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## PLANS FOR WARM DENSE MATTER EXPERIMENTS AND IFE TARGET EXPERIMENTS ON NDCX-II

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*The Heavy Ion Fusion Science Virtual National Laboratory (HIFS-VNL) is currently developing design concepts for NDCX-II, the second phase of the Neutralized Drift Compression Experiment, which will use ion beams to explore Warm Dense Matter (WDM) and Inertial Fusion Energy (IFE) target hydrodynamics. The ion induction accelerator will consist of a new short pulse injector and induction cells from the decommissioned Advanced Test Accelerator (ATA) at Lawrence Livermore National Laboratory (LLNL). To fit within an existing building and to meet the energy and temporal requirements of various target experiments, an aggressive beam compression and acceleration schedule is planned. WDM physics and ion-driven direct drive hydrodynamics will initially be explored with 30 nC of lithium ions in experiments involving ion deposition, ablation, acceleration and stability of planar targets. Other ion sources which may deliver higher charge per bunch will be explored. A test stand has been built at Lawrence Berkeley National Laboratory (LBNL) to test refurbished ATA induction cells and pulsed power hardware for voltage holding and ability to produce various compression and acceleration waveforms. Another test stand is being used to develop and characterize lithium-doped aluminosilicate ion sources. The first experiments will include heating metallic targets to 10,000 K and hydrodynamics studies with cryogenic hydrogen targets.*

### I. NDCX-II Design Status

The first phase of the Neutralized Drift Compression Experiment (NDCX-I) has successfully demonstrated simultaneous radial and longitudinal compression using the technique of imparting a velocity ramp on the ion beam, letting the beam drift through a neutralizing plasma to offset space-charge forces, and applying a high solenoidal field before the target.<sup>1,2</sup> To provide sufficient energy deposition over a time period less than the hydrodynamic expansion time, neutralized drift compression has been developed to produce ~1 ns, ~1 mm diameter beams from longer beams with modest energy. Experiments involving heating metal foils have begun.

To get uniform and efficient energy deposition for WDM target experiments, Bragg peak heating at the

center of planar targets will be employed in NDCX-II.<sup>3</sup> To achieve much higher target temperatures than NDCX-I for both WDM and IFE target experiments, higher ion energies and currents will also be required for NDCX-II. Figure 1 shows the main components of NDCX-II. A singly charged lithium beam has been chosen based on its modest Bragg peak energy of 3 MeV and existing expertise in fabricating alkali metal doped aluminosilicate ion sources. To get the total required charge of 30 nC from realistic Li<sup>+</sup> ion sources and assuming reasonable current density, the pulse at the injector is 450 ns. The ATA pulsed power system to drive the induction cells was built for a 70 ns electron beam. To make the most efficient use of the available hardware, the NDCX-II design implements an aggressive compression schedule so that the beam is compressed to 70 ns or less as soon as possible.<sup>4,5</sup> The volt-seconds of the induction cells can then be used at the maximum acceleration gradient. In addition to the acceleration to 3.5 MeV, there is also an imparted velocity tilt in preparation for the neutralized drift compression region. The maximum repetition rate is limited by the cost of charging power supplies and the pulsed transport solenoid cooling. The goal is to be capable of 0.5-1 Hz operation.

A 50 kV ion source test stand (STS-50) at LBNL is being used to develop the capability to produce and characterize the Li<sup>+</sup> aluminosilicate ion sources. The preliminary injector design requires a 3.6 cm diameter ion source which can produce a current density of 6.5 mA/cm<sup>2</sup>. A first run of smaller Li<sup>+</sup> sources have been fabricated both at LBNL and HeatWave Labs, and these are presently being characterized.

A test stand has also been built to evaluate the refurbished and modified ATA pulsed power and induction cell hardware. The refurbishment activities include disassembling the hardware, cleaning the parts, replacing seals and insulators, and reassembling. The modifications include replacing the 3 kG DC solenoid in the induction cell with a 3 T pulsed solenoid. There is a concern that the high pulsed field from the magnet may saturate some of the ferrite and reduce the available volt-seconds. The test stand will quantify the interaction between the high field pulsed solenoid and the ferrite cores, verify voltage waveform tuning flexibility, and characterize voltage holding and timing jitter.

