Heavy Ion Fusion Science Research

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U.S. Heavy Ion Fusion Science Virtual National Laboratory (HIFS-VNL)
A collaboration of LBNL, LLNL, and PPPL for HIF/HEDLP research

Fusion Power Associates
Annual Meeting

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We presented to NAS a development path based on *presumed success of NIF*: three R&D phases leading to an HIF-IFE Demo:

PHASE I (5 years): Integrated single beam accelerator experiments using NDCX-II, and HIF target design for indirect drive, direct drive shock, and X-target HIF options.

→***Deliverable:*** validation of heavy ion accelerator and implosion experiment design for Phase II, and for choice of target for Phase II.

PHASE II (10 years): Heavy-Ion-Driven Implosion Experiment (HIDIX): a 10-kJ-scale, multiple beam accelerator prototype which drives target implosions and learn precision pointing, balance, timing, etc. Includes supporting liquid chamber, target fabrication, and injection R&D for 5 Hz.

→***Deliverable:*** validation of approach to multi-beam accelerator and target for HIF ignition tests, using an accelerator designed for 5 Hz operation.

PHASE III: (>20 years) Construct 2-3 MJ HIF ignition test facility for single shot tests, then burst mode, using accelerator at 5 Hz. If successful, then add nuclear systems to upgrade to 150 MW ave. fusion power level HIF-IFE DEMO.

→*With the FY13 VNL budget cut to zero, we need a "Plan B"*

Near-term Plan: Utilize NDCX-II for IFE/HEDLP Research

(1) Commission NDCX-II using caryover funds + the $750k increment provided by FES, through May 2013.

(2) Proposals were submitted in response to FES' Program Announcement for HEDP science relevant to IFE:

- Intense beam physics and target coupling experiments using NDCX-II

- HIF target experiments using other ion or laser beam facilities (total available funding in the call was $5M)

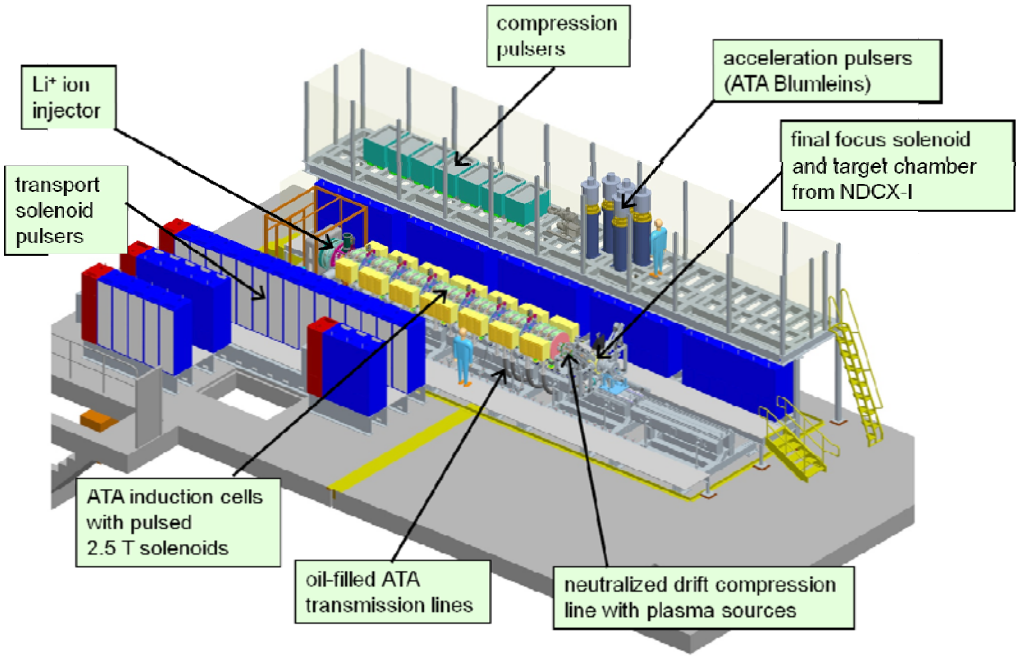
- The 2009 Fusion Energy Science Advisory Committee (R. Betti) report "Advancing the Science of High Energy Density Laboratory Plasmas" emphasized science needs in areas relevant to heavy ion fusion; (1) *HED Hydrodynamics (including advanced, high gain targets), (2) Intense Beam Physics, (3) Magnetized HED plasmas, and (4) Warm Dense Matter.*

- We are seeking collaborations between NDCX-II and other labs:

  SLAC-LCLS/MEC, LLNL-JLF, GSI-FAIR, IMP-HIRFL, LANL-LANSCE

NDCX-II is a user facility for studying HIF/HEDLP

- Neutralized Drift Compression eXperiment-II – for ns-scale intense ion pulses
- $11M ARRA-funded construction project completed in Feb 2012 (cost-saving by adapting many parts from LLNL's ATA)
- Commissioning is scheduled to complete by the summer of 2013.



NDCX-II applies drift compression to its dense beam *twice*

Initial non-neutral pre-bunching leads to a dense non-neutral beam in the accelerator

Final neutralized drift compression onto the target

inject → apply tilt → drift → accelerate → apply tilt → neutral-ized drift → target

NDCX-II will compress a 1 m long initial bunch to ~ 6 mm long at the target, with beam charge density similar to that of a driver beam at ~ few x 10^{12} cm^{-3}.

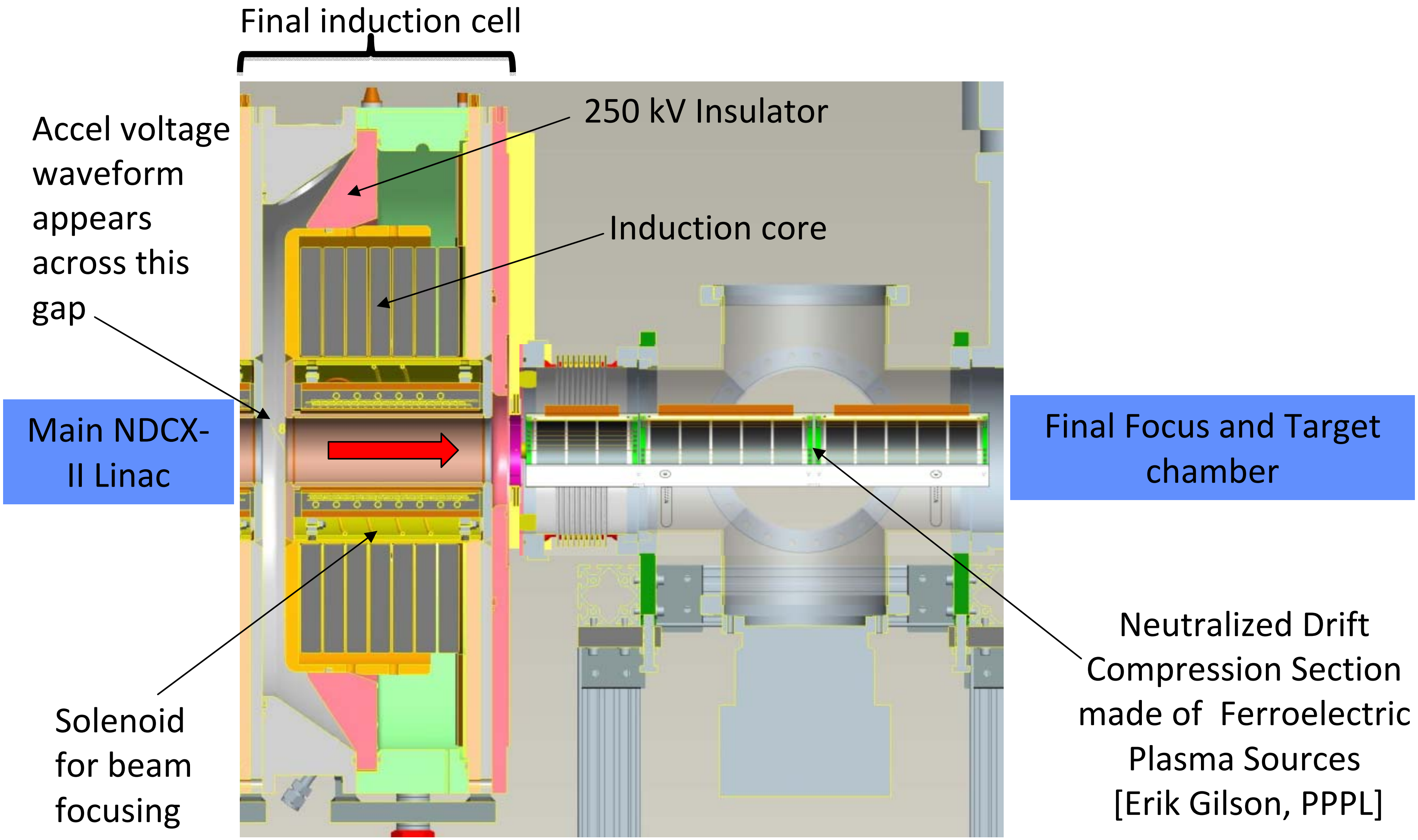
"Perveance" is space charge potential energy / beam kinetic energy:

$$K = \frac{2q\lambda}{4\pi\varepsilon_0 m v^2}$$

- Almost all beams have modest K; *e.g.*, the GSI linac has K ~ 4×10^{-6}.
- HIF driver beams will have K's of 10^{-4} - 10^{-3}.
- NDCX-II has a peak K of 10^{-2}

