National Nuclear Security Administration
Plasma Science Advancing Knowledge in the National Interest

Presented to:
The National Academies
Board on Physics and Astronomy
Plasma Science Committee

Presented by:
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Outline

• Plasma 2010 primary conclusion and recommendation – NNSA perspective
• Plasma Science within NNSA
  – Driving Physics
  – Inertial Confinement Fusion and NIF Update
  – Plasma-based experimental tools and advanced computations
• NNSA as a sponsor and steward of High Energy Density Physics
• How does stewardship of plasma science benefit NNSA?
• NNSA response to specific research challenges
  – Fundamental Low Temperature Plasma Science
  – Discovery-Driven, High Energy Density Science
  – Intermediate-Scale Plasma Science
  – Cross-cutting Research
• Conclusion

NIF is now a 4 MJ laser (1\(\omega\))!
Response to the Decadal Study

Principal Conclusion: The expanding scope of plasma research is creating an abundance of new scientific opportunities and challenges. These opportunities promise to further expand the role of plasma science in enhancing economic security and prosperity, energy and environmental security, national security, and scientific knowledge.

- OFES would be an excellent steward of Plasma Science
  - Exciting opportunities with ITER, growth of plasma applications, etc.
- NNSA has and will continue to lead many growth areas in High Energy Density Physics
  - A peer for OFES in stewarding HEDLP
  - Owner of the premier HEDP facilities
- Ignition and beyond will energize the HED community
- Many of our applications sit at the interface between plasma science with materials, nuclear physics, etc.
- Our investments in smaller facilities and university programs will help grow the community and the field
Summary Points

NNSA invests in plasma science in the broadest national interest, including discovery-driven science

• Fundamental low-temperature plasma science
  Although this is not part of NNSA’s portfolio, there are contributions

• Discovery driven, high energy density plasma science
  This is specifically supported by NNSA through: the HEDLP joint program, User Facilities (including NLUF), LDRD, University programs, workshops and individual contracts. Core program has led and will continue to generate discoveries

• Intermediate –scale plasma science
  NNSA continues to develop its intermediate scale User Facilities, where peer-reviewed academic use for discovery-driven science is growing

• Cross-cutting research
  NNSA is growing its collaborative partnerships with other agencies, institutions, and individuals through WFO, LDRD, User Facilities, and University programs. This is an effective method to optimize cross-cutting research

We agree with the committee in calling for broadening the horizons of plasma science
99.999999% of the energy from a weapon is generated in the high energy density state.

NNSA has championed the World’s three largest HED facilities.
**NIF Project Status as of September 26, 2008**

**Total 5589* LRUs Installed**

- **Laser Bay 1** 100%  
  2268 LRUs Installed
- **Laser Bay 2** 100%  
  2284 LRUs Installed
- **Switchyard** 89%  
  155 LRUs Installed
- **Target Bay** 56%  
  778 LRUs Installed

**98% Overall Project Completion**

**Beamlines Activated**

- **100% Overall 1ω Commissioning** (infrared laser light)
- **4.22 MJ 1ω Energy**
- **192/192 Beams**

*Laser Bay 2*
- Cluster 4
- Cluster 3

*Laser Bay 1*
- Cluster 2
- Cluster 1

*NIF-0607-13636r25VG

*Total also includes 104 LRUs installed in the Master Oscillator Room (MOR)
Ignition will be the start of a new scientific era for NNSA and the Nation

Ignition on NIF will be a defining moment for inertial confinement fusion energy
MVSS is adjusted using an array of measurement techniques using 6 surrogate targets and different diagnostics.

- **S** Entropy
- **M** Mix
- **V** Velocity
- **S** Shape

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<th>Technique</th>
<th>Description</th>
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<td>GXD</td>
<td>(shock sphericity)</td>
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<tr>
<td>FABS/ NBI</td>
<td>(laser coupling)</td>
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<tr>
<td>VISAR SOP</td>
<td>(shocks)</td>
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<td>FFLEX</td>
<td>(hot electrons)</td>
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<td>DANTE</td>
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<td>SXD</td>
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<tr>
<td>ARC Radiography</td>
<td>(compressed DT shape in THD targets)</td>
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<tr>
<td>GXD</td>
<td>(shape of gas filled surrogate implosion)</td>
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<tr>
<td>RadChem</td>
<td>(THD targets)</td>
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<tr>
<td>DANTE</td>
<td>(Drive spectrum)</td>
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Targets must be made to tight tolerances so MVSS requirements can be met reproducibly.
To lower the fuel entropy we have to gradually increase drive pressure to ~100 Mbar

