Heavy-Ion-Driven High Energy Density Physics and Fusion

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Interagency Task Force Workshop

Marriott Rio, Maryland

May 24, 2004

Heavy-ion scientific challenges and solutions to high energy density physics and fusion

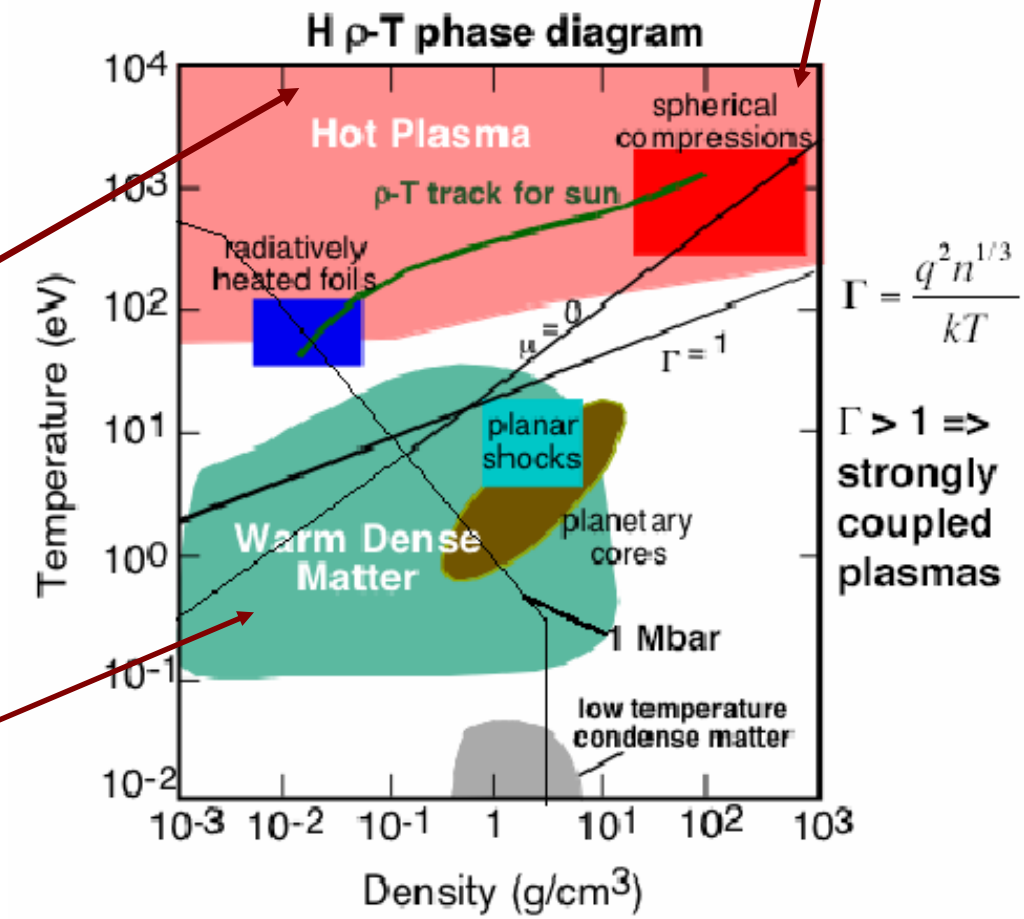
HEDP has rich discovery potential

***Fusion:* Effects of 3-D RT instabilities on burn propagation (NIF)**

Quark-gluon plasmas ***in heavy-ion nuclear collisions (way off scale in this chart)***

Fast igniter physics: ***fast electron dissipation enhancement via collective instabilities***

