BOARD ON
PHYSICS AND ASTRONOMY

THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

Plasma Science
Advancing Knowledge in the National Interest

Final Report of the National Academies Plasma 2010 Committee

16 July 2007

S. Cowley (Univ of California, Los Angeles) and J. Peoples, Jr. (Fermilab)

Genesis

- In late 2005, the National Academies convened the Plasma 2010 Committee as part of the decadal survey of physics
  - DOE, NSF, and NASA provided support for the project

- The committee was tasked as follows
  - Assess the progress and achievements of plasma science over the past decade.
  - Identify the new opportunities and the compelling science questions for plasma science, frame the outlook for the future, and place the field in the context of physics as a whole.
  - Evaluate the opportunities and challenges for the applications of plasma science to fusion and other fields.
  - Offer guidance to the government research programs and the scientific communities aimed at addressing these challenges and realizing these opportunities.

Committee membership

- A committee with broad membership was sought in order to critically examine the scientific stakes
  - Experts from inside and outside of plasma science were included
  - To help frame the agenda in a broadly compelling manner, one co-chair had extensive experience within plasma science; the other brought an external, independent perspective

Steven Cowley, UCLA	*John Peoples, Jr., Fermilab*
James Callen, Wisconsin	Franklin Chang-Diaz, Ad Astra Rocket
Todd Ditmire, Texas	William Dorland, Maryland
Walter Gekelman, UCLA	Steven Girshick, Minnesota
David Hammer, Cornell	Erich Ippen, MIT
Mark Kushner, Iowa State	Kristina Lynch, Dartmouth
Jonathan Menard, Princeton	Lia Merminga, J Lab
Eliot Quataert, Berkeley	Timothy Sommere, GE
Clifford Surko, San Diego	Max Tabak, LLNL

Summary

- The expanding scope of plasma research is creating an abundance of new scientific opportunities and challenges.

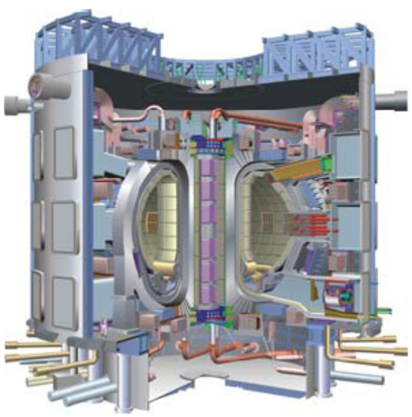
- These opportunities promise to further expand the role of plasma science in enhancing economic security and prosperity, energy and environmental security, national security, and scientific knowledge.

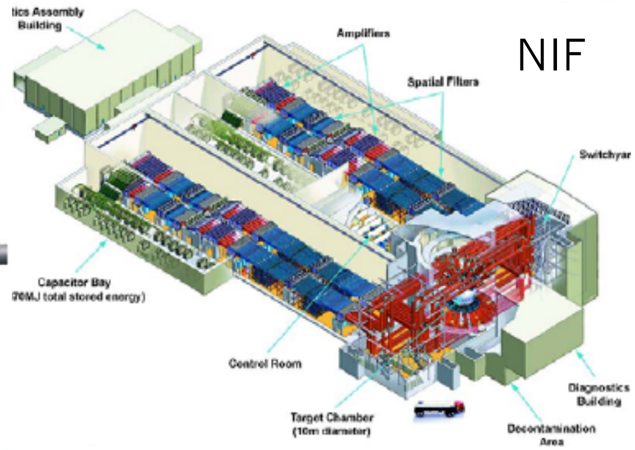
- To fully realize the opportunities in plasma research, a unified approach is required. The Department of Energy’s Office of Science should reorient its research programs to incorporate magnetic and inertial fusion energy sciences, basic plasma science, non-mission-driven high-energy density plasma science, and low-temperature plasma science and engineering.

