Status and new physics directions for heavy-ion-driven high energy density physics and fusion*

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## U.S. Institutions Participating in Heavy Ion Fusion Research

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Outline of talk

1. Research progress over the last year on selected key issues affecting high intensity heavy-ion beam propagation.

2. New research beginning on neutralized beam compression and focusing relevant to high energy density physics and fusion.

3. Conclusions
Heavy Ion Beam Research

An important scientific question fundamental to future applications of heavy ion beams to both high energy density physics and fusion:

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

Subsidiary science thrusts needed to address this top-level question:

- Determine the technical requirements for preserving high beam brightness during the acceleration, transport and focusing of intense high-current ion beams.
- Develop a basic understanding of how beam-plasma interactions can be used to optimize the focusing of intense ion beams to a small spot.
- Determine the conditions under which the shortest pulses are achievable with longitudinal drift compression.
- Determine how uniformly warm dense matter can be heated with tailored short-pulse ion beams.
- Develop integrated source-to-target simulation capability for robust modeling of intense heavy ion beam propagation from the source through final focus onto the target.
We have completed key experiments important to the quality of large, high current injected beams (LLNL)

- We measured and modeled beam optics of a large surface ionization source, successfully benchmarking simulations.

- We have tested new high current density, high brightness multiple beamlet sources needed for the next experiment test merging beamlets for compact driver-scale injectors.

STS-100 Source test stand

Two LLNL injector test stands

STS-500 Injector test stand
1stQTR-FY05: First step towards merging-beamlets in STS: extraction and merging of 61 beamlets at high current density >100 mA/cm² and full gradient > 100 kV/cm (not yet in converging geometry)

Normalized emittance (x and y) reaches steady state value

Excellent agreement between experimental data and simulation

Warp 3D simulation of beamlets expand and merge downstream

High Gradient Insulators held 30 kV/cm
Since 2002, HCX (LBNL) has explored transport to high fill factors in ten electric quads*, and gas/electron cloud effects in four magnetic quads.

The HCX with magnetic quad section (2003)  Gas, electron source diagnostic (GESD)

We have successfully simulated electron cloud effects on ion beam dynamics in HCX with WARP in 3D using models of electron emission and reflection, and a new electron mover algorithm (Ron Cohen).

HCX conditions: 1 MeV, 0.18 A K+ ion beam after 4 quadrupole magnets

Measured $v_x$ vs $x$.

3-D simulation of electron cloud affecting ion beam $v_x$ vs $x$

→This multi-species modeling capability is key to a predictive capability for electron cloud effects in any high intensity accelerator.
Electron-Ion Two-Stream (Electron Cloud) Instability*

Proton storage ring (PSR) experiment at Los Alamos observes strong electron-proton (e-p) two-stream instability.

Electron-proton instability could also limit the achievable beam intensities for the Spallation Neutron Source and other high intensity accelerators.

$\delta f$ simulations show that the $l=1$ dipole mode is destabilized by a background electron population. Mode characteristics and excitation frequencies are consistent with the BEST simulations.

*H. Qin, E. A. Startsev and R. C. Davidson, Phys. Rev. Special Topics on Accelerators and Beams 6, 014401 (2003)..
The Neutralized Transport Experiment gave us confidence that plasma could neutralize intense heavy-ion beam space charge for ballistic focusing without strong beam-plasma instabilities.
Plasma neutralization of space charge for a high perveance ($6 \times 10^{-4}$) 25 mA, 300 keV K$^+$ beam reduces beam focal spot size by 10 x, consistent with particle simulations*

After magnetic focus, data and calculated beam density profiles agree well, except for halo.

Creating warm dense matter and fusion ignition conditions requires *longitudinal* as well as *transverse* beam compression.

Induction acceleration is most efficient at $\tau_{\text{pulse}} \sim 100$ to 200 ns.

Near term High Energy Density targets require $\sim 1$ ns pulses; Fusion requires $\sim 10$ ns.

Bunch tail has a few percent higher velocity than the head to allow compression in a drift line.

Issues that need more study and experiments:

1. Beam-plasma instabilities during compression.
2. Beam heating due to compression (conservation of longitudinal invariant).
3. Chromatic focus aberrations due to velocity spread.

*New direction:* neutralize the beam space charge both in longitudinal drift compression as well as in final focus.
We are assembling an experiment to test neutralized beam compression: LSP-PIC simulations of proposed experiment show dramatically larger compressions of tailored-velocity ion beams inside a plasma column.

- Ramped 220-390 keV K\(^+\) ion beam injected into a 1.4-m-long plasma column:
  - Axial compression 120 X
  - Radial compression to 1/e focal spot radius < 1 mm
  - Beam intensity on target increases by 50,000 X.

