NIF and Indirect Drive Inertial Fusion Target Physics and Applications to High Energy Density Physics

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Presented to:
FESAC Panel on the Status of IFE and HED

October 28-29, 2003

*Work performed under the auspices of the US Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-ENG-48
NIF Early Light (NEL) is meeting its performance goals and experiments have begun with the first 4 beams

The ICF Program is making excellent progress on the baseline indirect drive ignition approach

Alternate indirect drive ignition target designs could allow much higher yields and target gains

The NIF indirect drive ignition program will provide the ignition data required for a range of drivers including HIF and Z-pinches

NIF is designed to test Direct Drive as well as Indirect Drive

The science of ICF targets is applicable to a wide range of astrophysical phenomena
NIF will test much of the physics for a wide range of targets being examined for IFE.
The National Ignition Facility gives the U.S. a unique opportunity for demonstrating critical elements of ICF target physics required for IFE.

- Demonstrate ignition and gain for both direct and indirect-drive and possibly for fast ignition
- Provide key data on target chamber and target fabrication technologies
- Confirm predictive target modeling capabilities
Both indirect drive and direct drive illumination geometries can be accommodated by the NIF design.

Irradiation configurations

(Advanced technology for compact chirped pulse amplification (CPA) being pursued to allow fast ignition on NIF)
NIF Target Chamber upper hemisphere
First four NIF beams installed on the target chamber

Quad 31b beamtubes and optics are installed and operational

View from inside the target chamber
Target positioner and alignment system inside target chamber
NIF has begun to commission its experimental systems

- The NIF Early Light (NEL) commissioning of four laser beams has demonstrated all of NIF’s primary performance criteria on a per beam basis
  - 21 kJ of $1\omega$ light (Full NIF Equivalent = 4.0 MJoule)
  - 11 kJ of $2\omega$ light (Full NIF Equivalent - 2.2 MJoule) - used baseline $3\omega$ crystals not optimized for $2\omega$
  - 10.4 kJ of $2\omega$ light (Full NIF Equivalent = 2.0 MJoule)
  - 25 ns shaped pulse
  - $< 5$ hour shot cycle (UK funded)
  - Better the 6% beam contrast
  - Better than 2% energy balance
  - Beam relative timing to 6 ps

- Initial Experiments on Laser Plasma Interaction are being carried out
NIF will map out ignition and gain curves for multiple target concepts

— Fast ignition potentially gives more gain and lower threshold energy but the science and technology is less well developed.
The US Indirect Drive ICF Program is based on an extensive data base developed on the Nova and Omega Lasers

- **Laser-Target Coupling**: U.V. lasers with smoothing gives excellent target coupling on Nova and Omega experiments - comprehensive predictive modeling has not been achieved

- **Symmetry**: X-ray Drive experiments (Nova and Omega) show adequate symmetry $P_n(t)$ and $\int P_n(t)dt$

- **Hydrodynamic Instabilities**: Quantitative Rayleigh-Taylor experiments show adequate reduction in $\gamma$ because of flow and $\nabla \rho$ effects

- **Integral Implosions**: Implosions on the Omega laser, using a NIF-like Illumination geometry, perform at near calculated levels for convergences greater than 20

- **Numerical Modeling**: Hohlraum (symmetry and energetics) and hydrodynamic instability experiments, as well as integral implosion experiments are well-modeled by 2D and 3D radiation-hydro codes
The NIF baseline indirect-drive target absorbs 1.35 MJ and produces a yield of 15 MJ, in detailed calculations.
Development of cryogenic targets are a central challenge for ignition on NIF

- Sufficiently smooth Deuterium-Tritium fuel layers have been formed
- We have fabricated three types of capsules
- Surface finishes meeting requirements have been achieved (for CH and PI and for graded dopant Be)
- Development of cryogenic hohlraums is underway
- Scientific prototyping of the cryogenic systems has started
We are doing 3D simulations of both hohlraums and capsules

3D hohlraum simulation with all of the beams, in NIF indirect drive configuration

