

The challenge and promise of studying burning plasmas

Richard J. Hawryluk and Hartmut Zohm

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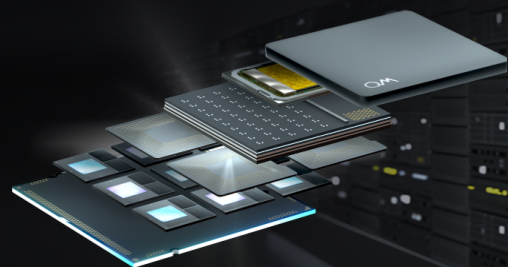
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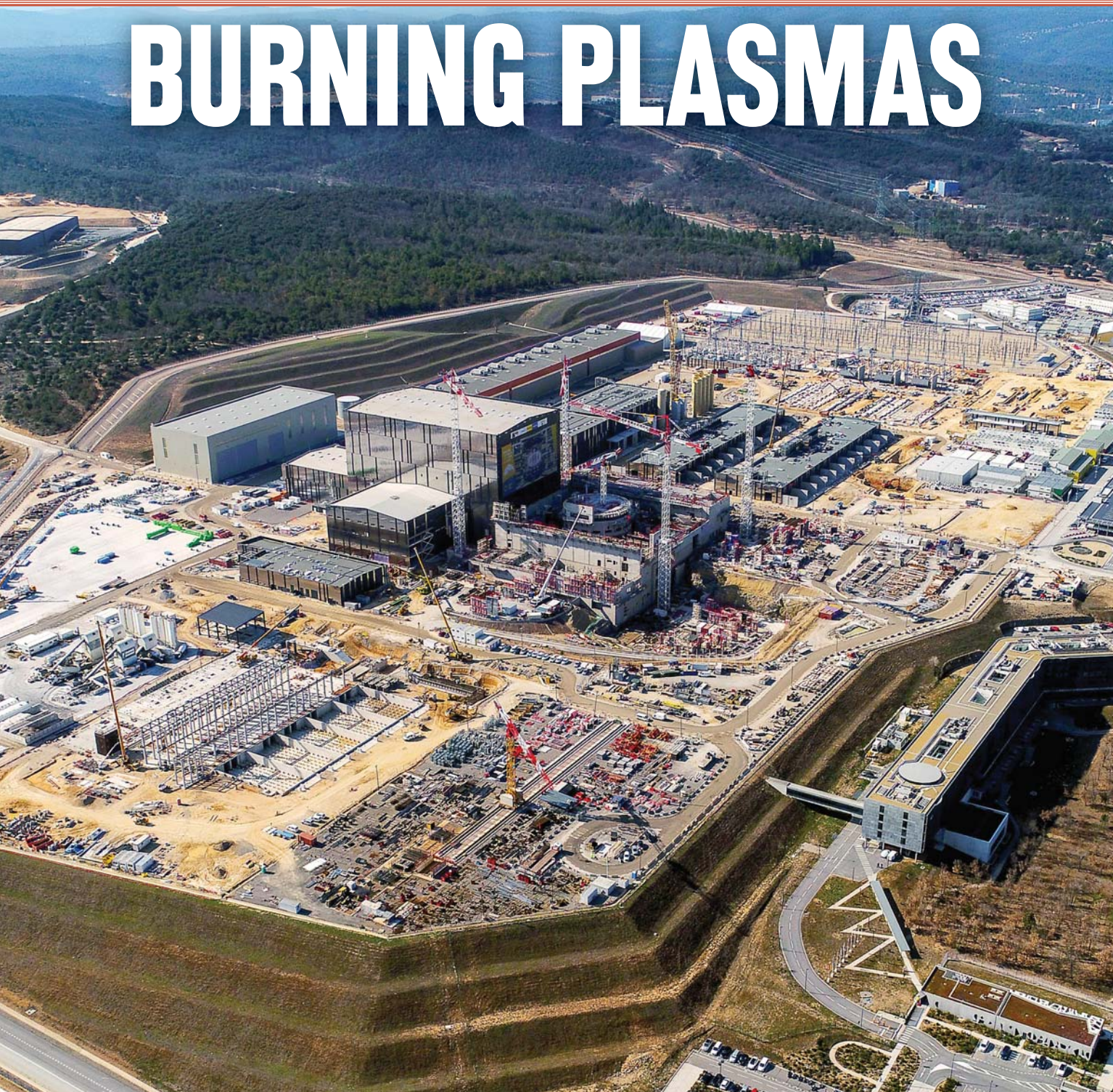
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The challenge and promise of studying

