Overview of Heavy Ion Fusion / High Energy Density Laboratory Physics *

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On behalf of the Heavy Ion Fusion Science Virtual National Laboratory (HIFS-VNL)****
LBNL, LLNL, PPPL

Presentation in two parts:

1. *Heavy ion driven HEDP*
2. *Heavy ion fusion potential*

2007 Fusion Power Associates Annual Meeting

Oak Ridge, Tennessee

December 4-5, 2007

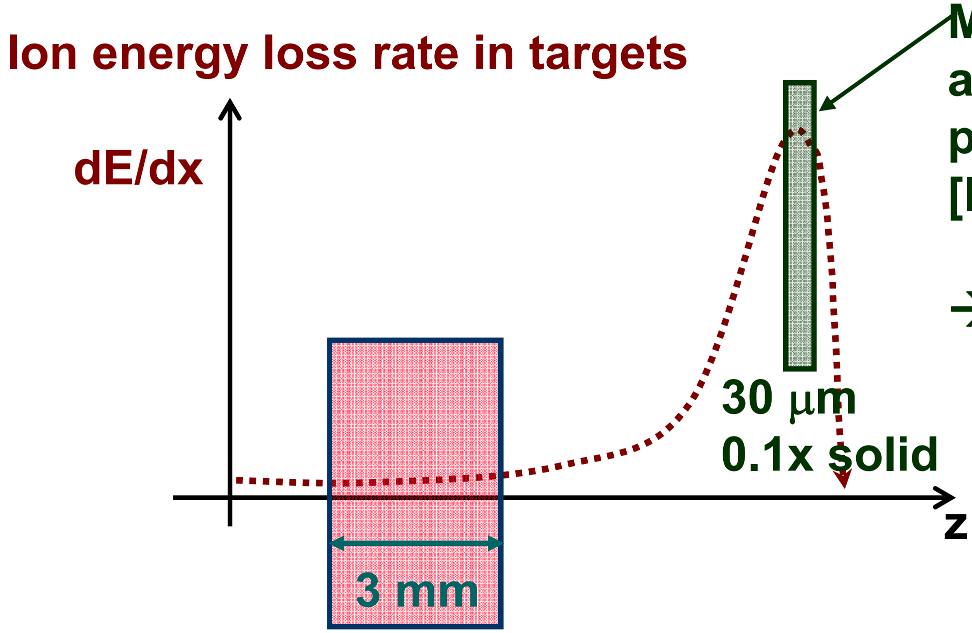
*This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Berkeley and Lawrence Livermore National Laboratories under Contract Numbers DE-AC02-05CH1123 and DE-AC52-07NA27344 , and by the Princeton Plasma Physics Laboratory under Contract Number DE-AC02-76CH03073.

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

Highlights of the US heavy ion fusion science program

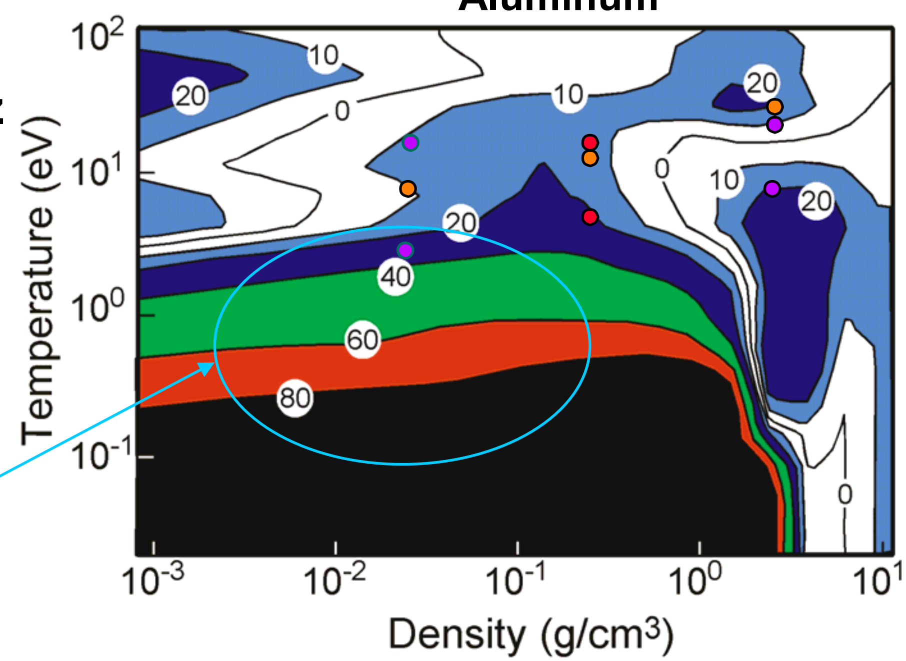
- Compressed intense heavy ion beams in neutralizing background plasma in NDCX-I: 150 ns down to 2 ns FWHM.
- Begun heavy-ion driven isochoric target heating experiments to 1 eV in joint experiments with GSI, Germany, to develop HEDP diagnostics.
- Unique diagnostic measurements of electron cloud effects on intense heavy-ion beam transport in both quadrupole and solenoid magnets.
- Computer simulation models that match the experimental results in both neutralized beam compression and e-cloud studies.
- ATA accelerator equipment sufficient for 3 to 6 MeV NDCX-II next step for both warm dense matter and ion direct drive target physics experiments.
- New LLNL Lasnex work on high gain HIF direct drive, and in-house capability to run HYDRA code for NDCX target design support, and to explore new heavy ion fusion direct drive target concept.

The HIFS-VNL pursues a unique approach to warm dense matter physics driven by intense, compressed ion beams



Maximum dE/dx *and* uniform heating at this peak require short (~ 1 ns) pulses to minimize hydro motion. [L. R. Grisham, Phys. Plasmas 11, 5727(2004)].

→Te ~ 0.5 eV in NDCX-I by FY09,
Te > 1 eV in NDCX-II by FY10+

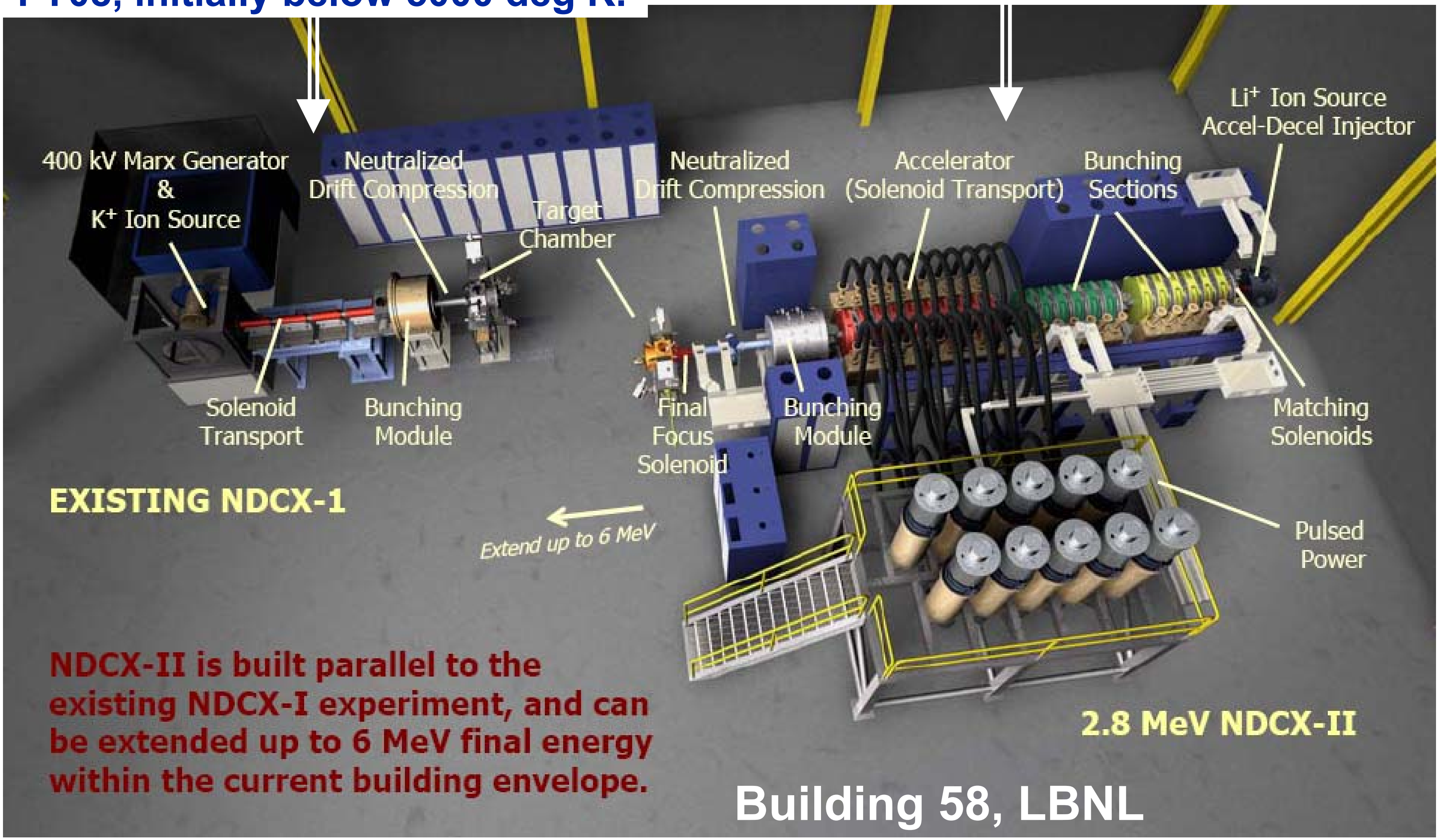


GSI: 40-100 GeV heavy Ions→
thick targets→ Te ~ 1 eV per kJ

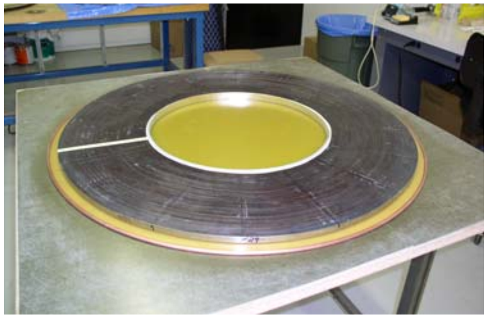
Dense, strongly coupled plasmas @ 10^{-2} to 10^{-1} *x* solid density are potentially interesting areas to test EOS models (Numbers are % disagreement in EOS models where there is little or no data)
(Courtesy of Richard W. Lee, LLNL)

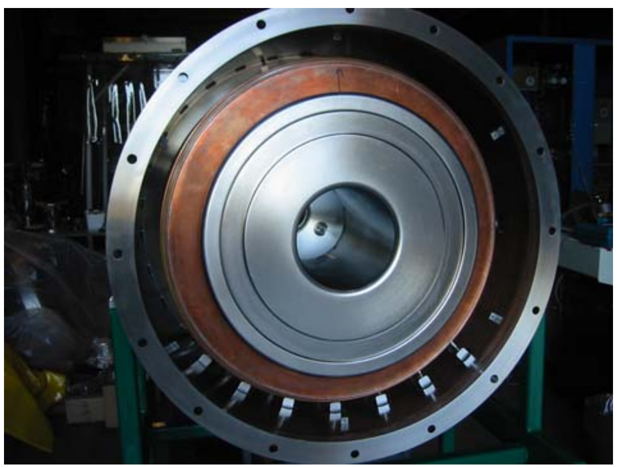
NDCX-I is being upgraded this year for first mm-scale warm dense matter experiments in FY08, initially below 5000 deg K.

NDCX-II, with 10X more beam energy using existing ATA induction nodules, is planned to be operational by 2010



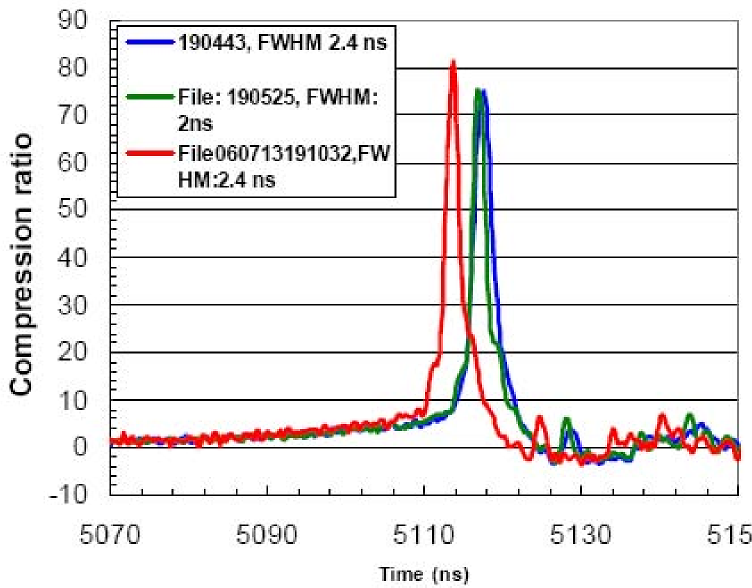
Induction Bunching Module #1 from First Point Scientific using Astron cores

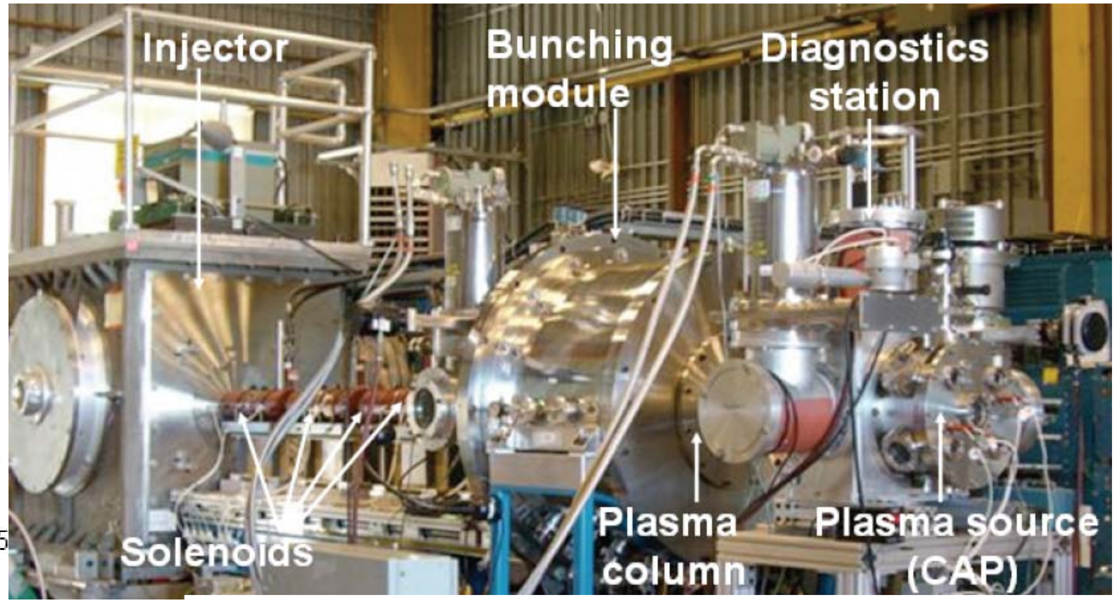




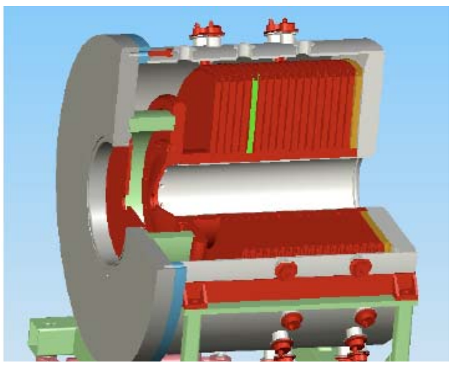
The neutralized drift compression experiment (NDCX-I) continues to improve longitudinal compression of intense neutralized ion beams

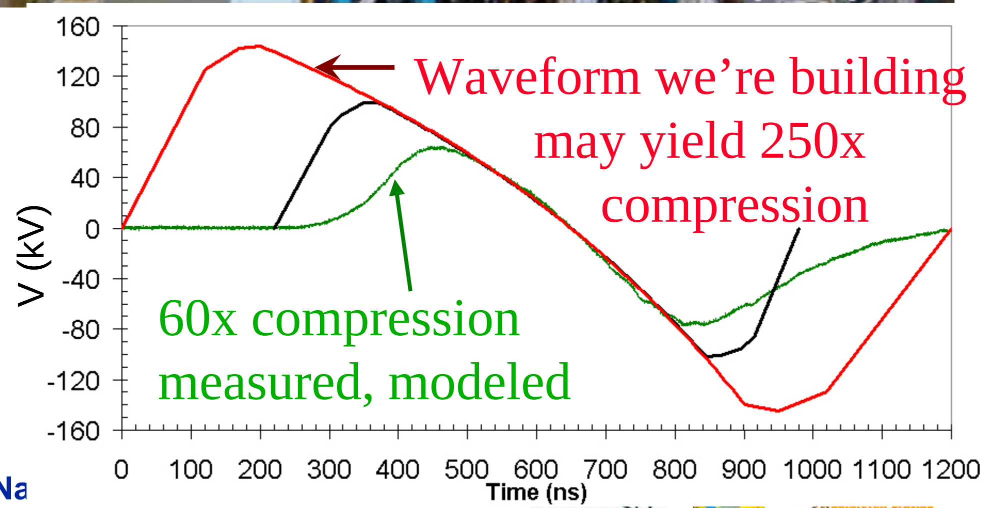
Shorter pulses (2.4 ns) obtained with new Ferro-electric plasma source





Simulations predict higher compression with new induction bunching module to be installed later this year

