Nonlinear Beam Dynamics and Nonneutral Plasmas

Research Activity Areas

➪ Heavy Ion Fusion (Davidson, Efthimion, Gilson, Grisham, Heitzenroeder, Jun, Kaganovich, Lee, Qin, Strasburg)

- Theory and simulation of intense beam propagation, and beam-plasma interactions in the target chamber.
- Experimental studies of preionized plasma formation, and multielectron loss events in the target chamber.
- Final focus magnetic system modeling and engineering design.

➪ Paul Trap Simulator (Davidson, Efthimion, Gilson, Kochin, Majeski, Qin)

- Paul trap experiment for simulating intense beam propagation in alternating-gradient field configurations (DOE OFES, new initiative).

Research Activity Areas (continued)

- Accelerator Physics for Nuclear and High Energy Physics Applications (Davidson, Kaganovich, Lee, Qin, Startsev, Stowell, Tzenov)
  - Theory and simulation of next-generation colliders (DOE HENP, new initiative).
  - Theory and simulation of electron-proton two-stream instability (Spallation Neutron Source).
- Trapped Nonneutral Plasmas and the Electron Diffusion Gauge (EDG) Experiment (Davidson, Jenkins, Morrison, Paul, Phillips)
  - Effect of neutral pressure on nonneutral plasma expansion (ONR).
  - Reaction rate measurements for solar neutrino production (LPDA).

Nonlinear Beam Dynamics

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 derivation 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.

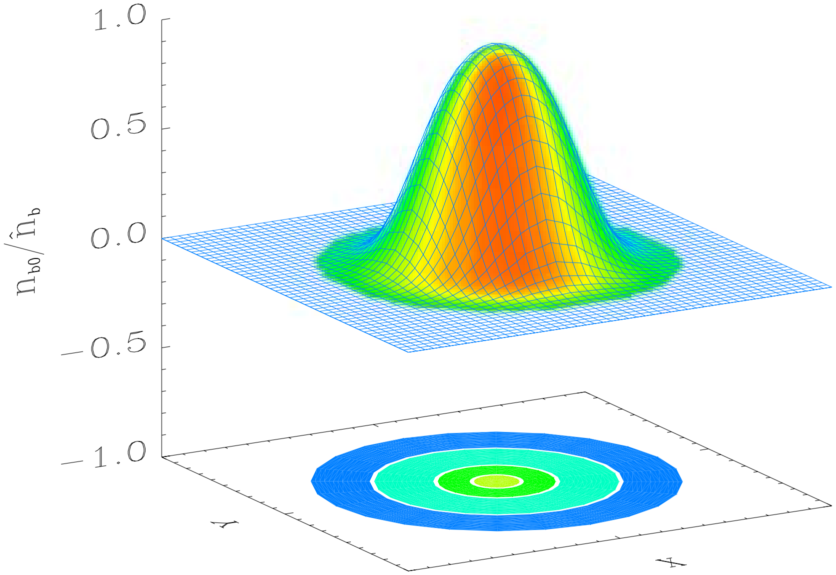
- ➪ Application of test-particle model to explore chaotic particle dynamics and halo formation induced by collective mode excitations in high-intensity ion beams, including estimates of the maximum radial excursion of the halo particles.

Selected Recent Accomplishments (continued)

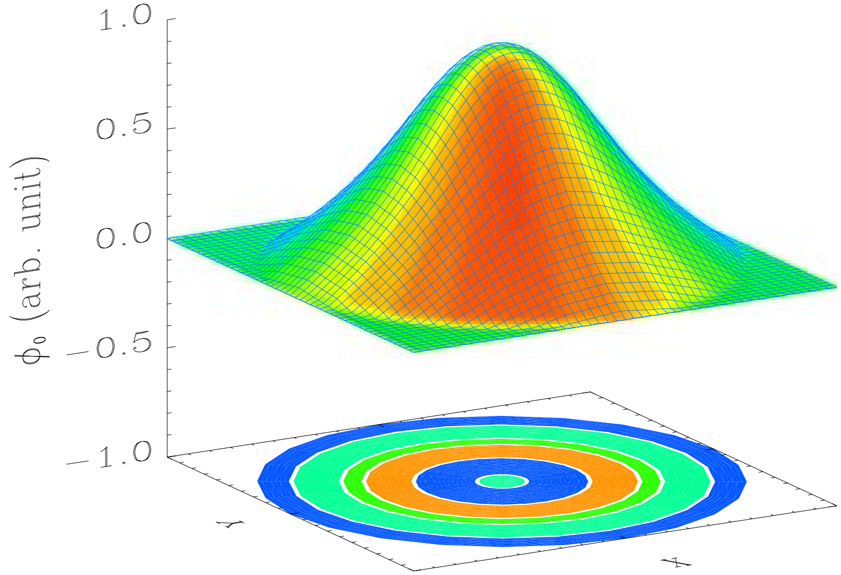
- Development of nonlinear 2D and 3D delta-f simulation schemes for intense beam propagation in periodic focusing systems, including application to stable, matched-beam propagation of a thermal equilibrium beam over hundreds of lattice periods, and detailed investigation of the nonlinear evolution of the two-stream instability at high beam intensities.