We will study this compressed beam - a stringent test of understanding

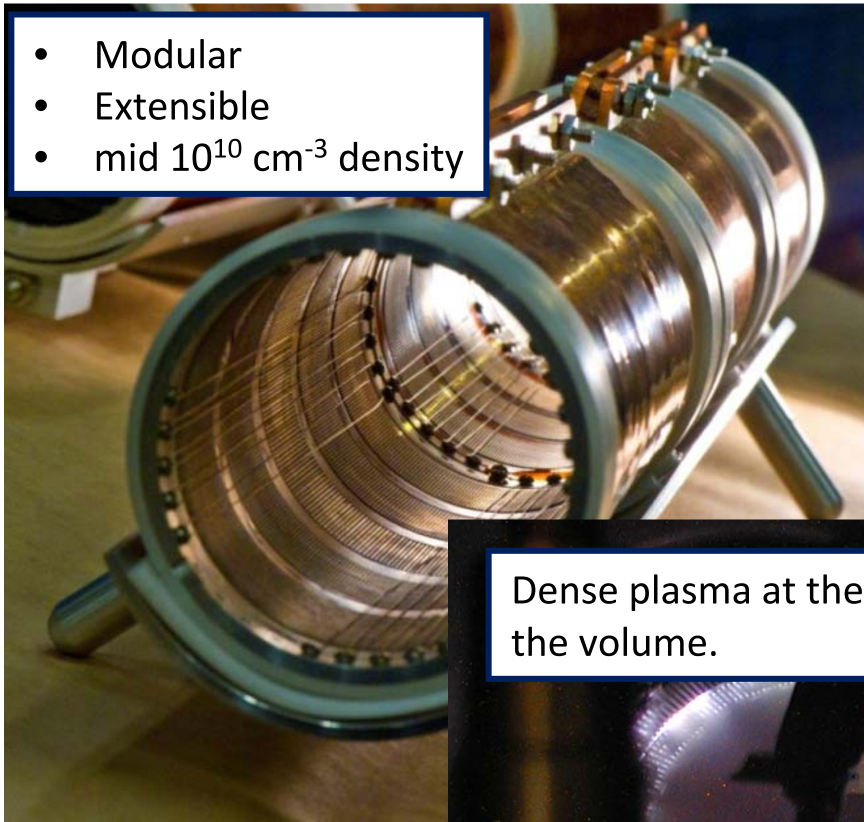
NDCX-II has 27 cells (12 powered), a neutralized drift section, a final focus lens, and a target chamber



[Will Waldron, LBNL]

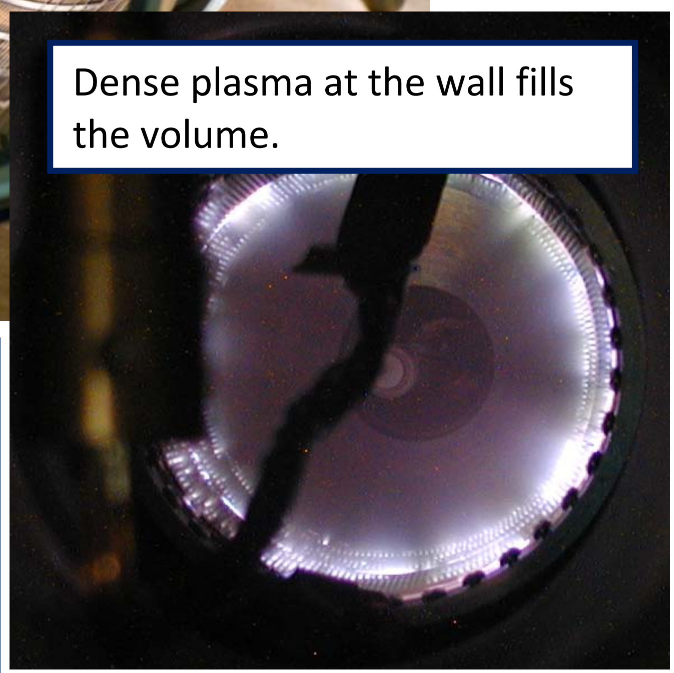
Ferroelectric Plasma Sources Developed at PPPL Provide Dense Plasma for NDCX-II Beam Neutralization and a Flexible Configuration

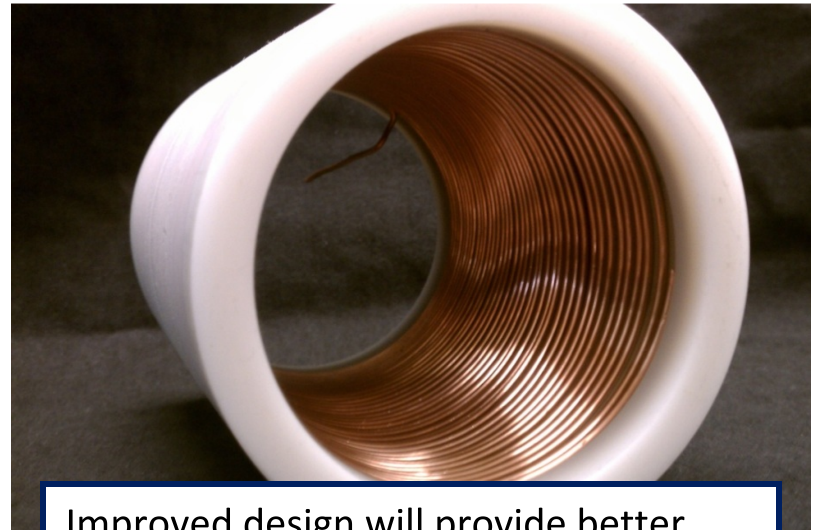
- Modular
- Extensible
- mid 10^{10} cm^{-3} density



Barium titanate's large dielectric coefficient creates large surface fields when pulsed, leading to a discharge.

Dense plasma at the wall fills the volume.





Improved design will provide better high-voltage stand-off and larger plasma density for future experiments.

NDCX-II Design Goals

Machine Characteristics:

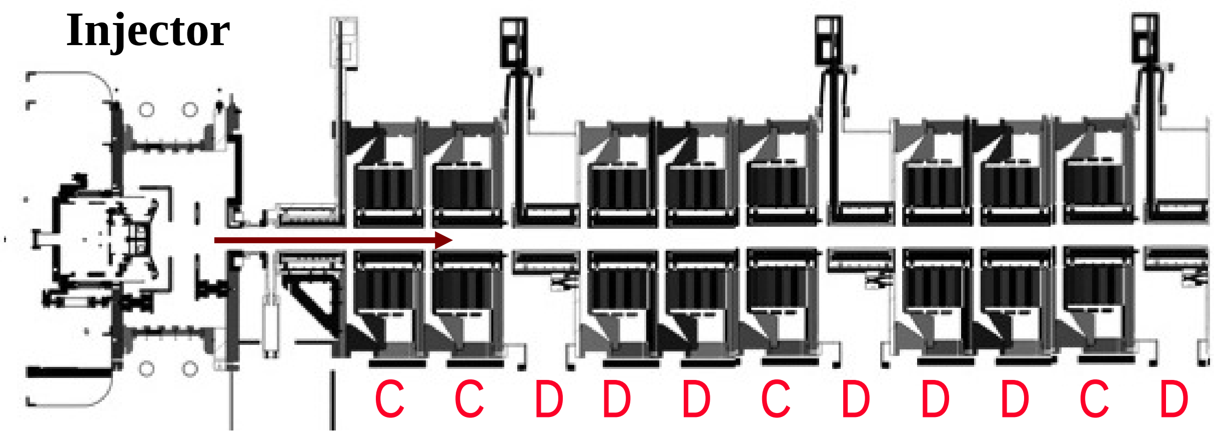
- 130 kV, ~ 500 ns Li^+ injector
- 12 induction plus 15 drift cells for acceleration and pulse shaping (500 ns → 1 ns compression @ 1.2 MeV)
- 2.5-3.0 Tesla solenoid magnet transport
- Neutralizing plasma drift section for final compression
- 8.5 – 9 Tesla Final Focus solenoid
- Intercepting and non-intercepting beam diagnostics
- Target chamber and instrumentation
- 2 shots/minute repetition rate

