DOE/SC-0029

Fusion Energy Science

Clean, Safe, and Abundant Energy through Innovative Science and Technology

DISCLAIMER

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Why Fusion Energy Science?

Fusion energy science combines the study of the behavior of plasmas—the state of matter that forms 99% of the visible universe—with a vision of using fusion—the energy source of the stars—to create an affordable, plentiful, and environmentally benign energy source for humankind. The dual nature of fusion energy science provides an unfolding panorama of exciting intellectual challenge and a promise of an attractive energy source for generations to come.

* The Fusion Energy Sciences Program is conducted by the Office of Science of the U. S. Department of Energy. For a complete description of the Program, see the Report of the Integrated Program Planning Activity (December 2000) available on the FESP website at http://wwwofe.er.doe.gov/.

The Goal

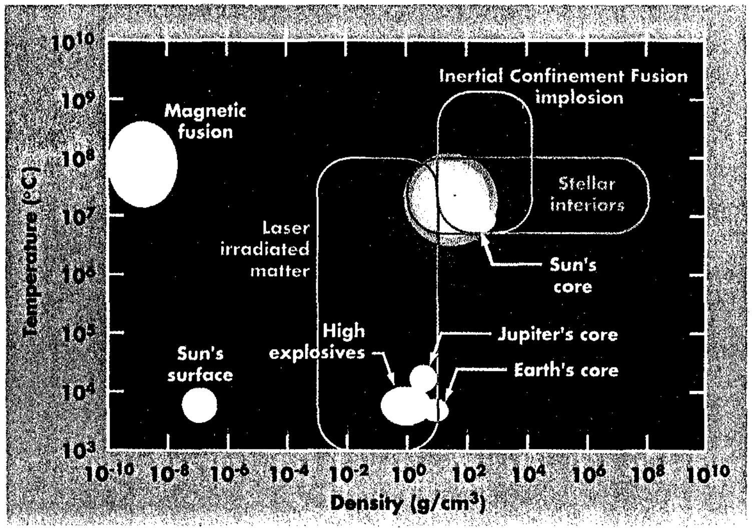
A comprehensive understanding of plasma behavior leading to an affordable and attractive fusion energy source.

About Plasma

Plasma, often called the fourth state of matter, is an ionized gas—a gas comprised of electrons and positively charged ions that can move independently of one another. Although plasmas are rare on the surface of the Earth, they constitute most of the visible universe. Plasmas make up the atmosphere and interior of stars, supernovas and quasars, the vastness of interstellar and intergalactic space, and the Earth's magnetosphere. Here on Earth, we see plasmas in lightning bolts, fluorescent lights, and the aurora borealis.

An ordinary gas, like helium, is a collection of electrically neutral atoms—each atom contains a number of negatively

Looking across the edge of the Sun. This photo, taken by a telescope on board the newly launched Transition Region and Coronal Explorer (TRACE) satellite, shows graceful arcs of intensely hot gas suspended in powerful, looping magnetic fields.



Plasmas exist in a wide range of temperatures and densities.

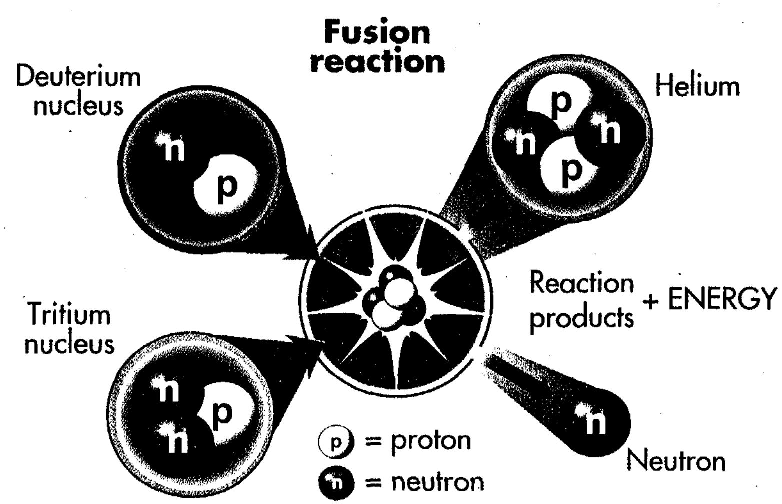
charged electrons orbiting a small central nucleus comprised of an equal number of positively charged protons and several electrically neutral neutrons. The orbiting electrons are locked together with the nucleus by atomic forces, forming a single, electrically neutral atom. Because of its neutral atoms, an ordinary gas shows little response to electric and magnetic forces and is a poor conductor of electricity.

Gas becomes plasma when heated enough to cause the electrons to rip free from the atom. The result is a fluid comprised of two charged gases: electrons and positive ions that interact through electromagnetic forces and often exhibit turbulent behavior.

The characteristics of a plasma are very different from that of an ordinary gas. Unlike ordinary gases, plasmas are good conductors that are not only strongly affected by electromagnetic forces but can also generate them. These self-generated forces, resulting from the collective motions of charged particles and electric currents in the plasma, produce remarkably complicated behavior that is incompletely understood. Learning to understand and describe the rich dynamical systems of plasmas is a fundamental scientific challenge.

About Fusion

Fusion, the energy source of the sun and other stars, is a reaction process that converts matter into energy. Fusion occurs in plasmas when two nuclei of hydrogen, such as deuterium or tritium, are combined—fused—together under enormous temperature and pressure to form a single nucleus of helium. During the fusion process, some of the matter involved in the reaction is converted directly into a much larger amount of energy. For example, the amount of deuterium in one gallon of sea water would yield the energy equivalent of 300 gallons of gasoline.



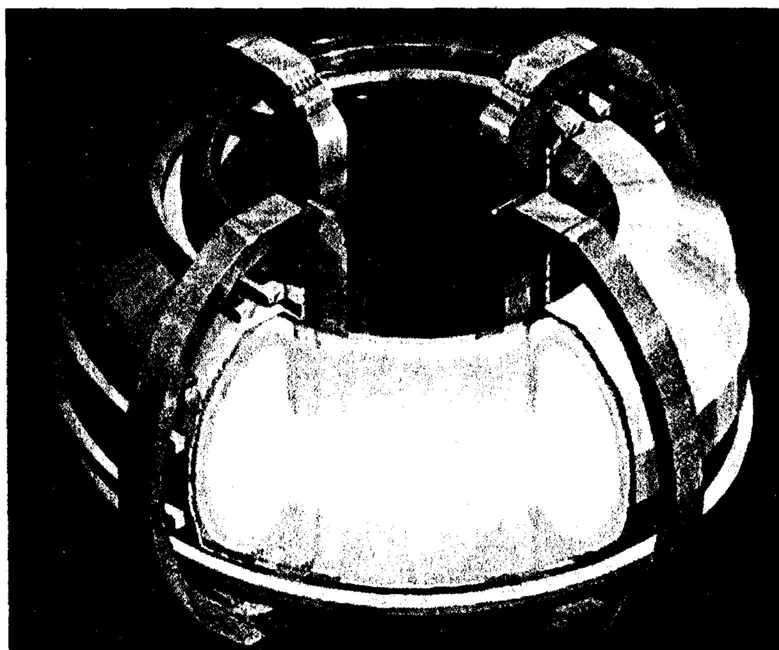
Approaches to Fusion

Scientists have taken two main approaches to producing fusion plasmas to explore the behavior of matter at extreme conditions: magnetic fusion and inertial fusion.

