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White Paper on Heavy-Ion-Beam-Driven High Energy Density Physics and Inertial Fusion

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Abstract

New opportunities are described for research over the next twenty years using intense, accelerated, compressed and focused heavy ion beams for high energy density physics and inertial fusion applications. Experimental and theoretical advances in pulse compression and focusing of intense ion beams neutralized in background plasma enable the first warm dense matter target experiments to begin in 2008. Near-term opportunities to study unique states of dense, strongly-coupled plasmas are described using volumetric ion beam heating with existing beams, and longer-term opportunities using upgrades of existing facilities to study the physics of high hydrodynamic coupling efficiency related to heavy-ion-driven direct drive inertial fusion. We describe how recent advances in near-term compression of neutralized beams developed for warm dense matter experiments, together with the unique properties of heavy ion beam energy deposition, can lead to higher gain heavy ion fusion targets at much lower drive energies.

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Executive Summary

Intense beams of heavy ions offer attractive opportunities for research in high energy density physics and inertial fusion energy science. These possibilities build on significant recent advances in generating, compressing, and focusing ion beams in the presence of a neutralizing background plasma. Such beams can provide uniform volumetric heating during a timescale shorter than the hydrodynamic response time; they thereby enable a rich set of experiments that will clarify the physics of poorly understood, dense, strongly-coupled plasma states. The innovations, knowledge and experimental capabilities developed in this basic physics program also created new 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.

Experiments examining the behavior of thin target foils heated into the warm dense matter regime are beginning this year, using the Neutralized Drift Compression Experiment (NDCX-I) apparatus at LBNL, and its associated target chamber and diagnostics. A near-term upgrade of this facility, NDCX-II, can be assembled at very modest cost using the induction modules and associated hardware from the decommissioned Advanced Test Accelerator (ATA) facility at LLNL. The NDCX-II device will enable a rich set of experiments that require highly uniform heating, using Li+ ions which enter the target with kinetic energy of ~ 3 MeV, slightly above the Bragg peak for deposition, and exit with energies slightly below that peak.

Illumination of a target capsule by ions with temporally ramped kinetic energy has been estimated to result in an unprecedented hydrodynamic coupling efficiency (ratio of shell kinetic energy to incident beam energy) in the range of fifteen to twenty-five percent, at moderate driver energy. This may offer a new and attractive heavy ion fusion (HIF) path to inertial fusion energy (IFE). With modest modifications, NDCX-II will enable experimental studies of this process.

The Integrated Beam-High Energy Density Physics Experiment (IB-HEDPX) facility will build on the knowledge base established by NDCX-II. As noted in the DOE-Office of Science's mission-need CD0 document for IB-HEDPX: "NDCX-II … is necessary R&D to assess the performance requirements of injection, acceleration and focusing of short pulses needed for the IB-HEDPX. Out of the $6M R&D cost (for IB-HEDPX), $5M is for hardware upgrade of NDCX-I to NDCX-II. IB-HEDPX will be a flexible user facility, with greater flexibility in choice of ion for Bragg-peak heating, higher kinetic energy (up to 25 MeV), advanced multiple-target handling capabilities, and a much richer set of native diagnostics than NDCX-II.

Beyond IB-HEDPX, and building on the anticipated achievement of ignition on the National Ignition Facility (NIF), high coupling efficiency allows heavy ion beams to explore implosions of mm-scale cryo targets at moderate energy and cost in the Heavy

Ion Direct Drive Implosion Experiment (HIDDIX). This would provide the capability to drive low-convergence-ratio (5-10) spherical implosions with ion beams for the first time, and to explore issues of hydrodynamic stability to Rayleigh-Taylor modes under the stabilizing influence of non-normal ion beam illumination. Encouraging results in those areas and others would motivate development of a Heavy Ion Fusion Test Facility (HIFTF).

This White Paper describes the state-of-the-art of, and the wide range of opportunities offered by intense beams of heavy ions, relevant to the two charges presented to the 2008 FESAC High Energy Density Laboratory Plasmas (HEDLP) panel. These are: "(1) identify the compelling scientific opportunities for research in fundamental HEDLP that could be investigated using existing and planned facilities in support of the OFES and NNSA/DP missions; and (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."

In the introduction, **Section 1** of this white paper, the regimes in density-temperature space corresponding to heavy-ion-beam-driven warm dense matter and fusion target interaction studies are discussed. The properties of ion-beam illumination of matter are reviewed, and issues and opportunities outlined.

Section 2 relates primarily to the FESAC Charge 1 on High Energy Density Laboratory Plasmas (HEDLP). Following the research thrust areas defined in the 2004 National Task Force Report on High Energy Density Physics (HEDP), it describes the compelling research opportunities, scientific progress, and technical challenges for warm dense matter research driven by heavy ions beams in the critical research thrust areas defined in that report. These opportunities include in the near term, beam induced transient emission and absorption experiments in transparent insulators; an experiment to measure target temperature and conductivity; a positive - negative halogen ion plasma experiment; two-phase liquid-vapor metal experiments; and critical point measurements. In particular, section 2.4 and 2.5 lay out the physics and engineering design and cost basis, respectively, for NDCX-II, a next step heavy ion facility for both beam driven HEDP as well as for planar direct drive coupling physics.

> ***Combining the compression and focusing of beams in background plasma developed in NDCX-I, the availability of sufficient numbers of ATA induction accelerator modules, and an innovative method for aggressive bunch compression simultaneous with induction acceleration, NDCX-II provides a cost-effective opportunity to quickly enhance beam-driven HEDP and fusion.***

Section 3 discusses the research opportunities related to the FESAC Charge (2). It describes innovations and scientific progress towards new research opportunities for heavy ion fusion which builds upon the advances in knowledge and experimental capabilities described in Section 2 for the acceleration, compression and focusing of intense heavy ion beams, and applications for warm dense matter target physics. Heavy-ion-beam-driven HEDP research opportunities for heavy ion fusion target physics is expected to grow after expected ignition in the US National Ignition Facility because of the need for higher products of driver efficiency and target gains required for fusion energy, and includes development of rotating-beam smoothing techniques for planar direct drive experiments in NDCX-II, IB-HEDPX, followed by multi-kilojoule implosion experiments in HIDDIX.

Section 4 includes a timeline for both near term and longer term planned new facilities to establish the physics basis for a Heavy Ion Fusion Test Facility (HIFTF) over the next twenty years. The timeline shows how two significant enhancements in the heavy ion program, the construction of IB-HEDPX, and the commencement of design and R&D for a heavy ion driven implosion experiment HIDDIX, could occur after successful experiments in NDCX-II, and after successful ignition in NIF, respectively. Fruition of all of the research opportunities for heavy ion driven HEDP and fusion over the next 20 years identified in this white paper and summarized in the timeline could establish the HEDP target physics knowledge base needed for a heavy ion fusion test facility, as well as for fundamental HEDP in beam driven warm dense matter physics applications.

There are several appendices that provide background material on how the heavy ion program contributes to the FESAC charges. Appendix A presents the heavy ion related portions of the 2004 National Task Force Report on HEDP. Appendix B presents the heavy ion related portions of the 2005 FESAC Fusion Priorities report. Appendix C describes modest-scale university programs that contribute to the physics of intense beam transport fundamental to heavy ion accelerators.

1. Introduction

Heavy-ion-beam-driven high energy density physics extends from the physics of warm dense plasmas of 0.2 to 1 eV that are strongly coupled, to the high energy density physics of heavy ion fusion targets heating up from cryogenic temperatures all the way up to fusion target temperatures (Fig. 1.1).

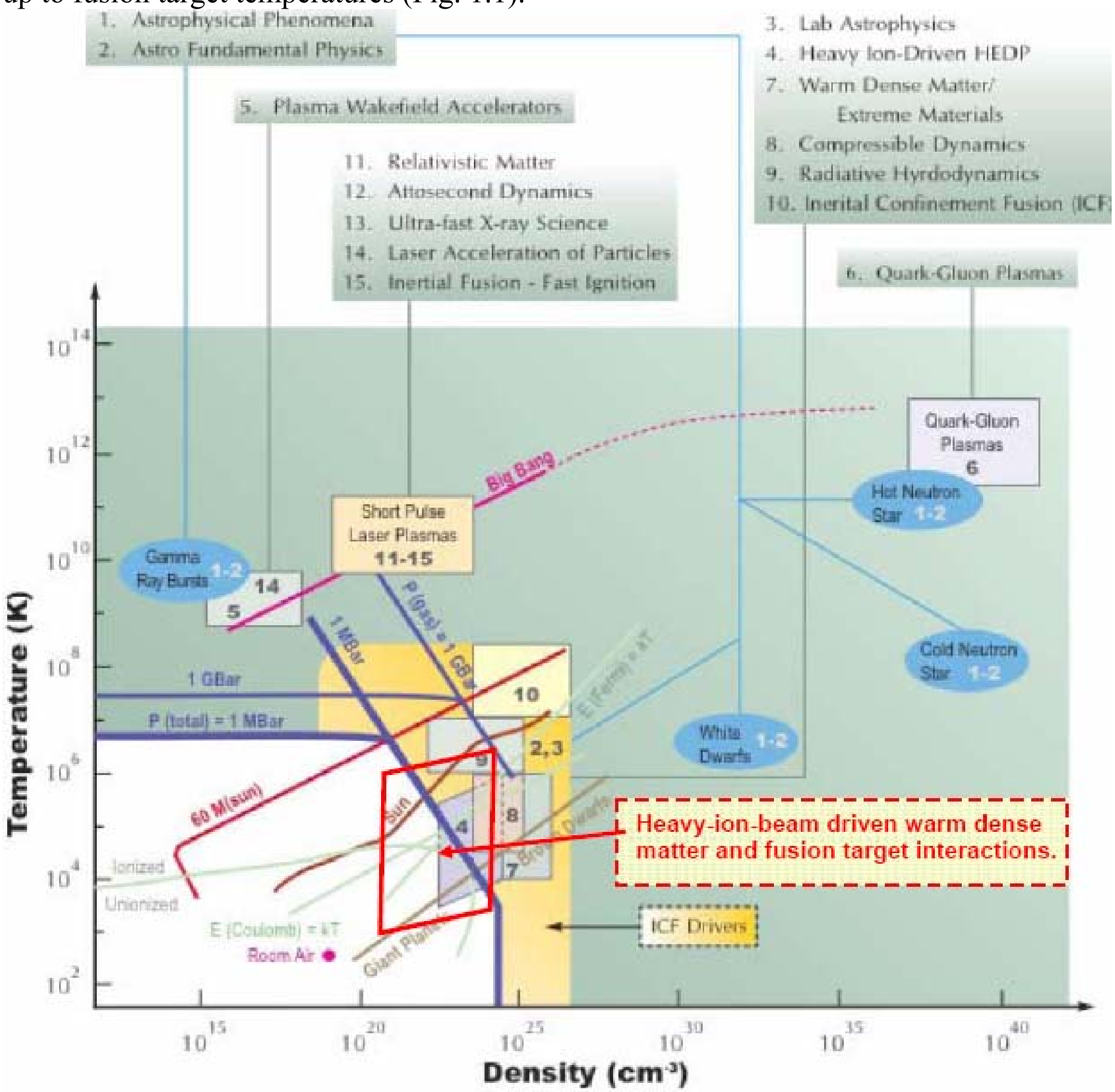


Figure 1.1: Map of the high energy density physics Universe (from National Task Force Report on High Energy Density Physics [1]). The red outlined inset area shows the region of heavy-ion-beam-driven warm dense matter and fusion target interactions. An expanded view of the beam driven area is shown on Fig. 1.2

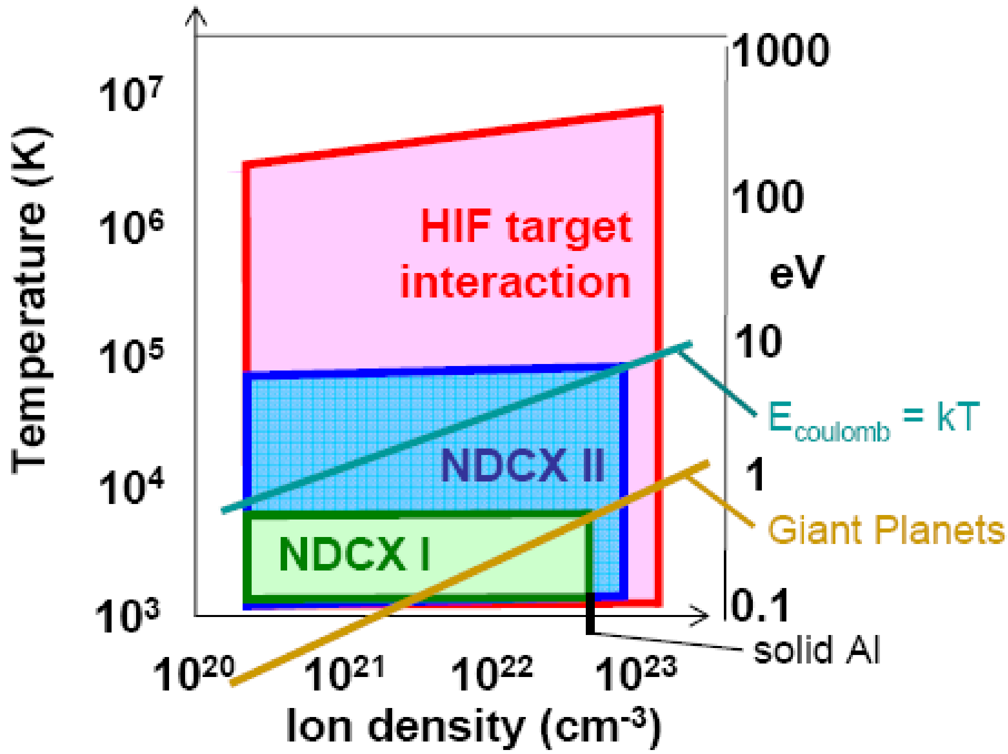


Figure 1.2 Expanded view of the heavy-ion-beam-driven area of WDM and fusion target interactions extracted from Fig. 1.1. The areas accessible to NDCX-I and NDCX-II, and future HIF beam target interaction are indicated in three shaded regions.

The regimes of heavy-ion-beam-driven warm dense matter and hydrodynamics are rich in physics phenomena which are incompletely understood. Some of the most challenging and interesting areas are dense plasmas created from the beam heating of foam targets below solid density, below p=1 Mbar, and below 1 eV, but where the plasma coupling is strong [below the E(coulomb)=kT line in Fig. 1.1]. The absence of small expansion parameters, and the presence of significant non-ideal effects, makes analysis very challenging. There are large error bars in the equations of state, and a lack of data, in these regimes. Novel experiments exploring aspects of this physics are accessible in the near term with existing heavy ion beams or with modest enhancements of present facilities. A compelling set of accelerator-driven experiments is described in this white paper. Accelerators producing appropriately tailored, intense beams of heavy ions can be useful tools for creating uniformly heated matter, and for providing efficient energy coupling to heavy ion fusion targets. They can enable the study of strongly-coupled plasma physics in the warm dense matter regime, and because of the unique ion beam energy deposition physics, ion beam direct drive would bring in new physics not heretofore encountered with laser direct-drive targets. The physics applications of heavy ion beams require understanding the fundamental physics limits to the compression of ion beams in both space and time before they reach the target, as well as a basic understanding of collective beam effects and beam-plasma interactions in the accelerator (e-cloud effects) as well as within dense plasma targets.

Heavy ion beams have a number of advantages as drivers of targets for high energy density physics and fusion. First, heavy ions have a range exceeding the mean-free-path of thermal x-rays, so that they can penetrate and deposit most of their energy deep inside the targets. This implies that no "entrance hole" is needed for indirect-drive targets, and that efficient volumetric deposition is possible for directly driven targets. Second, the range of heavy ion beams in dense plasma targets is determined primarily by Coulomb collisions with the target electrons. Ion beams slow down with minimal side-scattering, and their energy deposition has a pronounced peak in the rate of energy loss (dE/dx) that increases with the beam ion charge state, Z. Third, velocity-ramped heavy ion beam interactions with dense target plasmas may not experience strong beam-plasma instabilities that generate unwanted hot electrons that can cause target preheat. These unique properties make heavy ions an excellent driver for high energy density physics studies and fusion target physics.

Recent research in this area has been guided by the top-level question of high intellectual value described in the 2004 National HEDP Task Force Report [1.1] (relevant excerpts of this report are given in Appendix A), and in the 2005 FESAC Fusion Priorities Report [1.2], (relevant excerpts of this report are given in Appendix B).

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

Section 2 of this report relates primarily to the FESAC Charge 1 on High Energy Density Laboratory Plasmas (HEDLP) (fundamental HEDLP). Following the research thrust areas identified in [1.1], Section 2 describes the technical progress, compelling research opportunities, and challenges/gaps for warm dense matter research driven by heavy ions beams in the critical research thrust areas identified in [1.1] relevant to the FESAC Charge 1:

(1) ***High brightness heavy ion beam transport*** in magnets, particularly to understand the limits on beam-channel wall clearance (aperture fill) imposed by gas and electron cloud effects, together with beam matching and magnet non-linearities.

(2) ***Longitudinal compression of intense ion beams,*** particularly to understand limits on longitudinal compression within neutralizing background plasma, and the effects of potential beam-plasma instabilities over distances longer than 1 meter.

(3) ***Transverse focusing onto targets,*** particularly to understand limits on focal spot size set by chromatic aberrations due to uncompensated velocity spreads from upstream longitudinal compression, and beam temperature growth from imperfect charge neutralization.

(4) ***Advanced beam theory and simulation,*** particularly developing, optimizing and validating multi-species beam transport codes that can predict self-consistently the beam loss with gas and electron clouds, and developing integrated beam simulation models required to analyze source-to-target beam brightness (temperature) evolution.

(5) ***Beam- target interactions,*** particularly to understand beam deposition profiles within thin foil targets and the potential uniformity of isochoric heating, accounting for target and beam ion charge state conditions, including development of accurate beam deposition and laser-generated x-ray target diagnostics, and extension of integrated beam simulation models from source through target. Extensions of this research thrust area to heavy ion fusion targets is discussed in Section 3.

By making use of space-charge neutralization provided by dense background plasma, there has been significant progress in compressing intense ion beams in the transverse direction (by a radial factor of up to 10) to a small focal spot [1.3], and more recently, compressing the beam pulse in time (and length) to a pulse length (2 ns) that is comparable to the target disassembly time [1.4]. We believe that these important scientific advances will enable uniform regions of matter to be volumetrically heated to sufficient energy density to begin studies of strongly coupled, non-ideal dense plasmas within the year. High space-charge forces in intense ion beams would make such compression difficult, were it not for neutralization of the beam space charge by background plasma. Neutralization extends the allowed beam parameter space into high-intensity regimes where the beams would not otherwise propagate. Beam-plasma collective effects in these regimes (including an environment of longitudinal and azimuthal magnetic fields) have not been previously explored.

A basic understanding of the collective processes and nonlinear dynamics of intense, high-brightness, heavy ion beams, and a determination of how best to create, accelerate, transport, compress and focus these beams to a small spot size and short pulse length, are critical to achieving the scientific objectives of heavy ion fusion and ion-beam-driven studies of warm dense matter.

Section 3 relates primarily to FESAC Charge 2 (inertial fusion energy science). Heavy-ion-beam-driven fusion identifies new inertial fusion target physics issues due to the unique deposition properties of heavy ion beams [1.5]. In particular, there are new opportunities in high coupling efficiency for direct drive [1.6]. Section 3 summarizes the status, compelling research opportunities and technical challenges/gaps for heavy ion fusion target physics research. Finally, Section 4 describes the long-range (twenty-year) research plan for both high energy density physics (HEDP) and heavy ion fusion, because the success of heavy ion fusion depends both on fundamental HEDP science as well as on fusion target science, including equation-of-state at all temperatures ranging from cryo to fusion temperatures, beam-plasma interaction processes, neutralized beam compression and focusing, and beam deposition physics in targets. Related university research on the physics of intense heavy ion beams is briefly summarized in Appendix A.

2. Technical Progress and Campaign Readiness: Heavy-Ion-Beam-Driven High Energy Density Physics and Warm Dense Matter

2.1 Research opportunities and scientific challenges for heavy-ion-beam-driven warm dense matter

The greatest uncertainties in high energy density (HEDP) equations-of-state (EOS) occur in and around the liquid-vapor two-phase boundary. The highest pressure point of the two-phase region is called the "critical point". The critical point is above 1 Mbar for certain materials and is below 1 Mbar for others. There is uncertainty about the critical-point pressure of tungsten, gold and even aluminum. Some estimates are above 1

Mbar, and some are below. (Note: At a density ~ 1 g/cm^3, and a temperature T ~ 1 eV, the pressure is approximately 1 Mbar.)

Using an appropriate material one can carry out experiments at pressures below 1 Mbar that closely imitate higher energy phenomena. For this purpose the key concept is that of scaling. We can scale the properties of one material at one density-temperature to another material at a physically equivalent density-temperature. "Physically equivalent" means a similar ionization state Z*, similar ion-coupling parameter $\Gamma = Z^{*2}e^2/R_okT$, similar electron Fermi degeneracy parameter ($h = E_f/kT$), and, as far as possible, similar electrical or optical properties. (Here Z is the atomic number, e is the electron charge, $R_o = 1/n^{1/3}$ is the average distance between ions, n is the ion number density, T is the temperature, and k is Boltzman's constant). This allows us to perform high energy density experiments on a moderate-scale facility and obtain essentially equivalent data. The EOS uncertainty comes from the combined effects of ionization, interaction between atoms, and formation of molecules. These effects scale with the ionization potentials and binding energies for atoms and molecules. The parameters vary over a large range. For example, the ionization potentials range from 3.89 eV (Cesium) to 24.6 eV (Helium). Cesium at 2000 K will behave a lot like Helium at 20,000 K as far as ionization is concerned.

For ion-beam heating one has the important advantage of relatively uniform heating over a 1 micron ion range (for ion energies around 1 MeV per nucleon), making it much easier to prepare a homogeneous hot dense sample at or near thermal equilibrium. We believe that this advantage of uniform heating abundantly compensates for the pressure-limitation of today's ion-heated targets for the purpose of taking accurate scientific data.

