HED in NNSA Facilities

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A presentation to the
High Energy Density Physics Workshop
May 24-26, 2004
Gaithersburg, Maryland

We divided the topic of HED on NNSA Facilities into 4 thrusts:

1. Material Properties

2. Compressible Dynamics

3. Radiative Hydrodynamics

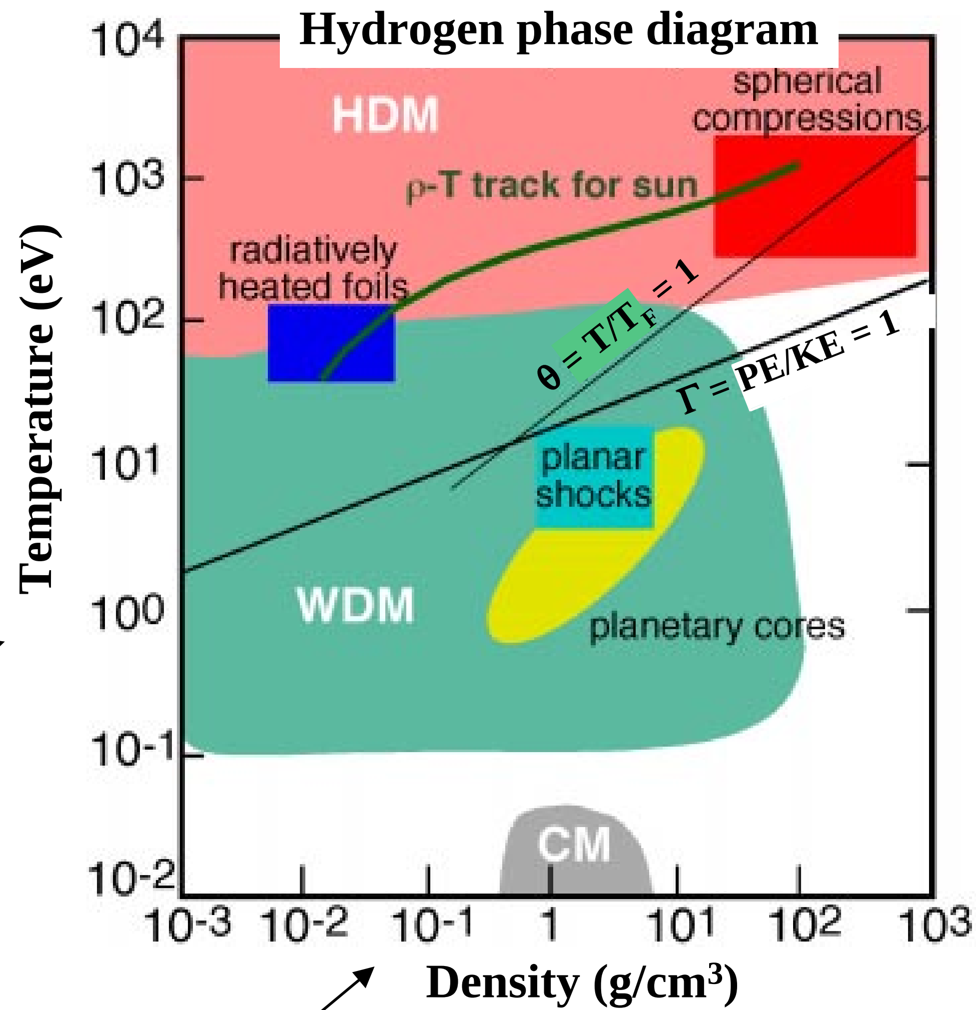
4. Inertial Confinement Fusion

The Material Properties thrust encompasses the study of fundamental properties of matter under extreme states of density and temperature

- **Material Properties describe:**
  - **Equation of State (EOS)**
  - **Radiative opacity**
  - **Conductivity, viscosity, …**
  - **Equilibration time**

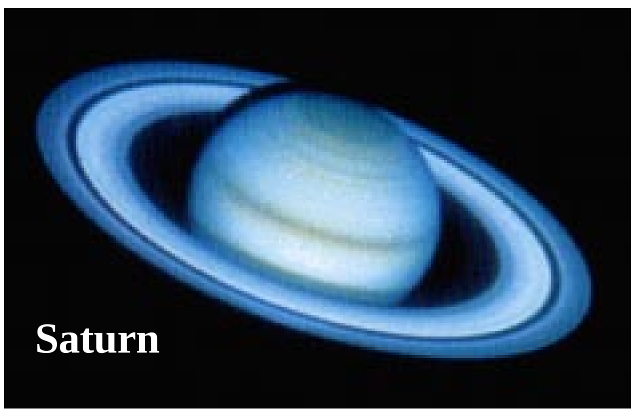
- **Hot Dense Matter (HDM) occurs in:**
  - **Stellar interiors, accretion disks**
  - **Laser plasmas, Z-pinches**
  - **Radiatively heated foams**
  - **ICF capsule implosion cores**

- **Warm Dense Matter (WDM) occurs in:**
  - **Cores of giant planets**
  - **Strongly shocked solids**
  - **Radiatively heated solid foils**

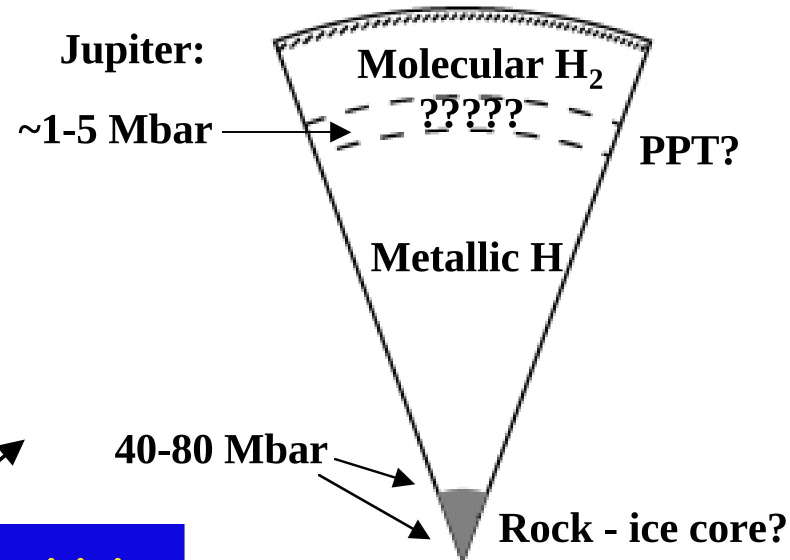


- **Tenuous plasma "easy": Γ = PE/KE << 1; condensed matter (CM) "easy": $\theta = T/T_F$ << 1**
- **Warm dense matter difficult: $\Gamma \sim 1$ and $\theta \sim 1$**

