Heavy Ion Beam Physics --- Theory and Modeling

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http://noneutral.pppl.gov/

PPPL Theory Department Five Year Plan

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Heavy Ion Beam Science for HEDP and Fusion

- Heavy ion beam theory and simulations to address a top-level scientific question central to both High Energy Density Physics (HEDP) and fusion*:

> *T7: How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion?*

- Principal science thrust areas:
  - High brightness beam transport
  - Focusing onto targets
  - Longitudinal beam compression
  - Beam-target interaction
  - Advanced theory and simulation tools

* From FESAC Priorities Panel Report (April, 2005).

PPPL Plays a Leading Role in Heavy Ion Fusion Research

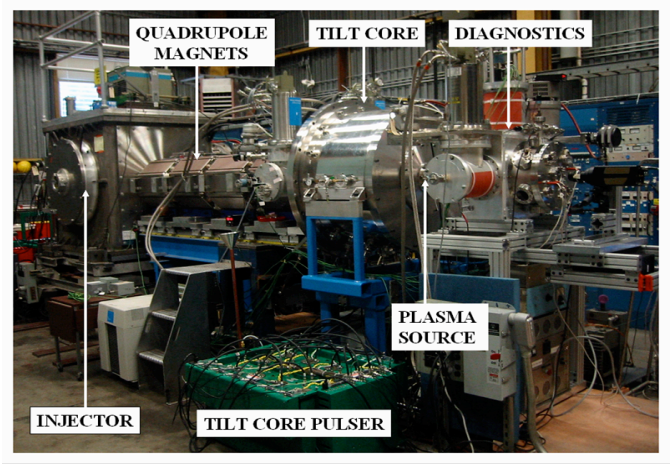
- Heavy Ion Fusion Virtual National Laboratory
  - Lawrence Berkeley National Laboratory
  - Lawrence Livermore National Laboratory
  - **Princeton Plasma Physics Laboratory**

- Other collaborating US institutions

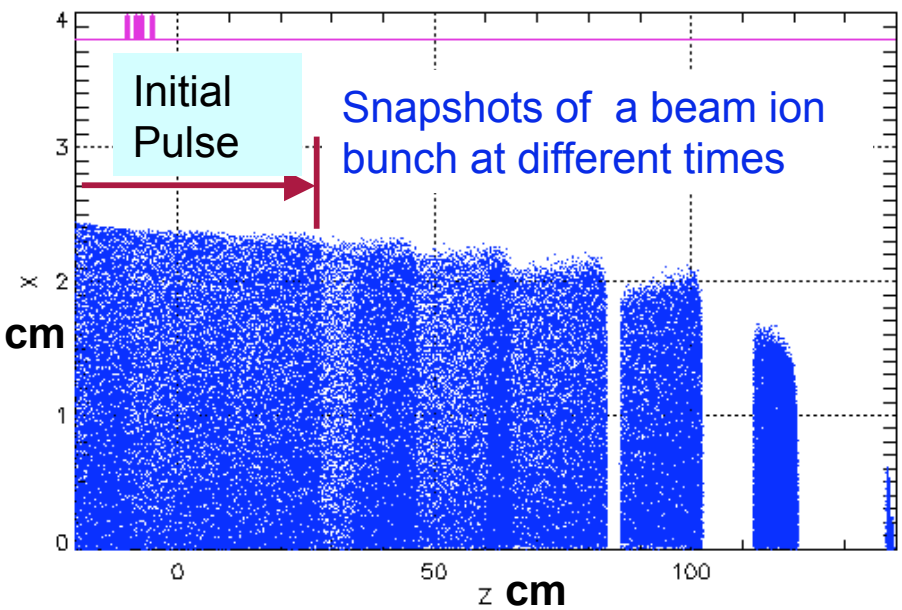
Mission Research Corporation
Sandia National Laboratories
University of Maryland
University of Missouri
Stanford Linear Accelerator Center

General Atomics
First Point Scientific
Tech-X
FAR-Tech

Unique Approach to Ion-Driven HEDP with Short Beam Pulses



- Short pulses (~ns) centered at Bragg peak.
- Background plasma for charge neutralization.
- 50X longitudinal compression achieved on Neutralized Drift Compression Experiment.
- 300 keV K+ ions @ 25 mA
- 200X transverse compression achieved in separate experiments.



- Simulations demonstrate dramatically larger compression and focusing using background plasma.
- Beam intensity on target predicted to increase by 50,000 X in accompanying LSP simulation.

Final Pulse

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Theory and Modeling of Heavy Ion Beams at PPPL

- Develop advanced analytical and numerical models to describe the nonlinear dynamics and collective processes in the compression, focusing, and transport of intense heavy ion beams and on beam-plasma interactions.
- Nurture accelerator physics applications and collaborative ties to other areas of physics with high discovery potential.
- Closely coupled with experimental studies of intense ion beam propagation and beam-plasma interactions in high-leverage areas that makes effective use of PPPL's established experimental capabilities.

