# Essay: Overcoming the Obstacles to a Magnetic Fusion Power Plant

Ambrogio Fasoli
*École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland*

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Fusion occurs when light nuclei combine to form heavier nuclei. The energy released in this process powers the stars and can provide humankind with a safe, sustainable, and clean source of baseload electricity, a valuable tool in the fight against climate change. To overcome the Coulomb repulsion of like-charged nuclei, fusion reactions necessitate temperatures of tens of millions of degrees or thermal energies of tens of keV, at which matter exists only in the form of plasma. Plasma is an ionized state of matter that is rare on Earth but characterizes most of the visible universe. The quest for fusion energy is thus intrinsically associated with plasma physics. In this Essay, I lay out my view of the challenges on the path to fusion power plants. As these need to be sizable and inevitably complex, large-scale collaborative enterprises are required, involving not only international cooperation but also private-public industrial partnerships. We focus on magnetic fusion, in particular on the tokamak configuration, relevant to the International Thermonuclear Experimental Reactor (ITER), the largest fusion device to be built in the world.

*Part of a series of Essays which concisely present author visions for the future of their field.*

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*Introduction.*—To create the extreme conditions needed to yield sustained fusion reactions on Earth, two main approaches are being considered by plasma physicists. In the magnetic fusion approach, different devices confine the plasma using magnetic fields. In tokamaks, these fields are produced by a combination of external coils and by currents induced in the plasma itself, while in stellarators, the fields are generated only by external coils. In the inertial confinement approach, high-power lasers or electrical discharges are used to compress hydrogen fuel to very high densities for billionths of a second. For both approaches, to reach net energy gain, a minimum value of the triple product—the product of plasma density, temperature, and time over which the plasma energy is confined—must be overcome. In magnetic fusion, such confinement time can be macroscopic (~0.1–10 s), which allows plasma number densities $10^5$ times lower than the air we breathe. In inertial fusion, confinement time is dictated by finite plasma inertia ($\sim 10^{-10}$–$10^{-9}$ s), and one needs densities that are about 3 orders of magnitude higher than ordinary solid matter.

Recently, record fusion energy production was demonstrated using magnetic confinement at the Joint European Torus (JET) [1], and ignition, as well as a positive plasma energy balance, was obtained in inertial fusion experiments at the National Ignition Facility (NIF) [2]. A stable plasma was maintained for up to 1000 s in the EAST tokamak [3], and a plasma energy turnover exceeding 1 GJ was achieved in the W7-X stellarator [4]. The assembly of the ITER tokamak is being completed [5]. The dream of lighting a star on Earth is getting closer and closer to reality.

*Physics challenges and gaps.*—Fusion plasmas involve multiscale and multiphysics phenomena due to nonlinear dynamics resulting from the interaction of charged particles and the electric and magnetic fields they contribute to produce [6]. Understanding and controlling these dynamics require a multidisciplinary approach, ranging from sophisticated experiments in large-scale devices to high-performance computing simulations, data science and artificial intelligence (AI) for real-time plasma control, and advanced diagnostics for tracking the plasma behavior.

Impressive progress in the understanding of fusion plasma physics has been achieved in the past decades. The scientific bases for generating, heating, and maintaining plasmas in a stable condition, with maximum plasma pressure relative to that of the magnetic fields that provide the confinement, have been established [7]. A number of actuators, such as magnetic coils that maintain the plasma in a prescribed position and with a given shape in the vacuum vessel and injection of microwaves that locally heat and generate currents to control local instabilities [8], are now routinely used.

Various performance indicators have been devised, including plasma temperature, density and pressure, plasma purity, confinement quality relative to empirical scaling laws, and the number of neutrons produced by fusion reactions. The optimization of these indicators is a complex exercise, as there are explicit and implicit interconnections among parameters. As a consequence, the design of a fusion power plant cannot be simply based on a combination of all possible best values achieved independently, as these are often mutually exclusive [9]. Given the size, cost, and timescales of fusion experiments, the role of theory and numerical simulations is continuing to grow with a wide range of open scientific questions being tackled by theory groups worldwide, providing building blocks for real-time plasma control [10].

Although many of the fundamentals are well known today, a number of gaps in our knowledge remain. In my subjective view the most notable areas for development in plasma physics for a fusion power plant are plasma scenarios, transients, exhaust, and the burning plasma regime.

