THERMONUCLEAR TOKAMAK PANEL REPORT

The Thermonuclear Tokamak Panel, summoned by Dr. R. Pellat, High Commissioner of C.E.A., to evaluate the physics basis of the ITER and Ignitor experimental proposals, met in Paris on the 25th and 26th of November 1999. The designated panel members were:

- Prof. James D. Callen, University of Wisconsin, Madison, WI, USA
- Dr. Geoffrey Cordey, JET, Abingdon, UK
- Dr. Otto Gruber, Asdex U, Max Planck Institut, Garching bei Muenchen, Germany
- Prof. Wendell Horton, IFS, University of Texas at Austin, TX, USA
- Dr. Jean Jacquinot, Director of JET, Abingdon, UK (now Director of DRFC, C.E.A., Cadarache, France)
- Prof. Guy Laval, **Chairman**, Ecole Polytechnique, Paris, France
- Prof. Jean-Francois Luciani, Ecole Polytechnique and C.E.A., Paris, France
- Prof. Franco Porcelli, Politecnico di Torino, Italy

A ninth panel member, Dr. Oleg Pogutse of JET, could not take part in the panel discussions.

On the first day of the meeting, the panel members heard a presentation of the Ignitor project by Prof. Bruno Coppi of the Massachusetts Institute of Technology, Cambridge, USA, and a presentation of the ITER-FEAT project by Prof. Karl Lackner of the Max Planck Institut and by Dr. David Campbell of EFDA, both from Garching bei Muenchen, Germany.

On the second day, the eight panel members discussed the physics basis of the two proposals, their expected performances and their contribution to the reactor-oriented strategy. At the end of the second day, initial conclusions were reached and presented to the High Commissioner.

It should be noted that several key issues were discussed at the meeting, for which two days was really too short a period of time to reach definitive conclusions. Some of the physics issues, such as the problem of plasma transport and confinement, are not fully understood. The panel members agreed that a common methodology and common guidelines to evaluate the different proposals should be agreed upon, and that this task would be best carried out by a dedicated study group. The High Commissioner himself, after he was briefed about the preliminary conclusions reached by the panel members, encouraged work to resolve discrepant points of view. It was agreed that a panel report would be issued that presents as closely as possible the common view of the panel members on the two experimental proposals under consideration. To that objective, an intense activity was initiated after the two-day meeting in Paris, which involved not only the eight panel members, but also a number of colleagues in the scientific fusion community who helped with comments, suggestions and sometimes actual work. The contribution of these colleagues is acknowledged at the end of this report, which is the result of this effort.

This report is organised as follows. The goals and the parameters of the two proposals, Ignitor and ITER-FEAT, are presented in Sec. I, together with a discussion of the significance of thermonuclear ignition. Section II presents a physics assessment of the Ignitor proposal. Section III presents a physics assessment of ITER-FEAT. Conclusions are presented in Sec. IV and recommendations are given in Sec. V.

I. ITER AND IGNITOR IN THE FUSION PROGRAM

The main parameters of the two devices under consideration are presented in Tables I and II. It should be made clear from the beginning that the two experimental proposals have different goals.

The goals of the ITER-FEAT experiment [1] are (1) to achieve extensive burn in inductively driven plasmas with a thermonuclear gain parameter $Q = (P_{\rm fus}/P_{\rm in})$ of order 10 for a range of operating scenarios and with a duration sufficient to achieve stationary conditions on the time scale characteristic of plasma processes; here, $P_{\rm fus}$ is the fusion power and $P_{\rm in}$ is the input heating power; and (2) to demonstrate steady-state operation using non-inductive current drive with at least $Q \sim 5$. In addition, the possibility of exploring controlled ignition for favourable confinement conditions is not precluded. The technological goals of the ITER-FEAT device include the demonstration of integrated operation of technologies essential for a fusion reactor, the testing of components for a future reactor, and the testing of concepts for a tritium-breeding module.

The goals of the Ignitor experiment [2, 3] are (1) to demonstrate ignition in a magnetically confined plasma; (2) to study the physics of the ignition process and alpha particle confinement; (3) to heat and control a burning plasma. According to the proponents, a high field, compact approach is likely to provide the cheapest and most expeditious path toward a first burning plasma physics experiment. In addition, Ignitor may indicate a possible path towards tritium-poor, neutron-poor fusion.

Ignition in Ignitor would be reached under non-steady-state conditions. However, the ignited regime would last a few (5 to 10) confinement times and many alpha particle slowing down times, which is adequate from the physics point of view.

The concept of ignition is defined by the Ignitor proponents as the plasma state where the heating power due to the fusion alpha particles compensates for all forms of power losses (due to anomalous transport and radiation). It is worthwhile to discuss this concept quantitatively, especially in view of non-steady-state operation. Consider the power balance equation,

$$\frac{dW}{dt} = P_{\rm ohm} + P_\alpha + P_{\rm aux} - P_{\rm loss},$$

where W is the plasma energy content, $P_{\rm ohm}$ is the ohmic power, P_α is the alpha particle heating power, $P_{\rm aux}$ is the auxiliary heating power, and $P_{\rm loss}$ is the loss power, including radiation losses. In the ignited state, $P_\alpha = P_{\rm loss}$ and the auxiliary power, $P_{\rm aux}$, may be switched off. Thus, ignition would correspond to an overheated state with $dW/dt = P_{\rm ohm} > 0$. One may introduce a parameter $Q_* = P_{\rm fus}/(P_{\rm loss} - P_\alpha)$ where the fusion power is given as $P_{\rm fus} = 5P_\alpha$ for a D-T reacting plasma. With this definition, $Q_* = \infty$ at ignition. Alternatively, using the power balance relation, one may write

$$Q_* = P_{\rm fus}/(P_{\rm in} - dW/dt),$$

where $P_{\rm in} = P_{\rm ohm} + P_{\rm aux}$.

The parameter Q_* is the one used by the Ignitor proponents to quantify the proximity to an ignited state. One can see that Q_* becomes equal to the usual $Q = P_{\rm fus}/P_{\rm in}$ when $dW/dt = 0$, i.e. Q_* is the natural extension of the thermonuclear gain parameter under non-steady-state operation. During transient regimes, the difference between Q and Q_* becomes important and should be kept in mind. For instance, for the simulation example in Table II of an ignited discharge in Ignitor, one finds $Q_* = \infty$, while $Q = 11.8$.

The panel members believe that a value of Q at least equal to ten, sustained for a duration of at least a few confinement times, is the minimum value required in order to study a burning plasma where alpha particle heating is the dominant form of heating. Indeed, $Q = 10$ implies $P_\alpha = 2(P_{\rm ohm} + P_{\rm aux})$. We note that both ITER-FEAT and Ignitor satisfy this criterion, although only marginally. In the case of a plasma with $P_{\rm aux} > P_{\rm ohm}$, such as the one that would be produced by ITER-FEAT, a significant fast ion population may be produced by auxiliary heating. Then, with Q below 10, issues of alpha particle physics, such as collective alpha instabilities, would be blurred due to the presence of the fast particles produced by auxiliary heating. Of course, auxiliary heating schemes exist, such that the induced fast particle population remains small, in which case alpha particle collective modes at $Q = 10$ would be easy to investigate.

Table III compares the main physical parameters of JET, Ignitor, and ITER-FEAT, including the three dimensionless parameters ρ_*, β_N and ν_*. This table shows that these tokamak plasmas have values of ρ_* within a factor of two of one another. The value of β_N is lowest for Ignitor, which is an asset from the point of view of improved MHD stability. The value of the collisionality parameter, ν_*, is significantly higher for Ignitor, which introduces a note of caution if the confinement time is extrapolated from the present international (ITER) database, which is dominated by low density-neutral beam driven discharge data.

During the discussions in Paris, problem areas emerged for both the proposed Ignitor and ITER-FEAT devices. The question was how to deal with these problems in an effective manner. For a fair and productive scientific assessment, it was considered to be important that the same guidelines be applied to all experimental proposals. The terms of references were stated by René Pellat as follows:

"The assessment will deal in particular with:

> – The physics basis for each device and the confidence in achieving the performance required for reaching the stated objectives. In particular, confinement, stability, power, and particle extraction, and D/T burning (with the possibility to reach ignition) will be examined.
>
> – The contribution of each facility to the above reactor-oriented strategy: enrichment of experimental databases with respect to thermonuclear α physics and control of burning plasmas; extrapolation of the expected results to reactor conditions."

These terms of reference will be taken as a basis for the report. Consequently, technical aspects of the projects, engineering feasibility and reliability of the proposed devices will not be assessed. Costs and construction opportunities should not be mentioned in this report.

Table I: Principal parameters of the ITER-FEAT design and plasma parameters at a nominal $Q = 10$ operating point.

