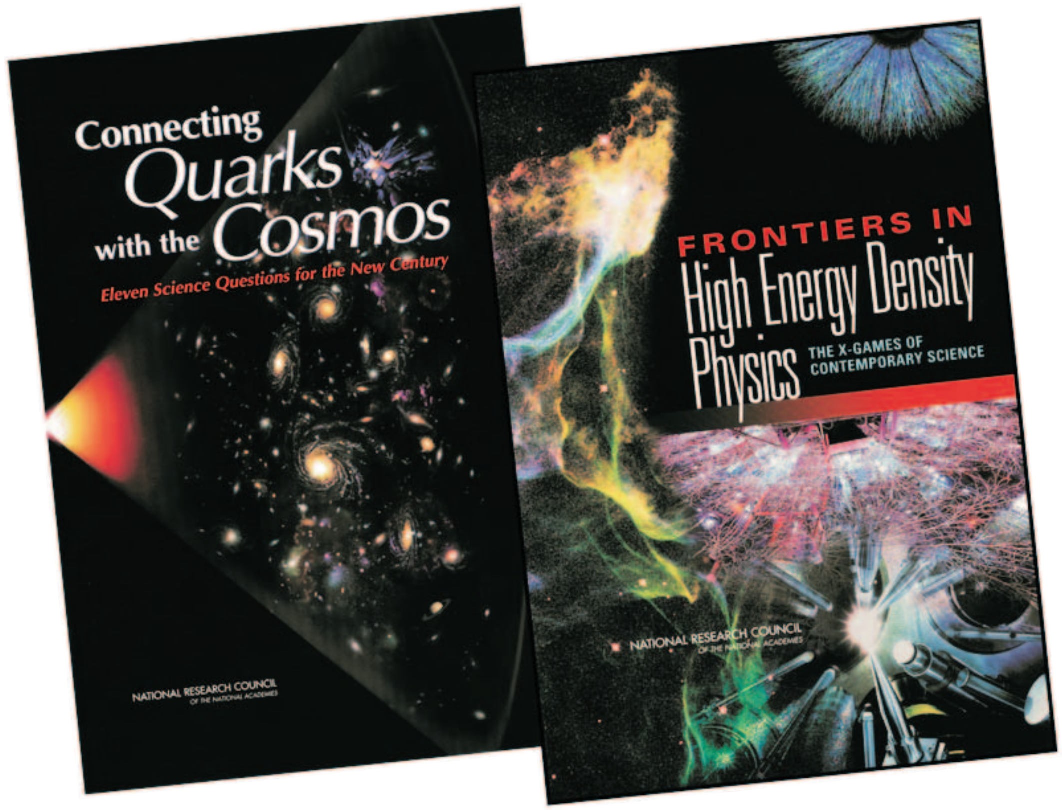
National Research Council Study on Frontiers in High-Energy-Density Physics



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Forum on the Future of Fusion
Fusion Power Associates
Washington, DC
19–21 November 2003

