

***Frontiers for Discovery
in High Energy Density Physics***

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Presented at

***U.S. - Japan Workshop on Heavy Ion Fusion
and High Energy Density Physics***

Utsunomiya University

September 28 - 30, 2005

Outline of Presentation

Provide overview of two national studies that identify research opportunities of high intellectual value in high energy density plasma science. Studies were commissioned by:

- National Academies - National Research Council (*Frontiers in High Energy Density Physics, - The X-Games of Contemporary Science* National Academies Press, 2003).
- Office of Science and Technology Policy's Interagency Working Group on the Physics of the Universe (National Task Force Report on High Energy Density Physics, July, 2004).

Charge by the National Research Council:

- 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.

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 included 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 final NRC report was published by the National Academies Press in 2003.

Follow-up study was commissioned by the Interagency Working Group on the Physics of the Universe in January, 2004.

Final report of the National Task Force on High Energy Density Physics was issued in July, 2004.

Scope of the National Research Council 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/m³), permitting the detailed exploration of physical phenomena under conditions not unlike those in astrophysical systems.

Scope of the National Research Council 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.

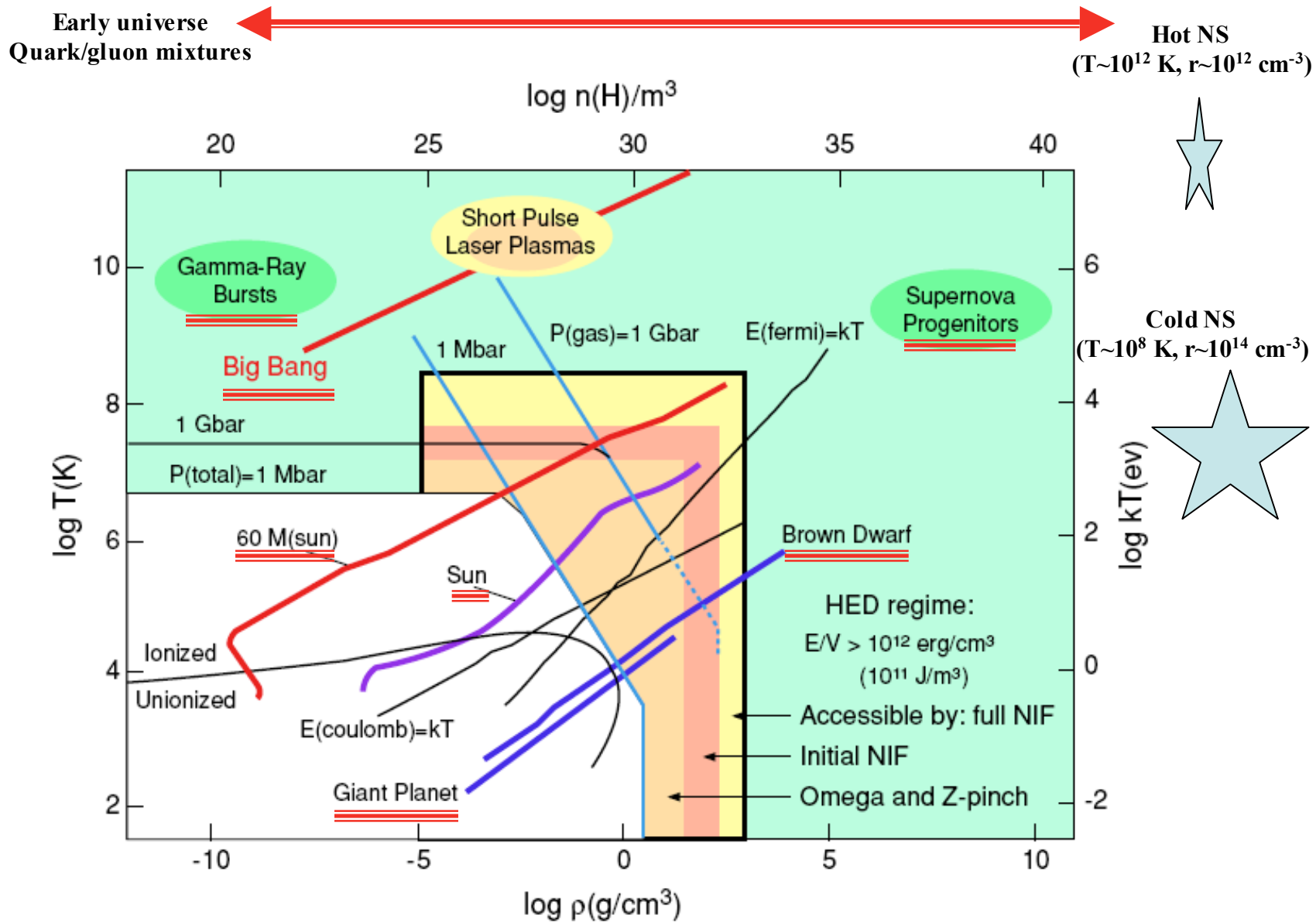
While a number of scientific areas are represented in high energy density physics, many of the techniques have grown out of ongoing research in plasma science, astrophysics, beam physics, accelerator physics, magnetic fusion, inertial confinement fusion, and nuclear weapons research.

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

Definition of High Energy Density

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

MAP OF THE HED UNIVERSE



Principal Findings

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.

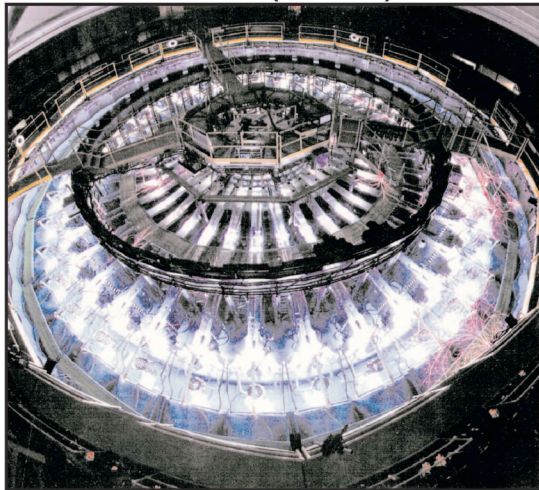
Principal Findings

d. New opportunities in understanding astrophysical processes

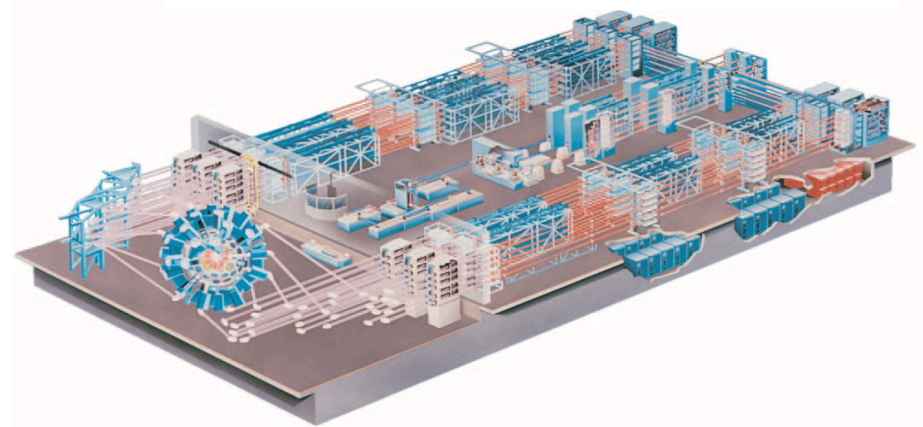
- The ground-based and space-based instruments for measuring astrophysical processes under extreme high energy density conditions are unprecedented in their sensitivity and detail, revealing an incredibly violent universe in continuous upheaval.
- Using the new generation of laboratory high energy density 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.

