Summary of Progress in U.S. Heavy Ion Fusion Science Research

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Abstract. The Neutralized Drift Compression eXperiment (NDCX-II), a newly completed accelerator facility at LBNL, will produce nanosecond Li^+ ion beam bunchs at ~1.2 MeV energy for volumetric heating of thin foils. Using specialized acceleration voltage waveforms, a beam bunch is compressed >500-fold longitudinally to ns time scale. Planned experiments on NDCX-II to study warm dense matter include: measuring dE/dx, equation of state, conductivity, and shock generation. Theoretically, we have studied transverse and longitudinal beam compression; transverse gradients and profile shapes on beam-plasma instabilities; nonlinear effects of beam-plasma instabilities on beam current neutralization; and beam "wobbler" as a beam smoothing technique. The HIF X-target design was improved to achieve a gain of 300. It uses multiple heavy ion beams to illuminate the target axially from only one side such that the fuel can be compressed and ignited at the X-vertex, with negligible RT growth thus providing a central clean DT ignition zone.

1. The Heavy Ion Beam-Driven IFE Approach and Development

The Heavy Ion Fusion approach for IFE is promising because its attributes are well matched to IFE driver requirements. Accelerators routinely demonstrate repetition rates higher than the required 5-10 Hz range, and efficiencies up to 40% are projected. Final ion beam optics (facing the target) is robust because the focusing magnet is shielded from line-of-sight radiation or debris from the targets [1]. Heavy ions are found to strip minimally in vapor of molten FLiBe, thus enabling the use of liquid protection of the inner chamber wall. With such protection, chamber materials would enjoy a thirty-year lifetime and qualify for shallow burial when the power plant is decommissioned.

In comparison to photon beams, heavy ions have a stopping 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-driven targets, and likewise 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. 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. Third, velocity-ramping of heavy ion beams that interact with dense target plasmas may suppress or reduce beam plasma instabilities that could otherwise generate unwanted hot electrons and cause target preheat. These unique properties make heavy ion beams an excellent choice for studies of high energy density physics and fusion target physics that can eventually lead to the design of very attractive high-gain HIF targets.

Typically, the required beam energy on target is 1-10 MJ, within about 10 ns, so the corresponding average power on target is 10^{14} - 10^{15} W. The choice of ion mass is somewhat arbitrary. Typical indirect-drive targets produce highest gain for incident ion ranges between 0.02 and 0.2 g/cm^2. Ions with a wide range of masses might be used, but because stopping power in an absorber is proportional to the inverse square of the ion velocity, the energy per ion must be lower with lighter ions, necessitating a higher total particle current, summed over all beams, to obtain the needed power. The required current increases inversely with decreasing ion mass, and for ions lighter than about 120 u, ballistic transport to a target becomes challenging due to the large total current needed. Most conceptual designs for HIF drivers, therefore, assume ions with a mass around 200 u. With this choice, the required ion kinetic energy is a few GeV, and the total current needed is roughly 200 kA. As dictated by the hydrodynamic expansion time scale, the beam pulse length is less than 10 ns (and much shorter for the ignition pulse in the case of fast ignition targets).

To provide this current, induction accelerators [3] are being developed in the US. Such accelerators can be thought of as a series of single-turn transformers, with the beam receiving the induced EMF from each as if it were the secondary winding. Pulsed power is applied to each induction cell to coincide with the beam arrival and accelerates the beam. Induction accelerators are attractive as HIF drivers. The accelerating structure has very low impedance, so currents as high as 100 kA can be accelerated. Also, particles are accelerated independent of their energy, so beams can have a head-to-tail velocity increase or “tilt”, allowing lengthwise compression of pulses during the acceleration stage. These two features eliminate the need for beam accumulation and bunching found with rf accelerators. Core losses, due mainly to eddy currents, are quite small with modern amorphous or nanocrystalline ferromagnetic materials, so induction accelerators can be designed with wall plug-to-beam efficiencies of 40% and perhaps higher. Other useful features of induction drivers are the possibility of repetition rates exceeding 1 kHz, far more than HIF drivers require, and the ability to accelerate several beams through a single magnetic core, so that core cost scales as the square root of the number of beams rather than linearly. A low-risk HIF driver system, including the accelerator, final focusing, shielding of the fusion chamber, can be designed to use multiple beams to produce the required energy-deposition profile on a target [4].

