Self-consistent simulations of high-intensity beams and electron-clouds.

Jean-Luc Vay

Heavy Ion Fusion Science Virtual National Laboratory
Lawrence Berkeley National Laboratory
Many thanks to collaborators

M. A. Furman, C. M. Celata, P. A. Seidl, M. Venturini
*Lawrence Berkeley National Laboratory*

R. H. Cohen, A. Friedman, D. P. Grote,
M. Kireeff Covo, A. W. Molvik
*Lawrence Livermore National Laboratory*

P. H. Stoltz, S. Veitzer
*Tech-X Corporation*

J. P. Verboncoeur
*University of California - Berkeley*
Outline

1. Who we are and why we care about electron cloud effects
2. Our tools and recent selected results
3. Application to High-Energy Physics
4. Conclusion
Heavy Ion Inertial Fusion (HIF) goal is to develop an accelerator that can deliver beams to ignite an inertial fusion target.

Target requirements:
3-7 MJ x ~ 10 ns \(\Rightarrow\) \(\sim 500\text{ Terawatts}\)
Ion Range: 0.02 - 0.2 g/cm\(^2\) \(\Rightarrow\) 1-10 GeV
dictate accelerator requirements:
A\(\sim\)200 \(\Rightarrow\) \(\sim 10^{16}\) ions, 100 beams, 1-4 kA/beam
We have a strong economic incentive to fill the pipe.

Which elevates the probability of halo ions hitting structures.

(from a WARP movie; see http://hif.lbl.gov/theory/simulation_movies.html)
Sources of electron clouds

Primary:

- Ionization of
  - background gas
  - desorbed gas
- ion induced emission from
  - expelled ions hitting vacuum wall
  - beam halo scraping
- photo-emission from synchrotron radiation (HEP)

Secondary: secondary emission from electron-wall collisions
Simulation goal - predictive capability

End-to-End 3-D **self-consistent** time-dependent simulations of beam, electrons and gas with self-field + external field (dipole, quadrupole, ...).

\[ T = 4.65 \mu s \]

From source...  

...to target.

Electrons
The means - WARP-POSINST code suite

Merge of WARP & POSINST + new e⁻/gas modules

1. **WARP**
   - Field calculator
   - Image forces
   - Ion mover
   - Diagnostics
   - Electron mover
   - Lattice description

2. **POSINST**
   - Python framework & user interface
   - Electrons source modules
   - Kicks from beam

3. **Additive Mesh Refinement**
   - Concentrates resolution only where it is needed
   - Speed-up $x10^{-4}$

4. **New e⁻ mover**
   - Allows large time step greater than cyclotron period with smooth transition from magnetized to non-magnetized regions
   - Speed-up $x10^{-100}$

Key: operational; partially implemented (4/28/06)
POSINST provides advanced SEY model.

Monte-Carlo generation of electrons with energy and angular dependence. Three components of emitted electrons:

backscattered: \[ \delta_e = \frac{I_e}{I_0}, \]

rediffused: \[ \delta_r = \frac{I_r}{I_0}, \]

true secondaries: \[ \delta_{ts} = \frac{I_{ts}}{I_0} \]

Phenomenological model:
• based as much as possible on data for \( \delta \) and \( d\delta/dE \)
• not unique (use simplest assumptions whenever data is not available)
• many adjustable parameters, fixed by fitting \( \delta \) and \( d\delta/dE \) to data
We use third-party modules.

- ion-induced electron emission and cross-sections from the TxPhysics* module from Tech-X corporation (http://www.txcorp.com/technologies/TxPhysics),

- ion-induced neutral emission developed by J. Verboncoeur (UC-Berkeley).
Benchmarked against dedicated experiment on HCX

1 MeV, 0.18 A, t ≈ 5 µs, 6x10^{12} K^+ per pulse, 2 kV space charge, tune depression ≈ 0.1

Short experiment => need to deliberately amplify electron effects: let beam hit end-plate to generate copious electrons which propagate upstream.
Comparison sim/exp: clearing electrodes and e⁻ supp. on/off

Time-dependent beam loading in WARP from moments history from HCX data:
  • current
  • energy
  • reconstructed distribution from XY, XX', YY' slit-plate measurements

Good semi quantitative agreement.
1. Importance of secondaries
- if secondary electron emission turned off:
  
  2. run time ~3 days
- without new electron mover and MR, run time would be ~1-2 months!

---

**Detailed exploration of dynamics of electrons in quadrupole**

- **Electrons**
  - 200 mA $K^+$
  - Potential contours
  - Simulations vs. Experiment
  - WARP-3D $T = 4.65 \mu s$

- **Bunching**
  - ~6 MHz signal in (C) in simulation AND experiment
The Heavy Ion Fusion Science Virtual National Laboratory

WARP/POSINST applied to High-Energy Physics

• LARP funding: simulation of e-cloud in LHC

1 LHC FODO cell (~107m) - 5 bunches - periodic BC (04/06)

AMR essential
X10^3-10^4 speed-up!