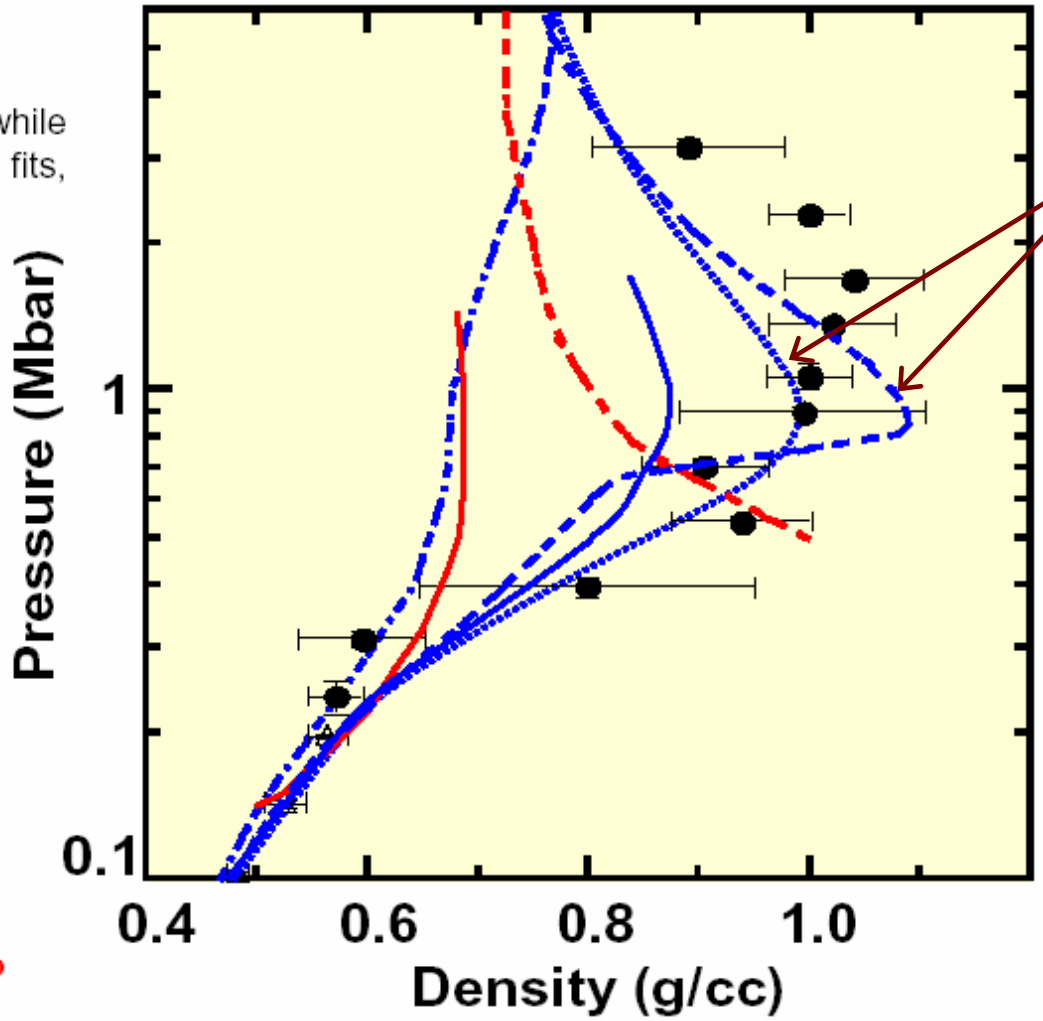
Strongly-coupled plasmas: ***Many ab-initio theories of strongly coupled plasmas remain un-resolved by existing laser data***



HEDP definition: U> 10^{11} J/m^3; P> 1 Mbar; kT > 1eV

Uniform isochoric heating is desirable to enable EOS measurements accurate enough to distinguish different *ab initio* WDM theories

- High pressure H data shows that no theory provides agreement; while models, with empirical fits, are better



Variations in temperature or density *less than a few percent over diagnostic resolution volumes* needed to distinguish various theories

We have an idea and several recent innovations to help us meet the challenge for HEDP

Idea: Ion beams entering a foil target just above the Bragg peak energy where $d^2E/dx^2 \rightarrow 0$ can provide more uniform deposition (Larry Grisham, PPPL).

Recent innovations:

- **Neutralized drift compression→ much shorter pulses *and* less expensive to test. Simulations show minimal impact of beam plasma instabilities.**

- **Solenoid/adiabatic plasma lens tolerate uncompensated velocity spreads with neutralized compression and focusing→ higher focus intensity.**

- **Injectors incorporating deceleration after initial acceleration and/or higher current density → shorter bunches needed for short pulse acceleration.**

Optimizing Uniformity and Magnitude of Power Deposition (Slide from Larry Grisham, PPPL)

Charge state equilibrium occurs rapidly in solids (0.3 - 0.5 microns for Ne to reach +7, Kaganovich); for ions heavier than helium, we assume beam of helium-like ions, so they enter the target at or very near equilibrium charge state; consequently energy deposition should be uniform almost immediately.

Bragg (dE/dX) curve peaks at 8 - 13 x 10^8 for beams from B to Cl, moving slowly higher with atomic number; peak location is only weakly dependent on target Z.

Because the rate of change of energy loss is smallest near the Bragg peak, picking a beam energy near, and preferably slightly above the peak, and a target thickness such that the beam exits before leaving the peak, gives the conditions under which both the energy deposited per unit volume and the uniformity through the target are maximized.