Projected Performance under Ideal Conditions

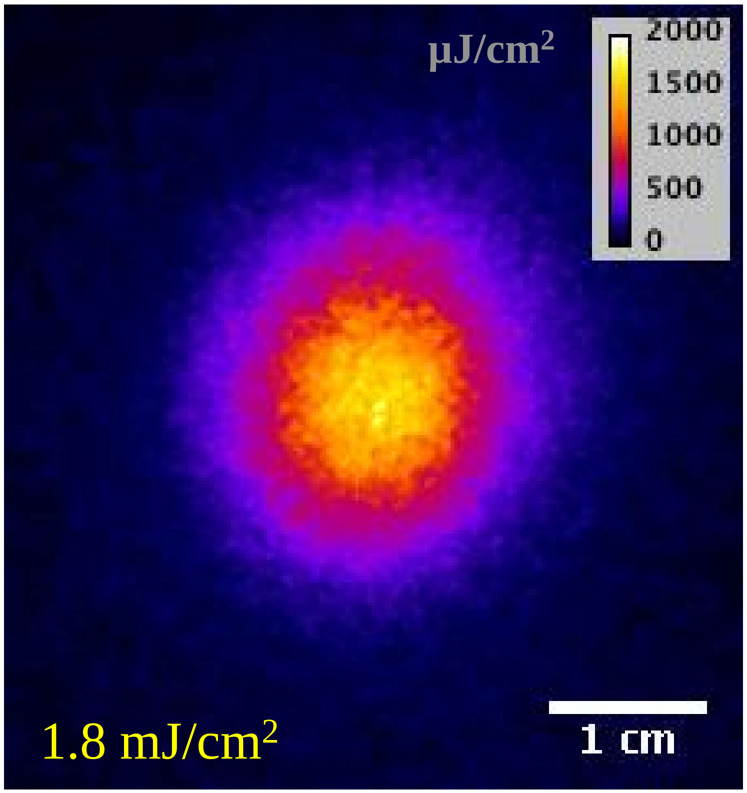
Based on Warp r,z simulations	NDCX-I	NDCX-II 27-cell (design goals)
Ion species	K^+ (A=39)	Li^+ (A=7)
Total charge	15 nC	50 nC
Ion kinetic energy	0.3 MeV	1.2 MeV
Focal radius (contains 50% of beam)	2 mm	0.6 mm
Bunch duration (FWHM)	2 ns	0.6 ns
Peak current	3 A	36 A
Peak fluence (time integrated)	0.03 J/cm^2	8.6 J/cm^2
Fluence w/in 0.1 mm diameter spot	0.03 J/cm^2 (50 ns window)	5.3 J/cm^2 (0.6 ns window)
Fluence w/in focal radius & FWHM duration	0.014 J/cm^2	1.0 J/cm^2

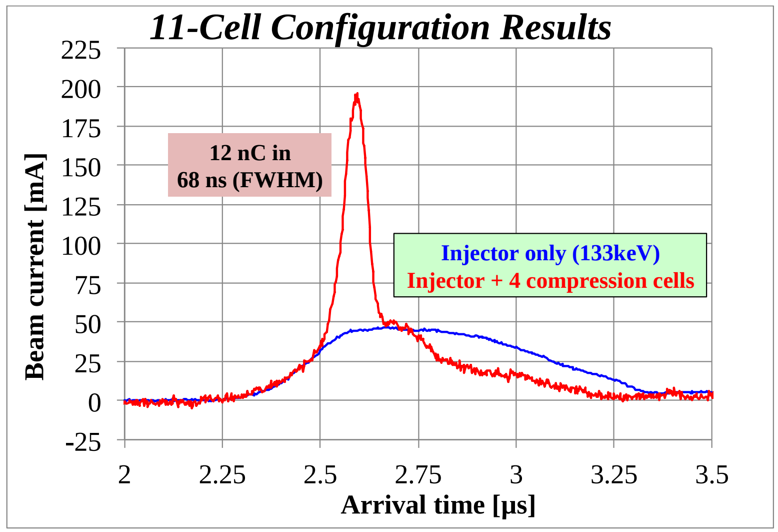
[Alex Friedman, LLNL]

Recent NDCX-II Commissioning Data



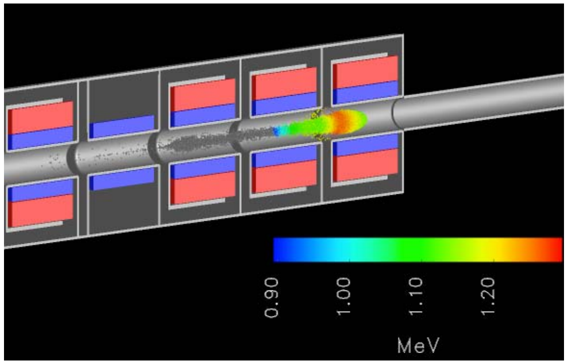
Injector + 11 Cells
160 kV, 4.6 mJ



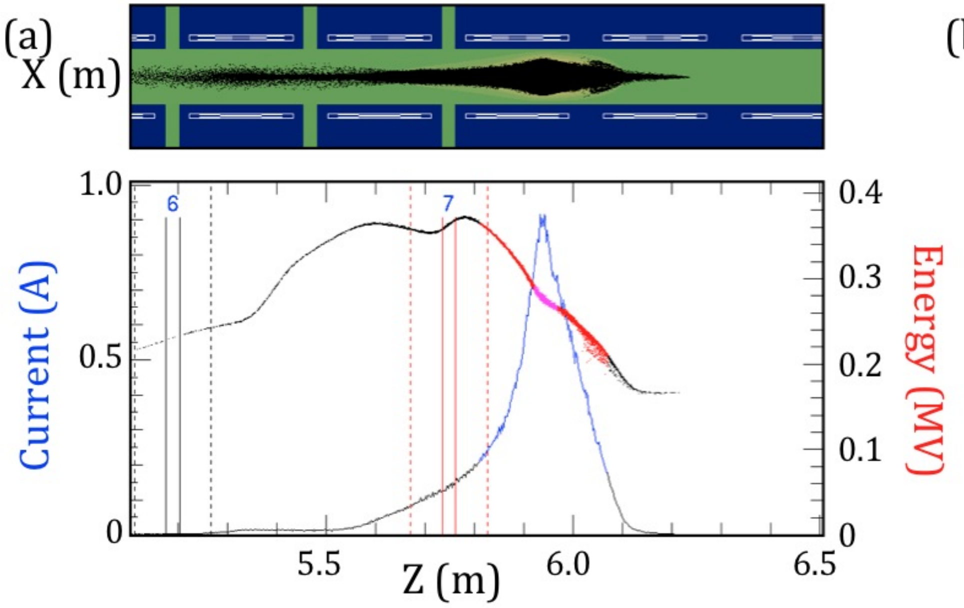


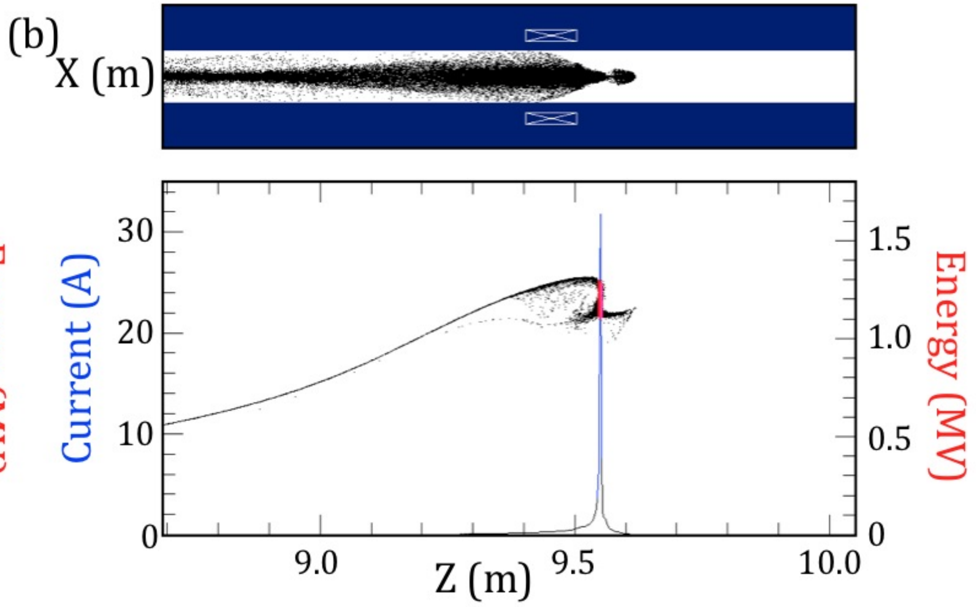
We started running beam through all 27 cells on Nov 30, 2012.

