Scientific Challenges, Opportunities and Priorities for the U.S. Fusion Energy Sciences Program

A Report to the Fusion Energy Sciences Advisory Committee

Presented by
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Stewart Prager
For the Panel on Priorities

April 7, 2005

FESAC Charge on Priorities
from Dr. Ray Orbach

- It is now time to focus the program in a more complete and fundamental way than we have done before.
- I would like FESAC to identify the major science and technology issues that need to be addressed, recommend how to organize campaigns to address those issues, and recommend the priority order for these campaigns.
- You will need to assemble a balanced domestic program that takes account of fusion programs abroad and that includes ITER as an integrated part of the whole. In each case, please recommend the relative priority of activities to pursue at any given time.
- It should be assumed that funding for ITER construction is provided in addition to (base program) funds.
- I would like FESAC to include Inertial Fusion and relevant aspects of High Energy Density Physics.
- Please look at the program through 2014, the year ITER operation is expected to begin.

FESAC Program Priorities Panel

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Vice-Chair: **Stewart Prager, *University of Wisconsin at Madison***

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Final Report Outline Content (Presenter)

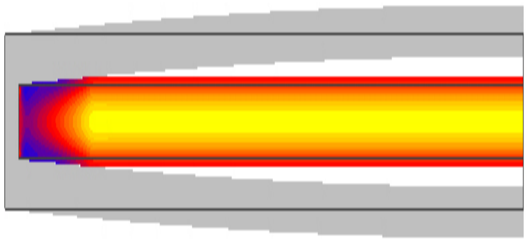
- Executive Summary
- Preface
- Ch. 1 – Major Scientific Challenges (Prager)
- Ch. 2 – Scientific Campaigns (Prager)
- Ch. 3 – Macroscopic Plasma Physics (Prager)
- Ch. 4 – Multiscale Transport Physics (Prager)
- Ch. 5 – High Energy Density Physics (Prager)
- Ch. 6 – Plasma Boundary Interfaces (Prager)
- Ch. 7 – Waves and Energetic Particles (Prager)
- Ch. 8 – Fusion Engineering Science (Baker)
- Ch. 9 – Enabling Research Activities (Baker)
- Ch. 10 – Understand Matter in the High Temperature Plasma State (Baker)
- Ch. 11 – Create A Star on Earth (Baker)
- Ch. 12 – Develop the Science and Technology to Realize Fusion Energy (Baker)
- Ch. 13 – Recommendations on Priorities (Baker)

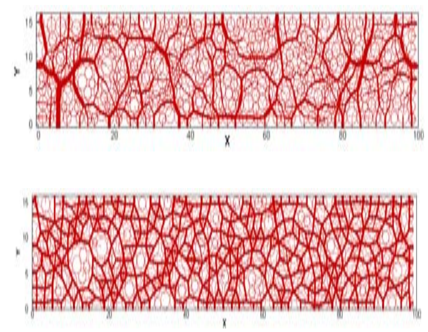
Fusion Engineering Science Campaign

T13 – How does the challenging fusion environment affect plasma chamber systems?

T14 – What are the operating limits for materials in the harsh fusion environment?

T15 – How can systems be engineered to measure, heat, fuel, pump, and confine steady-state or repetitively pulsed burning plasmas?





Fusion Engineering Science Campaign

Research Thrusts

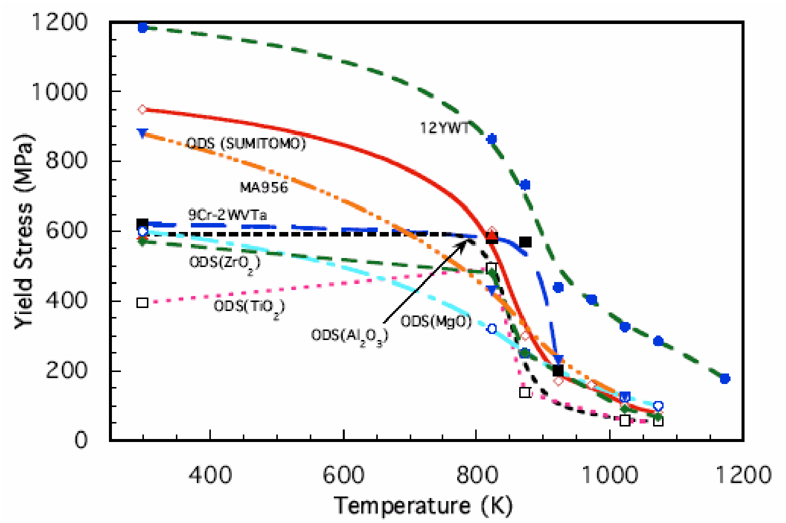
- Develop plasma chamber systems and materials knowledge to support ITER including testing blanket modules.
- Establish the engineering science base for the D-T cycle.
- Investigate performance limits for materials and chamber technologies.
- Develop long-pulse plasma control technologies for tokamaks including ITER.
- Provide plasma technology for developing other confinement approaches.