Summary

High-energy-density physics (HEDP) is a rapidly growing research area

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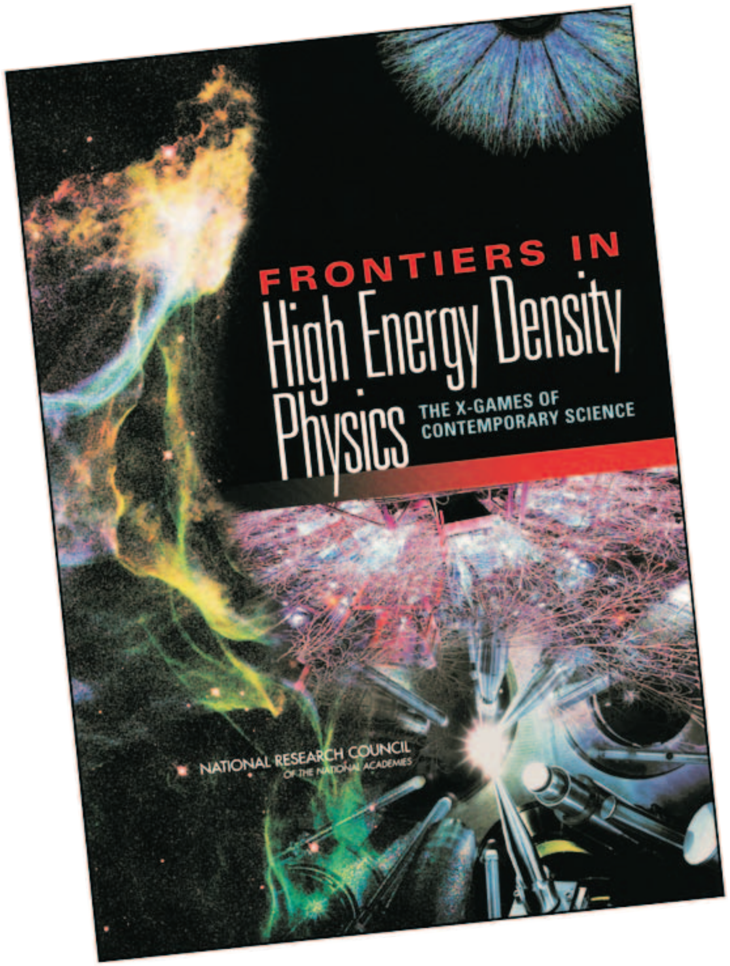
- Pressures in excess of 1 Mbar constitute high-energy-density conditions.
- Major advances in a number of areas are coming together to rapidly drive HEDP research:
  - astrophysical observations
  - high-power lasers and z-pinches
  - advanced computing
- The traditional paradigms and approximations become invalid in this regime.
- Synergies are developing among previously uncommunicative fields—laboratory astrophysics.
- Recent NRC reports have generated significant governmental interest.

HEDP research is likely to expand rapidly in the next few years.

National Academy studies have highlighted high-energy-density physics (I)

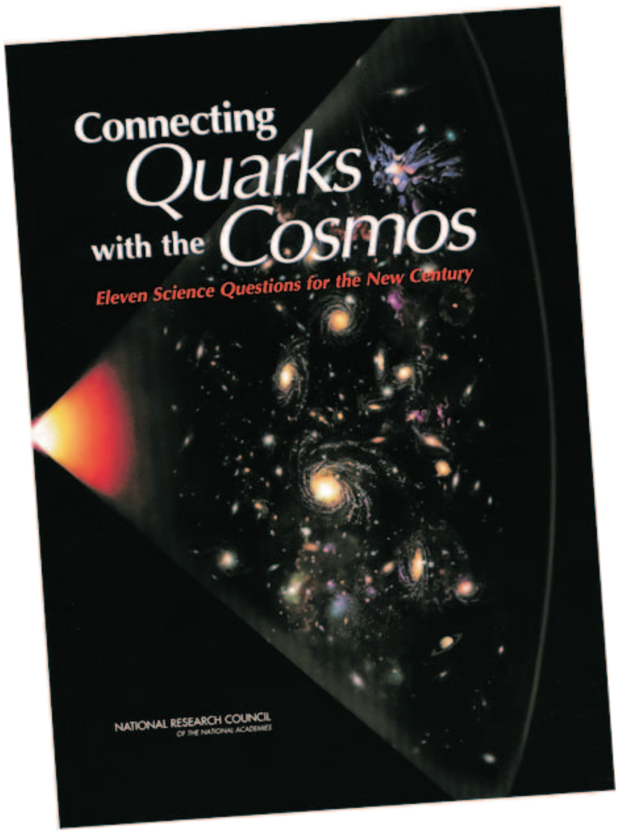


"Frontiers in High Energy Density Physics"
(R. Davidson *et al*.)

"..research opportunities in this crosscutting area of physics are of the highest intellectual caliber and are fully deserving of the consideration of support by the leading funding agencies of the physical sciences."