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

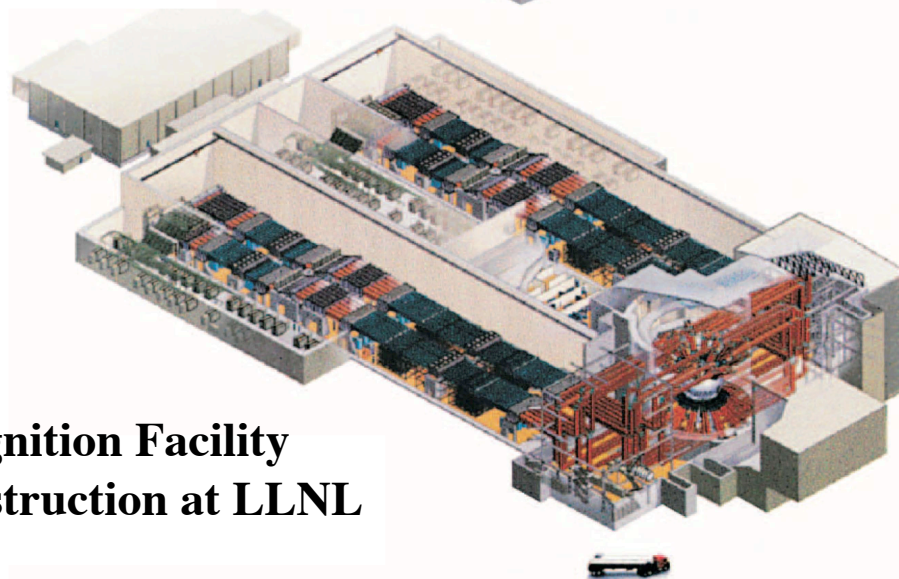
20 MA SNLA Z-Facility



30-kJ OMEGA laser (UR-LLE)



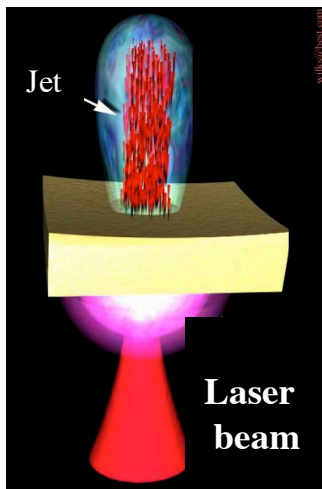
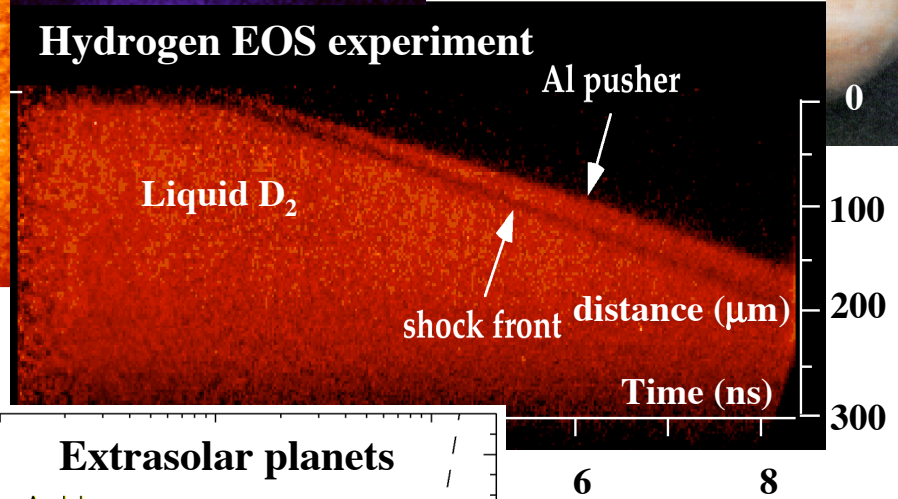
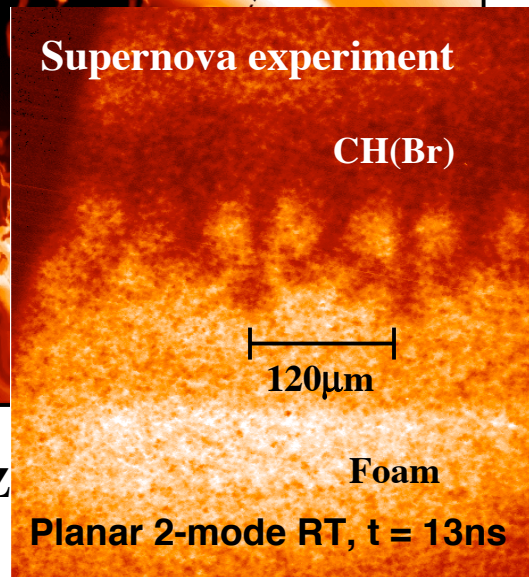
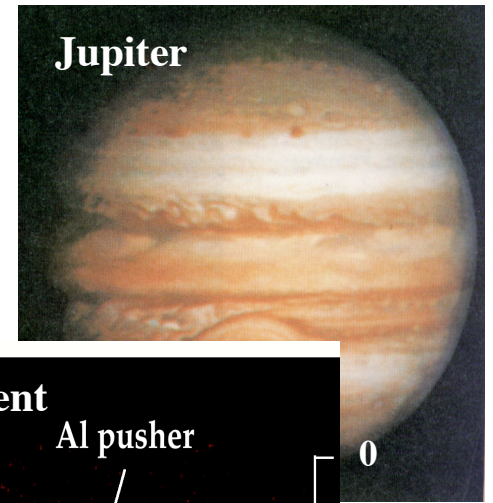
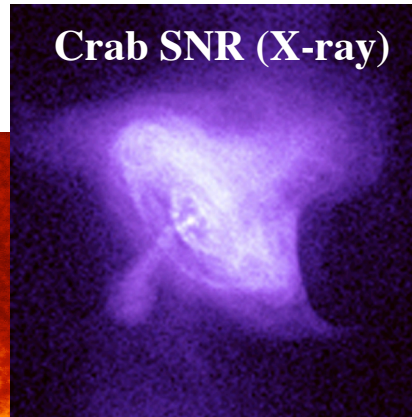
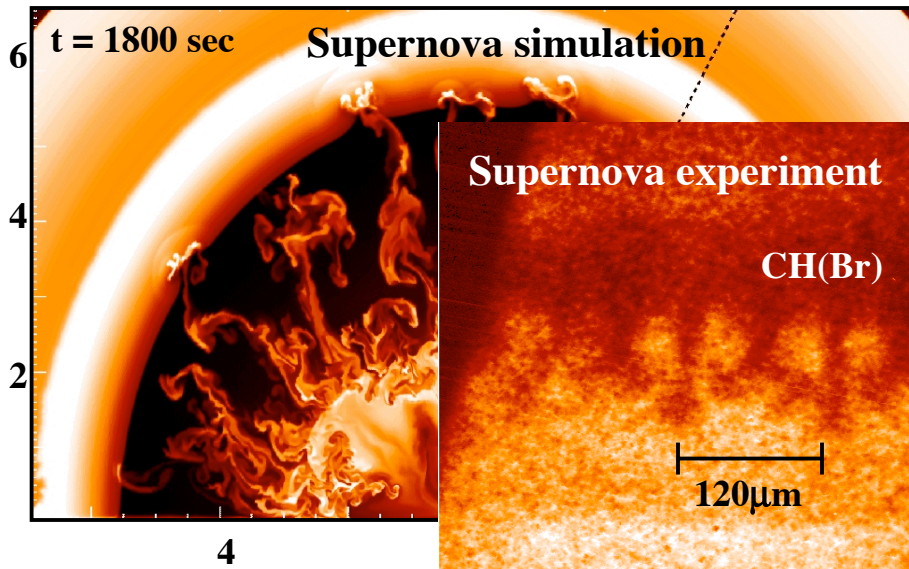
**2-MJ National Ignition Facility
(NIF) under construction at LLNL**