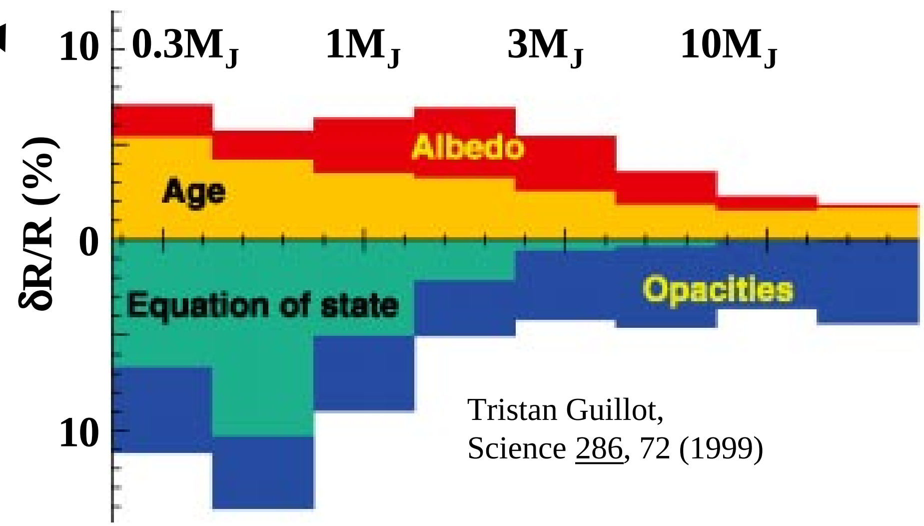
Models of planetary interiors depend sensitively on the properties of matter at extreme pressures, P > 1 Mbar



Fundamental questions remain regarding the EOS of pure elements and mixtures at extreme pressures, P > 1 Mbar



Model sensitivity



Tristan Guillot,
Science 286, 72 (1999)

Compelling question:

Can matter in the difficult warm dense matter (WDM) regime be isolated, defining its state while measuring the material properties of interest?

Principal scientific objective: map the material properties across the WDM regime

1. **Prepare the state (at desired density, temperature, etc.)**
   - **verify that gradients are sufficiently small**
   - **verify that time-dependent effects are unimportant**

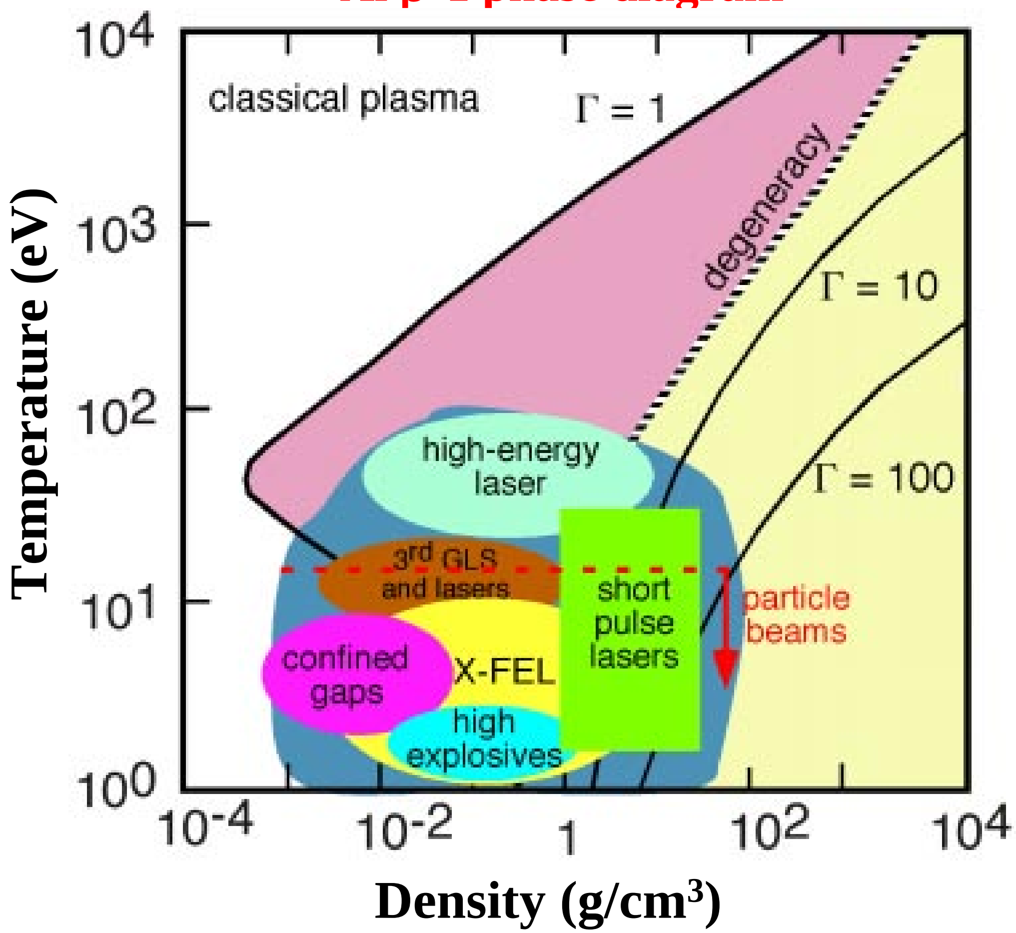
2. **Measure the material property of interest**
   - **opacity, ionization state, EOS, conductivity, etc.**

Additional objective:

- **Determine the material properties at high pressure that will enable models of the interior structures of the planets to be tested and validated**

Experiments over the full range of WDM will require the use of a diverse range of facilities

