3.3.1.3. MHD Stability: Issues and Assessment

Summary MHD stability limits are not a fundamental obstacle to the burning-plasma missions of the three proposed machines. The base scenarios are stable to ideal MHD (except the m/n=1/1 mode); IGNITOR in general operates farther from stability limits. Central m/n=1/1 sawtooth instabilities and edge localized modes (in H-mode operation) are anticipated in all three devices, but are not expected to prevent access to the burning plasma regime.

Active control of MHD instabilities will most likely be required in ITER and FIRE. Both have plans for neoclassical tearing mode (NTM) control through localized current drive, although the lower hybrid current drive approach planned for FIRE has less experimental validation. The advanced tokamak scenarios require wall stabilization of the n=1 kink mode, using feedback stabilization alone (FIRE) or feedback plus neutral beam-driven rotation (ITER).

Burning plasmas offer a regime not accessible in existing experiments. IGNITOR, FIRE, and ITER would all yield important new MHD physics in self-heated plasmas with a large population of energetic alpha particles. FIRE and ITER would address additional stability issues in higher beta H-mode plasmas and in advanced tokamak plasmas with a largely self-generated current profile. ITER's long-pulse (pulse length ~ 10 current relaxation times) advanced tokamak scenarios have the ultimate goal of studying the stability of plasmas in near steady-state operation. Much of the MHD stability physics learned in a burning tokamak plasma should be applicable to a broad range of confinement concepts.

Introduction Any magnetic configuration meriting serious consideration for a fusion reactor must satisfy constraints imposed by MHD equilibrium and stability. It is widely appreciated that ideal MHD theory can be used as a foundation for use in the design of next step options. However, non-ideal MHD effects are also important and are not as well understood; the effect of resistivity, neoclassical physics, energetic particles, etc. on next step devices cannot be predicted with as much certainty as ideal MHD. Burning plasma experiments will improve our present understanding of MHD physics by extending the operational space of various non-ideal plasma parameters and by addressing the role of self-consistent interactions of energetic particles, alpha heating, profile evolution and plasma stability.

FIRE and ITER occupy roughly the same regimes of dimensionless parameters relevant to MHD stability: beta, safety factor, etc. (see Fig. 1) The primary distinction between them is size and pulse length. IGNITOR is in a quite different parameter regime due to its lower beta. ITER, FIRE, and IGNITOR all provide the opportunity to study MHD stability in plasmas with relaxed pressure profiles driven by self-heating, with ratios of pulse length to energy confinement time of ~100, 25, and 10, respectively. In the conventional high-Q scenarios, all three devices have pulse lengths that are about 1-2 current relaxation times; ITER's long-pulse advanced tokamak mode would have a fully relaxed current profile with a pulse length of ~10 current relaxation times.

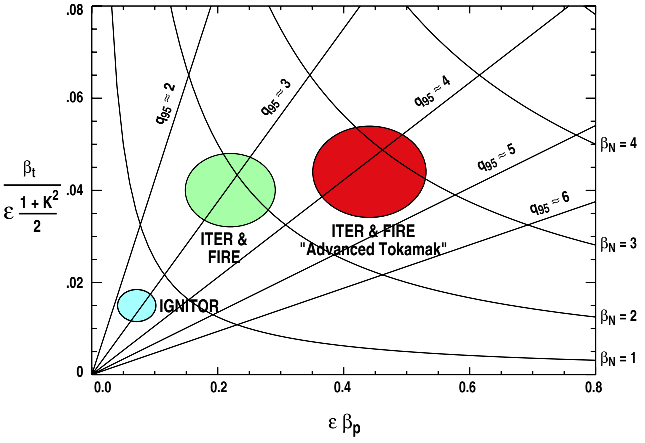

Fig. 1. Operating regimes of ITER, FIRE, and IGNITOR.

In order to provide a uniform assessment for the three burning plasma options, the MHD physics working group examined the important burning plasma physics issues in a number of topical areas. In each of these areas, we articulate the new physics to be learned from a burning plasma, assess the limitations imposed by MHD physics on the ability of the proposed experiments to achieve their full range of scientific goals, and identify the impact the physics to be learned will have on development of future tokamak and non-tokamak fusion devices. (Details of these studies can be found in the MHD Stability section of the Appendix to the Snowmass meeting report.)

Equilibria The MHD equilibria used in the detailed stability calculations are sample snapshot equilibria that were provided by the proponents for each experiment. For each of the devices, conventional tokamak scenarios were studied, as well as "advanced tokamak" (AT) scenarios for FIRE and ITER. In addition to reference cases for each device, equilibria with variations of the pressure and current density profiles were generated in order to perform sensitivity studies.

