Física de Altas Densidades de Energía en Fusión Inercial

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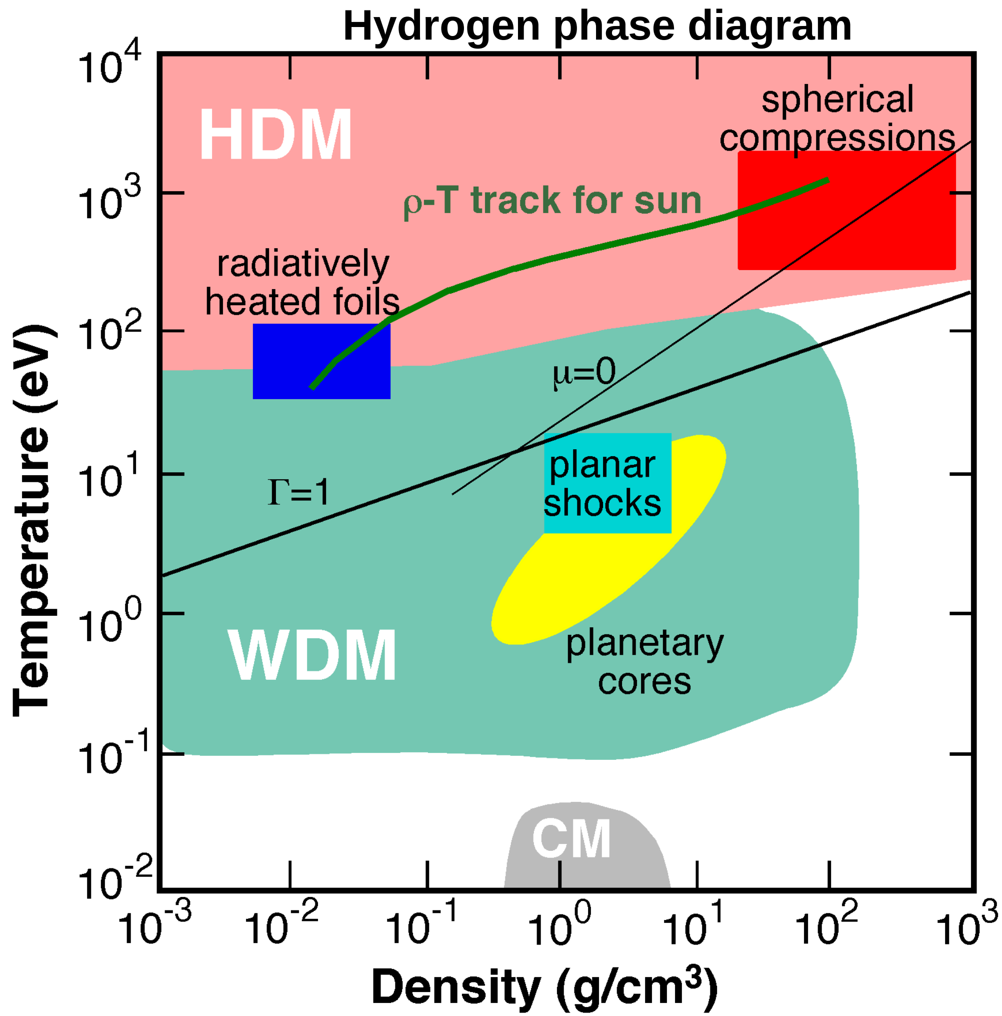
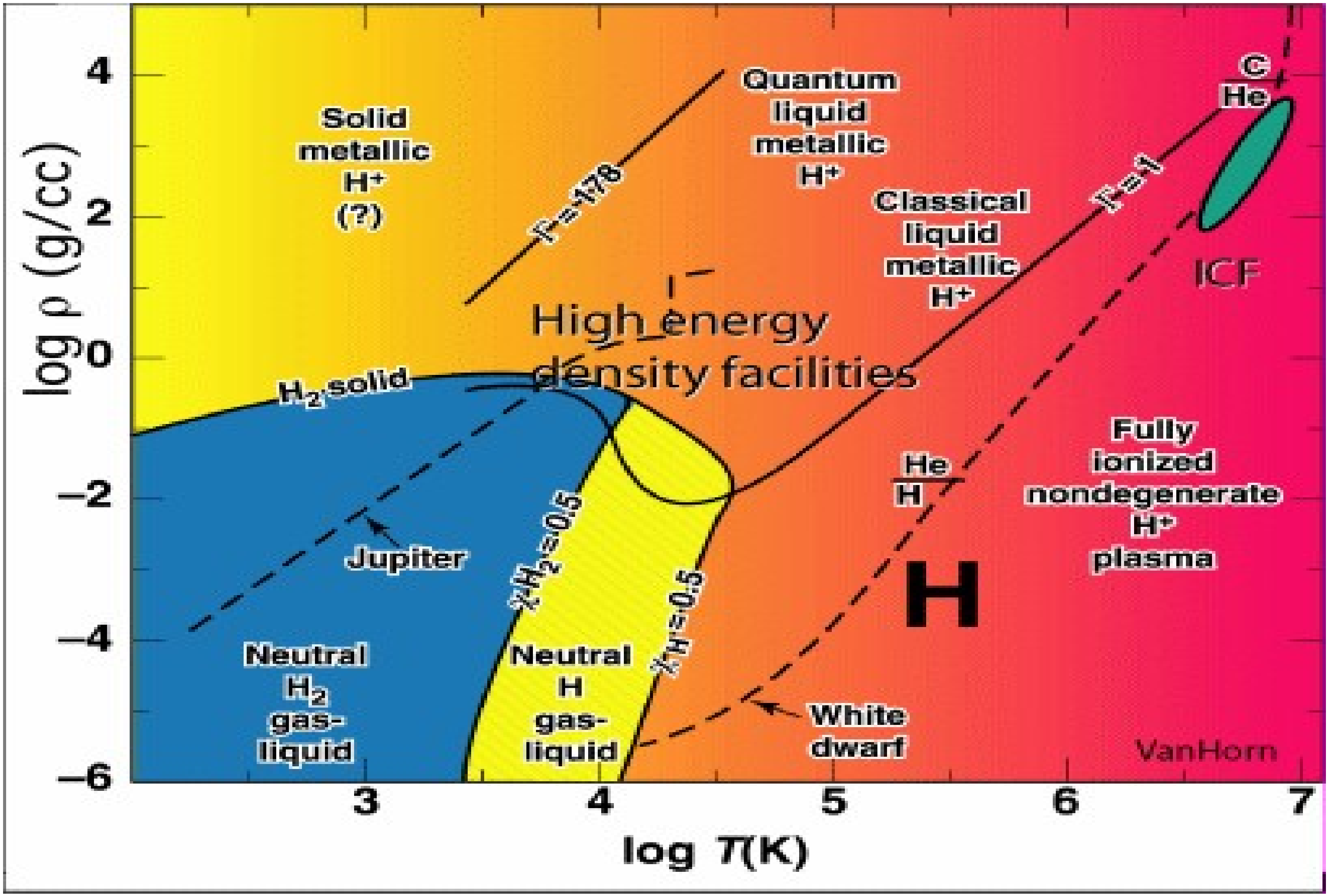
HEDS covers a vast region in T-ρ phase space and numerous physical regimes

- **Hot Dense Matter (HDM):**
  - Supernova, stellar interiors, accretion disks
  - Plasma devices: laser produced plasmas, *Z*-pinches
  - Directly and indirectly driven inertial fusion experiments

- **Warm Dense Matter (WDM):**
  - Cores of large planets
  - Systems that start solid and end as a plasma
  - X-ray driven inertial fusion experiments



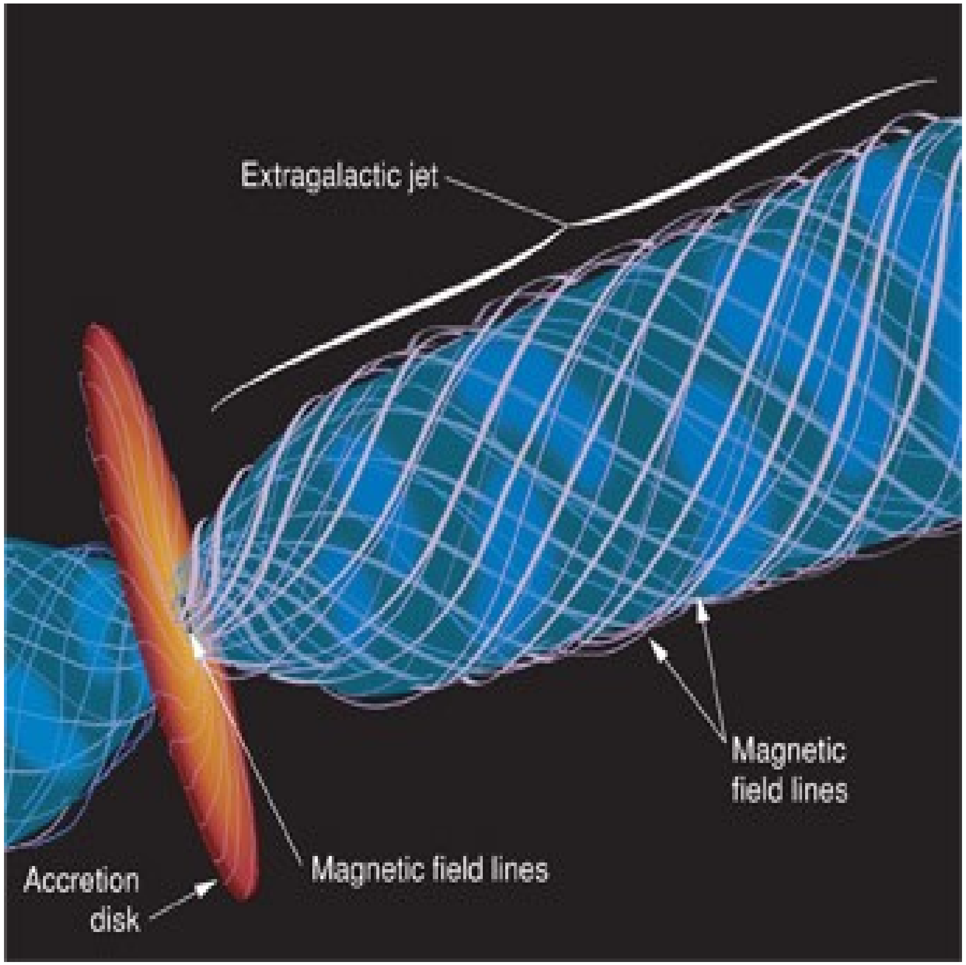
High Energy Density Matter occurs widely

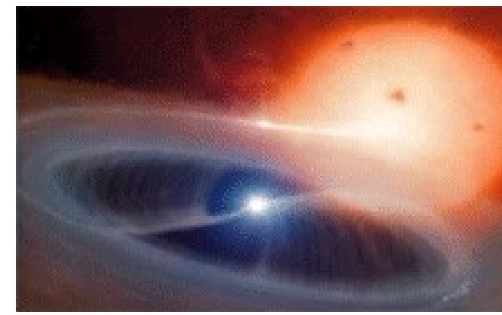


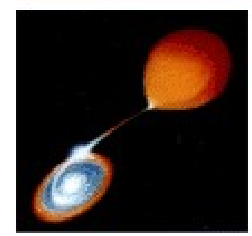
Plasma fills the universe

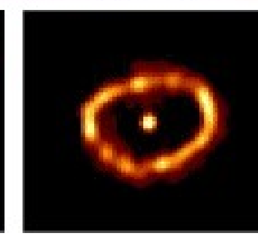
Catseye Nebula

High Energy Density Matter in the Universe



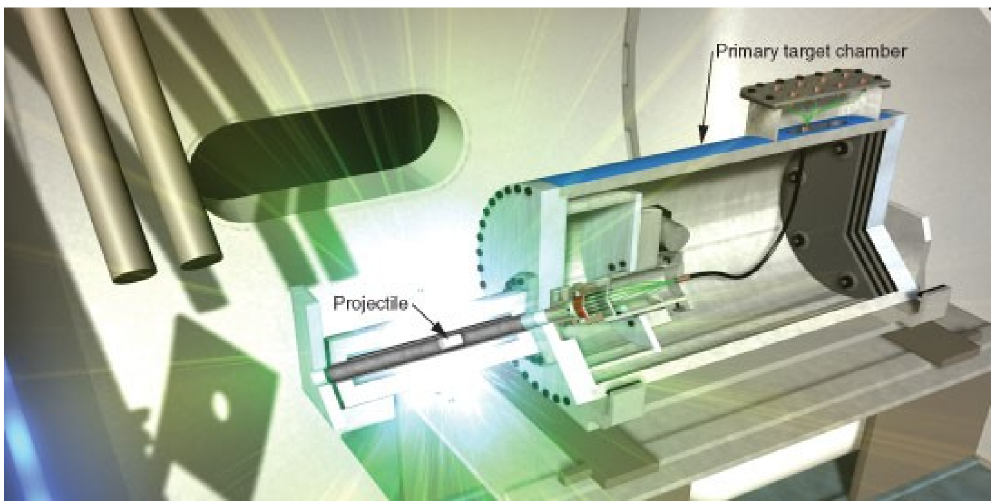




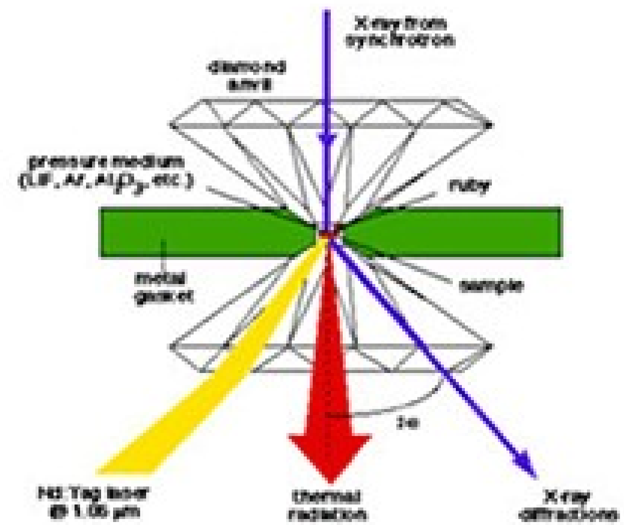


High Energy Density Matter in the Laboratory

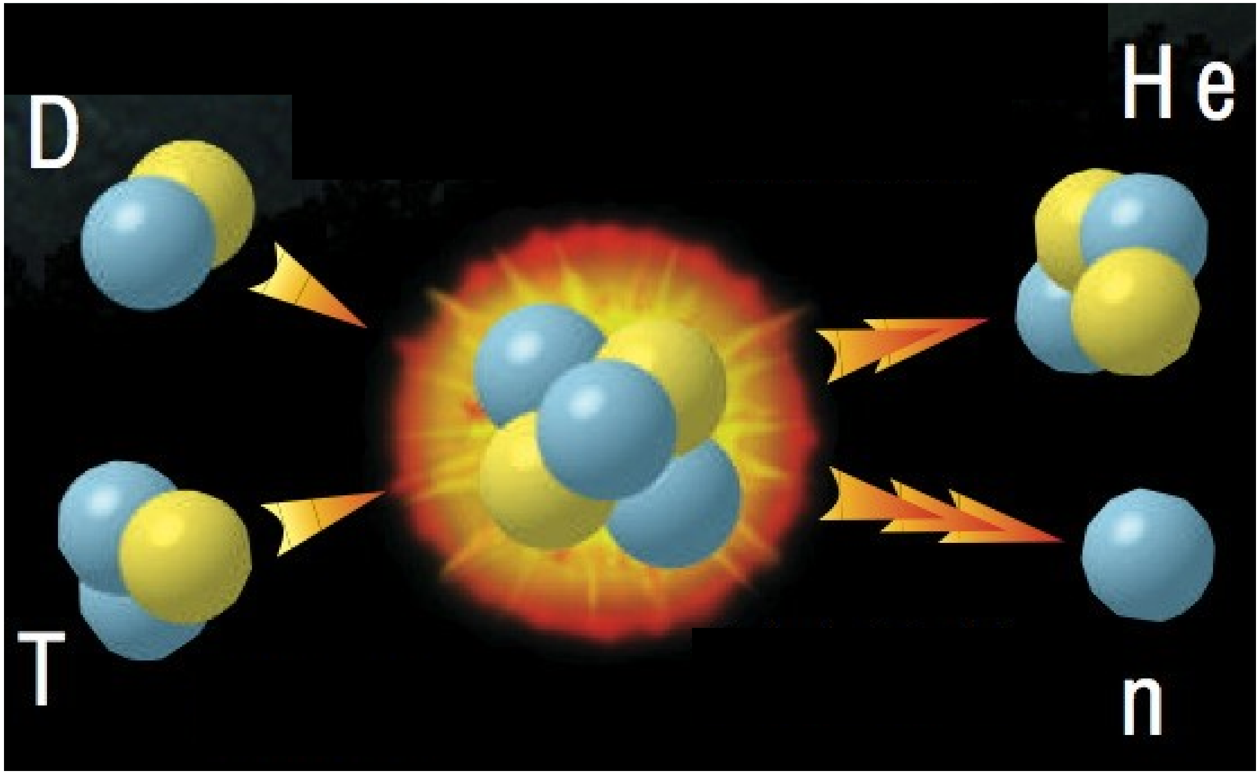
GAS GUN



DIAMOND ANVIL



Fusion occurs when light ions are joined together to make a heavier ion. This releases energy.



