Experiments and simulations of electrons in a linac with a 4 $\mu$s duration ion beam

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For the Heavy-Ion Fusion Science – Virtual National Laboratory

Electron Cloud Feedback Workshop

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**HIFS e-cloud effort**

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**Consultants**

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Irv Haber (U. Maryland)

R. Davidson, I. Kaganovich, H. Qin, A. Sefkow, E. Startsev, et al (PPPL)

Peter Stoltz, Seth Veizer (Tech-X Corp.)

John Verboncoeur (UC-Berkeley)
Outline

1. Who we are – why we care about e-cloud
2. Introduction – tools
3. Beam-surface interactions
4. Absolute measurements of gas and e-
5. Electrons in solenoids
6. Plasma oscillations
Heavy Ion Inertial Fusion or “HIF” goal is to develop an accelerator that can deliver beams to ignite an inertial fusion target

Target Requirements:
- 3 - 7 MJ \times \sim 10 \text{ ns} \Rightarrow \sim 500 \text{ Terawatts}
- Ion range: 0.02 - 0.2 g/cm^2 \Rightarrow 1-10 \text{ GeV}
- Ion charge: 7 MJ/few GeV \Rightarrow \text{few mCoul}

For A \sim 200 \rightarrow \sim 10^{16} \text{ ions}

\sim 100 \text{ beams}

1-4 kA / beam

Near term goal:
High Energy Density Physics (HEDP)
How important is e-cloud to heavy-ion IFE?

• Power plant cost decreases with increasing fill factor

IBEAM results\(^1\):

![Graph showing total driver cost vs. fill factor](image)

Fill factor = \( \frac{a_{\text{max}}}{R_{\text{pipe}}} \)

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

• Electron and gas emission are likely to limit fill factor.
• E-cloud may also limit beam current or spot size for WDM. With short pulses, gas desorption is unlikely to be a significant issue.
Heavy-ion beams can be degraded by electron clouds

- Compact phase-space essential to a small focal spot
- Ideal beam has minimum phase space
- Electrons can distort phase space, greatly increasing area of focal spot.

Artificially high electron density to exaggerate electron effects

\[ x = \text{horizontal location of ion} \]
\[ x' = \text{dx/dz of ion (transverse/axial)} \]
Heavy-ion beams can be degraded by electron clouds –2

- We look at extreme cases to validate models

- Electrons can distort phase space, greatly increasing area of focal spot.

\[ x = \text{horizontal location of ion} \]
\[ x' = \frac{dx}{dz} \text{ of ion (transverse/axial)} \]
We use long beam pulses with a 4 $\mu$s “flattop”

Beam current is measured with a Faraday cup at end of accelerator
New accelerators for WDM and HIF must push performance to cost ratio, and guarantee successful operation

- Electron and gas physics likely to determine operating limits, e.g.:
  - Maximum beam current
  - Compactness - how close can beam tube approach beam?
  - Electron-ion instabilities (as seen in PSR)

- Devise mitigation techniques to increase limits
  - Clearing electrodes remove electrons
  - Roughened walls reduce electron and gas generation
  - Materials or coatings reduce electron and gas generation
  - Halo scraping by apertures reduces electron and gas generation
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We perform 3-D self-consistent simulations with the WARP-POSINST code

Particle-in-cell (PIC) code that self-consistently handles
  beam dynamics
electrons (POSINST)
gas
Gas & e- sources, transport, and interactions

For $n_e \sim n_{\text{beam}}$ – Oscillations

Ref: Ron Cohen, Invited paper
DPP04
WARP-POSINST code – self-consistent 3-D & fast

merge of WARP & POSINST +
new e-/gas modules

1
WARP
field calculator
ion mover
diagnostics
electron mover
lattice description

POSINST

Python
framework &
user interface

ion mover

image forces
electron source
modules

kicks from beam

+ Adaptive Mesh Refinement
concentrates resolution
only where it is needed
Speed-up 3 x10-10^4

2

WARP ion PIC, I/O, field solve
f_{beam}, \Phi, geom.

