National Research Council Study on Frontiers in High Energy Density Physics

Presented by

Ronald C. Davidson
Princeton University

Presented at

High Energy Physics Advisory Panel Meeting
Lawrence Berkeley National Laboratory

March 7, 2003

Charge to the committee:

• The study will review recent advances in the field of High Energy Density plasma phenomena, both on the laboratory scale and on the astrophysical scale.

• It will provide an assessment of the field, highlighting the scientific and research opportunities. It will develop a unifying framework for the diverse aspects of the field.

• In addition to identifying intellectual challenges, it will outline a strategy for extending the forefronts of the field through scientific experiments at various facilities where high-energy-density plasmas can be created.

• The roles of industry, national laboratories, and universities will be discussed.

Aims of the study:

- Review advances in high energy density plasma physics on laboratory and astrophysical scales.
- Assess the field, and highlight scientific and research opportunities.
- Develop a unifying framework for the field.
- Identify intellectual challenges.
- Outline strategy to extend forefronts of the field.

Physical Processes and Areas of Research

High Energy Density Astrophysics

Beam- Plasma Interactions

Free Electron Laser Interactions

Equation of State Physics

Theory and Advanced Computations

Radiation-Matter Interaction

Laser-Plasma Interactions

Beam-Laser Interactions

High-Current Discharges

Atomic Physics of Highly Stripped Atoms

Inertial Confinement Fusion

Hydrodynamics and Shock Physics

The committee includes membership from universities, national laboratories, and industry:

- **Ronald Davidson, Chair, Princeton University**
- David Arnett, University of Arizona
- Jill Dahlburg, General Atomics
- Paul Dimotakis, California Institute of Technology
- Daniel Dubin, University of California at San Diego
- Gerald Gabrielse, Harvard University
- David Hammer, Cornell University
- Thomas Katsouleas, University of Southern California
- William Kruer, Lawrence Livermore National Laboratory
- Richard Lovelace, Cornell University
- David Meyerhofer, University of Rochester
- Bruce Remington, Lawrence Livermore National Laboratory
- Robert Rosner, University of Chicago
- Andrew Sessler, Lawrence Berkeley National Laboratory
- Phillip Sprangle, Naval Research Laboratory
- Alan Todd, Advanced Energy Systems
- Jonathan Wurtele, University of California at Berkeley

Review Process and Status

The committee divided its work into three areas.

- Laboratory High Energy Density Plasmas
- Astrophysical High Energy Density Plasmas
- Laser-Plasma and Beam-Plasma Interactions

The committee solicited input from the membership of a number of professional organizations and held Town Meetings at the 2001 and 2002 American Physical Society Division of Plasma Physics meetings.

The review process has been completed.

The final draft report was issued in November, 2002.

Scope of the Study

The committee recognizes that now is a highly opportune time for the nation's scientists to develop a fundamental understanding of the physics of high energy density plasmas.

The space-based and ground-based instruments for measuring astrophysical processes under extreme conditions are unprecedented in their accuracy and detail.

In addition, a new generation of sophisticated laboratory systems ('drivers') exists or is planned that create matter under extreme high energy density conditions (exceeding 10^{11} J/m^3), permitting the detailed exploration of physical phenomena under conditions not unlike those in astrophysical systems.

Scope of the Study – continued

High energy density experiments span a wide range of areas of physics including plasma physics, materials science and condensed matter physics, atomic and molecular physics, nuclear physics, fluid dynamics and magnetohydrodynamics, and astrophysics.

While a number of scientific areas are represented in high energy density physics, many of the techniques have grown out of ongoing research in plasma science, astrophysics, beam physics, accelerator physics, magnetic fusion, inertial confinement fusion, and nuclear weapons research.

The intellectual challenge of high energy density physics lies in the complexity and nonlinearity of the collective interaction processes.

Questions of High Intellectual Value

In the process of developing a unifying framework for the diverse areas of high energy density physics and identifying research opportunities of high intellectual value, the committee found it useful to formulate important scientific questions at the very frontiers of the field -- questions, which if answered, would have a profound effect on our fundamental physics understanding of matter under high energy density conditions.

Examples of important questions ranging from very basic physics questions, to questions affecting the frontier applications of the field are listed below.

