Overview of activities in the US Heavy Ion Fusion Science Virtual National Laboratory

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on behalf of the HIFS VNL

Japan – US Workshop on Heavy Ion Fusion

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The Heavy Ion Fusion Science Virtual National Laboratory

BERKELEY LAB

PPPL

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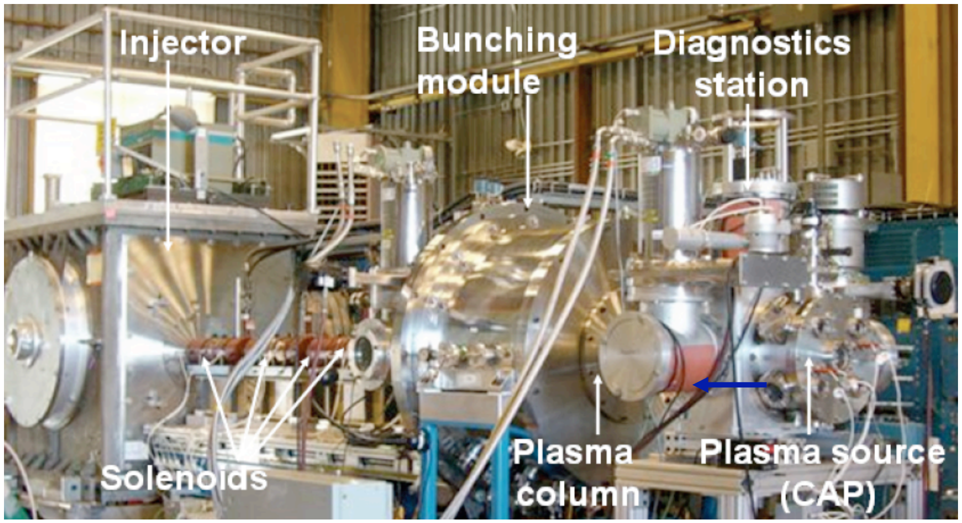
Outline of talk: Overview of HIFS VNL Activities

1. NDCX-I: Status
2. NDCX-II: New induction accelerator
   - Project completion expected before end of 2011 (due 3/2012)
   - Chamber expected in 2012
   - Injector now being tested
3. NDCX-II: physics experiments
   - Heavy ion fusion beam physics
   - Warm dense matter target physics
   - IFE relevant target physics
4. Target physics
   - X-target
5. Other theoretical and experimental investigations

NDCX I layed the groundwork for NDCX II

NDCX I
0.35 MeV,
0.015 μC
(compressed pulse)
(no longer operating at LBNL;
plan to move to PPPL)



- Explore metal liquid/vapor boundaries at T ~ 0.4 eV (uncompressed pulse)
- Evaporation rates/ droplet formation
- Test beam compression physics
- Test diagnostics

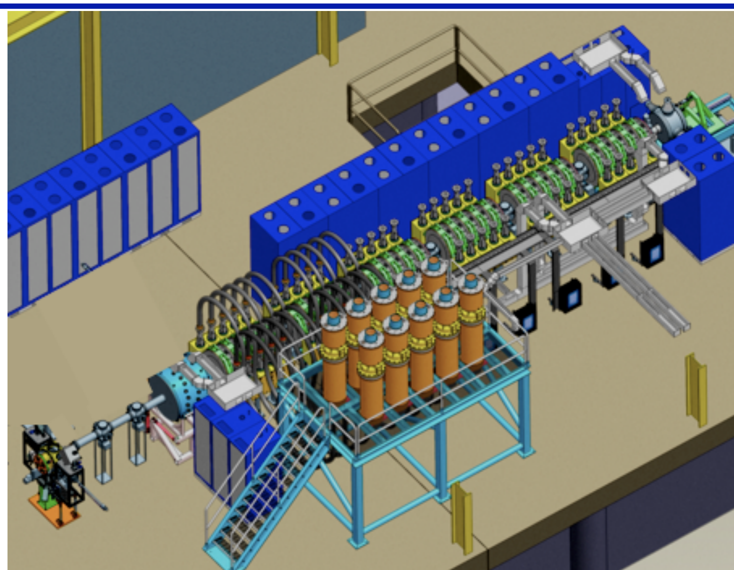
NDCX II

1 - 3 MeV,

0.050 μC

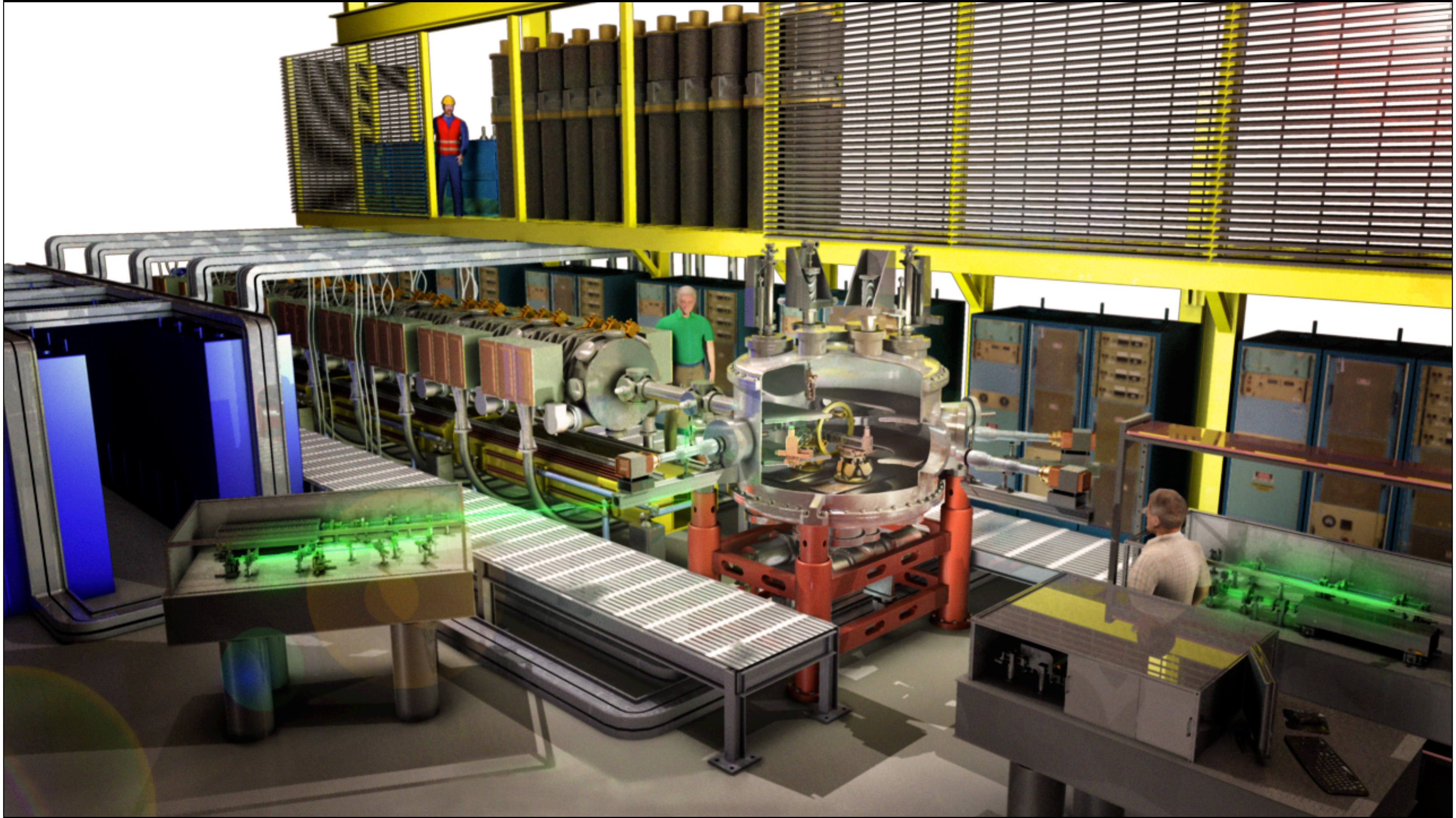
"Project"

Completion date: 2012



- Bragg peak (uniform) heating
- T ~1-2 eV in planar metal targets (higher in cylindrical/spherical implosions)
- Ion^+/Ion^- plasmas
- Critical point; complete liquid/ vapor boundary
- Transport physics (e-cond. etc)
- HIF coupling and beam physics

NDCX-II's compressed ion pulses will enable studies of Warm Dense Matter, ion-driven ablation for IFE, and intense beam physics.

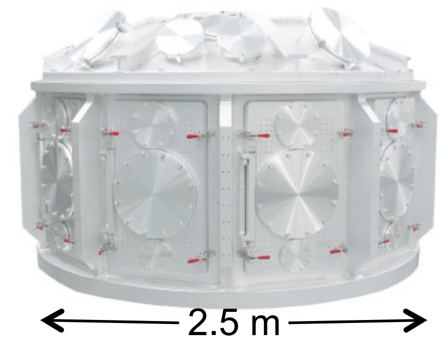


NDCX II

Heavy Ion Fusion Science Virtual National Laboratory

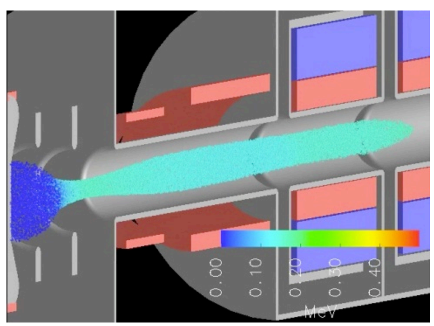
NDCX-II will enable studies of WDM, ion coupling physics, and the beam compression and focusing needed for heavy ion fusion.

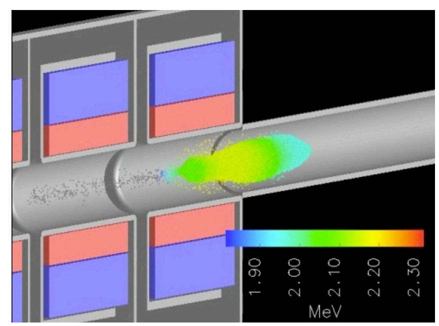
- The $11M ARRA project began in July 2009; completion is expected by end of 2011 (due 3/12).
- Commissioning will take ~ 1 year.
- Extensive re-use of components from LLNL ATA
- Detailed 3-D simulations using the Warp code set physics design & engineering requirements
- IFE target physics studies and WDM studies use HYDRA, ALE-AMR and 1-D codes



- A Titan/Trident/LCLS-like chamber is to be added (initial funds have been provided by DOE/FES) (2012)
- This will promote cross-platform HEDLP diagnostics/experiments

During injection →





← Entering final compression

Ref: A. Friedman, et al., *Phys Plasmas* (2010)

NDCX-II is extensible and reconfigurable; even the 12-cell baseline configuration will be far more capable than NDCX-I

	NDCX-I (bunched beam)	NDCX-II baseline* (➔advanced)
Ion species	K^+: A=39	Li^+: A=7
Total charge	15 nC	50 nC
Ion kinetic energy	0.3 MeV	1.25 MeV (➔ >4 MeV)
Focal radius (containing 50% of beam)	2 mm	0.6 mm
Bunch duration (FWHM)	2 ns	0.6 ns (➔< 0.20 ns)
Peak current	3 A	30 A (➔> 100 A)
Peak fluence (time integrated)	0.03 J/cm^2	8.6 J/cm^2 (➔> 20 J/cm^2)
Fluence within a 0.1 mm diameter spot	0.03 J/cm^2 in 50 ns window	5.3 J/cm^2 in 0.6 ns window; (➔> 30 J/cm^2 in 0.2 ns window)

* Estimates of ideal performance are from (r,z) Warp runs (no misalignments), and assume uniform 1 mA/cm^2 emission of ions, no timing or voltage jitter in acceleration pulses, no jitter in solenoid excitation, and perfect beam neutralization.