Many important physics questions can be addressed in the next decade

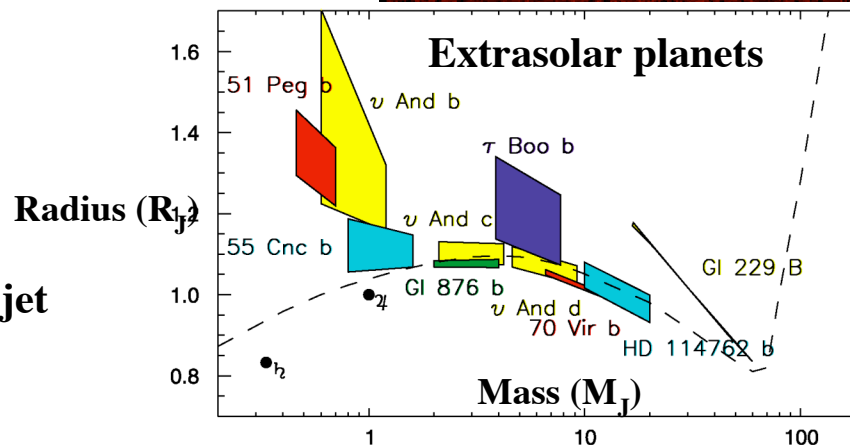
- How does matter behave under conditions of extreme temperature, pressure, density, and electromagnetic fields?
- Can high yield thermonuclear ignition in the laboratory be used to study aspects of supernova physics and nucleosynthesis?
- Can the transition to turbulence, and the turbulent state, in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



Au disk

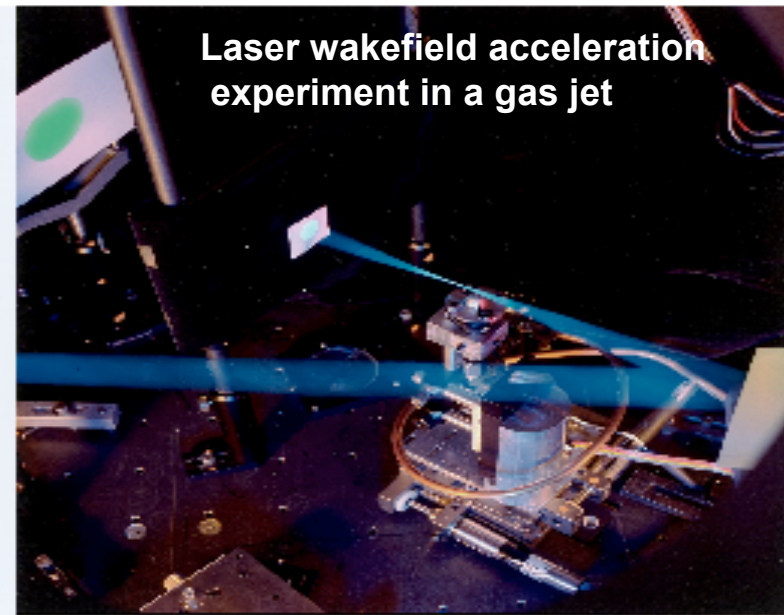
Lab relativistic micro-fireball jet



High Energy Density Plasma Science 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; and
 - Matter in the early universe.

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



Laser-Plasma and Beam-Plasma Interactions

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

Conclusions of the National Research Council Study

Accomplishments of the 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.

Illustrative future challenges:

- Prioritize research opportunities.
- Clearly identify research thrusts and compelling questions of high intellectual value.
- Foster federal support for high energy density physics by multiple agencies.

TASK FORCE CHARGE AND APPROACH

HEDP Task Force

In response to the January 13, 2004, charge letter from Joe Dehmer on behalf of the Interagency Working Group, the HEDP Task Force addressed the following key charge areas in order to identify the major components of a national high energy density physics program:

1. Identify the principal research thrust areas of high intellectual value that define the field of high energy density physics;
2. For each of the thrust areas, identify the primary scientific questions of high intellectual value that motivate the research;

TASK FORCE CHARGE AND APPROACH

HEDP Task Force

3. Develop the compelling scientific objectives and milestones that describe what the federal investment in high energy density physics are expected to accomplish;
4. For each principal thrust area, identify the frontier research facilities and infrastructure required to make effective progress; and
5. Identify opportunities for interagency coordination in high energy density physics.

KEY BACKGROUND REFERENCES FOR TASK FORCE DELIBERATIONS

HEDP Task Force

1. *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* (National Academies Press, 2003);
2. *Frontiers in High Energy Density Physics - The X-Games of Contemporary Science* (National Academies Press, 2003);
3. *The Science and Applications of Ultrafast, Ultraintense Lasers: Opportunities in Science and Technology Using the Brightest Light Known to Man* (Report on the SAUUL Workshop, June 17-19, 2002); and
4. Pertinent technical reviews and federal advisory committee reports.

TASK FORCE WORKING GROUPS

HEDP Task Force

A - HEDP in Astrophysical Systems

Rosner (Chair), Arons, Baring, Lamb, Stone

B - Beam-Induced HEDP (RHIC, heavy ion fusion, high-intensity accelerators, etc.) Joshi (Chair), Jacak, Logan, Mellisinos, Zajc

S - HEDP in Stockpile Stewardship Facilities (Omega, Z, National Ignition Facility, etc.) Remington (Chair), Deeney, Hammer, Lee, Meyerhofer, Schneider, Silvera, Wilde

U - Ultrafast, Ultraintense Laser Science

Ditmire (Chair), DiMauro, Falcone, Hill, Mori, Murnane

THRUST AREAS IN HIGH ENERGY DENSITY ASTROPHYSICS

HEDP Task Force

Thrust Area #1 - Astrophysical phenomena

What is the nature of matter and energy observed under extraordinary conditions in highly evolved stars and in their immediate surroundings, and how do matter and energy interact in such systems to produce the most energetic transient events in the universe?

Thrust Area #2 - Fundamental physics of high energy density astrophysical phenomena

What are the fundamental material properties of matter, and what is the nature of the fundamental interactions between matter and energy, under the extreme conditions encountered in high energy density astrophysics?

