Recent advances in ion-beam-driven high energy density physics and heavy ion fusion*

Presented by

Ronald C. Davidson
on behalf of the
Heavy Ion Fusion Science Virtual National Laboratory**

Presented at

2006 Fusion Power Associates Symposium
Washington, D.C. 20003

September 27 - 28, 2006

*This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Berkeley and Lawrence Livermore National Laboratories under Contract Numbers DE-AC02-05CH1123 and W-7405-Eng-48, and by the Princeton Plasma Physics Laboratory under Contract Number DE-AC02-76CH03073.

** HIFS-VNL: A collaboration between Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and Princeton Plasma Physics Laboratory, USA.

Outline

- Program objectives
- Neutralized drift compression
- Design of ion-beam-driven warm dense matter target experiments
- Pulse-Line Ion Accelerator (PLIA)
- High brightness beam transport
- Advanced theory and simulation tools
- Studies of neutralized drift compression applied to heavy ion fusion drivers
- Conclusions

Program objectives

Top-level scientific question fundamental to both high energy density physics and heavy ion fusion:

"How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion?"

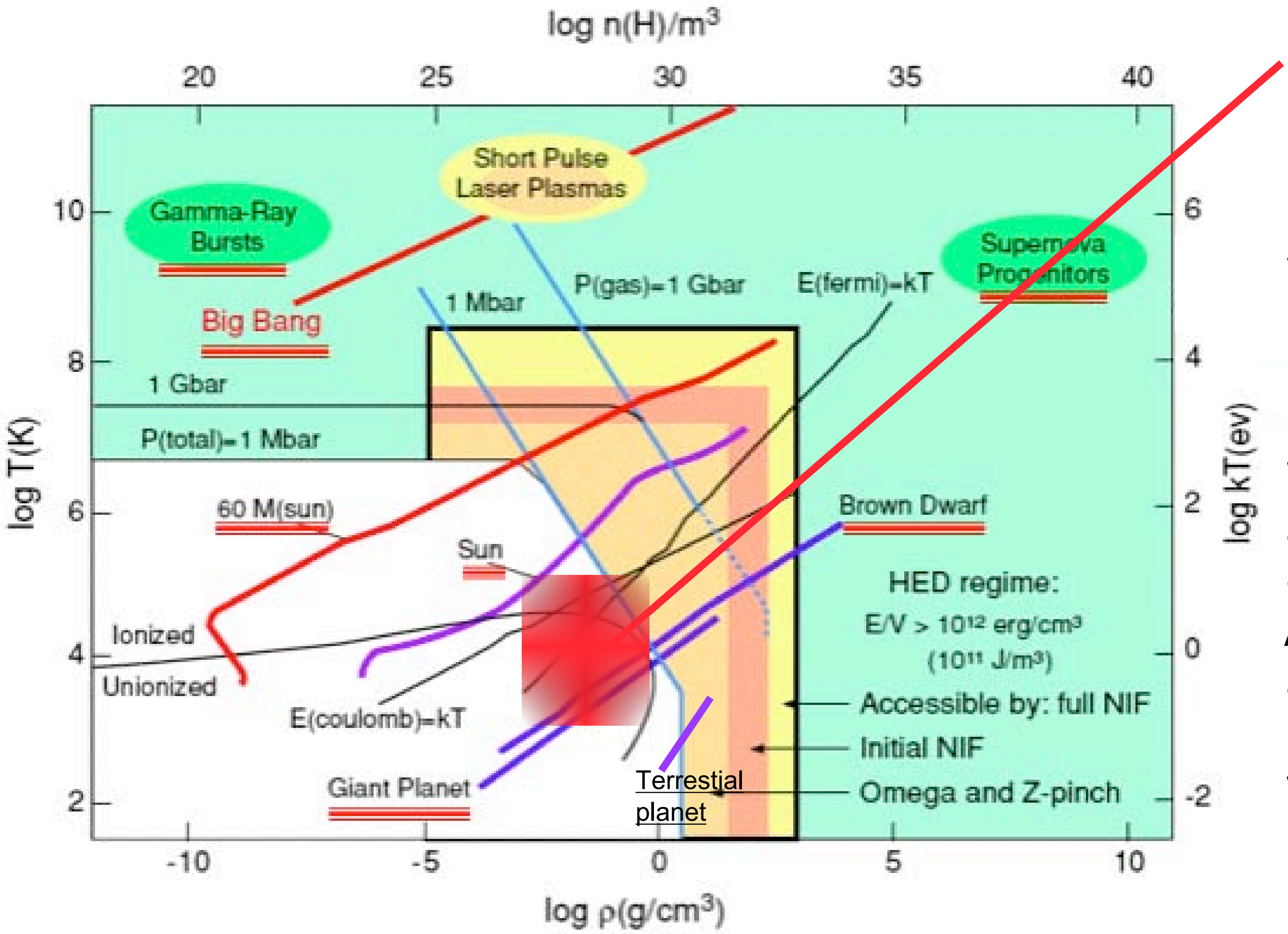
Goals: **Understand the beam and plasma target science to enable:**

- **An upgrade to the present Neutralized Drift Compression Experiment (NDCX).**
- **An integrated beam user facility Integrated Beam-High Energy Density Physics Experiment (IB-HEDPX).**

→Advances in the past two years will enable first heavy ion beam-target interaction experiments to begin in 2008.

The ρ - T regime accessible by beam-driven experiments is similar to the interiors of giant planets and low-mass stars

Figure adapted from “Frontiers in HEDP: the X-Games of Contemporary Science:”



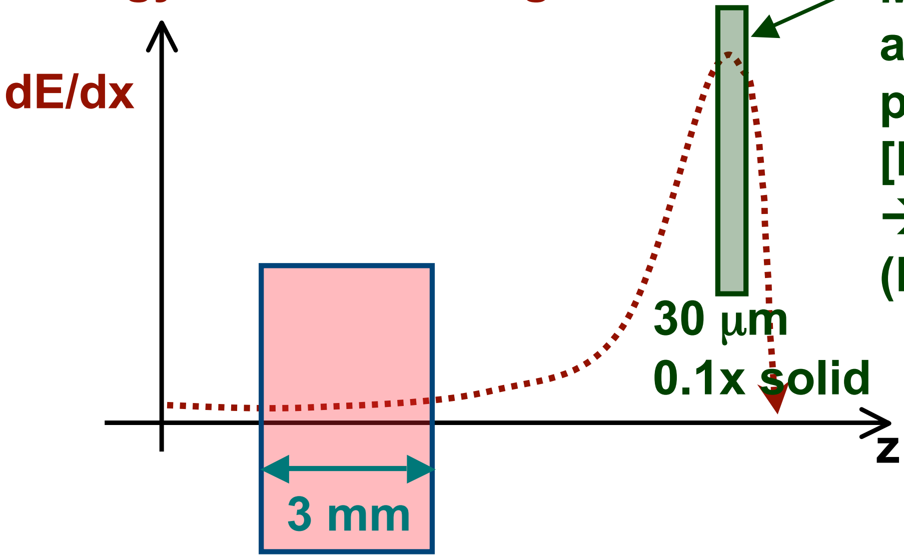
Accessible region using Intense beams

Region is part of Warm Dense Matter (WDM) regime

WDM lies at crossroads of: degenerate /classical and strongly Coupled/ weakly coupled

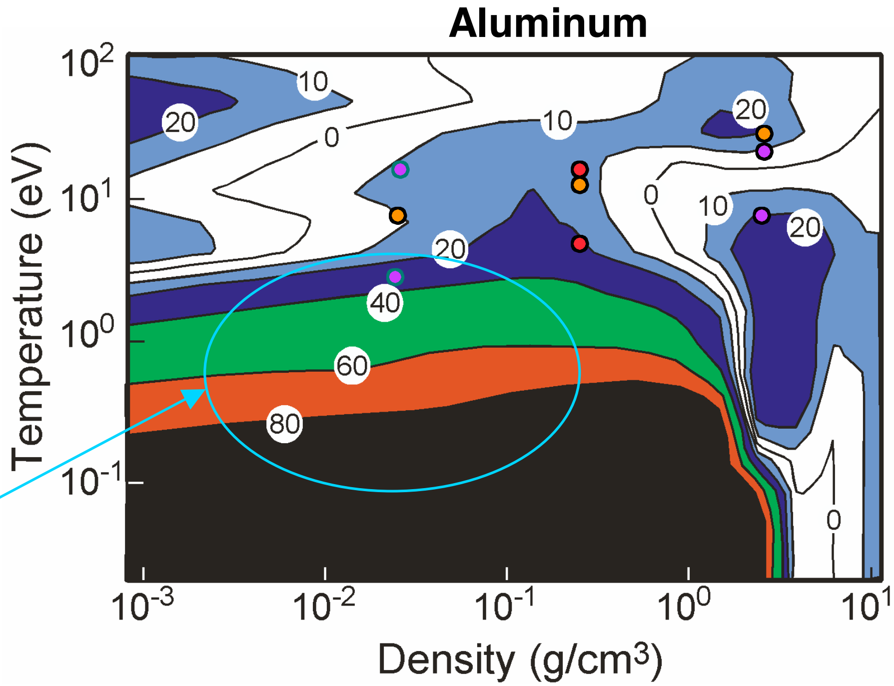
We are pursuing a unique approach to ion-beam-driven warm dense matter physics using short range ions