10-Year Goals

- Deliver blanket test modules to ITER.
- Determine the "phase space" for tritium self-sufficiency and power extraction.
- Determine performance limits, develop multi-scale models, and identify innovative solutions.
- Develop technologies to support U.S. in-kind contributions to ITER.
- Provide requested technologies for research programs.

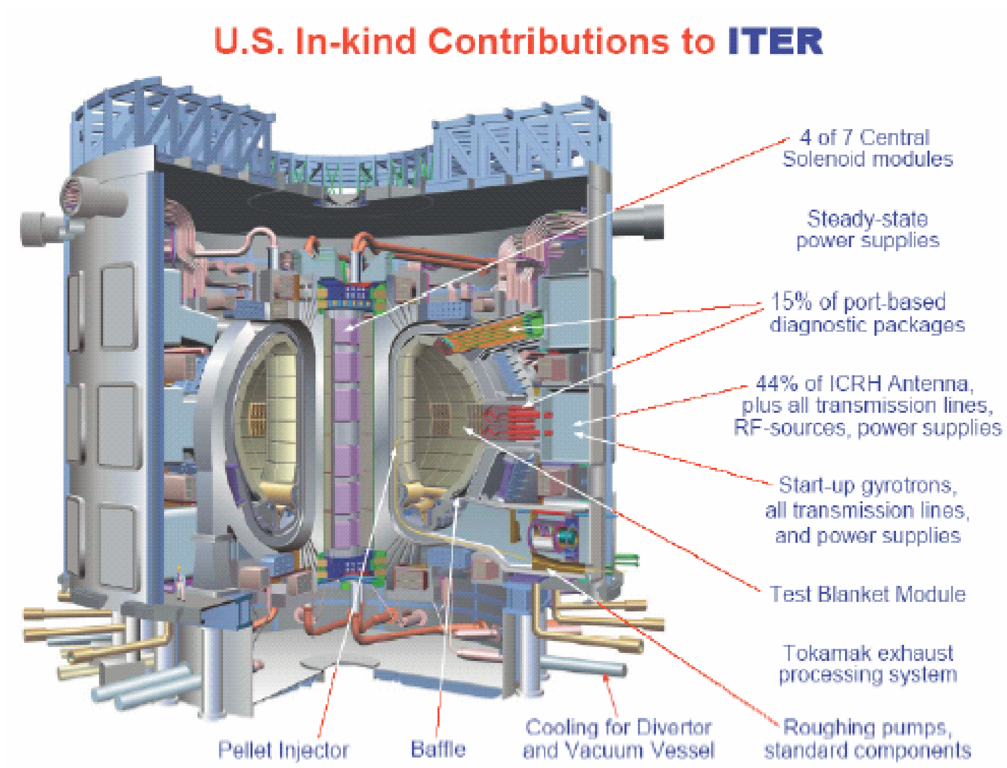
Fusion Engineering Science Campaign
Examples of Recent Progress

- Progress has been made in developing high-temperature ferritic steels.
- Experiments and theory have extended the understanding of conducting liquid flows in strong magnetic fields.
- The understanding of the requirements of the D-T fuel cycle has evolved and improved.
- The U.S. is a leader in several important plasma technologies.



Fusion Engineering Science Campaign
Relationships to Overarching Themes

- This campaign directly supports Theme 02 by enabling the design, construction, and operation of ITER.
- This campaign also directly supports Theme 03 by establishing the necessary materials and engineering science knowledge to attack key feasibility issues for fusion energy.
- This campaign also enables the Theme 01 by providing supporting plasma technologies.