	ITER-FEAT
κ_x	1.85
δ_x	0.48
$R(m)$	6.20
$a(m)$	2.0
R/a	3.1
$B(T)$	5.3
I_p (MA)	15.1
$t_{\rm burn}$ (s)	≥ 400
$\langle n\rangle/n_{\rm GW}$	0.8
$\langle n\rangle(10^{20}\ {\rm m}^{-3})$	0.97
$\langle T\rangle$(KeV)	9.0
β_N	1.6
$\beta(\%)$	2.3
$P_{\rm fus}$ (MW)	400
$L_{\rm wall}$ (MW m^{-2})	0.57
Q	10

Table II: Ignitor parameters for a simulation example with ohmic and alpha heating only (from Coppi *et al.*, Ref. 2).

Plasma Current I_p	11 MA
Toroidal Field B_T	13 T
Central Electron Temperature T_e	14.4 KeV
Central Ion Temperature T_{i0}	12.6 KeV
Central Electron Density n_{e0}	10^{21} m^{-3}
Central Plasma Pressure p_0	4.3 MPa
Alpha Density Parameter n_α	2.9×10^{18} m^{-3}
Average Alpha Density $\langle n_\alpha\rangle$	2.4×10^{17} m^{-3}
Plasma Stored Energy W	12.8 MJ
Ohmic Power $P_{0\rm H}$	10.5 MW
ICRF Power $P_{\rm ICRF}$	0
Alpha Power $P_{\alpha H}$	24.7 MW
Bremsstrahlung Power $P_{\rm brems}$	4.1 MW
Poloidal Beta β_p	0.27
Toroidal Beta β_T	1.16%
Central q_0	~ 1
Edge q	3.5
Bootstrap Current I_p	0.85 MA
Energy Confinement Time τ_E	0.6 sec
Alpha Slowing Down Time τ	0.07 sec
Average $\langle Z_{\rm eff}\rangle$	1.2

Table III: Comparison of Dimensionless Machine-Plasma Parameters.

Machine	B(T)	I(MA)	a(m)	$\langle n\rangle[10^{19}]$	W(MJ)	$T_i(0)$ KeV	$\langle T_i\rangle$ KeV	$\rho_*(0)[10^3]$	$\rho_*[10^3]$	β_N	$\langle\nu_*\rangle$
JET D-T ELMy H-mode	3.9	3.7	0.94	5.9	10	8	4.5	3.9	2.9	1.3	2.4
IGNITOR at ignition	13.0	11	0.47	62	13	13	4.2	3.0	1.7	0.7	11.0
ITER-FEAT	5.3	16	2.0	9.7	470	22	9.0	2.3	1.4	1.6	1.1

In this table we use the relations

$$\rho_* = 5.1\times 10^{-3} T_i^{1/2}/\mathrm{Ba}, \quad \beta_N = 0.85\,\mathrm{W}/a\kappa\,\mathrm{RBI}, \quad \langle\nu_*\rangle = 2.033\times 10^{-5} a^7 n^3 \kappa^2/\varepsilon^3 W^2.$$

II. IGNITOR PHYSICS ASSESSMENT

1. Goals of the Ignitor experiment

Ignitor [2, 3] is a physics demonstration experiment. Its main goal is to achieve thermonuclear ignition, defined as the regime where the fusion alpha heating compensates for the thermal energy losses due to anomalous transport and radiation. The relevant information that would be gained from such an experiment can be summarised as follows:

(i) Improved understanding of plasma turbulence and transport processes, by the exploration of high-plasma-density, high-magnetic-field regimes never accessed before. More specifically, Ignitor would provide insight into the ohmic confinement scaling laws and self-organised plasma profiles at high temperatures. Furthermore, it would provide relevant information on the conditions required for the spontaneous generation of plasma rotation through anomalous angular momentum transport. Plasma rotation is believed to play an important role in determining the level of turbulent fluctuations.

(ii) Alpha particle physics issues, in particular: alpha particle confinement, collective electromagnetic modes excited by the fusion alphas, and the nature of alpha particle heating. We note that an outstanding alpha physics issue is whether collective instabilities excited by the fusion alpha particles, such as fishbones and Toroidal Alfvén Eigenmodes (TAE), can seriously degrade the quality of confinement. A second outstanding physics issue is whether alpha particle heating causes the same degree of confinement degradation as other forms of auxiliary plasma heating.

(iii) The control of a fusion burning plasma over physically significant time scales. With a current flat top of a few seconds, Ignitor should have a long enough pulse-length to thoroughly examine alpha particle physics and thermal transients associated with the DT burn.

(iv) The Ignitor [2] experiment would give first indications about a possible development path to tritium-poor, reduced neutron production of fusion power.

In Ref. [1], it is stated that the Ignitor experiment has been designed with the capability of producing plasmas where the product of central plasma density times the confinement time is $n_0\tau_E \sim 4 \times 10^{20}\,\mathrm{m}^{-3}\,\mathrm{s}$ (assuming peaked density profiles) and the central plasma temperature exceeds 10 keV. Central densities of $n_0 \sim 10^{21}\,\mathrm{m}^{-3}$, well below the Greenwald density limit, should be achievable in Ignitor with a considerable degree of confidence. Thus, the energy confinement time needed to reach the desired performance is $\tau_E \sim 0.4\,\mathrm{s}$ to $0.6\,\mathrm{s}$. This confinement time is more than five times longer than the alpha particle slowing-down time, $\tau_\alpha \sim 0.07\,\mathrm{s}$, and considerably shorter than the discharge pulse length.

While Ignitor would represent a long-awaited fusion ignition demonstration and a possible way to study burning plasma issues at relatively low cost, it is noted that reactor-relevant technological issues are not a motivating factor. The Ignitor proponents endorse the statement by the US PCAST Report on Fusion Research [4], that *Ignition is analogous to the first aeroplane flight or the first vacuum-tube computer. As in those cases, the initial model need not resemble the one that is later commercialised.* It is noted, however, that some of the technological solutions found by the Ignitor team, such as the so-called bucking and wedging structural concept for the magnet coils system, have also been adopted by the ITER EDA design.

2. Ignitor operational flexibility

Tokamak plasmas are complex physical systems [5]. As such, it is generally accepted that our confidence in accurate quantitative predictions of plasma behaviour in future tokamak experiments is relatively limited. Experiments such as Ignitor are precisely designed having in mind the exploration of new plasma regimes and unforeseen plasma behaviour. In this respect, any new tokamak experiment must have sufficient flexibility in order to counter unexpected plasma behaviour. The flexibility of the Ignitor experiment is related to:

(i) Its ability to explore a wide range of plasma densities and currents;

(ii) The operation of a high-speed pellet injector for the control of plasma profiles and for the exploration of enhanced confinement regimes.

(iii) The presence of a 18-24 MW Ion Cyclotron Radio Frequency system capable of providing additional heating, thereby affecting the current density evolution, and also capable of producing a suprathermal minority ion population for the control of MHD instability and for the simulation of alpha particle behaviour. For instance, ICRH can be applied to relatively low density regimes, in which the plasma temperature can be raised to values considerably higher than the optimal values for ignition, to attain the desired ratios of fast particle pressure relative to the plasma pressure.

(iv) A highly flexible poloidal field coil system, able to produce a considerable variety of equilibrium configurations. This includes the possibility of producing a magnetic X-point as an added tool for the investigation of enhanced confinement regimes.

3. A short assessment of plasma performance in present high-field tokamak experiments

Ignitor belongs to a family of high-field tokamak experiments, pioneered by the Alcator machine at MIT in the 1970s and continued by the Alcator C/C-Mod and the Frascati FT/FTU series of experiments. A full assessment of plasma performance in these experiments is beyond the scope of the present work. It is noted, nevertheless, that a record value of $n_0\tau_E \sim 4 \times 10^{19}\,\mathrm{m}^{-3}\mathrm{s}$ was reached in ALCATOR C experiments [6, 7] with high density ($n_0 \sim 8 \times 10^{20}\,\mathrm{m}^{-3}$) and a confinement time of order $\tau_E \sim 0.05\,\mathrm{s}$. In Ignitor a value of τ_E higher by a factor of ten is needed to reach the target value $n_0\tau_E \sim 4 \times 10^{20}\,\mathrm{m}^{-3}\mathrm{s}$.

Recent experience from ALCATOR C-MOD [8] and from FTU [9] indicates that the confinement time in these machines follows the ITER89P L-mode scaling, both in ohmic and in auxiliary heated discharges at relatively high densities, while the neo-Alcator scaling is followed at lower densities. Regimes of improved confinement at high plasma density have been observed. H-modes have been observed in divertor as well as limiter configurations, in ohmic as well as in auxiliary heated discharges. Enhanced confinement in L-mode type of operation, such as the Improved Ohmic Confinement (IOC) regime of the type observed in Asdex-U [11], has been observed [7] in Alcator C at relatively high density in plasmas with peaked profiles.