Personnel

- R. C. Davidson, I. Kaganovich, W. W. Lee, H. Qin, and E. A. Startsev. [Experimentalists: P. Efthimion, E. Gilson, L. Grisham, D. Mueller]

Graduate Students

- A. Sefkow and W. Zhou

PPPL Has Achieved Major Scientific Advances

- Established the self-consistently Vlasov-Maxwell method for high intensity beam physics.
  - Nonlinear stability theorem. ►
  - Self-consistent theory for collective instabilities
    - Electron-ion two-stream instability ►
    - Electrostatic Harris instability
    - Electromagnetic Weibel instability
    - Resistive hose instability
  - Kinetic models for drift compression.

- Beam Equilibrium Stability and Transport (BEST) code for large scale delta-f PIC simulations of collective effects for high intensity beams.
  - Electron-ion two-stream instability. ►
  - Temperature anisotropy (Harris) instability.
  - Beam charge and current neutralization (EdPic,LSP). ►

"*Survey of Collective Instabilities and Beam-Plasma Interactions for Heavy Ion Beams*", R. C. Davidson, et al, Physical Review Special Topics on Accellerators and Beams **7**, 114801 (2004).

Nonlinear Stability Theorem

- Global conservation constrains satisfied by the nonlinear Vlasov-Maxwell equations.
- Determine class of beam distribution functions that are stable at high space-charge intensity.

$\psi(\mathbf{x})$

A sufficient condition for linear and nonlinear stability is

$$\frac{\partial f(H)}{\partial H} \le \frac{1}{2m_b}\mathbf{p}^2 + \psi(\mathbf{x}) + q_b\phi(\mathbf{x}),$$

where $\psi(\mathbf{x}) = \frac{1}{2}\gamma_b m_b \omega_{\beta\perp}^2 \left(x^2 + y^2\right) + \frac{1}{2}\gamma_b m_b \omega_{\beta z}^2 z^2 .$

--- self-space charge potential determined from .

--- external focusing potential .

- Generalization of Theorems by Gardener and Newcomb for electrically neutral plasma.
- Motivated and confirmed by the Paul Trap Simulator Experiment.

Physics of Intense Charged Particle Beams in High Energy Accelerators (World Scientific, 2001), R. C. Davidson and H. Qin, Chapter 4; R. C. Davidson, Physical Review Letters **81**, 991 (1998).

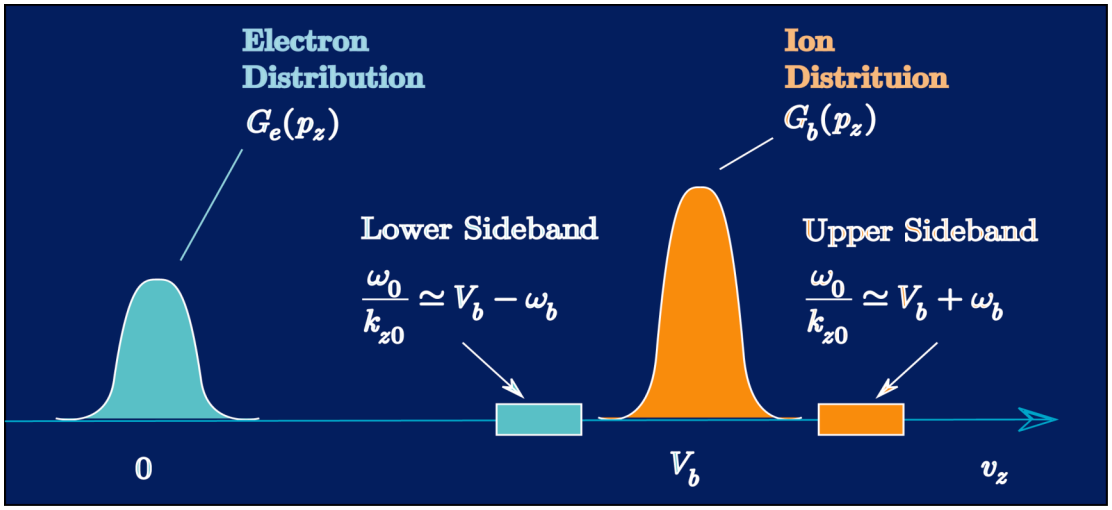
Beam Equilibrium Stability and Transport (BEST) Code