Magnetic Fusion

Scientists have found that magnetic forces can confine a plasma surprisingly well—long enough to heat it and observe key facets of its remarkable behavior. Magnetic fusion involves dilute plasmas that are confined by magnetic fields and heated by radio waves, energetic particle beams, and/or fusion self-heating.

Magnetic fusion takes advantage of the fact that although plasma particles and energy flow freely along magnetic fields, spiraling around them like beads on a coiled spring, the spiraling effect greatly inhibits the ability of charged particles to travel across field lines. A magnet system that produces magnetic lines spiraling around the surface of a doughnut-shaped device is an excellent way to confine a plasma. The magnetic field can confine the plasma energy for a few seconds and the configuration can be sustained indefinitely by replenishing particle and energy losses with external sources or the plasma-generated fusion power itself.

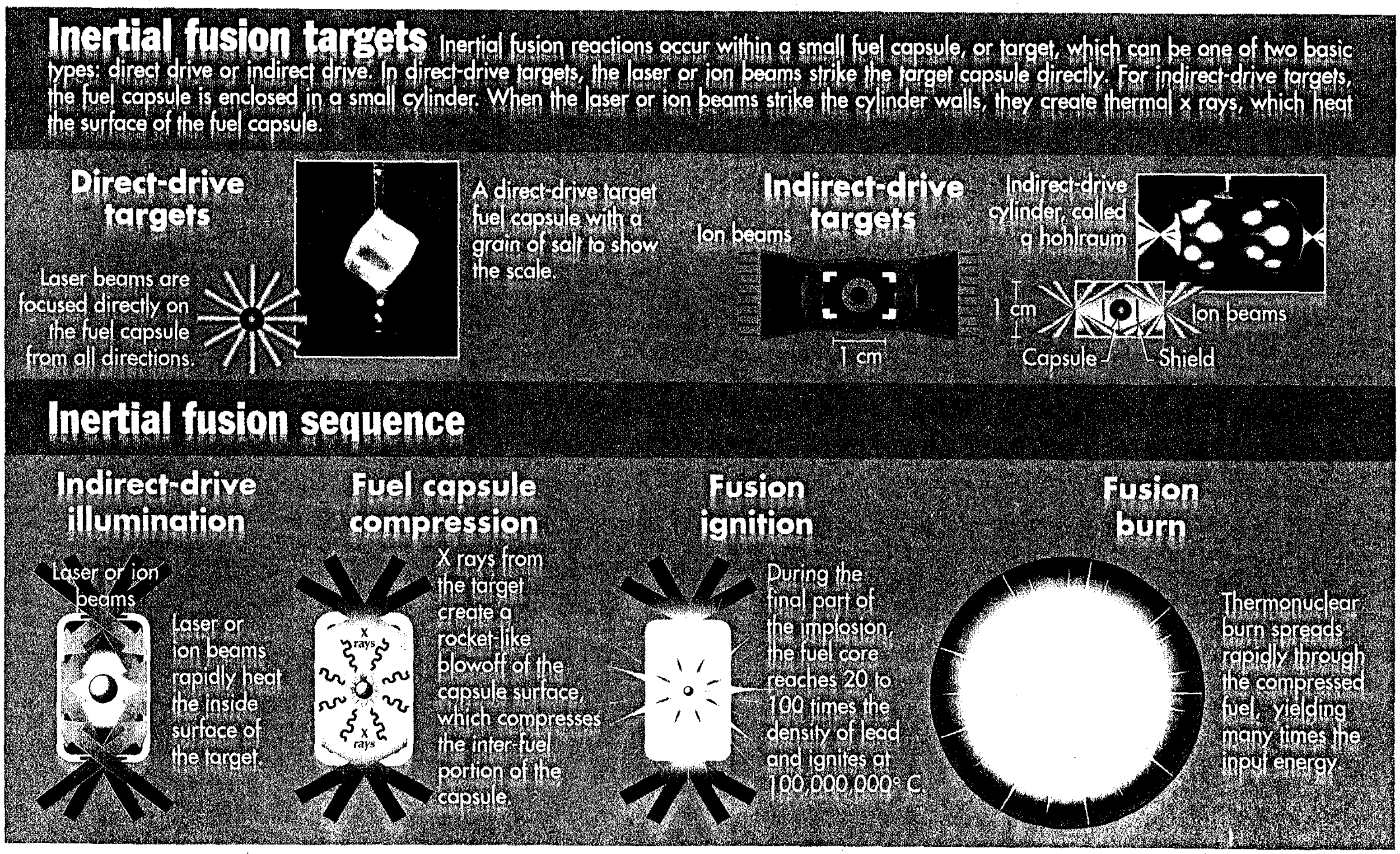


Magnetic fusion

Spiraling charged particles at temperatures of over one hundred million degrees Celsius—a temperature ten times hotter than the sun—follow magnetic field lines, seldom hitting the walls of this donut-shaped metal confinement device, called a tokamak, whose surface is closer to room temperature.

Inertial Fusion

Inertial fusion produces short-duration, extremely dense plasmas by compressing small pellets of fusion fuel. The pellet surface is quickly heated by an intense pulse of x rays, ion beams, or laser beams, which blasts away the outer layers of the pellet, causing the pellet to implode. The resulting shock waves compress the fuel pellet into a high-density plasma. The compressed pellet produces fusion energy until it disassembles, in about a billionth of a second.



Why Does the U.S. Pursue Fusion Energy Science?

Fundamental Contributions to Physics and Technology

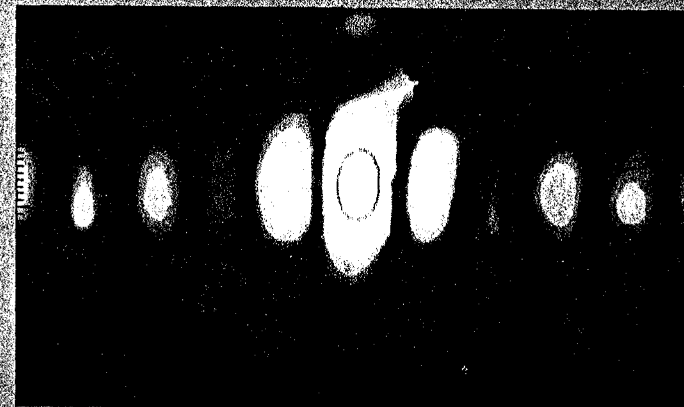
The challenge of fusion energy demands deep, creative scientific research. This research brings valuable insights and conceptual innovations to a broad range of scientific disciplines, including fluid mechanics, astrophysics, kinetic theory, and nonlinear dynamics, and stimulates major advances in computer simulations. The resulting growth in scientific understanding has contributed to a wide variety of technical applications: computer chip manufacture, high-power magnet design, and materials processing. Yet, despite its progress, fusion science continues to uncover unexpected phenomena, hard technical challenges, and profound scientific puzzles.