We note, however, that high-field operation in recent experiments has been limited. As a result, the available data bank is rather poor. Consequently Ignitor represents a substantial extrapolation from present high-field experiments.

4. MHD stability and collective alpha particle modes

One of the main advantages of the Ignitor experiment is the increased safety margin against MHD instabilities. The relatively low values of the plasma beta parameter and relatively large values of the safety factor needed at ignition guarantee this. Thus, Ignitor should operate well below the stability thresholds for ballooning modes and for neoclassical tearing modes. Likewise, the incidence of disruptions in Ignitor can be expected to be very low. However, a more precise quantitative assessment of MHD stability requires further work.

The assessment of stability against internal kink modes, leading to the well-known sawtooth internal relaxation oscillations and fishbone oscillations deserves a separate discussion. Here, the Ignitor team has carried out a considerable amount of detailed work [2, 3]. Indeed, it appears as if the ignition strategy in Ignitor is partly driven by the necessity to avoid the deleterious effects of sawteeth. The transient nature of the approach to ignition is such that the q profile develops a $q = 1$ surface only well into the current flat top, after ignition is reached. In this way, the $q = 1$ radius, which measures the extent of the central plasma region affected by sawteeth, should remain small. Thus, if sawteeth appear at all, their effect should cause only a minor redistribution of the plasma core properties. However, anomalous current penetration, for instance caused by double tearing modes, may lead to an early onset of sawtooth oscillations. In addition, a detailed analysis of the evolution of the current density profile and of the sawtooth trigger condition in the presence of alpha particles and of kinetic effects related to trapped thermal ions has not been carried out.

Fishbone oscillations may be excited by the fusion alpha particles in Ignitor. The relevant instability regime corresponds to modes oscillating at the thermal ion diamagnetic frequency [12]. Trapped alpha particles can resonate with these modes only at energies below 500 keV, i.e., only after they have deposited most of their energy in the plasma. The effect of fishbones on slowed-down alphas at these relatively low energies should be relatively mild. It is noted that the loss of slowed-down alpha particles may even be beneficial, as the deleterious effect of alpha ash accumulation would be reduced [13].

Since Ignitor is designed to reach ignition at relatively low plasma temperatures, the projected alpha particle pressure is relatively low, in particular lower than the threshold for the excitation of Toroidal Alfvén Eigenmodes (TAE). However, operation at lower density and ICRH injection lead to higher plasma temperatures and higher alpha particle pressures, which could then allow for the experimental observation of TAE modes.

Ignitor proposes to operate at such low poloidal beta that neoclassical tearing modes would only be very weakly excited, if at all. Also, even if they did occur they would probably grow too slowly to influence the approach to ignition. To the extent that a burning plasma regime is achieved and sustained for a time of the order of the skin diffusion time in Ignitor, neoclassical tearing modes might be observed and studied. However, at the high collisionality in Ignitor, the threshold island width is likely to be quite high. Thus, neoclassical tearing modes seems to be of little concern for Ignitor's basic mission.

5. Impurities

Another important advantage of the Ignitor experiment is the expected high purity associated with high plasma density operation. The self-cleaning ability of high-density plasmas has been well documented by Alcator C-MOD [8] and FTU [14] experiments. A scaling law relating plasma purity, radiated power, and machine dimensions has been derived from a number of experiments [15]. Based on these experiments, average Z_{eff} values of around 1.2 should be possible in Ignitor. However, the problem of plasma purity is associated with the problem of reducing the power load on the first wall, where sputtering and evaporation can produce impurities.

One possible solution to this problem is the divertor concept. However, while the Ignitor poloidal system is capable of producing an X-point within the vacuum vessel, the Ignitor first wall is not capable of handling the concentrated power load associated with divertor operation. Hence, this solution is excluded for Ignitor.

The solution proposed by the Ignitor team is the *cold radiating mantle* concept, with molybdenum tiles as the first wall material. Recent experimental results [11] have indicated the possibility of operating with a radiated mantle able to dissipate up to 90% of the total power lost by the plasma without energy confinement degradation. Thermal loads in Ignitor have been calculated for an ideal continuous first wall, under the conservative assumption that only 70% of the input power is radiated. Under normal operation, the maximum thermal load is estimated [3] to be 1.8 MW/m^2 with an average heat flux of less than 0.7 MW/m^2.

6. Transport considerations

The study of plasma transport is one of the outstanding problems in fusion research. Following Kadomstsev [5]:

> *At the beginning of tokamak research there was the hope that experiments would allow us to determine empirical expressions for the relevant transport coefficients, which would then be explained theoretically. This hope was supported for a decade by results from small and medium size tokamaks, which suggested that the ion thermal conductivity be close to the neoclassical value. As for electrons, there was hope that experiments might help to produce a universal formula applicable to all cases. Understanding of confinement deepened in the 80s partially as a result of more detailed investigations in medium-size tokamaks, but mainly as the result of the operation of the new generation of large size tokamaks. A new*

understanding has emerged as a result of the discovery of various confinement regimes.

It has become evident that self-consistent coupling of the turbulence with the plasma profiles plays a crucial role in the determination of the effective transport coefficients. Due to the feedback loops within this complex dynamical system, bifurcations arise analogous to those well known in turbulent neutral fluids. Thus, there are a variety of plasma confinements states. In some cases similar system control parameters result in discharges that take different confinement paths. A well-known example occurred for the matched discharges in TFTR, in which one ultimately deviates from the other through the bifurcation to a new state known as Enhanced Reversed Shear (ERS) confinement [16]. These issues of plasma confinement are of fundamental importance to plasma science and can be addressed in fusion-grade plasmas with Ignitor.

The Ignitor team bases its confinement predictions on a combination of empirical and theoretical 1-D flux-surface-averaged transport models [2]. While such 1-D models are intellectually appealing, the unfortunate reality of tokamak physics is that we do not have a generally accepted model of turbulent transport.

The confinement issue for Ignitor should be addressed with various methodologies and from many different perspectives in order to make sure that the confinement will be sufficient for the ignition objective. One methodology is to examine the heat diffusivity value needed for ignition in Ignitor relative to what has been achieved in other high field, compact tokamak experiments. Table IV provides one possible comparison:

Table IV: Comparison of Alcator C and C-Mod with IGNITOR

Machine parameters:

	Alcator C(1983)	Alcator C-Mod (1996)	IGNITOR
a(m)	0.165	0.22	0.47
$R_0(m)$	0.64	0.67	1.32
κ	1	1.65	1.83
B(T)	11.2	5.4	13
I(MA)	0.78	1	11

Plasma confinement performance:

	Alcator C(1983)		Alcator C-Mod (1996)		IGNITOR
	Normal density profile	Peaked density pellet	L-mode	H-mode	PTP 99/06 p. 33
$\tau_E(s)$	0.025	0.05	0.04	0.08	0.5
$\overline{\chi}_E$ (m^2/s)	0.27	0.136	0.5	0.25	0.2

In Table IV, as suggested on p. 33 of the February 2000 version of Ref [3], the definition $\overline{\chi}_E = a^2\kappa/4\tau_E$ has been used.

Table IV shows that an average heat diffusivity as low as that needed for ignition in Ignitor has been achieved – viz., in Alcator C in 1983, with the use of pellet injection to produce a peaked density profile, enhanced confinement regime plasma. However, normal density profile plasmas in Alcator C and a large number of later tokamak experiments throughout the world have apparently not been able to produce a low enough diffusivity for ignition in Ignitor.

It is not clear how to extrapolate these lower temperature ($T_i \sim 1.5\,keV$ in Alcator C and 3 keV in C-Mod) plasmas to the proposed Ignitor regime ($T_i \geq 10.5\,keV$) plasmas; however, both Bohm and gyroBohm scalings mostly indicate increases in the extrapolated values of average heat diffusivities that could be anticipated in Ignitor. The one exception is that for the gyroBohm extrapolation from C-Mod to Ignitor the factor is 0.53 to 0.57 (with mass and κ effects) which yields $\overline{\chi}_E$ values similar to those in Alcator C, whereas the same extrapolation from Alcator C to C-Mod is off from the experimental results in C-mod by a factor of 5.

A significant concern as one moves to the larger, higher temperature plasmas required for ignition is that of fueling. Early tokamak plasmas were mostly gas fueled from the edge by means of edge Frank-Condon and charge-exchange neutral sources, which yielded moderately peaked density profiles. However, as the plasma minor radius has increased over the past two decades, this fueling source has become more localized to the very edge ($\lesssim 3\%$ of the minor radius) of the plasma, the density profiles have become flatter, and the rate of core plasma density build-up has slowed considerably. On the other hand, almost all enhanced plasma confinement regimes have highly peaked density profiles and seem to require significant core sources of power and particles to build up the peaked profiles on the confinement time scale. In most present-day auxiliary heated plasmas the peaked density profiles are produced by the core fueling provided by energetic neutral beams. A very peaked density profile and enhanced (mainly in the ions) confinement was produced in Alcator C by pellet fueling.