On the cusp of a new era

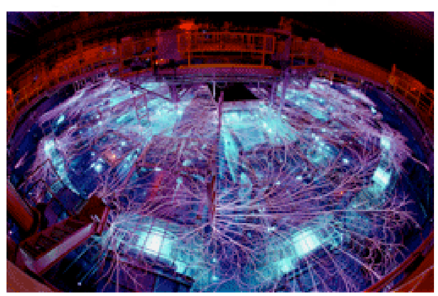
- "The expanding scope of plasma research is creating an abundance of new scientific opportunities and challenges."
- Committee was struck by the enormous scope of the plasma enterprise in the next decade >$1B per year. Success demands a lot of our community and our agencies. A good problem to have!

ITER

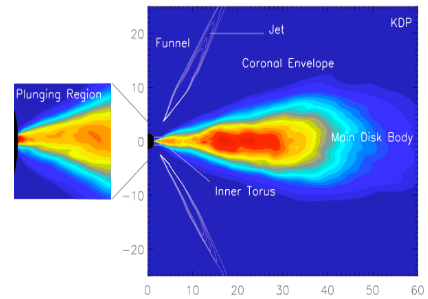




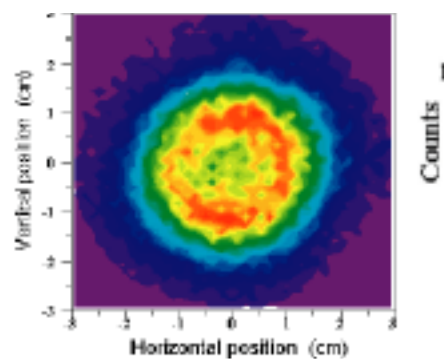
NIF



ZR



General Relativistic Plasmas



Anti-matter plasmas

On the cusp of a new era

- New regimes
  - Facilities of the next decade (e.g. ITER, NIF, Omega, ZR) will enable access to new regimes.
  - Increasing overlap with other scientific disciplines is driving whole new frontiers
    - High-power, short-pulse lasers
    - Control and manipulation of atoms and molecules connects low-temperature plasma science with atomic, molecular, and optical science
    - Even biology, healthcare, and environmental remediation

- Predictive capability
  - Advances in theoretical understanding, computational modeling, and experimental probes herald new capabilities in understanding, predicting, and controlling the behavior of plasmas

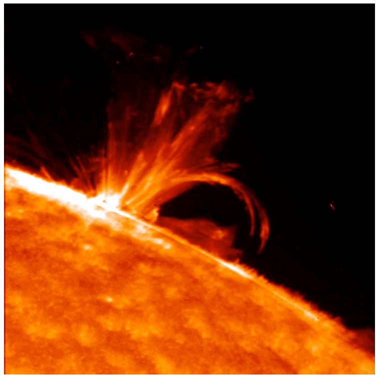
Science Assessment

Intellectual unity of plasma science

- Much of plasma behavior can be characterized in terms of universal processes that are, at least partially, independent of the particular context being considered.

- Progress on understanding any one of these (6) processes would advance many areas of plasma science simultaneously.

  - Explosive instability in plasma
  - Multiphase plasma dynamics
  - Particle acceleration and energetic particles
  - Turbulence and transport in plasmas
  - Magnetic self-organization in plasmas
  - Correlations in plasmas



EXAMPLE QUESTIONS: When, where, how fast? When is a limit soft or hard? …….

EXAMPLES: Solar Flares, Tokamak disruptions, Magnetospheric Substorms ..

Intellectual unity of plasma science

- Much of plasma behavior can be characterized in terms of universal processes that are, at least partially, independent of the particular context being considered.
- Progress on understanding any one of these processes would advance many areas of plasma science simultaneously.
  - Explosive instability in plasma
  - Multiphase plasma dynamics
  - Particle acceleration and energetic particles
  - Turbulence and transport in plasmas
  - Magnetic self-organization in plasmas
  - Correlations in plasmas

EXAMPLE QUESTIONS: How do we selectively excite species? How do stars and planets form from neutrals in an ionized environment? ….