Enormous Potential as an Energy Source

Energy availability plays an essential role in the well-being and security of the world and each of its nations. As world population and energy consumption continue to grow, fossil fuels will become too scarce, too unreliable, or too polluting to provide for global energy needs in the coming decades. Alternative energy sources must be pursued.

Fusion offers a safe, virtually inexhaustible, long-term energy option with major environmental advantages. Harnessing the power of the stars on earth is a scientific and technological grand challenge. While progress to the goal of fusion energy has been impressive, much remains to be done. Our challenges are to fully understand and optimize plasma behavior for long times or under rapid pulsing and to develop the materials and technology that can lead to attractive, reliable, and affordable energy systems.

Microturbulence



Simulation of plasma microturbulence

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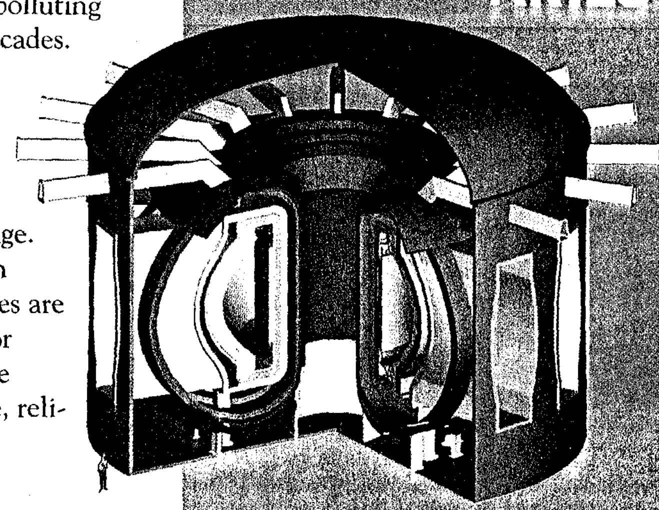
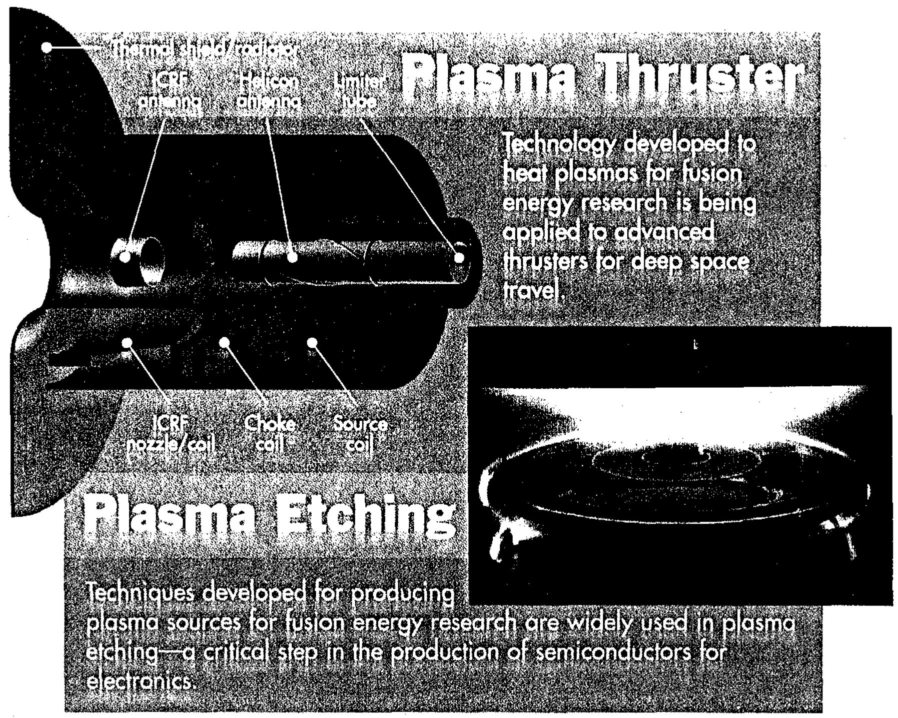


ARIES-AT advanced tokamak, advanced technology design. The ARIES Program, led by the University of California, San Diego, is a multi-insitutional program that explores the commercial potential of fusion as a future energy source.

Immediate Benefits of Plasma Science and Technology

Practical applications for plasmas and associated technologies continue to grow in importance to the government and the national economy. Fusion energy science R&D has resulted in a better understanding of plasma processes and in the ability to manipulate plasmas for many purposes. The technologies, theoretical models, and computational tools developed in the fusion program are being used in a variety of markets, including electronics, manufacturing, health care, environmental protection, aerospace, and textiles. Almost without exception, these applications require an interdisciplinary approach, integrating plasma science with chemistry, atomic physics, surface and materials science, thermodynamics, engineering, and economics.



Plasma Thruster

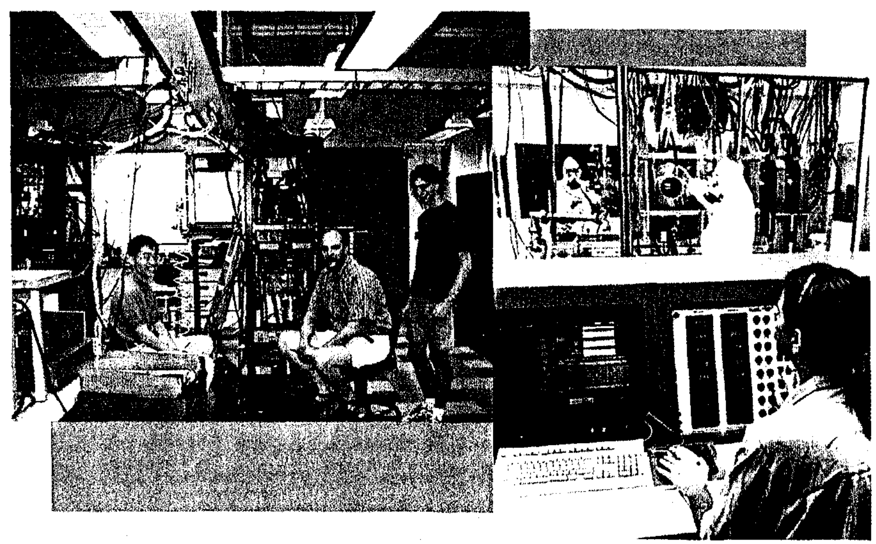
Technology developed to heat plasmas for fusion energy research is being applied to advanced thrusters for deep space travel.

Plasma Etching

Techniques developed for producing plasma sources for fusion energy research are widely used in plasma etching—a critical step in the production of semiconductors for electronics.

