BURNING PLASMA PHYSICS IN ITER

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1. Introduction

While much attention has been devoted to developing projections for ITER physics performance, it is illuminating to regard a reactor-scale tokamak as a new scientific facility and to inquire regarding the unique scientific contributions which one foresees it will contribute. For example, what physics can we anticipate investigating that is inaccessible to the current generation of tokamak facilities? Will there be new and important constraints imposed by technology? Will plasma-based design requirements exceed the capability of engineering to respond? The totality of answers to these questions comprises Burning Plasma Physics which can be generally defined as the physics which is dominant in reactor-scale device, with particular emphasis on those issues which cannot be investigated with contemporary tokamaks (and their evident upgrades). Of course, the proposition that there is important physics to be learned only from reactor scale devices implies that uncertainties exist in our projections for ITER plasma performance. From this perspective, the sources of uncertainties in plasma performance projections can be viewed as opportunities for research on ITER. In the final analysis, a judicious balance must be made between projection uncertainty and research opportunity in an acceptable and useful device design.

It is useful to divide Burning Plasma Physics into three elements: 1) Energetic Particle Physics, 2) Self-Heating and Thermal Stability, and 3) Reactor-Scale Plasma Physics. The last arises from the difference in physics engendered by the fact that a reactor must have a substantially larger magnetic field strength and size than present devices.

2. Energetic Particle Physics

Superficially, it would appear that the presence of energetic particles, specifically 3.5 MeV α-particles, is a key difference between present devices and a burning plasma. These particles have a centrally-peaked profile and have a characteristic velocity that exceeds the Alfvén velocity of the thermal plasma $M_\alpha V_{Alv}^2/2 \approx 1.3\,\mathrm{MeV}$. As such, they are capable of interacting with discrete stable MHD modes known as Alfvén Eigenmodes, and de stabilizing them through α-particle expansion free energy [1]. Since current tokamaks can also be heated by super-Alfvénic particles created by fast-wave ion-cyclotron heating or neutral beam injection, one must ask: How is it anticipated that energetic particles physics in reactor scale devices will differ from that in contemporary tokamaks, when the operational conditions are such that the characteristic velocity of the energetic particles exceeds the Alfvén velocity? First, it is evident that the fundamental drive is weaker in reactor scale devices because the relative fast particle concentration n_f/n is given by $n_f/n = (2T/E_f)\ (\tau_f/\tau_E)$, where τ_f is the fast particle slowing down time and E_f its characteristic energy. Based on representative ITER values [2], the relative concentration in a reactor scale device is approximately a factor-of-5 less than in present devices, and places ITER on the borderline of linear stability [1]. Some dissimilarities arise because of the isotropic velocity distribution of the α-particles differs from the anisotropic distributions arising from neutral injection or ion-cyclotron sources, but these can be accounted for by theory, which has proven a remarkably good guide [3]. The key difference of energetic particle physics in burning plasma devices derives from the third element of burning plasma physics — that the scale of the device is larger than that of present devices — and not just from the presence of super-Alfvénic particles. As Ref. [4] explains, the unstable toroidal mode numbers in reactors are expected to be appreciably higher because of the device size, and reactor scale devices may exhibit multi-mode Alfvén Eigenmode turbulence in contrast to the isolated modes found in present experiments [3].

3. Self-Heating and Thermal Stability

Self-heating via 3.5 MeV α-particles has the important consequence of transferring the majority of the α's energy to electrons, which eliminates the prospect of operational modes with $T_i >> T_e$ often found with neutral beam injection heating in current devices. Furthermore, in contrast to present devices heated by NBI, α-particle heating does not fuel the plasma core nor is it a source of angular momentum to induce the plasma rotation required for wall stabilization of external kink modes in candidate steady-state operational scenarios. Thus, this simple property constitutes a key constraint that precludes generalization of many advanced modes observed in present experiments to a reactor-scale device.

Controlled operation of an ignited fusion plasma requires that transport power loss from the core balance the self-heating from α-particles. The ITER ITER98H(y) confinement scaling relation can be recast as an expression for transport power loss as a function of density and temperature.

$$P_{loss} = \left(520\ \mathrm{MW}\right) \frac{n_{20}^{1.59}\, T_{keV}^{2.70}\, \kappa^{0.89}\, a_m^{0.27}}{B_T^{2.84}\, H_H^{2.70}\, A^{0.54}} \left(\frac{a}{R}\right)^{1.89} \left(\frac{a_m B_T}{I_{MA}}\right)^{2.62} \qquad (1)$$

The strong increase of transport losses with temperature is the factor that permits a stable thermal equilibrium in the presence of a thermonuclear reaction rate that is increasing (but less rapidly) with temperature. Ignited plasmas depend on control of core density to regulate fusion power. Since fusion power increases approximately as n^2T^2 while transport losses increase as $n^{1.6}T^{2.7}$, higher density will lead to higher fusion powers in thermal steady-state. For ignited operation, the relation is $P \propto n^{3.1}$. In actual operation, the constant H_H could change abruptly, reflecting a change in confinement mode or the creation of an internal transport barrier. In this case, the core density will have to respond to maintain a steady fusion power. Clearly, demonstration of thermal control will be an essential part of burning plasma physics. The characteristic time scales are the energy confinement time and the core density buildup time scale in response to peripheral plasma fueling. The latter time scale is not well characterized by an experimental database and, in all likelihood, depends on the fueling method.