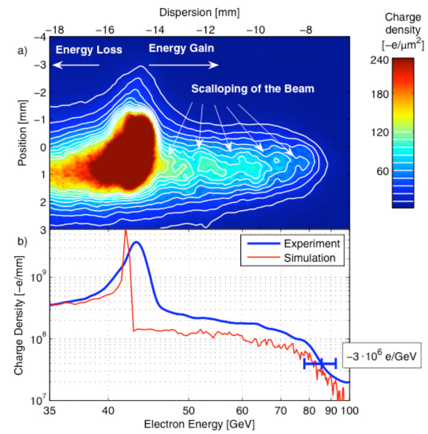
EXAMPLES:Industrial plasmas, Molecular clouds, ionosphere, Tokamak edge, ablating wires in Z, Aurora …..

Intellectual unity of plasma science

- Much of plasma behavior can be characterized in terms of universal processes that are, at least partially, independent of the particular context being considered.

- Progress on understanding any one of these processes would advance many areas of plasma science simultaneously.

  - Explosive instability in plasma
  - Multiphase plasma dynamics
  - Particle acceleration and energetic particles
  - Turbulence and transport in plasmas
  - Magnetic self-organization in plasmas
  - Correlations in plasmas



EXAMPLE QUESTIONS: How does nature accelerate particles so efficiently? Can we use plasmas to make the next generation of particle accelerator?

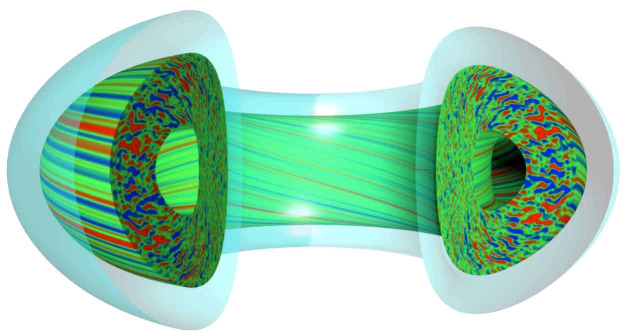
EXAMPLES: Cosmic Rays, beat wave accelerators, fast ignition, flares …..

Intellectual unity of plasma science

- Much of plasma behavior can be characterized in terms of universal processes that are, at least partially, independent of the particular context being considered.

- Progress on understanding any one of these processes would advance many areas of plasma science simultaneously.

  - Explosive instability in plasma
  - Multiphase plasma dynamics
  - Particle acceleration and energetic particles
  - Turbulence and transport in plasmas
  - Magnetic self-organization in plasmas
  - Correlations in plasmas



EXAMPLE QUESTIONS: Can we control plasma turbulence? Are there universal laws of plasma turbulence?

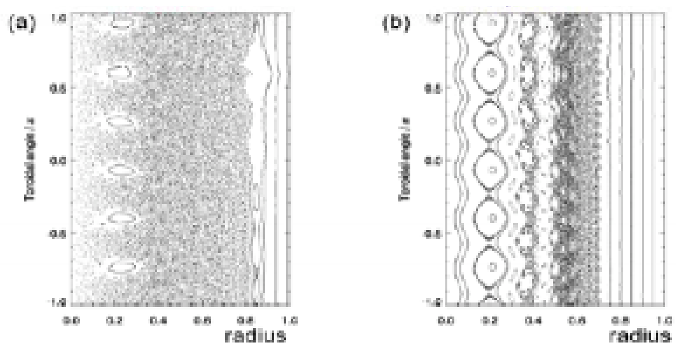
EXAMPLES: Tokamak transport, solar wind, laser-plasma interaction, Accretion discs, ……………

Intellectual unity of plasma science

- Much of plasma behavior can be characterized in terms of universal processes that are, at least partially, independent of the particular context being considered.

- Progress on understanding any one of these processes would advance many areas of plasma science simultaneously.

  – Explosive instability in plasma
  – Multiphase plasma dynamics
  – Particle acceleration and energetic particles
  – Turbulence and transport in plasmas
  – Magnetic self-organization in plasmas
  – Correlations in plasmas



EXAMPLE QUESTIONS: What are the “relaxed states”? When, where and how did the universe become magnetized?