BURNING PLASMAS



Richard Hawryluk is the associate director for fusion at the Princeton Plasma Physics Laboratory in New Jersey. **Hartmut Zohm** is a director at the Max Planck Institute for Plasma Physics in Garching, Germany, and an honorary professor of physics at Ludwig-Maximilians University Munich.



Richard J. Hawryluk and Hartmut Zohm

Answers to open questions that will be addressed by the ITER experiment should enable the production of fusion energy.

In burning plasmas, the energy from charged particles created by fusion reactions compensates for heat loss. Burning plasmas power the Sun and other stars, and they could provide abundant energy for humankind. In the Sun, proton fuel is used in fusion reactions. But on Earth, the highest performance fuel is composed of deuterium and tritium ions. Scientists have several ways of producing fusion energy in the laboratory, most notably through magnetic and inertial confinement.

The progress made on magnetic fusion has led to the planning and construction of ITER, the international fusion research facility. Significant fusion power has been achieved for a little less than a second in magnetically confined plasmas—up to 10 MW in the Tokamak Fusion Test Reactor in the US¹ and up to 16 MW in the Joint European Torus in the UK.² In those experiments, the deuterium–tritium fuel is self-heated by fusion products—alpha particles—which provide a modest fraction (less than 13%) of the total heat supplied to the plasma. Whereas the original ITER design was based extensively on empirical results, designs for tokamak power plants such as those run by EUROfusion increasingly use theoretical and computational research coupled with empirical results from current experiments.

The construction of ITER in Provence, France, is already underway as shown in the opening photo. The facility will provide the opportunity to study burning plasmas in which at least two-thirds of the total heating will come from fusion reactions that could produce 500 MW of power for more than 300 seconds. The facility will also enable the first in-depth study of burning plasmas in a magnetic confinement configuration.³ ITER will be one of the largest scientific experiments ever undertaken, with participation by China, the European

Union, India, Japan, Russia, South Korea, and the US. Despite the high cost of the project, the worldwide community's sharing of scientific and technical knowledge has contributed to the breadth of the international collaboration. Although project costs increased and the construction schedule was delayed early on, ITER has been successfully adhering to the current schedule in recent years after a major reorganization in 2015 (see *PHYSICS TODAY*, May 2015, page 21). It aims to begin experiments with hydrogen in the mid 2020s and to perform burning plasma experiments in the mid 2030s.

ITER will create an axisymmetric toroidal plasma inside a chamber, whose cross-sectional view is shown in figure 1. For deuterium–tritium plasmas with ion temperatures in the range of 10–20 keV (116–232 million K), the fusion power density is approximately proportional to the ion pressure squared. The plasma core has the highest pressure and reactivity. Its temperature there is determined by the balance of plasma heating and heat loss from the core to the edge of the plasma. The heating balance is mostly affected by small turbulent density fluctuations on the order of a few percent or less in amplitude. During the initial phase before the switch to deuterium–tritium fuel, the plasma will be mostly heated by an external source.

Once the plasma pressure is sufficiently high, the self-heated phase begins. During that burning phase, fusion reactions generate suprathermal alpha particles, which are confined by the magnetic field and heat the plasma as collisions with the background plasma slow them down. The alpha particles self-heat the plasma about twice as much as any external heating source, and 80% of the fusion power is released as energetic neutrons, which do not interact with the plasma.

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Their energy is transferred as heat to the surrounding blanket; in power plants, the blanket converts the heat to electricity. Twisting magnetic fields that lie on nested toroidal magnetic flux surfaces confine the plasma in the core. But outside of the last closed-flux surface, called the separatrix, the magnetic field lines are no longer closed and thus intersect the first wall, ideally in the so-called divertor region beyond the scrape-off layer, seen in figure 1. The separatrix is formed by the plasma field current interacting with the current that's carried by the large superconducting divertor coil below the plasma chamber. The large heat flux from the plasma core impinges on the divertor surface and needs to be carefully controlled.