- Strong shocks generate entropy
- Pressure changes of a factor of 4 generate little entropy
- Number of steps depends on 1st shock pressure and the peak pressure
- To reach ~ 100 Mbar we need 4 shocks
The NIC team have an aggressive schedule

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<th>2009</th>
<th>2010</th>
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- **NIF Project CD4**
  - Drive temperature $T_{\text{rad}}$
  - Symmetry, shock timing, and ablation rate technique validation
  - Layered dudded fuel (THD) implosions,
  - Layered THD
  - DT Ignition Implosions
  - DT high yield

- **192 beams**

*NIC runs into FY12*
The first simulated campaign with 3 ignition implosions: core images from simulated implosions are promising.

**HEXRI emission images at 10 – 20 keV, time integrated**

- **Hot**
- **Warm**
- **Hottest**

**ARC Compton Radiography absorption images at 70 – 200 keV, at bangtime**

- **small, dense, P₂**
  - $\rho R \sim 1.4 \text{ gcm}^{-2}$
  - $4 \times 10^{14}$ neutrons
  - DT ignition yield $\rightarrow (4 \text{ MJ})$

- **big, fluffy, P₂**
  - $\rho R \sim 1.15 \text{ gcm}^{-2}$
  - $3 \times 10^{14}$ neutrons
  - (100 kJ)

- **dense, P₂ & P₄**
  - $\rho R \sim 1.45 \text{ gcm}^{-2}$
  - $4 \times 10^{14}$ neutrons
  - (14 MJ)
Plasma science pervades the whole of our program

- **Computations**
- **Source Plasma Physics**
- **Diagnostics**
- **Targets**
- **Driver Technology**
Stimulated Raman Scattering (SRS) is a 3-wave instability that determines hohlraum heating

- Incoming laser resonantly couples with plasma waves
  - Scatters light and creates hot electrons (bad!)

- Using the state-of-the-art VPIC particle in cell code running on Roadrunner, the world’s fastest computer, the nonlinear physics that saturates SRS was discovered

- Intense laser light causes the plasma waves to “bow” and become non-resonant - shutting off SRS

- Lin Yin of LANL was awarded the APS Katherine T. Weimar award this year for “outstanding achievement in plasma physics by an early-career woman”
World’s fastest computer used to understand physics addressed by the world’s most powerful laser

- LANL’s Roadrunner is a true Petaflop computer
- Laser-plasma interaction (LPI) calculations performed during acceptance testing
- VPIC, a particle-in-cell code, is used to understand the fundamental physics of LPI

- **Demonstrated capability:**
  - 1 trillion particles
  - >374 Tflops sustained
- Discovery of instability saturation mechanisms may lead to improved ignition capsule performance

Comparisons to data with TRIDENT laser verify code physics
Our platforms also produce remarkable materials data in the HED regime.

**Stress versus density for diamond**

- Measurements have an uncertainty of $\leq 1\%$ due to large sample sizes and long time scales of pressure drive.

Complete melting at 10.6 Mbar

Melting begins at 6.5 Mbar

Fundamental material science driven by the mission of ignition
NNSA mission needs have driven the creation of HEDP environments that are ideal to study complex HED plasmas and materials.

- High Mach Number unstable flows
- Jets
- Mass Outflow
- Shocks and radiation transport
- Rayleigh Taylor Instabilities
- Materials in the Extreme
- MHD, thermo-electric, and “anomalous” heating
High Energy Density Physics is the Cornerstone of Science at NIF and Z
NNSA relies on plasma science in the broadest national interest, including ‘discovery driven’

• Direct mission needs
  – Signature world class facilities are being developed as User Facilities

• Indirect mission needs: Vitality and excellence
  – Personnel recruiting, retention, development
  – Collaborations
    (feeding back into other indirect mission needs)
  – Hardware, diagnostic, and technique development
  – Computational development
    (including verification, validation)
  – Implicit peer review

The quality and quantity of discovery-driven science can be quantified by peer reviewed publications, impact factors, h index, society fellowship, etc. By these metrics, LLNL and LANL ‘Physics and Astronomy’ are ranked in the top 10 international research institutions (lab and academia), with >1,000 peer reviewed publications a year, and staff equivalent to the best academic institutions
NNSA runs the Stewardship Science Academic Alliances Program: Centers of Excellence, Research grants, and Fellowships

- Recruiting for the NNSA Laboratories:
  — More than 70 SSAA-supported students have taken positions at the NNSA laboratories since 2002