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

BEST Simulation of Thermal Equilibrium Beam Propagation



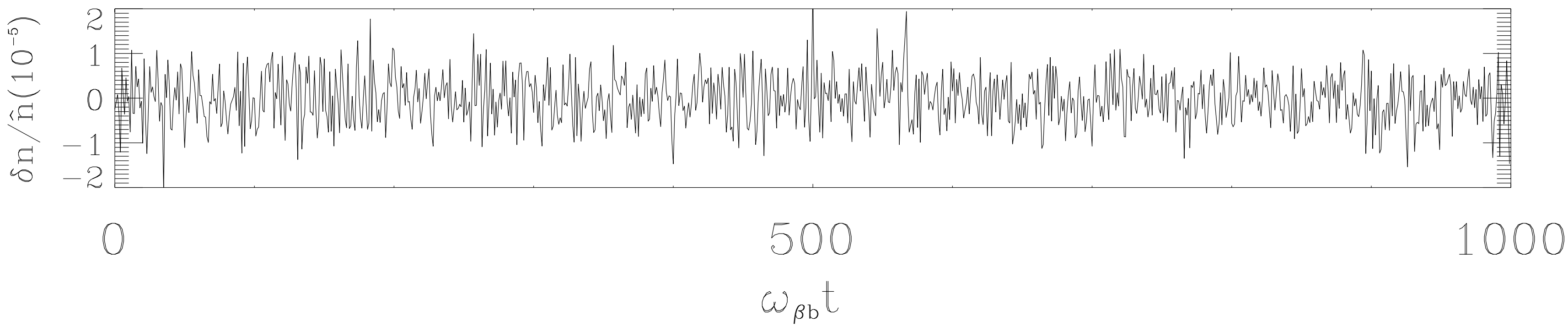
(a) Equilibrium Density

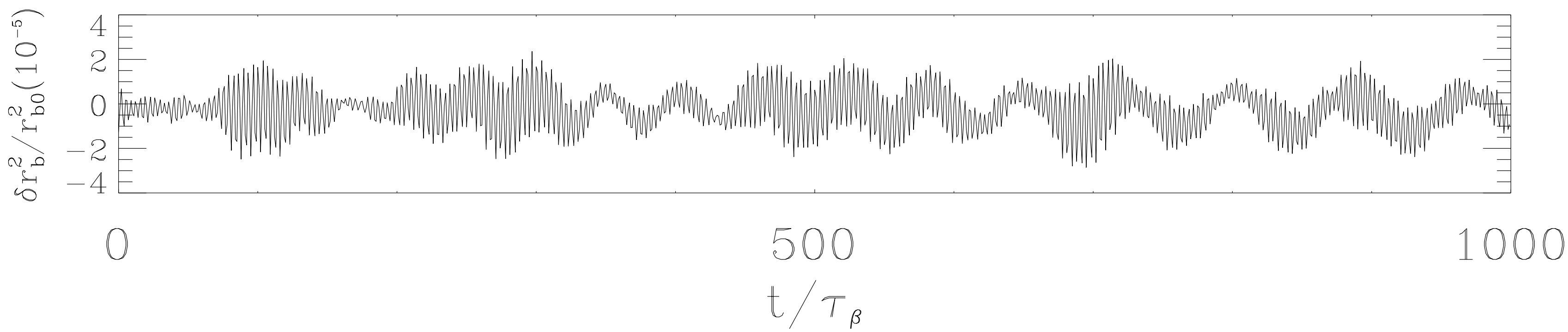


(b) Equilibrium Space-Charge Potential

- Equilibrium solutions (ϕ_0, A_{z0}, f_{j0}) solve the steady-state ($\partial/\partial t = 0$) Vlasov-Maxwell equations with $\partial/\partial z = 0$ and $\partial/\partial\theta = 0$.
- System parameter are chosen to be: $\gamma_b = 1.08$, $A = 133$, and normalized beam intensity $s_b \equiv \hat{\omega}_{pb}^2/2\gamma_b^2\omega_{\beta b}^2 = 0.95$.