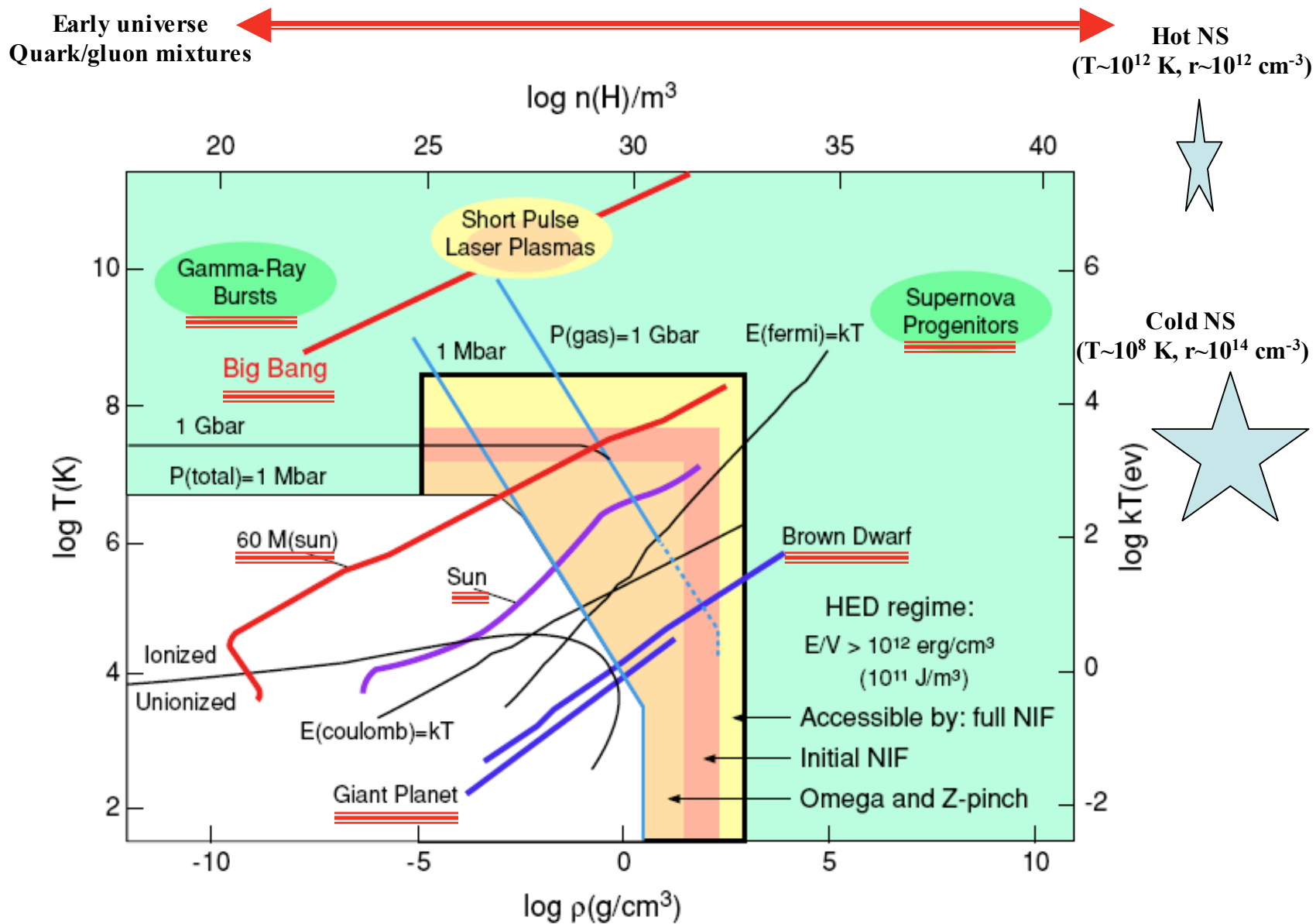
THRUST AREAS IN HIGH ENERGY DENSITY ASTROPHYSICS

HEDP Task Force

Thrust Area #3 - Laboratory astrophysics

What are the limits to our ability to test astrophysical model and fundamental physics in the laboratory, and how can we use laboratory experiments to elucidate either fundamental physics or phenomenology of astrophysical systems that are as yet inaccessible to either theory or simulations?

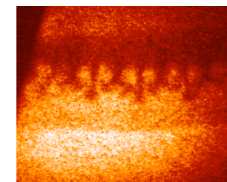
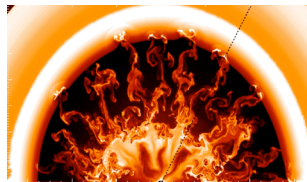
MAP OF THE HED UNIVERSE



Laboratory astrophysics

- Motivating question:
 - What are the limits to our ability to test astrophysical models and fundamental physics in the laboratory; and how can we use laboratory experiments to elucidate either fundamental physics or phenomenology of astrophysical systems as yet inaccessible to either theory or simulations?
- The four key science objectives
 - Measuring material properties at high energy densities: equations of state, opacities, ...
 - Building intuition for highly nonlinear astronomical phenomena, but under controlled lab conditions (with very different dimensionless parameters): radiation hydro, magnetohydrodynamics, particle acceleration, ...
 - Connecting laboratory phenomena/physics directly to astrophysical phenomena/physics (viz., in asymptotic regimes for Re , Rm , ...): late-time development of Type Ia and II supernovae, ...
 - Validating instrumentation, diagnostics, simulation codes, ... , aimed at astronomical observations/phenomena

Type II SN shock simulation (Kifonidis et al. 2000)



Type II SN shock experiment (Robey et al. 2001)

THRUST AREAS IN BEAM-INDUCED HIGH ENERGY DENSITY PHYSICS

HEDP Task Force

Thrust Area #4 - Heavy-ion-driven high energy density physics and fusion

How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion ignition conditions?

Thrust Area #5 - High energy density science with ultrarelativistic electron beams

How can the ultra high electric fields in a beam-driven plasma wakefield be harnessed and sufficiently controlled to accelerate and focus high-quality, high-energy beams in compact devices?

THRUST AREAS IN BEAM-INDUCED HIGH ENERGY DENSITY SCIENCE

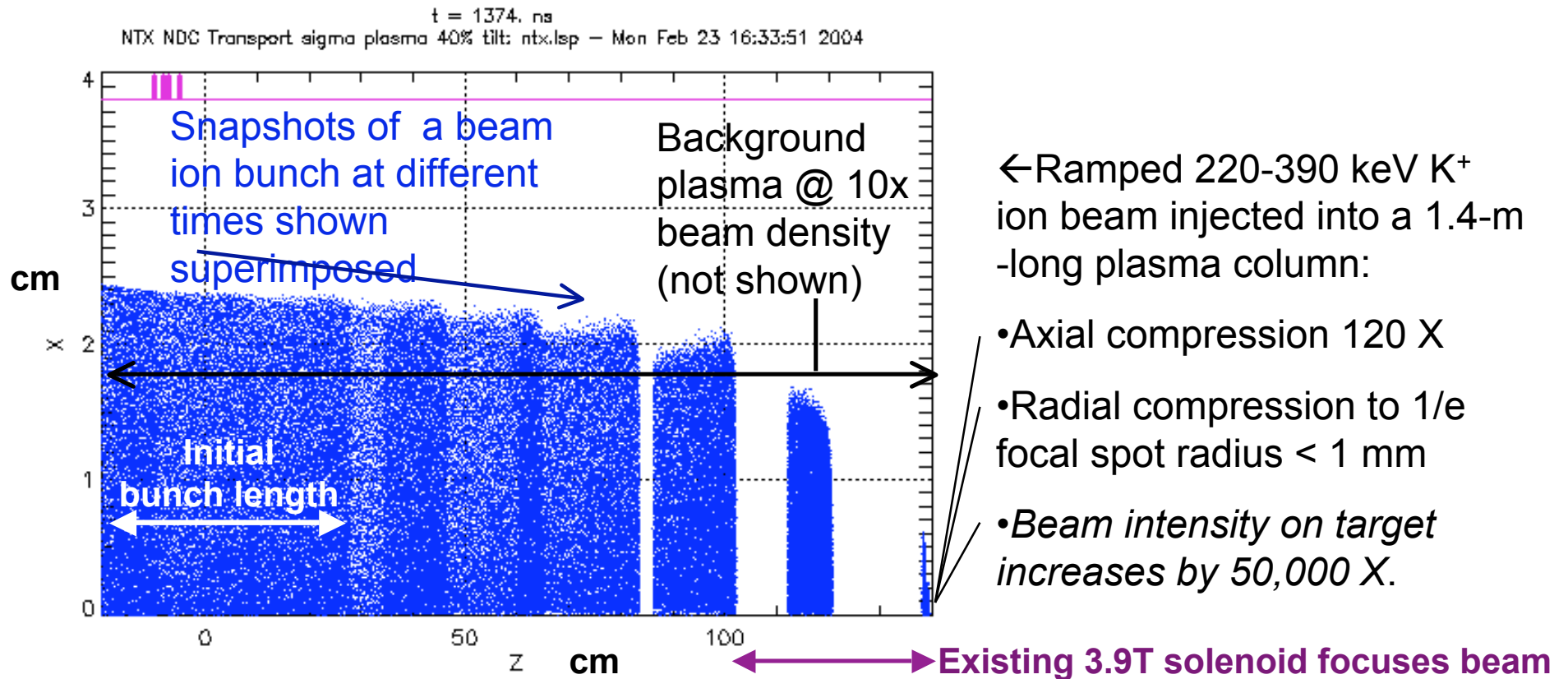
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Thrust Area #6 - Characterization of quark - gluon plasmas