E12543

Recent National Academy studies have highlighted high-energy-density physics (II)



“ **Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century” (M. Turner *et al.*) Report recommendation:**

> **“Discern the physical principles that govern extreme astrophysical environments through the laboratory study of high-energy-density physics. The committee recommends that the agencies cooperate in bringing together the different scientific communities that can foster this rapidly developing field.”**

HED conditions can be defined in a number of ways

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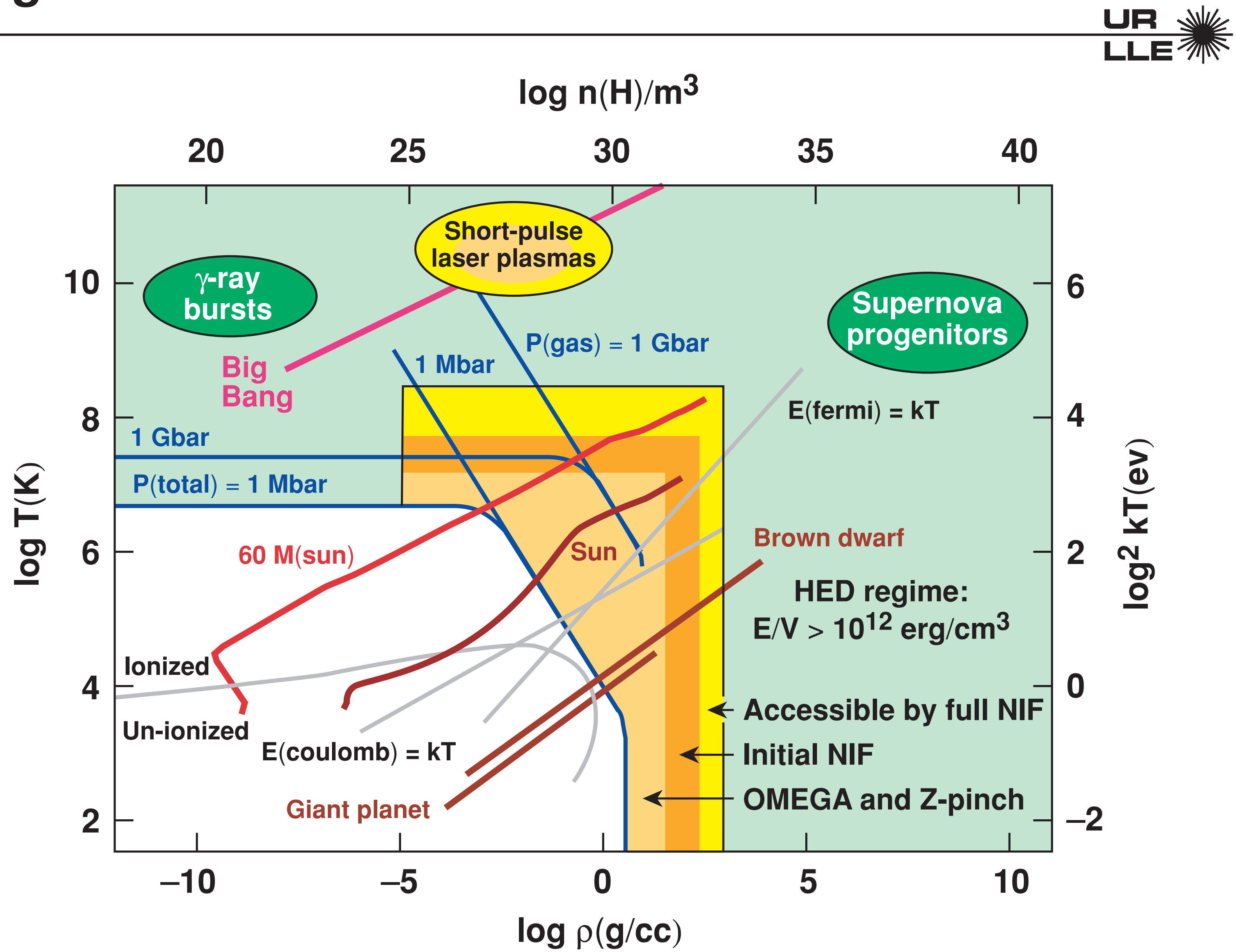
- In solid materials, when the shock strength is sufficiently large that the materials become compressible,
  - typical bulk moduli $<$ 1 Mbar
  - HED conditions for shock strengths $>$ 1 Mbar
  - 1 Mbar = 10^5 J/cm^3 = 10^{11} J/m^3