Producing a burning plasma requires plasma parameters that are different from those in current, nonburning experiments. Similar to fluid dynamics, dimensionless parameters for the core plasma can be determined theoretically and then the plasma's behavior can be scaled from one set of experiments to another.⁴ ITER will have to simultaneously achieve several conditions. Large values of system size, which are related to how many ion Larmor radii r_L fit along the plasma minor radius a , ($1/\rho^* = a/r_L$), will be required. The frequency of plasma collisions will need to be low, such that the mean free path between Coulomb collisions is much longer than the characteristic distance around the plasma along magnetic field lines. ITER will also need to produce modest values of the plasma pressure p that is normalized by the magnetic field pressure B , where the ratio β is proportional to p/B^2 .

Another parameter has been found to describe various limitations to the plasma density n_e achieved in experiments. The so-called Greenwald density n_e^{GW} is proportional to the plasma current and inversely proportional to the square of the plasma minor radius. Although n_e^{GW} does not come from idealized equations often used for plasma dynamics, it successfully describes the upper-density limits in the edge region where closed magnetic lines exist, the beginning of confinement degradation at high separatrix density, and the onset of magnetohydrodynamic instabilities. The instabilities may arise from atomic-physics effects in the edge region and from electromagnetic radiation emitted by impurities, such as tungsten and beryllium, from the first-wall material.

Present-day experiments, individually but not simultaneously, can achieve ITER's typical parameter values. Therefore, scientists will use ITER to study burning plasmas and the unique regime of dimensionless parameters, important for facilities that will produce electricity from burning magnetically confined deuterium-tritium plasmas.⁵

Transporting heat and particles in the plasma core

ITER was designed mainly using empirical projections of the confinement of heat in the plasma based on experimental results from around the world. The results come from a mode of operation in which there is reduced turbulent transport in the edge region.⁵ The so-called H-mode, or high-confinement mode, is a consequence of sheared plasma flow that breaks up turbulent eddies.⁶ The eddies generate a narrow zone of steep radial gradients in the edge that corresponds to the pedestal region shown in figure 2.

Since the ITER facility design began, scientists have made substantial progress in understanding the turbulent processes in the core and comparing detailed experimental results with

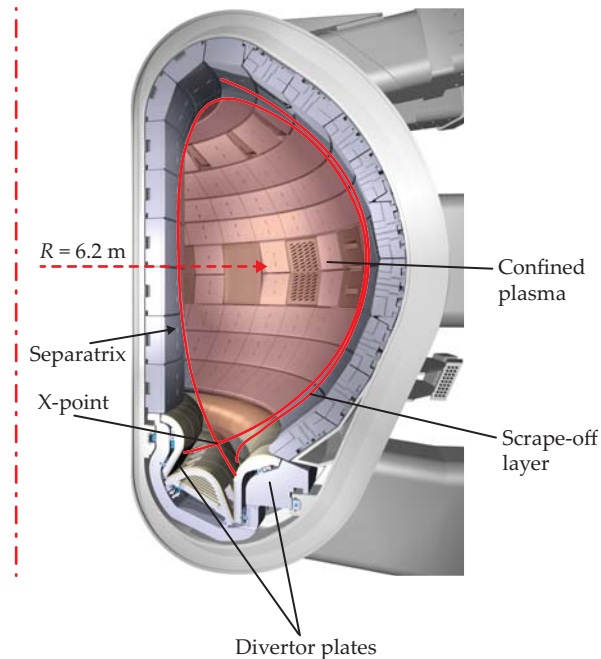


FIGURE 1. THE POLOIDAL CROSS SECTION OF ITER shows a magnetic separatrix that encircles closed magnetic flux surfaces. The separatrix is introduced by creating a so-called X-point, in which the plasma field current interacts with the current that's transported by a large superconducting divertor coil. Closed magnetic surfaces exist inside the separatrix, and the plasma outside it flows in the narrow, few-mm-wide scrape-off layer toward the divertor. The dashed, red line indicates the size of the major radius R measured from the torus's dash-dotted symmetry line to the plasma center. (Credit © ITER Organization.)