- How does matter behave under conditions of extreme temperature, pressure, density, and electromagnetic fields?
- What are the opacities of stellar matter?
- What is the nature of matter at the beginning of the universe?

Questions of High Intellectual Value - continued

- How does matter interact with photons and neutrinos under extreme conditions?
- What is the origin of intermediate-mass and high-mass nuclei in the universe?
- Can nuclear flames (ignition and propagating burn) be created in the laboratory?
- Can high-yield ignition in the laboratory be used to study aspects of supernovae physics, including the generation of high-Z elements?
- Can the mechanisms for formation of astrophysical jets be simulated in laboratory experiments?

Questions of High Intellectual Value – continued

- Can the transition to turbulence, and the turbulent state, in high energy density systems be understood experimentally and theoretically?

- What are the dynamics of the interaction of strong shocks with turbulent and inhomogeneous media?

- Will measurements of the equation of state and opacity of materials at high temperatures and pressures change models of stellar and planetary structure?

- Can electron-positron plasmas relevant to gamma ray bursts be created in the laboratory?

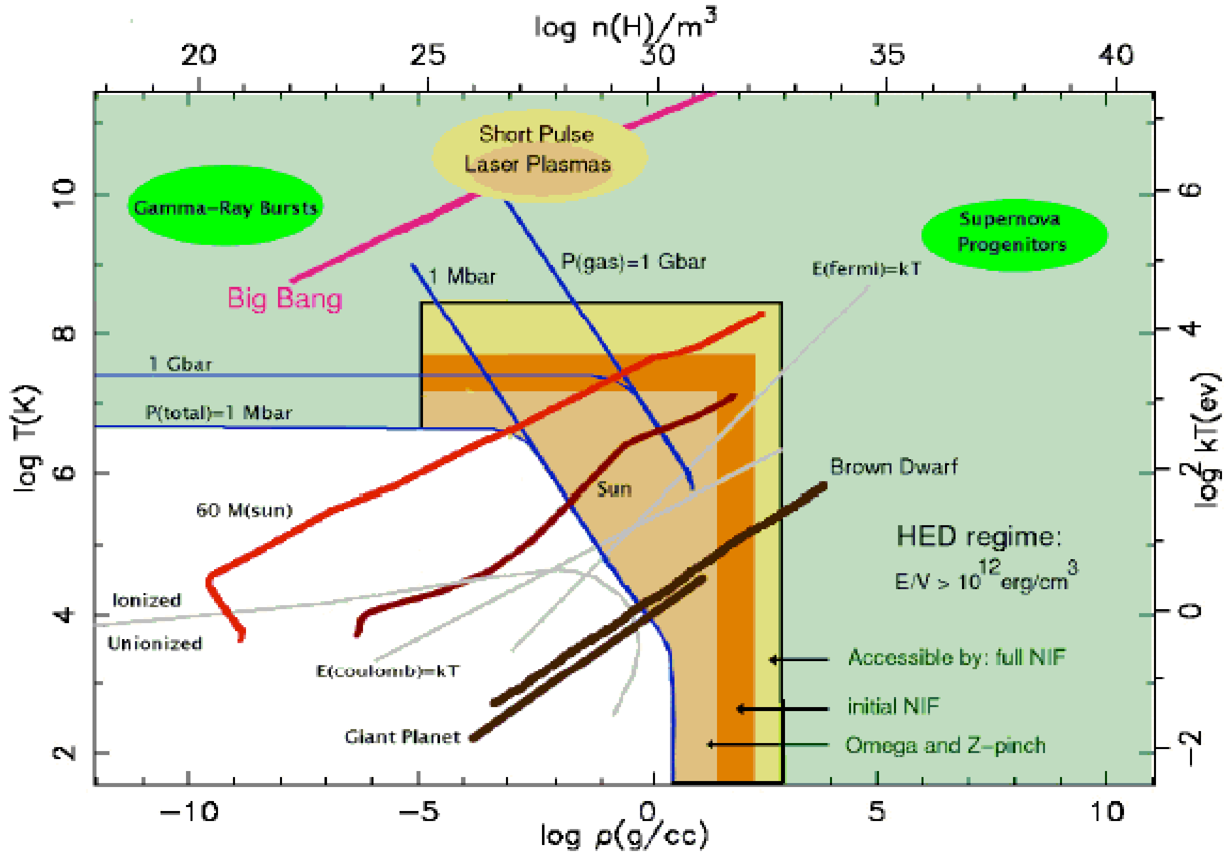
- Can focused lasers "boil the vacuum" to produce electron-positron pairs?