Fusion Engineering Science Campaign
Expected Accomplishments – Constant Funding

- The plasma technologies required to support the U.S. contributions to ITER will be developed.
- A comprehensive, experimentally-validated suite of multi-scale material modeling codes will be developed.
- The U.S. will contribute to testing of key ITER blanket technical issues but will rely mostly on European and Japanese efforts for full blanket tests.
- A comprehensive DT fuel cycle dynamics model will be developed.

Fusion Engineering Science Campaign
Opportunities for Enhancement

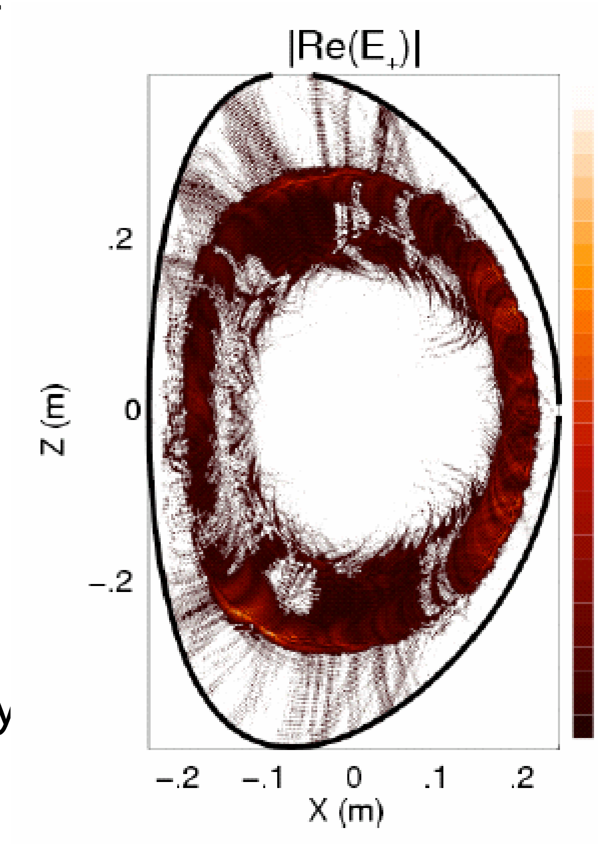
- Carry out additional science and technology activities supporting ITER.
- Conduct enhanced modeling and laboratory experiments for ITER test blankets.
- Increased support for nuclear design of the basic ITER machine.
- Explore high-temperature, high-power density capabilities of liquid walls.
- Support high-energy density physics research.

Research Activities Enable the Scientific Campaigns

- *<u>Diagnostic Development</u>* has paced our progress in plasma science. A burning plasma experiment presents major challenges.

- Major advances are leading to *<u>Integrated Predictive Simulation of Fusion Experiments</u>*.

- *<u>Advanced Design Studies</u>* provide insight to critical physics and technology issues necessary to realize fusion energy.



