1. AFRD FUSION PROGRAM

Reported by Grant Logan, Fusion Program Head
and Director of the Heavy Ion Fusion Virtual National Laboratory

The Fusion Program at LBNL leads the Heavy Ion Fusion Virtual National Laboratory (HIF-VNL) a collaboration that also includes Lawrence Livermore National Laboratory and the Princeton Plasma Physics Laboratory (Figure 1-1). The HIF-VNL was formed in 2000 and operates under a Memorandum of Agreement, now being considered for a 5 year renewal for 2005 through 2010. This chapter principally concerns the Fusion Program here at LBNL, along with work at the partner laboratories that has a strong and direct connection to what we did here.

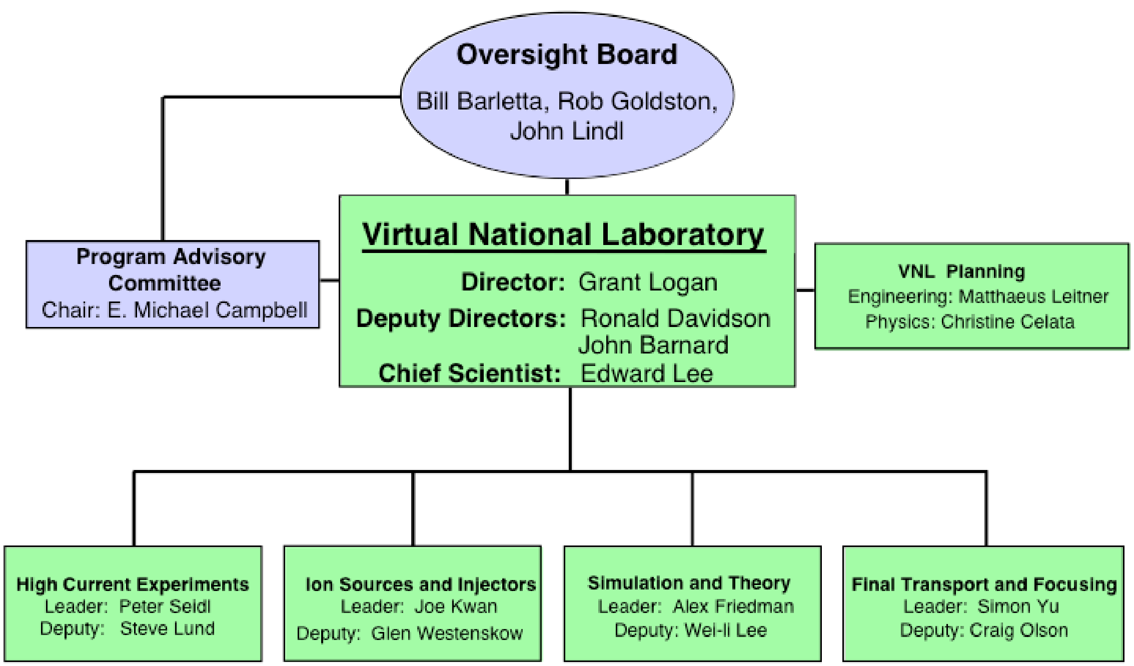


Figure 1-1. *The Heavy-Ion Fusion Virtual National Laboratory incorporates significant efforts at three laboratories—besides the AFRD fusion program whose achievements are reported here, Lawrence Livermore National Laboratory and Princeton Plasma Physics Laboratory play major roles.*

In the past year, our accomplishments included:

- Completing experiments on merging multiple beamlets for compact, high current heavy-ion injectors (work performed in the STS, a VNL facility at LLNL).
- Exploring electron cloud effects in transporting a high current beam in magnetic quadrupoles (in the HCX, a VNL facility at LBNL).
- Initiating a new heavy-ion beam experiment for longitudinal and radial compression of intense heavy ion beams in a neutralizing plasma background (in the NDCX, a new VNL facility at LBNL).

The HIF-VNL has also made progress on multi-species simulation codes to model intense heavy ion beams interacting with electron clouds and plasmas. (As you will see in this chapter, advanced simulation is a running theme in many of our efforts, and has spinoff benefits for other fields.)

We have also invented a novel accelerator, called the Traveling Wave Accelerator or TWA, that is especially suited to producing intense heavy ion beams with short (sub-microsecond) pulses. If the success promised by modeling and initial experimentation continues, the TWA could revolutionize the cost-effectiveness of accelerators that reach the parameter space we need.

The new experiments, modeling tools, and accelerator development came in response to a request that we redirect the heavy ion fusion program towards near term High Energy Density Physics (HEDP) research. The request came from the DOE Office of Science Director, the Office of Fusion Energy Science Director, and the White House Executive Office of Management and Budget.

Accordingly, have chosen a set of new experiments and research thrust areas that would enable two key achievements. Within five years, if funding is maintained, we will be able to heat targets to 1 eV. This will enable us to study the properties of warm dense matter--in particular, strongly-coupled plasmas at 0.01 to 0.1 times solid density, a frontier physics area within HEDP.