However, hydrogenic ice pellets have difficulty penetrating plasmas with temperatures above 2 keV unless their velocity is increased rather substantially. Inside launch pellets seem to penetrate better into medium density plasmas, but they have not yet been tried on high density plasmas.

Our preliminary assessment of confinement predictions in Ignitor is based, in the first instance, on 0-D empirical confinement scaling law. In particular, we consider a first estimate of confinement time in Ignitor based on the L-mode scaling law. This estimate should represent the expected lower bound on performance if no care is taken to control the plasma profiles. Then, we consider the possibility of enhanced confinement regimes in Ignitor. Finally, we present considerations based on the dimensional analysis of energy confinement.

One peculiar feature of the Ignitor experiment is its transient approach to fusion, which implies that relevant plasma parameters, in particular the ohmic and alpha particle heating powers, vary in time; consequently the confinement time should also be changing in time during the discharge duration.

A. Confinement time based on L-mode scaling laws

A good description of the L-mode database with approximately 3000 entries is given in Ref. [17]. We have used these formulae in comparison with drift formulae for χ_E in a recent EUR-CEA-FC report [18] that analyses confinement in Tore Supra. The Tore Supra database has 50 discharges with Fast Wave ICRH that deposits its energy into the electrons, $P_{\mathrm{ICRH}} = P_0 \exp(-r/L_p)$, in a highly localised core with $L_p \approx a/5$. Thus, the fast wave ICRH heating is a rough simulation of the alpha power heating to the electrons. In addition, Tore Supra operates routinely in L-mode and exhibits various levels of enhancement over the ITER-97 L mode scaling law as a function of density profile peaking. Thus, even though not a high field tokamak, Tore Supra is relevant to Ignitor considerations. In the Tore Supra electron confinement analysis, thermal diffusivity formulas from two drift wave models are compared with the ITER-97 L-mode global τ_E formula. The best discharges have an enhancement factor of $H = 1.4$ to 1.7 with respect to the ITER-97-L mode formula, which should be a conservative calculation of τ_E. The ITER97 L-mode formula is

$$\tau_E^{\mathrm{L97}} = 0.023\kappa^{0.64} R^{1.83} A^{0.06} B_T^{0.03} n_e^{0.4} m_{\mathrm{eff}}^{0.2} I_p^{0.96} P^{-0.73}$$

where P is the heating power that includes ohmic power, auxiliary injected power, the radiated Bremsstrahlung power and the fusion power deposited by the alpha particles.

For Ignitor, we use $P = P_{OH} = 10.5\,\mathrm{MW}$ for discharges with ohmic heating only and $P = P_{OH} + P_\alpha - P_{\mathrm{Brem}} = (10.5+24.7-4.1)\,\mathrm{MW} = 31.1\,\mathrm{MW}$ to see how the confinement drops as the fusion power rises to its final value given in Table 3.2 of Ref. [3] and given here in Table I of Sec. I. This table refers to a simulation example where ICRH heating was not used. The value $P_\alpha = 24.7\,\mathrm{MW}$ is reached at ignition, otherwise one should use $P_\alpha(t) \leq 24.7\,\mathrm{MW}$. From this we get

$$\tau_E^{L97}(\mathrm{Ignitor}) = 0.88 \left(\frac{10.5\,\mathrm{MW}}{10.5\,\mathrm{MW} + P_\alpha(t) - P_{\mathrm{Brem}}} \right)^{0.73} \mathrm{s} = 0.9\,\mathrm{s} \rightarrow 0.4\,\mathrm{s}.$$

Since Ignitor would operate in a driven, pulsed mode and ignition is reached transiently, the stored plasma energy increases with time, i.e., $dW/dt > 0$, and the effective power is $P_{\mathrm{eff}} = P_{\mathrm{aux}} + P_{OH} + P_\alpha - dW/dt$, which increases the estimated confinement time (i.e., $\tau_E = W/P_{\mathrm{eff}}$, which is the definition of confinement time used in the Ignitor report, Ref. [3]).

In a recent contribution by J. Johner [19], invited by some of the panel members, Ignitor L-mode confinement was analysed on the basis of the zero-dimensional thermal equilibrium code HELIOS. The analysis assumed the ITER-97P(th) scaling law and evaluated the enhancement factor, H_L, needed for ignition (defined as the condition where the alpha power can compensate for all forms of power losses) as a function of the profile peaking factors α_n and α_T, where $n(\rho) = (1-\rho^2)^{\alpha_n}$ and $T(\rho) = (1-\rho^2)^{\alpha_T}$. The ignition simulation example in the Ignitor report, Ref. [3], could be reproduced by the HELIOS code [19] by assuming the values $\alpha_n = 1.76$ and $\alpha_T = 2.43$ an enhancement factor $H_L = 1.44$. Clearly, the value of H_L required for ignition is lower for more peaked profiles and higher for less peaked ones. It should be pointed out that, in existing tokamak experiments, profile peaking and enhanced confinement normally come together (see the next section). The question arises as to whether adequate profile peaking can be produced and maintained in Ignitor for a sufficiently long time.

A key scientific issue that Ignitor would address is whether the ohmic power at multi-megawatt levels plays the same role as P_{aux} in the confinement scaling laws as assumed in the above estimate of the confinement time. The same kind of question arises for the alpha heating power since this would become the dominant form of heating in Ignitor. The answer to this question may profoundly affect our estimates of confinement time based on the available empirical scaling laws.

B. Improved confinement regimes with peaked density profiles

Since the Ignitor proponents suggest that ignition may be reached with ohmic heating only, it is convenient to start our discussion with the consideration of ohmic confinement modes. As is well known, the LOC (linear ohmic confinement) mode is a regime of ohmic confinement where a linear relationship between energy confinement time and density, i.e. neo-ALCATOR scaling, is valid [20]. The LOC regime corresponds to the best confinement mode. Unfortunately, at regular conditions with increasing density, the LOC regime makes a transition either into a saturated ohmic confinement (SOC) mode or into the L-mode with Goldston confinement scaling. The critical density at which the transition between LOC and SOC regimes occurs is the so-called Shimomura density [21], whose expression is

$$n_s \approx \frac{B_T\,\sqrt{A_i/2}}{q_\Psi R}\left[n\left(10^{20}\,\mathrm{m}^{-3}\right),\mathrm{B(Tesla)},\mathrm{R(m)}\right].$$

Different improved confinement regimes look like a LOC mode extended into the high-density region with subsequent saturation. One such improved confinement mode, the H-mode, will be discussed in Subsec. 6D. Here, we consider improved confinement regimes that can be reached with peaked density profiles. These regimes are listed as follows:

(i) The improved ohmic confinement (IOC) mode, initially discovered in ASDEX [10].

(ii) The radiative improved (RI) mode, discovered in TEXTOR [11].

(iii) The P-mode, which is a mode of improved ohmic confinement both in ohmic and in auxiliary heated discharges, first obtained with the help of pellet injection in ALCATOR-C [26].

(iv) The supershot, or S-mode, experimentally discovered in TFTR with central neutral beam injection (NBI) and strongly peaked density distributions [27].

In the experimental regimes listed above, energy confinement enhancement factors up to 2-3 over that for L-mode have been obtained. Clearly, the relevant question is whether Ignitor can access any of these regimes. Note that the key feature common to these improved confinement regimes is the realisation of peaked density profiles. Different methods and considerable operational skills in the four tokamaks mentioned above have achieved this. In ASDEX, peaked densities and the IOC mode were obtained after appropriate wall conditioning and decreased gas puffing. In TEXTOR, the transition from the L to the RI mode was obtained with impurity seeding. In this way, a strongly radiating layer was established at the edge, with a corresponding decrease of the edge temperature and a steepening of the density gradient deeper inside the plasma. In ALCATOR-C, pellet deposition in the plasma core resulted in peaked density profiles and the establishment of the P-mode. In TFTR, very peaked densities were obtained in supershots with central NBI deposition.

From a theoretical viewpoint, peaked density profiles are known to have a beneficial effect on plasma confinement through the quenching of the ion temperature gradient (ITG) driven turbulence. Peaked density profiles reduce the two dimensionless profile parameters,

η_i and η_e, that represent driving terms for the instability of ion and electron temperature gradient modes and their associated plasma turbulence for peaked density profiles. For flatter density profiles, the ITG stability condition is that L_{ti}/R exceed a critical value, which is typically not compatible with the overall required temperature difference between the edge and core plasmas. In the 80s, several theoretical investigations of ITG modes supported the conclusion that the improved confinement in Alcator C pellet fueling experiments [6] was correlated in time with the drop of the η_i parameter. Numerous other machines have shown discharges with improved confinement from density peaking. For instance, Ref. [22] predicts a suppression of the ion thermal flux due to ITG turbulence going from L-mode to the RI-mode in TEXTOR [23]. As far as the electron temperature gradient driven turbulence is concerned, there are two theoretical forms of the anomalous electron thermal diffusivity that are depressed by high density: the dissipative trapped electron turbulent diffusivity, and the short wavelength electromagnetic diffusivity with mixing length proportional to the collisionless skin depth [24].