Ion beams are plasmas; strong space charge forces and plasma effects require kinetic simulations along with experiments



- 3-D simulation of NDCX-II using Warp code, showing beam as it exits accelerator and is about to enter the neutralized drift line.
- Axisymmetric Warp simulation (a) during initial compression in accelerator and (b) at peak compression at the target. The long, low-density tail appears dense due to the large number of simulation particles, but almost all the beam is in the red-colored core.



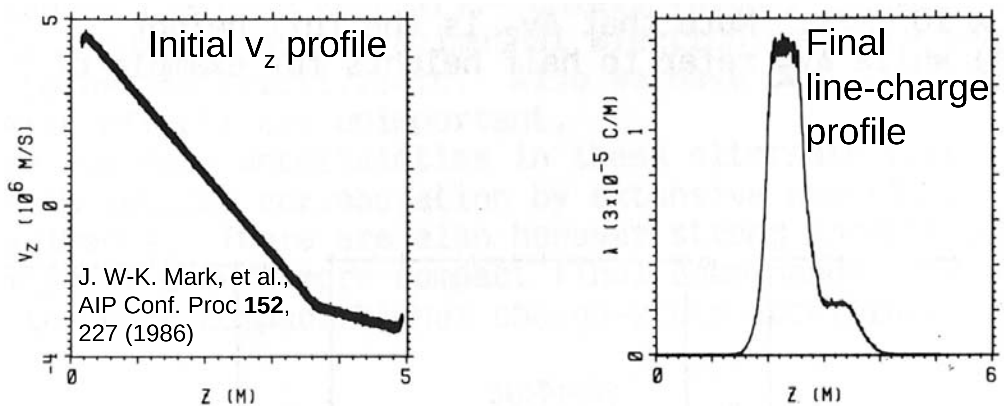


[Dave Grote, LLNL]

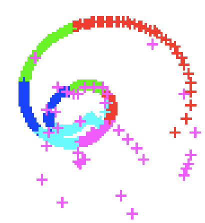
HIF-relevant beam experiments on NDCX-II can study …

- How well can space charge "stagnate" the compression to produce a "mono-energetic" beam at the final focus?

- How well can we pulse-shape a beam during drift compression (vs. the Robust Point Design's "building blocks")?



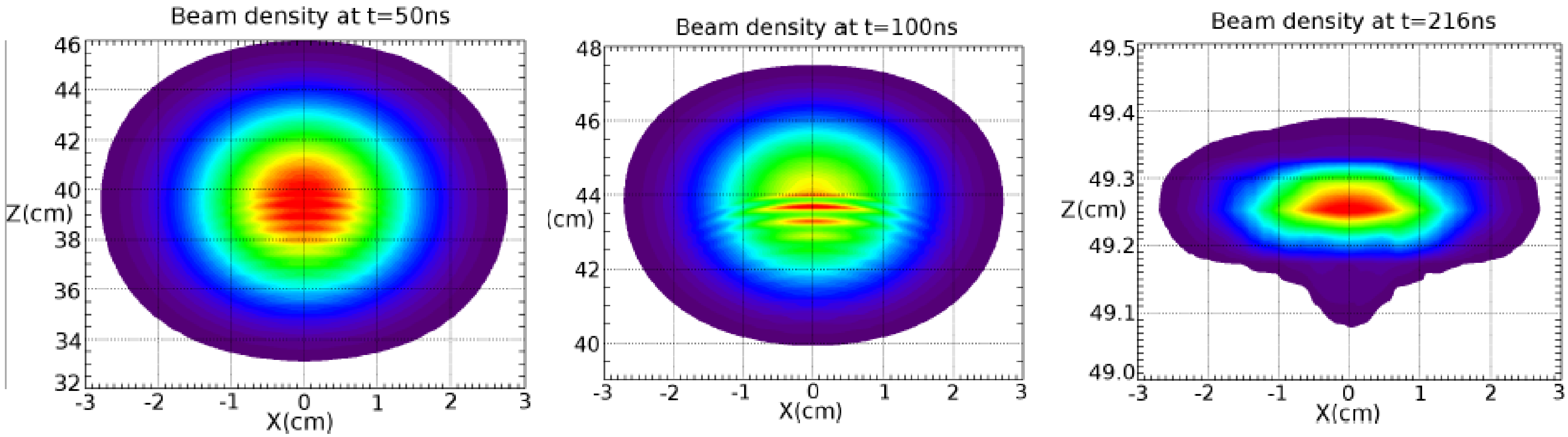
- Beam "wobbling" – NDCX-II has a "built-in wobbler" if we deliberately offset a solenoid; here, the simulated beam centroid (color partitioned by time) shows a crude wobbled pattern due to random misalignments. We will endeavor to create a controlled pattern.



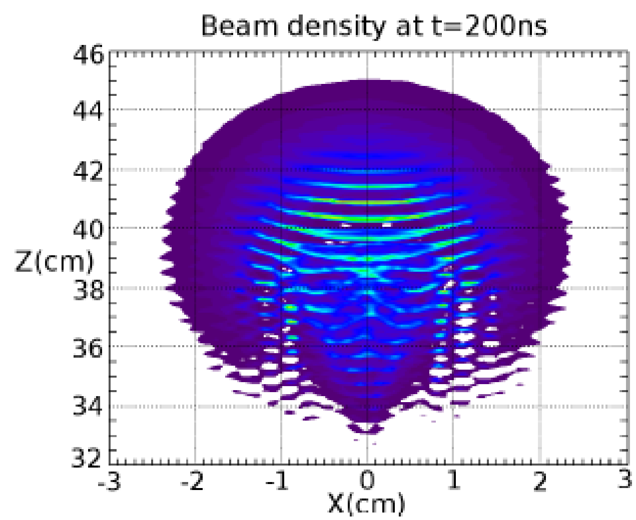
Most dimensionless parameters (perveance, "tune depression," compression ratio, etc.) will be similar to, or more aggressive than, those in a driver.

The compression velocity tilt suppresses two-stream instability that can disrupt a non-compressing beam in a plasma

Beam with 10% velocity tilt showed no breakup after 67x longitudinal compression.



Beam with no velocity tilt (thus no compression) showed beam breakup density variation up to 90%.



[Startsev, PPPL]

NDCX-II for target coupling experiments can yield basic science information for IFE and HIF

The topics of investigation most relevant to IFE fall into three broad areas:

1. Ion-beam stopping in heated material (relevant to inertial fusion ignition dynamics);

2. Hydrodynamic experiments on volumetrically heated targets, (important for heavy ion direct drive and heavy ion fast ignition targets);