Nonlinear Properties of Thermal Equilibrium Beams

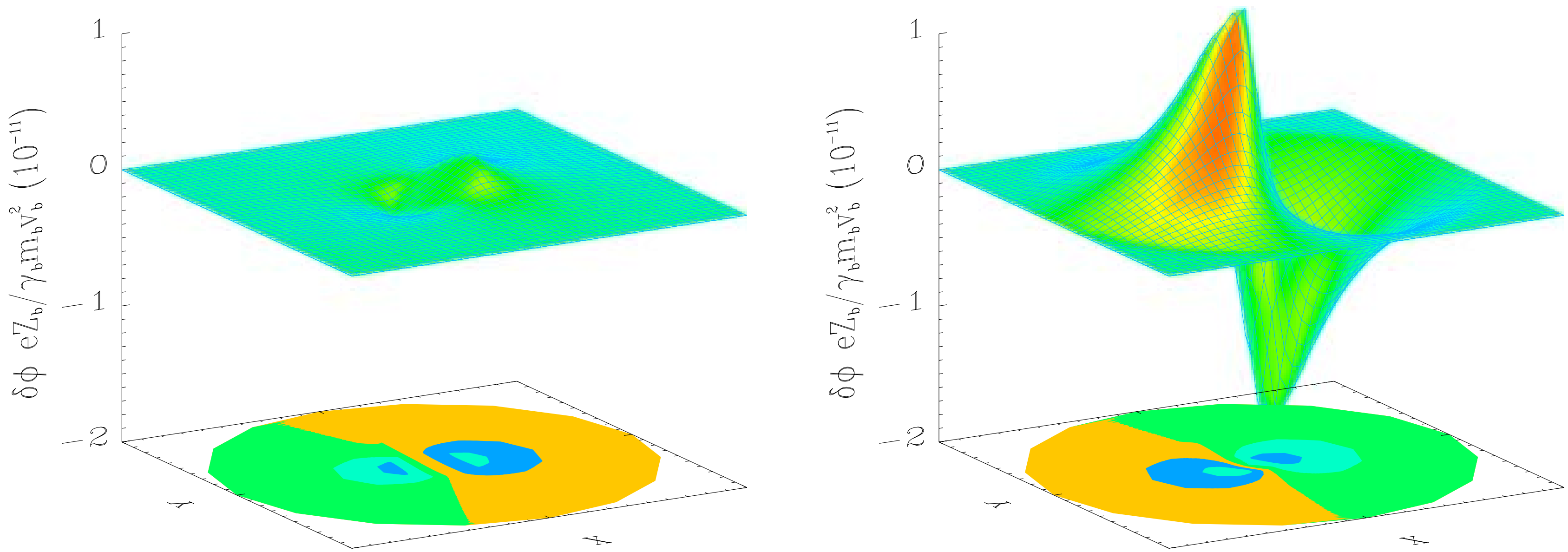




➪ BEST simulation results show that the perturbations do not grow and the beam propagates quiescently, which agrees with the nonlinear stability theorem for the choice of thermal equilibrium distribution function.

