The Potential Role of ITER in Magnetic Fusion Energy Research

Overview

The last decade has seen tremendous advances both in the scientific understanding of fusion systems, and in the energy produced by experimental fusion facilities. While much remains to be done to fully understand the hot gases, called "plasmas," used to produce fusion, and to optimize the magnetic containers used to hold fusion plasmas, the time has come to take a next major step in the development of fusion energy.

What is needed to make fusion practical?

Progress to practical fusion energy is paced by scientific understanding of hot plasmas, gasses in which ions and electrons are not attached as atoms or molecules, but rather move freely, and by advances in certain critical technologies. The key scientific questions in fusion research are:

- What limits the pressure of high-temperature plasmas?
- How do very energetic particles heat and sustain plasmas?
- How does heat escape from plasmas?

These questions are critical because plasma pressure is what makes fusion power, and so it must be maximized. The energetic particles created by the fusion process must sustain the temperature of a fusion plasma, so the heating process must be understood and controlled. And if heat escapes too quickly from a fusion plasma it will cool to too low a temperature, so the understanding of turbulence and heat transport is a critical element of fusion energy science.

These questions are not only scientific challenges; their solutions must be integrated successfully in a fusion plasma system. Thus there is an important integrative and innovative element of fusion research. The self-consistent solution to these questions lies in a plasma whose heat content is largely sustained by its own fusion reactions, i.e., a "burning plasma".

The most important technological issues for fusion are:

- Development of techniques to handle high heat fluxes from plasmas
- Development of structural materials to withstand high fusion neutron fluxes while incurring low radioactivity
- Development of large-scale superconducting magnets to produce the fields needed to contain plasmas

These development needs stem from the high heat and neutron fluxes that emerge from fusion plasmas, and from the need to sustain the magnetic container with a minimum of power, as is made possible by superconducting magnets. A self-sustaining burning plasma experiment requires and will drive substantial advances in each of these areas of technology.

What has been achieved over the last decade, and what is the focus of current fusion research?

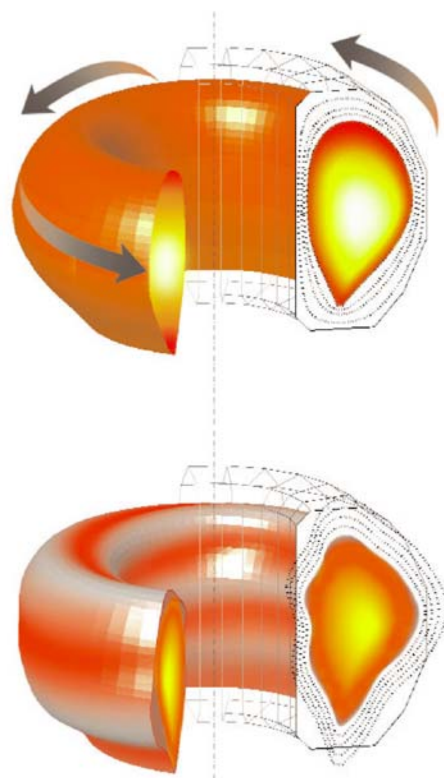
There have been dramatic achievements over the last decade in each of the key areas of fusion science and technology. Current research is both producing deeper scientific understanding and also uncovering new opportunities for innovation.

Global stability and plasma pressure limits

Fusion plasmas are generally confined by topologically toroidal systems, with magnetic fields traveling in both the toroidal (long way around the doughnut) and poloidal (short way) directions. The most developed configuration under study, the tokamak, is symmetrical in the toroidal direction, with an aspect ratio (major radius of torus divided by minor radius) of order three. The tokamak features a strong toroidal magnetic field, with a weaker poloidal magnetic field generated in large part by current flowing toroidally within the plasma.

One must be concerned about the global stability of fusion plasmas, because it is this stability which limits the factor β_T – the ratio of pressure in the plasma to pressure in the toroidally directed magnetic field, generated by expensive external magnet systems. For a given magnetic field strength, the fusion power density varies as the square of β_T, so the cost of fusion energy is sensitive to this factor. Understanding the limits to β_T and developing techniques to maximize it, while maintaining adequate plasma stability, has been a long-term focus of fusion research.