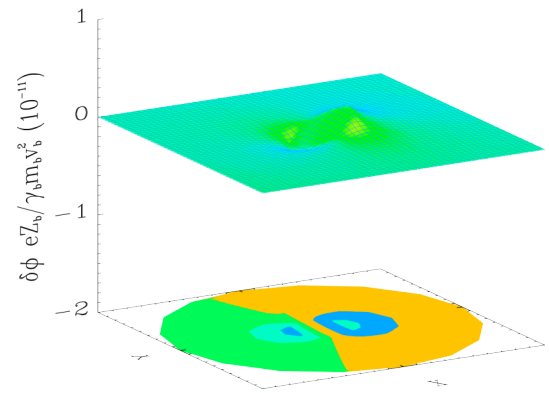
Physics

- Nonlinear delta-f particle simulation method to reduce noise.
- Linear eigenmodes and nonlinear evolution.
- 3D equilibrium structure (when it exists).
- Multi-species, electrons and ions, mass ratio ~ 0.5×10^6.
- Multi-time-scales, frequency span ~ 10^5.
- Large-scale parallel computing: particle x time-steps ~ 0.5×10^{12}.

Sixteen refereed publications

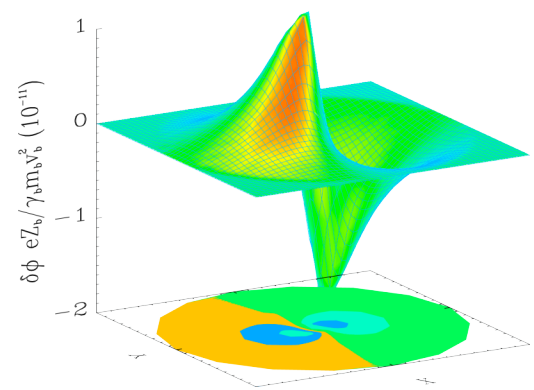
Electron-ion two-stream instability --- showstopper for high intensity ion accelerators





$t = 0$

- m=1 dipole mode destabilized by background electrons.
- Observed experimentally in high intensity ion beams.
- Showstopper for high intensity accelerators, e.g., SNS.
- Transverse geometry and damping are important.
- Simulations agree with experiments in the Proton Storage Ring in terms of mode structure, growth rate, and real frequency.

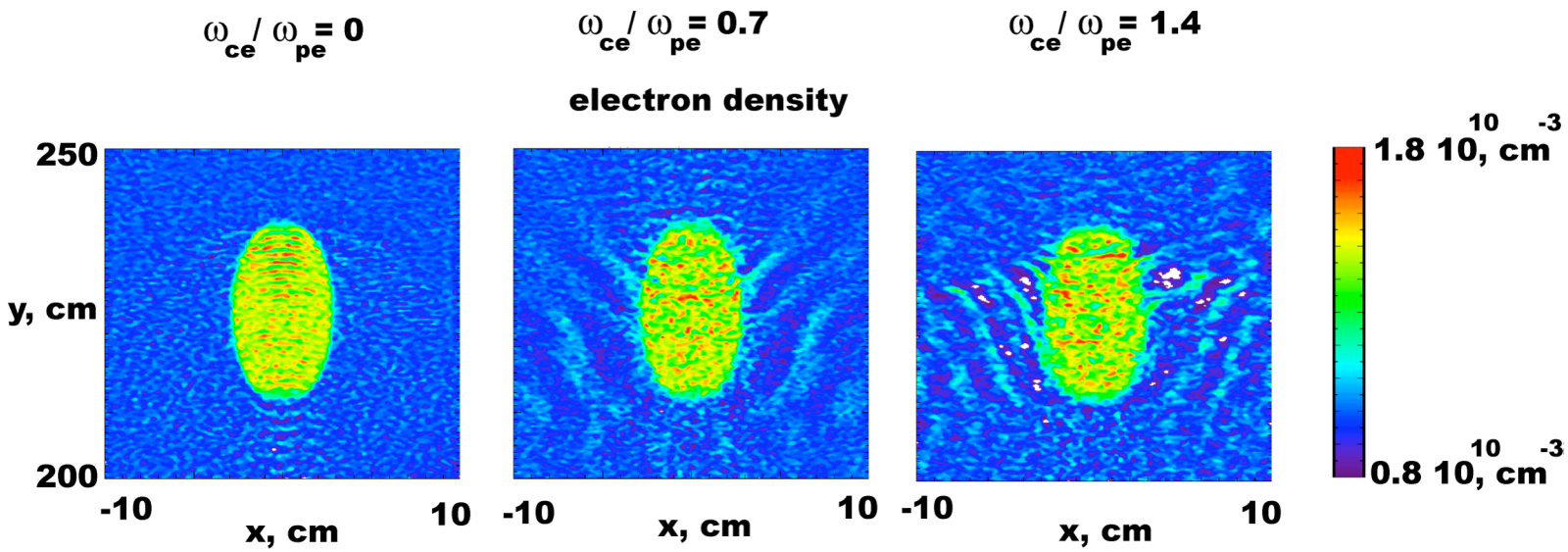


$t = 200/w_{bb}$

H. Qin, Physics of Plasmas 10, 2708 (2003); H. Qin, E. A. Startsev and R. C. Davidson, Physical Review Special Topics on Accelerators and Beams 6, 014401 (2003).