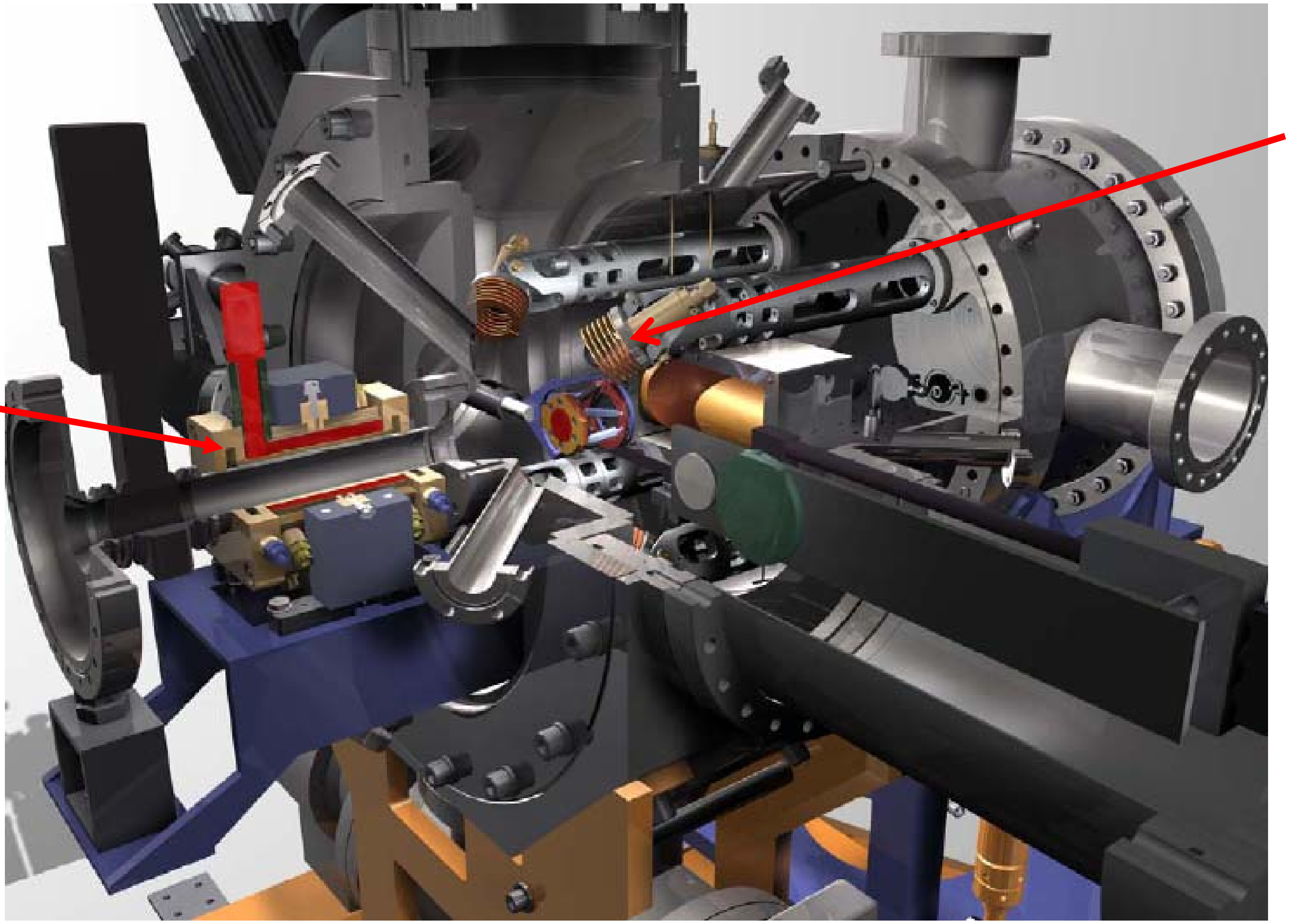




EXPERIMENTAL TARGET CHAMBER FACILITY FOR NDCX-1A INCLUDING DIAGNOSTICS NEEDED FOR FIRST TARGET MEASUREMENTS

M. LEITNER, F. BIENIOSEK, G. HANSEN, J.-Y. JUNG and P. NI

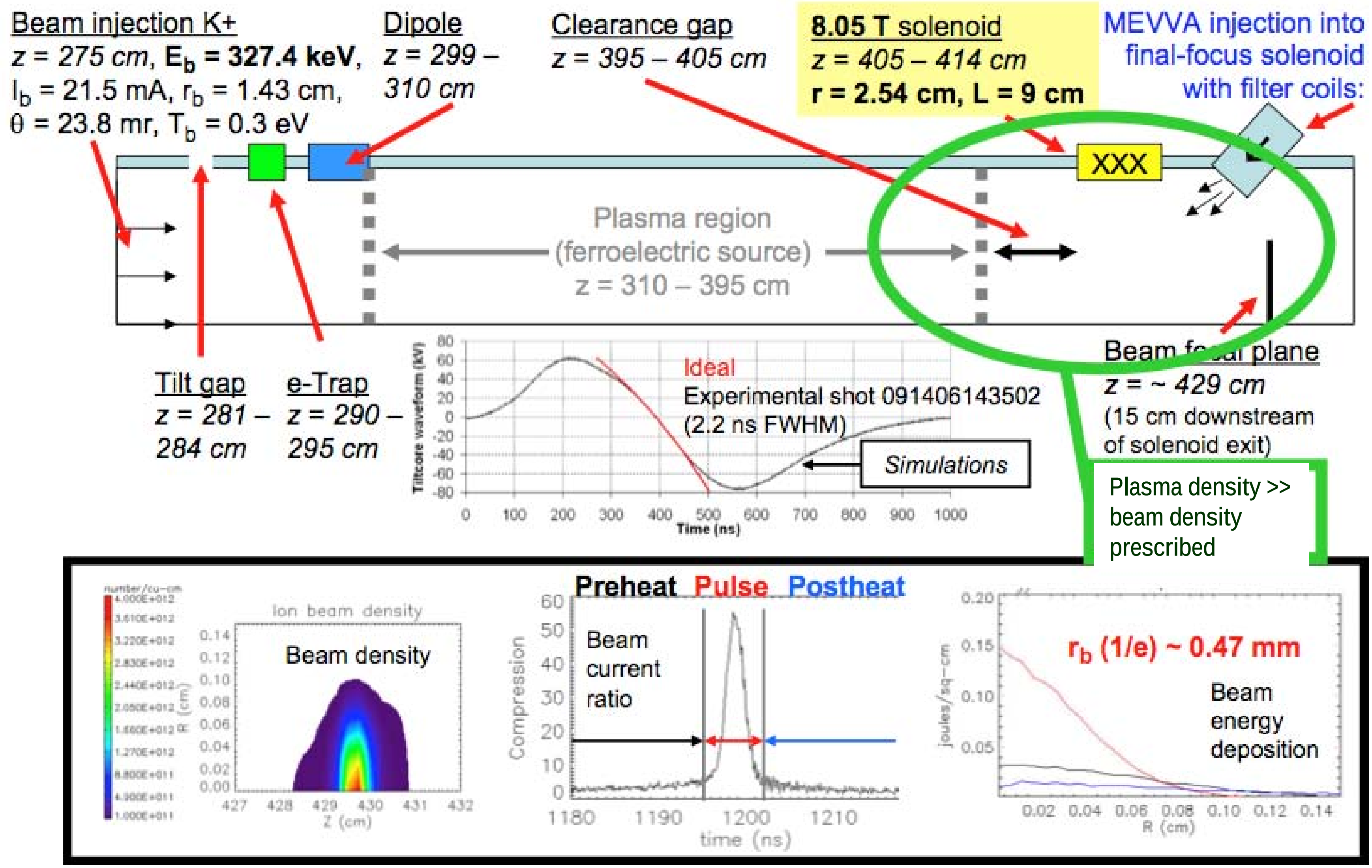
New 8 T pulsed focusing solenoid



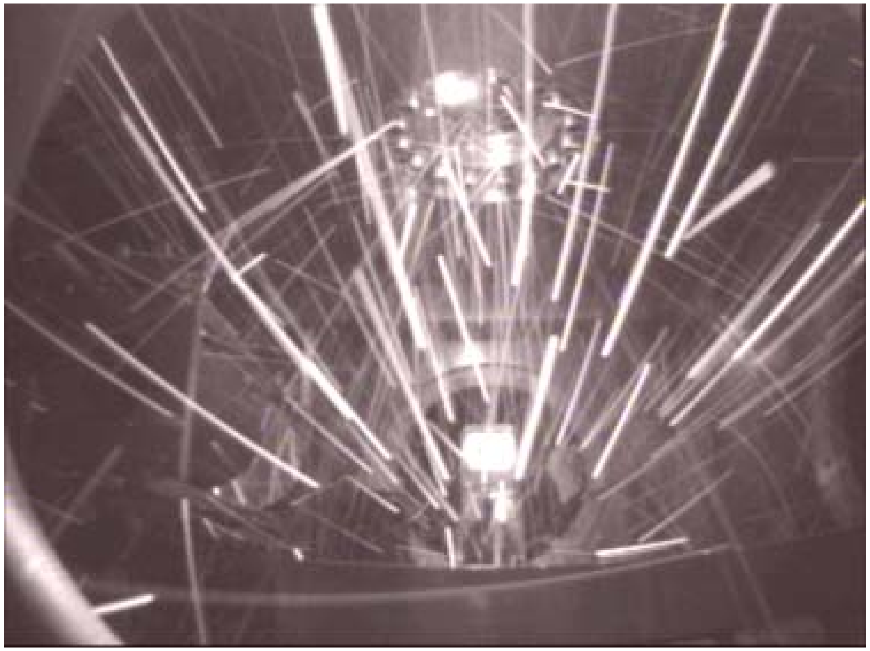
Four FCAP sources give > 20 X more plasma density near the focus!

Sept 15 2007

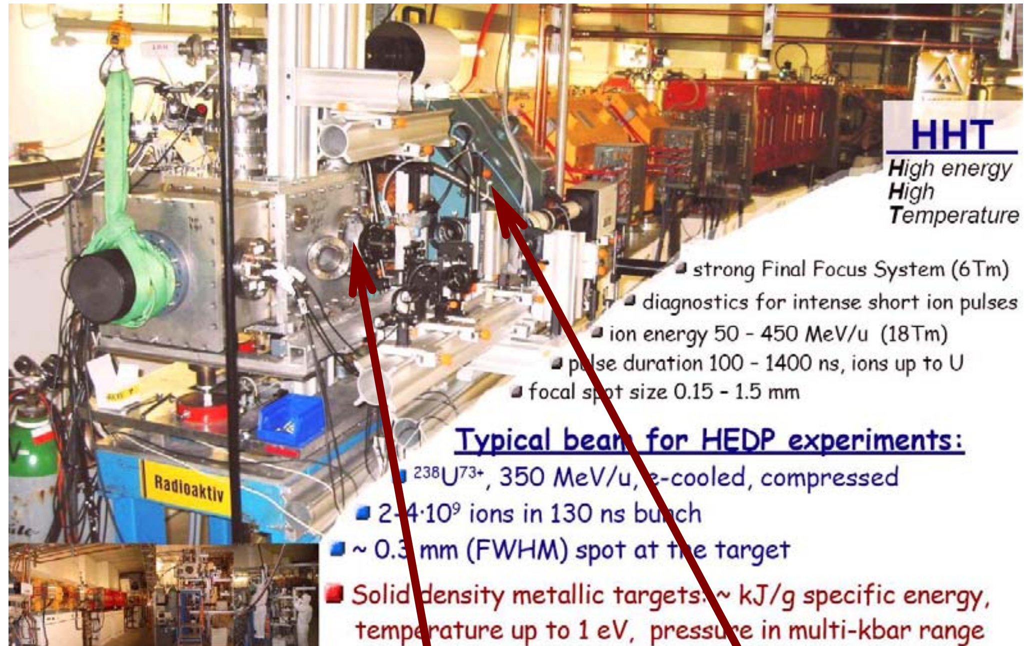
Simulations (Adam Sefkow, PPPL→SNL) show smaller NDCX-I focal spots will be possible with a higher field 8T focusing solenoid



We are developing diagnostics and two-phase EOS models in joint experiments with GSI for isochoric heating & expansion relevant to indirect drive HIF target radiators, and to droplet formation.



Visible ms camera frame showing hot target debris droplets flying from a VNL gold target (~ few mg mass) isochorically heated by a 100 ns, 100 J heavy ion beam to 10^{12} W/cm^2 and 1 eV in joint experiments at GSI, Germany.

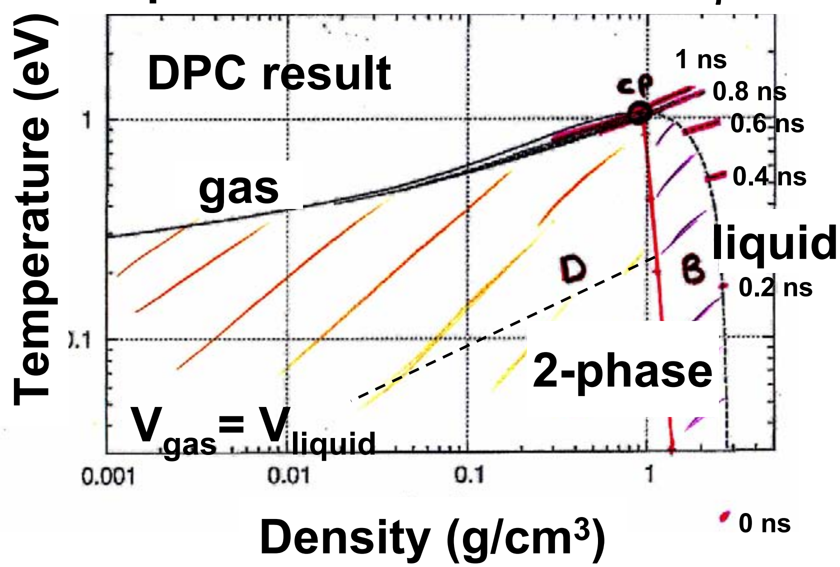


Final focus magnets

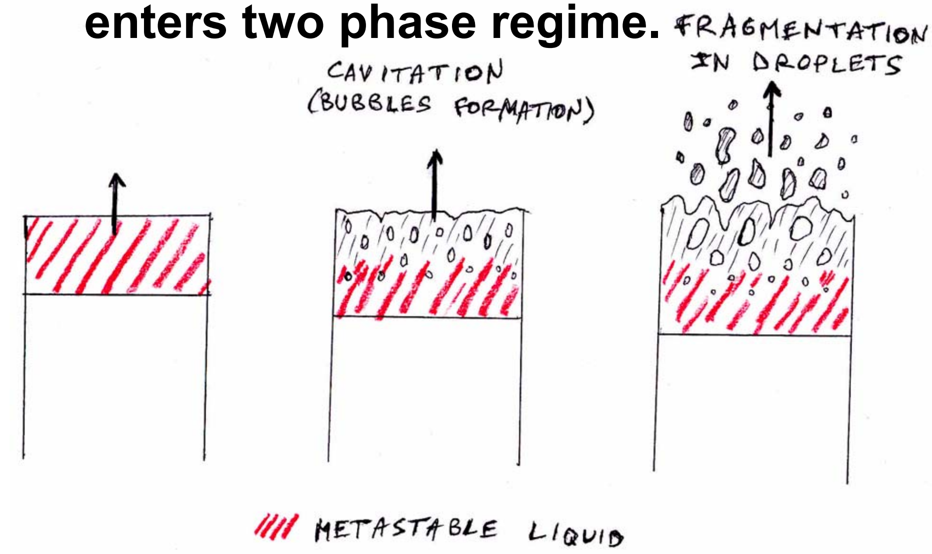
Measuring two-phase WDM EOS and expansion of target materials @ 1 eV can benchmark/improve models→ science that is also relevant to isochoric neutron heating effects in NIF high yield shots.

Formation of droplets during expansion of foil is being investigated

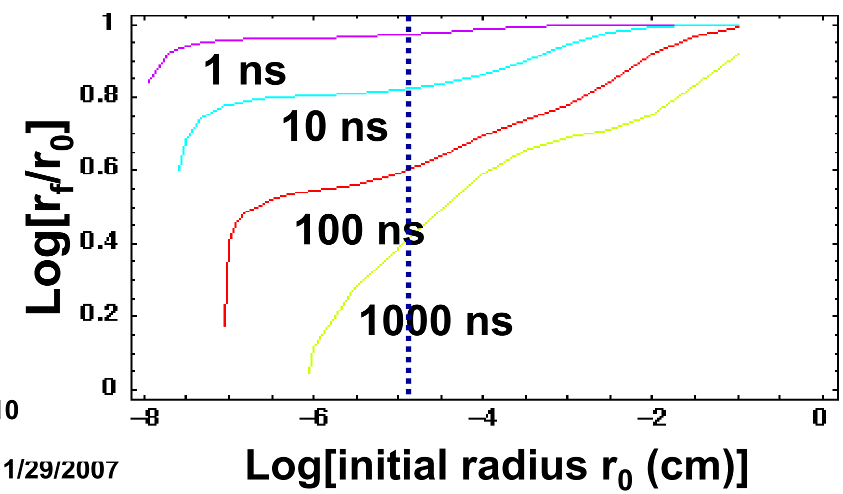
Example of evolution of foil in ρ and T



Foil is first entirely liquid then enters two phase regime.



Ref: J. Armijo, master's internship report, ENS, Paris, 2006.

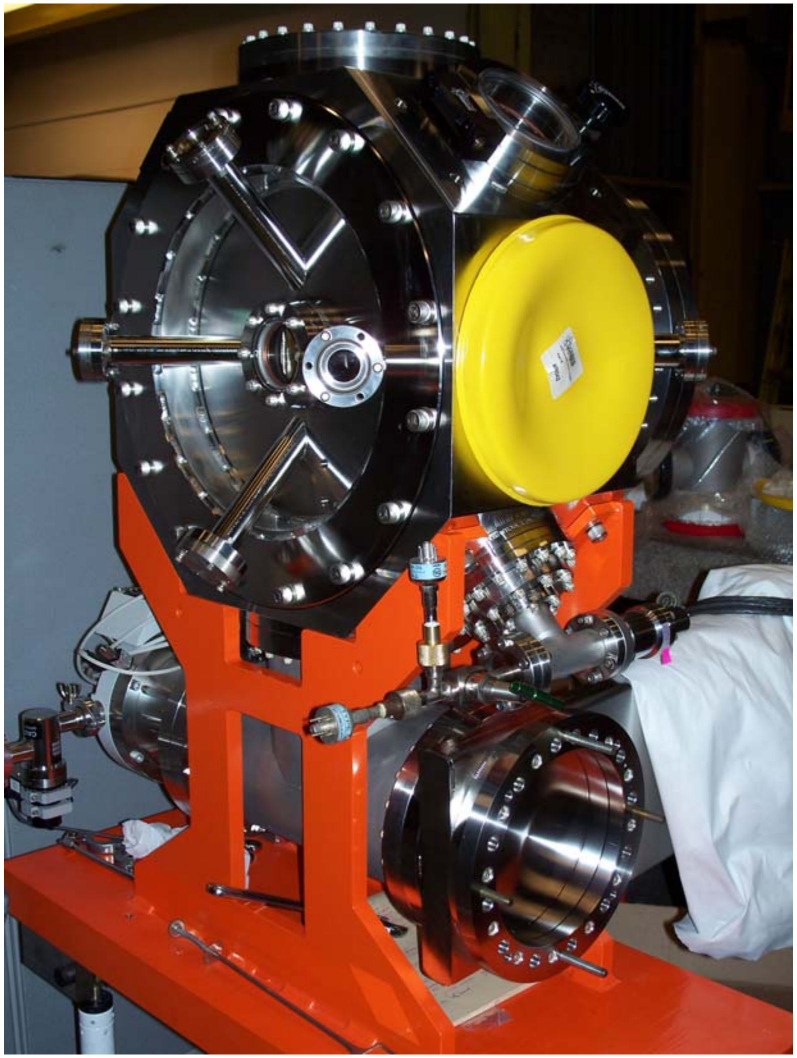


Evolution of droplet radius, (Armijo et al, APS DPP 2006, and in prep).

C. Debonnel and A. Zeballos are incorporating a model for surface effects into hydrodynamics code Tsunami

NDCX Infrastructure

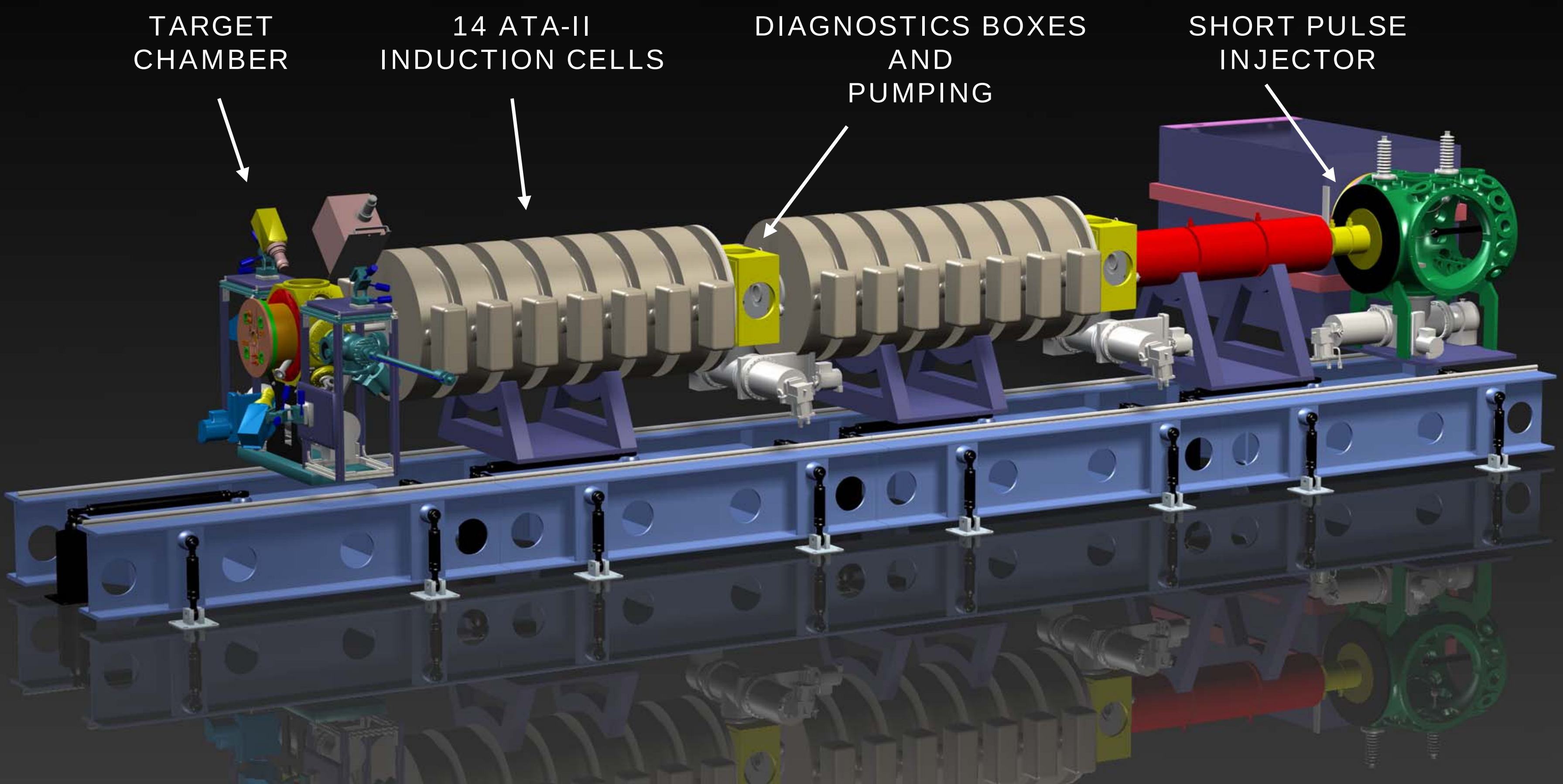
New target chamber



New optical diagnostics (“laser”) lab

The HIFS-VNL now has sufficient ATA parts on site to build NDCX-II, *enabling direct-drive coupling efficiency experiments*

Thanks to LLNL Beam Research Program, we have enough parts for 6 MeV of acceleration.
Our main cost item would be to replace solenoids to 1.5 to 2 T (6 m x 100K/m ~ $600K)



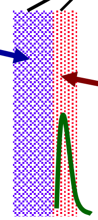
→NDCX-II: Validates CD-0 pre-requisite for IBX-HEDPX

SHOWN USING AVAILABLE ATA CELLS.
Blumlein pulsed power modules not shown.

Double-pulse or ramped-pulse planar target interaction experiments should reveal *unique* heavy-ion direct-drive coupling physics

Solid D_2 "payload"

Time just before first pulse

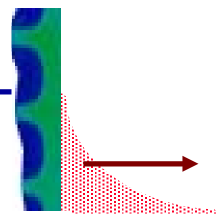


Payload and ablator D_2 layers are doped with different impurities to diagnose optical depth modulations

Ablator D_2 layer ~ > than initial ion range

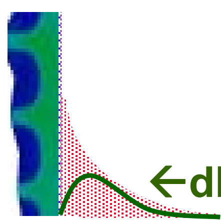
First ns ion beam pulse dE/dx (beam enters from the right)

Time ~ 10 ns later before second pulse arrives



RT "bubbles & spikes" grow measurable amplitudes.
(1) Can upstream beam GHz RF modulation reduce RT?
(2) Do RT non-uniformities in ablation plasma smooth out with time and distance (any "ablative stabilization")?

2nd higher energy ion pulse arrives, and stops *partly within ablation blow-off* (in 1-D)

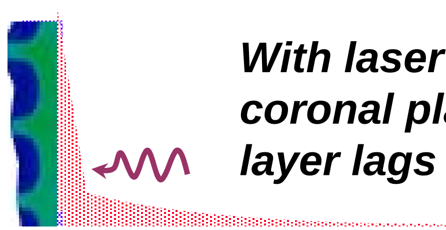


(1) "Rocket science": what ion range/ablator thickness maximizes hydro implosion efficiency with later ion pulses interacting with ablation layer mass?