Typical Bragg Curves as a Function of Energy (Slide from Larry Grisham PPPL)

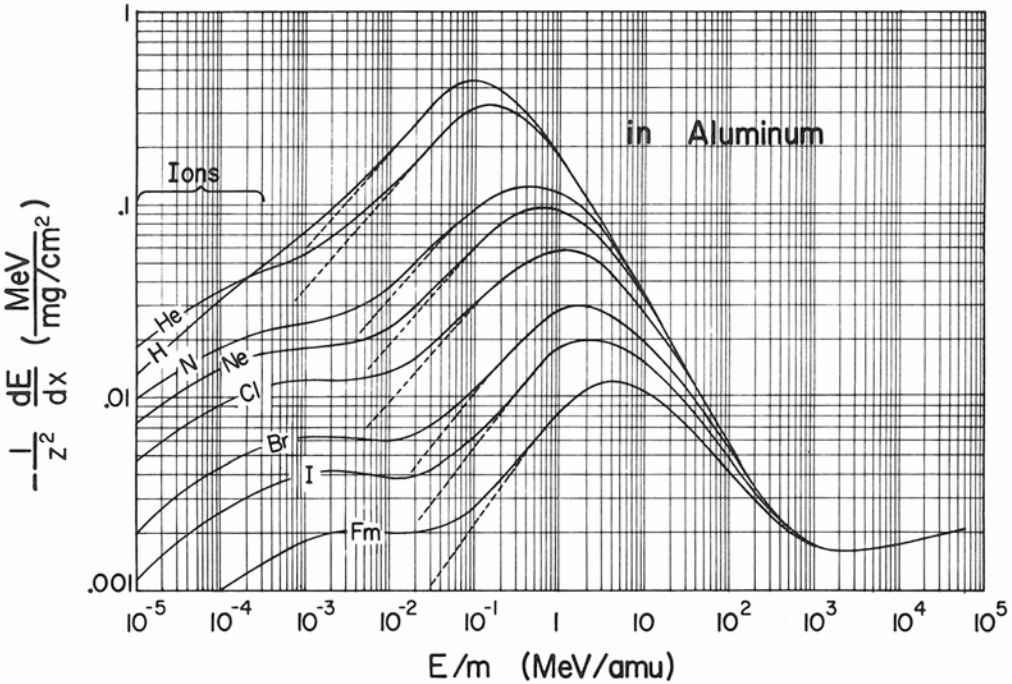
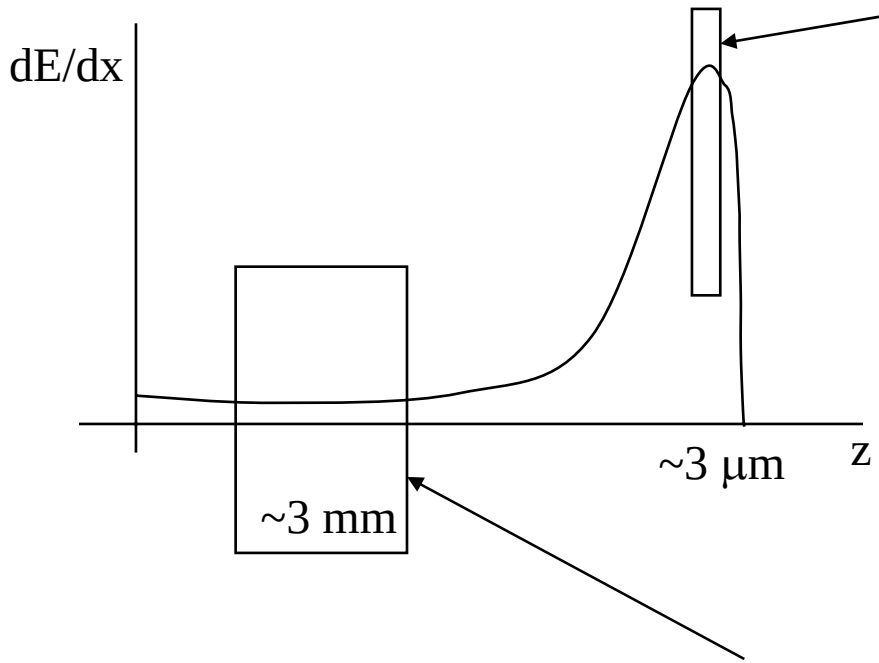


Fig. 1. Stopping-power curves for heavy ions in aluminum over a wide energy region

——— Semiempirical fit to available data
– – – – Electronic contribution at low energies; semitheoretical (Refs. 18, 19)

Two ion dE/dx regimes to obtain isochoric ion energy deposition in 1-to-few eV warm-dense matter targets

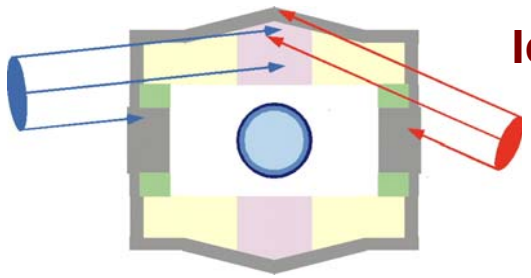


HIF linacs with ~ 0.5-1 J of ions @ ~0.3 MeV/u would work best heating thin foils near the Bragg peak where dE/dx~ 0