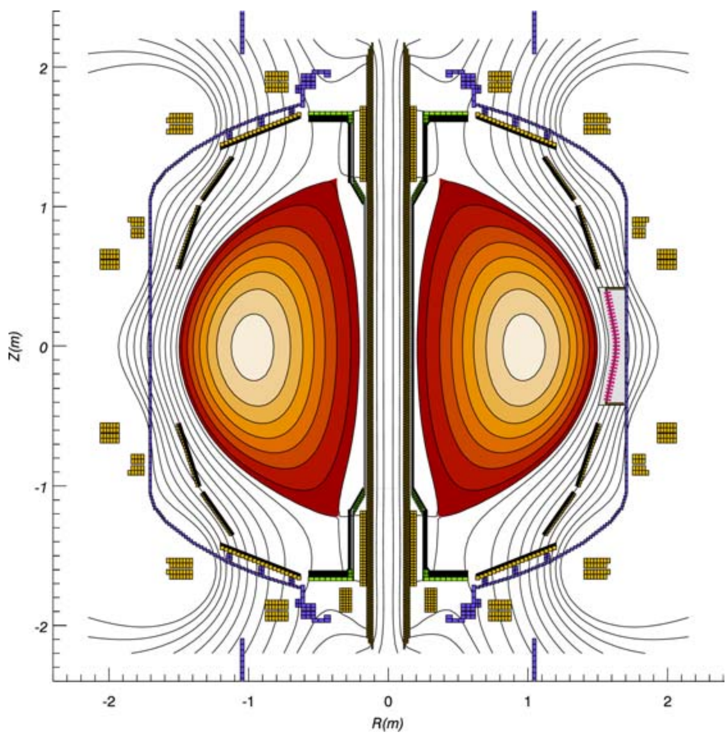
In 1992 many aspects of global plasma stability were well understood, and experimental results agreed well with theoretical and computational predictions over a wide range of plasma parameters. This agreement, however, was achieved only for short plasma pulses, < 0.1 second, shorter than the time required for electrical currents to damp out either in the plasma or in the walls of the vacuum vessel. The highest β_T achieved in a well-confined, high-temperature plasma was about 11%.



Toroidal rotation can stabilize a tokamak plasma in the presence of an electrically conducting shell.

By 2002 the understanding of global stability has progressed to the point where "resistive instabilities" which become important on the ~1 second time scale are reasonably well understood. Feedback control techniques, using microwaves to drive electric currents locally in the plasma, are being brought into play to stabilize oscillations internal to the plasma. Strongly driven plasma toroidal rotation is being used to allow the electrically resistive wall of the vacuum vessel that surrounds the plasma to better prevent the growth of external instabilities, by limiting the penetration of magnetic perturbations. Magnetic feedback is being used to cancel these perturbations.

A new configuration, the Spherical Torus (ST), has come under experimental investigation in the last decade. The ST is a low-aspect-ratio magnetic torus, in which the "doughnut-hole" has been shrunk to the minimum size. It can be characterized as the spherical limit of the tokamak. This configuration has recently achieved very high β_T of 35% in high temperature well-confined plasmas. Many of the additional stabilization techniques employed on the tokamak will soon be applied to the ST, taking this value higher.



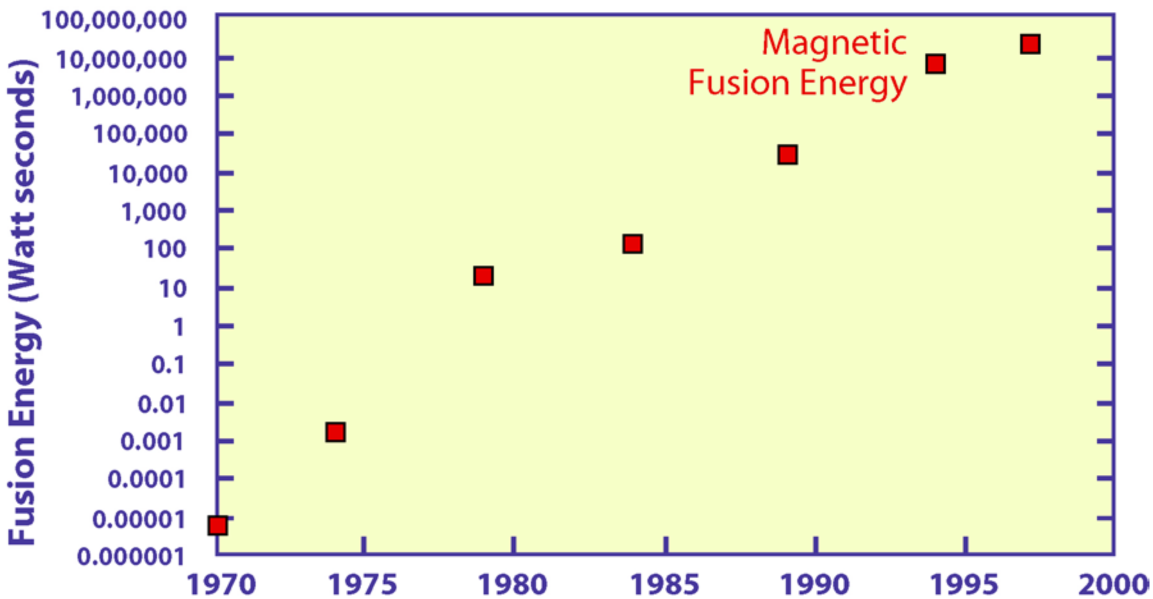
β_T of 35% has been achieved in well-confined Spherical Torus plasmas.