Pursuit of this five-year objective in HEDP has resulted in many innovations that will ultimately benefit heavy-ion fusion energy as well. These include neutralized beam compression and focusing, which hold the promise of greatly improving the stage between accelerator and target chamber in a fusion power plant, and the TWA, which may lead to compact, low-cost modular linac drivers.

Planned Science Campaigns

In response to constrained budgets, we are shutting down the STS facility at LLNL in mid FY05. With STS shut down, and if funding can be maintained at the FY05 level ($10M/yr for the VNL), we can support two integrated science campaigns with experiments and modeling.

1. Neutralized beam compression and focusing: Determine limits to neutralized beam longitudinal compression to short pulses and focusing in neutralizing background plasma. Carried out in a series of NDCX experiments (1A, 1B, 1C) at LBNL.
2. High brightness beam transport: Develop predictive capability for intense beam transport, including gas and electron cloud effects. Carried out primarily on the HCX facility at LBNL.

…and also support research in several critical thrust areas:

- Development of advanced theory and simulation tools for intense beams.
- Development of innovative short pulse sources and an injector to improve HEDP experimental capabilities.
- Design of unique beam-heated targets for HEDP.

The rest of this chapter gives selected highlights in six main areas of the LBNL Fusion Program: sources and injectors; high brightness beam transport; neutralization and beam compression; the TWA; and theory and advanced simulation. A concluding section takes a look at the road ahead for our HEDP research. For further in-depth reading on various topics, a publications list is appended to the chapter, with links to full-text versions of 11 selected publications in the refereed literature.

Source / Injector Highlights

Heavy ion fusion requires ion beams that have both high current and high brightness. In today's HIF experiments using hot plate contact ionization sources, the typical ion current density at the ion source is about 7 mA/cm^2. In the STS facility at LLNL, we have developed argon^{+1} plasma sources with over 100 mA/cm^2 in small beamlets of ~ 2 mm diameter.

We have recently merged 119 of these high current beamlets together into a single high current composite beam (Figure 1-2) to show how future heavy-ion injectors with such "merging beamlets" architectures can be made more compact than was previously envisioned. So far, the measured beam current agrees with WARP particle simulations showing no significant beam loss.