What is the nature of matter at the exceedingly high density and temperature characteristic of the Early Universe?

Does the Quark Gluon plasma exhibit any of the properties of a classical plasma?

Simulations show large compressions of tailored-velocity ion beams

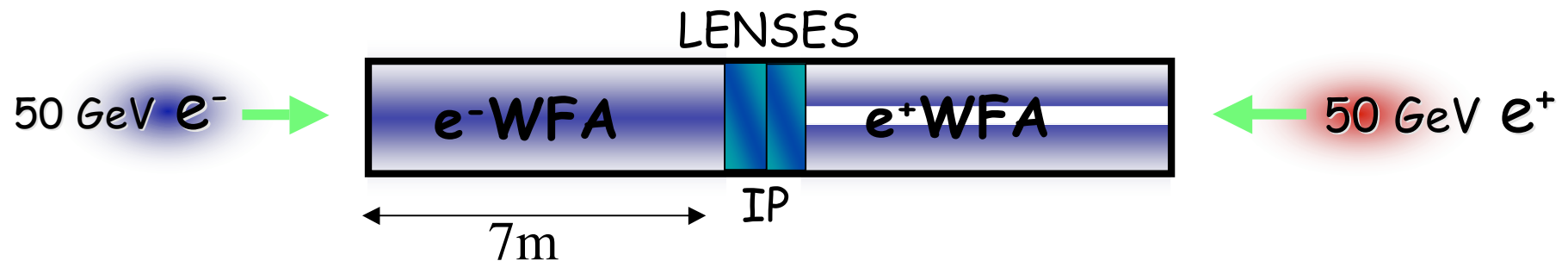


- Velocity chirp amplifies beam power analogous to frequency chirp in CPA lasers
- Solenoids and/or adiabatic plasma lens can focus compressed bunches *in plasma*
- Instabilities may be controlled with $n_p \gg n_b$, and B_z field (Welch, Rose, Kaganovich)

Plasma afterburner for energy doubling



- ◆ Double the energy of the collider with short plasma sections before collision point.
- ◆ 1st half of beam excites the wake --decelerates to 0.
- ◆ 2nd half of beams rides the wake--accelerates to $2 \times E_0$.
- ◆ Make up for Luminosity decrease $\propto N^2/\sigma_z^2$ by halving σ in a final plasma lens.



Physics of Quark - Gluon Plasmas

- **Create high(est) energy density matter**
 - Similar to that existing ~ 1 msec after the Big Bang.
 - Can study only in the lab – relics from Big Bang inaccessible.
 - $T \sim 200\text{-}400$ MeV ($\sim 2\text{-}4 \times 10^{12}$ K).
 - $U \sim 5\text{-}15$ GeV/fm³ ($\sim 10^{30}$ J/cm³).
 - $R \sim 10$ fm, $t_{\text{life}} \sim 10$ fm/c ($\sim 3 \times 10^{-23}$ sec).
- **Characterize the hot, dense medium**
 - Expect quantum chromodynamic phase transition to quark gluon plasma.
 - Does medium behave as a plasma? coupling weak or strong?
 - What is the density, temperature, radiation rate, collision frequency, conductivity, opacity, Debye screening length?
 - Probes: passive (radiation) and those created in the collision.

HIGH ENERGY DENSITY THRUST AREAS IN STOCKPILE STEWARDSHIP FACILITIES

HEDP Task Force

Thrust Area #7 - Materials properties

What are the fundamental properties of matter at extreme states of temperature and/or density?

Thrust Area #8 - Compressible dynamics

How do compressible, nonlinear flows evolve into the turbulent regime?

HIGH ENERGY DENSITY THRUST AREAS IN STOCKPILE STEWARDSHIP FACILITIES

HEDP Task Force

Thrust Area #9 - Radiative hydrodynamics

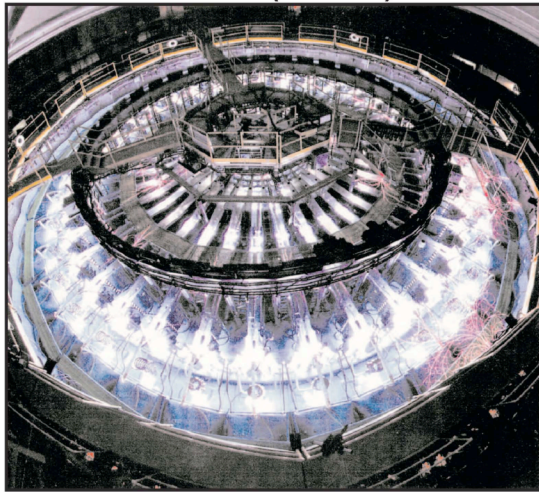
Can high energy density experiments answer enduring questions about nonlinear radiative hydrodynamics and the dynamics of powerful astrophysical phenomena?

Thrust Area #10 - Inertial confinement fusion

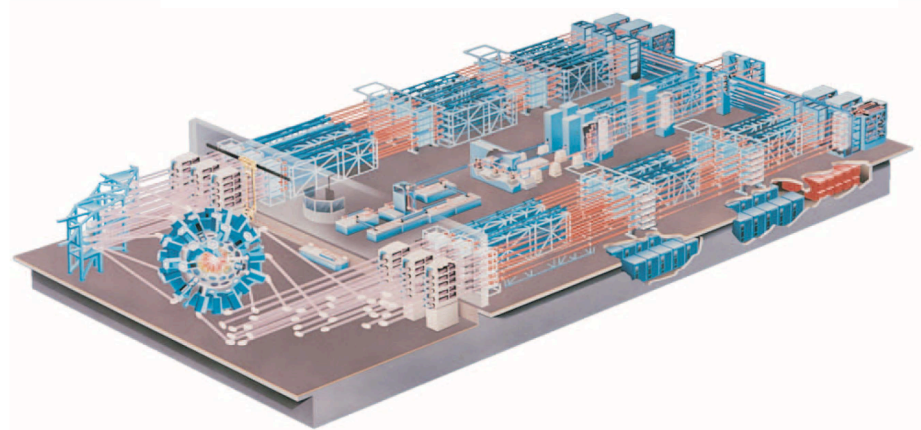
Can inertial fusion ignition be achieved in the laboratory and developed as a research tool?