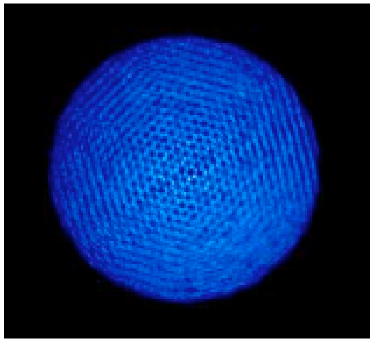
EXAMPLES: Solar Corona, Reversed field pinches, galaxies, wire-arrays,….

Intellectual unity of plasma science

- Much of plasma behavior can be characterized in terms of universal processes that are, at least partially, independent of the particular context being considered.

- Progress on understanding any one of these processes would advance many areas of plasma science simultaneously.

  - Explosive instability in plasma
  - Multiphase plasma dynamics
  - Particle acceleration and energetic particles
  - Turbulence and transport in plasmas
  - Magnetic self-organization in plasmas
  - Correlations in plasmas

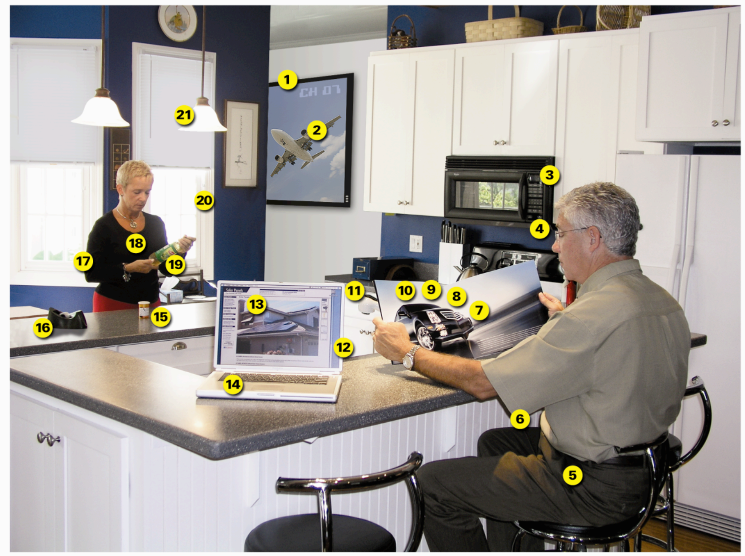


EXAMPLE QUESTION: What are the properties of strongly correlated plasmas?

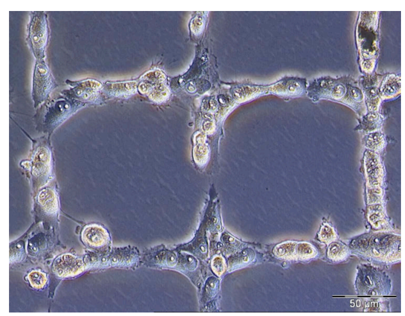
EXAMPLES: Cold ion plasmas, compressed HED matter, stellar interiors,

Importance of plasma research

- Economic security
- Energy & environmental security
- National security
- Scientific discovery



01—Plasma TV
02—Plasma-coated jet turbine blades
03—Plasma-manufactured LEDs in panel
04—Diamondlike plasma CVD eyeglass coating
05—Plasma ion-implanted artificial hip
06—Plasma laser-cut cloth
07—Plasma HID headlamps
08—Plasma-produced H_2 in fuel cell
09—Plasma-aided combustion
10—Plasma muffler
11—Plasma ozone water purification
12—Plasma-deposited LCD screen
13—Plasma-deposited silicon for solar cells
14—Plasma-processed microelectronics
15—Plasma-sterilization in pharmaceutical production
16—Plasma-treated polymers
17—Plasma-treated textiles
18—Plasma-treated heart stent
19—Plasma-deposited diffusion barriers for containers
20—Plasma-sputtered window glazing
21—Compact fluorescent plasma lamp



Policy Assessment

Structure of federal investment

- Plasma science is the focus of two of the largest new research facility projects in the country: ITER and NIF
- Historically, federal investments have been quite disaggregated despite the fact that they amount to ~ $1B per year
  - DOE's Office of Fusion Energy Sciences & Office of High Energy Physics
  - NNSA inertial fusion and laser/plasma programs
  - NSF's Physics Division & Astrophysics Division & Engineering programs
  - DOD basic research programs (waning)
- Each program has specialized to an extent, usually as a result of resource constraints

What is at stake?