HYDRA now has all the physics necessary to do 3D non-LTE integrated hohlraum simulations, as well as 3D capsule implosions
We now have a hohlraum design optimized in 3D with very nice 3D symmetry

Several design modifications resulted from 3D calculations:

• Increased LEH thickness
• Decreased gas fill density
• Adjusted power balance between cones
• Repointed inner cone beams to reduce m=4
• Moved outer cone to reduce P₄

Resulting implosion has rms deformation of hot spot at bang time 3 µm, factor of two safety margin
Polyimide Capsule 3D calculations have both asymmetry and surface roughness

Capsule-only simulations w/ asymmetry and fabrication perturbations

A few of these have been done, including a recent simulation with:

• 3D asymmetry inferred from integrated simulation
• Nominal “at spec” perturbations on ice and ablator in low, intermediate, and high modes
• Gave 21 MJ (90% of 1D calculation)

140 ps before ignition time
60 g/cc density isosurface

Ignition time
400 g/cc density isosurface (different scale)

Poly/DT interface
Hohlraum axis
Stagnation shock
New capsule designs using Be with graded Cu dopant are spectacularly robust.

Be next to fuel is undoped, dopant rises to max in two steps and back down again.

300 eV design:

- Be
- DT
- Cu(%) 0.0%, 0.35%, 0.7%, 0.35%, 0.0%
- Yield (MJ)
- Initial ablator roughness (rms, nm)

300 eV graded-doped Be(Cu) design, at same scale.

Polyimide capsule
Surface achieved with PI
Typical energy flow in an igniting ICF hohlraum/capsule
A combination of many small effects may allow a doubling of the hohlraum coupling efficiency. Improvements possible for a 250 eV capsule design.
NIF’s green light capability may allow much larger capsules and yields

- More energy allows larger capsules which require lower radiation temperatures

- Lower temperatures imply lower laser intensities consistent with LPI constraints based on current understanding and initial Omega experiments
The indirect drive Ignition Plan makes use of existing facilities, and early NIF, to optimize the ignition design.
The physics issues for ion beam target design for IFE and NIF targets have much in common

- Capsule physics (hydrodynamics, ignition, and burn propagation)
- Symmetry control
- Hohlraum energetics

Yield = 400 MJ
Driver (using NIF-like hohlraum to capsule radius ratio)
- 6 MJ of 4 GeV Pb ions  gain 67
- 7.5 MJ of 8 GeV Pb ions  gain 53

NIF target

HIF Target

Yield = 400 MJ
Driver (using NIF-like hohlraum to capsule radius ratio)
- 6 MJ of 4 GeV Pb ions  gain 67
- 7.5 MJ of 8 GeV Pb ions  gain 53
New symmetry control techniques allow target designs with larger spots for distributed radiator targets for heavy ion fusion.

**Hybrid target**
- Shine shields to control Legendre mode $P_2$
- Shim to control early time $P_4$

**Distributed radiator target**
- Pressure balance holds position of radiators

- Beam spot: 3.8 mm x 5.4 mm
- Effective radius: 4.5 mm
- 6.7 MJ beam energy
- Gain = 58

- Beam spot: 1.8 mm x 4.1 mm
- Effective radius: 2.7 mm
- 5.9 MJ beam energy
- Gain = 68

These symmetry control techniques can be tested on Z or Omega and ultimately on NIF.
Thin-shell capsules in double z-pinch hohlraums provide null cases for P4 shimming tests

Time-integrated P4 depends more strongly on capsule size than on hohlraum length
Predicted P2 = 0, P4 = -5% at L_{sec} / R_{sec} = 1.75 to be tested in September shot series
Calculations of the proposed Z experiment show that a shim can take out the P₄ asymmetry.
Calculations of the HIF Hybrid Target with a shim layer show the improvement in symmetry.

Shape of the imploded shell near ignition time.
A wide range of capsules for Fusion Energy applications have stability and symmetry requirements comparable to NIF targets.

- Enhanced NIF capsules may reach this scale.