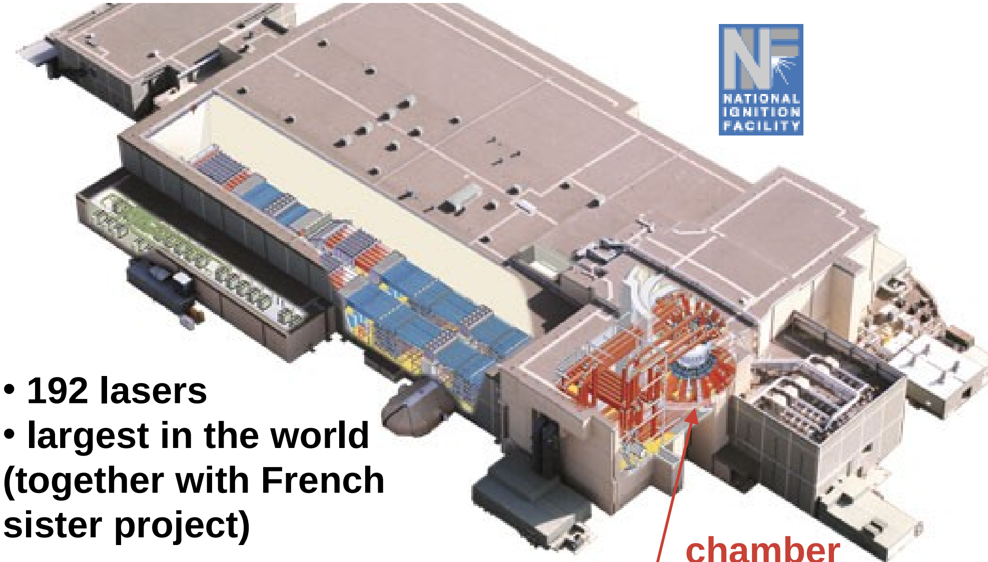
Fusion power plants will “fuse” two kinds of Hydrogen …

Deuterium (D) + Tritium (T) ⇒ Helium (He) + neutron (n) + energy

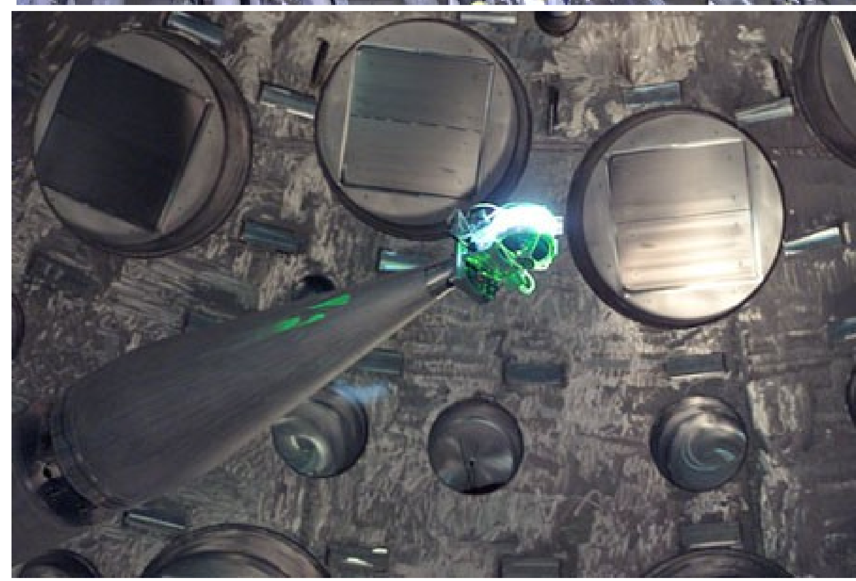
To fuse, the ions have to be hot enough (moving fast enough); they are a plasma

To make a lot of energy, this plasma must be kept together long enough for a lot of it to burn

National Ignition Laser Facility (NIF)

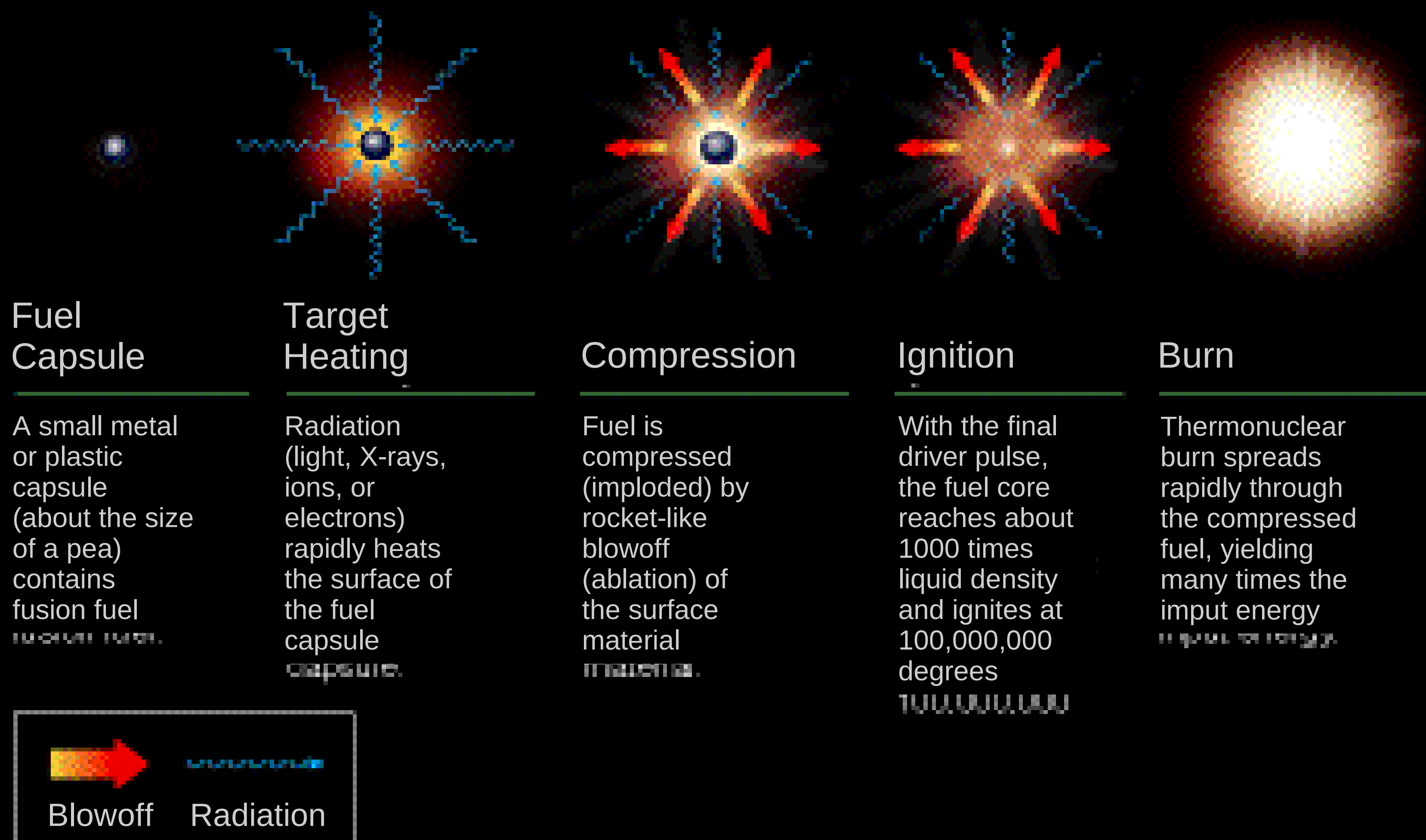


- 192 lasers
- largest in the world (together with French sister project)

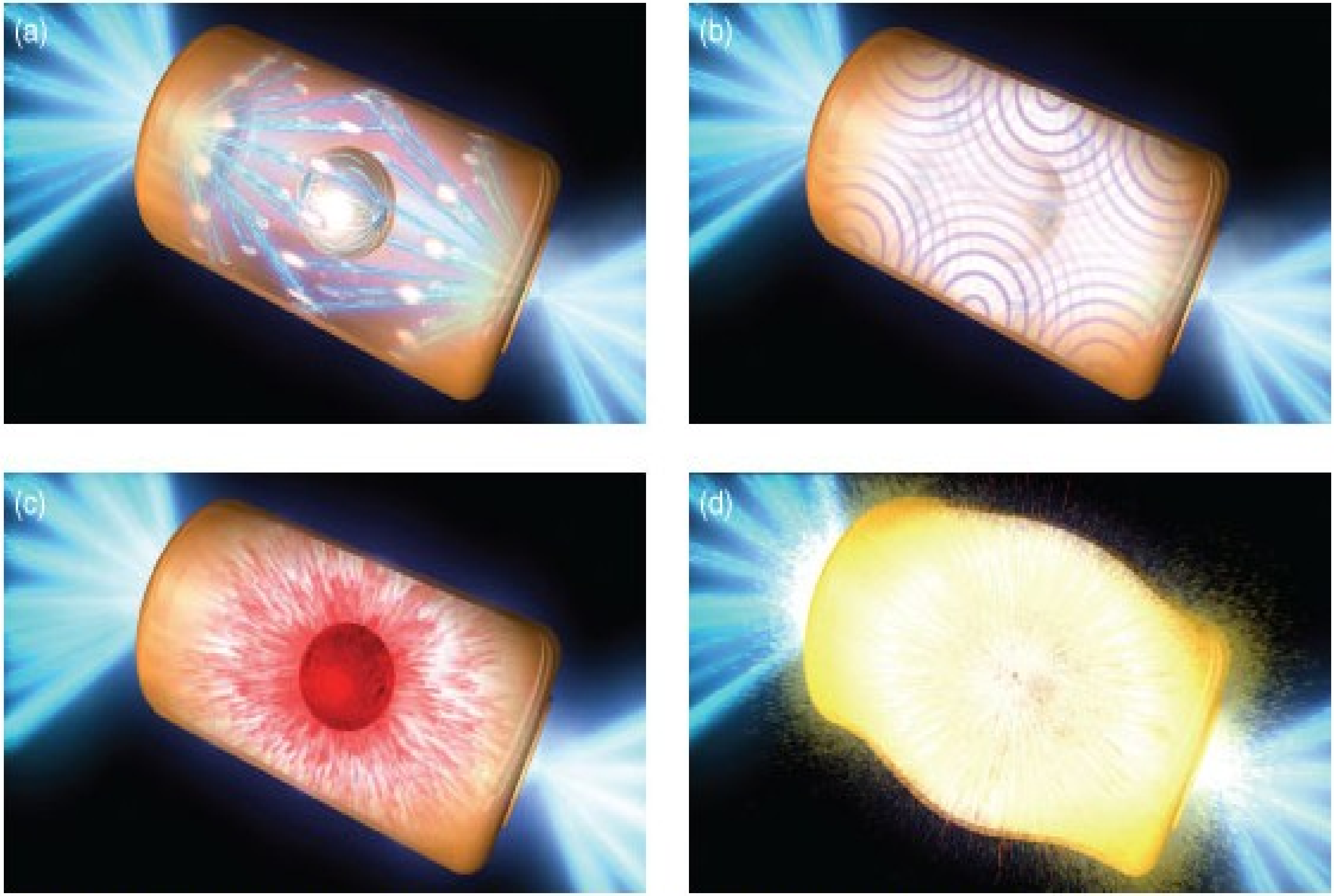


(pictures from NIF web site, courtesy of the University of California, Lawrence Livermore National Laboratory, and the U.S. Department of Energy)

Inertial Confinement Fusion Concept

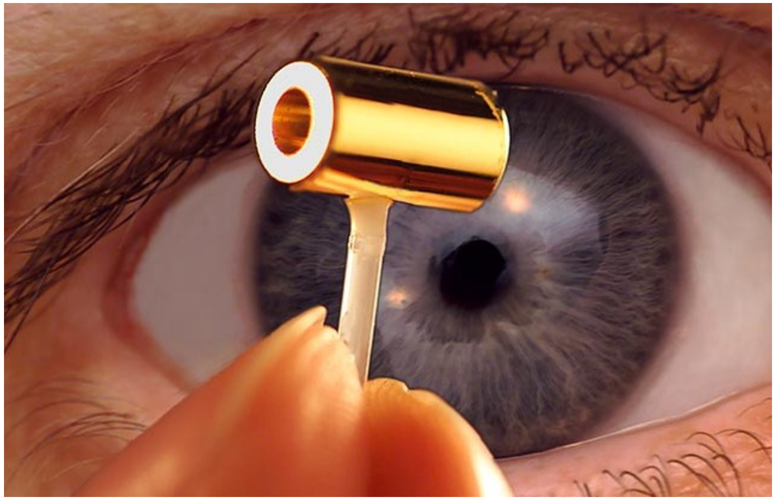


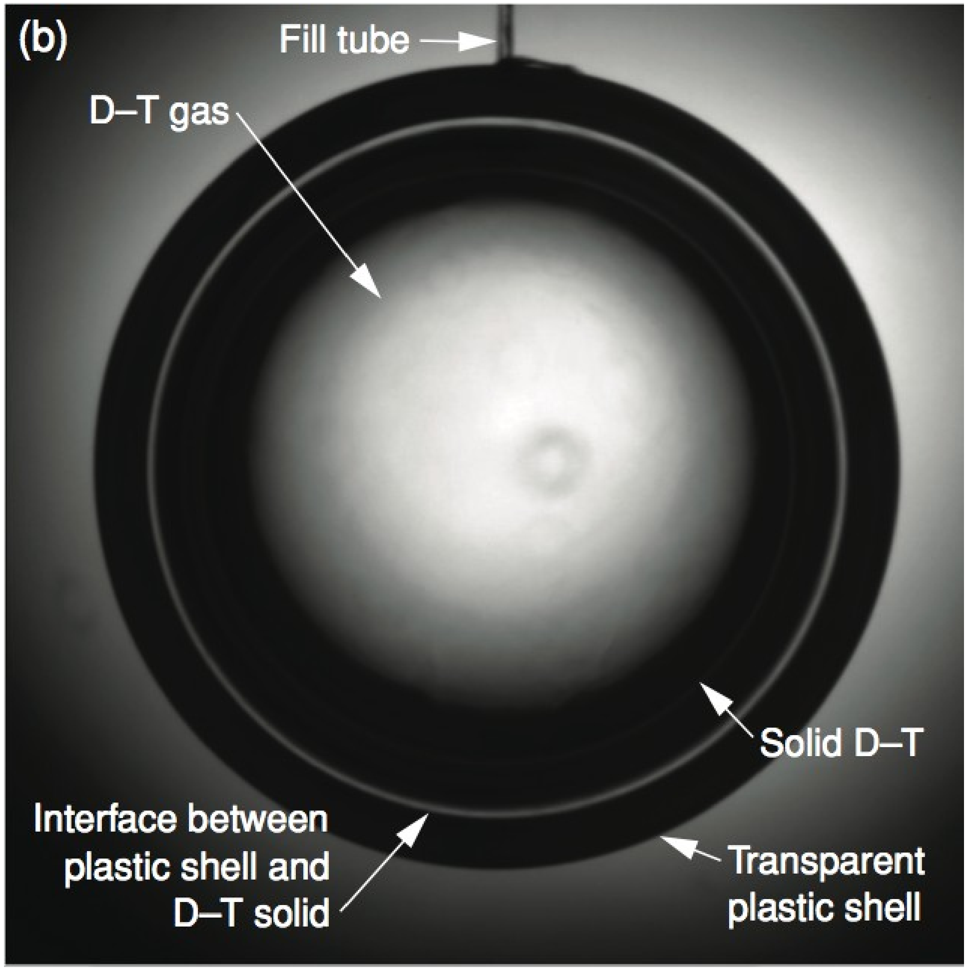
Ignition in NIF should motivate plans for expanded research towards inertial fusion energy (IFE)



Stills from an animated video of the National Ignition Facility (NIF) illustrate the fusion reaction that will occur when all 192 lasers are fired at a target inside a hohlraum. (a) Laser beams enter the hohlraum in the first one-billionth of a second (1 nanosecond) and (b) create x?rays within 10 nanoseconds. (c) At about 15 nanoseconds, the target begins to implode. (d) NIF achieves fusion ignition by 20 nanoseconds.

NIF HOHLRAUM AND CAPSULE

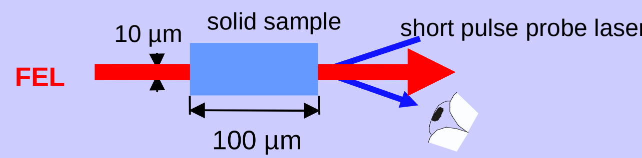




X-Ray FELs will enable a range of HED experiments (talk by R.W. Lee)

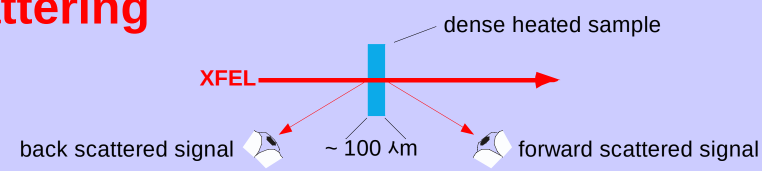
Creating Warm Dense Matter

- Generate ~ 10 eV solid density matter
- Measure the equation of state



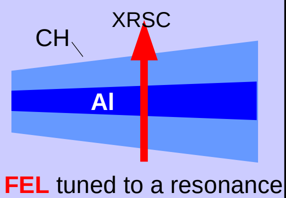
Probing dense matter with Thomson Scattering

- Perform scattering from solid density plasmas
- Measure n_e, T_e, <Z>, $f(v)$



Plasma spectroscopy of Hot Dense Matter

- Use high energy laser to create uniform HED plasmas
- Measure collision rates, redistribution rates, ionization kinetics



Probing High Pressure phenomena

- Use high energy laser to create steady high pressures
- Produce shocks *and* shockless high pressure systems
- Study high pressure matter on time scales < 1 ps
- Diagnostics: Diffraction, SAXS, Diffuse scattering, Thomson scattering

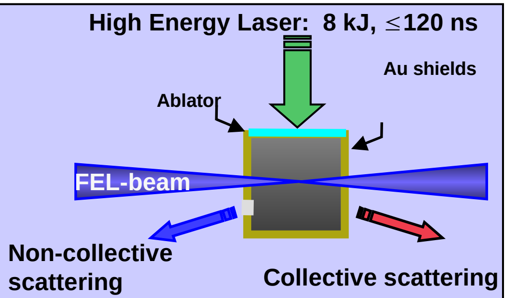
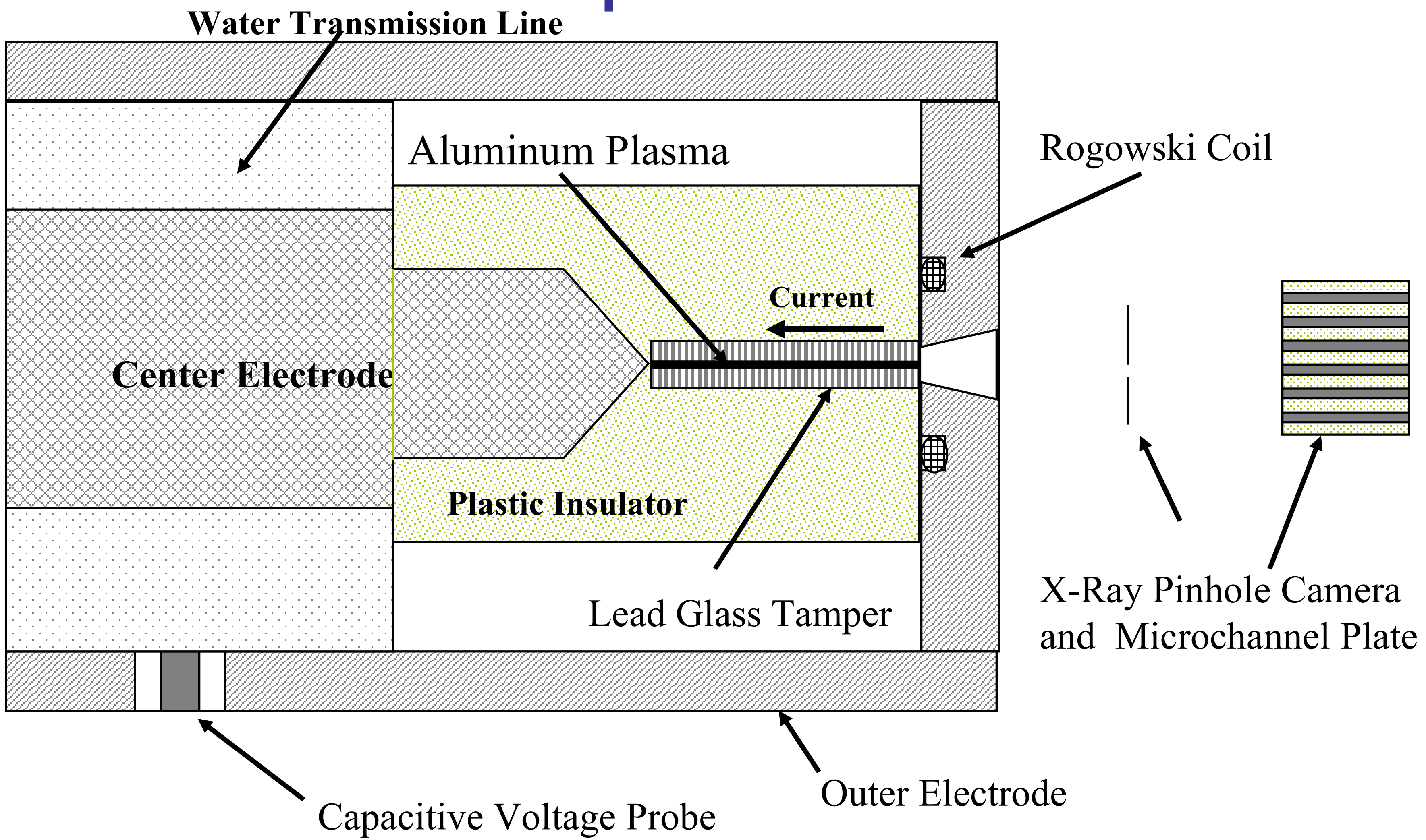