Solenoidal magnetic field reduces neutralization

- Whistler waves excited in a solenoidal magnetic field.
- Perturb the plasma ahead of the beam pulse.
  - Plasma density $n_p=10^{11}cm^{-3}$; B= 1014 G; $\omega_{ce}=\omega_{pe}$
  - 4.75 ns Beam at $V_b=0.2c$, I=48.0A, r_b=2.85.



I.D. Kaganovich, E. A. Startsev, R. C. Davidson and D. R. Welch, Nuclear Instruments and Methods in Physics Research **A544**, 383 (2005).

Five Year Task Areas and Specific Milestones

- Seven five-year task areas detailed in the Five-Year Plan.
- Specific milestones have been planned.

Example:

Task Area a)

Develop improved kinetic models based on the nonlinear Vlasov Maxwell equations to describe the equilibrium and stability properties of intense heavy ion beams propagating in periodic focusing accelerators and transport systems.

Milestone:

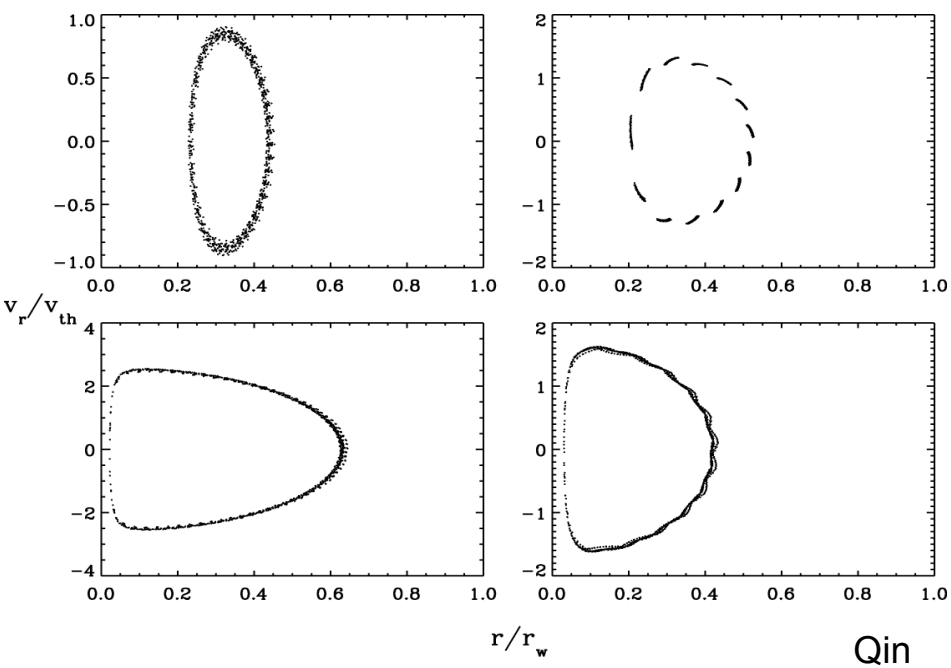
Complete development of improved analytical and numerical models of 3D bunched beams for detailed investigation of collective effects and instabilities (2006).

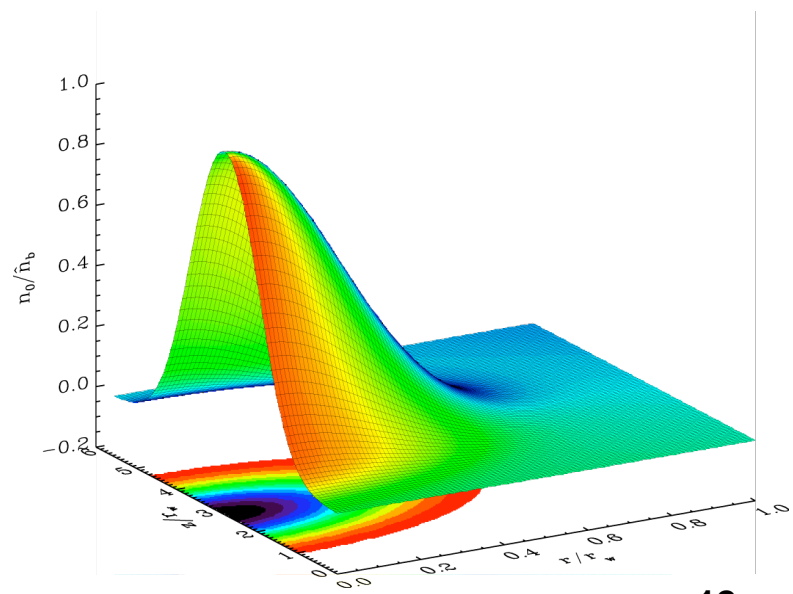
Task Area and Milestone Example: High Intensity Bunched Beams

- Nonlinear space charge field reduces the integrability of particle dynamics.
- Even for a well-defined isotropic thermal equilibrium beam, particles are chaotic.

$$\nabla^2\phi = -4\pi q \exp\left[-\frac{m\left(\omega_r^2 r^2 + \omega_z^2 z^2\right)}{2T} - \frac{q\phi}{T}\right]$$

- Any anisotropic equilibrium?
- Linear and nonlinear eigenmodes and instabilities?





