

## Physics Research Needs for ITER<sup>†</sup>

Ned R. Sauthoff  
Princeton Plasma Physics Laboratory  
Princeton University, Princeton, New Jersey 08543 USA

### ABSTRACT

Design of ITER entails the application of physics design tools that have been validated against the world-wide data base of fusion research. In many cases, these tools do not yet exist and must be developed as part of the ITER physics research program. ITER's considerable increases in power and size demand significant extrapolations from the current data base; in several cases, new physical effects are projected to dominate the behavior of the ITER plasma. This paper focuses on those design tools and data that have been identified by the ITER team and are not yet available; these needs serve as the basis for the ITER Physics Research Needs, which have been developed jointly by the ITER Physics Expert Groups and the ITER design team. Development of the tools and the supporting data base is an on-going activity that constitutes a significant opportunity for contributions to the ITER program by fusion research programs world-wide.

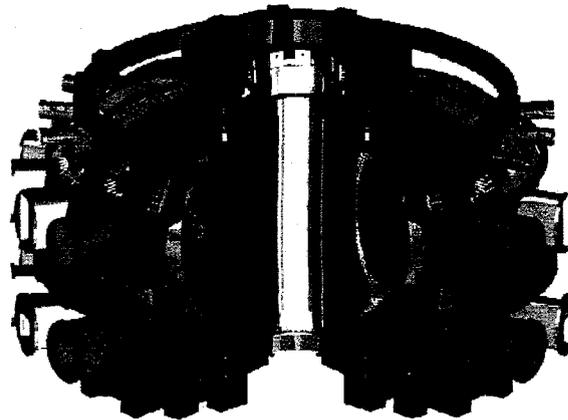
Performance forecasts for the current design point achieve sustained ignition at a fusion power of 1.5GW with plasma current  $I_p=21\text{MA}$ , major radius  $R=8.1\text{m}$ , minor radius  $a=2.8\text{m}$ , toroidal field  $B=5.7\text{T}$ , cross section elongation  $\kappa=1.6$ , helium confinement time relative to energy confinement time  $\tau_{\text{He}}/\tau_E \sim 10$  and beryllium impurity fraction  $n_{\text{Be}}/n_e=2\%$ . Access to enhanced confinement and stable shutdown require auxiliary heating power near 100 MW. If the plasma performance is degraded, such as  $\tau_E/\tau_{\text{ITER-90P}}=1.4$ , the mission power of  $P_{\text{fusion}}=1.5\text{GW}$  is projected to be achievable in a driven mode with auxiliary power of 100 MW.

### I. INTRODUCTION

The International Thermonuclear Experimental Reactor (ITER) is an international collaboration between the European Union, the Japanese government, the Russian Federation, and the United States to design and build an engineering test reactor.

The ITER mission includes the integrated demonstration of controlled ignition and extended fusion burn with a fusion power near 1500 MW for pulse lengths near 1000 seconds. As such, ITER would be a facility for resolving many plasma physics and technology issues for a fusion reactor. Major design features and parameters include:

- wall loading  $\sim 1\text{ MW/m}^2$  for integrated testing of high heat flux components;
- neutron fluence  $\sim 1\text{ MW years/m}^2$  for integrated testing of nuclear components;
- aim to demonstrate steady state - for improved reactor attractiveness; and
- demonstration of technologies essential for a reactor, such as superconducting coils and remote handling, plasma power and particle exhaust components, and design concepts for reactor-relevant tritium breeding blankets.



### II. Physics Research Needs

The ITER parties have appointed participants to physics expert groups, that have worked with the ITER physics design team to define the ITER physics research needs. The ITER physics research program offers an opportunity for contributions by the world-wide fusion research programs. A design-driven overview of these needs is the objective of this paper.

#### A. In-Vessel Structure

The current design of the main chamber's structure includes a beryllium-coated copper first wall facing the plasma and a thick ( $\sim 1$  meter) stainless steel and water shield that absorbs fusion neutrons before they could heat the superconducting magnets or compromise the reweldability of the vacuum

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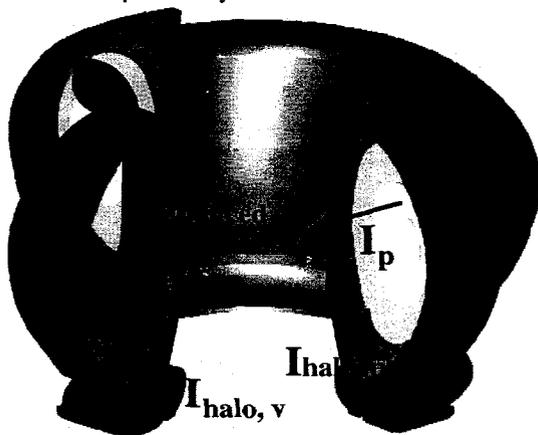
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vessel. To permit easier assembly and maintenance, the first wall/shield is composed of nearly cubical blocks that are individually installed or removed through a horizontal port. The segmentation of the shield complicates the current paths for plasma-induced eddy currents in the structure. Very short time-scale eddy currents flow in the first wall segments but must travel to and from a structural backing plate to pass between first wall elements. Longer time scale (~1 second) eddy currents flow mostly through the backing plate, which is nearly a meter from the plasma.