→ ~3 % uniformity possible (Grisham, PPPL). *Key-issue: can < 300 ps ion pulses to avoid hydro-motion be produced?*

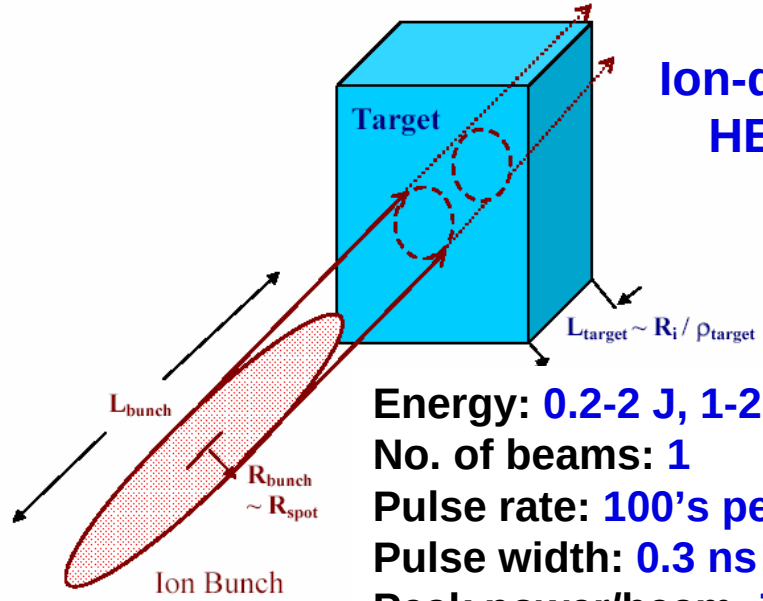
Heavy-ion beams of >300 MeV/u at GSI must heat thick targets with ions well above the Bragg peak→ kJ energies required @ <300 ns to achieve → ~15% uniformity.

Ion-driven targets for IFE and HEDP require common beam physics: high brightness injection and acceleration with precision waveforms, electron cloud control, longitudinal bunch compression, beam neutralization in chamber



Ion-driven IFE

Energy: 7 MJ, 4 GeV
No. of beams: 120
Pulse rate: 5 Hz
Pulse width: 8 ns
Peak power/beam: 5 TW
Focal spot radius = 2 mm
@ 6 meters focal length
Peak deposition 10^{12} J/m^3
(*per beam, into foam radiators*)