WARP/POSINST-3D - t = 300.5ns

• Fermilab: study of e-cloud in MI upgrade
• ILC: start work in FY07
“Quasi-static” mode added for codes comparisons.

A 2-D slab of electrons (macroparticles) is stepped backward (with small time steps) through the beam field and 2-D electron fields are stacked in a 3-D array, that is used to push the 3-D beam ions (with large time steps) using maps (as in HEADTAIL-CERN) or Leap-Frog (as in QUICKPIC-UCLA), allowing direct comparison.
Proposed Model for Instability Simulations

- Round bunch in a round pipe: 1e11 protons
- Uniform electron cloud with density 1e12 m⁻³
- Each bunch passage starts with a uniform cloud chamber radius 2 cm
- Uniform transverse focusing for beam propagation
- Zero chromaticity, zero energy spread
- No synchrotron motion
- Energy 20 GeV
- Beta function 100 m
- Ring circumference 5 km
- Betatron tunes 26.19, 26.24
- RMS transverse beam sizes 2 mm (Gaussian profile)
- RMS bunch length 30 cm (Gaussian profile, truncated at +/- 2 sigma_z)
- No magnetic field for electron motion
- Elastic reflection of electrons when they hit the wall

NEW: with open and/or conducting boundary conditions (please specify boundary assumed), with 1 and/or several interaction points per turn or continuous interaction (please specify)

Result: plot of x&y emittances vs time
Can 3-D self-consistent compete with quasi-static mode?  
- computational cost of full 3-D run in two frames -

**Lab frame**

\[ \delta x = \frac{\sigma_x}{n}; \quad \delta z = \min(\sigma_z, L)/n \]

\[ \delta t < \min[ \delta x/\max(v_x), \delta z/\max(v_z) ]; \]

\[ T_{\text{max}} = N_{\text{units}} \times L/V_b \]

\[ N_{op} = N_e \times T_{\text{max}}/\delta t \]

**Frame \( \gamma \)**

\[ \delta x^* = \frac{\sigma_x}{n}; \quad \delta z^* = \min(\sigma_z^*, L^*) = \gamma \delta z \]

\[ \delta t^* < \min[ \delta x^*/\max(v_x^*), \delta z^*/\max(v_z^*) ] = \min[ \delta x/(\max(v_x/\gamma)), \gamma \delta z/v_z ] = \gamma \delta t \]

\[ T_{\text{max}}^* = N_{\text{units}} \times L^*/(V_b-V_f) \sim T_{\text{max}}/\gamma \]

\[ N_{op}^* = N_e \times T_{\text{max}}^*/\delta t^* \sim N_{op}/\gamma^2 \]

=> Computational cost greatly reduced in frame \( \gamma \)
Comparison between quasi-static and full 3-D costs.

Quasi-static (HEADTAIL, QUICKPIC):

\[ \alpha \sim \Delta S / \sigma_z \]

\[ N_{op,qs} = N_{op} / \alpha \]

Frame \( \gamma \):

if \( \sigma_z^* = \Delta S^* \), \( \gamma^2 = \alpha \), \( N_{op}^* = N_{op,qs} \)

\[ \Rightarrow \text{cost of full 3-D run in frame } \gamma = \text{cost of quasi-static mode in lab frame} \]
Application to rings

- In bends, WARP uses warped coordinates with a logically cartesian grid. If solving in a frame moving at constant $\gamma$ along $s$, we need to extend existing algorithm to allow treatment of motion in relativistic rotating frame in bends.

- Meanwhile, in order to study electron cloud effects, including bends, where effects are dominated by the magnitude of the bending field rather than its sign, we propose to substitute a ring by a linear lattice with bends of alternating signs.

- For example, diagram 1 LHC FODO cell ($\square$ quadrupole; $\Box$ bend)
Conclusion

- We developed a unique combination of tools to study ECE

- **WARP/POSINST code suite**
  - Parallel 3-D PIC-AMR code with accelerator lattice follows beam [self-consistently](#) with gas/electrons generation and evolution,

- **HCX experiment addresses ECE fundamentals (HIF/HEDP/HEP)**
  - [highly instrumented](#) section dedicated to e-cloud studies,
  - extensive methodical [benchmarking](#) of WARP/POSINST,

- **Being applied outside HIF/HEDP, to HEP accelerators**
  - LHC, Fermilab MI, ILC,
  - Implemented “quasi-static” mode for direct comparison to HEADTAIL/QUICKPIC,
  - fund that self-consistent calculation has [similar cost](#) than quasi-static mode if done in [moving frame (with $\gamma \gg 1$)](#), thanks to relativistic contraction/dilatation bridging space/time scales disparities (applies to FEL, laser-plasma acceleration, plasma lens,...).