Heavy Ion Fusion Science Virtual National Laboratory
Year-end Progress Report for FY 2008

Simulations and Design Accomplishments for NDCX-I and NDCX-II

(This report describes work in fulfillment of the integrated LBNL and LLNL set of milestones and goals, carried out in collaboration with PPPL. A separate year-end report being submitted by PPPL describing research at that Laboratory on ion-beam-driven High Energy Density Physics and Heavy Ion Fusion Science)

1. We have developed a plasma modeling capability in the Warp code for NDCX experiments, and used both Warp and LSP to support our experimental studies.

The HIFS-VNL has developed and implemented a plasma modeling capability in our ion-beam simulation code, Warp. This enables us to use the code to simulate both the process of plasma injection into the beam line and the dynamics of the ion beam as it is focused and compressed in the presence of that plasma. The HIFS-VNL now has a state-of-the-art source-to-target simulation capability that will enable more effective support of ongoing experiments in the NDCX series and allow more confident planning for future ones. This is especially attractive because Warp is also used for most of our studies of the accelerating beam, and so end-to-end integrated simulations have been facilitated.

Both explicit and implicit electrostatic models, and an explicit electromagnetic model, are available. We carried out tests validating the behavior of the models employed; compared the results of electrostatic and electromagnetic models when applied to beam expansion in an NDCX-I relevant regime; compared Warp and LSP results on a problem relevant to NDCX-I; modeled wave excitation by a rigid beam propagating through plasma; and implemented and began testing a more advanced implicit method that correctly captures electron drift motion even when time-steps too large to resolve the electron gyro-period are employed [Cohen08].

The FY08 Q1 milestone was: “Report initial work on developing plasma modeling capability in Warp for NDCX experiments.” A detailed report [Friedman08a] was submitted describing the work that was carried in fulfillment of this milestone. Figure A (from that report) shows “snapshots” from a Warp simulation of neutralized drift compression and focusing; the results agreed well with those obtained using the LSP code.

Considerable additional progress in this area was made in the latter three quarters of FY 2008. Extensive simulations were carried out using both Warp and LSP [Welch08], and a concentrated effort on comparing the results of both codes with the latest experimental measurements is underway. Figure B shows two snapshots from a 3-D Warp simulation of plasma injection in NDCX.