- The energy density of a hydrogen molecule (dissociation) is similar.

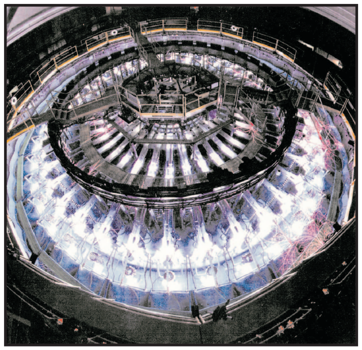
- HED systems typically show
  - collective effects
  - full or partial degeneracy
  - dynamic effects often leading to turbulence

High-energy-density conditions are found throughout the universe

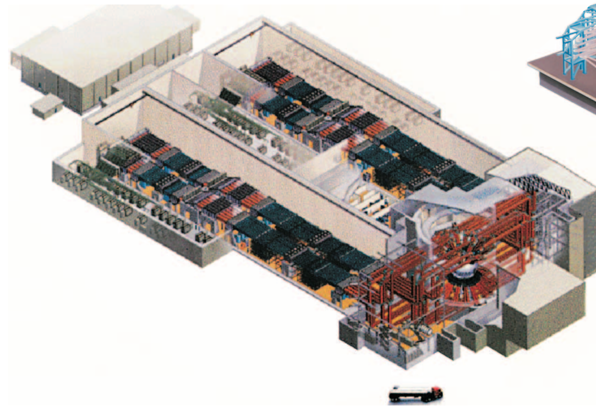


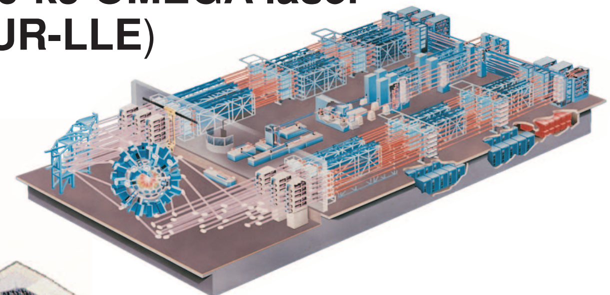
E12545

The United States will soon have three major compression facilities



20-MA Sandia (SNL) Z facility



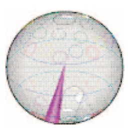
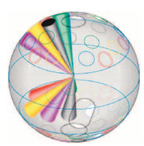


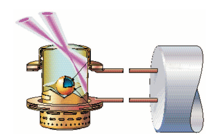
30-kJ OMEGA laser (UR-LLE)

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

The National Ignition Facility

NIF schedule:

First quad	First cluster	Eight-fold two cones	Full NIF
			
Beams: 4	48	120	192



Ignition cryo

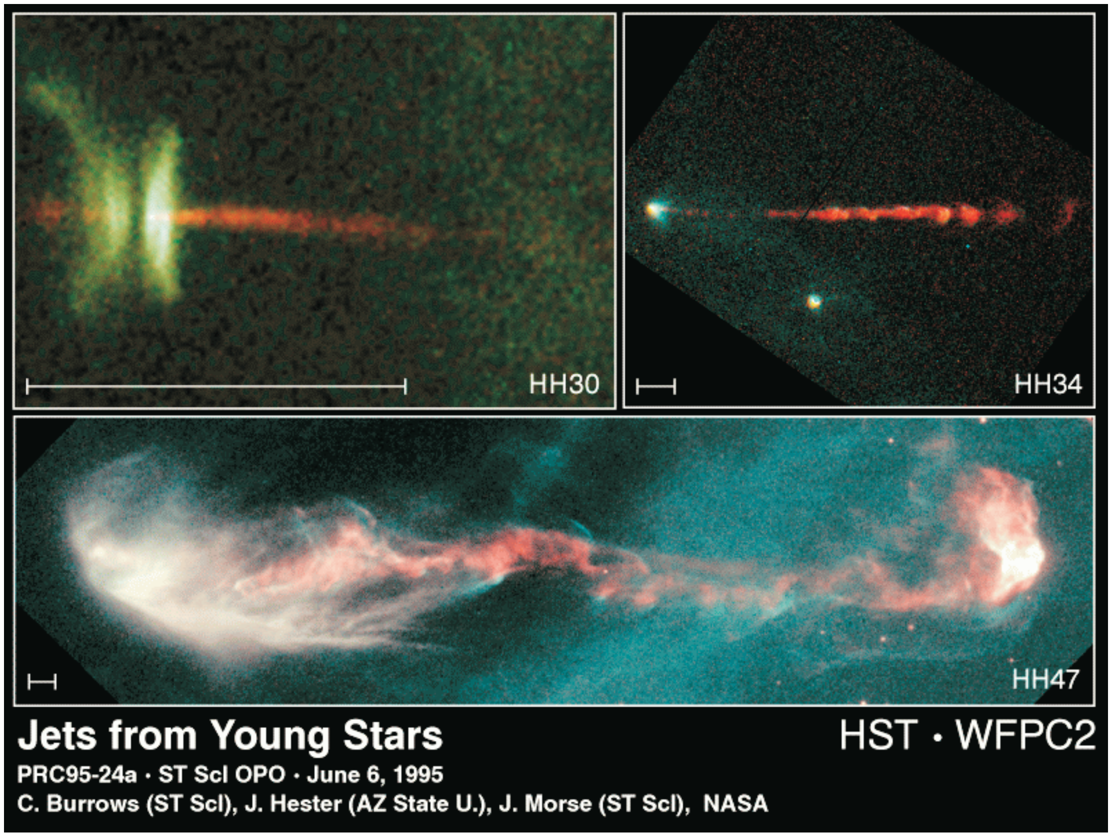
FY02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13

ZR OMEGA EP

All facilities are planning to add high-energy petawatt lasers.