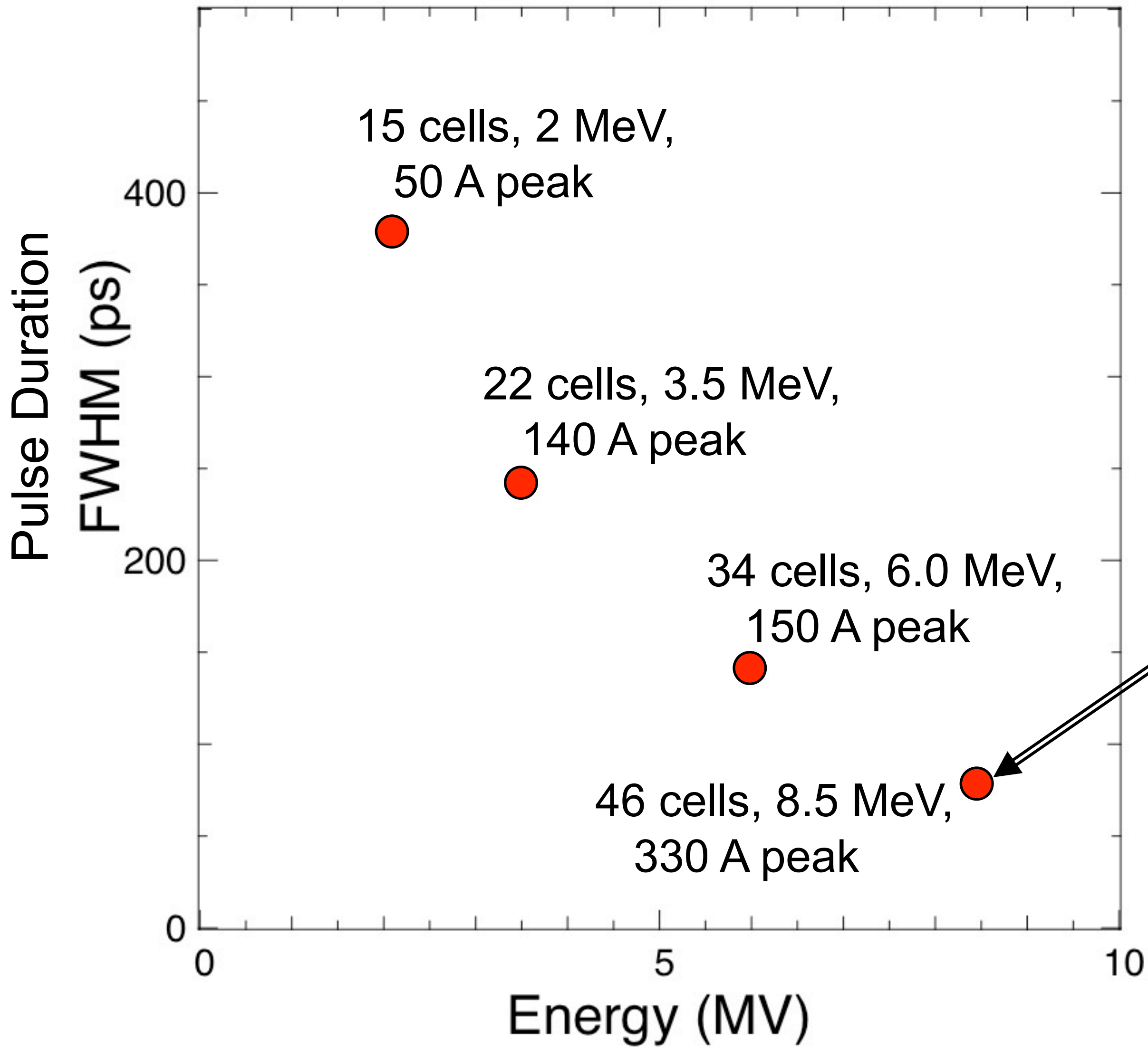
In near term, we expect a steady increase in beam parameters

Estimates of beam properties during next two years

Configuration: Li+, 12 active cells, 1.2 MeV final ion energy 600 ns initial pulse duration				
Date	**I_source**	**τ_target**	**r_target**	**F_target**
	Source current (mA)	Pulse duration at target (ns) (Biparabolic equivalent full) width)	Beam radius at target (mm) (50% current within radius)	Average Fluence (J/cm2) over r_target within τ_target
March, 2012	30	4	3	0.1
June, 2012	60	3.5	2	0.3
Sept, 2012	90	2.5	1.5	0.9
Dec, 2012	90	1.5	1	2.1
Sept, 2013	90	0.85	0.55	6.8

September 2011 HEDLP "call for proposals" requires VNL to provide a performance timeline for early users of the facility

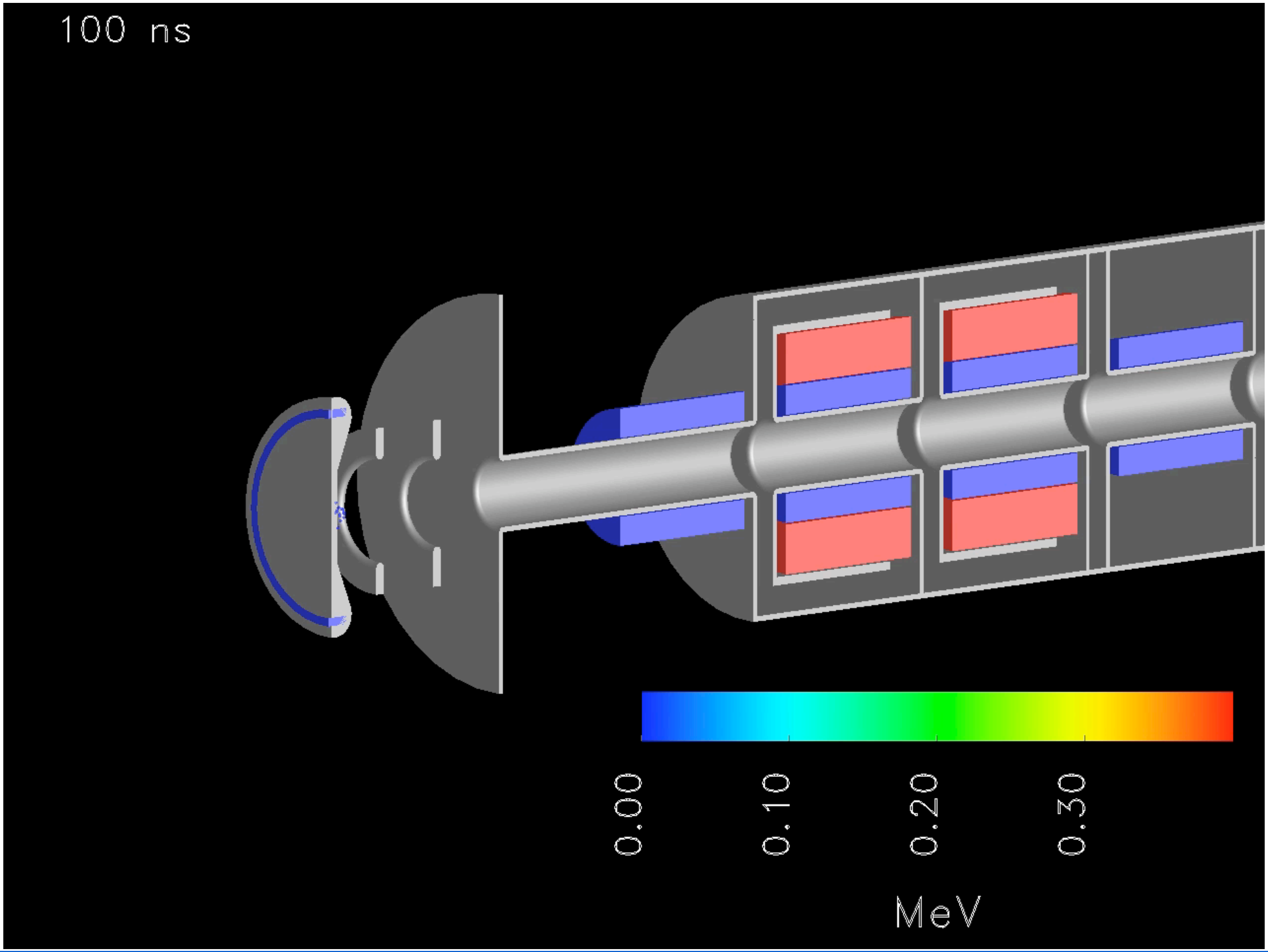
In longer term, we have additional ATA cells that allow higher ion energy and sub-ns pulses on NDCX-II