New plasma measurement techniques have been key to these successes. Methods to measure both the equilibrium magnetic fields and any growing perturbations have been critical to success. A major focus of current theoretical research is the development of nonlinear numerical codes capable of simulating global stability effects, including realistic "non-ideal" effects. This is a substantial challenge, as some such effects occur on very small spatial scales, and others require inclusion of particle motion in the calculation, substantially increasing the complexity of the problem.

There are strong connections between this area of plasma research and stability studies in both space and astrophysical plasmas. Researchers involved in fusion plasma physics are making significant contributions in these fields, and techniques developed in fusion plasmas are used widely.

Plasma sustainment and energetic particle physics

The very high temperature of a fusion plasma must be largely sustained by the charged fusion reaction products themselves, in order to minimize any external power required to sustain the plasma temperature. Furthermore either the magnetic fields must be fully externally supplied or currents in the plasma providing these fields must be sustained through the plasma's internal mechanisms.

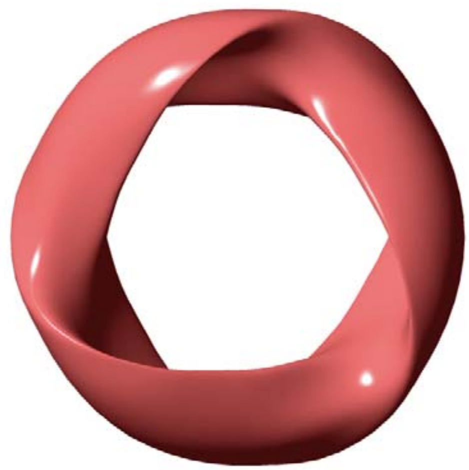


The energy produced in fusion plasmas has outpaced Moore's law for the advance of computer speed.

In 1992 the first experiments were performed using a mixture of deuterium and tritium fuel, the forms of heavy hydrogen anticipated to be used in fusion power plants, achieving a fusion power production of some 1.7 MW. By 2002 fusion powers of up to 16 MW had been achieved, with fusion energy production in a single pulse of 22 MJ. While fusion power only provided a modest fraction of the plasma heating even in the more recent high-power experiments, careful measurements indicated that the fusion power produced in the form of energetic alpha particles (helium nuclei) remained in the plasma as expected, and provided the desired plasma heating.

In 1992 it was not clear that it was even possible to sustain the steady state toroidal plasma current needed in the tokamak configuration in a practical manner. However in the late 1980's experiments had shown that the measured *self-sustaining* "bootstrap current," driven by pressure gradients in the plasma, was in good agreement with theoretical prediction. In the mid 1990's it was shown that this bootstrap current might in principle be used to sustain most of the plasma current in advanced modes of tokamak operation, although some current would still need to be externally driven. Developing these modes of operation is a key focus of current tokamak research.

More recently a new configuration has been invented, called the Compact Stellarator. In this configuration the plasma cross-sectional shape varies around the torus, allowing the freedom to design in desirable features. This configuration does not require any external drive to sustain the plasma current, relying completely on externally generated magnetic fields in superconducting coils, supplemented by the natural bootstrap current. This configuration also features a high level of global stability, and should not require rotation drive or microwave or magnetic feedback control to operate at attractive levels of plasma pressure, reducing the power input required for plasma sustainment and control. Advanced massively parallel computation has played a critical role in the design of Compact Stellarator configurations. This configuration will come under experimental investigation in the next few years.



The Compact Stellarator configuration uses variation in the toroidal direction to optimize stability and steady-state properties.

Energetic particle physics and plasma sustainment is an ongoing area of research, even though full-scale experiments will require a burning plasma. New energetic-particle-driven instabilities have recently been identified, and the rich nonlinearity of these systems has not been fully explained even with the most advanced simulations. This is an area of significant interaction with space and astrophysics. Wave-particle interactions are critical for such diverse phenomena as heating of the solar corona and isotropization of cosmic rays.