<table>
<thead>
<tr>
<th>Scale</th>
<th>NIF</th>
<th>ETF</th>
<th>Reactor (6Hz)</th>
<th>Reactor (3Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak $T_R$</td>
<td>300</td>
<td>246</td>
<td>223</td>
<td>203</td>
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<tr>
<td>IFAR</td>
<td>45</td>
<td>46</td>
<td>42</td>
<td>35</td>
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<tr>
<td>Convergence Ratio</td>
<td>36</td>
<td>37</td>
<td>36</td>
<td>40</td>
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<tr>
<td>Energy Absorbed (kJ)</td>
<td>150</td>
<td>631</td>
<td>1128</td>
<td>1841</td>
</tr>
<tr>
<td>Yield (MJ)</td>
<td>15</td>
<td>171</td>
<td>381</td>
<td>830</td>
</tr>
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</table>

- The target size appropriate for the first average fusion power facility in the IFE development plan.
The NRL target for KrF driven IFE uses wetted foam direct drive targets with zooming and a picket pulse.

- **Possible Pd layer ~ 1000 Å**
- **5-μm CH**
  - $\rho_{\text{CH}} = 1.07 \text{ g/cm}^3$
  - $0.25 \text{ g/cm}^3$
- **334-μm DT ice**
- **256-μm CH (DT)$_{32}$**
- **0.3 mg/cm$^3$**
- **DT vapor**

**High-gain KrF target**
- $E_{\text{laser}} = 2.6 \text{ MJ}$
- Gain = 150–170
- Margin = 52%

**Graphs**
- Laser pulse shape with and without spike
- Zooms
- No picket
- With picket
- Without picket

**A. Schmitt, TuO4.1**

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Wetted foam and “All DT” Direct Drive target designs are being explored for NIF

“All-DT”

3 μm CH

340

1693

1350

Gain = 45
Absorption = 60%
E_{\text{capsule}} \sim 1 \text{ MJ}

“Wetted-foam”

3 μm CH

CH (DT)$_4$

132

281

1784

1368

Gain = 81
Absorption = 90%
E_{\text{capsule}} \sim 1.5 \text{ MJ}
With appropriate beam pointing it may be possible to achieve Direct Drive Ignition on NIF with the Indirect Drive beam configuration.
ICF scientific issues are relevant to high energy density phenomena in Astrophysics

**Scientific**
- Opacities
- Radiation flow
- Equation of state
- Hydrodynamics
- Relativistic plasmas

**Astrophysical**
- Cepheid variables
- Supernova (SN) lgt crv
- Giant planets
- SN explosion hydro
- Protostellar jets
- Gamma-ray bursts

* = "input physics"
vs "output physics"
A wide variety of astrophysics phenomena can be investigated with experiments on intense lasers.
Summary/Outline

- NIF Early Light (NEL) is meeting its performance goals and experiments have begun with the first 4 beams
- The ICF Program is making excellent progress on the baseline indirect drive ignition approach
- Alternate indirect drive ignition target designs could allow much higher yields and target gains
- The NIF indirect drive ignition program will provide the ignition data required for a range of drivers including HIF and Z-pinches
- NIF is designed to test Direct Drive as well as Indirect Drive
- The science of ICF targets is applicable to a wide range of astrophysical phenomena
Backup Viewgraphs
Why do we believe that ignition will work on NIF?

- Numerical simulations provide a first principles description of x-ray target performance (except for laser-plasma interactions which are expected to be small for scaled NIF plasma conditions and beam smoothing.

- Predictions for NIF target gain have not changed qualitatively since 1990, despite 13 years/15,000 experiments on Nova, Omega and Nike to compare with codes.

- The Halite/Centurion experiments using nuclear explosives have demonstrated excellent performance, putting to rest fundamental questions about basic feasibility to achieve high gain.
The goal of the target design work is to identify the optimal targets for a broad spectrum of possible approaches to IFE.

