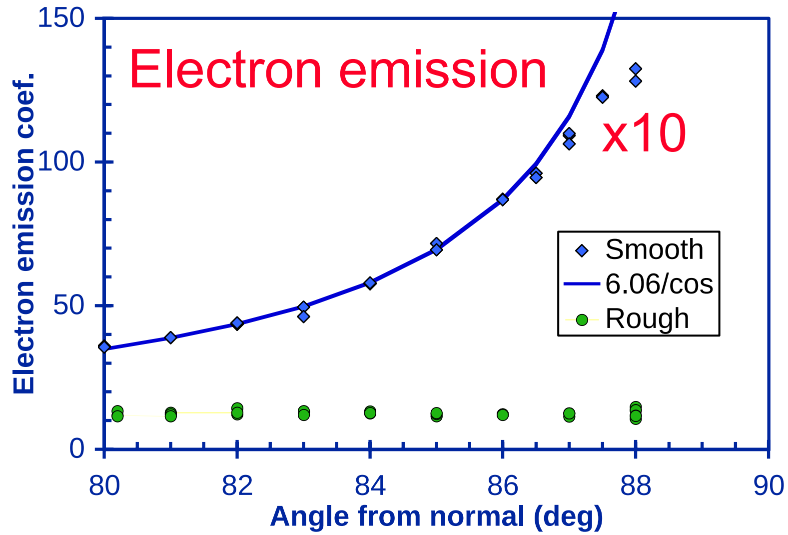


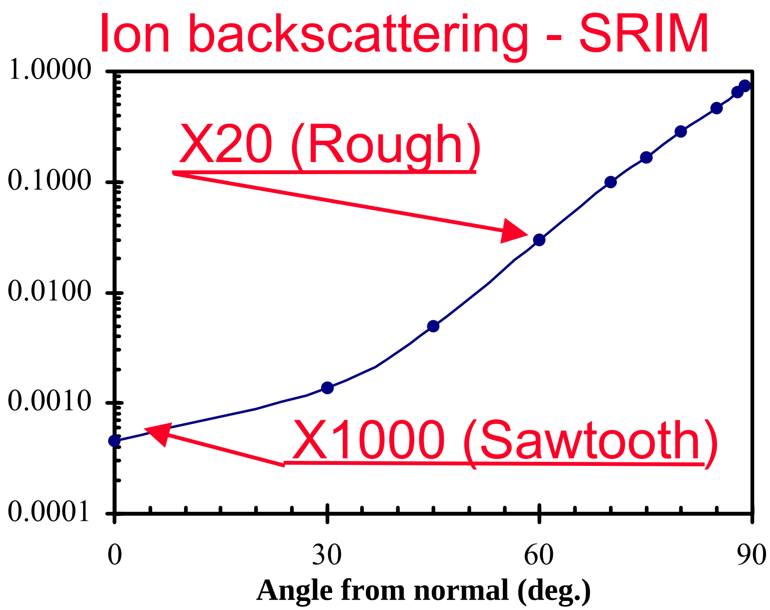


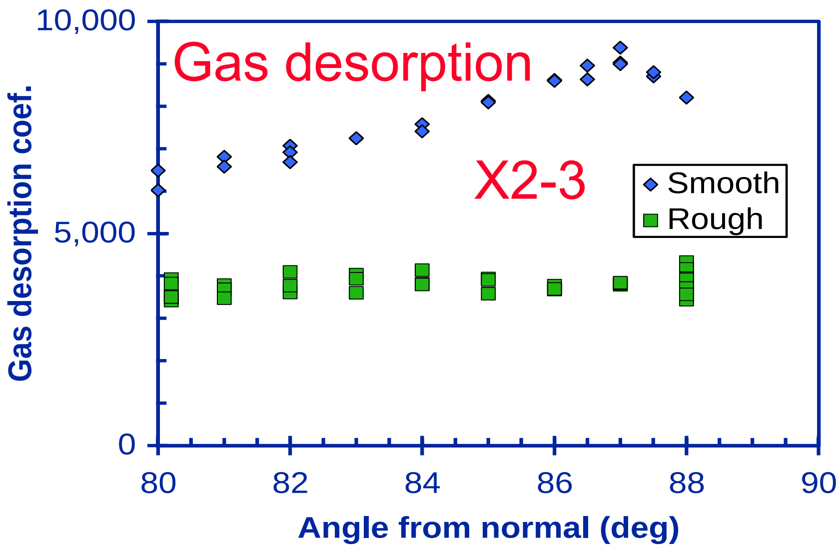
1. P. Thieberger,A. L. Hanson, D. B. Steski, et al., Phys. Rev. A 61, 42901 (2000).