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

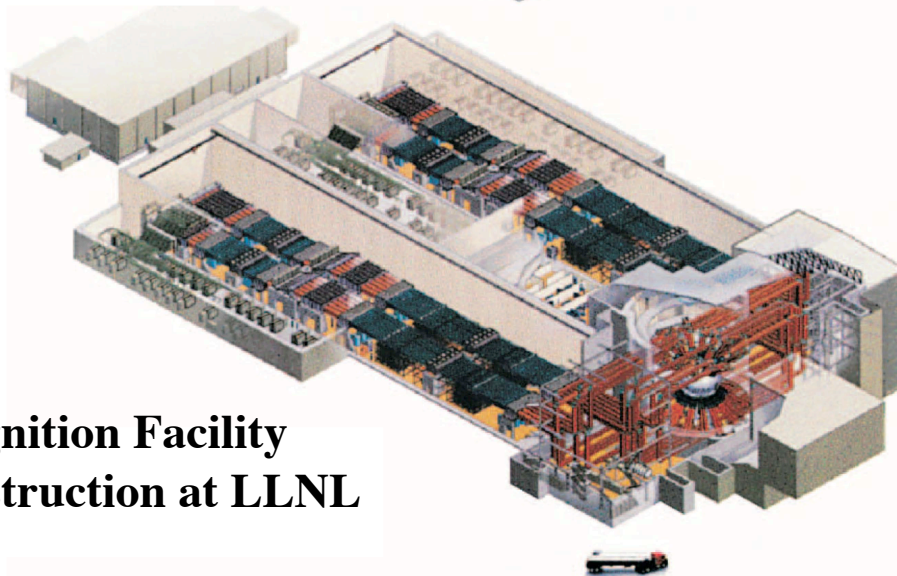
20 MA SNLA Z-Facility



30-kJ OMEGA laser (UR-LLE)

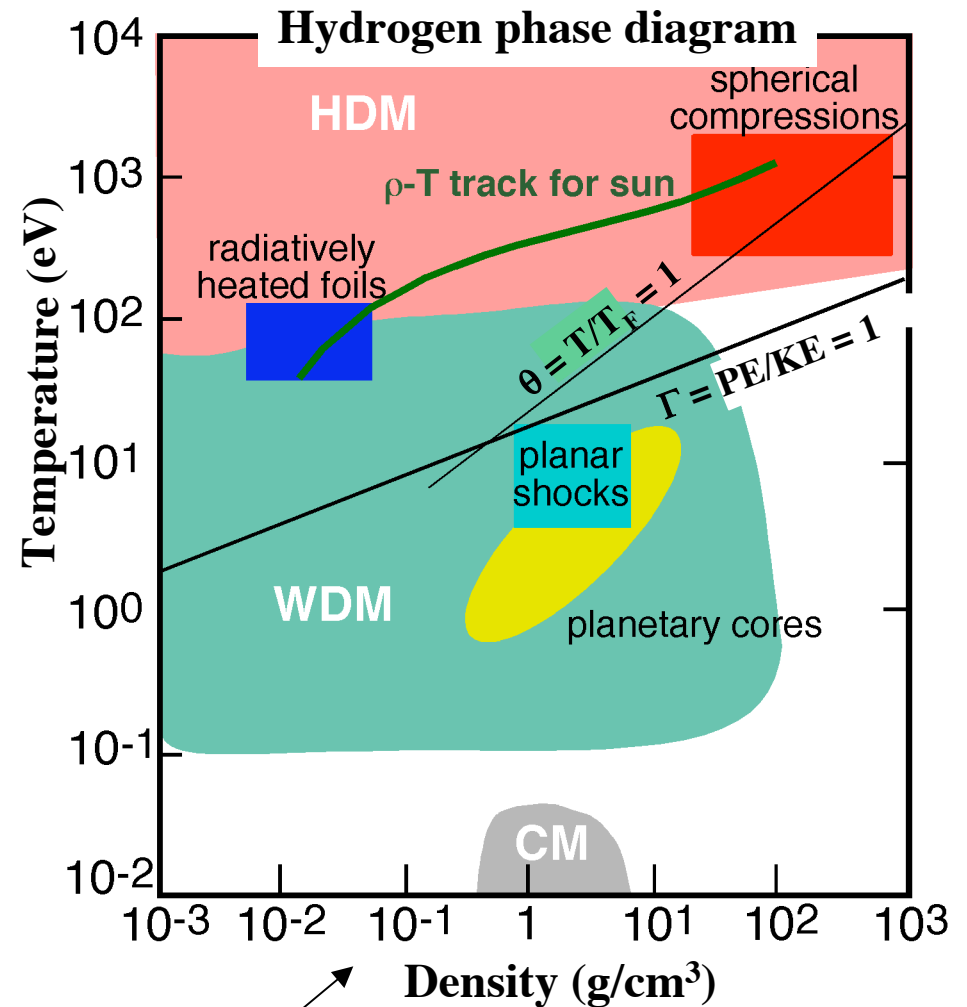


2-MJ National Ignition Facility (NIF) under construction at LLNL



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

- **Material Properties describe:**
 - Equation of State (EOS)
 - Radiative opacity
 - Conductivity, viscosity, ...
 - Equilibration time
- **Hot Dense Matter (HDM) occurs in:**
 - Stellar interiors, accretion disks
 - Laser plasmas, Z-pinch
 - Radiatively heated foams
 - ICF capsule implosion cores
- **Warm Dense Matter (WDM) occurs in:**
 - Cores of giant planets
 - Strongly shocked solids
 - Radiatively heated solid foils

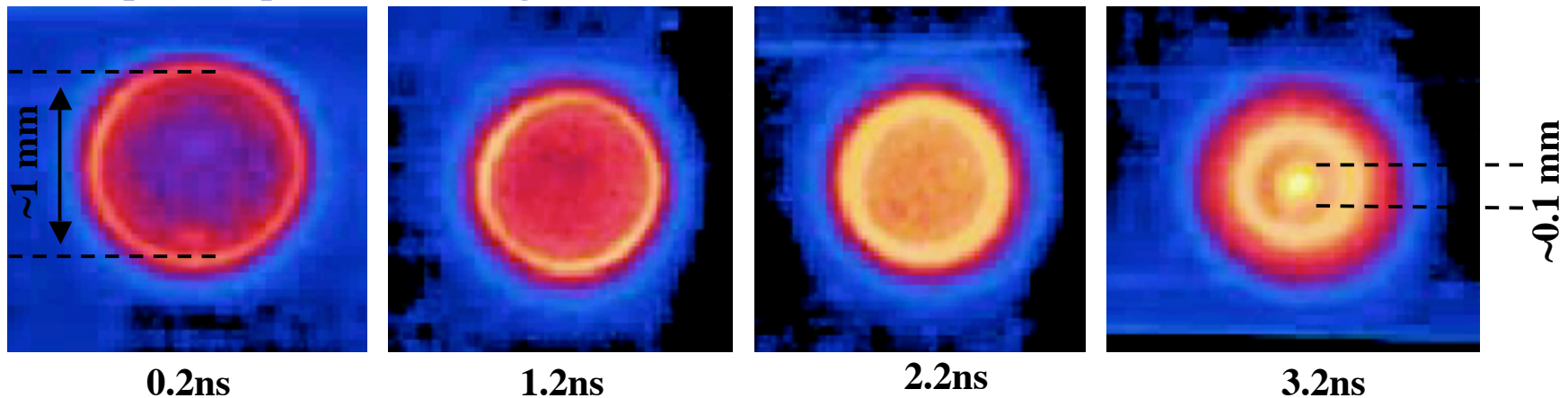


- Tenuous plasma “easy”: $\Gamma = PE/KE \ll 1$;
- Dense plasma “difficult”: $\Gamma \sim 1$ and $\theta \sim 1$