I1406b

Jets are part of stellar birth

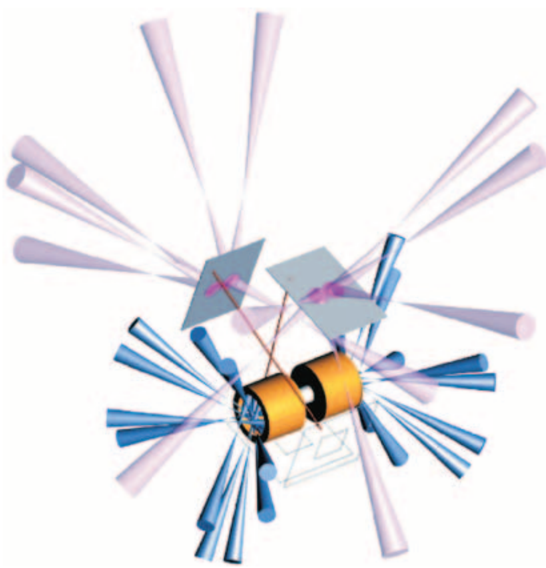


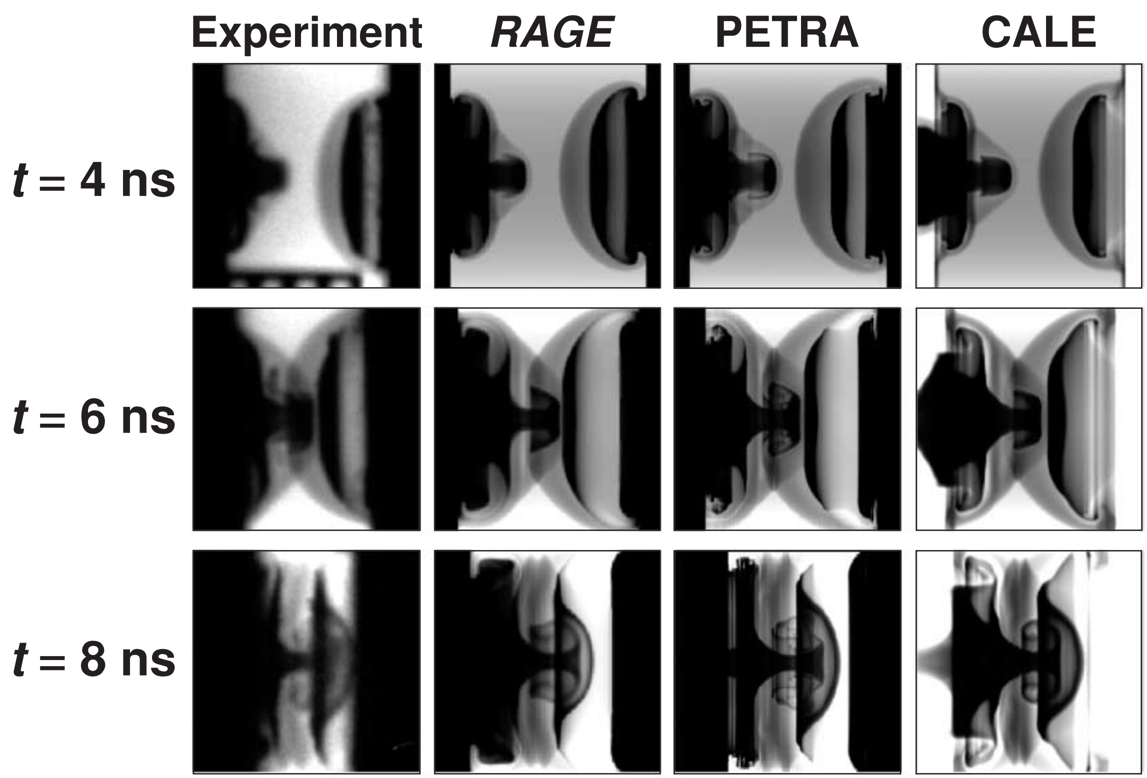
Jets from young stars show a range of jet sizes and morphologies; each scale bar is 1000 AU.

Supersonic jet experiments provided high-quality benchmark data for code comparisons

AWE

AWE jets





J. Foster, et al. Phys. Plasmas <u>9</u> 225 (2003).

The National Research Council commissioned a study of high-energy-density physics

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.

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

The goal of the study was a comprehensive review of the field and recommendations for its future

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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	Laser–plasma interactions
Beam–plasma interactions	Beam–laser interactions
Free electron laser interactions	High-current discharges
Equation-of-state physics	Atomic physics of highly stripped atoms
Theory and advanced computations	Inertial confinement fusion
Radiation–matter interaction	Hydrodynamics and shock physics

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.

The committee recognized 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

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

- A new generation of sophisticated laboratory systems ("drivers") exists or is planned that will 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.

The committee recognized 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

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LLE

- 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.

High-energy-density systems exhibit a variety of physical properties that can be useful in characterizing such systems

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- Nonlinear and collective responses
- Full or partial degeneracy
- Dynamic systems

E12709

The committee had eight principal findings

1. Attributes of high-energy-density physics (HEDP)

   High-energy-density physics is a rapidly growing field. It spans a wide range of physics areas.

2. The emergence of new facilities

   A new generation of sophisticated laboratory facilities and diagnostic instruments exist or is planned that will create and measure properties of matter under extreme high-energy-density conditions.

3. 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.

4. 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.