- Velocity chirp amplifies beam power analogous to frequency chirp in CPA lasers
- Solenoids and/or adiabatic plasma lens can focus compressed bunches in plasma
- Instabilities may be controlled with \(n_p \gg n_b\), and \(B_z\) field [D. Welch, D. Rose (MRC), , I. Kaganovich (PPPL)]
First Demonstration of Longitudinal Compression in NDCX

NDCX Beamline
(December 1, 2004)
First experiments (~FY06) to assess physics limits of neutralized ion beam compression to short pulses (NDCX-I, before upgrade to NDCX-II)

First neutralized drift experiment using existing equipment

Existing LBNL 400 kV injector, focusing magnets and induction core

Neutralized Drift Compression Experiment using PPPL large plasma source soon-2004

2nd step: Accel-Decel Bunching & Solenoid Transport Experiments using existing solenoids and pulsers

1.4 m drift section
Five-year goal: Integrated beam and target experiments at nominal solid target temperatures of 1 eV (NDCX-II)

- Use existing NTX injector, but with ~1 A Helium or lithium beam source instead of present 25 mA K⁺, and larger B·a solenoid
- Goal: ~1 eV in targets
- Limited-shot and/or non-intercepting target focus diagnostics
- Short acceleration and compression tilt section to 0.5 - 2 MeV (use existing induction cores or traveling wave line)
- 1.4 m long Neutralized Drift
- Solenoid and Z-Pinch focus

Existing 400 kV NTX Marx

Existing 400 kV NTX Marx

Short Pulse accel-decel Injector
New research examines using short pulses with neutralized compression for high energy density physics experiments.

Maximum $dE/dx$ and uniform heating at Bragg peak require short (< 1 ns) pulses to minimize hydro motion. [L. R. Grisham, Physics of Plasmas, in press (2004)].

$\rightarrow Te > 10 \text{ eV} @ 30 \text{J,} 30 \text{MeV}$ (Future US accelerator for HEDP)

Ion energy loss rate in targets

GSI: 40 GeV heavy ions $\rightarrow$ thick targets $\rightarrow$ $Te \sim 1 \text{ eV per kJ}$

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)
Key areas for further research in neutralized beam drift compression and focusing for high energy density physics and fusion:

- Injection/acceleration/bunching to high beam space charge (perveance > 10^{-2}) with sufficiently low parallel and transverse emittances before plasma neutralization.

- Beam transitions at high line-charge densities from Brillouin flow into neutralizing plasma columns with tolerable emittance increases.

- Control of beam plasma instabilities over long regions of drift compression in background plasma, and controlled stripping.

- For fusion, validation of symmetry control techniques in large-focal-spot hybrid targets (LLNL and SNL joint experiments on Z)
Research on neutralized rift compression and focusing of velocity “chirped” beams for HEDP could lead to improved concepts for heavy ion fusion

“Hybrid” target allows large 5 mm radius focal spots (D. Callahan). Uses low cost manufacturing methods for hohlraums with foam x-ray converters (D. Goodin).

Neutralized ballistic, solenoid-focused, plasma-filled liquid Flibe-wall vortex chamber concept (Per Perterson, UCB)
SUMMARY

With advanced theory and simulation tools, we have made excellent progress over the last three years understanding limits to high intensity heavy-ion beam propagation at higher currents (25-180 mA) in the STS, HCX, and NTX heavy ion beam experiments.

With NTX experiments and advanced theory and simulation tools, we have learned how to apply plasma neutralization to improve intense beam focusing and to apply that knowledge to new experiments for neutralized beam longitudinal compression.

Over the next 5 years we hope to show the feasibility of delivering 1 ns heavy-ion pulses for high energy density physics applications.

Neutralized beam compression and focusing may also lead to future improved heavy-ion fusion.

The new heavy-ion research is directed to address the scientific question central to both high energy density physics and IFE: How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion ignition conditions?
Backup slides
Strategy: maximize uniformity and the efficient use of beam energy by placing center of foil at the Bragg peak in dE/dx

In simplest example, target is a foil of solid or “foam” material

Example: He

Deposition rate and uniformity best if driven at Bragg peak (Larry Grisham, PPPL).

ΔdE/dX ∝ ΔT

(ΔdE/dX figure from L.C. Northcliffe and R.F. Schilling, Nuclear Data Tables, A7, 233 (1970))
HEDP has rich discovery potential

Quark-gluon plasmas in heavy-ion nuclear collisions (way off scale in this chart)

Fast igniter physics: fast electron dissipation enhancement via collective instabilities

Strongly-coupled plasmas: Many ab-initio theories of strongly coupled plasmas remain un-resolved by existing laser data

Fusion: Effects of 3-D RT instabilities on burn propagation (NIF)
Uniform isochoric heating is desirable to enable EOS measurements accurate enough to distinguish different \textit{ab initio} WDM theories.