*Plasma scenarios.*—Magnetized plasmas are complex self-organized systems with limited external control whose parameters and spatial profiles cannot necessarily be prescribed *a priori*. It is only possible to prepare experimental conditions that facilitate a particular scenario, i.e., a set of properties that is mutually compatible and can be reproducibly maintained long enough using actuators. Research in present devices and through numerical modeling aims at identifying the optimal plasma scenarios for a fusion reactor or at predicting scenarios that can exist in power plants but are not accessible in today's experiments.

In power plants, the plasma must reach sufficiently large pressures in the core for good fusion performance that are stable with respect to macroscopic perturbations. It should also be characterized by low turbulence levels to guarantee good energy and particle confinement, yet with no accumulation of impurities, i.e., species other than the hydrogen isotopes that constitute the fuel. At the same time, the edge region must remain relatively quiescent, thereby avoiding transient events detrimental to the surrounding material walls. A number of questions still remain open. For example, the specific consequences on the core transport of turbulence that is primarily driven by ion temperature gradients need to be clarified. The physics underlying one of the most promising scenarios, referred to as the hybrid regime [11], characterized by a particular magnetic field structure in the core related to internal dynamo effects [12], needs to be fully understood in view of extrapolating it to power plant conditions. Research on ideal combinations of properties must result in fully predictive capability. This can be achieved through validation of the theoretical and numerical descriptions of the plasma dynamics on devices that attain reactor-relevant values for key elements such as plasma pressure, collisionality, mass composition, and heating mix.

*Plasma exhaust.*—Powers of the order of several hundreds of MW must be exhausted from the edge region of a magnetic fusion power plant. In addition to withstanding large heat fluxes ($\sim 10\ \mathrm{MW/m^2}$), the plasma-facing materials must be subject to minimal sputtering to limit erosion and the production of impurities that could penetrate the core plasma and reduce the fusion reactivity. In addition, materials must minimize retention of tritium and dust production and allow removal of the fusion-reaction helium ashes. Edge plasma configurations must also provide adequate boundary conditions for core fusion performance without giving rise to extreme transient events (see section entitled "Plasma transients").

The concept of a divertor, a magnetic field structure that forces plasma particles to flow long distances along the magnetic field before impinging on material surfaces, hence losing energy by collisions and radiation, and limits erosion and impurity production, promises to comply with these requirements. In particular, regions of sufficiently low plasma temperatures ($T < 10$ eV) can be achieved in front of the material surfaces [13]. Here, strong energy exchange with the neutral particles can occur, further reducing the temperature and allowing for volumetric recombination to occur. This buffer neutral layer isolates the surfaces from the hot plasma—a situation referred to as *detachment* [14]. Detachment is crucial to allow a very large fraction of the plasma exhaust power to be irradiated, as opposed to being transferred by conduction or convection to the material targets.

While detachment is clearly demonstrated in present-day devices [15], how to achieve it stably and to control its dynamics in a way that is compatible with core plasma conditions are still open questions. It is necessary to determine which geometry and field line topology are optimal. Also needed is how to predict and optimize the width of the unconfined plasma layer through which power is channeled.. For all of these questions, experimentation on flexible devices that can test various configurations, validation in larger devices that approach reactor conditions, and integrated core-edge numerical simulations are needed.

*Plasma transients.*—A crucial challenge for fusion in tokamaks is the occurrence of transient events at the plasma edge, in the core, or across the whole plasma volume. At the edge, the high confinement regime or H mode [16], the workhorse scenario that allowed strong advancement in tokamak plasma performance over the past decades, features a very steep pressure gradient that drives instabilities. These develop nonlinearly and lead to cyclical short-lived events, called edge localized modes (ELMs). These modes generate outward bursts of energy and particles, hence large localized thermal loads, putting the integrity of the plasma-facing components at risk. In ITER, for example, ELMs could expel up to 15 MJ in 0.2 ms, leading to unmanageable thermal loads [17]. A large research effort is dedicated to finding ways to mitigate ELMs, e.g., using magnetic perturbations that locally affect the field topology and reduce the strong edge pressure gradient, weakening the source of instability, while affecting only minimally the core plasma performance [18]. A comprehensive, self-consistent physics description of the effect of these perturbations on hot plasmas is still lacking.

Even more promising, in view of limiting the complexity of fusion power plants, is the development of plasma scenarios that are intrinsically free from large ELMs, while guaranteeing stability, confinement, and impurity accumulation that are compatible with high fusion gains. These scenarios are developed by exploring different plasma shapes (including the so-called negative triangularity [19]), various profiles of the magnetic field helicity and of the plasma density, plasma fueling methods, and combinations of these characteristics [20]. The potential of these empirically discovered scenarios must be assessed for reactor-relevant conditions, and a large effort is devoted to developing predictive understanding.

