Overview of Selected Research Activities in Heavy Ion Fusion

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Heavy Ion Fusion

- PPPL is a participant in the Heavy Ion Fusion Virtual National Laboratory (HIF-VNL) together with LBNL and LLNL.
- Senior positions in the HIF-VNL filled by PPPL personnel include Deputy Director, and Deputy Head of Theory and Modeling.
- Technical focus of PPPL participation includes:
  - Advanced analytical and numerical modeling of intense beam propagation and beam-plasma interactions.
  - Develop and apply rf techniques for preionized plasma formation.
  - Measurement of multielectron loss events.
  - Feasibility study of negative-ion-based heavy ion neutral beam driver.
  - Advanced engineering design (e.g., final focus magnets, and target chamber interface).

Background

- The primary focus of the PPPL effort in heavy ion fusion is to develop a fundamental understanding of nonlinear space-charge effects on the propagation, acceleration and compression of high-intensity heavy ion beams, and beam-plasma interactions in the target chamber.
- This is essential to:
  - Identify operating regimes in which emittance growth and beam losses are minimized in the accelerator system and transport lines.
  - Identify operating regimes for quiescent beam propagation in the target chamber.

Heavy Ion Fusion

Objectives

- Develop advanced analytical and numerical models describing the nonlinear dynamics and collective processes in intense heavy ion beams propagating in periodic focusing accelerators and transport systems, and on beam-plasma interactions in the target chamber.
- Carry out experimental studies of intense ion beam propagation and beam-plasma interactions in the target chamber in high-leverage areas that make effective use of PPPL's established experimental capabilities.
- Carry out engineering design studies in selected high-leverage areas, e.g., final focus magnets and nonlinear beam optics, and target chamber interface.

Personnel

R. C. Davidson, P. Efthimion, E. Gilson, L. Grisham, P. Heitzenroeder, C. Jun, I. Kaganovich, P. Kolchin, W. W. Lee, D. Mueller, H. Qin, E. Startsev, S. Strasburg and S. Tzenov.

Selected Recent Accomplishments

- Developed kinetic (Vlasov-Maxwell) model for description of intense nonneutral ion beam propagation in periodic focusing field configurations, including development of Hamiltonian averaging techniques, and application of nonlinear kinetic stability theorem for quiescent beam propagation over large distances.

- Application of a kinetic model to determine detailed properties of the electron-ion two-stream instability when an (unwanted) electron component is present in the acceleration region or transport lines, including the effects of axial momentum spread.

- Application of test-particle model to explore chaotic particle dynamics and halo formation induced by collective mode excitations in high-intensity ion beams, including estimates of the maximum radial excursion of the halo particles.

- Development of 3D multispecies δf simulation technique for intense beam propagation in periodic focusing systems, including detailed investigations of the linear and nonlinear evolution of the two-stream instability at high beam intensities.

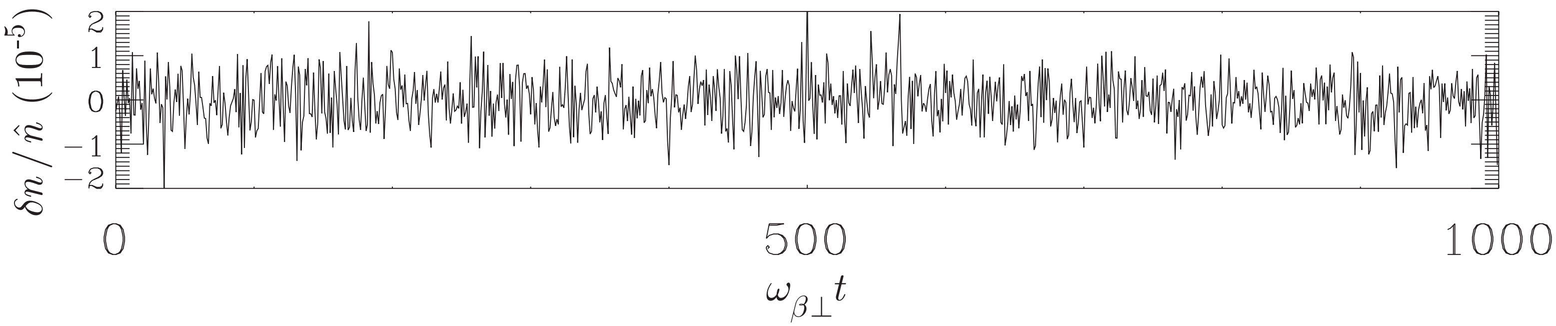
- Application of a macroscopic warm-fluid model describing collective processes in high-intensity beams, including investigations of collective instability driven by pressure anisotropy when $P_\perp > P_\parallel$.

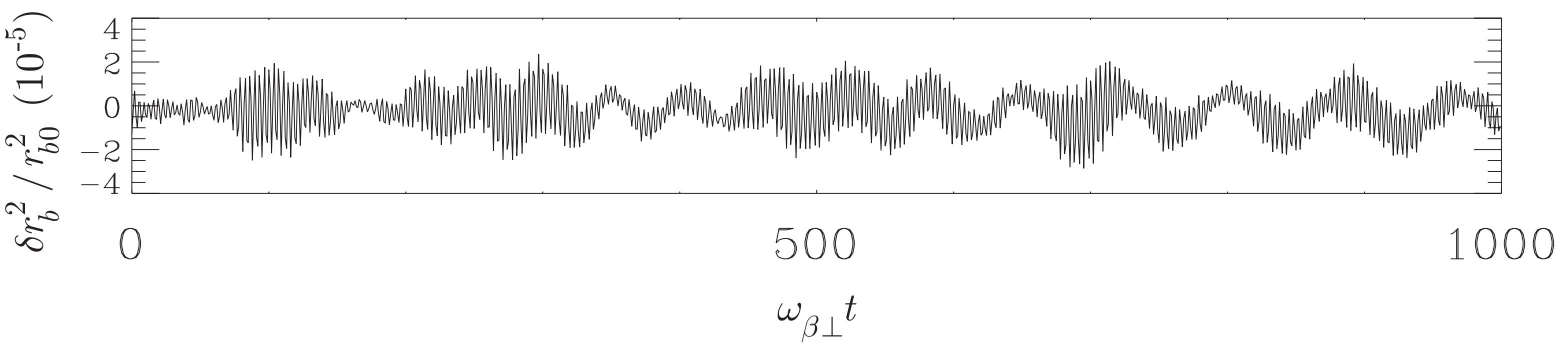
The BEST Code

Application of the 3D multispecies nonlinear δf simulation method to PSR is carried out using the Beam Equilibrium Stability and Transport (BEST) code at the Princeton Plasma Physics Laboratory.