← dE/dx of second ion beam pulse /later part of a ramped-pulse

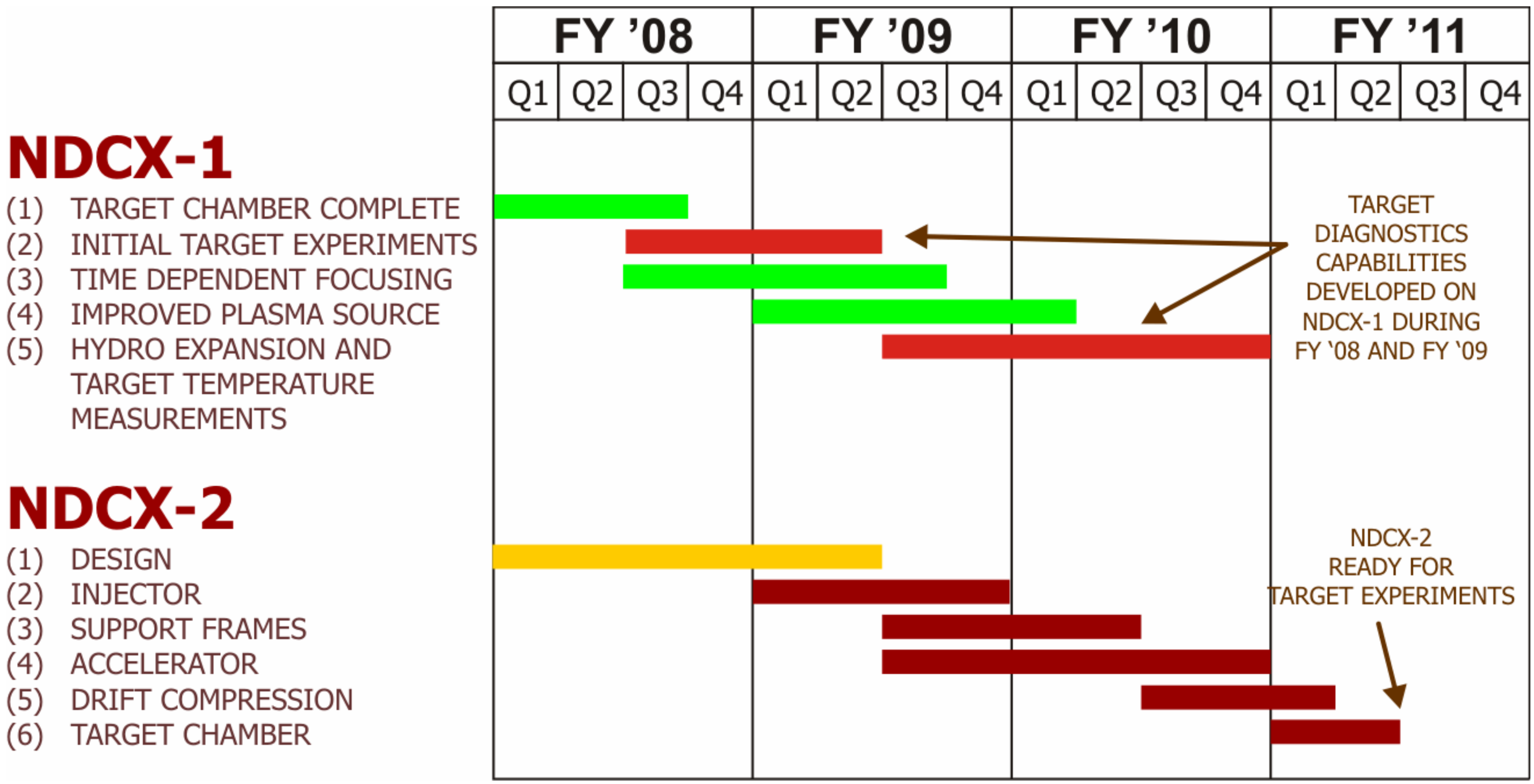
(2) How is RT growth affected (any "cloudy day" effect?)

With laser direct drive, later pulse ablates at fresh critical density layer further left



With laser direct drive, light transmits through most coronal plasma → Absorption in inverse bremsstrahlung layer lags behind dense shell trajectory

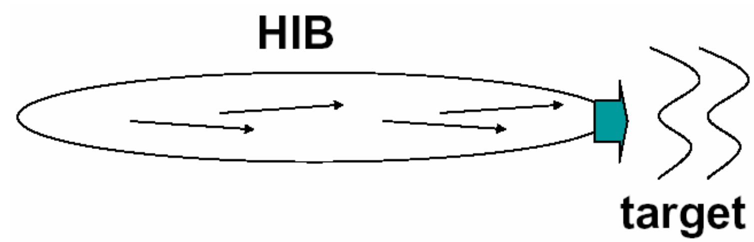
Proposed schedules for NDCX-I and NDCX-II in the updated HIFS-VNL Five Year Plan for FY09-FY13



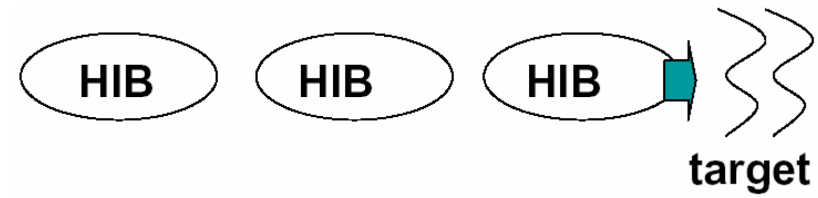
Hardware mods/assembly cost \$4.7M= \$1.7M (09) + \$2.5M (10) + 0.5M (11)

S. Kawata (Utsunomiya U.) has proposed several techniques to reduce RT growth in ion-beam-driven direct drive

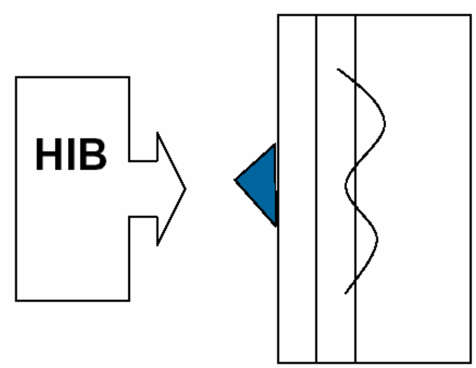
HIB axis rotation or swing
-> reduce the R-T growth!



Successive HIBs induce a dynamically Oscillating *g*!
-> reduce the R-T growth!



Large-scale HIB-energy deposition profile
-> Large-scale density gradient
-> Reduce the R-T growth!



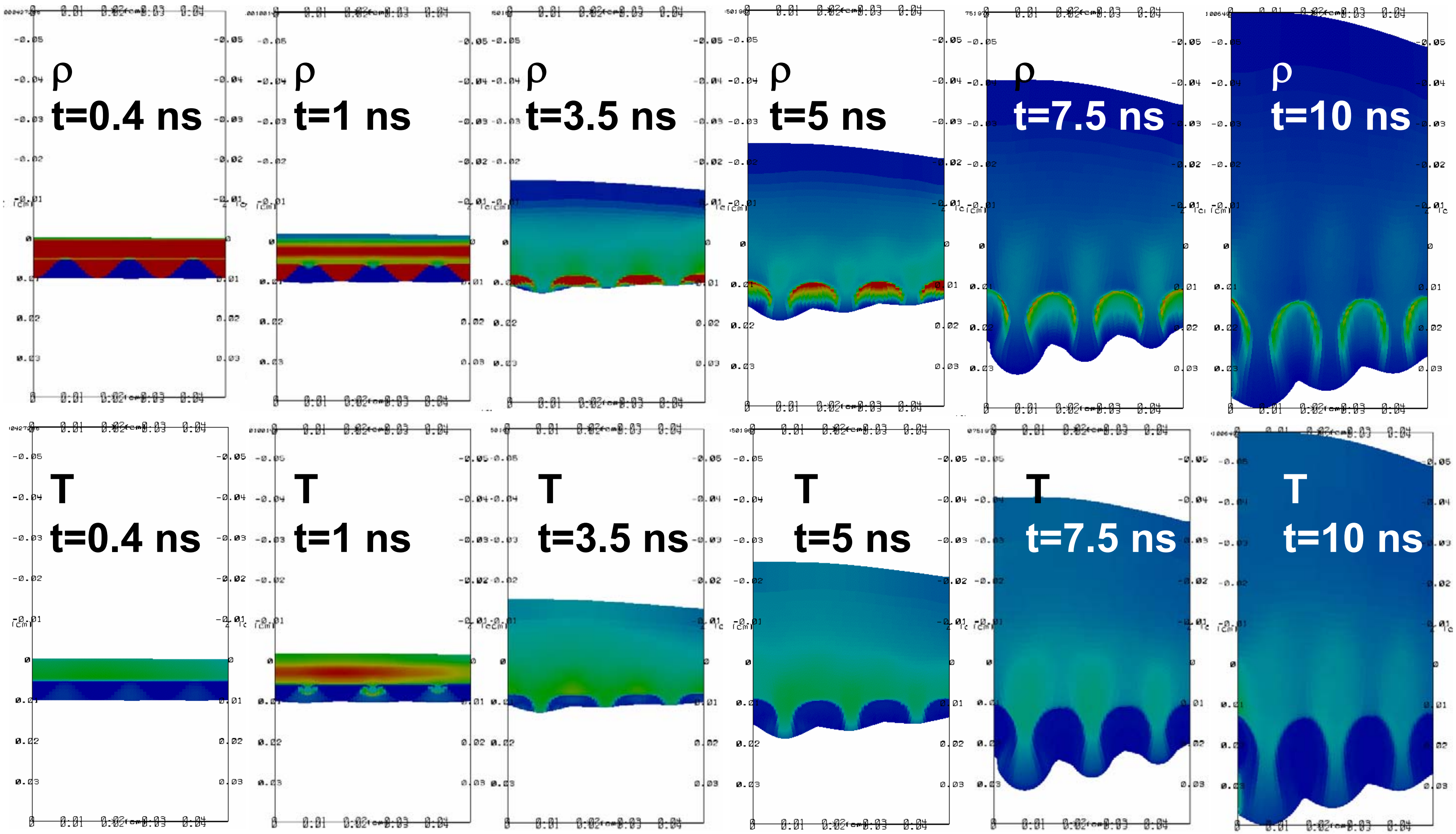
δg(x), induced by an shaped Ablator, controls R-T phase & growth

L&PB, 11(1993)757

Shaped target with an Ablator for R-T phase control

→These techniques can be explored on NDCX-II or IB-HEDPX

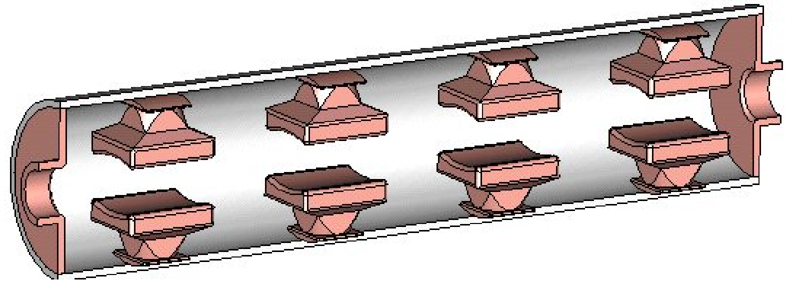
We have used the LLNL HYDRA code to show how unique heavy ion direct drive hydrodynamics as well as WDM can be studied on NDCX-II



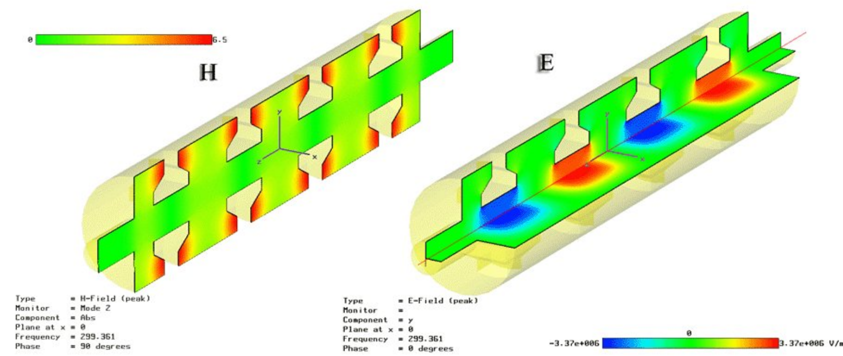
Can modulated beams stabilize ion Rayleigh-Taylor modes? (S. Kawata)

Our GSI/ITEP collaborators are developing the tools we would need to test dynamic stabilization of ion direct drive RT instability

ITEP design of RF HIB GHz Wobbler for GSI

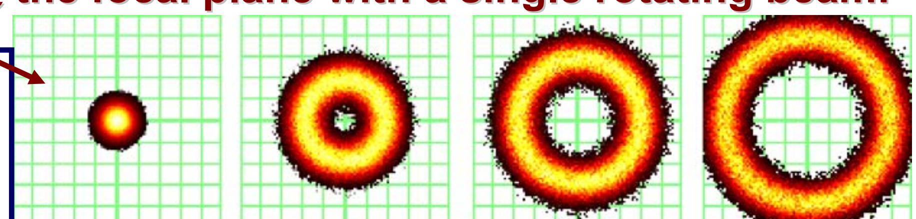


(Much lower RF fields are required to modulate 100 MeV Ar beams compared to 200 GeV Uranium beams!)



Beam spot rotation improves symmetry for direct drive: fewer beams needed for azimuthal symmetry

Transverse beam intensity distributions @ the focal plane with a single rotating beam!



→Two sided (polar) direct drive implosion studies may be possible with two twirled ion beams from two linacs, each with 10-pulse picket fences

RF wobblers: rapid beam rotation about a polar axis:

- **More natural approach to two-sided polar drive geometry most compatible with preferred long-lasting liquid-wall chambers**

- **With sufficient rotation frequency, possible improved drive symmetry and smoothness with much fewer beams compared to designs with fixed beam pointing- simpler driver-chamber interface.**

- **Fast RF beam deflection wobbers designed for beam rotation can *also* incorporate control to "zoom" the beam radius off axis during the implosion to improve beam target coupling efficiency.**

- **Fast beam rotation might reduce Rayleigh Taylor instability growth.**

We invite our Japanese collaborators to join us with our Russian collaborators to explore these topics with a goal of beam experiments within the next four years.
→success may revolutionize HIF target design!

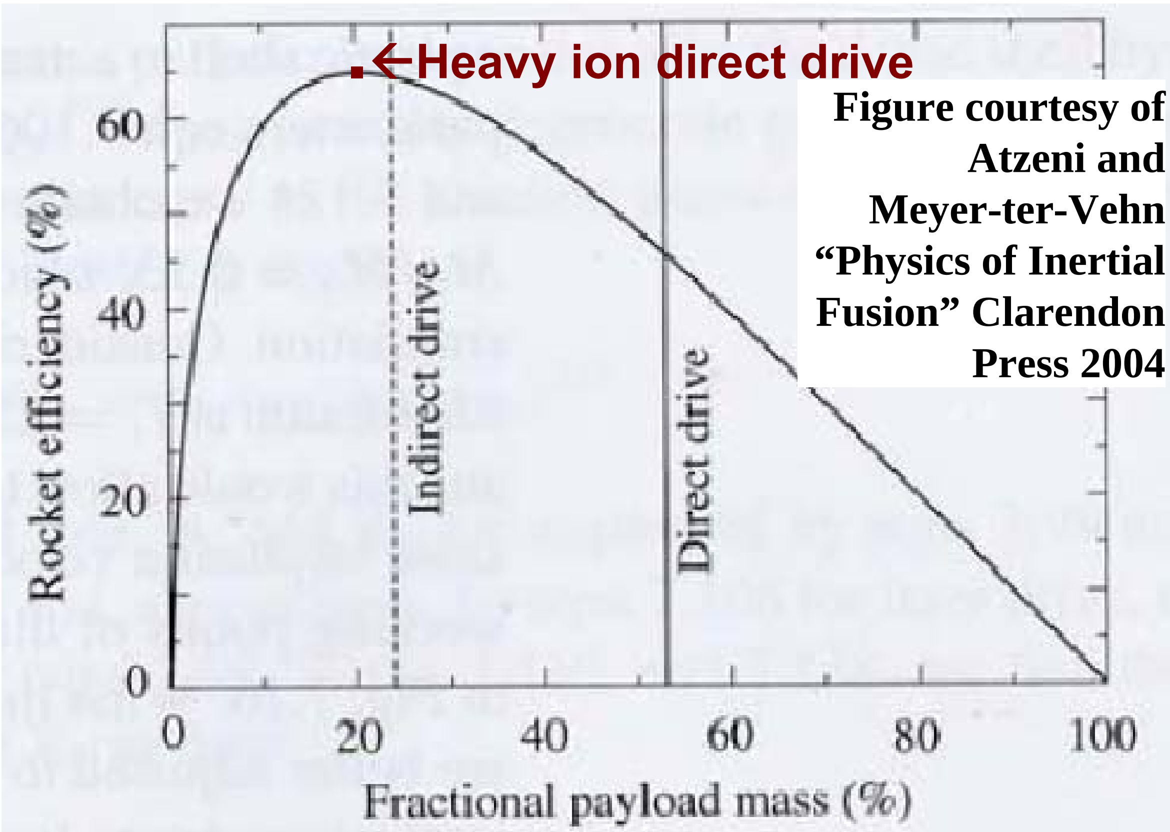
We are exploring heavy-ion-driven direct-drive target physics in the ablative rocket regime enabled by compressing and focusing low-range ions in neutralizing background plasma:

- Double-pulse target experiments planned for NDCX-II: Coupling efficiency of low range ions in cryogenic H2 or D2 ablators, RT instability effects with an upstream beam wobbler.

- Analytic and hydro code studies of incident drive beam profiles (intensity and range variations in r and θ) required to support two-sided polar direct drive experiments in future facilities.

- Conceptual heavy-ion fusion reactor studies that could exploit neutralized beam compression and focusing, and polar direct drive.

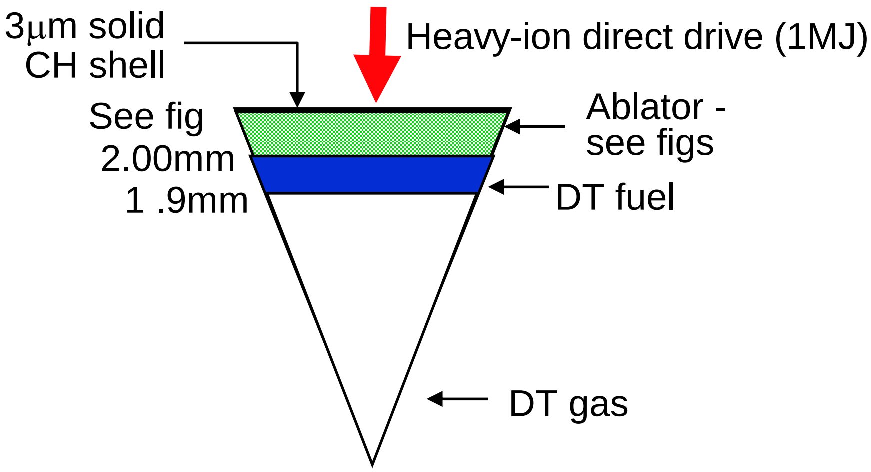
Heavy ions with the right range can in principle drive targets at the peak of rocket efficiency like x-rays, but without the energy penalty of conversion to x-rays, and with lower ionization loss using H_2 ablators.

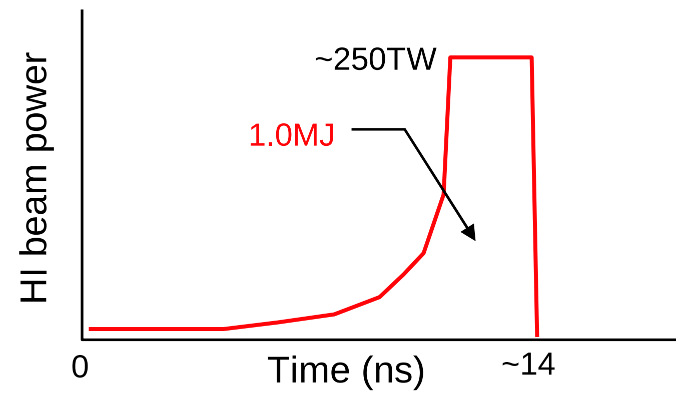


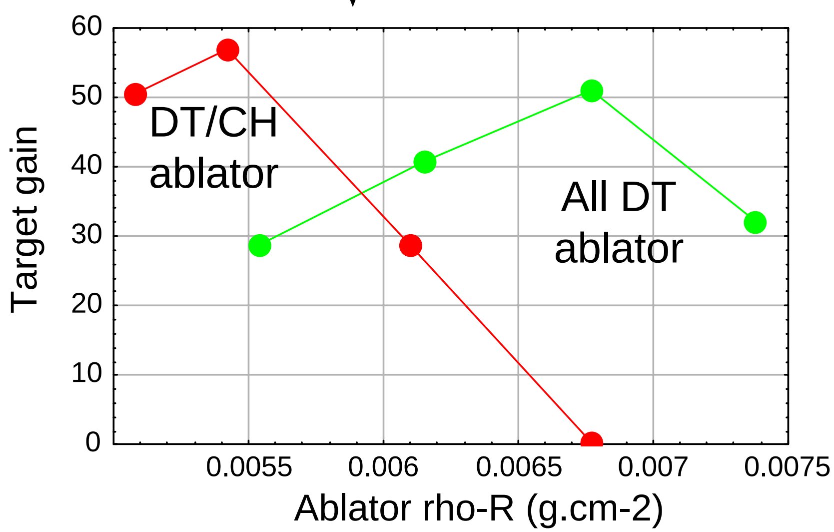
- Pure hydrogen ablators for ion direct drive have only 13.6 eV ionization loss
- Beryllium ablators have 180 to 400 eV ionization (three to four electrons ionized)
- Laser coupling is reduced ~ 2 x by electron transport from critical density to ablation front

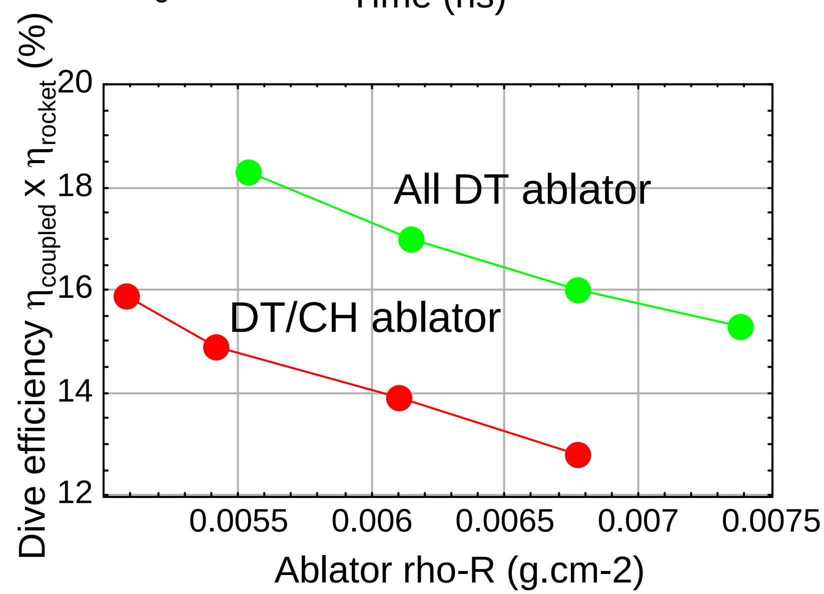
Heavy ion beams can suffer more parasitic beam losses on out-going ablation corona plasma than either x-ray or laser photons -but our work shows overall coupling efficiencies can still be several times higher.