Another severe challenge for the tokamak reactor is posed by plasma disruptions, sudden losses of the entire plasma, leading to large wall energy deposition [21]. The absence of disruptions due to the absence of plasma currents is in fact a potential advantage of the stellarator configuration [22]. In ITER, disruptions could lead to peak energy densities on the divertor of 5–20 $\mathrm{MJ/m^2}$ over 3 ms; the tungsten divertor would not withstand more than a few hundreds of such events [23]. Our knowledge of the operational limits should be refined such that only failure of technical components could provoke disruptions. Nevertheless, it is also important to develop methodologies to mitigate their consequences. In particular, one must guarantee a benign termination of the electron beam (practically unaffected by collisional drag) that would be accelerated to relativistic energies by the electric field that remains after the plasma current decay, which could potentially damage the vacuum containment system. Injecting fragments of pneumatically or electromagnetically accelerated pellets of frozen deuterium, neon, or argon to rapidly decrease the plasma temperature appears at present the most promising method to mitigate disruptions [24]. However, a detailed understanding of the effect of these shattered pellets on the plasma, of the applicability of this technique, and of its consequences on the machine conditions still needs to be reached.

*Burning plasma regime.*—Fusion power plants will operate in the burning plasma regime, in which the heating by the $\alpha$ particles, byproducts of the deuterium-tritium (DT) fusion reactions, dominates over the externally provided heating (see Fig. 1). These $\alpha$ particles are isotropic in velocity space and strongly suprathermal, as they are generated at 3.5 MeV in a quasi-Maxwellian background plasma that has temperatures of the order of 10 keV. The burning plasma regime is entered when fusion power gains exceed 5, a situation that has not yet been reached in magnetic fusion. As a result of $\alpha$-particle heating, unexplored couplings among plasma parameters will characterize this state. Burning plasmas will skim operational limits in conditions that are partly inaccessible in present devices, in particular in terms of collisional properties and of the ratio of the size of the device to that of thermal and nonthermal particle orbits (more than a few hundreds), which influences turbulent interactions. The ultimate experimental validation of this regime will only be possible in actual burning plasmas. This is one of the prime motivations for the ITER experiment. Completing the assessment of its independent building blocks is possible through tracing the progress achieved in this area over the past three decades [25].

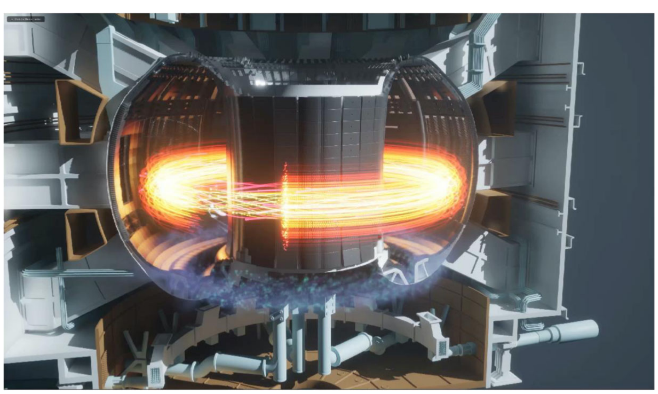

FIG. 1. Particles in a tokamak plasma at the core of a fusion power plant.

Suprathermal $\alpha$ particles must be well confined, because they provide the heating necessary to maintain the fusion reactions and because even a small fraction of losses (in ITER, $\alpha$ particles will carry up to 100 MW of power) could lead to significant damage to the plasma-facing components. One needs to understand and minimize the effect of redistribution and loss mechanisms, namely magnetic field imperfections, low-frequency instabilities, turbulence, and resonant interactions with waves. Fundamentals of these elements are known but their combination still represents an open question. The $\alpha$-particle population can also reduce microinstabilities and have a beneficial effect on thermal plasma transport [26], an important effect observed in recent experiments yet to be fully understood.

Variations of the power deposited by the $\alpha$ particles and by the external heating sources or variations of the plasma density, due, for example, to unsteady fueling, can lead to large fluctuations in the fusion power production [27]. These effects necessitate a quantitative understanding, which is becoming possible with increasingly sophisticated integrated modeling suites.

*Technology challenges and gaps.*—Enabling technology for magnetic fusion must be at the cutting edge of an impressive range of fields, from remote handling to cryogenics, real-time control, and high-power microwave sources, to name a few. Although all of these present significant issues, the most urgent research and development (R&D) effort is needed for the breeding blanket (for which no viable design exists to date) and for materials. These elements are discussed below, together with superconducting magnets, which are crucial design and cost drivers.