sophisticated theoretical models. One such model indicates that heat flux is not simply proportional to the temperature gradient but can be highly nonlinear. The heat flux strongly increases above a threshold value for the normalized temperature gradient R/L_T , where R is the major radius of the torus and the gradient scale $1/L_T = |\nabla T|/T$. The value of R determines the curvature of the magnetic field lines, which is responsible for the microinstabilities that give rise to strong turbulent transport once the threshold value of R/L_T is exceeded.⁷ Strong turbulent transport implies that R/L_T is relatively constant for parameters of interest. It also means that the shape of the radial temperature profiles $T(r) \sim C \exp(-r/L_T)$ is approximately self-similar to the plasma edge at the top of the pedestal. Those expectations are supported by theoretical calculations that predict the critical normalized temperature gradient for the increase in heat flux and the dependence of the heat flux on the gradient. That dependence is also affected by additional plasma parameters, including the gyroradius.

ITER is predicted to operate in a range in which those turbulent processes are important, so the temperature in the plasma core is approximately proportional to the temperature at the top of the pedestal. The sensitivity of the predicted fusion power to the pedestal temperature is illustrated in figure 3. Whereas the transport model predictions of power amplification Q versus pedestal temperature T_{ped} were based on sophis-

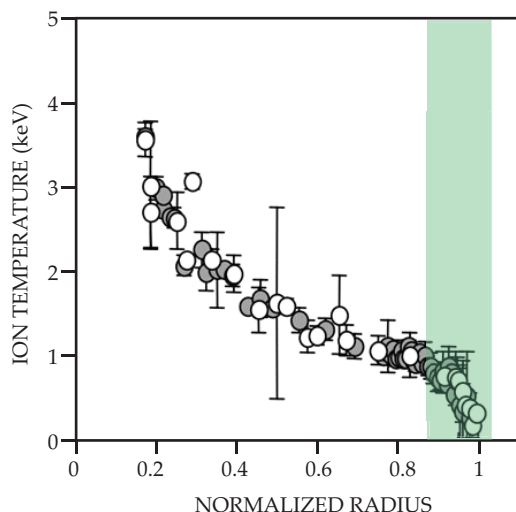


FIGURE 2. A TYPICAL ION TEMPERATURE PROFILE, plotted versus the normalized minor radius of the confined plasma, features a pedestal region (green) of steep gradients at the plasma edge. In ITER, the expected temperature values will be about five times as high. (Adapted from ref. 14.)

ticated turbulence simulations using some of the largest supercomputers a decade ago, some simplifications were assumed. Higher performance is expected based on estimates that include various stabilizing effects—density peaking, magnetic components of turbulence, and beam-driven rotation—that were neglected in figure 3.

The modeling of the nonlinear, turbulent plasma state has become increasingly more sophisticated. Some have described how the rotation in the plasma arises from a combination of externally applied torque from the injection of neutral beams and from turbulence-induced processes, a phenomenon known as Reynold's stress in fluid dynamics. So the same turbulence that mainly determines the loss of heat can enhance the plasma rotation and help in determining the saturation level of turbulent transport. Even for plasmas with no applied torque, significant rotation is observed. Although the applied torque for ITER is smaller than in current experiments, it may still drive enough

rotation to improve performance, and additional rotation may be driven by turbulent processes. Modeling now simultaneously considers turbulence at both ion- and electron-scale lengths, the role of shear in the profile of plasma rotation, and the effect of fast ions in the relationship between the heat flux and the normalized temperature gradient.⁸ Experiments have shown regimes of operation in which the heat flux may decrease because of an increase in the plasma rotation or the presence of fast ions.