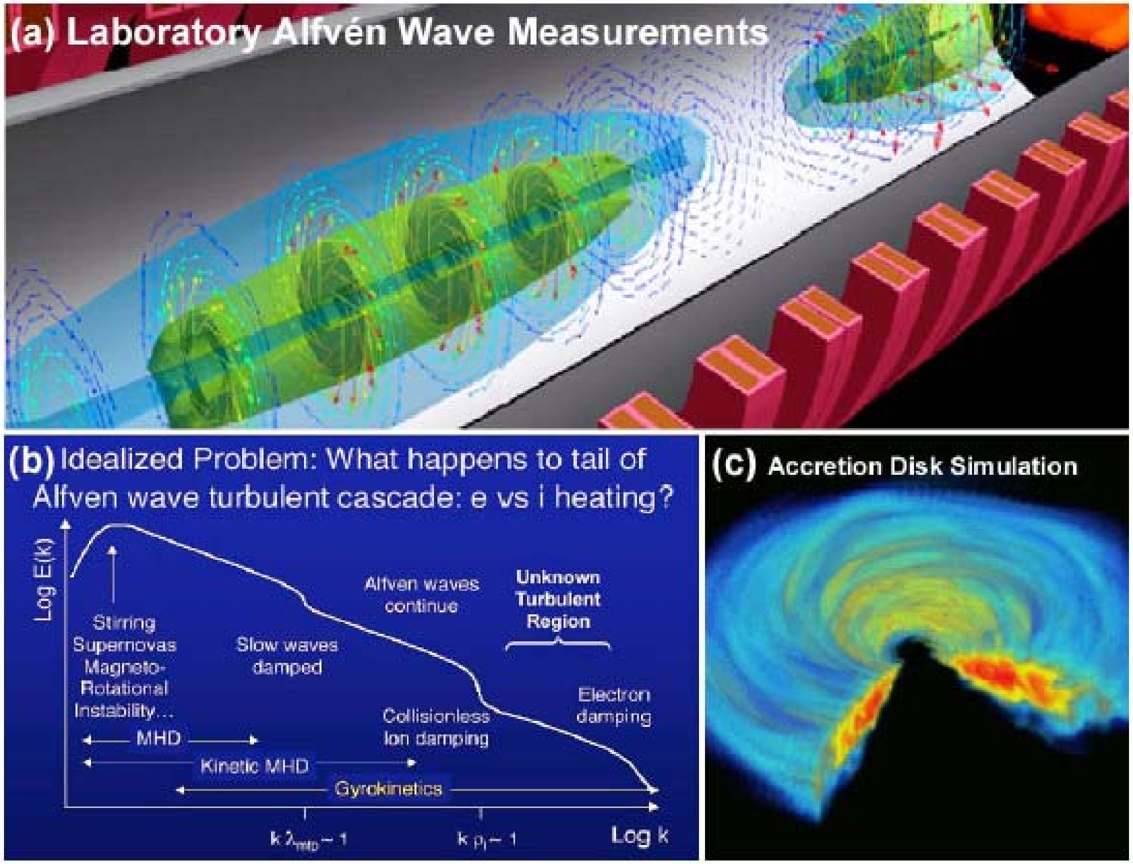
Three Overarching Themes

01	-	Understand Matter in the High-Temperature Plasma State
02	-	Create a Star on Earth
03	-	Develop the Science and Technology to Realize Fusion Energy

- These themes express the essential motivations for fusion energy science research.
- They also provide a necessary cross-cutting perspective of the six scientific campaigns.

Overarching Theme 01
Understand Matter in the High-Temperature Plasma State

- The plasma state of matter constitutes the core of fusion systems and nearly the whole of the visible universe.
- The dynamics of plasmas are nonlinear and complex, yet fundamental principles of plasma physics have been developed.
- Answers to fundamental questions, e.g., how is turbulence generated and dissipated, are within reach.



Overarching Theme 01

Understand Matter in the High-Temperature Plasma State

Understand the role of magnetic structure on plasma confinement and the limits to plasma pressure in sustained magnetic configurations.		
Key Questions	**Fusion Science Examples**	**Related Science Examples**
T1. How does magnetic field structure impact fusion plasma confinement?	Optimize the magnetic configuration	Coronal loops; planetary magnetospheres
T2. What limits the maximum plasma pressure that can be achieved in laboratory plasmas?	Maximize fusion power density	The Earth's magnetotail; Jupiter's magnetosphere
T3. How can external control and plasma self-organization be used to improve fusion performance?	Radio frequency, bootstrap and dynamo generated currents	Dipole confinement; Magnetospheres

Understand and control the physical processes that govern the confinement of heat, momentum, and particles in plasmas.		
Key Questions	**Fusion Science Examples**	**Related Science Examples**
T4. How does turbulence cause heat, particles, and momentum to escape from plasmas?	Energy confinement, helium removal	Astrophysical accretion flows; Solar convection zone
T5. How are electromagnetic fields and mass flows generated in plasmas?	Generation of flows leading to transport barriers, and confining magnetic fields	Astrophysical, solar and planetary dynamos
T6. How do magnetic fields in plasmas reconnect and dissipate their energy?	Performance limiting instabilities	Solar flares; Magnetospheric storms

Overarching Theme 01
Understand Matter in the High-Temperature Plasma State

Investigate the assembly, heating, and burning of high energy density plasmas.		
Key Questions	**Fusion Science Examples**	**Related Science Examples**
T7. How can high energy density fusion plasmas be assembled and ignited in the laboratory?	Implosion of plasmas to high energy density	Stellar interiors
T8. How do hydrodynamic instabilities affect implosions to high energy density?	Retention of symmetry in implosions	Stellar explosions
T9. How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion conditions?	Increased peak ion beam power for fusion targets	Multi-species beam-plasma physics for high energy ion accelerators

