NDCX-II, A NEW INDUCTION LINEAR ACCELERATOR FOR WARM DENSE MATTER RESEARCH*

M. Leitner#, F. Bieniosek, J. Kwan, G. Logan, W. Waldron, LBNL, Berkeley, CA 94720, U.S.A.
J.J. Barnard, A. Friedman, B. Sharp, LLNL, Livermore, CA 94550, U.S.A.
E. Gilson, R. Davidson, PPPL, Princeton, NJ 08543, U.S.A.

Abstract

The Heavy Ion Fusion Science Virtual National Laboratory (HIFS-VNL), a collaboration between Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), and Princeton Plasma Physics Laboratory (PPPL), is currently constructing a new induction linear accelerator, called Neutralized Drift Compression eXperiment NDCX-II. The accelerator design makes effective use of existing components from LLNL's decommissioned Advanced Test Accelerator (ATA), especially induction cells and Blumlein voltage sources that have been transferred to LBNL. We have developed an aggressive acceleration "schedule" that compresses the emitted ion pulse from 500 ns to 1 ns in just 15 meters. In the nominal design concept, 30 nC of Li^+ are accelerated to 3.5 MeV and allowed to drift-compress to a peak current of about 30 A. That beam will be utilized for warm dense matter experiments investigating the interaction of ion beams with matter at high temperature and pressure. Construction of the accelerator will be complete within a period of approximately two and a half years and will provide a worldwide unique opportunity for ion-driven warm dense matter experiments as well as research related to novel beam manipulations for heavy ion fusion drivers.

INTRODUCTION

Warm Dense Matter (WDM) Research

A US National Task Force [1] has identified exploration of fundamental properties of "warm dense matter" (WDM) as a major, future research area. Warm dense matter consists of extreme states of matter that are neither in a "cold, condensed-matter" state, nor in a "hot, plasma" state, but rather somewhere intermediate. Warm dense matter is typically a strongly-coupled, many-body charged particle system with energy density exceeding 10^{10} J/m^3, conditions that are extremely difficult to study analytically and by numerical simulation. However, many astrophysical systems as well as common laboratory experimental conditions, where plasma is created quickly from a solid, fall into this regime. Because of the short timescales involved, attempts to isolate warm dense matter for study have proven to be a major challenge.

The U.S. Heavy Ion Fusion Science Virtual National Laboratory (HIFS-VNL) is currently developing an ion-accelerator based driver system, including fast diagnostics, to experimentally probe WDM equations of state. In simplest terms, an equation of state attempts to describe the relationship between temperature, pressure, density, and internal energy for a given substance or mixture of substances. The HIFS-VNL plans experiments with targets in the density range between 10^{21} to 10^{23} ions/cm^3 (solid aluminum density: $6 \cdot 10^{22}$ atoms/cm^3) around a temperatures of 1 eV (11,000 K).

Heavy Ion-Driven WDM Research

Heavy ion beams have a number of advantages as drivers for warm dense matter experiments. 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 rate of energy loss in the target, dE/dx, is dependent on the energy of the incoming projectile and displays a pronounced peak, which occurs at higher energies for higher (atomic number) Z projectiles.

These properties make heavy ions an excellent candidate for warm dense matter physics studies, where thin (μm) target plasmas could be uniformly heated by locating the energy deposition peak ("Bragg peak") near the target center (see reference [2] for a more detailed description). To achieve the most uniform target heating volume (in contrast to non-uniform heating with laser or X-ray heating) the main strategy is to pick a target thickness and beam energy such that the ion beam enters the target slightly above (~1.5 E_{peak}) the energy of maximum dE/dx, deposits most of its energy inside the thin target foil, and exits the target slightly below the dE/dx peak at ~0.5 E_{peak}. From an accelerator standpoint, the most cost-effective way of heating targets at the Bragg peak is to use lighter ion projectiles (e.g. Li^+) on low-mass target foils (e.g. aluminum) where the maximum dE/dx occurs at rather low energies. For NDCX-II, a combination of a Li^+ ion beam and an Aluminum target foil, the Bragg peak is located at 1.8 MeV, and the ion range is ~ 5 μm.

