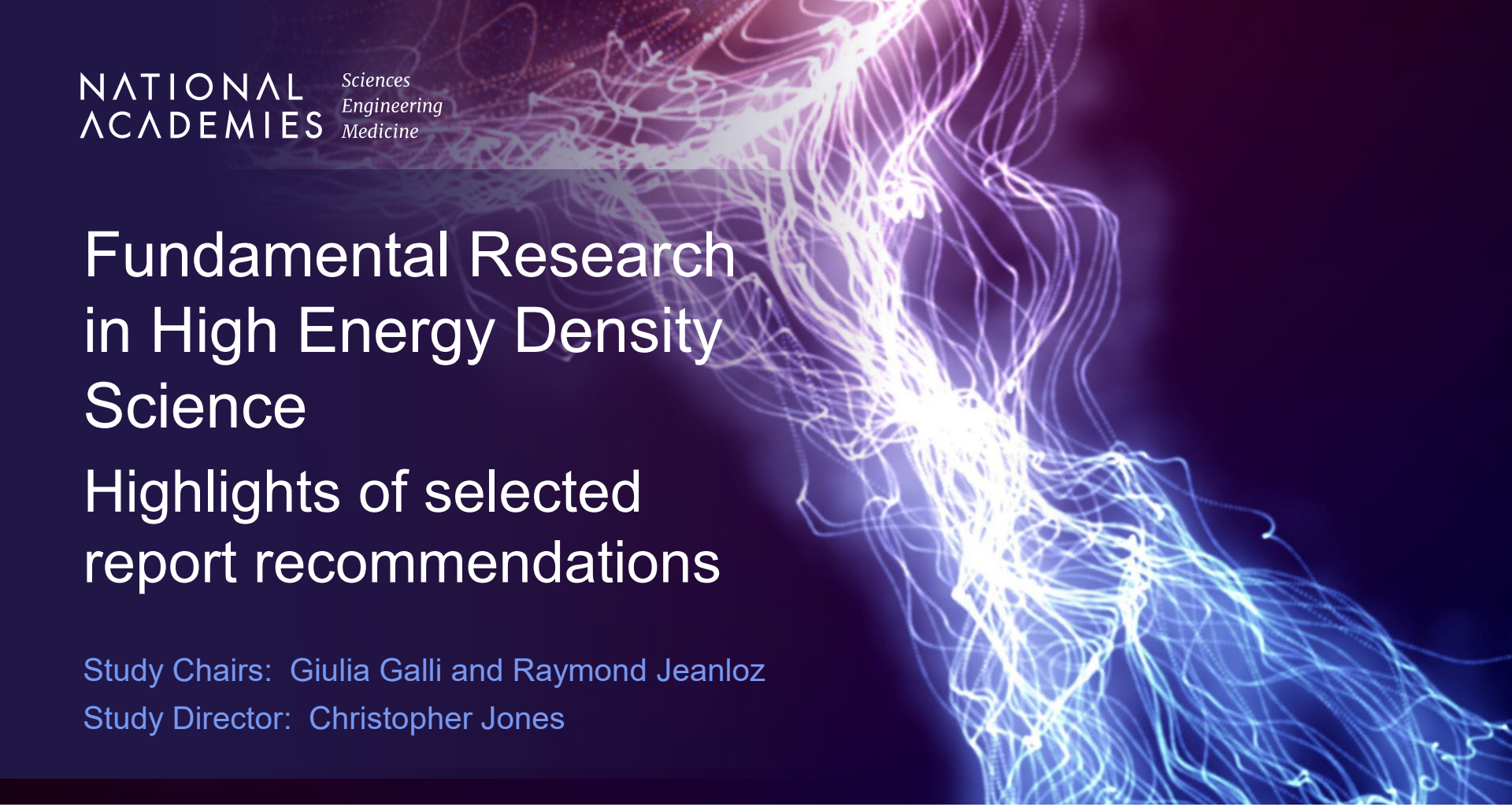


NATIONAL ACADEMIES Sciences Engineering Medicine

Fundamental Research in High Energy Density Science

Highlights of selected report recommendations

Study Chairs: Giulia Galli and Raymond Jeanloz

Study Director: Christopher Jones

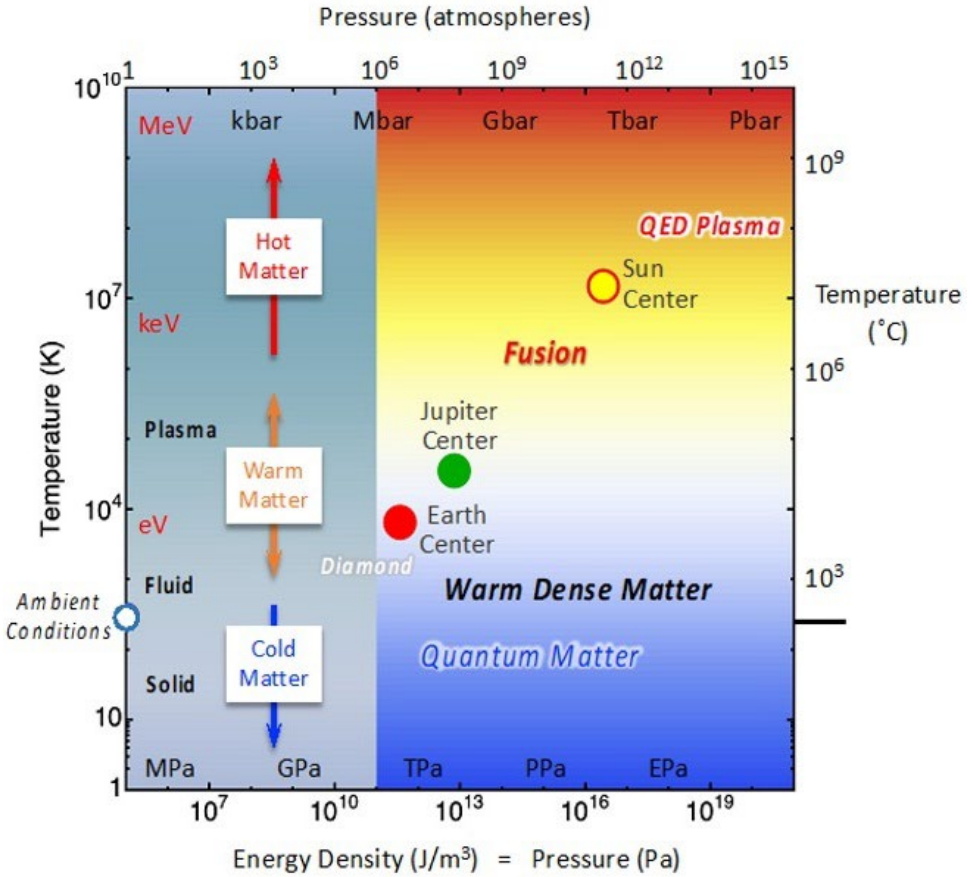
FEBRUARY 2023

What is High Energy Density?

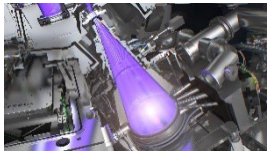
Extreme conditions that can
- change atomic structure
- cause nuclear fusion

High Energy Density Science (HEDS) has critical applications for society, from inertial confinement fusion, discovery of technologically important materials and sustaining the nation's nuclear deterrent to understanding planets and their origins.

Our report identifies key challenges and science questions for the coming decade and proposes ways to address them.