Learn to control the interface between the 100 million degree plasma and its room temperature surroundings.		
Key Questions	**Fusion Science Examples**	**Related Science Examples**
T10. How can a 100-million-degree-C burning plasma be interfaced to its room temperature surroundings?	Fuel and power exhaust	Plasma processing

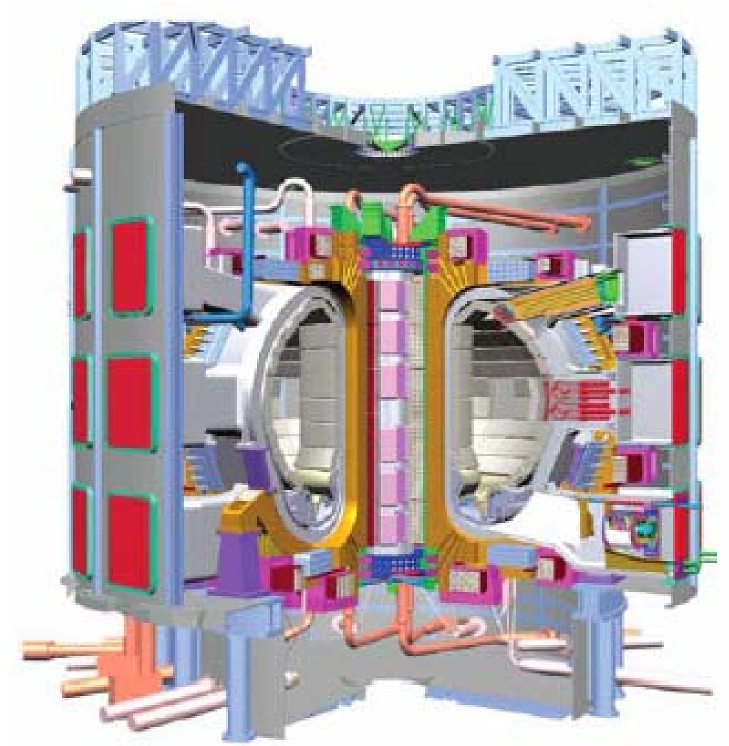
Overarching Theme 01
Understand Matter in the High-Temperature Plasma State

Learn to use energetic particles and electromagnetic waves to sustain and control high temperature plasmas.		
Key Questions	**Fusion Science Examples**	**Related Science Examples**
T11. How do electromagnetic waves interact with plasma?	Heating and control of current profiles in plasmas	Radio emission from space; Communication disruptions
T12. How do high energy particles interact with plasma?	Confining fusion alpha particles	Aurora Borealis; Astrophysical jets; Solar flares

Understand the fundamental properties of materials, and the engineering science in the harsh fusion environment.		
Key Questions	**Fusion Science Examples**	**Related Science Examples**
T13. How does the challenging fusion environment affect plasma chamber systems?	Plasma-material interactions	Plasma processing; Nuclear physics; Fluid mechanics
T14. What are the operating limits for materials in the harsh fusion environment?	Lifetimes of fusion components	Neutron effects on material structure
T15. How can systems be engineered to heat, fuel, pump, and confine steady-state or repetitively pulsed burning plasmas?	Tools to carry out fusion science	Technical spinoffs to other areas of science

Overarching Theme 02
Create a Star on Earth

- The worldwide fusion community is about to embark on the construction of the first magnetic confinement burning plasma experiment.
- The National Ignition Facility is being constructed and is crucial to realizing inertial fusion energy.
- All six campaigns are essential ingredients to creating a star on earth.