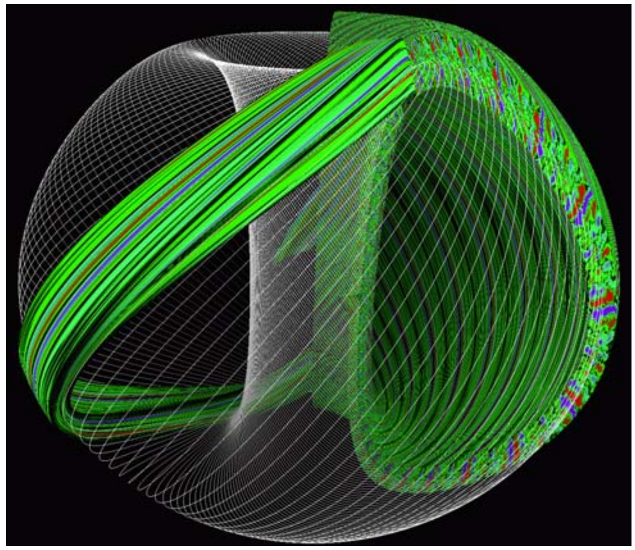
Turbulent heat loss

Heat is lost from a high temperature plasma through turbulent eddies that are driven by the extreme gradients in both the ion and electron temperatures. If this turbulence is too great, heat is lost faster from the plasma than it can be replaced by fusion reactions, and the temperature cannot be practically sustained.

In 1992 empirical scaling relations were well established, allowing reasonable predictions of turbulent losses. However the underlying mechanism of the turbulence was only understood in a generic sense, and there were serious concerns about the reliability of such predictions.

By 2002 rather dramatic advances have been made in both the understanding and the control of plasma turbulence. Conditions have been generated where ion turbulence is suppressed and has little effect on plasma losses. Furthermore the mechanism of ion turbulent losses has been identified, and a “standard model” of the underlying ion physics is widely accepted. This mechanism explains a number of earlier mysteries, including the rising intensity of plasma turbulence towards the outside where the plasma is cooler, and the strong sensitivity of the plasma to edge conditions. It is likely that similar, but possibly smaller scale, physics underlies turbulence in the electron channel. This is an active area of current investigation.

Advanced numerical simulation has played a major role in the development of this field of research. Unlike classical fluids, magnetically confined plasmas support largely two-dimensional turbulence, aligned along the magnetic field, which consequently undergoes inverse energy cascade – from shorter to longer wavelengths – resulting in a narrower range of wavelengths. Thus despite the necessity of including particle motion, direct numerical simulation of some of the key effects is within reach of modern massively parallel computers. This theoretical and numerical work, in tandem with advanced measurement tools for the visualization of turbulence, is a very exciting area of modern research.



Simulation of field-aligned turbulence in Spherical Torus plasma.

The Reversed Field Pinch, a less well-developed magnetic configuration, resembles a tokamak with a relatively weak toroidal magnetic field but a strong plasma current. This configuration is generally subject to intense magnetic turbulence, which plays a large role in the self-organization of the system, but also significantly enhances heat loss. In the last decade methods have been developed to reduce this turbulence dramatically, significantly improving heat confinement. These experiments involved the use of transient techniques to adjust the current profile to more nearly match the theoretical requirements for stability. Extending these techniques to longer time periods, and finding methods that can be extrapolated to fusion system conditions, is an active area of research.

The Reversed Field Pinch is itself the most developed of a wider range of exploratory magnetic configurations under investigation, many of which also rely heavily on self-organization. Such configurations promise reduced-cost fusion systems, due to their low externally generated magnetic fields. The recent successes of the Reversed Field Pinch suggest new avenues of research for these systems.

Turbulence is a ubiquitous feature of plasmas, as well as neutral fluids. The mathematical understanding of turbulence has been an area of connection between plasma physics and other fields. Magnetic turbulence is of special importance in the solar wind and in astrophysical plasmas, and techniques developed in fusion plasma physics have been used extensively in these arenas.

Handling high heat fluxes

The stream of plasma flowing out of a fusion system must eventually encounter a first material wall. It is important that both the heat flux at this wall and the plasma-induced erosion rates be acceptable.

As of 1992 it was found that a "high recycling" regime could be achieved in the plasma stream magnetically diverted from the edge of the fusion system. This operating regime, which features a strong reflux of plasma in the form of neutral atoms, lowered the plasma temperature at the plasma-facing surfaces dramatically. However heat fluxes and erosion rates were still unacceptable. A further problem is that plasma configurations which carry large currents may "disrupt" suddenly and rapidly when stability boundaries are accidentally crossed, dumping large off-normal heat loads, inducing very strong electromagnetic forces, and generating very penetrating high-energy "runaway" electrons. These effects can be quite problematic for fusion energy applications.