Al ρ-T phase diagram

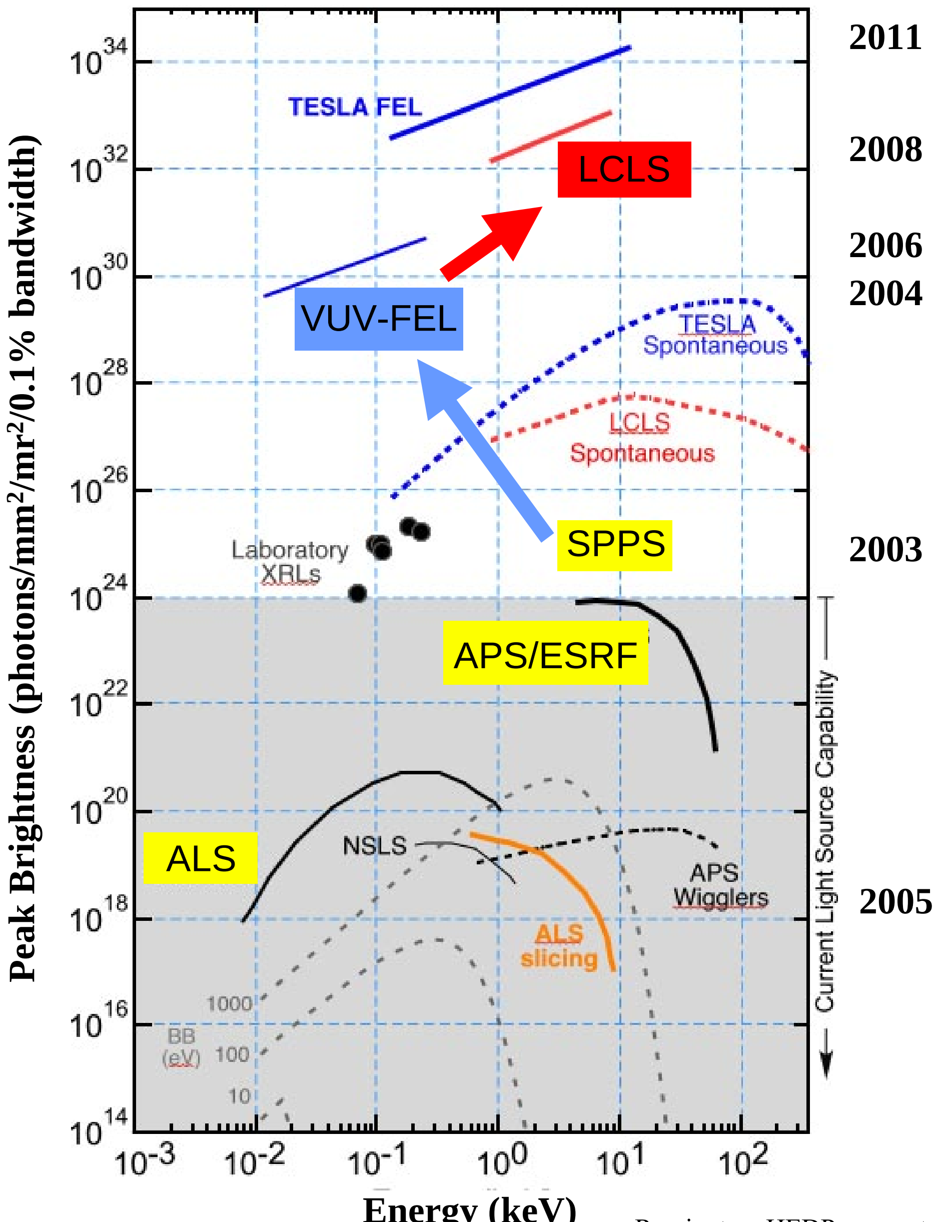


Different facilities to span WDM:

- **High energy lasers:**
  - **Omega, NIF**
- **Short pulse lasers:**
  - **Direct, e^-, proton heating, ...**
- **Particle beams:**
  - **SLAC, RHIC**
- **High explosives**
- **3rd generation light sources coupled to lasers:**
  - **ALS, APS, SPPS**
- **Gap confined plasmas**

Timeline for x-ray light sources

- Currently:
  - –Ongoing experiments on crystal compression, heating to melt, and solid-liquid transitions:
    - ALS (2 ps streak camera)
    - APS (2 ps streak camera)
    - ESRF (10 ps streak camera)
    - SPPS (80 fs x-ray diffraction)
- Next Year:
  - –VUV-FEL initial experiments
- In 2008:
  - –LCLS initial experiment



Timeline for other facilities:

- **Small nanosecond-laser produced WDM - now**
- **Short pulse lasers producing and probing WDM - now**
- **High explosives - now**
- **Particle beams - now**
- **3rd generation x-ray light sources coupled with short pulse lasers - now**
- **3.5th generation short pulse x-ray light sources**
  - **SPPS/SLAC - now; ALS Slicing source - 2005**
- **High energy lasers**
  - **Omega - now; NIF - 2008**
- **4th generation x-ray FEL (LCLS, Tesla FEL) - 2009**

Resource requirements: two examples using large HED facilities

Independent effort:

Developing a major effort (e.g., EOS) "from scratch", through fruition (successful, high accuracy measurements of the desired materials at the desired conditions), at one of the large HED facilities, like the light sources, would require ~10 FTE/yr over 5 years, plus ancillary expenses, ie, ~$3M/yr over 5 yrs.

Collaborative effort:

Smaller efforts on major facilities, much less resource intensive, can be executed if the research interest is aligned with program interests at the facility, and doesn't require new hardware or experimental techniques. This requires collaboration with program scientists at the facility. Cost: ~$300k/yr for 3-5 yrs per project, to cover a postdoc, 1-2 students, professor summer salary, travel and ancillary costs.

Interagency efforts:

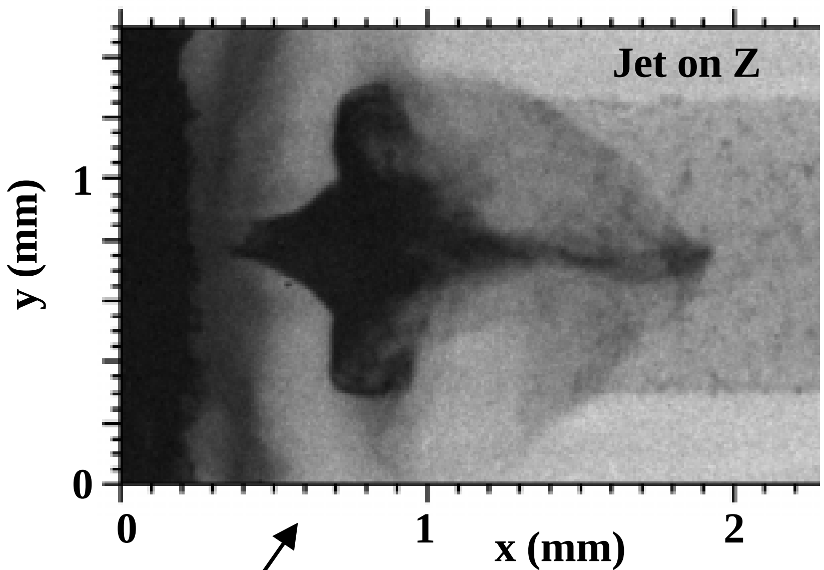
- Using multiple facilities, the key regions of WDM can be accessed

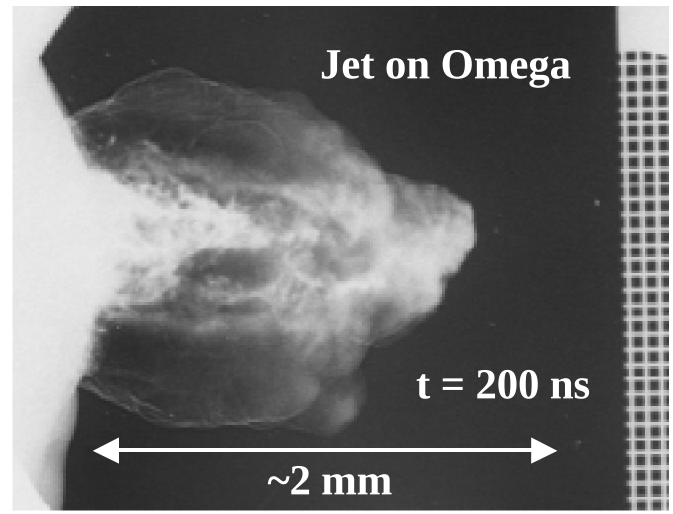
- This will require the cooperative support from multiple agencies