The plasma challenges related to the in-vessel structure deal mostly with

- eddy and halo currents associated with plasma disruptions, and
- the time delays introduced into the plasma control system by the structures' electromagnetic shielding, which is exacerbated since the poloidal control field coils are separated from the plasma by the vessel and in-vessel structures.



Vessel currents      Plasma currents

Plasma motions and changes of the plasma current induce currents in the structure, which then interact with the magnetic fields to create forces; both the rate of plasma current decay and the plasma location during decay are important in modeling the structural system dynamics. In ITER, the larger thermal and magnetic energies can introduce new effects into the disruption dynamics --- effects such as the vaporization of large amounts of plasma-facing material. The larger plasma current introduces a new avalanche process for runaway electron generation; in this process, runaway electrons can create new runaways by collisions, leading to an exponentiation of the runaway population. Physics research on generic disruptions includes:

- probability and severity spectrum;
- current quench rates in impurity-influx-dominated plasmas (due to vaporization of material in ITER disruptions); and
- runaway electron generation in high current plasmas.

Significantly more severe loads are created by the flow of current from the disrupting plasma to the vessel and returning to the plasma at another vessel location; such "halo currents", so-called since they pass through the edge plasma "halo" to and from the plasma facing components, interact with both

poloidal and toroidal magnetic fields, generating very significant forces. Related physics research includes:

- characterization of halo currents from Vertical Displacement Events; and
- non-axisymmetric disruption halo currents, wherein toroidal asymmetries of the halo currents create forces that are particularly difficult to handle.

Due to the large ITER power and current, which exceed experience by large factors, forecasts of the ITER disruption characteristics must be developed based on modeling the ITER disruptions' power deposition on the wall, the wall's response via impurity release, impurity transport and radiation, radiation transport, and plasma response (including generation of runaways by the avalanching process). The ITER Physics Research Needs document describes the needed integrated disruption model.

### B. Poloidal Field System and Conducting Structures

Control of the plasma shape, position and current is achieved by a combination of the active modification of the currents in the poloidal coils and the passive responses of the large adjacent conducting structures. Associated physics research needs include:

- operations limits - particularly the MHD beta limit (which seems to be dependent on currents induced in the nearby conducting walls), density upper limits such as the Greenwald and the Borras limits, density lower limits imposed by locked modes (which are related to the magnitude of plasma rotation) and constraints on divertor performance, and required ranges of poloidal beta and internal inductance (including provision for advanced scenarios);
- plasma control responses, particularly those targeted at controlling the plasma while minimizing the eddy current heating of the superconducting magnets;
- ELM control;
- effects of alpha particles on MHD activity; and
- disruption avoidance and mitigation.

### C. Divertor Power and Particle Handling

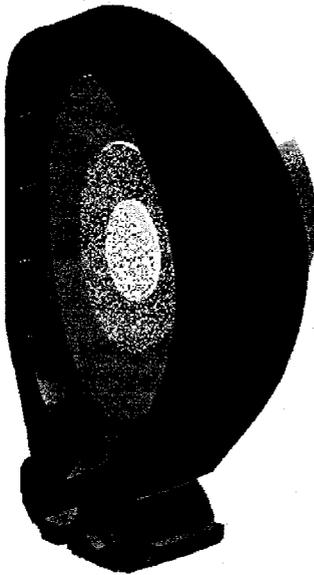
Of the 1500 MW of fusion power, only the 300 MW of alpha power is captured by the plasma. In the standard scenario, roughly 100 MW of this is radiated from the plasma core to the plasma facing components by bremsstrahlung; of the remaining 200 MW, roughly 50 MW is radiated by impurities in the plasma edge; the remaining 150 MW must be handled by the divertor. In the divertor, roughly 100 MW is to be dispersed to the divertor walls by divertor charge exchange, hydrogen radiation and impurity radiation. The remaining 50 MW is expected to be incident on the divertor end-target in the forms of conducted and convected power.