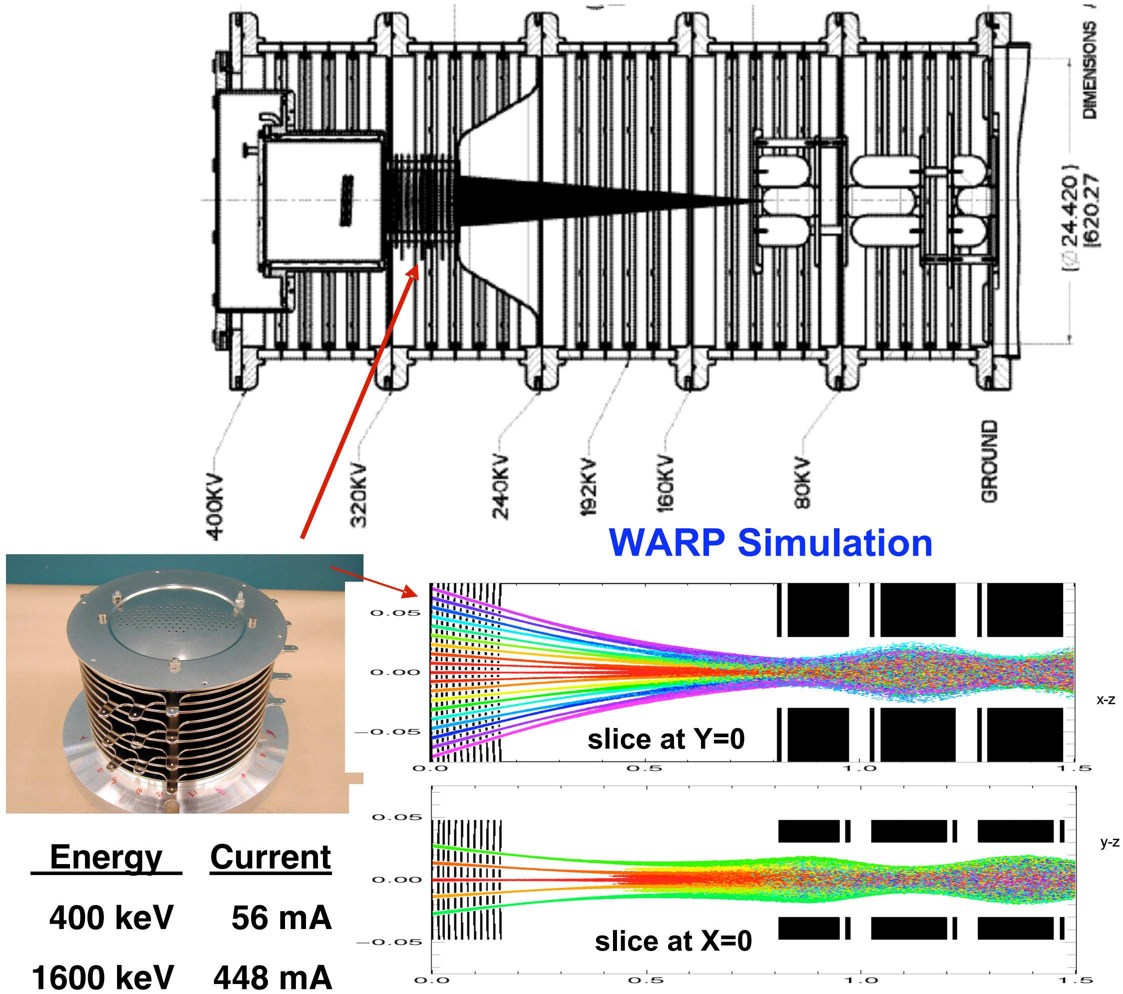


Figure 1-2. *The STS-500 has successfully merged 119 high current density beamlets into a single high-current beam. Measured beam loss agrees thus far with WARP simulations.*

High Brightness Beam Transport Highlights

The High Current Experiment or HCX (Figure 1-3) has studied high current beam transport in both electric and magnetic quadrupoles. In particular, negligible emittance growth has been observed in electrostatic transport where the beam filled 80% of the aperture (which is the maximum excursion of the beam envelope).

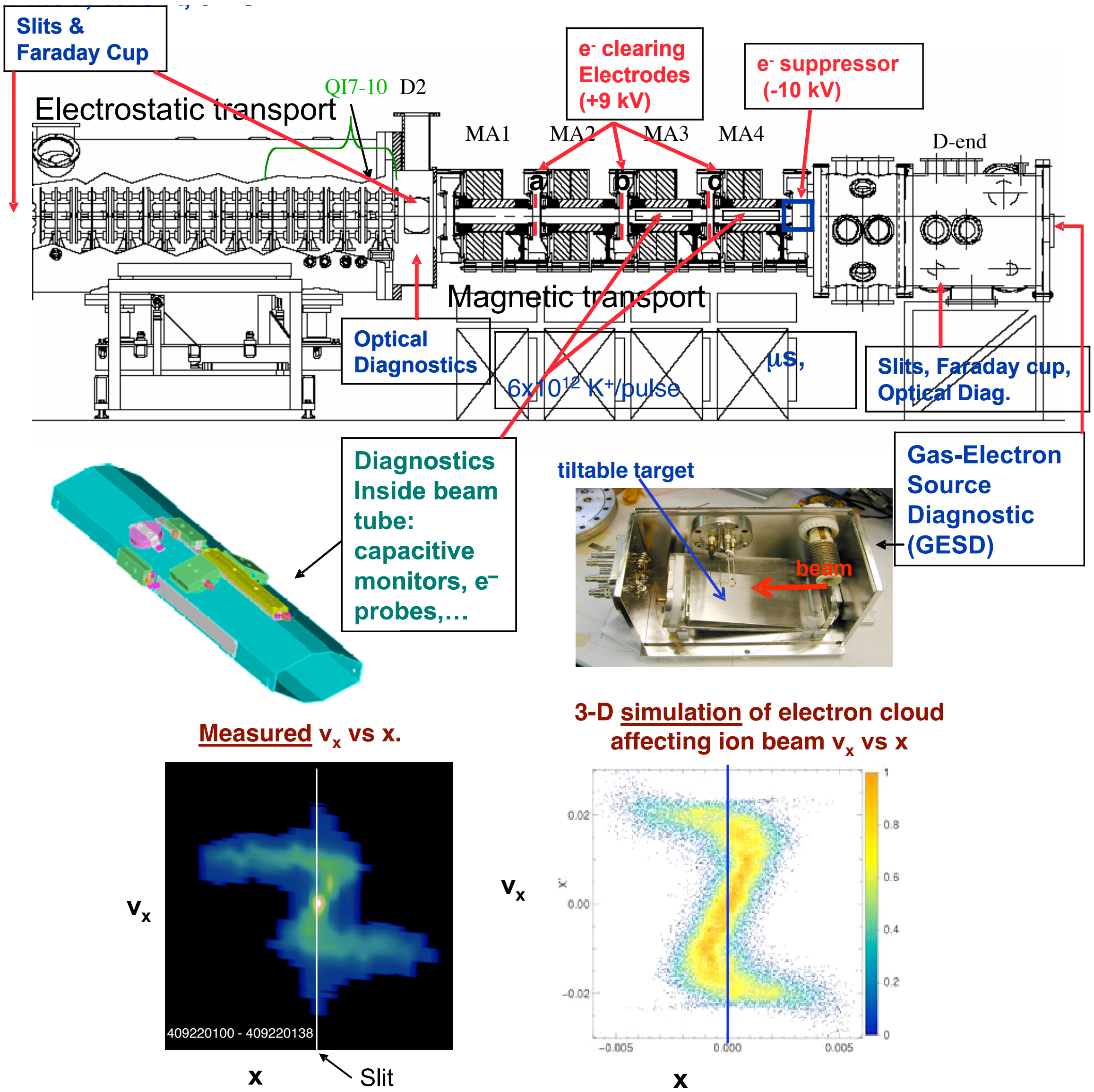


Figure 1-3. Layout of the HCX (elevation view). Some of the 15 diagnostic systems are indicated. There are electron clearing electrodes between each of the four magnetic quadrupoles, and an electron suppressor electrode at the end, to provide experimental control of electron cloud density levels. Diagnostics in the bore of the last two magnetic quadrupoles are sensitive to secondary electrons and ions that may perturb the beam distribution. Simulations (bottom of figure) *successfully model beam phase space distortions in the beam after traversing the four magnetic quadrupoles.*

Experiments involving transport through four pulsed quadrupole magnets (Figure 1-3) began in May 2003, especially to study gas and electron effects. Simulations using both envelope and discrete-particle WARP models are guiding the experiments, which require matching into a magnetic quadrupole lattice that has a half-period significantly different from that of the upstream electrostatic transport line.