HEDS is significantly enriching society today

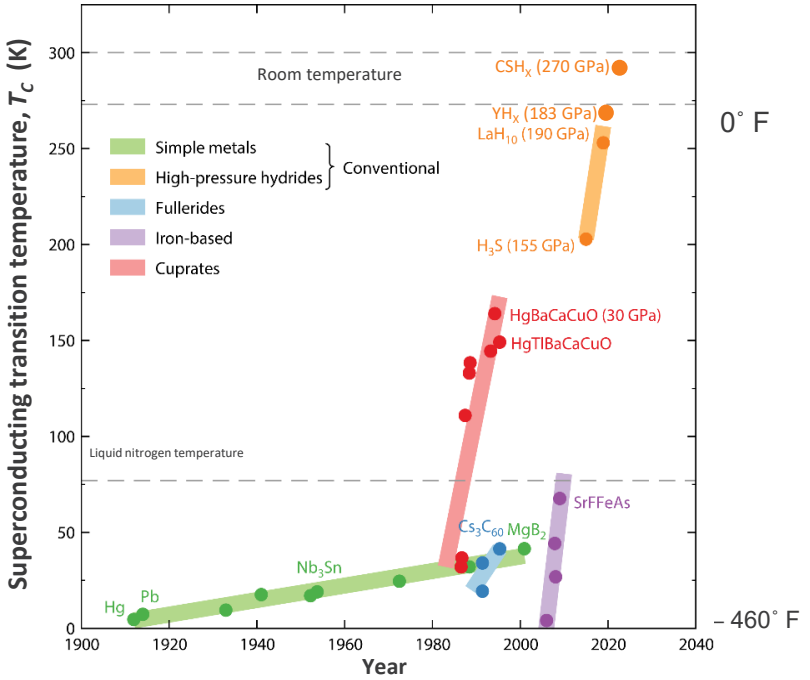


Past

- Development of extreme ultraviolet lithography for microelectronics fabrication ($100s B/yr)
- Synthesis and widespread application of diamond in technology and science ($10s B/yr)
- Discovery of the violent origins of Moon and planets
- Creation of metallic forms of hydrogen, helium, carbon, nitrogen, oxygen, …
  - primary constituents of stars, planets

Emerging

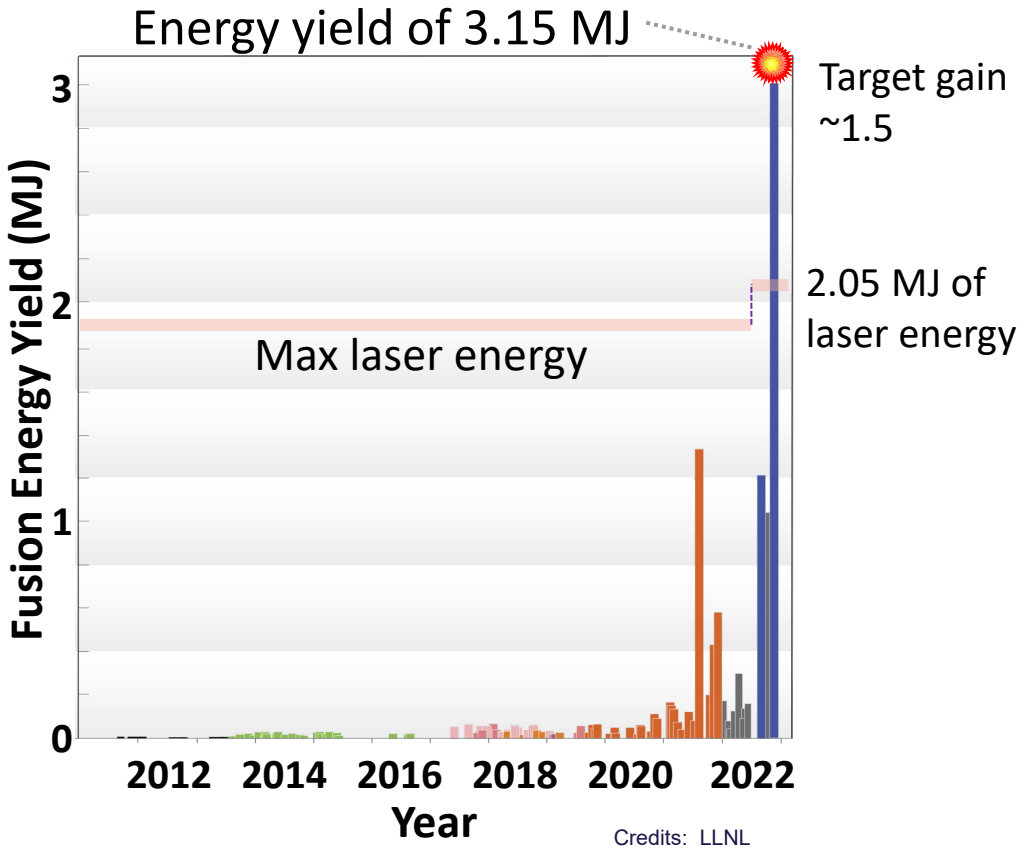
- Discovery of room-temperature electrical superconductors
- Controlled nuclear fusion in the laboratory