2. Ion Beams for Studying HEDLP Physics

Most inertial fusion target hydrodynamic experiments to date have been carried out using laser beams. Lasers deposit their energy at the critical surface, roughly where the plasma frequency equals the laser frequency. In laser direct drive, as the ablator material and the critical surface expand outward and as the shockwave propagates inward, over the course of the pulse the shock front separates from the location of the energy deposition. In heavy ion direct drive targets, ions deposit their energy volumetrically, and the ion mass and energy can be chosen (possibly time varying) so that the ion range is a significant fraction of the ablator thickness following the shock front. How to maximize the shock intensity and optimize the conversion of ion energy into fuel fluid kinetic energy by varying the intensity and energy of the ion beam is an area of investigation that is wide open for exploration both theoretically and experimentally (e.g. using the new NDCX-II accelerator, photo in Fig.1.).

In comparison to other means such as lasers and x-ray irradiation, using ions as drivers to create HEDLP conditions offers some unique advantages such as:

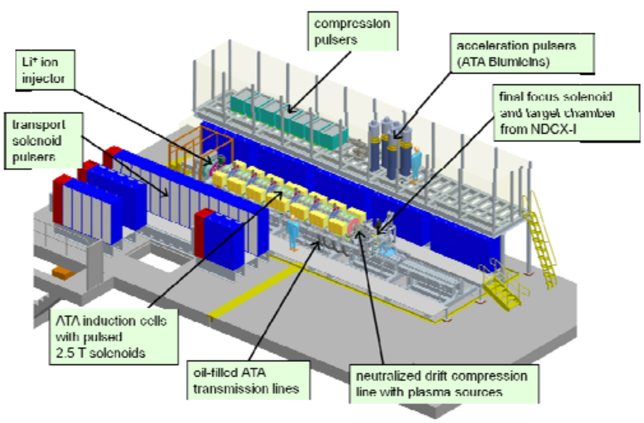
- Spatially uniform and volumetric energy deposition over a diagnosable volume,
- Large selection of materials or surfaces (not restricted to metal),

- Precise control of energy deposition with an intrinsic energy spread of a few per cent,
- Minimal shot-to-shot variation in energy and intensity,
- Ability to do energy accounting by measuring the transmitted beam ions,
- Low debris and radiation background noise for target diagnostics,
- High shot rates (~ 1 per minute),
- Energy deposition that leaves the target in local thermodynamic equilibrium,
- Small beam-induced magnetic fields.

3. Highlights of Recent Progress and Plans in HIF and HEDLP Science Research

3.1. NDCX-II Facility and Status

In June 2009, Lawrence Berkeley National Laboratory (LBNL) received $11 M American Recovery and Reinvestment Act (ARRA) funding from the Fusion Energy Sciences (FES) Program in DOE to construct a new user facility called Neutralized Drift Compression Experiment - II (NDCX-II) for the purpose of enabling ion-beam-driven HEDLP and heavy ion fusion (HIF) science research. Compared to NDCX-I, an earlier machine, NDCX-II can produce beam pulses with a much higher energy and shorter pulse length resulting in an experimental condition that is suitable for Warm Dense Matter (WDM) studies.