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Conclusions

- PPPL heavy ion beam theory effort benefits considerably from local expertise in nonlinear delta-f simulations, collective instabilities and nonneutral plasmas.
- Major progress has been made in identifying collective processes in one-component charged particle beams and beam-plasma interactions, and determining operating regimes for quiescent beam propagation.
- Future task activities will focus on identifying optimum conditions for beam transport and neutralized drift compression.

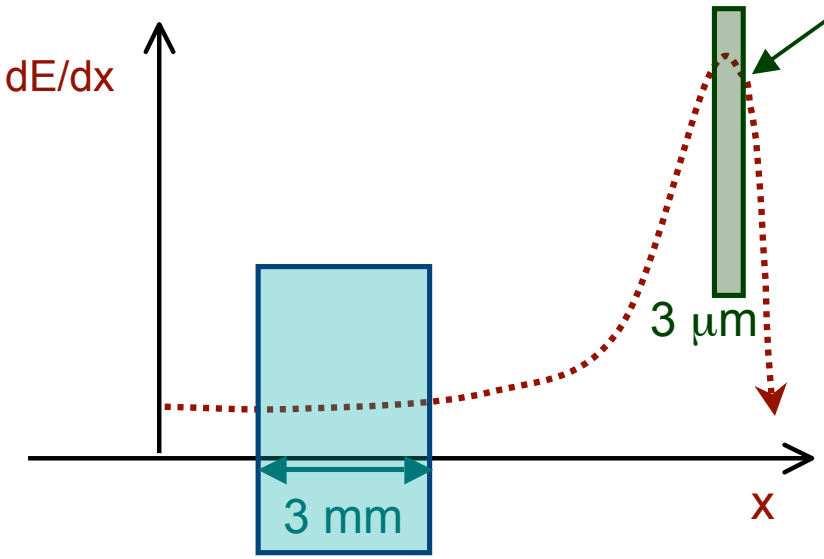
FY2001-2005 have been a period of high research productivity

- 71 refereed papers, 25 invited papers, 28 published conference proceedings.
- One graduate level textbook on high intensity beam physics.
- IEEE Particle Accelerator Science and Technology Award (2005).
- Presidential Early Career Award for Scientists and Engineers (2004).
- Formal exchange programs with Japan and GSI Darmstadt.
- Collaborations on electron cloud effects/two-stream instabilities:
  - Proton Storage Ring: Los Alamos.
  - Spallation Neutron Source: Oak Ridge.
  - Electron production: Tech-X.
- Providing scientific leadership:
  - National Task Force on High Energy Density Physics (chair).
  - NRC Panel on High Energy Density Physics (chair).
  - APS Division of Physics of Beams (chair).
- Teaching advanced graduate courses at US Particle Accelerator School.
- Co-organized plasma-nuclear physics workshop on quark-gluon plasmas.
- Organized 2004 International Symposium on Heavy Ion Fusion in Princeton.

- Backup Vugraphs

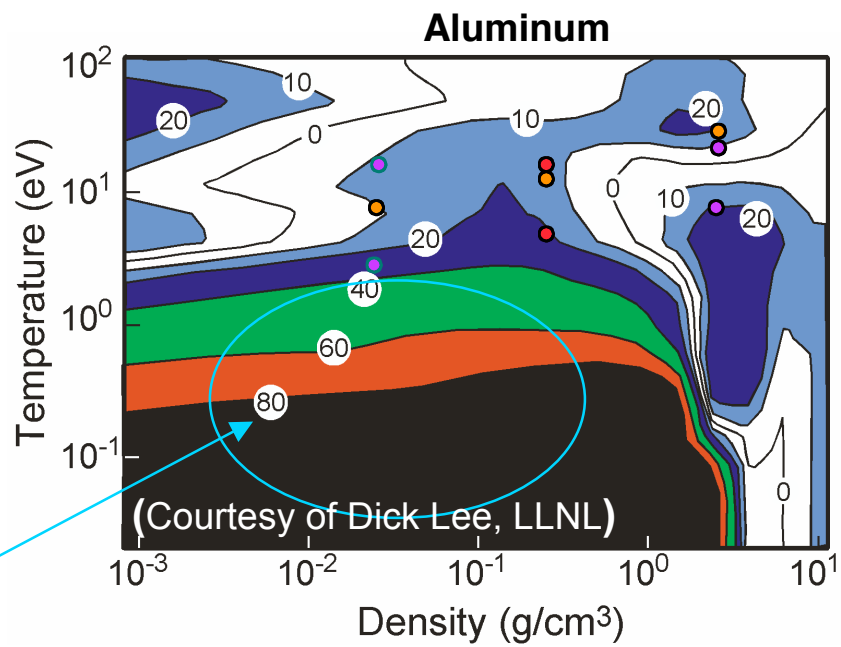
Unique Approach to Ion-Driven HEDP with Short Pulses