The divertor plasma research needs deal with the development and validation of methods for achieving such a distribution and dispersion of the power. The design goal is to disperse the power such that surfaces see less than 5 MW/m<sup>2</sup>

incident power. Present concepts involve a high density plasma/neutral mixture in the divertor chamber to radiate the power to the divertor chamber walls. Achievement of large divertor power dispersal may require not only higher density but also greater impurity fraction in the divertor; in this configuration, a significant challenge is the isolation of the main plasma chamber so as to maintain the low neutral gas density required for good confinement (a ratio of divertor neutral density to main chamber density of nearly  $10^4$ ) and to avoid core plasma dilution by impurities.

There are two current design options for the ITER divertor:

- a "vertical plate" design in which the separatrix is incident on an inclined solid plate; and
- a "gas bag" design in which the plasma radiates all its power and recombines in a chamber of neutral gas.



### *C.1 Steady-state divertor power handling*

Plasma research tasks in the area of steady-state power handling include:

- assessment of options for radiating significant power from the plasma edge, to reduce the divertor power load;
- assessment of radiation from the plasma scrape-off layer, near the X-point, and in the divertor;
- studies of the edge plasma, including characterization of the profiles outside the separatrix;
- experiments and models relating to the achievement of detachment of the plasma from the divertor structures via recombination of the plasma in a neutral gas;
- experiments on and models of the enhancement of radiation in the divertor chamber by increased density and impurity fraction, also addressing methods for confining the impurities and neutrals in the divertor to avoid core plasma modification (a recent concept involves entrainment of impurities in the divertor by friction between the impurities and a strong flow of gas from the main chamber); and

- experiments on density limits, which are relevant since detachment is expected at densities near density limits due to both experience and considerations of edge power balance.

### *C.2 Transient Divertor Power Handling*

The divertor power dispersal is upset by the incidence of bursts of power due to disruptions and ELMs. Physics research on divertor transients deals with:

- characterization of the disruptive thermal quench, in particular the speed and energy-loss mechanisms;
- modifications of the scrape-off layer width during the quench and during ELMs, in particular the modification of the power deposition on neighboring structures;
- characterization and control of the types of ELMs and their distribution of power on the plasma-facing surfaces; and
- studies of the performance of various divertor target geometries.

### *C.3 Divertor Particle Handling*

Since the divertor's power dispersal function may be implemented by a combination of high neutral density and increased impurity fraction in the divertor, a major concern is the maintenance of the low neutral pressure in the main chamber (to sustain good confinement and fueling control) and lower impurity fraction in the main chamber. The current plan is to use careful baffling to contain the neutrals and friction of a in-flowing plasma to entrain the impurities (countering the thermal force that drives the impurities up the temperature gradient into the main chamber). Physics research in the divertor particle handling area includes:

- modeling and experiments on baffle geometry; and
- control and modeling of impurity behavior, particularly in the situation with large main chamber fueling to achieve impurity entrainment.

### *C.4 Fueling and Pumping*

The fueling of ITER is planned to involve a combination of gas injectors both in the main chamber and in the divertor and pellet injectors with speed sufficient to penetrate well into the ELMing radius. Competing uncontrolled sources, such as the wall under plasma and power bombardment, must be minimized, particularly since control of the fusion power is by density control. The fueling is also coupled with the divertor impurity entrainment process since the gas injection intended to feed the entraining plasma flow will also fuel the plasma. Associated plasma research deals with:

- wall impurity and fuel sources;
- pellet fueling;
- erosion near the fueling locations; and
- studies of helium pumping.

## D. First Wall Power and Particle Handling

Steady-state power handling focuses on making the power deposition to the first wall both considerable (to off-load the divertor) and less than  $0.5 \text{ MW/m}^2$  (due to the limited power handling capabilities of the first wall). Associated physics research deals with control of the radiation from the plasma in the main chamber.

Transient power and particle handling concerns are dominated by considerations of localized radiation (as from MARFES) and runaway bombardment following disruptions. Associated physics research deals with configurations with materials such as beryllium, carbon and tungsten under both steady state and transient conditions, with the runaway generation and loss to the first wall and with localized alpha particle loss.

## E. Auxiliary Heating, Current Drive, and Rotation Drive

The functions of the auxiliary power systems are:

- heating the plasma to ignition;
- driving plasma current non-inductively and controlling the plasma current profile for steady-state;
- driving plasma rotation to stabilize MHD modes; and
- controlling plasma shutdown to avert density-limit disruptions.

The approaches under evaluation (either as part of the EDA or by some parties) include:

- ion cyclotron (IC) heating / fast wave (FW) current drive (20-60 Mhz), where coupling to a distant plasma is an issue;
- electron cyclotron (EC) heating and current drive (170 Ghz), where availability of the gyrotrons and efficiency are issues;
- neutral beam (NB) heating (E~500 keV), where access is an issue; and
- lower hybrid (LH) current drive (~5 Ghz), where coupling to the distant plasma and survival of the launcher are issues.