- Publications Awards
  — Over 1,300 peer reviewed articles published since 2005

- Fellowships Awards
  — 14 Graduate Fellowships

- Symposia bring together material, low energy nuclear, hydrodynamics and HEDP scientists – encourage cross-cutting networking

- Awards
  — DOE EO Lawrence Awards for National Security and Non-Proliferation
  — Roebling Medal, highest award of the Mineralogical Society of America
  — Gregori Aminoff Prize of the Royal Swedish Academy of Sciences
  — American Physical Society’s Maxwell Prize for Plasma Physics
  — IEEE Plasma Science and Applications Committee Awards
The OMEGA/OMEGA EP laser system is currently NNSA’s largest Users’ Facility

- OMEGA/OMEGA EP is located at the University of Rochester’s Laboratory for Laser Energetics

- ~70% of time for NNSA mission-related research
  - ICF
  - HED Physics

- ~25% of time for peer-reviewed basic science
  - Laboratory Basic Science
  - National Laser Users’ Facility Program

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OMEGA laser system
- Operating since 1995
- Up to 1500 shots/year
- 60 beams
- >30-kJ UV on target

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OMEGA EP laser system
- Complete 25 April 2008
- 4 NIF-like beamlines 6.5 kJ-UV (10 ns)
- Two beams can be high energy Petawatt:
  - 2.6-kJ IR in 10 ps
  - Can propagate to the OMEGA or EP target chamber
High impact discovery driven science is generated through NLUF on OMEGA

Proton Radiography of Inertial Fusion Implosions


Fig. 3. Images of a 430-μm-radius spherical plastic capsule with attached Au cone, before and during implosion. (A and C) The unimploded capsule used in OMEGA shot 46531. (B and D) A capsule at 1.56 ns after the onset of the laser drive (OMEGA shot 46529). The dark areas correspond to regions of higher proton fluence [in (A) and (B)] and regions of lower proton energy [in (C) and (D)]. The energy image values in the region shadowed by the cone are mostly noise because very few protons were detected in that region. See lineouts in Figs. 4 and 5 for image values.
High impact discovery driven science is generated through NLUF on OMEGA

Astrophysically-relevant experiments are carried out by a number of users

University of Michigan – R.P. Drake
Supernova Physics

Rice University – P. Hartigan
Shock wave interactions with “clumpy” media

Muller, Fryxell, and Arnett (1991)

H. F. Robey et al., Phys. Plasmas 8, 2446 (2001),
SUNY Stonybrooke, U. Maryland, NRL, UR/LLE, U. Eastern Michigan, CEA Saclay

The NNSA/SC Joint Program in Laboratory High Energy Density Plasmas was created to steward HEDLP within DOE

- 2004 Davidson report provided the starting point for the HEDP Interagency Task Force

- Key DOE finding: Stewardship of HEDLP needs to be improved

- DOE has taken action to improve stewardship of HEDLP:
  - Joint Program in Laboratory HEDP announced 2/5/07
  - Oversight of HEDLP now a joint NNSA/SC responsibility, with Dr. A Hauer (NNSA) and F. Thio (SC/OFES), the joint federal program managers

- Recent activities:
  - Workshop, 8/25-27/08, Washington, D.C.; 80 participants from Universities, Industry, and NNSA laboratories
  - Joint solicitation for proposals for FY09 funding: 130 excellent wide-ranging proposals received; review process initiated
  - The DOE has charged the Fusion Energy Science Advisory Committee (FESAC) to “work with the HEDLP community to provide information to develop a scientific roadmap for the joint HEDLP program in the next decade”
  - A FESAC subpanel has been formed to address the charge; Chair is Riccardo Betti (University of Rochester)
130 Proposals Received

- 72 university-led, 45 lab-led
- 53 different universities (10 foreign)
- 16 major laboratories (6 foreign)
- Over 300 principle investigators and collaborators
Specific actions by NNSA on the four topics in the report

NNSA invests in plasma science in the broadest national interest, including discovery-driven science

- **Fundamental low-temperature plasma science**
  Although this is not part of NNSA’s portfolio, there are contributions and needs

- **Discovery driven, high energy density plasma science**
  Core program has led and will continue to generate discoveries. We will team with OFES to advance and grow the field.

- **Intermediate –scale plasma science**
  NNSA continues to develop its intermediate scale User Facilities, where peer-reviewed academic use for discovery-driven science is growing and we are increasing access

- **Cross-cutting research**
  NNSA is growing its collaborative partnerships with other agencies, institutions.