- Adiabatic field pusher for light particles (electrons).
- Solves Maxwell's equations in cylindrical geometry.
- Written in Fortran 90/95 and extensively object-oriented.
- NetCDF data format for large-scale diagnostics and visualization.
- Achieved an average speed of $40\mu s/(\text{particle}\times\text{step})$ on a DEC alpha personal workstation 500au computer.
- The code has been parallelized using OpenMP and MPI.
  - NERSC: IBM-SP2 Processors.
  - PPPL: Dec-α Processors.
- Achieved 2.0×10^{10} ion-steps + 4×10^{11} electron-steps for instability studies.

Nonlinear Properties of Thermal Equilibrium Beams

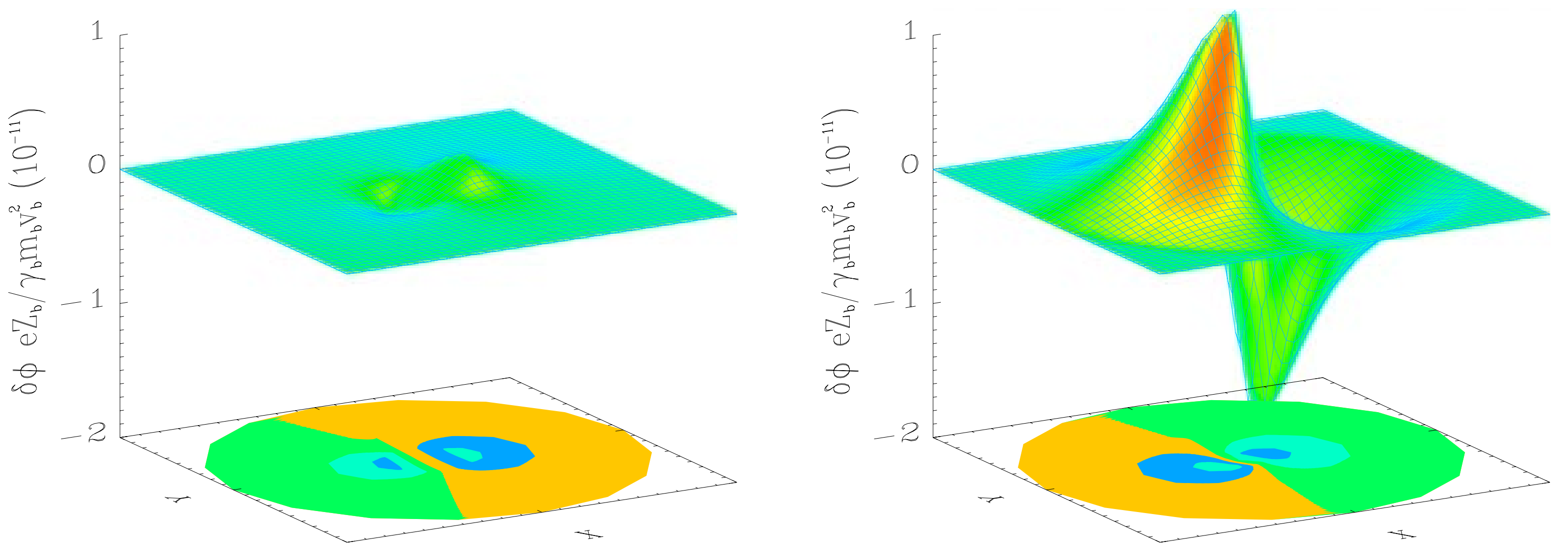




➪ BEST simulation results show that beam propagates quiescently over large distances, which agrees with the nonlinear stability theorem for the choice of thermal equilibrium distribution function.

BEST Simulation of Two-Stream Instability

- When a background electron component is introduced with $\beta_e = V_e/c \simeq 0$, the $l = 1$ "surface mode" can be destabilized for a certain range of axial wavenumber and a certain range of electron temperature T_e.



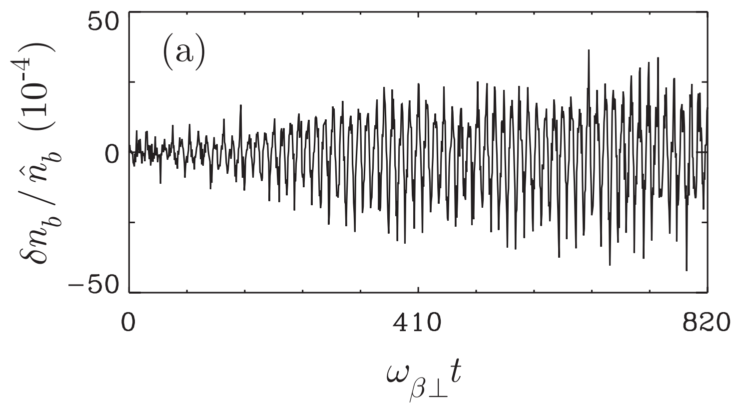
(a) $t = 0$ (b) $t = 200/\omega_{\beta\perp}$

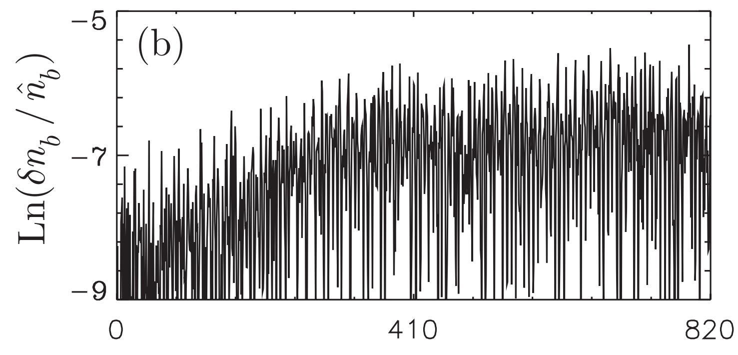
- Linear growth phase shows strong dipole mode structure.