The Thomas-Fermi EOS has a well-known scaling law, involving powers of the atomic number Z (i.e., pressure $p \sim Z^{7/3}$, temperature $T \sim Z^{4/3}$, density $\rho \sim Z$), and that scaling is built into the inertial confinement fusion simulation code LASNEX (through the QEOS inline equation-of-state). The Thomas-Fermi scaling is an approximation, good to about 10%, but it illustrates how experiments at pressures below 1 Mbar on a low-Z material can predict phenomena found above 1 Mbar in a high-Z material.

Laboratory astrophysics groups have used the scaling concept to great advantage in doing astrophysical experiments on NOVA, OMEGA, GEKKO, and on the Sandia Z machine. Scaling is generally accepted as a useful strategy for basic research, although there is often debate about the details in any specific case.

The study of materials in and near the two-phase region is not just a study of EOS. There are fundamental questions about the hydrodynamic behavior of these materials: Is the two-phase flow abnormally slow as predicted by the two-phase sound speed? Does material remain in evaporation-equilibrium as it expands? What is the kinetics of evaporation, droplet formation and growth? Does a hydrodynamic code need to model super-heating, super-cooling and non-equilibrium bubble/droplet dynamics? These are both quantitative and qualitative questions and can be answered by high-speed photography of the flow produced by VISAR, pulsed laser reflection, etc.

A class of important questions concerns the homogenization of porous materials ("foams") rapidly heated by volume deposition. Certain proposed National Ignition Facility (NIF) targets rely on modeling the behavior of such foams under x-ray preheat, but the hydrodynamic codes need validation by experiments in this range of conditions.

The degree of homogenization will play an important role in setting initial perturbation amplitudes for the Rayleigh-Taylor instability.

There are other questions, for example, concerning the metal-insulator transition, and these are potentially high-leverage fundamental scientific questions, while also being important to models for pulsed-power heating of thin wires. The metal-insulator transition also occurs in the low-temperature part of the warm dense matter range and may occur at pressures less than 1 Mbar.

2.2 Heavy-ion-beam-driven HEDP approach

A proposed approach is to use ion beams to heat matter to the warm dense matter regime, because, unlike lasers which typically deposit the energy in a surface layer and thus require shocks to propagate inward to heat bulk matter, ion beams deposit their energy volumetrically. Specifically, we plan to heat targets with incident ion energies just above the Bragg peak in dE/dx, such that that peak occurs in the center of the target, resulting in both maximum beam energy deposition as well as improved uniformity of heating. Simulations of such beam-heated targets near the Bragg peak indicate that target heating non-uniformities of less than 5 % can be achieved, small enough to allow differentiation of various EOS models. We have also found that similar uniformities can also be achieved in thin target foils with beam energies well below the Bragg peak, such as NDCX-I at 10 keV/amu, because of the competing effects of nuclear scattering and electron drag. Among the potential advantages of such ion beam heating are:

1. Precise control and uniformity of energy deposition is possible;
2. The large sample sizes compared to diagnostic resolution volumes greatly eases the requirements of diagnosing the state of the matter;
3. The longer time scales associated with the larger volumes increases the likelihood that equilibrium conditions are established;
4. Ion beams can heat a variety of target materials (including both insulators and conductors);
5. A benign environment for diagnostics (low debris and radiation background) is possible. In contrast with experiments underway at GSI, at multi-GeV energies, heavy ions create neutrons and radioactive nuclear fragments, which can lead to significant facility shielding expenses. Also, with the modest pulse energies envisioned here, only about ten micrograms of target material are vaporized with each shot, making target debris from a large number of shots and rapid bursts of shots tolerable before diagnostic windows need to be cleaned or replaced; and
6. High pulse repetition rates (10/hour to 1/second) are easily attainable with accelerator technology with multiple beamlines, target chambers, and for targets replaceable in situ. This ensures that aiming, calibration, and data collection can be performed in reasonable time periods.

The most straightforward heating approach for facilitating interpretation of data in the warm dense matter (WDM) regime is to heat the material on a time scale comparable to or less than the hydrodynamic timescale of the target. For early investigations of this regime, targets composed of foils at 0.1 to 0.01 solid density can be used, so that hydrodynamic time scales larger than a few ns will compare favorably to achievable pulse lengths (of order 1 ns). Examining the physics of these lower density foils (and wire arrays or foams of similar average density) has the additional benefit that these materials are of particular interest to the inertial fusion community, as they are often used in inertial fusion energy and inertial confinement fusion targets. Our scientific approach in the near term will be to lay the scientific groundwork for investigations of these types of targets with the goal of determining equation-of-state and transport properties of material in the WDM regime. Our immediate goal is to take advantage of the intensity of the present ion beams in NDCX-I for initial WDM experiments below 1 eV, and then extend these studies to 1 eV and above in the NDCX-II device. Simulations using both the WARP and LSP simulation codes will be used to optimize WDM experiments on NDCX-I and on NDCX II to provide a relevant basis for the design of the Integrated Beam – High Energy Density Physics Experiment (IB-HEDPX). We will first use different EOS models and hydrodynamic codes (such as HYDRA 3D) to explore computationally various possible candidate WDM targets for future experiments, initially for NDCX-I and GSI beams at low intensity, and later for NDCX-II and IB-HEDPX at higher intensity. We will make use of low-intensity beam heating experiments, first to begin characterizing beam-target interactions, and to develop and calibrate new diagnostics that will be needed for future ion-beam-driven WDM and direct-drive hydro experiments at higher intensity.

There are many opportunities to explore the atomic, solid state and plasma physics of matter excited and heated by the present ion beams:

Beam-induced transient emission and absorption experiments in transparent insulators. Here the beam excites electrons to higher energy bands, e.g, 2p to 3s bands in SiO_2 allowing photons to be absorbed. The 2p holes permit strong photon absorption (2s to 2p), resulting in a darkening of otherwise transparent material. The goal is to determine physical parameters of the glass material, and help clarify and corroborate the understanding of phenomena observed at higher temperature.

Experiments to measure target temperature and conductivity using a beam compressed both radially and longitudinally on NDCX-I. Here, the best focus (both longitudinally and transversely) that can be obtained on the current NDCX facility will be used to raise target temperature as high as possible, and begin to make hydrodynamic and conductivity measurements.

A positive - negative halogen ion plasma experiment requires kT > 0.4 eV (NDCX-I with enhancements, or possibly on HCX with a focusing solenoid). 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 plasma conductivity may have similarities to semi-conductors, so the exploration of this novel plasma state has the potential for rich scientific payoff, such as high power plasma switches.

Two-phase liquid-vapor metal experiments require kT > 0.5 - 1 eV (on NDCX-I with upgrades, or on NDCX-II). The location of the liquid-vapor phase transition boundary for a number of metals is unknown and the hydrodynamics of metals crossing this phase boundary is also not clearly understood.

Properties of liquid metals heating up towards their critical poitns. The critical point occurs at the highest temperature for which a distinction between the gaseous and liquid state can be made. The critical point for a number of metals is not known. Therefore, experimental determination of this fundamental quantity would be of general scientific interest. Experiments in this regime can begin with collaboration at GSI. The special conditions of NDCX-1 favor an interesting class of experiments likely to provide important information about hot liquid metals and the liquid-vapor two-phase region.

NDCX-1 produces a compressed pulse (~ 2 nsec duration) above a broad uncompressed pulse. For high-pressure experiments the compressed pulse is necessary, but interesting experiments can be done with the uncompressed pulse. This pulse potentially contains much larger energy. We estimate that it is possible to deposit 10 - 100 kilojoules/cm3 in a 0.3 micron layer during a 1-10 microsecond ion pulse.

Because the heating rate is slow compared to the time required for thermal expansion, the heated material will expand during heating and remain at low pressure. It will melt and rise up the high-density side of the two-phase boundary. With sufficient energy it can go well above the boiling point and can even approach the critical point. Of course as the temperature rises the surface evaporation rate increases. Apart from evaporation, the liquid metal will retain a sharp surface sustained by surface tension. (We expect during the prepulse the foil temperature will be determined by an equilibrium between heating by the beam and cooling due to evaporation and electron emission. During the compressed pulse, a higher temperature can be reached because of the 60 times higher heating rate.)

Bubble formation provides another cooling mechanism, but the nucleation size of bubbles affecting the formation rate is uncertain, and so we should look experimentally for evidence of temperature limits that may be set by bubbles (boiling). If bubble formation occurs this would decrease the estimate for the maximum temperature achievable. The foil temperature can be measured by fast optical pyrometry, a new diagnostic we have developed that can be calibrated by using high-melting samples as standards. Thus, NDCX-I heating experiments allow us to explore the extent to which bubbles and droplet formation alter the basic picture of heated material evolving along the two-fluid boundary.

Today the critical points are not known for metals such as aluminum, iron, tantalum, molybdenum, tungsten. (Estimates in the literature differ by factors of two.) Experiments on NDCX-1 can greatly reduce this uncertainty. We calculate that temperatures of 0.7 eV (~ 8000 K) might be obtained in aluminum foils in the absence of bubbles, in samples having nearly uniform density and temperature. The vaporization point of Al is 2792 K. The evaporation rate can be determined by optical laser probe reflection and by monitoring beam transmission through the foil as it evaporates. This information will greatly improve EOS models for matter in the WDM range of temperatures and densities.

2.3 Technical progress in heavy-ion-beam-driven HEDP

In order to provide the needed target energy density for WDM, we must produce a short pulse (~1-3 ns) and a high line charge density beam focused onto a thin (few micron) target, preferably porous at a fraction of solid density. To do this we have worked on: a high-current, high-brightness ion source; an accelerator with solenoid focusing for high line charge density transport with electron cloud mitigation; a neutralized drift compression section to provide longitudinal compression of the intense ion beam, enabled by a neutralizing plasma; a final focus using a high field solenoid to compress the beam transversely, also neutralized with background plasma; a target chamber with a target tailored to the beam characteristics; and finally diagnostics to measure the beam-target interaction. We summarize below technical progress in these 5 research thrust areas.

2.3.1 High-Brightness Beam Transport

Electron cloud effects and gas-pressure rise limit the performance of many major accelerator rings, and these effects constrain the architectures of linacs being developed as drivers for high energy density physics and heavy ion fusion. The accumulation of electrons in an ion beam can lead to brightness degradation and ultimately to beam disruption. The Heavy Ion Fusion Science- Virtual National Laboratory has studied these effects through experiments, simulations, and through code modifications to reconcile the differences.

Code development carried out in support of this effort included: adding electron and gas source modules to WARP [2.1], developing a "drift-Lorentz" particle mover that accurately captures electron dynamics in regions of both weak and strong magnetic fields [2.2], and applying adaptive-mesh refinement (AMR) techniques to the WARP particle-in-cell (PIC) simulations [2.3] (as described below in Section 2.3.3). The latter two enhancements have increased the speed of WARP simulations with electron clouds (by up to 2 orders-of -magnitude for fusion applications). In addition, the agreement between code results and experimental data was greatly improved by adjusting the physics parameters in WARP that are not known from first principles and by modifying the WARP solenoid representation to account for eddy currents in nearby metal components.

Electron-cloud and gas-cloud effects were studied in a four magnetic quadrupole transport experiment in the High Current Experiment (HCX) by allowing the heavy ion beam to impinge on a stainless-steel plate at the end, desorbing neutral gas and freeing electrons [2.4]. With GSI, we discovered the scaling of gas desorption with ion dE/dx [2.5]. Trapping electrodes (negatively-biased rings or plates between quadrupole magnets, or at the exit of the transport lattice) and clearing electrodes (positively-biased rings inserted into the drift regions between quadrupole magnets) control electron flow into the beam region. Trapped electrons reduce the net beam potential by partial charge neutralization. A small number of cold ions are generated within the beam by beam-impact ionization of background gas, and the net beam potential then expels these ions. The energy distribution of expelled ions is measured with a retarding field analyzer (RFA), from which we determine the peak potential of the beam and its variation during the beam pulse [2.6]. We have simulated these experiments with WARP and find qualitatively good agreement.

We have also studied the interaction of the electron cloud with the ion beam. The beam phase space was measured at the end of the accelerator using a slit scanner; with the suppressor electrode turned off, a characteristic z-shaped phase-space plot (x versus x') is obtained, while with the suppressor on, the distortion is largely eliminated. Good agreement with simulations is found. The electron density develops oscillations as electrons drift upstream through the last quadrupole; this was discovered concurrently in WARP simulations and in the experiment, and as seen in Fig. 2.1, we find good agreement for the frequency, wavelength, and amplitude of the oscillations [2.7].

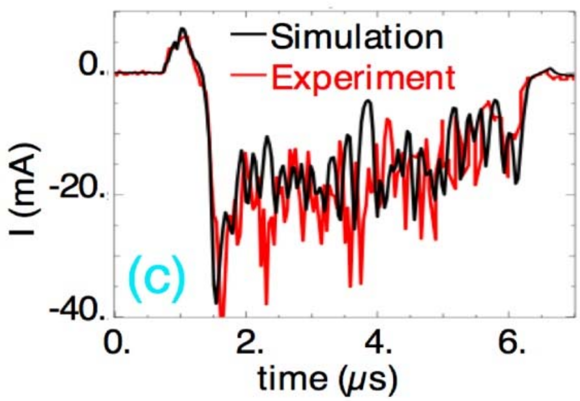


Figure. 2.1: Current to the clearing electrode (biased to +9 kV) upstream of the fourth quadrupole in HCX. Simulation and experiment are compared.

From a practical standpoint, we found that intentionally flooding the quadrupole channel with electrons had a substantial effect on the beam phase space. In experiments with simple suppression of the backstreaming electrons from the end diagnostic led to measurements of transverse phase space that were well represented by simulations without e-cloud effects, despite the measurement of a relatively low yield of halo generated or beam-impact ionization generated electrons between the quadrupoles [2.8]. Consequently, the beam emittance is expected to be conserved for beams filling over 50% of the physical beamline aperture, an important consequence and encouraging outcome for high energy density physics and heavy ion fusion applications.

We have also studied electron-cloud effects in a four-solenoid transport experiment in NDCX. Experiments were performed to study the matching and transport of a space-charge dominated ion beam in the solenoid transport channel shown in Fig. 2.2. These experiments provide a basis for comparison of solenoid transport with magnetic quadrupole transport in accelerators, for application to warm dense matter and heavy ion fusion. The beam energy and current was the same as indicated in Section 2. Beam diagnostics are provided in an end tank and compared to data at the exit of the ion injector.

Long electrodes in the gaps were placed between magnets, and intercept magnetic flux that expands between the magnets and passes through the outer half of the beam radius in the center of the solenoids. These "gap electrodes" are biased positively, in the clearing mode, to remove electrons. Short electrodes are provided in the center of each solenoid; these "solenoid electrodes" are biased negatively, in the clearing mode, to expel electrons from the solenoids. The biases can be reversed for a trapping mode: negatively-biased gap electrodes emit electrons due to ion or photon impact and repel trapped electrons, and positively-biased solenoid electrodes trap electrons in the center of each solenoid magnet. The trapping mode forms a Penning-trap-like configuration with magnetic radial confinement and electrostatic axial confinement of electrons.

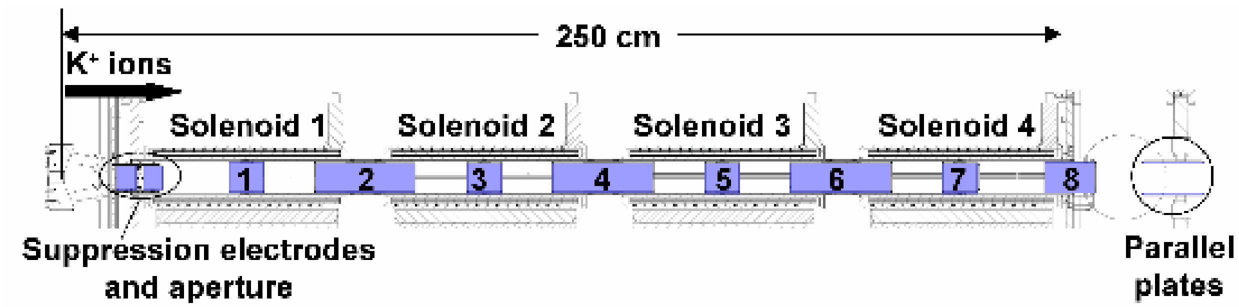


Figure 2.2: Layout of the aperture and suppression electrodes, electron cloud diagnostics in NDCX: solenoid electrodes (1, 3, 5, and 7), gap electrodes (2, 4, 6, and 8); and parallel plate diagnostic relative to the four-solenoid lattice. All of the diagnostics have cylindrical symmetry except for the parallel plate diagnostic.

Images of the transverse beam structure taken about 5 μs into a 10 μs beam pulse with a 10-ns gate showed a clear difference between the clearing and trapping bias patterns. A bias set to trap electrons had a larger spot size, a very irregular density profile, and an emittance that was five times larger than was found for the other bias pattern. The case with unbiased electrodes gave intermediate results, closer to the clearing case than to the trapping case, with 40-50% higher emittance than the clearing case. This emittance increase was inconsequential to the drift compression experiments planned.

Simulations of the clearing and trapping cases provide reasonable agreement with the clearing case, but show little difference in the trapping case. This may be due to beam halo that scrapes the electrodes, producing electron and gas emission from the surfaces. Emission currents are measured from negatively biased electrodes consistent with this hypothesis. Without a mechanism to generate the observed gap-electrode current in the trapping case, simulations will not be able to reproduce the trapped electron density or its effects on the beam emittance. When electrons are minimized in the solenoids with the bias electrodes, we find that the measured beam envelope (size and convergence angle) agrees well with simulations [2.9,2.10, 2.11], but there is a 40-50% emittance increase when the beam current is limited with the aperture at the exit of the injector. This suggests that we have a fair understanding of beam dynamics, in the absence of electron effects, or when they can be ignored for these relatively short experiments.

2.3.2 Longitudinal Beam Compression and Transverse Focusing of Intense Ion Beams

In order to achieve the best transverse focusing and emittance-limited longitudinal compression, the background plasma density must exceed the local beam density (see, for example, [2.12] and the extensive discussion and related bibliography in Section 2.3.3). Depending on the beam and plasma densities, collective instabilities may limit the focused beam intensity, but for NDCX-I (based on both experiment and theory) and NDCX-II (based on theory) these instabilities appear to be benign.

The scaled final focusing experiment demonstrated the successful neutralization of an initially space-charge-dominated beam by a background source of electrons in order to achieve an emittance limited focal spot [2.14]. The experiment was scaled from a design of a final focusing system for a heavy ion fusion driver using quadrupole magnets for beam transport (driver parameters: 10 GeV Bi+ at 1.25 kA/beam). With a beam current of 400 μA and a perveance of 5 x 10^{-5}; space-charge limited the minimum focal spot size near the focal plane, so that the spot radius with neutralization was ~2 X smaller than without, in agreement with modeling assuming 80% and no neutralization. LSP simulations [2.15] also showed good agreement with the experiments.

This was followed by the Neutralized Transport Experiment (NTX) as a precursor to the additional feature of axial bunching of the ion beam. The NTX operated at a higher current (~25 mA) and higher energy (250-350 keV) K^+ beam. The beam perveance (~10^{-3}) was effectively neutralized with RF and a cathodic-arc plasma sources[2.16]. This demonstrated the feasibility of neutralization of higher perveance beams .

In order to amplify the beam current and create a short (~ ns) pulse with duration suitable for the study of warm dense matter, our approach has been to modulate the energy of the non-relativistic beam. The axial compression is achieved with an induction bunching module (IBM) inserted after the matching section. Operating at +/-80 kV, a ±15% velocity ramp was imparted to 150-200 ns subset of the several-microsecond beam pulse. The beam then drifts through a neutralizing plasma in a drift compression section a few meters in length. Current amplification of ≈ 50 was demonstrated in the first NDCX experiments [2.17]. To establish a neutralizing plasma along most of the length of the drift compression section, the RF plasma used in NTX was replaced with a ferro-electric plasma source [2.18], and cathodic arc plasma sources injected a higher density plasma near the focal plane where the beam density is greatest.

A fundamental limit to the current amplification and pulse duration is the longitudinal energy spread (longitudinal phase space and emittance) of the injected beam, which was measured with an electrostatic energy analyzer. The measured energy spread of the injected 300 keV unbunched beam, $\Delta E \approx 0.17$ keV, corresponds to an axial temperature of $T_z = 0.05$ eV, adequate for achieving nanosecond-duration bunches. Other limits are set by the uniformity and density of the background neutralizing plasma, and imperfections of the bunching module waveform. In general, simulations have shown that if the background plasma density is greater than the local beam density, then the effectiveness of the neutralization is independent of the details of the plasma density distribution [2.12]. For near-term warm dense matter experiments, the beam density increases steeply as the beam approaches $n_b = 10^{13}$ / cm^{-3} near the target plane. We have measured plasma densities in that range with cathodic arc plasma sources. The plasma temperature should be low enough so as not to heat the beam and we have found that plasma temperatures in the few eV range have a benign influence on the beam.

In the induction bunching module (IBM) radial electric fields are generated in the gap across which the IBM voltage is applied that include a net radial defocusing effect on the bunching beam. Following an analysis of this effect [2.20], it was determined that tuning the initial beam envelope to compensate for the defocusing of the IBM enabled simultaneous transverse focusing and axial compression, as shown in Fig. 2.3[2.21].

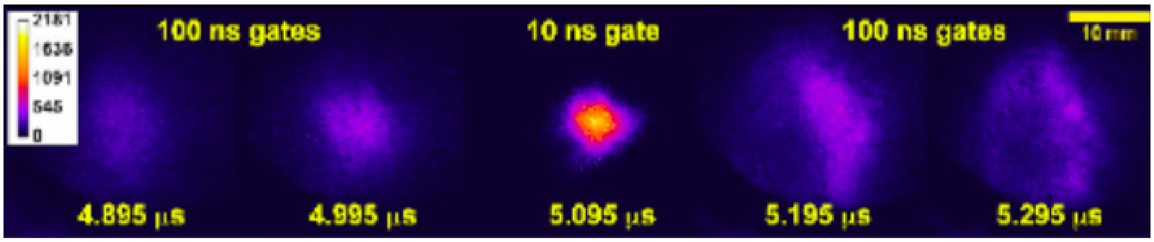


Figure 2.3: Time-dependent transverse beam distributions demonstrating the simultaneous focal plane.