First heavy-ion direct drive (no late shock) LASNEX runs by John Perkins (LLNL) suggests gains ≥ 50 at 1MJ with high drive efficiencies that can be further improved



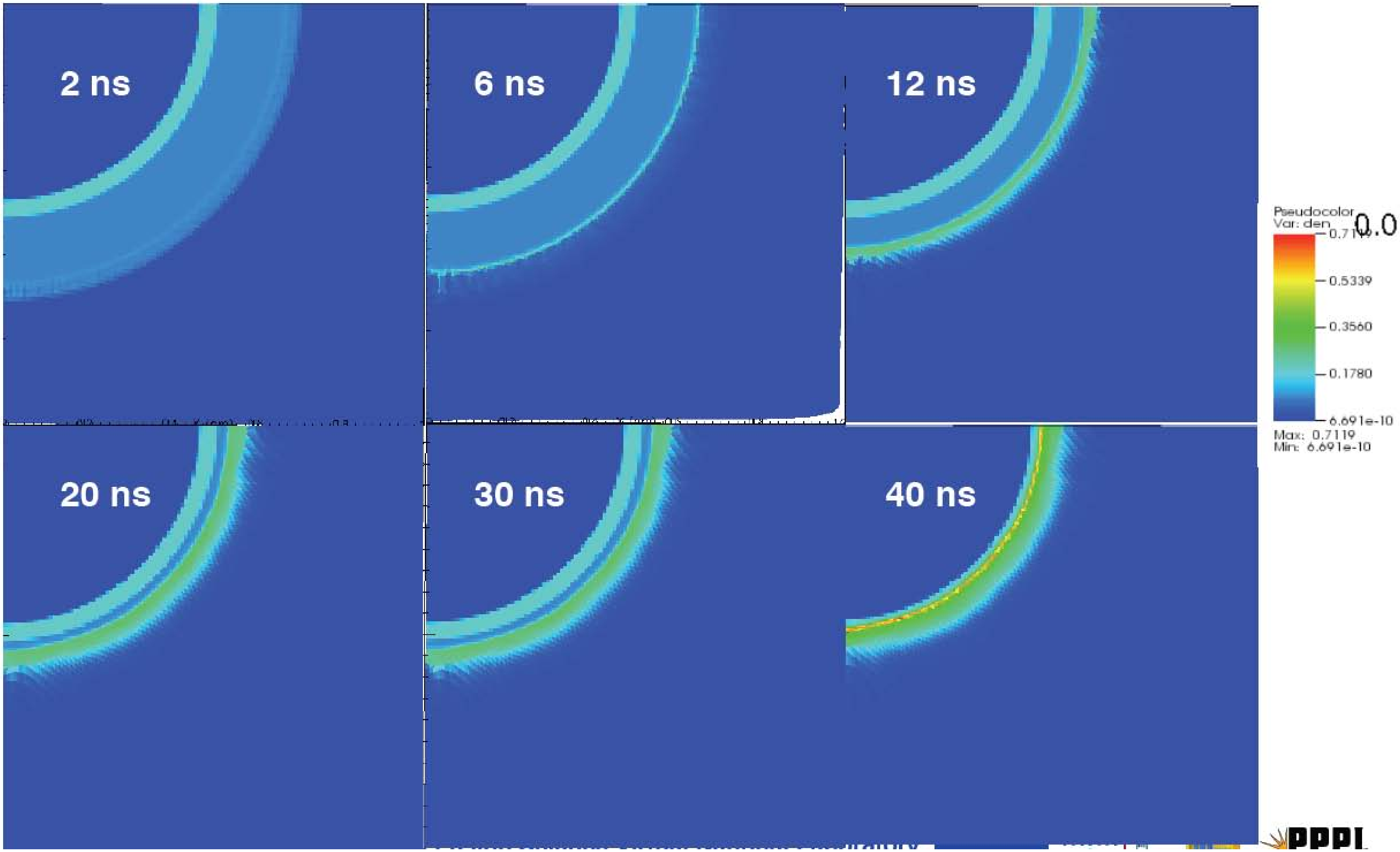






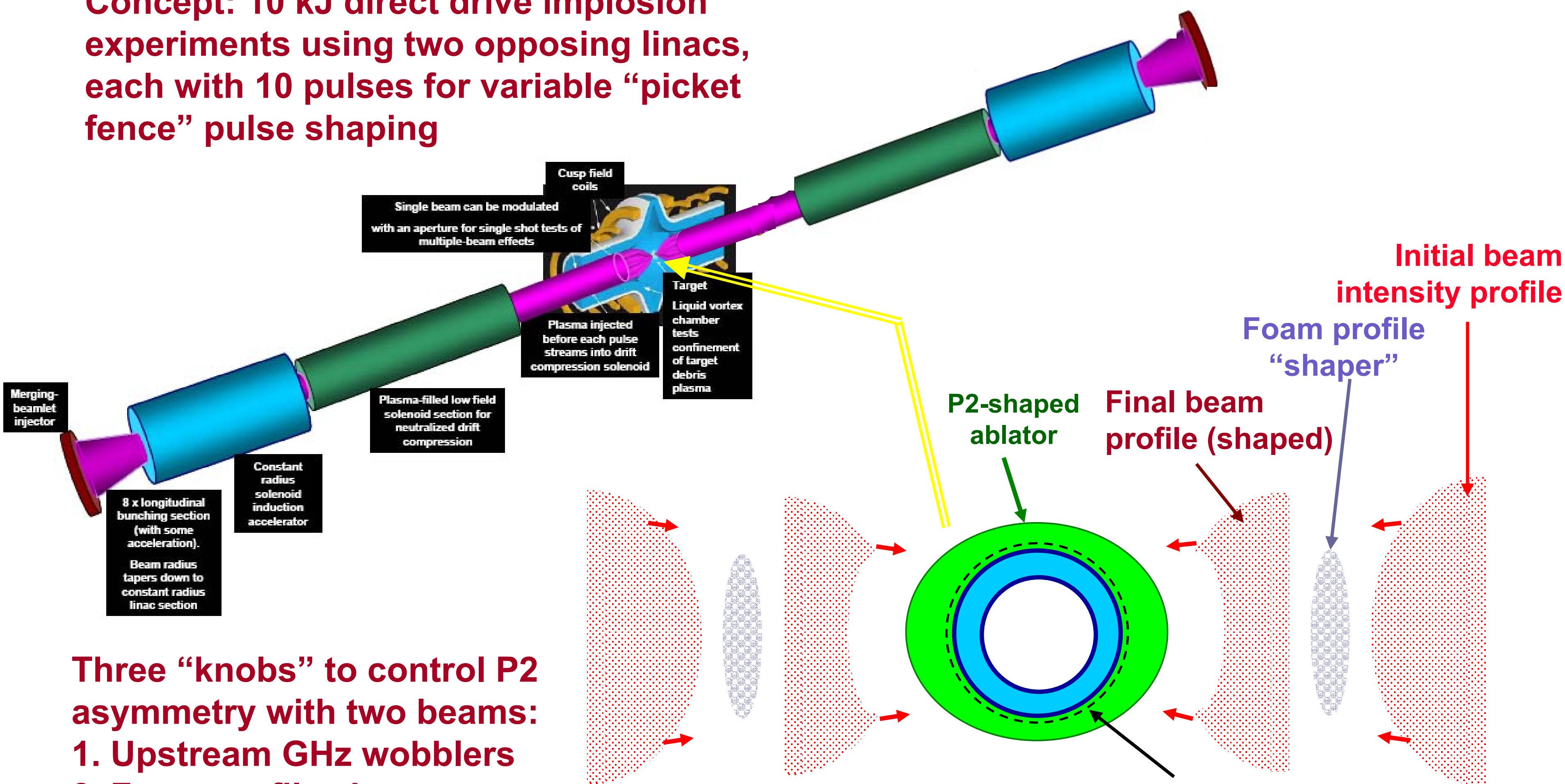
Higher drive efficiencies ≥20% may be possible by tuning the ion kinetic energy, 50 → >200MeV, as the capsule implodes

We are also beginning to use the LLNL HYDRA code in to explore heavy ion direct drive coupling efficiency in 2-D (John Barnard, LLNL)



An IRE-scale new accelerator tool to explore polar direct drive hydro physics with heavy ions in parallel with NIF

Concept: 10 kJ direct drive implosion experiments using two opposing linacs, each with 10 pulses for variable “picket fence” pulse shaping



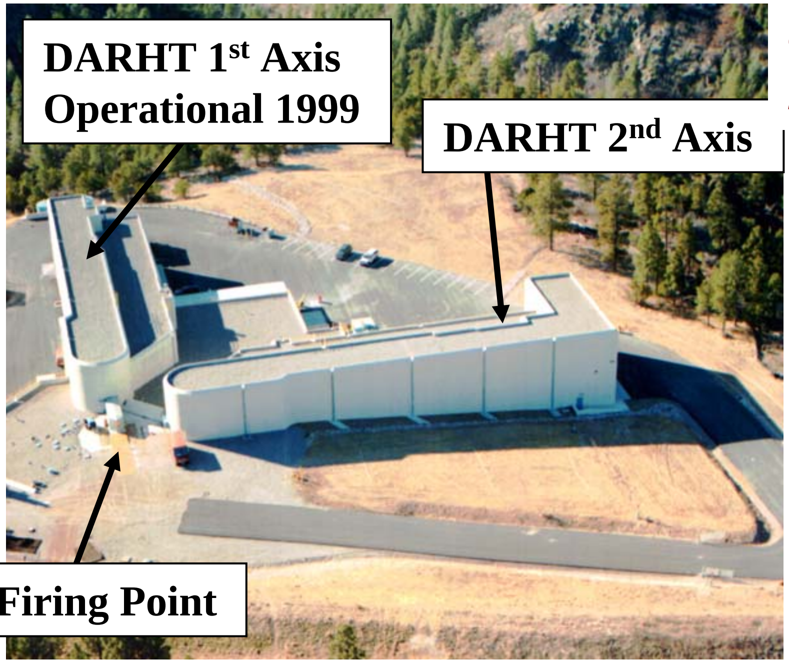
Three “knobs” to control P2 asymmetry with two beams:

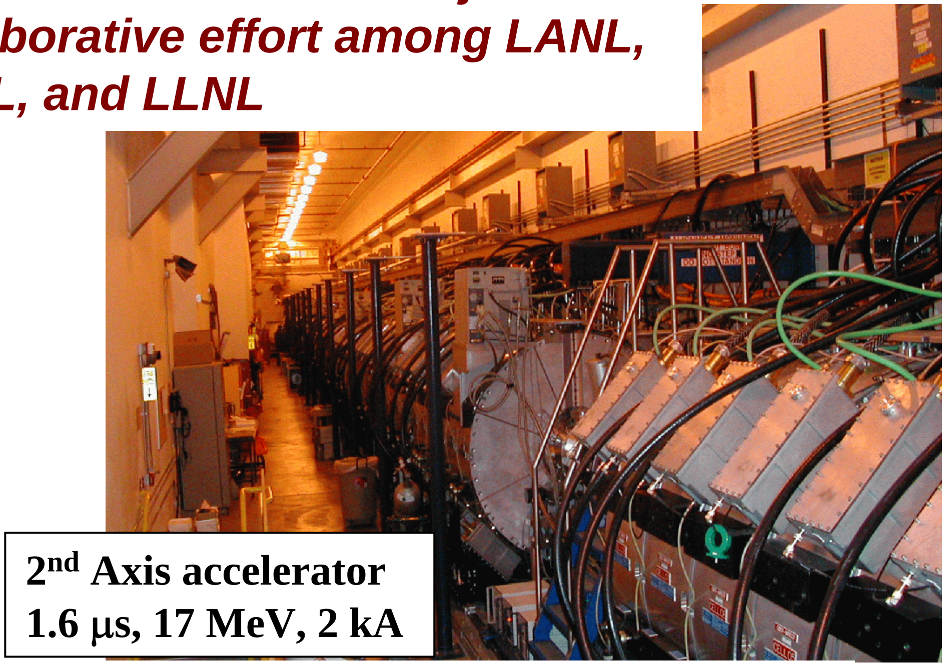
1. **Upstream GHz wobblers**
2. **Foam profile shapers**
3. **Ablator shaping**

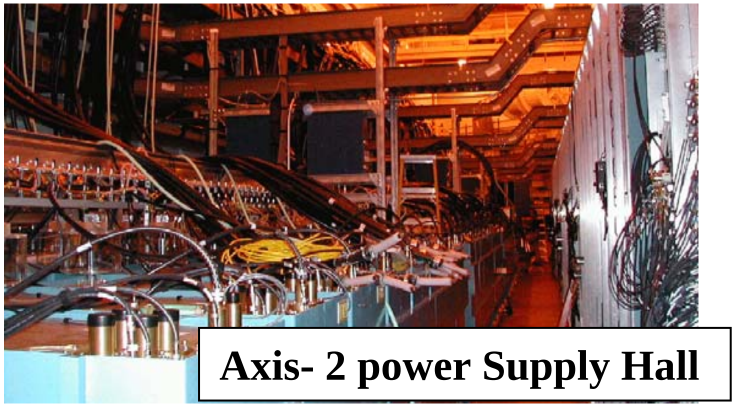
Goal is implosion drive pressure on the Cryo D_2 payload with < 1 % non-uniformity

The DARHT 2nd Axis: a state-of-the-art induction accelerator @ >50 kJ/ electron beam pulse. Technology *relevant to induction lina*

The DARHT 2nd Axis Project is a collaborative effort among LANL, LBNL, and LLNL







Heavy ion driven HEDP and fusion: Conclusions

- **Heavy Ion Fusion Science experiments and simulations on NDCX I are making outstanding progress in neutralized beam compression and focusing in background plasma.**

- **Warm Dense Matter experiments are beginning**
  -- Transient darkening experiments on HCX
  -- Metallic foam studies at GSI
  -- Target heating experiments (~.2 - .5 eV) to begin this year on NDCX I
  -- 1 eV experiments on NDCX II by 2010

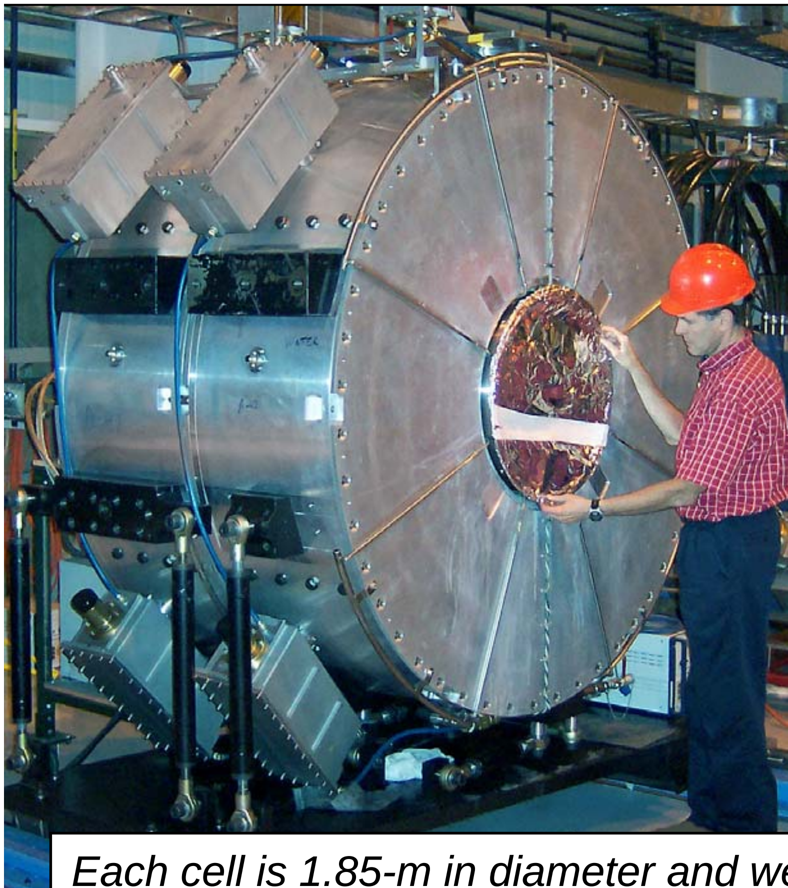
- **Hydrodynamics experiments for stability and ion ablative direct drive physics are being studied for NDCX II.**

- **Analytic and hydro code calculations are being pursued for heavy ion fusion in two-sided polar direct drive geometry.**

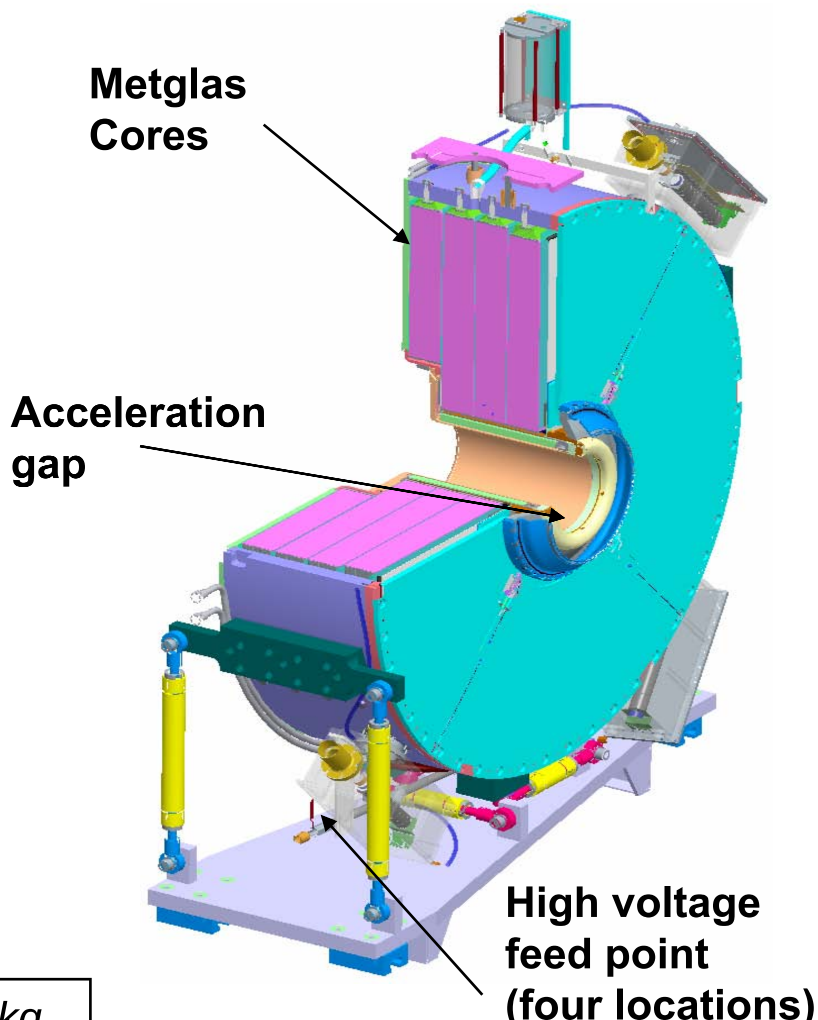
BACKUP SLIDES

All ADRHT-II Induction Cells Have Been Refurbished and Tested at LANL, Meeting All Requirements