Experiments and theory predict that turbulence results in particle transport and produces a peaking of the electron density profile in low-collisionality plasmas, in which the mean free path between Coulomb collisions is much longer than the characteristic distance around the plasma along magnetic field lines.⁹ That is advantageous for fusion reactivity because the fuel concentrates in the high-temperature part of the plasma. In present-day experiments, low collisionality is only achieved at low normalized density. ITER and future power-producing experiments, however, will operate at high normalized density. Such experiments will therefore be important in validating the theoretical models in new regimes where the fast ion effects are due to alpha particles operating at very low collisionality and in large systems. In addition to transporting the main fuel species, it's important to transport the alpha-particle ash from the deuterium–tritium reactions to the edge and subsequently pump the ash to avoid accumulating impurities and diluting the fuel. Turbulent processes are expected to dominate collisional processes and will help determine the fuel dilution and the presence of impurities in the core from plasma material interaction at the edge.

Pedestal performance

The reduced transport in the edge region associated with H-mode plasma results in steep temperature and pressure gradients, as shown in figure 2, and has many ramifications in addition to the confinement in the core. The steep pressure gradient in the edge region generates parallel currents through a mechanism similar to that in thermoelectric-driven currents. Large pressure and current gradients affect the magnetohydrodynamic (MHD) stability of the edge region and can trigger edge instabilities, or edge-localized modes¹⁰ (ELMs) that can be seen in figure 4. The resulting operating boundaries due to ELMs are relatively well understood by MHD models that simulate the stability of the edge.

Whereas the global pedestal stability is described well by linear, ideal MHD modeling, the parameters at the top of the pedestal are determined by a combination of MHD stability and the transport mechanisms between the edge of the plasma and the top of the pedestal. The edge pedestal (EPED) model successfully predicts the width and height of the pedestal pressure by combining linear MHD stability analysis of the pedestal with a simplified assumption about the transport in the region.¹¹

However, recent experiments using tungsten as a wall ma-

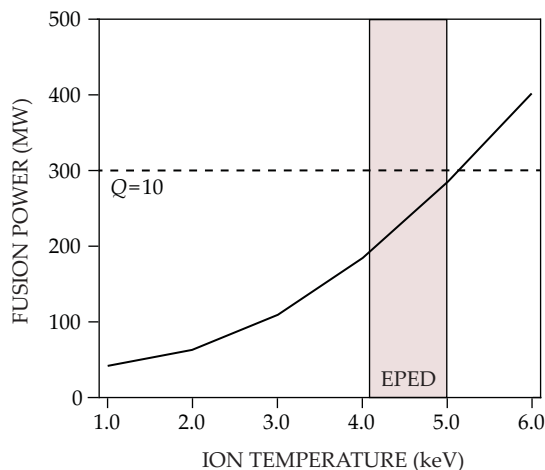


FIGURE 3. THE FUSION POWER P_{fus} AND POWER AMPLIFICATION Q FOR ITER depend strongly on the ion temperature at the top of the edge pedestal shown in figure 2. The box labeled EPED shows the range of pedestal temperature T_{ped} predictions from a leading model.¹¹ (Adapted from ref. 15.)