Reflected
ions

f_{b,wall}
f_{b,wall}

n_b, v_b
ions

gas module
emission from walls
ambient
gas transport

charge exch.

volumetric
(ionization)
electron source

wall electron source

\Phi

electron dynamics
(full orbit; interpolated drift)
sinks

ne

3

+ New e- mover
Allows large time step
greater than cyclotron
period with smooth
transition from
magnetized to non-
magnetized regions

Speed-up x10-100

4

beam
e- motion in a quad

12
Key: operational; partially implemented (4/28/06)
The High Current Experiment (HCX) is a small, flexible heavy-ion accelerator (at LBNL)

1 MeV, 0.18 A, $6 \times 10^{12}$ K$^+$/pulse, $t \approx 5 \mu$s, 2 kV beam potential

Quadrupole magnets Q1 - Q4 for beam transport
Diagnostics within magnetic quadrupole bores

Magnet Q3

FLL: 8-biased electrodes at ends of field lines: measure capacitive signal + electrons from wall

Magnet Q4

Capacitive and grid-shielded electrodes

BPM (3)

FLS(2)

GIC (2)
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Control of accelerator beam-surface interactions is important

Charged particle beams transport efficiently with ‘strong focusing’, alternating gradient magnetic quadrupoles

**Primary:**
- Ionization of background or desorbed gas
- Ion-induced gas & electron emission from
  - expelled ions hitting vacuum wall
  - beam halo scraping

**Secondary:**
- secondary emission from electron-wall collisions
Electron emission & gas desorption vs angle of incidence measured and mitigated (1 MeV K+)

\[ L = \frac{\delta}{\cos(\theta)} \]

Electrons emitted with Maxwellian $T_e \sim 30$ eV

Mitigation – Roughened target surface eliminates grazing collisions to reduce emission
- glass-bead blast
- alumina dust-blast


Electronic gas desorption scales with \((dE/dx)^2\), like electronic sputtering

Conventional sputtering driven by large-angle nuclear scattering

Electronic sputtering more copious.

- Well known for ions onto thick insulating layers,
- Scales with \((dE_e/dx)^n\) where \(1 \leq n \leq 3\).

Electronic desorption, \(n \approx 2\).

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

Model electron yield (electrons/ion) versus
- ion energy
- angle of incidence

Reasonable agreement with our measurements

Not $1/\cos \theta$ at these lower ion energies

Modified Sternglass model** evaluated with TRIM code

\[ \gamma_e \propto \frac{\delta}{\cos(\theta)} \left( \frac{dE}{dx} \right)_e \]

We measure velocity distribution of desorbed gas

Observation: desorbed gas in beam emits light

View expanding gas cloud from side – \( f(v_0) \) normal to target [with gated camera]
Line integral of images indicates an expansion velocity of up to a few mm/µs

Estimated velocity:
Slope ~1 mm/µs

Corresponds to room temperature H₂, consistent with residual gas measurements

Axial distance

Time
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We measure electron sources – ionization

1. Ionization of gas by beam \((n_e/n_b \leq 3\%)\)

Beam current known; from expelled ion current infer
- Ionization rate
- Also, gas density in beam

We measure electron sources – walls

2. Electron emission – beam tube ($n_e/n_b \leq 7\%$)

![Electron emission diagram]

3. Electron emission – end wall ($n_e/n_b$, 0, 100\%)

![Electron emission diagram]

For low ion scrape-off, expect current near-zero

![Current measurement graph]
1st measurement of absolute electron cloud density* — used retarding field analyzer (RFA) and clearing electrodes

- RFA measures max. expelled ion energy $E_i$
  (scan bias on successive pulses)
- $E_i = \phi_b$, max. beam potential
- $\phi_b$ depressed by electrons
- Clearing electrode current:
  infer minimum $n_e$, and corroborate higher $n_e$

**Absolute electron fraction can be inferred from RFA and clearing electrodes**

<table>
<thead>
<tr>
<th>Beam neutralization</th>
<th>B, C, &amp; S on</th>
<th>B, C, off S on</th>
<th>B, C, S off</th>
</tr>
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<tr>
<td>Clear. Electr. A</td>
<td>~ 7%</td>
<td>~ 25%</td>
<td>~ 89%</td>
</tr>
<tr>
<td>RFA</td>
<td>(~ 7%)</td>
<td>~ 27%</td>
<td>~ 79%</td>
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We have begun experiments studying e-clouds in solenoid magnets.