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<th>Target Requirement</th>
<th>HED Scientific Issue</th>
<th>Power Plant Impact</th>
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<tr>
<td>Power/Energy</td>
<td>Drive Temperature</td>
<td>Driver Beam Quality</td>
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<td>Symmetry</td>
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<td>Stability</td>
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<td>Pulse shaping/pulse length</td>
<td>Fuel adiabat/EOS</td>
<td>Driver Beam Conditioning</td>
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<td>Spot size/Intensity</td>
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<td>Transport/Focusing</td>
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<td>Beam geometry</td>
<td>Symmetry/Radiation</td>
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<td>Transport</td>
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<td></td>
<td>Focusing</td>
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<td>Target Material (hohlraum/capsule)</td>
<td>Wall albedo ...</td>
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<td>Coupling Efficiency</td>
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<td>Capsule Stability</td>
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<td>Target Precision</td>
<td>Hydrodynamic Instability</td>
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<tr>
<td></td>
<td>Symmetry</td>
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The principal approaches to ICF utilize direct drive or indirect drive implosions to compress the fuel.

**Direct drive**

- Ablator (low-Z foam or solid)
- Solid or liquid fuel
- Gaseous fuel (at vapor pressure of solid or liquid fuel)

**Advantage:**
- High coupling efficiency
- Reduced Laser Plasma Interaction effects

**Indirect drive**

- Ion target
- Ion beams
- Radiation converter

**Advantages:**
- Relaxed beam uniformity
- Reduced hydrodynamic instability
- Significant commonality for lasers and ion beams
## Aggressive use of advanced computation has been a hallmark of the ICF Program

### January 1977

- **2D LASNEX**
  - Laser raytrace, multigroup diffusion, suprathermal electrons, MHD, charged particle diffusion, ion species diffusion, XSNQ, EOS tables

  LASNEX  4 MFLOPS on CDC 7600

- Capsule instability analysis: 1D sim. postprocessed with Artic, or 2D single mode
- First 2D hohlraum simulations with capsule ~1500 zones, ran for weeks

### January 2002

- **2D LASNEX and 2D/3D HYDRA**
  - Include Arbitrary Lagrange Eulerian grid motion, material interface reconstruction, multigroup diffusion and realistic radiation transport, charged particle diffusion, laser raytrace, Lee and More conductivities, XSNQ and online opacity servers, QEOS, EOS tables - SESAME, LEOS...
  - Basis interface, Yorick postprocessing
  - MPI parallel with threads - both have run on over 1600 processors

  HYDRA 104 MFLOPS / processor on IBM White x 640 processors (8% of machine)
  67 GFLOPS (x 16750)

- Direct simulations of multimode surface perturbation growth 2D/3D, to 16.8 million zones
- First full 3D simulations of NIF ignition hohlraum ran 1 week, 1 million zones, 4.8 million photons
- Full 3D capsule simulation of drive asymmetry 4.4 million zones
Lasnex is a highly versatile computer code with a wide range of physical models for processes important to ICF.

- **Laser light:**
  - 3D ray tracing
  - 1D EM wave

- **Electrons:**
  - Thermal conduction (FD&FE)
  - Non-local conduction
  - Multigroup diffusion

- **Radiation (multigroup):**
  - Frequency dependent sources
  - Diffusion (FD&FE)
  - Transport eqn.

- **Burn products (n, γ, CP):**
  - TN reaction source
  - Multigroup diffusion

- **Ions:**
  - Thermal conduction

- **Hydrodynamics (2D):**
  - Langrangian (quads)
  - Semi-Eulerian (SALE)
  - Slide lines

- **Atomic physics (LTE&NLTE):**
  - Average atom (XSN)
  - SCA
  - DCA
  - Tabulated opacity (LTE)
  - Tabulated EOS (LTE)
  - Inline LTE EOS
With Nova, the ICF program brought together advances in laser performance, precision diagnostics, and advanced modeling tools required for ICF to become a mature quantitative scientific effort.

— Nova was a 10 beam laser capable of producing 40 kJ of laser energy at 0.351 μm.
Key results from the Nova program established the specifications for NIF

- Hohlraums can achieve adequate symmetry and 10-25% coupling with multiple cones of beams

- Precise pulse shaping can be achieved as required for Fermi degenerate compression

- Hohlraums with pulse shaping are limited to ~300 eV with 0.35 µm lasers (I ~2x10^{15} w/cm^2)

- Hydrodynamic instabilities limit shell to R/ΔR ~35

![Capsule energy gain plotted versus compression graph]
Advanced diagnostics have been central to measuring the phenomena critical to understanding NIF.