Ion energy loss rate in targets



Maximum dE/dx *and* uniform heating at this peak require short (~ 1 ns) pulses to minimize hydro motion.
[L. Grisham, Phys. Plas. 11, 5727 (2004)]
→Te > 10 eV @ 20J, 20 MeV
(Future US accelerator for HEDP/fusion)

GSI: 40-100 GeV heavy Ions→
thick targets→ Te ~ 1 eV per kJ



Dense, strongly coupled plasmas @ 10^{-2} to 10^{-1} *x* solid density are potentially interesting areas to test EOS models (Numbers are % disagreement in EOS models where there is little or no data)

(Courtesy of Richard Lee, LLNL)

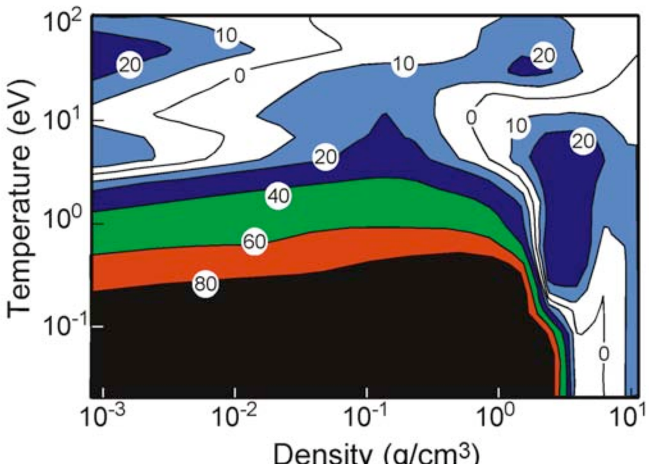
New theoretical EOS work meshes very well with the experimental capabilities we will be creating

Large uncertainties in WDM region arise in the two phase (liquid-vapor) region.

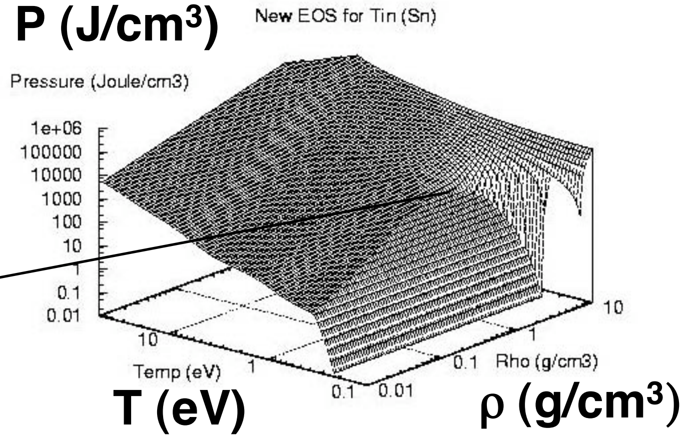
Accurate results in two-phase regime essential for WDM.

Richard More has recently developed new high-quality EOS for Sn.

Interesting behavior in the T~1.0 eV regime.



Richard Lee plot of contours of fractional pressure difference for two common EOS

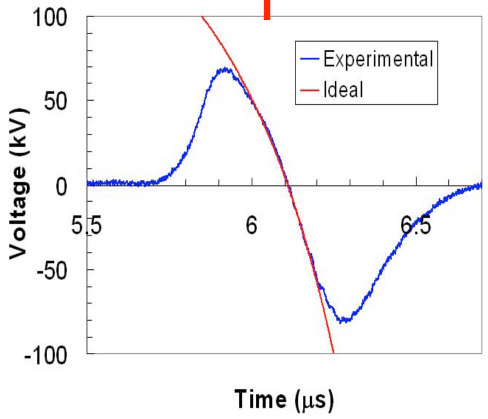


Critical point unknown for many metals, such as Sn

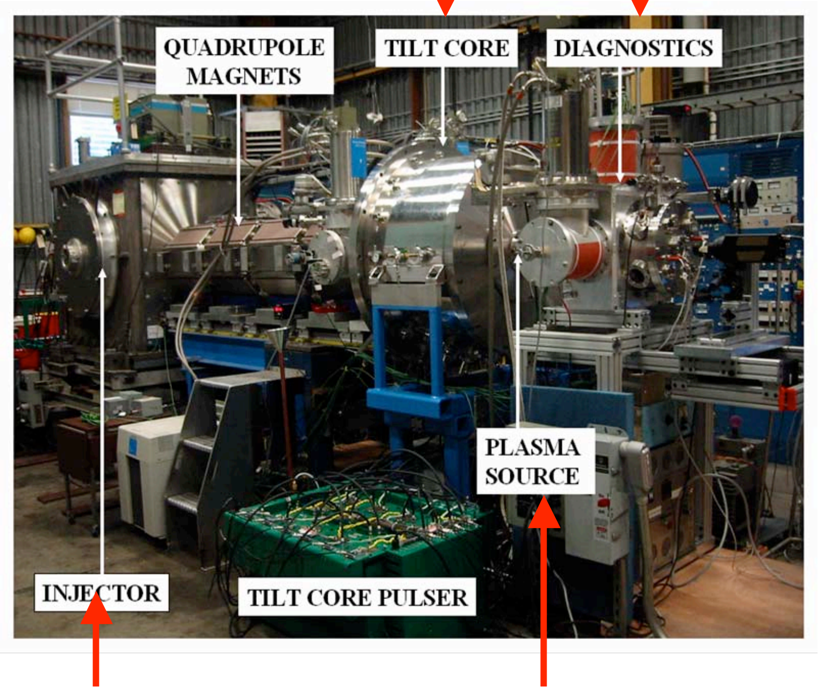
EOS tools for this temperature and density range are just now being developed.

Longitudinal bunch compression in the Neutralized Drift Compression Experiment (NDCX)*: *pulses now short enough to begin target experiments*

Induction core impresses head-to-tail velocity ramp (“tilt”) on 200-ns slices of injected 300 keV K^+ ion beam, compressing the slices to few nanoseconds.