Ideal MHD For each of the equilibria generated, we assessed ideal MHD stability with respect to Mercier, ideal ballooning and n=1, 2, 3 internal and external kink modes using the stability codes DCON and PEST. All the equilibria were stable to high-n ballooning modes, unless q(0) was less than unity when the related Mercier criterion was violated. Generally, when a q=1 surface is present, ideal MHD instability to an m=1 internal kink is predicted for sufficiently high plasma $\varepsilon\beta_p$. Therefore, beta limits for ideal MHD modes must be assessed by varying q(0) in a range slightly below and slightly above unity. With q(0) greater than unity, the conventional tokamak scenarios for all three machine designs are generally well away from ideal stability limits. With q(0) less than unity, ITER and FIRE are ideally unstable to an m/n=1/1 instability, while IGNITOR by virtue of its lower beta, is stable to somewhat lower q(0). The implications of the unstable 1/1 mode are assessed in the following section. The AT scenarios for ITER and FIRE require wall stabilization for ideal stability.

m=1 stability A crucial issue in all three of the burning plasma experiments is the interaction of the alpha particles with m=1 modes, including the effect of an isotropic alpha particle population on the stability properties of the m=1 mode and the redistribution of the alpha population following a sawtooth crash. (Note that the interaction of alpha particles with MHD modes is also discussed in the Energetic Particles section of this report.) Present experiments in regimes relevant to ITER and FIRE [$\varepsilon\beta_p$~0.2, q_{95}~3.0] indicate that sawteeth do not have a significant direct effect on stored energy. Previous D-T experiments have found that alpha particles are redistributed at a sawtooth crash, but are not lost. More important is the potential impact of a large sawtooth in triggering MHD instabilities such as the neoclassical tearing mode, leading to locked modes or disruptions.

A linear theory of m=1 modes has been developed by Porcelli, et al. that accounts for the ideal MHD stability properties of the internal kink and kinetic effects coming from trapped thermal and alpha particle contributions. Marginal stability of the linear mode can be used to predict the onset of sawteeth. When this calculation is coupled with the TSC transport code, predictions for the sawtooth period and mixing radius can be made with either complete or partial reconnection assumptions. Simulations indicate that for all three devices, large-amplitude, long-period sawteeth will have little direct effect on the total stored energy or fusion power. We note that detailed predictions are complicated by uncertainties in the transport and reconnection models used, and in the precise mathematical structure of the ideal MHD δW used in the sawtooth simulations.

It is important that the experiments have methods for controlling sawteeth through current profile control, either by maintaining q(0) above unity or by stimulating small-amplitude sawteeth. Ion cyclotron heating (ICRH), electron cyclotron current drive (ECCD) and lower hybrid current drive (LHCD) can all be used for this purpose. All three proposed experiments provide good opportunities to investigate the m=1 instability and reconnection physics in the presence of an isotropic population of energetic alphas, a key issue for future reactors.

NTM stability A crucial issue for any long pulse, high temperature tokamak is the appearance of neoclassical tearing modes (NTMs). Empirical observations indicate that the critical beta for neoclassical tearing mode onset scales with normalized ion gyroradius $\rho^*=\rho_i/a$. Since this scaling is not favorable for larger plasma experiments and there are uncertainties in theoretically predicting the nonlinear island width threshold and seed island mechanisms, NTM physics is one of the key MHD science questions to be addressed in a burning plasma experiment. From analytic estimates, the anticipated saturated island widths produced by NTMs in ITER and FIRE (w/a ~ 0.1- 0.2 with poloidal beta ~ 0.5-1.0) are large enough to cause significant reduction of energy confinement and potentially lead to locked modes, loss of H-mode or disruption. The saturated island size is significantly smaller for IGNITOR because of the lower beta, and is not likely to pose a problem. NTMs are expected to be a less severe problem in AT scenarios that have q>2 everywhere and NTM-stabilizing negative magnetic shear in the core.

With the uncertainties in the theory and the anticipation that sawteeth will trigger large NTMs, techniques for controlling NTMs are crucial for ITER and FIRE. ITER plans to use localized ECCD, a technique that has proven successful in ASDEX-Upgrade, DIII-D, and JT-60U. FIRE has proposed using LHCD for NTM control, but this technique is less well validated experimentally. Additionally, methods for controlling the sawtooth amplitude (and hence the seed island mechanism) may be employed to avoid NTM excitation. FIRE and ITER offer opportunities to study NTM stability with ρ^* and magnetic Reynolds number S (important for reconnection physics) intermediate between existing machines and reactor-scale plasmas.