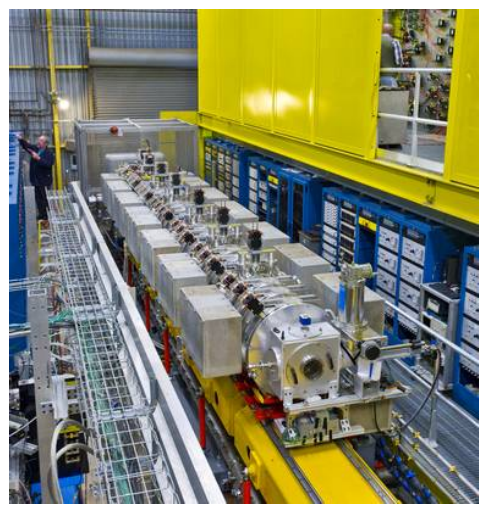


Fig.1. NDCX-II facility at LBNL

NDCX-II was built by reusing existing hardware (from the retired LLNL ATA machine) to maximize the energy on target while minimizing cost. With an $11 M ARRA investment, the facility is estimated to be worth well over $30 M if built with totally new parts. The construction project was completed in early 2012, and commissioning of the accelerator is in progress. The completed NDCX-II accelerator will produce ion beams with unprecedented intensity for its operating kinetic energy range (e.g. GSI is more powerful but at a much greater kinetic energy and pulse length). The brightness of the ion beam, and the flexibility of the accelerator to manipulate the beam energy profile, will make this facility unique in terms of coupling beam energy to material targets on sub-hydrodynamic time scales.

NDCX-II is designed to capture, accelerate, control, and ultimately compress a Li^+ ion beam bunch to nanosecond duration and mm spot at the target, so as to be suitable for rapid volumetric heating of thin foils – rapid here means shorter than the hydro-expansion time. Strong solenoids along the accelerator (~2 T) provide the transverse beam confinement, and novel acceleration waveforms from the induction cells drive the acceleration and pulse compression – the beam has an extraordinarily high perveance (the ratio of beam potential over the ion kinetic energy) and is a challenge to confine and control. Following an initial stage of rapid compression from ~600 ns to ~70 ns, the beam bunch is accelerated by voltages from Blumlein voltage sources at the rate of 250 kV per cell. At present, NDCX-II has 27 cells for producing beams with 1.25 MeV. Future upgrades by adding induction cells can raise the energy to above 3 MeV (at 2-3 MeV, the Li^+ ion deposition is nearly homogeneous over ~1 micron depth). Extensive simulations were carried out to develop the NDCX-II design and to establish error tolerances. TABLE I shows the nominal beam parameters for the initial 27-cell configuration when mature, and for a future upgraded configuration with 37 cells, possible using additional induction cells from ATA now available for NDCX-II.

TABLE I. Nominal NDCX-II design ion beam parameters at target plane.

	NDCX-II (27-cell)	NDCX-II (37-cell)
Ion species	Li+ (A=7)	
Total charge	50 nC	
Ion kinetic energy	1.2 MeV	3.1 MeV
Focal radius (containing 50% of beam)	0.6 mm	0.5 mm
Bunch duration (FWHM)	0.6 ns	0.4 ns
Peak current	38 A	86 A
Peak fluence (time integrate)	8.6 J/cm^2	18 J/cm^2
Fluence within 0.1 mm spot diameter	5.3 J/cm^2	12 J/cm^2
Total ion energy per pulse	0.1 J	0.25 J

3.2. Ion Beam Experiments on NDCX-II Relevant to Heavy Ion Fusion

NDCX-II is, in key respects, a microcosm of a fusion driver and target environment [5]. We plan to do first-of-kind studies of the longitudinal compression and transverse focusing of dense, isolated ion pulses in neutralizing plasma; pulse-shaping on targets; and nonlinear dynamics of non-neutral beams. With PIC simulations and theory, these experiments will examine:

- The physics of beam neutralization by plasma; beam-plasma interactions, including instabilities; collective focusing; and neutralized focusing. All current HIF concepts involve beams in plasmas.
- The nonlinear dynamics of the dense, space-charge-dominated, non-neutral ion beam in the accelerator. HIF drivers require high peak power but moderate energy per ion, and so they require dense beams.
- Shaping (in space and time) of beam pulses on targets: tuning or eliminating pre-pulse, producing ultra-short pulses, ramping kinetic energy or intensity with time, and "wobbling" the focal spot during the pulse to symmetrize the deposition (see below). NDCX-II, because it uses solenoids to confine the beam, provides a natural wobbler capability obtainable by using "corkscrew" beam displacements in a beneficial manner. The performance of HIF targets depends to varying degrees on such beam manipulations.