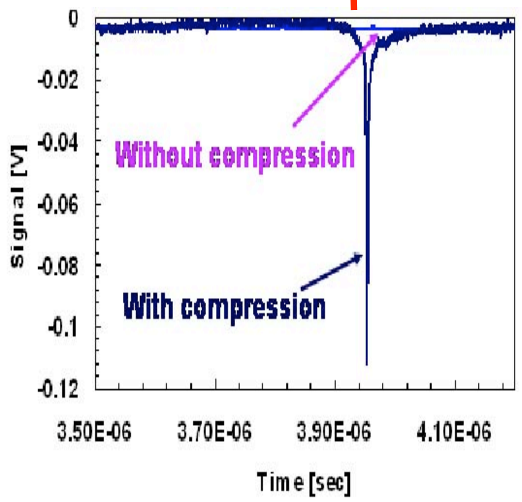


Induction waveform



Same injector as the previous NTX experiment

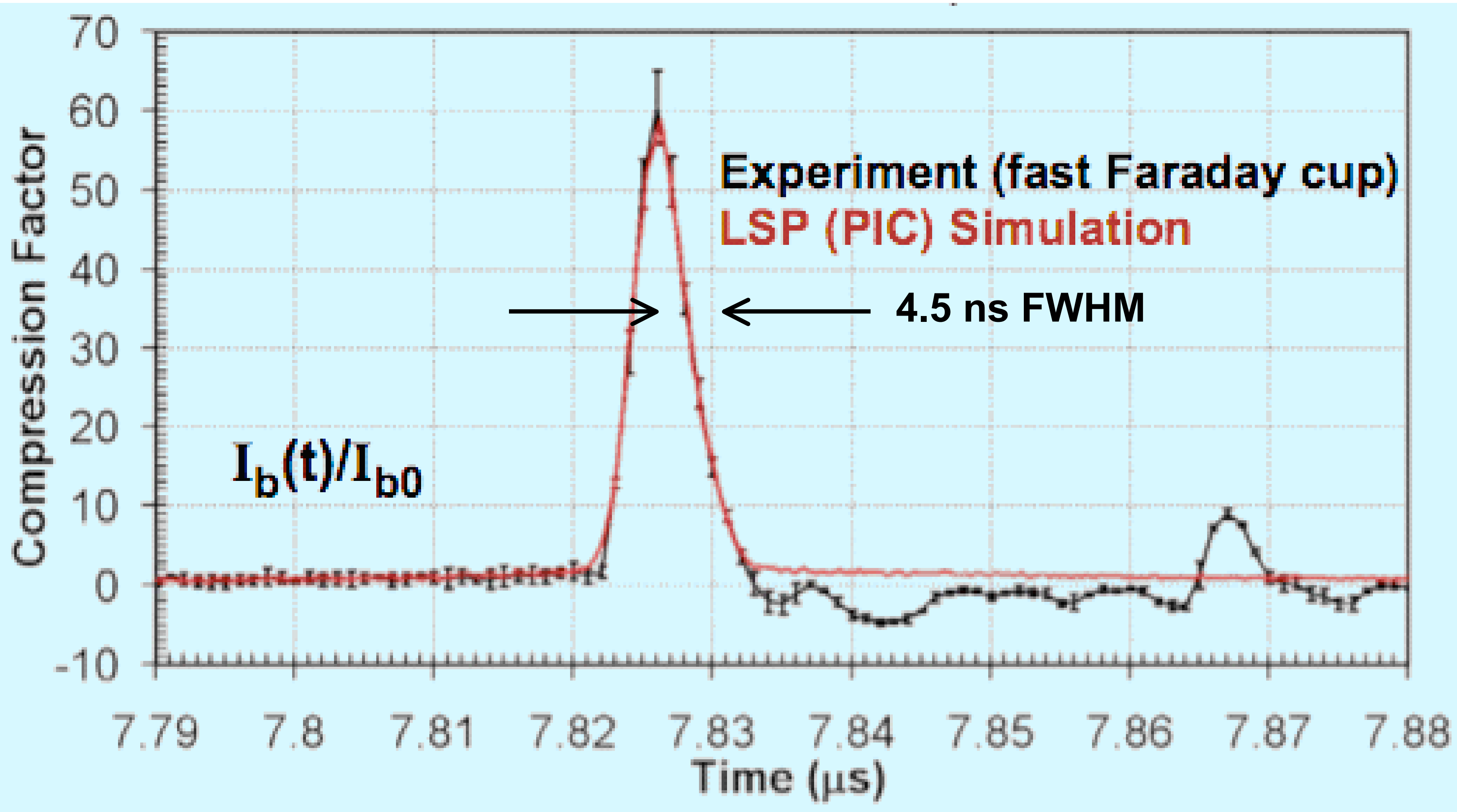
Longer plasma source ~1 m



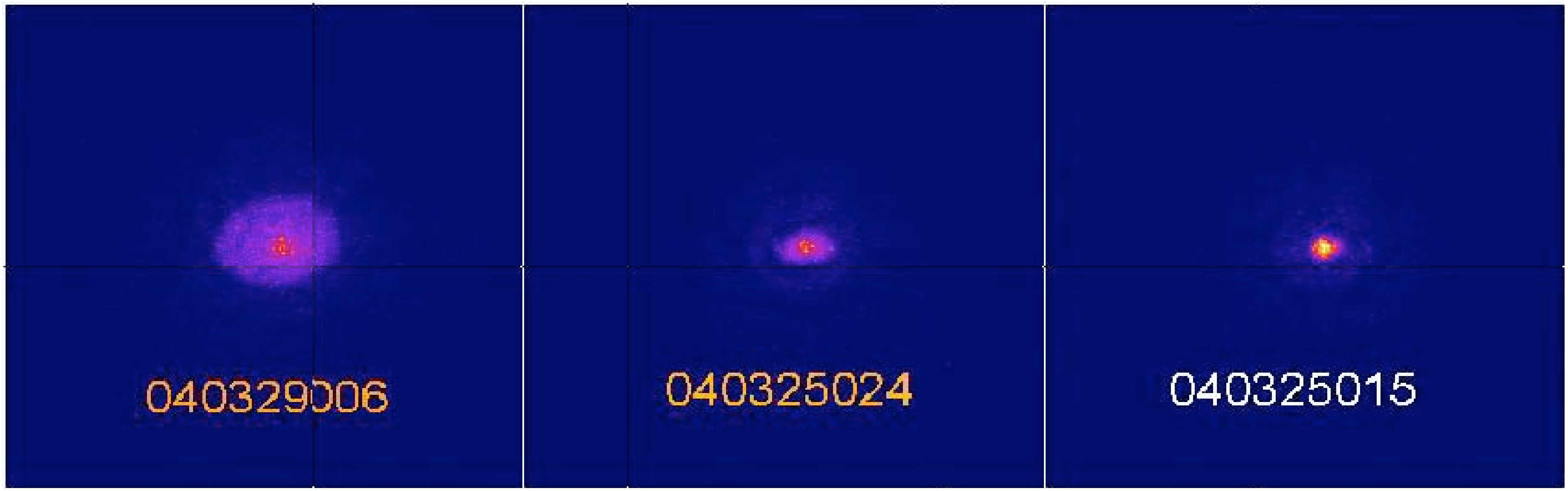
End beam current with/ without velocity ramps

* P.K. Roy et al., Phys. Rev. Lett. 95, 234801 (2005).

Simulations of neutralized beam compression (red curve) are in very good agreement with the NDCX data (black curve) when experimental induction waveforms are used in the simulations.



Transverse focusing in background plasma has been demonstrated in the Neutralized Transport Experiment



Neither plasma plug nor volumetric plasma.

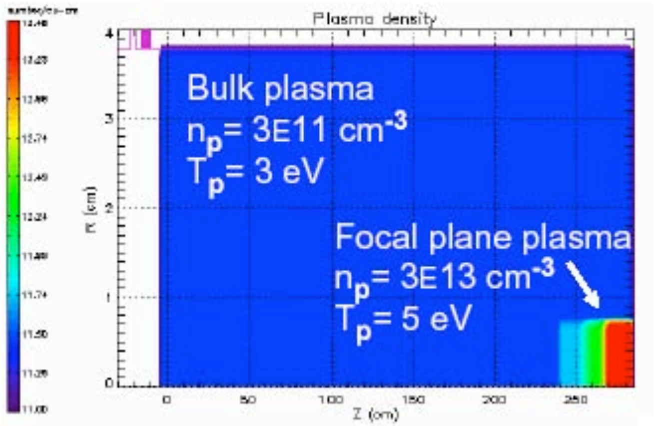
Plasma plug.

Plasma plug and volumetric plasma.

Measurements on the Neutralized Transport Experiment (NTX) demonstrate achievement of smaller transverse spot size using volumetric plasma.

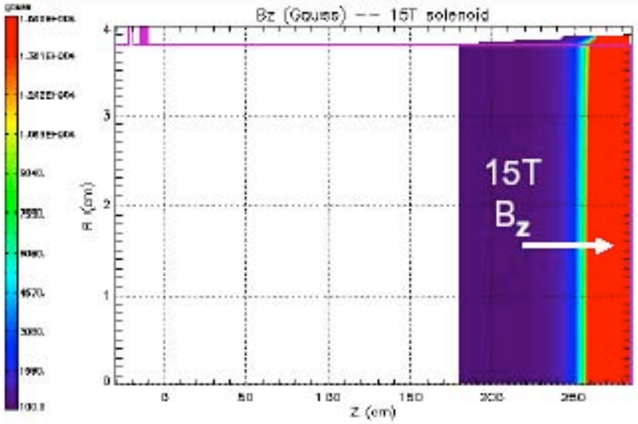
LSP PIC simulations: Optimizing approach to 2008 WDM experiments

- 400 keV K^+, 80 mA, r = 1.9 cm, T = 0.2 eV
- (4 rms) Normalized emittance 0.089 mm-mrad
- 0.6 μs initial pulse length (~0.4 μs compressed)
- 2.90 m focal length, 21.2% tilt (in red, on right)
- B = 15 T for transverse focusing
- n_p = 3E11 cm^{-3} bulk to 3E13 cm^{-3} in focal region
- EM kinetic simulation, conserves energy well



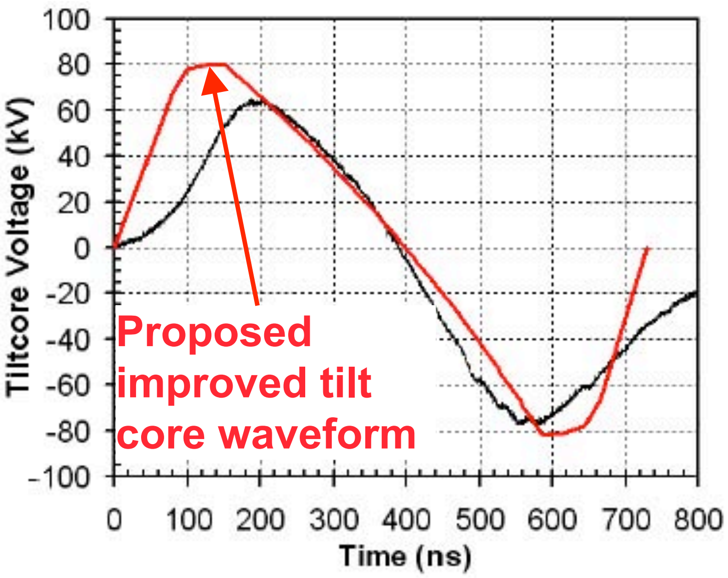
Bulk plasma
n_p= 3E11 cm^{-3}
T_p= 3 eV

Focal plane plasma
n_p= 3E13 cm^{-3}
T_p= 5 eV



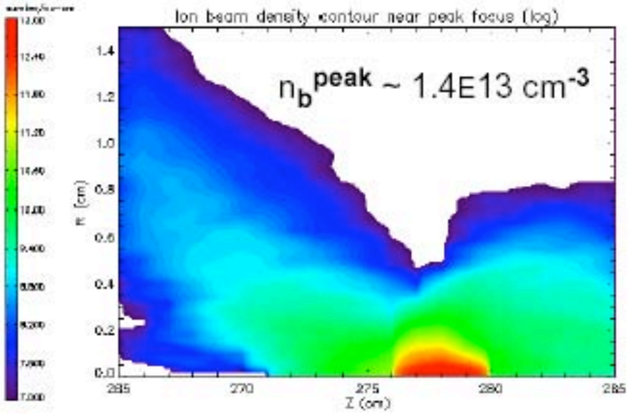
15T
B_z

(Simulations by Adam Sefkow, PPPL)