200 kV/cell
1.6 μs; ± 0.65% ΔV

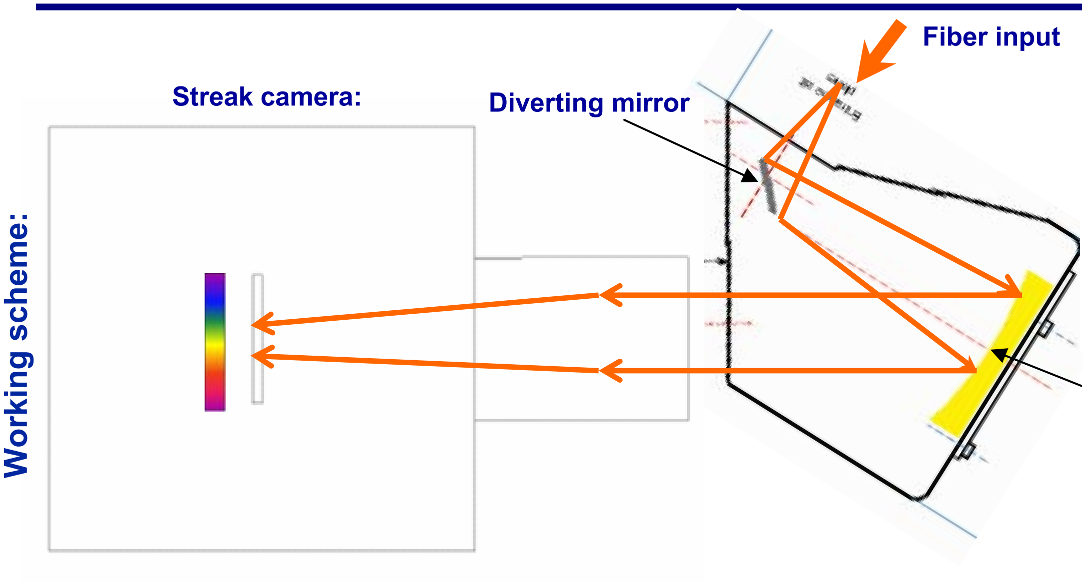


Each cell is 1.85-m in diameter and weighs 7,300 kg



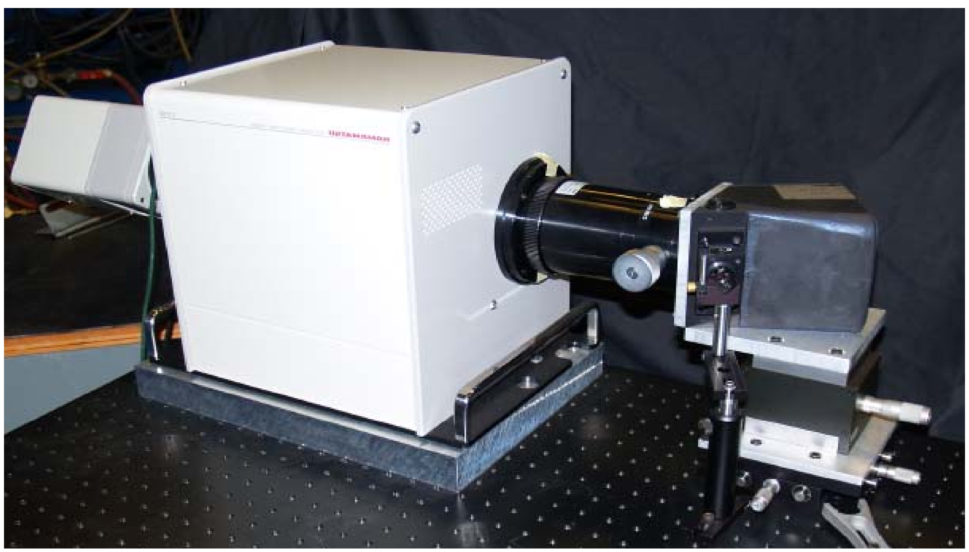
Streak camera for time resolved spectroscopy of target

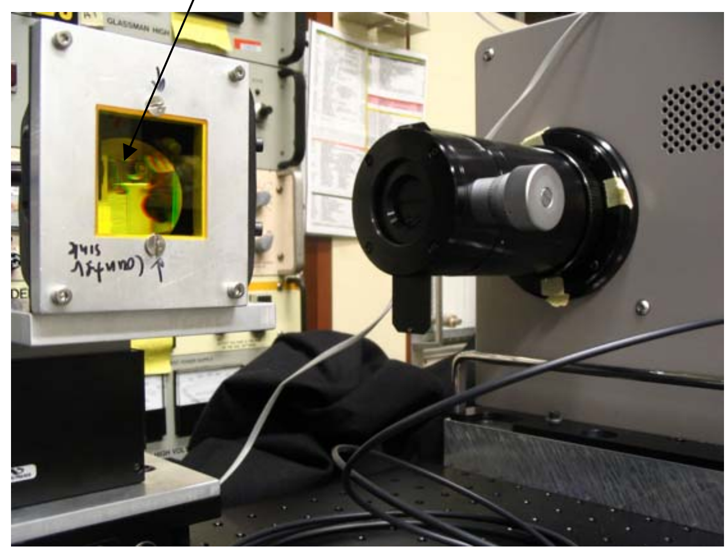
Working scheme:



- Records continuous spectrum from 500 nm to 850 nm
- Temporal resolution down to 5 ps
- When calibrated with tungsten lamp, can be used for temperature determination

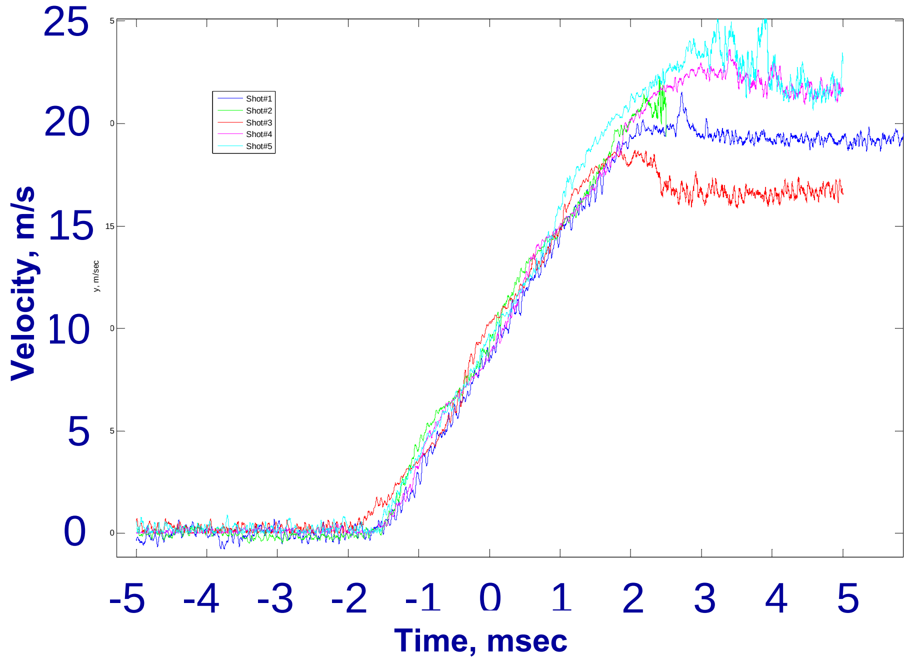
Implementation:



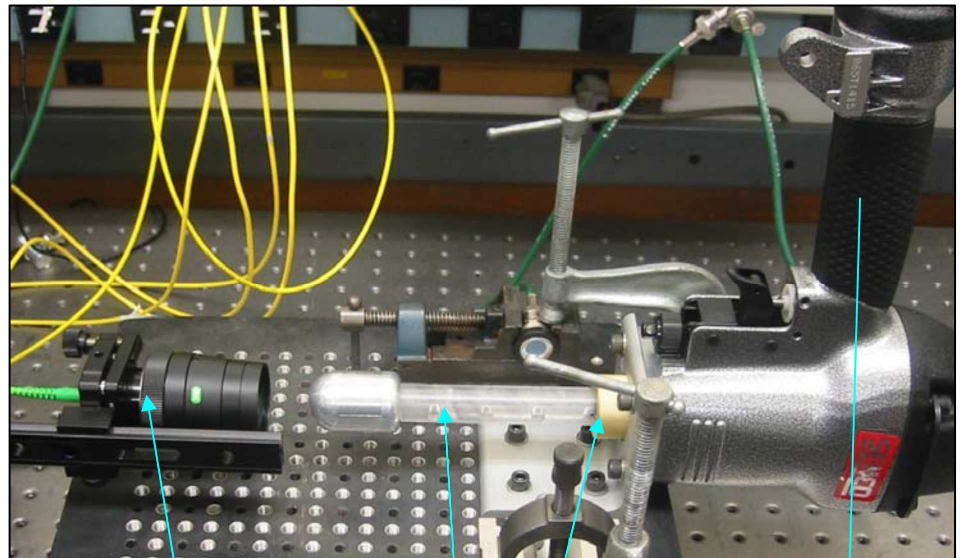


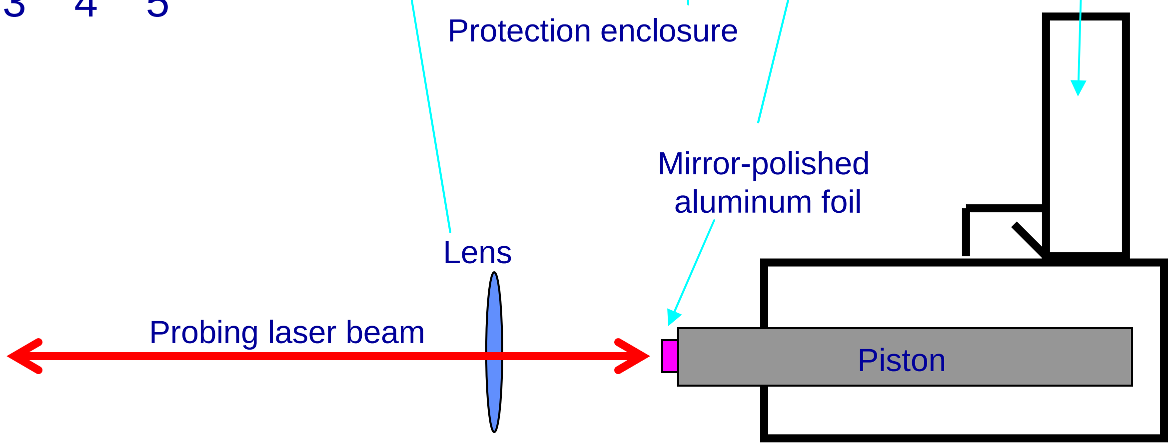
VISAR for target pressure measurement

Velocity of a piston (6 shots):

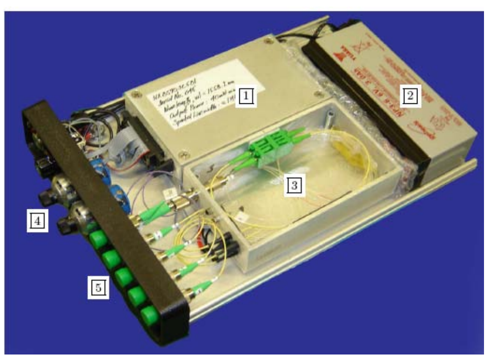


Setup for testing of VISAR:

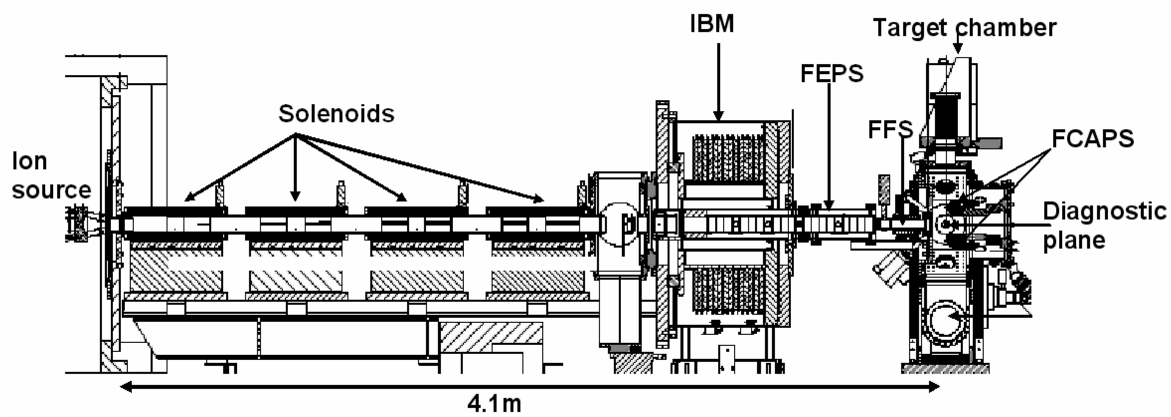




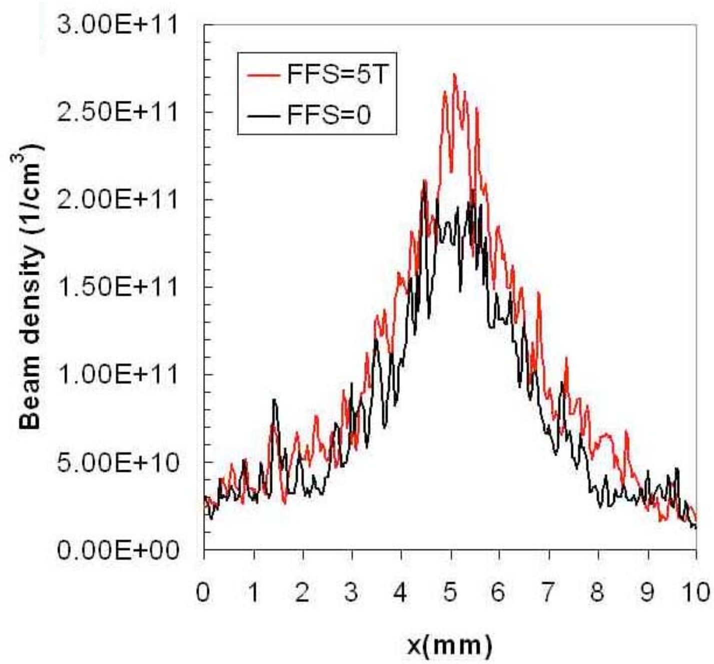
Martin, Froeschner & Associates All Fiber Push-Pull Doppler Velocity Interferometer (VISAR)



In June 2007, first tests using a 5 T final focus magnet increased final focus beam intensity on axis -further optimization in progress

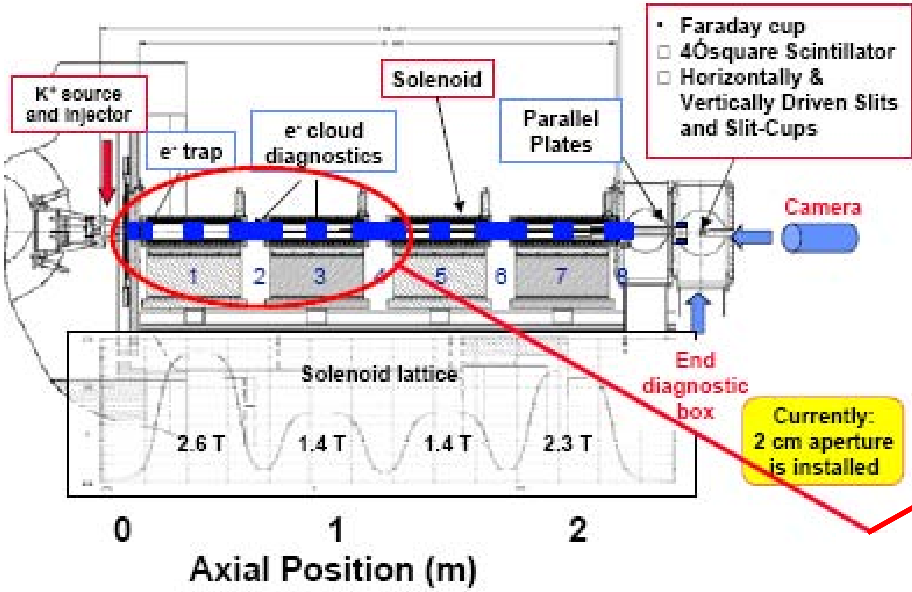


NDCX Left to right: 315 keV, 25 mA K+ ion source, solenoid transport section, induction bunching module (IBM) which imparts the velocity ramp on a 150 ns slice of the injected beam, ferroelectric plasma source (FEPS), 5T final focus solenoid (FFS), and new target chamber containing diagnostics at the target plane and two filtered cathodic arc plasma sources (FCAPS).

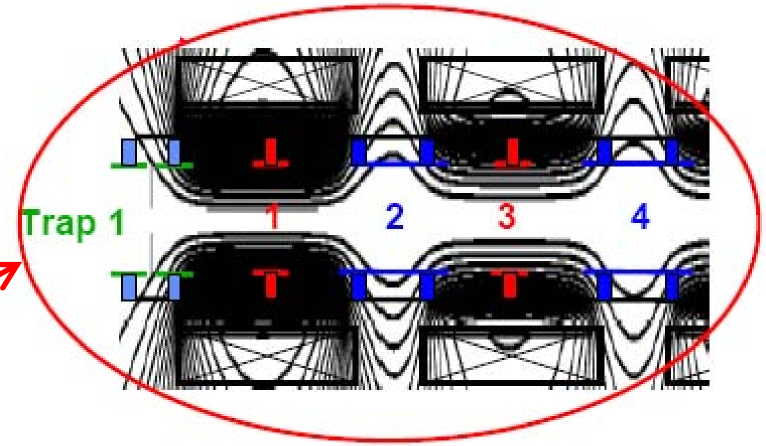


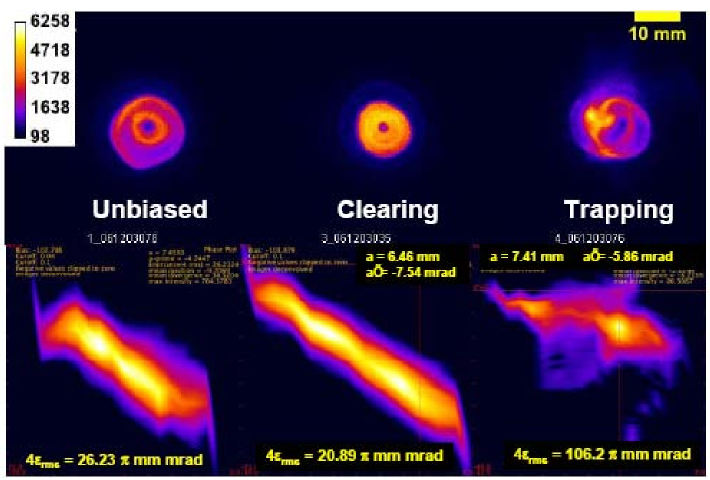
Beam density profiles at the target focal plane with the final focus solenoid on (FFS=5T) and off (FFS=0).

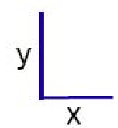
Solenoid transport experiments in 2006: when e-clouds were *not* trapped with biased wall electrodes, measured beam envelopes agreed well with simulations.



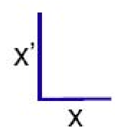
Cylindrical electrodes in solenoid bores used to clear or trap e-clouds







←Transverse X-Y beam images



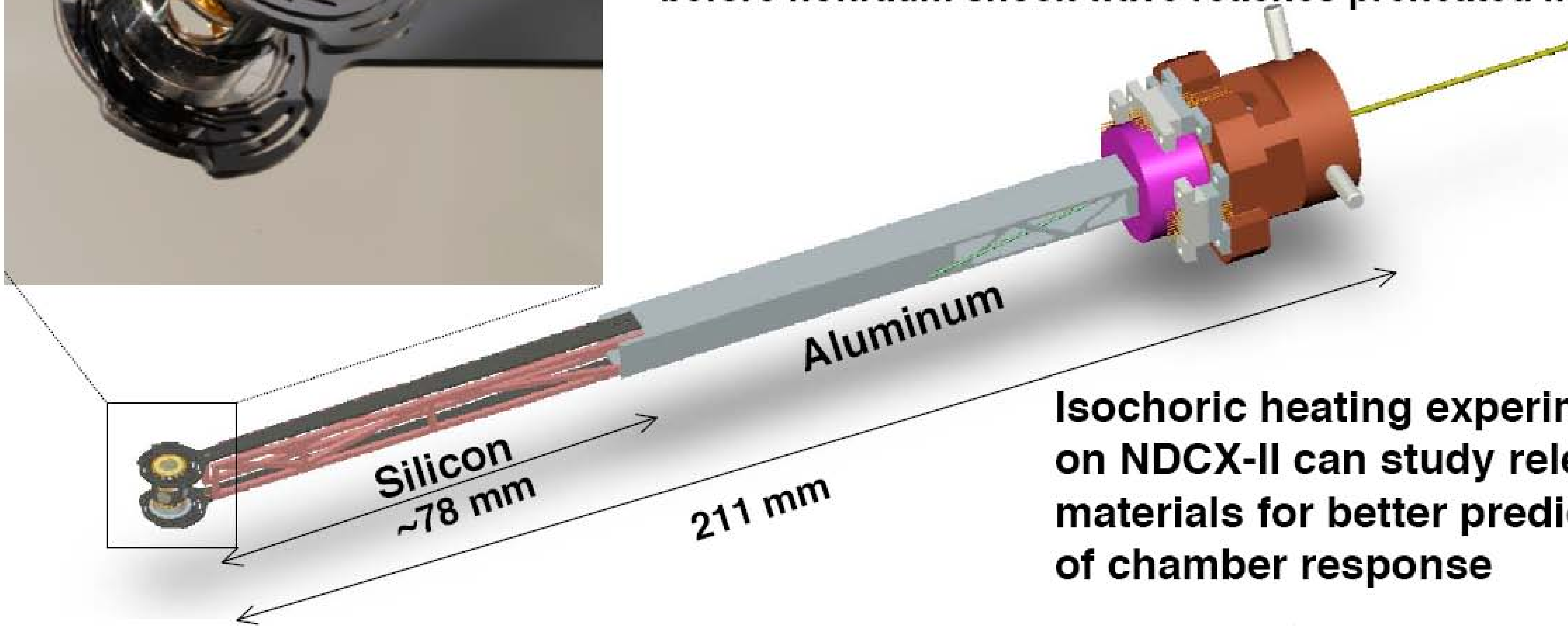
← X-X' phase space beam measurements

Isochoric heating by ion beams can simulate neutronic isochoric heating near NIF target (Dave Eder, LLNL)

Exposure: 10^{17} - 10^{19} neutrons per shot

$kT \sim 4\ eV\ (1\ cm/r)^2\ (N_n/10^{19})(\sigma/10^{-24}\ cm^2)$

Near target, material is vaporized, but some material a few cm away is volumetrically preheated by neutrons to melting point or lower, changing material properties, before hohraum shock wave reaches preheated material



Isochoric heating experiments on NDCX-II can study relevant materials for better predictions of chamber response

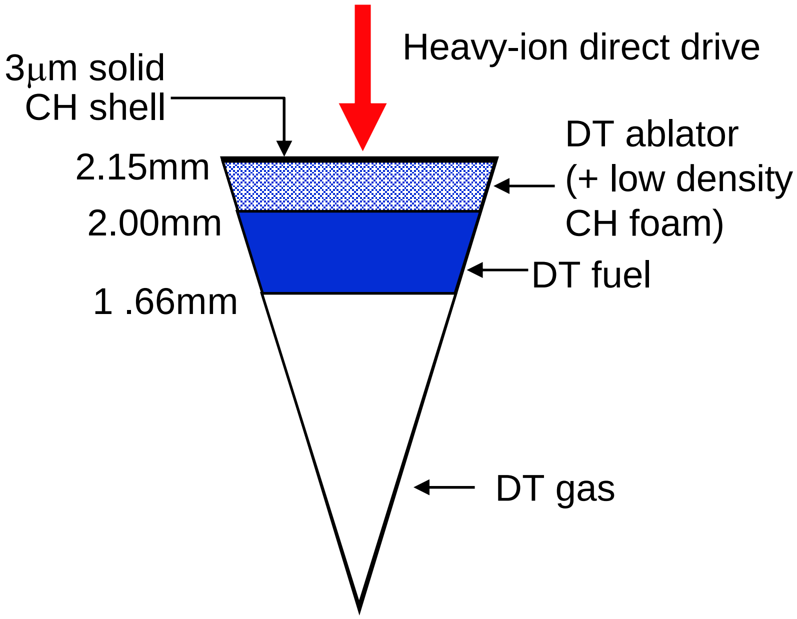
Is it Time to Reconsider Direct Drive for HIF (John Perkins, LLNL)?