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

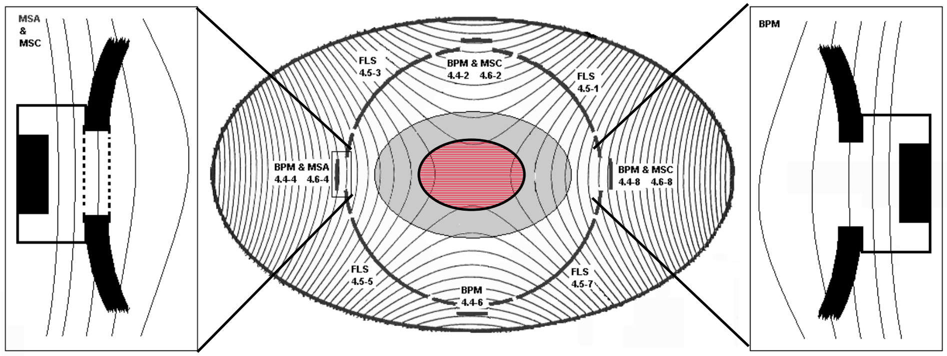
- Surface roughened by glass-bead blasting (Inexpensive, but can warp surface)
- Angle of incidence: grazing ⇒ ~60° [from 1/cos emission]
- Sawtooth surface (CERN-SPS/LHC) more effective, but more expensive.

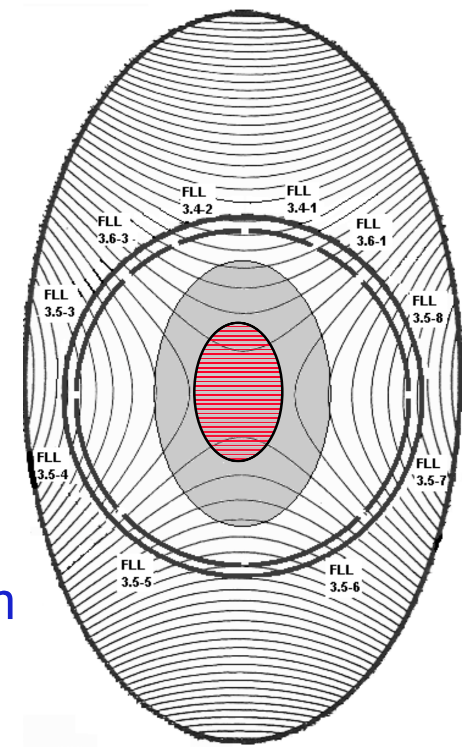






Electron studies in magnetic quads – Initial studies with diagnostics mounted on 5.5 cm diameter tube in quad.