Electrodes installed in center of each solenoid and between solenoids to provide control of e-emission and trapping on outer magnetic field lines.
E-cloud electrodes have clear effect on apertured beam quality (26 mA)

Unbiased
4ε_{rms} = 26.23 \pi \text{ mm mrad}

Clearing
a = 6.46 \text{ mm}
a' = -7.54 \text{ mrad}
4ε_{rms} = 20.89 \pi \text{ mm mrad}

Trapping
a = 7.41 \text{ mm}
a' = -5.86 \text{ mrad}
4ε_{rms} = 106.2 \pi \text{ mm mrad}
Trapping electrons degrades the beam quality; diagnostics may not be needed for unapertured beam (43 mA)
Clearing electrons decreases slight time dependence of unapertured beam envelope.

070131 4-STX clearing e⁻

Full Beam Envelope Parameters at Horizontal Slit Plane vs Time

070131 4-STX e⁻ cloud 0V

Full Beam Envelope Parameters at Horizontal Slit Plane vs Time
Outline

1. Who we are – why we care about e-cloud
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4. Absolute measurements of gas and electrons & mitigation
5. Electrons in solenoids
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Electron oscillations – simulation & experiment agree

Current to clearing electrode (c) agrees in frequency ~ 6 MHz

Currents to capacitive electrode array agree in wavelength ~5 cm, and amplitude (below)

Quest - nature of oscillations?

Progressively remove possible mechanisms in simulations

Not ion-electron two stream

Other mechanisms:
- Virtual cathode oscillations near end wall and at quad. end
- Kelvin Helmholtz / diocotron (plausible, shear in drift velocities)
- $\delta$-Density $\Rightarrow$ $\delta$-potential, feedbacks to drift velocity
Summary – We have established a sound basis to understand and mitigate electrons and gas

- Increased understanding of beam-surface interactions
  - Electron emission measured and modeled, $\propto \frac{dE_e}{dx}$
  - Discovered gas desorption $\sim (\frac{dE_e}{dx})^2$

- Major electron sources measured:
  - Wall emission from beam-scrape-off dominates ($\sim 7\%$) + gas
  - End-wall emission suppressed to $\sim 0\%$ (if not suppr. $\sim 80\%$)
  - Gas ionization small ($\sim 3\%$)

- Absolute measurement of e- accumulation as function of time
- Electrons in solenoids can be controlled with electrodes
- Electrons bunch, generating oscillations
  - Simulation & experiment agree – freq., wavelength, & amplitude
  - Experimental validation of simulations provides credibility
Future – understand & mitigate electron and gas effects – push performance / cost

• Quantitative calibration of optical gas desorption diagnostic
  – Measure desorption from non-evaporable getter (NEG)
• Continue work to understand oscillation mechanism
• Measure effects on beam vs electron accumulation, find limits
• Compare electron effects in solenoids and quadrupoles
• Apply models to high-energy physics accelerators: LHC, ILC, …
• Seek operating mode in existing and future WDM/HIF machines with negligible to tolerable gas and electrons
  - Apertures to scrape halo – how can these minimize halo?
  - Extend limits by other mitigation techniques
Spatial distribution of electrons in quadrupole magnet varies with the source

Electrons in a quadrupole magnet

Electrons ejected from end wall drift upstream in 2 quadrants (top & bottom)

Electrons from ionization of gas map out beam profile

Electrons desorbed from beam pipe in quad upon ion impact fill beam tube

Electron clouds impact beams of positively-charged particles

Electrons from:
- ionization of gas
- e-, ions, or photons strike wall
- end wall emission

- Electron clouds can severely limit the performance of
  - present $e^--e^+$ colliders and ion rings (e.g. PEP-II, PSR, SNS)
  - next generation high-intensity rings (LHC, GSI-FAIR, ILC).
  - warm-dense matter (WDM) heavy-ion accelerators
  - heavy-ion inertial fusion (HIF) accelerators

HIF beam edge (halo) scraping will generate gas and electrons, which limit beam current. Need to mitigate halo, electrons, and gas.