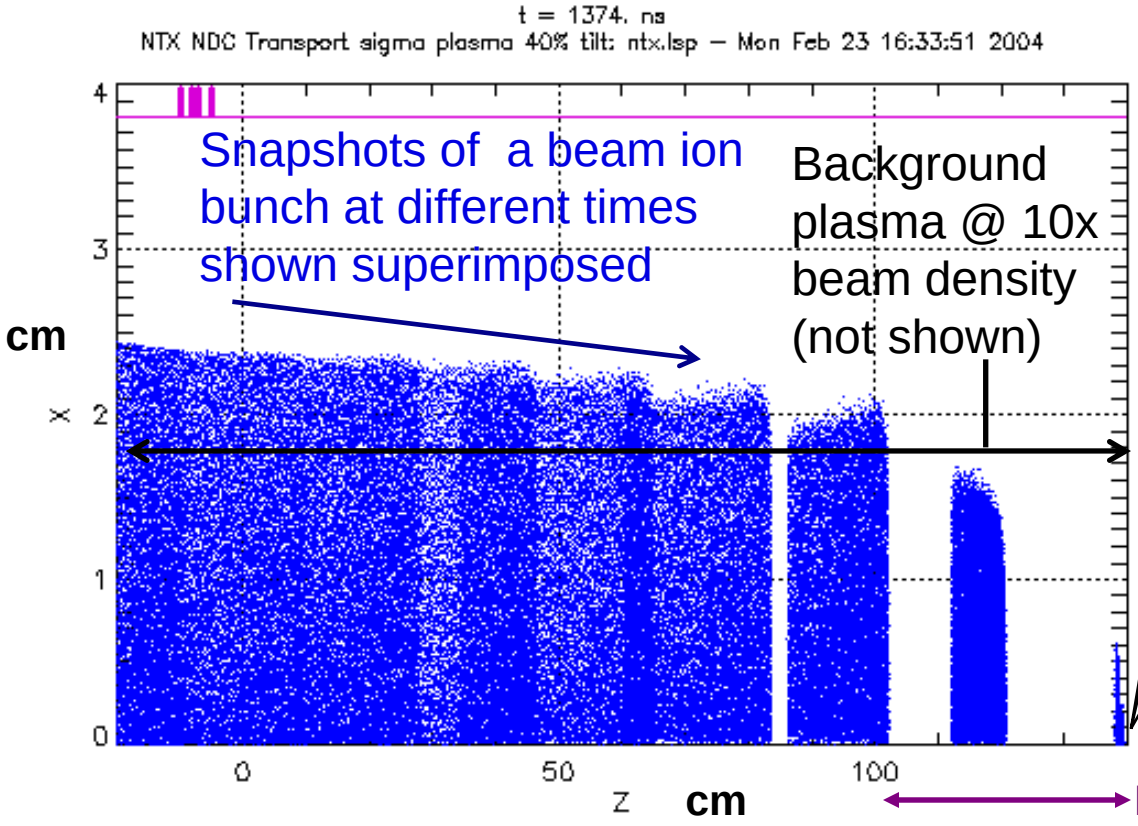


Ion-driven HEDP

Energy: 0.2-2 J, 1-2 MeV
No. of beams: 1
Pulse rate: 100's per day
Pulse width: 0.3 ns
Peak power/beam: 7 GW
Focal spot radius: 0.5-1 mm
@ 10 cm focal length
Peak deposition 10^{11} J/m^3
(*for 1 Mbar, 1 eV, WDM*)

A key new requirement for HEDP is sub-ns pulses (needs neutralized drift compression as well as chamber neutralization).

LSP-PIC simulations of proposed experiment (NDCX-I) show dramatically larger compressions of tailored-velocity ion beams *inside a plasma column* (Welch, Henestroza, Yu 3-11-04)



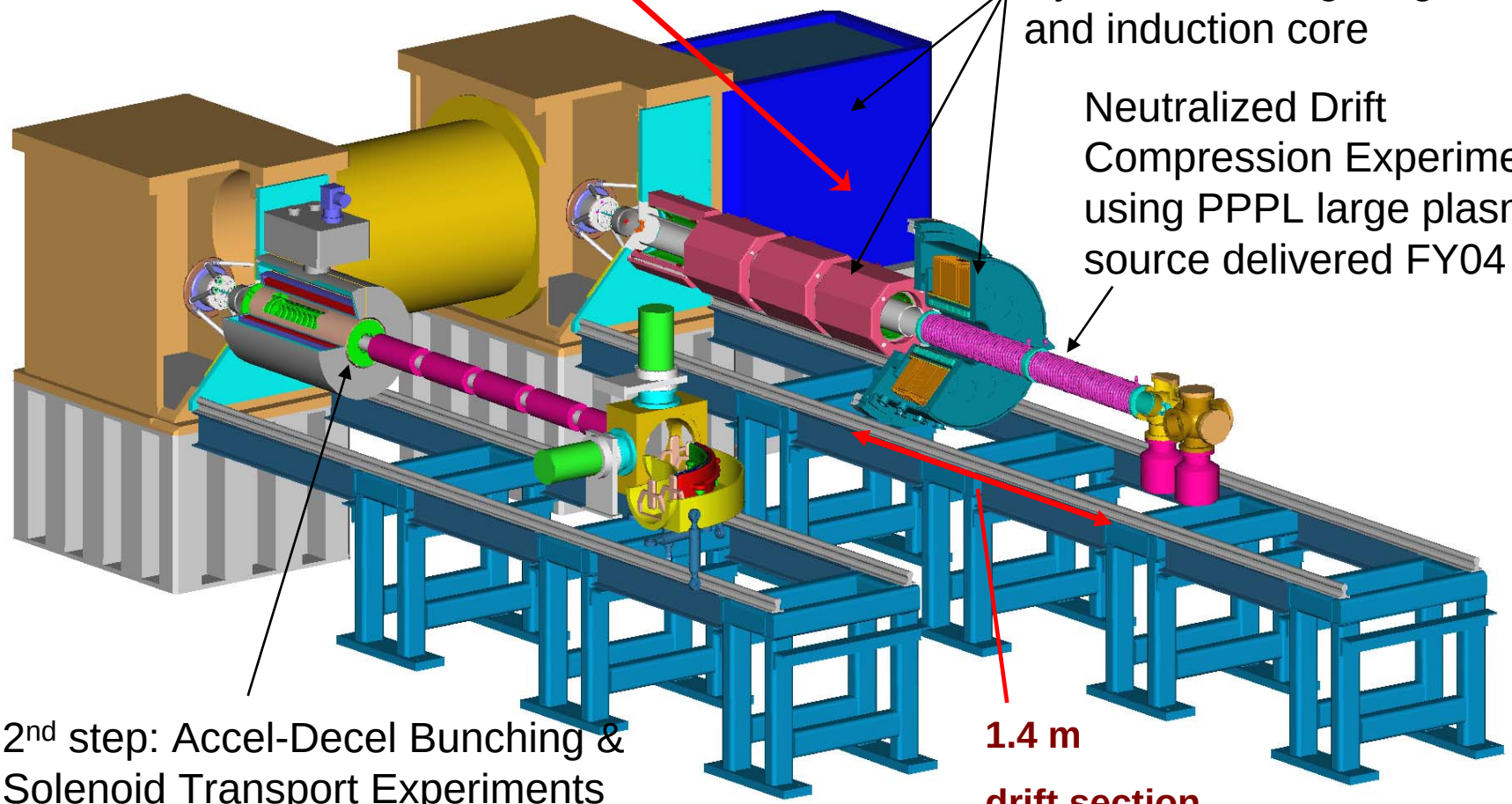
←Ramped 220-390 keV K^+ ion beam injected into a 1.4-m - long plasma column:

- Axial compression 120 X
- Radial compression to 1/e focal spot radius < 1 mm
- *Beam intensity on target increases by 50,000 X.*

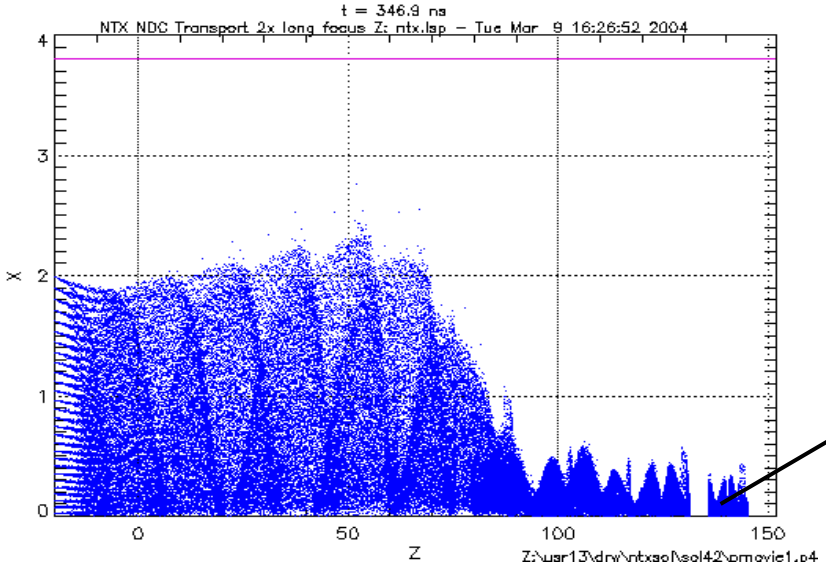
Existing 3.9T solenoid focuses beam

- **Velocity chirp amplifies beam power analogous to frequency chirp in CPA lasers**
- **Solenoids and/or adiabatic plasma lens can focus compressed bunches *in plasma***
- **Instabilities may be controlled with $n_p >> n_b$, and B_z field (Welch, Rose, Kaganovich)**

Intermediate experiments (~FY06) to assess physics limits of neutralized ion beam compression to short pulses (NDCX-I, before upgrade to NDCX-II)

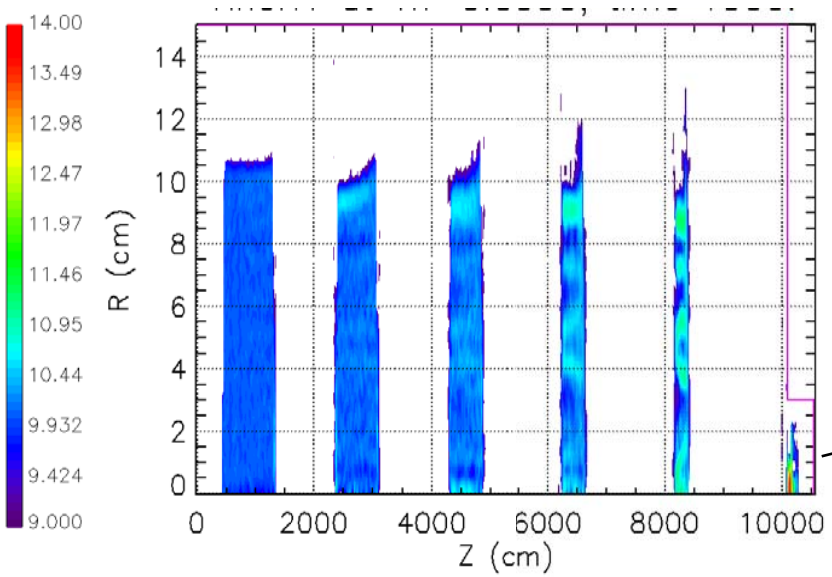


Additional preliminary simulations show neutralized compression and focusing may extend to higher energy regimes of interest to HEDP/IFE (Welch, et.al. MRC)



Example for FY09 integrated exp. (NDCX-II) for neutralized compression and focusing