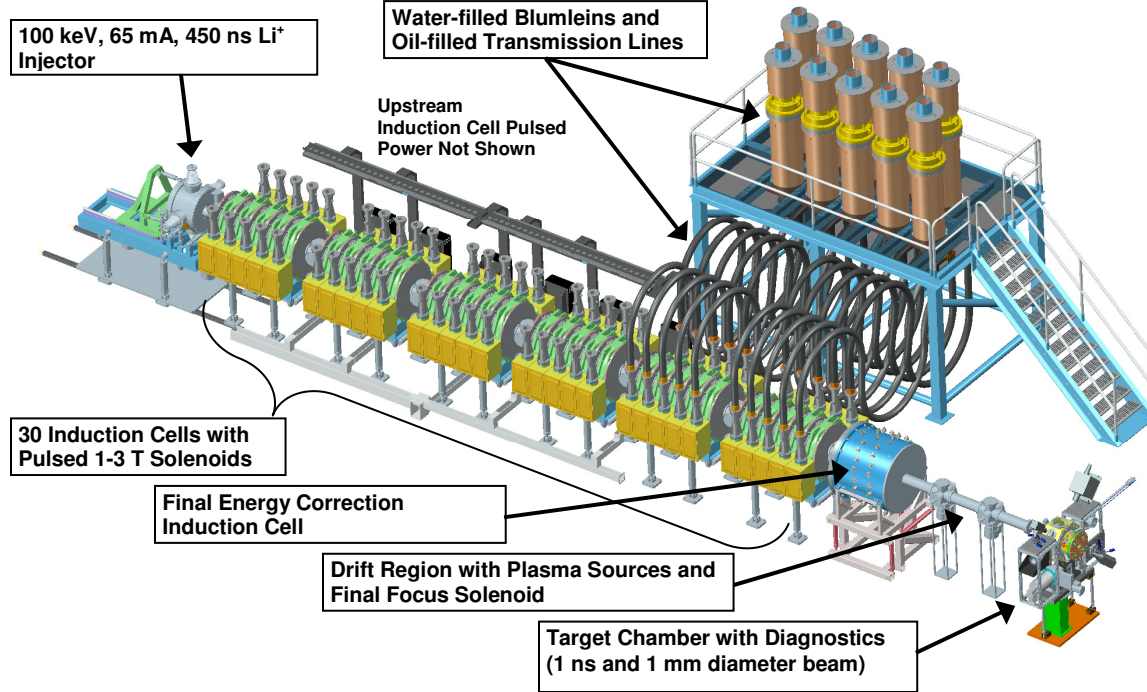


Fig. 1. Major components of a 3.5 MeV  $\text{Li}^+$  NDCX-II. The total length is  $\sim 15$  m.

## II. PLANNED EXPERIMENTS

### II.A. NDCX-I and NDCX-II Warm Dense Matter Experiments

At present, experimental tests on NDCX-I include commissioning diagnostics, optimizing beam and target alignment methods, exploring techniques to increase the deposited energy density on target, and heating metal foil targets.<sup>6</sup> A gold cone has been used as a grazing incidence mirror to increase beam energy density on target by reflecting the particles from the outer edge of the beam to the target and by providing secondary electrons for beam space-charge neutralization. Exploring liquid-gas phase transitions in foils is planned by using beam preheat to reach the boiling point and then using the compressed beam to heat rapidly. Au, Al, Pt, W, and Si foils of 100-400 nm thickness are the initial targets which are comparable to the range of the 350 keV  $\text{K}^+$  beam of NDCX-I.

Because NDCX-II will be able to provide up to 100x greater beam energy (see Table 1), a wider range of WDM equation of state experiments will be possible.<sup>6,7</sup> These experiments will concentrate on studying two-phase dynamics in metals, and identifying critical points and the liquid-vapor transition at temperatures near the critical point. Studies of the properties of high electron affinity targets and the behavior of porous targets are also planned.