Questions of High Intellectual Value - continued

- Can macroscopic amounts of relativistic matter be created in the laboratory and will they exhibit fundamentally new collective behavior?
- Can we predict the nonlinear optics of multiple, interacting, unstable beamlets of intense light or matter as they filament, braid and scatter?
- Can the ultra-intense field of a plasma wake be used to make an ultra-high-gradient accelerator with the luminosity and beam quality needed for applications in high energy and nuclear physics?
- Can high energy density beam-plasma interactions lead to novel radiation sources?

Definition of High Energy Density Physics

The region of parameter space encompassed by high energy density physics includes a wide variety of physical phenomena at energy densities exceeding $10^{11} J/m^3$. In the figure below, the "High-Energy-Density" conditions lie in the shaded regions, above and to the right of the pressure contour labeled "P(total)=1 Mbar".



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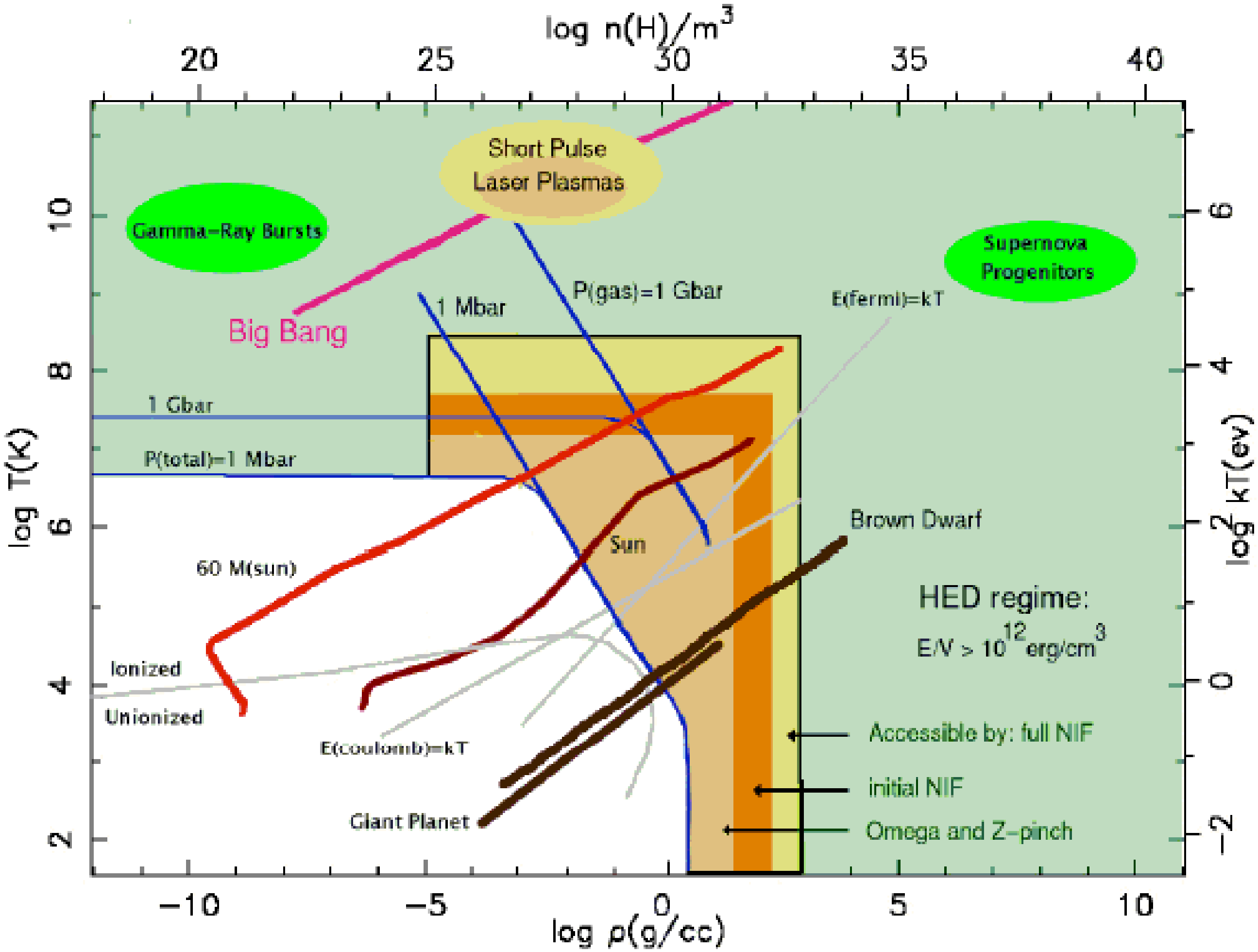