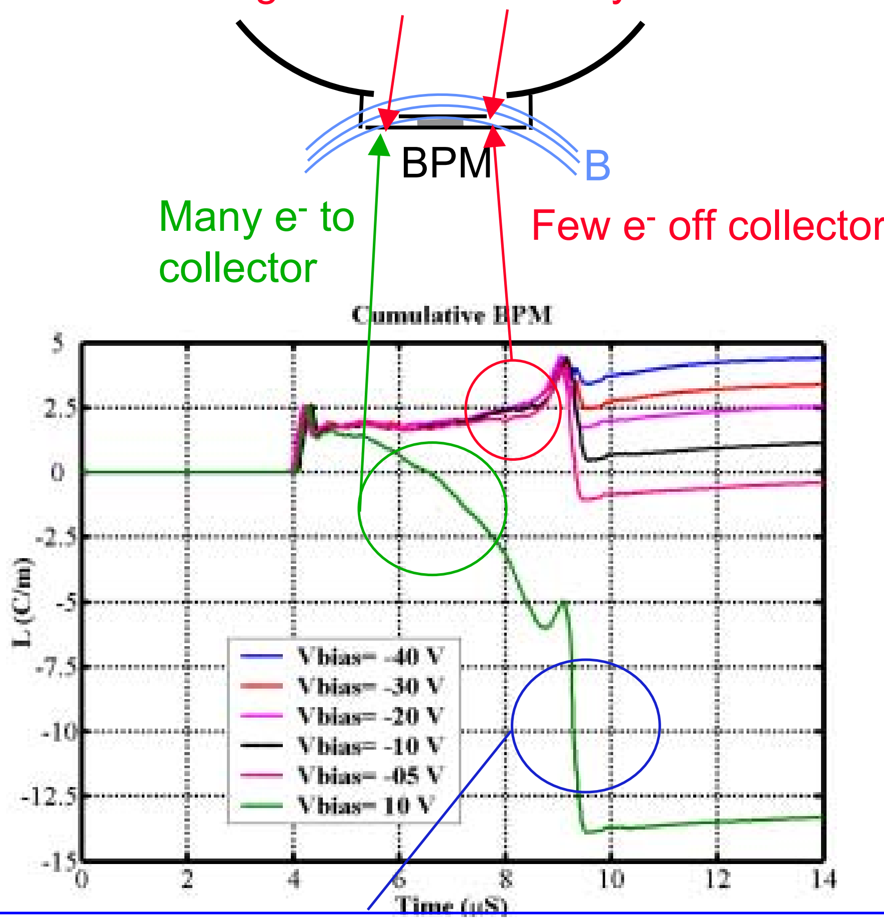
- 180 mA full beam – scraped cylindrical diag. tube
  - Diagnostics difficult to interpret
- 15-25 mA apertured beam, mostly not scraping wall
  - Capacitive probes measure ϕ_b (With apertured beam signals approximate expectations $\Rightarrow n_e \leq n_b$)
  - Flush probes (right) measure secondary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

Goal – measure accumulation of electrons and gas
– Compare with effects on beam

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

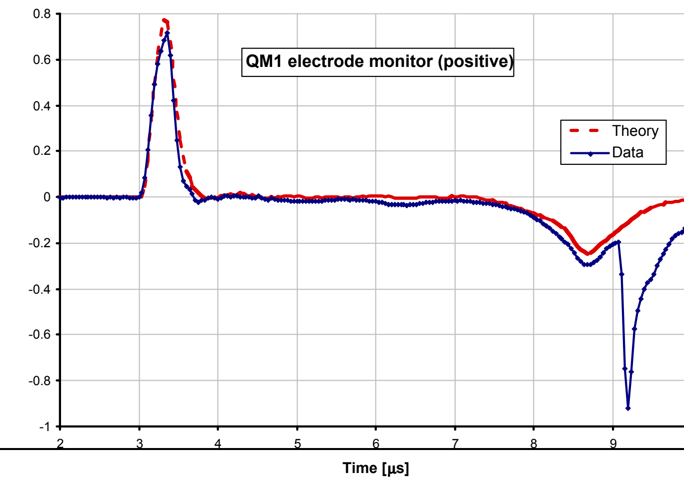
Joel Fajans, UC Berkeley – not confinement!

Halo loss and scattered ions generate secondary e^-



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

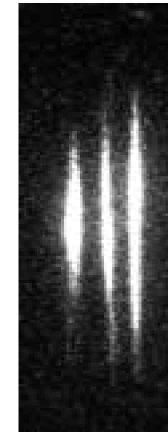
ESQ currents (capacitive pickup) match $dI_{Rogowski}/dt$ except for burst at end of pulse [L. Prost, Ph.D thesis]