- Two-stream instability can be stabilized by modest axial momentum spread of beam ions.

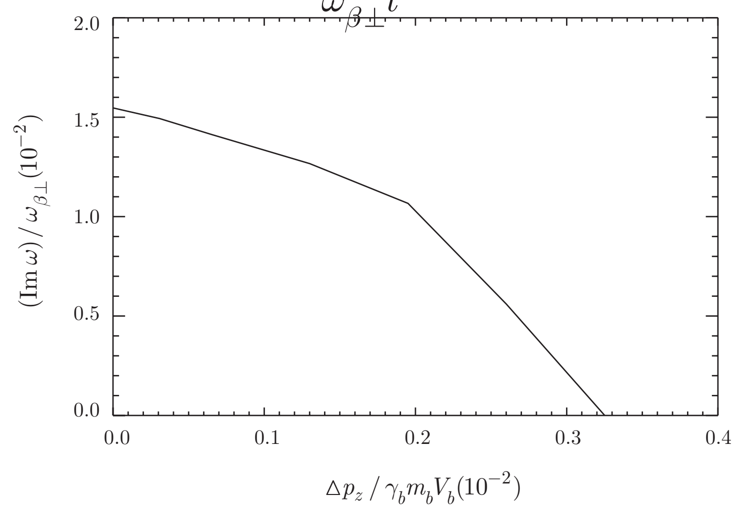
BEST Simulation of Two-Stream Instability

- Nonlinear perturbation saturation level $\delta n_b \sim 3.0 \times 10^{-3} \hat{n}_b$.





- The maximum linear growth rate $(Im\omega)_{max}$ of the electron-proton instability decreases as the axial momentum spread of the beam ions increases.

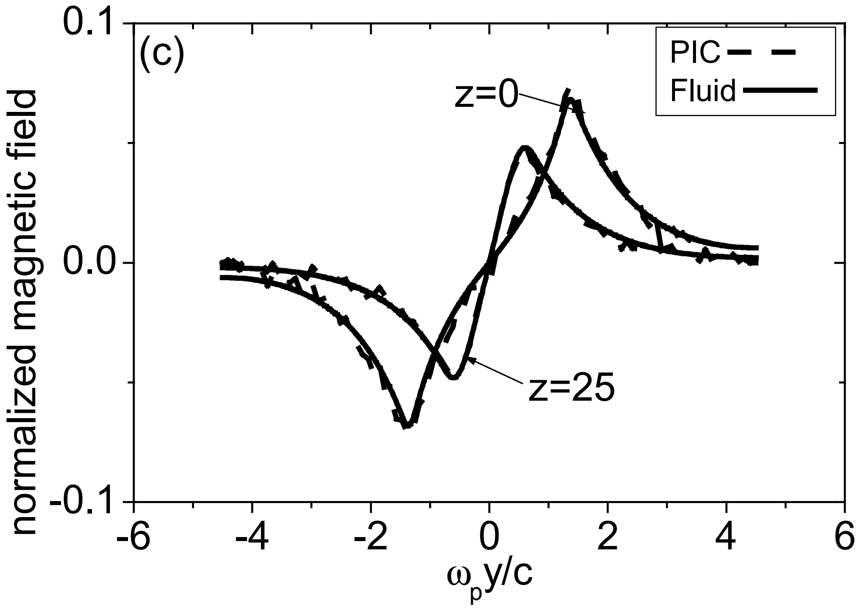


- H. Qin, *et al*, Physical Review Special Topics on Accelerators and Beams **3**, 084401 (2000).

Multiple descriptions of beam propagation in plasma

1. **Fully electromagnetic relativistic PIC code.**
2. **Semi-analytical mode for long beams l_b>> r_b**
   - **Electron fluid description.**
   - **Assumption of conservation of generalized vorticity.**

I.Kaganovich, G. Shvets, E. Startsev and R.C. Davidson, Phys. Plasmas **8**, 4180 (2001).