Tungsten "brush" capable of handling 25 MW/m^2 heat flux.

By 2002 a new "detached" regime of operation for the diverted plasma stream was discovered, which greatly reduces heat flux and erosion rates, by allowing the plasma stream to fully or partially recombine to neutral atoms before striking the material surface. This spreads heat loads and reduces erosion rates substantially. New high-heat-flux components have also been developed, raising the technological state of the art for steady heat flux handling from 5 MW/m^2 up to 25 MW/m^2.

Furthermore, techniques have been found which mitigate disruptions in present-day tokamaks through the injection of large amounts of neutral gas – which absorbs the plasma energy, controls the production of runaway electrons, and ameliorates electromagnetic forces. Because these techniques require both adequate warning and highly reliable operation, even if they are verified at larger scale, tokamak fusion systems will still need to be designed to withstand the effects of a limited number of full-power disruptions. An attraction of the Compact Stellarator configuration is that stellarator systems, in normal modes of operation, even when carrying moderate plasma currents do not suffer from disruptions.

A very active, but speculative, recent area of research has been in the development of liquid metals for plasma-facing surfaces. The concept is that a flowing liquid metallic surface can absorb heat effectively, and will not suffer due to erosion. Potentially such a surface could be resilient to plasma disruptions. In addition, liquid lithium is a very effective pump for hydrogenic species, and by reducing the density of neutrals atoms at the plasma edge may permit higher edge temperatures, which correspond theoretically and experimentally with higher confinement. Finally, and most speculatively, rapidly flowing metals may be able to serve much the same function as plasma rotation, helping to prevent the growth of magnetic perturbations through the walls of the system.

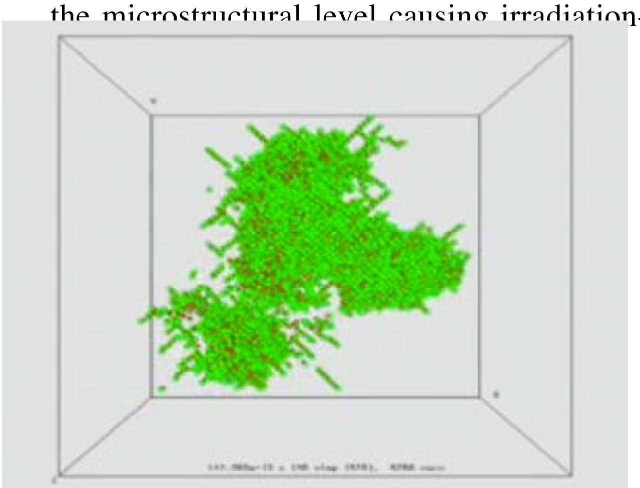
Recent advances in high-heat-flux systems, both in solid and liquid form, are likely to have substantial spin-offs in other areas of technology.

Low activation structural materials

The function of the first wall and "blanket" of a fusion power plant is to transfer neutron and plasma power to a thermal system for the production of electricity. In addition, the blanket must regenerate the tritium consumed in the plasma, through reactions between the emerging neutrons and lithium. The first wall and blanket of a practical fusion system must handle a neutron flux of 2 – 4 MW/m^2, with a lifetime of at least 5 years. The resulting fluence requirement of 10 – 20 $MWyr/m^2$ is very challenging. At the same time these components should demonstrate low activation levels and relatively short half-lives, so that afterheat is low and only shallow land burial is required for disposal.

By 1992 a first generation of experimental studies was completed to evaluate the feasibility of two candidate materials systems for fusion energy structural applications: ferritic steels and vanadium alloys. Basic understanding was available for irradiation damage production (displacements and transmutations) in the fusion neutron spectrum. Lifetime-limiting irradiation effects were identified through traditional nuclear metallurgical experimental techniques, exploring empirically the effects of irradiation damage on the properties of candidate alloy systems. Early phenomenological models were available for microstructural evolution, irradiation induced swelling and creep, and some aspects of mechanical behavior. Compatibility limits for various coolants and tritium breeding media were identified.

As of 2002, very-low-activation silicon-carbide composites have been added to the list of candidate materials systems. For both ferritic steels and vanadium alloys, mechanisms at the microstructural level causing irradiation-induced embrittlement at low temperatures and dimensional instability at high temperatures have been identified. Promising approaches are under investigation to greatly reduce strength and ductility degradation rates and increase stability over a wide range of fusion conditions. The research approach is now based on fundamental theory and modeling, using advances in nanotechnology and computational materials sciences to understand fusion materials irradiation damage phenomena over vast ranges of space (from atomic dimensions) and time (from initial atomic collisions lasting pico seconds). This has enabled quantitative



Molecular dynamics calculation of displacement damage due to neutron impact.

predictions and simulations of fusion materials' microstructural evolution that are being tested with measurements from experiments that simulate key fusion environmental conditions. The demonstration of the equivalency between displacement damage from fission and fusion neutrons has greatly increased usefulness of fission reactor testing as a research tool for fusion materials.