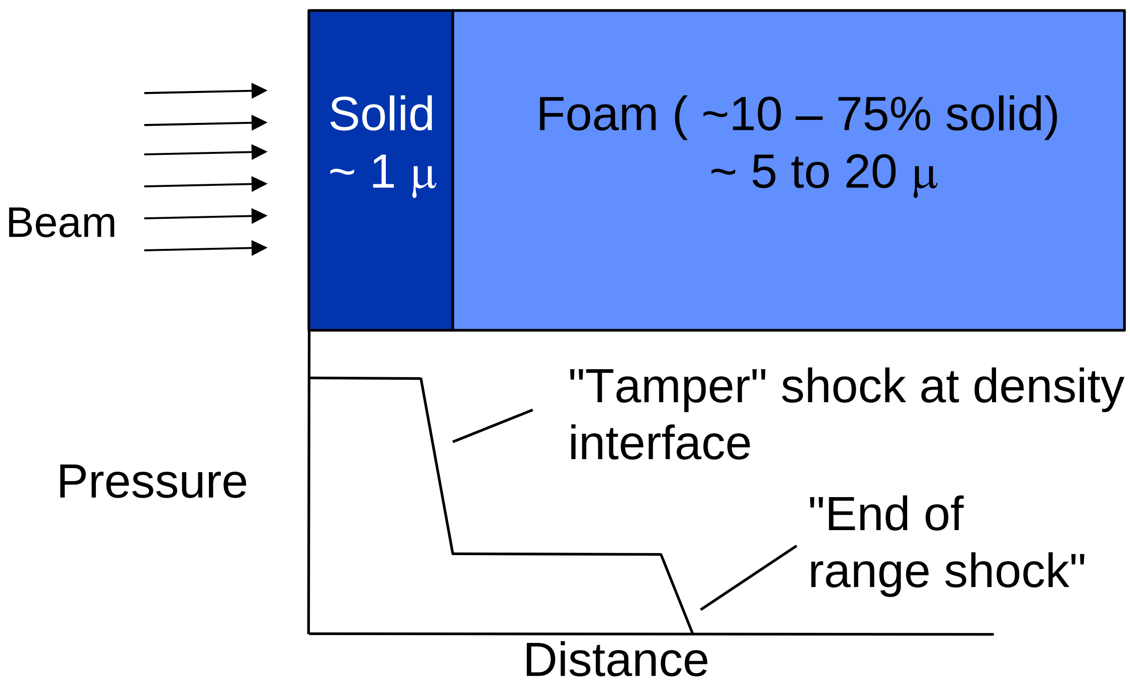
3. Conductivity in heated matter (relevant to the understanding of the physics of IFE capsule implosions).

Other physics, such as measurements of critical points and other EOS properties, is also accessible.

This work will test theories and benchmark codes that are used for IFE in regimes where they have not yet been tested.

Hydrodynamics of ion deposition with tampers (that can be used in HI direct drive targets) can be studied on NDCX-II

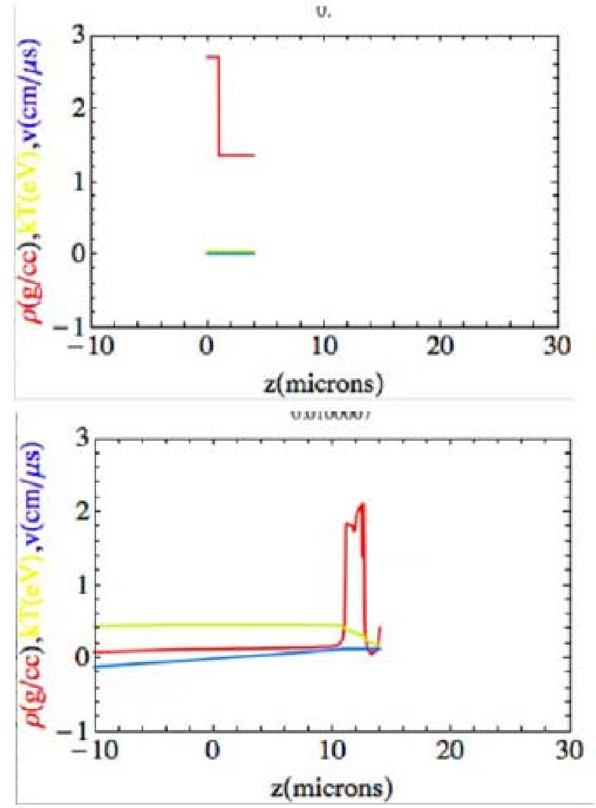
An example of NDCX-II HEDP experiment:



"Tamper shock" can catch up with "end of range shock"

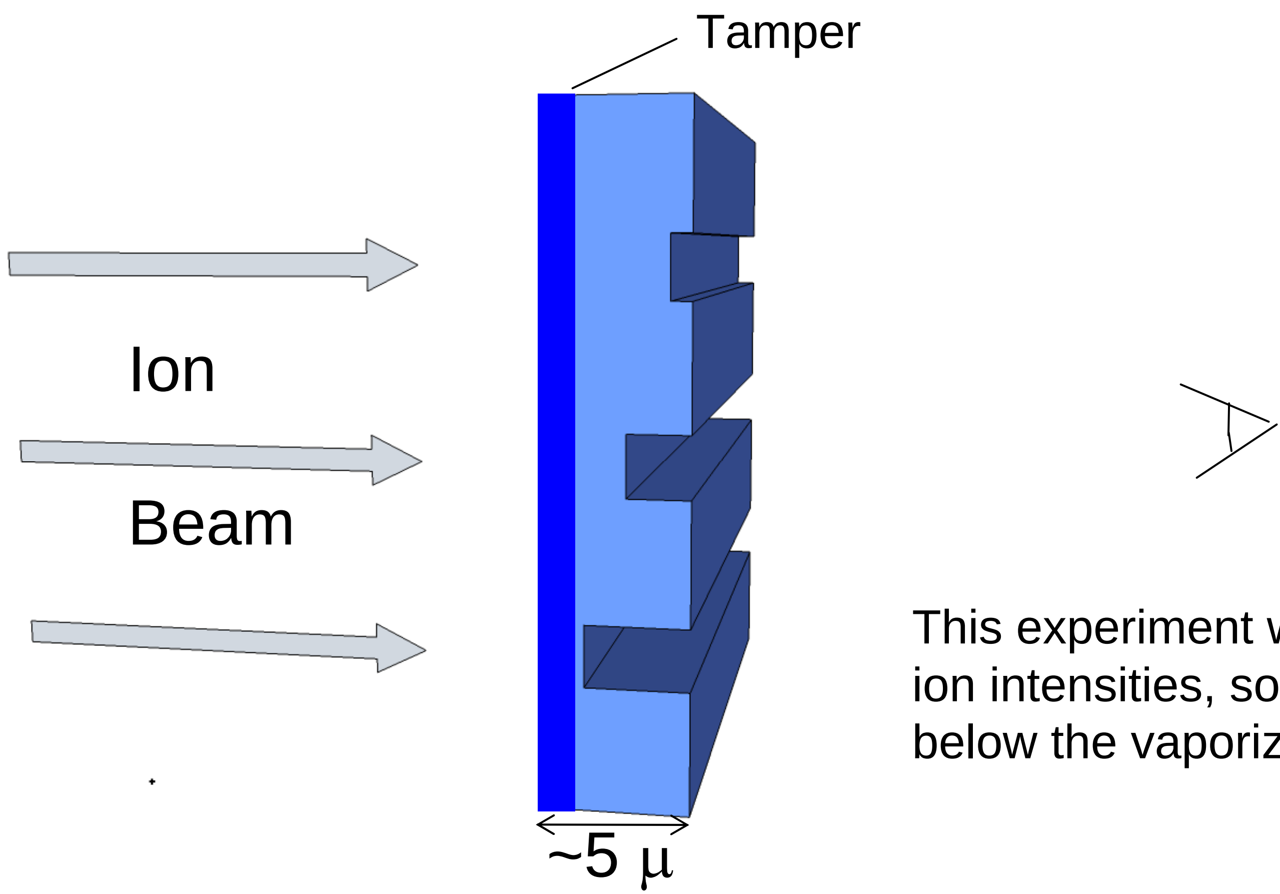
Tamper absorbs energy that is not necessarily converted to mass flow—thus need to optimize its thickness and density to maximize flow kinetic energy.

[John Barnard, Matt Terry, LLNL]



HYDRA simulation of a beam heated tamped aluminum target with 1 micron solid tamper followed by 4 microns of 50% metallic foam Al. The initial density (red) at beam center as a function of longitudinal position z is shown above, and the resulting acceleration of a slab at near liquid density is shown below after 10 ns. The temperature profile is shown in yellow and velocity profile in blue. The final velocity was about 0.1 cm/us in the example.

Thermal conductivity can be measured by determining time for heat to reach various depths in foils thicker than range of ions



This experiment will be carried out at low ion intensities, so that the material is below the vaporization temperature

Schematic for "stepped target" conductivity measurements. Ion beam heats tamper and rest of target nearly uniformly. Thermal wave from higher temperature tamped region 'breaks out" at various times depending on depth of grooves and heated material conductivity.