Training Students—The Next Generation

Fusion energy science research spans a variety of academic disciplines—physics, engineering, computer applications, and materials science—at many leading universities and colleges across the nation and around the world. This research educates students in a multidisciplinary approach to challenging questions of basic science, basic engineering, and a growing number of practical applications. National laboratories involved in fusion research continue to provide exciting opportunities for training students.



Fusion Energy Sciences Program

Advancing fusion science—Building a strong foundation for fusion energy

"We simply cannot afford to fail to pursue fusion energy aggressively."

Secretary of Energy Advisory Board, 1999

The U.S. federal government continues to invest in fusion energy science research because of its substantial scientific and technical challenges, and its high potential for an essential new energy source for this country and the world by the middle of the next century and beyond.

In 1996, the Department of Energy's (DOE's) Fusion Energy Sciences Program adopted an enhanced science-based strategy for developing fusion energy. The strategy emphasizes advancing the knowledge base in fusion science and technology, including basic plasma science, that is required to develop an economically and environmentally attractive fusion energy source.

Several independent review committees, such as the President's Committee of Advisors on Science and Technology (PCAST) and the Secretary of Energy Advsiory Board (SEAB), have approved the Program's science-based strategy. In 1999, the SEAB said "The threshold scientific question—namely whether a fusion reaction producing sufficient net energy gain to be attractive as a commercial power source can be sustained and controlled—can and will be solved… We simply cannot afford to fail to pursue fusion energy aggressively."

Photo courtesy of SOHO-EIT Consortium

The ball of plasma that we call the Sun is powered by fusion reactions in its core. This picture of the Sun, a composite of three images made by an extreme ultraviolet imaging telescope, shows bright active regions strewn across the solar disk, along with magnificent plasma loops.

Mission

Advance plasma science, fusion science, and fusion technology—the knowledge base needed for an economically and environmentally attractive fusion energy source.

Policy Goals

- Advance plasma science in pursuit of national science and technology goals.
- Develop fusion science, technology, and plasma confinement innovations as the central theme of the domestic program.
- Pursue fusion energy science and technology as a partner in the international effort.

The Integrated Program Plan

The DOE and the fusion science community have developed an Integrated Program Plan that includes both magnetic fusion energy (MFE) and inertial fusion energy (IFE) and integrates theory, experiments, and technology. The Integrated Program Plan focuses on six key program goals (see box) for MFE and IFE. The Plan describes approaches for achieving these goals, increasing the interconnections among the diverse parts of the program, and improving communication and performance accountability throughout the program.

Program Goals

- Advance understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through comparison of well-diagnosed experiments, theory, and simulation.
- Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems by investigating a broad range of innovative magnetic confinement configurations.
- Advance understanding and innovation in high-performance plasmas, optimizing for projected power-plant requirements; and participate in a burning-plasma experiment.
- Develop enabling technologies to advance fusion science; pursue innovative technologies and materials to improve the vision for fusion energy; and apply systems analysis to optimize fusion development.
- Advance the fundamental understanding and predictability of high-energy-density plasmas for inertial fusion energy (IFE).
- Develop the science and technology of attractive rep-rated IFE power systems.

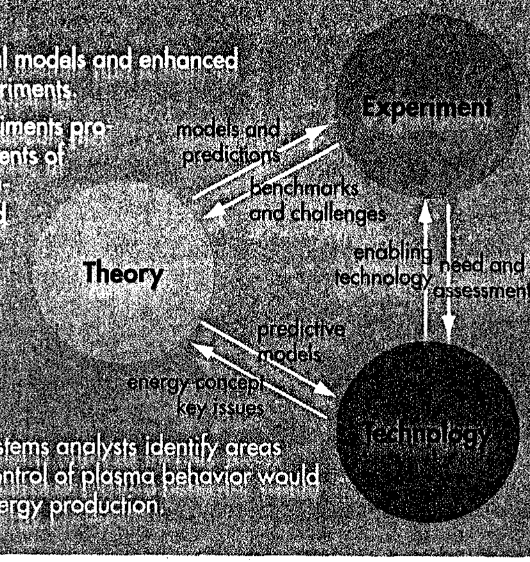
Fusion Energy Sciences Program

Interconnections—The Key to Progress in Fusion Energy

Meeting the challenges of fusion energy science requires a multidisciplinary and innovative program that has strong interconnections among theory, experiment, and technology.

Theory/Experiment

- Models and predictions: Theoretical models and enhanced predictive capabilities lead to experiments.
- Benchmarks and challenges: Experiments provide detailed diagnostic measurements of plasma profiles and turbulent fluctuation levels. These are incorporated into advanced fundamental understanding of plasma behavior.



Technology/Theory

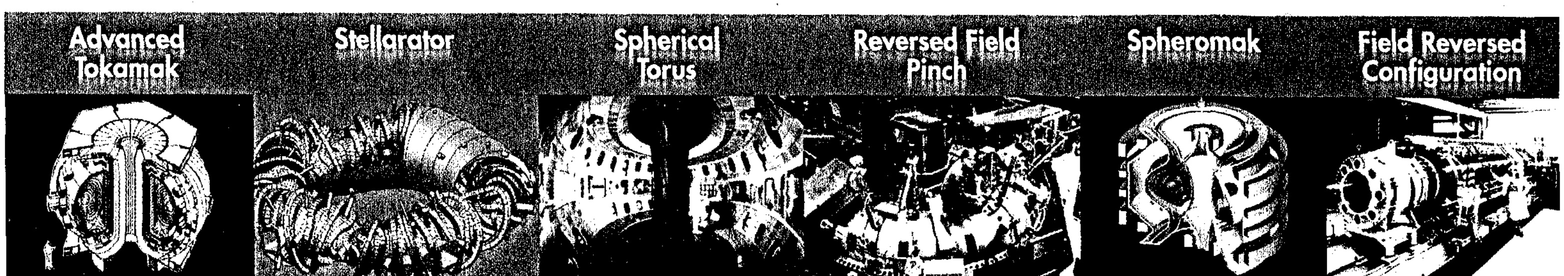
- Predictive models: Theory provides models for systems analysis.
- Key issues for energy concepts: Systems analysts identify areas where better understanding and control of plasma behavior would significantly improve visions for energy production.

Experiment/Technology

- Enabling technologies: Developments in technology enable innovative and high-performance plasma studies with control tools, plasma diagnostics, experiment design and systems analysis.
- Needs and assessment: Experiments identify needs for further technological development and provide performance projections for designing future facilities.