Work in progress includes use of electron clearing electrodes, a variety of new diagnostics, in particular, use of optical imaging of the whole beam cross-section using fast scintillators. When the electron clearing and suppression voltages are turned off, so that electrons can stream into the magnetic quadrupoles from the end, 3-D WARP simulations with a novel large time-step electron mover successfully model the Z-shaped distortions of the exiting ion beam Vx-x phase space (bottom of Figure 1-3). *This world-leading multi-species modeling capability is key to a predictive capability for electron cloud effects in any high intensity accelerato*r.

Neutralization and Beam Compression Highlights

The first phase (1A) of the new HIF-VNL experimental facility, called the Neutralized Drift Compression eXperiment (NDCX-1A), began operation in December 2004. This facility (Figure 1-4) will be used to study the physics limits of longitudinal compression of intense heavy ion beams that are neutralized with a pre-formed background plasma. (The purpose of the background plasma is to eliminate the strong beam space charge forces that would otherwise resist compression.) This new experiment, the first of a series of NDCX experiments, was motivated by the DOE request to develop new capabilities for HEDP within five years.

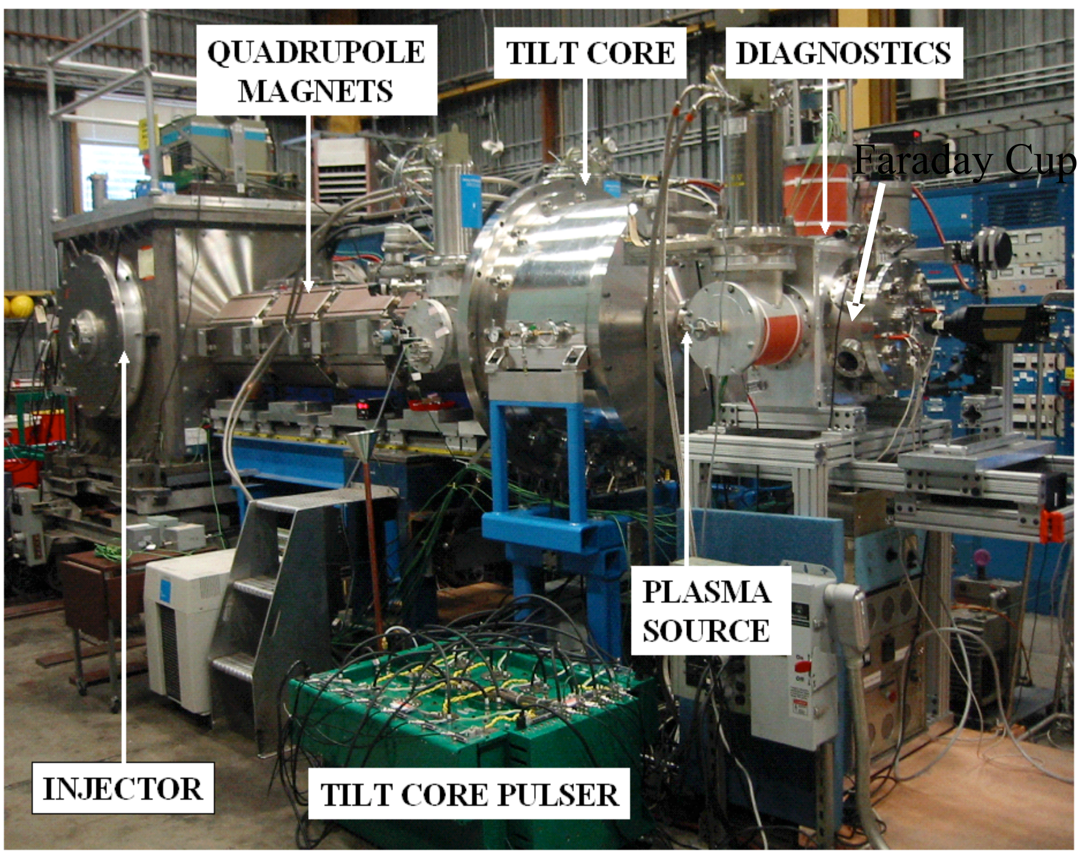


Figure 1-4. *The new NDCX-1A facility began operation in December 2005. The facility utilizes the 25-mA, 255 keV beam from the previous NTX experiment, together with an induction "tilt" core, to induce a velocity ramp to compress the beam. There is also a longer plasma-filled drift tube between the tilt core and the end diagnostics, compared to NTX.*

One year ago, we calculated that heavy-ion-heated HEDP targets of a few microns' thickness (equal to the range of our MeV ion beams) would hydro-expand in a few ns at 1 eV temperature. Therefore we needed a way to get short pulses (a few ns instead of the few μs we had previously). Simulations using the LSP particle-in-cell code showed that we could get ns pulses by adding a velocity ramp to a beam so it longitudinally drift-compresses in a neutralizing plasma background. Theory and simulations also showed that beam plasma instabilities should not limit on the achievable beam pulse compressions.