Diagram of LANL tamped exploding wire experiment



An example of HEDS science: liquid carbon

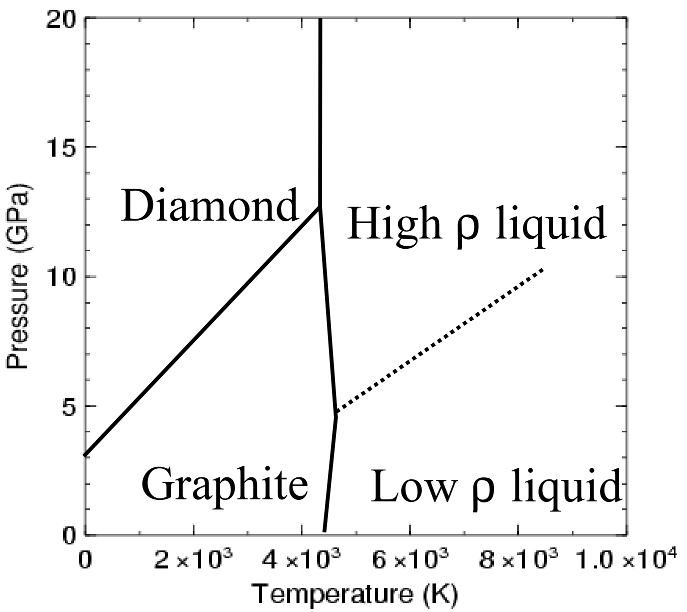
Molecular dynamics calculations predict:

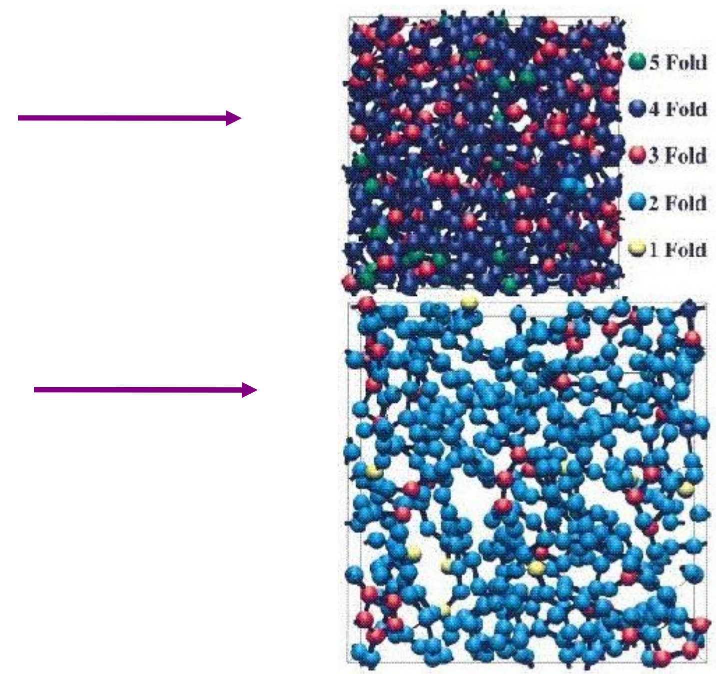
high density liquid

- mainly sp^3 coordinated

and low density liquid:

- mainly sp coordinated

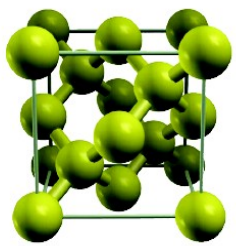




Glosli, et al, PRL *82*, 4659 (1999)

Phases of Carbon

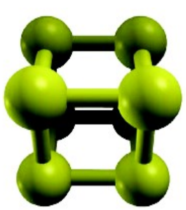
The goal is to study these phases
under extreme conditions,
liquid phases and melting lines



Diamond

BC8 ($P > 1100$ GPa)

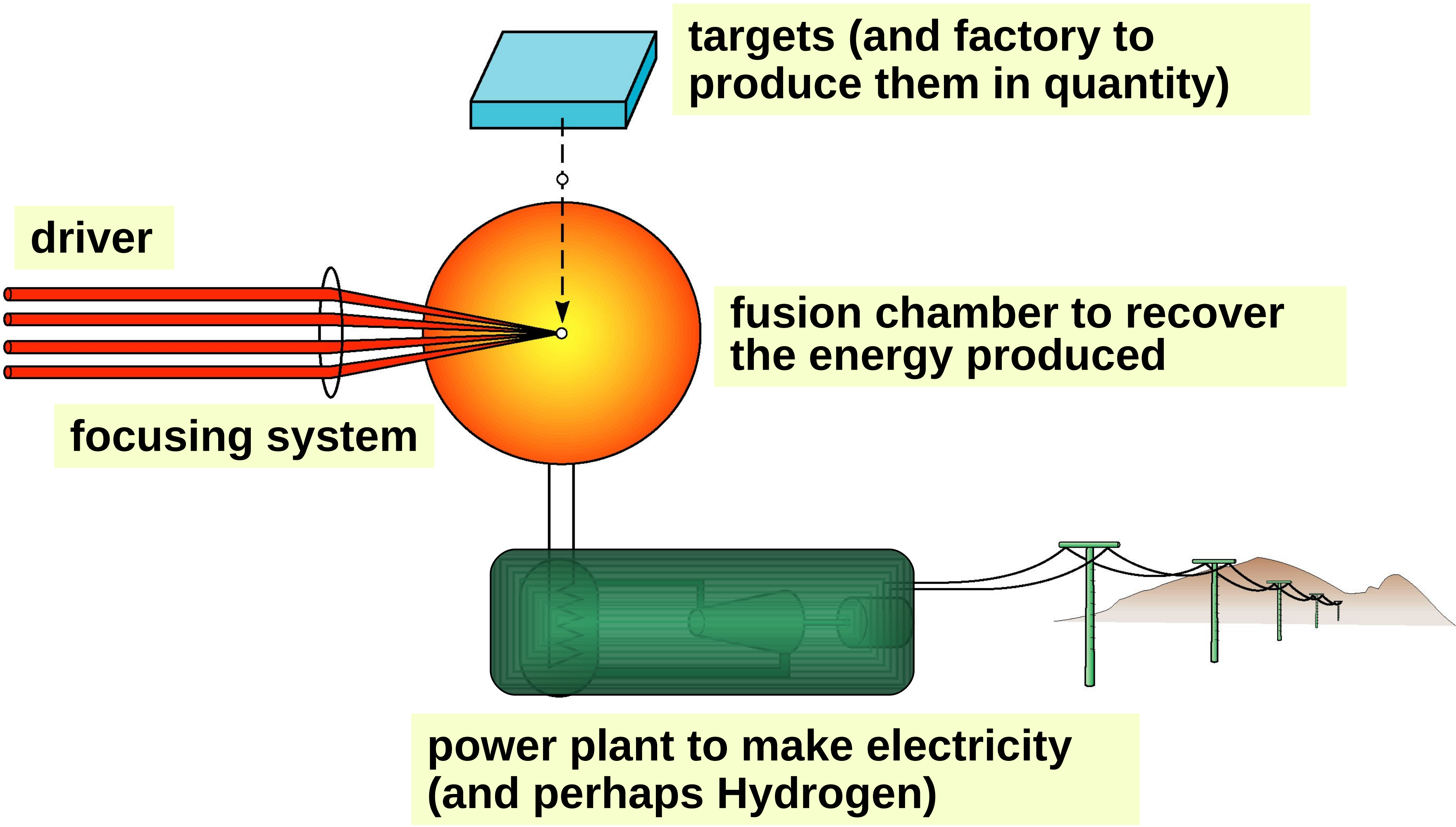
- Body Centered Cubic with 8 atom basis
- Theoretical phase proposed in analogy with Si
- Semi-metallic, not yet found experimentally



Cubic

- Metallic, not yet found experimentally

Inertial Fusion Energy (IFE) concepts are modular, and differ significantly from Magnetic Fusion Energy concepts

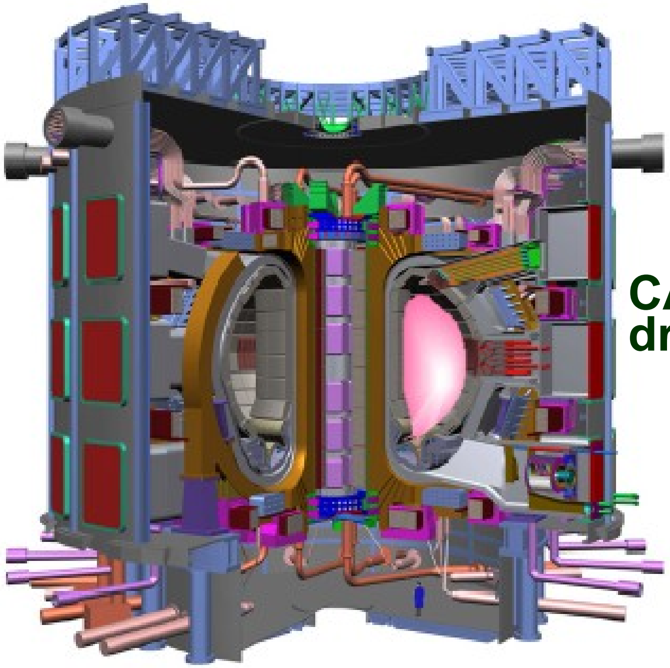


As NIF nears, we can anticipate increasing support for IFE research

Actual photo

$3B US National Ignition Facility (NIF) at LLNL will be the first demonstration of fusion ignition (alpha self-heating) in the world

ignition perhaps as early as 2011



CAD drawing

$10B International Thermonuclear Experimental Reactor (ITER) in France

ignition perhaps as early as 2021

Today's HIFS program is directed at beam & Warm Dense Matter physics in the near term, and IFE in the longer term

Heavy Ion Fusion Science experiments:

The physics of compressing beams in space and time

-- Drift compression and final focus

-- High brightness beam preservation

-- Electron cloud, beam halo, non-linear processes

Warm Dense Matter (WDM) experiments

-- Equation of state

-- Two-phase regime and droplet formation

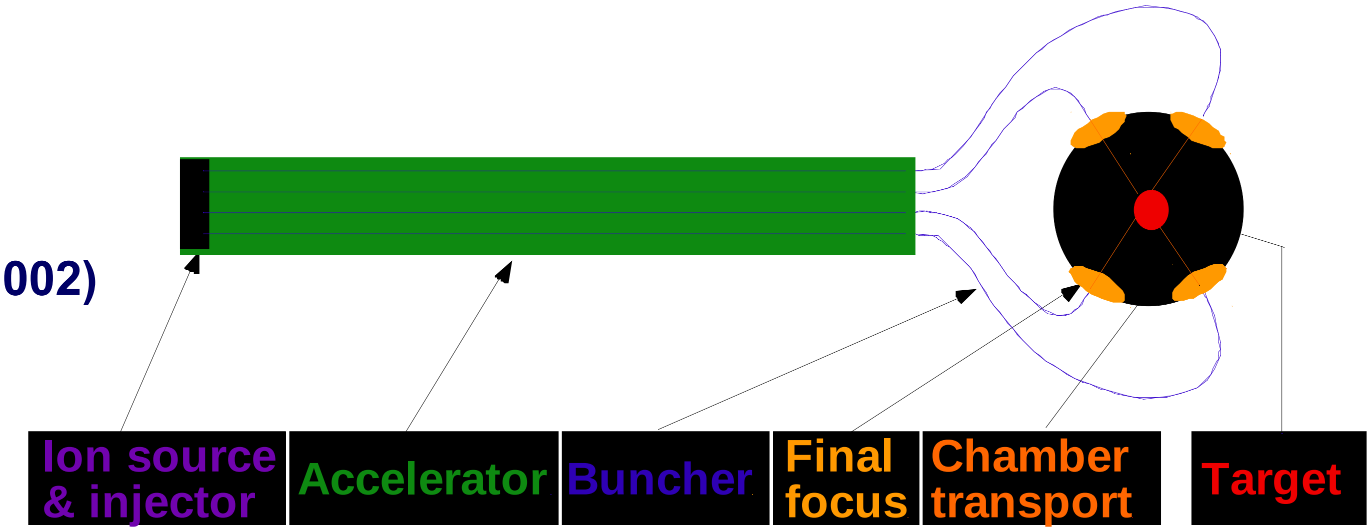
-- Insulator and metals at WDM conditions

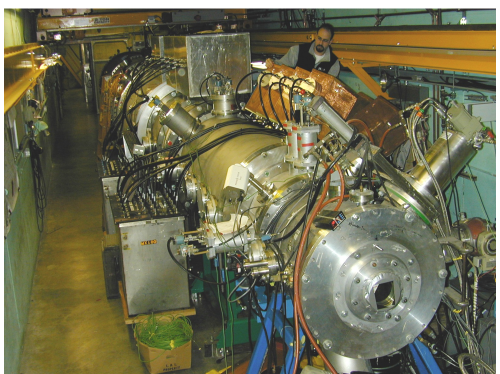
Hydrodynamics experiments relevant to HIF targets

-- Hydrodynamic stability, volumetric ion energy deposition, and Rayleigh-Taylor mitigation techniques

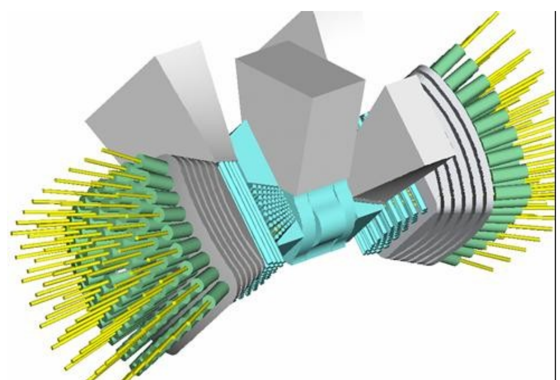
We look forward to resuming coordinated Heavy-Ion Fusion R&D, on drivers, chambers & targets that have to work together for IFE

(Slide from Snowmass 2002)

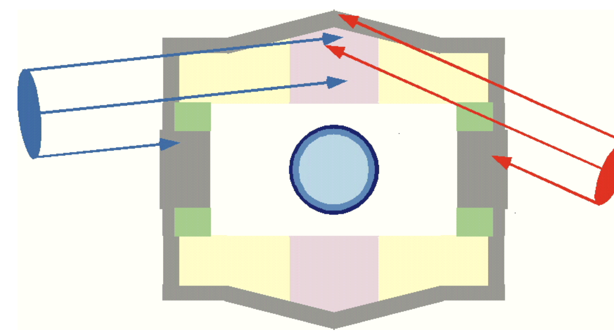




Beams at high current and sufficient brightness to focus

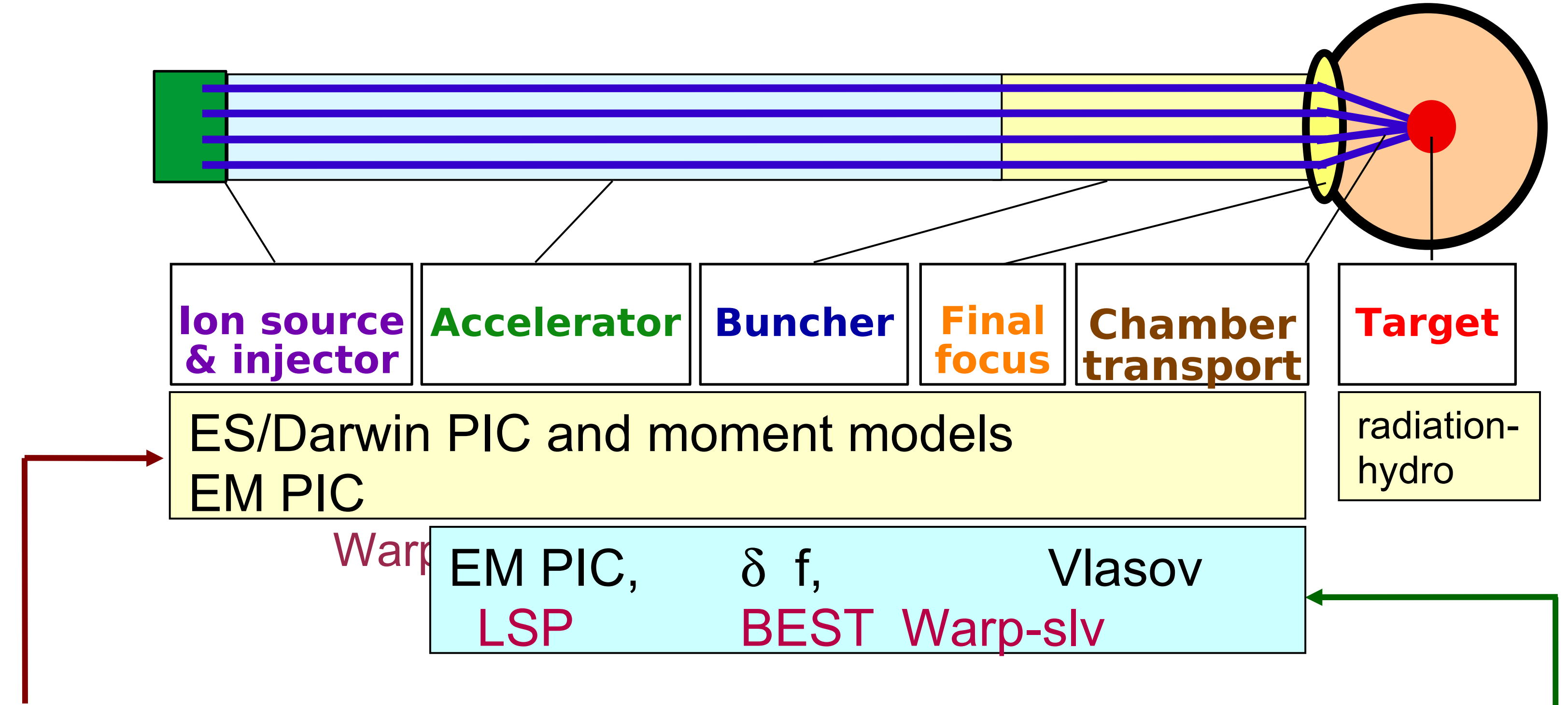


Long lasting, low activation chambers that can withstand 300 MJ fusion pulses @ 5 Hz