BEST Simulation of Two-Stream Instability

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



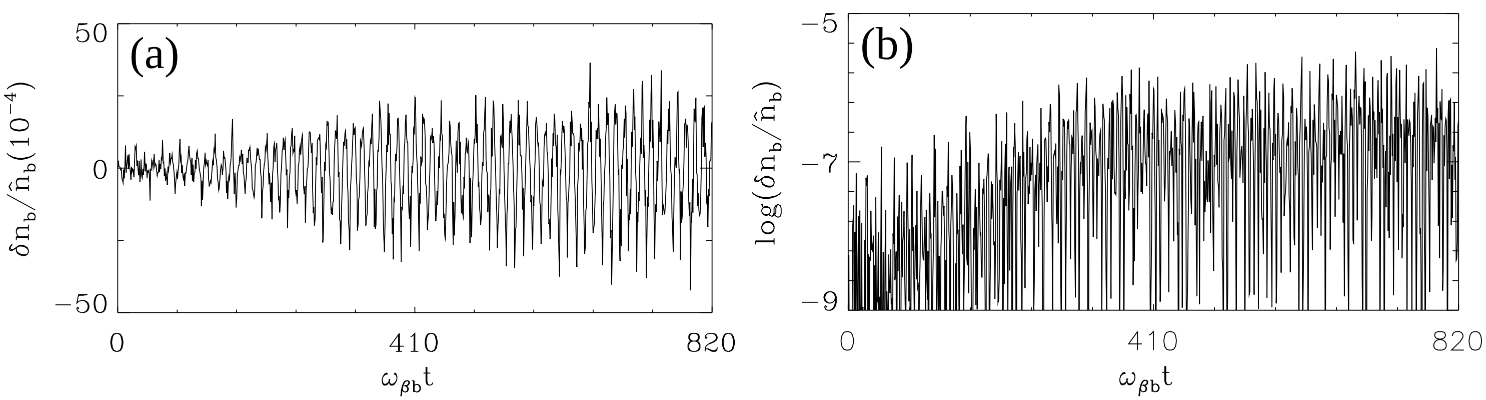
(a) $t = 0$ (b) $t = 200/\omega_{\beta b}$

➪ Linear growth phase shows strong dipole mode structure.

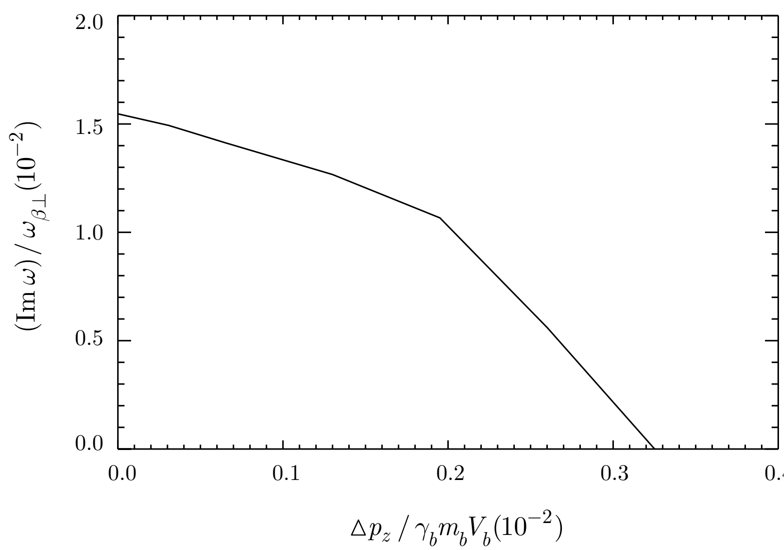
➪ Two-stream instability can be stabilized by modest axial momentum spread of beam ions.

BEST Simulation of Two-Stream Instability

- Nonlinear perturbation saturation level $\delta n_b \sim 3.0 \times 10^{-3} \hat{n}_b = 6 \times 10^{5} \text{cm}^{-3}$.



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



Future Plans – Heavy Ion Fusion

- ➪ Develop improved kinetic models based on nonlinear Vlasov-Maxwell equations describing equilibrium and stability properties of intense heavy ion beams propagating in periodic focusing field configurations.

- ➪ Investigate collective instabilities and identify optimum beam distribution and parameter regimes for quiescent beam propagation over large distances.

- ➪ Explore collective excitation mechanisms for halo formation, and identify regimes for halo-free operation.

- ➪ Investigate beam-plasma interactions in the target chamber. Identify operating regimes that mitigate the effects of two-stream and filamentation instabilities.

Future Plans – Heavy Ion Fusion(continued)

- Apply the 2D and 3D nonlinear delta-f simulation schemes developed at PPPL to augment and validate the analytical studies, with particular emphasis on collective instabilities, halo formation and control, and emittance growth. Explore effects of two-stream instabilities for beam propagation in the target chamber, and in beam transport lines.
- Technical focus of PPPL experimental and engineering activities:
  - Develop and apply rf techniques for preionized plasma formation in the target chamber.
  - Measure multi-electron loss events.
  - Feasibility study of negative-ion-based heavy ion neutral beam driver.
  - Advanced engineering design of final focus magnet system.