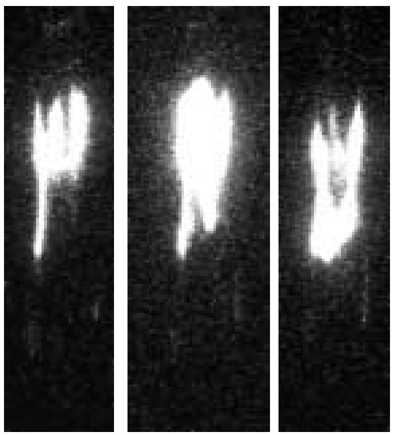


T_e = 20 eV

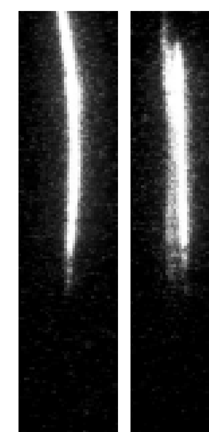
Progress towards high quality beam transport – electron effects only part of picture

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





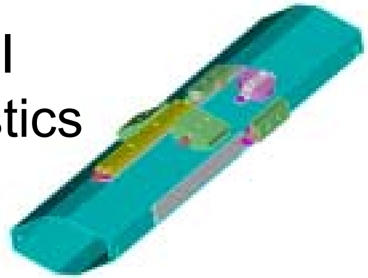
- Slight improvement from opening bore to 6 x 10 cm elliptical bore without suppressor.
- 3-shots shown: still not reproducible.



- Electron suppression added between quad. magnets and scintillator – blocks secondary electrons ⇒ trifurcation an ECE
- Quad magnetic field errors: Peter Seidl – **Th.P-22**
- Simulations predict retuning of electrostatic and magnetic quads will eliminate beam loss.
- Beam envelope similar with or without Phase-II diag. installed.

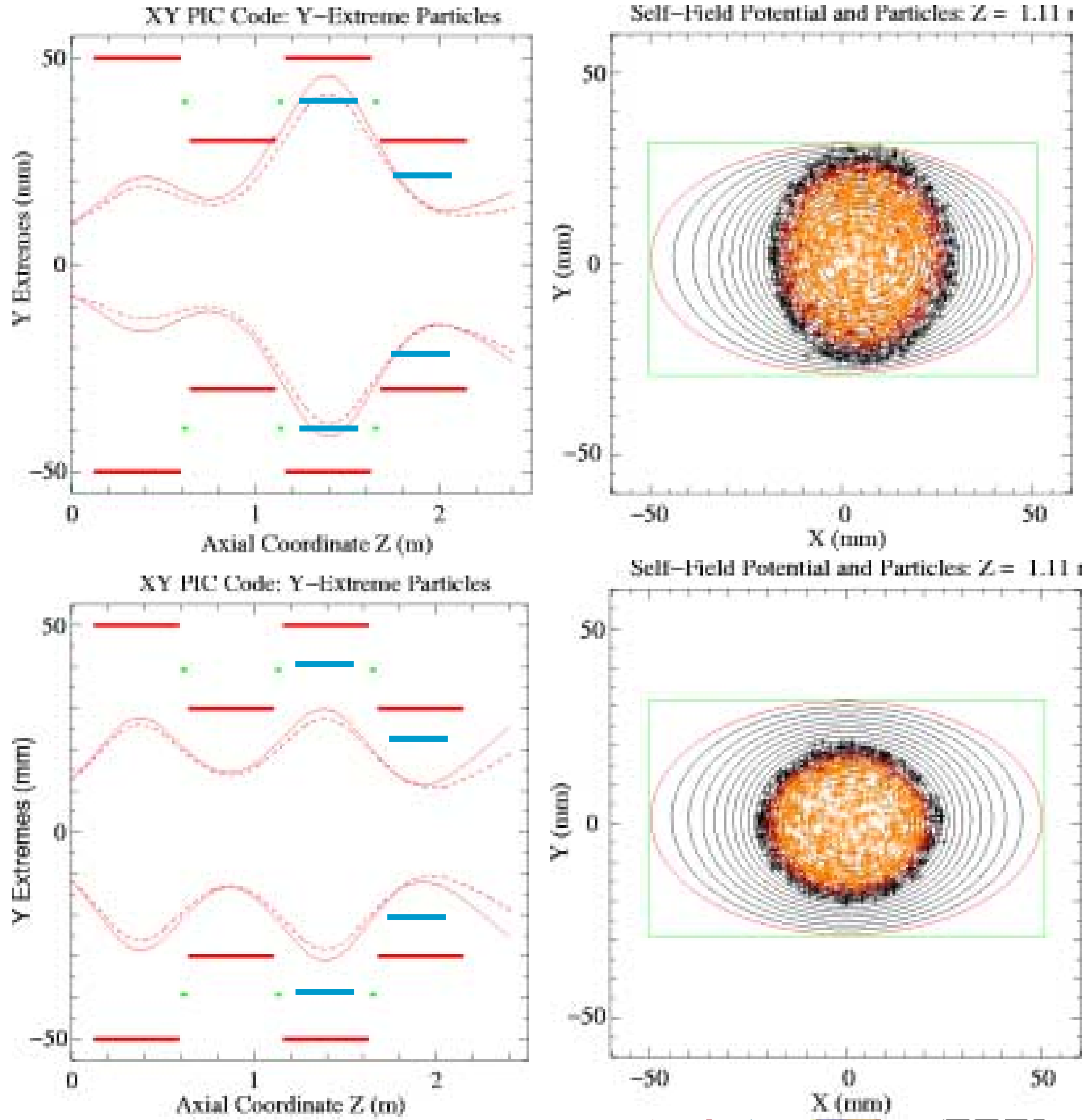
Simulations: centering beam and minimizing envelope changes reduces halo growth*