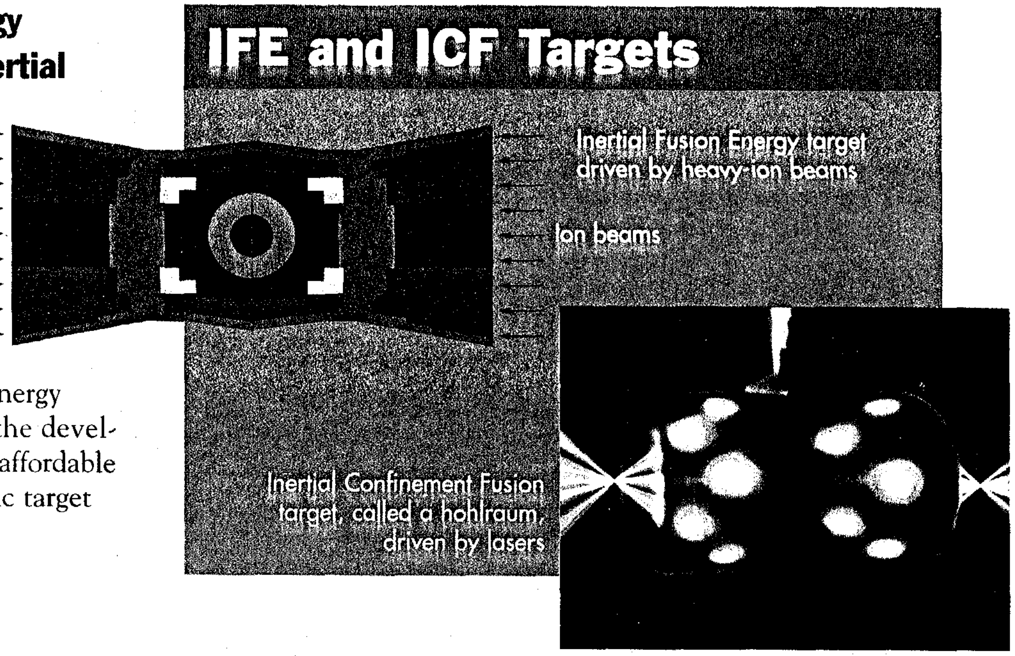
Shared Science—Magnetic Fusion Concepts

Experiments and theory on the full range of magnetic fusion experiments—from externally controlled to self-organized plasmas—increase scientific understanding. Learning how to control plasma instabilities on one configuration could provide key opportunities for stabilization in other configurations. Power and particle control are key issues for all magnetic fusion configurations, as are understanding and controlling turbulence and transport.



Linked Programs—Inertial Fusion Energy Program and the Defense Program's Inertial Confinement Fusion Program

Requirements for higher target gain at high pulse-repetition rates for IFE demand unique target design features that depend on the characteristics of the driver. The DOE Defense Program-funded Inertial Confinement Fusion (ICF) Program provides a major part of the target physics research needed for IFE. As a result, the Office of Fusion Energy Sciences Program, at modest cost, can focus on the development of high pulse-rate, efficient, reliable, and affordable drivers and associated fusion chambers; IFE-specific target design; target fabrication; and target injection.



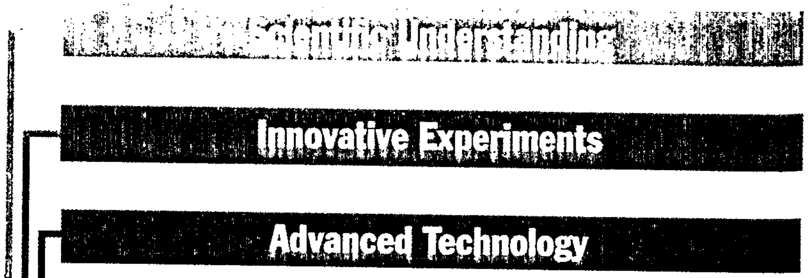
The U.S. Program—Partner in an Integrated Worldwide Program

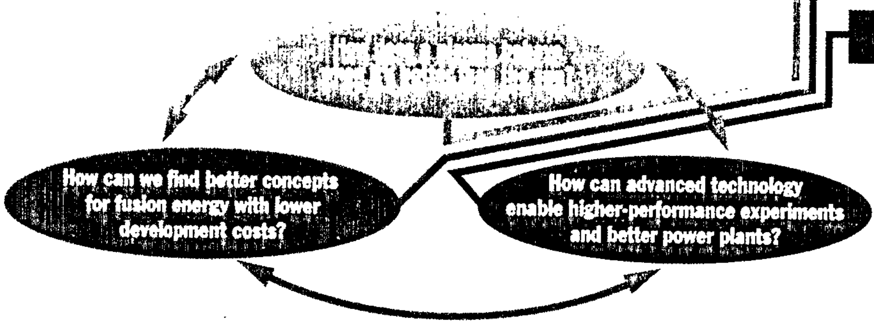
The U.S. fusion research effort is embedded in a much larger international fusion program. The international fusion program, based on strong cooperation among participants, brings the world's best minds to address the scientific and technological grand challenges of fusion science. This creates added excitement and opportunities for all. The U.S. MFE program is paced by the international program. Worldwide fusion funding exceeds $1 billion annually, of which the U.S. contributes approximately 15%.

Achieving the Goal

The Path Forward

Progress in fusion energy research comes from the integration of scientific understanding, innovative experiments, and advanced technology.





Plasma loops on the Sun's corona

Scientific Understanding

How does matter behave when it's hotter than the sun?

Understanding fusion plasmas requires recreating in the laboratory the same extreme conditions that prevail in a star: a confined plasma at the unimaginably high temperature and density found in the Sun. How do we produce such a plasma? How do we heat it to 300 million degrees C? How do we hold it together it to keep it from flying apart as a result of its intense internal pressure? After decades of research, fusion scientist have discovered that magnetic confinement and inertial confinement can produce laboratory-size plasmas that mimic conditions in the Sun, thereby providing the opportunity to understand the basic physical behavior of plasmas and paving the way to a fusion reactor.

Plasma behavior is so complex that it continues to stimulate deep and challenging questions of physics, including fluid mechanics, magnetohydrodynamics, kinetic theory, nonlinear dynamics, and computer simulation. Some of these deeper but crucial questions are:

- What are the fundamental mechanisms underlying the rapid diffusion of particles and heat, as observed in the Sun and laboratory fusion experiments? What roles do magnetic shear, plasma flow, and stochastic magnetic field lines play in these processes?
- What is the nonlinear evolution of an intense electromagnetic wave propagating through a plasma? Can such waves