A number of beam manipulations and plasma source designs are under study to improve the beam intensity on target for warm dense matter are under study:

1. We are studying and experimenting with a short, high-field solenoid (B = 8 Tesla, 10-cm coil length) after the ferroelectric plasma source and before the target plane (see Figure 2.4) to impart a steep convergence angle on the beam before the focal plane. LSP modeling suggests that sub-mm radii might be possible, leading to a several-fold increase in the energy deposition. This assumes sufficiently high plasma density can be injected into the bore of the solenoid [2.22]. Beam experiments are underway, along with extensive measurements of the plasma density distribution in the solenoid and region near the target.
2. Since mirroring of the plasma injected from outside the solenoid can limit the plasma density in the bore of the focusing element, we are exploring modification of the magnetic field topology near the target plane to allow more efficient plasma transport to the region where the beam density is highest. Modeling of plasma flow with auxiliary coils is underway. Also, more compact plasma sources are possible in principle. Smaller sources can be placed closer to the target plane, reducing the cross-field plasma transport.
3. We are conducting experiments to increase energy deposition in the target by taking advantage of the high probability of scattering beam ions near grazing incidence, with relatively low energy loss using a high-Z cone or funnel.
4. We have recently constructed a new IBM. Based on LSP and analytic study, the new IBM, which has twice the volt-seconds of our IBM, should be accompanied by a longer drift compression section in order to achieve a predicted doubling of the energy deposition on future warm dense matter targets. This will be accomplished by constructing a longer (2m) ferroelectric plasma source.
5. Time-dependent focusing to compensate for the large, and otherwise limiting chromatic aberration in the bunched beam is desirable. For the near-term experiments, chromatic aberrations due to the large velocity spread of the beam increase the rms focal spot size by about a factor of two. A first examination of

requirements for a time-dependent lens indicates that a pulsed electric einzel lens or quadrupole doublet with relatively low potentials (10-20 kV) can easily meet the requirements. A quadrupole triplet would allow correction of non-axisymmetric rms-envelope parameters at injection to the bunching module to be brought to an axisymmetric distribution at the focal plane. This would increase the overall length of the correction element and will be studied in numerical simulations.

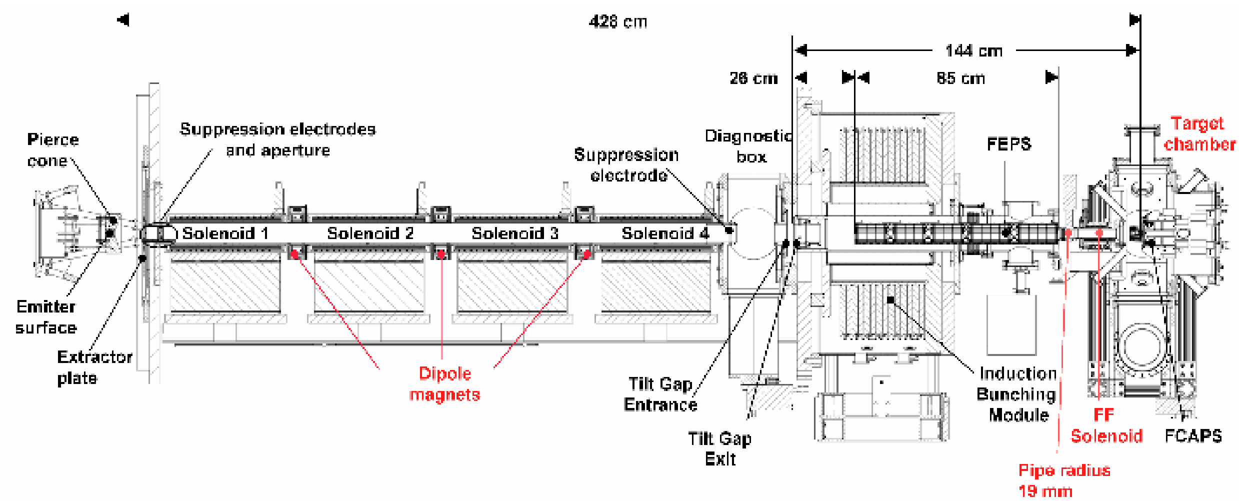


Figure 2.4: Elevation view of the Neutralized Drift Compression Experiment (NDCX).

These are aimed at achieving beam intensity on target, and short pulses capable of exploring warm dense matter with relatively low energy ion beams.

2.3.3 Advanced Theory and Simulations

Advanced theory and simulation progress includes analytical and numerical investigations of nonlinear beam dynamics, collective beam-plasma interaction processes, and intense beam compression and focusing. To achieve the high focal spot intensities necessary for high energy density physics and heavy ion fusion applications, the ion beam pulse must be compressed longitudinally by about a factor of one hundred, and transversely by a factor of ten or more before it is focused onto the target. To achieve maximum compression, the space charge of the ion beam is neutralized by propagation of the beam pulse through a dense neutralizing background plasma. If the space charge is fully neutralized by the plasma, the final compression is limited only by the initial temperature of the beam ions and possible collective processes (such as the two-stream and filamentation instabilities) which may prevent full neutralization of the beam space charge. In one scenario, transverse compression of the beam ions is facilitated by using solenoidal focusing magnets. This section summarizes several recent theoretical advances in understanding and optimizing the nonlinear beam dynamics, collective interaction processes, and beam compression and focusing.

***Self-Consistent Plasma Neutralization Models**:* Ion beam pulse propagation through a background plasma in a solenoidal magnetic field has been extensively studied both analytically and numerically [2.23 – 2.24]. The neutralization of the ion beam pulse current by the plasma has been calculated using a fluid description for the electrons, extending our previous studies of beam neutralization without an applied magnetic field [2.26]. Analytical investigations show that the solenoidal magnetic field starts to influence the radial electron motion if electron cyclotron frequency is larger than electron plasma frequency times the speed of the beam ions divided by the speed of light. This condition already holds for relatively small magnetic fields: for example, for a 100MeV, 1 kA singly-charged neon ion beam, the magnetic field B corresponds to about 100G. Particle-in-cell simulations show that the ion beam excites lateral waves, and their properties have been investigated theoretically.

Collective Stability Properties of Intense Ion Beams: We have carried out detailed analytical and numerical studies of the collective processes and beam-plasma interactions affecting intense heavy ion beam propagation [2.27-2.29]. In the acceleration and transport regions, the investigations have included: determination of the conditions for quiescent beam propagation over long distances; the electrostatic Harris instability [7 - 10] and the electromagnetic Weibel instability [2.30, 2.34] in strongly anisotropic one-component non-neutral ion beams; and the electron-ion dipole-mode two-stream (electron cloud) instability driven by an (unwanted) component of background electrons using the 3D nonlinear delta-f code BEST [2.35, 2.36]. In the plasma neutralization and target chamber regions, collective processes associated with the interaction of the intense ion beam with a charge-neutralizing background plasma have been assessed, including: the electrostatic two-stream instability, the electromagnetic multi-species Weibel instability, and the resistive hose instability [2.27, 2.28, 2.37]. Detailed properties of collective excitations and instabilities have also been examined in the presence of a solenoidal magnetic field [2.23,2.38]. Operating regimes have been identified where the possible deleterious effects of collective processes on beam quality are minimized.

Dynamic Stabilization of Two-Stream Instability During Longitudinal Beam Compression: Detailed properties of the electrostatic two-stream instability can change substantially during longitudinal compression of the beam pulse. In a recent calculation [2.39, 2.40], the electrostatic two-stream instability for a cold, longitudinally-compressing intense ion beam propagating through a dense background plasma has been investigated both analytically and numerically using a simple one-dimensional model in which transverse spatial variations are neglected. The linear development of the instability and its saturation are examined from the point of view of wave dynamics, where the plasma waves are represented as quasi-particles characterized by their position, wavenumber, and energy (or frequency). It is found that the longitudinal beam compression strongly modifies the space-time development of the instability. In particular, the dynamic compression of the beam pulse leads to a significant reduction in the growth rate of the two-stream instability compared to the case without an initial velocity tilt [2.39].

Ionization, Charge Exchange and Stripping Cross Sections: Detailed estimates of ion-atom charge-changing cross sections are essential in many applications employing the propagation of fast ions through matter. A hybrid method has been developed for calculation of the charge-changing cross sections of ions or atoms by fast ions by combining the quasi-classical approach and the Born approximation of quantum mechanics in the regions of impact parameters in which they are valid, and summing the results to obtain the total cross section [2.41, 2.42]. As a result, typical computations can be carried out rapidly. This approach has been tested by comparison with available experimental data and full quantum mechanical calculations. A new scaling formula for the ionization and stripping cross section of atoms and ions by fully stripped projectiles has also been developed [2.41, 2.43].

Compression and Focusing of Intense Heavy Ion Beams: After acceleration, the beam pulse duration is reduced using longitudinal drift compression. (A longitudinal velocity gradient or "tilt" is imposed on the beam, and it is then allowed to drift axially.) For heavy ion inertial fusion energy applications, either un-neutralized [2.44 – 2.46] or neutralized [2.47 – 2.54] compression may be considered. The following two paragraphs describe these, in turn.

Neutralized Drift Compression: For near-term high energy density physics and warm dense matter applications, with corresponding short-pulse requirements on the target, the intense ion beam must be charge neutralized during compression. Advanced numerical simulations have shown that large compression factors, limited only by the beam thermal spread, the accuracy of the compressing waveform, and the completeness of neutralization, can be achieved. Simulations and analysis have been carried out [2.48 – 2.51] in direct support of the Neutralized Drift Compression Experiment (NDCX). Space-charge forces must also be minimized while the beam passes through the target chamber and onto the target, and so in this region the beam must be neutralized by background plasma. Neutralized focusing has been studied in simulations for the general case [2.48] and for experiments in the Neutralized Transport Experiment (NTX) [2.52, 2.53]. Finally, for the case of neutralized drift compression, a fully kinetic model based on the Vlasov equation has been developed that describes the longitudinal compression and transverses focusing of an intense ion charge bunch propagating through a background plasma that provides complete charge and current neutralization in a solenoidal magnetic field [2.54]. Mean-free paths for beam ions scattering on background plasma ions and electrons are much longer than the drift lengths, so that collisions can be neglected.

Un-neutralized Compression: As indicated earlier, for heavy ion inertial fusion energy applications, either un-neutralized [2.44 – 2.46] or neutralized [2.47 – 2.54] compression are possible options. In the un-neutralized case, to describe the drift compression dynamics and the final focus of the beam particles to a common axial plane and prescribed focal spot size, a warm-fluid model has been employed to describe the longitudinal dynamics of drift compression, coupled nonlinearly to envelope equations that describe the self-consistent transverse dynamics and focusing of the ion beam as it propagates through the quadrupole focusing lattice [2.44, 2.45]. To assure the focus of different slices of the beam onto a common axial plane and prescribed focal spot size, a non-periodic quadrupole lattice design has been developed with four time-dependent quadrupole magnets at the beginning of the drift compression phase. This robust model is capable of describing the layout of the magnet lattice, the drift compression phase, and the final focus dynamics for a wide range of system parameters and velocity tilt pulse shapes [2.44, 2.45].

Analytical solutions for continuously focused beams and single-species non-neutral plasmas in thermal equilibrium*:* Historically, simple two-dimensional Vlasov-Poisson descriptions of thermal equilibrium have been applied to both an unbunched ion beam propagating in a continuous linear focusing channel and an unneutralized, single-species non-neutral plasma confined in a Malmberg-Penning trap geometry. In scaled variables, these two thermal equilibrium systems result in an identical nonlinear equation that must be solved to describe the radial density and/or potential of the equilibrium. Numerous publications have been based on *numerical* solutions of the highly nonlinear equilibrium equation. In a recent work [2.53], approximate *closed-form analytical* solutions were, for the first time, derived for such thermal equilibrium systems. The scaled solutions are functions of the radial coordinate (in cylindrical geometry) expressed in terms of Debye lengths, and depends only on a single dimensionless parameter Δ. The parameter Δ, which varies between zero and infinity, measures the strength of the space-charge defocusing forces relative to that of the linear applied focusing forces acting on the particles. The solution is highly accurate for $\Delta < 0.1$, which corresponds to a broad range of strong relative space-charge strength and produces a highly nonlinear density profile with a flat core region characteristic of strong Debye screening. The solution can be employed in a variety of practical problems in beam and nonneutral plasma physics. For example, the expressions can be applied to calculate simplified expressions for the distribution of particle frequencies and angular momenta, in thermal equilibria with strong space-charge. These solutions are expected to be useful both in intense beam and in nonneutral plasma physics studies, and may enable analytical progress on topics that have been previously explored only numerically.

Beam dynamics in misaligned solenoid channels: A formulation has been developed to systematically correct misalignment-induced oscillations of the transverse beam centroid in solenoid beam transport lattices. Linear equations of motion have been derived to describe small-amplitude centroid oscillations induced by displacement and rotational misalignments of the focusing solenoids in the lattice, steering dipole elements placed in the lattice, and initial centroid offset errors. These equations were analyzed in a local rotating Larmor frame to derive *alignment functions* and *bending functions* that describe the characteristics of the centroid oscillations induced by the misalignments of the solenoids together and the dipole steering elements, in terms of properties of the ideal lattice in the absence of errors and steering. The centroid orbit was systematically decomposed in terms of the alignment and bending functions superimposed on the ideal orbit in the absence of alignment errors and steering fields. The structure of this expansion was exploited to formulate optimal centroid steering algorithms, and to derive equations of constraint giving the solenoid misalignment parameters of the lattice based on centroid measurements accumulated at discrete locations in the lattice. This formulation is being applied to the solenoidal transport lattice in the Neutralized Drift Compression Experiment (NDCX) at the LBNL to improve the quality of the focused beam on the target.

Adaptive mesh refinement for kinetic simulations: Modeling of ion beam transport from source-to-target in a high energy density physics or heavy ion fusion driver involves space and time scales that span a range of at least several orders of magnitude; such problems can be very challenging computationally. To make them tractable, we merged the adaptive mesh refinement (AMR) technique (which concentrates grid resolution where it is needed) and the particle-in-cell technique, for the first time, and implemented a robust algorithm into WARP [2.56-2.62]. The greatly improved resolution provided by AMP-PIC in front of an ion-emitting surface has proven critical to our injector modeling effort, where a high level of agreement between experiment and simulation would not otherwise have been attainable [2.57,2.58, 2.63]. The capability has also been valuable in our modeling of the interaction of beams with electron clouds in accelerators for high energy density physics and heavy ion fusion applications [2.64] and high energy physics accelerators [2.65]. We anticipate that adaptive mesh refinement will become equally valuable for reducing computational costs in modeling beam pulse compression and propagation through the target chamber, since the beam must be compressed longitudinally by about a factor of one hundred, and transversely by a factor of ten or more, before it is focused onto the target.

Development of plasma simulation capability in WARP: Much development has been done on the WARP code, giving it advanced capabilities for modeling plasmas and beam-plasma interactions, primarily for simulations of neutralized drift compression and focus. We describe some of the more important additions here. Automatic sub-cycling of the particle calculation has been implemented, whereby particles with smaller velocity, and/or in an area of weak fields, are advanced less often with a larger time-step. If a particle's velocity or environment changes, the time-step size used to advance the particle is automatically adjusted, so as to satisfy a "Courant" condition. This allows more efficient calculation, since unnecessary computational work is avoided. An implicit electrostatic PIC algorithm was implemented in WARP, in 2-D and 3-D. The implementation includes the full susceptibility tensor (for magnetic fields). This capability allows faster simulations for dense plasmas by removing the need to resolve the electron plasma frequency. An energy-conserving field gather was implemented. In most cases of interest, this removes the necessity of resolving the Debye length, allowing use of fewer grid cells and consequently fewer particles and larger time-steps. Without this model (using the conventional momentum-conserving mover), the simulation would undergo artificial numerical heating if the Debye were not resolved. A model allowing space-charge limited emission off of arbitrary conductor surfaces has been implemented. This model is useful for maintaining charge neutrality in simulations of plasmas near conductors when the Debye length, and therefore the sheath physics, is not resolved. A scheme was implemented in WARP to model the effect of small-impact-parameter Coulomb collisions. These collisions do not arise naturally in the PIC algorithm because of the smoothing of the short-range effects by the grid. The scheme adjusts particle velocities by a random scattering angle, with a frequency given by a collision frequency calculated from the local density of particles. The technique is mainly of importance to very dense plasmas, when the simulation time is comparable to or greater than the collision time. To increase the scalability of WARP in parallel processing environments, as needed for large-scale plasma simulation, the domain decomposition scheme is being generalized to allow 1-D, 2-D, and 3-D decompositions. This is now operational for the electrostatic field solvers, including the 2-D and 3-D implicit solvers, and including mesh refinement. To test the new capabilities, a number of basic plasma test problems have been simulated, showing overall good agreement with theory and with the other main simulation code used by the Heavy Ion Fusion Science-Virtual National Laboratory, the LSP code.

Drift-Lorentz particle mover*:* There are a number of applications of interest to the Heavy Ion Fusion Science-Virtual National Laboratory where it is desirable to follow charged-particle trajectories through regions where the particles are strongly magnetized (gyroradius small compared to macroscopic scale lengths) as well as regions with little or no magnetic field, with time-steps large compared to the smallest cyclotron period. Examples include stray electrons in quadrupole-based accelerators, and plasma electrons and ions injected from a magnetized source or into a solenoidal field for neutralized drift compression. To address this need we have developed the drift-Lorentz particle mover. In its basic implementation [2.66], it is an explicit advance scheme that interpolates between full particle dynamics (Boris scheme) and drift kinetics in such a way as to preserve proper particle drifts, motion along the magnetic field, and gyration radius about the magnetic field in the large-B limit, while smoothly matching on to full-particle dynamics at small B. This scheme was used for the successful simulations of the High Current Experiment (HCX) electron-cloud experiments, and enabled a substantial reduction (~ 25 X) in the running time required for these simulations. In order to be able to apply the mover to high-density problems (where the plasma frequency is comparable to or exceeds the cyclotron frequency) we have added implicitness to the mover. The first step in this direction was the addition of the polarization charge density to the susceptibility in the electrostatic field equation [2.67], and most recently, we have formulated and implemented a fully implicit version (still electrostatic); the resulting code has been successfully verified on a magnetized electron-ion two-stream instability, and further tests are in progress.

Implementation of electromagnetic solvers in WARP: We have implemented 1-D, 2-D and 3-D electromagnetic solvers in WARP. In 1-D, we implemented both the finite-difference Yee scheme and the advective scheme [2.68]. This is used mostly for testing of new algorithms. Both the 2-D and 3-D solvers use a finite-difference time-domain (FDTD) scheme on a Yee grid, with periodic or open (perfectly matched layer) boundary condition, and parallelized with 1-D domain decomposition. The 3-D solver was tested on a Weibel-like instability case. Good scaling was observed on the Fusion Linux cluster at LBNL and on Bassi at NERSC, using up to 32 processors. 3-D domain decomposition will be implemented in the near future. We have developed a technique based on "substitution" for applying refined patches in electromagnetic PIC calculations [2.69] that was implemented in the 2-D solver, and tested on the modeling of a fast-ignition relevant problem. We also implemented a novel 'dispersionless' 2-D electromagnetic solver [2.70] in WARP. The solver is based on a discretization of the Maxwell equations on a Yee mesh, using enlarged stencils for stabilization of the solution when the time-step size is set by the 1-D Courant condition. It is dispersionless along the major axes. This will offer great benefits for 'discrete impedance' matching between grid patches in an adaptive mesh refinement electromagnetic system. Testing of adaptive mesh refinement calculations using this new solver will be performed in the near future. Finally, we extended the applicability of the subcycling for fields and dynamic time stepping for particles in WARP to the electromagnetic mode. A speedup of two was demonstrated on the simulation of a fast-ignition relevant problem.

Modeling of relativistic beams: Connection of the heavy ion fusion science program to the high energy physics community offers us opportunities for benchmarking our computational tools in different regimes. Several of the computational techniques that we use in the heavy ion fusion science program are applicable to the regimes of interest to high energy physics community. We have recently vastly enhanced the domain of applicability of our main computational tools to high energy physics problems, by uncovering a previously unnoticed consequence of special relativity, with the result that the first-principles modeling of some systems containing ‘objects’ (particles or light) crossing at relativistic velocity can be sped up by orders of magnitude, via choice of a proper Lorentz-boosted frame for the calculation [2.71]. Three domains of applicability using the new *Lorentz boost* technique have been identified so far: (a) interaction of electron clouds with relativistic beams, (b) free electron lasers, and (c) wakefield accelerators. Thanks in addition to the development of a novel algorithm for solving the relativistic Newton-Lorentz equations of motion [2.72], we have successfully performed the simulation of an electron-cloud driven beam breakup instability in the Large Hadron Collider [2.73]. Very good agreement between Warp and the Headtail code from CERN [2.74] was obtained recently on electron cloud driven instabilities; agreement on electron cloud build-up was also obtained between Warp and the LBNL code Posinst. We have recently adapted the WARP code to simulate, with the Lorentz boosted frame approach, several free electron laser problems, including coherent spontaneous emission from prebunched electron beams, strong exponential gain in a single-pass amplifier configuration, and emission in undulators contained multiple harmonic components. We compared the results with those from the standard free electron laser simulation approach (the Ginger code [2.75] which applies the eikonal approximation for propagation of the radiation field), and obtained good agreement. We are starting to model laser-wakefield accelerators using WARP. Other groups reported preliminary results using our technique: speedups of up to 150 and 1,500 were obtained using respectively the UCLA code Osiris (in 2-D and 3-D) and the Tech-X code Vorpal (in 1-D).