The committee had eight principal findings

5. **National Nuclear Stewardship Administration support of university research**

   The NNSA has 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.

6. **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 has lagged behind the scientific imperatives and compelling research opportunities offered by this exciting field of physics.

7. **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 that are currenty accessible.

8. **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.

Many important physics questions can be addressed in the next decade

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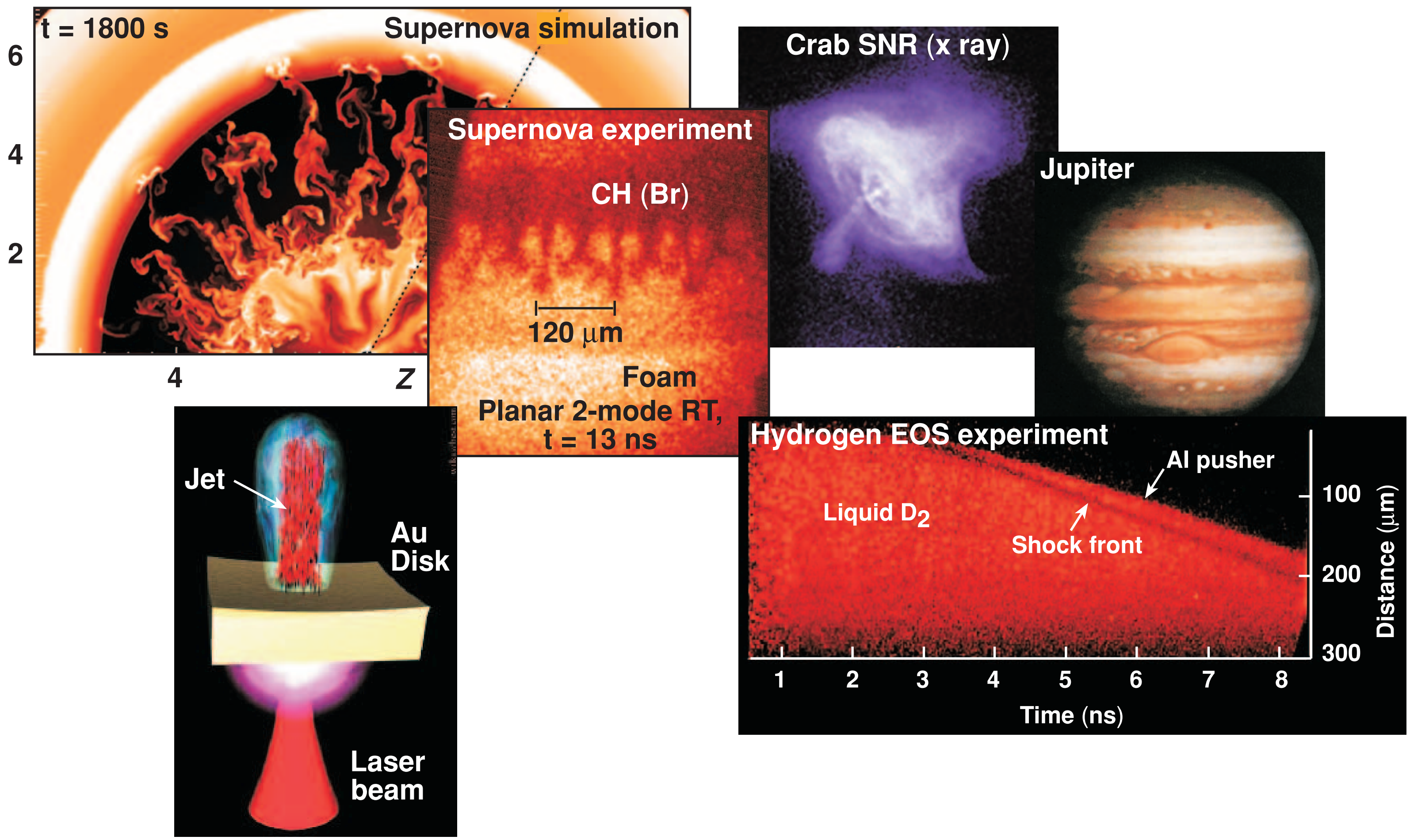
- How does matter behave under conditions of extreme temperature, pressure, density, and electromagnetic fields?
- Can high-yield thermonuclear ignition in the laboratory be used to study aspects of supernova physics and nucleosynthesis?
- Can the transition to turbulence, and the turbulent state, in 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?