NATIONAL ACADEMIES Sciences Engineering Medicine

Credits: ASML, Irifune & Hemley (2012); Pickard, et al., (2020)

A nuclear fusion experiment on December 5, 2022 demonstrated net energy output – a laboratory first



Credits: LLNL

NATIONAL ACADEMIES Sciences Engineering Medicine

Abbreviated Statement of Task

- Articulate recent advances, status and future directions of HED physics in the United States
  - Assess the progress and achievements in HED physics over the last decade
  - Identify major scientific gaps and potential new directions

"Opportunities"

- Identify challenges that the field may face over the next decade

"Facilities"

- Evaluate the role of HED physics in developing an expert workforce

"Human Capacity"

- Assess the state and recent advances made by other countries in HED physics and discuss the relative standing of the United States

The National Academies assembled a committee of experts with a diversity of experiences

Giulia Galli (NAS)
(Co-Chair)
University of Chicago

Raymond Jeanloz (NAS)
(Co-Chair)
University of California, Berkeley

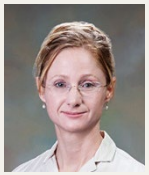
Félicie Albert
Lawrence Livermore National Laboratory

David M. Ceperley (NAS)
University of Illinois Urbana Champaign

Gilbert 'Rip' Collins
University of Rochester

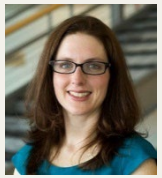
Franklin Dollar
University of California, Irvine

Nathaniel J. Fisch
Princeton University.



Stephanie B. Hansen
Sandia National Laboratories

Russell J. Hemley (NAS)
University of Illinois at Chicago



Carolyn Kuranz
University of Michigan

Charles F. McMillan
Los Alamos National Laboratory (ret.)

Sekazi Kauze Mtingwa
U.S. Nuclear Regulatory Commission

Donna Strickland
University of Waterloo

Questions?

Contact: Colleen Hartman (chartman@nas.edu)
and James Myska (jmyska@nas.edu)

The Committee received invaluable input from across the HEDS research community

- Technical input from National Academies and American Physical Society Community Planning Process reports
- Presentations by and discussions with NNSA and related HEDS Labs
- Public town halls
- Solicited additional input on website

The extreme nature of HEDS demands cutting-edge facilities

Leading Recommendation #1: To strengthen its global leadership in HEDS, the National Nuclear Security Agency (NNSA) should

- Exploit and enhance the capabilities of flagship HED facilities: National Ignition Facility, Z and Omega
  - Establish plans to extend, upgrade or replace
  - Broaden and increase remote access
- Enhance academic capabilities, mid-scale facilities
- Promote technology development, including high intensity lasers

Collaborations among academia, industry and national laboratories drive discovery and technological impact

Recommendations: NNSA should

- Work with the academic and national laboratory user community, relevant government agencies, and industry to develop a high-performance computing (HPC) strategy for HEDS over the next 2 years

- Set expectations for rigorous validation and benchmarking experiments that can provide solid foundations for multi-scale HED simulations

NNSA should enact the above with the national security labs and in coordination with partner science agencies (including DOE and NSF)

Initial results in inertial confinement fusion (ICF) emphasize the importance of advancing basic science

Recommendation: The ICF community should redouble efforts to focus on the underlying basic science to

1. Achieve robust ignition and maximum yield with optimal efficiency
2. Establish the best uses of laboratory burning plasmas
3. Identify best path for future experimental and computational facilities

Sustainment of innovation and breakthrough research will require a careful balance between yield-producing and non-ignition experiments