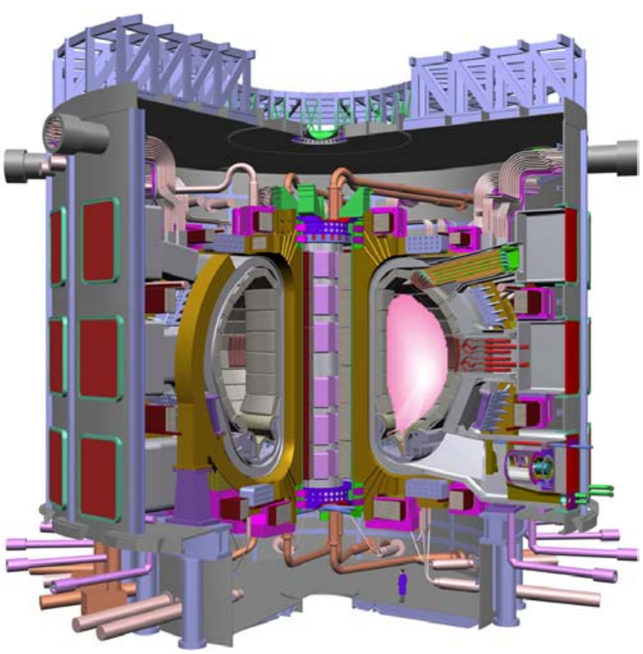
Work in the development of neutron-interactive materials is very much interconnected with other areas of nanoscience. Advances in understanding for fusion systems are likely to benefit fission systems as well as systems used for neutron science.

Large-scale superconducting magnets

The high magnetic fields required for fusion systems will most likely require the use of large superconducting magnets, to essentially eliminate resistive magnet power losses. In some cases these magnets must operate in a pulsed mode, which is challenging for superconductors.

As of 1992 the largest-scale test of superconducting coils for fusion was the "Large Coil Test" at Oak Ridge National Laboratory, which had confirmed the maximum capability of "first generation" niobium-titanium superconductors with 9 T at the conductor, for steady fields, in a toroidal array. One coil used the "second generation" niobium-tin superconductor, but operating at the same field. The maximum stored energy per coil was 160 MJ.

By 2002 the ITER Model Coil test confirmed the capability of niobium-tin superconductors with 13 T at the conductor, and a rapidly changing field of 0.6 T/s, in a solenoidal coil with a total stored energy of 640 MJ. The cable-in-conduit conductor configuration for this coil has set the standard for future high field, steady or pulsed, large fusion magnets, as well as for other applications outside of fusion.



ITER final design

The effort in superconducting magnets for fusion is coupled strongly to R&D for such magnets in support of high energy and nuclear physics. Indeed the lead in the development of high-current superconducting strand has moved back and forth between these two communities, and close connections are maintained so that advances are rapidly shared.

What can be gained from ITER?

ITER is designed to provide major advances in all of the key areas of plasma science and technology. It will cross important scientific frontiers in all areas. Because of ITER's large size and magnetic field, it extends some of the key parameters that characterize plasma stability and turbulent transport into unexplored territory. Due to the intense plasma heating by fusion products, it also accesses previously unexplored regimes of energetic particle physics. Because of the very strong heat and particle fluxes emerging from ITER plasmas, it will extend regimes of plasma-boundary interaction well beyond previous experience. The new regimes of plasma physics that can be explored, and the interactions amongst the anticipated phenomena, are characterized together as the new regime of “burning plasma physics.”

ITER also represents a major advance in essentially all areas of fusion technology. Plasma facing components will be pressed to previously unexplored limits in heat flux and fluence. A testbed will be provided for studying the behavior of low-activation blanket modules. And the performance of large-scale, high-field superconducting magnets will be demonstrated. In addition, a whole class of important technologies needed for heating and fueling plasmas, as well as for driving plasma current will be brought up to the next level of development. All of these systems will be challenged to perform in a high duty factor fusion environment, requiring remote maintenance of many components.

Global stability and plasma pressure limits

ITER is larger in size and in magnetic field than any previous fusion system. As a result, the ratio of the plasma size to the size of the gyrating ion trajectories (ion gyroradii) is much greater than has ever previously been investigated. Both theory and experiment have shown that instabilities that depend on the electrical resistivity of the plasma are highly sensitive to this parameter – which is likely to be large in almost any fusion system. ITER will provide an opportunity to study these important effects for the first time.

