3.1.1.3. MHD science in a burning plasma

A burning plasma represents a new and unique regime for magnetically confined plasmas, allowing us to investigate scientific questions related to the stability of a complex, self-organized thermonuclear system and the interaction of MHD modes with an isotropic population of fast ions. While not requiring self-heating, a burning plasma-scale experiment will allow us to investigate the dependence of macroscopic stability on plasma size, and the importance of key kinetic effects in plasmas wih very low collisionality, small gyroradius, and high Lundquist number.

The production and control of plasma in a self-consistent state with strong self-heating and self-generated current, and the crucial role of MHD stability in determining that state, can only be investigated in a "burning plasma" experiment. In a plasma that is largely self-sustained through alpha heating and bootstrap current drive, the internal profiles of pressure, current density, and rotation will be determined primarily by internal processes that are linked in a complex, nonlinear way. In addition, these profiles can all be modified by MHD instabilities, whose thresholds in turn depend on the profiles. Systems for avoiding or controlling instabilities through profile control or direct feedback stabilization may act differently in such a tightly coupled system. All these interactions are difficult to simulate in present inductively driven, externally heated tokamaks.

The effects of energetic alpha particles on MHD modes, and of MHD modes on confinement of alpha particles, also require a burning plasma for complete study. In conventional tokamak operation, the physics of the $m = 1$ internal kink mode (sawtooth instability) plays a central role since it can lead to a large-scale redistribution of the plasma pressure and hence of the fusion reaction profile. Theoretical work indicates that MeV alpha particles can provide stabilizing mechanisms for the sawtooth. However, a complete understanding of the alpha particle, q profile evolution and sawtooth instability interaction has not been established experimentally. Only a burning plasma experiment allows a realistic study of the nonlinear interaction between a population of fast ions with an isotropic velocity distribution, the MHD instabilities that it may drive, and the redistribution of fast ions that may result.

Issues related to the scaling of non-ideal MHD stability with plasma size require a high beta plasma with larger radius and/or magnetic field than existing experiments, although not necessarily a burning plasma. For example, present experiments are consistent with an unfavorable scaling of the neoclassical tearing mode (NTM) threshold island size versus normalized ion gyroradius $\rho_i{}^*=\rho_i/a\sim(aB)^{-1}$. However, uncertainties about the dependence on collisionality and a predicted favorable scaling of the seed island amplitude with magnetic Reynolds number S make the NTM stability threshold in a tokamak reactor difficult to predict with confidence. Edge pedestals with low collisionality and small $\rho_i{}^*$ are also a regime not easily accessible in present experiments. A burning plasma experiment should bridge the gap between existing tokamaks with aB~1-4 m-T and a reactor prototype which may have aB~16, and provide crucial new understanding of NTM physics.

A burning plasma experiment that lies between existing and reactor-size plasmas, as measured by size scaling parameters such as aB, can address most or all of the macroscopic stability issues that will be present in a reactor-size plasma, and will provide a strong basis for extrapolation in scale of stability limits, alpha-particle effects, and integration issues. Much of the underlying physics should transfer to burning plasma physics in other magnetic configurations such as the ST stellarator, and RFP. Extrapolations in scale and especially in configuration require that the burning plasma experiment be well-diagnosed, in order to provide detailed experimental validation of theoretical and numerical models. MHD science with predictive capability is needed to impact the development of any magnetic configuration, tokamak or other, in a complete and reliable way.

A burning-plasma tokamak experiment also has the potential to make significant contributions to plasma stability science in fields outside of fusion energy, through expanded understanding and validation of non-ideal MHD physics (incorporating effects such as resistivity, FLR, energetic ions, plasma flow, etc.). Validation of the underlying physics in laboratory experiments will increase the confidence in applying these models in settings (extraterrestrial plasmas, for example) where controlled experiments and detailed internal measurements are more difficult.