In summary, the advantages of such a low-range ion heating approach ("Bragg heating") are:

- The target is heated isochorically (uniformly).
- By placing the center of the target foil at the Bragg peak the heating uniformity is maximized and the accelerator beam energy is used most efficiently.
- Bragg heating requires low energy (~MeV) and thus much smaller accelerators.

* This work was supported by the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.
#MLeitner@lbl.gov

However, this approach introduces also quite unique accelerator design challenges in different areas:

- Because of the low ion range, very thin targets are required (~3-5 µm aluminium foil for NDCX-II).
- In order to reach sufficient energy densities, the target has to be heated fast enough compared to the hydro-expansion time of the target which is in the nanosecond range for micron thick foils. This requires accelerator technology, where >30 A of beam current has to be compressed to approx. 1 ns (~1 cm at approx. 3 MeV) long and 1 mm diameter beam bunches.
- To reach 1 eV target temperature, sufficient beam power (fluence ~30 J/cm^2) is required. Because of the low-energy Bragg peak (1.5 MeV), significant beam charge (~30 nC) has to be delivered on target. This is not possible without the HIFS-VNL invention of neutralized drift compression [3], where an ion beam is focused longitudinally within a space-charge neutralizing plasma channel and ultimately compressed radially by an 8 T final focus solenoid within a high-density neutralizing plasma environment.

NDCX-I

Over the last few years the first phase of the Neutralized Drift Compression Experiment (NDCX-I, [3]), currently operating at LBNL, 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 volumetric neutralizing plasma to offset space-charge forces, and applying a high solenoidal field before the target. To provide sufficient energy deposition over a time period less than the hydrodynamic expansion time, the neutralized drift compression technique has been developed to produce ~1 ns, ~1 mm diameter beams from longer (µsec) beams with modest (~300 keV) energy. Experiments involving heating metal foils have begun on NDCX-I. The goal of the first phase of the experiment was to demonstrate the concept of using simultaneous neutralized drift compression in transverse and longitudinal direction. However, the goal of the second phase (NDCX-II) of the experiment is now to get uniform and efficient energy deposition for interesting WDM target experiments. For this purpose, Bragg peak heating will be employed at the center of planar targets in NDCX-II. To achieve the required higher target temperatures, higher ion energies and currents compared to the current NDCX-I will be necessary.

BASELINE DESIGN OF NDCX-II

Fig. 1 shows schematically the main components of NDCX-II [4], and table 1 summarizes the main parameters of this new accelerator facility. A short-pulse injector (100 mA, ~500 ns pulse width) provides approx. 30 nC of Li+ ions. The ion beam has to be accelerated to approximately 3.5 MeV by using an induction linear accelerator. In simplest terms, an induction cell is similar to a 1:1 transformer with ferrite material (to minimize losses because of the short pulse lengths involved) as transformer core. In the case of NDCX-II, a 200 kV