*Tritium breeding blanket.*—Electricity production in fusion plants relies on the conversion of the power carried by the fusion-produced 14 MeV neutrons into heat. Such conversion takes place in the blanket, a structure surrounding the plasma, where the neutrons, after multiplication and moderation, react with lithium to produce tritium, providing a self-sufficient intrinsic tritium fuel cycle. The blanket also provides necessary shielding to the surrounding components and environment [28]. While the next few decades will provide a window of opportunity for harnessing initial tritium primarily from CANDU-type fission reactors (CANDU denotes Canada Deuterium Uranium), any fusion power plant must operate from the start with a full breeding blanket to produce and recover its own fuel reliably.

Urgent R&D is necessary to develop a concept for the blanket, the relevant remote handling system, and the associated tritium plant and bring it to an adequate technology readiness level. The choice of the primary coolant, at present water or helium, is a plant design driver that should be finalized. How to minimize the tritium reprocessing time is also a key open question, as it may significantly enlarge the range of possible values for the necessary tritium breeding ratio and decrease the doubling time for fusion reactor developments. A challenge in this area is that testing blanket designs under realistic integrated conditions requires dedicated facilities that are not available at present.

*Materials.*—Fusion structural materials must withstand large high-energy neutron fluxes that lead to atomic displacement cascades and transmutation nuclear reactions, generating helium and hydrogen gas in the lattice of the steels currently considered for the blanket and the main vacuum vessel. They should be characterized by activation levels as low as possible and operate at high temperature to optimize the efficiency of the electricity-producing thermodynamic cycle. These constraints significantly reduce the pool of possible choices for materials [29].

Experimental knowledge of material behavior in fusion reactor conditions is incomplete, and full numerical simulations are still prohibitively complex due to the range of temporal and spatial scales involved. Extrapolation from current conditions to fusion power plants presents major challenges, because there is no direct way of testing and qualifying materials subject to high-energy neutron fluxes with appropriate orders of magnitude for the fluence and the resulting value of displacements per atom (dpa). In Europe, the IFMIF-DONES is being launched to provide such a neutron source [30]. Results obtained in a small volume (0.5 l at 20 dpa/y) can be extrapolated to obtain material irradiation test data for reactor design, although how to conduct such extrapolation using small-specimen test technology is in itself an important open question.

*Magnets.*—Magnetic fusion power plants need high magnetic fields over large volumes, as the fusion triple product scales with $B^a$, where $a \geq 2$ [31]. Large steady-state current densities are needed as is low dissipation in the coils to reduce the recirculating power in the plant. This makes the use of superconductors mandatory. Beyond those obstacles posed by the thermal operational conditions [at large $B$ values, tens of MW of electric power are needed to remove heat loads of tens of kW at low temperature for both low- and high-temperature superconductors (LTS and HTS)] and posed by the electrical system, in particular for quench detection and damping, the main challenges for fusion magnets are of mechanical character [32]. Fusion magnets experience large electromagnetic loads, originating from the $\boldsymbol{J} \times \boldsymbol{B}$ force, causing most of their volume to consist of structural material and, more importantly, possible degradation in the cable, tape, or strand properties.

While ITER provides a viable LTS technology for future fusion power plants, innovative approaches could simplify the design and reduce the overall coil volume and cost, limit the superconducting material degradation, and increase the achievable $B$, e.g., by reducing the need for turn to turn isolation, separating the helium containment function from the mechanical one for the steel jacket, or combining LTS and HTS to take advantage of HTS where it is needed, i.e., in the highest-field portion of the magnet. Test facilities that can qualify components of the magnet system at high operating fields and currents and in the relevant cryogenic conditions are needed.

*Integration toward the prototype power plant and conclusions.*—The most formidable challenge for achieving fusion energy does not derive from any one of the physics or technology issues mentioned above, but rather from their integration into a reliable, available, long-lived, and economically competitive power plant [33]. The ultimate R&D step before a full commercial deployment of fusion consists in proving that such integration is possible. This step, often referred to as DEMO (demonstration fusion reactor), must capitalize on fusion intrinsic safety features and must complete the scientific, technological, innovation, and industrial bases of a commercial fusion power plant. DEMO will need to be able to generate hundreds of MW of net electrical power with a closed, self-sufficient fuel cycle, an availability that is compatible with commercial applications and a degree of waste production that does not involve geological timescales [34].