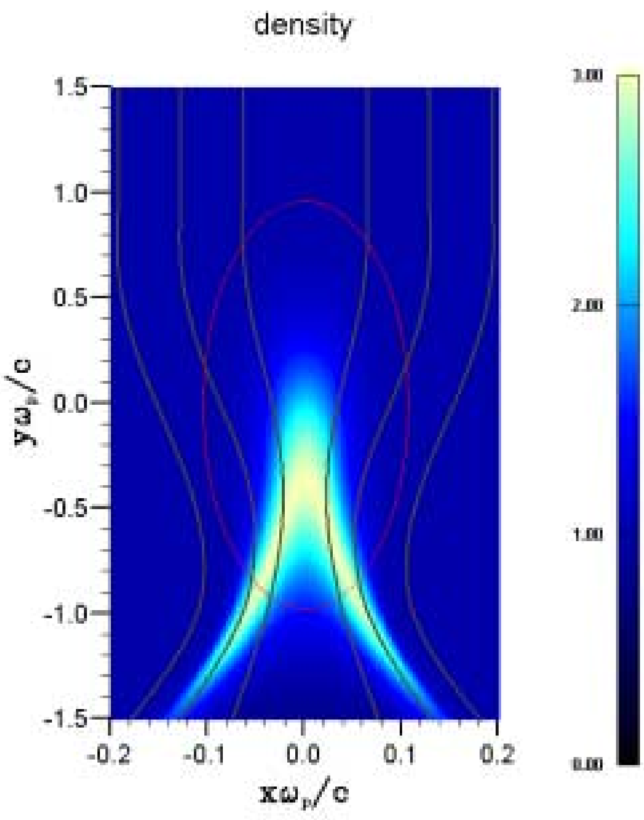


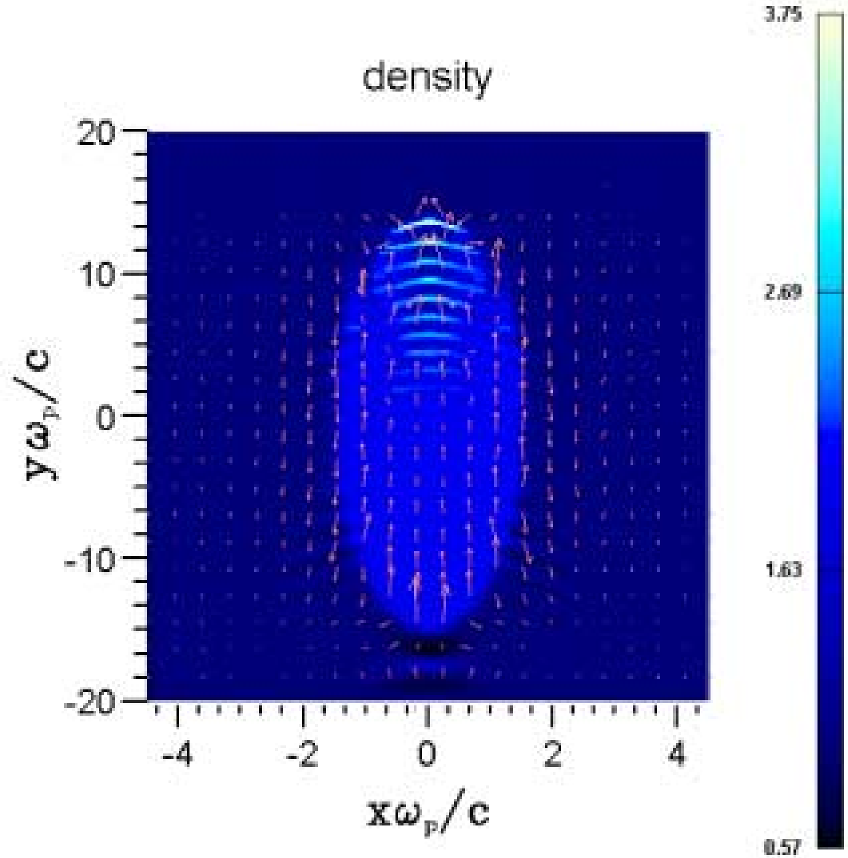
Comparison of (1) and (2) for System parameters:

$$r_b = 1.5c/\omega_p \qquad l_b = 15c/\omega_p$$

$$n_p = n_b \qquad V_b/c = 0.5$$

Analytic theory of chamber transport: excitation of plasma waves by beam depends on bunch length