In Ignitor, ignition would be reached with densities well below the Greenwald density limit, which must be considered as a distinct advantage. However, density peaking is crucial to gain access to improved confinement regimes. Strong density peaking in Ignitor depends on the existence of an inward particle pinch. There are two theoretical models used to explain the particle pinch that occurs in tokamaks. The classical mechanism known as the Ware pinch is the off-diagonal transport coefficient that is conjugate through symmetries to the experimentally verified bootstrap current. While no clear experimental verification exists for the Ware pinch, an inward convection is required for transport modelling to be consistent with the measured density profiles. The density pinch effect is also modelled through drift wave turbulence driven by the temperature gradients, where again symmetries dictate an off-diagonal transport matrix producing a turbulent inward particle transport [25].

As noted in Sec. 5, Ignitor has adopted the cold radiating mantle solution, which may turn out to be advantageous for the formation of peaked density profiles. Indeed, the qualifier *radiative* in the RI-mode refers to the fact that this mode was discovered in TEXTOR while the cold plasma mantle concept was being established as a feasible means to solve the reactor exhaust problem [6]. Modelling the density profile with the RITM code has shown [28] that an essential ingredient for peaking of the density profile is the action of the radiative mantle on the anomalous inward pinch velocity $v_{\rm in}$, which is taken to have the form $v_{\rm in} = (1/2T_e)(dT_e/dr)D$, where D is the perpendicular particle diffusivity. This form may be justified by arguments of profile consistency, but more generally as a fundamental off-diagonal contribution of the transport matrix for fluctuation-driven particle transport [29].

It was also found to be essential in explaining the SOC-IOC transition in ASDEX [30].

The question of the degree of profile control by high-speed pellet injection, which translates to the question of the penetration of the pellet particles in high-density plasmas, thus becomes a crucial issue for the Ignitor project. Possible solutions for how to inject pellets from the high field side and facilitate pellet penetration must be investigated. Control of the plasma edge density during start-up and current flat top is also important, since it regulates the current penetration rate, as well as being related to the edge temperature.

C. Reversed magnetic shear modes

In the Ignitor device, transient effects can be exploited to reach ignition in ohmically heated plasmas. When the current ramp is considered, the plasma current increases by adding skin layers on the outer surface of the plasma column. The current penetration time based on neoclassical resistivity is comparable to the pulse length time scale. As a consequence, non-monotonic q profiles may form during the current ramp and during a significant fraction of the current flat top. Since ignition is expected to be achieved near the end of the current ramp, Ignitor is well suited for a Reversed Shear (RS) mode of operation [16] of the type observed in JET and in TFTR, among other devices. The PEP mode [31], which is the JET variant of the RS mode, was obtained with central ICRH and pellet injection. For these modes of operation, enhancement factors of $H \sim 2-3$ can be achieved. The physics of confinement enhancement for a non-monotonic q profile clearly has basic differences with that in a monotonic q profile. a gap in the density of the mode rational surfaces where q reaches its minimum value. This gap changes the plasma mode wave functions and reduces the drift wave growth rates. Comparing the guiding centre transport for fixed turbulence levels shows that reversed shear strongly reduces the resonance overlap parameter that controls the onset of chaotic diffusion. It is possible that reversed magnetic shear is only one factor in achieving reduced turbulence, with sheared plasma rotation and/or peaked profiles also playing important roles. Thus, although non-monotonic q profiles may occur spontaneously in Ignitor, the assistance of pellet injection and ICRH in accessing enhanced RS regimes of operation seems rather important.

D. H-modes

H modes of operation normally require the presence of a magnetic X-point and heating power levels above a threshold value. The L-H power threshold formula recommended by the ITER physics expert group is

$$P_{\mathrm{LH}}^{\mathrm{IPB99(5)}} = 3.24\bar{n}_{20}^{0.6} B^{0.75} R^{0.98} a^{0.81} m_{\mathrm{eff}}^{-1}.$$

If an H mode is accessed, the ITER ELMy H-mode scaling law predicts a confinement time according to the formula

$$\tau_E^{\mathrm{IPB98}} = 0.0562\kappa^{0.78} R^{1.97} A^{-0.58} I_p^{0.93} B_T^{0.15} n_e^{0.41} m_{\mathrm{eff}}^{0.19} P^{-0.69}.$$

For Ignitor, these formulae give a power threshold

$$P_{\mathrm{LH}}^{\mathrm{IPB98}}(\mathrm{Ignitor}) \approx 17\,\mathrm{MW},$$

easily exceeded by a combination of ohmic and ICRH or alpha heating, and a confinement time of

$$\tau_E^{\mathrm{IPB98}}(\mathrm{Ignitor}) \approx 1.78 \left(\frac{10.5\,\mathrm{MW}}{10.5\,\mathrm{MW} + P_\alpha(t)} \right)^{0.69} s \geq 0.78\,\mathrm{s}.$$

Again, the parameters of the example simulation in Table 3.2 of Ref. [3] have been used in these estimates. With these values for the confinement time, there should be no problem to reach ignition in Ignitor. Similar conclusions were reached by Johner [19].

Note that the Ignitor poloidal field system is capable of producing an X-point within the vacuum vessel, in which case Ignitor has sufficient power for a transition to H-mode confinement. However, the Ignitor first wall would not be capable of handling the localised heat fluxes associated with divertor operation. Thus, standard H-mode operation is not desirable in Ignitor.

On the other hand, H-mode quality plasmas have sometimes been obtained with the magnetic X-point outside the vacuum vessel. Indeed, H-modes have been observed in limiter configurations [32]. Furthermore, there is evidence from Alcator C-MOD of an enhanced L-mode with the magnetic X-point inside the vacuum vessel [33]. In this case, the plasma is prevented from entering the H-mode by reversing the toroidal magnetic field so to set the ∇B drift away from the single null divertor. For power thresholds well in excess of those that would be required for an L-H transition (if the ∇B drift were in the favourable direction), enhancement factors of 1.2-1.4 relative to L-mode have been obtained.

In all these cases, a more favourable, i.e. more uniform, heat flux distribution to the first wall may result. Thus, improved confinement assisted by X-point operation is a possibility worth exploring in Ignitor, although at present the available experimental information is insufficient to be able to rely on this.

E. Dimensional analysis of energy confinement

The dimensional analysis approach is widely used for ordinary fluids, for instance to analyse gas flow in a pipe or wind tunnel experiments. However, tokamak plasmas are much more complex objects than gas turbulent flow. This means that in practice this approach may be successful for tokamak plasmas provided a large number of appropriate dimensionless parameters are tracked simultaneously. The question then arises how many parameters may be required. If we use drift wave turbulence theory and simulations as a guide, then we can count that there are on the order of 15 dimensionless parameters to describe drift wave instabilities accurately. For example, one well-developed model of ITG turbulence called the IFS/PPPL model uses eight parameters for the hydrogenic working gas, 6 parameters for the low Z impurity (carbon in the TFTR calibrations of the model), and 2 parameters for the energetic ion component from neutral beam injection (these parameters and the complex heat diffusion coefficient and critical gradient formulas are given in Eqs. (69)-(77) of Ref. [24]). The databases are not sufficient to validate models with more than a few parameters, so the choice of key transport parameters becomes paramount. While there is a group of three dimensionless parameters, ρ_*, ν^* and β_N, that were widely used by the ITER design group, it is by no means clear that this truncated parameter set is sufficient to describe all the possible confinement states of a reactor grade plasma.

A correct application of the dimensional analysis approach would first require the experimental production of Ignitor-like discharges in existing tokamak devices, i.e., discharges with well-defined profiles and confinement modes of operation as foreseen in Ignitor. An attempt could then be made to extrapolate to actual Ignitor performance according to a truncated set of dimensionless parameters. However, in so doing, a judgment should be made as to whether the confinement mode realised in the experiment is also feasible for the projected Ignitor parameters.

7. Burn control

Development of burn control techniques is one of the major areas of investigation for Ignitor. Transport simulations indicate that precise time-dependent burn control through variation of the plasma density is difficult if the particle confinement time is longer than the energy confinement time, as would be expected for Ignitor. Much better control is possible by operating in a slightly sub-ignited state driven by a small amount of ICRH heating. This may be the preferred mode of operation for a reactor and would constitute an important physics demonstration on the path to a reactor that could be carried out in an ignition experiment.