Complementing earlier Heavy Ion Fusion Science-Virtual National Laboratory research on magneto-inductive models [2.76], we have derived a simplified set of Maxwell equations for calculating the fields of relativistic beams [2.72], in which retardation and wave propagations are discarded, as with the Darwin system, while inductive effects are retained in the direction of propagation of the beam only. The latter condition allows reduction of the computational complexity significantly; it requires only two Poisson solves, which is much less demanding than solving the Darwin system of equations. We are exploring whether this algorithm, or an extension of it, is applicable to the modeling of the beam during the neutralized drift compression phase of NDCX-II.

2.3.4 Beam-Target Interactions

The Heavy Ion Fusion Science-Virtual National Laboratory (HIFS-VNL) has completed the fabrication of a new experimental target chamber facility for future warm dense matter (WDM) experiments, and implemented initial target diagnostics to be used for the first target experiments in NDCX-1. The target chamber has been installed on the NDCX-I beamline. This achievement provides to the HIFS-VNL unique and state-of-the-art experimental capabilities in preparation for the planned target heating experiments using intense heavy ion beams. The completion of this target chamber facility, met the HIFS-VNL FY2008 third-quarter milestone, and the details may be found in [2.77].

The US heavy ion fusion science program is developing techniques for heating ion-beam-driven warm dense matter targets [2.78-2.83]. Intense ion beams have several attractive features as a technique for generating warm dense matter. These features include: precise control of local beam energy deposition dE/dx; nearly uniform density throughout a given volume and not strongly affected by target temperature; large sample sizes (about 1 micron thick by 1 mm diameter); the ability to heat any target material, for example, foams, powders, conductors, insulators, solid, gas, etc. Uniformity of target heating and efficiency of beam energy deposition are obtained by heating with the Bragg peak located near the center of the target. This approach allows operation with moderate beam energy (~1 MeV/amu). Other scenarios take advantage of two other regions where the dE/dx curve for heavy ions is nearly flat: high energy approaching 1 GeV/amu (as at GSI), and low energy in the range of ~10 keV/amu. The range of the low and moderate energy beams planned for the HIFS-VNL experiments is about 1 micron in solid matter targets, which can be lengthened by using porous targets at reduced density. Because of the short range, it is necessary to compress the beam pulses to approximately 1 ns to be consistent with the hydrodynamic expansion time of the target. The range can be extended by heating low-density porous targets, for example, with density in the range of 1-10% of solid density, extends the ion beam range and hydrodynamic expansion time by factors of 10-100. Initial experiments will be at low beam velocity, below the Bragg peak, using the existing NDCX-1 accelerator (0.3-0.4 MeV K +). Intense ion beam currents must be focused to a spot size less than 1 mm in order to achieve sufficient heating power on target for these low kinetic energy ions. This is only made possible by the neutralized drift compression technique recently developed in the Heavy Ion Fusion Science-Virtual National Laboratory. The ion beam will undergo combined longitudinal and transverse neutralized drift compression to provide a hot spot on the target with a beam spot size $\leq$1 mm, and pulse length about 1-2 ns.

This approach has significant consequences for the experimental target and target chamber setup. Design of the experimental target chamber was reported in the 2007 fourth-quarter milestone report. The target chamber as built is designed to provide: (a) sufficiently dense (10^{12} to 10^{14} cm^{-3}) plasma injection to neutralize the space charge of the incoming ion beam; (b) a strong (8 Tesla) final focus solenoid for radial ion beam compression; (c) vacuum pumping; (d) retractable ion beam diagnostics; (e) a retractable target holder with in-situ alignment capabilities; (f) fast optical target diagnostics with access to the front, side and back of the target foil; and (g) accurate (micron-range) alignment capabilities We have developed a warm dense matter target chamber and a suite of target diagnostics including a high speed multi-channel optical pyrometer, optical streak camera, VISAR, and high-speed gated cameras. The target chamber and diagnostics will be installed downstream of the induction bunching module on NDCX-1. We are investigating the properties of a gold cone for focusing a moderate energy ion beam on target. The cone has been modeled with the TRIM code, and prototypes tested on the 300-keV potassium NDCX-1 beam. Maximum estimated sputtering yields of ~10^{12} gold atoms per shot are not sufficient to contaminate one monolayer on the target foil, which is changed out every shot. Initial warm dense matter targets will focus on gaining experience with diagnostics for WDM targets. The targets will be approximately a range thick, for example 350-nm Al and 150-nm Au, which means the entire thickness of the foil is heated, and its temperature can be measured on the backside of the foil. Simulations of target heating using HYDRA indicate heating to approximately 0.2 eV, depending on the beam final focus parameters achieved in initial experiments. We have begun a series of planned experiments in warm dense matter.

These experiments include a 2006 porous target experiment at GSI that compared the response of solid and porous gold and copper targets, and planned or possible experiments on NDCX-I or NDCX-II such as: (a) initial beam-driven target experiments, expected in late FY-2008, measuring temperature of beam heated materials; (b) low density porous targets; (c) high electron affinity (e.g., halogen) target study ; (d) two-phase liquid/vapor targets to study fragmentation and droplet formation; (e) beam/shock wave coupling in cryogenic or foam targets (as will be discussed in section 3.4); and (f) equation-of-state studies near the critical point.

Although, simple planar targets may be ideal for achieving uniform temperature conditions from volumetric energy deposition by short pulses of ion beams, we are also looking at novel ways to reach beyond the warm dense matter regime by taking advantage of the uniform energy deposition of ions. It was soon realized during our simulations of foams (initially modeled as 1D slabs of solids separated by layers of void) that when the slabs collided, relatively high temperatures and pressures can be generated at the collision interface. The same effect will be even stronger in 2D and 3D. When an ion beam volumetrically heats a solid surrounding a cylindrical hole or a spherical hole (i.e., bubble), the pressure mismatch between the solid and the cavity, results in compression of the cavity, and this compression can yield pressures and temperatures near the stagnation regions of the implosions much higher than the initial pressure of the solid. We have simulated (using the DISH and/or HYDRA codes) both hollow cylinders and hollow bubbles, and are considering options for diagnosing the multi-megabar pressures that result when heating ~ micron scale cavities using NDCX-II beam parameters. The diagnosis of small stagnation regions from such cavity implosions are a diagnostic challenge, but the convergence ratios are predicted to be very different depending on the EOS model used, and so the convergence ratios may be a useful tool for EOS benchmarking.

The codes that we rely on for all of our target simulations require models for both the ion deposition, and the equation-of-state (EOS). The ion deposition model in turn depends on understanding the contributions to energy loss from ion collisions off of bound electrons, free electrons, and nuclei (at low energy). The effective ion charge state must also be calculated and there is interplay between the equation-of-state and the ion stopping (as for example, the number of free electrons depends on the equation-of-state, and the stopping depends on the number of free electrons). Heavy Ion Fusion Science-Virtual National Laboratory collaborators have installed improved models for the ion stopping, that include nuclear scattering and also model electron stopping based on algorithms developed for the SRIM code (based on scaling from experimental measurements), into LLNL's workhorse code HYDRA and the algorithms are available for installation elsewhere.

One of the reasons warm dense matter is of intense scientific interest is that the equation-of-state (EOS) in this regime is uncertain. In our simulations we have used a number of different equations of state that help us determine the expected range in experimental response to ion beam heating. The equations-of-state range from the simple Van der Waals equation-of-state (useful for modeling the two-phase region and which results in nearly incompressible fluid beyond liquid density but can accurately model the weak attraction of particles in the vapor phase), to QEOS (based on the Thomas-Fermi model for the electron component of the pressure and is believed to be accurate at high density and pressure), to equations-of-state based on the Saha equation (which may be the most accurate in the warm dense matter regime, when the ionization levels of the ions are appropriately adjusted for density effects [2.84]).

2.4 NDCX-II goals and physics design

We have developed the basis for an attractive physics design for NDCX-II. Our goal is a machine concept capable of meeting the needs of the high energy density laboratory physics and warm dense matter research program described above, and after straightforward extension, of supporting a compelling set of ion-beam-driven target experiments to explore fundamental aspects of ion direct drive. Here, we briefly outline the options considered, and then review the basic features of the concept selected as our baseline and our calculations in support of it [2.85, 2.86].

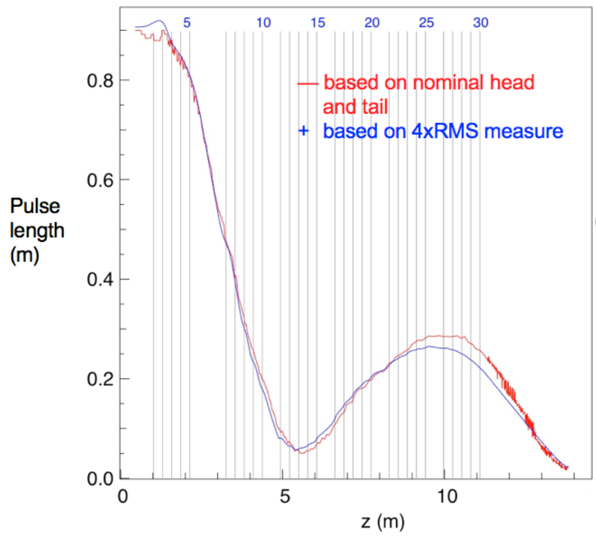
An effective means of generating an initial beam with a high line charge density is to extract a long, high-current pulse from a diode at relatively high energy, and then pass the beam through a decelerating field to compress it. To understand this, consider a lossless steady injection: the current is constant along the axis, so that the slower downstream beam has an increased line-charge density. The low-energy beam bunch is directed into a solenoid and matched into a Brillouin flow. A Brillouin equilibrium is independent of the energy if the relationship between the beam size (a), solenoid magnetic field strength (B), and line charge density (λ) is such that $(Ba)^2$ is proportional to λ. Thus it is possible to accelerate a matched beam at constant line charge density. Such an *accel-decel* system serves as the front end of the physics design concept for NDCX-II. To explore this type of injector, an experiment has been formulated [2.87] in which we would extract a 1μs, 100 mA, K^+ beam at 160 keV and decelerate it to 55 keV ($\lambda \sim 0.2$ μC/m).

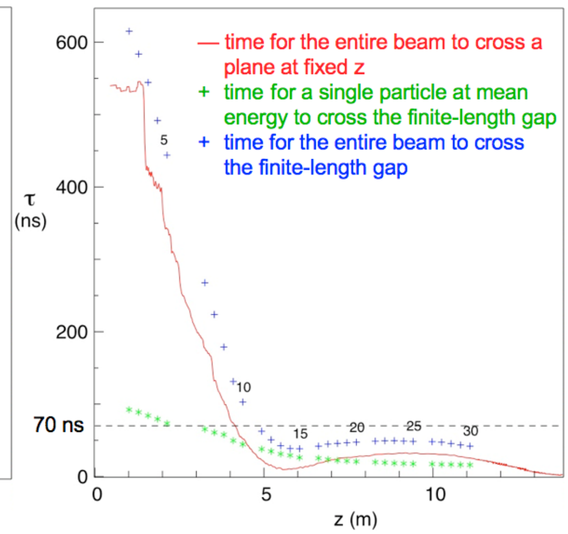
A study [2.88] of ion beam drivers for creating WDM conditions explored several approaches to accelerate and compress 30 nC of Li^+ ions to 2.8 MeV or more. Three options were considered, all beginning with an accel-decel injector producing a 100 keV beam: (a) a 3-m electrostatic column (with 10kV/cm gradient); (b) a sequence of pulse-line ion accelerator (PLIA) sections, running in the "snowplow" mode; and (c) an induction accelerator using cells from the decommissioned Advanced Test Accelerator (ATA) accelerator at LLNL. All three concepts appeared feasible, but the maturity of the induction approach and the existence of much of the hardware has led us to select that approach as our baseline. Research into the pulse-line ion accelerator (PLIA) approach continues as a background activity; a PLIA might serve as an improved front end or an "afterburner" for higher energy.

The arrangement of induction cells and applied accelerating waveforms that is proposed is novel, but the system is based on well-established technologies. It takes full advantage of the available ATA ferromagnetic cells and Blumleins. The system is compact, and relies heavily on passive circuit elements to provide the requisite accelerating waveforms. The adaptation from ATA, which accelerated electrons, has been nontrivial, because of the need to aggressively compress the ion pulse from its initial ~ 500 ns duration to ~ 1 ns, as required for the warm dense matter physics mission. The applied waveforms must simultaneously impose a head-to-tail velocity "tilt," compensate for the beam space charge, and accelerate the beam.

Using a 1-D particle-in-cell simulation code designed for this purpose, we have developed an acceleration schedule in which six blocks of five ATA cells each (twenty cells driven by the ATA Blumleins, plus ten with lower-voltage sources) accelerate a Lithium beam to 3.5 MeV and impart an 8% tilt. To reduce the axial extent of the gap fringe fields, the 6.7-cm radius of the ATA beam pipe is reduced to 4.0 cm. About 75% of the 30 nC beam charge passes through the focal plane in a 1-ns window, with a minimal pre-pulse. A novel two-part strategy is employed to accelerate and compress the beam. In (approximately) the first half of the lattice, the pulse is aggressively compressed via "nonneutral drift compression." The beam transit time through an acceleration gap (including the axially extended fringe field) must be less than 70 ns for a high-voltage (up to ~ 200 kV) ATA Blumlein to be used as the pulser. Custom pulsers at lower voltage are required for longer pulses; to minimize the number of these, we use the volt-seconds of the first two cell blocks to impose a head-to-tail velocity tilt, with space between tilt cells for drift compression and longitudinal control. To avoid short-wavelength density irregularities, we choose the tilt-cell fields to maintain, insofar as possible, a linear velocity tilt and a smooth density profile. We determine appropriate waveforms using a least-squares optimization algorithm that penalizes both nonlinearity and nonuniformity.

In the second half of the lattice, the beam is allowed to lengthen as it is accelerated, with only enough ramped pulses added to keep the duration under 70 ns. The idea here is to use as much of the available volt-seconds as possible for acceleration. The initial compression is slowed by the increasing space-charge field; after the beam passes through a longitudinal waist, it begins to lengthen as a consequence of acceleration and space charge. Since the beam length at the waist is less than the longitudinal extent of the gap fields, those fields cannot prevent this "bounce;" however, as the length increases, tilt cells can keep the beam duration from exceeding 70 ns. We find that two tilt cells in each block of five are sufficient. A final block with five ramped pulses applies the tilt for neutralized drift compression onto the target. Figure 2.5 shows the evolution of the beam length and pulse duration in such a scenario. All the waveforms in this 1-D acceleration schedule, except for the longitudinal-control fields or "ears" applied in the first two blocks, are simple enough to be formed with passive circuits in the "compensation boxes" that are attached to the ATA cells.





(a) (b)

Figure 2.5: (a) Pulse length in meters versus axial coordinate *z*; (b) pulse duration in nanoseconds vs. *z*; the key measure is the time for the entire beam to cross the finite-length gap, including its fringe field. Numbers label the accelerating gaps in both cases.

For the case discussed here, all the tilt-cell waveforms in the final four cell blocks have been generated by solving applicable circuit equations, producing the nearly triangular pulses seen in Figure 2.6. Similar circuits are being studied to form the tilt waveforms in the first two blocks. The low-voltage "ear" waveforms, shown in black, may require programmable circuits like those developed by First Point Scientific.

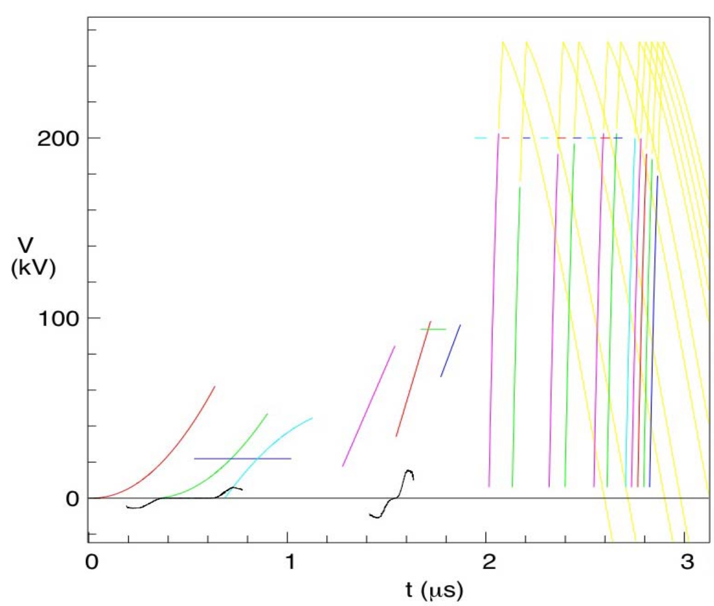


Figure 2.6: Waveforms for each accelerating gap, with "ear" waveforms for beam-end confinement shown in black, and extended-time circuit model solution shown in yellow.

Figure 2.7 shows the beam phase space and line-charge density at selected times during acceleration and compression. The focal plane in the final plot is estimated by an RMS measure [2.89] and then refined by explicitly finding that plane through which the most current flows in an optimized 1-ns window.

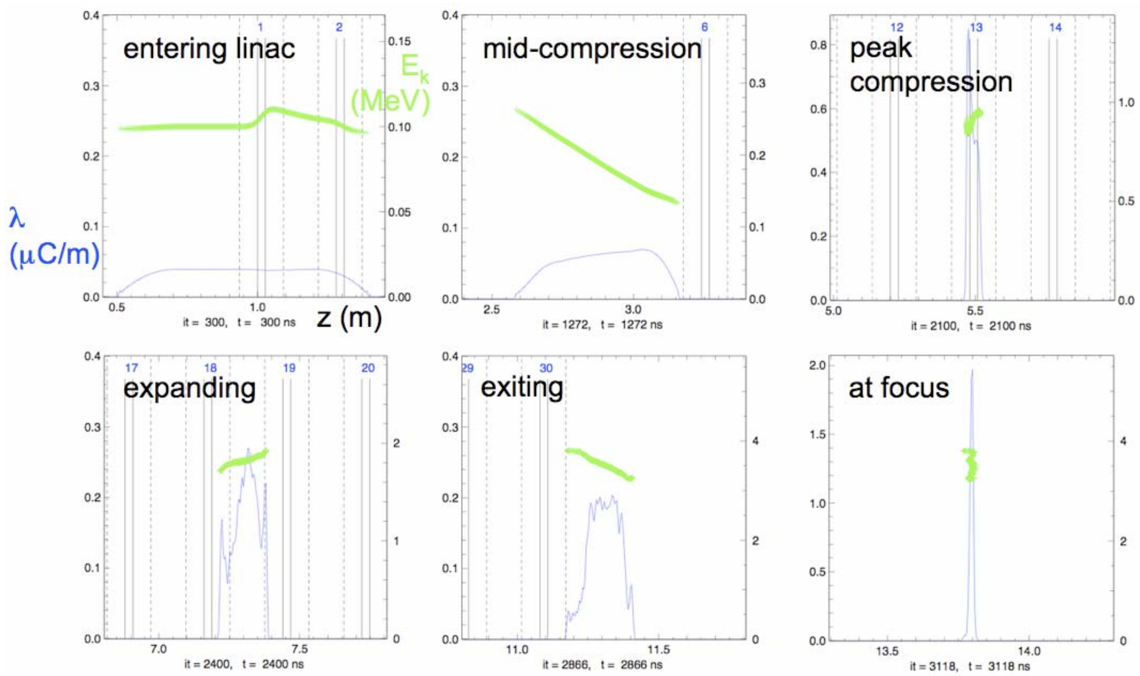


Figure 2.7: Simulated longitudinal phase space (energy versus z position) in green (right axis) and line charge λ (averaged over about 4 mm) in blue (left axis) at selected times.

While results from these 1-D simulations are encouraging, the model necessarily omits transverse variation of the acceleration and space-charge fields, as well as the physics of transverse confinement and focusing. Initial axi-symmetric (*r*,*z*) simulations using WARP to validate the 1-D model. When we use the acceleration fields shown in Fig. 2.6 and an initial WARP beam with the same line-charge, energy, and longitudinal profile, no particles are lost, and the energy and pulse duration evolve similarly to the 1-D results in Figure 2.7. Particle plots for this WARP case, shown in Figure 2.8, indicate adequate transverse confinement with solenoids fields of 2 T or less. However, we see slightly more feathering of the longitudinal distribution at low energy, giving a higher final longitudinal emittance, and somewhat poorer lengthwise compression. We are still in the process of refining the solenoid lattice to improve transverse matching and to focus the beam radially at the point of maximum longitudinal compression. Careful optimization of the WARP waveforms is also planned.

Efforts are in progress to use WARP to simulate the NDCX-II beam from the source to maximum compression. These simulations are more challenging than the run described above (which was initiated with a uniform-energy beam) because an emitted ion beam already has a significant energy variation when it reaches the first gap, due to both transit-time effects in the diode and the longitudinal space-charge field.

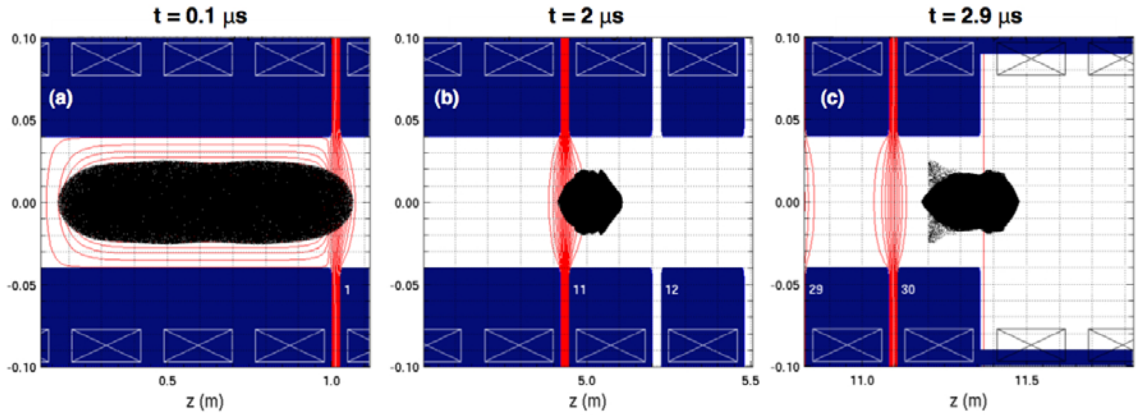


Figure 2.8: Axisymmetric WARP simulations of a beam accelerated with fields from the 1-D code. In this case, the beam was initialized with a uniform-energy distribution. The red lines are equipotential contours.