This work will clarify important HIF beam physics, result in improved NDCX-II on-target performance, and enable NDCX-II users to field a broader set of IFE- and basic science-motivated target experiments. These studies will establish the degree to which the intense-beam physics inherent in HIF is well captured by simulations, lending confidence in our ability to deliver the required ion beams onto each target in a Heavy Ion Fusion IFE system.

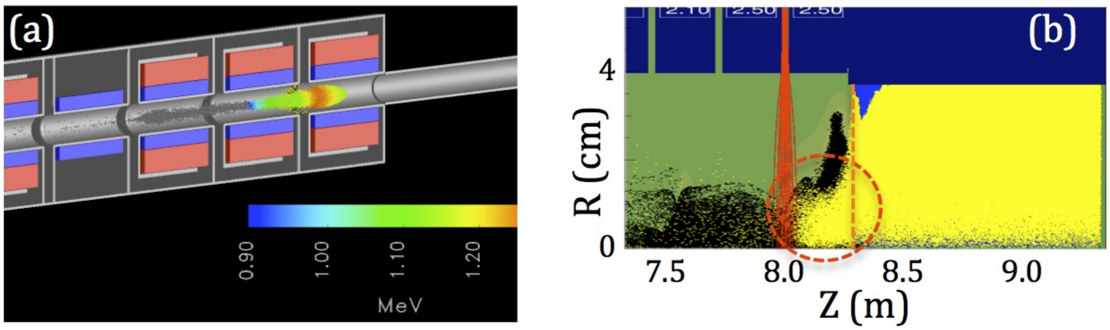


Fig. 2. Warp (PIC) code simulations of NDCX-II: (a) beam as it exits accelerator and is about to enter neutralized drift line; (b) beam entering plasma: beam ions in black, plasma electrons yellow, plasma ions blue. The dashed red line marks the nominal plasma entrance, showing how plasma can be drawn upstream; closely spaced red lines show effective potentials of accelerating field.

3.3. Ion-Coupling to Target Experiments at NDCX-II in the WDM Regime

The equation of state and the transport properties of warm dense matter (WDM) are essential to the understanding of high energy density physics and the design of IFE targets. Many of these important properties are not well known due to the lack of experimental data that can be obtained by measurements on ion beam heated targets. Near-term, experiments at NDCX-II will investigate the followings: ion-beam stopping in heated material, thermal conductivity in heated matter, and hydrodynamic experiments on volumetrically heated targets.

Studying ion stopping in heated matter is important for improving the understanding of inertial fusion ignition dynamics. The stopping of ions in cold matter is well studied from experimental and theoretical viewpoints. However, ICF ignition plasmas are highly ionized and the free electrons dominate the energy deposition by fusion products (alphas), a key process in fusion ignition and burn propagation. Free electrons are very effective at stopping ions because they can absorb even small energy transfers (unlike the bound electrons in cold matter). Having the stopping power models correct in the codes is critical in determining whether conditions are met for ignition. Despite this importance, we do not know of adequate experimental tests of ion stopping in this regime, and theory and code models have not been verified by laboratory experiments in well-characterized dense hot plasmas. Similarly for thermal conduction in dense plasmas, a fundamental process that can limit the success of hot-spot ignition, fusion target design codes (e.g., HYDRA) use a conductivity model that has not been sufficiently thoroughly tested by experiments.

For studying these processes, the NDCX-II facility will be equipped with time dependent diagnostics that can measure temperature by emission photometry and pyrometry (including polarization), fluid velocity by VISAR, density distribution by X-ray absorption, ion charge state(s) by spectrometry, and optical properties by a laser probe beam. For physics studies, NDCX-II can experimentally control and change key variables such as pulse length, degree of velocity ramp, and time-dependent upstream modulations of the ion beam. In NDCX-II, we can explore techniques to make pulses as short as a few hundred picoseconds and two-stage focusing to focus to 200 micron diameter spots, hopefully generating the 10 MBar shocks needed for some high gain HIF targets that are more robust to hydrodynamic instabilities.