β_b=0.5, l_b=1c/ω_p, r_b=0.1c/ω_p, n_b/n_p=0.5

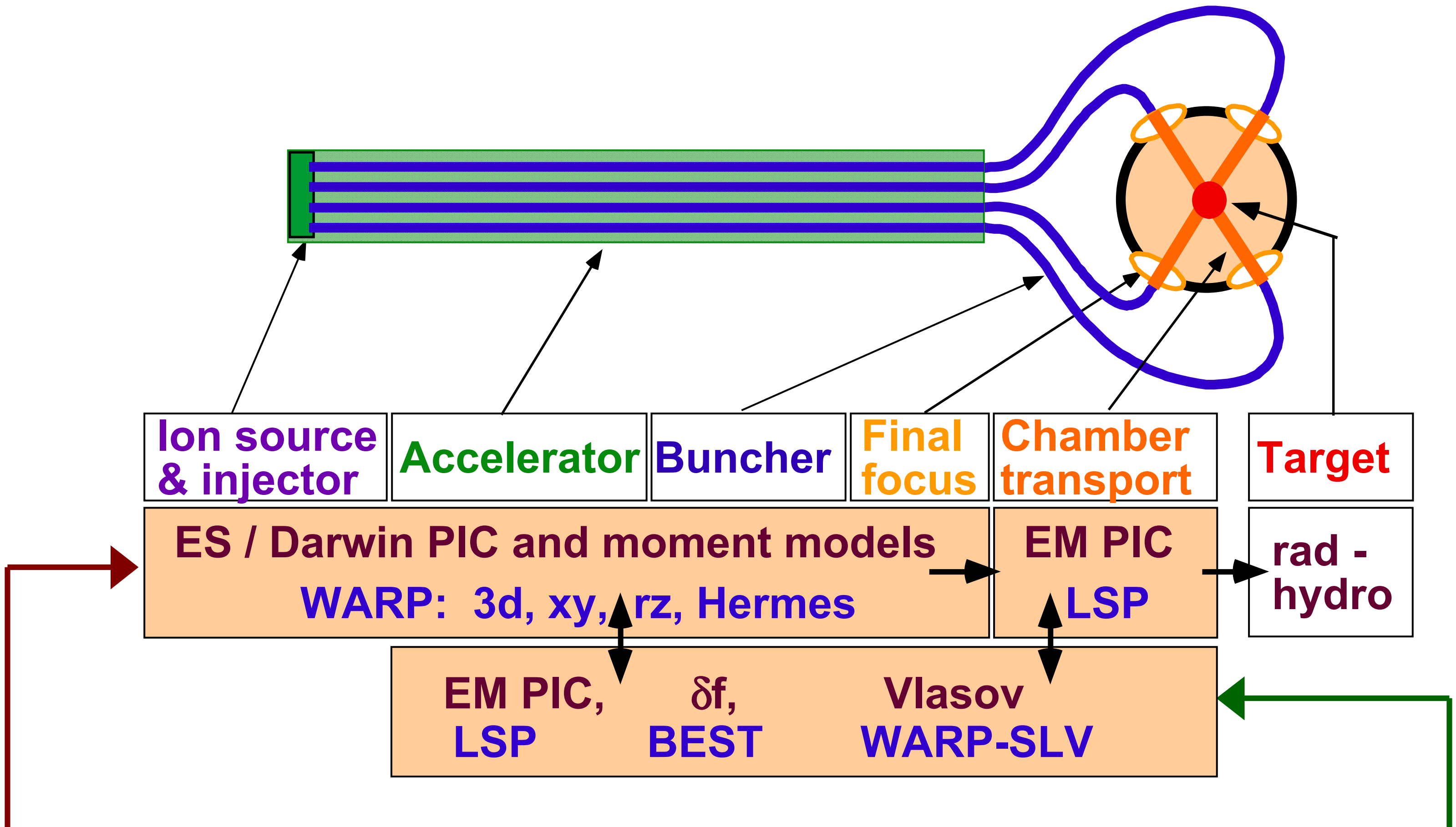
Red line: ion beam size

Brown lines: electron trajectory in beam frame

l_b=15c/ω_p, r_b=1.5c/ω_p, n_b/n_p=1

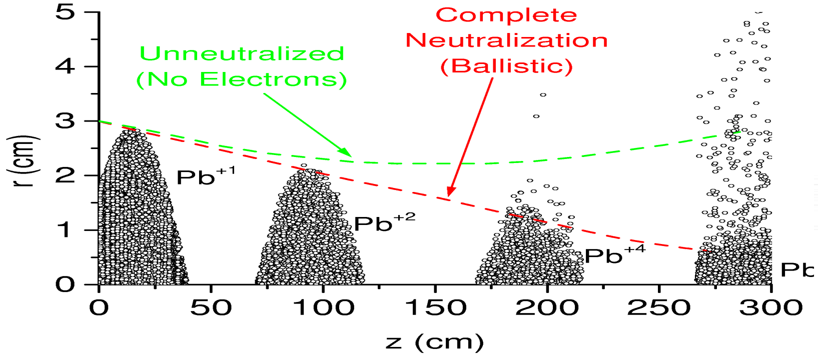
Vector lines: current

Our goal is an *integrated*, *detailed*, and *benchmarked* source-to-target beam simulation capability

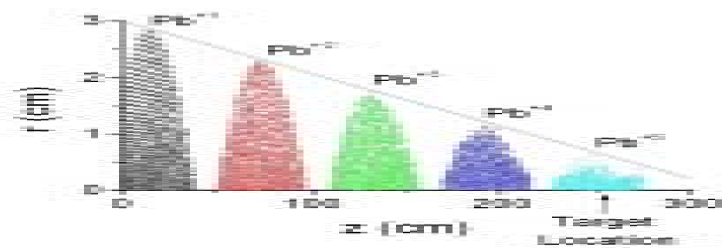


- Track beam ions consistently along entire system
- Study instabilities, halo, electrons, ..., via coupled detailed models

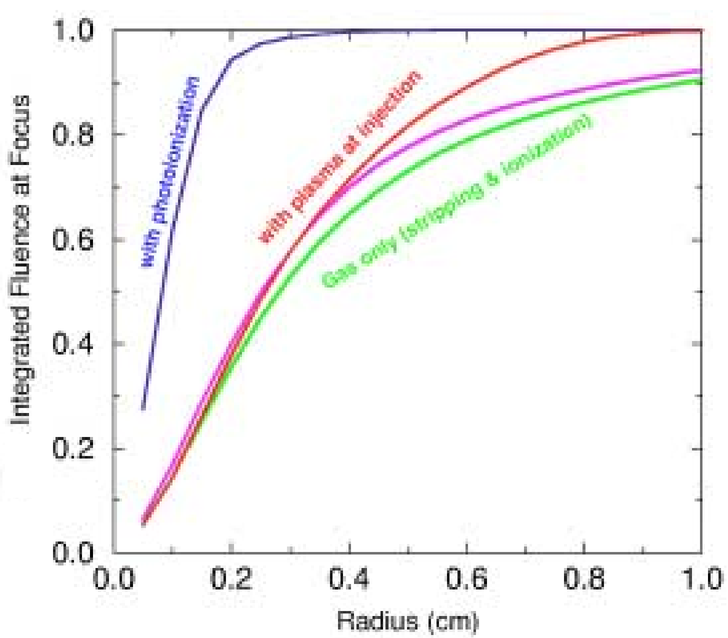
LSP Simulations of Chamber Transport: Plasma is essential to overcoming beam space charge



Gas effects only (stripping & ionization)