Plasma sustainment and energetic particle physics

ITER will be the first fusion system to be largely heated by its own fusion products. As a result, a large population of energetic ions will be present, which may excite high-frequency instabilities in the plasma. Being a large, high-field device, the size of the plasma relative to the gyrating orbits of the energetic fusion products will also be much greater than has been previously explored. This is predicted to permit a class of energetic particle oscillations that did not previously “fit” inside of experimental plasma systems. The study of these oscillations, and their possible effects on plasma heating, will be a central part of ITER’s scientific mission**.**

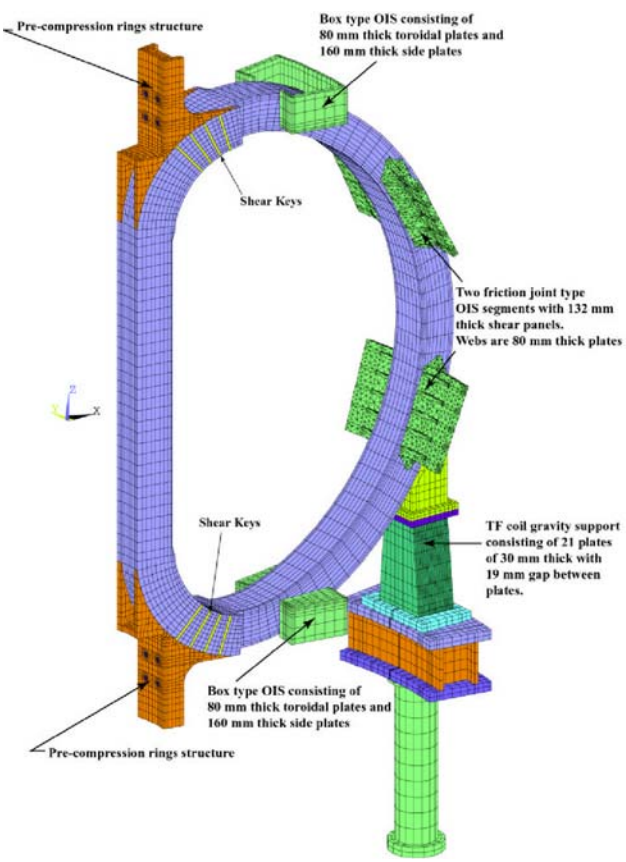
Energetic particles are well known to affect global plasma stability – both favorably and unfavorably. ITER will explore this area of physics in the previously unexplored regime afforded by its large size and magnetic field, and its intense energetic particle population.

ITER is also being designed to allow studies of plasma current sustainment via both external drive and the internally self-generated bootstrap current. This is a crucial element required to allow the tokamak to operate cost-effectively in steady-state. ITER will permit these studies for the first time in operating regimes consistent with intense self-heating by fusion products.

Turbulent heat loss
The parameter of system size to ion gyroradius is the most critical one controlling the confinement of energy in fusion systems. ITER will press this parameter further than ever before. With advanced plasma measurement tools and a flexible scientific operating plan, ITER will provide very important contributions to the understanding of turbulent transport in high temperature plasmas. Key questions include the scaling of turbulent eddy size with system size, and the role at large system size of self-generated and externally induced flows in breaking up these eddies.

As can be seen, a range of new scientific phenomena will be generated in ITER. The understanding of these phenomena, and the integration of that understanding into an attractive plasma configuration for fusion energy production forms the core of the excitement and challenge of the new regime of burning plasma physics.

Handling high heat fluxes
The heat and particle fluxes and fluences in ITER will far exceed anything studied in present plasma experiments. The development of means to minimize erosion of plasma facing components and of techniques to ameliorate the effects of plasma disruptions will be a major challenge. The high duty factor of ITER operation will allow stringent tests of the techniques that are developed. The planned ability to change out key power and particle handling systems will allow tests of a range of approaches to this problem.



ITER toroidal field coil design

Low activation structural materials
While ITER itself will not be constructed with advanced low activation structural materials, it will provide an opportunity to test components constructed from such materials in a fusion environment. ITER will be capable of exposing test modules to intense neutron fluxes in a realistic fusion environment. The neutron flux and fluence is anticipated to be lower than would be present in a practical fusion power plant, however, so these tests will focus on the operation of the test modules in terms of thermohydraulics and tritium production (needed to provide the fusion fuel), as well as maintainability in the fusion environment, but will not provide end-of-life experience.

Large-scale superconducting magnets
ITER will provide realistic tests of superconducting magnets at the scale

that is likely to be required for fusion energy systems. Experience with these magnets will provide realistic data on cost and maintainability, which will be invaluable for planning future fusion systems.