To accommodate this initial energy nonuniformity, we use an ear cell to remove the variation, to the extent possible. Initializing the 1-D code with a beam containing such an energy variation, we have used this approach to develop an acceleration schedule that produces a beam with nearly the same final parameters as those found for an initially mono-energetic beam, but with a small fraction of straggling ions at lower energies. Preliminary WARP results with this new schedule give a beam with the correct final energy and head-to-tail velocity tilt, and we are presently beginning to evaluate and refine the design.

Ultimately, full 3-D simulations will be needed to establish error tolerances and to develop steering techniques. We must establish the sensitivity of the beam to errors in the alignment and field strength of solenoids, and must determine tolerances for timing and voltage errors in the applied fields. The 1-D simulations indicate that the ion beam is insensitive to waveform details after the initial compression, but this finding needs to be validated with WARP simulations. While the research carried out to date has concentrated on an initial configuration aimed at warm dense matter studies, a smaller effort has considered the modifications necessary to produce higher kinetic energies, multiple pulses, and/or longer pulses with ramped energy, to study energy coupling and hydrodynamic stability issues in ion direct drive.

2.5 NDCX-II engineering/cost/schedule

In order to allow uninterrupted scientific output for the heavy ion program and to provide the basis for IB-HEDPX as soon as possible, NDCX-II construction is planned in parallel with the ongoing NDCX-I experimental program. Starting from the first year NDCX-II is approved, it will take $5M in equipment over 2.5 years to assemble existing ATA equipment into a 3 MeV accelerator for NDCX-II. Along with the equipment funding, 3 $M/yr increment in operating to restore scientific as well as engineering staff to FY05 levels sufficient to continue running NDCX-I while assembling NDCX-II. A proposed construction schedule in parallel with experiments on NDCX-I is shown in Fig. 2.9, with the assumption that NDCX-II assembly starts in FY09. Fig. 2.10 shows a building layout of the LBNL experimental hall demonstrating how NDCX-II can be assembled parallel to NDCX-I.

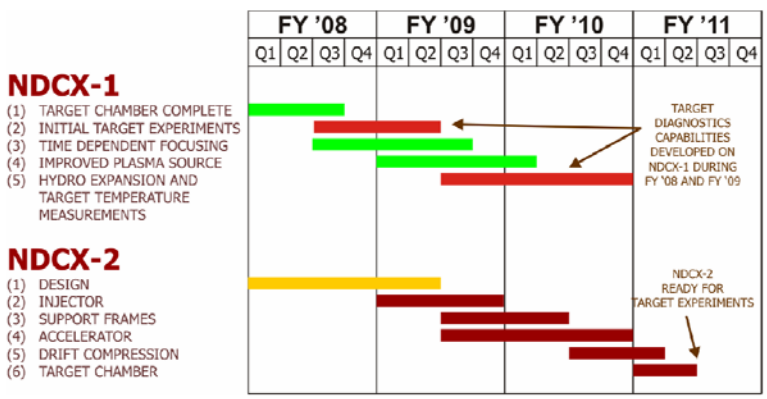


Figure 2.9: Construction schedule for NDCX-II and experimental plan for NDCX-I

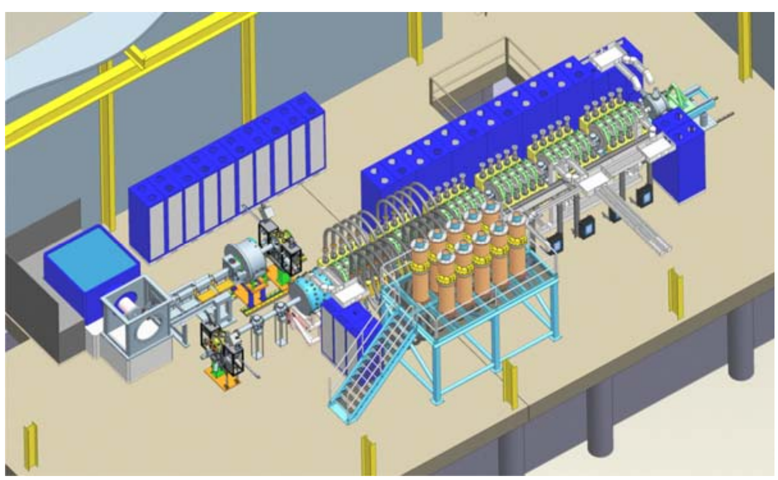


Figure 2.10: Building Layout for NDCX-I and NDCX-II

NDCX-II will use existing induction cells from the decommissioned Advanced Test Accelerator facility at LLNL, which formerly were used to accelerated intense electron beams, but will now accelerate ion beams with reverse polarity. Since NDCX-II will accelerate ions with larger net space charge forces, the ATA transport magnets will be replaced with pulsed, 3 Tesla solenoids, similar to those successfully build and operated in NDCX-I. In addition, the pulsed power system will be adapted and reconfigured for the required beam compression on NDCX-II.

The NDCX-II design makes use of a 3.56 cm diameter Li^+ ion source. At a current density of 10 mA/cm^2, and pulse length of ~300 ns, the ion source will produce 100 mA corresponding to ~30 nC per pulse. The Li^+ ion source is being developed based on our experience in making the K^+ (potassium doped alumino-silicate) hot-plate ion source.

The status of readiness for NDCX-II is such that final assembly of the NDCX-II injector as well as the installation of the first set of induction cells can commence in the second half of FY 2009. Figure 2.11 shows a conceptual design of the NDCX-II injector which includes the ion source, the accel-decel extraction grids, a pair of matching solenoids, and the support and alignment components. The injector can be fully assembled by the end of FY 2009, assuming $1.7 M out of the $5M in needed hardware is available in 2009.

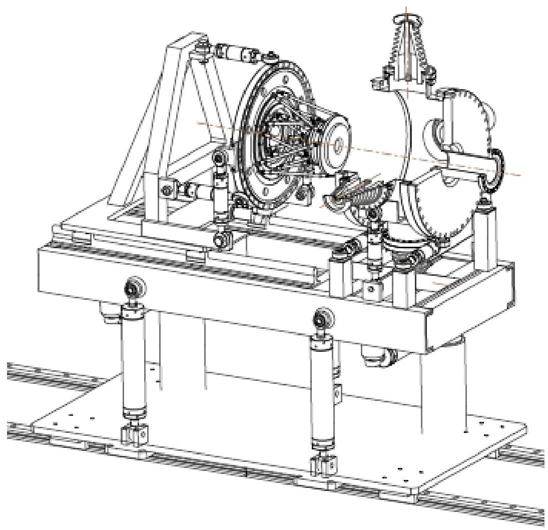


Figure 2.11: NDCX-II injector design

Depending on the longitudinal compression sequence, the NDCX-II accelerator layout will consist of approximately 30 to 40 ATA induction cells, which are currently available (see figure 2). Installation of these 40induction cells, including the diagnostics junction boxes and alignment structures, will be the primary focus for the second year of the construction schedule for NDCX-II. Significant effort will also be spent on aligning and assembling the high-field solenoids inside the induction cells.

With these assumptions, the NDCX-II accelerator assembly can be completed by the end of the second year. In the second quarter of the third year, we would duplicate the existing target chamber and final focus magnet configuration of NDCX-I for installation on NDCX-II. The first target experiments on NDCX-II could then be launched in the second half of third year of NDCX-II construction.

3. Technical Progress and Campaign Readiness: Heavy-Ion-Beam-Driven Fusion Physics

Heavy ion inertial fusion target physics and the chamber response depends both on understanding the equation-of-state (EOS) of target materials that heat up through warm dense matter states, as well as on the unique target hydrodynamic responses that depend on the details of ion beam energy deposition. Recent initial experiments on the Neutralized Drift Compression Experiment (NDCX) that combine radial and longitudinal compression of intense ion beams propagating through background plasma have resulted in on-axis beam densities increased by 700 X at the focal plane. With further improvements, we expect to be able to increase the overall beam density compression on target to over 10,000 in the next few years, to the values required for future fusion targets (at much larger beam energies). Theory and simulation permit such beam compression once the beam space charge is neutralized by dense background plasma. We are presently assessing how these beam compression techniques apply to low-cost fusion target drivers for inertial fusion energy. In particular, it is found that high coupling efficiency is possible in direct drive with ion energies ramping up during the drive pulse, as in the techniques presently used to compress the beams in the NDCX experiment.

3.1 Ion heated foam radiator targets for indirect-drive hohlraum targets.

One area being explored in the NDCX experiments and in theory and modeling, is the physics of metallic foams. In inertial confinement fusion (ICF) targets, including heavy ion fusion (HIF), foams have been employed in a number of designs. In indirect-drive targets for heavy ion fusion, for example, foams are used as radiation converters, that stop the ion beams and convert the ion energy to X-rays. High-Z materials are desired for their opacity and pressure properties (due to the abundant electrons), but low densities are needed to match the ion range and to minimize the energy required to heat the converters. Foams are also used in some laser ICF targets, including double-shelled targets where the foam acts as the structural material separating the fuel shells. Precise target predictions require understanding the equation-of-state of foams in all of these situations. Heavy Ion Fusion Science-Virtual National Laboratory (HIS-VNL) experiments aim to characterize the equation-of-state by measuring the characteristics of rarefaction waves, created when the ion beams volumetrically heat the material. Since a foam with a density about 10% of solid density will have an ion range ten times longer than the corresponding solid, the physical depth of the foam will be ten times longer, with a corresponding ten-fold increase in the hydrodynamic time scale. This eases the requirements on the pulse duration on the ion beam, which makes the NDCX experiments ideal for such equation-of-state studies. The foams have been initially modeled using hydrodynamics codes such as HYDRA, DPC, and DISH, by assuming that the foam is composed of layers of solid slabs, to understand the physics of homogenization and impact on the density and velocity profiles during foam expansion. Ultimately, two- and three- dimensional simulations will be needed to fully characterize the equation-of-state.

3.2 Formation of micro and nano-particles from expansion of hohlraum target plasmas into vacuum chambers.

Another area of intense interest for inertial confinement fusion (ICF), is the production of micron- to nanometer- size particles during an ICF microexplosion. These droplets may arise in two broad scenarios. In ICF single-shot operation, the target holder will receive the X-ray, neutron, and charged particle exposure from the fusion micro-explosion. Since the target holder extends from the chamber wall to the target itself, there will be a distance (~ several cm's) where the blast will heat the target holder to temperatures between the melting and vaporization point. Droplets and debris can result from material reaching this *warm dense matter* regime, and the size and velocity of such debris resulting from sudden internal heating (e.g., by neutrons or penetrating particles such as ion beams) is expected to be different from surface laser-induced shock waves. The final optics of a laser-driven ICF system must be carefully protected against such debris. The second scenario of interest involves condensation of material from the target itself. The fusion microexplosion is expected to fully vaporize all components of the hohlraum (for indirect drive) and capsule, in both single-shot (ICF) and multi-shot (IFE) applications. As the very hot vaporized material expands and cools, the density and temperature decreases through the two-phase boundary (in density-temperature parameter space). At this point, droplets can then form in the outflowing vapor. The Heavy Ion Fusion Science-Virtual National Laboratory (HIS-VNL) has been carrying out advanced numerical simulations, and integrating kinetic equations for the droplets, which can be benchmarked against experiments on the NDCX facility and at GSI to shed light on the size and velocity spectrum of droplets that are formed from such condensations. Simple experiments are envisioned in which ion beams heat candidate materials to the vaporization point, and witness plates or aerogels record the debris produced from the ion pulse. These experiments and calculations will help suggest threat minimization and protection schemes for inertial confinement fusion and inertial fusion energy chambers (whether the driver is an ion beam, laser beam, Z-pinch, or even a magnetized target fusion target).

3.3 RF Wobbler for beam smoothing

Currently, the concept of beam wobbler is being investigated by the Heavy Ion Fusion Science-Virtual National Laboratory (HIS-VNL) as an effective beam smoothing technique which enables uniform deposition of beam energy onto an annular region on the target, and is capable of suppressing the Rayleigh-Taylor instability [3.1, 3.2]. The wobbler system consists of two sets of electrode plates in the two transverse directions driven by RF voltages. As the beam passes through these electrode plates, the beam centroid is accelerated in the transverse direction by the imposed electrical field. However, different slices of the beam will be accelerated differently because the plates are driven by time-dependent RF voltages (see Figure 3.1).

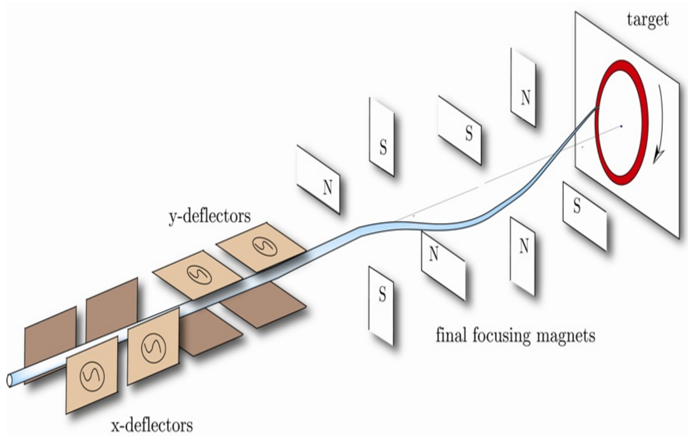


Figure 3.1: Schematic of wobbler and final focusing system.

The design goal of the wobbler system is to ensure that different slices are uniformly distributed onto a desirable annular region on the target. The beam passes through the final focusing magnets after the wobbler plates, to reach a small focal size on the target. Therefore, the centroid dynamics, which describes the trajectory of the beam, and the envelope dynamics, which determines the transverse dimensions of the beam, are coupled together.

We have derived the following set of coupled centroid-envelope equations which describes the centroid and envelope dynamics of the beam passing through the wobbler and final focusing system,

$$\begin{aligned}
&\frac{d^2}{ds^2}\mu = -\kappa_x(s)\mu - F_x(s),\\
&\frac{d^2}{ds^2}\nu = -\kappa_y(s)\nu - F_y(s),\\
&\frac{d^2}{ds^2}a = -\kappa_x(s)a - \frac{\varepsilon_x^2}{4a^3} - \frac{1}{a}\left\langle \frac{\partial\psi}{\partial x}(x-\mu)\right\rangle,\\
&\frac{d^2}{ds^2}b = -\kappa_y(s)b - \frac{\varepsilon_y^2}{4b^3} - \frac{1}{b}\left\langle \frac{\partial\psi}{\partial y}(y-\nu)\right\rangle,
\end{aligned}$$

where $F_x(s)$ and $F_y(s)$ are the applied external forces due to the electrode plates, ψ is the normalized space-charge potential of the beam, (μ,ν) is the transverse position of beam centroid, and $\langle\ \rangle$ denotes statistical average over the transverse phase space. The beam envelopes are defined relative to the centroid position as $a=\langle(x-\mu)^2\rangle^{1/2}$ and $b=\langle(y-\nu)^2\rangle^{1/2}$. The beam emittances $(\varepsilon_x, \varepsilon_y)$ are defined relative to the beam centroid as well. The effect of the first-order non-uniform electrical field of the wobbler plates is included in the linear focusing constants $\kappa_x(s)$ and $\kappa_y(s)$. If the beam density is uniform in the transverse plane, then it can be shown that the transverse emittances $(\varepsilon_x, \varepsilon_y)$ are exactly conserved.

This set of centroid-envelope equations are being used in the design studies of the wobbler and final focusing system for heavy ion beam drivers for inertial confinement fusion. In particular, a wobbler and final focusing system for a 50MeV Ar+ beam is being designed with current intensity in the range of multi-kA, and with and without space-charge neutralization provided by background plasma. The final focusing system has two functions: (i) Focusing the beam envelopes from 30mm to 1mm on the target; and (ii) Translating the initial velocity kick imposed by the deflectors into a 1mm displacement of the centroid relative to the target center. The design frequency of the deflector potential is 1GHz. The dual functionalities of the final focusing system present new challenges. However, the initial study indicates that this goal can be achieved with modest additional hardware investment, compared with the standard final focusing system without the wobbler system.

3.4 Direct-drive heavy-ion-beam inertial fusion at high coupling efficiency

Efficient coupling of heavy ion beams to compress direct-drive inertial fusion targets without hohlraums requires the ion range to increase several-fold during the drive pulse. One-dimensional implosion calculations [1.6] using the LASNEX inertial confinement fusion target physics code shows that the ion range increases four-fold during the drive pulse to maintain the ion energy deposition following closely behind the imploding ablation front, resulting in high coupling efficiencies (shell kinetic energy/incident beam energy) of 16% to 18%. Increasing the DT ablator mass by 2.5X, or changing from DT to hydrogen for the same ablator mass could increase the ion stopping more than a factor of four for the same ablator mass, requiring incident ion energies increasing from 100 MeV for the foot, up to 400 MeV at the end of the drive pulse. Increased ion deposition closer to the ablation front can improve the coupling efficiency, perhaps to as high as 25 %, but at the expense of steepening the pressure gradient behind the ablation front, which increases Rayleigh Taylor growth factors. Off-normal (oblique) ion beam irradiation may lead to improved Rayleigh Taylor stability, along with higher coupling efficiency (creating a future research opportunity).

The National Ignition Facility (NIF), for example, is designed to test ignition with 0.24 mg of DT fuel (0.45 mg including residual Beryllium ablator) at 3.68 x 10^7 cm/s peak implosion velocity, a total fuel payload energy, including the residual Beryllium pusher, of 30 kJ, producing 20 MJ of fusion yield [**3.3**]. This NIF capsule design absorbs 200 kJ of hohlraum x-rays, for a capsule coupling efficiency of 15%, about the same efficiency as we calculate for ion direct drive with low Z CH:DT ablators. In future work, we will extend this work to consider driving low-Z capsules the size of the NIF capsule with heavy ion beams (assuming we can focus heavy ion beams to the 1 mm radius target size, with say, heavier Krypton ions for the lower ranges required, and with short-focal-length copper final-focus magnets). If successful designs emerge, and, if the National Ignition Campaign on NIF is also successful, the prospects for heavy ion fusion development might be very attractive: gain 100 at 200 kJ total drive energy! Further into the future, if we can optimize coupling efficiencies to, say, 25% for larger-mass targets, then large fuel assembly energies of 1 MJ might be possible with 4 MJ of beam drive energy. Such large fuel assembled with T-lean fuel [**3.4-3.8**] (DD fuel with a small inner DT sparkplug) at compressed $\rho r \sim 10$ g/cm^2 would self-breed tritium without external blankets, and internally capture the neutron energy into primarily plasma energy for direct conversion. In that event, prospects for inertial fusion energy might also be radically changed.

3.5 Opportunities to study heavy ion beam coupling efficiency in planar targets

Hydrodynamics experiments involving ion deposition, ablation, acceleration and stability of planar targets will be possible for the first time on NDCX-II at energy density well above the cohesive energies of cryogenic hydrogen, and high enough for optical measurements of hydro motion with dopant lines, at energy densities low enough to neglect radiation transport. Unlike lasers, ion beams do not in general have "speckles", i.e., intensity variations with high spatial frequency and high amplitude. However, low spatial frequency variations (on the scale of the beam radius or somewhat smaller) will exist and the effect of these variations on the ablation and acceleration of a planar target can be explored. (Theoretical work by Kawata, [3.9] suggests that even these low mode number variations can be mitigated by "wobbling" the beam). Furthermore, the deposition of ion beam energy is volumetric, and therefore ablation effects (that stabilize Rayleigh-Taylor growth in laser-plasma interactions) may be quite different, simply because the temperature and pressure variation of the ablation layer will be quite different than that arising from the near-surface deposition of lasers. Thus experiments which examine acceleration of planar target layers would be of great scientific interest. Experiments with imprinted density variations could allow study of the Rayleigh-Taylor instability under a variety of experimental situations. Solid hydrogen or noble element layers would be possible and useful as payloads because, their low heats of vaporization would allow limited beam energies over larger target dimensions to study fluid hydro physics, and because these targets may be transparent to doped impurity radiation enough to allow local and real-time optical diagnostic imaging of the beam-target interactions. Furthermore, cryogenic hydrogen targets could be of particularly high scientific value, directly relevant to both inertial fusion energy, and to planetary science. A reliable hydrogen and/or noble solid equations-of-state may have value for directly comparing interior models of the giant planets, which have high precision data on their gravitational moments from direct spacecraft orbital data.

New computational research will be focused on computational studies of fundamental physics of ion beam direct drive that can be experimentally tested in NDCX-II. Figure 3.2 illustrates an example of a concept to test the efficacy of energy ramping to increase coupling efficiency that is crucial for recent theoretical inertial fusion energy target work, which can be explored on NDCX- II.