Shock-free and shocked deposition will be studied on NDCX-II. When the ion stopping range is longer than the thickness of the material, ion beam deposition results in controlled, shock-free increases in temperature. When range of the ion beam is shorter than the target thickness, at the end of the ion range the strong pressure gradient will induce an "end-of-range" shock. For targets in which the ion beam crosses a material boundary (as in Fig.3.), differential heating rates in the two regions will cause a pressure imbalance and can also drive a shock (the "tamper shock"). The tamper shock could contribute to fuel preheat, but can also contribute to the implosion drive. The ion beams produced at NDCX-II will have sufficient range and intensity to experimentally study these phenomena.

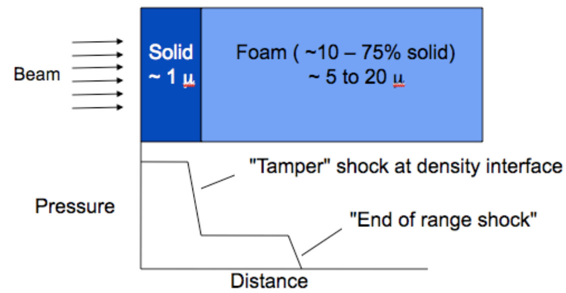


Fig. 3. Schematic of tamped target experimental setup.

In a homogeneous material, controlled volumetric energy deposition will allow us to investigate optimization of the conversion of ion beam energy into target material kinetic energy. For example, shock strength maximization involves determining the optimum velocity tilt and the optimum focusing angle. One of the issues we are planning to examine is the degree to which shock-front following, increasing the ion energy (and hence the range) to continuously place the deposition energy near the propagating shock front, can increase the conversion efficiency.

3.4. Advanced Heavy Ion Beam Theory and Numerical Simulations

The theory of beam current and charge neutralization in plasma is well established and has been validated by comparison with particle-in-cell (PIC) codes [6]. Analytic and modelling work on enhanced collective focusing of intense ion beams by weak solenoidal magnetic fields has been carried out [7]. Simulation results show that this scheme can be employed for focusing of the NDCX-II beam. An intense beam propagating in plasma is subject to collective streaming instabilities – electrostatic streaming instabilities between the beam ions and plasma electrons and ions (see Fig.4.), and electromagnetic Weibel instabilities driven by large longitudinal/transverse energy anisotropy. It has been found, though, that the deleterious effects of instabilities on beam focusing are mitigated due to the large ion mass, the finite duration of the beam pulse, the velocity gradient along the beam, and favourable choices of plasma density, beam parameters, geometry, spatial inhomogeneity, and applied field [8].

In inertial confinement fusion, the compression dynamics of the target is subject to the well-known Rayleigh-Taylor instability. A technology reducing the growth of the instability has been proposed, using oscillating wobbler fields to temporally smear the beam deposition pattern (see [9, 10] and references therein). The improvement of stability properties can be attributed to two factors; uniform illumination reduces the initial seeding amplitude of the Rayleigh-Taylor instability, and at a given location on the target, the energy/momentum input is pulsating rapidly with time resulting in a dynamic stabilization effect for the instability Recent research has begun to address whether a realistic wobbler system can be designed using technologies that are currently available.

3.5. HIF Target Designs

The novel HIF X-target has a simple cylindrical metal case filled with DT fuel and a conical insert with an “X” shaped cross-section. The fuel can be compressed and ignited at the X-vertex using multiple heavy ion beams to illuminate the target axially from only one side [9].