[Richard More, Pavel Ni, LBNL]

THE X-Target is a simple, robust, and high-gain heavy ion target for IFE

Illuminated from one side with a beam array near a polar axis to facilitate thick-liquid protected chamber designs

Simple fabrication with extruded DT fill, robust RT and mix stability with very small fuel convergence ratios (~ 5 to 7)

The compressed fuel should be able to be ignited with a beam of similar characteristics as the one used for compression

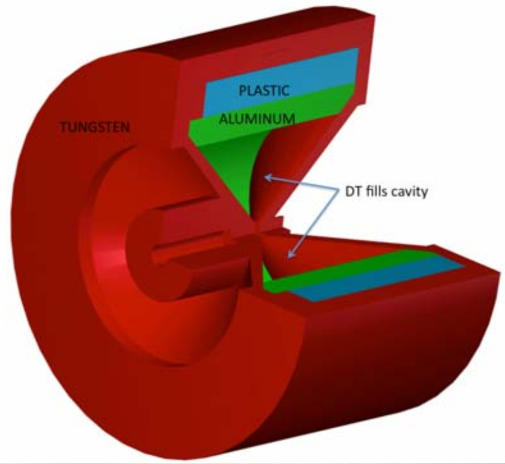
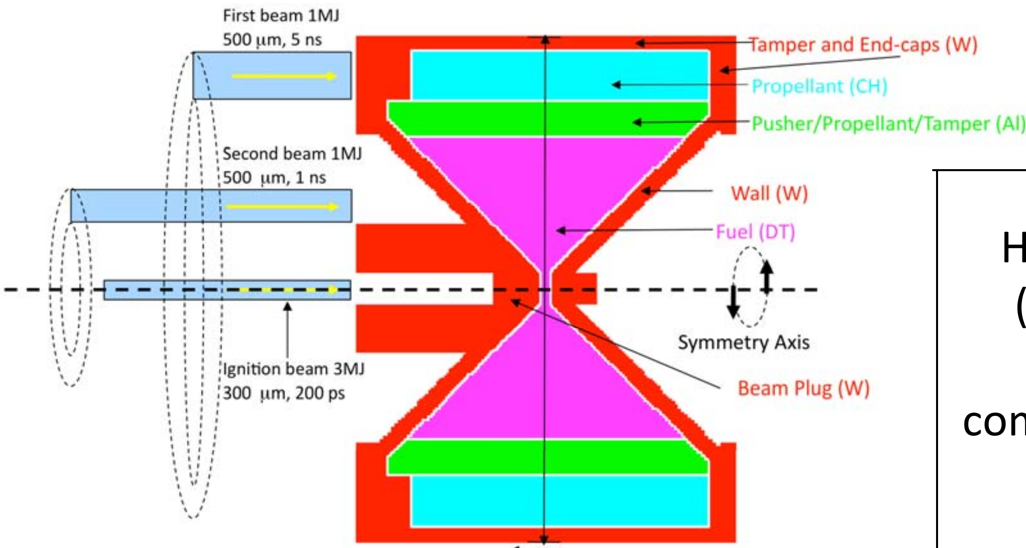


Photo of a plastic model (by GA)

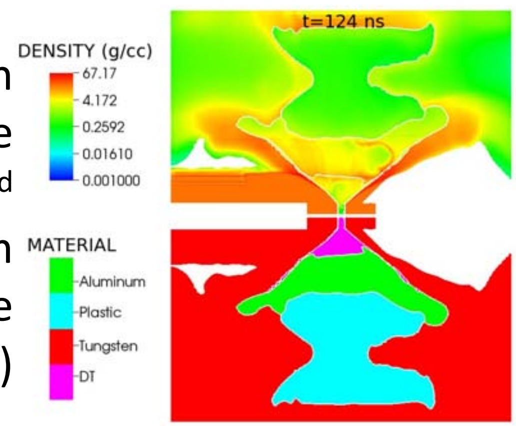
20 GeV Rubidium beams (1.0+1.0+3.0 = 5.0 MJ)
Yield = 1.5 GJ → Gain = 300

1st, 2nd, and ignition beams are many beams with overlapping spots modeled as annuli



[E. Henestroza & G. Logan, LBNL]

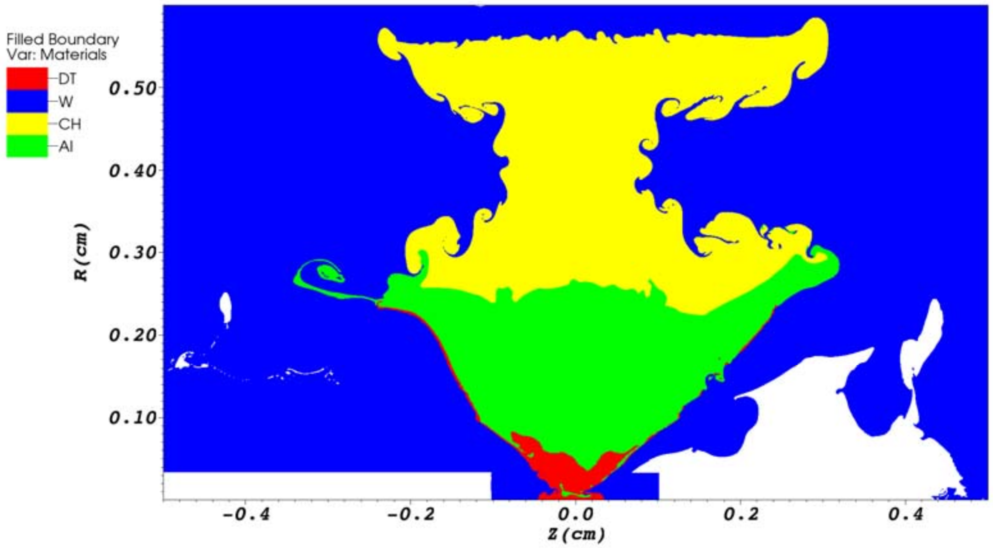
Hydra simulation (snapshot at the time the 2nd compression beam explodes the pusher)

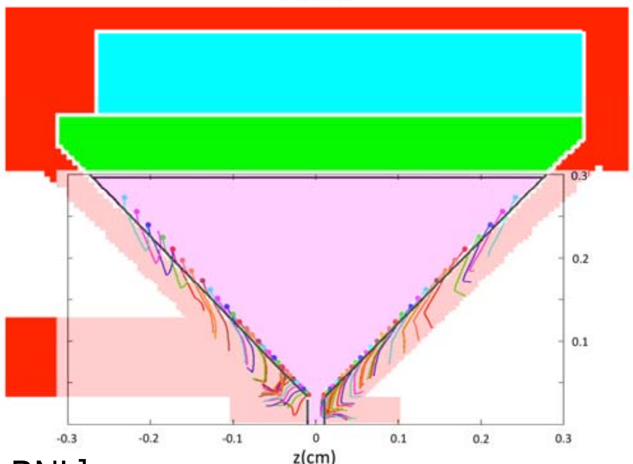


Simulation of Kelvin–Helmholtz instability in the X-Target

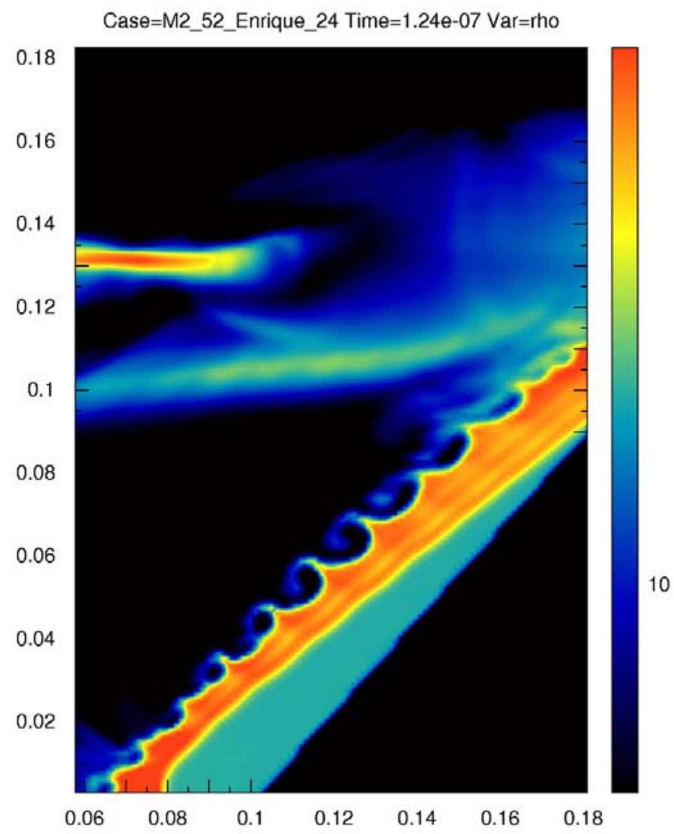
Kelvin–Helmholtz instability: Only numerical calculations using HYDRA and MULTI-2D.
Tracing fluid elements along wall during implosion do not show particles convecting to the ignition region

HYDRA Simulations





MULTI-2D Simulations



A strong B field can potentially stabilize the KH instability.