Proposed improved tilt core waveform

Induction module waveform (above):
Experimental: 320 keV K^+, 20mA → **60X**, *4.3ns* (f=2.34m)
Simulation: 400 keV K^+, 80mA →**125X**, *3.0ns* (f=2.90m)



n_b^{peak} ~ 1.4E13 cm^{-3}

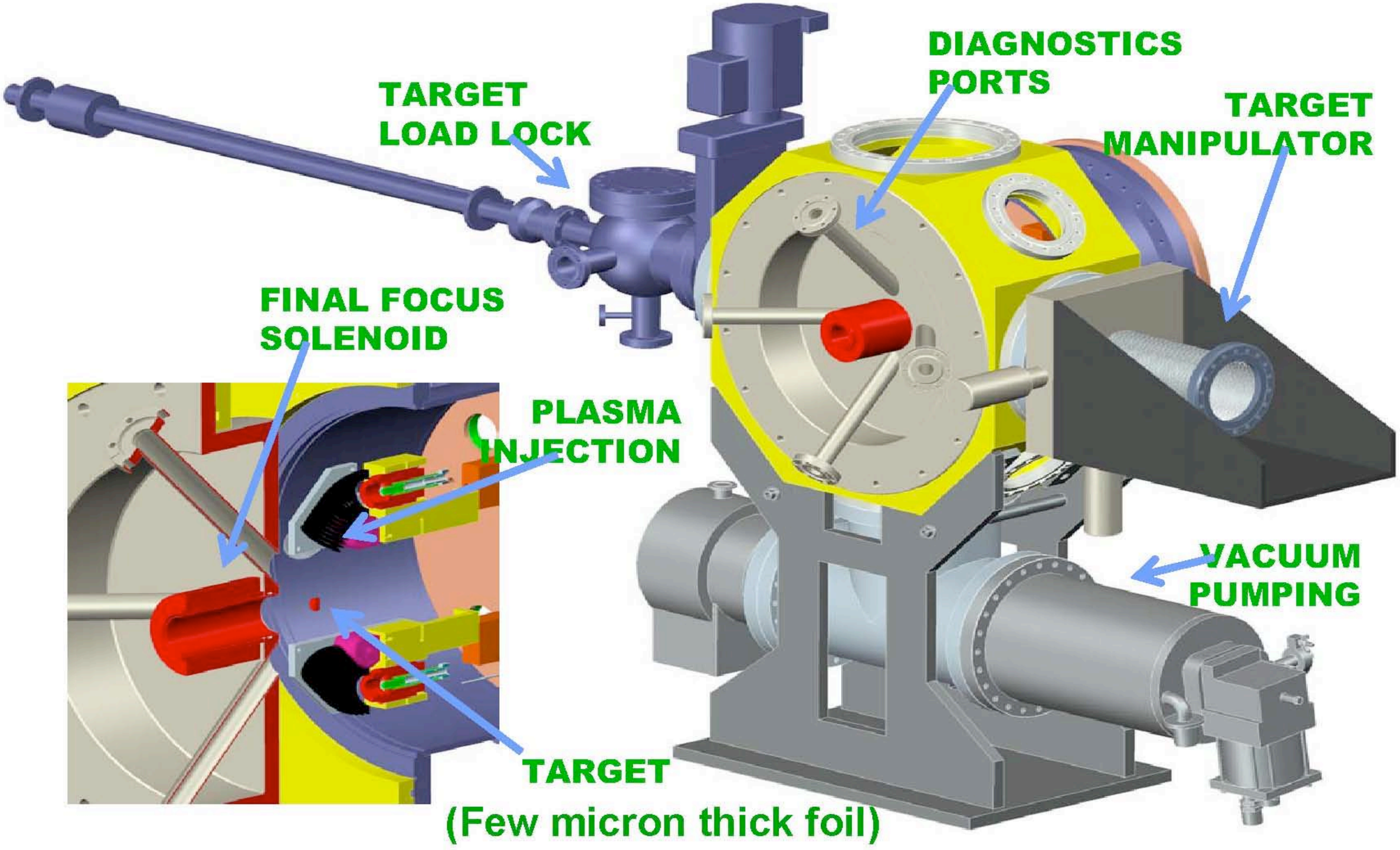
We are preparing for a sequence of WDM experiments, beginning at low beam intensities and target temperatures

	Target T	**NDCX-1 or HCX**	**NDCX-2**
Transient darkening emission and absorption experiment to extend previous observations in the WDM regime	**Low (0-0.4 eV)**	√	
Thin target dE/dx, energy distribution, charge state, and scattering in a heated target	**Low**	√	
Measure target temperature using a beam compressed both radially and longitudinally.	**Low**	√	
Positive - negative halogen ion plasma experiment (semiconductor properties)	**>0.4 eV**	√	
Two-phase liquid-vapor metal experiments	**0.5-1.0**	√	√
Critical point measurements	**>1.0**	**?**	√

time

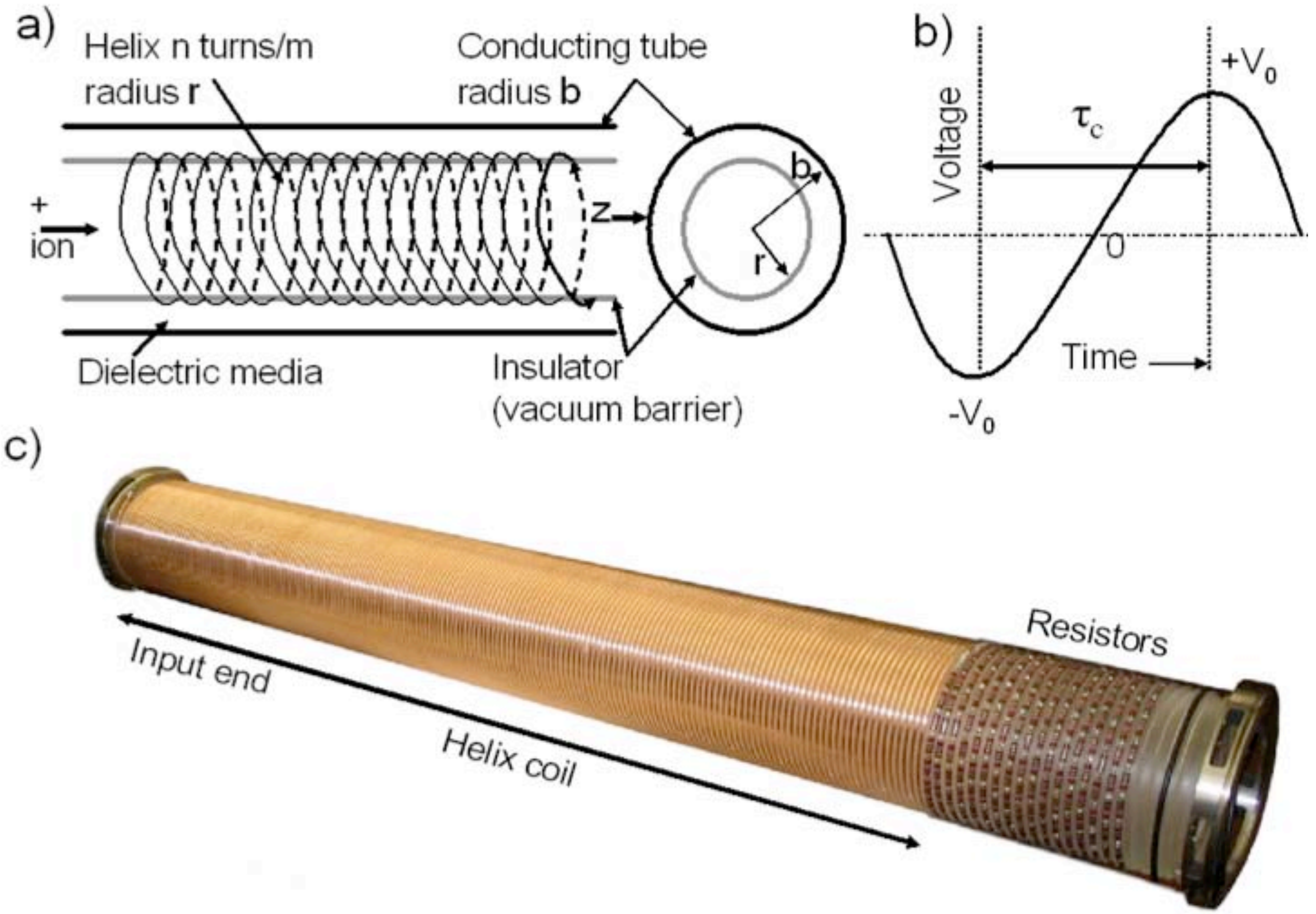
We are also discussing near-term collaborative experiments with GSI, Sandia, and other laboratories.