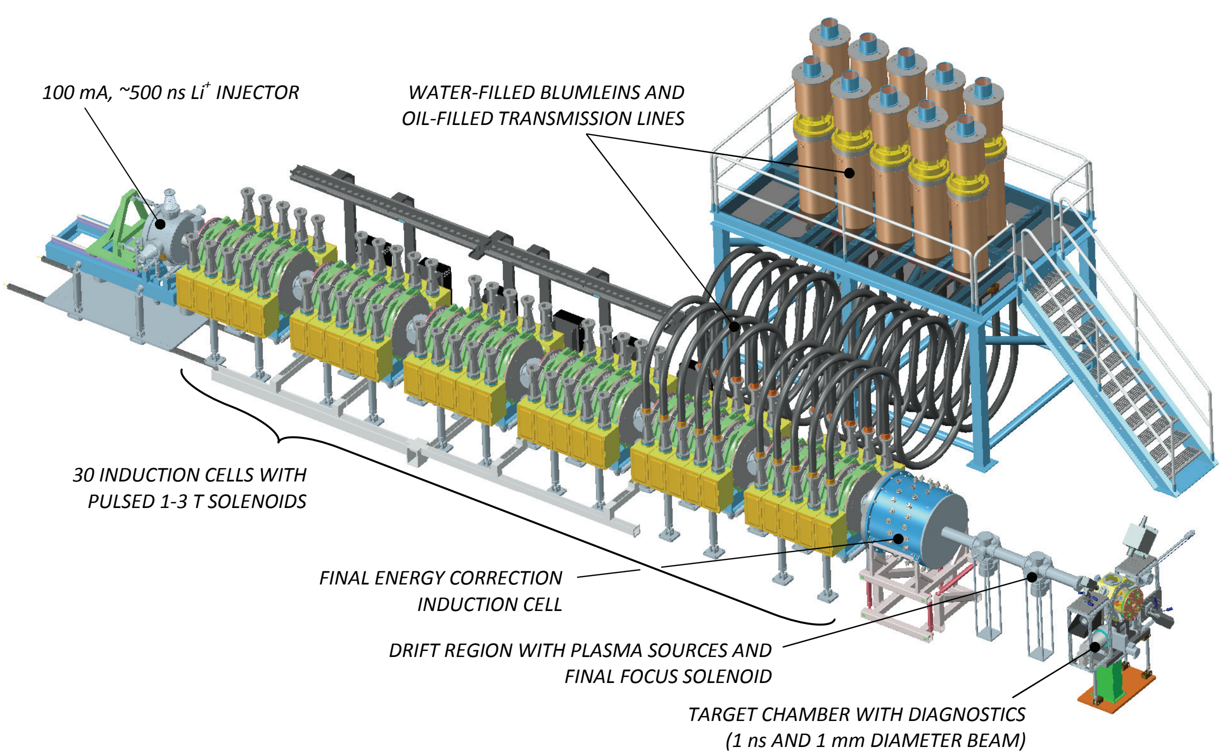

Figure 1: Schematic layout of the new NDCX-II facility. The accelerator is approx. 15 m long.

primary high voltage pulse is timed with the accelerating ion beam to develop the same high voltage across an insulating gap inside the accelerator beam pipe. Because of the short pulse length of the NDCX-II induction cell (70 ns), thousands of Amperes flow through the primary circuit of the induction core to develop the voltage. This requires substantial pulsed-power engineering, a specialty field in accelerator technology. Because of the high current flow, on the other hand, the induction cell is fairly insensitive to any beam loading, allowing to accelerate kilo-Amperes of beam. This is the primary advantage of induction accelerators compared to RF linacs. As with all linear accelerators the outside of the induction accelerator structure stays at ground potential.

Table 1: NDCX-I and NDCX-II Parameters

	Ion	Ion Energy [MeV]	Focal Diameter [mm]	Pulse Length [ns]	Peak Current [A]
NDCX-I	K^+	0.35	~2	2-4	~2
NDCX-II	Li^+	3.5	1	1	~30

As described in more detail further below, NDCX-II will rapidly compress the ion beam in longitudinal direction resulting in the transport of a high line-charge density ion beam at low energy. Magnetic solenoids have been chosen for the accelerator transverse focusing since they are efficient in transporting high beam currents at low energy. For NDCX-II, each accelerator cell requires a < 2 T pulsed solenoid for beam focusing.