[E. Henestroza, LBNL]

Conclusions:

- Although there is a long-term plan for HIF development, we must adapt to the recent budget cut and allow more time to assess NIF results.

- Continue to optimize heavy ion target designs, because target physics affects target designs that set requirements for heavy ion accelerator drivers, and vise versa.

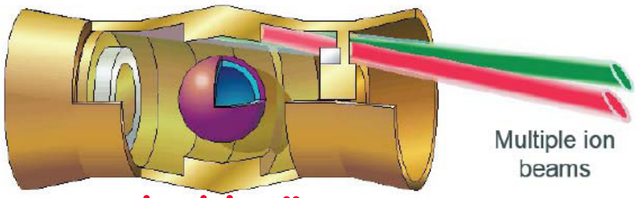
- NDCX-II can address many key beam-target coupling and warm dense matter physics over the next 5 years with 0.1 J sub-ns ion pulses.

- Over the next 10 years, we have opportunity to consider kJ-scale heavy ion beam target experiments via international collaborations such as the facilities now under construction at FAIR/GSI, Germany and the IMP-HIRFL at Lanzhou, China.

Extra Backup Slides

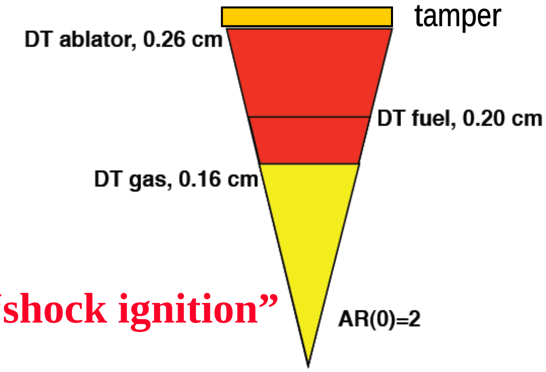
There are three basic classes of heavy ion fusion target options. No downselection is planned until NIF data is completed and assessed.

- **Indirect drive** (2-sided hohlraum) *2-D Lasnex design (2002):* 7 MJ, 3& 4 GeV Bi^{+1} , gain 68. Two-sided illumination, like NIF.



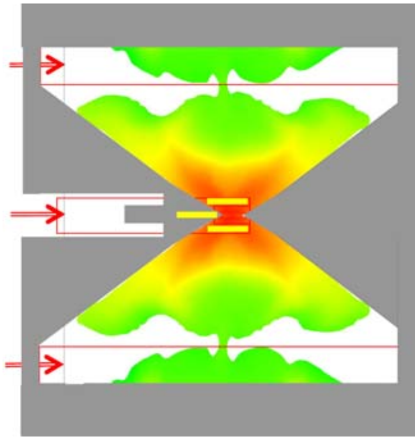
"hot-spot ignition"

- **Polar direct drive** *1-D Lasnex design (2010):* 3 MJ, 3 GeV, Hg^{+1} ion beams, gain ~150. Future 2-D design planned for polar drive illumination, with tamper & shock ignition assist.



"shock ignition"

- **X-target** single-sided direct-drive *2-D Hydra design(2011)* [Henestroza, Logan & Perkins, Phys. of Plasmas 18 (2011)] Gain 50 @ 6 MJ, range ~1 g/cm^2 ions. Now, with an aluminum pusher→ **gain> 400** with 3 MJ of 2 g/cm^2 range ions.

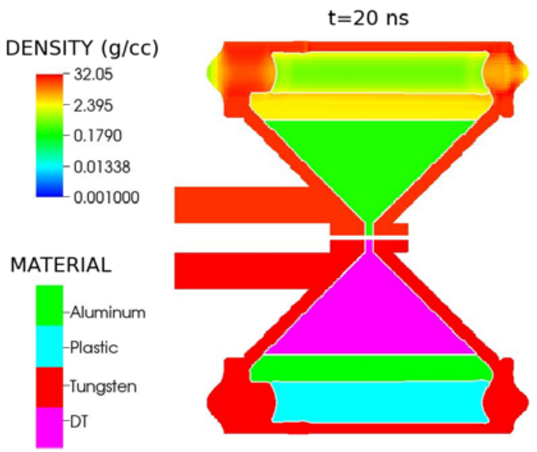


"fast ignition"

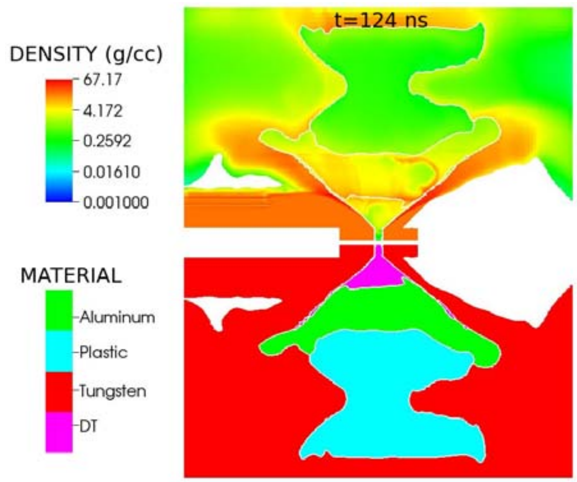
→All three options are intended to use multiple-beam linac drivers with thick-liquid-protected chambers to mitigate material neutron damage risks.

HYDRA Simulation of the X-Target implosion and ignition

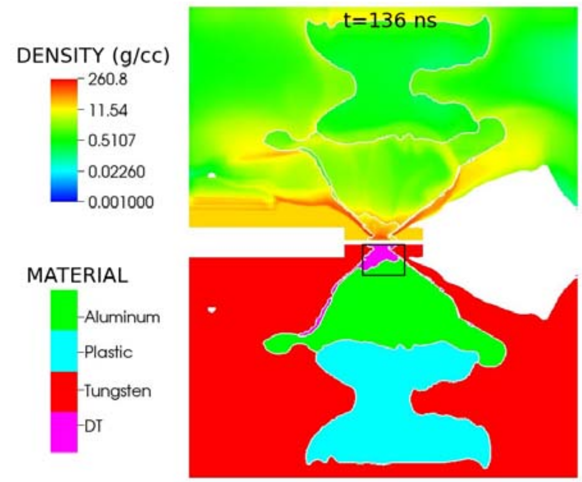
First beam explodes the end-caps and propellant



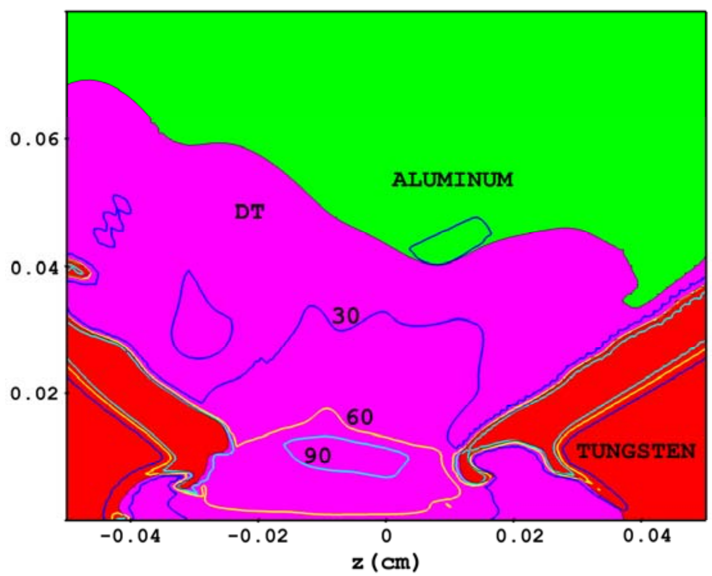
Second beam explodes the pusher



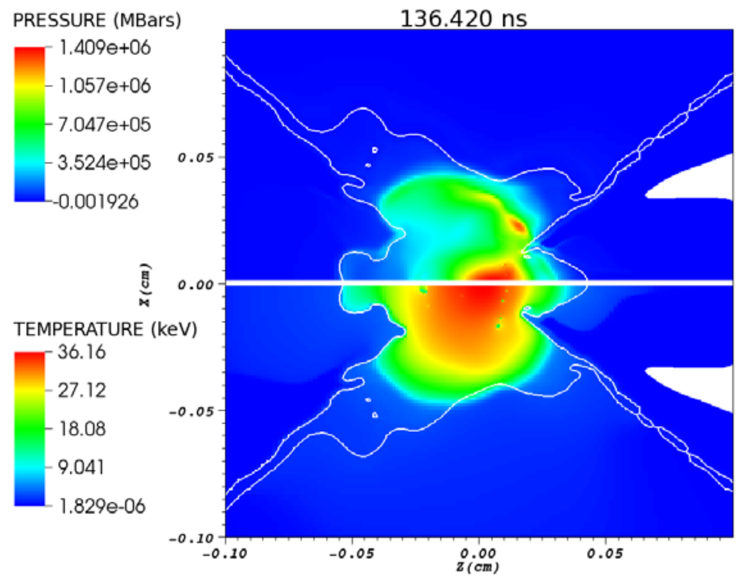
Time of “maximum” compression



Time of “maximum” compression (zoom)