Table I. NDCX-I and NDCX-II Parameters

	Ion	Final Ion Energy (MeV)	Beam Energy (J)	Target Pulse Width (ns)	Range in solid Al (microns)	Energy Density ( $10^{11} \text{J/m}^3$ )
NDCX-I	$\text{K}^+$	0.35	0.001-0.002	2-3	0.3	0.04-0.08
NDCX-II	$\text{Li}^+$	3.5	0.1	1-2	4	0.3

### II.B. IFE Target Coupling Experiments

In the 2002 Robust Point Design and the later Modular Point Design effort, the assumed targets are indirect drive with close-coupled hohlraums in which multiple shocks are used to compress the fuel.<sup>8,9</sup> The coupling efficiency (shell kinetic energy / incident beam energy on hohlraum) is  $\sim 4\%$ . Recent radiation-hydrodynamic calculations using direct drive targets have shown that by ramping up the ion kinetic energy, which increases the ion range to follow the ablation front of the implosion, the coupling efficiency can be increased to 16-18%.<sup>10</sup> Higher efficiencies are predicted from analytic calculations with optimization of the target ablator properties and the tailoring the beam energy profile. This effect will be explored using a single pulse with a ramped ion energy profile, or using two pulses with the second pulse having a higher energy (longer ion range), and cryogenic hydrogen planar targets.

### III. DIAGNOSTICS

A new target chamber and diagnostic suite are now operational on NDCX-I at LBNL and will serve as the development platform for NDCX-II diagnostics.<sup>11</sup> These diagnostics include commercially available systems such as an all-fiber doppler-shift interferometer (VISAR) and a streak spectrometer which can record a continuous spectrum from 500 nm to 800 nm with a temporal resolution down to 5 ps. A fast pyrometer has been developed for sub ns resolution and high sensitivity (>2000 K blackbody). At present, the pyrometer has 750 nm, 1000 nm, and 1500 nm channels and can be upgraded to have a total of seven channels. For each channel, there is a photoreceiver and amplifier with DC to 4 GHz bandwidth. The DC response is important so that an absolute calibration can be performed with a tungsten ribbon lamp which is traceable to the National Institute of Standards and Technology.

### IV. BUDGET AND SCHEDULE

The estimated cost of constructing NDCX-II is 6.1 M\$, which includes 30% contingency and does not include labor costs for existing engineering and technical staff. Re-using existing ATA hardware results in cost savings of ~10 M\$. The fabrication and installation schedule is estimated to span 2.5 years (see Fig. 2). The physics and engineering design will continue under the base program until the incremental funding needed for this project has been allocated. An advanced injector may be developed in FY2009 with base program resources. This project is a pre-requisite for the Integrated Beam-High Energy Density Physics Experiment (IB-HEDPX), for which DOE has approved Critical Decision Zero (CD-0). IB-HEDPX would be a user facility for heavy ion driven high energy density physics and IFE target physics.

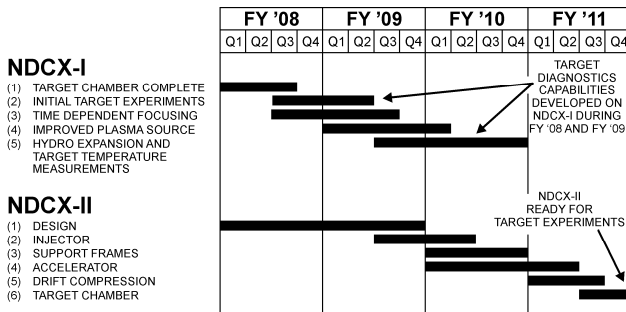


Fig. 2. A possible NDCX-1 and NDCX-II schedule if incremental funding is allocated in FY2010.

### V. CONCLUSIONS

Ion beams can be used effectively to heat targets for Warm Dense Matter and IFE target experiments. By placing the Bragg peak at the center of a target, the beam can be used for uniform and efficient target heating. A new accelerator which can provide higher energy beams for Warm Dense Matter experiments is needed to capitalize on the hardware and technology developed for NDCX-I. The preliminary NDCX-II design can accelerate 30 nC of Li<sup>+</sup> to 3.5 MeV and provide a 1 ns, 1 mm diameter beam for various Warm Dense Matter and IFE target experiments. The hardware and technology for NDCX-II is based on years of ATA and NDCX-I experience, and a test stand has just become operational to test refurbished ATA cells and pulsed power hardware. The design will continue to develop until incremental funding defines a project start.

### ACKNOWLEDGMENTS

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