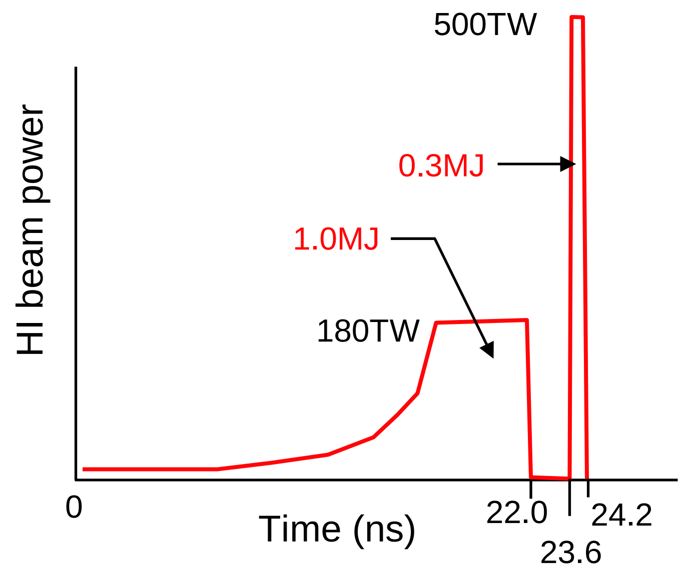
With modern (mainly DT) direct drive capsules, efficient heavy-ion beam coupling and shock ignition, ~1MJ drive may suffice for gains ≥ 200 and ηG >20!

- **Adiabat shaping and SSD beam smoothing makes direct drive viable for NIF**
- **LLE/NIF polar-direct-drive will test geometries suitable for liquid protected chambers**
- **Direct drive capsule radii >2mm allow large beam spots**
- **Neutralized drift compression allows multiple pulses of lower ion ranges**
- **Shock ignition direct drive enables high gains/yields without the need for separate PW lasers**

⇒ Pursuit of direct drive <u>and</u> shock ignition allows HIF to take advantage of ongoing progress in modern laser facilities as it had for indirect drive

Initial LASNEX results (John Perkins, LLNL) also suggest promise for shock-ignited heavy-ion targets at ≥1MJ drive.





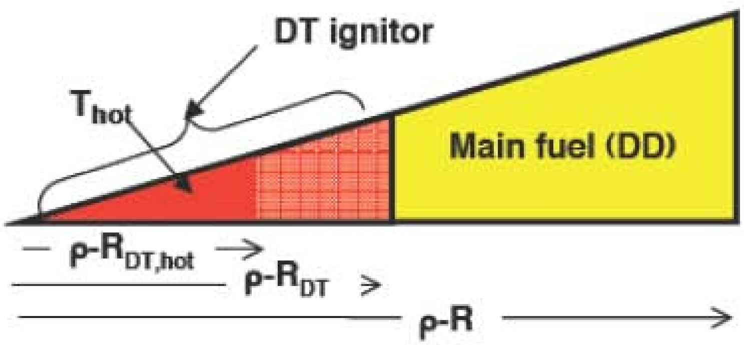
Heavy-ion drive	**50MeV Ar (z = +8 accel, +16 drift/focus)**
Drive energy	**1.0(main) +0.3(shock) = 1.3MJ**
Yield	**199MJ**
Gain	**153**
Peak velocity	**2.2e7cm/s**
Drive efficiency ($\eta_{coupled}$ x η_{rocket})	**8.6% (not yet optimized for low velocity fuel assembly)**
rho-R	**2.25 g.cm-3**

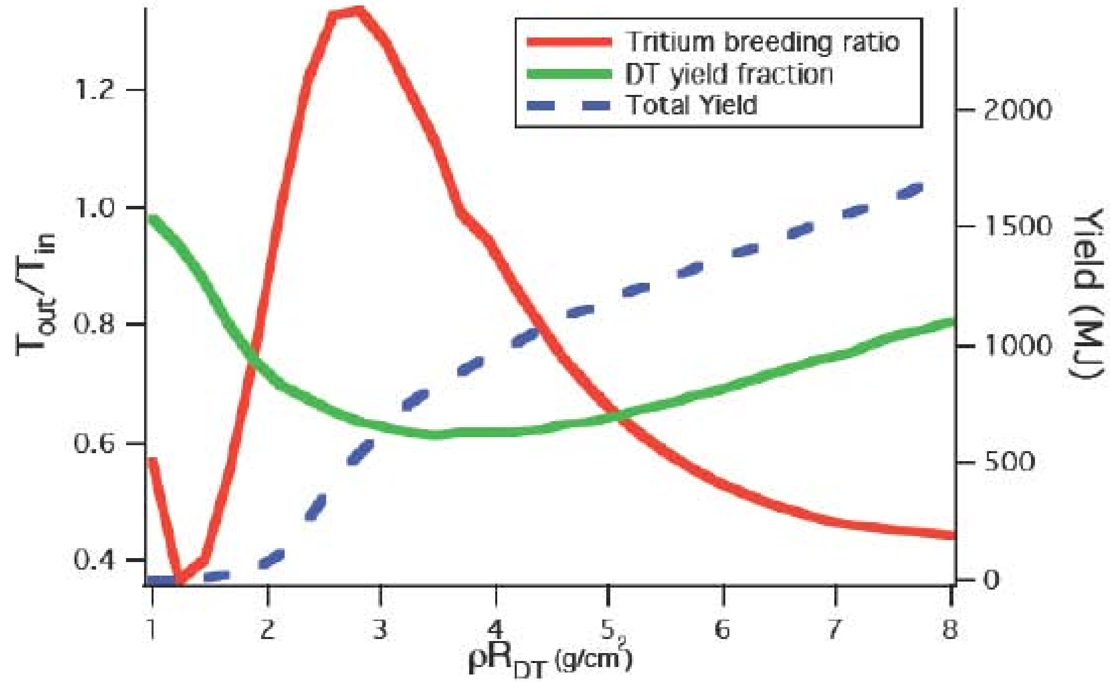
Recent LASNEX work confirms T-lean targets can self breed tritium @ ρR_{tot}~ 10 g/cm^2 and 500 MJ yields (Kai LaFortune, LLNL)

H. Takase, S. Kawata and K. Niu: , J. Phys. Soc. Jpn., 52 (1983)

Max Tabak, Nuc. Fusion 36, No2 (1996).

Atzeni and Ciampi Nuc. Fusion 37, 1665 (1997)

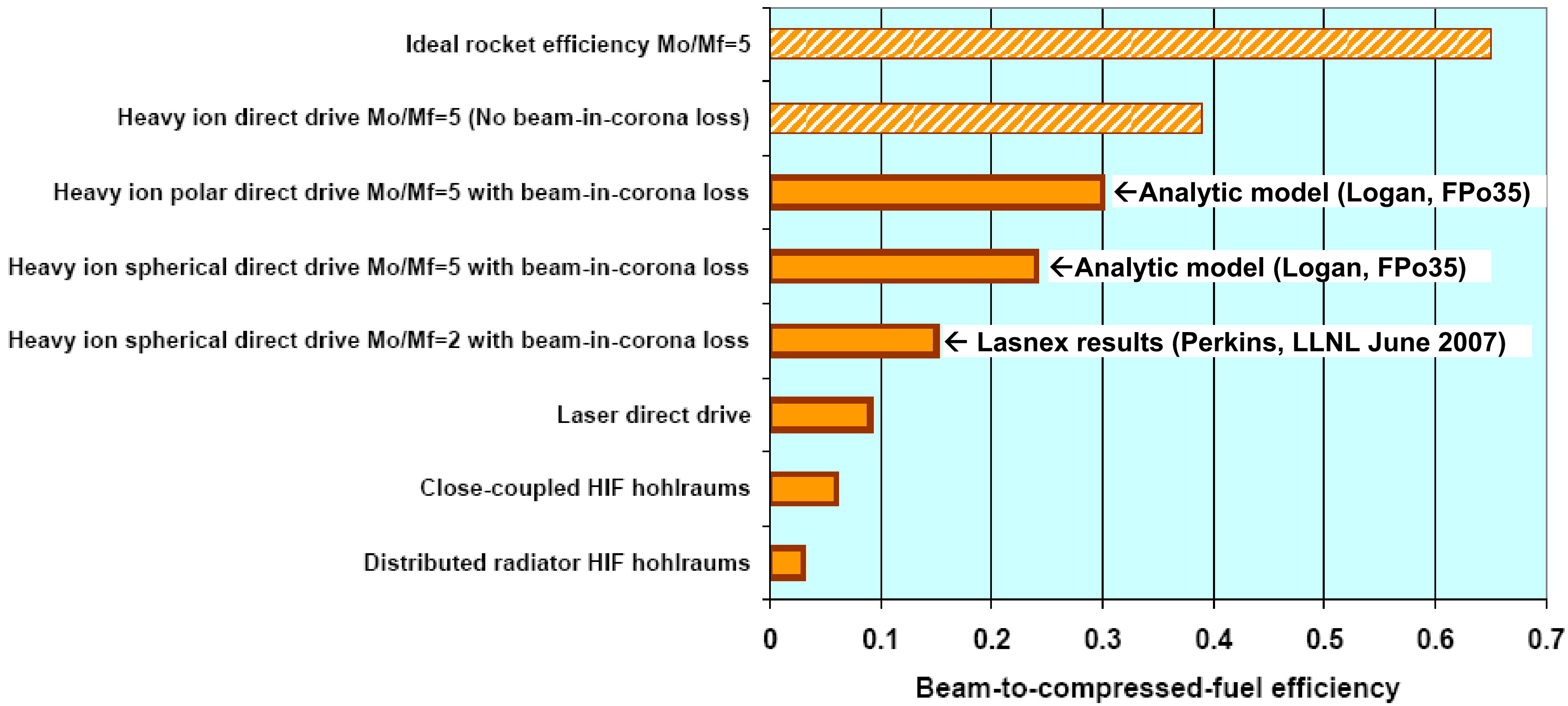




T- breeding ratio, DT yield fraction (mostly from T originating from D(d,p)T reactions of the majority DD fuel), and total fusion yield as a function of the DT core ρR_{DT}.

→ Required 1 MJ compressed fuel assembly energy → 3.3 MJ (5 MJ) drive energy with heavy-ion direct drive coupling efficiency of 30% (20%).

Preliminary results for heavy-ion direct-drive efficiency are very encouraging. Validation with 2-D hydro codes are planned.



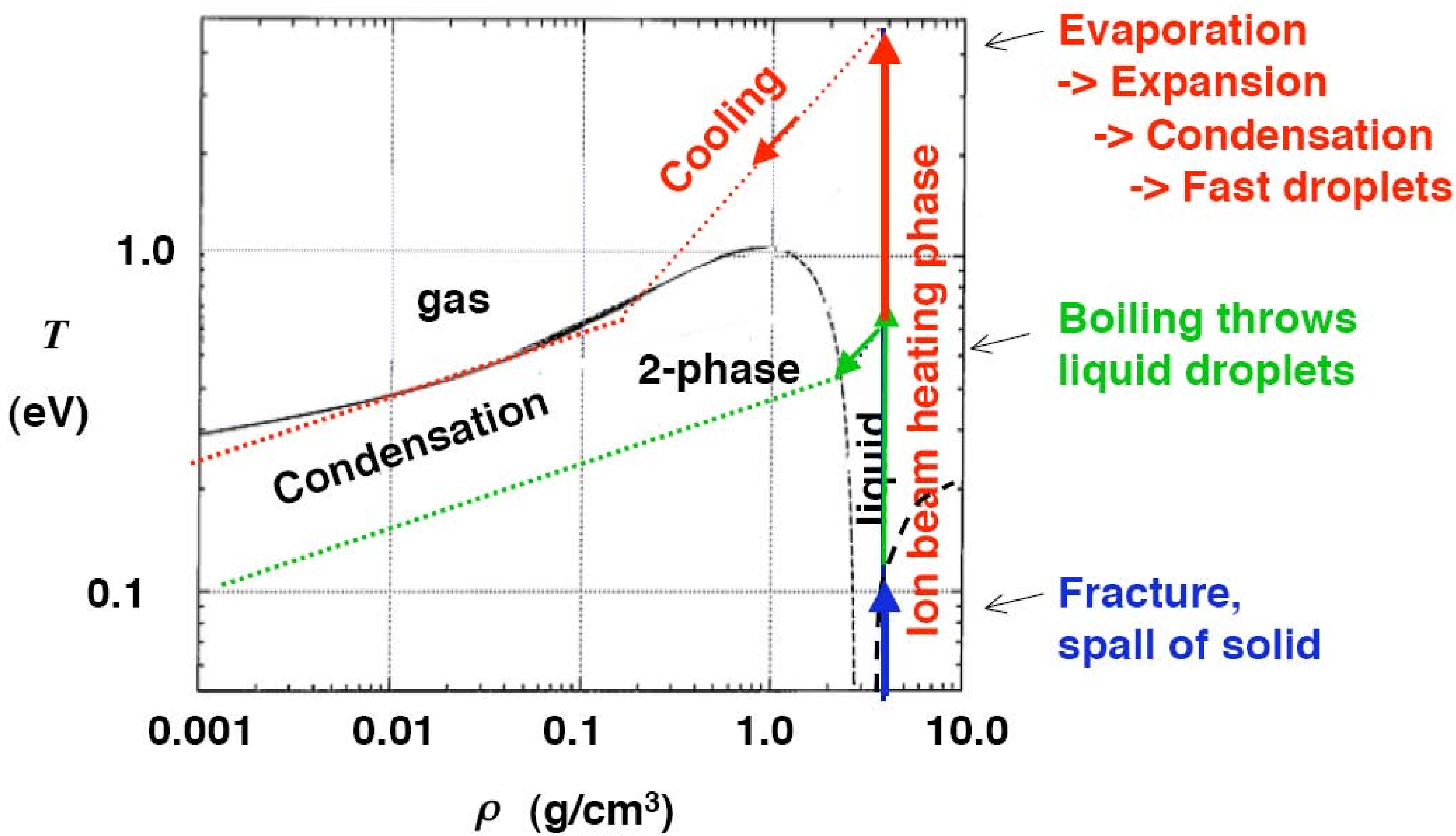
Recent HIF target implosion calculations (John Perkins*) using state-of-the-art codes at LLNL confirm the unique potential of HIF direct drive.

1. Overall beam-to-compressed fuel coupling efficiencies >15%, despite major parasitic beam losses that can be further reduced by optimizing parameters in the next set of calculations.
2. Use of low range ions synergistic with neutralized beam drift compression and focusing as in current NDCX program.
3. Ion ranges set at 25% of the initial ablator thickness allows sufficient shock timing control to get low adiabat implosions α<1.5 enabling gains > 60 at 1MJ, higher with more fuel mass.
4. Potential example demonstrates use of a late ion-driven shock for two-step implosion and ignition benefits like fast ignition.

*(Joint paper in progress, to be submitted to Nuclear Fusion)

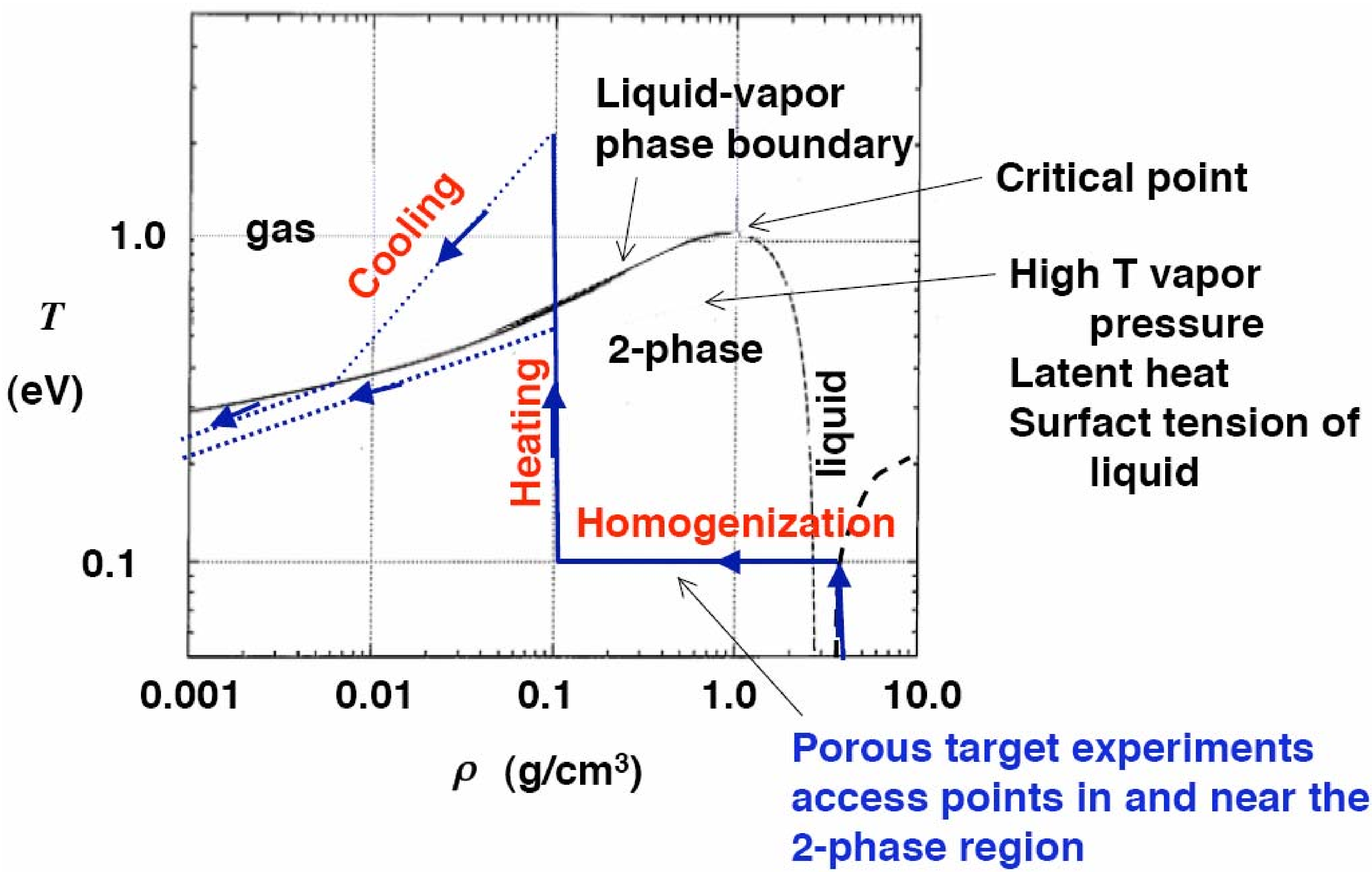
→These advances enable T-lean implosions with larger fuel masses sufficient to capture most neutron energy for low cost direct plasma MHD direct conversion. (See second talk)

With eV-scale volumetric ion heating of foams and solids a variety of physics is opened to exploration

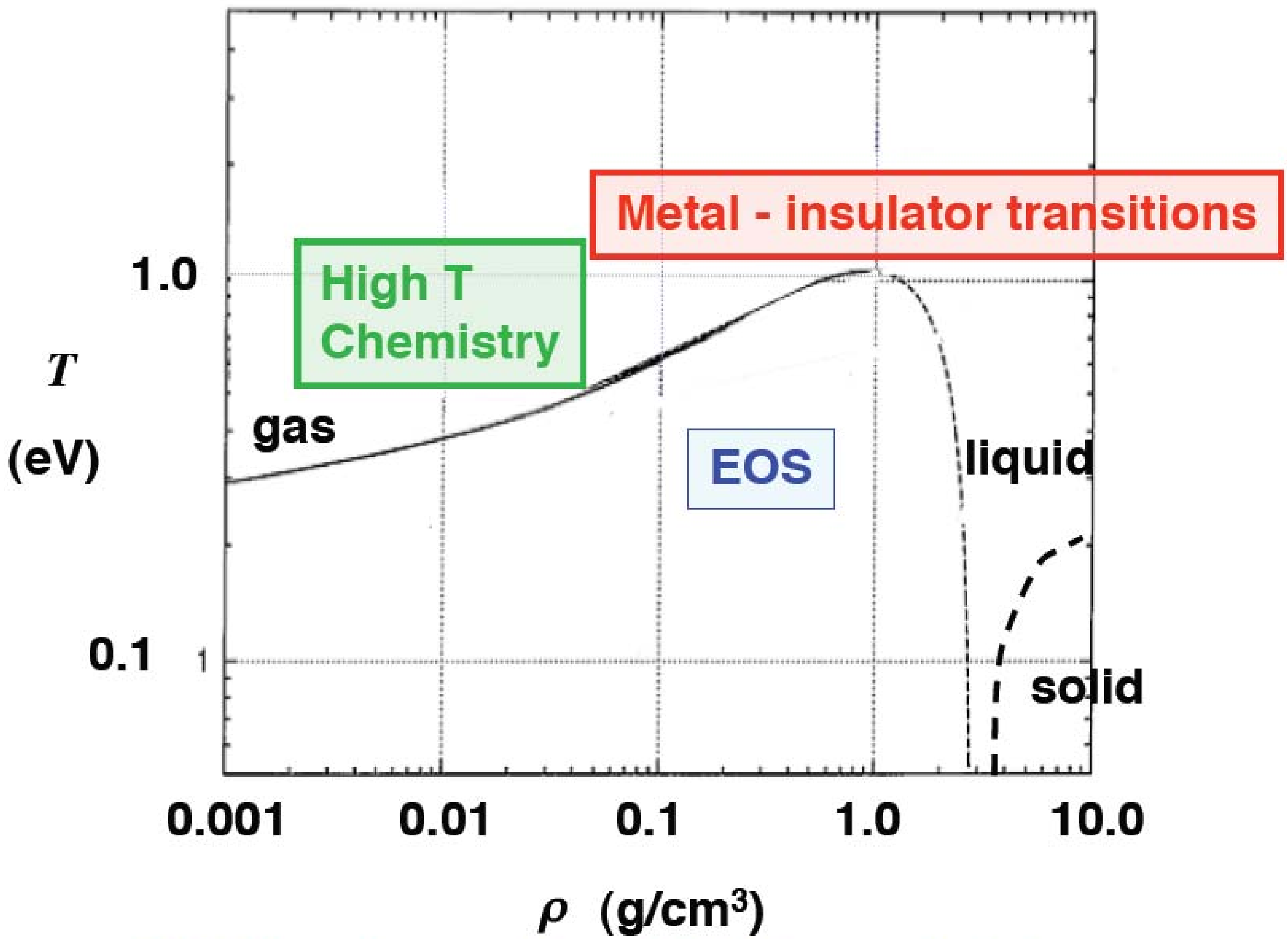


→These three process need both improved WDM theory and well-characterized data, and so are early candidates for experiments and modeling!