Future Plans – High Energy and Nuclear Physics

- ➪ Determinate the sensitivity of the production of energetic halo particles to beam intensity and luminosity, the amplitude of collective excitations, and beam mismatch and bunch length in present and next-generation hadron colliders and electron-positron colliders.

- ➪ Apply 3D multispecies nonlinear perturbative simulation techniques to investigate detailed nonlinear processes and collective interactions involving two charge components, with particular emphasis on:

  - ❍ Electron cloud instability in high-energy hadron colliders.
  - ❍ Beam-beam interactions in electron-positron colliders.
  - ❍ Electron-proton two-stream instability in proton storage rings.

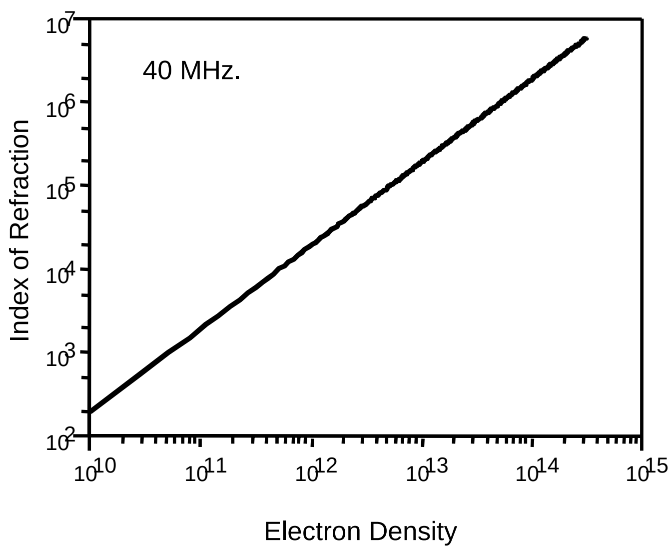
- ➪ Identify operating conditions for optimum performance (beam stability, luminosity, *etc.*).

Pre-ionized Plasma Formation

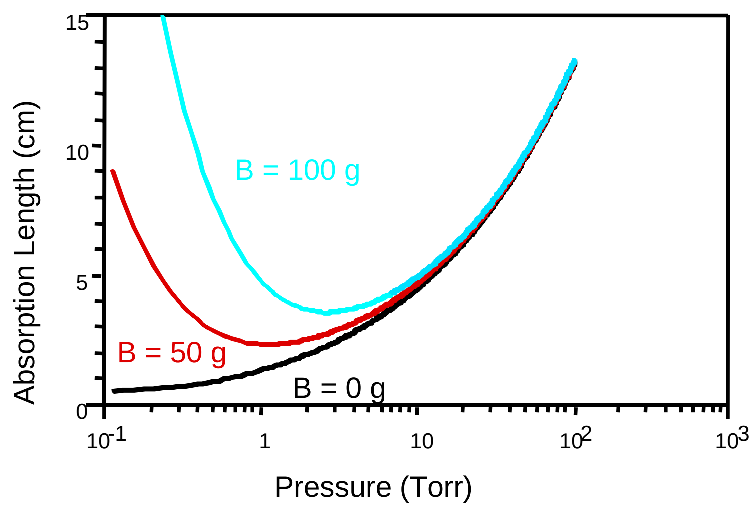
- **Personnel:** P. Efthimion, E. Gilson, R. Davidson, P. Kolchin