These new ideas and simulations led to the construction of NDCX-1A in FY04 by adding an existing induction acceleration module and a longer neutralizing plasma drift tube to the end of the former Neutralized Transport Experiment (NTX). The induction tilt core adds a velocity ramp from the head to the tail of a selected 250 to 500 ns portion of the 25 mA , 250 kV NTX beam. The ramp is applied with a specially-shaped induction drive pulse of 100 kV amplitude. The rear of the selected beam section catches up with the head particles in a 1 meter drift distance that is pre-filled with a background plasma confined in a weak solenoid magnetic field.

Figure 1-5 shows a series of progressively shorter pulse widths achieved in NDCX 1A over the last few months of initial operation. Such rapid and dramatic progress shows what we are looking for in these experiments. For *neutralized ion beams, velocity tilt may revolutionize high peak power accelerators* in a manner analogous to the role frequency chirp played in CPA lasers.

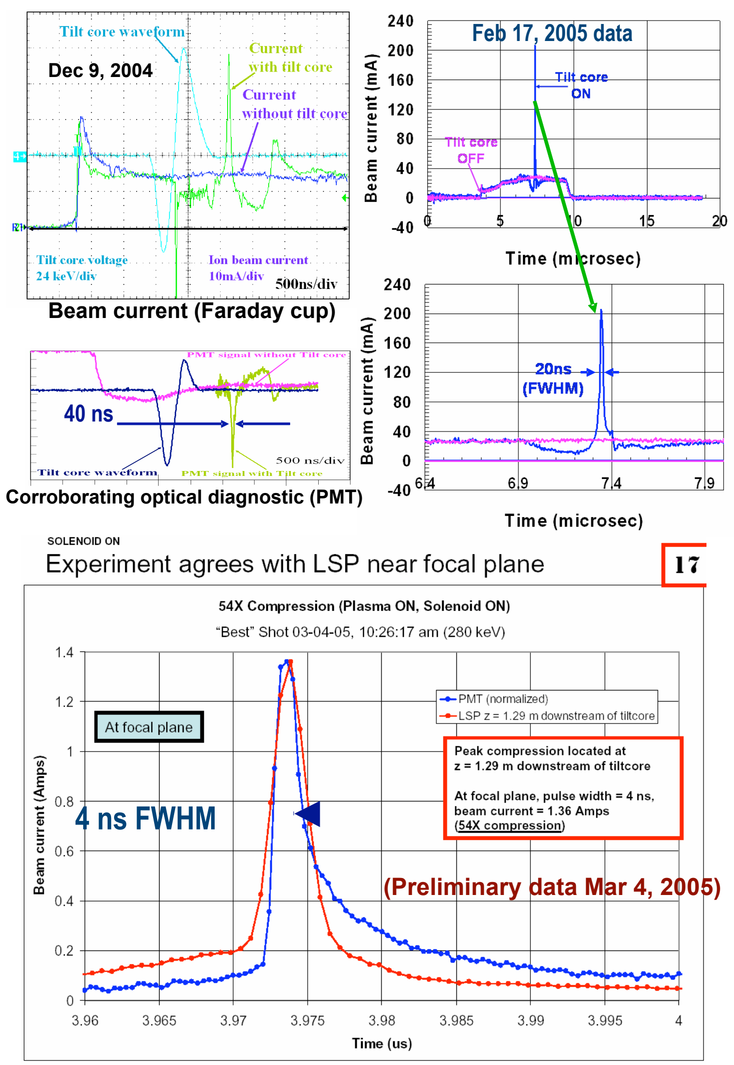
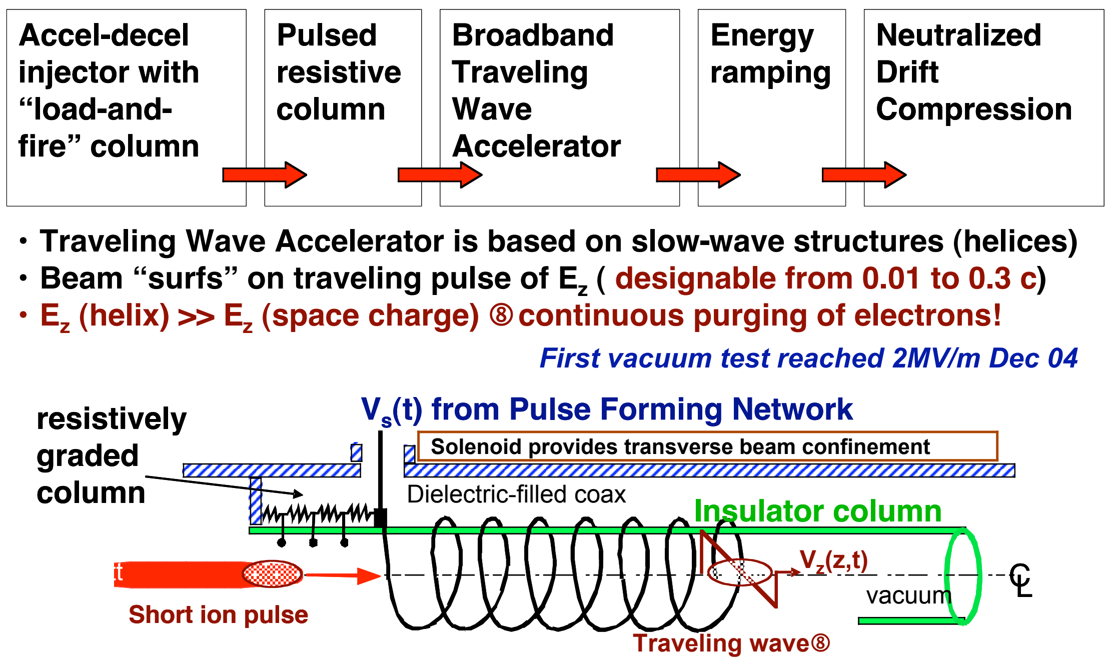