Gated MCP x-ray imager

Sequence of x-ray backlit images of imploding capsule

MCP gated imagers were operated between 100 eV and 10 keV with 5-50 µm, 30 -300 ps resolution.
The choice of laser wavelength is central to the ICF Indirect Drive Ignition Program

- Backscatter reduces laser absorption and energy coupled into the capsule
- Unequal absorption between cones can spoil beam balance
- Beam bending, beam spray and cross beam effects can spoil symmetry

- Time dependent scatter can spoil pulse shape
- Hot electrons from plasma waves can preheat the fuel making it less compressible

![Diagram showing implosion/compression to high density]
The ICF ignition region in power and energy is based on constraints for LPI and hydrodynamic instabilities

- There is a wavelength dependent maximum hohlraum temperature determined by laser-plasma interaction - shown by lines labeled $2\omega$ and $3\omega$

- There is a minimum $T_R$ that is dictated by keeping hydrodynamic instabilities under control. The red dashed line corresponds to those temperatures needed for a surface roughness of $\sim 200\text{Å}$
NIF’s 2w capability may provide an operating window for larger capsules with yields much greater than the baseline.
There is a well established physics basis for ignition at 3\(\omega\) and experiments are beginning to address critical ignition requirements for 2\(\omega\).

- 2\(\omega\) looks very appealing in Lasnex designs
- Preliminary experiments are encouraging
The Nova ignition physics program utilized hohlraums and capsules which were scaled to test key issues:

- Capsules
  - hydrodynamic instability
  - implosion symmetry
  - pulse shaping
  - implosion dynamics

- hohlraum plasma condition
- laser-plasma interaction
- hohlraum drive
- x-ray wall loss
- x-ray flux symmetry

3-µm-thick tungsten hohlraum
Ten-beam irradiation
Laser energy ~18 kJ (total)
Wavelength = 0.35 µm
Pulse length = 1 ns (FWHM)
We have validated our ability to model laser heated hohlraum drive against a broad range of experiments.

**Scaling of peak drive temperature**

Vacuum and gas-filled hohlraums with 2.2 ns shaped pulses (3:1 and 5:1 contrast ratio)

**Detailed $T_R^4$ comparison from a scale 0.75 hohlraum**

Lasnex can predict hohlraum drive to +/- 10% in x-ray flux.
Implosion symmetry can be controlled by varying the hohlraum geometry.
The measured growth of planar hydrodynamic instabilities in ICF is in quantitative agreement with numerical models.
Using a NIF-like Illumination Geometry on Omega, Implosion performance is in excellent agreement with calculations.
The target/driver combination for IFE must meet a minimum product of driver efficiency times gain ($\eta G$)

- $P_{\text{net}} = P_{\text{gross}} - P_{\text{driver}} = P_{\text{gross}}(1 - \eta a - \frac{1}{\eta G M E})$

  ME $\sim 40\%$ where $M$ is the blanket multiplication and $E$ is the thermal to electric conversion efficiency

- $\eta_G > 7 - 10$ (recirculating power fraction of 25 - 35%)

  $\eta_{\text{Laser}} < 10\% \Rightarrow G > 70 - 100$

  $\eta_{\text{HI}} < 35\% \Rightarrow G > 20 - 30$

- A safety margin of a factor of 2 in target gain is important for making a case that we can strongly defend

  $\Rightarrow G_{\text{Laser}} > 140$

  $G_{\text{HI}} > 40$
We look at a broad range of target options to maximize flexibility.