Phase-II diagnostics

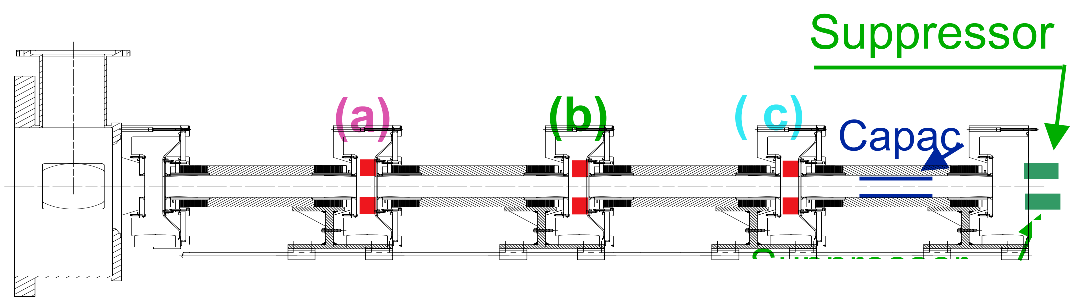


- Elliptical-quad-magnet beam tube ——
- Diagnostic tube-II ——
- Dashed red lines from envelope code, solid from XY PIC Code – PIC shows larger excursions
- Beam envelope through Phase-II diagnostics ~same as without diag. tubes installed.

*Steven Lund, private communication 2004.



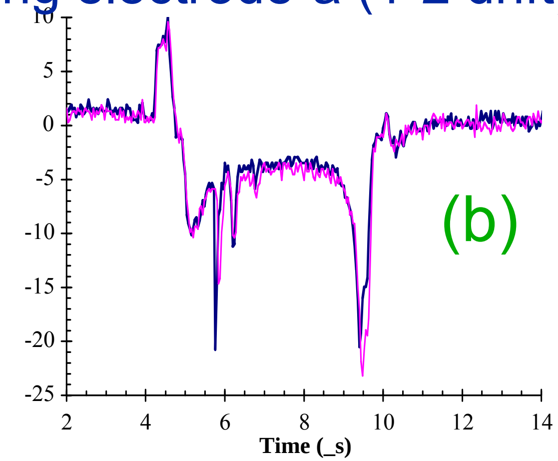
Suppressor electrode at 0, or -10 kV: clearing electrode (c) collects e⁻ before they reach (b) or (a)



Currents unaffected before (c)

Clearing electrode-b (2-3 drift)

Clearing electrode-a (1-2 drift)