Near term plans: NDCX experimental target chamber is under construction, and diagnostics are being developed



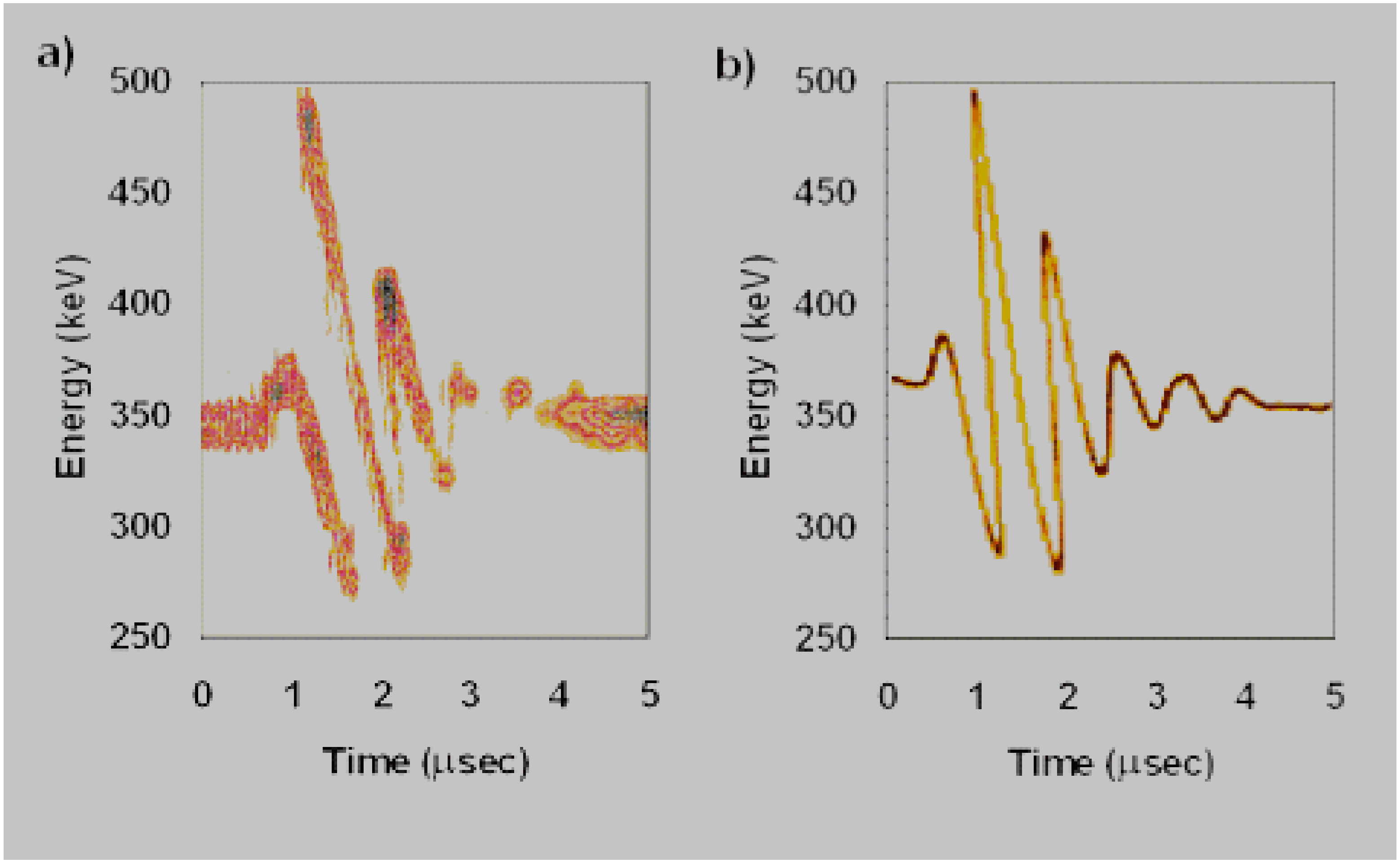
The Heavy Ion Fusion Science Virtual National Laboratory

Evaluating the feasibility of a new Pulse-Line Ion Accelerator (PLIA) (Concept proposed by R.J. Briggs)



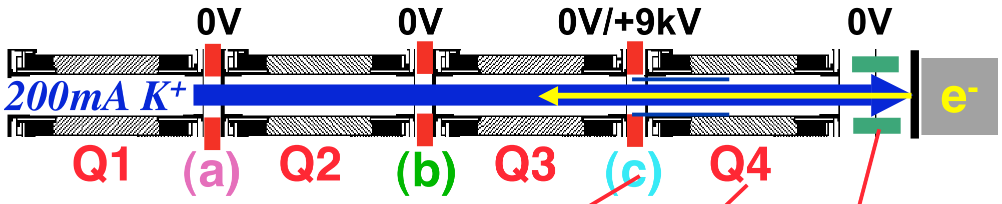
(a) The helical pulse line of radius r is located inside a conducting cylinder of radius b, and a dielectric medium is located in the region outside the helix; (b) schematic of a drive voltage waveform applied at the helix input; and (c) a one-meter-long helix constructed for the PLIA experiments.

First PLIA test validates acceleration principle

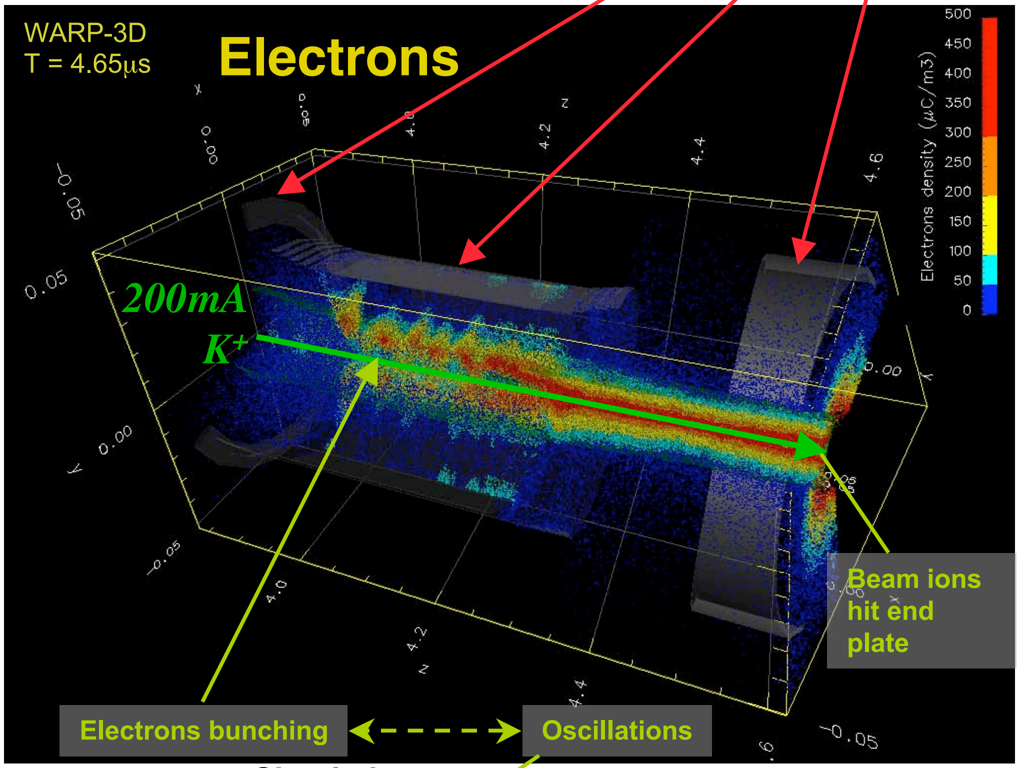


The measured ion output energies (a) are modulated depending on the ion phase with respect to the ringing waveform. WARP-3D simulations (b) reproduce the measured energy modulation (P.K. Roy, E. Henestroza, J. Coleman, A. Friedman et al).

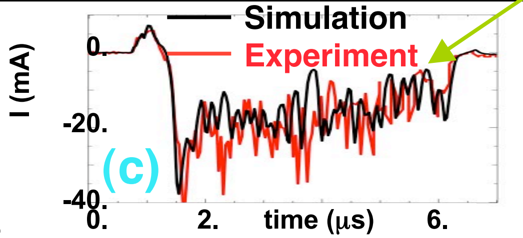
High Current Experiment (HCX) benchmarks models for unique modeling capability for electron cloud and gas effects



←Four HCX magnetic quadrupoles



Electron and gas cloud modeling critical to all high current accelerators, including high energy physics: LHC, ILC, …and future HEDP/fusion drivers: NDCX-II, IB-HEDPX .