High Energy Density Physical Properties

High energy density systems exhibit a variety of physical properties that can be useful in characterizing such systems. Some of these are summarized below.

- Nonlinear and Collective Responses
- Full or Partial Degeneracy
- Dynamic Systems

Principal Findings

a. Attributes of high energy density physics.

High energy density physics (for example, pressure conditions exceeding 1 Mbar) is a rapidly growing field, with exciting research opportunities of high intellectual challenge. It spans a wide range of physics areas, including plasma physics, laser and particle beam physics, materials science and condensed matter physics, nuclear physics, atomic and molecular physics, fluid dynamics and magnetohydrodynamics, and astrophysics.

b. The emergence of new facilities

A new generation of sophisticated laboratory facilities and diagnostic instruments exist or are planned that create and measure properties of matter under extreme high energy density conditions. This permits the detailed laboratory exploration of physics phenomena under conditions of considerable interest for basic high energy density physics studies, materials research, understanding astrophysical processes, commercial applications (e.g., EUV lithography), inertial confinement fusion, and nuclear weapons research.

Principal Findings

c. The emergence of new computing capabilities

Rapid advances in high performance computing have made possible the numerical modeling of many aspects of the complex nonlinear dynamics and collective processes characteristic of high energy density laboratory plasmas, and the extreme hydrodynamic motions that exist under astrophysical conditions. The first phase of advanced computations at massively parallel facilities, such as those developed under the Advanced Strategic Computing Initiative (ASCI), is reaching fruition with remarkable achievements, and there is a unique opportunity at this time to integrate theory, experiment and advanced computations to significantly advance the fundamental understanding of high energy density plasmas.

d. New opportunities in understanding astrophysical processes

The ground-based and space-based instruments for measuring astrophysical processes under extreme high energy density conditions are unprecedented in their sensitivity and detail, revealing an incredibly violent universe in continuous upheaval. Using the new generation of laboratory high energy density facilities, macroscopic collections of matter can be created under astrophysically relevant conditions, providing critical data and scaling laws for on hydrodynamic mixing, shock phenomena, radiation flow, complex opacities, high-Mach-number jets, equations of state, relativistic plasmas, and possibly quark-gluon plasmas characteristic of the early universe.

Principal Findings

e. National Nuclear Stewardship Administration support of university research

The National Nuclear Security Administration has recently established a Stewardship Science Academic Alliances Program to fund research projects at universities in areas of fundamental high energy density science and technology relevant to stockpile stewardship. The National Nuclear Security Administration is to be commended for initiating this program. The Nation's universities represent an enormous resource for developing and testing innovative ideas in high energy density physics, and training graduate students and postdoctoral research associates—a major national resource which has heretofore been woefully underutilized.

f. The need for a broad multi-agency approach to support the field

The level of support for research on high energy density physics provided by federal agencies (e.g., National Nuclear Security Administration, the non-defense directorates in the Department of Energy, the National Science Foundation, the Department of Defense, and the National Aeronautics and Space Administration) has lagged behind the scientific imperatives and compelling research opportunities offered by this exciting field of physics. An important finding of this report is that the research opportunities in this cross-cutting area of physics are of the highest intellectual caliber and fully deserving of consideration of support by the leading funding agencies of the physical sciences. Agency solicitations in high energy density physics should seek to attract bright young talent to this highly interdisciplinary field.