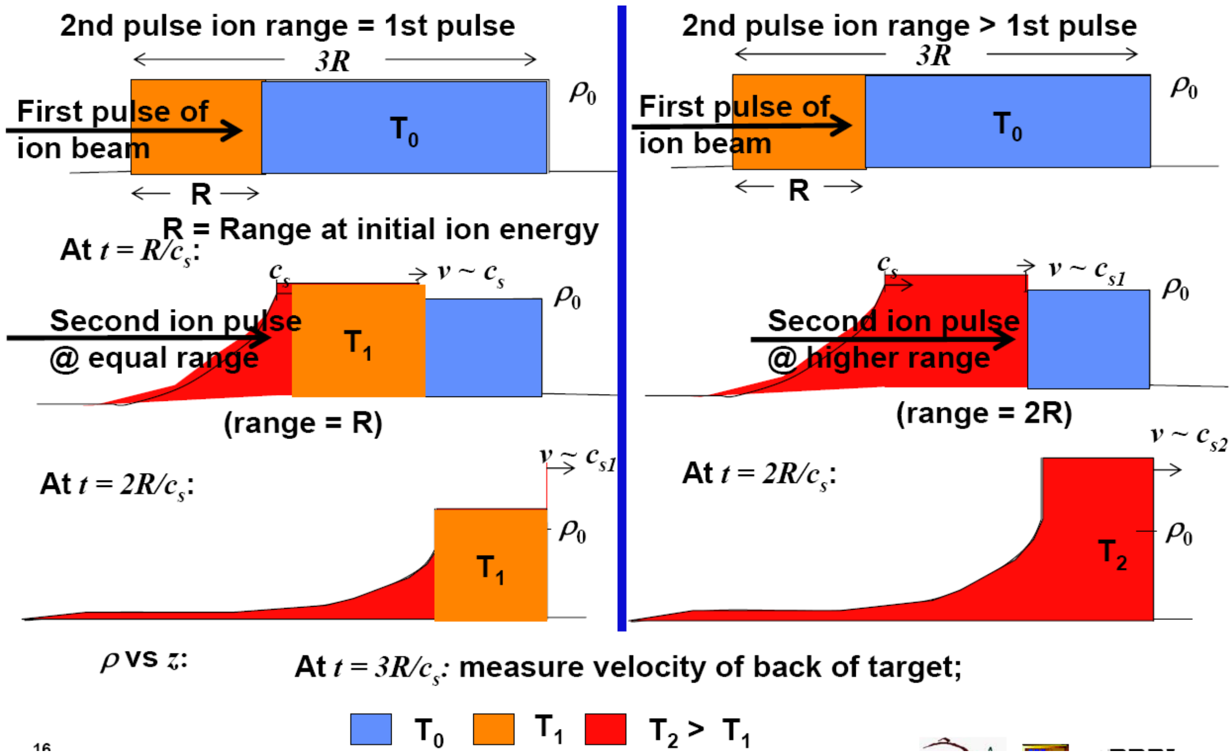


Figure 3.2: Schematic of two-pulse ion experiment for NDCX-II. (See text for description of experiment).

In the left column of Figure 3.2, the first pulse of an ion beam deposits energy in one ion range *R* (here the target is about three times the thickness of the ion range). After one hydrodynamic time (R/c_s, where c_s is the sound speed) the ablation pressure wave has propagated a distance ~ R/c_s, and has raised the temperature from an initial temperature T_0 to a temperature T_1. Meanwhile a second pulse at the same ion energy is stopped in the outflowing plasma, and does not add any energy to the ablation pressure. However if the second pulse has a higher ion energy (right column) and hence larger range, the second pulse energy deposition will be right behind the ablation wave, adding to the pressure and temperature T_2 of the wave. In an ion direct-drive target, a temporally ramping ion energy (as in the right column) will lead to efficient coupling of the ion beam energy into ablation pressure, which ultimately leads to an efficient acceleration of the fuel layer in the target, and thus efficient coupling of ion energy into fuel kinetic energy. In the experiment, the coupling efficiency can be calculated by measuring the velocity of the material at the right side of the target, after the pressure wave has reached it. Simulations of these experiments have been carried out by researchers working with the Heavy Ion Fusion Science-Virtual National Laboratory, and an example of the results are shown in Figure 3.3.

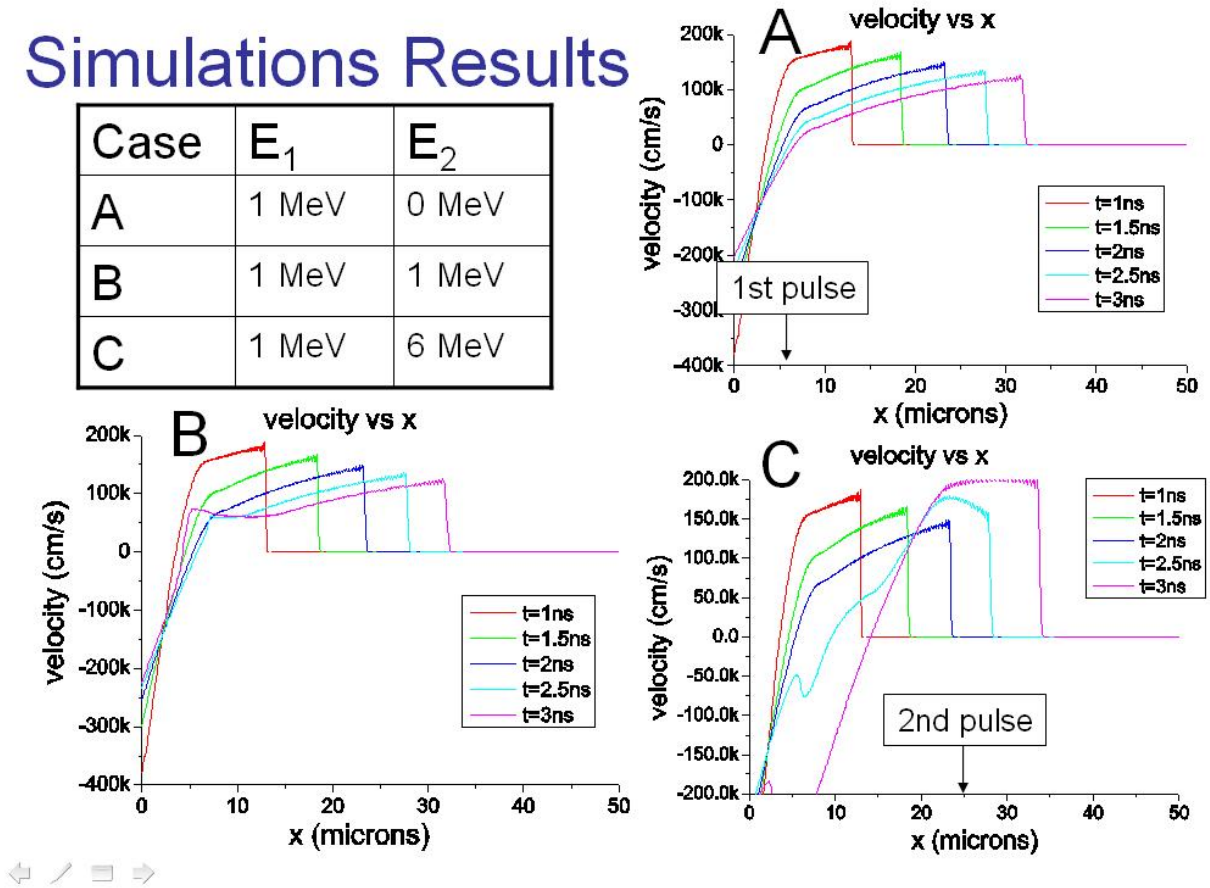


Figure 3.3: Simulations using the DISH code by S. F. Ng of the double-pulse experiment outlined in Figure 3.2 (see text below for explanation).

In Figure 3.3, an ion pulse of length one ns, and energy of 1 MeV impinges upon a 50 micron thick slab of solid Ar at x=0, creating a weak shock wave that propagates to the right. A second pulse also of duration 1 ns impinges upon the slab at t= 2 ns. Snapshot of the velocity profile within the slab are shown for three different cases A, B, and C, having second pulse ion energies of 0, 1, and 6 MeV respectively. As can be seen from the figure, the velocity of the shock wave is not changed if the second pulse has an ion energy of 1 MeV or is not there at all (0 MeV), but is greatly enhanced if the ion energy increases to 6 MeV energy, so that its increased range can keep pace with the shock front.

Other theoretical work will include upgrading the ion stopping algorithms in the code HYDRA, and systematic studies of the acceleration and stability of planar foils. When funding permits, we can perform initial ion range calibration experiments in NDCX-I in sub-eV, initially frozen planar hydrogen targets. First experiments calibrating cryo planar target acceleration and hydro response with single and then ramped/double pulses for various ablator/payload areal densities relative to ion range would require completion of NDCX-II.

For fixed radial pointing, the number of beams is considered a major factor determining beam non-uniformity seeding Rayleigh-Taylor growth [3.10-3.12]. However, noting the beneficial effect of off-radial ion trajectories and beam energy spread in [3.13] for reduced Rayleigh-Taylor growth rates, we suggest delivering most ion beam energy in off-radial trajectories, which we call oblique irradiation, by use of hollow beam spot profiles, created by rapid beam spot rotation. We expect the same multi-GHz RF modulation of ion beams as proposed by Sharkov [3.14] for driving cylindrical heavy ion targets with a hollow, rotating beam spot can also be applied to provide a hollow beam for heavy ion direct drive of spherical ablators with mostly oblique incident ion rays. A series of phased RF cavities would be used to impress a helical beam centroid variation upstream of the target before beam drift compression and focusing; this perturbation maps into hollow beam spots on the target with radii controlled by the RF amplitude.

The RF amplitude can be reduced in time (amplitude decreasing during the beam pulse) such that the radius of the hollow beam projected onto the target ablator surface would shrink during the implosion (zooming). Rotating beams may provide smoother beam deposition uniformity with fewer beams. In addition, S. Kawata has suggested that the pulsating nature of the beam energy deposition with a rotating beam spot may produce a type of dynamic stabilization of Rayleigh-Taylor growth [3.15].

We are beginning to develop the theoretical beam models that can describe beam spot smoothing/rotation in neutralized drift compression and focusing, and we are developing plans to test/employ these new tools in NDCX-I and NDCX-II target experiments in the near future.

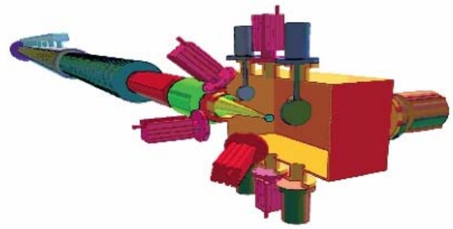
4. Research Opportunities and Expected Accomplishments Over the Next Twenty Years: Heavy-Ion-Beam-Driven High Energy Density Physics and Fusion.

In this section we describe research opportunities and expected accomplishments with existing and planned new facilities for heavy-ion-beam-driven high energy density physics and fusion for the next twenty years. The ten-year heavy ion research plan presented in the National Task Force Report on High Energy Density Physics [Ref. 4.1—see also Appendix A] is extended to twenty years because the DOE Office of Science considers new facilities on a twenty year time horizon, and because there are prospects for expanded research for inertial fusion energy science assuming that the National Ignition Campaign culminates in a successful demonstration of fusion ignition and energy gain in the National Ignition Facility (related to the second FESAC HEDLP charge). Figure 4.1 presents an excerpt for one of the 28 future facilities described in the DOE-SC report "Facilities for the Future of Science-a Twenty Year Outlook" which was updated in August, 2007 (see DOE Office of Science web site), called the Integrated Beam-High Energy Density Physics Experiment (IB-HEDPX).

Integrated Beam-High Energy Density Physics Experiment (IB-HEDPX)

High energy density physics is the study of matter under conditions of extremely high temperature and densities and encompasses areas ranging from astrophysics to laboratory plasma physics.

Update: Mission Need for the IB-HEDPX (formerly called the Integrated Beam Experiment, or IBX), an intermediate-scale experiment using heavy ion beams for research on Warm Dense Matter (a midway state between solid matter and plasmas), was approved by the Department in 2005. Small-scale experiments are planned in 2008-2009 as part of R&D to provide a scientific basis for the new facility.



An IB-HEDPX capability for integrated acceleration compression and focusing on high current, space-charge-dominated beams would be unique—not available in any existing accelerator in the world.

- Two National Academy of Sciences reports identified high energy density physics (HEDP) as a compelling emerging science for the Nation. In 2004, a community-based National Task Force on HEDP developed a science-driven roadmap for a National Initiative in HEDP. One of the fifteen "Thrust Areas" identified in the roadmap includes research in Warm Dense Matter driven by heavy ion beams.
- The fundamental requirements for using heavy ion beams in Warm Dense Matter research include compression of the beam, focusing of the beam, and high repetition rates. These critical scientific issues for developing IB-HEDPX have been resolved.
- The Office of Science Fusion Energy Sciences program and the National Nuclear Security Administration have created a new joint program in High Energy Density Laboratory Plasmas to advance this and related research. In addition, there is a broad international community engaged in this research, with which U.S. scientists coordinate activities.

Figure 4.1: The integrated beam high energy density physics experiment (IB-HEDPX)

On December 1, 2005, the DOE Office of Fusion Energy Sciences approved Mission Need CD0 for the IB-HEDPX. Key findings are summarized below from that CD0 document, particularly relating to the goals and pre-requisite R&D needs for the IB-HEDPX:

"The Integrated Beam High Energy Density Physics Experiment (IB-HEDPX) with neutralized drift compression would provide beam physics essential to both HEDP and heavy ion fusion, enabling the research called for in recent FESAC reports for both fundamental plasma science as well as fusion energy. The IB-HEDPX is needed to achieve the physics objectives described in the 2005 FESAC report on fusion program priorities [Ref. 4.2], and this provides the basis for the IB-HEDPX project mission need.

The overall IB-HEDPX program addresses a critical issue for high energy density physics in the near term, and inertial fusion energy in the long term, namely, the integration of the generation, injection, acceleration, transport, compression, and focusing of an ion beam of sufficient intensity for creating high energy density matter and fusion ignition conditions. The heavy ion beams required are very intense yet virtually collisionless, so that the beam distribution retains a long memory of effects from each region the beam passes through. Thus, the beam distribution that heats the target depends on the evolution of the beam distribution in all of the upstream regions. An integrated beam experiment IB-HEDPX is therefore essential for testing integrated beam models, and for accurate prediction of the beam energy deposition in target physics experiments. A secondary, but equally important, objective of the program is to create a critically needed user facility for experimental research in warm dense matter. Such a facility is lacking at present. The IB-HEDPX will be unique compared to other HEDP facilities:

1. Heavy ion beams for precise control of energy deposition -e.g., very uniform heating at the Bragg peak in dE/dx;
2. High repetition rate (>10 per hour) will allow more frequent experiments and better statistics;
3. More easily accessible to science users than large laser-based facilities;
4. A benign environment for diagnostics (low debris and radiation background); and
5. Usable to test target setups at modest cost, before going to larger facilities.

An approximate estimate for the Total Project Cost is $69 million. The R&D cost spread over Year 1 and 2 of the project is $6M in preparation for the MIE project …expected to take a total of 6 years. NDCX-II… is necessary R&D to assess the performance requirements of injection, acceleration and focusing of short pulses needed for the IB-HEDPX. Out of the $6M R&D cost (for IB-HEDPX), $5M is for hardware upgrade of NDCX-I to NDCX-II, which serves as a prototypical test-bed for the critical physics and engineering for developing the design and construction methodology of IB-HEDPX."

Table 4.1 presents the scientific objectives and key parameters for a proposed sequence of increasingly capable heavy ion beam experiments envisioned to advance heavy-ion-driven high energy density physics and fusion over the next twenty years. It begins with the existing NDCX-I facility, followed by NDCX-II, and then by IB-HEDPX. Note that the IB-HEDPX description in the DOE twenty-year plan cited above recognizes the role NDCX-I has already played in developing the neutralized beam compression and focusing techniques needed for NDCX-II, and for IB-HEDPX. The CD0 also states that NDCX-II is a pre-requisite to IB-HEDPX. Section 2.5 on NDCX-II estimates that assembly of NDCX-II from existing Advanced Test Accelerator modules would take about 2.5 years beginning when the $5M incremental funding for the assembly begins. Along with the assembly funds is a comparable increment for operating costs. Assuming NDCX-II starts in FY09, IB-HEDPX could be completed in FY15, consistent with the general time frames discussed in the DOE Future Facilities update. After inertial fusion energy ignition and gain are achieved in the National Ignition Facility, the plan envisions new heavy ion fusion target physics facilities requiring significantly larger beam energies on target. Design and pre-construction accelerator R&D for the heavy ion fusion physics facilities are assumed to begin after NIF ignition, running concurrently with IB-HEDPX construction and operation. A range of parameters is presented in Table 4.1 to reflect several technical options being studied to optimize the likelihood of each facility achieving its scientific objectives. Figure 4.2 summarizes a twenty-year timeline for the heavy-ion-beam-driven research thrust areas, and shows how and when each facility in Table 4.1 can contribute to advancing the research thrust areas supporting the scientific objectives.

Table 4.1. Scientific objectives and key features of a sequence of heavy-ion-beam-driven facilities for high energy density physics and fusion.

HEDP/Inertial Fusion Energy Science Objective **(Facility)**	Ion	Linac voltage - MV	Ion energy - MeV	Beam energy - J	Target pulse - ns	Range -microns (in ..)	Energy density 10^{11}J/m^3
Beam compression physics, diagnostics. Sub-eV WDM. **(NDCX-I) (1 beam)**	K+	0.35	0.35	0.001-0.003	2-3	0.3/1.5 (in solid/ 20% Al)	0.04 to 0.06
Beam acceleration and target physics basis for IB-HEDPX. **(NDCX-II) (1 beam)**	Li^{+1}, or Na^{+3}	3.5 - 5	3.5 - 15	0.1 - 0.28	1-2 (or 5 w hydro)	7 - 4 (in solid Al)	0.25 to 1
User facility for heavy-ion driven HEDP. **(IB-HEDPX) (1 beam)**	Na^{+1} or K^{+3}	25	25 – 75	3 – 5.4	0.7 (or 3 w hydro)	11 – 8 (in solid Al)	2.2 To 5.8
Heavy-ion direct drive implosion physics. **(HIDDIX) (2 beams)**	Rb^{+9}	156	1000	2x7.5 (kJ)	2 - 4	1000 (in solid Z=1)	18
Heavy ion fusion test facility --high gain target physics. **(HIFTF) (40-200 beams)**	Rb^{+9}	156	1000	300 to 1500 (kJ)	12 -24	1000 (in solid Z=1)	90

Table 4.1 includes the ranges of ion beam energies (in joules and kJ, where noted), ion ranges (in microns), and associated target energy densities (in units of 10^{11}J/m^3), to indicate the capabilities for achieving HEDP and fusion science objectives. Target pressures depend on the material equation-of-state, and in general are not linear in deposited energy density, but as a guide, 10^{11} J/m^3 corresponds to a pressure of 1 MBar.

NDCX-I: For the past three years NDCX-I has been, and continues to be, the premier existing facility developing the critical new techniques and the fast diagnostics for compression of intense heavy ion beams in time and space to the few nanosecond pulse regime [4.3, 4.4] needed for high energy density physics and fusion applications. Fundamental limits have not yet been reached, and therefore the ranges in Table 4.1 reflect several planned near-term enhancements to the facility. NDCX-I is expected to support several frontier research areas in warm dense matter (WDM), including equation-of-state and expansion dynamics of two-phase metals in sub-solid density foams heated above the boiling point, and the conductivity of electronegative ion-ion plasmas where electron densities are smaller than negative ion densities.

NDCX-II will be assembled out of existing Advanced Test Accelerator (ATA) accelerator modules capable of reaching 3.5 to 5 MV. We are considering at least two ion options, Li^{+1} and Na^{+3}, which have nearly the same charge-to-mass ratios and accelerations. The higher mass sodium option requires pre-stripping to + 3 state on a dense plasma jet, with potential scattering to consider, but with the advantage of a higher source current density and a higher stopping power in the target at 15 MeV. The NDCX-II physics design summarized in Section 2.4 has a novel feature of rapid bunch compression following injection, which maximizes the average downstream induction acceleration gradient for a fixed number of induction modules and machine length, and minimizes the final pulse duration on target (~ 1 ns). The NDCX-II target temperatures can exceed 1 eV, extending the WDM parameter range that can be studied in NDCX-I. The accelerator flexibility with solenoid transport also allows beam bunches with large head to tail velocity ramps to first study the effects of velocity ramps on hydro coupling efficiency in planar cryo targets (relevant to heavy ion direct drive). At the same time, NDCX-II can explore the application of beam spot rotation using an upstream RF beam "wobbler", a set of electrostatic deflectors that impresses a controlled helical perturbation on the beam centroid upstream of the neutralized drift compression. The 20 X longer ion ranges and 10 X higher pressures in NDCX-II compared to NDCX-I could support exploration of unique spherical bubble cavity implosions in solids to stagnation pressures exceeding many tens of MBars.

IB-HEDPX: Following the capabilities described in the IB-HEDP CD0 document, we would provide for maximum beam energy deposition at just above the Bragg peak energies for sodium/neon and/or for potassium/argon, either of which would require a linac voltage of 25 MV, assuming the higher mass ion options would be pre-stripped to charge state 3 as was considered for NDCX-II. As much as possible, we will base the IB-HEDPX physics design on the NDCX-II data. We describe a reference case for IB-HEDPX based again on modified ATA accelerator modules, only more of them, as they are available, scaling NDCX-II beam physics. The required IB-HEDPX voltage of 25 MV would require about 5 X more ATA modules as for NDCX-II, and since there were enough ATA modules to supply 50 MV in ATA, we expect to be able to build IB-HEDPX also out of modified ATA modules as is the case for NDCX-II. The total Estimated Cost of $69M includes $6M in pre-project R&D, the accelerator, several target chambers, and initial target diagnostics needed for IB-HEDPX as a user facility. For the same average induction gradient as in NDCX-II, the estimated maximum accelerator length for IB-HEDP of about 55 m, plus 35 m for the injector, neutralized drift compression system and target chamber, giving a total facility length of about 90 m. (This can fit within LBNL Bldg 46 as indicated in the ten-year LBNL facility plan). The energies per amu are 2.2 (for Na) to 3.8 (for K) times the values for NDCX-II. Thus the *velocities* of these ions are higher than in NDCX-II by factors of 1.48 and 1.95. Therefore, the bunch lengths are proportionately longer than in NDCX-II, and still fit within the 70 ns flattop ATA-core acceleration pulse. The IB-HEDPX shot rate capability will be designed to support up to one shot per second for some dense gas jet target experiments. The higher beam energies in IB-HEDPX would create conditions corresponding to several eV temperatures and several MBar pressures in planar targets, including direct drive planar targets with beam spot rotation, and cavity implosions to stagnation pressures higher than in NDCX-II, to perhaps above 100 Mbar.