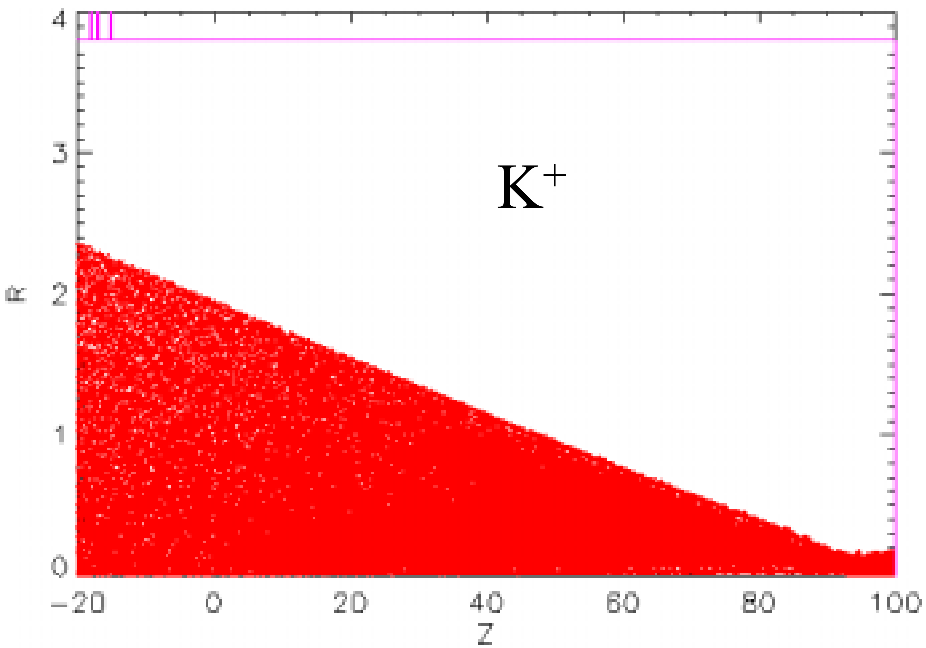
With photo-ionized plasma

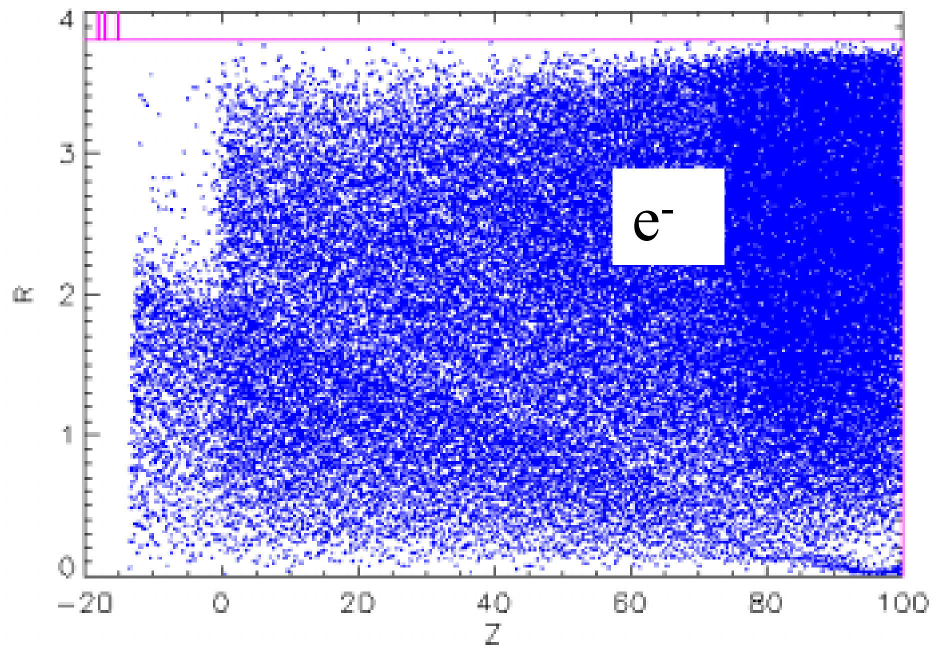


- 4-kA, 4-GeV, 8-ns Pb^+ beam
- 3-cm "parabolic" profile (constant J_b)
- 30 πmm-mrad un-normalized emittance
- R. Olson stripping X-sections for all states
- 5×10^{13} cm^{-3} FLiBe ambient gas
- Photo-ionized FliBe$^+$ plasma has 5×10^{13} cm^{-3} maximum density

Volumetric Plasma Simulation (LSP)

- Neutralization fraction ~0.99
- Small ion beam spot





Selected Recent Accomplishments (Continued)

- Initiated two experimental activities and one feasibility study in high-leverage areas that make effective use of PPPL's established experimental capabilities and off-site facilities. These activities include:

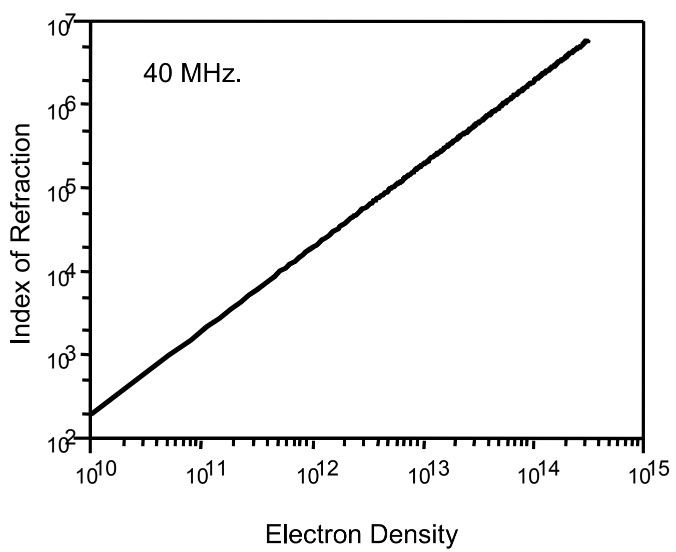
  - ⇨ Development and application of rf techniques for formation of preionized plasma in the target chamber, including demonstration of plasma production (Efthimion, Gilson).
  - ⇨ Measurement of multielectron loss events for intense ion beam propagation through background gas, including initial measurements with Xe^{+11} and Kr^{+7} ions using the Texas A&M cyclotron (Grisham, Mueller, Kaganovich).
  - ⇨ Feasibility study of developing a heavy ion neutral beam driver based on the acceleration of negative ions (Grisham).

- Engineering capability being developed in beam compression/final focus optics and target chamber interface areas (Heitzenroeder, Jun, Qin).

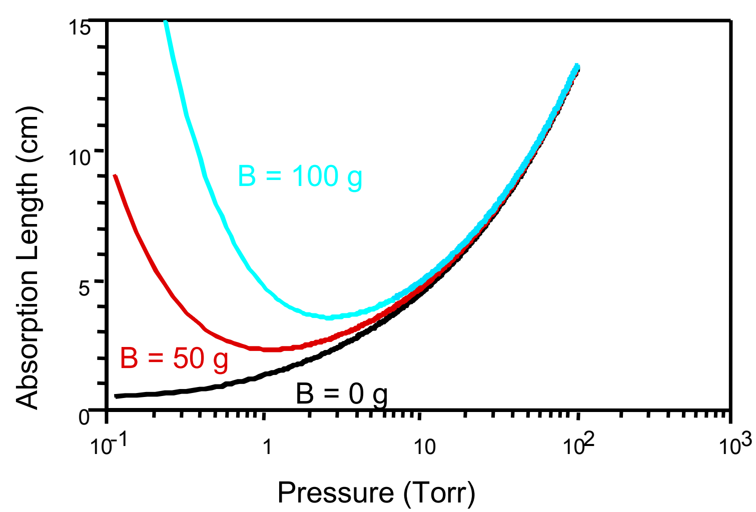
Pre-ionized Plasma Formation

- **Personnel:** P. Efthimion, E. Gilson, R. Davidson, P. Kolchin
- **Objective:** Develop RF techniques for preionized plasma formation for application to charge neutralization of intense heavy ion beams in the target chamber.