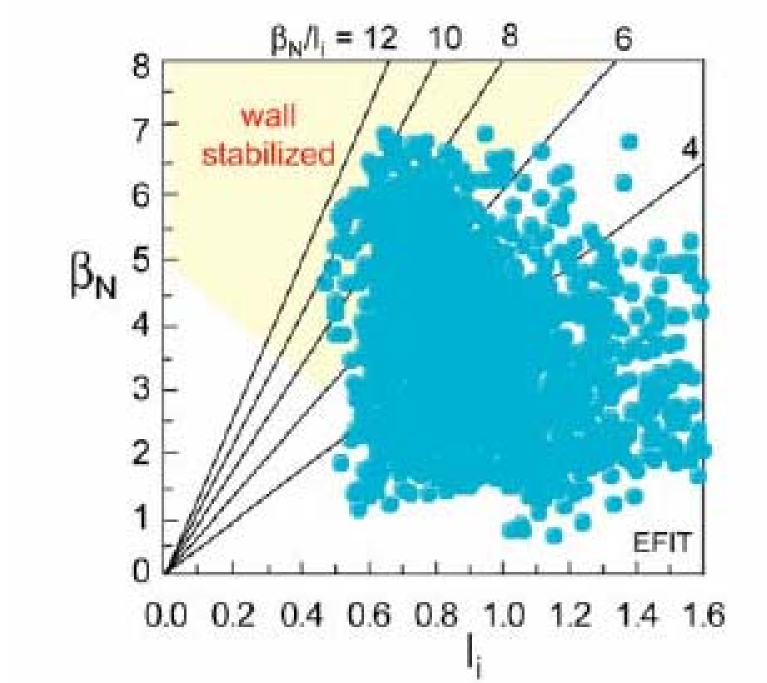
Contributions from the U.S. Domestic Program are Essential to the Success of ITER

- Results from U.S. confinement experiments will impact ITER design and operational decisions.
- Work on advanced tokamak modes will provide the basis for improved ITER operation.
- U.S. contributions to ITER diagnostics are crucial to realizing its scientific mission.
- Advanced theory and simulation will provide the capability to plan and carry out experiments on ITER.
- Fusion engineering science research will underpin U.S. in-kind contributions and participation in ITER’s test blanket module program.

Overarching Theme 03

Develop the Science and Technology to Realize Fusion Energy

- Realizing fusion energy is a major challenge to both physics and engineering science.
- There is a highly nonlinear and complex interaction among plasma and engineering science for both magnetic and inertial fusion energy systems.
- The NRC Report on Burning Plasma recommends “the US fusion program focus on addressing compelling scientific issues and thereby strengthen the underlying science base of a fusion energy source.”

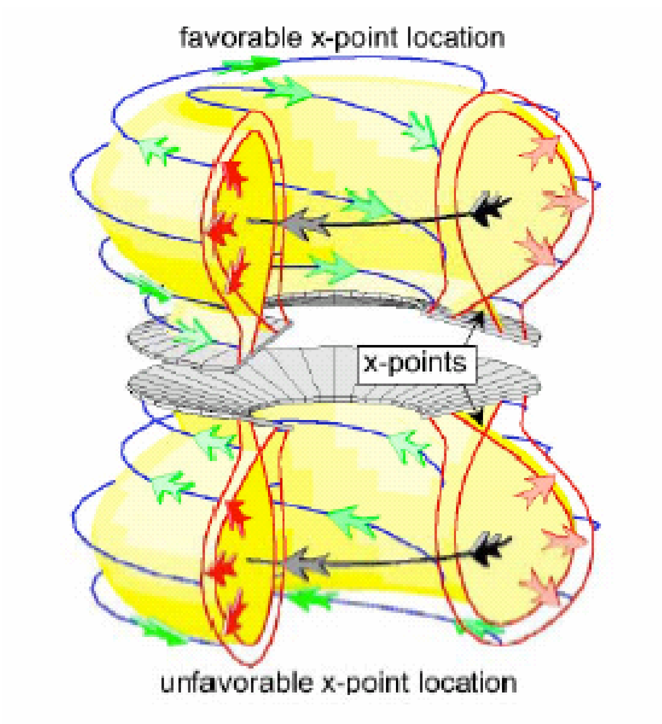


All Campaigns Contribute to Realizing Fusion Energy

- The central thrust of ***Macroscopic Plasma Physics*** is to learn how to optimize magnetic confinement configurations.

- Understanding ***Multi-scale Transport Physics*** is necessary to maximize the energy gain of fusion energy systems.

- Controlling the ***Plasma Boundary Interfaces*** is necessary to optimize plasma performance and obtain adequate lifetime of plasma-facing components.