A singly charged lithium beam has been chosen based on its modest Bragg peak energy of 1.8 MeV and existing expertise in fabricating alkali metal doped alumino-silicate ion sources. To get the total required charge of 30 nC from realistic Li^+ ion sources and assuming a reasonable current density, the pulse at the injector is approx 500 ns. However, the original ATA pulsed power system to drive the induction cells was built for a 70 ns cell pulse. To make the most efficient use of the available hardware, the NDCX-II design implements an aggressive compression schedule to match the beam to this time structure of 70 ns or less as soon as possible [5]. The volt-seconds of the induction cells can then be used at the maximum acceleration gradient. The maximum repetition rate is limited by the charging power supplies and the pulsed transport solenoid cooling. The goal is to be capable of running at 0.2-1 Hz. In addition to the acceleration to 3.5 MeV, there is also an imparted velocity tilt in preparation for the longitudinal compression in the neutralized drift region.

A 50 kV ion source test stand (STS-50) at LBNL is being used to develop the capability of producing and/or characterizing the Li^+ alumino-silicate ion sources. The preliminary injector design requires a 4-5 cm diameter ion source which can produce 1-2 mA/cm^2 current density.

In addition, a dedicated test stand has been built to evaluate the refurbished and modified ATA pulsed power

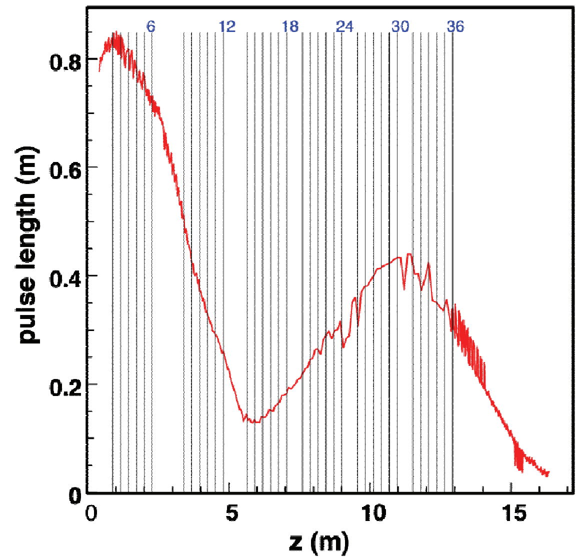

Figure 2: Beam pulse length evolution along the NDCX-II beamline. The unique, rapid beam compression in the first part of the accelerator, followed by a re-bounce and the final compression through the neutralizing section can be seen clearly. See text for a more detailed description.

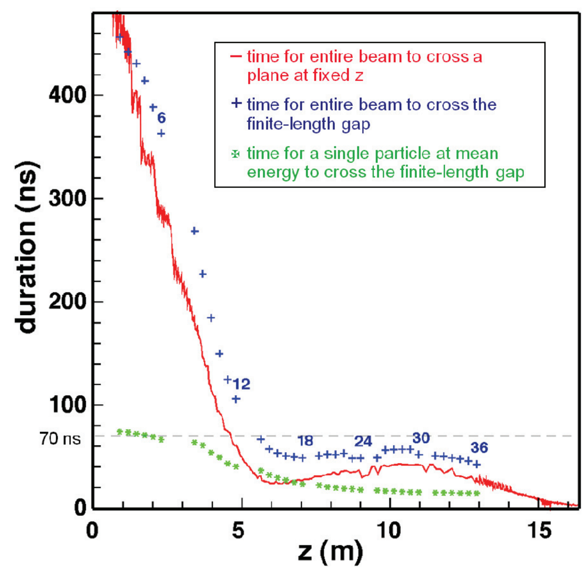

Figure 3: Beam pulse duration along the NDCX-II beamline. In the first part of NDCX-II the beam is compressed to fit within 70 ns, which corresponds to the pulse length of the main ATA acceleration cells. The beam is ultimately compressed to 1 ns on target.

and induction cell hardware. The refurbishing activities include disassembling the hardware, cleaning the parts, replacing seals and insulators, and reassembling. Since the ATA cells were originally used for the acceleration of an electron beam, the magnetic field strength of the focusing elements in the cells need to be upgraded from 3 kG DC solenoids to 2 T pulsed solenoids. This high pulsed magnetic field is a concern for the project as it may saturate some of the induction cell ferrites and reduce the available volt-seconds. An important task to be completed using the test stand will be to quantify the