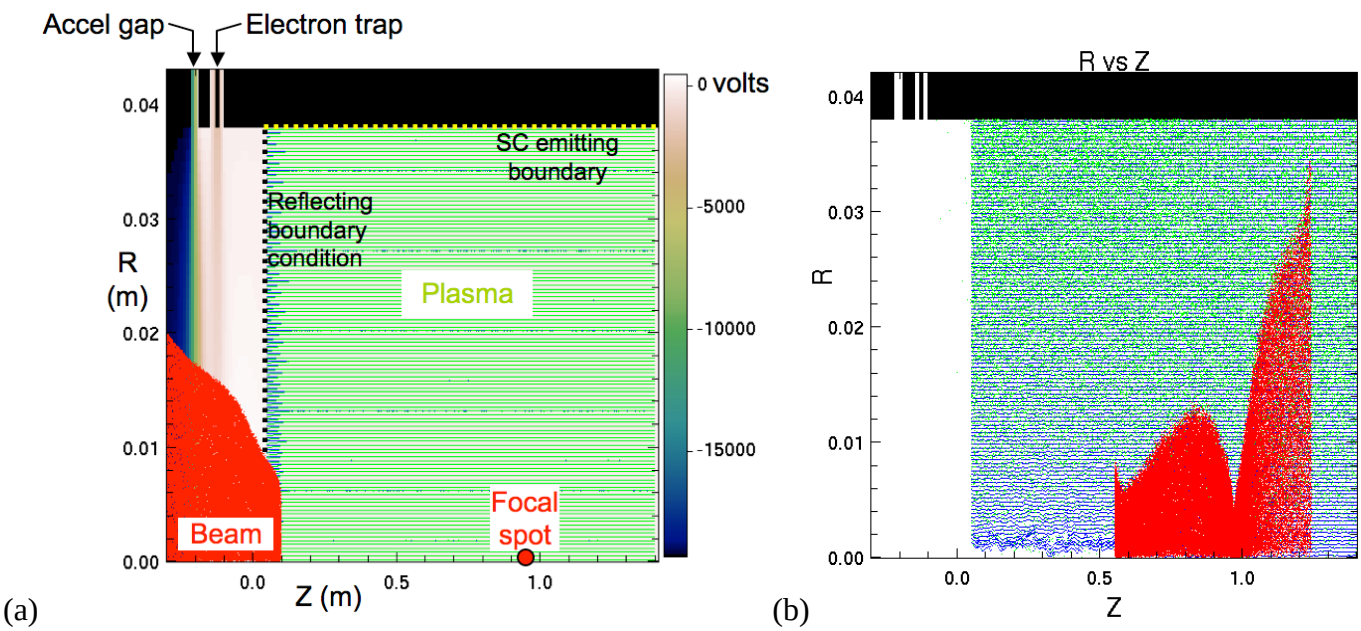


Figure A. Snapshots of the beam and plasma (a) as the beam enters the plasma and (b) just past the time of peak compression and focus. The red dots are the beam, the green dots plasma electrons, and the blue dots plasma carbon ions. In (a) the background colors show the value of the electrostatic potential. Note the large negative value at the left edge – it is from the negative swing of the tilt waveform. In (b), most of the current is in the small region near z = 1 meter.

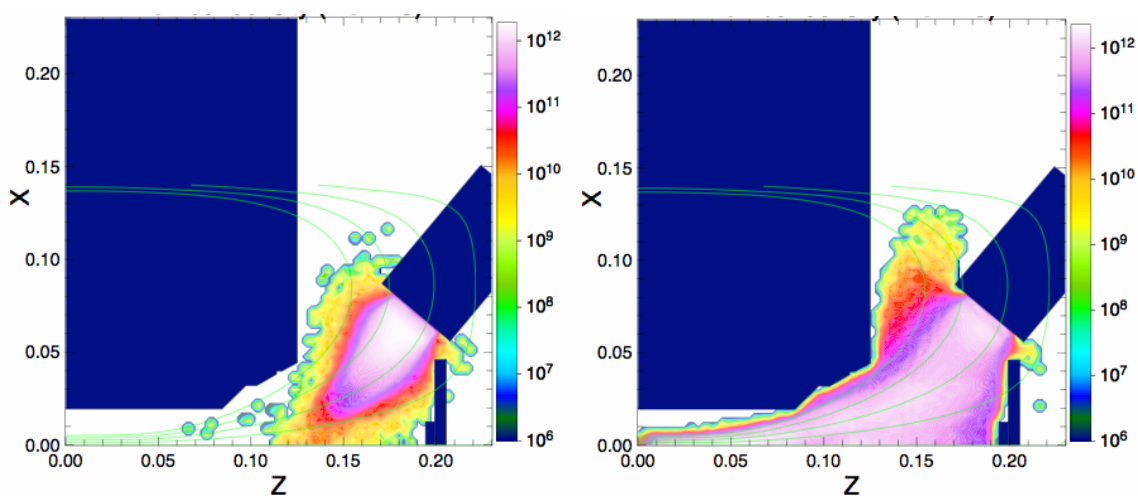


Figure B. "Snapshots" from a 3-D Warp simulation of plasma injection into NDCX at times (a) 1.2 μs and (b) 4.5 μs. This is an elevation view of the top half of the system; the beam will enter from the left once the plasma is fully formed, and the target plane is at z = 0.2 m. The large blue structure at upper left in each panel is the final-focus solenoid, and field lines are shown in light green. The continuous-tone colors indicate the electron number density in units of cm^{-3}, as indicated by the scale on the right.

References to FY08 publications in this area:

[Friedman08a] A. Friedman, R. H. Cohen, D. P. Grote, J-L. Vay, *et al.*, "HIFS-VNL Milestone Report to Office of Fusion Energy Sciences for First Quarter of FY 2008," December 13, 2007. Available on the Web at: http://hifweb.lbl.gov/public/Friedman/FY08Q1Milestone_rpt_HIFSVNL.pdf .