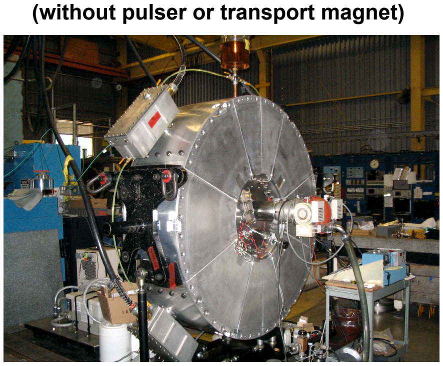
***Figure 1-5.** Preliminary results on longitudinal drift compression in the NDCX 1A: over a period of three months of initial operation, minimum compressed pulse widths, starting with a 200 ns selected portion of a 255 kV beam, progress from 40 ns to 4 ns minimum pulse widths.*

A NEW ACCELERATOR INVENTED FOR ION-DRIVEN HEDP

In October 2004, LBNL hosted an HIF-VNL Workshop on Accelerator-Driven HEDP attended by accelerator specialists from LBNL, SLAC, ANL, and FNAL. They explored different ways to meet a common HEDP requirement: accelerate 10^{13} Ne^{+1} ions to 20 MeV and deliver them to a 1 mm focus on an HEDP target within 1 ns pulse width. Multi-beam induction, drift tube, and RF linacs with and without an accumulator/stacker ring were considered, along with one totally new concept (Figure 1-6): a traveling wave helical-pulse line concept that we call the TWA for short.



Induction Module for the Dual-Axis Radiographic Hydrotest Facility (DARHT:
0.4 V·s (200kVx2μs)
~10,000 kg, 1 M$
(without pulser or transport magnet)



Traveling Wave Helix Accelerator No-beam test module (LBNL, Dec 04)
0.4 V·s (2MVx0.2μs)
~40 kg, 10 K$
(without pulser or transport magnet)

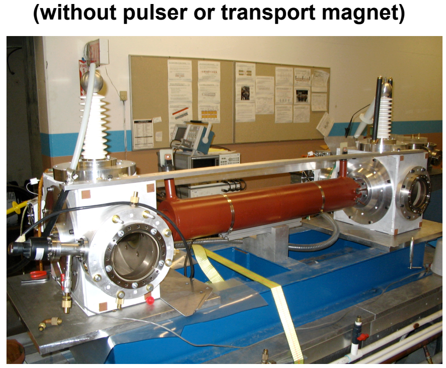


***Figure 1-6**. Top: Schematic of the TWA concept. Bottom: Comparison of two devices to couple pulsed power into a high current beam: the DARHT induction module (bottom left), and a 1 m long TWA test module that gives the same total volt-second product for beam acceleration. The TWA may ultimately prove to have a cost per volt as little as 1% that of a conventional induction linac (itself a relatively inexpensive type of accelerator), with obvious benefits for the cost-effectiveness of both HEDP experiments and heavy-ion fusion energy.*

Advanced Theory and Simulation Tools

Most of our simulation and theory work has already been mentioned as an integral part of the science campaigns discussed above. Here, we describe research aimed at the development of computational and theoretical tools in preparation for known upcoming needs, along with studies in anticipation of future science campaigns.

Electron Effects

One of the key issues is the electron-cloud effect. An initial comparison of simulation with experiment was the final FY04 milestone for the High Brightness campaign, as described in the report submitted to the Office of Fusion Energy Sciences at that time. Then we completed development of an "interpolated" drift-kinetic algorithm in WARP3D for magnetized electron motion that reverts to a direct orbit calculation in regions of weak magnetic field, and this algorithm went into production use; this was the FY05 first-quarter milestone.