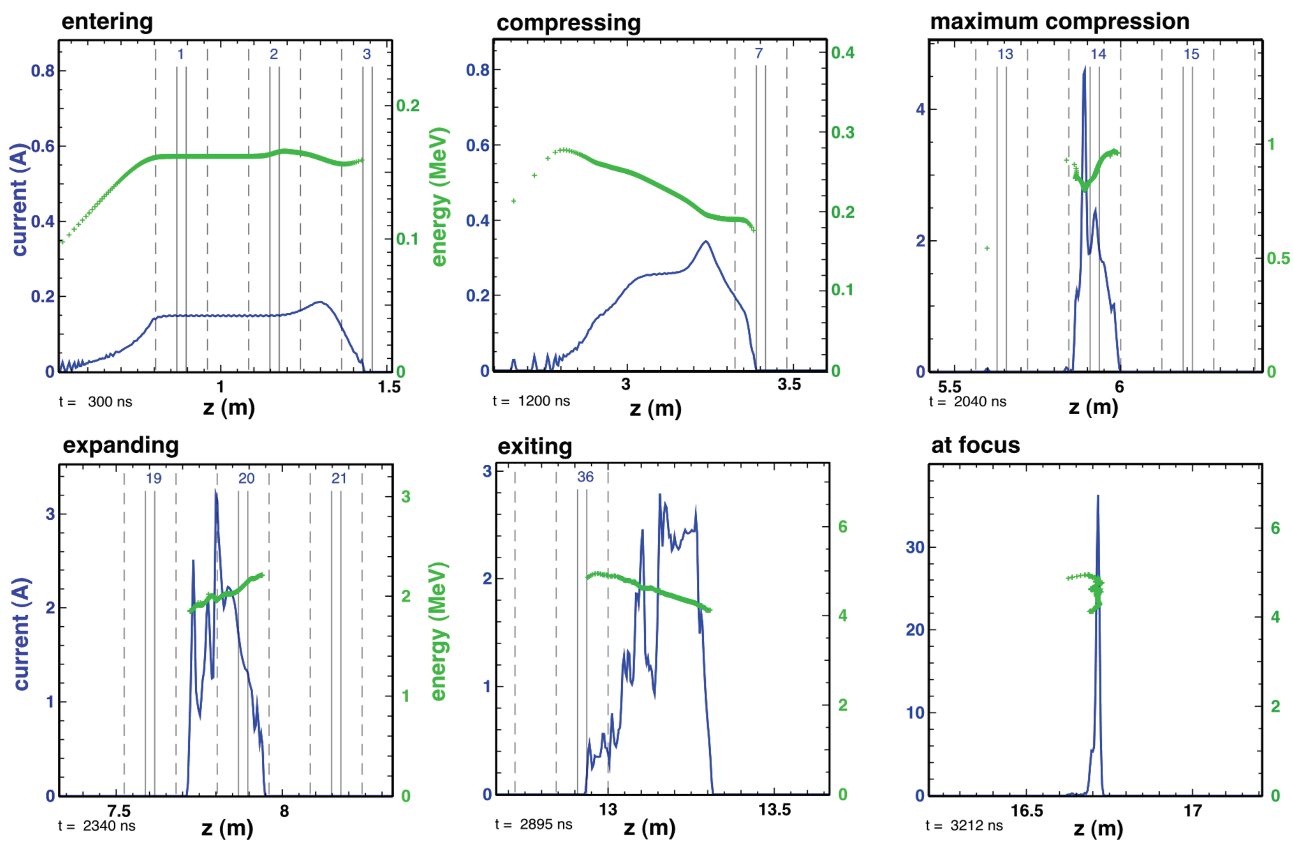

Figure 4: Evolution of the beam phase space and line-charge-density profile along NDCX-II. The second and third panels on the top illustrate the initial beam compression with subsequent beam expansion in the accelerator (panel 1 on bottom). At the exit of the accelerator (panel 2 on the bottom) the beam exhibits a superimposed velocity tilt which compresses the beam to the final pulse length on target of 1 ns with greater than 30 A peak current.

interaction between the high field pulsed solenoid and the ferrite cores, to verify voltage waveform tuning flexibility, and to characterize voltage holding and timing jitter.

