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Intense beams of heavy ions offer a very attractive tool for fundamental research in high energy density physics and inertial fusion energy science. These applications build on the significant recent advances in the generation, compression and focusing of intense heavy ion beams in the presence of a neutralizing background plasma. Such beams can provide uniform volumetric heating of the target during a time-scale shorter than the hydrodynamic response time, thereby enabling a significant suite of experiments that will elucidate the underlying physics of dense, strongly-coupled plasma states, which have been heretofore poorly understood and inadequately diagnosed, particularly in the warm dense matter regime. The innovations, fundamental knowledge, and experimental capabilities developed in this basic research program is also expected to provide new research opportunities to study the physics of directly-driven ion targets, which can dramatically reduce the size of heavy ion beam drivers for inertial fusion energy applications.

Experiments examining the behavior of thin target foils heated to the warm dense matter regime began at the Lawrence Berkeley National Laboratory in 2008, using the Neutralized Drift Compression Experiment - I (NDCX-I) facility, and its associated target chamber and diagnostics. The upgrade of this facility, called NDCX-II, will enable an exciting set of scientific experiments that require highly uniform heating of the target, using Li^+ ions which enter the target with kinetic energy in the range of 3 MeV, slightly above the Bragg peak for energy deposition, and exit with energies slightly below the Bragg peak.

This document briefly summarizes the wide range of fundamental scientific experiments that can be carried out on the NDCX-II facility, pertaining to the two charges presented to the 2008 Fusion Energy Science Advisory Committee (FESAC) panel on High Energy Density Laboratory Plasmas (HEDLP). These charges include:

"(1) Identify the compelling scientific opportunities for research in fundamental HEDLP that could be investigated using existing and planned facilities in support of the Office of Fusion Energy Sciences and the National Nuclear Security Administration/Defense Program missions;

(2) Identify the scientific issues of implosion and target design that need to be addressed to make the case for inertial fusion energy as a potential future energy source."

Compelling research opportunities of high intellectual value that can be carried out on the NDCX-II experimental facility are briefly summarized below, grouped into four main research areas. Page 4 lists several national and internationally-attended user workshops that have provided much of the input for the experimental campaigns describe below. More detailed information can be provided upon request.

(1) Detailed studies of the basic physics of the warm dense matter regime using uniform volumetric ion heating

The capability to study target foils requires a wide range of diagnostics, including optical pyrometry, visible and UV spectroscopy, high-speed cameras, VISAR, ion beam probes, and laser probes, etc. Many of these diagnostics have already been implemented in experiments on the NDCX-I facility.

Experiments to measure target temperature and conductivity using intense ion beams compressed both transversely and longitudinally: In these experiments, the optimum focus (both longitudinally and transversely) that can be obtained on NDCX-II will be used to raise the target temperature as high as possible, and to make detailed hydrodynamic and conductivity measurements.

Positive - negative halogen ion plasma experiments: These experiments would require target temperatures kT > 0.4 eV. Due to the larger electron affinity of the halogens, the Saha equation predicts that at temperatures near 0.4 eV the plasma will consist primarily of positive and negative ions, with a much lower density of electrons. The ion-ion plasma conductivity may have several similarities to a semiconductor, so that the detailed exploration of this novel plasma state has the potential for significant scientific payoff, including applications such as high-power plasma switches.

Two-phase liquid-vapor metal experiments: These experiments would require target temperatures kT > 0.5 - 1 eV. The physics of droplet and debris formation, the location of the liquid-vapor phase transition boundary for a number of metals, and the hydrodynamics of metals crossing this phase boundary are not clearly understood, and would greatly benefit from the precision measurements that could be carried out on NDCX-II.

Properties of liquid metals heating towards their critical points: The *critical point* occurs at the highest temperature for which a distinction can be made between the gaseous and liquid states. The critical point for a number of metals is not well known. Therefore, a precise experimental determination of this fundamental quantity would be of considerable basic scientific interest.