  - DOE/OBES light sources - 3rd and 4th generations - could be used by DOE/NNSA, NSF, and DOD to study the WDM regime

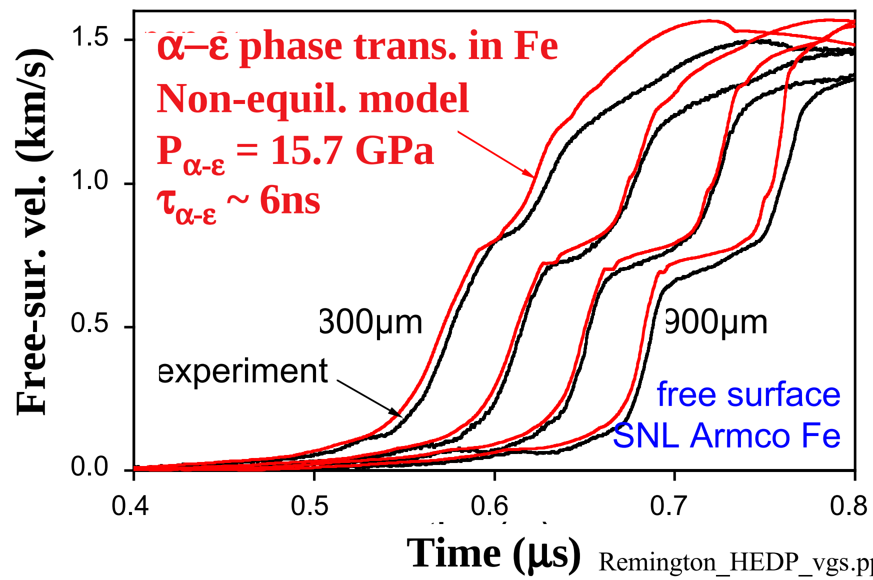
  - DOE/NNSA facilities could be used by NASA, NSF, and DOD to study aspects of HED material properties.

The Compressible Dynamics thrust encompasses high Mach-# flows, strong shock phenomena, and high rate compression effects





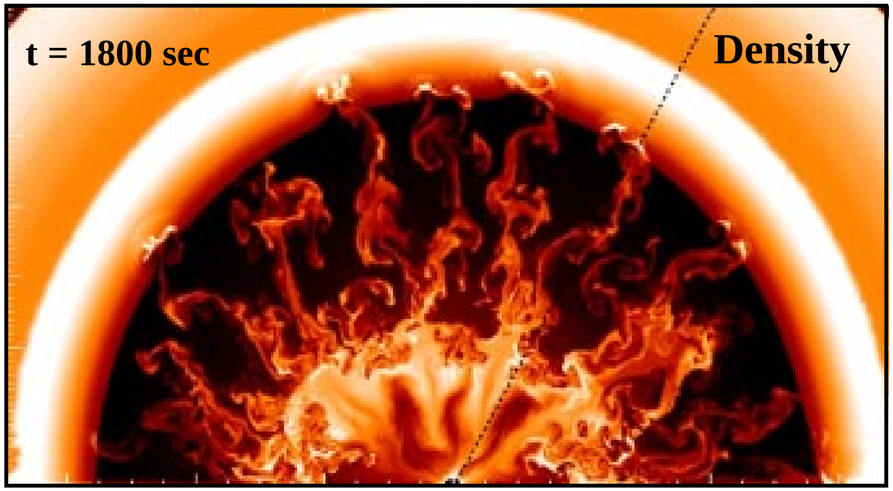
- High Mach-# flows
- Transition to turbulence
- Kinetics of phase transitions



Fund'l questions remain in our understanding of the dynamics of compressible flows

Astrophysics hosts numerous examples of compressible dynamics

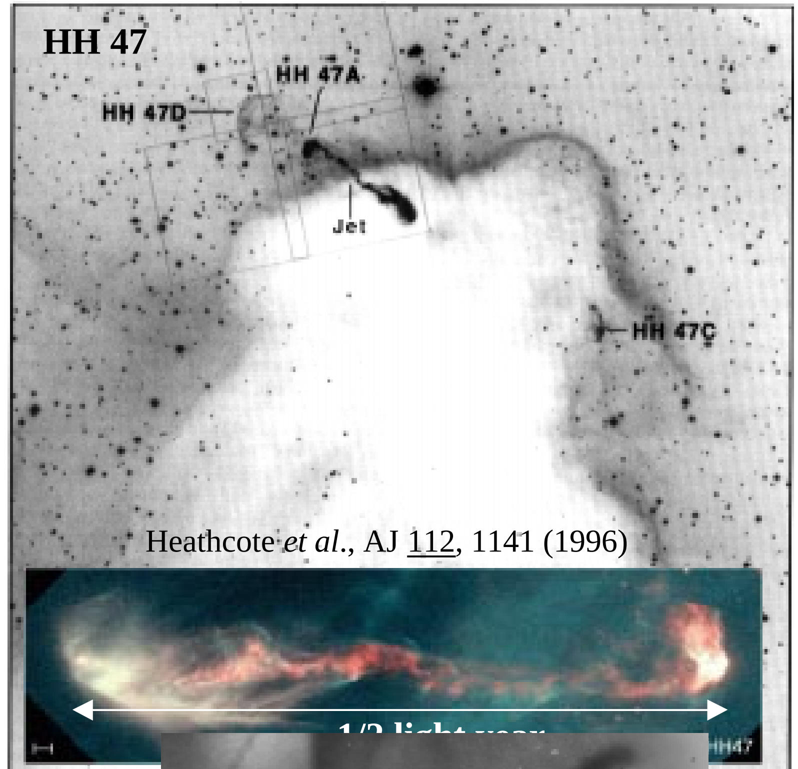
Standard (spherical shock) model for core-collapse supernova explosion



10^{12}cm

Kifonidis *et al.*, Ap. J. 531, L123 (2000)

Protostellar jets (HH objects) are high M# flows through an ambient medium



Heathcote *et al.*, AJ 112, 1141 (1996)

- **Unanswered questions in astrophysics:**
  role of turbulence in SN explosions
  formation and propagation of high M# jets
- **Scaled experiments on HED facilities could help answer these questions**

Compelling questions:

- **Can we understand the evolution of compressible, nonlinear flows into the turbulent regime?**
  - **interaction of strong shocks, high Mach-# jets with ambient media**
  - **homogeneous vs heterogeneous,**
  - **static vs turbulent,**
  - **non-magnetized vs magnetized**

- **Can we understand the kinetics of high-pressure phase transitions and high strain-rate lattice dynamics microscopically and macroscopically?**

Key scientific objectives for 2005-2008:

- **Characterize the evolution of compressible, nonlinear flows into the turbulent regime**
  - **high Mach-# jets: non-magnetized, magnetized**
  - **strong shock induced instabilities**
  - **shock, jet interactions with ambient media: non-magnetized, magnetized; homo-, heterogeneous**

- **Measure the structural changes and kinetics of high-pressure phase transitions in materials**

- **Develop scaled testbeds for astrophysical jet and supernova explosion dynamics studies**

Key scientific objectives for 2009-2014 (ZR, NIF, Omega-EP):

- **Understand the evolution of hydrodynamic and magnetized jets into the turbulent regime, including the interactions of high Mach number jets and shocks with heterogeneous media**

- **Understand the structural changes and kinetics of high-pressure phase transitions in materials**

- **Answer fundamental questions relating to the propagation of protostellar and intergalactic jets, using scaled experiments and simulations, such as:**
  - **why, how do they stay so well colimated**
  - **are they, do they need to be magnetized**
  - **where do the currents flow**

- **Test and validate models of supernova explosion dynamics, using scaled experiments and simulations**

Research tools and facility requirements:

- **A hierarchy of facilities will be needed**
  - **Many and sustained experiments are needed to make real progress scientifically**
  - **Large facilities will have limited time for outside science use**

- **Smaller facilities can answer subsets of questions, and develop techniques and diagnostics**
  - **maintaining and enhancing their capabilities is absolutely essential for HED science to prosper**

- **Use the big facilities only when there is a need for and readiness for the high-end performance**
  - **high pressure EOS, phase, and dynamics**
  - **high M# shocks or flows over long distances, turbulence**

- **Critical to have scientific partners within the labs at the big facilities**

- **Basic science target needs could be unique; needs to be supported**

- **Advanced diagnostics need to be developed to maximize the science return**
  - **micron resolution x-ray imaging over mm-length flows**
  - **current distribution in compressed z-pinches and magnetized jets**

- **Combined facility capabilities, lasers + (pulsed power, synchrotrons, FELs) could be the next frontier**

Timeline and resource requirements (2004-2008):

Support for basic-HED-science use and development of the following facilities:

Lasers:

Omega (15% of shots)
Enhanced science-use capability for Janus/JanUSP, Trident, Z-Beamlet laser facilities
The Texas SSAA Center for High Intensity Laser Science
The NNSA suite of ultra-short pulse and planned high energy PW lasers

Z-Pinches and ICE:

Saturn (15% of shots)
Zebra
The 1-MA plus drivers at Cornell and Imperial College
Longer pulse ICE drivers planned at Sandia and WSU

Gas guns:

Gas guns at WSU

- **The target costs for using the large facilities (Omega, Saturn, etc.) need to be budgeted for:**
  Omega: (10 NLUF grants/yr)(20 shots/grant)($5k/target) = $1M/yr NLUF targets
  Saturn, if it were used at the same level would have similar target costs

Timeline and resource requirements (2009-2014):

Support for basic-HED-science use of the following facilities:

NIF, ZR, and Omega-EP (15% of shots)
- cost would be ~20 M$/yr (facility + target cost)

Continuing program on the smaller facilities

Shot allocation based on merit and facility match
- will require a facilities-coordinated selection process

Each user facility needs a basic-science user support program that supports the experiments, diagnostics, target fabrication, and staff

The NNSA SSAA program should continue to provide a funding framework for the universities,

The other agencies (NSF, Office of Basic Science, NASA) should start supporting parallel HED programs, aligned with their overall science and technology interests

Opportunities for interagency cooperation:

A new-blood program to encourage new HED researchers – in particular, fluid dynamicists, condensed-matter scientists, and astrophysicsts, into studying HED compressible dynamics problems. Opportunities here for cooperative NNSA, OBES, NSF, NASA support.

- $50 K seed-money grants to design, develop ideas for experiments on the NNSA facilities

Develop cooperative funding where NNSA funds experiments on NNSA facilities in conjunction with NSF, OBES, OFES, and NASA funding the participating academic groups

- this is currently missing, impeding the growth of the HED field

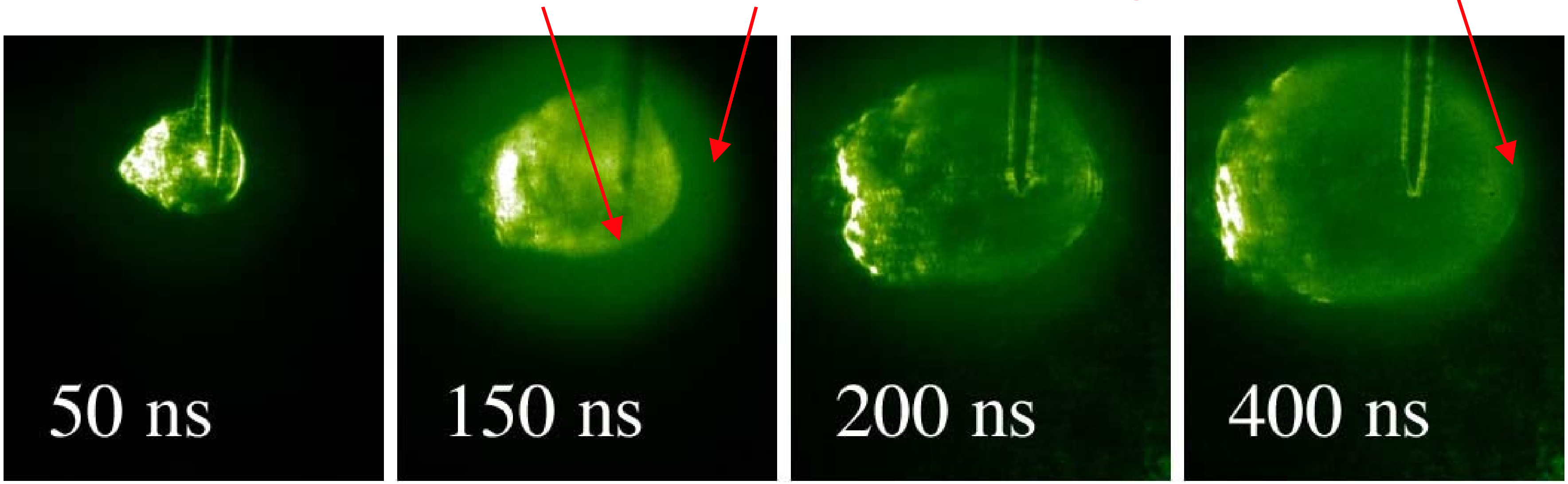
NNSA and OFES should collaborate, maybe with NASA, to much more aggressively pursue the broad and new science opportunities offered by petawatt-class ultraintense lasers on the big NNSA facilities. This clearly is a new frontier, and being pursued vigorously by Europe and Japan.