[Cohen08] R. H. Cohen, A. Friedman, D. P. Grote, and J.-L. Vay, "An implicit 'Drift-Lorentz' particle mover for plasma and beam simulations," *Proc. 17th International Symposium on Heavy Ion Inertial Fusion (HIF2008)*, Tokyo, August 2008; accepted for publication in Nuclear Instruments and Methods in Physics Research A. Available on the Web at: http://hifweb.lbl.gov/public/HIF2008/cohen.hif08.ms.v1.pdf .

[Welch08] D. R. Welch, J. E. Coleman, P. A. Seidl, P. K. Roy, E. Henestroza, E. P. Lee, A. B. Sefkow, E. P. Gilson, T. C. Genoni, and D. V. Rose, "Source-to-target simulation of simultaneous longitudinal and transverse focusing of heavy ion beams," *Phys. Rev. Special Topics Accel. Beams* **11**, 064701 (2008).

2. We have developed an attractive concept for an improved platform, NDCX-II, which re-uses components from the ATA accelerator at LLNL.

We have developed the basis for an attractive physics design for NDCX-II. Our goal is a compact and inexpensive machine capable of meeting the needs of the ion-driven Warm Dense Matter research program and of a rich set of target experiments that will explore fundamental aspects of ion direct drive.

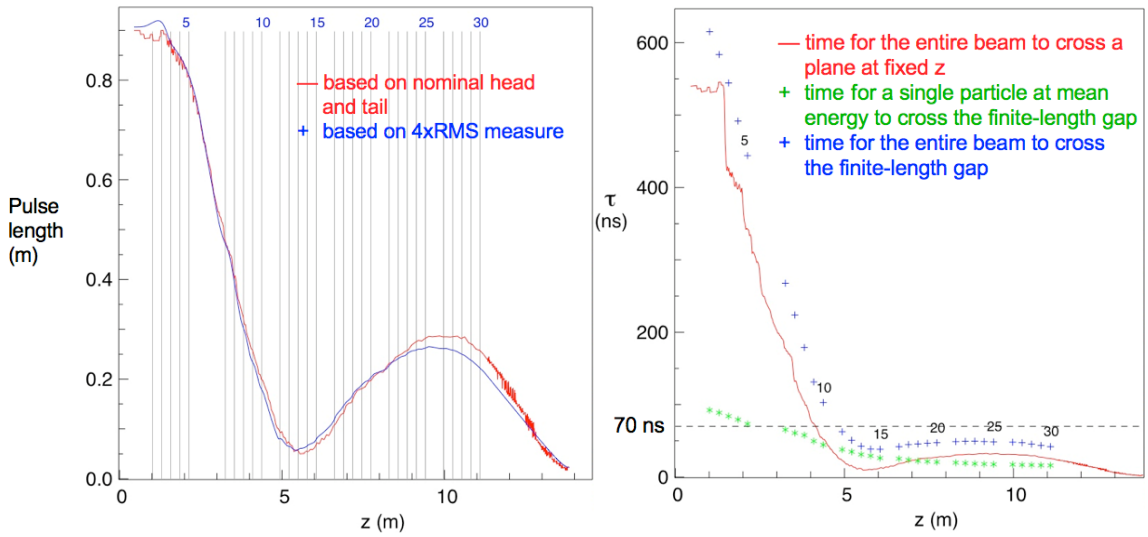
The approach gains great advantage by re-using, as its principal components, available ferromagnetic cells and Blumleins from the decommissioned Advanced Test Accelerator. The conversion from an electron accelerator to an ion accelerator is nontrivial, in large part because of the need to aggressively compress the pulse from its initial ~ 500 ns duration to ~ 1 ns as required for Warm Dense Matter physics studies.

The main features of the emerging design are (a) an "accel-decel" injector to produce a 540-ns beam of 100-keV Li^+ ions, (b) a compression section that imposes a head-to-tail velocity gradient ("tilt") which causes the beam to compress longitudinally as it drifts, (c) an acceleration section that interleaves flat-topped waveforms that increase the beam energy and triangular pulses that maintain the velocity tilt, and (d) a neutralized drift section in which the beam compresses toward its minimum duration at the target plane as it is compressed radially by a strong solenoid.