HIDDIX: The mission of the Heavy Ion Direct Drive Implosion Experiment (HIDDIX) is to provide the minimum heavy ion beam capability to drive low-convergence-ratio (5-10) implosions for the first time using unique ion beam deposition for direct drive in the ablative regime, to benchmark direct drive implosion codes used to design heavy ion fusion targets. Because fusion-related target implosion experiments require 1000 X more beam energy (a few kJ) compared to planar experiments (a few J) in IB-HEDPX, and because new induction driver components would have to be built, cost is a key consideration. Because the anticipated cost will be significant, in the range of \$100M to \$200M, we assume that NIF ignition has to be demonstrated before CD1 for the DDX project could be granted. In addition, R&D to reduce linac costs is warranted. We assume that CD0, R&D and pre-conceptual design for DDX can begin with NIF ignition around 2012 and continue concurrent with IB-HEDP operation until CD1. The proposed concept uses a minimum of two rotating beams using RF wobblers to accomplish the mission. The characteristic drive times to study non-ignited scaled implosion hydrodynamics would be of order 3 ns with approximately 10 MBar drive pressures, about 3 times longer drive pulses than the nominal 1 ns values needed for isochoric IB-HEDP experiments. In addition, ion beam velocities in the range of 0.15c - 0.16c are required for optimal ion ranges for ablative direct drive at 10 to 12 MeV/u, i.e., 400 MeV for Argon/K, or 1 GeV Kr/Rb. Injector requirements are mitigated by accelerating Rb+1 first to 50 MeV, and then stripping the beam to the next closed shell Rb+9, and accelerating the ions over the next 950 MeV at +9 charge state. The stripped ions also require 9 times higher neutralizing plasma density in downstream drift compression, but scattering losses are estimated as small. At a nominal 1 MV/m average induction gradient, this scheme maintains modest linac length and cost (156 m), and delivers 7.5 kJ in each of two beams for two-sided direct drive implosion experiments. Such linacs, estimated to have a wall plug efficiency of 13%, may also be replicated to provide more beam energy for a high gain facility (see next section).

HIFTF: With regard to the Heavy Ion Fusion Test Facility (HIFTF), the range of beam energies required for high target gains of 50 to 100 in an indirect drive hohlraum would range from 6 to 8 MJ (ref RPD design), so we are pursuing research to determine if the driver energy requirement can be reduced by using direct drive. A recent study (not yet optimized) has estimated a direct drive gain of 50 at 1 MJ [Ref. 4.6]. We note that NIF ignition will demonstrate an x ray capsule gain of 100 (20 MJ fusion yield/ 200 kJ of x-rays absorbed), with a capsule x-ray drive coupling efficiency of 15%, on a 1 mm radius fuel capsule, the same coupling efficiency as we recently calculated for 1 MJ drive on a 2 mm radius fuel capsule, at a much higher than necessary implosion velocity. Thus, 200 kJ to 1 MJ ion beam energy (into the ablator) should bracket the beam energy required for a Heavy Ion Fusion Test Facility based on direct drive. We have not yet determined the optimal number of beams required for symmetry, even for rotating beam spots, and often the best symmetry is obtained with some beam spillage, even for zoomed-in beam spots with increasing ion energies during the pulse. Thus we estimate the HIFTF beam energy in the range of 300 to 1500 kJ. Our recent paper [Ref 4.6] describes the research needed in key stability and beam coupling techniques to be explored in such a facility.

Finally, Figure 4.2 presents the twenty-year timeline for the heavy ion beam scientific campaign plan and research thrust areas. It also summarizes when each heavy ion beam facility can contribute to and advance each of the research thrust areas.

Twenty-year science campaign plan* for heavy-ion-beam-driven HEDP and fusion research

Science Area	FY07 through FY09	Five-Yr-Plan FY10 through FY14	FY15 through FY 18	FY19 through FY26
Beam-Target Interaction	Target design, initial WDM experiments, fast beam diagnostics, beam dE/dx	Explore a variety of new WDM and Initial beam-cryo D2 target interaction at 1 eV.	-Construct IB-HEDPX. -Develop beam target physics basis for HIDDIX on NDCX-II.	-Operate IB-HEDPX user facility 1-10 eV HEDP, critical point properties -Physics of beam-driven heavy ion fusion targets
Focusing onto Targets	Optimize high-B final focus together with near target plasma sources	Beam target interaction with ramped ion ranges. Time dependent focusing corrections.	NDCX-II planar direct drive experiments with ramped range and rotating beam spots	Optimize techniques for two sided direct drive-tailor beam ion range on target in time and in radius.
Longitudinal Beam Compression	Optimize longitudinal and transverse focusing with new induction buncher	Compress ramped range beams with beam spot rotation to high rotation frequencies.	Optimize compression and focusing using ramped and rotating beams	Optimize techniques for ramping up the beam power on target for low adiabat compressions.
High Brightness Transport	E-cloud in quads and solenoids, beam steering and brightness optimization	Perpendicular and parallel brightness of beams in neutralized drift and for beam stripping on plasma jets.	Develop high brightness injectors for HIDDIX with beam stripping and ramped energy beams	Identify sources of beam emittance growth and ways to mitigate those mechanisms to minimize target spot sizes
Advanced Theory and Simulations	Advanced source-to-target models, and source-through-target modeling	Develop models for beam compression, rotation and zooming. Develop beam-driven target hydro and Rayleigh Taylor stability model	Integrated accelerator-to-target models for IB-HEDPX exps. Physics design support for HIDDIX linac and targets.	Integrated accelerator beam dynamics and brightness evolution together with target hydro-response modeling to guide IB-HEDPX and HIDDIX experiments
Facility & resource needs (estimated in constant dollars)	1. Optimize NDCX-I with new tilt core, plasma sources, and higher-B final focus magnet. 2. Test ATA equipment for NDCX-II. 3. Develop diagnostics. **$7.8 M/yr total**	1. Operate NDCX-I for 0.5 eV WDM --two phase and ion-ion plasmas. 2. Assemble NDCX-II using existing ATA accelerator modules. 3. Operate NDCX-II for 1eV HEDP and planar direct drive experiments. **$10M/yr increasing to $16 M/yr tot.**	1. Construct IB-HEDPX and develop users ($20M/yr) 2. Design and R&D for HIDDIX (Use NDCX-II with mods + component R&D ($20M/yr) **~ $40M/yr total**	1. Operate IB-HEDPX and support users ($20M/yr) 2. Construct heavy ion direct drive implosion physics facility HIDDIX (30M/yr) 3. Target & chamber R&D needed for IFE and for HIFTF ($10M/yr) **~ $60 M/yr tot.**

First heavy ion WDM experiment @ < 1 eV

NDCX-II assembly starts

NIF National Ignition Campaign

NDCX-II validates IB-HEDPX design. Begin IB-HEDPX construction. Begin Design and R&D for HIDDIX.

Begin HIDDIX construction

20yr Objective: Develop the beam and HEDP target physics knowledge base for a heavy-ion fusion test facility (HIFTF)

* Updated and extended from Fig. 3.1 of National HEDP Task Force Report

Figure 4.2: The twenty-year timeline for the heavy ion beam scientific campaign.

4.1 Research Issues and Opportunities for Heavy Ion Beam Driven Warm Dense Matter and for Heavy Ion Fusion

Table 4.2 below summarizes the major research issues and opportunities in the form of scientific questions for heavy ion beam-driven HEDP/warm dense matter and heavy ion fusion that have been described in sections 2, 3 and 4, and lists the facilities needed to address those research needs.

Table 4.2: Key research issues and opportunities for heavy ion beam driven HEDP/warm dense matter and heavy ion fusion and associated facilities.

Beam driven HEDP/Warm Dense Matter	**Facility**
(1) How can heavy ion beams be compressed to the intensities required for HEDP and fusion?	NDCX-I and NDCX-II
(2) What are the Equations of State properties for important materials at and above the boiling point near solid density? How do you quantitatively model material dynamics in this regime?	NDCX-I and NDCX-II
(3) How do initially porous targets homogenize and expand after rapid heating?	NDCX-II
Heavy Ion Fusion	
(1) What sets the upper limits to hydro coupling efficiency in heavy-ion direct drive fusion?	NDCX-II and HIDDIX
(2) How does ablative stabilization for Rayleigh Taylor instabilities scale with obliqueness of ion irradiation, time-dependent beam spot rotation, and electron temperature profiles?	NDCX-II and HIDDIX
(3) What constraints do beam plasma instabilities place on neutralized drift compression and final focusing for power-plant-scale beams and plasmas?	HIDDIX
(4) What are the major sources of beam brightness degradation, from source to target?	HIDDIX

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Appendix A HEDP Task Force Report (heavy ion section)

3.2 Heavy-Ion-Driven High Energy Density Physics and Fusion

Accelerators producing appropriately tailored energies of intense heavy ion beams can provide a useful tool for creating uniform high energy density matter to study the strongly-coupled plasma physics of warm dense matter in the near term, and for inertial fusion in the longer term. Both fusion and high energy density physics applications of heavy ion beams require understanding the fundamental physics limits to the compression of ion beams in both space and time before they reach the target, as well as a basic understanding of collective beam-plasma interaction processes and beam energy deposition profiles within the dense plasma targets. This thrust area focuses on the beam and target physics knowledge base needed over the next ten years for future heavy ion beam applications to high energy density physics and fusion. The emphasis during the first five years is on determining the physics limits to heavy ion beam longitudinal compression and transverse focusing upstream of the target, and during the second five year period, an increased effort is planned for beam-target interaction physics and target diagnostic development for high energy density physics. This heavy ion high energy density physics thrust would also make significant contributions towards heavy-ion-driven inertial fusion.

Motivating Intellectual Question

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

Heavy ion beams have a number of advantages as drivers of targets for high energy density physics and fusion. First, heavy ions have a range exceeding the mean-free-path of thermal x-rays, so that they can penetrate and deposit most of their energy deep inside the targets. Second, the range of heavy ion beams in dense plasma targets is determined primarily by Coulomb collisions with the target electrons. The ions slow down with minimal side-scattering, and their energy deposition has a pronounced peak in the rate of energy loss dE/dx that increases with the beam ion charge state Z. These properties make heavy ions an excellent candidate for high energy density physics studies, where thin target plasmas would be uniformly heated by locating the deposition peak near the target center. The primary scientific challenge in exploiting these desirable properties in the creation of high energy density matter and fusion ignition conditions in the laboratory is to compress the beam in time (by 1000 times overall, requiring 10-100 times more longitudinal bunch compression than present state-of-the-art) to a pulse length that is short compared to the target disassembly time, while also compressing the beam in the transverse direction (by 10 times) to a small focal spot size for high local deposition energy density. Proposed new experiments compressing intense ion beams within neutralizing plasma would significantly extend the beam current into high-intensity regimes where the beam would not otherwise propagate in the absence of background plasma, and where beam-plasma collective effects with longitudinal and azimuthal magnetic focusing fields have not been previously explored.

A basic understanding of the collective processes and nonlinear dynamics of intense, high-brightness, heavy ion beams, and a determination of how best to create, accelerate, transport, compress and focus these beams to a small spot size are critical to achieving the scientific objectives of heavy ion fusion and ion-beam-driven studies of warm dense matter. Most of the kinetic energy of heavy-ion beams is in the directed motion of the beam particles, but a small fraction is in random kinetic energy, characterized by the effective temperature of the beam particles. Plasma electrons can be used to neutralize much of the repulsive space charge that resists the beam compression in time and space, but the beam temperature ultimately limits the smallest achievable spot size and pulse duration after the space charge forces are removed from the beam inside plasmas. To minimize the beam temperature, and thereby maximize the energy deposition in the target, the beam dynamics must be controlled with high precision throughout the entire dynamical trajectory, using accurately positioned and tuned confining magnets, carefully tailored accelerating fields, and final charge neutralization techniques that do not degrade the beam quality.

There are key synergistic relationships of the research on intense heavy ion beams to understanding the nonlinear dynamics of intense charged particle beams for high energy and nuclear physics applications, including minimization of the deleterious effects of collective processes such as the two-stream (electron cloud) instability, and the use of a charge-neutralizing background plasma to assist in focusing intense beams to a small focal spot size (plasma lens effect).

3.2.2 Research Opportunities

Target and Accelerator Requirements: A recent sub-panel of the Fusion Energy Sciences Advisory Committee [1] reports, "*Inertial fusion energy capabilities [laser, accelerator and z-pinch drivers for fusion energy] have the potential for significantly contributing to high energy density physics and other areas of science. For example, isochoric heating of substantial volumes to uniform, elevated temperatures should be achievable using heavy ion beams…Moreover, the rapid turnaround capabilities envisioned for inertial fusion energy drivers could accelerate progress in HEDP science by enabling a wide community of users to conduct "shot-on-demand" experiments with data rates and volumes far exceeding those obtained on large systems that currently require long times between shots.*" As indicated by the scientific question and supporting narrative for heavy-ion-driven high energy density physics and fusion, the primary scientific challenge is to compress intense ion beams in time and space sufficiently to heat targets to the desired temperatures with pulse durations of order or less than the target hydrodynamic expansion time. For low energy ions (in the few to tens of MeV range), requirements to study strongly-coupled plasma properties in the warm dense matter regime are: target foils of thickness a few to tens of microns, 1 to 20 Joules (in a single beam), 0.5 to 10 eV temperature, 0.2 to 2 nanosecond final pulse duration, and 0.5 to 2 mm-diameter focal spot size. Target diagnostics for high energy density physics studies should have spatial resolution small compared to the focal spot size, temporal resolution small compared to the target hydrodynamic expansion time after heating, and energy deposition measurement accuracy better than 3%. For x-ray production in inside indirect-drive fusion targets, ion beams must heat foam layers 1-

100% that of solid-density with 50 to 200 kJ per beam (many beams), 200 eV target radiation temperature, 5 to 10 nanosecond final pulse duration, and 4 to 10 mm-diameter focal spot size. For high energy density physics studies, ranges of ions with 0.2 to 1 MeV/u should be larger than the target thickness, with the deposition peak centered in the target in order to achieve maximum uniformity inside the target for accurate measurements of the heated plasma properties, and to allow analysis of transmitted ion energies and charge states as a diagnostic. Hydrodynamic codes with a capability for calculating energy deposition from a distribution of incident ion energies and angles should evaluate changes in observable target properties for different equation-of-state models. For fusion, radiation transport is a key additional target code capability that is required. Ion ranges with 10 to 20 MeV/u should be less than the target radiator thickness, but larger than the mean free path of the target x-rays so that the peak ion deposition can occur inside the radiation case (hohlraum) surrounding the fusion fuel capsule.

The minimum pulse length and focal spot radius depend on the final longitudinal and transverse effective temperatures, respectively, accumulated from all non-ideal effects experienced by the ion beam as it travels from the source through the accelerator, and through longitudinal compression and final focus onto the target. Accelerators for both high energy density physics and fusion must initially inject sufficiently bright (low temperature) beams, accelerate the heavy ions to the desired energy range, and then longitudinally compress and radially focus the beams onto the target with minimal growth in the longitudinal beam temperature (much less than a factor of 10 to allow overall axial bunch compression by a factor of 100 or more), and with minimum transverse temperature growth (much less than a factor of 10 to allow radial focusing by more than a factor of 10).

Scientific Objectives and Milestones: Advances over the past several years include: (i) high current ion sources and injectors (0.1 to 1 A of potassium) have been shown to have adequate initial beam brightness (sufficiently low transverse and parallel temperatures) to meet the above requirements at injection; (ii) negligible beam brightness degradation has been observed in transport of 200 mA potassium ion beams through electric quadrupole focusing magnets; and (iii) more than 95% of potassium beam space charge has been neutralized with pre-formed plasma over ~ 1 meter lengths without deleterious beam-plasma instabilities. Over the next five years, before beam-on-target experiments begin, the research will address the key remaining beam physics issues necessary to meet the accelerator requirements described above. These fall into four scientific areas:

High brightness heavy ion beam transport in magnets, particularly to understand limits on beam-channel wall clearance (aperture fill) imposed by gas and electron cloud effects, together with beam matching and magnet non-linearities.

Longitudinal compression of intense ion beams, particularly to understand limits on longitudinal compression within neutralizing background plasma, and the effects of potential beam-plasma instabilities over distances longer than 1 meter.

Transverse focusing onto targets, particularly to understand limits on focal spot size set by chromatic aberrations due to uncompensated velocity spreads from upstream longitudinal compression, and beam temperature growth from imperfect charge neutralization.

Advanced beam theory and simulation, particularly developing, optimizing and validating multi-species beam transport codes that can predict self-consistently the beam loss with gas and electron clouds, and developing integrated beam simulation models required to analyze source-to-target beam brightness (temperature) evolution.

After the beam physics issues identified above are favorably addressed over the next five years, emphasis will be placed on the fifth scientific thrust area:
Beam- target interactions, particularly to understand beam deposition profiles within thin foil targets and the potential uniformity of isochoric heating, accounting for target and beam ion charge state conditions, including development of accurate beam deposition and laser-generated x-ray target diagnostics, and extension of integrated beam simulation models from source *through* target.

These scientific areas will be pursued with an overall 10-year objective of providing the beam and target physics knowledge base for a future ~$50M-class heavy-ion accelerator-based high energy density physics facility for achieving 1-10 eV solid-density plasmas by isochoric ion heating with uniformity and diagnostic resolution adequate to discriminate the predictions of various *ab initio* theories for strongly-coupled plasmas. Successful achievement of this objective will address the Office of Management and Budget/Office of Fusion Energy Sciences 10-year measure for inertial fusion energy/high energy density physics: *"With the help of experimentally validated theoretical and computer models, determine the physics limits that constrain the use of inertial fusion energy drivers in future key integrated experiments needed to resolve the scientific issues for inertial fusion energy and high energy density physics"*. In addition, such an accelerator-driven high energy density physics facility would represent an important step towards the long-term objective of heavy-ion-driven inertial fusion.

Research Tools, Facility Requirements, and Milestones: Several specific facility requirements with intermediate two-year and five-year milestones (for experiments and modeling) are required to measure progress towards the 10-year objective. These include:

Two-Year Science Goals (FY06):

A2: Intermediate experiments to assess the physics limits of neutralized ion beam compression to short pulses. Measure the parallel and transverse temperature of a high perveance ion beam (space-charge potential / kinetic energy larger than 10^{-4}) before and after longitudinal compression by a factor of ten in neutralizing background plasma, and before and after pre-bunching of initially non-neutral ion beam in an acceleration-deceleration system. This series of experiments and modeling is needed to design integrated experiments combining neutralized drift compression and final focusing.

B2: Intermediate experiments to develop a predictive capability for gas and electron effects. Compare measured and calculated effects of gas and electron clouds on beam temperature as a function of beam aperture fill factors initially in transport lines with four magnets (quadrupoles and solenoids). This series of experiments and modeling will provide the scientific basis for future experimental upgrades.

Five-Year Science Goals (FY09):

A5: Integrated beam experiments on neutralized compression and focusing onto targets. Compare the measured and simulated focal spot beam intensity profiles in integrated experiments with beam current and energy upgraded from that used in A2, with a goal of 1 eV temperature in targets (a temperature corresponding to the high energy density threshold level of 10^{11} J/m^3 at solid density). This series of experiments and modeling of compression and focusing will provide the physics basis for a future heavy-ion high energy density physics facility.

B5: ***Demonstrate predictive capability for gas and electron effects for a heavy-ion high energy density physics facility***. Compare measured and calculated effects of gas and electron clouds, in combination with beam matching and magnet errors, assuming B2 results warrant an upgrade to longer lattice transport experiments. This series of experiments and modeling is essential to determine the magnet apertures of quadrupole and solenoid transport options for a future heavy-ion high energy density physics facility.

Figure 3.1 gives a timeline with milestones and resource requirements.

Opportunities for Interagency Cooperation: Several opportunities exist for scientific cooperation between the heavy-ion-driven high energy density physics/fusion thrust area sponsored by the Office of Fusion Energy Sciences (OFES) and other federal agencies. These include:
Office of Basic Energy Sciences (OBES), with the Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory, in common areas of need for data on wall secondary electron production and gas desorption induced by beam loss [2], and in multi-species particle-in-cell simulation models of the impact of gas and electron clouds on the beam, including two steam instabilities [3, 4]. This area may be critical to the achievement of full average beam power and neutron production in the SNS.
National Nuclear Security Agency (NNSA), with the Proton Storage Ring (PSR) and Dual Axis Radiographic Hydro Test facility (DARHT) at the Los Alamos National Laboratory [3, 4], in common areas of modeling multi-species gas/electron effects including two-stream instabilities (PSR), and in efficient computational techniques with multi-species modeling of electron beam neutralization from gas and ions back streaming from the targets (DARHT).
Collaborations with the high energy and nuclear physics accelerator communities on joint development of advanced computational tools are important to predict and control electron cloud effects, beam halo production and associated losses, including use of Adaptive Mesh Refinement techniques [5] and nonlinear perturbative (δf) particle simulation techniques [3] developed for modeling heavy ion experiments. Sharing these computational tools can greatly increase the range of intense beam physics problems that can be modeled for a variety of scientific applications.
Within strongly-coupled plasma regimes of high energy density physics, scientific progress would benefit from comparisons of equation of state and constitutive properties data obtained using heavy ion isochoric heating with similar data obtained using other future high energy density physics drivers, including lasers, Z-pinches, and X-ray free electron lasers (XFELs)[6].

Figure 3.1: **Timeline and Resource Requirements for Heavy-Ion Driven HEDP/fusion**

Science Areas	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14	FY15
High Brightness Beam Transport	4 quadrupoles 4 solenoids		Upgrades (larger and more magnets)			Upgrades of injectors and diagnostics to further reduce beam temperature					
Longitudinal Beam Compression	10x compression		100x compression with 10x focusing			Active beam correction experiments to explore potential 1000x compressions					
Focusing onto Targets	Large plasma source		Plasma lens and time dependent corrections			Advanced focusing experiments e.g., induced self-pinching					
Beam-Target Interactions			Target design and fast beam diagnostics			Beam energy loss and deposition profiles, target T_e (t) n_e(t) diagnostics and modeling					
Advanced Theory and Simulations	Source to target models					Source through target models					
Estimated resource needs	**$12 M/yr**		**$14M/yr**			**$16M/yr**					

2yr Milestones:
A2: 10x neutralized compression
B2: Gas/electron limits in 4 magnets

5yr Milestones
A5: 100x neutralized compression and focusing
B5: Gas/electron predictive capability for HEDP accelerators

10yr Objective:
Beam and target physics knowledge base for heavy-ion-driven HEDP user facility

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Appendix B FESAC Priorities Report (heavy ion section)

Excerpts related to heavy ion beam research from the Report to FESAC on:

Scientific Challenges, Opportunities, and priorities for the US Fusion Energy Sciences Program (April 2005)

Motivating topical scientific questions, research thrusts, and the principal ten-year goal and supporting goals included in the high energy density physics campaign:

T9: How can heavy ion beams be compressed to the high intensities required to create high energy density matter and fusion conditions?