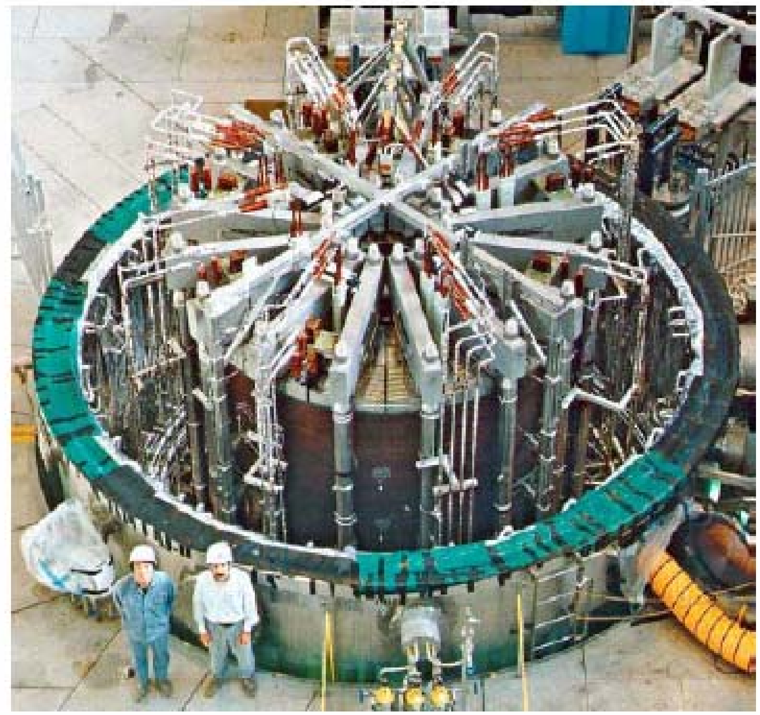


All Campaigns Contribute to Realizing Fusion Energy

- Understanding the physics of *Waves and Energetic Particles* is necessary to achieving extended operation and controlling self-heated plasmas.

- *High Energy Density Physics* is critical to realizing inertial fusion energy.

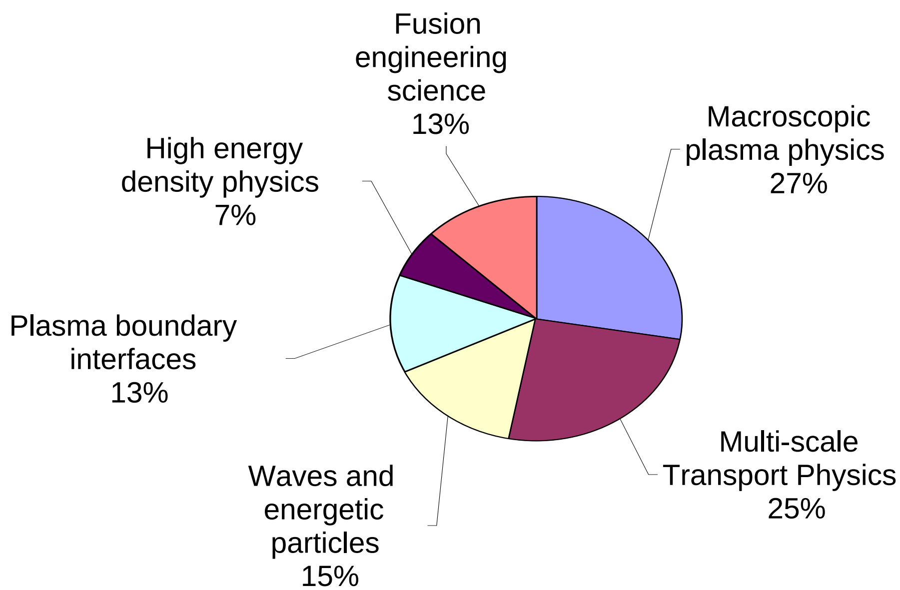
- Critical issues in *Fusion Engineering Science* need to be addressed over the next decade simultaneously with plasma science research.



Recommendations

Recommendation 1: The scientific challenges of fusion energy and the opportunities for discovery in plasma physics should be addressed by a research program that encompasses a broad range of key scientific questions.