In parallel, ongoing experimental tests on the existing NDCX-I include commissioning fast diagnostics, optimizing beam and target alignment methods, exploring techniques to increase the deposited energy density on target, and heating metal foil targets. Because NDCX-II will be able to provide up to 100 times greater energy deposition on target, a wider range of WDM equation of state experiments will be possible [6]. 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.

ELEMENTS OF THE NDCX-II DESIGN

The arrangement of induction cells and applied accelerating waveforms for NDCX-II is novel, but the system is based on well-established technologies. It takes full advantage of available ATA induction cells and Blumlein high voltage pulsers. The system is compact, and relies heavily on passive circuit elements to provide the requisite waveform shaping. The adaptation from ATA, which accelerated electrons is challenging, because of the need to aggressively compress the ion pulse from its initial ~500 ns duration to ~1 ns, as required for the WDM 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 developed an acceleration schedule employing thirty ATA cells (twenty driven by the ATA Blumleins, plus ten driven with special designed lower-voltage pulsed sources). 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. This system accelerates a Li^+ beam (100 keV as injected, with a 67 mA flat-top) to 3.5 MeV at ~2 A, and imparts an 8% tilt. The beam then drifts for approximately 2 m through a neutralizing plasma channel ("neutralized drift compression") until the 30 nC of beam are longitudinally compressed to less than 1 ns. The current of the compressed beam (averaged over that 1 ns window) is ~23 A, with a peak (averaged over a 0.1 ns window) of ~32 A, and a full-width at half maximum of ~1 ns.

A novel two-part strategy is employed to accelerate and compress the beam. In (roughly) the first half of the lattice, the pulse is rapidly compressed via "non-neutral drift compression." The beam transit time through an acceleration gap (including its 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 velocity tilt, with space between tilt cells for drift compression and longitudinal control. 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 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 at the waist is shorter 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 suffice. The modularity of these blocks is an attractive feature, since more can be added if a higher final kinetic energy is desired. A final block with five ramped pulses applies the tilt for neutralized drift compression onto the target; this is another attractive feature, since no high-voltage "tilt core" is required. Fig. 2 shows the evolution of the beam length, while Fig. 3 shows the evolution of the pulse duration. Fig. 4 shows the evolution of the beam phase space and line-charge-density profile; its final panel shows the beam when its centroid is at the "best longitudinal focus" plane.

BUDGET AND SCHEDULE

The construction of the accelerator is expected to be completed by October 2011. The estimated cost of constructing NDCX-II is 11 M$. Re-using existing ATA hardware results in cost savings of approximately 10 M$. 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 larger-scale user facility for heavy ion driven high energy density physics and IFE target physics in the future.

REFERENCES

[1] National Task Force on High Energy Density Physics, "Frontiers for Discovery in High Energy Density Physics (Frontiers for Discovery in HEDP)", Office of Science and Technology Policy, Washington DC, 2004.

[2] L.R. Grisham, Phys. of Plasmas 11(2004), 5727

[3] P.K. Roy, et al, Phys. Rev. Lett. 95 (2005), 234801

[4] W.L. Waldron, et al., Proc. of the 18th Topical Meeting on the Technology of Fusion Energy, San Francisco, CA, Sept 28 to Oct 2, 2008, to be published in Fusion Science and Technology

[5] A. Friedman, et al., Nucl. Instr. And Meth. A (2009), in print, http://dx.doi.org/10.1016/j.nima.2009.03.189

[6] J.J. Barnard, et al., Nucl. Instr. And Meth. A (2009), in print, http://dx.doi.org/10.1016/j.nima.2009.03.221