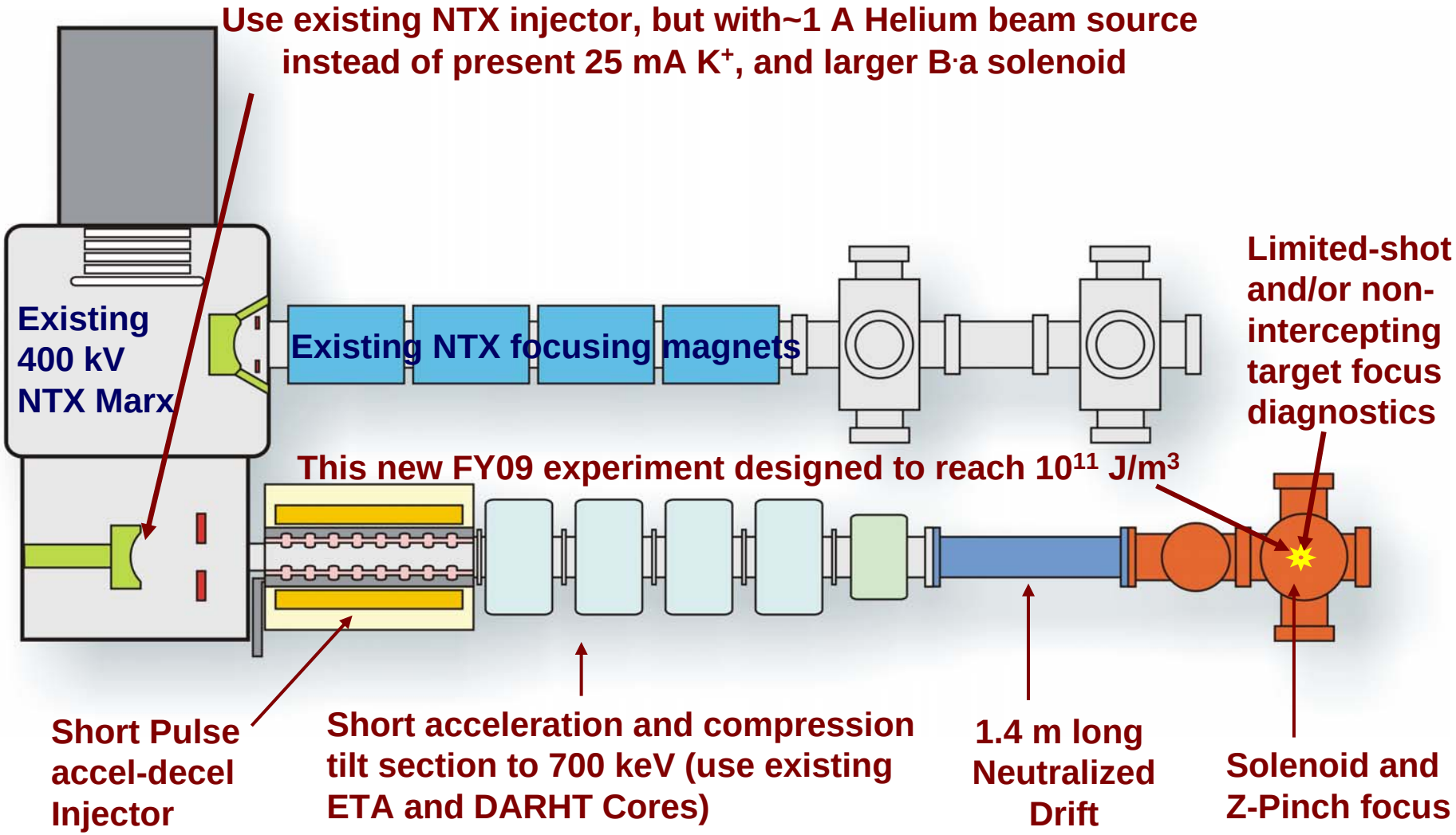
←Ramped 500-1000 keV, 10 A, 100 ns, 0.7 J He^+ ion beam injected into a 1.5-m -long plasma column compresses to 750 A @ <1 mm focus and ~ 1 ns→ $>10^{11}$ J/m^3



Possible modular driver example for IFE

←Ramped 200-240 MeV, 3 kA, 210 ns, 140 kJ Ne^+ ion beam injected into a 100-m -long plasma column shows filamentation but still compresses nicely to 140 kA, 5ns <5 mm focal spot radius for a hybrid-distributed radiator target.

FY09 milestone: Integrated beam experiments on neutralized compression and focusing to targets (NDCX-II)



Ten-year plan* to address the compelling question:
How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion ignition conditions?