Most elements of the roadmap for self-consistent modeling of electron effects were implemented during FY04 and early FY05 (see Figure 1-7).

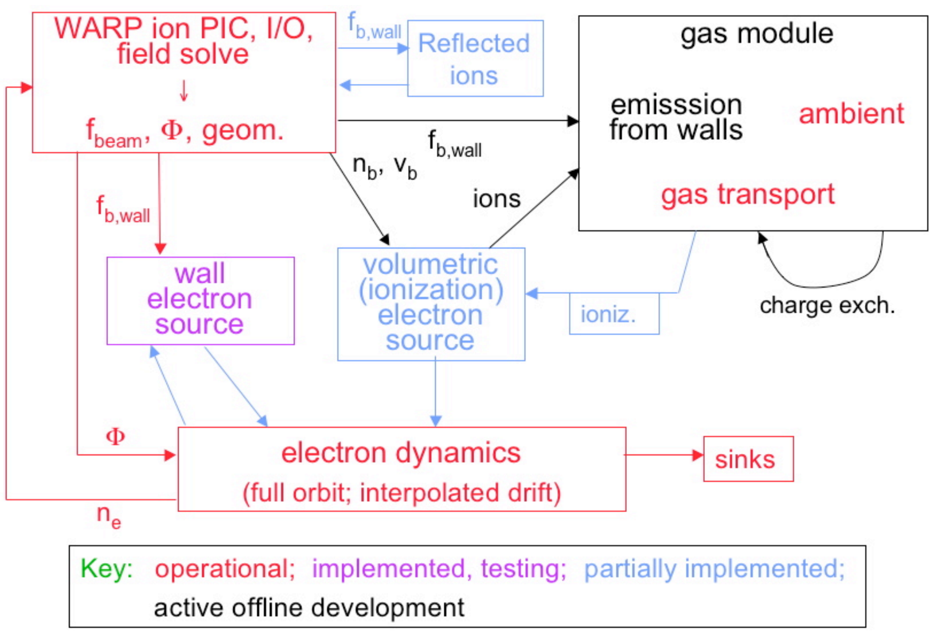


Figure 1-7. *Roadmap for developing self-consistent modeling of electron and gas cloud effects in high intensity ion accelerators. This work has been published, was presented as an invited talk at the 2004 American Physical Society-Division of Physics of Plasma meeting, and will be presented as an invited talk at the 2005 Particle Accelerator Conference.*

Our novel integration of Adaptive Mesh Refinement (AMR), a technique that concentrates grid resolution where it is most needed, into WARP has proved critical to the injector modeling effort. Agreement with experiment is excellent, and it is likely that this technique will be useful and essential in other such calculations, especially in injectors, in many types of accelerators. Papers on the AMR technique and its use have been published.

Our modeling of integrated experiments incorporating acceleration, compression, and focusing has shifted to nearer-term HEDP systems. Final WARP3D studies of an Integrated Beam Experiment (IBX) modeled after an IFE driver were carried out in FY04. A side benefit from this work is a clearer understanding of how a diode can launch a “matched” beam head, even though the transverse space charge force there is much less than in the body of the beam.

Our capabilities for analysis of beam phase space data, and synthesis of particle distributions from experimental data for use as the initial conditions of particle simulations, as described in last year’s Field Work Proposal, were further refined and exercised. We extended the synthesis technique to the case of the optical-slit diagnostic, and carried out simulations using the initial conditions so obtained.

We carried out simulations of the modular solenoid approach to an ion driver, using the LSP code. Considerable analysis was carried out of final-focus scaling, gas effects, and other aspects of this novel concept. A report on key aspects of solenoids fields is in preparation, covering such topics as cross talk among parallel channels, tilted magnets, magnetic field in acceleration gaps and induction cores, periodic lattices, and global return flux of a system.

Plans for High Energy Density Physics

Assuming the NDCX experiments validate the possibility of compressing intense ion beams to 1 ns and focusing them, Figure 1-8 shows a unique approach we plan to take to contribute to high energy density physics within the next five years: uniform isochoric heating of thin targets using ~ 1 MeV/amu ions at the Bragg peak in dE/dx.

LBNL is supporting this work through the Laboratory-Directed Research and Development program to assess potential ion-driven HEDP targets and develop appropriate fast diagnostics.

Because of severe budget constraints and competition with lasers for HEDP studies, we need to build an accelerator capable of driving HEDP experiments in about five years for roughly the price of a table-top CPA laser. Of all the concepts we have studied so far, the TWA looks to be the most promising and affordable.

Figure 1-9 depicts an upgrade of the NDCX, called NDCX-II, that would cost about $5M in incremental hardware if based on the TWA. We plan a series of tests of the TWA concept as part of the current NDCX program. A decision to upgrade to NDCX-II could be made at the end of FY07, if the NDCX pulse compression experiments and the TWA tests are successful, and if current funding levels are maintained.