- **Distributed radiator:** "Baseline" target
- **Close-coupled target:** High gain at low driver energy
- **CH capsule design:** Easier target fab
- **Fast ignitor target:** High gain with low accelerator peak power
- **Hybrid target:** Large beam spot
- **Large-angle distributed radiator:** Large beam entrance angle

We look at a broad range of target options to maximize flexibility.
Small spot sizes have high leverage to increase target gain and reduce driver energy

Ion beam characteristics: 4 GeV Pb+ions
5.9 MJ input energy
2.7 mm effective radius spot
Gain 70

Ion beam characteristics: 3.5 GeV Pb+ions
3.3 MJ input energy
1.7 mm effective radius spot
Gain 130
Symmetry in indirect drive is controlled by the position and strength of the sources

Need to balance low order Legendre modes:

- Sources at zeros of $P_4$ and with strengths set to balance $P_2$

- Source behind a shine shield and radiation flows around shield near zero of $P_2$

- Case-to-capsule ratio with or without a shim to correct $P_4$

Callahan 6/2002
The LLNL Beamlet laser - NIF’s scientific prototype - is now operational as a diagnostic backlighter source on Z at Sandia Albuquerque.

- The intense x-ray backlighting available from Beamlet has imaged z-pinch implosions with a resolution not previously available on Z.

Substantial progress has been made on the symmetry of z-pinch driven indirect drive targets.
Substantial progress has been made on the symmetry of double z-pinch driven indirect drive targets.

- Z830
- 68-75 eV peak drive
- ~10 kJ absorbed
- Peak density ~40 g/cc
- CR >14

G. Bennett, M. Cuneo, R. Vesey
Backlit Implosions on Z measure capsule convergence and implosion symmetry
Ignition will be pursued either by heating some of the fuel during compression or by rapid injection of energy into a precompressed cold fuel volume.

- Central hot spot ignition relies on precise control of implosion symmetry and hydrodynamic instability.
- Fast ignition would utilize new concepts in short pulse laser technology and will require significant advances in the understanding of charged particle production and transport at ultra-high intensity.
Fast ignition can utilize a re-entrant tube and cone to provide access for the ignitor beam to the imploded, compressed core:

*Flexibility for compression driver: Lasers, ion beams z-pinch (Tabak 1991)*

*Potential compatibility with liquid wall chamber*
Experiments on Gekko XII have seen enhanced neutron output from fast heating of a direct drive target with a reentrant cone.

Fast heating scalable to laser fusion ignition

2.5 KJ compression pulse + (60-500), 0.5 ps fast heating pulse
Proton ignition is a newer concept avoiding the complexity of electron energy transport

- Same driver and fuel assembly options
- Novel physics of Debye sheath proton acceleration

- Simpler proton energy transport by ballistic focusing
- Larger laser focal spot-easier to produce

Recent 100TW, 100fs expt. shows first evidence of ballistic proton focusing (to 50 µm) and enhanced isochoric heating.

Streak images of Planckian emission
Advanced Technology will allow Multi-beamline HEPW deployment compatible with existing NIF architecture.

192 beam National Ignition Facility has a short pulse potential of 0.2 Exawatts per beamline.

Thin-optic pulse compressor and focusing lens are “plug and play” compatible with existing Final Optics Assembly (FOA).

Front end modifications can fit within the existing NIF pre-amplifier module (PAM).
We have compared ignition and burn propagation for NIF capsules and possible future high yield capsules.

<table>
<thead>
<tr>
<th>NIF capsule</th>
<th>High yield capsule</th>
</tr>
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<tbody>
<tr>
<td>CH + 0.25% Br + 5%O</td>
<td>Be</td>
</tr>
<tr>
<td>DT solid (0.2 mg)</td>
<td>DT solid (7.2 mg)</td>
</tr>
<tr>
<td>DT gas 0.3 mg/cc</td>
<td>DT gas 0.3 mg/cm³</td>
</tr>
<tr>
<td>Radiation temperature</td>
<td>= 300 eV</td>
</tr>
<tr>
<td>Implosion velocity</td>
<td>= 4 x 10⁷ cm/sec</td>
</tr>
<tr>
<td>Capsule absorbed energy</td>
<td>= 0.15 MJ</td>
</tr>
<tr>
<td>Capsule yield</td>
<td>~ 15 MJ</td>
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</tbody>
</table>
Although NIF will not directly test full scale targets for IFE, NIF and high-yield capsules have almost identical ignition conditions and burn propagation physics.
High Energy Density matter is interesting because it occurs widely