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

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

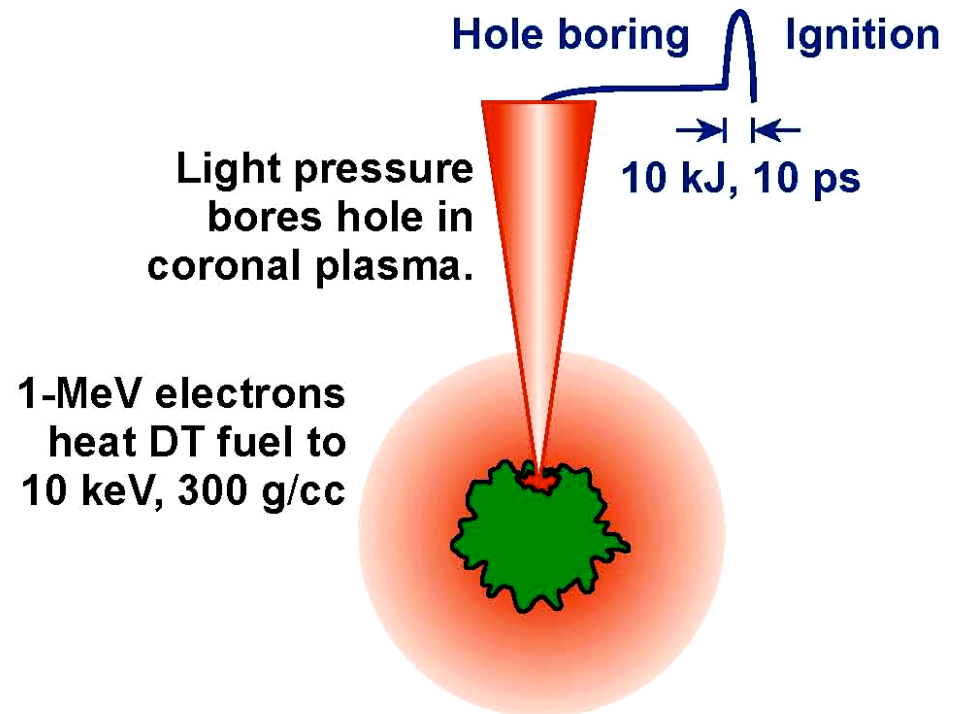
ICF capsule implosion on Omega



- ICF research involves a multitude of coupled phenomena, all occurring in a few nanoseconds on sub-millimeter spatial scales
 - Laser coupling, laser-plasma instabilities, hydrodynamic instabilities,
 - radiation transport, electron heat transport, thermonuclear fusion reactions

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

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



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

THRUST AREAS IN ULTRAFAST ULTRAINTENSE LASER SCIENCE

HEDP Task Force

Thrust Area #11 - Laser excitation of many-particle systems
at the relativistic extreme

How do many-body systems evolve in a light field under extreme relativistic conditions where an electron is accelerated to relativistic energies and particle production becomes possible in one optical cycle?

Thrust Area #12 - Attosecond physics

Can physical and chemical processes be controlled with light pulses created in the laboratory that possess both the intrinsic time- (attoseconds, $1 \text{ as} = 10^{-18} \text{ s}$) and length- (x-rays, 1 \AA) scales of all atomic matter?

THRUST AREAS IN ULTRAFAST ULTRAINTENSE LASER SCIENCE

HEDP Task Force

Thrust Area #13 - Ultrafast, high-peak-power x-rays

Can intense, ultra-fast x-rays become a routine tool for imaging the structure and motion of “single” complex bio-molecules that are the constituents of all living things?

Can nonlinear optics be applied as a powerful, routine probe of matter in the XUV/x-ray regime?

Thrust Area #14 - Compact high energy particle acceleration

How can ultra-intense ultra-short pulse lasers be used to develop compact GeV to TeV class electron and or proton/ion accelerators?

THRUST AREAS IN ULTRAFAST ULTRAINTEENSE LASER SCIENCE

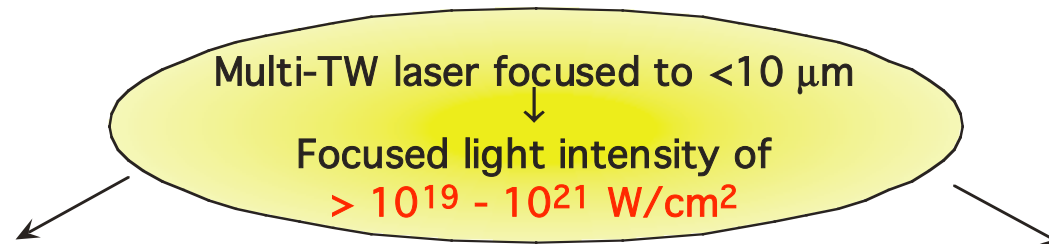
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Thrust Area #15 - Inertial fusion energy fast ignition

Is it possible to make controlled nuclear fusion useful and efficient by heating plasmas with an intense, short pulse laser?

Chirped pulse amplification lasers access extremes in field strength and energy density

HEDP Task Force



High Field Science

High electric fields

$$E \sim 10^{10} - 10^{11} \text{ V/cm}$$

Field strength is 10 to 100 times that of the electric field felt by an electron in a hydrogen atom

High electron quiver energy

$$U_{osc} = 60 \text{ keV} - 3 \text{ MeV}$$

Electron motion can become relativistic ($U_{osc} > m_e c^2 = 512 \text{ keV}$)

