Experimental study of electron effects in heavy-ion beams

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Stray electron production is a concern in accelerators – but incompletely understood

Electrons can be trapped in potential well of positive particle beam

• These effects limit present accelerators and put future accelerators at risk

• We are beginning coordinated experiments, theory, and simulations to understand phenomena and develop mitigating mechanisms to expand limits.
Beam hitting gas or walls creates electrons and gas – these can can multiply

Beam on gas, \( I_b \)

Beam loss to walls, \( I_{bw} \)

1.0-1.8 MeV

\( K^+ \) Beam

2-5 kV potential

\( e^- \)

\( K^0 \)

\( K^{2+} \)

These interaction products create opportunities for diagnostics, but provide a hostile environment
TRIM Monte Carlo Code predicts significant beam ion scattering near grazing incidence

- 60-70% scatter at 88-89°
- 0.05-0.5% scatter at 0-45°
- Scattering approaches 90° (1.57 rad), difficult to eliminate by collimation.
- Issue - causes electron emission
Hostile environment for diagnostics

Beam loss to walls

- Energetic ($\geq$1 MeV) ions strike wall near grazing incidence, generate electron emission, gas desorption, and scattered beam ions.

Scattered ions:

- TRIM Monte Carlo Code predicts $\sim$70% reflection at $89^\circ$, at angles mostly $\leq 30^\circ$, but a few approaching $90^\circ$, with energies ranging from zero to near beam energy.
- These cause electron emission from walls
- Series of anti-reflection apertures in beam tube could reduce scattered ions by orders of magnitude.

Secondary electron suppression:

- Cannot suppress electrons with biased grids, when both grids and collector are impinged by scattered ions.
- Magnetic suppression in the lobes of magnetic quadrupole fields appears feasible as shown at left.

Capacitive coupling from beam:

- Magnitude $\sim$500 times expelled ion current
- Shield with grids. Subtract remaining contribution.

Signal to noise:

- Signals as low as $\sim$1 $\mu$A, noise from spark-gaps
- Shield, preamps near collectors.
Some simple diagnostics can measure electron related parameters in magnetic quadrupoles

**Flush probes:**
- (Current/electron emission coefficient [from GESD]) = Halo loss + scattered ions to wall

**Capacitive probes:**
- Signal $\propto \phi_b \propto (n_b - n_e)$ [measure $n_e / n_b \geq \text{few \%}$]

**Gridded collectors:**
- Grids shield collectors from $\phi_b$ (~$10^3$ larger signal)
- Expelled ion current proportional to gas pressure in beam and electron generation rate
  \[ I_i \propto P_0 \propto I_{e-trap} \] [measure $n_e / n_b \geq 0.1\%$]
- Expelled ion energy is equal to beam potential at ion birth radius ‘r’, compare with simulations to $E_i = \phi_b (r)$,
- Detrapped electrons at end of beam pulse - if shielded from incident and scattered ions
  \[ \int I_e \, dt = \text{total number trapped} \text{ (should = } \int I_{e-trap} \, dt) \]
- $I_e \, V_s \, \phi_b$ gives the depth of trapping
Electron emission from ion beam loss is suppressed by magnetic insulation of electrodes

Diagnostics mounted on outside of beam-tube liner sample particle flux near axial center of quadrupole magnet

- Liner provides smooth surface facing beam
- Diagnostics can be assembled on tube, then easily installed in quadrupole magnet

**BPM** – Beam Potential (Position) Monitor capacitive pickup (~50 µA/cm²)

**MSC** – magnetically suppressed collector, grid(s) reduce capacitive pickup, measures expelled ‘gas’ ion current (~0.1 µA/cm² at 10⁻⁷ torr; \( I_i \)=ionization rate \( \propto \) pressure \( P(t) \) \( \propto \) electron ionization rate (\( I_{e-trap} \))

**MSA** – magnetically suppressed analyzer, like MSC but larger gap insulates 5 kV, measures expelled ion energy = beam potential where ionized
Flush collectors run length of beam tube in one quadrupole

Collectors in quadrupole magnets
• Measure secondary electron current, infer beam loss, gas reflux, $n_e(t)$ and $n_0(t)$ [from GESD]
• Measure number and trapping-energy of electrons at end-of-pulse [Difficult, $\leq 1\% I_{\text{capacitive}}$]
• 2 collectors per quadrant determine beam loss. Collectors are effective wall.

4 collectors per quadrant (top) to compare loss at lobes Vs cusps
Gas desorption and electron emission predicted to scale with ion stopping rate $dE/dx$

- Gas desorption attributed to electronic energy loss of ions\(^1\) (which is the largest part of the total stopping power): scaling quadratically with $dE/dx$ at low temp, linearly with $dE/dx$ above 100 K.

- Electron emission also scales linearly with electronic stopping power.\(^2\)

We measure electron emission and gas desorption from 1 MeV $K^+$ beam impact on target

Gas, electron source diagnostic (GESD)

- Measure number & energy of electrons and gas per incident $K^+$ ion
- Calibrate secondary electron measurements vs. beam loss
- Evaluate mitigation techniques: baking, cleaning, surface treatment…
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.
GESD electron emission coefficient (EEC) varies with $\cos(\theta)^{-1}$

- Simple model gives $\cos(\theta)^{-1}$
  - Electrons from depth $> \delta$ ($\delta \sim 1$ nm) cannot leave surface
  - Ion path length in depth $\delta$ is $L$.

- Results depart from this near grazing incidence where the distance for nuclear scattering is $< L^1$

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

GESD gas desorption coefficient varies with $\cos(\theta)^{-\alpha}$, $\alpha < 1$

Hypothesis:
- Gas desorption results from electronic sputtering of gas film on surface plus dust on surface.
- Film results in $\cos(\theta)^{-1}$.
- At grazing incidence on dust, some dust particles are partially or totally hidden behind others, if ion penetrates it is at reduced energy and $dE/dx$.
- Then dust desorption scales more slowly than $\cos(\theta)^{-1}$.

![Graph showing relationship between angle of incidence and gas desorption coefficient.](image)
Possible areas for collaboration

**At GSI**
- Measure gas desorption and electron emission coefficients for ion energies in range of 1.4(?) to 20+ MeV/amu

**At HIF-VNL**
- GESD measure gas desorption & electron emission coefficients for ions in range of 25-45 keV/amu
- Mitigation techniques:
  - Cleaning
  - Scattered ion suppression
  - Halo scrape, electron trap
  - Trapping efficiency for secondary electrons
  - Detrapping electrons by induction cell

  *Now, FY03, ‘03-04, ‘04?*
Summary

Overview
- Electron clouds may establish “floor” on HIF driver costs
- Coordinated theory, computation, and experimental program initiated on electron effects in heavy-ion beams

Experimental program
- Electron emission coefficients scale with $\cos^{-1}(\theta)$ for 1 MeV $K^+$ incident on stainless-steel near grazing incidence.
- Gas desorption scales with $\cos^{-\alpha}(\theta)$ for either $\alpha << 1$, or $\alpha \sim 1$ with zero offset. Also desorption $\propto dE/dx$ between 0.08 and 1 MeV.
- Hostile environment in quads evaluated, and an array of diagnostics constructed to measure electron parameters.
- Four magnetic quadrupoles with electron diagnostics ready to be installed in the High-Current Experiment (HCX).