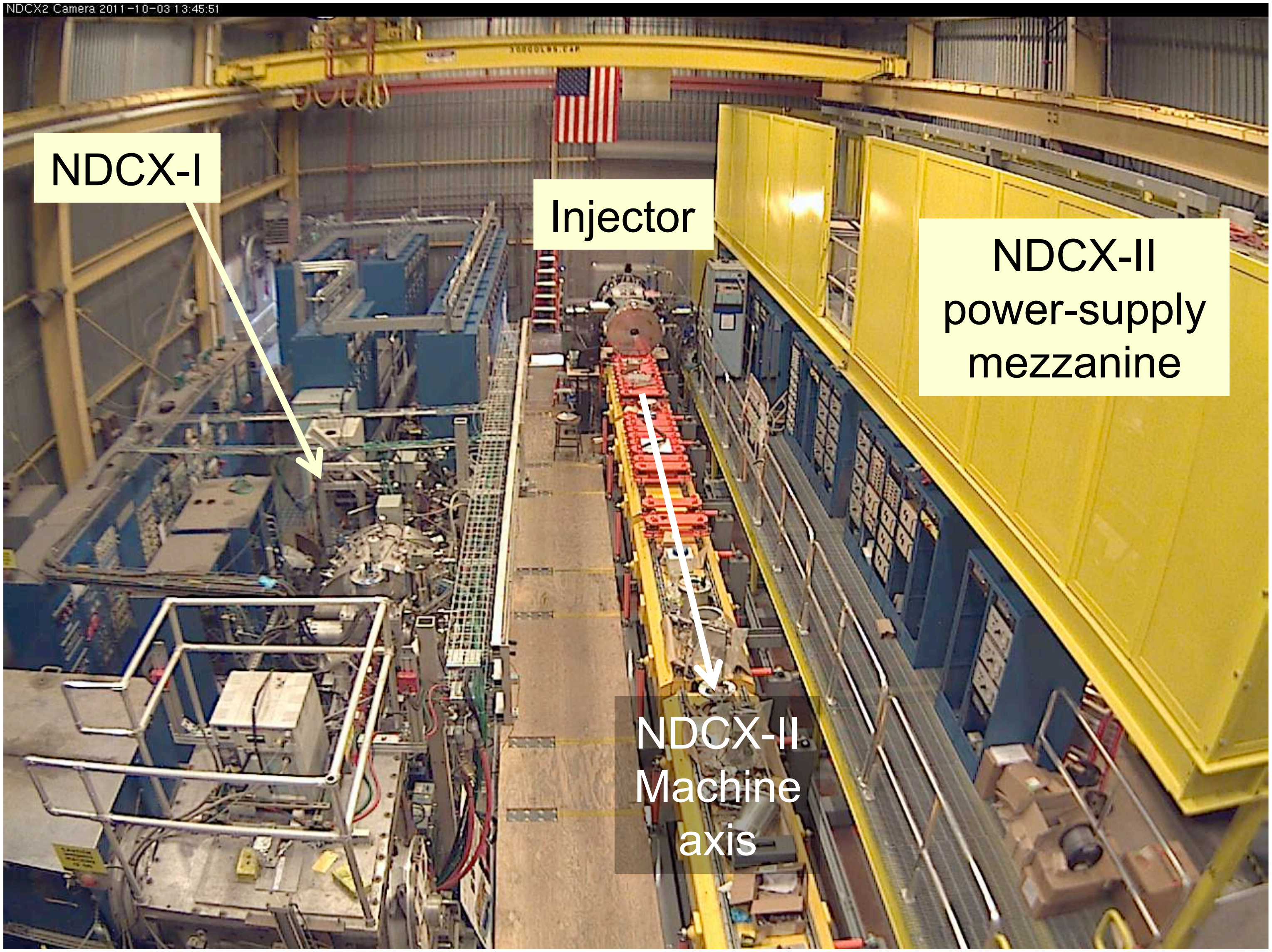
Motivates short pulse experiments related to warm dense matter, shock ignition, and fast ignition

We have 50 ATA cells and can extend NDCX-II

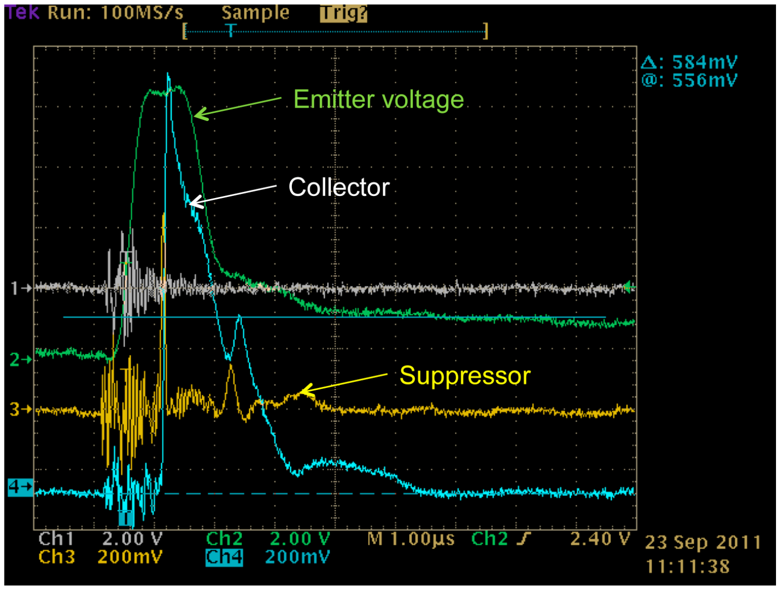
3-D Warp simulation with perfectly aligned solenoids

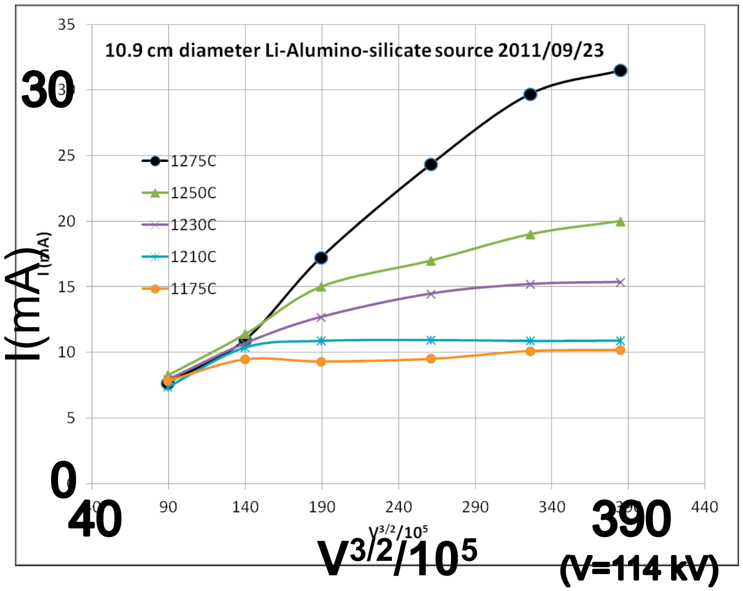


LBNL Building 58, as viewed from webcam on October 3, 2011



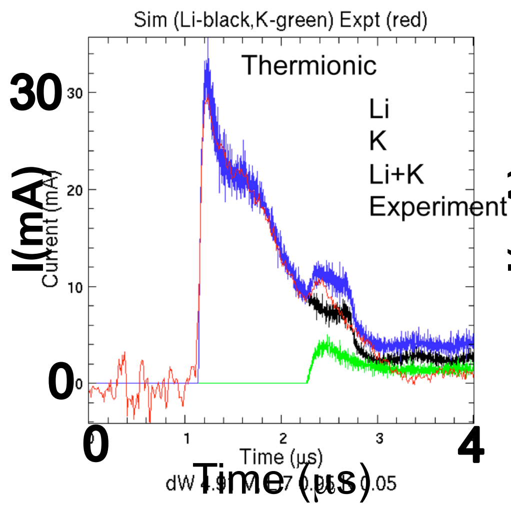
Injector now being tested

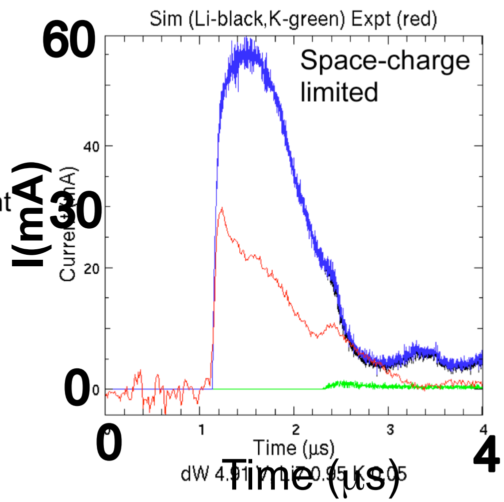




← Variation of lithium current with surface temperature and extraction potential.

↑ Oscilloscope record of lithium ion beam delivery from the NDCX-II injector.