Ion energy loss rate in targets



Maximum dE/dx *and* uniform heating at Bragg peak require short (< few ns) pulses to minimize hydro motion. [L. R. Grisham, PoP, (2004)].
→Te > 10 eV @ 20J, 20 MeV
(Future US accelerator for HEDP)

GSI: 40 GeV heavy Ions→ thick targets→ Te ~ 1 eV per kJ



Dense, strongly coupled plasmas 10^{-2} to 10^{-1} *below* solid density are potentially productive areas to test EOS models (Numbers are % disagreement in EOS models where there is little or no data)

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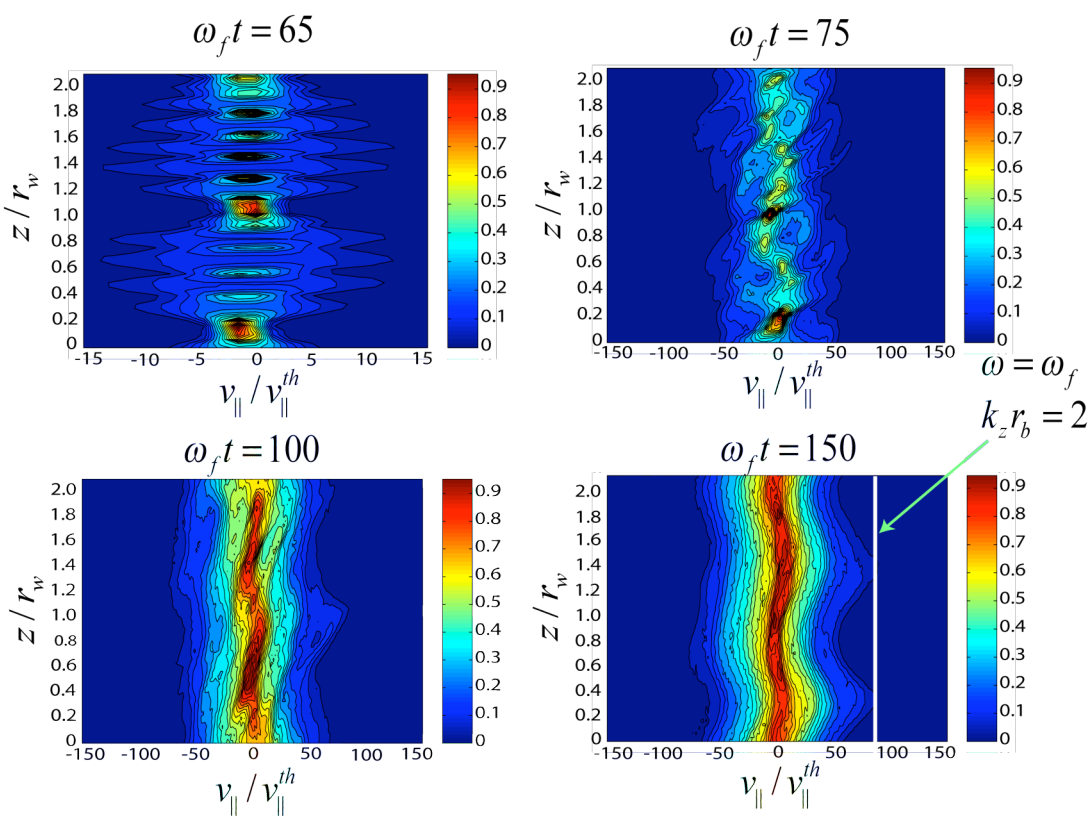
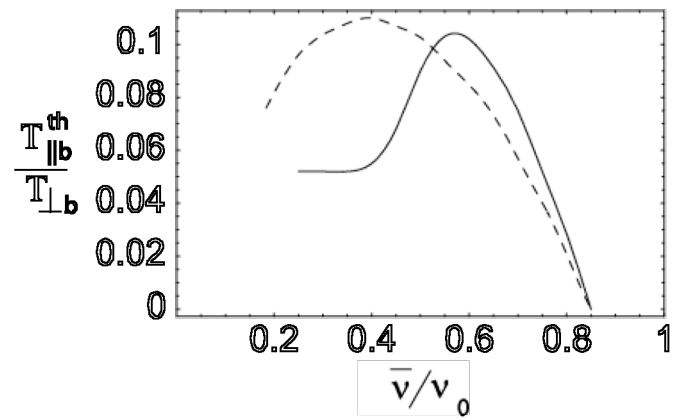
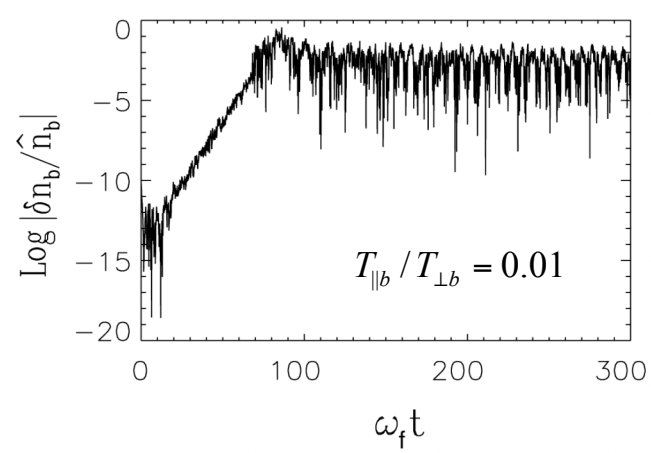
Strong Harris instability for beams with large temperature anisotropy