(2) Fundamental investigations of ion-beam-driven inertial fusion energy science

Direct-drive beam-to-capsule coupling efficiency experiments: One-dimensional implosion calculations show that increasing the ion range four-fold during the drive pulse can maintain the ion energy deposition surface close to the imploding ablation front. This results in high coupling efficiencies (shell kinetic energy/incident beam energy) of 16% to 18%, and calculations show 25% efficiencies are possible; this could have dramatic consequences for an inertial fusion energy power plant. NDCX-II experiments, in which the ion energy increases by a factor of two or more in an energy-ramped pulse or in a pair of pulses, will be able to explore the physics of transforming beam energy into hydrodynamic motion.

Ion-heated foam radiator targets for indirect-drive hohlraum targets: One important research area that will be explored on NDCX-II is the physics of metallic foams. In inertial confinement fusion targets, foams are employed in several designs, for example, as radiation converters in heavy ion fusion and as the structural material in double-shelled laser targets. Experiments on NDCX-II will characterize the equation-of-state by measuring the characteristics of rarefaction waves created when ion beams volumetrically heat material.

Formation of micro- and nano-particles from the expansion of hohlraum target plasmas into the vacuum chamber: During an inertial fusion microexplosion, droplets and debris can develop in the warm dense matter regime; the size and velocity of the debris resulting from sudden internal heating (e.g., by neutrons or penetrating particles such as ion beams) is expected to be different from that due to surface heating (laser-induced shock waves). Experiments on NDCX-II will fully characterize the formation of droplets and particles under a wide range of operating conditions, emphasizing the critical transit through the warm dense matter regime.

Hydrodynamics in the warm dense matter regime: Several target geometries for NDCX-II will be used in the study of hydrodynamics in the warm dense matter regime. For example, after a planar foil, with an imbedded spherical or cylindrical bubble, has been uniformly heated by an ion beam, the bubble will implode. The central temperature and pressure have been shown in simulations to be sensitive to the equation-of-state. Inertial fusion targets pass through this regime before reaching fusion conditions, and their *"initial conditions"* (the seeds to instabilities) will be affected by the hydrodynamic processes that occurs while passing through the warm dense matter regime.

(3) Dynamics of space-charge-dominated particle beams

Space-charge-dominated beams are one-component nonneutral plasmas with intense self-fields that exhibit a rich set of collective behavior. NDCX-II will be uniquely suited for the study of this important physics; it compresses the ion pulse from ~500 ns to ~10 ns, re-expands it spatially, and neutralizes it for further compression. Related experiments on NDCX-II will include:

The dynamics of pulse compression in un-neutralized beams: A compressing beam is not in a quasi-equilibrium state. Internal flows arise in response to space-charge forces and applied fields. NDCX-II offers unique opportunities for comparison between experiments and advanced simulations, to elucidate the underlying physical processes that govern pulse compressibility.

Instabilities in space-charge-dominated beams: An intense beam can suffer unstable collective interactions, such as the electrostatic Harris instability driven by thermal energy anisotropy, and resistivity-driven modes. With flexible pulse manipulations and adjustable wall impedance, NDCX-II will allow the quantitative study of this behavior by detailed phase-space measurements.

Interactions of intense beams with secondary electrons: Positively-charged particle beams can entrain stray electrons (an "electron cloud"). Electron-ion two-stream instabilities and "multipactoring" (a cascade of electrons from the walls) can occur. NDCX-II can be configured to apply a variety of beam-confinement fields and will enable study of electron cloud physics, an essential instability mechanism that affects the performance of the Spallation Neutron Source and the Large Hadron Collider.