The ITER project is a crucial milestone in the quest for fusion, as it will provide a comprehensive demonstration of the scientific and technological feasibility of large-scale energy production by fusion, and of its safety. Crucial lessons are drawn from ITER through all of its phases, from design to assembly, first operations, and ultimately full power DT campaigns. The licensing process, the production, tests, and assembly of major elements, such as the vacuum vessel, the cryogenic facility, the magnets, and the heating and current drive systems, are progressively providing essential information for the design of DEMO. ITER experience with safety and waste production, remote handling and civil engineering, the hot cell, the

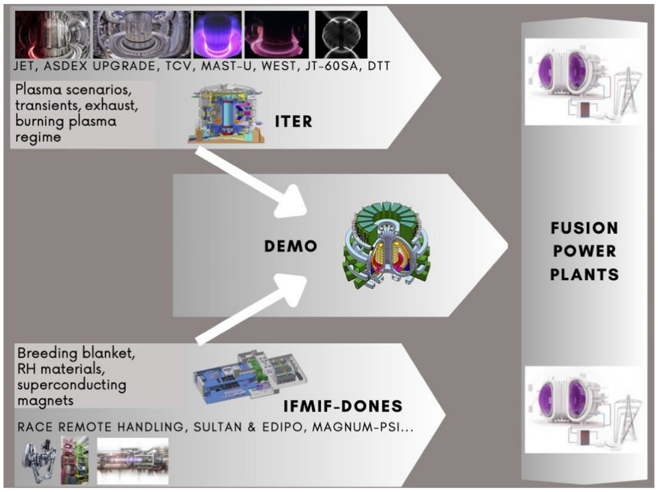


FIG. 2. Possible strategy toward a magnetic fusion power plant.

management of tritium and radioactive wastes, will also constitute a reference. The demonstration of the burning plasma regime on ITER will complete the basis for the plasma scenarios to be used in DEMO that is being developed in a variety of devices, including the main operating tokamaks in Europe (JET, ASDEX-Upgrade, MAST-U, TCV, and WEST), the U.S. (DIII-D and NSTX-U), China (EAST, HL-2A, and J-TEXT), India (SST-1), and South Korea (KSTAR), and the upcoming JT60-SA in Japan and DTT in Italy.

Nevertheless, the urgency to develop DEMO before the middle of the century, after which a fusion reactor economy can begin, requires us to proceed as much as possible parallel to ITER, rather than adopting a sequential approach that fully depends on ITER milestones. Such an approach in Europe corresponds to a revision of the present Roadmap [35] (see Fig. 2), which contains the main elements of a reactor-oriented program and the logical links between them, but is based on budget, timing, and personnel assumptions that are no longer valid. It is crucial to strike a balance between consolidated knowledge and innovation, to explore higher-risk–higher-potential solutions than have been undertaken so far, and to ramp up public-private partnerships, as DEMO will inevitably be built in an industrial frame with fully industrial practices.

A large-scale deployment of numerical simulations is needed to sustain this accelerated approach [36], combining the first-principles description of the hot core plasma region with that of the colder edge that interacts with the material surfaces, an *ab initio* description of materials properties, and increasingly realistic and comprehensive system codes, also benefiting from using AI at different levels, including plasma control [37]. This effort will guide not only the definition of the experiments, the interpretation and extrapolation of the data in present and future plasma devices but also the design of DEMO.

Fusion R&D is a long-term multidisciplinary effort that requires experts in fields such as plasma and atomic physics, robotics, AI, material science, mechanical engineering, and advanced control. In addition, the transdisciplinary character of fusion research feeds transversal competencies to numerous other scientific and industrial areas. Plasmas are used beyond fusion, potentially being a game-changer in several fields, including space propulsion, microwave technologies, pollution reduction for freight ships, sterilization and medicine, and are a vehicle for innovative ways to accelerate particles for high-energy physics research [38].

These exciting developments and the cutting-edge themes that the fusion program addresses, integrating plasma physics with fusion technology, constitute a unique appeal and provide an optimal environment for the education and training of new generations of plasma scientists and engineers. This is a crucial asset in the success of the global and transgenerational undertaking that the quest for fusion energy represents.

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**Ambrogio Fasoli**

Ambrogio Fasoli is the Director of the Swiss Plasma Center at EPFL, the Chair of the General Assembly of the European Consortium for Fusion Energy, EUROfusion, and the Associate Vice President for Research at EPFL. Professor Fasoli studied at the University of Milan and obtained his PhD at EPFL, then, after conducting experiments on the European JET tokamak, became a professor at MIT, where he worked from 1997 to 2001, before being appointed at EPFL. From 2014 through 2020 he was the Editor-in-Chief of the Nuclear Fusion journal, of the International Atomic Energy Agency. He is a Fellow of the American Physical Society.

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