NNSA and the OBES could collaborate on bringing small-scale HED platforms to synchrotrons and X-FELs

Once US collaborative programs have been established, the US community could look for similar programs with other countries with established HED interests, e.g. UK, France, Russia, Japan, Germany

The Radiative Hydrodynamics thrust focuses on “hot flowing matter”, where the radiation and material flows are coupled

Radiative shock on Janus laser:



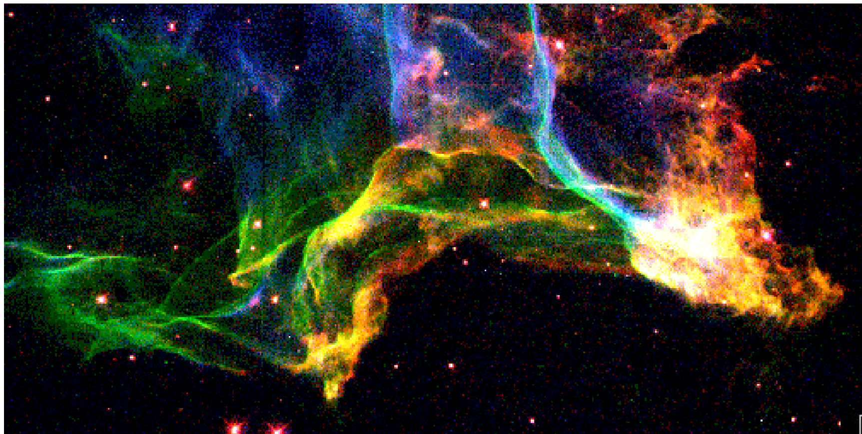
J.F.Hansen, submitted, Phys. Rev. Lett. (2004)

- **Radiative shocks & jets, supersonic radiation flow, photoionized plasmas, and radiation-dominated dynamics are examples of radiative hydrodynamics**

- **Quantitative modeling of such flows is difficult; benchmark data is needed**

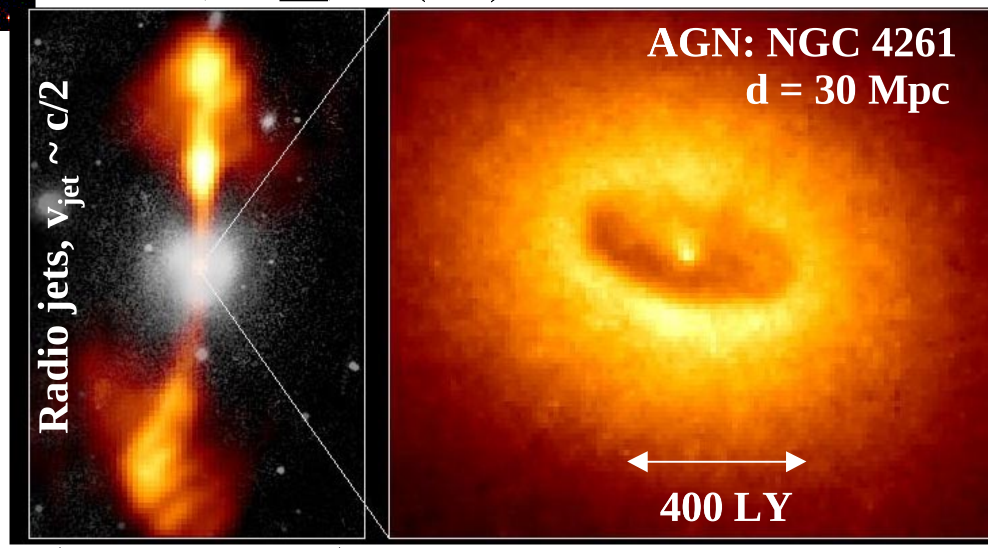
Radiative hydrodynamics abound in energetic astrophysics

Radiative shocks in the Cygnus loop SNR



Radiation dominated flows in an accreting massive black hole

Piner *et al*., A.J. 122, 2954 (2001)



88,000 LY

Ferrarese *et al*., Ap. J. 470, 444 (1996)

- **Additional examples of rad-hydro in astrophysics:**

  - Radiatively cooled jets

  - Radiatively driven molecular clouds

- **Our understanding of these phenomena would improve significantly if we could develop scaled rad-hydro experimental testbeds to validate modeling**

Compelling question:

Can HED experimental facilities become a routine tool for testing rad-hydro models and simulations of powerful astronomical phenomena in a scaled laboratory setting?

Key scientific objectives:

Develop radiative-hydrodynamic experimental testbeds for:

- **Radiation-dominated hydrodynamics**
  - **low densities: photoionized plasmas**
  - **high densities: radiation pressure dominates**

- **Radiation Flow and Material Opacities**
  - **supersonic radiation flow**
  - **expansion opacities**

- **Radiative Shocks**
  - **Vishniac instabilities**
  - **radiative collapse**

- **Photoevaporation Front Hydrodynamics**
  - **directional hydrodynamic instabilities**

- **Establish the scaling criteria to correlate with their astrophysical counterparts**

Research tools and facility requirements:

- **The large facilities:**
  - **Omega**
  - **NIF**
  - **Z/ZR**
  - **Saturn**

- **Smaller supporting facilities:**
  - **Janus laser**
  - **Trident laser**
  - **Nike laser**
  - **Z-beamlet**
  - **Short pulse, high intensity lasers**
  - **Magpie**
  - **Zebra**

Timeline and resource requirements:

Phenomenon	Temperature	Density	Facility	Timeline
Photoionized plasmas	20 – few x 100 eV	10^{-3}-10^{-5} g/cm^3	ZR, NIF	Present - 2014
Radiation dominated dynamics	~200 eV – ~2000 eV	1-100 g/cm^3	NIF, Z/ZR, Omega + petawatts, other ultrahigh intensity lasers	2009-2014
Expansion opacities	20 – few x 100 eV	10^{-3}-10^{-5} g/cm^3	ZR, NIF	2009-2014
Radiative shocks	~100 eV	~0.1 g/cm^3	Omega, Z, Nike, smaller HED facilities	Present - 2008
Photoevaporation front dynamics	50-100 eV	~0.2 g/cm^3	Omega, Z	Present - 2008

- **Assume 1 university group/key objective above: (5 groups)($300k/group) = $1.5M/yr**