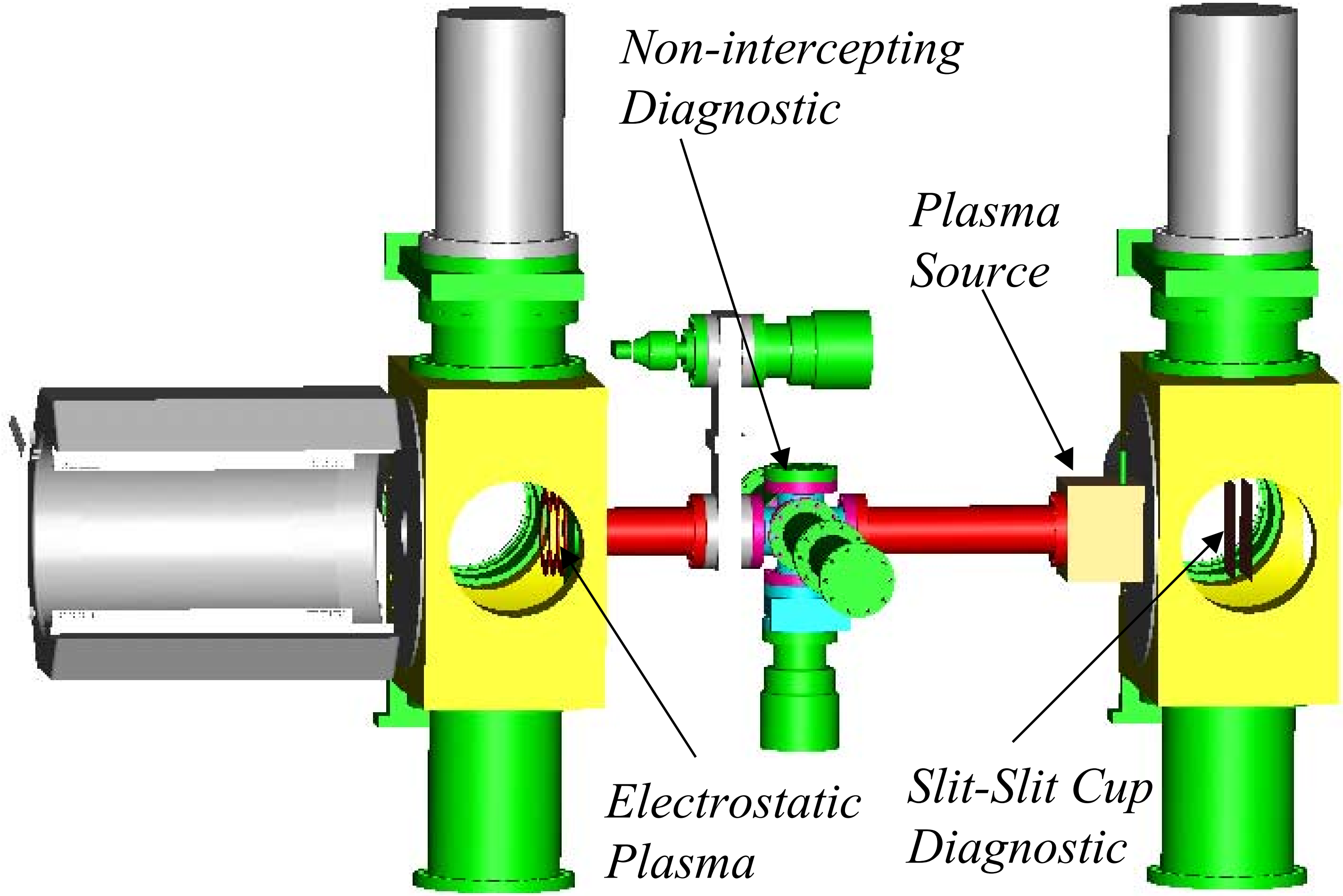
Whistlers propagate at all densities



Weak B-field extend plasma length



Volumetric Neutralization Experiment



Multielectron Loss Events

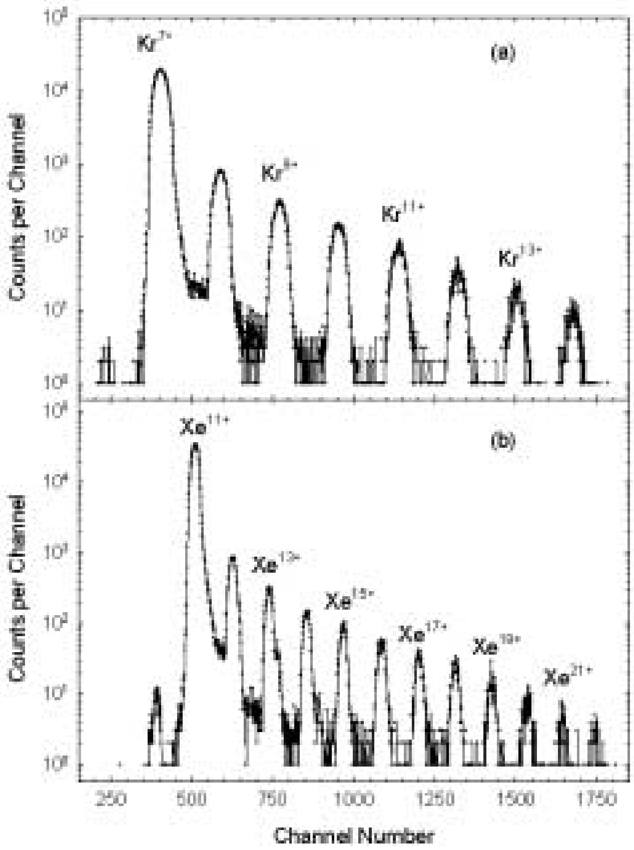
- **Personnel:** L. R. Grisham, D. Mueller, I. Kaganovich

- **Objective:** Determine possible impact of multielectron loss events upon the charge state distribution in a heavy ion driver beam traversing the target chamber medium.

  - High ion charge states caused by multielectron loss events could jeopardize ability to focus beam to small spot size [D. Mueller, L. Grisham, I. Kaganovich, et al, Phys. Plasmas 8, 1753(2001)].
  - Initial gas cell experiments carried out using Texas A&M cyclotron (Xe^{+11} at 3.4 MeV/amu through nitrogen, a good model for FLIBE vapor).