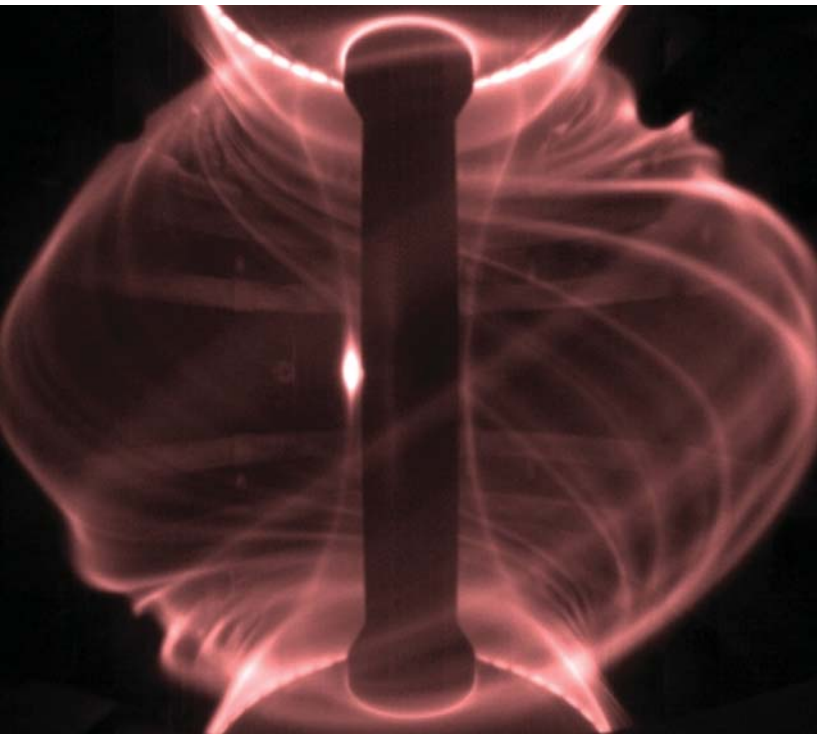


FIGURE 4. AN EDGE-LOCALIZED MODE (ELM)

INSTABILITY appears on this fast camera image from the Mega Amp Spherical Tokamak. The wide-angle view shows the whole plasma, and the enhanced hydrogenic line emission clearly delineates plasma filaments, which are ejected from the edge by the ELM instability.¹⁶ (Courtesy of Andrew Kirk.)

terial in the Axially Symmetric Divertor Experiment (ASDEX) Upgrade and the Joint European Torus tokamaks have shown a degradation that could not be explained by the MHD model. The temperature and density profiles can respond differently, partly because of an influx of recycled neutral particles from the wall into the region between the plasma edge and the pedestal top. Consequently, additional transport physics will have to be incorporated into the EPED model to improve predictions.

ITER will be operating in a different system-size regime from its predecessors, so the role of neutrals may change. ITER's combination of low collisionality and large system size may alter the turbulence characteristics in the pedestal region and affect the height of the pedestal. As the first device to combine a pedestal with low-collisionality parameters and operate at high densities relative to the Greenwald density, ITER provides a unique opportunity to validate the understanding of the edge pedestal.

For ITER, the large ELM instabilities could damage divertor components. Techniques have been developed to suppress those instabilities, such as by operating within the stability boundary with additional coils that give rise to small three-dimensional perturbations of the tokamak axisymmetry, \tilde{B}/B , on the order of 10^{-4} , where B is the magnetic field.

Plasma-boundary interactions

A major challenge for ITER will be controlling the heat and particle exhaust. The sharp pressure gradients in the edge region extend to just beyond the last closed-flux surface from which heat and particles are rapidly transported along the open magnetic field lines to the divertor plates. Recent experiments on various devices have shown that the heat flux width at the plane where the plasma has its largest radial extension is narrow and would extrapolate to as low as 1–2 mm in ITER. Advances

in transport modeling across the magnetic field on the open field lines describe the heat flux width in current experiments reasonably well. When the same model is applied to ITER, it indicates that turbulence changes in the edge may increase the heat flux width up to 5 mm. That prediction requires stringent experimental tests that may only be possible using ITER.

To illustrate the magnitude of the heat-exhaust challenge, consider that the heat flux into the ITER boundary will be 150 MW if the power lost by radiation is ignored. Taking into account the extrapolated experimental heat-flux-width range, that heat exhaust would far exceed the approximately 10 MW/m² power-handling capability of steady-state, high-heat-flux components with tungsten armor that will be used in the ITER divertor.

Two approaches are used to reduce the heat flux on the divertor plates. In the first, the incident angle of the magnetic field lines carrying the heat flux is reduced by expanding the magnetic flux surfaces in the vicinity of the divertor plates and tailoring the angle of the plates so that they are nearly tangential to the magnetic field. That approach demands accurate alignment of individual target plates to ensure that the leading edges do not overheat. The heat flux on the target would be substantially reduced to about 40 MW/m² in the ITER geometry.¹² The decrease depends on the heat-flux-width assumptions, but the value is comparable to the heat flux on the surface of the Sun, which is roughly 60 MW/m².

In the second approach, part of the heat flux is dissipated by intentionally injecting seed impurities, such as nitrogen, into the divertor plasma. The impurities will emit line radiation to distribute the heat load homogeneously in all directions. At constant-impurity concentration, the radiation losses increase with the square of the electron density. A high density at the separatrix is also required for effective power dissipation. Both techniques have been successfully demonstrated for various experiments. Figure 5 shows how the radiation losses from the divertor and X-point regions can be enhanced by adding nitrogen.