Physics research in these systems includes:

- studies of coupling and current drive efficiencies at higher  $T_e$ ; and
- studies of methods for current profile control, especially off-axis profile control with NB, FW, EC, and LH current drive.

## F. Plasma Performance

The development of models for the performance of reactor-like plasmas has been a major part of the world-wide fusion research program for decades. The ITER activities focus attention on aspects which affect the design decisions. The design implications range from the selection of overall parameters for the device to the specification of requirements for auxiliary heating systems and subsystems' power and particle handling capabilities.

## F.1 Energy Transport

Physics research needs include projection of existing plasma regimes and development of more attractive regimes:

- development of transport models that are consistent with the experimental data and as consistent as possible with theoretical constraints, to maximize extrapolability;
- acquisition of a global transport database and development of scaling laws, including L-mode, H-mode, hot ion, supershots and high  $\beta_p$  modes; of particular significance are isotope scaling, L-H and H-L mode transition powers, and transport near  $\beta$  and density limits;
- modeling of sawteeth activity;
- modeling of edge transport barrier and pedestal in ELM free and ELMy H mode including ELMs; and
- investigation of advanced tokamak scenarios for ITER, which are expected to be particularly significant for the steady-state scenarios, since available auxiliary heating (~100 MW) cannot drive more than a small fraction of the plasma current, even in low-current (~15 MA) plasmas.

## F.2 Particle Transport

Plasma performance projections suggest that the ITER ignition margin is strongly dependent on sufficient transport loss of the thermalized alpha particles. Similarly, the fuel dilution and radiation from impurities (whether from the plasma facing components or from the gases injected into the divertor to improve the divertor power handling) significantly impact performance projections. Related physics research includes:

- study of helium ash control;
- study of differential transport of helium and hydrogen isotopes;
- study of impurity density profiles (Be, C, high Z) in ITER relevant conditions; and
- development and testing of particle transport models in L and H mode.

## F.3 Rotation Transport

Avoidance of locked modes, wall stabilization of MHD modes, and achievement of enhanced confinement suggest a need for plasma rotation in ITER. Related physics research includes:

- modeling of plasma rotation; and
- development of requirements for plasma rotation for stability and enhanced confinement.

## F.4 Energetic Particle Stability and Related Transport

Design implications of energetic particle behavior include the effect on transport and stability, and steady-state and transient localized power deposition. Physics research needs include:

- experimental studies of the effect of TF ripple on the plasma performance;

- studying and forecasting the effect of MHD (islands, sawteeth, fishbones, locked modes) and TAE instabilities on transport;
- studying the effects of alpha-particles on MHD;
- experimental and theoretical studies of Alfvén modes excited by fast particles; and
- experimental demonstrations of enhanced confinement, high-bootstrap fraction, steady state scenarios.

### *G. Diagnostics*

Plasma diagnostic needs have been prioritized based on the application of the data. Highest priority goes to those that are needed for plasma control, followed by those for performance assessment and optimization, and lastly those that are needed for understanding of physical phenomena. Issues include:

- steady state operations;
- radiation environment;
- temperature excursions (from cryogenic temperatures to 200°C - 350°C bakeout); and
- remote maintenance.

### III. SUMMARY AND OPPORTUNITIES

ITER is targeted at demonstrating the scientific and technological feasibility of fusion power. It is being designed to achieve and sustain an ignited plasma at reactor-relevant power level, based on conservative physics and technology. ITER operations would address physics and technology issues and contribute to the basis for a demonstration fusion reactor. ITER physics has the functions of:

- defining the overall device configuration and parameters;
- specifying requirements for the subsystems;
- defining plasma scenarios; and
- defining the physics research needed for the design of ITER.

The ITER physics participants have developed a list of physics research needs, specifying the data and design tools needed for the physics design of ITER. This process has been particularly important in that it affords an opportunity for the constructive and coordinated involvement of the base physics programs of the world-wide fusion research programs in addressing physics issues important to a fusion reactor. The ITER physics needs list may serve as a tool for planning the fusion research programs of the world program, even including those groups not now formally partners in the ITER process.

### IV. ACKNOWLEDGMENTS

This paper's description of the ITER physics research needs has been based on the most recent needs list developed by the ITER Physics Expert Groups and issued by the ITER Joint Central Team. The ITER design activity is part of the ITER Engineering Design Activities under the auspices of the IAEA; the ITER physics research program is part of the 4 parties' base programs. The author thanks the ITER JCT Physics Integration Unit and the members of the ITER Physics Committee and the ITER Physics Expert Groups for many fascinating discussions, reports and meetings that have contributed to the development of the author's understanding of the ITER physics research needs.