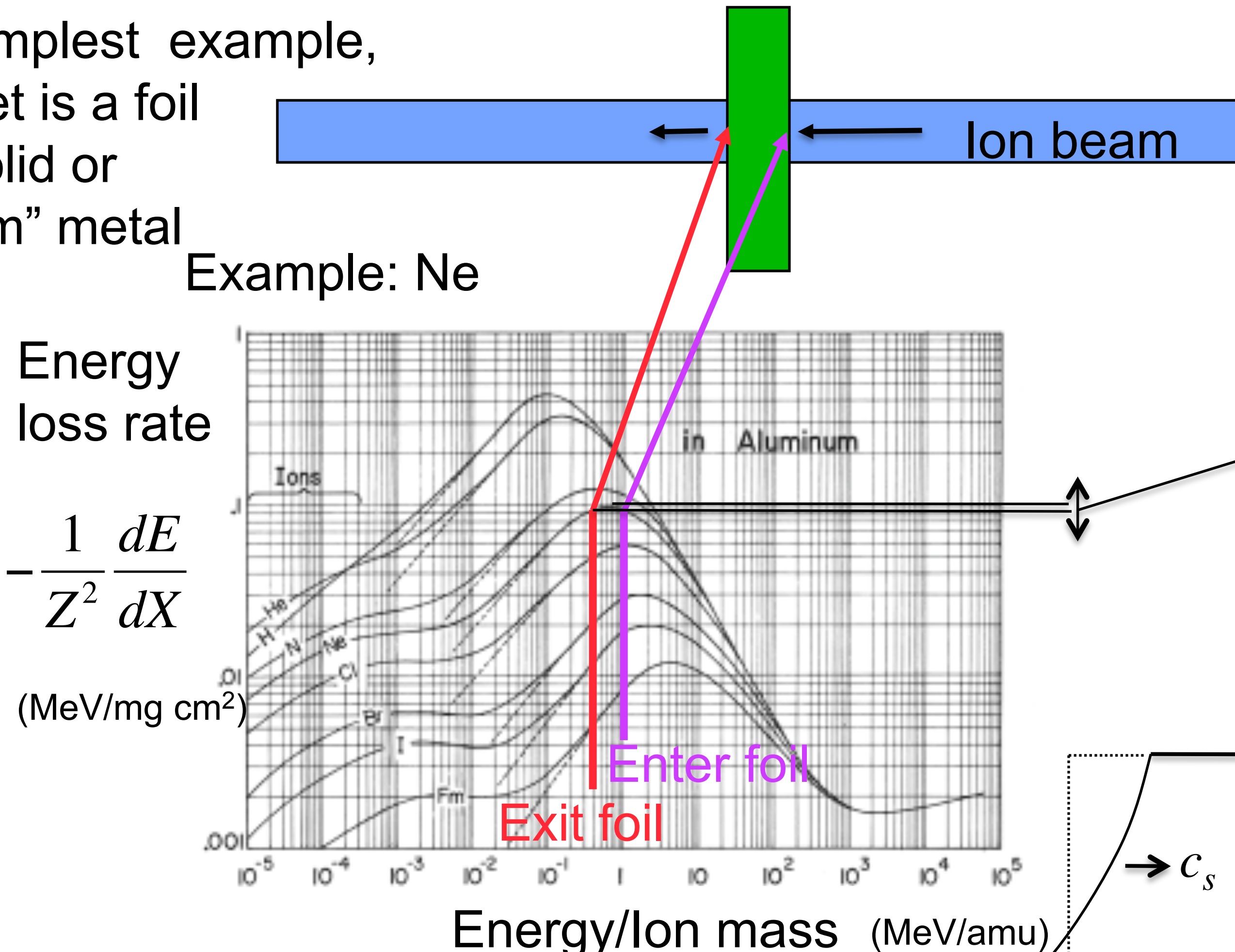




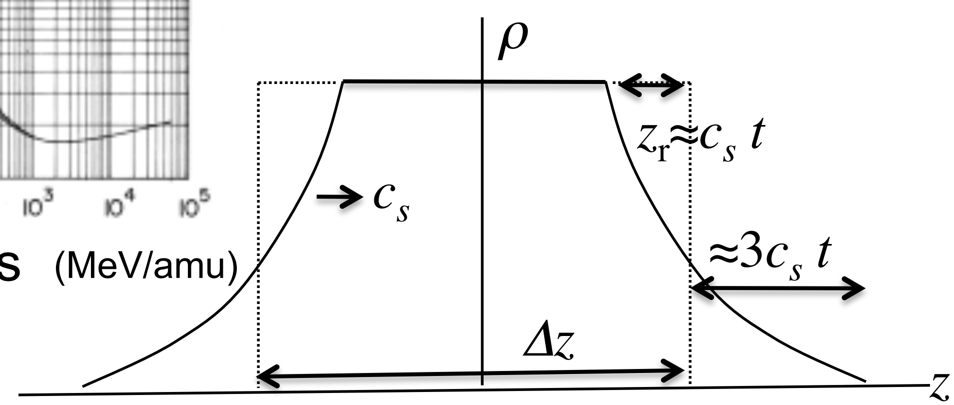
← WARP-rz simulations

Strategy: maximize uniformity and efficiency by placing center of foil at Bragg peak

In simplest example, target is a foil of solid or “foam” metal



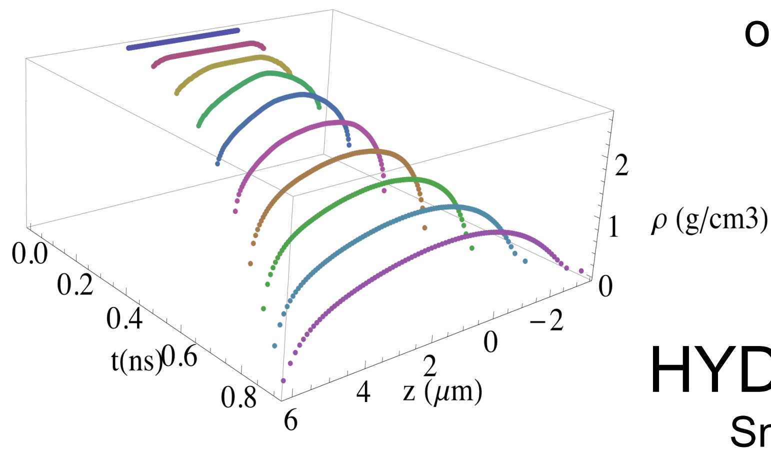
Fractional energy loss can be high and uniformity also high if operate at Bragg peak (L. R. Grisham, Physics of Plasmas, **11**, 5727 (2004).)



(dEdX figure from L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, A7, 233 (1970))

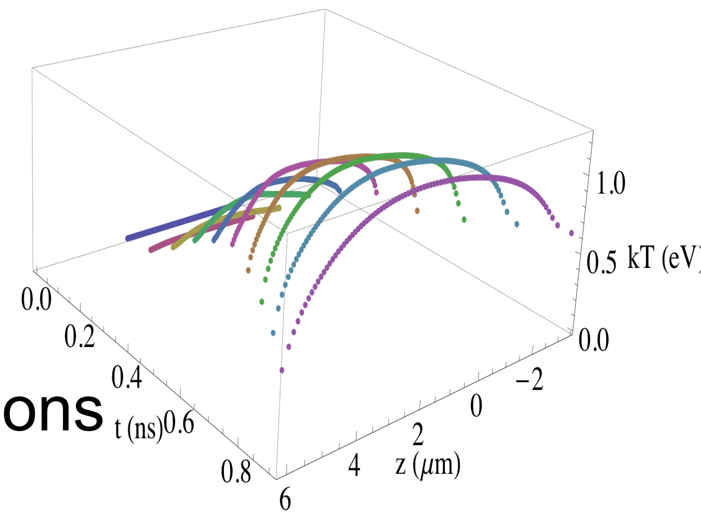
Hydrodynamic simulations show that approximately uniform conditions can be created

density



Assumed fluence: 30 J/cm^2; Li beam on Al target

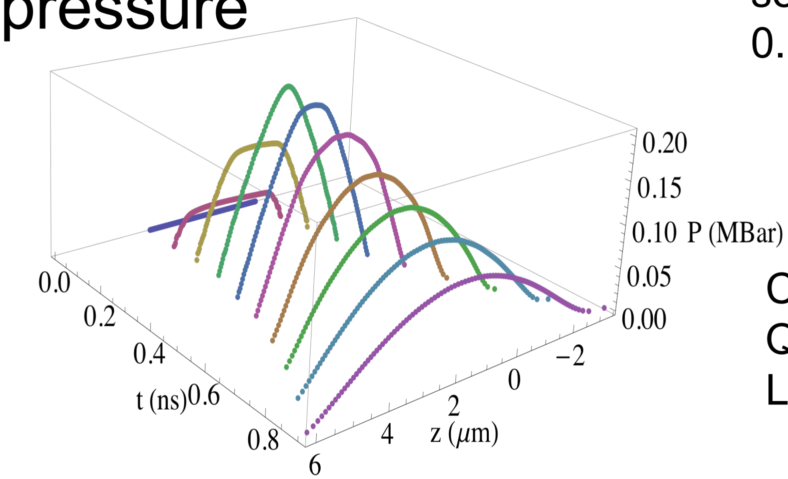
temperature



HYDRA[1] simulations

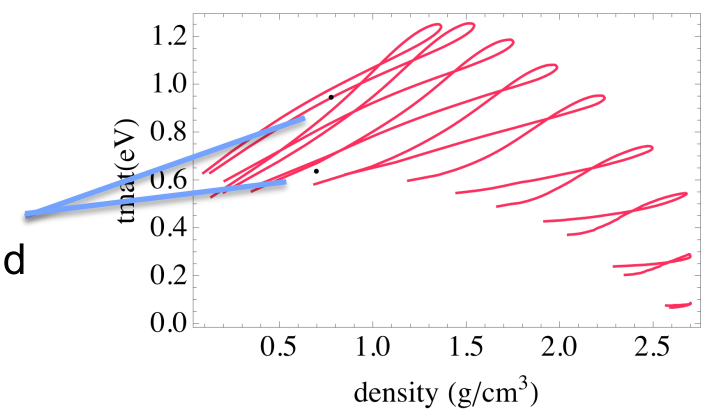
Snapshots separated by 0.1 ns

pressure



temp vs. density trajectories

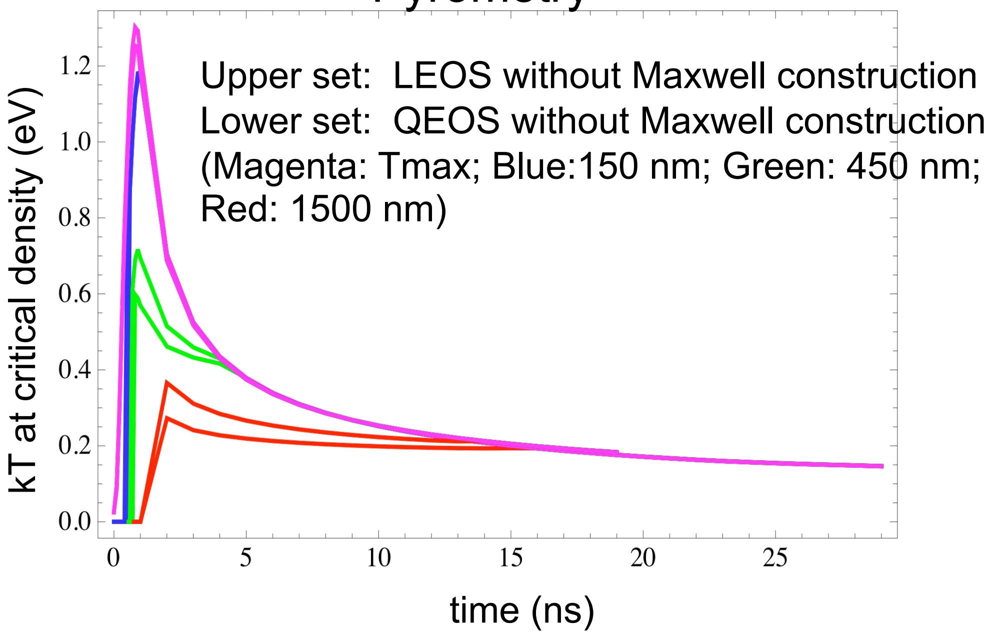
Critical points for QEOS (upper) and LEOS (lower)



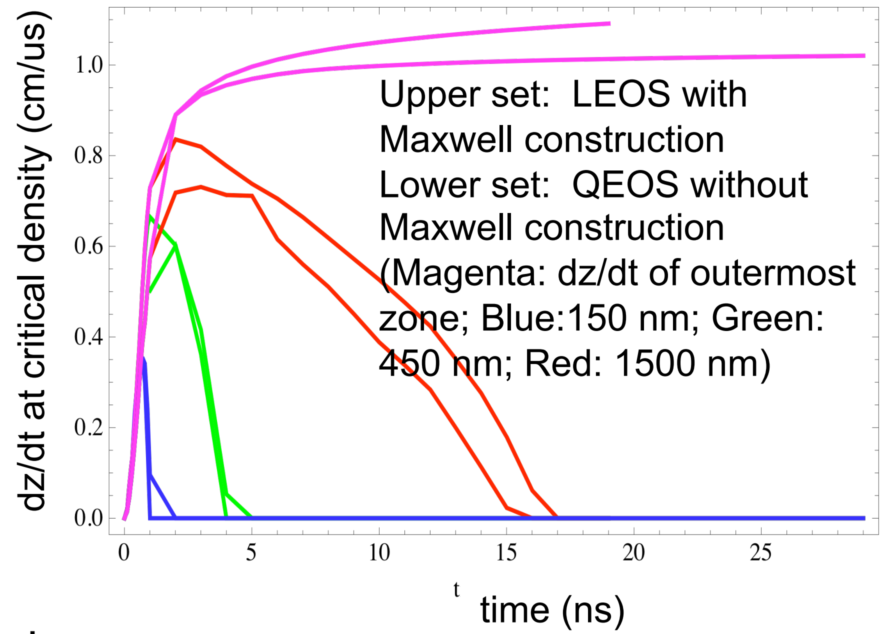
1. M. M. Marinak et al, Phys. Plasmas **8**, 2275 (2001)