High gain targets that can be produced at low cost and injected

HIF-VNL's approach to self-consistent beam simulation (HEDP & IFE) employs multiple tools

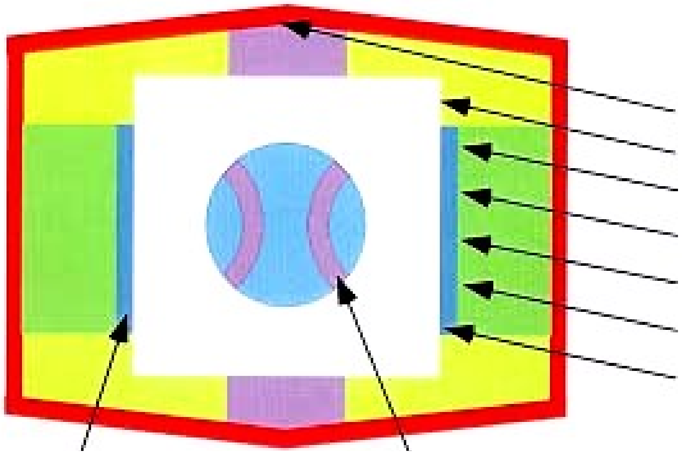


Track beam ions consistently along entire system

Study instabilities, halo, electrons, ..., via coupled detailed models

"Conventional" HIF targets build on indirect-drive NIF target concepts

Hybrid target

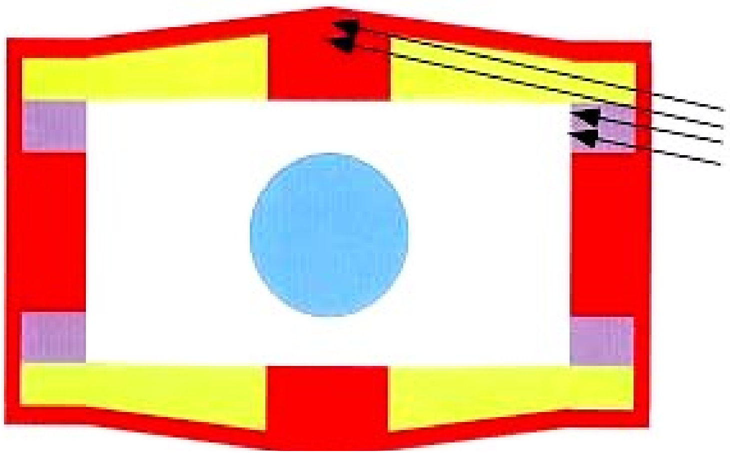


shine shield to control P_2

radiation shim to control early time P_4

Beam spot 3.8 mm x 5.4 mm
6.7 MJ beam energy
Gain = 58

Distributed radiator targets



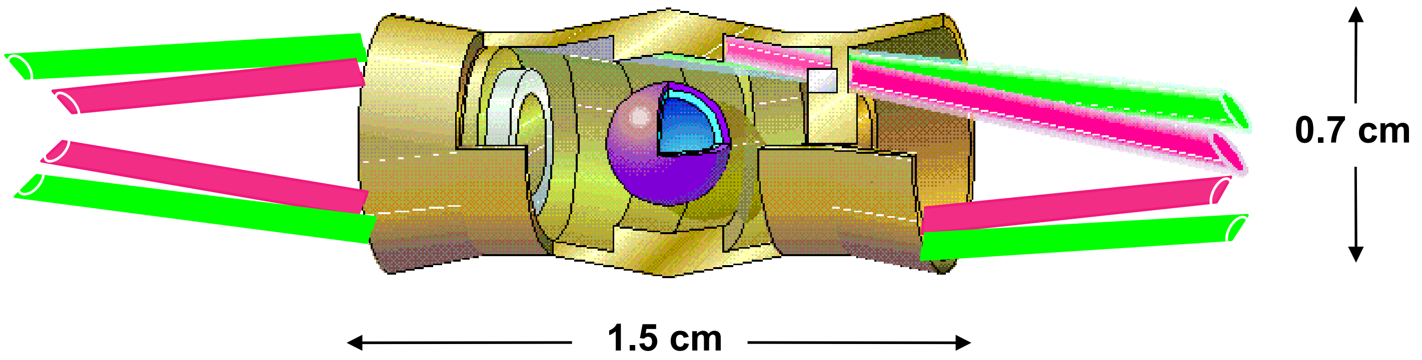
Original:

- Beam spot 1.8 mm x 4.1 mm
- 5.9 MJ beam energy
- Gain = 68

Close-coupled:

- Beam spot 1.0 x 2.78 mm
- 3.27 MJ beam energy
- Gain = 133

Target requirements imply multiple, intense beams



3 - 7 MJ x ~ 10 ns ⇒ ***~ 500 Terawatts***

Ion Range: 0.02 - 0.2 g/cm^2 ⇒ ***1 - 10 GeV***

⇓

Example, for A ~ 200 →

~ 10^{16} ions

1-2 kA / beam

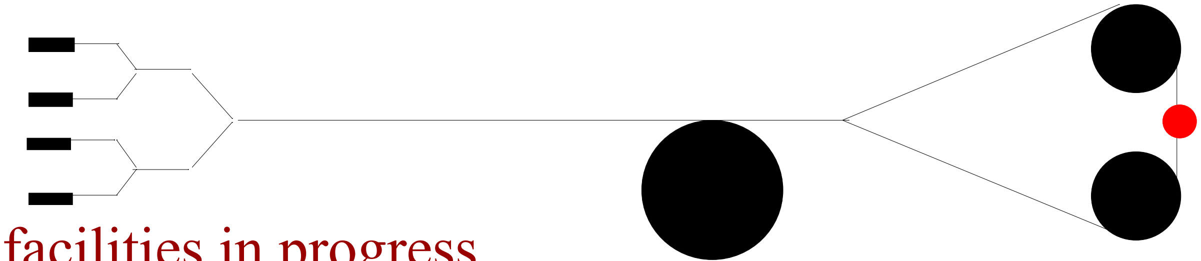
~ 100 beams

High currents → ***space charge dominated*** **beam dynamics**

→ nonneutral plasma physics

(a difference from high-energy physics accelerators)

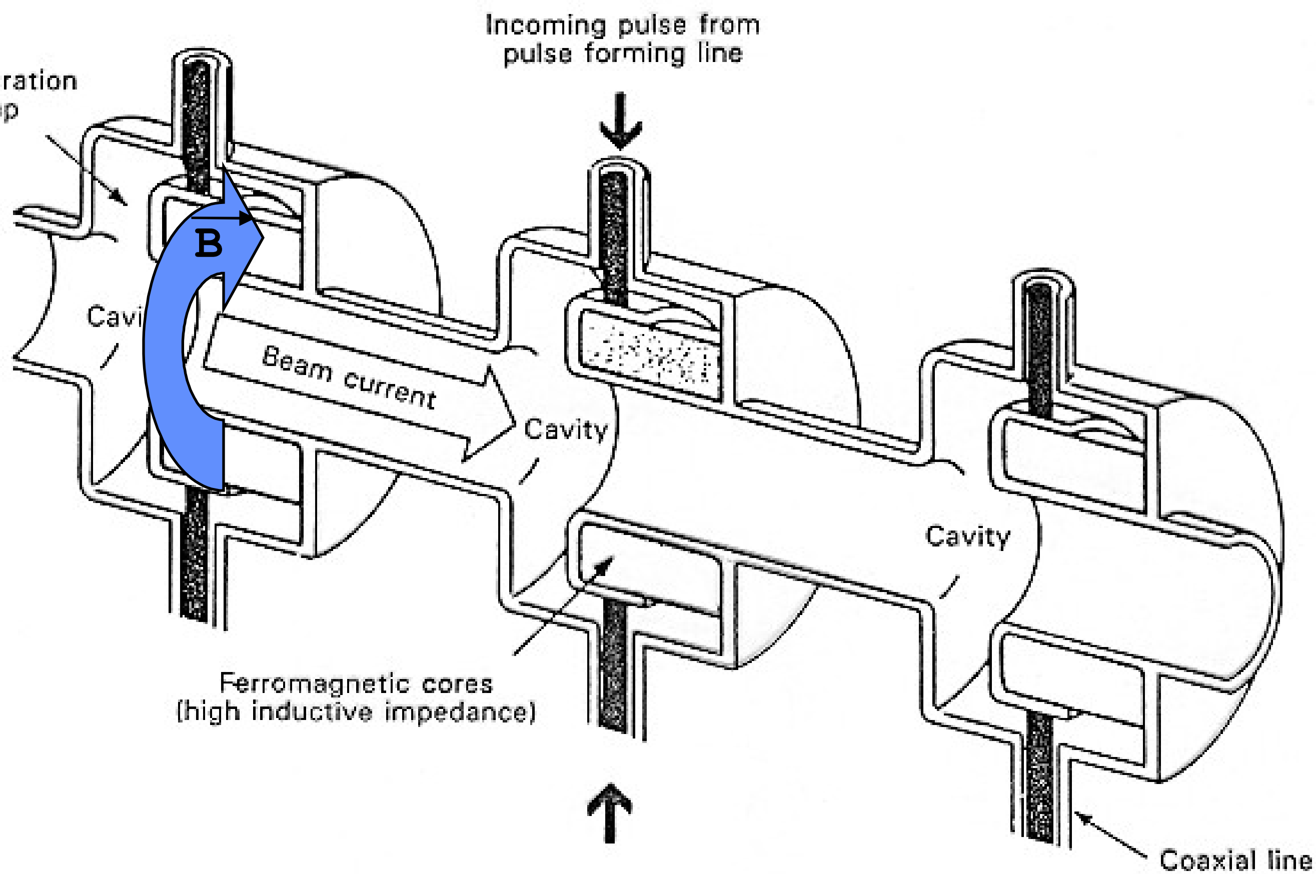
Overseas HIF-related research is primarily rf-based, and exploits dual use of nuclear physics facilities



- Accelerator facilities in progress
  - GSI (Darmstadt): "FAIR" project ~10 y: > 10's of kJ, U^{28+} in 50 ns FWHM focused to ~ 1 mm spot, for 1.5 TW, 10 eV in solid target
  - ITEP (Moscow): TeraWatt Accumulator (planned): laser ion source ($5x10^{10}$ ions of Al^{11+} or Co^{25+}) focused to ~ 1 mm spot, 100 ns, 1 TW
- Target experiments
  - ion energy deposition (GSI, Tokyo Inst. of Tech.)
  - ion transport through the target chamber (Utsunomiya U.)
  - Warm Dense Matter experiments (GSI, KEK)
- Reactor studies in Russia
  - interest in fission / fusion hybrids
  - work on "x-ray and ion debris impact on the first wetted wall of an IFE reactor"

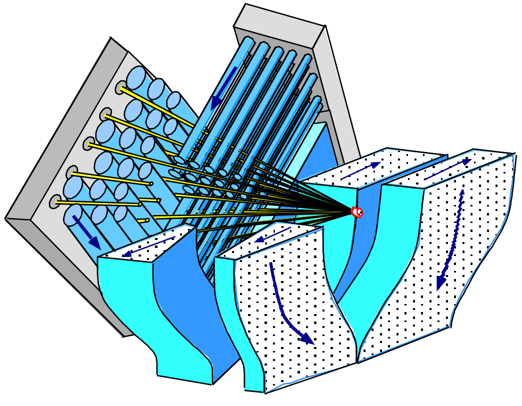
US is pursuing induction linacs for HIF

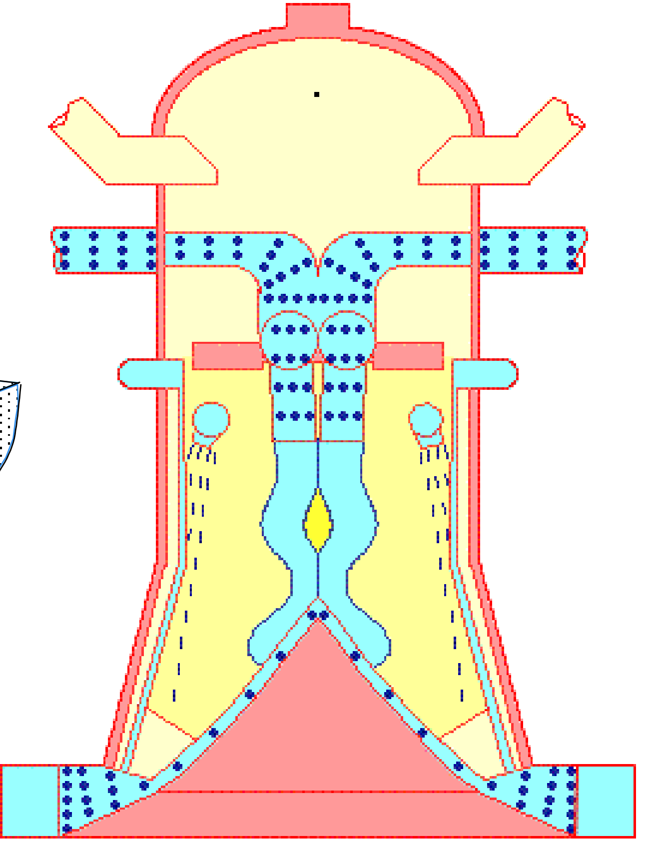
- In contrast with RF systems, they naturally support the high line-charge densities required, without storage rings
- They are efficient - can couple a large fraction of stored energy into beam
- Beam is secondary of a transformer



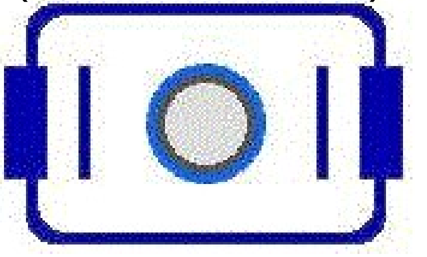
Schematic cutaway of an induction Linac

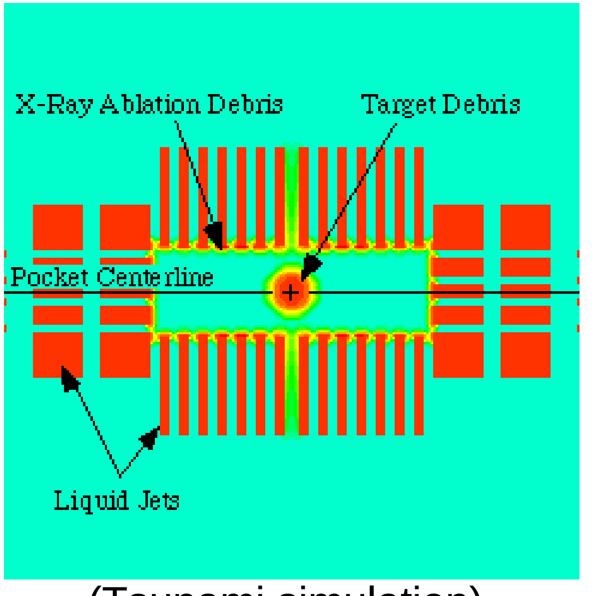
Inside the chamber





(Lasnex simulation)





(Tsunami simulation)

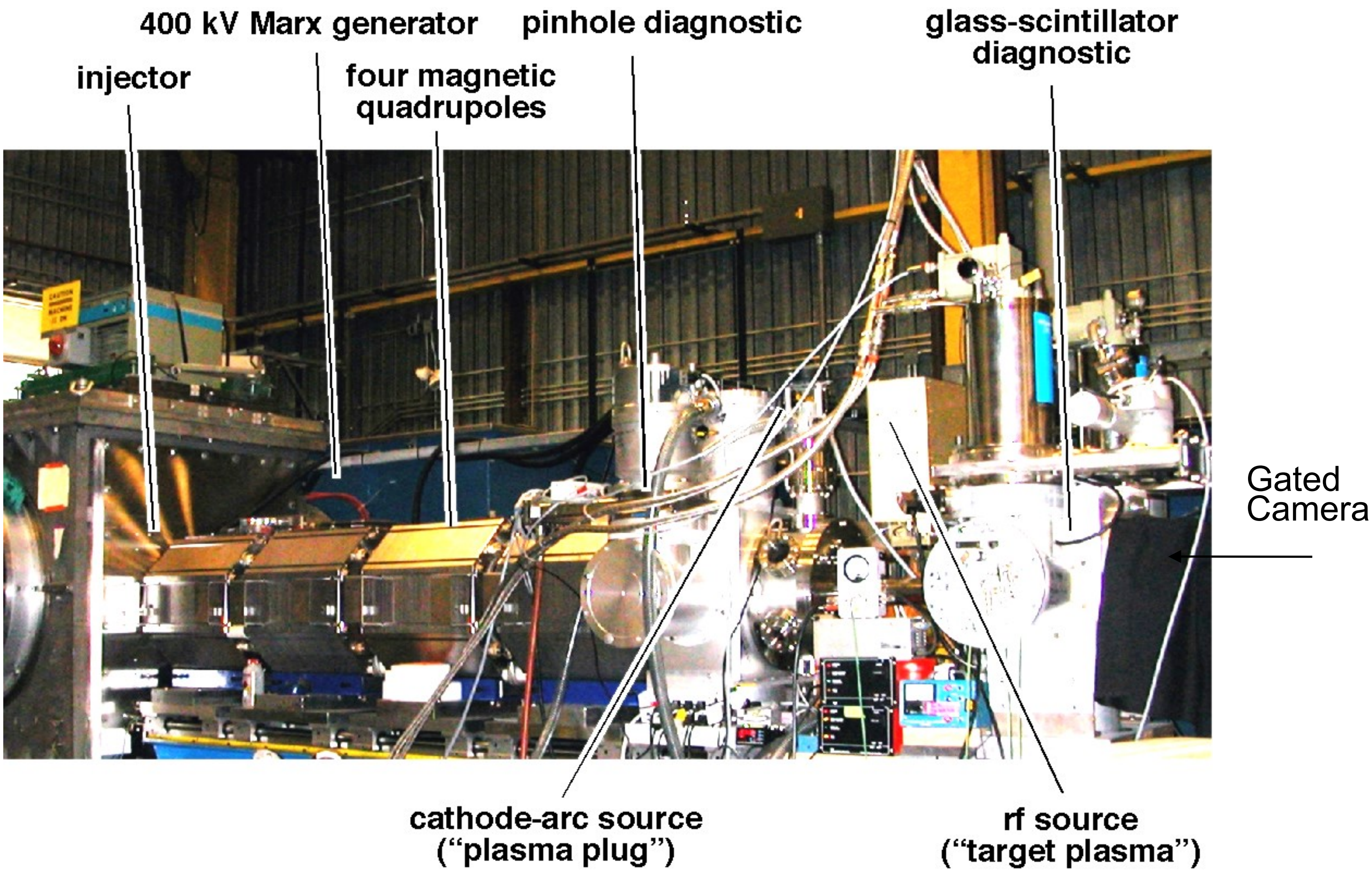
HIF/WDM beam science: neutralized focusing and drift compression are now being tested for use in WDM and HIF

- Both techniques virtually eliminate the repulsive effects of space charge on transverse and longitudinal compression

- Transverse compression (= focusing the beam to a small spot, raising the watts/cm^2): Recent VNL experiments, eg. scaled final focus experiment, (MacLaren et al 2002), NTX (Roy et al 2004), and current NDCX-1 have demonstrated benefits of neutralization by plasmas, also required for HIF.