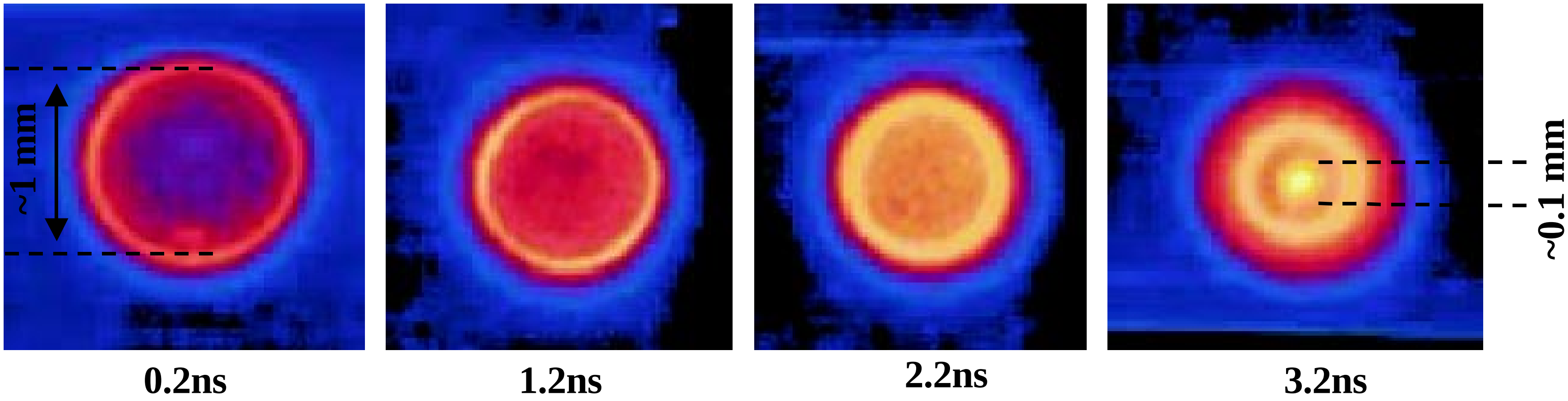
Opportunities for interagency cooperation:

- DOE/NNSA should fund the design, execution of experiments on the NNSA facilities.
- NASA should fund simulations using astrophysical models and codes, and future observations linking the HED experiments to the astrophysical phenomena.
- NSF and DOE/OFES should participate in areas where fundamental theory is required, eg, generation of ultrastrong magnetic fields on ultraintense lasers

The Inertial Confinement Fusion (ICF) thrust is focused on achieving thermonuclear ignition within the decade

- The achievement of ICF ignition and gain is a a grand challenge goal of NNSA
- Ignition experiments will commence on the NIF laser at LLNL in ~2010.
- Supporting experiments and physics development are carried out on OMEGA (UR-LLE), Z/ZR (SNL), and smaller facilities.

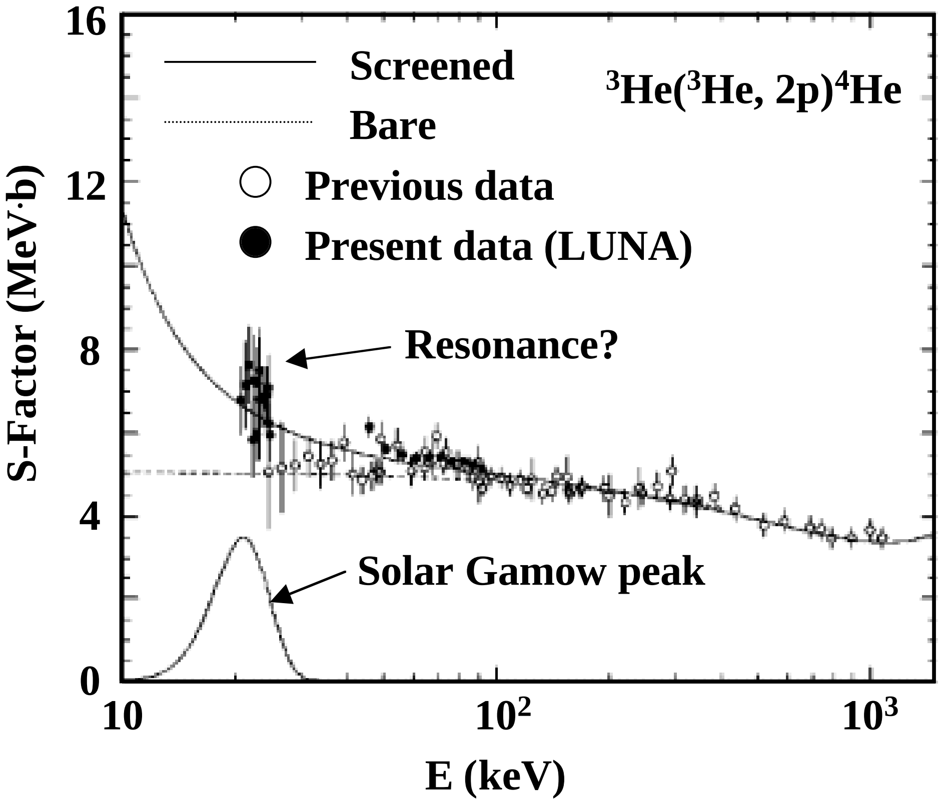
ICF capsule implosion on Omega



- ICF research involves a multitude of coupled phenomena, all occurring in a few ~ns
  - -Laser coupling, laser-plasma instabilities, hydrodynamic instabilities,
  - -radiation transport, electron heat transport, fusion reactions

The achievement of ignition will provide unique research opportunities in astrophysics, SSP physics, and inertial fusion energy studies

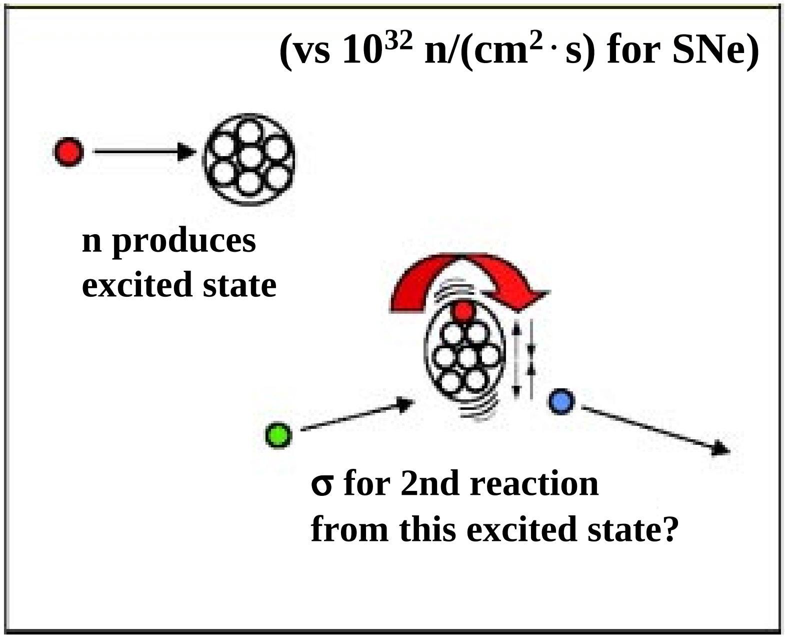
Screened reactions in dense plasma



M. Junker et al., PRC 57, 2700 (1998)

- **Strongly screened reactions are relevant to stellar evolution**

Multi-hit reactions from 10^{33} n/(cm$^2\cdot$s) flux



- **First hit gives excited nuclear state**
- **Reactions from excited states, relevant to r-process nucleosynthesis of heavy elements**
- **Second hit reaction cross section uncertain**