The primary scientific challenge in creating high energy density matter and fusion conditions in the laboratory with intense ion beams is to compress the beam in time (by 1000 times overall, requiring 10–100 times more longitudinal bunch compression than present state-of-the-art) to a pulse length that is short compared to the target disassembly time, while also compressing the beam in the transverse direction (by 10 times) to a small focal spot size for high local deposition energy density. Planned new experiments, compressing intense ion beams within neutralizing plasma, would significantly extend the beam current into high-intensity regimes where the beam would not otherwise propagate in the absence of background plasma, and where beam-plasma collective effects with longitudinal and azimuthal magnetic focusing fields have not been previously explored.

The heavy ion beams, once compressed in time and radially focused, will not themselves alone reach an energy density that satisfies the definition of high energy density physics (>100 kJ per cubic centimeter), but will be able to deposit an energy density in the targets sufficient to reach high energy density conditions, because the ion stopping range at energies near the Bragg peak in energy loss rate dE/dx (a few to tens of microns) in near-solid targets is much shorter than the compressed beam bunch length. The resulting near-solid-density target plasmas can exhibit strong-coupling effects between the target ions at temperatures below 10 eV, conditions where there have not been accurate enough measurements to validate equation-of-state theories for such non-ideal plasmas characteristic of the interiors of giant planets and brown dwarfs. In particular, it is planned to study plasmas of about 1 eV at densities 0.01 to 0.1 times solid density, because there is very little data in such regimes, while predicted pressures from existing equation-of-state models differ the most.

To improve measurement accuracy in such strongly coupled plasmas, it is planned to use tailored ion beams with the Bragg peak located in the center of the target diagnostic volume to achieve unprecedented uniformities (<5 % nonuniformity in temperature and density) in the target. A basic understanding of the collective processes and nonlinear dynamics of intense, high-brightness, heavy ion beams, and a determination of how best to create, accelerate, transport, compress, and focus these beams to a small spot size are critical to achieving the scientific objectives of heavy ion fusion and ion-beam-driven studies of warm dense matter. There are key synergistic relationships of the research on intense heavy ion beams to understanding the nonlinear dynamics of intense charged-particle beams for high energy and nuclear physics applications, including minimization of the deleterious effects of collective processes such as the two-stream (electron cloud) instability, the use of a charge-neutralizing background plasma to assist in focusing intense beams to a small focal spot size (plasma lens effect), the production and control of halo particle production by beam mismatch and collective excitations, and the development of advanced numerical simulation techniques, theoretical models, and diagnostic instruments to understand and control charged-particle beam propagation at high intensities, to mention a few examples.

Research Thrusts: Heavy-ion-driven High Energy Density Physics
High-brightness heavy ion beam transport
Develop a basic understanding of the limits on beam-channel wall clearance (aperture fill) imposed by gas and electron cloud effects, together with beam matching and magnet nonlinearities.
Longitudinal compression of intense ion beams
Develop a basic understanding of the limits on longitudinal compression within neutralizing background plasma, and the effects of beam-plasma instabilities over distances greater than one meter.
Transverse focusing onto targets
Develop a basic understanding of the limits on focal spot size set by chromatic aberrations due to uncompensated velocity spreads from upstream longitudinal compression, and the beam temperature growth from imperfect charge neutralization.
Advanced beam theory and simulation
Develop, optimize, and validate multi-species beam transport codes that can predict self-consistently the beam loss with gas and electron clouds, and develop integrated beam simulation models required to analyze source-to-target beam brightness (temperature) evolution.
Beam-target interactions
Develop a basic understanding of the beam deposition profiles within thin-foil targets and the uniformity of isochoric heating, accounting for target and beam ion charge state conditions, including the development of accurate beam deposition and laser-generated x-ray target diagnostics, and extension of integrated beam simulation models from the source through the target.

Technical progress and campaign readiness:
Heavy-ion-driven High Energy Density Physics

Advances over the past several years include: (i) high-current ion sources and injectors (0.1 to 1 Ampere using a potassium source) have been shown to have adequate initial beam brightness (sufficiently low transverse and parallel temperatures) to meet the above requirements at injection; (ii) negligible beam brightness degradation has been observed in transport of 200-milliamperes using potassium ion beams through electric quadrupole focusing magnets; and (iii) more than 95% of potassium beam space-charge has been neutralized with pre-formed plasma over one meter lengths without deleterious beam-plasma instabilities. Figure 5.1 shows the beam focal spot sizes for three cases of space-charge neutralization: a large focal spot of several centimeters without any pre-formed plasma (left panel), a spot size reduced by almost a factor of 10 with a localized “plug”

plasma just beyond the last focusing magnet (center panel), and a further 25% reduction in the full-width-at-half-maximum of the spot size is seen (right panel) when both “plug” and “volume” plasmas are used. Particle-in-cell calculations using the hybrid LSP code predict a root-mean-square spot radius of 1.4 mm for the case of a plug plasma (center panel), in very good agreement with the experimental results.
Over the next five years, the research will use existing experimental facilities, with modest upgrades of equipment, to test the limits of longitudinal as well as transverse compression of neutralized beams. This is the key to enable creation of uniform 1 eV, 0.01 solid density plasmas where the predictions of equation-of-state models can best be discriminated.

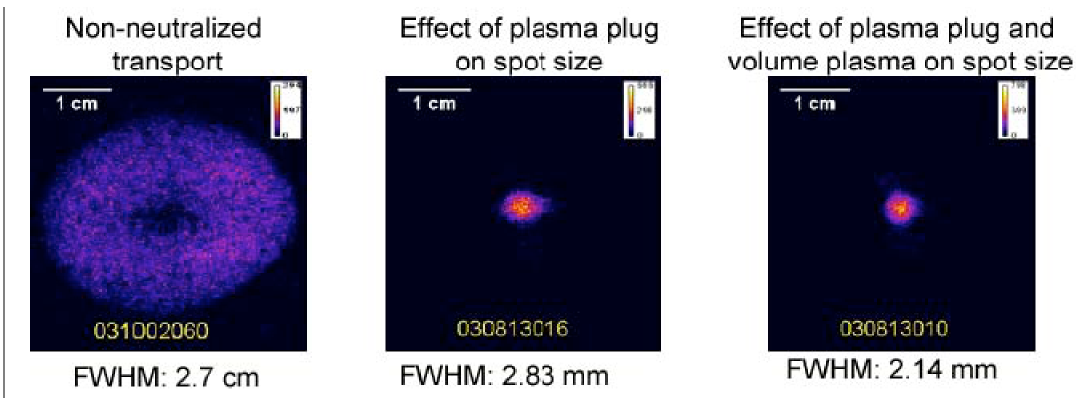

Figure 5.1. Plasma neutralization reduces the final focus spot size of an intense heavy ion beam, encouraging experiments on longitudinal and transverse compression for neutralized beams. (Courtesy of Simon Yu)

Expected accomplishments in the next ten years:
Heavy-ion-driven high energy density physics

Over the next five years, an integrated program of beam experiments, theory, and simulations will be carried out to understand the limits to neutralized drift compression and the focusing of intense ion beams onto targets (Heavy Ion Research Thrusts in high-brightness beam transport, longitudinal compression, transverse focusing, and advanced theory and simulation). If the optimized beam parameters are found to be sufficient to create and study 1-eV warm dense matter with sufficient spatial uniformity, over the following five years experiments will be conducted to measure the equations-of-state for 1-eV targets in the range of 0.01 to 0.1 solid density (Heavy Ion Research Thrust in beam-target interaction). Predictive models will also be developed for gas and electron cloud effects in short (<10 magnet) transport sections (Heavy Ion Research Thrust in high-brightness beam transport).

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Appendix C Supporting University research in physics of intense heavy ion beams

C.1 University of Maryland Recirculator Ring

C.2. PSTX

C.1 University of Maryland Ongoing and Proposed Research on HIF

UMER is a scaled circular accelerator using 10 keV intense electron beams to model the dynamics of high-current proton and heavy ion beams. The current (up to 100 mA), emittance (normalized effective about 1 micron) and other beam parameters are selected to produce the same relative space charge forces one encounters in a heavy ion fusion driver. We have been using UMER to investigate both transverse and longitudinal space-charge-dominated beam dynamics over a long path length. To date, we have demonstrated storage of extremely intense beams for many turns in UMER. We have circulated beam for over 200 turns (> 2 kilometers) at 0.6 mA, which exceeds our design specification of 100 turns at that current. At higher currents, though we lose beam more quickly, we have nevertheless circulated beams with tune shifts of several integers longer than any other machine.

We plan to continue these investigations and also to continue our collaboration with VNL, benchmarking their workhorse code WARP against UMER experiments, and transferring our solenoid tomography diagnostic to NDCX in support of Warm Dense Matter experiments.

Plans for Future. The current vision of an HIF driver is a massive linac employing a large number of costly induction cores to accelerate tens or hundreds of high-current beams simultaneously up to 4 GeV. The beam-beam interactions inside the accelerating gaps create additional difficulties. The development of fast ignition targets in recent years [8] call for a different arrangement. A single rotating 100 GeV heavy ion beam is to deliver about 5 MJ of compression beam energy over 100 ns to compress the DT fuel, which is then ignited on the other end of the cylinder with a 500 kJ, 200 ps pulse, again at 100 GeV. Design scaling studies comparing linacs to recirculators in terms of cost conclude that a ring geometry is more cost-effective than a linac for energies above 10 GeV [9]. Hence, the ideal driver for a heavy ion facility with fast ignition targets is a recirculator delivering a 100 GeV ion beam.

We propose to explore a recirculating accelerator as a possible driver for Heavy Ion Inertial Fusion (HIF). We propose to take advantage of our existing facility, namely the University of Maryland Electron Ring (UMER), to experimentally test the concept and answer the basic physics issues associated with designing and constructing a working recirculator. Research is needed to fully demonstrate the recirculator concept and learn how to make it most efficient. For the modest cost associated with adding an acceleration capability to the existing ring, we propose to answer many of these scientific questions in a matter of a few years. Our research will identify the major scientific issues associated with designing and building a working recirculator.

A realistic plan is 3 years for the design stage where we decide on the optimal parameters and identify and address the main technological challenges. For UMER these challenges are dominated by the requirements for ramping the dipoles. During the following 3-year period, we plan to implement the upgrade and begin an experimental program on acceleration and fast resonance crossing.

References for C.1

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[9] Wayne Meier, LLNL, private communication, 2005.

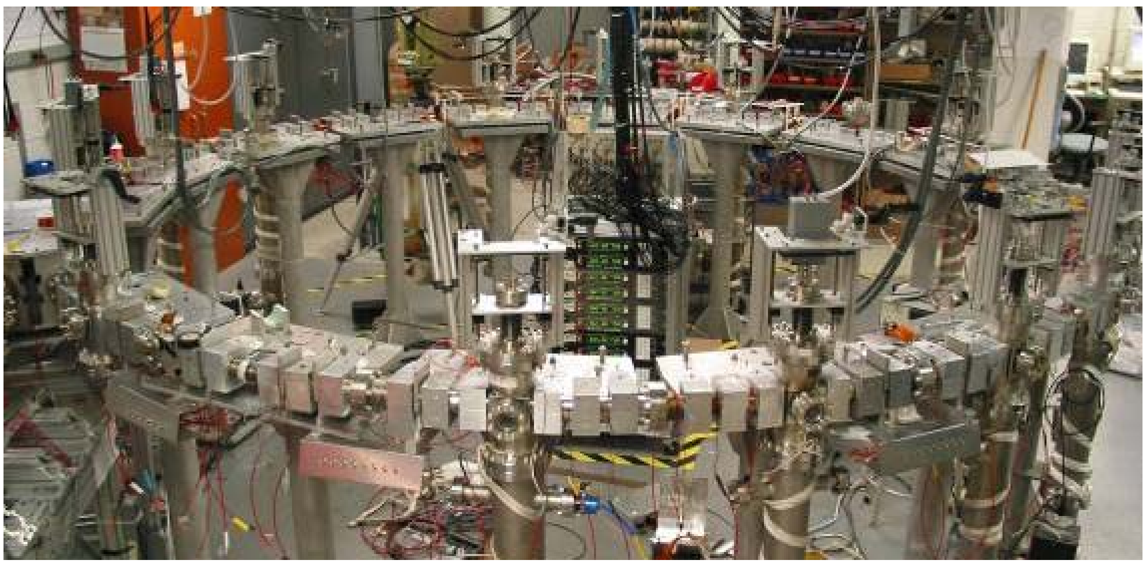

Fig. 3.1: Photograph of UMER

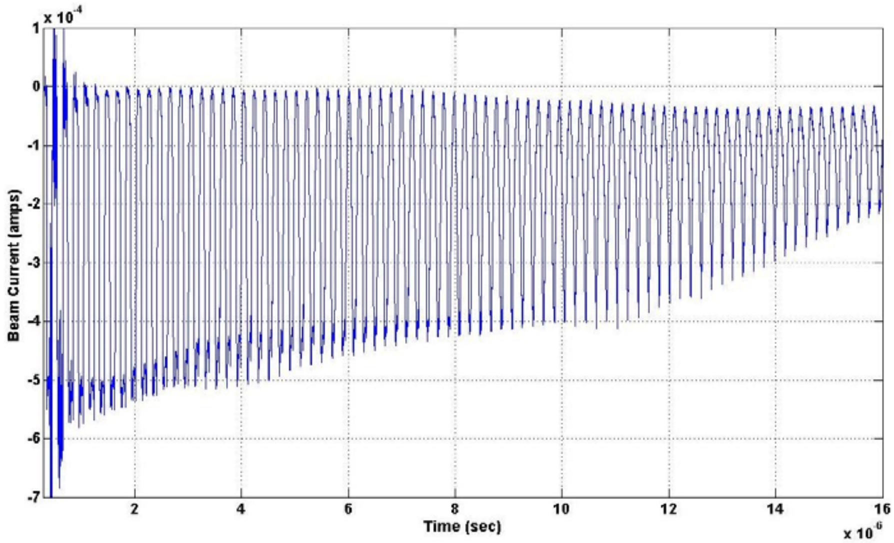

Fig. 3.2: Multi-turn circulation of pencil beam (0.6 mA injected, or a tune depression of 0.8): beam current over multi-turn from wall-current monitor at RC10, with a restored baseline to compensate for the detector's ac response. Each oscillation represents one turn (duration approx. 200 ns).

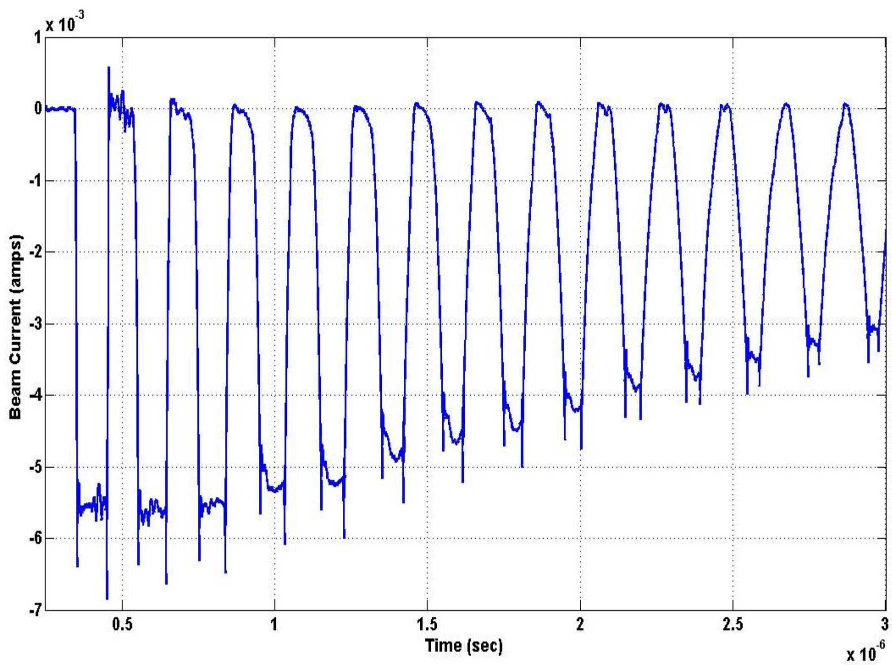

Fig. 3.3: Multi-turn circulation of space-charge-dominated beam (7 mA injected corresponds to a tune depression of 0.45): beam current over multi-turn from wall-current monitor at RC10, with a restored baseline to compensate for the detector's ac response. Each oscillation represents one turn (duration approx. 200 ns).

Parameter	At Injection	After Acceleration
Kinetic Energy (keV)	10	40
beta (v/c)	0.20	0.40
Peak Current (mA)	100	200
Generalized Perveance, K	0.0015	0.000375
4*rms unnorm. Emittance (□m)	60	30
Lattice period (m)	0.32	0.32
Zero-Current Tune	7.6	5.37
Beam Radius (mm)	9.5	6.8

C.2. PSTX The Paul Trap Simulator Experiment (PTSX)

The Paul Trap Simulator Experiment (PTSX) at PPPL is a compact laboratory Paul trap that studies the transverse dynamics of high-intensity, long, thin charge bunches propagating through a kilometers-long magnetic alternating-gradient transport system [1]. This is made possible because the time-oscillating quadrupolar electrostatic fields of a linear Paul trap exert forces on the trapped charges that have precisely the same form as the forces that the spatially periodic quadrupolar magnetic fields of alternating-gradient transport system exert on a long, thin beam. The PTSX apparatus effectively places the physicist in the frame-of-reference of the beam. Various magnetic lattice configurations are simulated by programming the PTSX confining waveform's amplitude V_0 and frequency f.

Figure 1: The Paul Trap Simulator Experiment (PTSX) is a compact laboratory experiment that studies the transverse dynamics of high-intensity beam propagation.

An experimental campaign has been completed in which lattice waveform changes have been made to transversely compress the plasma. When the phase advance is kept small, the smooth-focusing model is applicable and the average transverse focusing frequency scales as V_0/f. It has been experimentally confirmed that adiabatic increases in the average transverse focusing frequency either by increasing V_0 or by decreasing f are equally effective in compressing the plasma [2, 3]. For depressed tunes ν/ν_0 of ~ 0.9, the compression may be considered adiabatic as long as the transition is made over at least ~4 lattice periods. Since the transverse emittance is conserved during the adiabatic compression, the depressed tune rises towards unity even while the on-axis plasma density is increasing. Experimental results also demonstrate that instantaneous changes in the voltage waveform amplitude and frequency of up to 50% that leave the ratio V_0/f unchanged do not alter the radial density profile or increase the transverse emittance [4].

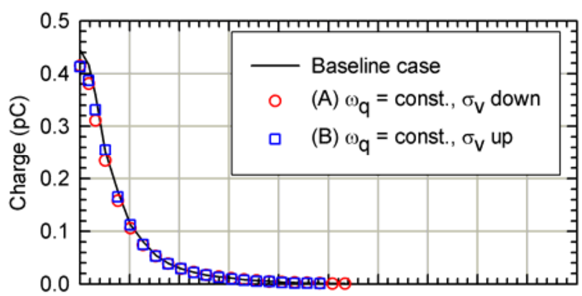

Figure 2: The plasma's radial density profile is not affected by instantaneous changes in the voltage waveform amplitude and frequency of up to 50% if the average transverse focusing frequency, which scales as V_0/f, is left unchanged.

Other recent experiments explored emittance growth and the generation of halo particles due to beam mismatch. When an intentional mismatch is created between the fixed-diameter PTSX ion source and the equivalent transport lattice defined by the PTSX oscillating voltage waveform, a population of halo particles is observed [5]. The radial extent of the halo is reduced when the average transverse focusing frequency is increased to provide a better match. Separate experiments begin with relaxed, well-matched plasma that is then suddenly perturbed by instantaneously changing the lattice amplitude. The resulting plasma oscillations ultimately decay, thereby increasing the emittance, and finally leading to broader radial density profiles [4].

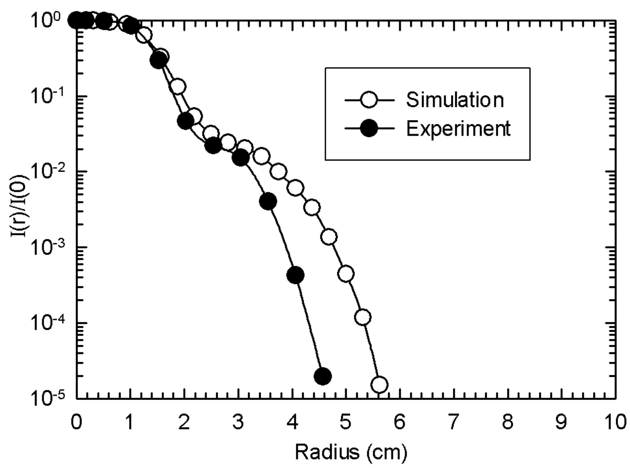

Figure 3: The radial profile of the axial current streaming from the ion source to the collector exhibits a shoulder corresponding to the presence of halo particles in both PTSX experiments and 3D WARP PIC simulations when the ion source is poorly matched to the transverse confinement lattice.

Planned experiments include studies of the accumulation of the effects of random errors in the lattice waveform in order to better understand and define the design tolerances of transport systems. Initial experiments have been performed to explore the use of collective plasma modes as diagnostics of plasma properties such as the depressed tune. By masking the PTSX ion source, distribution function effects will be studied, such as the stability of hollow beams, off-center beams, and the dynamics of multiple beamlets in a single transport system.

Future upgrades to the ion source and the electrical system will allow access to a broader range of depressed tunes. This access is important in order to explore the space-charge dependence of the above-mentioned phenomena. Specifically, it is important to understand the transverse dynamics of space-charge-dominated beams at depressed tunes near 0.1, similar to those used in NDCX.

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