Principal Findings

g. Upgrade opportunities at existing facilities

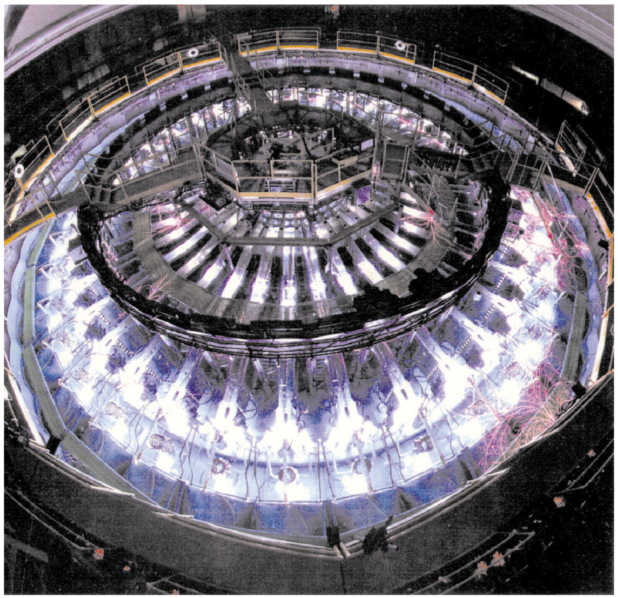
Through upgrades and modifications of experimental facilities, exciting research opportunities exist to extend the frontiers of high energy density physics beyond those which are accessible with existing laboratory systems and those currently under construction. These opportunities range (for example) from the installation of ultra-high-intensity (petawatt) lasers on inertial confinement fusion facilities, which would create relativistic plasma conditions relevant to gamma ray bursts and neutron star atmospheres, to the installation of dedicated beamlines on high energy physics accelerator facilities for carrying out high energy density physics studies, such as the development of ultra-high-gradient acceleration concepts, and unique radiation sources ranging from the infrared to the gamma ray regimes.

h. The role of Industry

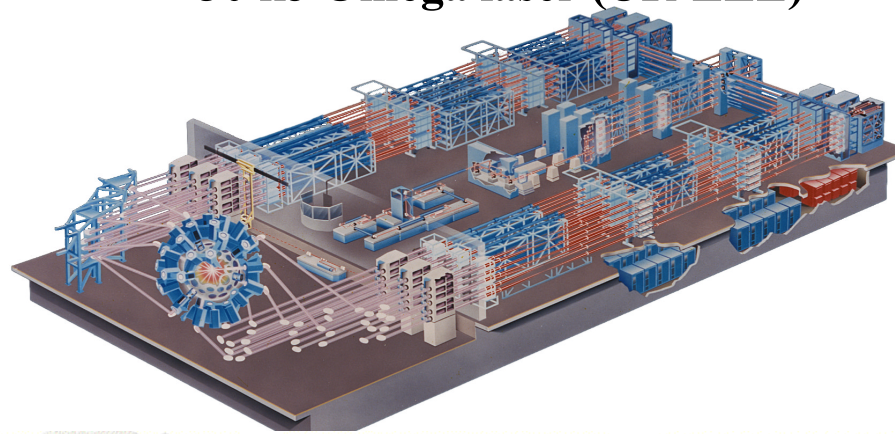
There are existing active partnerships and technology transfer between industry and the various universities and laboratory research facilities that are mutually beneficial. Industry is both a direct supplier of major hardware components to the field and has spun-off commercial products utilizing concepts first conceived for high energy density applications. Further, it is to be expected that industry will continue to benefit from future applications of currently evolving high energy density technology, and that high energy density researchers will benefit from industrial research and development on relevant technologies.