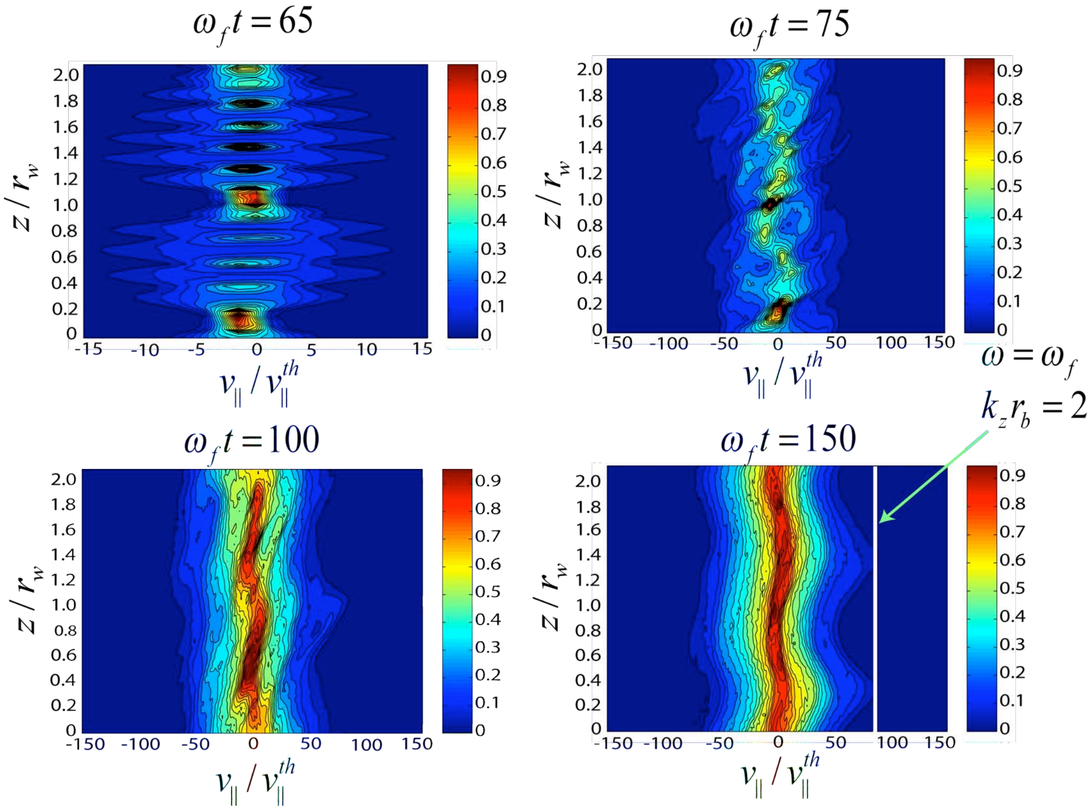


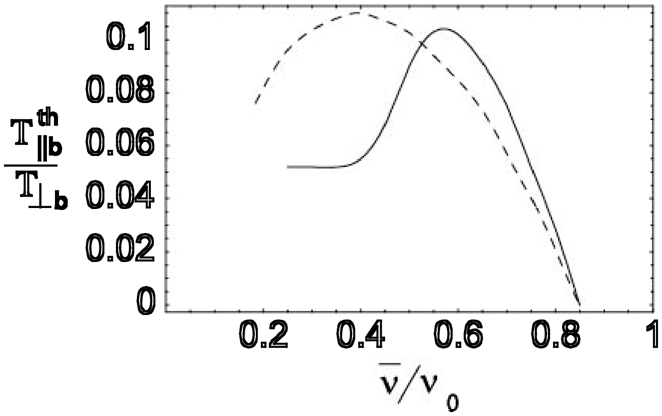
6 MHz oscillations in (C) in simulation AND experiment

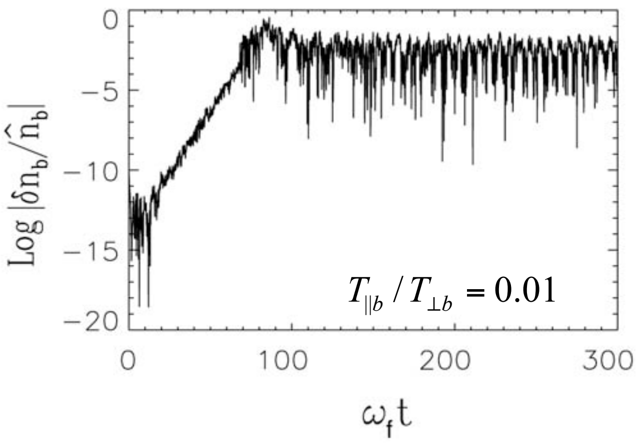
Strong Harris Instability for Beams with Large Temperature Anisotropy

(This *may* limit minimum $T_{par}<T_{perp}$ → longitudinal compression)*

- Moderate intensity → largest threshold temperature anisotropy.
- BEST simulations show nonlinear saturation by particle trapping → tail formation.