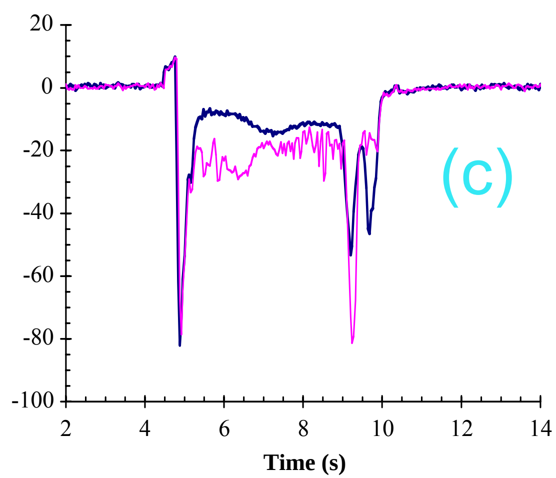


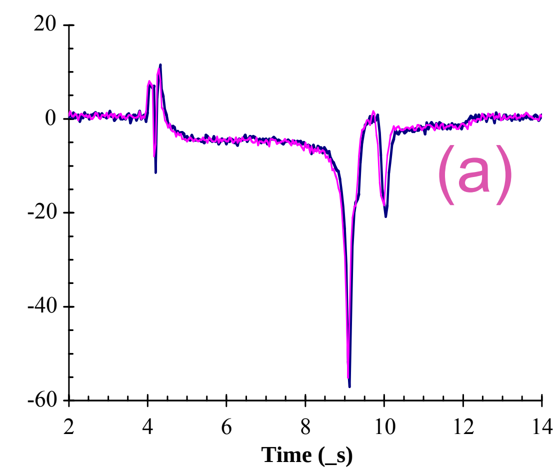
Currents vary from end through (c)

Capacitive electrode in 4th quad

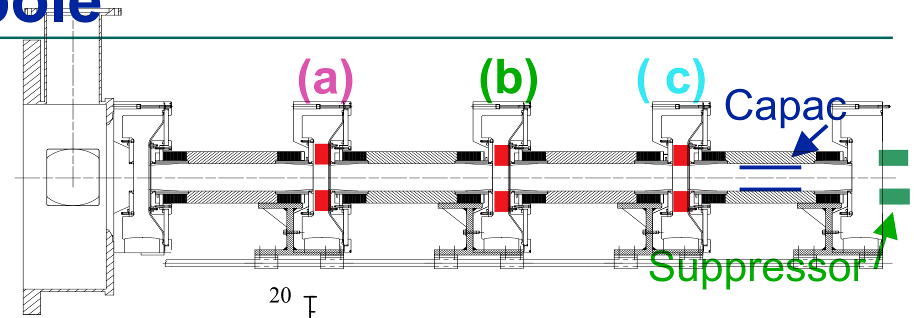
Clearing electrode-c (3-4 drift)

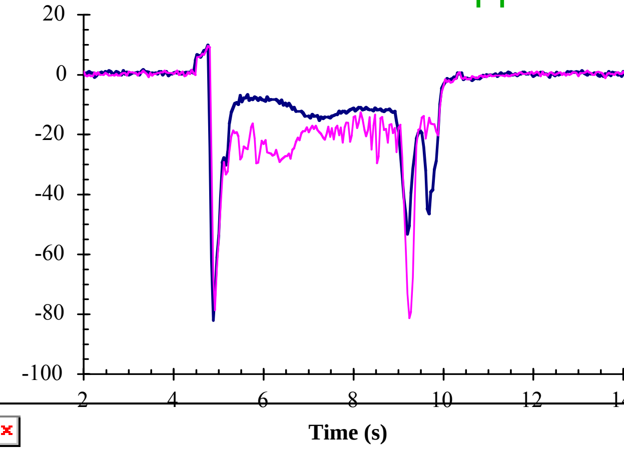
Capac.