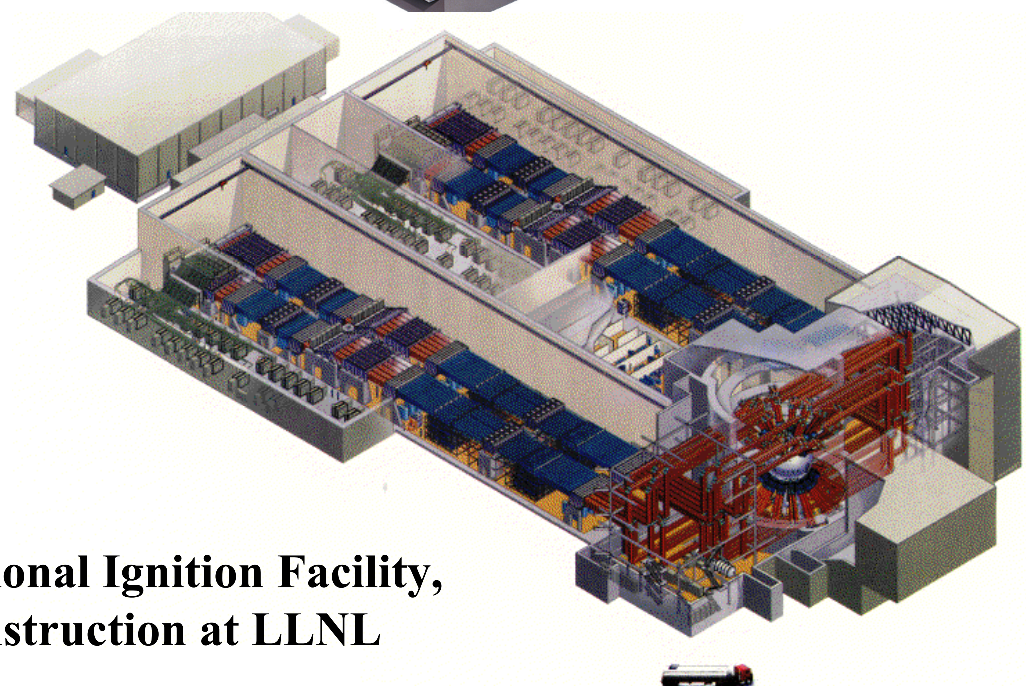
Current and future HED facilities open new frontiers in experimental high energy density science

20 MA Sandia (SNL) Z facility



30 kJ Omega laser (UR-LLE)