- **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



Multielectron Loss Events

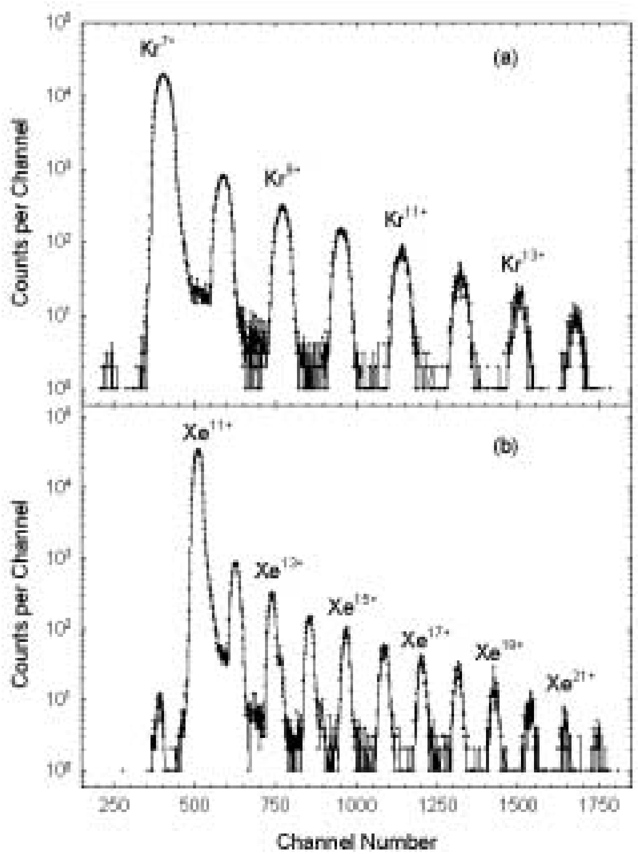
- **Personnel:** L. R. Grisham, D. Mueller, I. Kaganovich

- **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).

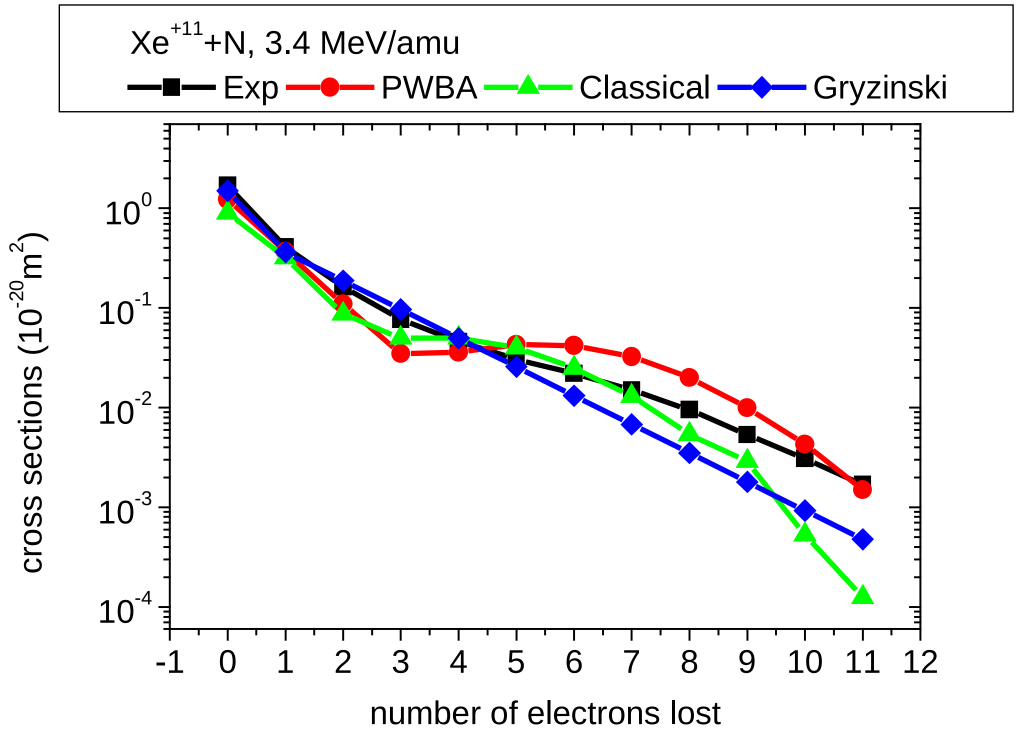
Multielectron Losses

- 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 Losses Cross Sections in Xe