Emergency methods of burn control include the firing of a *killer pellet* into the plasma to rapidly quench run-away ignition conditions and prevent or mitigate a possible disruption. This method has been adopted in Ignitor.

Fusion reactions with low rates of neutron production, utilising advanced fuels such as $D-^3$He or possibly D-D, may be more attractive than the D-T reaction, which produces 80% of its energy in 14 MeV neutrons. To begin exploring fusion with advanced fuels, a D-T burning plasma experiment at high field is much closer to the required parameters than present-day large size tokamaks. Ignitor would allow initial studies at the level of approximately 1 MW of power in charged particles from the $D-^3$He reaction cycle.

8. Conclusions

Ignitor is essentially an ignition physics experiment, which is projected to bring a long-awaited demonstration of the scientific feasibility of magnetic fusion and a possible way to study alpha particle and burning plasma issues. The main assets of Ignitor are its high magnetic field and low beta, which increase safety margins with respect to MHD instabilities, and its expected high purity plasma. With high ohmic heating and intense ICRH, it should be possible to access interesting regimes without relying on alpha particles and a highly irradiated environment. Thus, the physics exploration of confinement regimes and optimisation could go far before the difficult ignition runs.

Any tokamak experiment in unexplored plasma domains should possess sufficient versatility to counter unexpected adverse behaviour and to explore a wide range of operational scenarios. Ignitor flexibility lies in its ability to produce a wide range of plasma densities and currents and a variety of equilibrium configurations, including the capability of producing a magnetic X-point. The key to Ignitor success, however, relies on adequate density profile control with the assistance of a high-speed pellet injector and adequate power injection from an ICRH system, capable of sustaining the plasma temperature at relevant values should ohmic scenarios fall short due to poorer than expected confinement properties. Pellets and ICRH would also allow relevant burn control studies at slightly sub-ignited states.

Ignition in limiter discharges is a distinct possibility in Ignitor. However, this relies importantly on accessing improved confinement regimes with an enhancement factor of about 1.4 over predictions of confinement time based on L-mode scaling laws. Improved confinement regimes, such as the IOC, RI, P and S confinement modes, may be accessed in Ignitor, provided that peaked density profiles are produced. Again, pellet injection is expected to play an important role in this. Reversed Shear and PEP modes may also be realized, since non-monotonic q profiles may form during the transient approach to ignition. H-modes are not desirable in Ignitor, given the intolerable levels of localised heat flux to the first wall that would result. However an appropriate use of the magnetic X-point may provide some degree of enhancement in L-mode type of behaviour. It should be remarked, nevertheless, that transport in tokamak plasmas is not fully understood and that predictions about confinement performance should be taken with great caution.

III. ITER-FEAT PHYSICS ASSESSMENT

Goals and present status of the ITER-FEAT experimental proposal

As stated in Sec. I, the goals of the ITER-FEAT (Fusion Energy Advanced Tokamak) experiment are (1) to achieve extensive burn in an inductively driven plasma with a thermonuclear gain parameter $Q = (P_{\rm fus}/P_{\rm in})$ of order 10 for a range of operating scenarios and with a duration sufficient to achieve stationary conditions on the time scale characteristic of plasma processes; and (2) to demonstrate steady-state operation using non-inductive current drive with at least $Q \sim 5$. The technological goals of the ITER-FEAT device include the demonstration of integrated operation of technologies essential for a fusion reactor, the testing of components for a future reactor, and the testing of concepts for a tritium-breeding module.

The possibility of achieving ignition in ITER-FEAT is not excluded. However, this is viewed as problematic by the panel members, since it would require operation close to density, beta, and confinement limits simultaneously.

The objective of a reactor-scale thermonuclear experiment motivated the governments of the Four Parties – the European Union, Japan, the Russian Federation and the United States – to initiate, in 1987, the International Thermonuclear Experimental Reactor/Conceptual Design Activities (ITER/CDA). This phase, which was completed in 1990, led, in 1992, to the ITER Engineering Design Activities (ITER/EDA) Agreement, aimed at developing an integrated engineering design for a reactor scale tokamak facility that would achieve controlled ignition and extended burn. As envisioned by the Agreement, the ITER device would be the central element of an international, "one step to a reactor" strategy [34].

Because of the way the project was set up, the original ITER proposal (whose Final Design Report is referred to as ITER-FDR) [35]), enjoyed a broad base of participation. From the point of view of clarification of the relevant physics issue, a tremendous experimental and theoretical effort was set in motion, which involved a large fraction of the international scientific community. This effort culminated with the preparation of the ITER Physics Basis document [36]. The panel members are satisfied that the ITER physics assessment in this document represents the state of the art for knowledge of plasma physics issues applied to ITER-FDR.

As is well known, the US withdrew as a partner from the ITER project in 1998, partly due to cost considerations. This has forced the remaining three partners to reconsider the project, mainly to define a reduced-cost ITER device that would be affordable by the three partners alone [1]. This reduced cost version, ITER-FEAT, has been worked out very recently. The cost of ITER-FEAT (i.e., about 3.3 billion US$) is about half of the cost of the original ITER-FDR device. We may expect that most physics considerations that applied to ITER-FDR, detailed in the ITER Physics Basis Document, remain valid also for ITER-FEAT. However, some of the panelists expressed uneasiness about the fact that, since the ITER-FEAT proposal has been put on the table only very recently, not enough time has been allowed to reconsider the relevant physics issues for ITER-FEAT considering the reduced dimensions and modified objectives of the device. Nevertheless, the general impression was that the recent moves of the ITER project toward a reduced fusion technology emphasis and toward the objective of sustained burn at $Q = 10$, along with enhanced flexibility for exploiting advanced tokamak modes of operation, are appropriate steps toward reducing the cost and enhancing the scientific viability and flexibility of ITER.

The scientific assessment that follows is limited to the few problem areas for ITER-FEAT that emerged at the Paris meeting, namely: (1) Transport and confinement; (2) Resistive MHD stability; (3) Alpha particle issues; and (4) Thickness of the scrape-off layer.

1. Transport and confinement

The reference scenario for the operation of ITER-FEAT at $Q \sim 10$ is the ELMy H-mode. According to the ITERIPB98(y,2) scaling law, a confinement time of about 4 s is predicted, which together with the expected plasma density and temperature would be appropriate for the attainment of the declared goals with a good margin of confidence.

It is noted, however, that the projected ITER-FEAT plasma would differ from existing plasmas in large size devices in two important aspects:

(i) ITER-FEAT plasmas would operate close to the Greenwald density limit. In present experiments, a deterioration of confinement is often observed, starting from density values about 70% of the Greenwald density [37]. This is certainly an issue that deserves further attention.

(ii) ITER-FEAT plasma will have a relatively low toroidal rotation velocity as compared to present experiments, in view of the large size of the plasma. Velocity fields are known to quench turbulent fluctuations and to ameliorate MHD stability. Therefore caution is needed when extrapolating from present experimental data to a slowly rotating plasma in ITER.

2. Resistive MHD stability of ITER-FEAT

The ITER-FEAT reference scenario corresponds to plasmas operating at about half of the ideal MHD limit. While this appears as a significant margin with respect to ideal MHD macroscopic instabilities, the present understanding is that the actual beta limit is established by resistive MHD modes, which are driven in part by pressure gradients and neoclassical effects, most notably resistive internal kinks and neoclassical tearing modes.

A. Resistive internal kink and monster sawtooth oscillations

Sawtooth oscillations are expected to play an important role in ITER, not as much because of their direct impact on confinement, but because of possible couplings between sawteeth and other (non-ideal) MHD activity. Indeed, recent experimental evidence from DIII-D [38] suggests that sawteeth may induce seed islands for the growth of neo-classical tearing modes. Furthermore, sawteeth may couple to locked modes and edge perturbations, such as ELMs and external kink [39]. These couplings may effectively limit the achievable values of the parameter in ITER. On the other hand, recent ITER demonstration experiments on JET [40] and long pulse demonstration plasmas in other tokamaks [41, 42] indicate that sawtooth activity at ITER relevant dimensionless parameters is either absent or, if present, does not necessarily hinder the plasma performance. In addition, sawteeth can be controlled by current drive and auxiliary heating methods, which will also be operational in ITER.

The sawtooth crash is triggered by the instability of an internal kink mode when the value of the helical winding index for magnetic field lines, q, drops below unity in the central plasma region. It is worth recalling that the theoretical ideal MHD beta limit, β_{MHD}, assumes optimal profiles for which, in particular, $q \geq 1$ is satisfied everywhere. When q drops below unity, a new class of ideal MHD instabilities is predicted to occur with $\beta < \beta_{\mathrm{MHD}}$, internal kinks being one of them. However, it is clear from experiments that ideal MHD theory is not accurate in predicting the threshold for the onset of the sawtooth crash. For instance [43], sawtooth crashes can be suppressed for long periods in discharges where a significant population of high energy ions is present, even when the value of $q_0 \equiv q(0) <1$ is less than unity and the value of the thermal plasma poloidal beta, β_p, is well in excess of the threshold value for ideal internal kinks [44, 45].