The longitudinal dynamics of such a short (15 m) machine represent the greatest physics design challenge. In our approach, we shorten the beam first (before the main acceleration) via "non-neutral drift compression." We desire to reach a sub-70 ns transit time through the accelerating gaps (with fringe field) as soon as possible, so that we can then use 200-kV pulses from the ATA Blumleins (which can't supply a longer pulse). Rapid inward motion (in the beam frame) is required to get the pulse duration below 70

ns. Space charge ultimately inhibits this compression, and the beam necessarily "bounces," that is, starts to lengthen. By design, the longer beam still takes less than 70 ns to cross an extended gap because it is moving faster. We allow it to lengthen while applying acceleration and longitudinal confinement pulses. Then, a final set of cells with ramped pulses applies the "exit tilt" needed for the final neutralized drift compression to the target.

In an example acceleration schedule, 30 ATA cells (20 of them driven by the ATA Blumleins, 10 by lower-voltage sources) accelerate a Lithium beam to 3.5 MeV and impart an 8% tilt. Of the beam's total 30 nC of charge, 22.7 nC (76%) intersect the focal plane in a 1-ns window, with minimal pre-pulse. Figure C shows the history of the beam length and the pulse duration in such a scenario.



(a) (b)

Figure C. (a) Pulse length in meters vs. 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.

Because the design space of NDCX-II is large, the "acceleration schedule" and pulser waveforms were developed using a fast-running 1-D particle-in-cell code. The waveforms employed are simple and can be synthesized using passive circuits attached to the acceleration cells. This 1-D code was validated by comparing the results with output from the Warp particle-in-cell code, run with the same lattice and acceleration fields. So long as the Warp beam was initialized with an axisymmetric distribution having the same radius, emittance, average velocity, and line-charge density as assumed in the 1-D code and transported with appropriate transverse focusing to maintain a nearly constant radius, results from the two codes agreed well. Details are given in [Friedman08b] and [Sharp08]. An important finding of these Warp simulations is that the transverse emittance shows little secular growth during acceleration and compression, despite the severe changes in the longitudinal phase space.