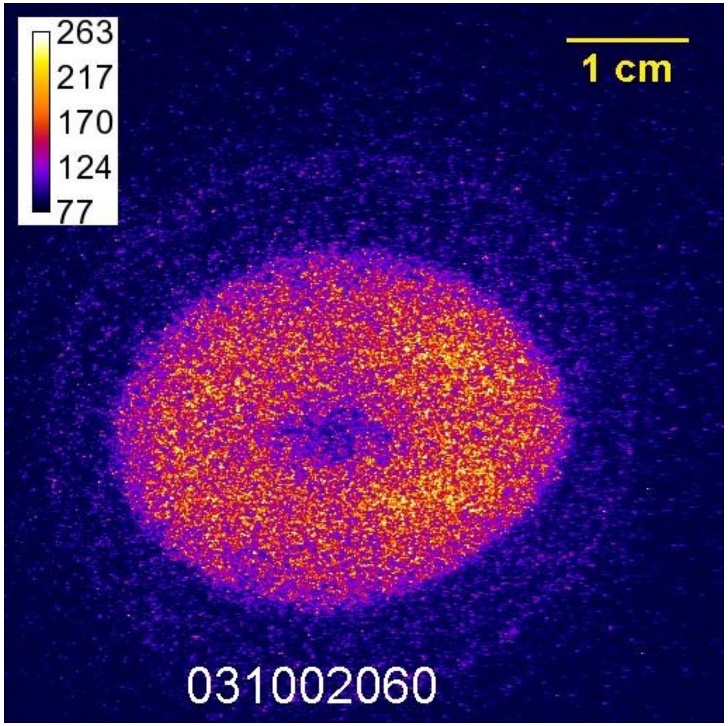
- Longitudinal compression (= raising the watts): WDM experiments require very short, intense pulses (<~ 1 ns) (shorter than needed for HIF). Neutralization allows high current/high power beams. Modular HIF concept also pushes limit of high current.

The Neutralized Transport Experiment (NTX) examined the benefits of plasma for focusing



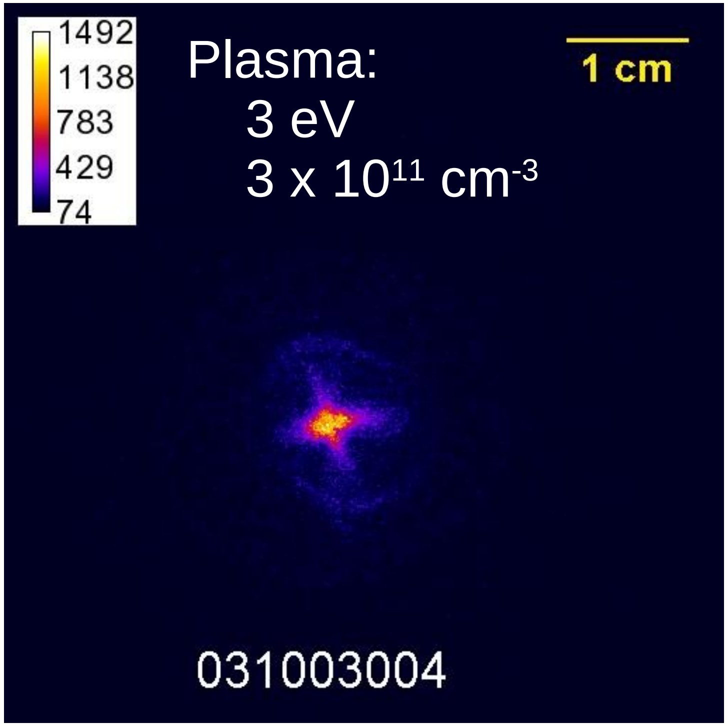
Spot Size is dramatically reduced by neutralization

Non-neutralized



14.7 mm beam radius

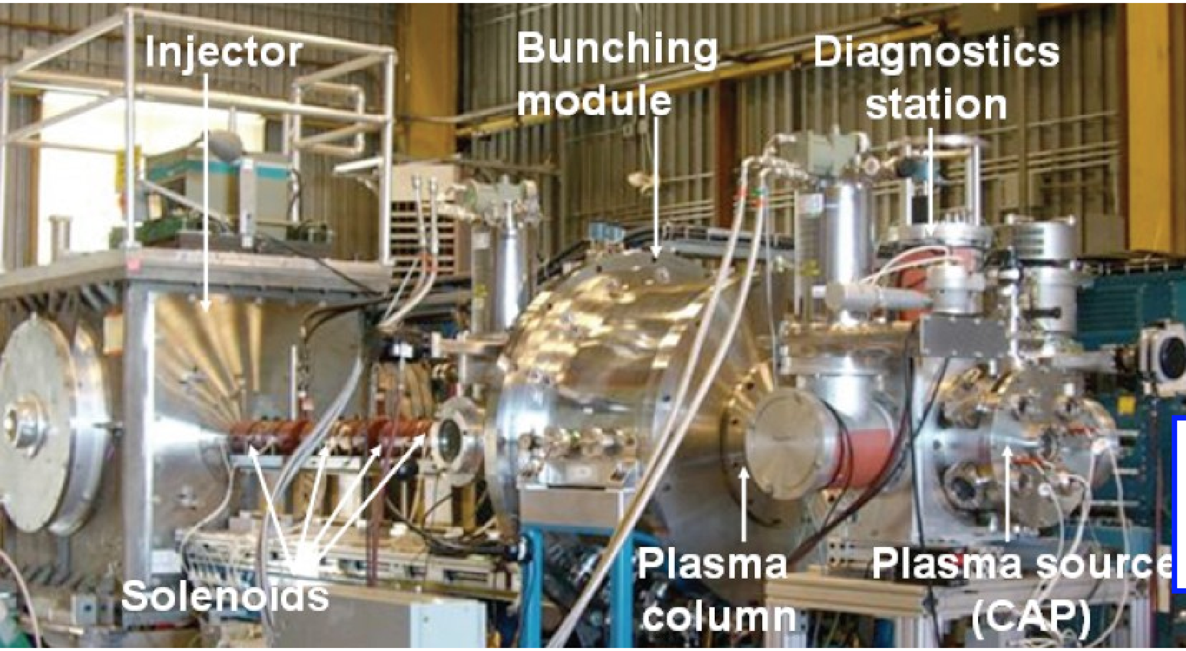
Neutralized

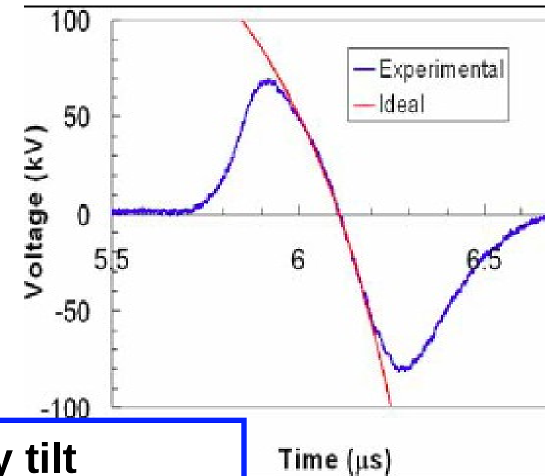


1.26 mm beam radius

25 mA, 255 keV transported through a 7.6 cm diameter tube.
Mesh liner was used to control neutralization by halo electrons.

NDCX-1 has achieved > factor 70 pulse compression, and kinematically limited spot radius, consistent w/ simulations



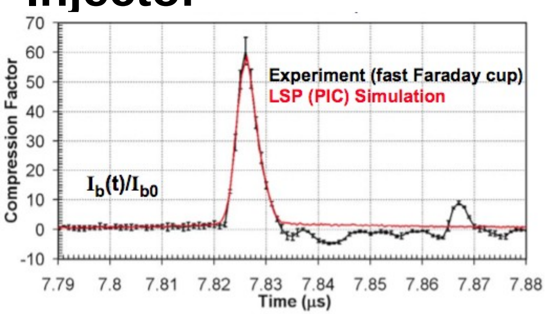


Velocity tilt accelerates tail, decelerates head

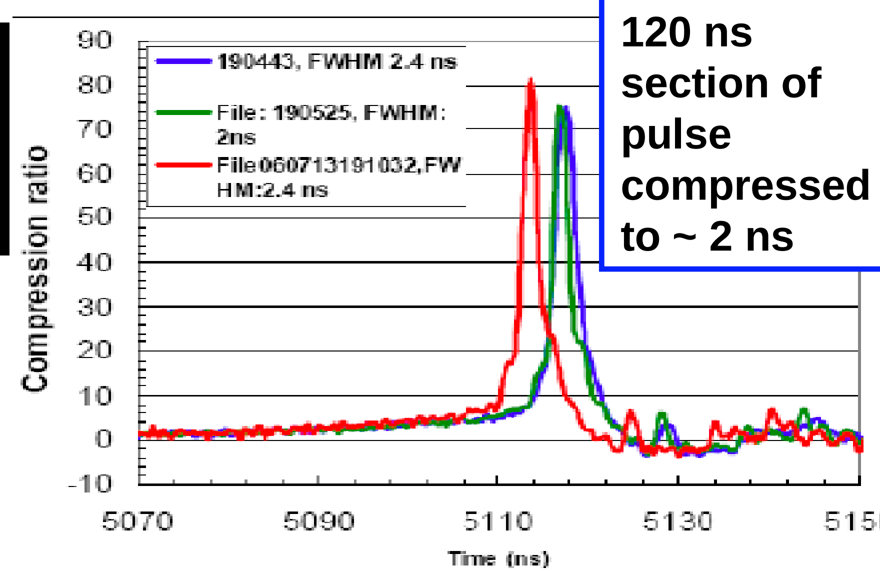
(Like chirped pulse compression)

Injector

Solenoids

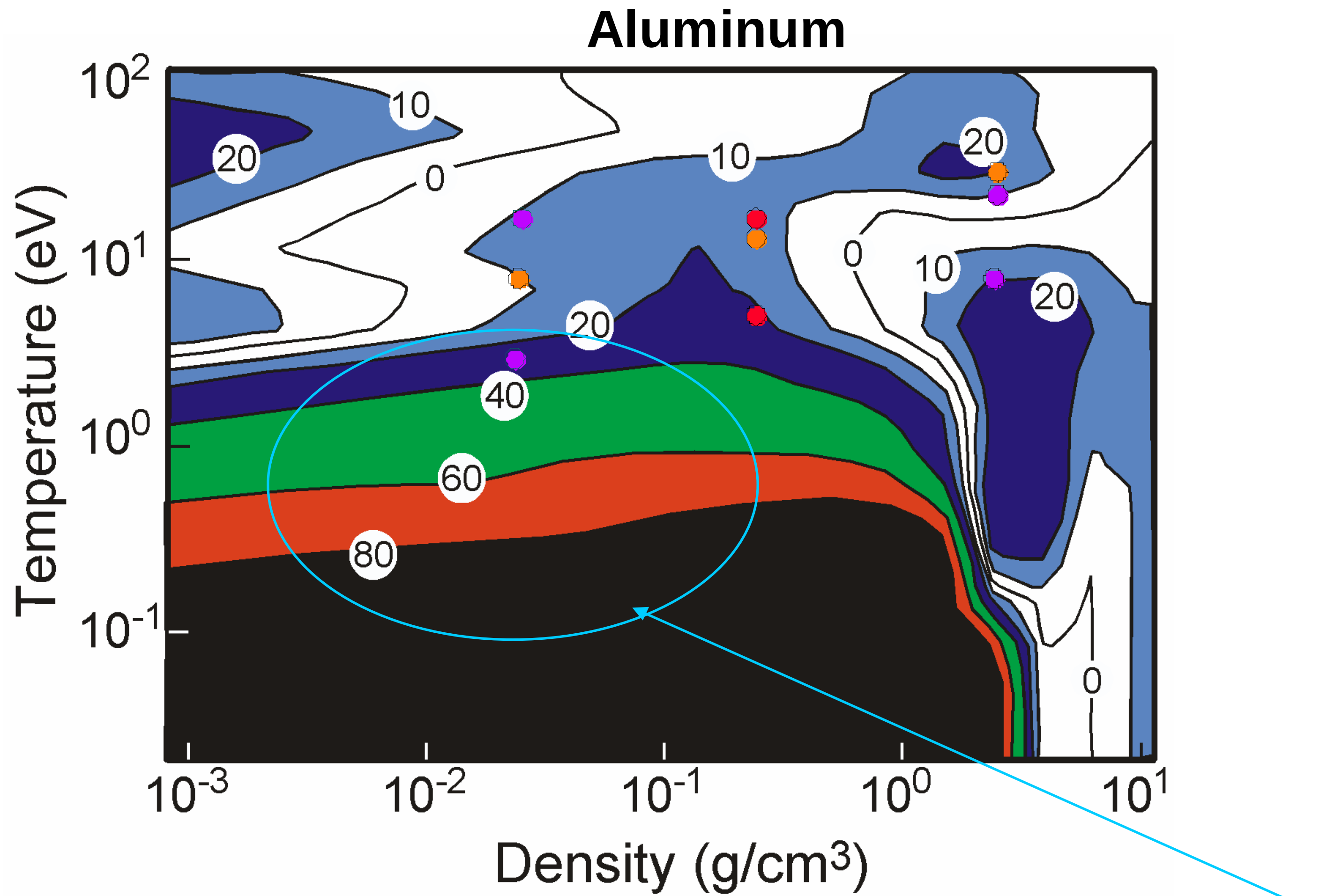


Plasma column/ Neutralized drift section (2 m)



120 ns section of pulse compressed to ~ 2 ns

Strongly coupled plasmas at 0.01 - 0.1 of solid density are interesting areas to measure EOS



Numbers are % disagreement in EOS models; they are large where there is little or no data (Courtesy of Richard W. Lee, LLNL)

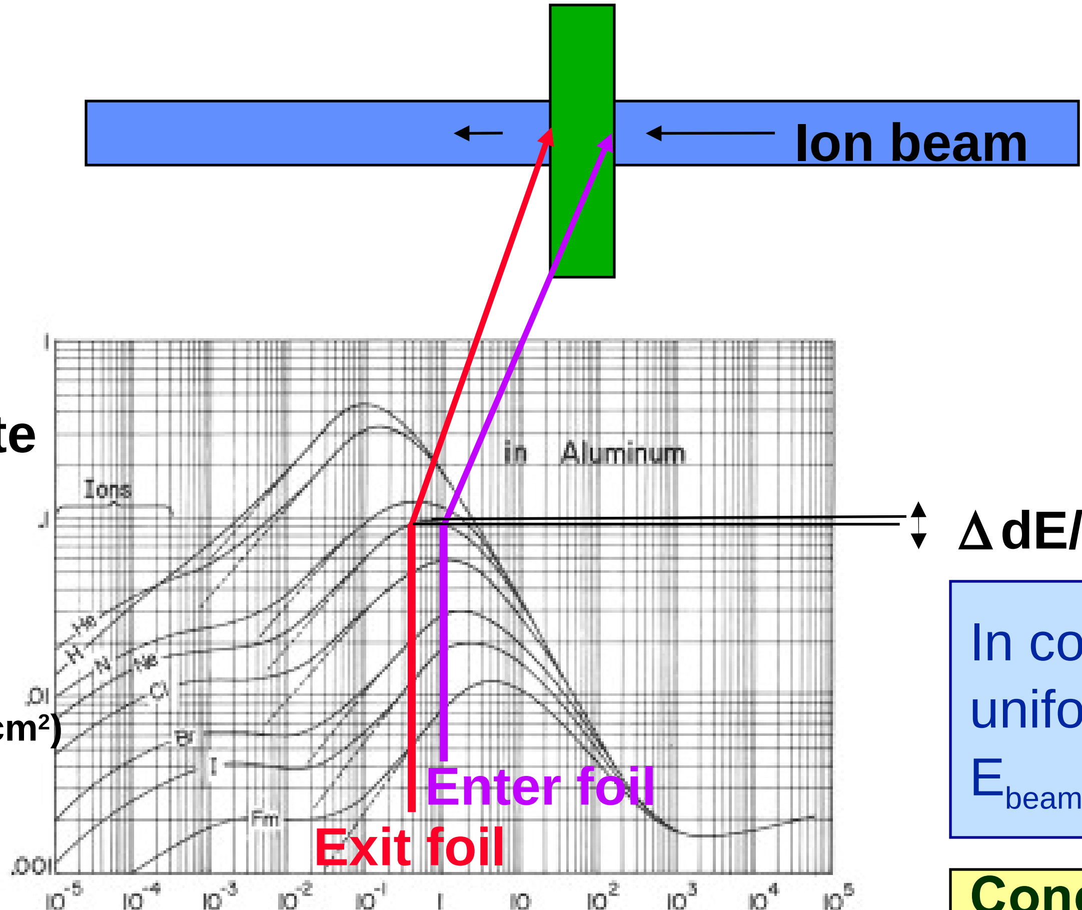
HIFS-VNL WDM strategy: maximize uniformity and use of beam energy by operating at Bragg peak