- The emergence of new research directions necessitates a concomitant evolution in the structure and portfolio of programs at the federal agencies that support plasma science.

- The committee has identified four significant research challenges that the current organization of federal plasma science portfolio is not equipped to exploit optimally.

  – Fundamental low-temperature plasma science & engineering
    - Basic research in low-temperature plasmas fuels a plethora of applications ranging from sterilization in healthcare and environmental remediation to surface-coating treatments for high-performance alloys and plasma processing in semiconductor manufacturing.

  – Discovery-driven high energy density physics
    - Warm, dense matter; high-intensity, short-pulse lasers

  – Intermediate-scale plasma science
    - Key questions such as magnetic reconnection could be addressed at scales between individual laboratory and international facility

  – Cross-cutting research
    - There are significant opportunities at the interfaces between the subfields. Intellectual juxtaposition of disparate elements can force dialogue on common issues and questions.

Options

- Recognizing the significance of any recommendation to integrate research programs in plasma science, the committee considered four options in great detail and weighed the pros and cons.

  - Continue the current structure
  - Form an interagency coordinating committee for plasma science
  - Create an office for all of plasma science
  - Expand the stewardship of plasma science at DOE's Office of Science

Principal recommendation (1)

- To fully realize the opportunities in plasma research, a unified approach is required.

- The Department of Energy's Office of Science should reorient its research programs to incorporate magnetic and inertial fusion energy sciences, basic plasma science, non-mission-driven high-energy density plasma science, and low-temperature plasma science and engineering.

Principal recommendation (2)

- The new stewardship role for the Office of Science would expand well beyond the present mission and purview of the Office of Fusion Energy Sciences.
- It would include a broader portfolio of plasma science as well as the research OFES currently supports. Included in this portfolio would be two new thrusts
  - Non-mission-driven high-energy density plasma science
  - Low-temperature plasma science and engineering
- The stewardship framework would not replace or duplicate the plasma science programs in other agencies; rather, it would enable a science-based focal point for federal efforts in plasma-based research.
- These changes would be more evolutionary than revolutionary, starting modestly and growing with the expanding science opportunities.

Looking to the future

- DOE’s magnetic fusion and inertial fusion programs are currently focused on large developing facilities (ITER, NIF, Omega and ZR). The next decade will see these facilities mature into vibrant and exciting scientific programs.
  - NNSA’s support for high-energy density science will become uncertain when NIF and Z complete their stockpile stewardship missions. Yet, by that time, HED science will have flowered and expanded in many directions.
  - If ITER is successful, 15 years from now DOE’s fusion science program is likely to change dramatically. The fusion-energy development effort may move outside the Office of Science.
- Who will then become the de facto steward of plasma science?

Bottom line for federal agencies

- Plasmas have a special story to tell this decade
  - Significant opportunities are coming within reach
  - Impact is broad and nearly unparalleled, particularly in an era supportive of the ACI and basic research in the physical sciences
- Principal recommendation calls for action at the level of the DOE Under Secretary for Science
  - Coordinating, integrating, optimizing stewardship of chief elements of plasma science and engineering will require wisdom and foresight from many program managers
  - The risks are high, the rewards higher
  - Synergies of even just improving communication are undeniable
- OSTP Task Force on High Energy Density Physics provides an action plan addressing several aspects of the Plasma 2010 agenda
  - This process is a welcome step forward
  - Other communities and elements of plasma science and engineering could benefit from similar analyses—and strategic planning

Bottom line for scientific community

- Plasmas have a special story to tell this decade
  - Significant opportunities are coming within reach
  - Impact is broad and nearly unparalleled, particularly in an era supportive of the ACI and basic research in the physical sciences

- Leadership from the scientific community will be required to make progress on the Plasma 2010 agenda
  - Disaggregation of plasma science community and its sponsors makes this hard and yet is the primary driver for evolution
  - Building communication and trust among diverse elements will take patience and persistence

- This is where the future is!