A quantitative assessment of sawtooth stability in ITER-FDR was presented in Ref. [46]. We expect this analysis to remain essentially valid for the new design, ITER-FEAT. Based on this analysis, we may conclude that sawteeth will not hinder the performance of ITER-FEAT, as far as the approach to a burning plasma regime is considered. However, in the presence of fusion alpha particles, giant, monster-like sawteeth may appear, which may limit the duration of the good performance phase to times of the order of $10 - 50\,$s. On the other hand, feedback stabilisation methods can be used and should be investigated in present experiments.

More specifically: A fully penetrated q profile for a typical ITER reference discharge has its $q = 1$ radius at about half the plasma minor radius. This profile is likely to be unstable to internal kink modes. The situation, however, is not dissimilar from that of the ITER demonstration discharges mentioned above. In non-ignited ITER discharges, the sawtooth period is predicted to be about 1 s, i.e., a fraction of the expected confinement time, and the sawtooth amplitude is small [46]. The likely consequence of small amplitude, frequent sawtooth activity is to prevent full penetration of the current, i.e., to keep q on axis close to unity (perhaps $q_0 \approx 0.8$), and to keep the pressure profile relatively flat from the axis up to the sawtooth mixing radius. The ITER team has already allowed for this in transport simulations [46], with the finding that this situation does not degrade significantly the energy confinement time.

Of more concern would be monster-like sawtooth crashes, which could couple to edge activity (external kinks, ELMs etc.), causing a significant degradation of plasma confinement. Monster sawteeth may arise in ignited ITER discharges due to the presence of energetic alpha particles, which would play a role similar to that of fast minority ions produced by ICRH in JET. Fast ions are believed to be the cause of monster sawteeth in that machine. In this respect, several considerations can be made.

The period of monster sawteeth in ITER-FEAT is predicted to be on the order of (10-50 s). This figure is an extrapolation from JET, where the monster sawtooth period is a few seconds long, given that the ratio of the resistive diffusion times for the two machines is of order 10. Thus, the period between monster crashes in ITER is several confinement times, which should allow reaching ignition between monster sawtooth crashes, or maintaining ignition for a relatively long time before the onset of the first monster crash. For instance, if the discharge duration were limited to 50 s, the adverse consequences of monster crashes could be avoided.

Heating and current drive scenarios were proposed for ITER-FDR, such that the onset of the first (monster) sawtooth crash is delayed by *several* hundred seconds. This exploits the fact that the projected global current diffusion time in ITER-FDR was exceedingly long, of the order of $10^4\,$s, so that ignition can be reached well before the current is fully penetrated. Similar scenarios should be applicable to ITER-FEAT as well, although quantitative simulations to ascertain this for realistic power levels should be performed.

Heating and current drive schemes can also be used to *induce* frequent, small amplitude sawteeth, thereby avoiding the adverse effect of monster crashes. One possible scheme was demonstrated in JET with fast wave current drive. It is essential that dedicated experimental time be allotted in JET and other large-size devices to demonstrate the possibility of monster sawteeth at values of the resistive MHD dimensionless parameters that are relevant to ITER-FEAT.

B. Neoclassical tearing modes

While neoclassical tearing modes [47] usually grow too slowly to be of concern during the initial heating phase and approach to a burning plasma regime, on longer time scales (fractions of the diffusive skin time – for sustained burn regimes) these modes may cause confinement to deteriorate or perhaps cause a major disruption. Possible remedies would be to operate at lower poloidal beta, which however is not viable in ITER-FEAT, or to use feedback stabilisation [48]. Potential new issues for the smaller ρ_* (compared to present experiment) plasmas in ITER-FEAT are that neo-classical tearing mode thresholds may be lower and that more than one mode may appear simultaneously and complicate feedback stabilisation strategies. Since these modes apparently would not influence the approach to a burning plasma regime, but only potentially limit the duration or performance of a burning plasma regime, and since feedback stabilisation seems possible, the neo-classical tearing mode issue presently seems like a tractable one that needs to be addressed carefully, not one that is a substantial threat to the ITER-FEAT mission.

C. Alpha particle physics issues

The next step fusion experiment must have as one of its main scientific goals the study of alpha particle physics. This implies the production of a burning plasma, in which the alpha particles represent the dominant form of heating and the dominant fast ion population. ITER-FEAT has the potential for fulfilling these conditions; however the margin is small at $Q \sim 10$, to the extent that we find it necessary to raise the issue as an area that deserves more attention on the part of the fusion community.

Note that $Q = 10$ implies $P_\alpha = 2P_{\rm aux}$ (we neglect the ohmic power, which in ITER-FEAT is negligible compared with the auxiliary power). Thus, the alpha power would be twice the auxiliary power, which may fulfil (qualitatively) the notion of being the dominant form of heating. For values of Q below 10, the notion would become highly debatable.

A second point of concern is that high performance in ITER-FEAT would be reached at peak temperature values approaching 30 keV and densities not greater than 10^{20} particles/m^3. At these values of n and T, the alpha particle slowing-down time $\tau_{\rm sd}$ becomes comparable to the plasma confinement time. The implication is that, if the alpha confinement time is also of the same order as the thermal plasma confinement time, the alpha particles would be lost before they can transfer all their energy to the t hermal plasma, thus reducing the efficiency of alpha heating [49, 50].

A third point is that, if the auxiliary power is such as to produce significant fast ion populations, these may compete with the alphas in driving collective modes such as fishbones and Toroidal Alfvén Eigenmodes. It would be difficult, in that case, to separate the effect of the alpha particles from that of the other fast ions. This situation would arise with minority ion cyclotron heating (if the minority ion concentration is kept relatively small) and with energetic neutral beam heating. Of course, there are ICRH schemes that will not produce a significant fast ion population, such as resonant tritium absorption in a 50-50 D-T mixture. These are therefore highly recommended in order to avoid this potential difficulty.

4. The thickness of the scrape-off layer

This point was raised by Jean Jacquinot in Paris. His contribution would be welcome.

IV. CONCLUSIONS AND OPEN ISSUES

The panel members are convinced that magnetic fusion has made significant progress over the years and that, in spite of incomplete understanding, the world fusion program is now in a position to proceed to the design and construction of a burning plasma experiment. Here, a burning plasma is defined as a plasma where the fusion-produced alpha particles are the dominant form of heating. In quantitative terms, this implies values of alpha particle power, P_α, significantly exceeding the input power, which is the sum of ohmic and auxiliary heating powers, $P_{\rm in} = P_{\rm ohm} + P_{\rm aux}$. In terms of the thermonuclear gain parameter, $Q = P_{\rm fus}/P_{\rm in}$, where $P_{\rm fus} = 5P_\alpha$, a fusion burning plasma should have $Q \geq 10$, for periods that are long on the relevant plasma evolution time scales. The two experiments under consideration, Ignitor and ITER-FEAT, are both capable of reaching this target, with important differences in the objectives of the two experiments.

ITER design is the result of a broad base effort on the part of the fusion community, while Ignitor has not enjoyed such a broad base participation, which must be born in mind in any comparison. It is clear that successful operation of a plasma confinement experiment such as Ignitor would greatly benefit in exploring operational modes for eventual operation of a fusion proto-reactor device such as ITER.

A number of open issues apply to Ignitor and to ITER-FEAT. Hence in the following the two machines are dealt separately. These problems listed below are being addressed with high priority by the international community, but should not be used as an excuse to delay decisions to proceed with the final design and construction of either, or both, of the two experimental programs under consideration.

IGNITOR

Significant progress on the Ignitor concept has been made recently. Most notably, as compared with previous versions, the new Ignitor proposal has increased flexibility by incorporating adequate ICRH power levels and pellet injection in the design. These systems are considered to be essential in providing a degree of confidence for access to improved confinement regimes. In addition, the poloidal field system now has the capability of producing a variety of equilibrium configurations, including magnetic X-points.

The Ignitor design does not include a divertor. Consequently, the reference mode of operation is the L-mode. However, an Ignitor that performed no better than what one projects from the ITER89 L-mode scaling law would be disappointing as it would reach values of the thermonuclear gain parameter Q not larger than 3 [19]. On the other hand, if peaked density profiles in Ignitor can be produced and maintained, then ignition requires an enhancement between 1.2 and 1.5 relative to L-mode, depending on the degree of profile peakedness. It should be pointed out that profile peaking and enhanced confinement occur together in existing experiments, albeit together with impurity accumulation again degrading the performance. Tokamak operating regimes (other than H-mode) with enhancements of the required magnitude have been observed at least transiently, so that ignition in limiter configurations is a distinct possibility. However, producing and maintaining an adequate density profile in Ignitor for a sufficiently long time are still open issues which have to be faced owing to their critical importance for achieving the required performances. Although present experiments show that enhancement factors of the required magnitude are obtained in peaked density likmiter discharges, the empirical database for extrapolation to ignition needs to be developed.