Diagnostics for temperature, velocity and density will be compared to simulated diagnostics

Pyrometry

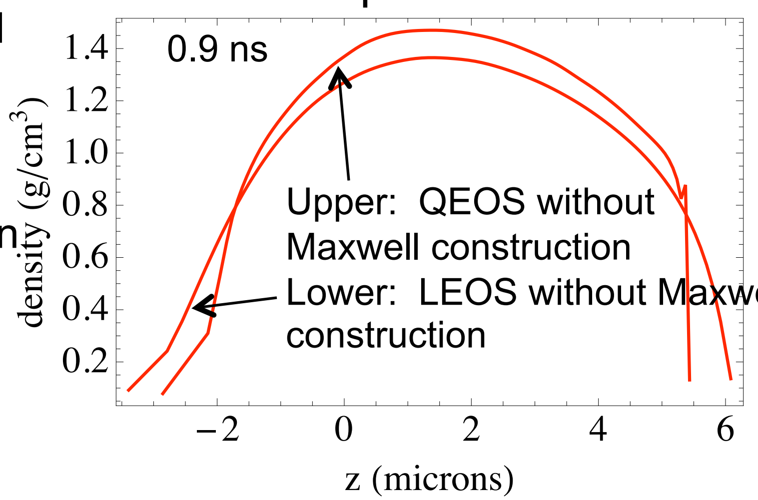


VISAR



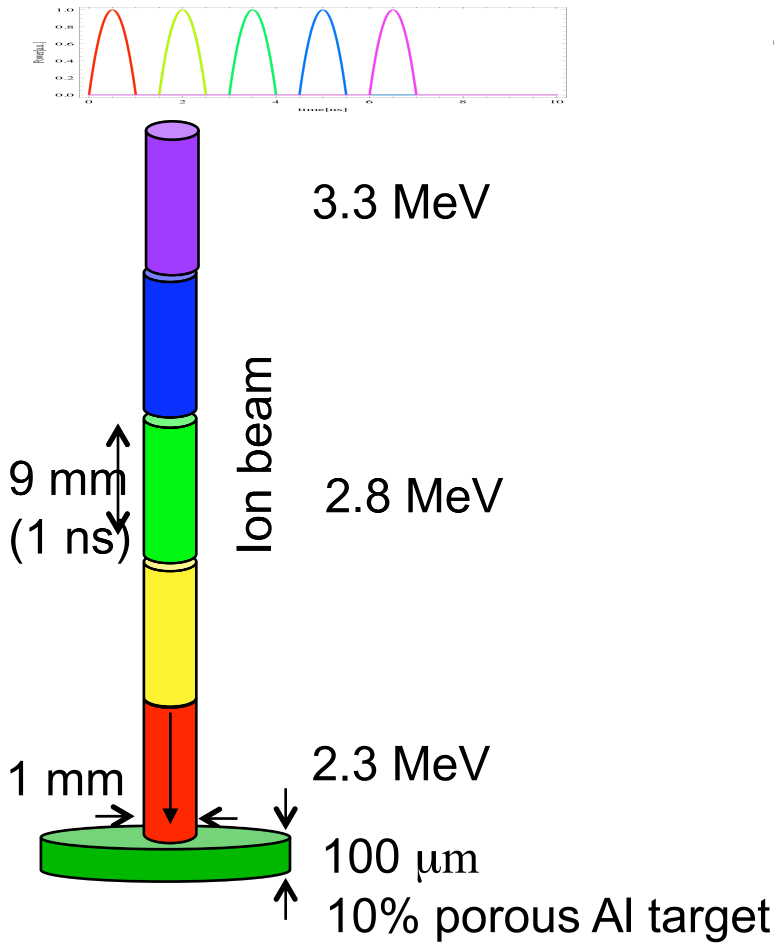
Multi-frequency (upper left) and multi-angle pyrometry measurements, together with multi-frequency Visar measurements (upper right) can also distinguish between candidate EOSs.

X-pinch



X-ray imaging of density profile (lower) can distinguish between EOS and for "instantaneous" heating and in simple wave regime can measure $c_s(\rho)$ and $P(\rho)$ directly (Foord et al Rev Sci Inst. (2004)).

Simulations show that experiments on NDCX II can explore effects of energy ramp on coupling

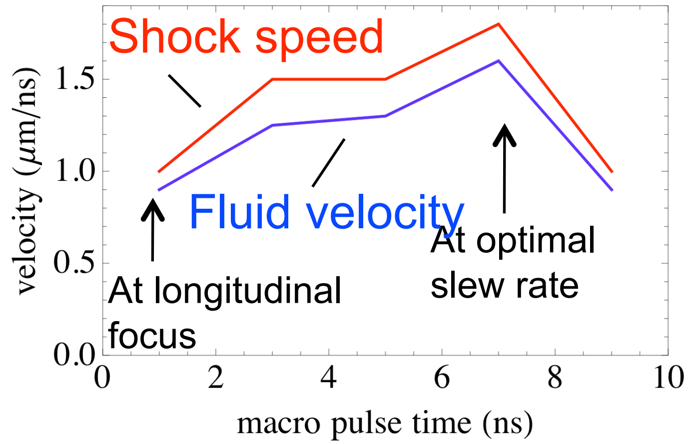


The ion range increases with energy:

$$\Delta z \approx 20\mu\left(E/1\ \text{MeV}\right) \qquad \text{(10\% Al foam)}$$

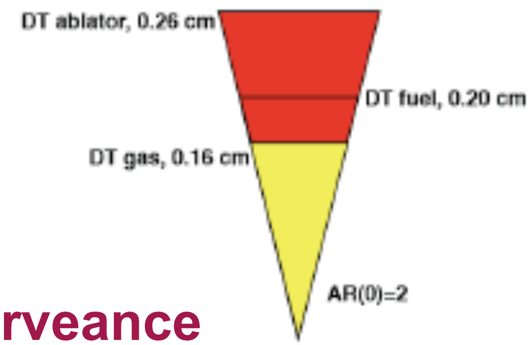
To "follow a shock", (where $v_{shock} \sim c_s$) the energy slew must be sufficiently rapid:

$$\frac{dE}{dt} \cong E\frac{c_s}{\Delta z} = 0.10\ \frac{\text{MeV}}{\text{ns}} \qquad \text{(10\% Al foam)}$$

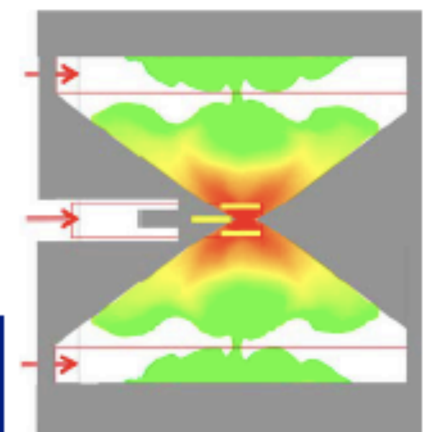


We are studying three types of targets for Heavy Ion Fusion

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



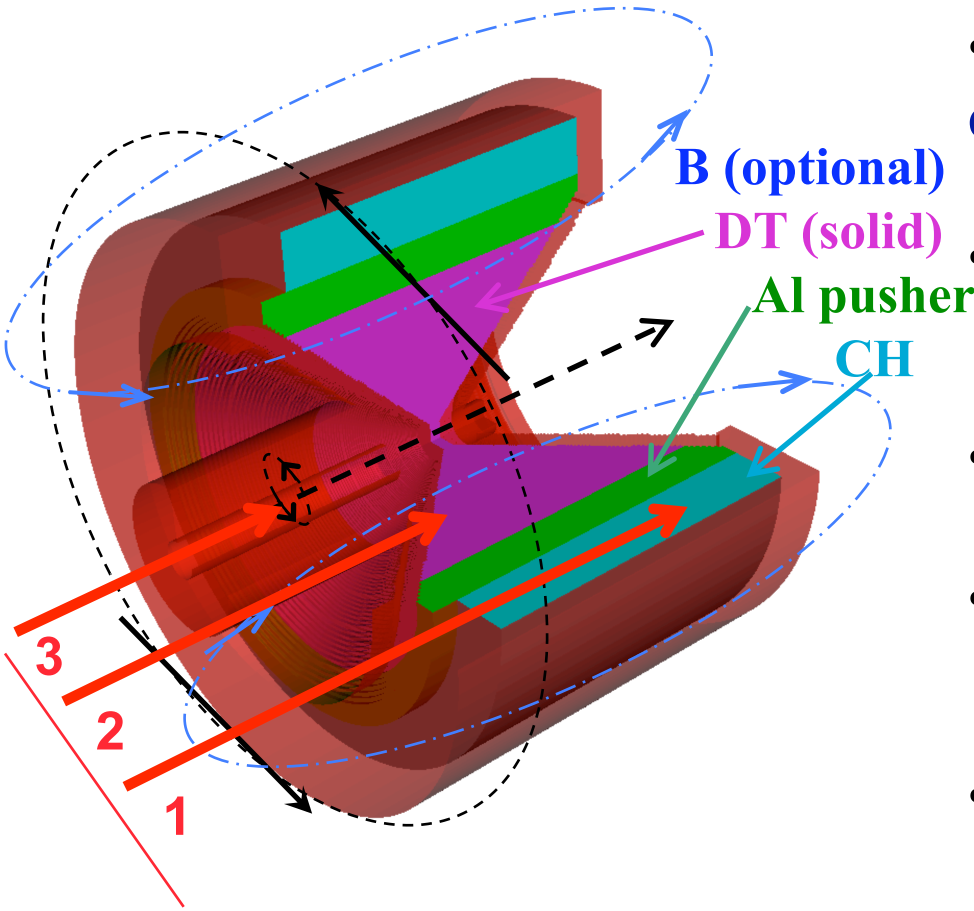
2. **Heavy-ion direct drive** ***1-D Hydra design (2010):*** **3.6 MJ, 0.22 → 2.2 GeV, Hg^{+1} ion beams, gain 150.**
   Future 2-D design planned for polar drive illumination; tamped targets for lower beam perveance



3. **X-target direct drive** ***2-D Hydra design*** **(2010)** 2 MJ compression + 3 MJ ignition, all 90 GeV U beams, gain 300. **One-sided illumination**