One role of ITER is to test ideas to stably exhaust power and particles in a future fusion power plant at relatively high separatrix densities while simultaneously optimizing the fusion power. Among the questions to be addressed are Will confinement be degraded because of the high density in the scrape-off plasma as seen in present-day experiments? And will the fuel concentration in the core be decreased by impurity ions penetrating the core from the divertor plasma, which reduces the plasma reactivity?

Control of burning plasmas

Perhaps the most important question is whether the high-energy alpha particles that sustainably heat the burning plasma deposit their energy to the ions and electrons via Coulomb colli-

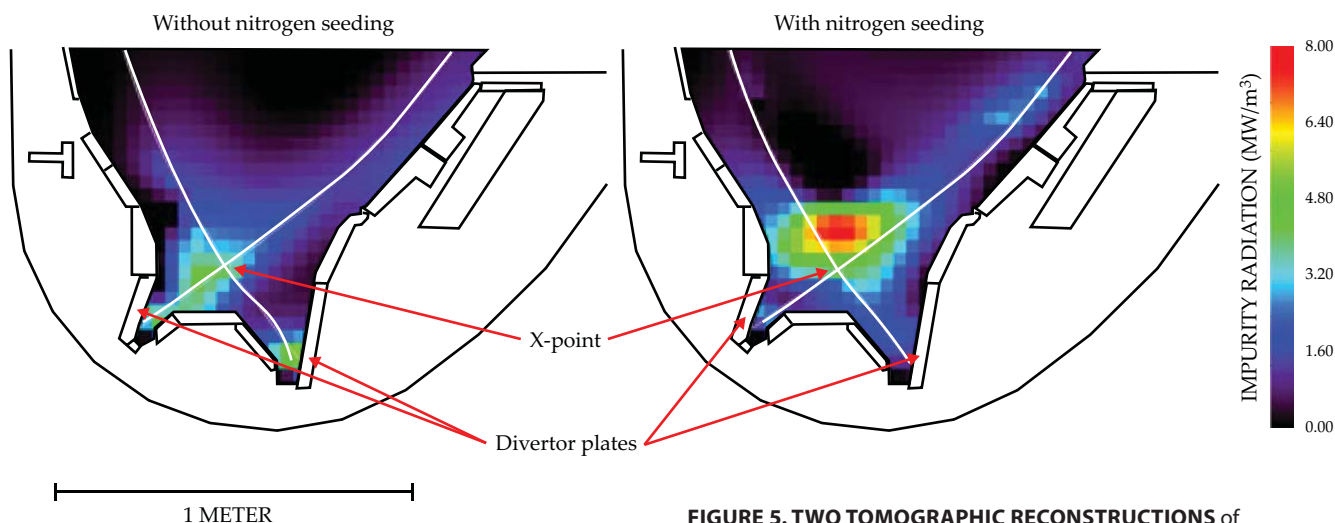


FIGURE 5. TWO TOMOGRAPHIC RECONSTRUCTIONS of impurity radiation from the divertor and X-point regions show clear differences in their enhanced radiation losses. For an experiment of the ASDEX Upgrade tokamak without additional impurities (left), about 50% of the heating power is dissipated by electromagnetic radiation. But when nitrogen seeding is added (right), a zone of high radiation occurs at the X-point, and the radiated power fraction rises to values in excess of 80%. (Adapted from ref. 17.)

sions or whether their interaction with electromagnetic waves results in a spatial redistribution or loss of alpha particles. (See the article by David Pace, Bill Heidbrink, and Michael Van Zeeland, *PHYSICS TODAY*, October 2015, page 34.) Deuterium-tritium experiments on both the Joint European Torus and the Tokamak Fusion Test Reactor found initial indications of alpha-particle heating. The slowing of the 3.5 MeV alpha particles to energies comparable to the core ion temperature is in good agreement with calculations tested in plasma conditions that are most similar to what's planned for ITER's first set of high fusion power experiments.