Wall Stabilization Advanced tokamak scenarios for FIRE and ITER need wall stabilization of the n=1 kink mode, since the anticipated broad current profiles, elevated q(0), and large β_N make these plasmas susceptible to ideal external kinks. In these cases, the plasma can be unstable to resistive wall modes in the presence of a wall with finite conductivity. Resistive wall modes can be stabilized in the presence of sufficient plasma flow and in principle can be controlled using active feedback. MARS modeling, using a sound wave damping model, predicts that stabilization can be achieved with rotation frequencies on the order of 0.5-1.5% of the Alfven frequency at rational surfaces (comparable to typical values of the critical rotation frequency observed in DIII-D), although precise predictions are sensitive to the plasma profiles. The estimated rotation driven by the planned neutral beam power for ITER and FIRE is marginal to sub-marginal, but there is sensitivity to the model used for momentum transport. RF-induced plasma rotation is too poorly understood to make accurate assessments.

The characteristic time constants of the passive stabilizer and conducting structures near feedback control coils differ in FIRE and ITER. The faster response of the anticipated FIRE feedback system indicates that stabilization approaching the ideal wall beta limit can be obtained. With the slower feedback coils of the ITER configuration, only a modest improvement of the beta above the no-wall beta limit can be realized. However, neutral beam-induced rotation would improve the stability further. Both FIRE and ITER will be able to address the resistive wall stability properties of a large burning plasma tokamak experiment in a reactor-relevant regime of little or no external torque.

Error fields and critical rotation Relatively small non-axisymmetric magnetic fields can slow plasma rotation and cause locked modes or produce seed islands for neoclassical tearing mode growth. Observationally, slowly rotating plasmas with resonant surfaces in the plasma are susceptible to the penetration of field errors with resonant magnetic helicities. This sensitivity rises as β approaches the n=1 ideal kink limits. Analytic estimates, based on field error penetration with rotation at the electron diamagnetic drift frequency, give upper limits on the amplitude of (2,1) resonant error fields to avoid low density locked modes during ohmic startup. These limits should be readily achievable. The error field limits become somewhat smaller for AT plasmas in ITER and FIRE in order to avoid drag from the "error field amplification" effect in AT plasmas above the no-wall stability limit, but should still be achievable with the planned correction coil systems and the possible addition of neutral beam-driven rotation. The three devices would provide an opportunity to investigate the plasma's sensitivity to error fields in a reactor-relevant regime of little or no external torque.

Pedestal stability Edge localized modes (ELMs) constitute an important concern for any burning plasma experiment relying on H-mode operation. Chiefly, large ELMs have a deleterious effect on divertor lifetime and can adversely impact high performance operation. In ITER and FIRE, the power loads to the divertor plates from the largest conceivable Type I ELMs are at the respective design limits. However, ELMs also have the beneficial effect of reducing impurity and ash accumulation and allow for steady state density control. Present theoretical efforts toward understanding edge MHD properties focus on intermediate-n ballooning/peeling modes, which may be destabilized by steep edge gradients and the associated edge bootstrap current. The limiting pedestal height predicted by MHD stability is in the range needed for good performance in all three devices, assuming the pedestal width is similar to present experiments ($\Delta/a \sim 0.03$). It is becoming clear that these instabilities play an important role in Type I ELM onset. Several tools are known for reducing Type I ELM size, creating a transition to smaller Type II ELMs, or eliminating ELMs – discharge shaping, counter-injection of neutral beams, variation of edge plasma collisionality, and shallow pellet injection. There is not sufficient understanding of the crucial physics parameters required to attain alternative, more benign regimes to permit scaling to burning plasma parameters. Nevertheless, it is expected that each of the experiments has sufficient flexibility in varying shape or edge conditions to avoid serious divertor problems.

Relation to other confinement concepts An important scientific outcome for the burning plasma experiment would be the generation of MHD science that could be applied to a broad range of magnetic fusion energy concepts. The physics of magnetic reconnection, wall stabilization, plasma rotation and neoclassical effects are directly relevant not only to future tokamaks but also to other concepts, including STs, stellarators and RFPs. Therefore, it is important that MHD theory and modeling efforts be closely coupled to burning plasma activities. In order to facilitate detailed comparisons between theory and experiment, a burning plasma experiment must be well diagnosed. Critical diagnostics include external magnetic field measurements plus profile measurements of plasma density, temperature, rotation and current density for equilibrium reconstruction; and fluctuation measurements of external magnetic field and internal profiles to determine the toroidal, poloidal, and radial mode structure. Validation of theories and numerical models is the means by which a burning plasma experiment can benefit a broad range of fusion concepts, and perhaps plasma science applications beyond fusion.