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

X-targets – motivated for heavy ion drivers

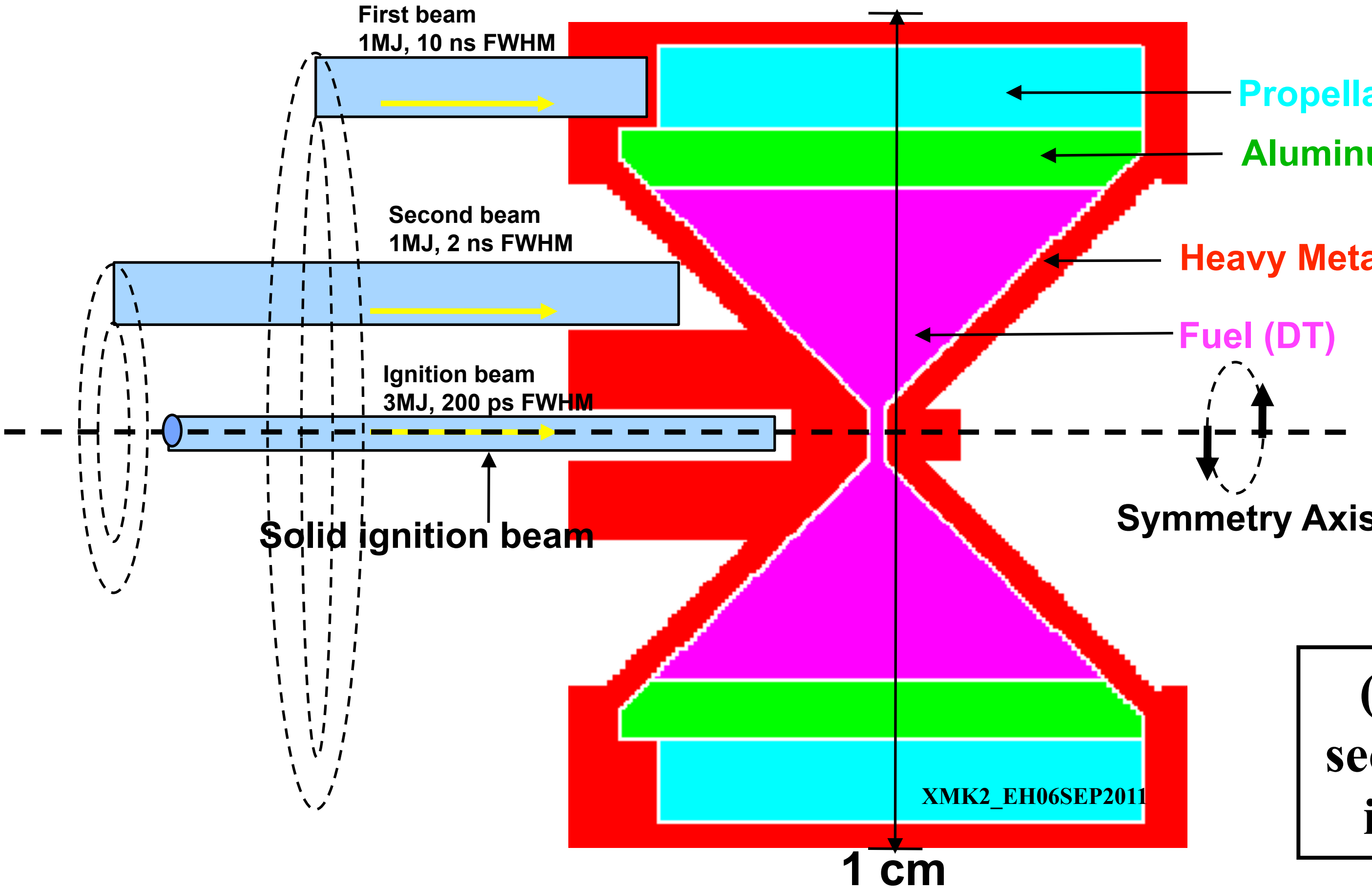


Illuminated by 2-sequential annular heavy ion beam pulses for compression followed by 3rd pulse on axis for ignition

- The beams illuminate the target from one side, relying on volumetric deposition
- Geometry gives quasi-spherical implosion
- Target gain ~ 300 for 5 MJ beam pulse
- The target range is ~2 g/cm^2 (e.g. 90 GeV U)
- All three pulses have the same ion energy
- The thermal inertia of the metal case would protect the DT during exposure to hot chamber vapor during injection.

MARK2 series of X-target added an aluminum pusher exploded by second beam pulse, doubling peak fuel ρ (>100 g/cm^3) and ρr (>2 g/cm^2). *Metal mix appears with finer mesh!*

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

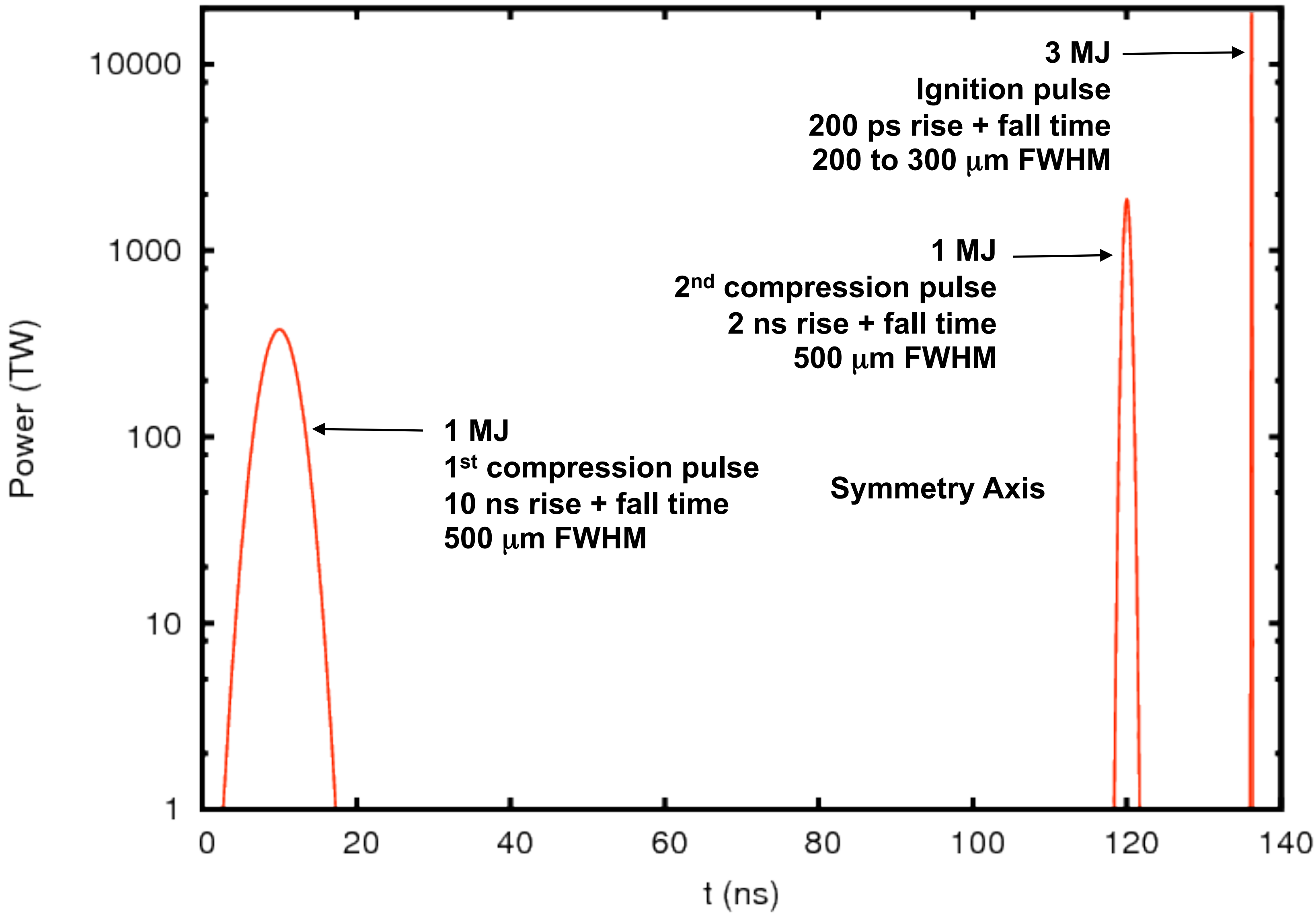


IMC radiation with 50 energy groups. 1 to 3 micron mesh spacings near vertex!

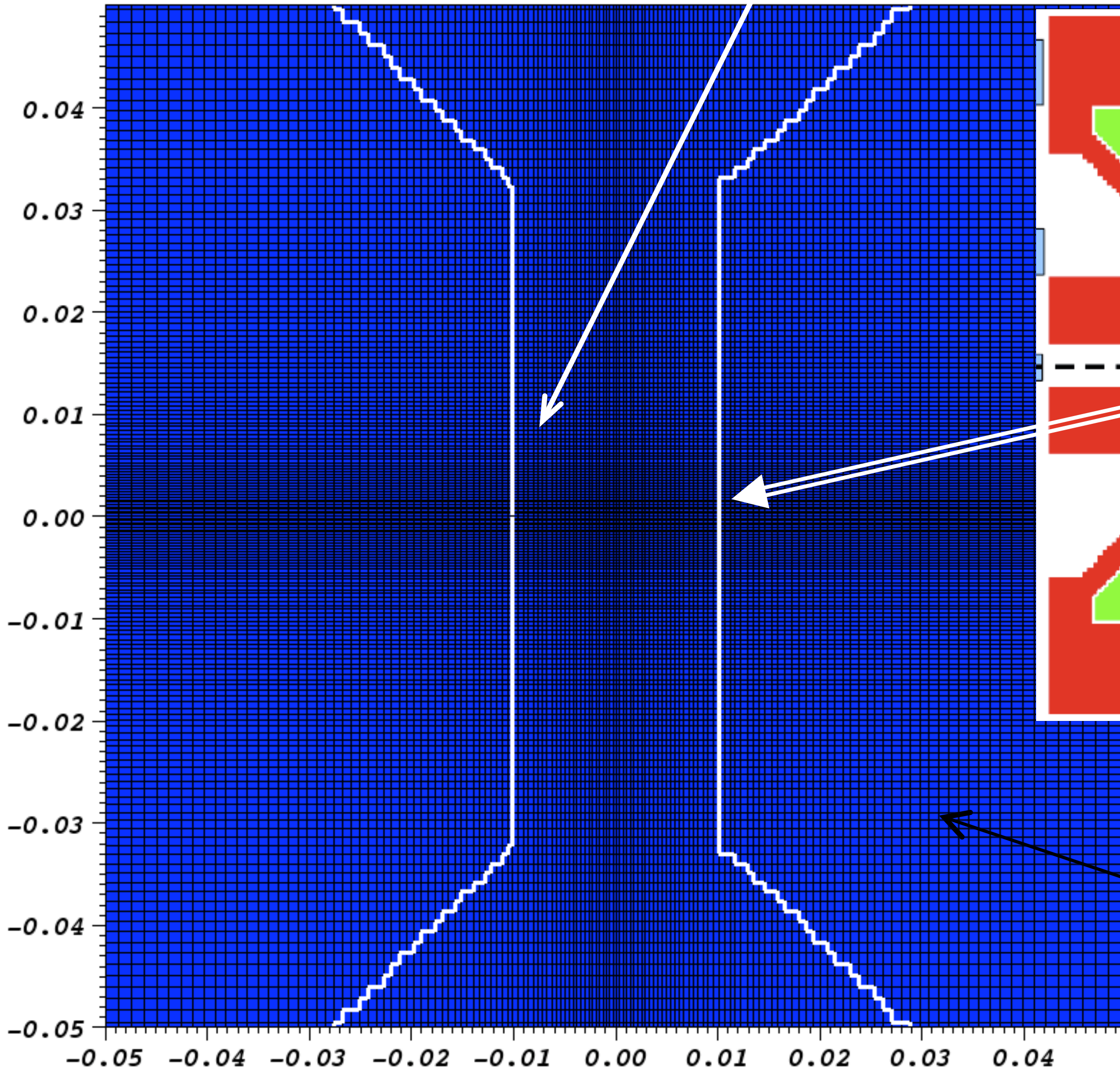
(E. Henestroza: second publication in preparation)