However, in those experiments, the ratio of intrinsic alpha-heating to external heating was small, about 10% or less. ITER will be the first device to conduct experiments that have the alpha-heating dominating the heating power, that address the nonlinear wave-particle interaction, and that decrease the uncertainty associated with low-power alpha-heating experiments. ITER will be able to test whether electromagnetic waves generated by the energetic alpha particles are less stable than in current experiments due to the large system size. Those results will enable researchers to determine optimal operating conditions and minimize or even avoid such instabilities.

Controlling fusion power in a burning plasma would appear to be straightforward. The fusion reactivity in ITER decreases with increasing temperature, and the confinement time of the plasma energy decreases with heating power, which enables a stable operating point. The problem becomes more interesting when the consequences of changes in confinement are considered. In future power plants, a 10% increase in confinement could roughly double the fusion power. The power increase could provide feedback control because it occurs over the time scale of several energy confinement times. Large concentrations of fast ions can reduce the plasma confinement and decrease the efficiency of the alpha-particle heating by interacting with electromagnetic waves. Hence there is significant uncertainty about how the fast ions will affect the burn-control dynamics and whether the system will respond nonlinearly. Only ITER, with its dominant self-heating by alpha particles, will enable a comprehensive exploration of burn control.

Researchers do know that burn control is affected by additional operational constraints related to the maximum density;

the MHD stability of the plasma, which is strongly related to the plasma pressure; and the heat flux to the plasma-facing components. Consider the effect of increasing the plasma density. In principle, it's advantageous because it increases plasma reactivity and the power radiated. However, as the density approaches its maximum, observations show that the confinement time degrades. Experimental physicists are using theoretical models to help fine-tune the experimental conditions to optimize the performance and prevent the plasma from touching the operational boundaries. Sophisticated plasma control systems manage various actuators, such as fueling by gas valves, frozen deuterium pellets, and the auxiliary heating power.

The simulations used to predict the discharge performance for ITER will need to take into account the alpha-heating dynamics and the plasma control systems to avoid breaching an operational boundary. The challenge is that the control actuators, such as for auxiliary heating, have a smaller effect on burning plasmas than in present experiments because alpha heating will play a larger role in the power balance.¹³

Demonstrating control of a burning plasma in ITER for both inductive and noninductive regimes is essential before extrapolating to a power plant. During the flat-top phase of the discharge, the current for an inductive regime is driven by a flux change from a central solenoid, whereas the flux change is essentially zero in a noninductive regime. The required power amplification in a plant is expected to be higher, $Q \sim 20$ –50, than ITER's $Q = 10$ and $Q = 5$ in a fully noninductive, steady-state operation. For a noninductive, steady-state tokamak power plant, a large fraction of the current would be self-driven by temperature and density gradients. As alpha heating will be the dominant heating mechanism that determines the temperature gradient, controlling the heat becomes more challenging.

Touching an operational boundary can lead to the occur-

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rence of MHD instabilities that can terminate the plasma discharge. In present experiments, the worst plasma confinement disruption occurs when a substantial plasma current of the order of 1 MA is lost rapidly on a time scale of several milliseconds. In ITER, 15 MA of plasma current could be rapidly terminated over a somewhat longer time. A sudden termination of the plasma discharge generates large toroidal electric fields that can drive energetic runaway electron currents, transmit heat fluxes to the plasma-facing components, and apply large forces to the vacuum vessel and its components. Mitigation systems are being implemented to ameliorate the disruptions if the operating boundaries are exceeded, and active control systems will be used to ensure that the plasma operates within safe boundaries. Furthermore, active control of MHD instabilities—including by driving an additional current in the plasma by injecting RF waves or by applying 3D magnetic field perturbations—has made a lot of progress. Research has demonstrated that a localized current of a few percent of the total plasma current created through the injection of RF waves can be sufficient to remove magnetic islands that are responsible for some disruptions and will likely be used in ITER.

Experiments with the forthcoming ITER will be a unique opportunity to study burning plasmas, develop the tools needed to better understand them, and validate outstanding predictions. The experiments will provide seminal answers to questions that are central to the prospects for fusion. ITER will be a major step in bridging the gap between current under-

standing and the knowledge needed to design and operate fusion power plants as safe, sustainable energy sources.

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