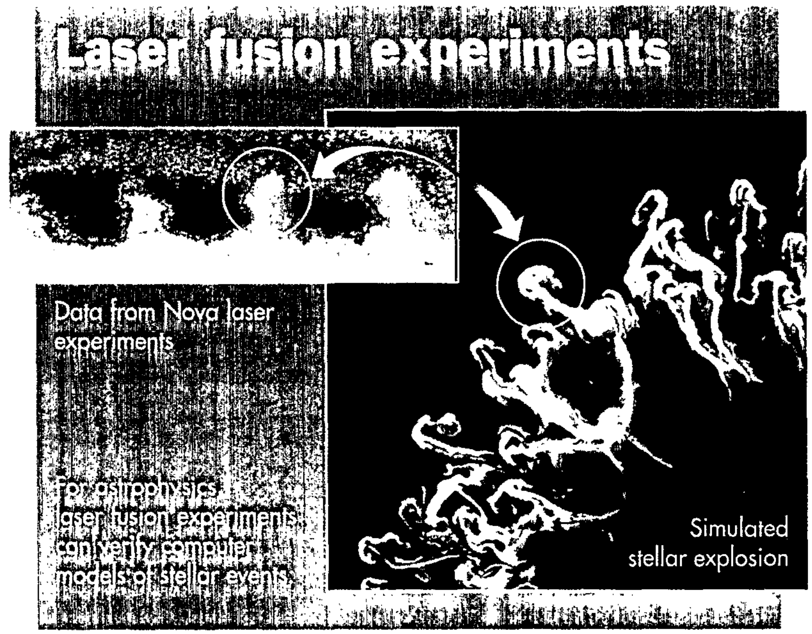
be used to accelerate charged particles to extreme energies? These issues are important for both magnetic and inertial fusion. In magnetic fusion we must learn how to heat plasma to fusion temperatures by means of electromagnetic waves. The problem in inertial fusion is even more complicated. We must understand the large amplitude, nonlinear interaction of the wave with the fuel pellet to insure that sufficient compression occurs to initiate a fusion reaction.

- What causes a plasma to relax to a localized, self-organized, self-generated equilibrium state? Answering this fascinating and deep plasma physics question could make a major contribution to understanding plasma confinement.
- How is a magnetized plasma affected by the presence of fusion heating and fusion products? To date, the amount of plasma self-heating due to fusion reactions has been small or, at most, comparable to the heating from external sources (e.g. microwave heating). In a fusion reactor, the self-heating will dominate. How plasma confinement and transport are modified by self-heating is a fundamental plasma physics question, with huge practical implications for fusion reactors.

How do we address the fundamental scientific issues?

With a combination of theory, well-diagnosed experiments, and computer simulation, fusion energy science can advance the fundamental understanding and predictability of high-temperature plasmas. Here are some approaches:

- Use magnetic confinement to study long-duration dilute plasmas held together by twisting magnetic fields, including their heating, transport, and possible self-organization. Apply the resulting knowledge to study fusion experiments, the surface of the sun, the earth's magnetosphere, and astrophysical phenomena (such as jets). This understanding can also be applied to industrial and commercial uses of plasmas, for example incandescent and fluorescent lighting, and arc welders.
- Use inertial confinement to study short-duration, ultra-high-pressure plasmas, including laser-ignited plasma pellets held together by inertia. Apply the resulting knowledge to study inertial fusion experiments, the structure of the stars, and the core of the Sun.



Achieving the Goal

Innovative Experiments

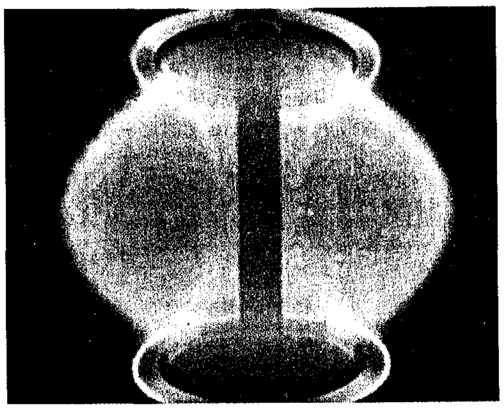
How can we find better concepts for fusion energy with lower development costs?

Innovation in fusion energy science means developing new concepts that exploit the underlying science. Innovation provides potential benefits both for magnetic and inertial confinement of plasmas and for affordable paths to fusion energy. To innovate better approaches, fusion energy science needs to find answers to some important questions about fusion plasma experiments.

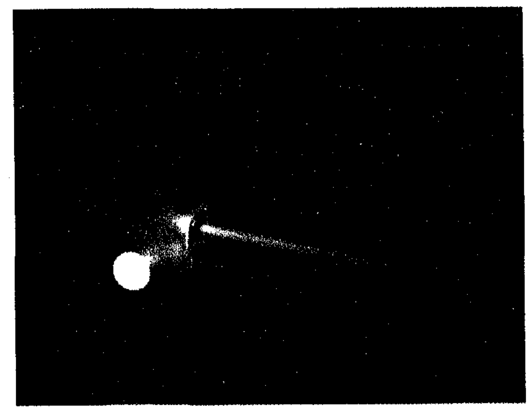
The Issues	The Questions
• Conducting more capable and lower-cost experiments to improve the economic potential of fusion.	What technology improvements can enhance scientific productivity in reduced-cost fusion experiments?
• Increasing plasma energy confinement and pressure.	How can we achieve improved confinement at higher plasma pressure through both self-organized and external-field-dominated magnetic plasma configurations?
• Controlling fusion plasma for long, useful periods of time. • Controlling the effects of self-heating.	How can we control the relationships between high-pressure magnetic configurations and high-temperature heat confinement to sustain the fusion process in such configurations?
• Reducing the cost of producing intense beams (drivers) for inertial fusion targets for energy.	What are the required and achievable beam qualities and beam-coupling efficiencies for inertial fusion target plasmas to achieve high-energy gain?
• Designing fusion chambers that last a long time.	What do we need to understand about plasma interactions with chamber walls to achieve long fusion-chamber lifetimes in both steady-state and high-pulse-rate fusion configurations?

How do we use our understanding to build a fusion machine that will be cost-effective?

- Use improved knowledge and innovation to optimize magnetic and inertial plasma configurations on a modest scale that have potential for improved fusion power plants.

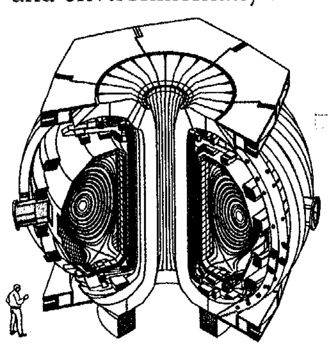


Magnetically confined toroidal plasma experiments

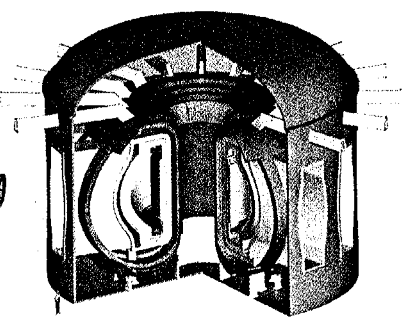


Inertially confined planar plasma experiments

- Optimize both magnetically confined and inertially confined high-performance plasma configurations to be cost-effective and environmentally attractive.