- In plasma, many physical effects couple together to form a complex, nonlinear system.
- The panel recommends the approximate division of effort for the next ten years as shown in the figure. This division of effort is similar to that of the present program, however the activities within each category will evolve over the next decade as we approach the first operation of a burning plasma experiment.



Expected Progress at Constant Level of Effort

Substantial progress can be made in addressing the fifteen topical scientific questions described in the report under the assumption of constant level-of-effort for the domestic program (in addition to ITER construction), over the next decade. These efforts will broaden and advance the basic understanding of plasma physics and related sciences, enable effective utilization of a burning plasma experiment, and provide the underpinnings to realize the advancement of fusion energy.

Recommendations

Recommendation 2: U.S. strength in fusion energy sciences research, U.S. impact on international burning plasma research, and progress towards answering the key scientific questions will be enhanced by an additional allocation of $100M per year for the domestic program for the following selected high-priority activities:

- Carry out additional science and technology activities supporting ITER. *(Most campaigns)*
- Predict the formation, structure, and transient evolution of edge transport barriers. *(Plasma boundary interfaces)*
- Mount a focused enhanced effort to understand electron transport. *(Multi-scale transport physics)*
- Pursue an integrated understanding of plasma self-organization and external control, enabling high-pressure sustained plasmas. *(Macroscopic plasma physics)*
- Study relativistic electron transport and laser-plasma interaction for fast ignition high energy density physics. *(High energy density physics)*
- Extend understanding and capability to control and manipulate plasmas with external waves. *(Waves and energetic particles)*
- Increase energy ion pulse compression in plasma for high energy density physics experiments. *(High energy density physics)*

Recommendations, continued

- Simulate through experiment and modeling the synergistic behavior of alpha-particle-dominated burning plasmas. *(Waves and energetic particles)*

- Conduct enhanced modeling and laboratory experiments for ITER test blankets. *(Fusion engineering science)*

- Pursue optimization of magnetic confinement configurations. *(High energy density physics)*

- Resolve the key plasma-material interactions, which govern material selection and tritium retention for high-power experiments. *(Plasma boundary interfaces)*

- Extend the understanding of reconnection processes and their influence on plasma instabilities. *(Multi-scale transport physics)*

- Carry out experiments and simulation of multi-kilo-electron-volt megabar plasma. *(High energy density physics)*

- Expand the effort to understand the transport of particles and momentum. *(Multi-scale transport physics)*

While many activities can be pursued at a reduced pace under level resources, opportunities exist for substantially enhanced progress on critical ongoing research programs with additional funding.

Recommendations

Recommendation 3: If less incremental funding were available, in the range of $50M per Year, then the first six activities identified below should receive priority attention.

The first six activities are viewed today as the most critical in further preparing the U.S. to Participate in a burning plasma experiment and for enhancing progress in vital aspects of the six Scientific campaigns.

- Carry out additional science and technology activities supporting ITER. *(Most campaigns)*
- Predict the formation, structure, and transient evolution of edge transport barriers. *(Plasma boundary interfaces)*
- Mount a focused enhanced effort to understand electron transport. *(Multi-scale transport physics)*
- Pursue an integrated understanding of plasma self-organization and external control, enabling high-pressure sustained plasmas. *(Macroscopic plasma physics)*
- Study relativistic electron transport and laser-plasma interaction for fast ignition high energy density physics. *(High energy density physics)*
- Extend understanding and capability to control and manipulate plasmas with external waves. *(Waves and energetic particles)*

Recommendations

Recommendation 4: The fusion energy sciences program should assess the need for additional major domestic experimental facilities in about five years.

- The study of burning plasmas is one of the overarching themes of the program. Present facilities are not able to access this important scientific regime thus requiring the construction of a new facility.
- Just as the construction of ITER is driven by compelling scientific questions requiring scientific regimes with unique combinations of confinement and pressure, other scientific questions may motivate the construction of new facilities beyond those currently under construction, or major upgrades to existing facilities.

Priorities Panel Process

- The panel met seven times and held typically biweekly conference calls.
- A general access website was established to inform the broader community and to provide a mechanism for comments.
- Six working groups were established to provide community input to defining research thrusts and goals.
- Panel members gave numerous briefings to their home institutions and at a variety of national community meetings.
- A town meeting was held at the November 2004 APS/DPP meeting.