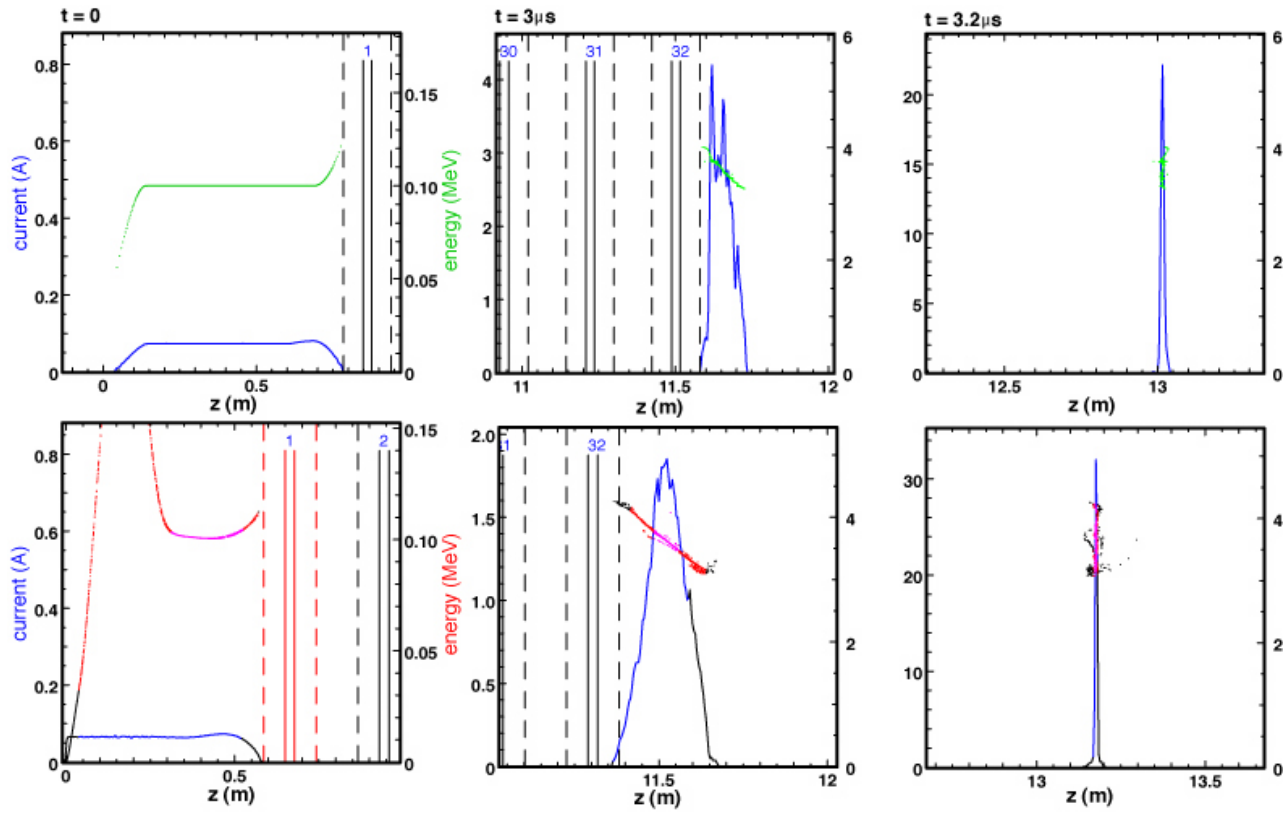


Figure D. Longitudinal phase space and line-charge density at selected times from the 1-D code (above) and an axisymmetric Warp simulation (below). The solid vertical lines indicate physical gap boundaries and dashed lines mark the axial locations where the gap field has decreased to 2.5% of its maximum value. Note that the timing of the absolute gap locations in the runs are offset, due to different initializations.

More recently, we have used acceleration schedules from the 1-D code in Warp runs with beams from an accel-decel injector. Setting up these schedules is more challenging because the injected beam has a substantial energy variation along its length. However, when we initialize the beam velocity and line-charge density of the 1-D code to mock up what is seen in Warp, we are able to work out an acceleration schedule similar to that discussed above. Running Warp using this schedule and appropriate transverse focusing produces a longitudinal phase space that is very tightly bunched after final compression, as seen in Fig. D. Again, this beam has little emittance growth during transport.

Tests of the ATA experimental hardware complement the physics design studies. We have refurbished one ATA induction cell and one Blumlein to drive the cell. The test stand has been assembled and is waiting for the last of the safety reviews before operation. A prototype 3T solenoid for the ATA cell has been designed and wound and is in the process of being potted before installation into the second refurbished ATA cell. The test stand will be used to verify voltage waveform tuning flexibility and to quantify the interaction between the high-field pulsed solenoid and the ferrite cores in the induction cell. These activities will confirm that the hardware from ATA can be

refurbished and modified to meet the requirements of NDCX-II. Figure E depicts the test stand as of September 2008.

Figure E. Test stand for studies of ATA hardware, enabling its future use in NDCX-II. Blumlein voltage source is on elevated stand at left, while induction core is at lower right.

References to FY08 publications in this area:

[Friedman08b] A. Friedman, "Some kinematic aspects of neutralized drift compression," LLNL Research Note LLNL-TR-402447, March 18, 2008. Available on the Web at: http://hifweb.lbl.gov/public/Friedman/kinematics-of-compression-note.pdf .

[Friedman08c] A. Friedman, J. J. Barnard, R. J. Briggs, R. C. Davidson, M. Dorf, A. Faltens, D. P. Grote, E. Henestroza, E. P. Lee, M. Leitner, B. G. Logan, A. B. Sefkow, W. M. Sharp, W. L. Waldron, D. R. Welch, and S. S. Yu "Toward a physics design for NDCX-II, an ion accelerator for warm dense matter and HIF target physics studies," *Proc. 17th International Symposium on Heavy Ion Inertial Fusion (HIF2008)*, Tokyo, August 2008; accepted for publication in Nuclear Instruments and Methods in Physics Research A. Available on the Web at: http://hifweb.lbl.gov/public/HIF2008/friedman.hif08.ms.v1a.pdf .

[Sharp08] W. M. Sharp, A. Friedman, and D. P. Grote, "Developing acceleration schedules for NDCX-II," *Proc. 17th International Symposium on Heavy Ion Inertial Fusion (HIF2008)*, Tokyo, August 2008; submitted to Nuclear Instruments and Methods in Physics Research A. Available on the Web at: http://hifweb.lbl.gov/public/HIF2008/sharp.hif08.ms.v1.pdf .