High Energy Density Science

Concentrated energy

Energy density in a femtosecond pulse is 10^9 J/cm^3

Corresponds to $\sim 10 \text{ keV}$ per atom at solid density

High brightness and pressure

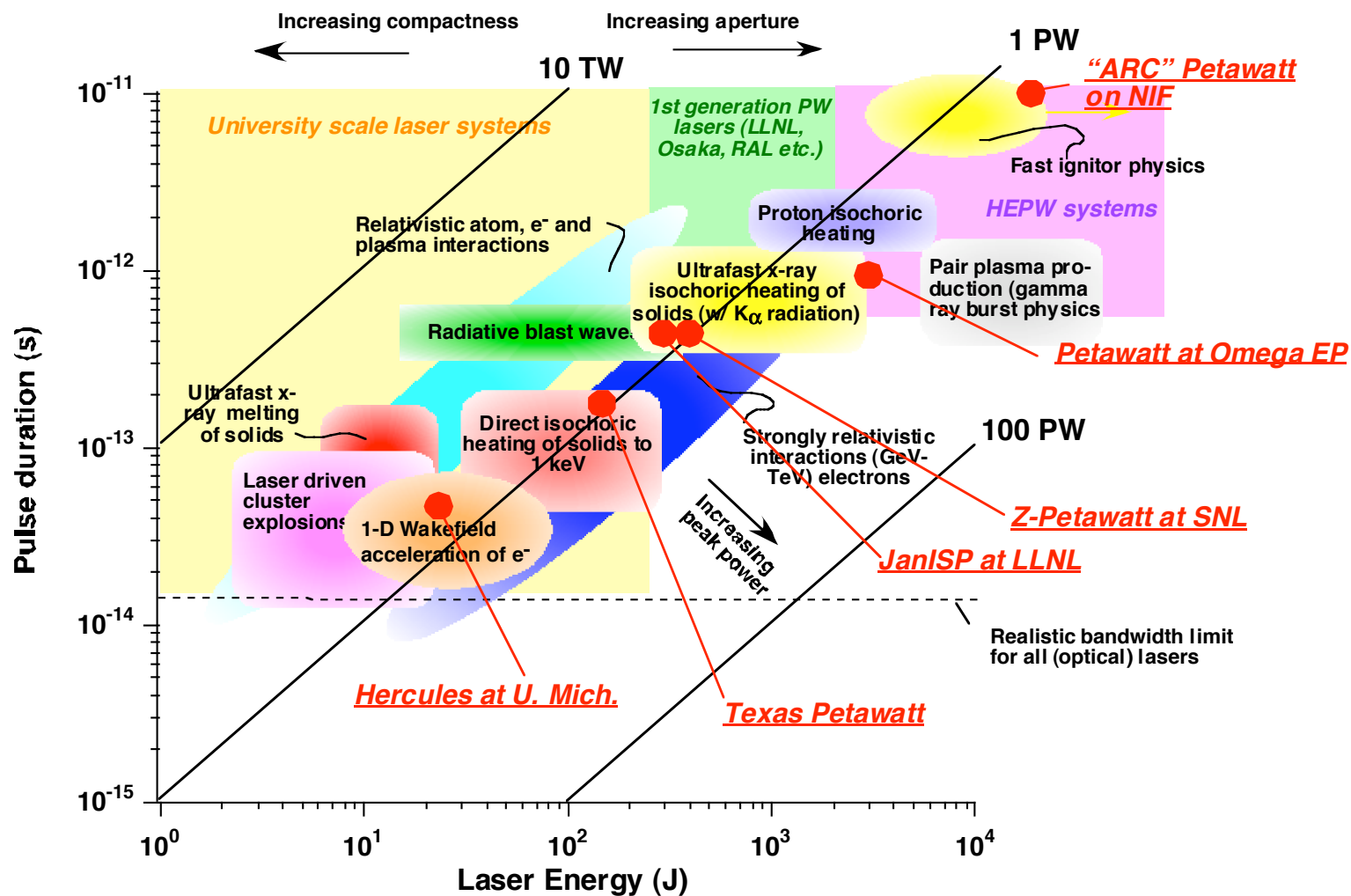
Radiance exceeds that of a 10 keV black body

Light pressure $P = I/c = 0.3 - 30 \text{ Gbar}$

A variety of different types of Petawatt class lasers are under development, accessing many potential applications

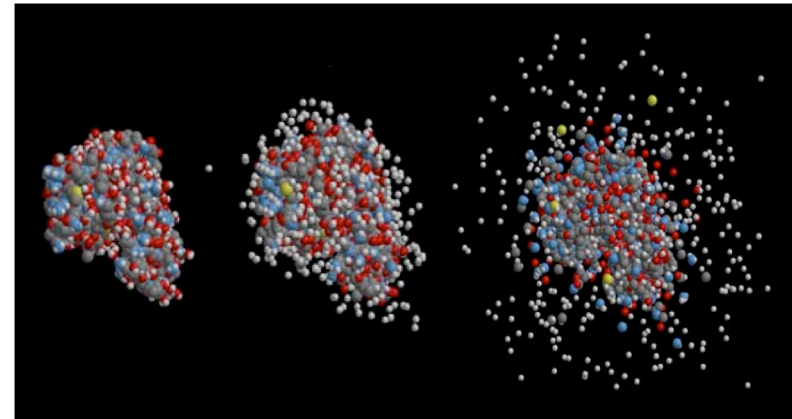
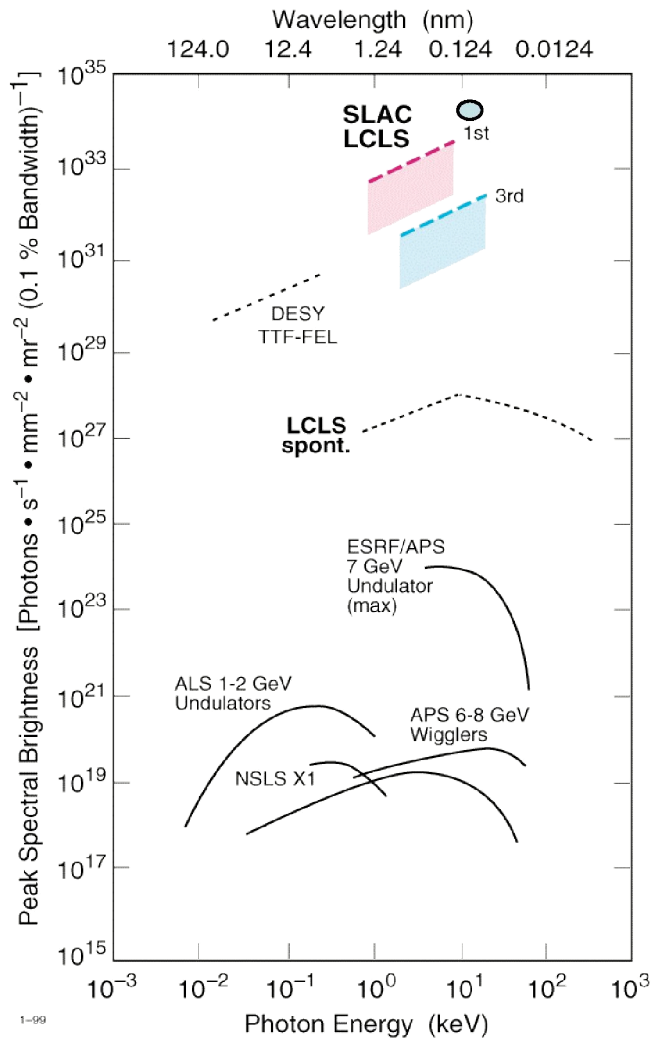
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Applications and Petawatt lasers under development in the US



The LINAC Coherent Light Source (LCLS) will revolutionize ultrafast x-ray science

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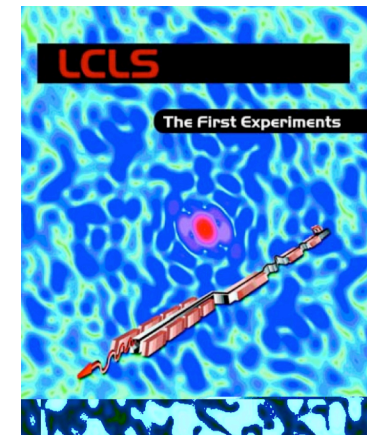


“potential for biomolecular imaging with femtosecond x-ray pulses”

Neutze R, Hajdu J et al., Nature 406, 752 (2000).

Baseline performance:

- 15-1.5 Angstrom
- 10 GW peak power
larger by 10^9 to current sources
- ultra-short, 200 fs - ???
exceeds 3rd generation by $\geq 10^3$
- coherent
- large degeneracy factor $\geq 10^9$



CONCLUSIONS

HEDP Task Force

High energy density plasma science is a rapidly growing field with enormous potential for discovery in scientific and technological areas of high intellectual value.

The opportunities for graduate student training, postdoctoral research, commercial spin-offs, and interdisciplinary research are likely to increase for many decades to come.