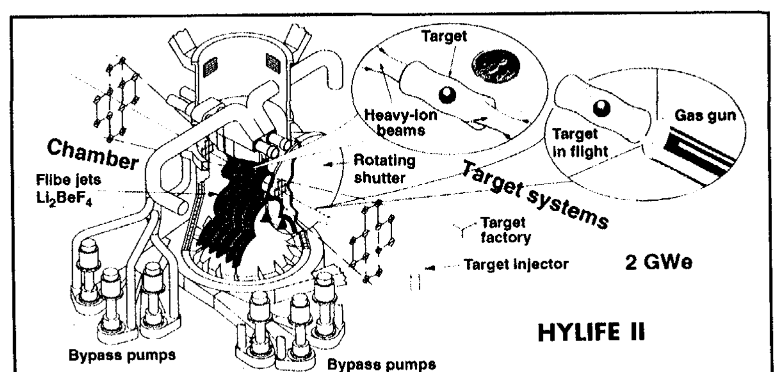


Cutaway of D-III-D



ARIES-AT

Experiments in current devices (e.g. D-III-D) show the promise of more attractive energy systems (ARIES-AT).



HYLIFE-II, an inertial fusion chamber concept, uses a thick liquid blanket to reduce radiation damage, resulting in long-life, low-activation structures.

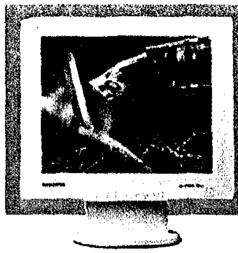
Achieving the Goal

Advanced Technology for Science and Energy

How do we advance technology for higher-performance experiments and better energy systems?

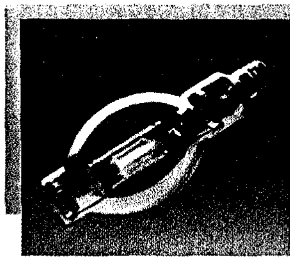
Theory and experiments teach us about the nature of plasmas, but technology builds the devices to produce and control them. What method can we use to heat matter efficiently to temperatures hotter than the Sun? And then how can we develop containers and special materials to hold stars in the laboratory? To harness the fusion power of the stars, how do we capture the energy in a practical engineering system?

To realize the potential of fusion as a new energy resource, technological breakthroughs will be needed to produce useful products at a competitive price and with attractive safety and environmental features. Along this path to fusion energy, research and development projects are finding many useful near-term applications.



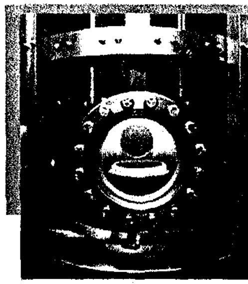
Plasma flat panel display

(Photo courtesy of Samsung)



High-intensity plasma arc lamp

(Photo courtesy of OSRAM Sylvania)



Plasma etching of silicon wafer

Important Questions for Fusion Technology

- What new tools/techniques are needed to realize advanced plasma performance in current and next-step experiments?
- What are the limiting phenomena in developing advanced materials and technology for fusion energy?
- How can we maximize the reliability and affordability of fusion products?
- How can we maximize the safety and environmental features of fusion energy?
- What is the optimum logic for defining an affordable path to fusion energy?

Improving technology for today's fusion science and tomorrow's fusion energy systems

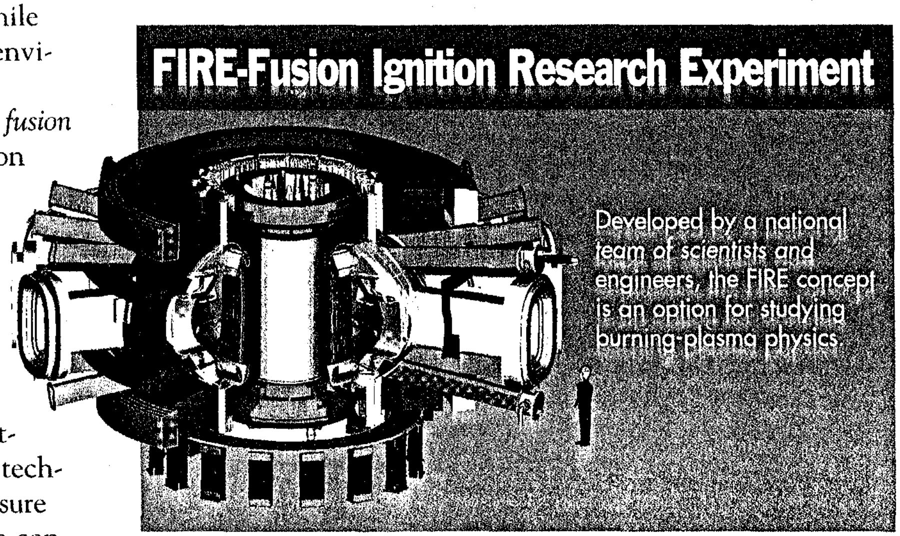
By identifying, developing, and applying advanced fusion technology, fusion energy science can enable better near-term experiments and improve the attractiveness of future fusion energy systems.

- *Develop tools and techniques to realize enhanced plasma performance in current and next-step experiments.* Near-term scientific progress in fusion energy science research depends upon advances in plasma technologies for both current and next-generation plasma experiments to achieve their full potential. Plasma technologies include fueling, plasma heating and current drive, magnetics, and plasma-facing materials and components. For next-generation experiments, researchers must perform validating R&D to address fabrication, performance, and operational safety, plus the affordability of major components and systems.

- *Advance understanding and innovation in fusion technologies and materials to improve the vision of fusion energy.* During the last two centuries, innovations in science and technology have been coupled to advances in materials. Fusion technologies that include materials innovation are key to realizing fusion's potential as an attractive and cost-competitive energy system. Advanced materials research is necessary to develop the scientific understanding to push the envelope of stress, temperature, chemical environment, and large fluences of energetic neutrons. Key fusion technologies include plasma and fusion-energy chamber technology, remote handling, safety and environment, and fuel processing. The challenge is achieving high-power density with high thermal efficiency while maximizing reliability, maintainability, safety, and environmental attractiveness.
- *Perform studies of next-step experiments and advanced fusion energy systems.* Advanced design studies guide fusion R&D toward attractive and achievable fusion power systems and provide critical technical information for major program decision points. Burning-plasma experiments, as well as technology and material-testing facilities provide data to support critical program decisions. This research links broad national and international interests in fusion development, and explores options representing substantial variation in performance, cost, and technology requirements. Conceptual design studies ensure that projects are technologically feasible within the constraints imposed by physics, materials, and technology to produce a system that is both economically and environmentally attractive.