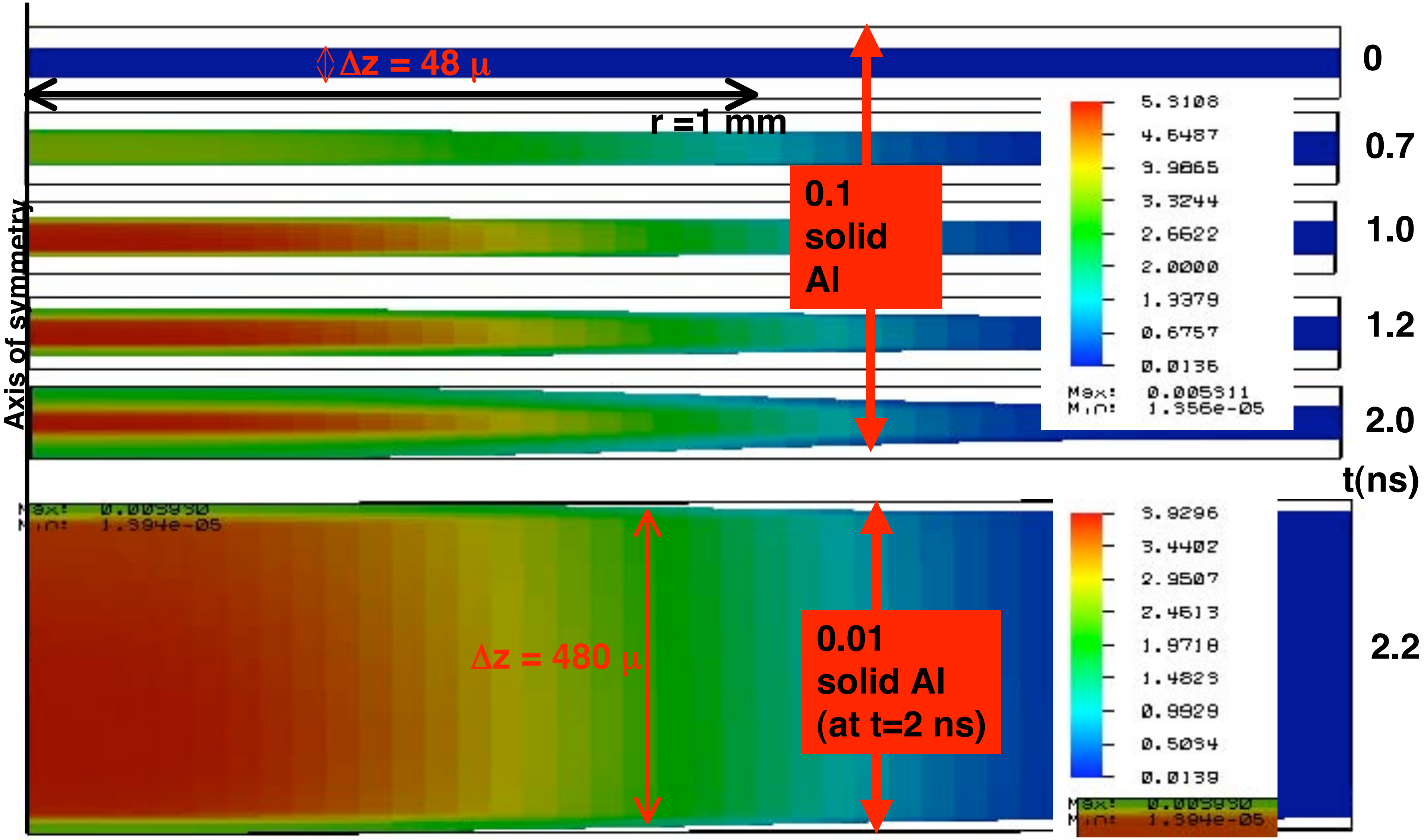




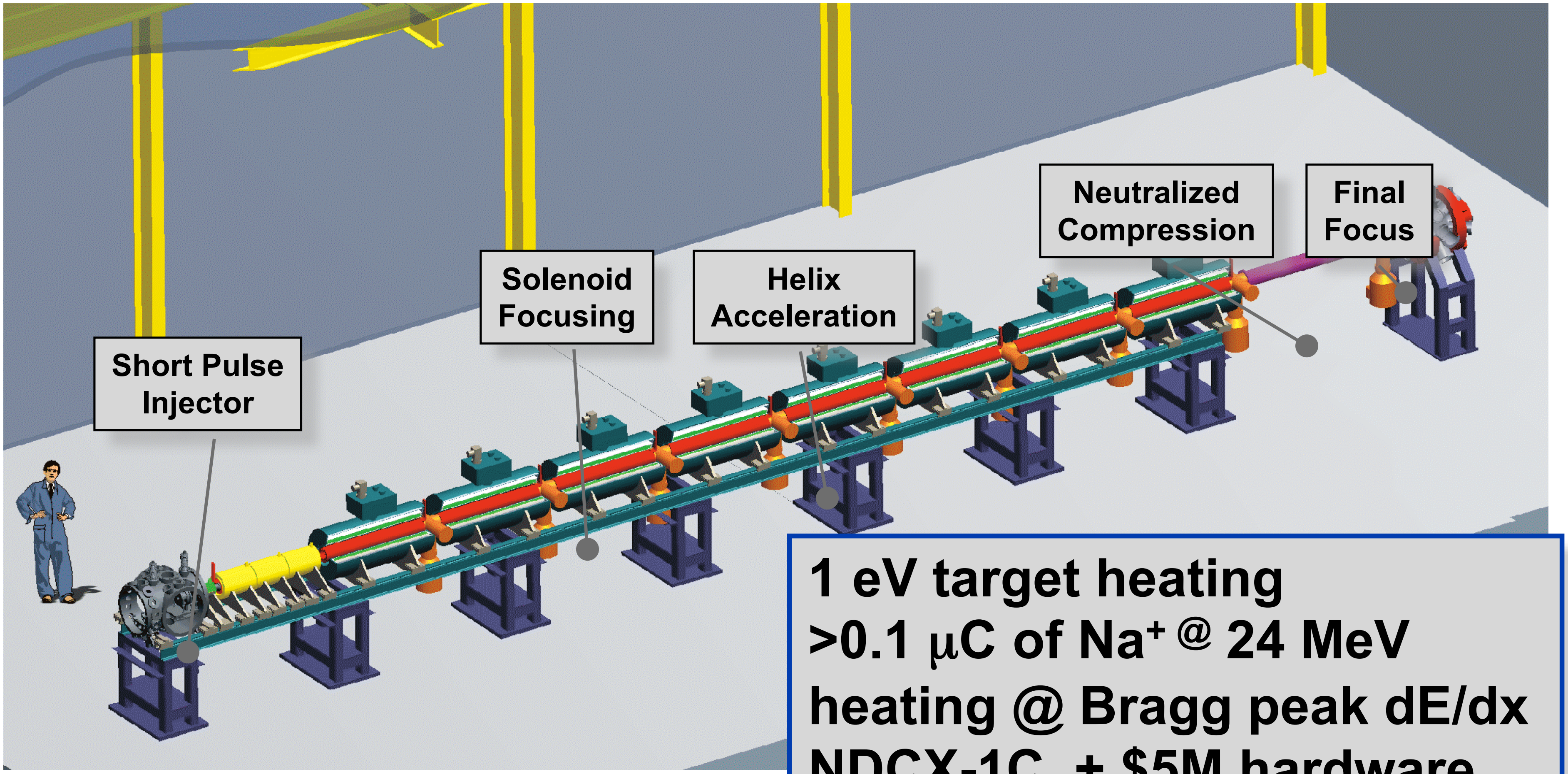


- **E. A. Startsev, H. Qin and R. C. Davidson, *Physical Review Special Topics on Accelerators and Beams* 8, 124201 (2005).**

Hydra simulations confirm temperature uniformity of targets at 0.1 and 0.01 times solid density of aluminum (20 MeV Ne+)



To validate IB-HEDPX (heavy-ion HEDP user facility) we plan a modest increment to upgrade NDCX-I →NDCX-II



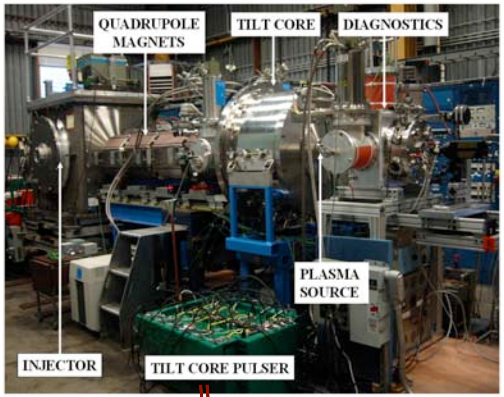
1 eV target heating
>0.1 μC of Na^+ @ 24 MeV
heating @ Bragg peak dE/dx
NDCX-1C + $5M hardware

Concept above uses a PLIA for 24 MeV Na^+, assuming gradient improves. Alternative: 2.8 MeV Li^+ using induction.

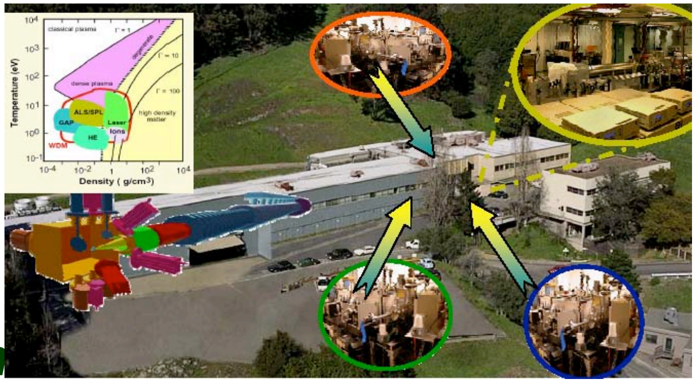
Outlook for next 10 years

Challenge 1: **(NDCX-I) Understand limits to compression of neutralized beams.** ***Excellent progress (>50X longitudinal; > 200 transverse). Opportunities for many improvements***

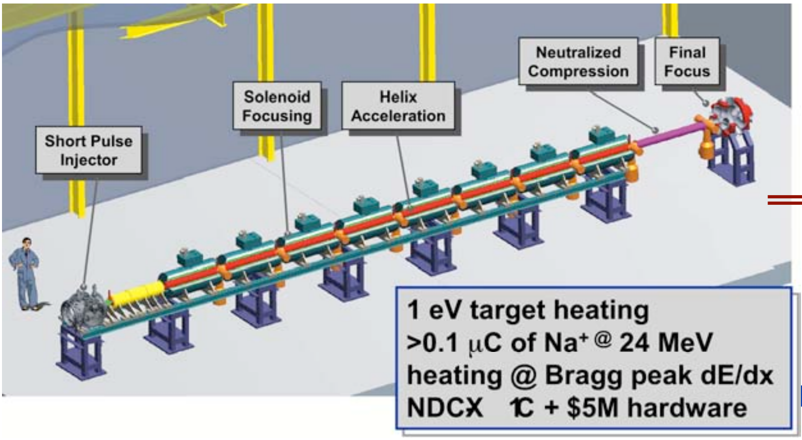
Challenge 3: **Ion-HEDP user facility** ***DOE Mission Need 12-1-05. CD-1 requires NDCX-II pre-requisite. May prototype approach to HIF***



Challenge 2: **Integrated compression, acceleration and focusing sufficient to reach 1 eV in targets:** ***Assessing backup induction approach with 2.8 MeV Lithium.***



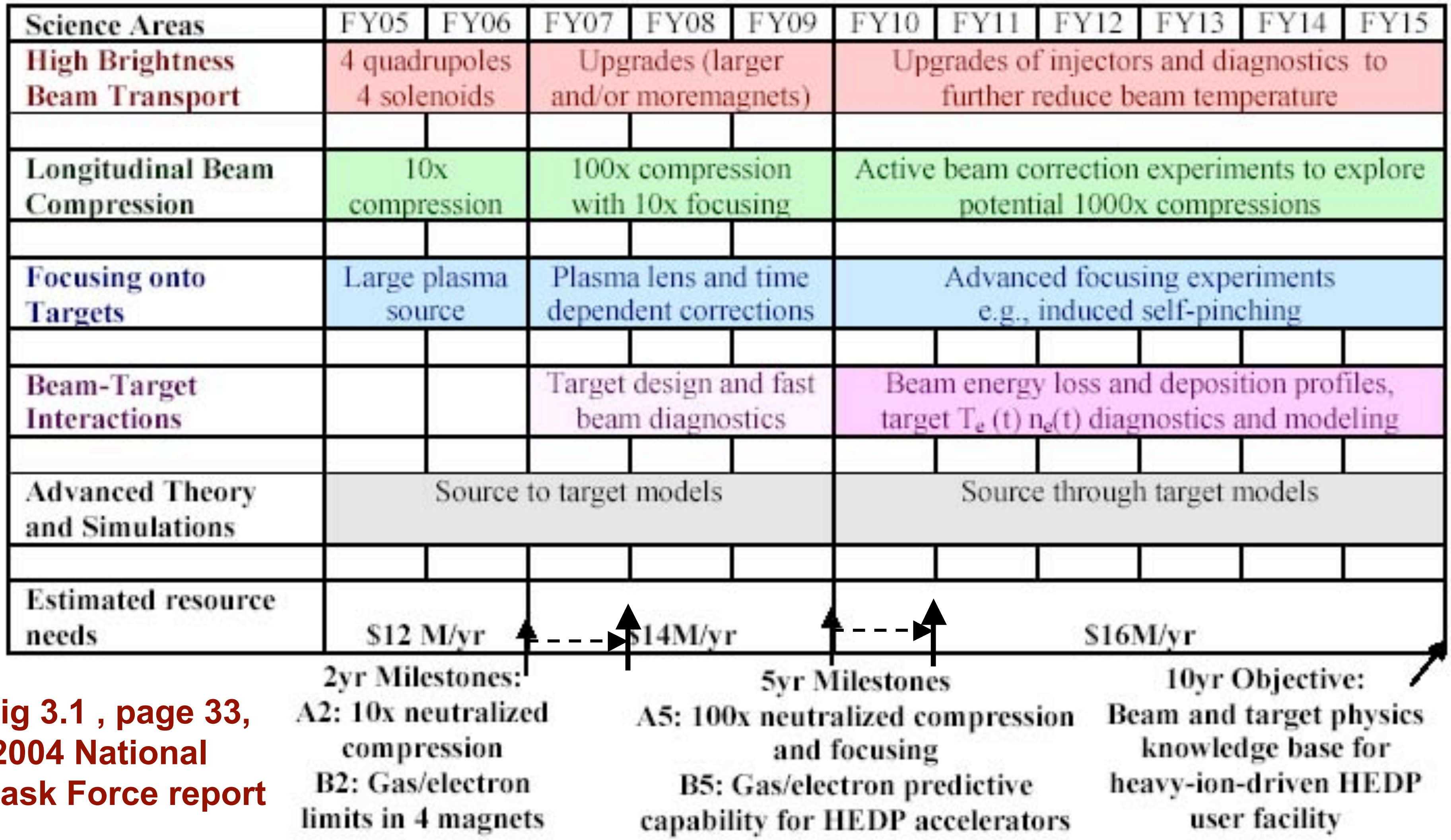
Add acceleration *(either PLIA or induction-TBD)*



1 eV target heating
>0.1 μC of Na$^+$ @ 24 MeV
heating @ Bragg peak dE/dx
NDCX 1C + $5M hardware

Add chambers, targets, HEDP diagnostics

The National Task Force report on HEDP summarizes the ten-year plan for heavy ion beam science. *HIF target and chamber science are missing.*