The panel members note that several questions related to Ignitor performance are still open and require further studies and dedicated experimental campaigns in existing tokamaks. In particular, we offer the following recommendations:

(i) Develop a database for high field, compact (i.e., large B/R) experiments. We expect that ENEA could play a major role in this, with an aggressive Ignitor campaign on FTU. Unfortunately, FTU has a circular cross-section; therefore it cannot address specific questions related to the Ignitor geometry. Alcator C-MOD may also be in a position to contribute with dedicated experiments. Key questions are whether peaked profiles can be produced and maintained in these experiments, with particular attention to fueling and enhanced confinement possibilities, and whether high purity is maintained with a radiating mantle at the plasma edge, with particular attention to wall power handling issues. The access to improved confinement regimes of relevance to Ignitor should be investigated experimentally also in other devices such as JET.

(ii) Perform independent transport calculations with codes such as PRETOR and BALDUR in order to directly compare Ignitor and ITER-FEAT. Also, these codes should be tested against the available experimental database. Apply first-principle (e.g., gyrokinetic plasma turbulence) codes to investigate relevant transport physics issues. Existing transport codes in Europe and the US should be considered for these tasks.

(iii) Perform computational and experimental pellet penetration studies in Ignitor-relevant plasma conditions.

(iv) Perform comprehensive MHD stability studies, with special attention to major disruptions, which may limit high field operation at full current. Also, electromechanical effects of disruptions and the production of runaway electrons during disruptions as well as possibly during current ramps need be assessed.

(v) Proceed with designs of ICRF antennas and high-speed pellet injectors, in order to find out whether prospects for these systems are realistic.

(vi) Clarify diagnostic systems that can be implemented in the Ignitor machine.

(vii) Begin engineering system integration and detailed industrial cost assessment.

ITER-FEAT

The panel members noted that a significant international effort was set in place in order to clearly define the goals, the physics basis, and the engineering aspects, including costs, of the original ITER-FDR experimental proposal. Even though open problems remained, it was clear that these problems were being addressed with maximum priority by a large section of the international physics community.

The new proposal, ITER-FEAT, represents a scaled-down, reduced-cost version of ITER-FDR. The goals of ITER-FEAT are less ambitious than those of ITER-FDR. This new proposal has been put on the table very recently. It is tempting to say that the physics and engineering considerations that applied to the old proposal are now valid for the new one. However, adequate time should be allowed for a proper reassessment, including dedicated ITER demonstration experiments that take into account the modified geometry (different elongation, triangularity, etc.) of the new ITER as compared to the old one. It is also noted that confinement scaling laws and H-mode threshold scaling laws for ITER-FEAT have changed somewhat as compared to the ones used in the ITER Physics Basis document.

ITER-FEAT should reach the goal of $Q \sim 10$ in steady-state, ELMy H mode operation. The panel is confident that this objective during 400 sec of operation is within reach. Ignition is not precluded; however this requires an enhancement of 20% over ELMy H-mode scaling predictions and operation close to beta (MHD) and Greenwald density limits. Thus, the achievement of ignition in ITER-FEAT is viewed as problematic.

There are four problem areas that have been identified for ITER-FEAT. These must be dealt with in order to allow a proper judgment on the physics factors listed above:

(i) The consequences of the small scrape off layer thickness on divertor loading is an issue that must be considered carefully.

(ii) An experimental demonstration, in existing tokamak devices, on the possibility of avoiding or mitigating monster sawtooth crashes in preferred scenarios must be given, under experimental conditions (i.e. auxiliary power levels, q profiles, confinement regimes and values of relevant dimensionless parameters) as close as possible to those foreseen for ITER-FEAT. These experiments as well as others in the database should be used to calibrate codes based on sawtooth models. Predicted performance in scenarios which safely avoid sawteeth by profile control or by utilising the long skin time should be estimated. We point out that the typical time scale for the monster sawtooth period is estimated to be a few tens of seconds in ITER-FEAT. If the plasma performance is degraded after the first monster sawtooth crash, then the burning plasma phase of the discharges would be significantly limited in time.

(iii) Issues of MHD stability – in particular neoclassical tearing modes and the influence of low plasma toroidal rotation at which ITER is expected to operate – leading to reduced performance, should be explored.

(iv) Alpha particle physics issues. In particular, it would be desirable to operate in regimes where the alpha particle population is by far the dominant fast ion population, so to facilitate the identification of possible collective instabilities driven by the fusion product. At $Q = 10$ with intense auxiliary heating, this requires attention. In addition, regimes where the alpha particle slowing down time is comparable with the plasma confinement time should be avoided, as in these regimes the alphas may be lost before they transfer all their energy to the reacting plasma.

The panel members trust that these problems can be dealt with satisfactorily provided dedicated experimental time is allotted in large-size tokamak devices such as JET and appropriate numerical simulations are performed.

V. RECOMMENDATIONS

Recommendation 1: *In the near term, a vigorous program should be launched to acquire a degree of confidence on the remaining open issues (by appropriate R&D, dedicated experiments in existing tokamaks and numerical investigations) and complete the design of a* *compact, high-field tokamak ignition experiment.*

There is near-term need for a new tokamak experiment that can produce a burning plasma. For this purpose, the plasma regimes addressed by a compact high-field device cannot be adequately explored in existing machines. Also, a compact, high-field tokamak device has the potential for providing a path to the creation of a laboratory burning plasma whose temperature would exceed that required for nuclear ignition. Such an experiment would be on the frontier of plasma physics and thus have both risks and opportunities, a feature in common with other great physics experiments.

Recommendation 2: *The plasma performances required for reaching the stated objectives of ITER-FEAT rely on extrapolations from validated experimental databases. Panel members believe that the ITER-FEAT proposal will reach its main objectives. The remaining issues, although not critical, could reduce performances and deserve to be addressed.*

The objectives of ITER-FEAT are more far reaching than those of Ignitor, which explains the difference in cost and construction time of the two machines. The main physics target of ITER-FEAT is to achieve values of $Q \sim 10$ under steady state with respect to the relevant plasma evolution time scales, albeit only marginally with respect to the global current diffusion time scale. The machine would be pulsed, with discharges lasting approximately one to two global current diffusion times. According to its proponents, ignition in ITER-FEAT is not precluded. In addition, ITER aims at addressing reactor-relevant engineering issues. However, since it will take at least twelve years to produce the first burning plasma in ITER-FEAT, it has to be considered as a long-term fusion research objective.

By contrast, the high field, compact approach championed by Ignitor aims at providing the most expeditious and cost-effective path toward a first burning plasma physics experiment, where high values of Q in Ignitor would be reached transiently over time intervals lasting between five and ten energy confinement times. The main goal of Ignitor is to realise the experimental conditions where the energy deposited to the plasma by the fusion alpha particle can compensate for all forms of energy losses.

A major strategic question remains to be resolved. Will the world fusion program pursue an aggressive approach to fusion energy development – involving both science and technology in the next step, in order to reduce the number of steps to a reactor – by getting ITER construction underway? Or, will its next major step be focused on the key remaining fusion scientific objective, namely, that of demonstrating and exploring burning plasma physics?

Recommendation 3: *Establish an international burning plasma study group.*

A broader scientific dialogue should be encouraged, so as to elicit the best inputs from the world fusion community, aimed at developing common guidelines and methodologies.

It is proposed that this task be coordinated through an international study group, composed of a network of participating fusion laboratories and research centers. The purposes of this study group would be (i) to contribute to the physics basis of burning plasma experiments; (ii) to provide a stimulus for the performance of dedicated experiments relevant to burning plasma issues in existing tokamak facility; (iii) to help guarantee a cooperative international effort and the application of similar investigation methodologies for the various burning plasma experiments under consideration; (iv) to contribute to the training of a new generation of fusion scientists; and (v) to promote fusion physics as fundamental plasma science. The existence of this study group is subject to support by the European fusion program.

The setting up of an international study group is not motivated simply by the technical need to resolve burning plasma issues. We have to address the problem of the time gap between now and the first burning plasma experiment. The burning plasma study group will contribute to the task of preserving and transferring the relevant knowledge to young scientists, who will reach maturity when the next-step generation of fusion experiments will become a reality.

Acknowledgments

The authors would like to acknowledge useful discussions with several colleagues, in particular with P. Buratti, B. Coppi, M. Greenwald, J. Johner, M. Ottaviani, M. N. Rosenbluth, J. Van Dam, and A. Wootton.

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