Clearing electrode current – obtain lower limit on e^- drift velocity in magnetic quadrupole





- Suppressor switches electrons: passes or blocks from quads • Clearing electrodes work: upstream indep. of down-stream changes
- Calculate e^- drift velocity: e^-: drift upstream through 2 quadrants with area $A_b/2$.

$$I_b = q n_b v_b A_b$$

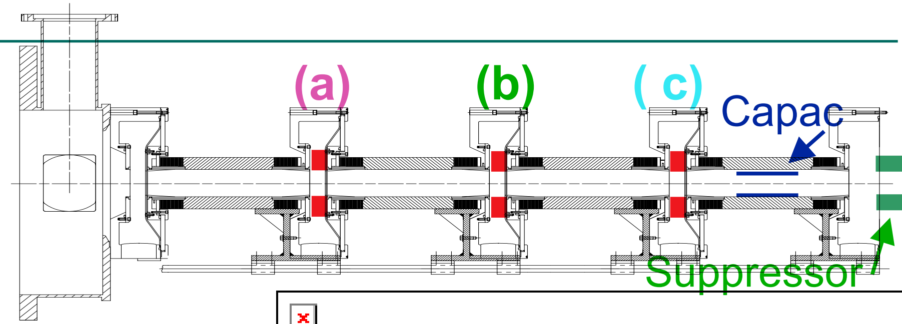
$$I_e = q n_e v_d A_b / 2$$

$$n_e \le n_b$$

- Then lower limit on drift velocity relative to beam velocity is

$$\frac{v_d}{v_b} \ge \frac{2 I_e}{I_b}$$

Clearing electrode removes all electrons from a drift region



- **Suppressor bias = 0 V, electrons can leak back into quads along beam.**

- **Vary clearing electrode (c): constant current to (b) until $V_c \leq$ 3 kV, then (b) and (c) vary oppositely and (a) remains constant.**

- **Vary clearing electrode (b): with V_c= 0, current to (c) remains at 0, no change in current to (a) until $V_c \leq$ 3kV then (a) and (b) vary oppositely.**

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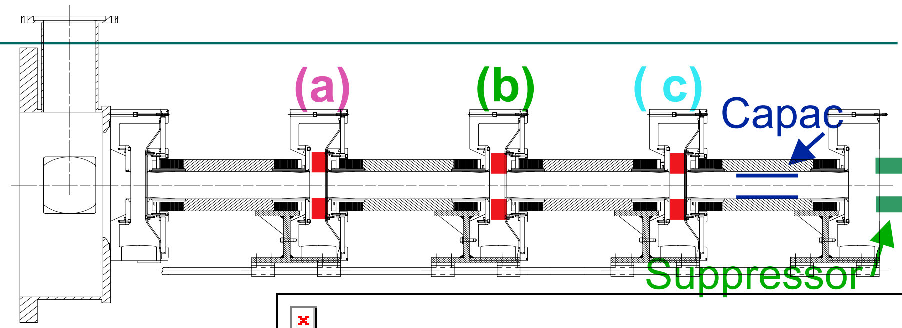

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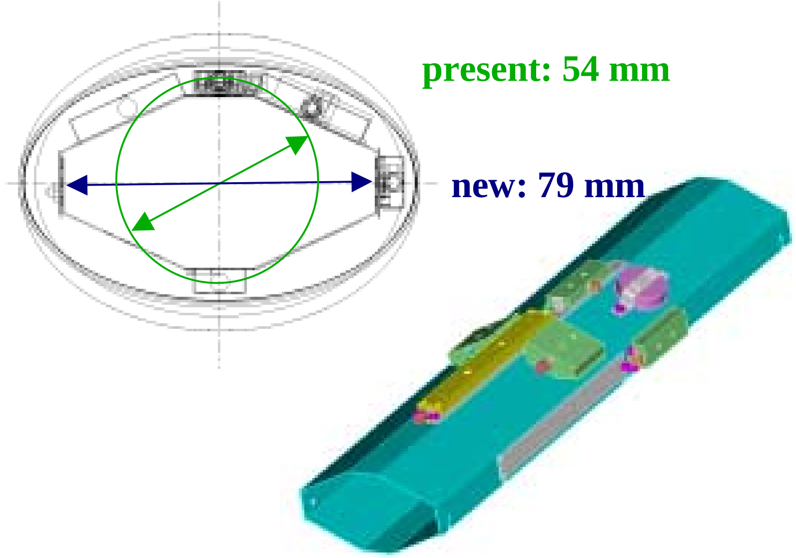
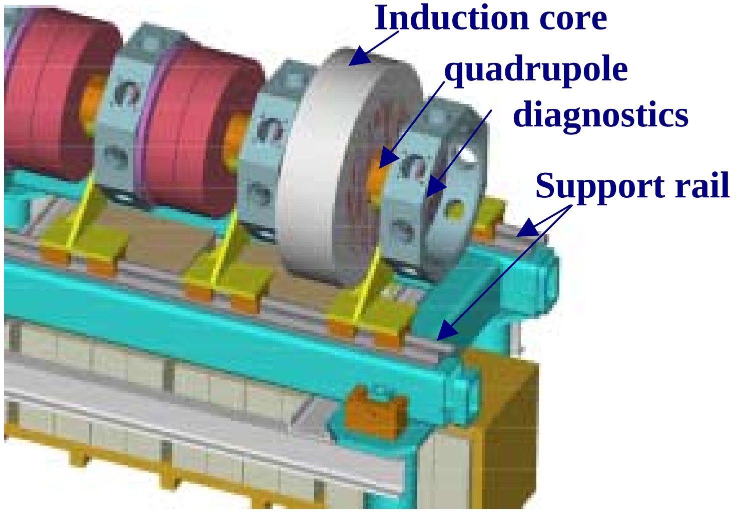
Upgrades to ECE experiments on HCX

