Experimental study of electron effects in heavy-ion beams

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

Proton Storage Ring

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 multiply

Beam on gas, I_b

Beam loss to walls, I_{bw}

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 (≥ 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° , at angles mostly $\leq 30^\circ$, but a few approaching 90° , 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:

Capacitive coupling from beam:

Signal to noise:

- 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.
- Magnitude ~ 500 times expelled ion current
- Shield with grids. Subtract remaining contribution.
- Signals as low as $\sim 1 \mu\text{A}$, 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 ϕ_b ($\sim 10^3$ larger signal)
- Expelled ion current proportional to gas pressure in beam and electron generation rate

$$I_i \propto P_0 \propto I_{e\text{-trap}} \quad [\text{measure } n_e/n_b \geq 0.1\%]$$

- 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
- $\int I_e dt$ = total number trapped (should = $\int I_{e\text{-trap}} dt$)
- I_e Vs ϕ_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 ($\sim 50 \mu\text{A}/\text{cm}^2$)

MSC – magnetically suppressed collector, grid(s) reduce capacitive pickup, measures expelled 'gas' ion current ($\sim 0.1 \mu\text{A}/\text{cm}^2$ at 10^{-7} torr; I_i =ionization rate $\propto$ pressure $P(t)$) $\propto$ electron ionization rate ($I_{e\text{-trap}}$)

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 ions¹ (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

1. W. L. Brown, et al., Phys. Rev. Letters 45, 1632 (1980).
2. P. Thieberger, et al., Phys. Rev. A 61, 042901-1 (2000).

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 δ is L .
- 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).

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 reduce energy and dE/dx .
- Then dust desorption scales more slowly than $\cos(\theta)^{-1}$.

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	Now
• Mitigation techniques: Cleaning	Now
Scattered ion suppression	FY03
Halo scrape, electron trap	?
• Trapping efficiency for secondary electrons	'03-04
• Detrapping electrons by induction cell	'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 $\alpha \ll 1$, 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).