- Moderate intensity → largest threshold temperature anisotropy.
- Nonlinear saturation by particle trapping → tail formation.







E. A. Startsev, et al., Nucl. Instr. and Methods in Physics Research A554, 125(2005)

Five-Year Task Activity Areas

a) Develop improved kinetic models based on the nonlinear Vlasov-Maxwell equations to describe the equilibrium and stability properties of intense heavy ion beams propagating in periodic focusing accelerators and transport systems.

b) Investigate collective instabilities in intense heavy ion beams, including ion-electron two-stream interactions, and identify optimum parameter regimes for stable beam propagation.

c) Investigate collective beam-plasma interactions in the target chamber. Identify operating regimes that mitigate the effects of two-stream, multispecies Weibel, and resistive hose instabilities.

d) Develop robust numerical and analytical models of beam compression dynamics and nonlinear beam dynamics in the final focus system, including neutralized drift compression to short pulse lengths in background plasma.

Five-Year Task Activity Areas

e) Develop self-consistent theoretical models of charge and current neutralization for intense beam propagation in the target chamber, benchmarked against simulation and experimental results.

f) Explore mechanisms for halo formation through detailed comparisons between theory, simulation, and experiment. Identify operating regimes that minimize the production of halo particles.

g) Apply the 2D and 3D nonlinear delta-f simulation schemes to augment and validate the analytical studies in (a)–(f) above, with particular emphasis on collective instabilities, halo formation and control, and emittance growth. Explore the influence of three dimensional effects on stability behavior, including beam-plasma interactions in the target chamber, and ion-electron two-stream instabilities in the beam transport lines.

Selected FY 2005 - FY 2007 Milestones

- Optimize analytical and numerical models describing the pulse shaping and neutralized and unneutralized drift compression dynamics for high-intensity heavy ion beams and the Neutralized Transport Experiment (NTX) upgrade options, with emphasis on important second-order effects such as emittance growth and coupling between longitudinal and transverse dynamics (2005).
- Complete nonlinear delta–f simulation studies of collective instabilities driven by strong temperature anisotropy for intense coasting heavy ion beams (2005).
- Complete development of the reduced multispecies electromagnetic Darwin model for simulation of transverse electromagnetic effects in charged particle beams. Implement Darwin model in the 3D BEST simulation code (2006).
- Complete development of improved analytical and numerical models of 3D bunched beams for detailed investigation of collective effects and instabilities (2006).
- Complete initial large-scale particle simulation studies of optimized pulse shaping and neutralized drift compression scenarios for heavy ion beam pulses using the LSP and/or WARP-3D simulation codes (2006).

Selected FY 2005 - FY 2007 Milestones

- Develop and apply optimized analytical models for beam charge and current neutralization in solenoidal and dipole magnetic field configurations with neutralized drift compression (2006).
- Complete initial large-scale nonlinear perturbative particle simulations of electron-ion two-stream interactions in 3D bunched beams using optimized numerical models, with electron production mechanisms self-consistently included (2006).
- Complete assessment of the effects of strong temperature anisotropy instability on finite-length bunched beams (November, 2006).
- Complete the development of optimized models for beam charge and current neutralization in solenoidal magnetic field configurations with neutralized drift compression (2007).
- Develop analytical and numerical models describing the pulse shaping and neutralized drift compression dynamics for the NDCX experiment, with emphasis on emittance growth, collective interactions, effects of solenoidal magnetic field, and coupling between ongitudinal and transverse dynamics (2007).