Science Areas	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14	FY15
High Brightness Beam Transport	4 quadrupoles 4 solenoids		Upgrades (larger and/or moremagnets)			Upgrades of injectors and diagnostics to further reduce beam temperature					
Longitudinal Beam Compression	10x compression		100x compression with 10x focusing			Active beam correction experiments to explore potential 1000x compressions					
Focusing onto Targets	Large plasma source		Plasma lens and time dependent corrections			Advanced focusing experiments e.g., induced self-pinching					
Beam-Target Interactions			Target design and fast beam diagnostics			Beam energy loss and deposition profiles, target T_e (t) n_e(t) diagnostics and modeling					
Advanced Theory and Simulations	Source to target models					Source through target models					
Estimated resource needs	$12 M/yr			$14M/yr				$16M/yr			

2yr Milestones:
A2: 10x neutralized compression
B2: Gas/electron limits in 4 magnets

5yr Milestones
A5: 100x neutralized compression and focusing
B5: Gas/electron predictive capability for HEDP accelerators

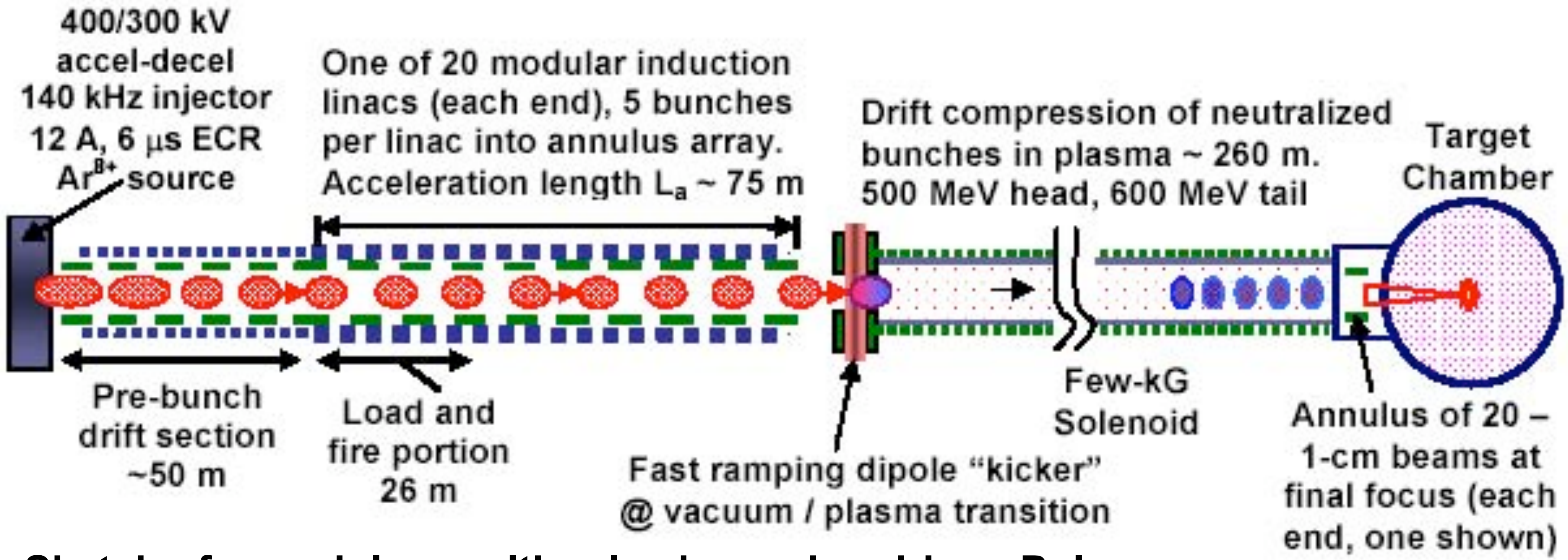
10yr Objective:
Beam and target physics knowledge base for heavy-ion-driven HEDP user facility

Fig 3.1 , page 33, 2004 National Task Force report

At the budget levels identified in the National Task Force report, we would continue to pursue WDM physics on NDCX as well as opportunities for additional driver, chamber and target science

1. We can complete the knowledge base needed to evaluate both quadrupole as well as solenoid-based drivers for HEDP and HIF:
    - First data on e-cloud effects with heavy ion beams in solenoids.
    - HCX could test halo scrapers and induction gaps to mitigate e-clouds in magnetic quadrupoles (at modest incremental cost)
    - Resume negative ion source research
2. Optical drive solid state switching + fast kickers (LLNL Beam Research innovations) may enable linac multi-pulsing and time-dependent corrections for compression velocity tilts→ improved target pulse shaping capability with fewer beams for both HEDP and HIF (can test on NDCX).
3. Compact liquid vortex chambers with embedded magnetic field may allow higher pulse rates and shorter focal lengths → smaller focal spot size. (Can use existing UC Berkeley laboratory equipment.)
4. Advanced HIF target design plus NIF and Z data may lead to lower heavy ion fusion driver requirements.

Work in progress: we are evaluating ways to apply what we learn from our HEDP research towards heavy ion fusion energy



Sketch of a modular, multi-pulse heavy ion driver. Pulses overlap at the target→ 500 TW peak power in 2 ns

Key enabling advances that will help both HEDP and fusion:

Neutralized drift compression and focusing.

Time-dependent correction for improved achromatic focusing.

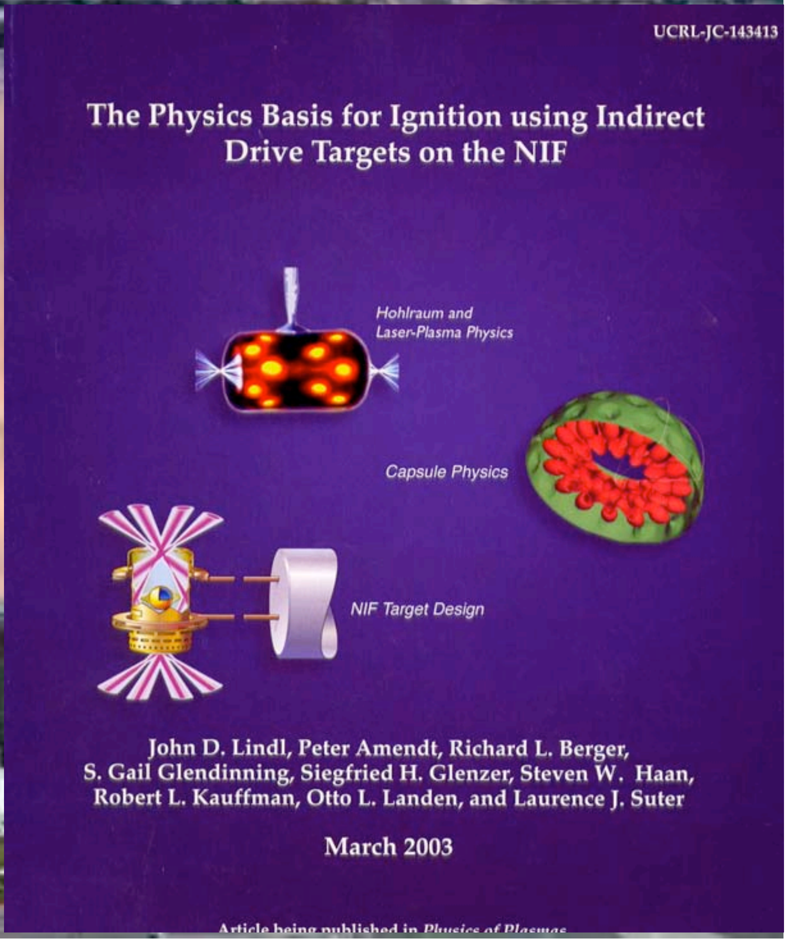
Multi-pulse longitudinal merging and pulse shaping.

Fast agile optically-driven solid state switching.

- NIF has demonstrated its performance specifications on early beams
- The facility will be completed in 2009
- Ignition baseline innovations make it significantly more robust
- The systems to support ignition including cryogenic targets, high reliability diagnostics, and user optics have been demonstrated and will be deployed for a 2010 campaign

The National Ignition Facility:

NIF ignition can validate hohlraum x-ray transport and capsule physics relevant to indirect drive approaches like heavy ion fusion



UCRL-JC-143413

The Physics Basis for Ignition using Indirect Drive Targets on the NIF

John D. Lindl, Peter Amendt, Richard L. Berger,
S. Gail Glendinning, Siegfried H. Glenzer, Steven W. Haan,
Robert L. Kauffman, Otto L. Landen, and Laurence J. Suter

March 2003

Article being published in *Physics of Plasmas*

Conclusions

- There have been many exciting scientific advances and discoveries during the past year that enable:
  - Demonstration of compression and focusing of ultra-short ion pulses in neutralizing plasma background.
  - Unique contributions to High Energy Density Physics and Heavy Ion Fusion
  - Contributions to cross-cutting areas of accelerator physics and technology, e.g., electron cloud effects, diagnostics, advanced simulation techniques, beam interaction targets.
- Heavy ion research on neutralized drift compression and e-cloud effects is of fundamental importance to both HEDP in the near term and fusion in the longer term.
- Experiments heavily leverage existing equipment and are modest in cost.
- Theory and modeling play a key role in guiding and interpreting experiments.
- There are new tools and knowledge to update studies of heavy ion fusion.

Back-up