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

Energy loss rate

$$-\frac{1}{Z^2}\frac{dE}{dX}$$

(MeV/mg cm²)



Energy/Ion mass (MeV/amu)

ΔdE/dX ∝ ΔT

Example:
Ne beam on Al
$E_{entrance}$=1.0 MeV/amu
E_{peak}= 0.6 MeV/amu
E_{exit} = 0.4 MeV/amu
(ΔdE/dX)/(dE/dX)≈0.05

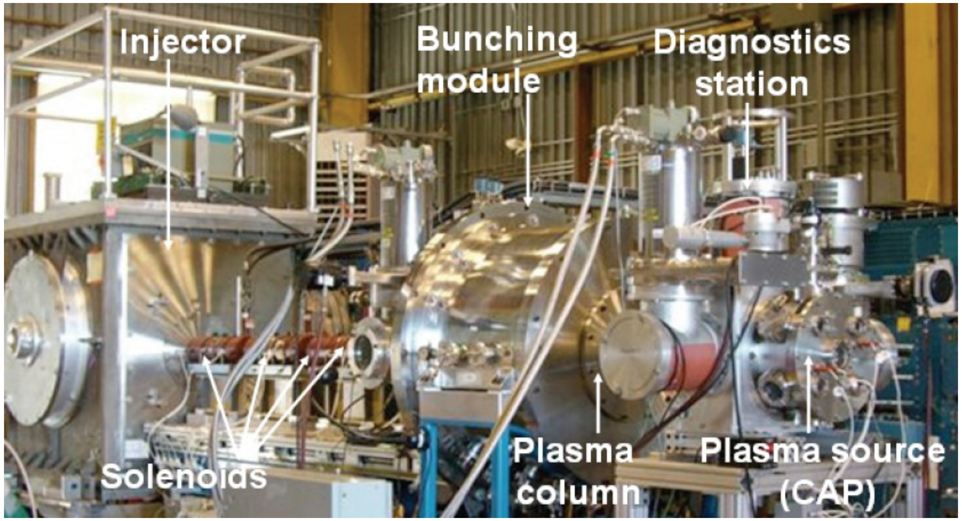
In contrast, GSI achieves uniformity by operating at E_{beam} >> Bragg peak

Require ~ ns pulses to minimize hydro motion

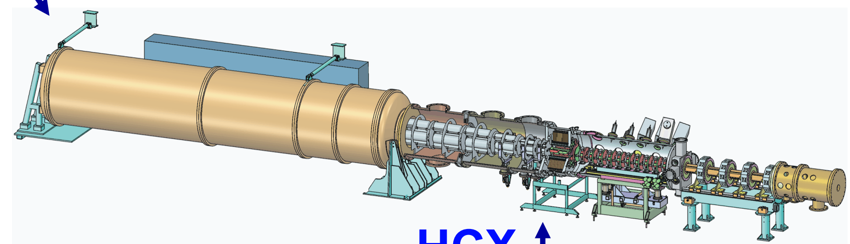
Concept: L. R. Grisham, Phys. Plas. 11, 5727 (2004)

dEdX figure: L.C Northcliffe & R.F.Schilling, Nuclear Data Tables, **A7**, 233 (1970)

The HIFS VNL has developed a plan for using present and future accelerators for WDM and HIF experiments



Today:



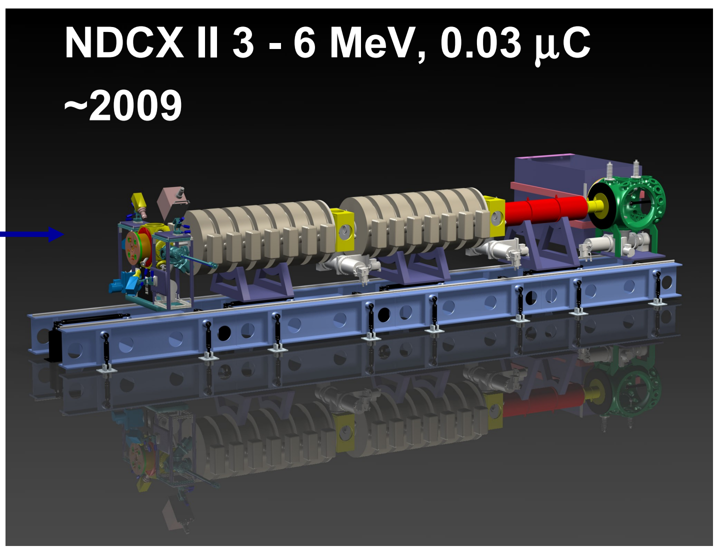
NDCX I

0.4 MeV, 0.003 μC

HCX

1.7 MeV, ~0.025 μC

Soon



Future

IB-HEDPX (with CD0)
5 - 15 year goal
20 - 40 MeV, 0.3 - 1.0 μC
WDM User facility

10 kJ Machine for HIF
10 - 20 year goal
Target implosion physics

A user facility for ion beam driven HEDP/WDM will have unique characteristics

Precise control of energy deposition

Large sample sizes compared to diagnostic resolution volumes (~ 1's to 10's μ thick by ~ 1 mm diameter)

Uniformity of energy deposition (<~ 5%)

Ability to heat all target materials (conductors and insulators, foams, powders, ...)

Pulse long enough to achieve local thermodynamic equilibrium

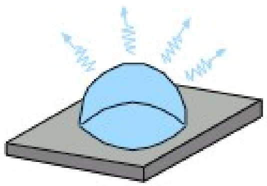
A benign environment for diagnostics

High shot rates (10/hour to 1/second)

Potential for multiple beamlines/target chambers

Intense heavy ion beam is an excellent tool to generate large-volume HED samples

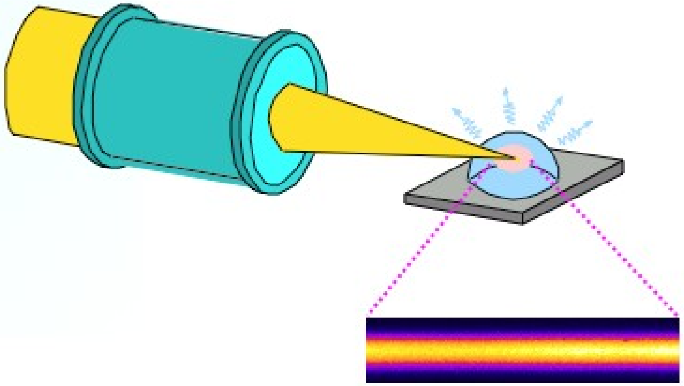
High Energy Density Matter
(Warm Dense Matter)



T ~ 2,000 – 200,000 K
ρ ~ solid density
P ~ kbar, Mbar

Intense heavy ion beams:

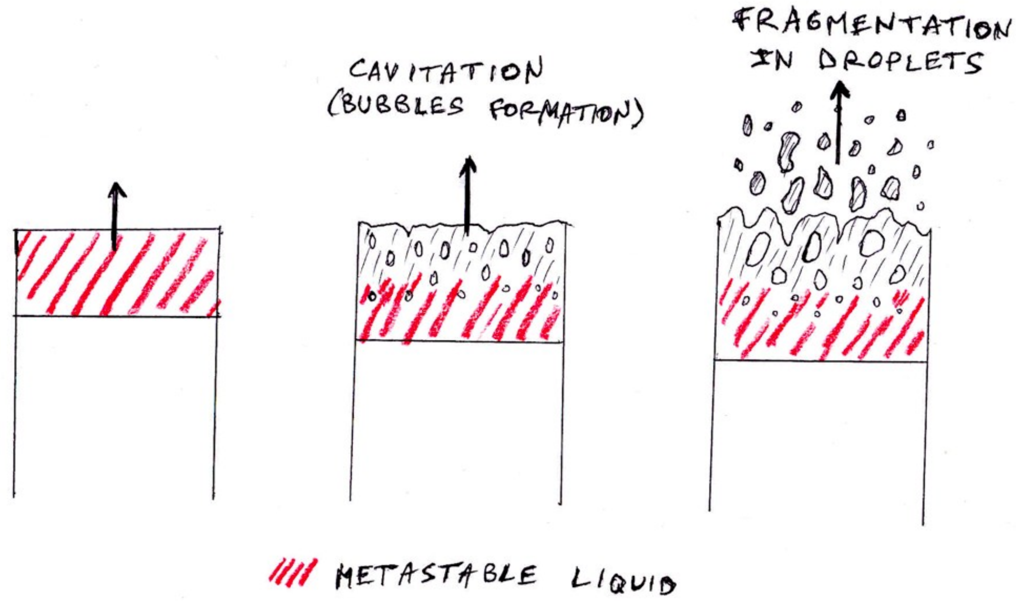
- ☑ large volume of sample (mm^3)
- ☑ fairly uniform physical conditions
- ☑ high entropy @ high densities
- ☑ high rep. rate and reproducibility
- ☑ any target material



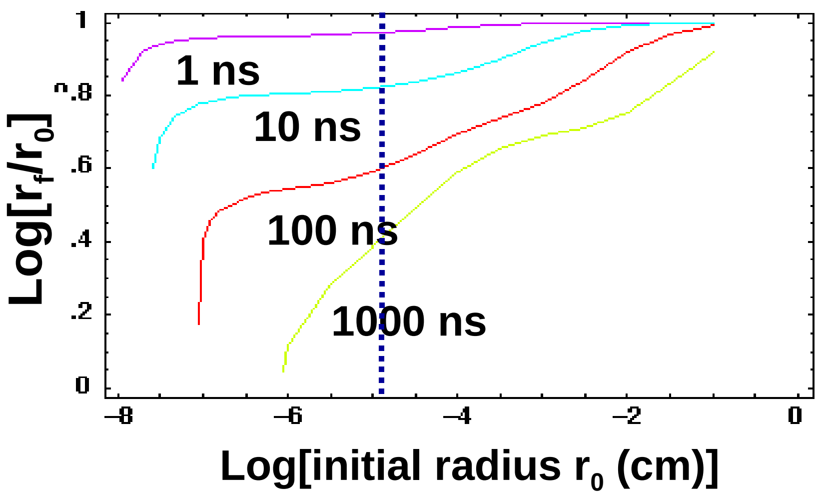
Formation of droplets during expansion of foil is being investigated

Foil is first entirely liquid then enters two phase regime

[J. Armijo, master's internship report, ENS, Paris, 2006.]

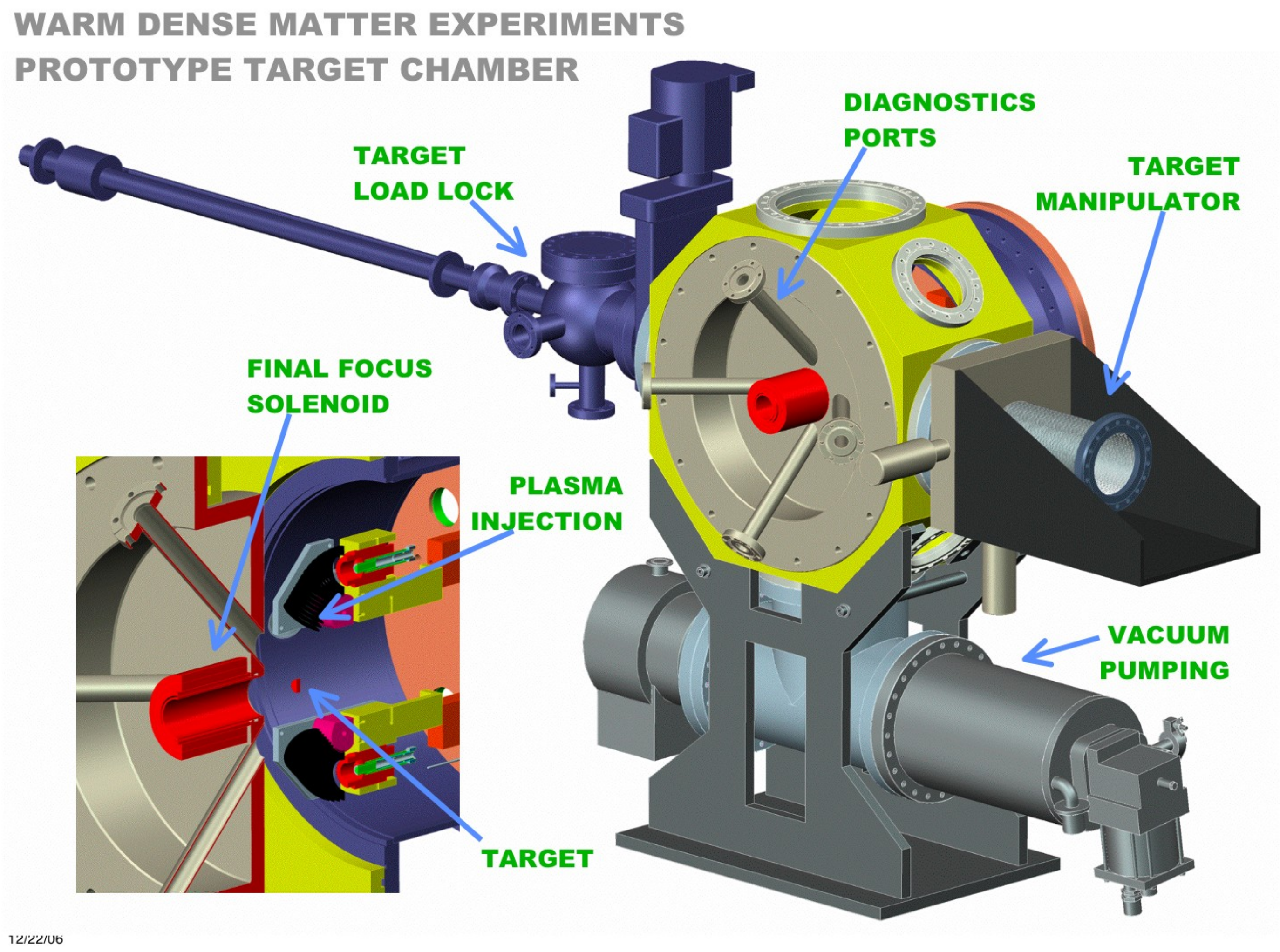


C. Debonnel and A. Zeballos are incorporating a model for surface effects into hydrodynamics code Tsunami



Evolution of droplet radius [Armijo et al., APS DPP 2006, and in prep.]

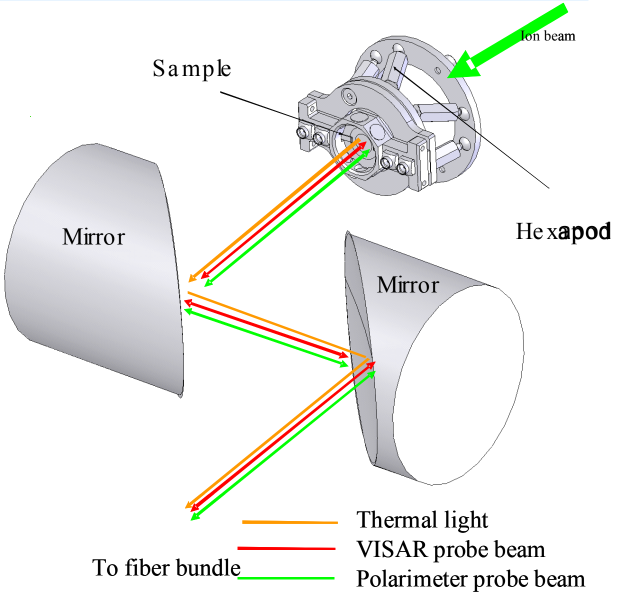
WDM target chamber is designed and being fabricated



We are developing target diagnostics for first target experiments on NDCX-I

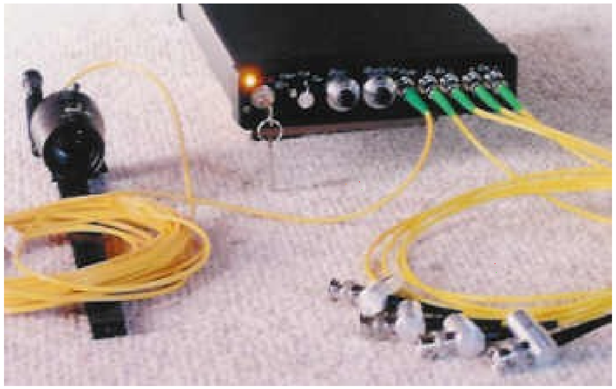
Fast optical pyrometer – *now being assembled*

- New design by P. Ni for fast response (~150 ps) and high sensitivity
- Temperature accuracy 5% for T>1000 K
- Spatial resolution about 10 micron at 1 eV