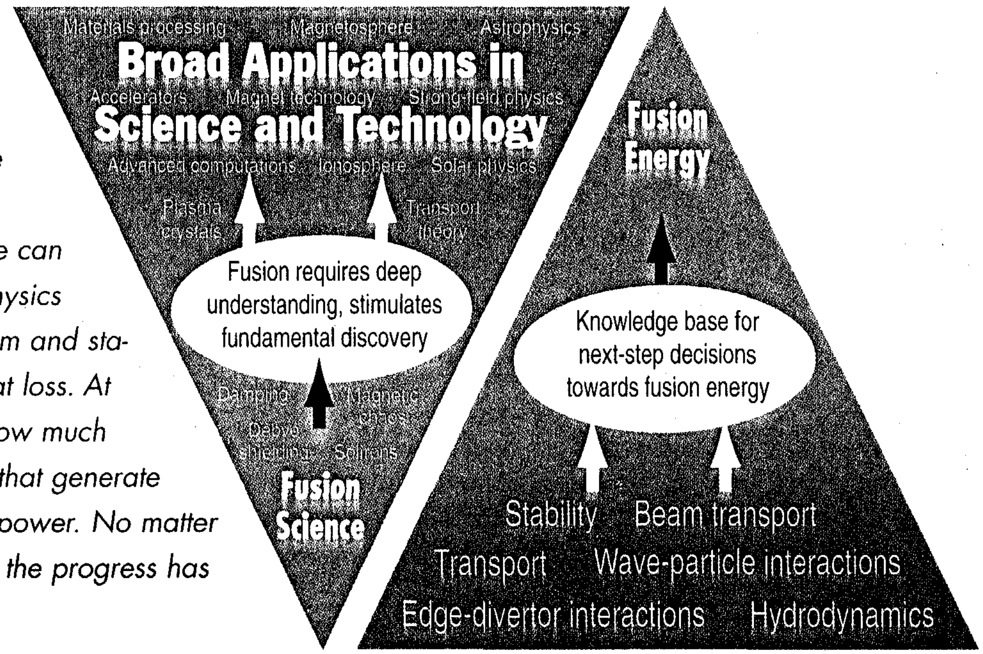
"We have labeled civilizations by the main materials which they have used: the Stone Age, the Bronze Age, and the Iron Age...a civilization is both developed and limited by the materials at its disposal. Today, man lies on the boundary between the Iron Age and the New Materials Age."

Dr. George P. Thomson
Nobel Laureate in Physics



Measuring Progress in Fusion Science

A practical approach to measuring the progress of fusion science would be to think of fusion energy science as a continuum that is anchored at one end by scientific understanding of plasma physics and at the other by commercial electric power plants fueled by fusion energy. At the science end of the spectrum, we can ask how deep is our understanding of the plasma physics describing the basic issues of macroscopic equilibrium and stability, heating, and turbulent plasma particle and heat loss. At the fusion-energy end of the spectrum, we can ask how much progress has been made toward producing devices that generate large amounts of commercial electricity using fusion power. No matter what point on the continuum we choose to measure, the progress has indeed been impressive. Here are some examples.



Evolution in basic understanding of plasma physics

From its beginning, the fusion program has made crucial contributions to the understanding of plasma physics. The experimental techniques and diagnostics developed for fusion research, as well as the theoretical and conceptual innovations that have resulted from that research, have advanced the frontiers of science and technology in fields as diverse as space physics and computer chip manufacture.

Today, fusion scientists predict the equilibirum and stability of high-temperautre magnetized plasma with remarkable accuracy. Using sophisticated diagnostics and advanced computation, scientists assembling a first-principles understanding of a wide range of plasma physical phenomena.

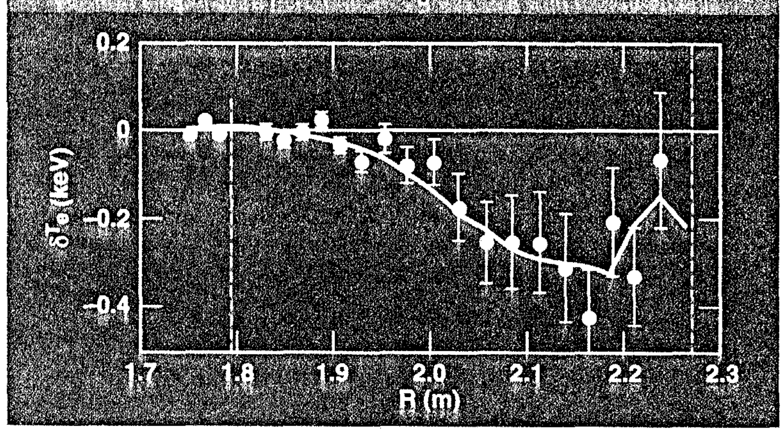
Progress in basic understanding of plasma physics

Issue	Early 70s	Mid 80s	Mid 90s	Near Future
Macroscopic stability and β limits	•			
Plasma heating and current drive	••			
Self-heating (α physics)	••	••	•	
Energy and particle transport	•	•		
Plasma–wall interactions	••	•		

•• Highly Uncertain • Primitive Understanding Significant Understanding Predictive Capability

Agreement of theory and experiments

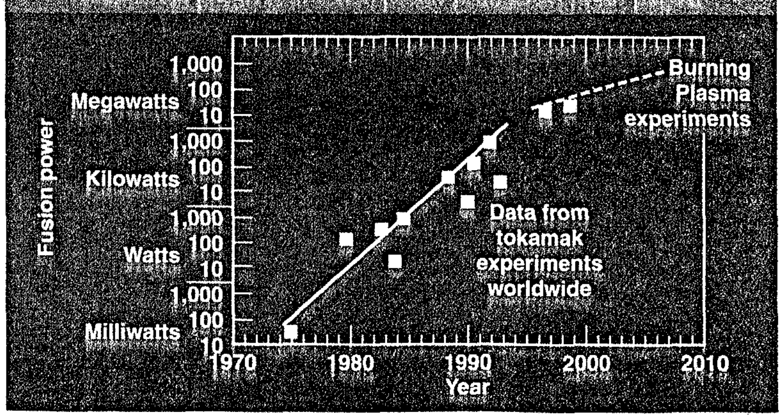
Calculated radial structure of resistive-wall-mode electron-temperature pertubations agrees well with measurements



Starting from general kinetic models, scientists have developed reliable fluid models that cover at least six different time scales and range over eight orders of magnitude. Experimentally, new diagnostics using advanced spectroscopy and test particle beams have been developed to measure local profiles of plasma temperature, density, and magnetic field. This is an extremely difficult task because high plasma temperatures prohibit the insertion of any material probes into the plasma interior. As an example of the level of scientific understanding achieved, the accompanying diagram shows a comparison of experimental data and theoretical predictions for a particular type of macroscopic plasma instability known as the resistive-wall mode. This instability is quite important because if excited strongly enough, it can lead to termination of the plasma discharge. The diagram shows what most scientists consider to be reasonably good agreement between theory and experiment. This diagram does not show the incredibly sophisticated theoretical modeling and experimental diagnostic development that has been required to achieve this agreement. The fusion community takes great pride in such hard-won comparisons.

Fusion power production

Worldwide progress in fusion power production (short pulses)



As our knowledge of plasma physics and fusion engineering has progressed over the past three decades, the amount of fusion power produced in our experiments has increased accordingly. Fusion power output has grown steadily since 1970. From early experiments in the 70s to modern high-performance tokamaks, the fusion power output has grown from the range of hundreds of milliwatts to tens of megawatts, an astounding gain of 100 million. Though progress has been dramatic, we still have work to do before we reach the thousand megawatts of power produced by a typical commercial power plant. As we continue to make the same strides as we have in the past, fusion power production will become a reality.