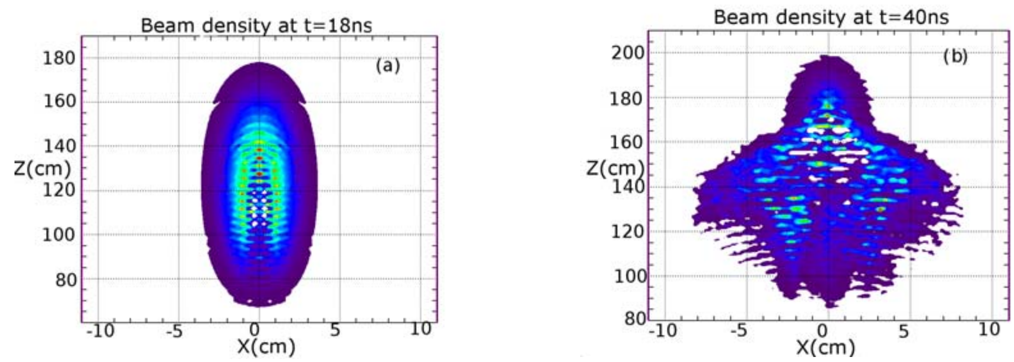


Fig. 4. Longitudinal beam density profile modulated by the two-stream instability. Color plots of the beam density are shown at (a) t = 18 ns and (b) t = 40 ns. The maximum beam density is n_b = 2.1 X 10^{10} cm^{-3}, the background plasma density is n_p = 10^{10} cm^{-3}; and the beam velocity is one-half of the speed of light. The ion beam pulse has gaussian profiles in the z- and x- directions.

For the fuel compression, radiation drive is unimportant relative to hydro pressure. Using HYDRA simulation to design the X-target, it was found that adding an aluminum pusher and radial tamping increases fusion gain from 50 to 300 and doubles the stagnation fuel density to 100 g/cm^3 at peak compression, with ρr ~2 g/cm^2 [12]. At stagnation fuel densities below 100 g/cm^3, the Al-DT interface shows negligible RT growth; any Al spikes from the pusher deceleration could not reach the ignition zone in time to affect the burning process.

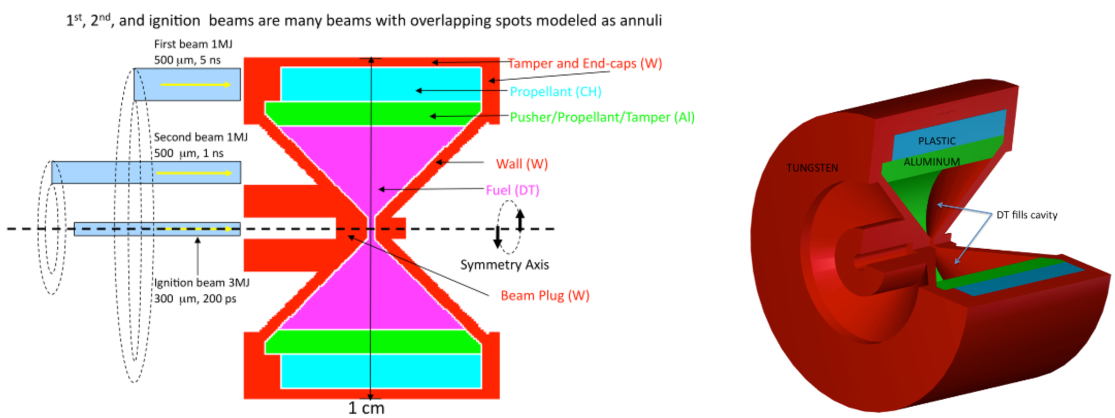


Fig. 5. The X-target 2-D diagram and 3-D rendering.

Preliminary numerical calculations using a very fine mesh to study the shear flow of the DT fuel moving along the metal X-side-walls, which drives Rayleigh–Taylor and Kelvin Helmholtz instabilities, show that metal mixing is limited to regions that stay close to the side walls, leaving a central clean DT ignition zone. Any ion species with a stopping range of 1.3 to 2 g/cm^2 (e.g., 90 GeV U or 20 GeV Rb) can be used. Estimates show that ion beams in linacs can have the required brightness to produce a 200 ps compressed beam with a spot radius <200 microns, for fast ignition at the vertex of the X. Scaled beam compression and focusing physics experiments relevant to the X-target are planned. The X-target geometry is conducive to low cost, low precision, mass manufacture (no beta-layering is needed). The X-target has a rigid case with high tolerance for offset and tilt errors, and is thus suitable for injection into a fusion chamber.

In a separate effort, we have also developed a directly driven, spherical, tamped, hot-spot ignited target that has high hydrodynamic efficiency while relaxing accelerator phase-space constraints. This target is driven by a combination of an exploding pusher followed by radiation driven ablation.

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