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

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

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**H \(\rho\)-T phase diagram**

- **Hot Plasma**
- **\(\rho\)-T track for sun**
- **Spherical compressions**
- **Radiatively heated foils**
- **Planar shocks**
- **Planetary cores**
- **Low temperature condense matter**

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Density (g/cm\(^3\))

Temperature (eV)
Jupiter contains hydrogen in a complicated regime

- Strongly coupled ions
  \[ \Gamma = \frac{E_{\text{pot}}}{E_{\text{kin}}} \gg 1 \]
- Partially degenerate electrons
- Thermal Energy \sim Fermi Energy
- Partial Ionization
  - Continuum lowering
  - Pressure Ionization

\[ \log \rho (\text{g/cm}^3) \]
\[ \log T(\text{K}) \]
A wide range of Laboratory and Astrophysical phenomena can be characterized by their degree of correspondence

<table>
<thead>
<tr>
<th>Hydrodynamics and Shocks</th>
<th>Hydrodynamic Instabilities</th>
<th>Atomic Physics and X-ray Transport</th>
<th>Laser-produced Relativistic Plasmas</th>
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<tr>
<td>Electron Energy Transport</td>
<td>A. Sameness</td>
<td>B. Similarity</td>
<td>C. Resemblance</td>
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<tr>
<td>Hydrodynamics and Shocks</td>
<td>2. EOS Giant Planets</td>
<td>3. Interaction of Molecular Cloud with Strong Shock by SNR (Morphology)</td>
<td>1. Non-local Transport of Neutrinos in a Baby Neutron Star</td>
</tr>
<tr>
<td>Hydrodynamic Instabilities</td>
<td>5. RT Instability of SN Explosion</td>
<td>6. Hydro-instability in Neutrino-driven SN Explosion</td>
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<td>Laser-produced Relativistic Plasmas</td>
<td>10. Stellar Jets</td>
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<td>11. Radiation Hydro. in Early Galaxy</td>
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<td>12. Photo-ionized Plasmas</td>
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<td>13. Vishniac Instability of SNRs</td>
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<td>14. X-ray Lasers in the Universe</td>
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<td>15. Fireball of Gamma-ray Bursts</td>
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<td>16. Cosmological Jets (Rel.)</td>
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<td>17. Weibel Instability in GRB</td>
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<td>18. Non-LTE QED at AGN Core</td>
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The Rayleigh-Taylor instability occurs when a heavy fluid ($\rho_H$) "sits on top of" a light fluid ($\rho_L$)… and in astrophysical situations such as expanding nebula.


A similar situation occurs in ICF implosions.
Observations from SN1987A suggest strong mixing of the radioactive core into the envelope.
Initial experiments relevant to the hydrodynamics of core collapse supernovas were done on Nova.
More “Star-like” instability experiments have been developed on the Omega laser.

More “star-like”
- 3-layers
- Divergent geometry
  — Cylindrical
  — Spherical

Three-layer experiment

Cylindrical experiment

Spherical Experiment
Astrophysical and Laboratory turbulent blast waves show many similar features

Image of Tyco SNR by Chandra X-ray Satellite (2001)

Laser Produced Blast Wave in Xe Gas (Courtesy B. Ripin, NRL, 1991)
An example Cepheid variable is seen in M100
Cepheid variables are the most accurate distance indicators, and establish $H_0$ in the nearby universe.

- Opacities are an essential ingredient to understanding Cepheid variables.
Cepheid variables are stars whose intrinsic brightness varies periodically with time.

- Period ~ size ~ intrinsic brightness
- "Standard candle" = dist. indicator

Cepheid variables are stars whose intrinsic brightness varies periodically with time.

Each Bump causes a $\frac{dk}{dT}$ which can lead to pulsation.

- The “beat Cepheids” are very sensitive to the opacity of Fe.

- The “opacity problem” was solved through experiments on the Nova and Luli lasers.