*We agree with the committee in calling for broadening the horizons of plasma science*
Although not in NNSA’s portfolio, contributions are made to low-temperature plasma science

• NNSA lab experiments and codes address processes from photon absorption through plasma creation and Coulomb explosion
   Optics, diagnostics and experiments for high-fluence sources (e.g., LCLS, PW lasers) rely on understanding photon – material interactions and damage. Bio-imaging is based on modeling and understanding the transition to plasma.

• NNSA utilizes low-temperature plasmas in control and hardware applications
   A key component invented and developed by NNSA labs for the NIF is the plasma electrode Pockels cell (PEPC). This allows four passes through the main amplifier.

   NNSA labs design and build multi-layers of extreme precision. The required sputter sources involve low-temperature plasma physics. Applications include energy storage, turbines, PW gratings, and x-ray mirrors.

   **NNSA will be interested in the results of low-temperature plasma stewardship**
We will continue to encourage discovery HED science – hopefully we can increase funding!

First evidence of plasmons in Warm Dense Matter

Proton Temporal Diagnostic studies time-dependent burn and ion temperature

Radiative shock waves relevant to astrophysics

Discovery of coherent kinetic non-linear states in laser-plasma interactions

Coherent high harmonic generation x-ray sources
NNSA relies on intermediate scale plasma science facilities

Examples of intermediate size plasma facilities:

• Jupiter at LLNL (lasers): support of NIC and NIF; mission; users
• Trident at LANL (laser): support of NIF and NIC; mission; users
• Texas Petawatt at UTX (laser): discovery-driven research; users
• Z-Beamlet / Z Petawatt at SNL (laser): diagnostic for ZR; users
• Nevada Terawatt at UNR: pulsed power
• NIKE (NRL): Inertial Fusion Energy

Intermediate-size plasma facilities provide both direct and indirect mission support, and we are encouraging user access at our intermediate facilities
NNSA-supported Texas Petawatt Laser at UT Austin achieves power milestone: March 31, 2008

- Power = 190 J / 170 fs = 1.12 PW
- Primary mission:
  - Train students in HED physics
  - Create a workforce to utilize large-scale NNSA HED facilities
- Constructed in collaboration with LLNL and SNL
- Will be used for fundamental experimental studies in:
  - HED plasmas
  - Astrophysical phenomena
    - Supernovae explosions
    - Formation of galactic jets
    - Properties of matter in dense stars
  - Fast ignition approach to ICF

Director: Professor Todd Ditmire
Intermediate scale facilities are successfully developing as User facilities, a new concept for NNSA

Jupiter Laser Facility at LLNL
- All FY09 use is determined by merit based, peer review with referees and program advisory committee (50% external)
- 17 U.S. universities, 8 International universities, 8 external labs (LANL, NRL, NIST, GA, AWE, CEA, GSI, RAL)
- Almost 50% of time is for academic use

Trident at LANL
- 27 proposals received for 1st half of FY09 -- 4x oversubscription
- 21 unique institutions represented
- >60 unique users (students, post-docs)

University Facilities
- We are encouraging our HEDP centers (Cornell, UNR, and Texas) to increase external access
- Some call for proposals have already been sent out
Bio-imaging projects, examples of cross-cutting research, are based on, and feed back into, NNSA programs.

High-profile bio-imaging projects with DOE OS (BES, BER) are based on, and feed back into, NNSA programs.

Femto second time-delay holography, invented and developed by NNSA labs, and high resolution ab-initio 3D coherent x-ray diffraction imaging, developed by NNSA labs, enable the proposed flash imaging of proteins using fourth generation light sources. E.g. *Nature* 448, 676–679, 2007

The same R&D feeds back into NNSA mission requirements: implosion and explosion of microspheres, material response on atomic time scales, target metrology, and design of damage-resistant optics and diagnostics.

Cross-cutting projects provide high-impact discovery-driven science; results feed back into NNSA’s personnel, hardware and technique toolkit.
NNSA is working on possible cross cutting programs with Basic Energy Science.

A high energy density end station for LCLS

Build on HPCAT to obtain DC-CAT at Argonne Photon Source
While broadest-interest plasma science, involving users, is undertaken by NNSA, it is under pressure:

- Intermediate scale NNSA facilities must often be funded through institutional channels
- While a large response to calls for HEDLP proposals illustrates a healthy interest, only a few will likely be funded
- The importance and quality of use-inspired science to the NNSA-DP mission is not fully appreciated

Path Forward:

- The NNSA HED Program recognizes the value of discovery science, especially the role of intermediate facilities
- We commit to stable funding with (hopefully) growth
- Joint Program will be main vehicle
- We must widely disseminate information about our facilities and provide support to facilitate external use
Conclusions

• NNSA continues to advance and support high energy density plasma science – we need it
• Our core program in ICF has:
  – Completed the World’s largest laser
  – Is on-track to attempt ignition in 2010
• We will continue to steward the field at national laboratories and within the broader community
• NNSA congratulations the Plasma Science Panel on an excellent report
• Our facilities and university partners have:
  – Conducted discovery-HED science
  – Provided unique and high quality HED data to the materials, astrophysics, plasma and fusion communities
  – Increased access to our intermediate facilities
• We are developing new ideas for cross-cutting science
BACKUP
The Laboratory Directed Research and Development sponsors discovery-driven research.