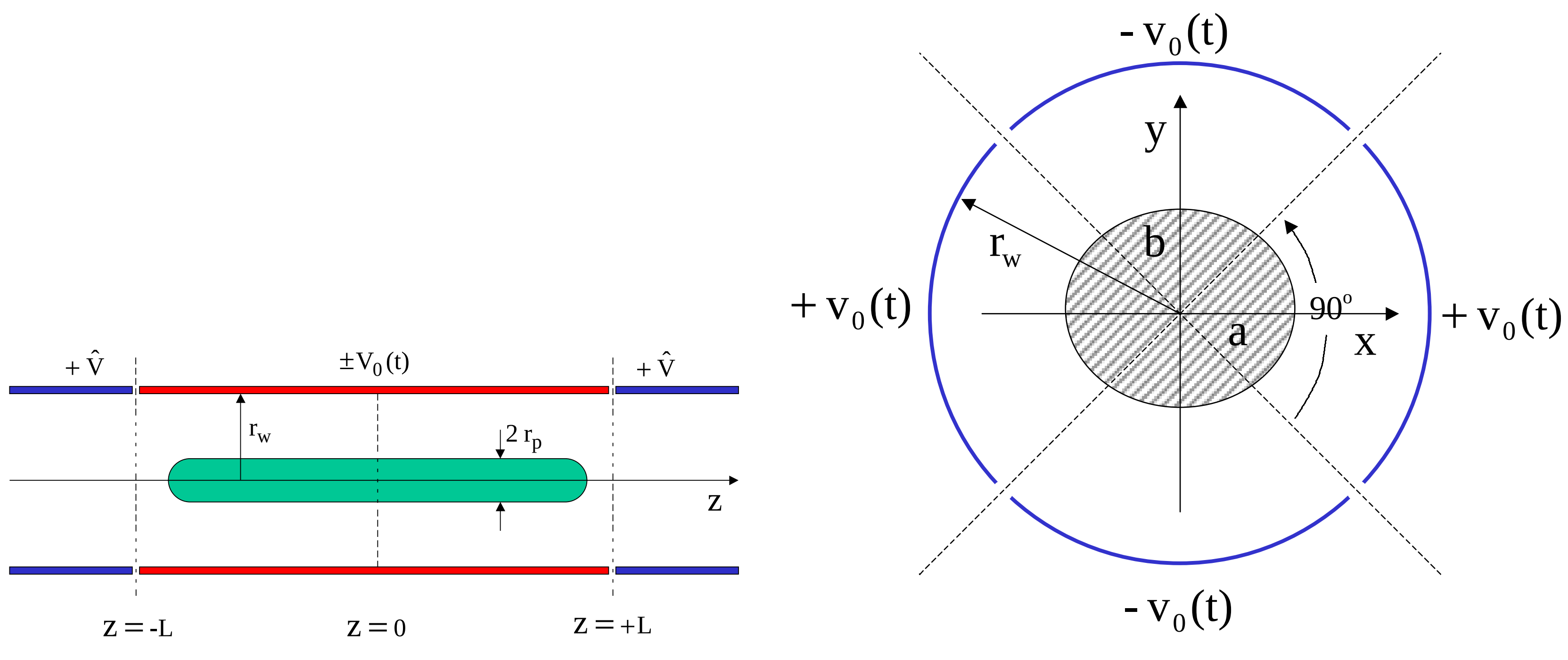
- Average cross-sections for electron loss from 3.4 MeV/m Xe^{11+} in N_2 per one nitrogen atom determined from the data taken at cell pressures ≤ 8 mTorr.



Paul Trap Simulator

- **Personnel:** R. Davidson, P. Efthimion, E. Gilson, P. Kolchin, 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)

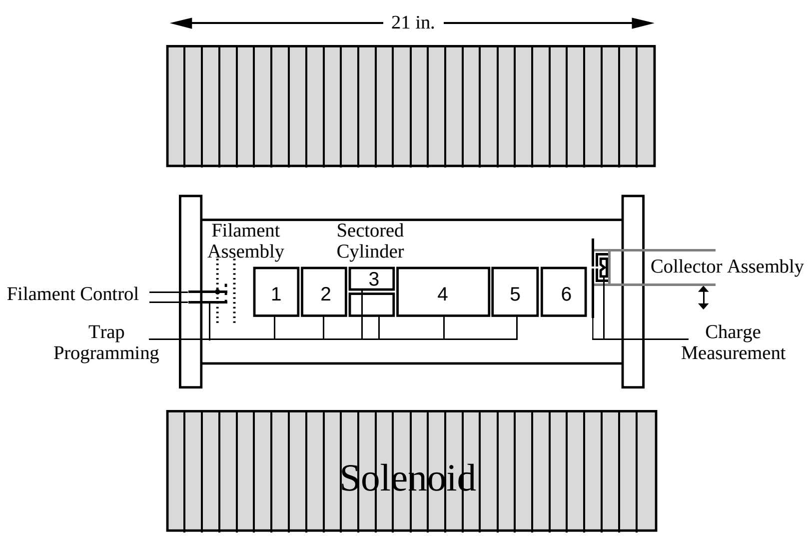
- Plasma column length — 2m
- Wall electrode radius — 10cm
- Plasma column radius — 1cm
- Maximum wall voltage — 400V
- End electrode voltage — 500V
- Voltage oscillation frequency — < 240kHz

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).