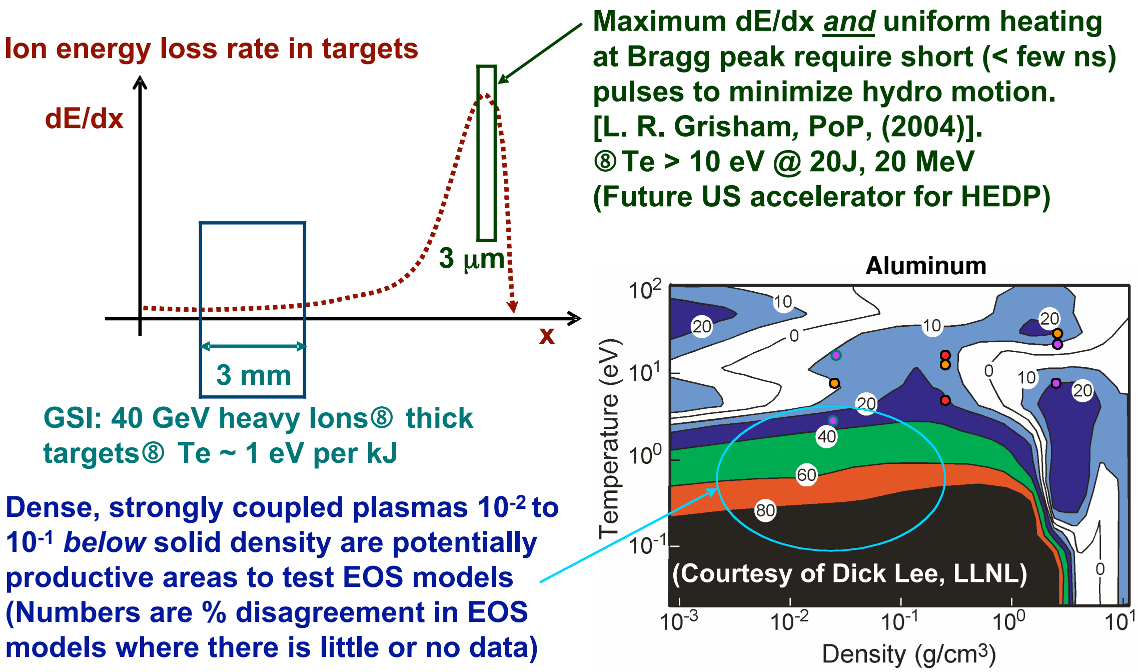


Figure 1-8. *The energy deposition of fast ions as a function of distance into the target (dE/dx) exhibits a sharp rise called the Bragg peak that typically occurs where the ion speed matches the orbital velocity of bound electrons. We propose to use ions with energy just above the Bragg peak so that both deposition and uniformity can be maximized.* Above, lower right corner*: We plan to apply this technique to thin targets at one to ten percent of solid density, a regime of HEDP where there is little or no data, and where we can best discriminate among the predictions of various equation-of-state models.*

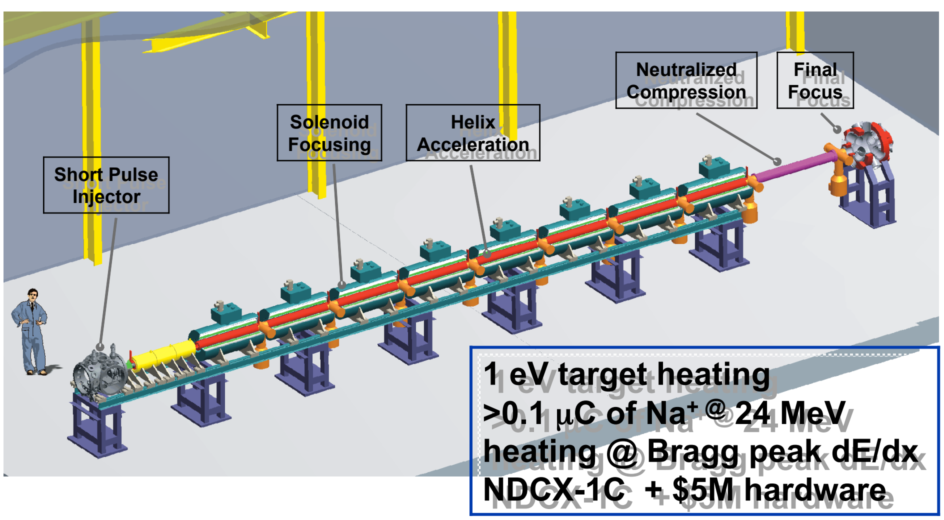


Figure 1-9. *A conceptual design for NDCX-II, an upgrade of NDCX-1C adding a 20 MeV TWA accelerator section. NDCX-II would provide proof-of-principle for accelerator-driven HEDP with a capability of heating single targets to 1 eV. Further upgrades for higher pulse rates, a beam switchyard with multiple experimental chambers, and laser driven HEDP diagnostics would be required to constitute an LBNL HEDP user facility.*

Featured Publications

These papers were chosen as exemplary descriptions of important aspects of our work. All were all published, or are under consideration, by refereed journals. The links take you to full text in the best version available to us.

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Full Publications List

A listing, in alphabetical order by first author, of papers published by the LBNL Fusion Program in fiscal 2004 through early calendar 2005. Asterisks designate papers associated with invited talks at major conferences.

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