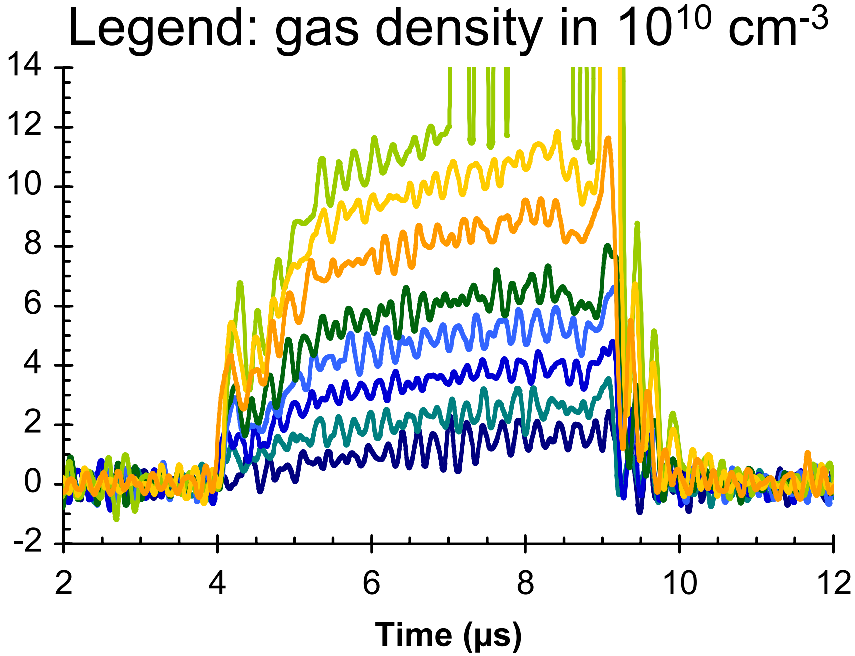
May '04: New octagonal diagnostic tubes approximate elliptical shape to pass larger beams without scraping walls – study full beam without aperturing.



Later '04: 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.



New real-time measurements: gas density in beam and electron ionization rate



Double grid shields electrode from beam potential, collect expelled ion from beam-ionized gas.

- **Initial threshold background gas, measured with ion gauges**
- **Ramp due to desorbed gas reaching beam**

- Initial current proportional to background argon gas density– varied with valve
- **Verifies that gas density measurement is valid**
- Electron ionization rate = Current - charge-exchange

HIF-ECE Experimental Summary/conclusions

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

- Electron emission coef. Γ_e and gas desorption Γ_0 large
- Rough surface reduces emission, desorption, & scattering.
- Demonstrated new measurement – gas density and electron ionization rate within magnetic quad.
- Clearing electrodes remove electrons in drift region
- Electron suppressor necessary at magnet exit in linac
- Simulation plays significant role in improving performance.

new tools for ECE in linacs