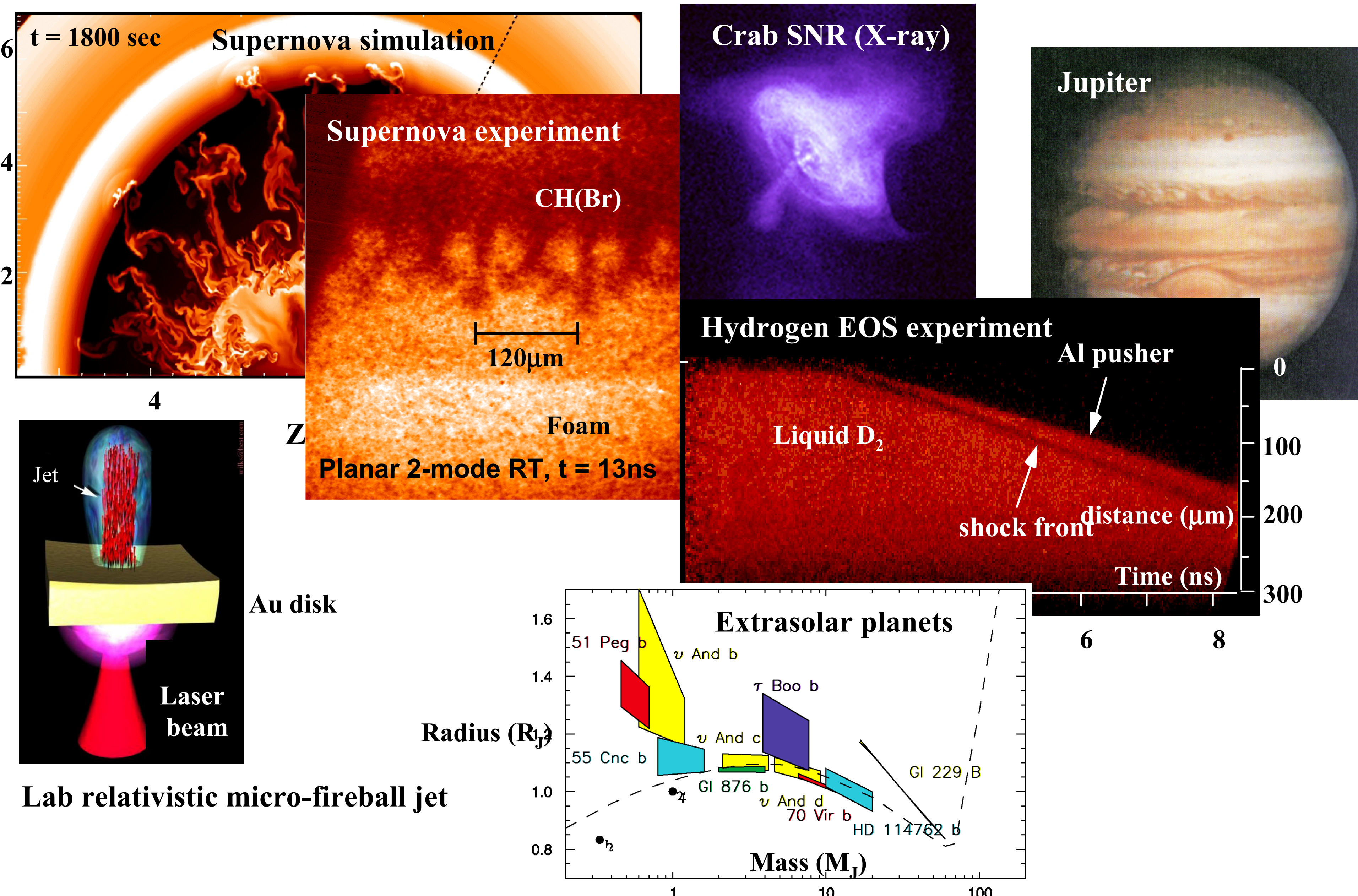


2 MJ National Ignition Facility, under construction at LLNL

Many important physics questions can be addressed in the next decade

- How does matter behave under conditions of extreme temperature, pressure, density, and electromagnetic fields?
- Can high yield thermonuclear ignition in the laboratory be used to study aspects of supernova physics and nucleosynthesis?
- Can the transition to turbulence, and the turbulent state, in high energy density systems be understood?
- What is the dynamics of strong shocks interacting with turbulent and inhomogeneous media?
- Can conditions relevant to planetary and stellar interiors, white dwarf envelopes, neutron star atmospheres, and black hole accretion disks be recreated in the laboratory on next-generation HED facilities?

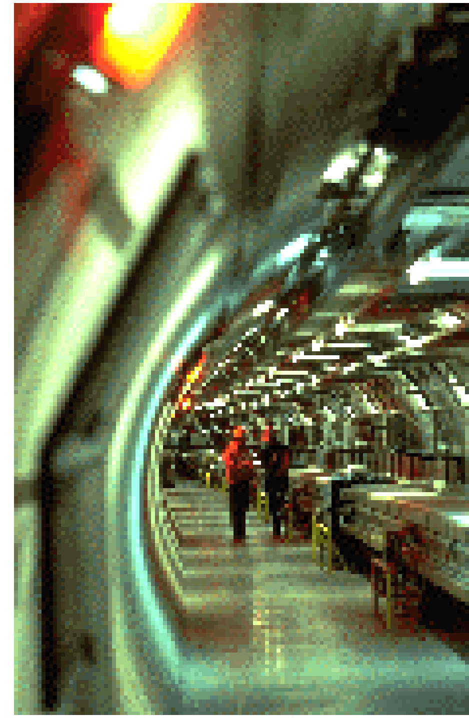
High Energy Density Physics and Astrophysics