(4) Collective beam-plasma interaction processes

NDCX-II will propagate an ion beam through a background plasma over a distance of several meters, to enable temporal compression and transverse focusing (500 ns to 1 ns, cm-scale to mm-scale). It will provide an ideal platform for studying collective beam-plasma interactions, intense-beam focusing, and pulse compression in neutralizing plasma. Synthetic diagnostics from end-to-end simulations can be compared against particle phase space measurements based on collimating slits, scintillators, and other techniques. Related experiments on NDCX-II will include:

Energy-chirp pulse compression of intense beams in plasmas: By imposing a head-to-tail energy gradient ("chirp") on the beam and allowing it to drift through neutralizing plasma, large temporal compression factors can be achieved. Factors limiting such compression include beam temperature, imperfect energy chirp, and insufficient neutralization. This physics will be explored quantitatively using scintillator imaging, Faraday cup measurements, and an energy analyzer.

Plasma flows in magnetized systems to enable beam neutralization: As increasingly dense beams are generated by the energy-chirp process, it becomes more challenging to provide sufficient background neutralizing plasma. NDCX-II will be periodically refitted with optimized plasma sources, and will serve as a test bed for studying plasma flows along and across magnetic fields.

Focusing of intense ion beams in plasmas using magnetic optics: NDCX-II will enable studies of beam focusing onto a small spot in the presence of chromatic aberrations, beam temperature, and imperfect charge neutralization. Novel time-dependent optical elements will be explored.

Collective focusing of intense beams using plasma effects: NDCX-II will enable studies of collective focusing processes including the Robertson lens effect and a process wherein electrons are tied to weak, converging magnetic field lines, and so apply focusing forces to an ion beam.

Instabilities of intense beams in plasmas: These include electrostatic two-stream instabilities and the multi-species electromagnetic Weibel (filamentation) instability, both associated with beam–plasma interactions. These modes can be diagnosed using spatially distributed sensors with sufficient frequency response, and by measuring their effects on the beam particle phase space.

NDCX-II user community workshops and inputs

We have held a series of meetings (2 workshops and a winter school) on NDCX-I and II-related topics for the user community. These meetings were well attended with approximately 100 researchers, some international. Proceedings have been posted as indicated. More workshops are planned.

- 2008 Warm Dense Matter Winter School, Berkeley, January 10-16, 2008: http://hifweb.lbl.gov/wdmschool

- Accelerator-Driven Warm Dense Matter Workshop, Pleasanton, February 22-24, 2006: http://ilsa.llnl.gov/wdm/

- Workshop on Accelerator Driven High Energy Density Physics, LBNL, October 26-29, 2004: http://hifweb.lbl.gov/public/hedpworkshop/toc.html

The following letters of intent related to NDCX-I were submitted for the OFES-NNSA- solicitation for experiments in HEDLP (August 18, 2008, under review), all of which can apply as well later on in NDCX-II with more energy available for an extended range of accessible experimental parameters:
(Principal Investigator/Institution/Title of Proposal)

- Tim Renk (Sandia National Lab) Investigation of phase transitions in thin foils using Si reflectivity as a marker
- Alice Koniges (Lawrence Livermore National Lab) Modeling ion-heated Warm Dense Matter experiments with full stress tensor, material history, and phase transitions
- Jing Zhou (Massachusetts Institute of Technology) Beam Brightness and Emittance Optimization Techniques for Heavy Ion Beam Approach to HEDLP
- Andrew Forsman (General Atomic) Dynamic evaporation rates of liquids and solids
- Richard More (R-More Physics) Silicon dE/dx due to the semiconductor-metal transition at melting using the NDCX beam
- Rami Kishek (U. Maryland) Beam Tomography to Optimize NDCX Warm Dense Matter Experiments
- Seth Veitzer (Tech-X Corp.) Particle-solid focusing elements for beam-driven HIF experiments
- Davidson, Gilson, Grisham and Kaganovich (Princeton Plasma Physics Lab) Advanced Plasma Source Development and Ion-Ion Plasma Studies in a 100 Kilovolt Test Stand
- Dale Welch (Voss Scientific) Optimization of neutralized ion beam transport

An international user not on the above list is Hitoki Yoneda of the University of Electro-Communications of Tokyo, Japan. He is working with us on several topics concerning optical diagnostics of WDM targets.