Key EOS parameters we are pursuing in the Warm Dense Matter regime



Additional fundamental scientific opportunities of WDM



WDM is a key region of EOS uncertainty

High-T chemistry includes +/- ion Br, I plasma

Selected scientific questions that can be pursued in NDCX–I and II (R. More, J. Barnard, F. Bieniosek)

1. **Quartz transient darkening emission and absorption experiment.**

→*What is the physical mechanism for changes in the optical properties of glass, as matter approaches the WDM regime?*

2. **Measure target temperature, using a beam compressed both radially and longitudinally.**

→*How can we measure the thermodynamic properties of matter, heated by ion beams compressed in space and time?*

3. **Thin target dE/dx, energy distribution, charge state, and scattering in a heated target.**

→*Can an ion beam (after it heats and exits a target) be used as a unique diagnostic tool for WDM exploration?*

4. **Positive - negative halogen ion plasma experiment (kT >~ 0.4 eV)**

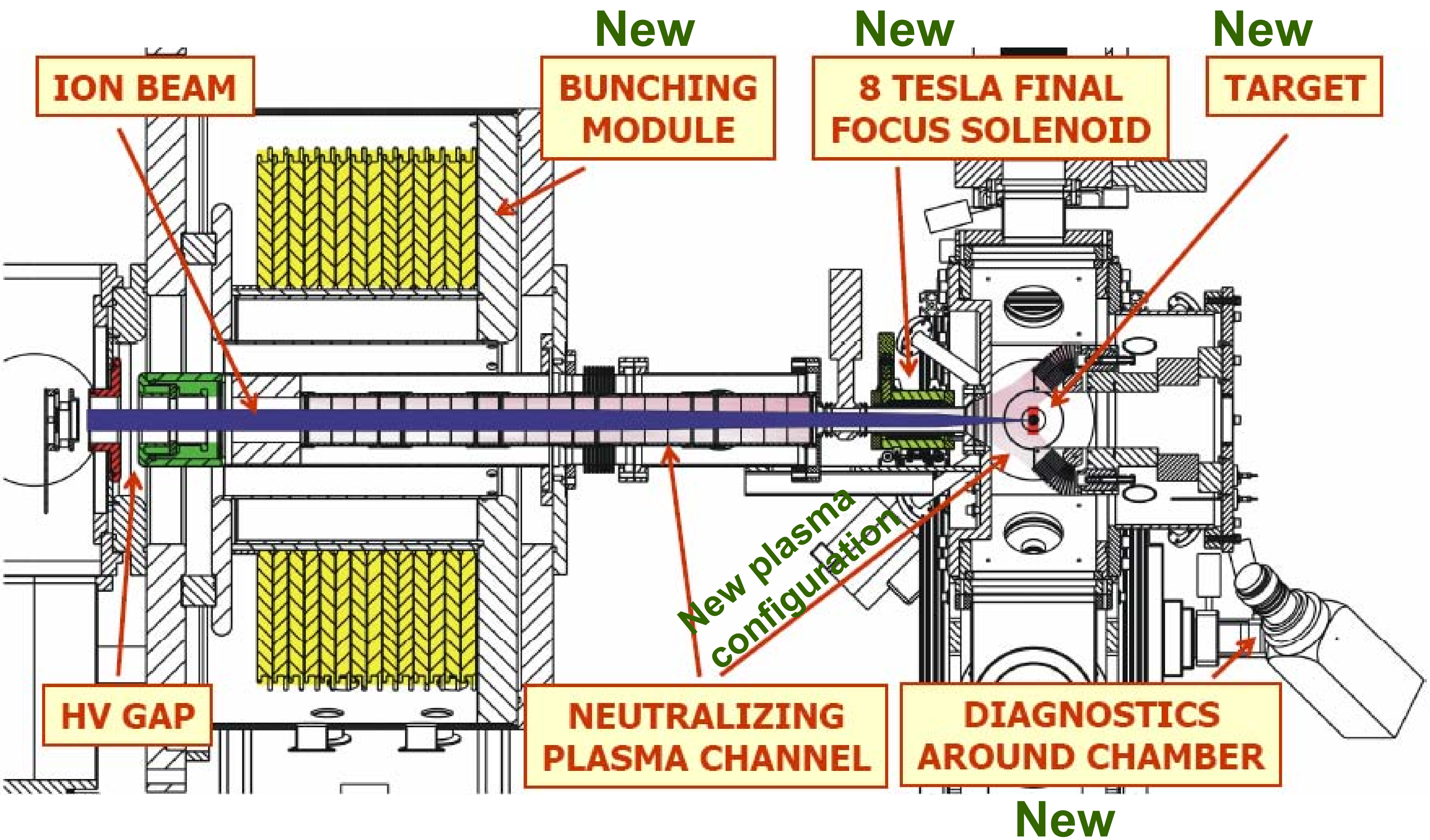
→*Can unique states of matter be created with nearly equal quantities of positive and negative ions (and few electrons)?*

5. **Two-phase liquid-vapor metal experiments (e.g. kT > 0.5 - 1 eV for Sn)**

→*In the two-phase regime, what is the best way to make predictive simulations of the EOS and dynamics including the effects of droplets?*

→See 2006 international workshop on accelerator-driven warm dense matter (http://hifweb.lbl.gov/public/AcceleratorWDM/TableOfContents.html)

Improving NDCX-I for FY08-09 warm dense matter experiments



With new improved bunching module to be installed later this year, plus a higher field 15T focusing magnet in FY09, NDCX-I is predicted to support >0.5 eV target conditions with 2 ns pulses

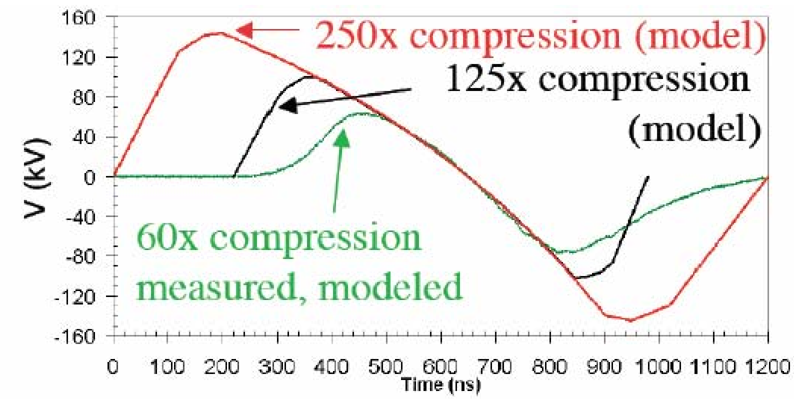
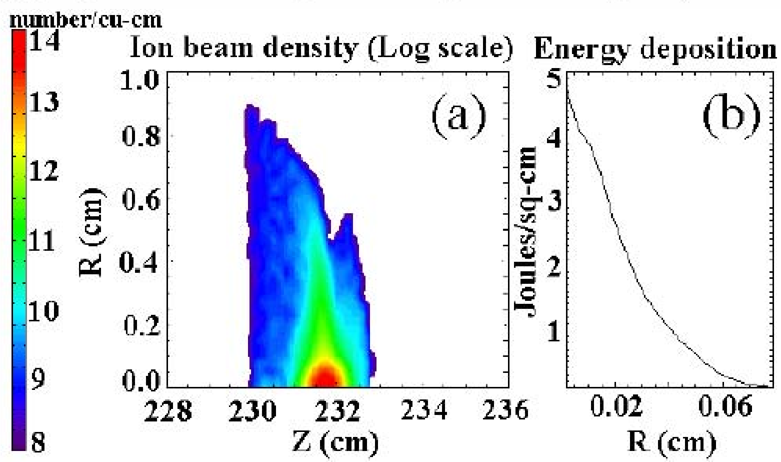


Fig. 4. The IBM for the simulation in Section II used the upgraded optimized voltage waveform (red) shown in the figure in order to apply an axial velocity tilt to the ion beam as it traverses the acceleration gap region. The existing IBM voltage waveform (green) is shown for comparison.



Actual achievable NDCX-I intensity for WDM targets in FY09 will range between > 0.15 J/cm² (previous slide) and this simulation of best possible case < 4 J/cm² .

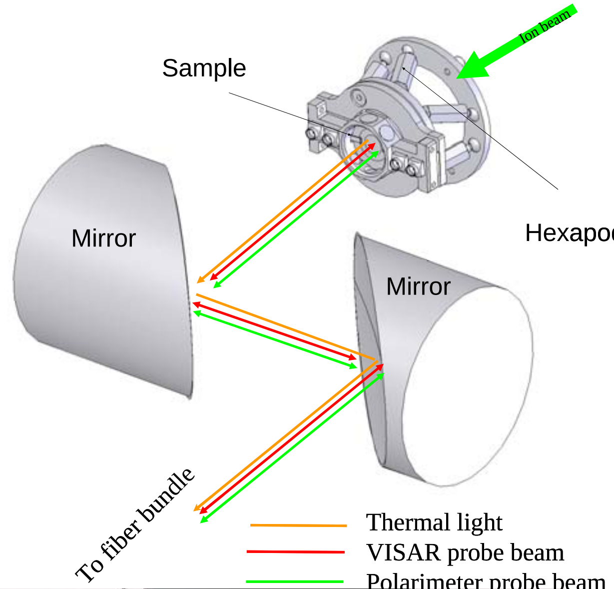
Fig. 6. Ion beam properties at the simultaneous focal plane (within a 150 kG final-focus solenoid): (a) density (log scale); and (b) radial profile of cumulative energy deposition through the focal plane.

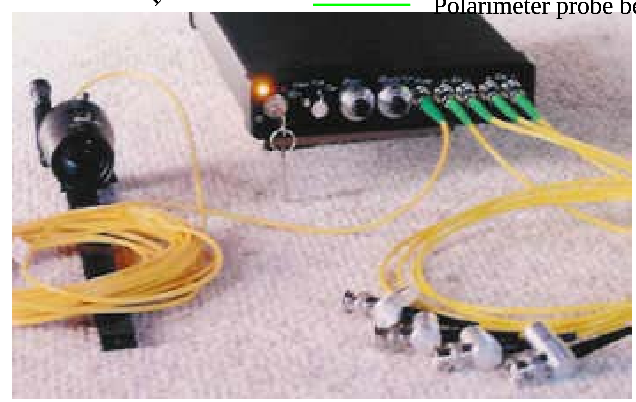
Initial NDCX-I Target diagnostics

- **Fast optical pyrometer**
  - **Similar to GSI pyrometer, improved for faster response (~1 ns) and greater sensitivity**
  - **Temperature accuracy 5% for T>1000 K**
  - **Position resolution about 400 micron**
  - ***Parts are being ordered – to be assembled in FY07***

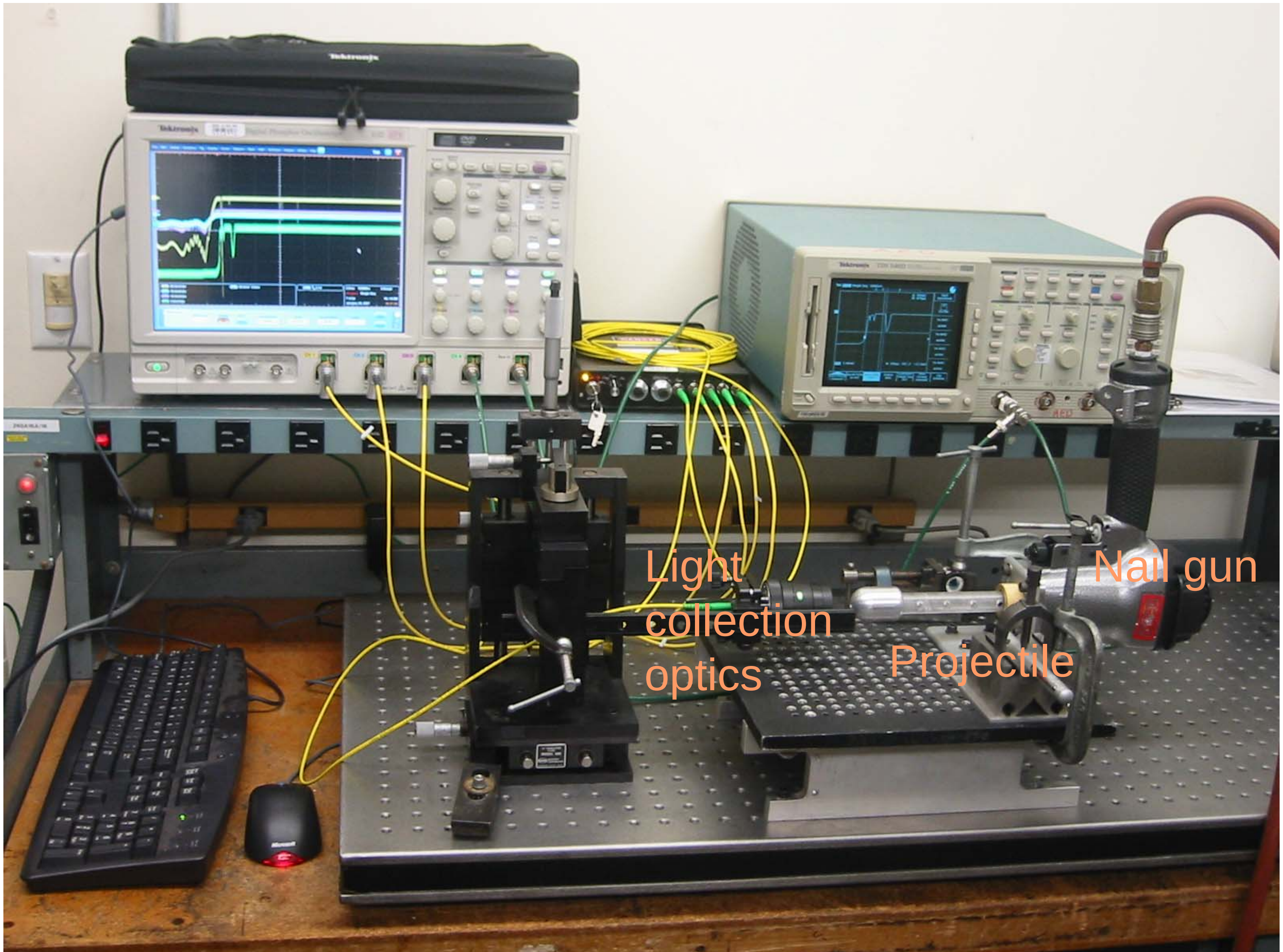
- **Fiber-coupled VISAR system – *now under test***
  - **Martin Froescher & Associates**
  - **Sub-ns resolution**
  - **1% accuracy**

- **Hamamatsu visible streak camera with image intensifier**
  - **Sub-ns resolution**
  - ***arrived Feb. 2007***

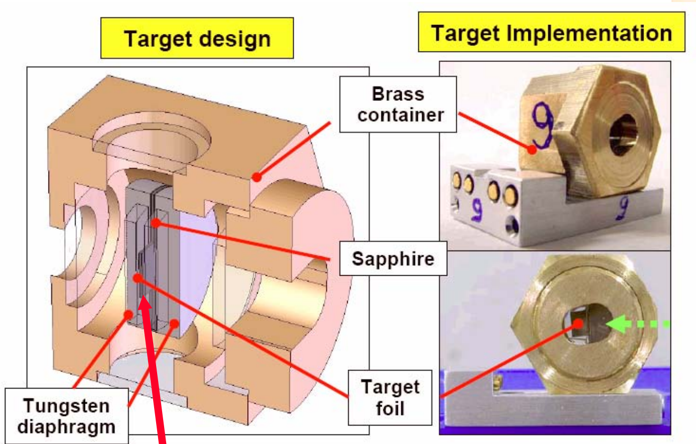


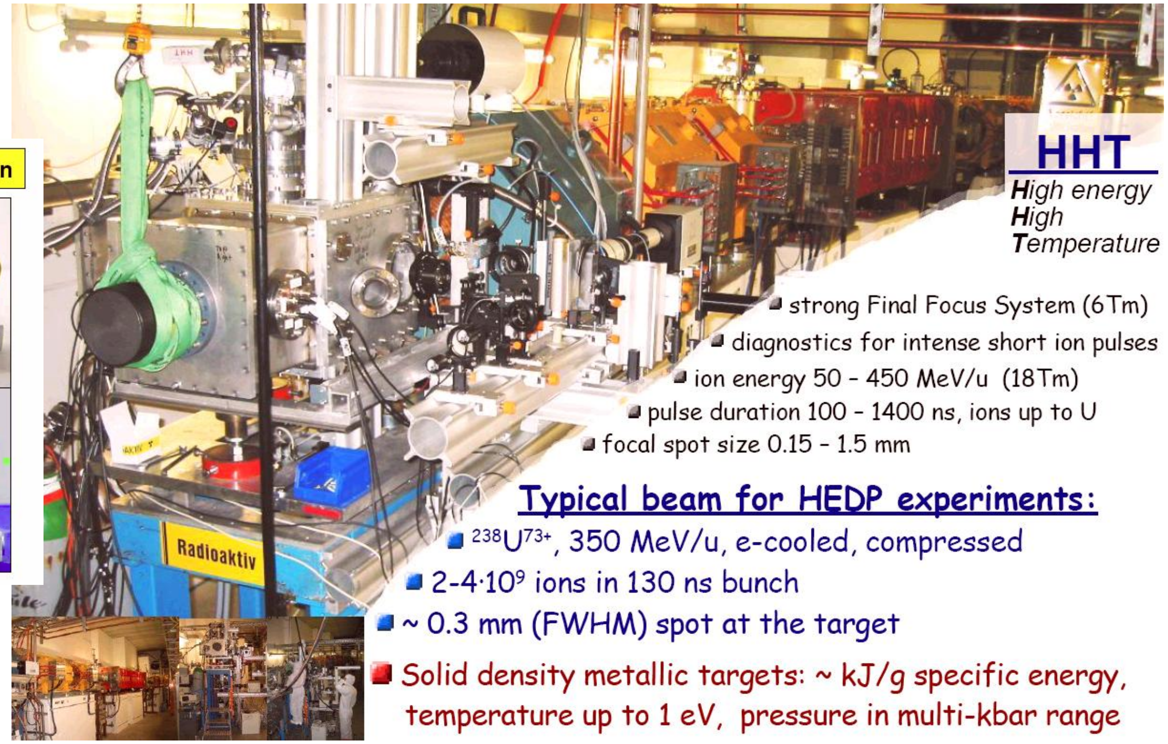


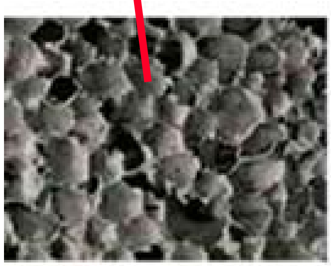
Diagnostic development and testing: VISAR for NDCX-I



VNL porous target experiments at GSI have already begun



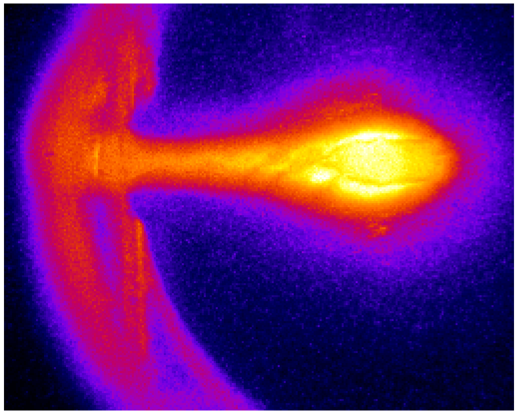




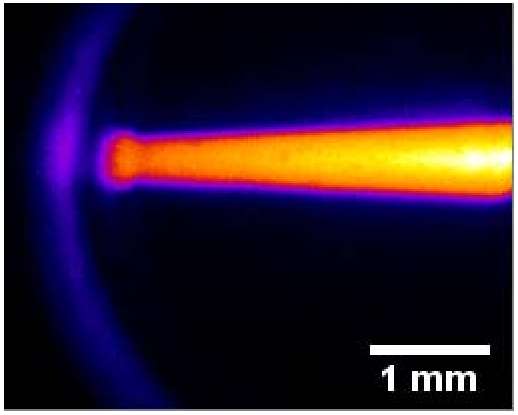
- Replace target foil with porous material.
- Study effect of pore size on target behavior using existing diagnostics.
- Sample targets: LLNL (Au, 50 nm), Mitsubishi (Cu, 50 micron).