Fiber-coupled VISAR system – *now under test*

- ps resolution
- 1% accuracy

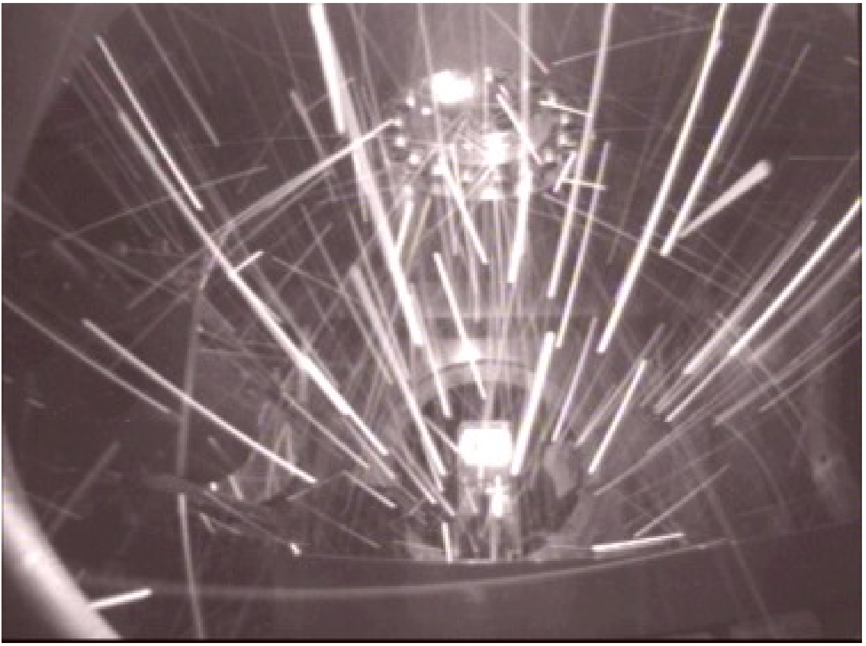


Hamamatsu visible streak camera with image intensifier

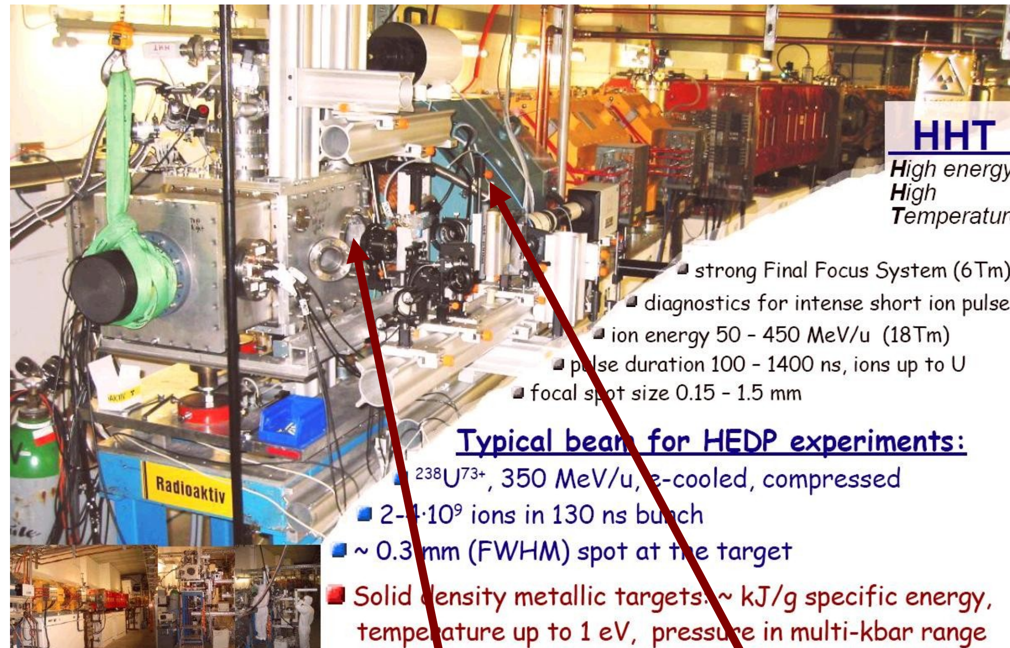
- ***arrived Feb. 2007***
- ps resolution

Pyrometer tested in March 2008

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



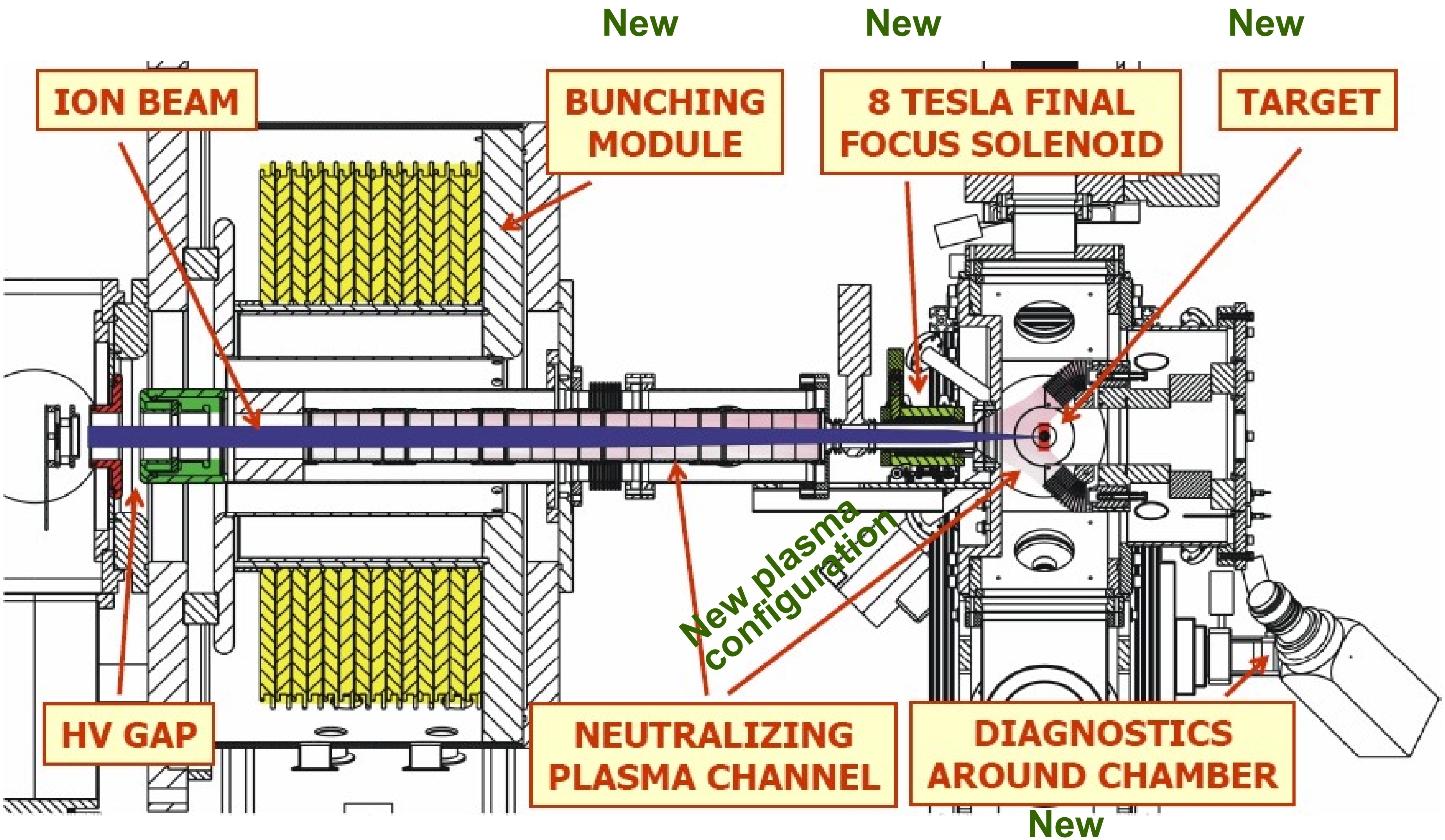
Visible ms camera frame showing hot target debris droplets flying from a VNL gold target (~ few mg mass) isochorically heated by a 100 ns, 10 J heavy ion beam to 1 eV in joint experiments at GSI, Germany



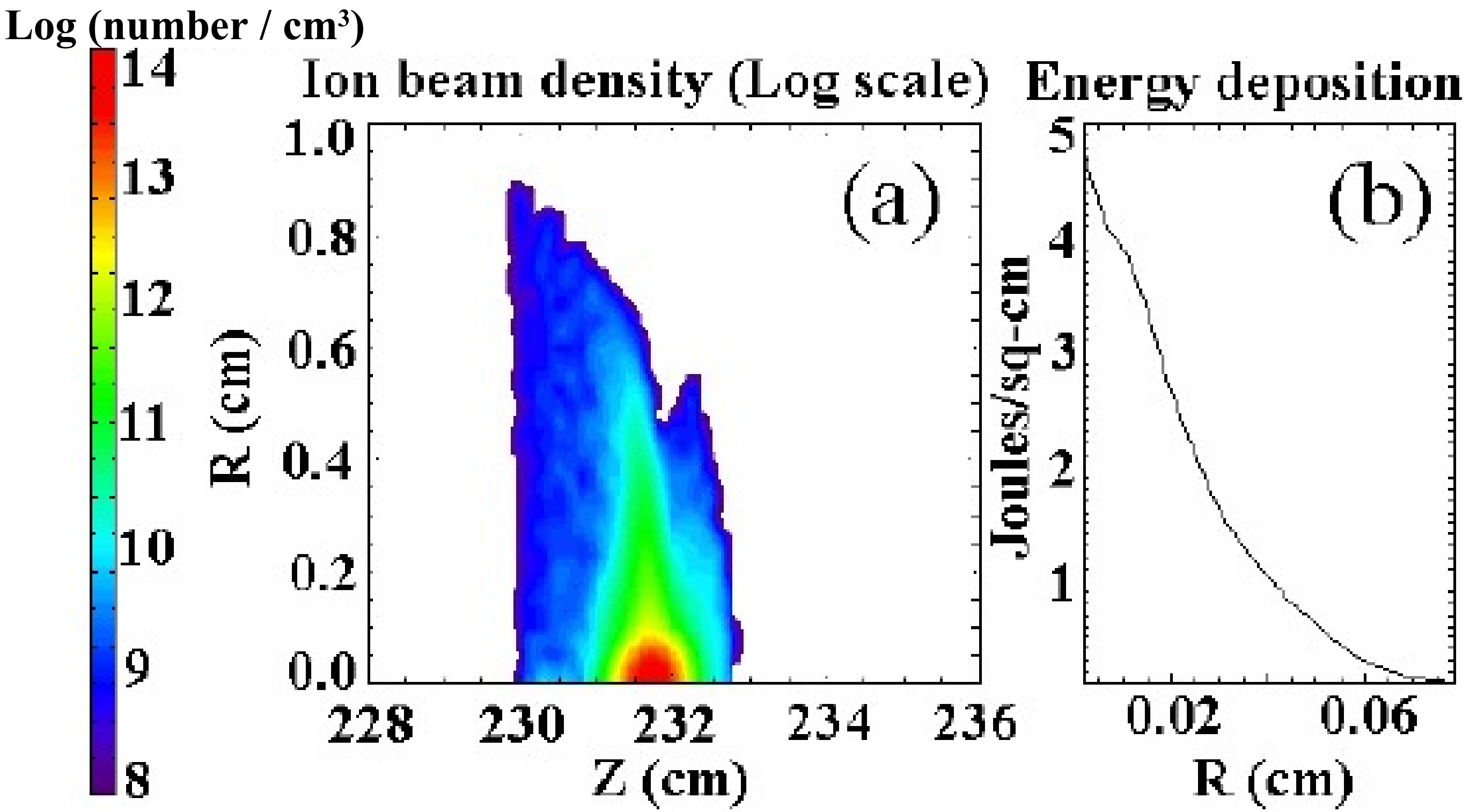
Final focus magnets

Optical diagnostic windows need to be periodically cleaned of target debris and sometimes replaced.

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



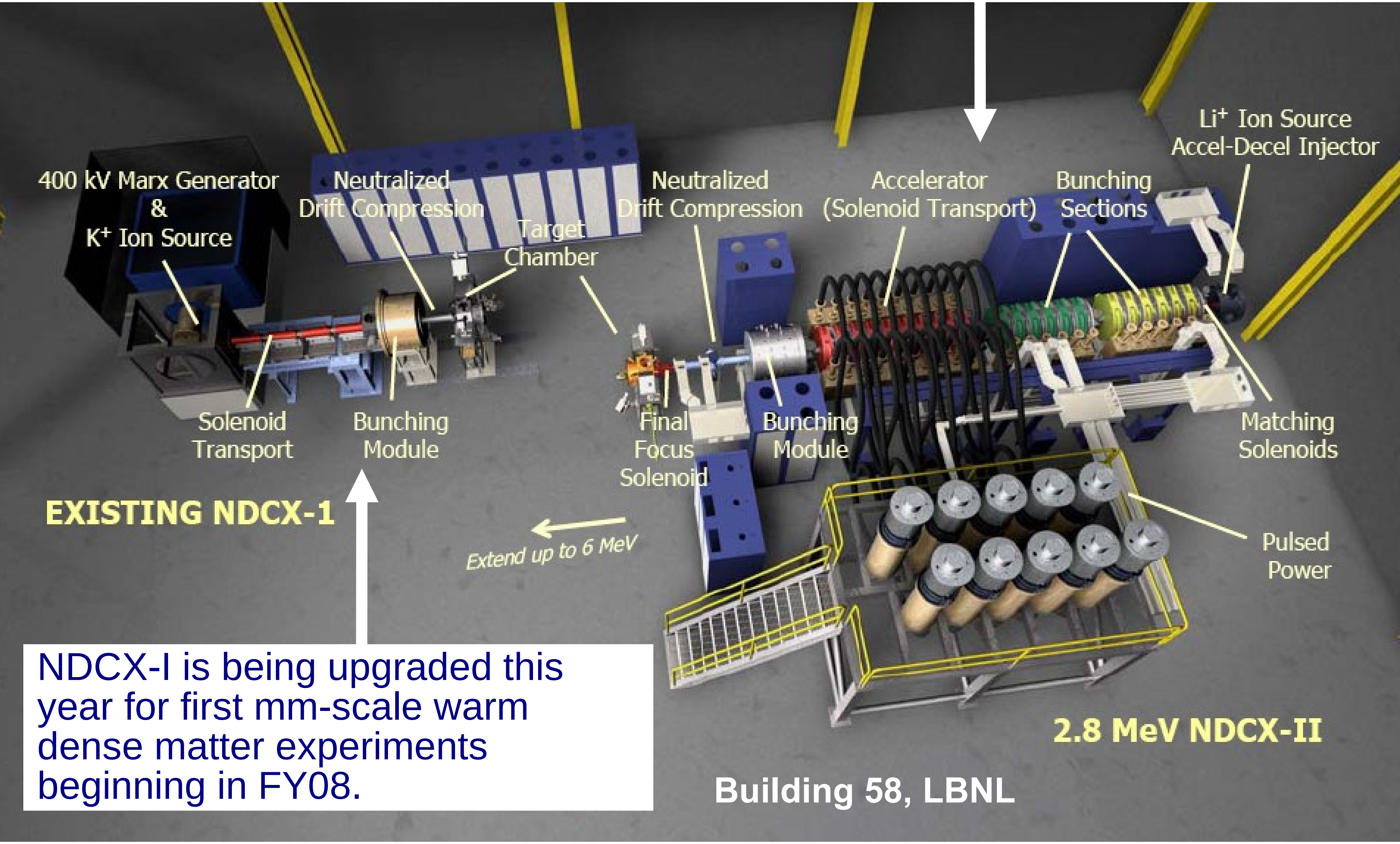
With new bunching module to be installed later this year, plus a higher field 15T focusing magnet in FY09, NDCX-I is predicted to support > 0.5 eV target conditions with 2 ns pulses



Actual achievable intensity on WDM targets in FY09 will range between 0.15 J/cm^2 (with an 8T magnet) and this simulation of best possible case ~ 4 J/cm^2.

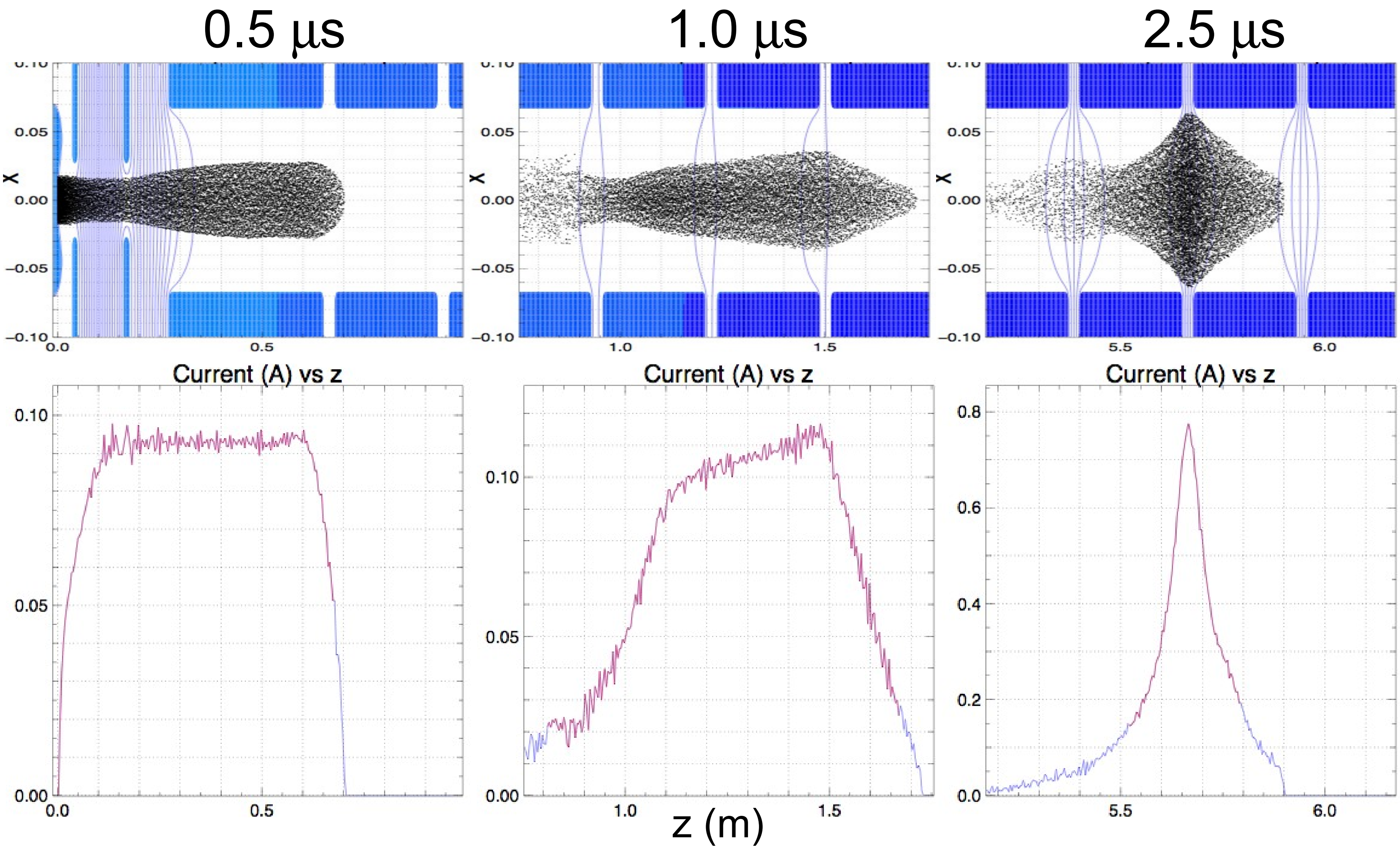
Target temperature ~ 1 eV/ per J/cm^2 for NDCX-I ions, neglecting hydro motion

NDCX-II, using ATA components for more beam intensity and uniform deposition, could be completed by FY10 w/ incremental funding of $1.5 M