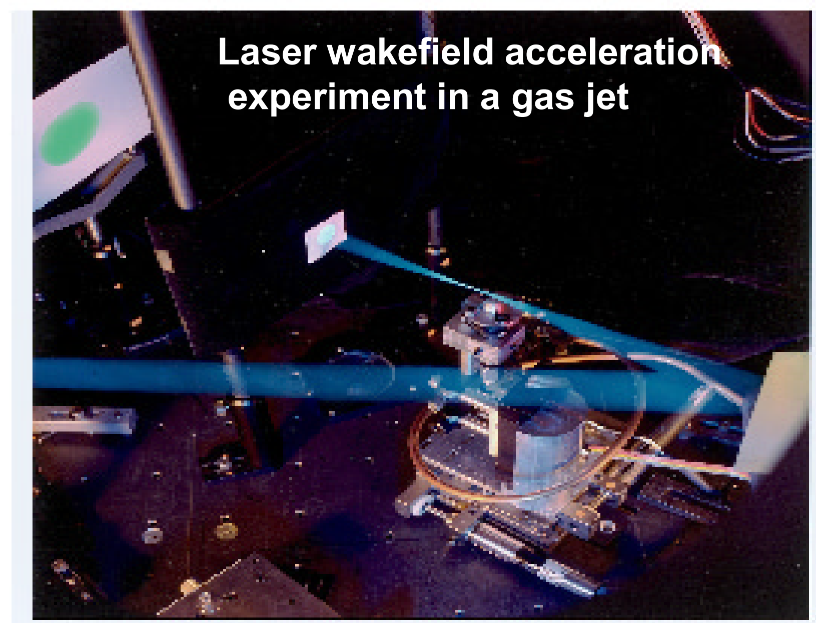


High Energy Density Physics and Astrophysics

- High Energy Density Physics aims to explore and understand the physics of matter under extraordinary conditions of temperature and density, e.g., the physics of
  - Type Ia and Type II supernovae
  - Interiors of giant gaseous planets in the solar system and beyond
  - Relativistic plasmas: neutron stars and gamma ray bursters
  - Matter in the early universe

Facilities for Laser-Plasma and Beam-Plasma Interactions Range from Very Large to Tabletop





Laser-Plasma and Beam-Plasma Interactions

- Intense laser-plasma interactions
  - Extreme non-linear optics including multiple beamlets filamenting, braiding and scattering
- Ultra-high gradient multi-GeV electron accelerators using plasma wakefields
- Fast ignition
- Novel light sources from THz to fs X-rays

Principal Recommendations

a. It is recommended that the National Nuclear Security Administration continue to strengthen its support for external user experiments on its major high energy density facilities, with a goal of about 15% of facility operating time dedicated to basic physics studies. This includes the implementation of mechanisms for providing experimental run time to users, as well as providing adequate resources for operating these experiments, including target fabrication, diagnostics, etc. A major limitation of present mechanisms is the difficulty in obtaining complex targets for user experiments.

Principal Recommendations

b. It is recommended that the National Nuclear Security Administration continue and expand its Stewardship Academic Alliances Program to fund research projects at universities in areas of fundamental high energy density science and technology. Universities develop innovative concepts and train the graduate students who will become the lifeblood of the Nation's research in high energy density physics. A significant effort should also be made by the federal government and the university community to expand the involvement of other funding agencies, such as the National Science Foundation, the National Aeronautics and Space Administration, the Department of Defense, and the non-defense directorates in the Department of Energy, in supporting research of high intellectual value in high energy density physics.

Principal Recommendations

c. A significant investment is recommended in advanced infrastructure at major high energy density facilities for the express purpose of exploring research opportunities for new high energy density physics. This is intended to include upgrades, modifications, and additional diagnostics that enable new physics discoveries outside the mission for which the facility was built. Joint support for such initiatives is encouraged from agencies with an interest in funding users of the facility as well as the primary program agency responsible for the facility.

Principal Recommendations

d. It is recommended that significant federal resources be devoted to supporting high energy density physics research at university-scale facilities, both experimental and computational. Imaginative research and diagnostic development on university-scale facilities can lead to new concepts and instrumentation techniques that significantly advance our understanding of high energy density physics phenomena and in turn are implemented on state-of-the-art facilities.

Principal Recommendations

e. It is recommended that a focused national effort be implemented in support of an iterative computational-experimental integration procedure for investigating high energy density physics phenomena.

f. It is recommended that the National Nuclear Security Administration continue to develop mechanisms for allowing open scientific collaborations between academic scientists and the Department of Energy National Nuclear Security Administration laboratories and facilities, to the maximum extent possible, given national security priorities.

Principal Recommendations

g. It is recommended that federal interagency collaborations be strengthened in fostering high energy density basic science. Such program collaborations are important for fostering the basic science base, without the constraints imposed by the mission orientation of many of the Department of Energy’s high energy density programs.

Conclusions

Accomplishments of the present study:

- Reviewed advances in high energy density physics on laboratory and astrophysical scales.
- Assessed the field, and highlighted scientific research opportunities.
- Developed a unifying framework for the field.
- Identified intellectual challenges.
- Outlined strategy to extend forefronts of the field.

Future challenges (illustrative):

- Prioritize research opportunities.
- Foster federal support for high energy density physics by multiple agencies.