Data analysis from GSI experiments is underway (Bieniosek)

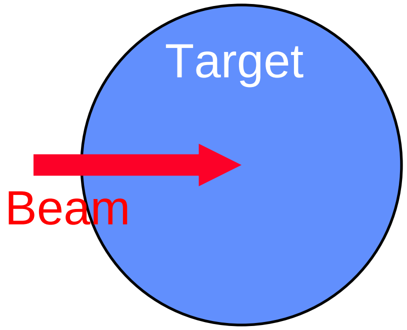
- Gold targets heated to about 6000 K (T-boil = 2435 K). Solid and porous gold targets show similar behavior (temp, 1.4 km/s expansion).



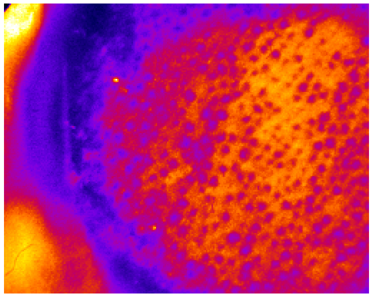
solid gold (note Bragg peak)

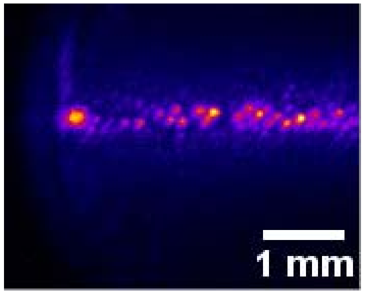


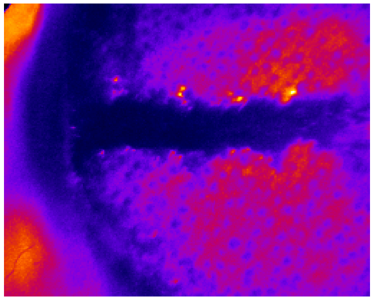
Porous gold



- Copper targets heated to about 3000 K (T-boil = 3200 K). Porous copper broke up into droplets.







Porous copper – before, during, after beam pulse

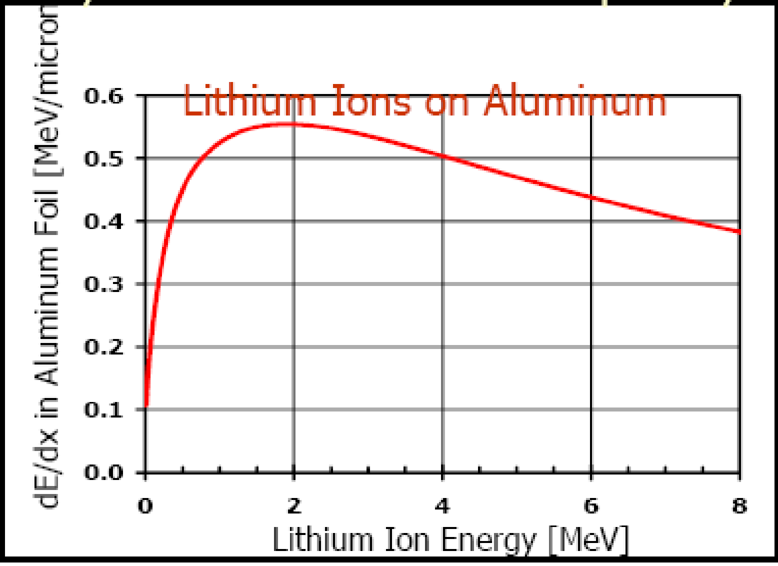
NDCX-II is the next step towards IB-HEDPX as well as towards a heavy-ion-fusion direct drive capability following NIF ignition

GOALS FOR NDCX-II:

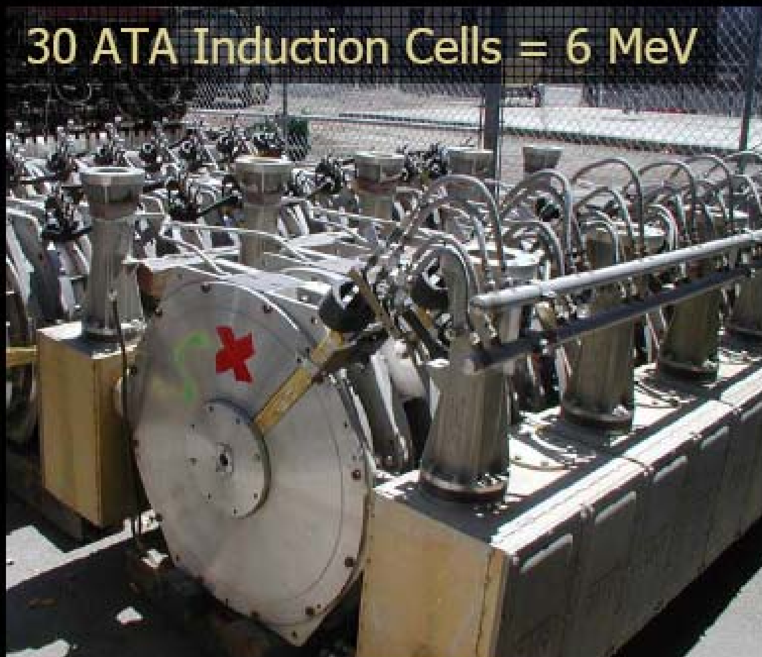
- Integrated compression, acceleration, and focusing sufficient to reach 1 eV in targets and to drive hydrodynamics experiments relevant to asymmetric direct drive heavy ion fusion.
- Incorporate short-pulse injector to minimize accelerator cost
- Diagnostics, target, and target chamber development for IB-HEDPX user facility to be constructed after NDCX-II, and for future heavy ion fusion direct-drive capability

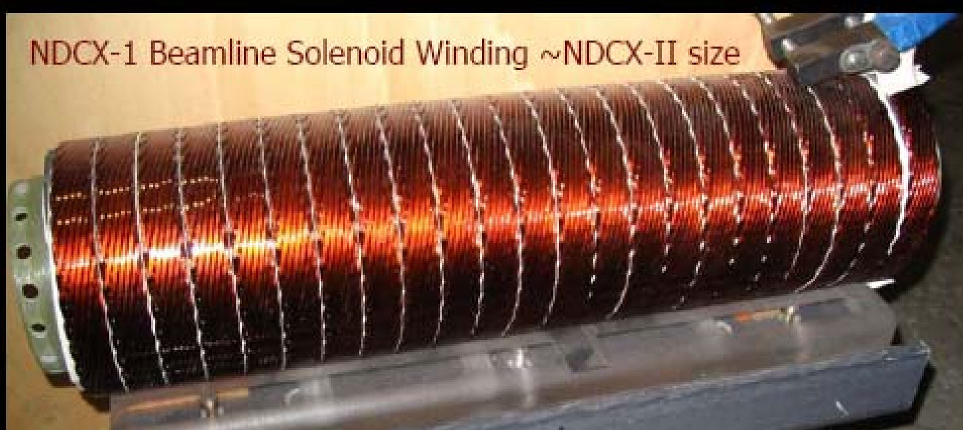
TARGET POINT DESIGN:

Bragg Peak:	1.8 MeV
dE/dx at Bragg Peak:	2 MeV cm^2 / mg
Ion Range:	~5 micron
Required Fluence for > 1 eV Heating:	>29 J/cm^2



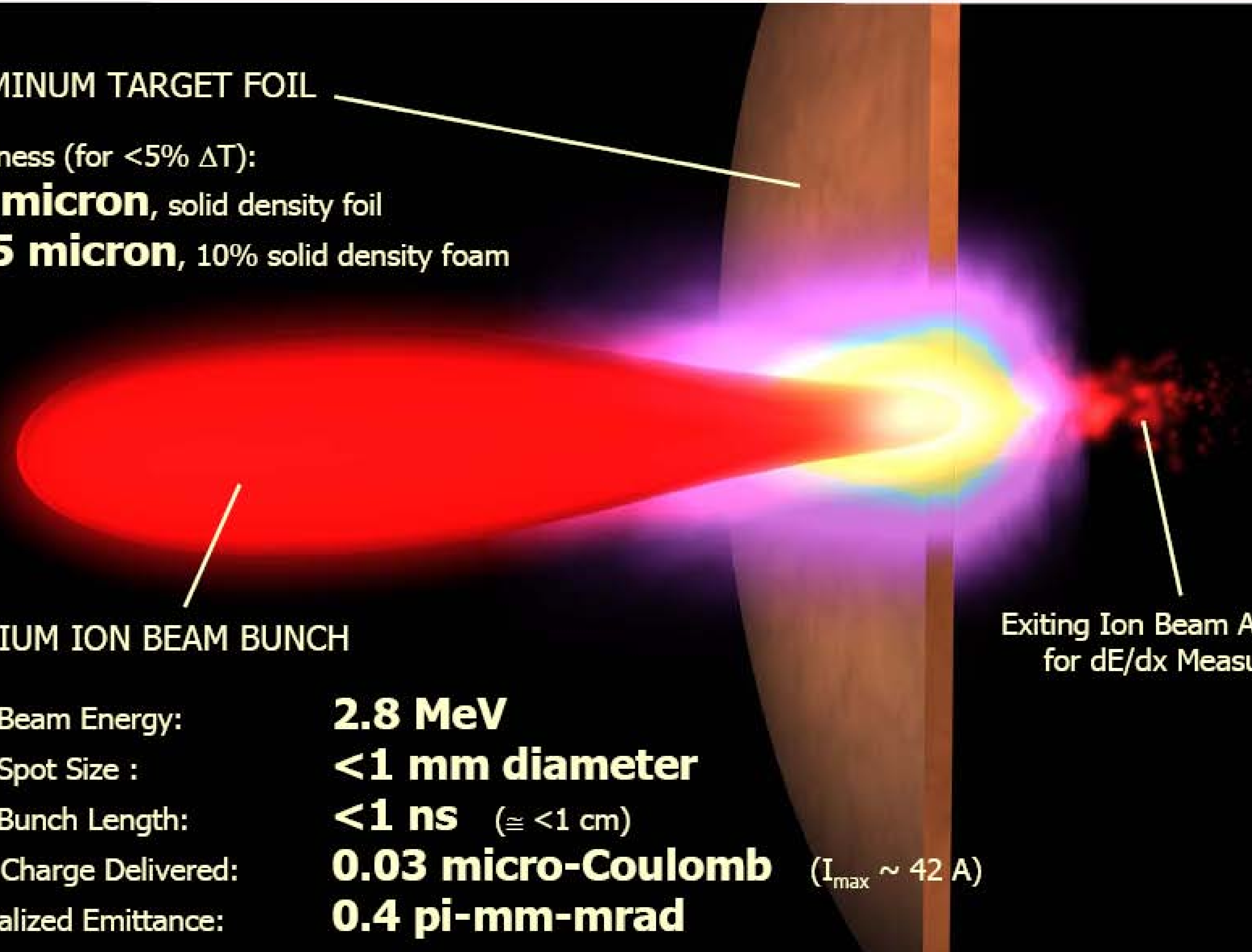
LLNL has donated 30 surplus ATA induction modules now located at LBNL- sufficient for NDCX-II





- We have shipped hardware for 30 induction cells to LBNL.
- We are building a high-field pulsed solenoid to fit into an ATA induction cell for tests.
- Hardware for two cell units has been refurbished for testing.

NDCX-II TARGET POINT DESIGN AND DRIVER REQUIREMENTS FOR >1 eV TARGET HEATING



ALUMINUM TARGET FOIL

Thickness (for <5% ΔT):

~3 micron, solid density foil

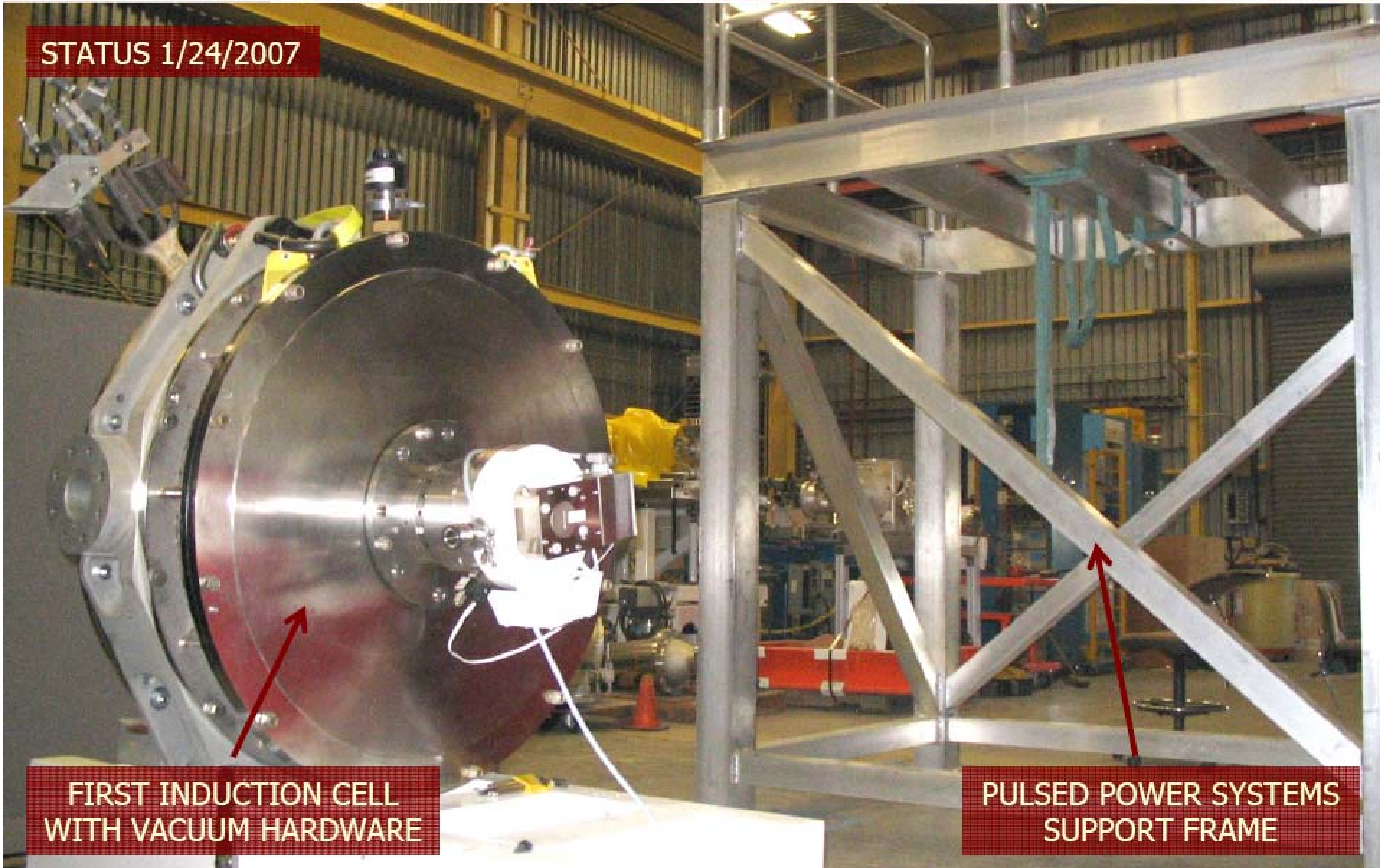
~25 micron, 10% solid density foam

LITHIUM ION BEAM BUNCH

Final Beam Energy:	**2.8 MeV**
Final Spot Size :	**<1 mm diameter**
Final Bunch Length:	**<1 ns** ($\cong$ <1 cm)
Total Charge Delivered:	**0.03 micro-Coulomb** (I_{max} ~ 42 A)
Normalized Emittance:	**0.4 pi-mm-mrad**

Exiting Ion Beam Available for dE/dx Measurement

NDCX-2 TESTSTAND IS CURRENTLY UNDER CONSTRUCTION TO VERIFY CELL PERFORMANCE AND TO TEST HIGH FIELD SOLENOID



For a very modest investment of $1.5M, the NDCX-II accelerator can be assembled and offer high shot rates available for HEDLP science users:

- Precise control of beam energy deposition
- 5 % uniformity over large sample sizes ~ mm^2
- Pulses long enough to achieve local thermodynamic equilibrium
- Maximum # of NDCX experiments ~100’s of shots per day for user-available targets, ~ 500 more/day for beam/diagnostic tune-up.
- Benign environment (no intense x-rays or neutrons that require shielding for people or diagnostics)
- NDCX-I-II would be dedicated to HEDLP users-not encumbered by other programmatic priorities
- Easily accessible site to visiting scientists and students

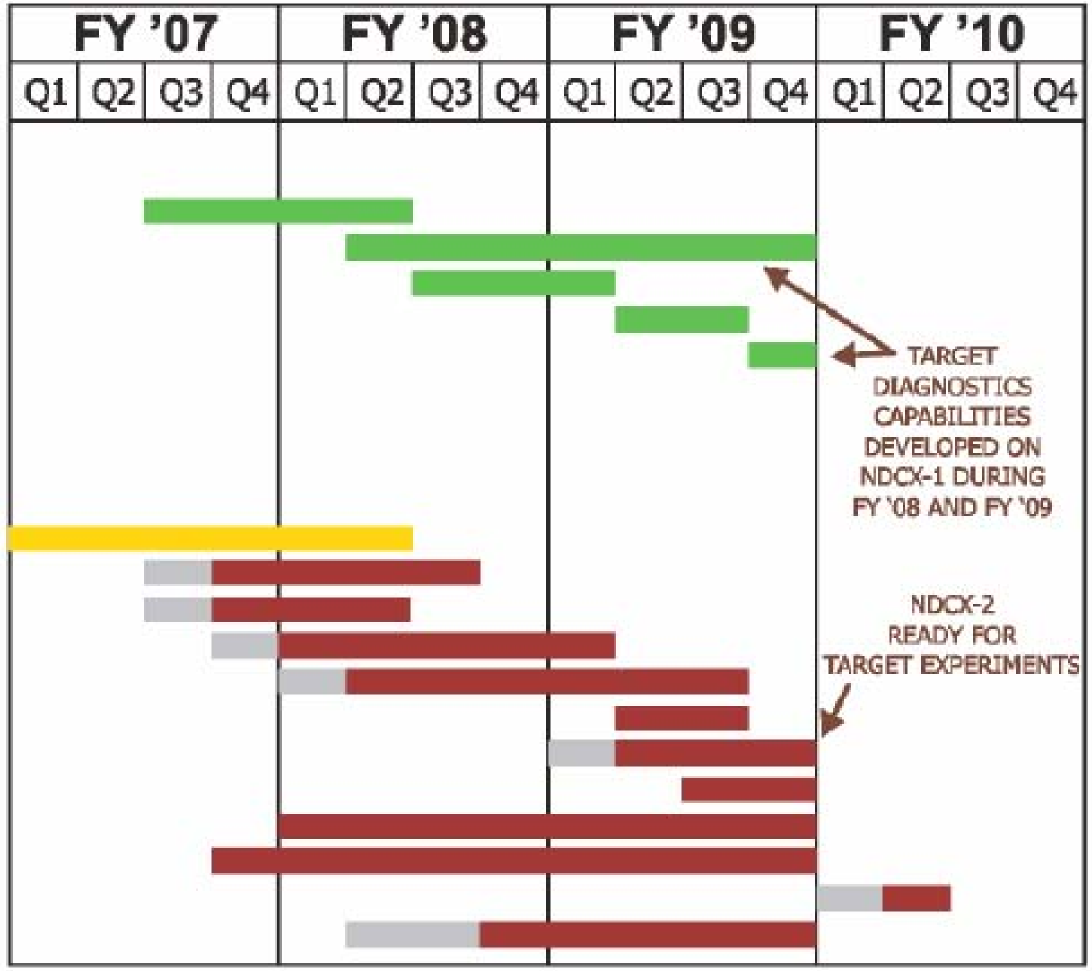
POSSIBLE NDCX-2 SCHEDULE
(PRESIDENT'S BUDGET DOES NOT CURRENTLY SUPPORT NDCX-2 CONSTRUCTION)

NDCX-1

(1) COMPRESSION IMPROVEMENT CAMPAIGN
(2) TARGET EXPERIMENTS
(3) TIME DEPENDENT FOCUSING EXPERIMENTS
(4) PLASMA SOURCE IMPROVEMENT
(5) HYDRO EXPANSION AND TARGET TEMPERATURE MEASUREMENTS

NDCX-2

(1) CONCEPTUAL DESIGN
(2) INJECTOR
(3) INJECTOR SOLENOIDS
(4) PRE-BUNCHING SECTION
(5) ACCELERATOR
(6) DRIFT BUNCHING MODULE (EXISTING)
(7) DRIFT COMPRESSION
(8) TARGET CHAMBER INCL. MAGNET (EXISTING)
(9) CONTROLS
(10) SUPPORT HARDWARE
(11) DOUBLE PULSING HARDWARE
(12) SUPERCONDUCTING FF SOLENOID



→Requires $1.5M incremental funding for hardware to complete