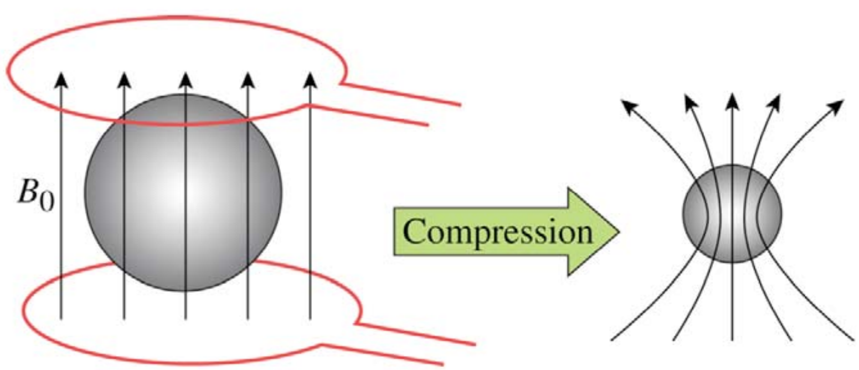


Pressure and temperature at peak fusion power



Possibility of stabilizing the KH instability with a magnetic field

- High B-fields with the "right" topology can be obtained by imploding a magnetized target
- The fields provide thermal insulation of the hot spot
- This can be tested at the OMEGA facility which can generate solenoidal magnetic fields at ~10 T.



[Grant Logan, LBNL]

Hohenberger *et al.* Phys. Plasmas **19**, 056306 (2012)

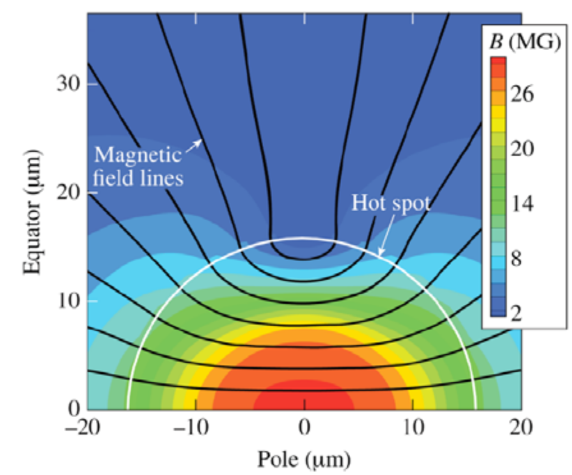
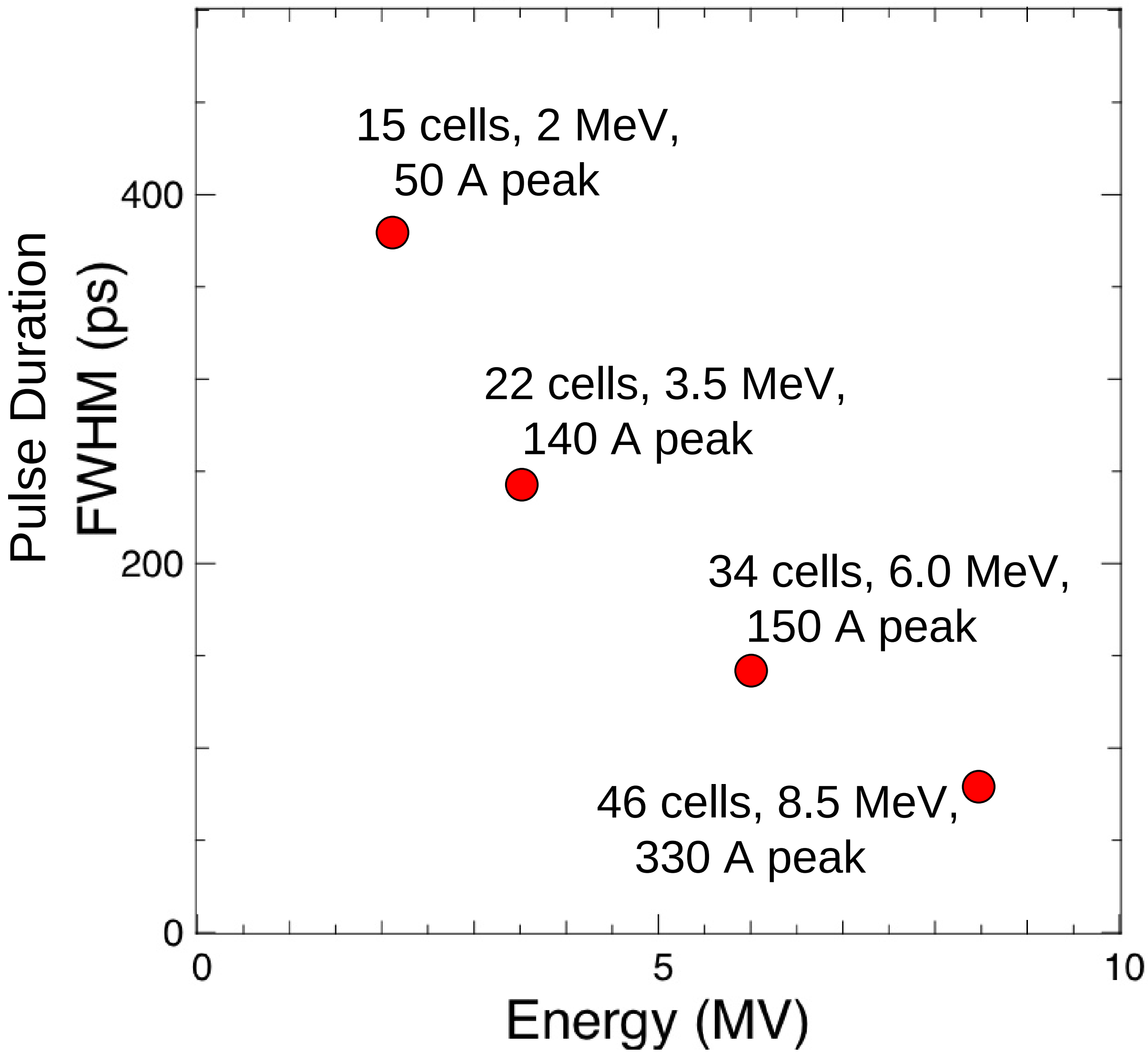


FIG. 12. Result from a 2-D post-processed 1-D simulation of a magnetized spherically imploding target. The black lines represent magnetic-field lines, and the color denotes field strength. In this simulation, the initial seed field of 50 kG has been compressed to ∼25 MG inside the hot spot.

Assuming ideal neutralization, an extended NDCX-II with 46 induction cells could compress beam pulse down to ~100 ps FWHM at 8.5 MeV



Results of Warp simulations, using highly optimized waveforms and assuming ideal pulse timing, voltage accuracy, neutralization, and source uniformity

- Separate studies have examined effects of:
  - timing jitter and voltage ripple in accelerating waveforms
  - injector voltage ripple
  - misalignments
  - source emission (2 mA/cm^2 assumed here)
  - source temperature
- Modest degradation due to these effects is observed

NDCX-II is a facility for studying both intense beam compression and Warm Dense Matter (WDM)

A scientific question for heavy ion beams identified in the National HEDP Task Force Report and in the April 2005 FESAC Fusion Priorities Report:
How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion ignition condition?

STAGE-I (Long pulse, 0.9 ns, 13 J/cm2)

- EOS of matter at under-solid density (foam targets, cryo target) ←long pulse implies expansion to densities below solid density

STAGE-II (Short pulse, 0.2 ns, 22 J/cm2)

- Isochoric heating→ EOS of solid density matter
- First ion-beam driven shock-waves.
- Hydro instabilities studies → Very critical to ICF.