Task Area and Milestone Example:

Example:

Task Area d)

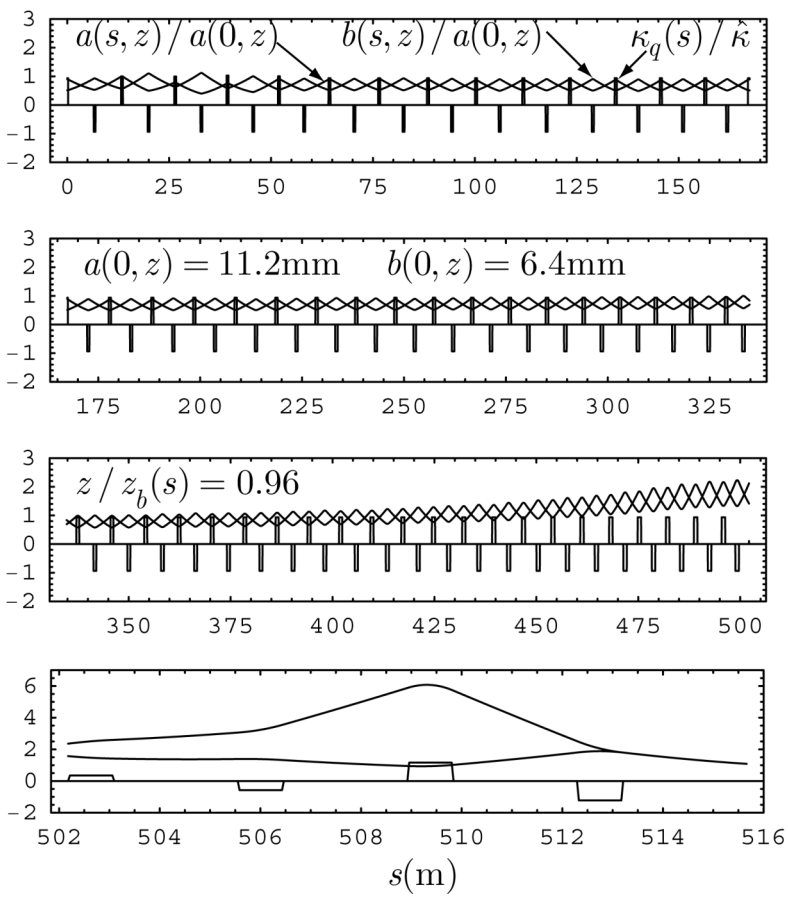
Develop robust numerical and analytical models of beam compression dynamics and nonlinear beam dynamics in the final focus system, including neutralized drift compression to short pulse lengths in background plasma.

Milestone:

Develop analytical and numerical models describing the pulse shaping and neutralized drift compression dynamics for the NDCX experiment, with emphasis on emittance growth, collective interactions, effects of solenoidal magnetic field, and coupling between longitudinal and transverse dynamics (2007).

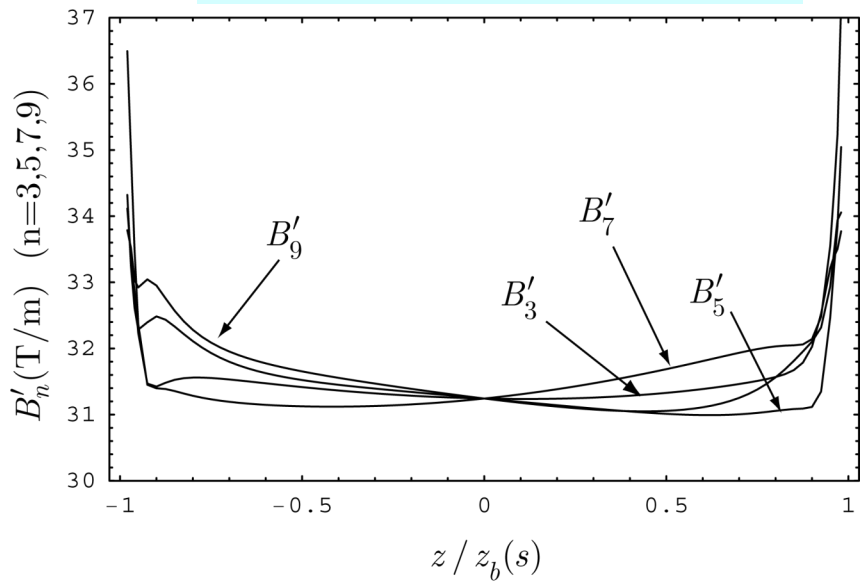
Leading-order drift compression and final focus design

- A large compression ratio and entire pulse being focused.
- Self-similar drift compression scheme and time-dependent magnets.
- Instabilities?



Beam envelope dynamics

- 2.5 GeV, 2.25kA, Cs+
- 11.7m → 0.54m
- Focal spot: 1.2mm



Time-dependent magnets

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