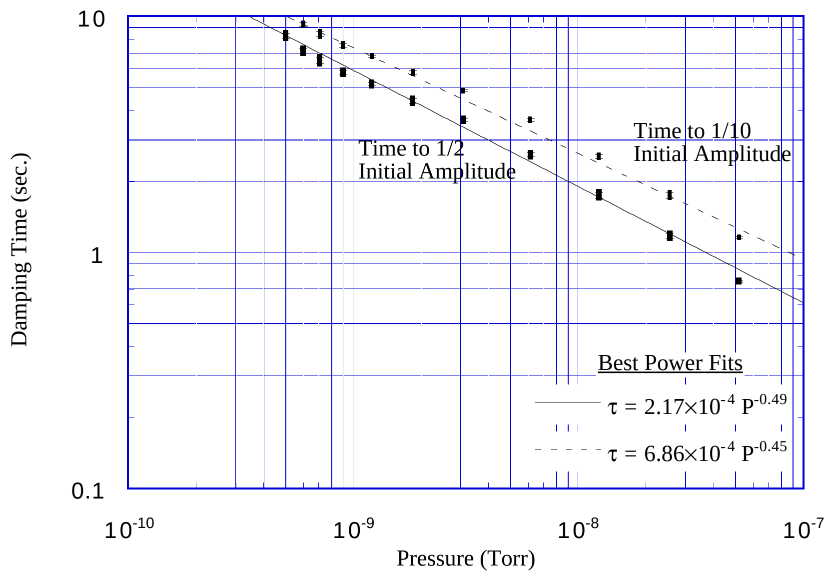
Electron Diffusion Gauge (EDG) Experiment

- **Personnel:** R. C. Davidson, T. Jenkins, K. Morrison, and S. Paul
- **Objective:** Explore the effects of background neutral gas on the stability of and transport in pure electron plasmas in a Malmberg-Penning trap.
- **Motivation:** A fundamental understanding of how electron collisions with background neutral gas atoms affect the plasma dynamics could lead to methods of inferring the background neutral gas pressure or deducing electron-neutral collision cross-sections.



Magnetic Field: 300 – 600G
Electron Density: $5\times10^{6} - 3\times10^{7}\text{cm}^{-3}$
Debye Length: 2 – 3mm
Plasma Radius: 1.2 – 2.5cm
Background
Gas Pressure: $> 10^{-10}$Torr

Damping is Sensitive to Background Neutral Gas Pressure



- The m=1 diocotron mode exhibits non-exponential damping in the presence of a finite background gas pressure P.
- The time τ for the measured m=1 diocotron mode amplitude to decay to one-half of its initial value is plotted as a function of the background gas pressure.
- Measurements of the diocotron mode amplitude evolution show sensitivity to the background pressure down to the base pressure of 5×10^{-10} Torr.

Research Productivity

1999-2001 has been a period of high research productivity in the nonlinear beam dynamics and nonneutral plasma area.

- Fourty-one journal publications, including thirty-one refereed papers and ten published conference proceedings.
- Graduate-level treatise "Physics of Intense Charged Particle Beams in High Energy Accelerators" completed by Davidson and Qin.
- Eight papers presented at the International Symposium on Heavy Ion Fusion (March, 2000).
- Eleven paper presented at 2001 Particle Accelerator Conference (June, 2001).

Conclusions

- Many of the advanced analytical and simulation techniques developed in the study of nonneutral plasmas and magnetic fusion plasmas are being extended and applied to describe the nonlinear dynamics and collective processes in intense charged particle beams.

- Experimental activities emphasize innovative approaches to studies of preionized plasma formation in the target chamber (heavy ion fusion), intense beam propagation in periodic focusing systems (Paul trap simulator), and neutral-collision-induced transport in nonneutral plasmas (Malmberg-Penning trap).