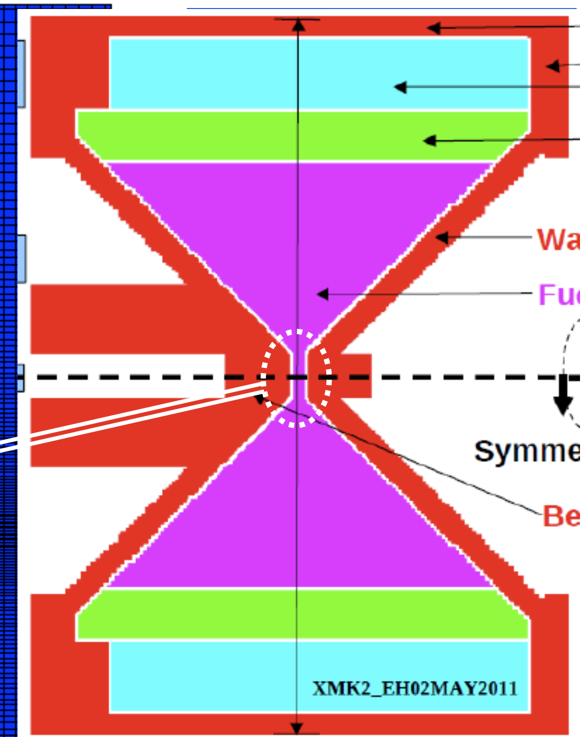
5MJ drive = 1 + 1 MJ for compression + 3 MJ for ignition → 1.5 GJ yield, gain = 300. All beams 2 g/cm^2 (e.g., 20 GeV Rb or 90 GeV U).

Gaussian power(t) and radial profiles for three XMK2 beam drive pulses:



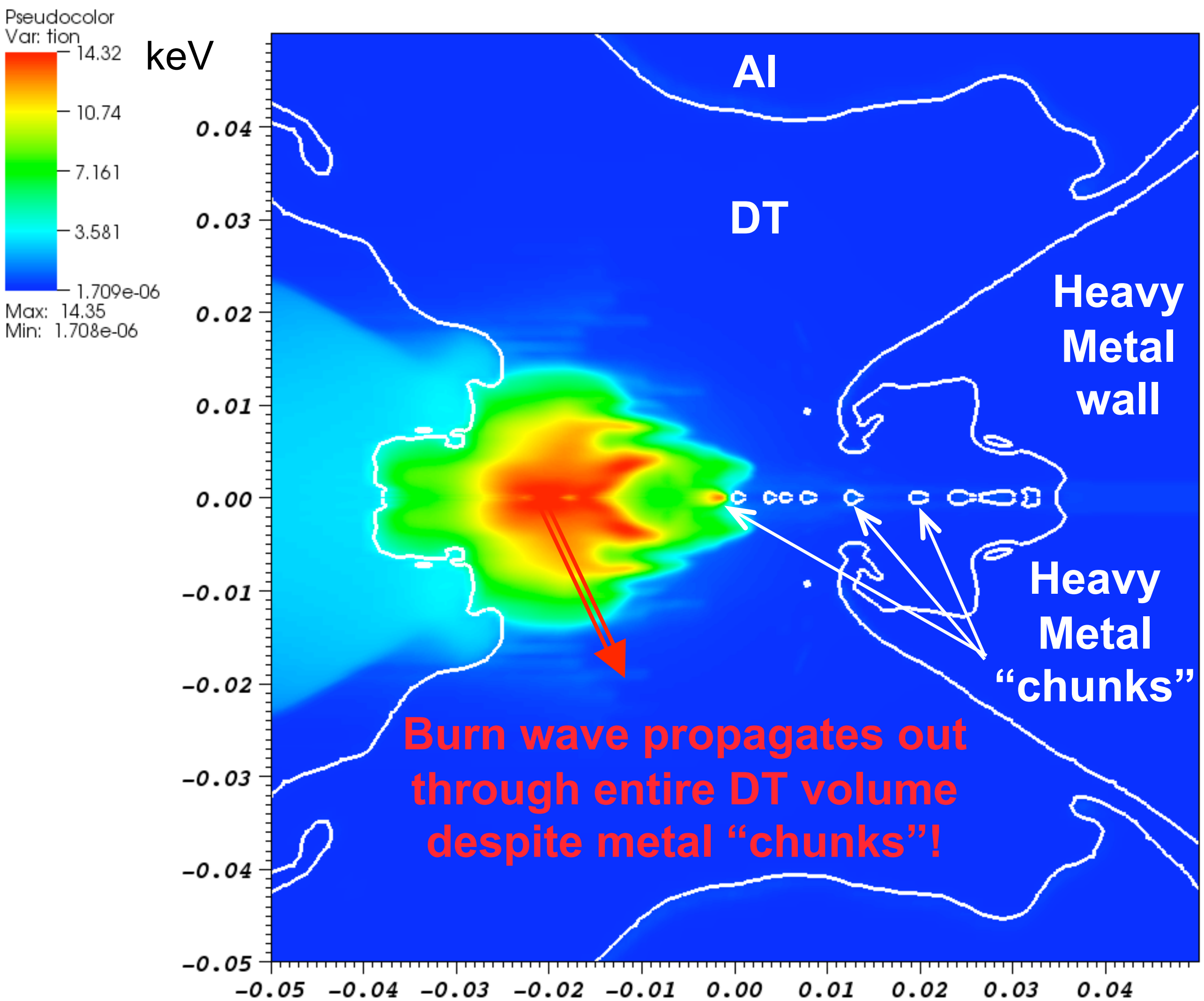
“Metal chunks” (mix from the X-side walls) appear when we run with a sufficiently fine mesh (few-micron spacings near vertex)





Fine black lines are the mesh lines!

Temperature profile at time of maximum beam power: 200 ps after "maximum compression"



Other beam and target physics areas under investigation in VNL

Paul Trap Simulator Experiment (PTSX) simulates nonlinear dynamics of long-distance beam propagation in a compact laboratory experiment.

Carry out advanced plasma source development for NDCX-I and NDCX-II (Ferro-electric plasma sources (PPPL) and Cathodic Arc Plasma Sources)

Beam dynamics/physics activities include:

Advanced analytical and numerical modeling of intense beam propagation, nonlinear dynamics, beam-plasma interactions, and pulse compression.
(e.g. Distribution of betatron frequencies in space charge dominated beams; Wobbler beam dynamics)

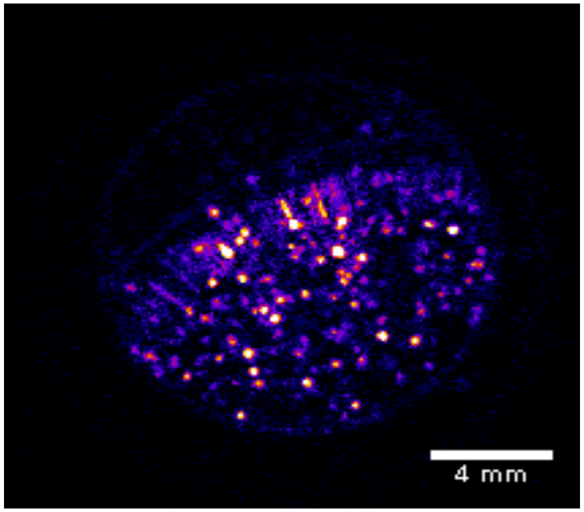
Mitigation and control of collective interactions and instabilities; optimization of beam quality and brightness; halo particle production and control.

Beam pulse compression and focusing in neutralizing background plasma (plasma lenses). (e.g. two-stage focusing using beam self-pinch)

Atomic physics and ionization cross sections; develop improved ionization models.

Ion source development (Li sources; laser assisted sources)

Droplet formation in ion heated targets is an area of theoretical and experimental investigation



NDCX 1 image

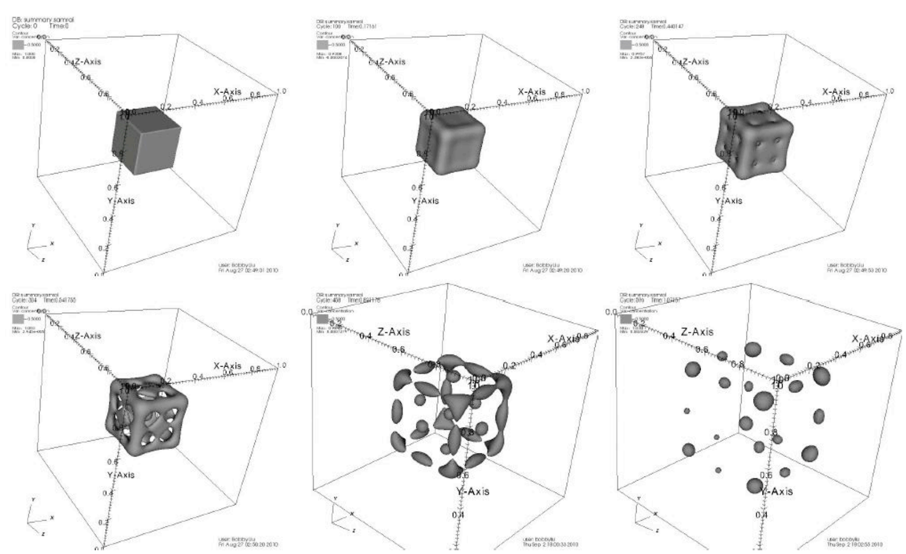
$$g = \frac{\Delta P_{vap}}{\rho \Delta x} = 5.7\ 10^6\ \mathrm{m/s^2}$$

$$a_c = \sqrt{\frac{\alpha}{\rho g}} = 2.6 \mu m$$ (capillary length)

$$\gamma \cong \sqrt{\frac{g \Delta x}{2 a_c^2}} \sim 0.6 \mu s^{-1}$$

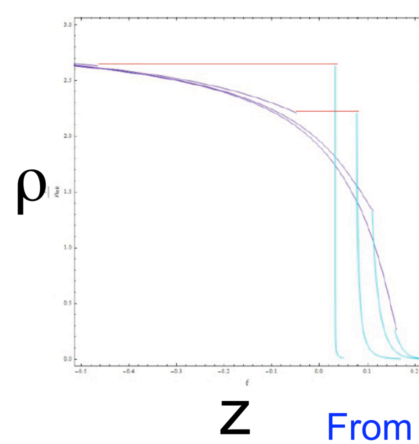
Droplet formation in warm dense matter experiments on NDCX-I may be the result of the Rayleigh-Taylor instability caused by an imbalance in vapor pressure on the two sides of the thin foil. This imbalance is due to evaporation at slightly different rates. (Alternate theory: Marangoni)