A key contribution of ITER to any contemplated magnetic fusion configuration is experience with reliability and maintainability of fusion-scale components, operating at high duty factor in a realistic fusion environment. Other approaches to creating burning plasmas currently being considered, which do not rely on superconducting magnets, would have dramatically lower duty factors (typically 0.25% as compared with 25%). As a result such systems could make somewhat smaller contributions to fusion science, and much smaller contributions to the development of fusion technology. However if the construction of ITER on an international scale proves to be too difficult, such experimental facilities would provide a path to move fusion energy science forward very substantially.

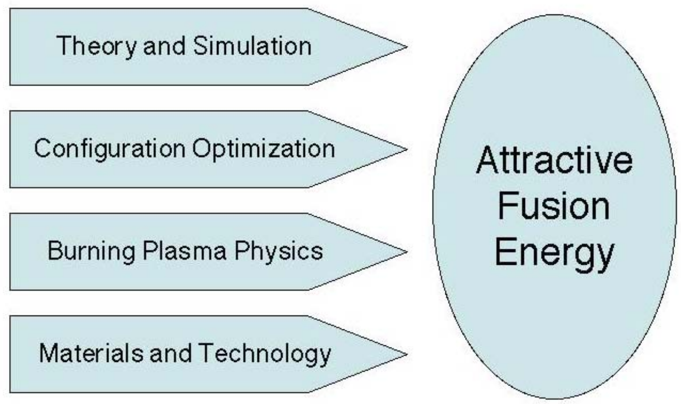
What else is needed?

ITER will be a substantial step towards a fusion power source, but much work is required in parallel with ITER in order to allow the next major step to be the demonstration of practical fusion power production.

ITER will produce neutron wall loading in the range of ~0.5 MW/m^2, a factor of 4 to 8 below what is needed in a practical fusion power source. To obtain the necessary levels of neutron production will require larger size and/or higher magnetic field (both of which involve increased cost) or – preferably – means to obtain higher β_T. ITER will run for limited pulses, not in full steady state. Practical steady state operation will require reduced recirculating power (power plant output recirculated for maintaining the plasma), involving either operating modes with higher bootstrap current, or use of a stellarator type of configuration. ITER may suffer from serious plasma disruptions, which might be very problematic in a power plant. Means will be needed to provide essentially disruption-free operation. Plasma-boundary interactions may give rise to levels of erosion of plasma-facing components that would not be tolerable in a fusion power plant. Means must be found to minimize this. Finally, ITER will provide a testbed for fusion blanket modules, but will not test materials and components to their lifetime limits.

ITER's design is based on the tokamak configuration, because at this time the tokamak is the only configuration advanced enough to provide high confidence of reaching the regimes required to achieve ITER's scientific and technological goals. As a result of its design, ITER can provide an excellent test-bed for optimization of the tokamak configuration.

It is critical, however, that other magnetic fusion configurations, which might offer higher β_T, lower recirculating power and/or more stable operation are developed in parallel with ITER, albeit in very much smaller and lower-cost facilities. Work on these configurations, and continuing advances in theory and simulation, not only deepen the understanding of fusion plasma science, which may be critical for overcoming roadblocks even for the tokamak, but may also provide more attractive ultimate fusion power systems. The advancement of fundamental understanding and continuing optimization of advanced configurations plays the strategic role of putting the U.S. in a position to capitalize on results from ITER, and so construct the most cost-effective fusion demonstration power plant in the future.



Four thrust areas defined by the Fusion Energy Sciences Advisory Committee.

ITER will not provide a full testing capability for developing low-activation and long-lifetime fusion materials and components for a demonstration power plant. There is discussion at this time about the most cost-effective means to acquire the necessary technical information in parallel with the operation of ITER. Clearly in the near term advanced numerical simulation can play a very important role in developing the nanoscience of neutron interactive materials. There may also be a relatively near term role to be played by spallation neutron sources, in the U.S. or abroad. Later an intense accelerator-based neutron source, with a more optimized spectrum, may then be needed to test small material samples. A larger plasma-based neutron source may be needed to provide realistic tests of components in parallel with the last phase of ITER, and in advance of a demonstration power plant. The proper balance in emphasis and phasing between these elements requires further analysis and discussion.

Conclusion

Tremendous advances have been made in addressing the key issues of fusion science and technology over the last decade. A very aggressive and exciting program is currently in place to push forward the science and innovation needed for fusion energy. The time is ripe to take a major scientific and technological step to allow fusion science to enter the regime of burning plasma physics, and to demonstrate fusion technology at a new scale.