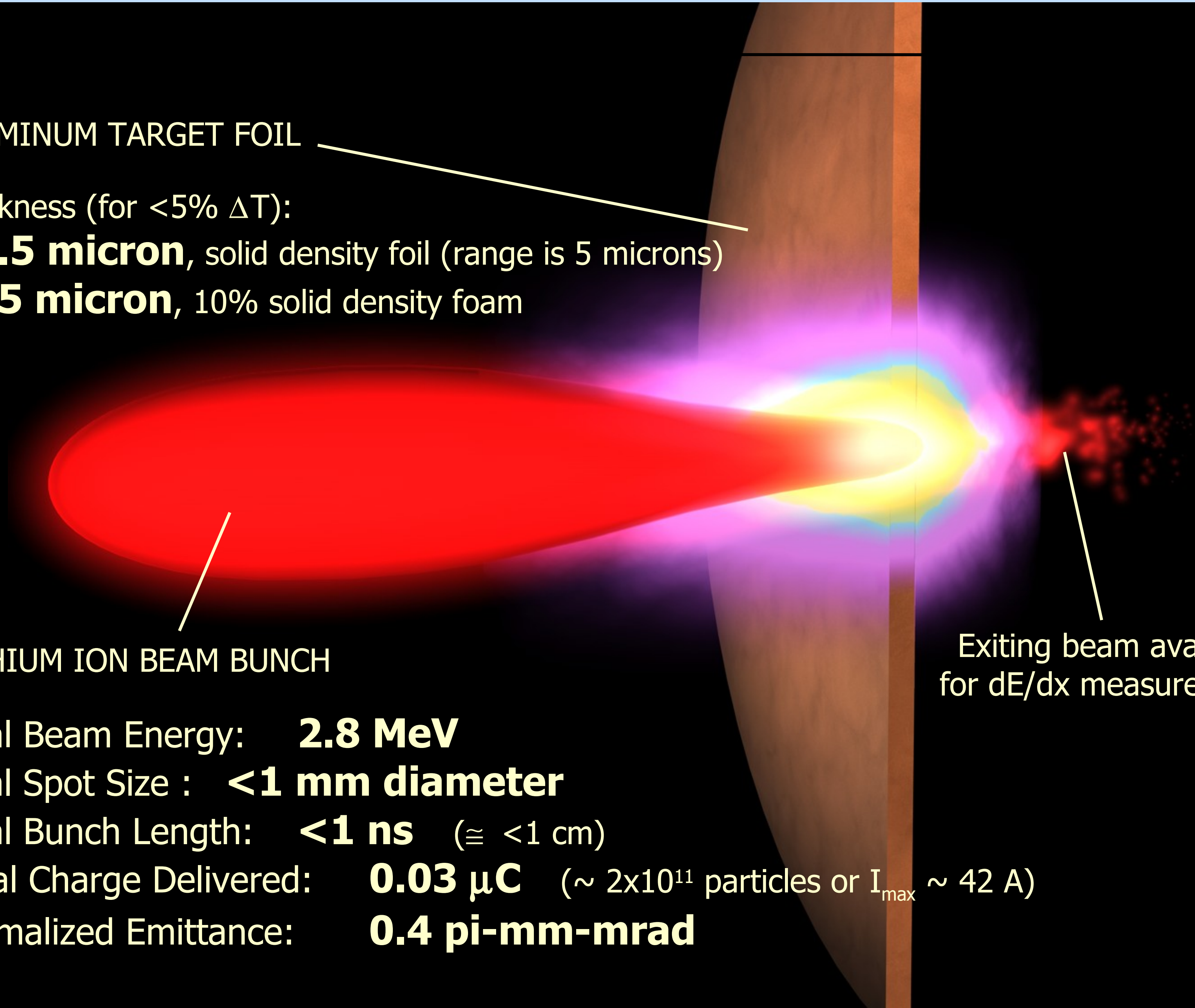


NDCX-I is being upgraded this year for first mm-scale warm dense matter experiments beginning in FY08.

Self-consistent Warp simulations of NDCX-II, from source through "tilt" core, guide the design



NDCX-II target concept, and driver requirements for > 1 eV



Thickness (for <5% ΔT):

~3.5 micron, solid density foil (range is 5 microns)

~35 micron, 10% solid density foam

Final Beam Energy: **2.8 MeV**

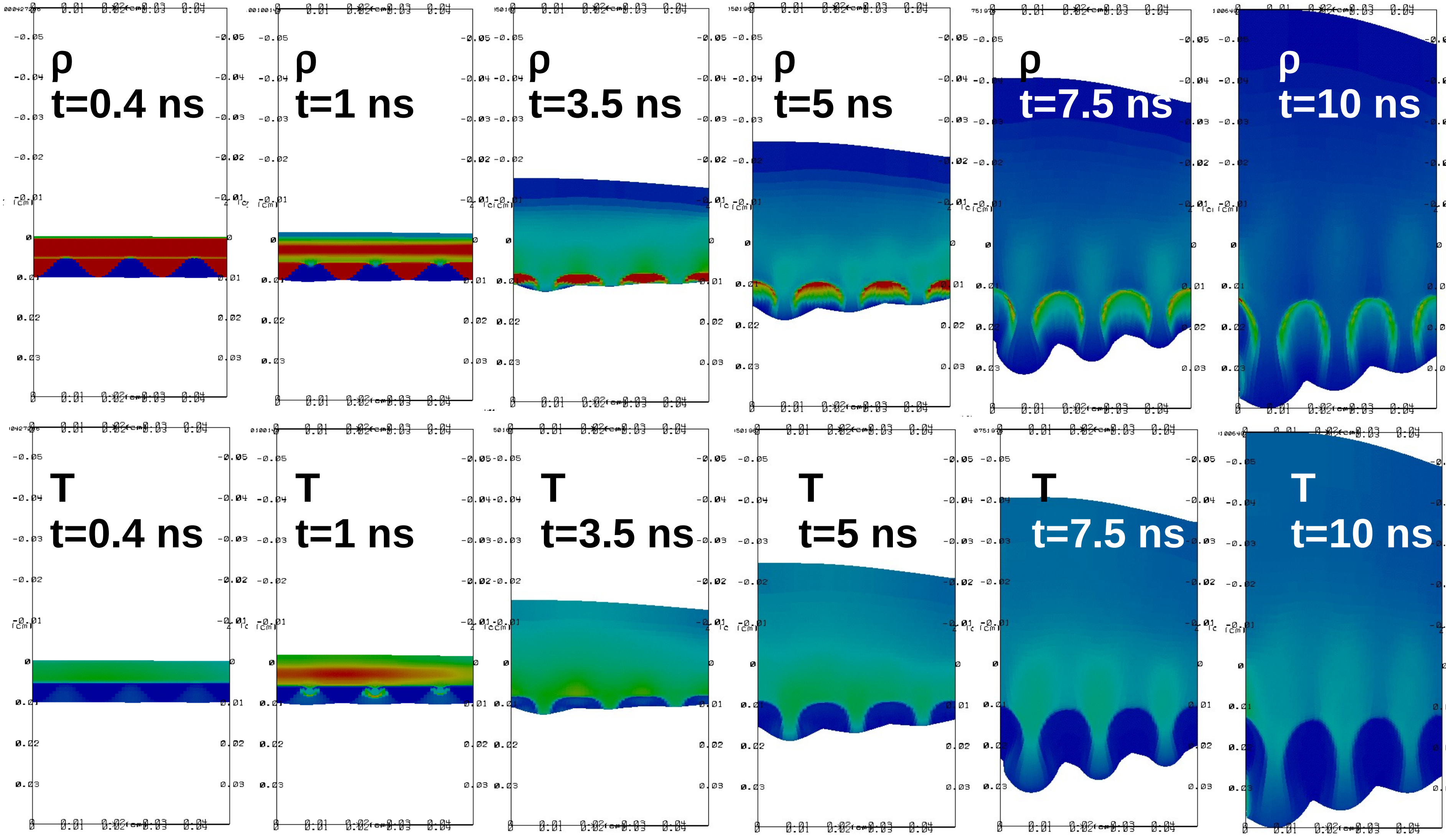
Final Spot Size : **<1 mm diameter**

Final Bunch Length: **<1 ns** ($\cong$ <1 cm)

Total Charge Delivered: **0.03 μC** (~ 2×10^{11} particles or I_{max} ~ 42 A)

Normalized Emittance: **0.4 pi-mm-mrad**

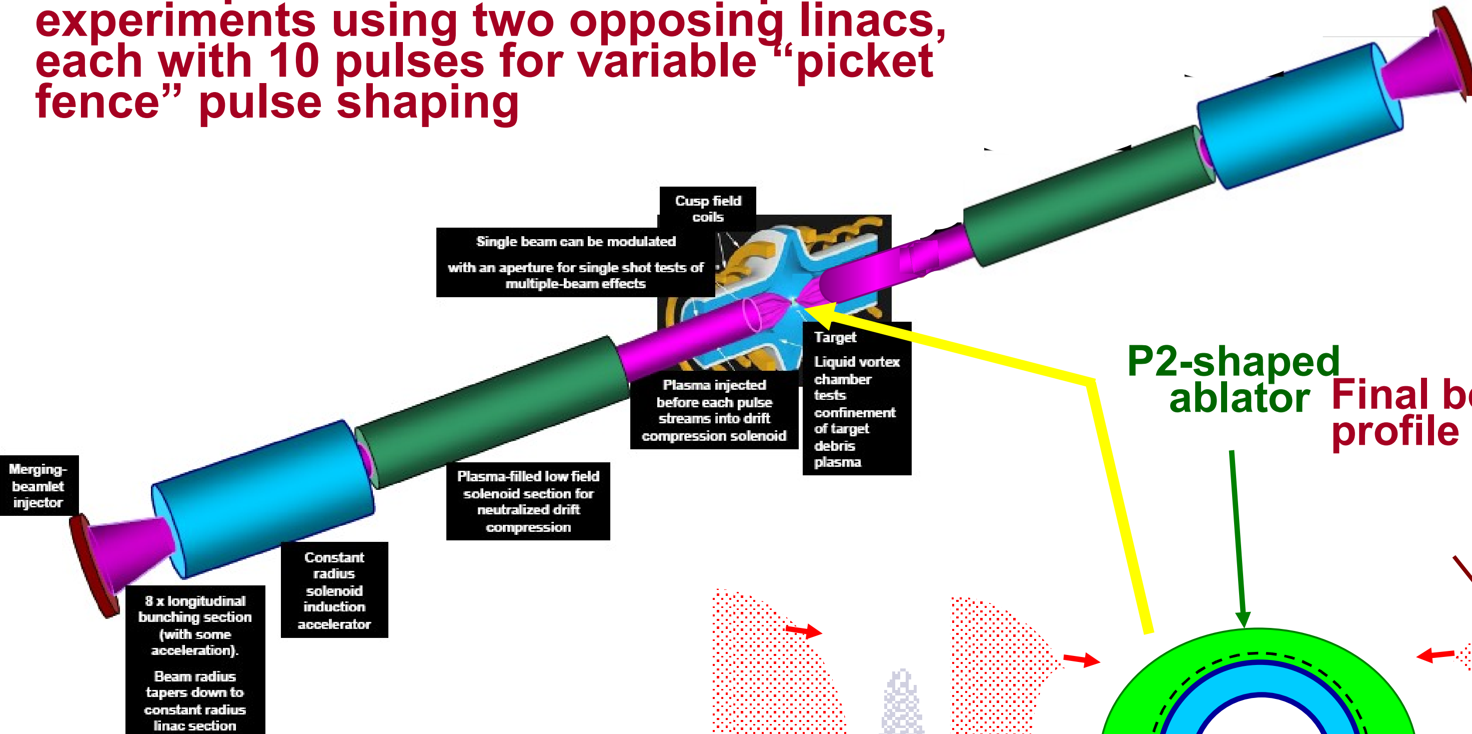
We have used the LLNL HYDRA code to show how unique heavy ion direct drive hydrodynamics as well as WDM can be studied on NDCX-II



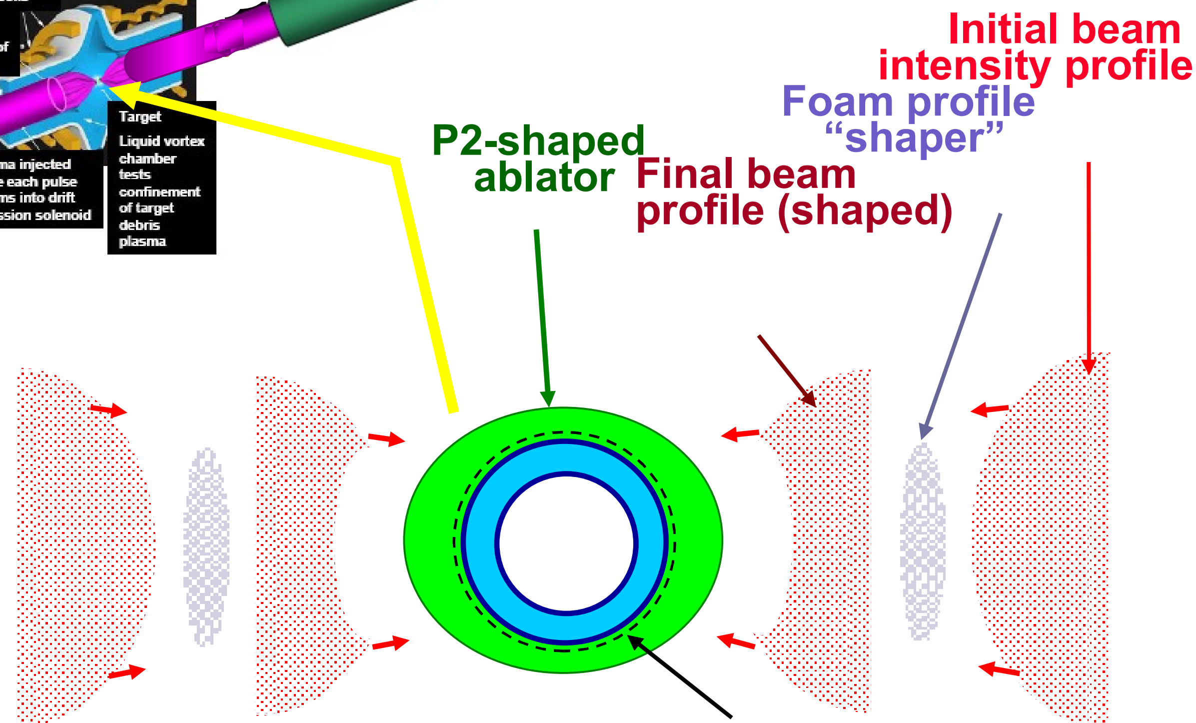
Can modulated beams stabilize ion Rayleigh-Taylor modes?

After NDCX-II (in parallel with NIF operation & IB-HEDPX): a new tool to explore heavy-ion-driven fusion target physics and 100-eV foam HEDP

A concept: 10 kJ direct drive implosion experiments using two opposing linacs, each with 10 pulses for variable "picket fence" pulse shaping

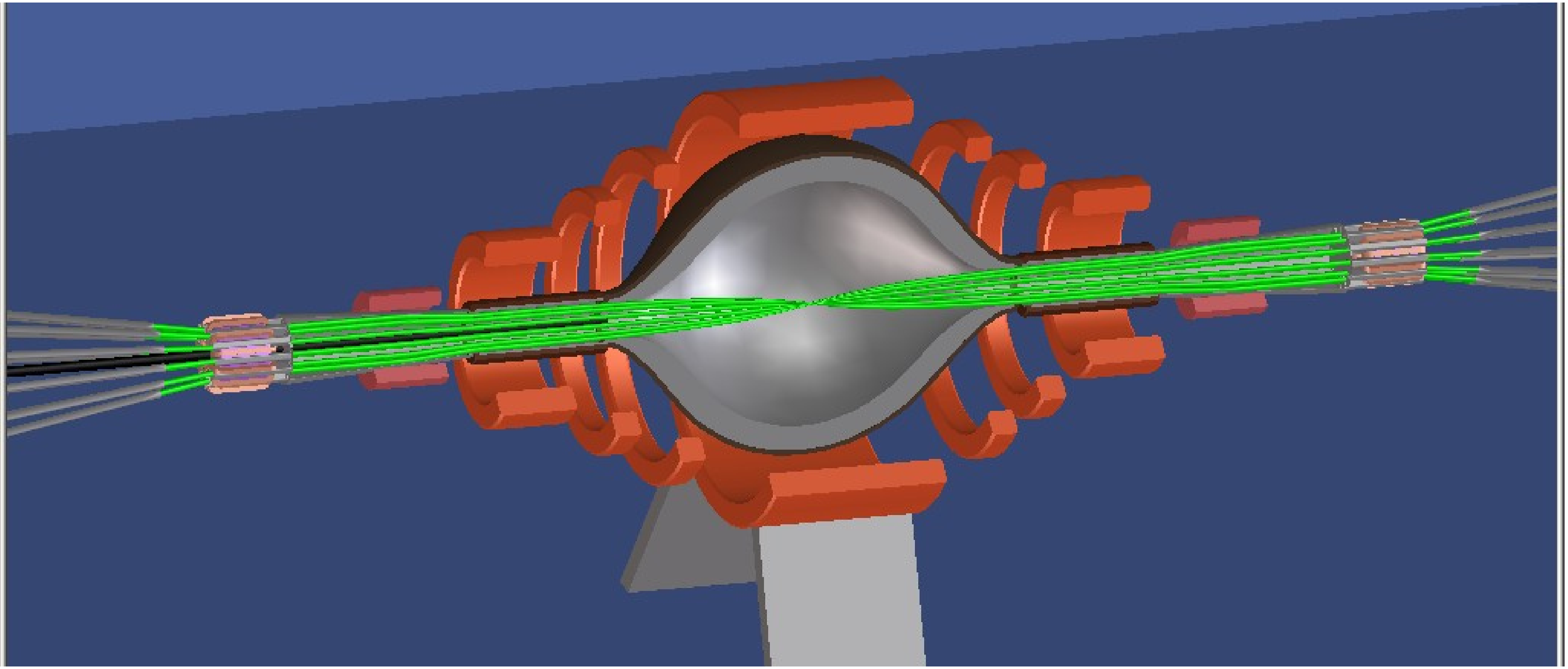


Three "knobs" to control P2 asymmetry with two beams:
1. Upstream GHz wobblers
2. Foam profile shapers
3. Ablator shaping



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

Research on compression & focusing of "velocity chirped" beams suggests improved concepts for heavy ion fusion



Neutralized ballistic, solenoid-focused, plasma-filled liquid Flibe-wall vortex chamber concept (Per Peterson, UC Berkeley)

~ 20 beams/end x 3-5 pulses = 120 to 200 bunches for pulse shaping.
NDC enables 5X higher peak beam power than older concepts.

Concluding thoughts

- NDCX-I is a productive platform for science
  - beam compression and focusing methods
  - diagnostics
  - WDM experiments (beginning next year)
- Theory and simulations closely support our experimental program
- NDCX-II is a key step toward unique WDM studies and heavy-ion IFE
  - ATA parts enable us to build it with a modest $1.5 M investment
  - will be the basis for "IB-HEDPX" WDM user facility, as per CD-0
- NDCX-II + NIF provide basis for a ~ 10 kJ heavy-ion implosion facility
  - architecture close to that of a modular-driver module
  - enables study of direct drive HIF
- This program may lead to an improved vision for HIF
  - direct conversion
  - self-T-breeding targets.