- **Model Describing Thin Foil Transformation into Liquid Droplets, I. D. Kaganovich, E. A. Startsev and R. C. Davidson, High Energy Density Physics 7, 343 (2011).**



From W. Liu, thesis, UCLA, 2010

Surface tension is being added to the hydrodynamics code ALE-AMR to enable detailed predictions for experiments

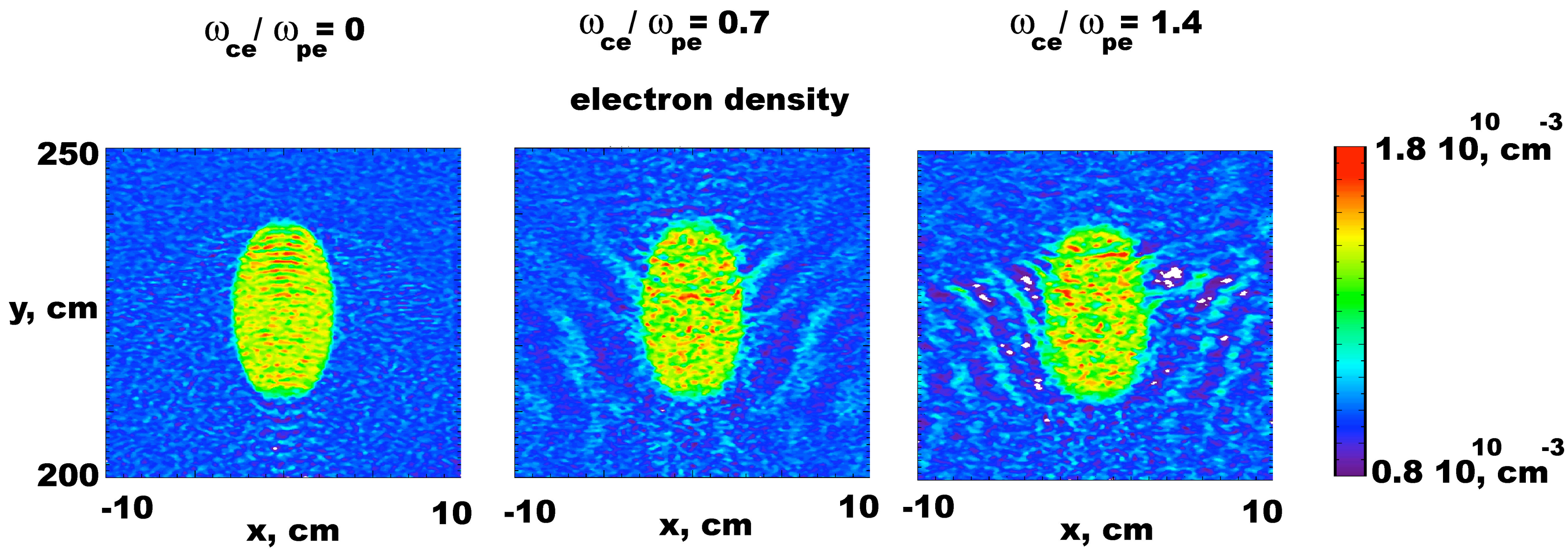


Using Maxwell construction, analysis shows: plateaus in density during phase change, vary depending on initial temperature

From A. Yuen et al, APS DPP 2011

Analytical studies show that the solenoidal magnetic field influences the degree of neutralization

Plots of electron charge density contours in (x,y) space, calculated in 2D slab geometry using the LSP code with parameters: Plasma: $n_p=10^{11}cm^{-3}$; Beam: $V_b=0.2c$, 48.0A, r_b=2.85 cm and pulse duration 4.75 ns. A solenoidal magnetic field of 1014 G corresponds to equal electron cyclotron and plasma frequencies.



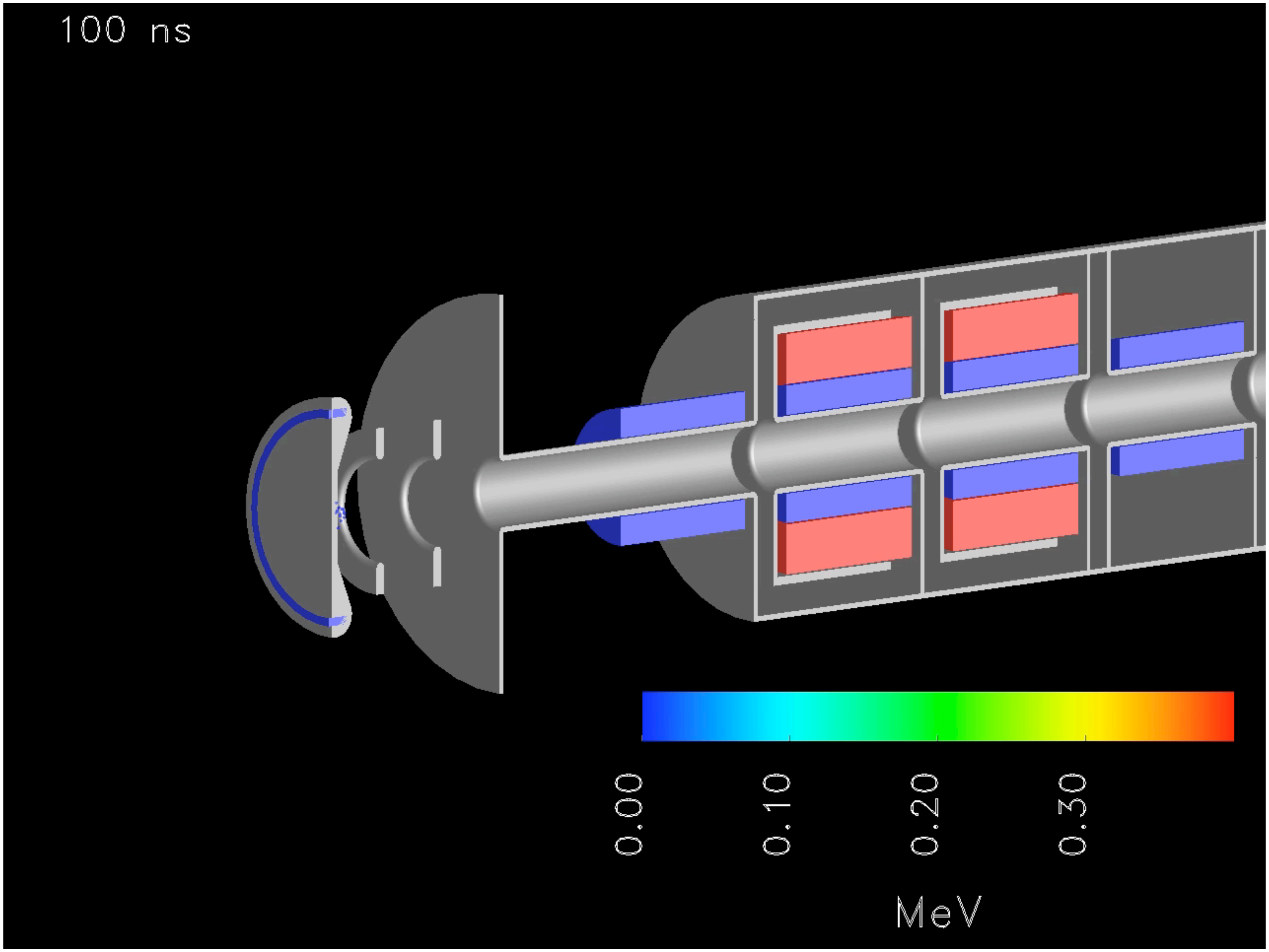
- In the presence of a solenoidal magnetic field, whistler waves are excited, which propagate at an angle with the beam velocity and can perturb the plasma ahead of the beam pulse.

I. D. Kaganovich et al., Phys. Plasmas 17, 056703 (2010).

Conclusions and summary

1. NDCX-I: layed groundwork for NDCX-II; plans for move to PPPL
2. NDCX-II: Project completion expected before end of 2011
   - Chamber patterned after Titan/Trident/LCLS target chambers, expected in 2012
   - Injector now being tested
3. NDCX-II: a user facility, allowing investigations of:
   - Heavy ion fusion beam physics
   - Warm dense matter target physics
   - IFE relevant target physics
4. IFE Target physics:
   - X-target: a one-sided, ion direct drive fast ignition target, quasi-spherical compression with high gain;
   - Indirect drive and direct drive targets still of interest
5. Non-neutral and neutral beam physics continues to be explored theoretically, computationally, and experimentally

3D Warp simulation with solenoids having 1 mm offsets



US/Japan workshops on HIF/HEDP

1. March 13-15, 1997 Osaka
2. November 12-14, 1997 Berkeley
3. December 7-9, 1998 Tokyo
4. March 11, 2000 San Diego
5. December 7-8, 2000 Tokyo
6. March 4-5, 2002 Berkeley, Livermore
7. June 10-12, 2004 Princeton
   http://nonneutral.pppl.gov/HIF04/usjapan.php
8. September 28-30, 2005 Utsunomiya University
   http://www.ee.utsunomiyau.ac.jp/~kawatalab/workshop/USjapanWorkshop.html
9. December 18-20, 2006 Berkeley, Livermore
   http://hifweb.lbl.gov/public/USJapanWorkshop2006/
10. September 17-19, 2007 Tokyo
11. December 18-19, 2008 Berkeley, Livermore
    http://hifweb.lbl.gov/public/USJapanWorkshop2008
12. September 7-8, 2009 San Francisco
    http://hifweb.lbl.gov/public/USJapanWorkshop2009
13. October 12-14, 2011 Osaka