For the case of steady-state operation of a tokamak, self-heating generalizes to self-generation of plasma (bootstrap) current via pressure gradients and the degree of self-consistency between the required current density profile and the bootstrap current density profile. The current density profile, in turn, controls internal transport coefficients and barriers which close the loop via their influence on pressure gradients and hence the bootstrap current. Two time scales exist in this system, the energy/density scale and the magnetic flux diffusion scale. Only with very long pulses appreciably exceeding flux diffusion times (~300 sec for ITER parameters) will definitive data regarding the prospects for steady-state operation of a reactor be available. A stable equilibrium solution is not guaranteed.

4. Reactor-scale plasma physics

The simple size, plasma current, and magnetic field strength of a tokamak device in which fusion power balances transport losses can change the relative importance of physics processes and can introduce qualitatively new physics which is negligible in present devices. Four illustrative examples have been chosen to convey the importance of size to the investigation of Burning Plasma Physics. We note that we have already argued that plasma scale is the dominant parameter regarding the difference in energetic-particle, Alfvén-eigenmode physics between present devices and a reactor.

Our first example concerns the scaling of the plasma density in ITER Demonstration Discharges relative to edge-plasma density limits as exemplified by the Greenwald value. The Greenwald-normalized density is defined by $n/n_{GR} \propto nRq/B$. This definition, combined with the constant β and ν^* scaling of $n \propto B^{4/3}R^{-1/3}$, indicates that if a reactor is at the Greenwald density value, as ITER parameters indicate, then Demonstration Discharges in present experiments at identical β and ν^* values must have densities which scale as $n/n_{GR} \propto B^{1/3}R^{2/3}$ and are appreciably below the Greenwald value. Thus, the integrated system of core confinement and edge density limit physics can only be directly investigated on a reactor-scale device.

The second illustration is again an example of the coupling between core and edge physics processes and involves changes in proximity to operational boundaries. Empirical scaling relations for two powers — the transport power loss from an H-mode discharge and the power flow through the separatrix required to maintain H-mode edge conditions — differ. For ITER Demonstration Discharges in present devices, which are prepared to have core values of β and ν^* identical to those anticipated for ITER, the transport power loss considerably exceeds the requisite H-mode power threshold, thereby assuring operation in H-mode. For an ITER-scale plasma, these two powers are roughly equal and questions arise as to whether operation near the threshold power boundary will realize the full benefits of H-mode confinement. Again, integrated experimental investigations of core-edge compatibility constitute an important part of Burning Plasma Physics.

The third illustration concerns the thermal quench phase of full-power ITER disruptions, in which the thermal energy content of the plasma is rapidly deposited onto the plasma facing components in the vicinity of the divertor strike points. The magnitude and short duration of the pulse will cause vaporization and melting (or sublimation) [5] of divertor strike-point material as well as a portion of the divertor chamber wall. This regime is not encountered in present tokamaks, where the thermal pulse associated with the thermal quench can be accommodated by the heat capacity of solid material. In the case of ITER, the vaporization will release carbon and tungsten into the subsequent current quench phase disruption, acting to cool this plasma and abet the formation of a runaway electron avalanche (see below). In this case, reactor-scale plasma physics is subject to a phenomenology which is unattainable in present devices.

Lastly, we turn to the avalanche theory of runaway electron generation [6] wherein a collision between a runaway electron and an ambient electron increases the energy of the ambient electron so that it too will runaway. The key results are that runaways will arise in the cold, current-quench phase of a disruption and that the number of avalanche e-foldings in runaway electron density is proportional to the plasma current and of order unity in present experiments. However, in an ITER-class device, the number of e-foldings $\gamma\tau = I_p(I_{Alf}\ln\Lambda)^{-1}$is large, making runaways generally negligible in present machines but of clear importance to reactors. Here $I_{Alf} = 4\pi m_e c(\mu_o e)^{-1} = 17$ kA.

5. Conclusions

Each of the many physics phenomena in tokamaks has its own scaling relation. It follows that in the transition from contemporary to reactor-scale tokamaks, the relative importance of various physics processes will change. In particular, a tokamak reactor will operate near the edge-density and H-mode operational limits. Experiments on ITER itself are needed to experimentally determine the integrated effect of differing core and edge physics scalings.

References

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