NNSA should work with relevant government agencies and private industry to leverage research in inertial fusion energy and – where possible – partner in research

Partnering with industry provides important benefits to research, technology and society

NNSA can develop partnerships with companies to strengthen the HED science workforce

- Doing so will stimulate new technologies beneficial for both fundamental science and industrial applications
- Without strong partnership with industry, NNSA risks increased competition for the top-caliber workforce and decreased capability to meet the technology needs of the future

Recommendation: NNSA should develop industry-relevant technical roadmaps for critical capabilities in computation, diagnostics and targets, with more funding opportunities for industry to provide these capabilities

A robust HEDS workforce requires early-stage investment and diversity

Leading Recommendation #2: To enhance human capacity for HEDS research, NNSA should

- Broaden its current programs for achieving excellence through diversity, equity and inclusion, while improving the workplace climate
- Develop a strategic plan for balancing security and proliferation concerns with openness and accessibility, including for international and private sector collaborators

NNSA faces a growing challenge in recruitment and retention of its expert workforce because of the evolving influence of the private sector, developments in other nations, and challenges to the workplace climate.

A healthy workplace climate is essential for continued excellence in HEDS

Recommendations: NNSA should

- Enable institutions working on HED research to (1) assess climate; (2) use subject-matter experts to set explicit, quantifiable diversity, equity, inclusion and accessibility goals; and (3) implement and ensure achievement of these goals
- Enforce concrete policies for accountability to promote a positive and inclusive workforce environment
- Invest in educational (apprenticeship) programs at institutions for training of technicians and technical staff at the Associate/Bachelor/Master's or equivalent level, in line with the laboratories' DEIA goals

Enhance NNSA lab collaborations with academia to ensure continuing intellectual vitality

Recommendation: NNSA should periodically assess and, where possible, reduce barriers to university collaborations

Recommendation: NNSA laboratories should

- Support more internships, postdoctoral opportunities, faculty visits and early career programs in HEDS, coordinating across NNSA in a manner similar to DOE's Office of Science
- Recognize national laboratory scientists for their collaborations, mentorship and outreach with the fundamental research community and public
- Promote collaborations with academia by sharing data related to unclassified research (in consistent data format), providing open/educational versions of their computational codes

National and international collaborations are vital to sustaining nation's capabilities and scientific leadership

The U.S. is a leader in traditional HEDS with high energy lasers and pulsed power Z-pinches, but changes are occurring that could alter that situation

- High-intensity lasers in Europe and Asia far exceed the power of those in the U.S.

International collaborations strengthen the HEDS workforce, and enhance the use of HEDS facilities. Remote access to these facilities would help both domestic and international users

The nation will need to find ways to attract domestic students and retain international scholars in relevant domains of science and technology, and devise solutions allowing international students trained in the U.S. to remain in the country

Advances in international HEDS facilities challenge NNSA to upgrade its facilities to stay at the cutting edge

Recommendations: NNSA should

- Increase the promotion of forefront technology development to strengthen its global leadership in HEDS and address future national needs

- Promote international collaborations and increase remote access to NNSA facilities to enhance HEDS research and career pathways

Looking Forward – HED Science Grand Challenges

- How can **nuclear fusion** be controlled and harnessed for society's energy, security and technology needs?
- What are the quantum states of matter in the HED regime leading to **new classes of materials for energy transport, storage and quantum information science**?
- How can we **understand matter** and processes at extreme HED conditions over a vast range of distances, times: atomic to cosmic?
- How can **extreme astrophysical phenomena** be studied in the laboratory to **increase our understanding of the Universe**?

nationalacademies.org/heds

Looking Forward – HED Science Grand Challenges

- How can **nuclear fusion** be controlled and harnessed for society's energy, security and technology needs?
- What are the quantum states of matter in the HED regime leading to **new classes of materials for energy transport, storage and quantum information science**?
- How can we **understand matter** and processes at extreme HED conditions over a vast range of distances, times: atomic to cosmic?
- How can **extreme astrophysical phenomena** be studied in the laboratory to **increase our understanding of the Universe**?

nationalacademies.org/heds