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

submitted to Interagency Task Force & FESAC Priorities panels

Conclusion

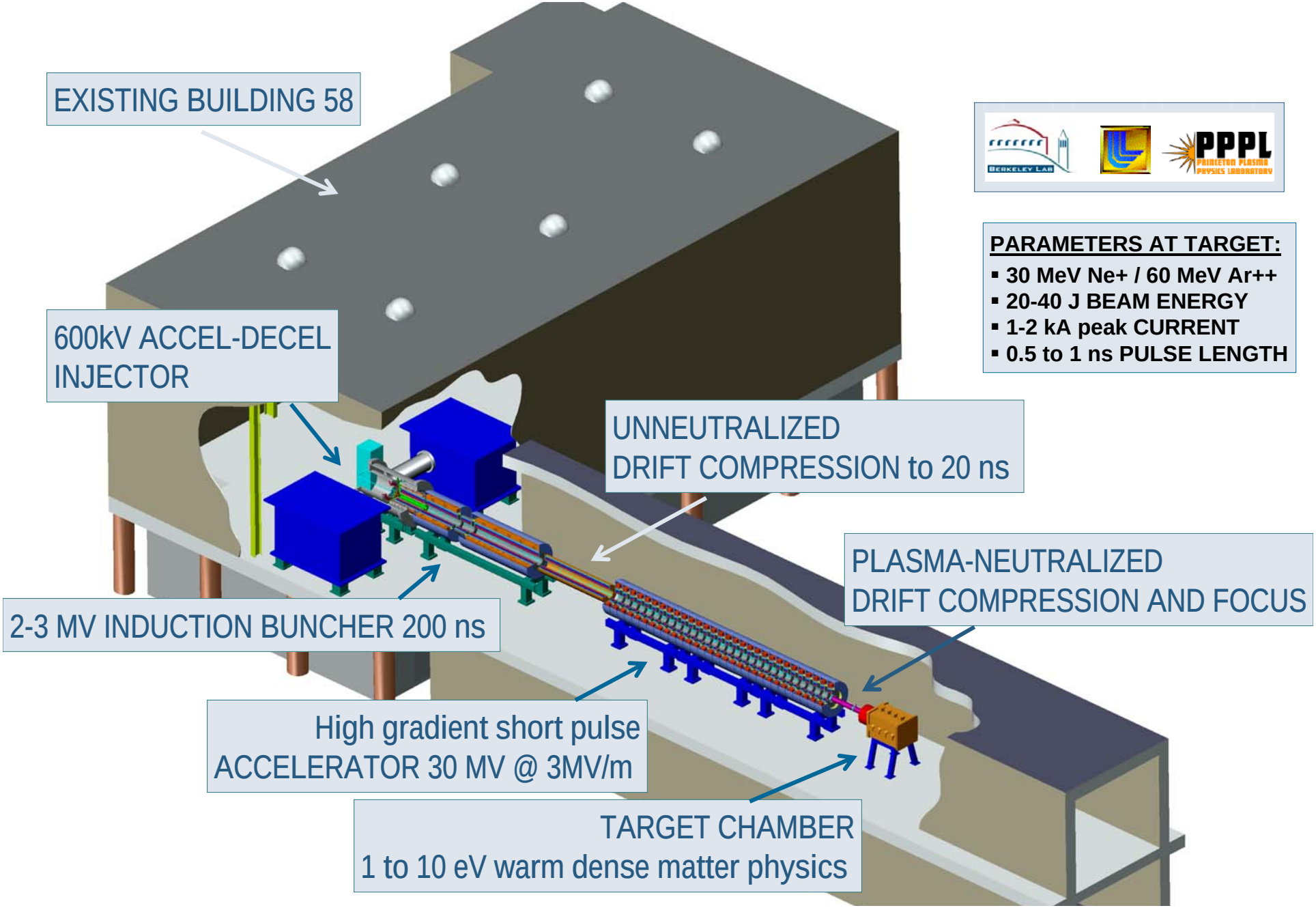
- **Scientific campaigns in high brightness transport, compression, focusing, advanced computational tools, and beam-target interaction address the top-level scientific question central to both HEDP and IFE:**

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

- **Understanding how beams can be compressed to 10^{11} J/m^3 (HEDP threshold) is a compelling intermediate step towards 10^{13}J/m^3 needed for IFE.**

- **The new 10 year plan would meet the OMB/OFES 10-Year Measure for IFE/HEDP: *"With the help of experimentally validated theoretical and computer models, determine the physics limits that constrain the use of IFE drivers in future key integrated experiments needed to resolve the scientific issues for inertial fusion energy and high energy density physics".***

Backup slides



PARAMETERS AT TARGET:

- 30 MeV Ne+ / 60 MeV Ar++
- 20-40 J BEAM ENERGY
- 1-2 kA peak CURRENT
- 0.5 to 1 ns PULSE LENGTH

NDCX-III High Energy Density User Facility Layout (FY 2015)