- High pressure H data shows that no theory provides agreement; while models, with empirical fits, are better
  - Kerley/Sesame
  - Redmer-Beule
  - Saumon-Chabrier
  - Ross

Variations in temperature or density less than a few percent over diagnostic resolution volumes needed to distinguish various theories.
HEDP science would benefit from a variety of facilities offering different tools, shots on demand, and different convenient locations for students.

WDM regimes are presently accessed by heating a solid (most useful) or by compressing/shock heating a gas. Volume and uniformity set limits to accuracy of EOS measurements.

- Foils preheated by hard x-rays
- Supersonically heated foams or low Z materials (thermal x-rays)
- Shock compressed and heated thin foils
- Ion heated thin foils

Ultra-hard X-rays

XFEL heating uniform but small volumes (10’s of millijoules). High range electrons can heat < 1 mm spots—but too small for diagnostics

MJ of soft-x-rays available on Z but limited number of shots

Lasers absorb at critical density << solid density → large density/pressure gradients

Fast heating of a solid with penetrating ions → lower gradients → more accurate EOS

- 100TW lasers → 10-50 mJ, ps ion bunches → large energy spreads, non-uniform deposition
- GSI-SIS-100 plans 10-40 kJ of ions @100GeV, 100 ns → large volumes but limited T < 1 eV
1-D hydro calculations of aluminum foam target examples driven by “Ten-yr goal machine” parameters. (Slide courtesy of D. Callahan and M. Tabak, LLNL)

Ne+1 ions, 30 J total beam energy, 30 MeV kinetic energy, 20 - 40 MeV energy spread, 1 mm radius at best focus, 3.8 TW/cm² center of beam, 0.5 ns pulse duration

1% solid density
800 microns thick

15% solid density
53 microns thick
Combining low Bragg peak energy, target energy densities \( >10^{11} \text{ J/m}^3 \), and pulses shorter than target expansion times (<1 ns) leads to \( >10^{13} \) ions/cm incident on target \( \rightarrow \) needs beam compression experiments

\[ \Gamma_i = Z^* e^2 n_i^{1/3} / kT \]

\[ N_{\text{ions}} / (r_{\text{spot}} / 1\text{mm})^2 / 10^{12} \]

\[ \Delta t \ (\text{ns}) \]

\[ U \ (\text{J/m}^3) / 10^{11} \]

Example: Neon \( Z=10, A=20.17, E_{\text{min}}=7.7 \text{ MeV}, E_{\text{center}}=12.1 \text{ MeV}, E_{\text{max}}=20.1 \text{ MeV} \) \( \Delta z_{\text{min}} = 40 \text{ m} \) (Eq. of state, \( Z^* \): Zeldovich and Raizer model from R.J. Harrach and F. J. Rogers, J. Appl. Phys. 52, 5592, (1981)).
A US-DOE and German Government agreement supports cooperation in dense plasma physics

- Beam loss/vacuum issues and accelerator activation
- Petawatt laser for ion-driven HEDP diagnostics
- Beam physics basis for high intensity ion drivers
  - space charge effect on resonances
  - models of beam halo generation
  - longitudinal instabilities
  - compression schemes for short pulses

GSI and HIF-VNL have agreed to the technical content of a new proposed annex on gas desorption and electron cloud effects in accelerators.

Technical Coordinators:
Arthur Molvik   LLNL
Hartmut Reich-Sprenger   GSI

Unilac and SIS-18 storage ring (present)

New 600 M Euro SIS-100 Upgrade (approved)

Simulation of a cylindrical target driven by GSI heavy ion beam
Neutralized compression might lead to an improved IFE driver with a modular development path.

Example 6.7 MJ Ne\(^+1\) at 200 MeV

- High \(\lambda\) injector
- Induction linac
- Solenoid focusing (Lee) or adiabatic plasma lens/assisted pinch (Yu, Welch)
- Target
- Neutralized drift compression (100-200 m)
- 200 m

- Large spot “Hybrid Target (Callahan)"
- Liquid vortex chamber concept (Peterson)

The Heavy Ion Fusion Virtual National Laboratory
Neutralized drift compression/focusing + hybrid targets may reduce costs ~ 50% for both conventional multiple-beam quadrupole and modular solenoid driver options for IFE (See talk by Meier F.I-05)
We find good agreement between measured and simulated large-aperture diode dynamics*

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Results on risetime benefited from a novel simulation method (based on Adaptive Mesh Refinement), that has moved the state-of-the-art.