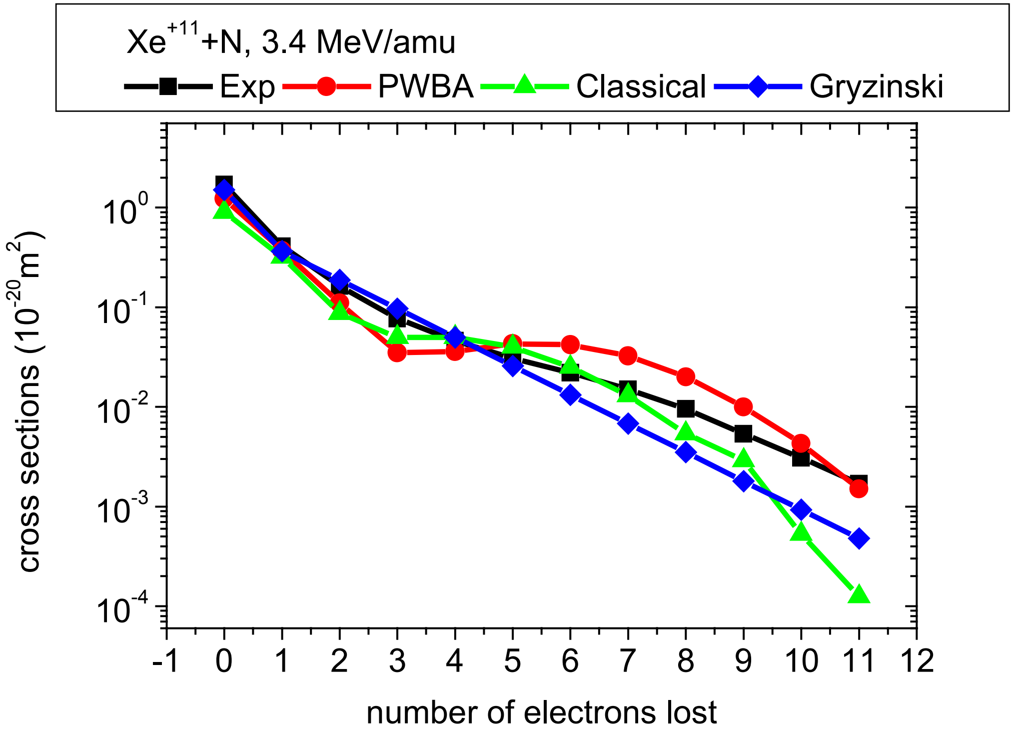
Multielectron Losses

- Charge distributions for 3.4 MeV/u beams of (a) Kr^{+7} and (b) Xe^{+11} showing the number of detected ions as a function of position along the detector with a N_2 pressure of 4 mTorr in the gas cell.



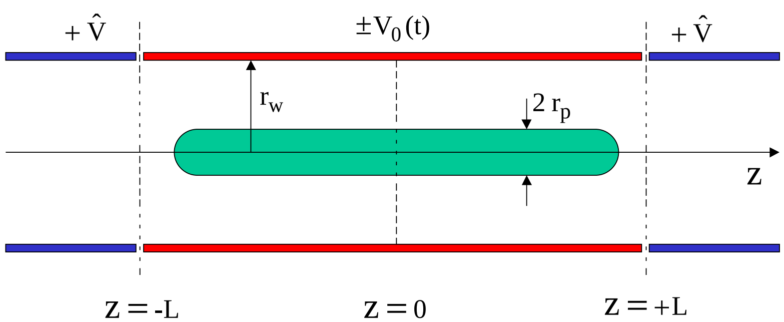
Multielectron Loss Cross Sections in Xe

- Average cross-sections for electron loss from 3.4 MeV/m Xe^{11+} in N_2 per one nitrogen atom determined from the data taken at cell pressures ≤ 8 mTorr.

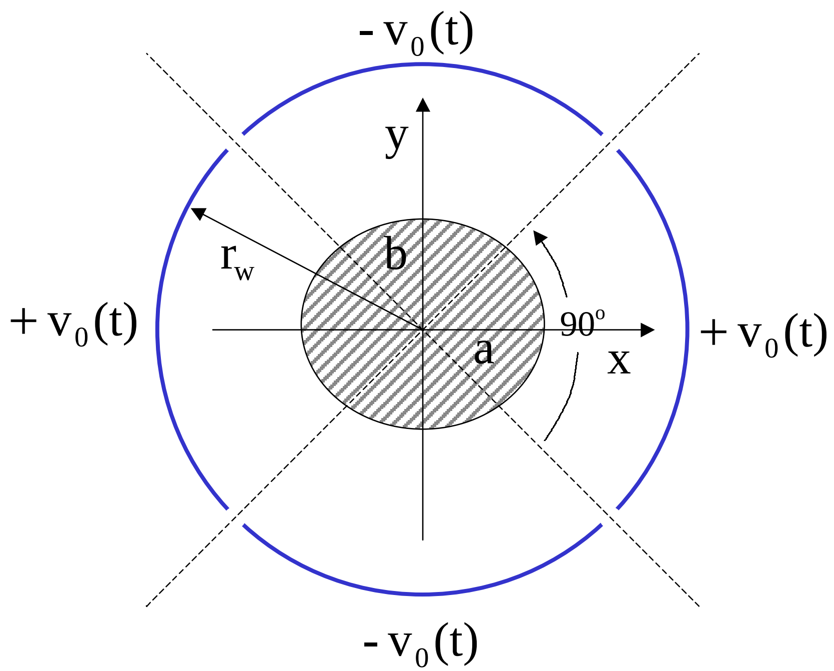


Paul Trap Simulator

- **Personnel:** R. Davidson, P. Efthimion, E. Gilson, R. Majeski, H. Qin
- **Objective:** Simulate collective processes and dynamics of intense charged particle beam propagation through an alternating-gradient focusing field using a compact laboratory Paul trap.



(a)



(b)

Nominal Operating Parameters (Barium Ions)

- Plasma column length — 2m
- Wall electrode radius — 10cm
- Plasma column radius — 1cm
- Maximum wall voltage — 400V
- End electrode voltage — 500V
- Voltage oscillation frequency — 60kHz

Paul Trap Simulator

- Experimental studies will include:
  - Beam mismatch and envelope instabilities.
  - Collective wave excitation.
  - Chaotic particle dynamics and production of halo particles.
  - Mechanisms for emittance growth.
  - Effects of distribution function on stability properties.
- Plasma will be formed using a barium coated platinum or rhenium filament. Plasma microstate will be determined using laser-induced fluorescence (Levinton, FP&T).

PPPL Research Productivity

2000-2001 has been a period of high research productivity in the nonlinear beam dynamics and nonneutral plasma area.

- Thirty-three journal publications, including twenty-two refereed papers and eleven published conference proceedings.
- Eight PPPL papers presented at the International Symposium on Heavy Ion Fusion (March, 2000)

Graduate-level text on intense particle beams in high-energy accelerators by Davidson and Qin (World Scientific, 2001)