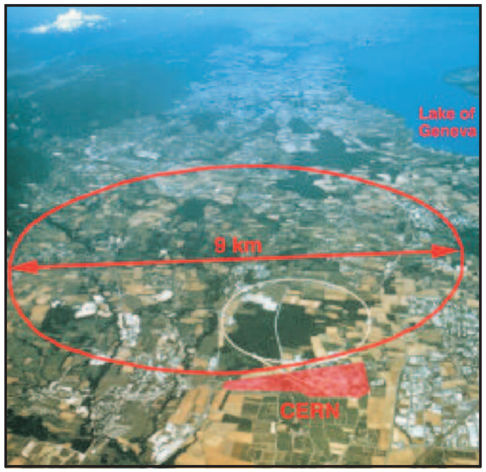
High-energy-density physics is an essential part of astrophysics



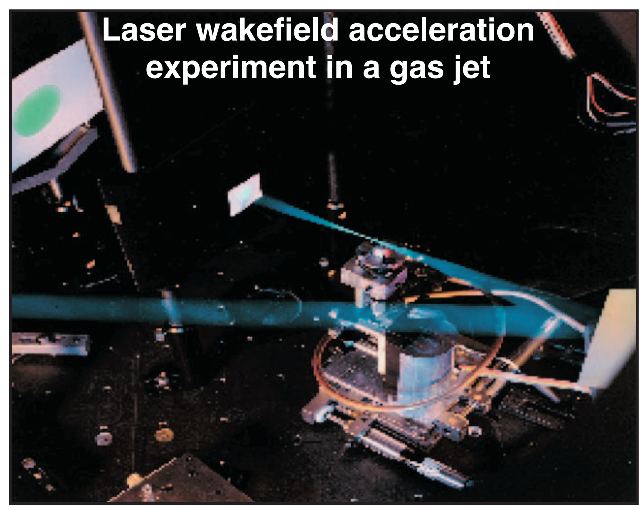
Lab relativistic micro-fireball jet

E12715

Facilities for laser–plasma and beam–plasma interactions range from very large to tabletop size




Aerial view of SLAC


Laser wakefield acceleration experiment in a gas jet

E12717

Laser–plasma and beam–plasma interactions lead to novel high-energy-density conditions

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- Intense laser–plasma interactions, including
  - extreme nonlinear optics including multiple beamlets filamenting, braiding, and scattering
- Ultrahigh gradient multi-GeV electron accelerators using plasma wakefields
- Fast ignition
- Novel light sources from THz to fs x rays

The committee had seven principal recommendations

1. 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.

2. 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. A significant effort should also be made by the federal government and the university community to expand the involvement of other funding agencies.

3. 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.

The committee had seven principal recommendations (continued)

4. It is recommended that significant federal resources be devoted to supporting high-energy-density physics research at university-scale facilities, both experimental and computational.

5. 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.

6. It is recommended that the NNSA continue to develop mechanisms that will allow open scientific collaborations with academic scientists.

7. It is recommended that federal inter-agency collaborations be strengthened in fostering high-energy-density basic science.

Questions of high intellectual value were identified

- 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?
- 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 were identified (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 were identified (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?

E12723

Summary/Conclusion

High-energy-density physics (HEDP) is a rapidly growing research area

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- Major advances in a number of areas are coming together to rapidly drive HEDP research:
  - astrophysical observations
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- The traditional paradigms and approximations become invalid in this regime.
- Synergies are developing among previously uncommunicative fields—laboratory astrophysics.
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HEDP research is likely to expand rapidly in the next few years.