S. Libby, IFSA proceedings (2004)

Compelling questions:

• **Can inertial confinement fusion ignition be achieved in the laboratory?**
  - **can high gain be achieved?**
  - **can ICF be developed as an economic energy source?**

• **Will the "fast ignition" concept for inertial confinement fusion lead to higher target gains for the same driver energy?**

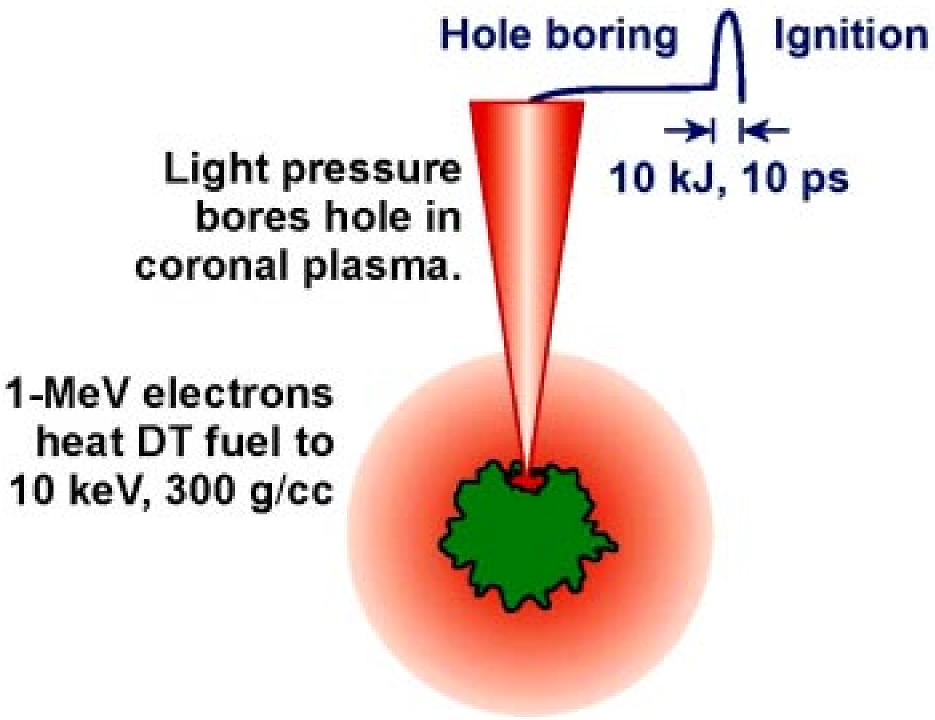
The most important milestone in ICF is demonstrating ignition and gain in the laboratory this decade

- **Achieving ICF ignition is a major programmatic goal of NNSA.**
- **Fusion burning occurs in stars and has been demonstrated in thermonuclear weapons.**
- **Ignition is a very complicated problem, bringing together many areas of HED physics.**
- **The physics basis for ignition is being tested and refined by a national program including LLNL, LANL, SNL, UR-LLE, NRL, with target fabrication at GA.**
- **The OMEGA laser (UR-LLE) and the Z facility (SNL) are the current experimental workhorses.**
- **The National Ignition Facility (NIF) will be completed in 2008**

ICF ignition experiments will begin on the NIF in ~2010

Fast Ignition offers the potential to increase ICF target gains and reduce driver energy requirements

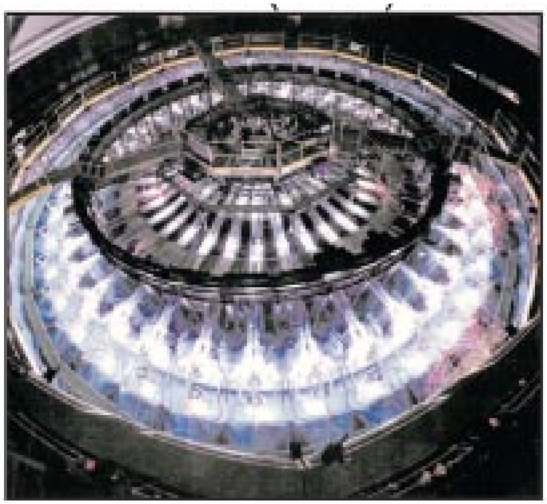
- In 1994 Tabak et al. proposed the Fast Ignition concept.
- In Fast Ignition, the compression and heating processes are separated.
- Preliminary experiments, including integrated ones at ILE, continue to increase confidence in this concept.
- All three of the large NNSA HED facilities are planning to add high energy petawatt capability.
- These combined facilities will address the fundamental question:



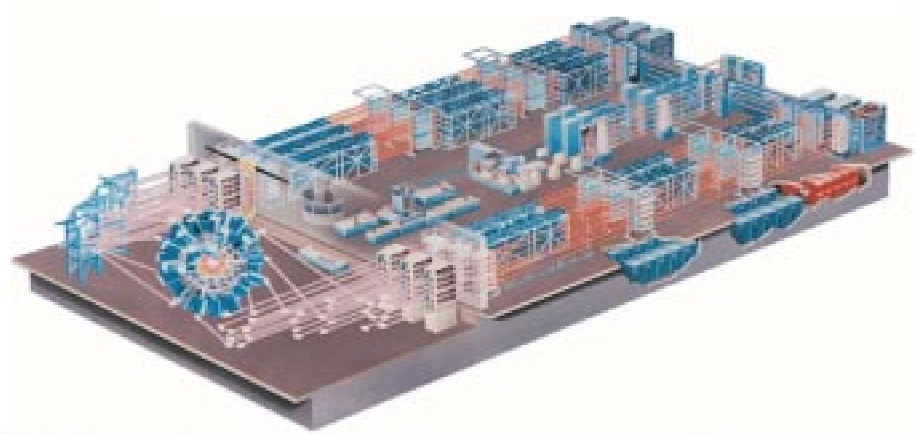
Will the Fast Ignition concept lead to higher target gains for the same driver energy?

NNSA's current and future HED facilities are the core of its inertial confinement fusion ignition program

20 MA SNLA Z-Facility



30-kJ OMEGA laser (UR-LLE)



2-MJ National Ignition Facility (NIF) under construction at LLNL

Many opportunities for interagency collaboration exist to take advantage of ICF ignition

- **For the scientific community to fully take advantage of ICF ignition appropriate resources must be provided to**
  - **develop and carry out preparatory experiments on OMEGA, Z/ZR and smaller facilities including:**
    - **Student and PI support, travel, etc.,**
    - **Availability of necessary numerical and target fab. capabilities,**
    - **Availability of facility time.**
- **NNSA's current mission is to achieve ignition; many of the uses are not included in their program**
- **Interagency collaboration could significantly increase the scientific productivity associated with ignition:**
  - **OFES, NNSA: energy production and fast ignition,**
  - **NNSA, NSF, OFES, NASA: uses of ignition for a variety of scientific problems, especially relating to astrophysics**