Taken from DOE directive order O 413.2:

1. **OBJECTIVE.** To establish Department of Energy (DOE) requirements for laboratory directed research and development (LDRD) while providing the laboratory director broad flexibility for program implementation. The objectives of the LDRD program are to—

   - maintain the scientific and technical vitality of the laboratories;
   - enhance the laboratories’ ability to address future DOE/NNSA missions;
   - foster creativity and stimulate exploration of forefront science and technology;
   - serve as a proving ground for new concepts in research and development; and
   - support high-risk, potentially high-value research and development.

**Up to 6% of laboratory funds is currently used for this program, which specifically requires discovery-driven research**
NNSA runs University Programs with the specific intent and expectation of nurturing discovery driven plasma physics

- The National Laser Users’ Facility Program on OMEGA began in 1979

- University and Industrial Users apply for shot time and funding
  - none from LLE

- Proposals are peer-reviewed by external scientists
  - none from LLE

- NNSA funds Users and facility operations

- An OMEGA Laser Users Group has been formed
  - R. Petrasso (MIT), Chair

For FY09-FY10
- 11 User’s funded (~$1.2 million)
- ~50% of requested shot time and funding
Conclusion

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Success of ignition is crucially dependent on Mix, Velocity, Entropy and Shape ("MVSS")

\[ \frac{\Delta R_{\text{mix}}}{\Delta R_{\text{shell}}} < 0.2 \]

\[ \frac{\Delta R_{HS}}{R_{HS}} < 0.18 \]

\[ \alpha < 1.5 \]

\[ V > 350 \text{ km/s} \]
Increasing collaboration between NNSA and other agencies will naturally enhance cross-cutting science

- Collaborations are an effective means to optimize NNSA human capital and capabilities
- It is expected that collaborations will grow
- Programs used to maintain and grow collaborations include: Work-for-Others, LDRD, User Facilities, and University programs
NIF’s Scientific Environments

• These are the conditions of Extreme Laboratory Astrophysics
  – $T > 10^8$ K matter temperature
  – $\rho > 10^3$ g/cc density
  – Those are both 7x what the sun does! Helium burning, stage 2 in stellar evolution, occurs at $2 \times 10^8$ K!

• Core-collapse Supernovae, colliding neutron stars, operate at $\sim 10^{20}$ n’s/cc
  – NIF: $\rho_n = 10^{26}$ neutrons/cc

• These apply to Type Ia Supernovae!
  – Electron Degenerate conditions
  – Rayleigh-Taylor instabilities for (continued) laboratory study

• Only need $\sim$Mbar in shocked hydrogen to study the EOS in Jupiter & Saturn
  – Pressure $> 10^{11}$ bar
GA and LLNL have moved target components and subassemblies from R&D to production.

- **Be Capsules**
- **Si Arm / TMP Subassembly**
- **DU Hohlraum**
- **CH Capsules**
- **Capsule/Fill Tube Assembly**
- **Aluminum Can**
- **Si Arm / TMP Subassembly**

**Terms**:
- **Si** – silicon
- **DU** – Depleted uranium
- **TMP** – Thermo-mechanical Package

The NNSA-based plasma community has produced many accomplishments

- 2007 Maxwell Prize – Dr. John Lindel for Pioneering Inertial Fusion Target Designs
- 2008 Outstanding Young Scientist Award – Dr. Lin Yin for new developments in Particle in Cell (PIC) modeling methods
- For the last 20 years, about 25% of APS / DPP Fellows have been associated with NNSA programs
- More to come
NIF will provide a unique environment for astrophysical science
Dynamic compression experiments at the Advanced Photon Source at Argonne National Laboratory

A workshop was held at the APS (June 23 – 24, 2008) to explore the scientific opportunities of integrating compression platforms and x-ray probes for in situ investigations of the microscopic response of shocked materials

A proposal will be put forward to build a Dynamic Compression Collaborative Access Team (DC-CAT) beamline at the APS