Summary Report of the
Workshop on Burning Plasma Science: Exploring the Fusion Science Frontier
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(III) Macrostability in a Burning Plasma

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1) What are the compelling scientific issues which could be addressed by a burning plasma experimental facility?

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. Additionally, while not requiring self-heating, a burning plasma-scale experiment will allow us to investigate the dependence of macroscopic stability on plasma size. These issues are discussed in more detail below.

2) Identify those burning plasma scientific issues which are inaccessible for study in existing or near-term non-burning plasma experiments.

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 (in long-pulse scenarios) a large component of bootstrap current drive, the internal profiles of pressure, current density, and rotation will be determined primarily by internal processes which are linked in a complex way. For example, the pressure profile is determined by alpha heating and transport, while the alpha heating profile depends on the pressure profile, and the current density profile depends on the pressure profile through the bootstrap current. This is a qualitatively different regime from present experiments where the profiles are determined by inductively driven current and auxiliary heating sources (neutral beams and rf), and are thus subject to some degree of individual modification. The pressure, current density, and rotation profiles can all be modified by MHD instabilities, whose thresholds in turn depend on the profiles. Systems for avoiding MHD instabilities through profile control or direct feedback stabilization may act differently in such a tightly coupled system.

A clear need exists for self-consistent simulations including transport, stability, and systems for profile control, in order to predict the behavior of a burning plasma and identify the possible dynamics of such a complex system. However, the tightly coupled, non-linear nature of the system suggests that its state could be sensitive to uncertainties in modeling any one of these elements; therefore an experiment is the only way to be certain of understanding its behavior. To fully address these issues of self-organization, the pulse length must much longer than the energy confinement time and at least a few times longer than the current profile relaxation time.

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. The most important unknown physics is arguably the interaction of the m=1 internal kink mode (sawtooth instability) with alpha particles. Previous experiments have shown that rf-heated MeV ions with a strongly anisotropic velocity space distribution can have a strong effect on the sawtooth instability, leading ultimately to a giant sawtooth with a large-scale redistribution of the plasma pressure and hence of the fusion reaction profile. In a plasma with low safety factor, the giant sawtooth may trigger a neoclassical tearing mode or a disruption. Theoretical work indicates that MeV alpha particles may also lead to transient sawtooth stabilization; however, this prediction cannot be tested in existing experiments as available auxiliary heating schemes are not capable of producing MeV particles with nearly isotropic distributions. Energetic alpha particles will also lead to kinetic modifications of high-n ballooning modes. While MeV ions can have a stabilizing effect on MHD modes in moderately shaped, low beta plasma, fast ions may be destabilizing if strong discharge shaping at high beta leads to a reversal of the ion drift orbits. Fast ion-driven instabilities including Alfven eigenmodes and energetic particle modes will also be important in the presence of a large population of energetic alpha particles. All of these issues may be studied to some extent with beam-injected or RF-heated fast ions in existing experiments. But a burning plasma experiment is required in order to study 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. These issues are discussed further in the summary of the Energetic Alpha-Particle Physics group.

Although ideal MHD stability limits are readily calculated, non-ideal instability thresholds represent nonlinear behavior that is less well understood and depends on the plasma size and temperature. Issues related to the scaling of MHD stability with plasma size require a high beta plasma with larger radius and/or magnetic field than existing experiments, but not necessarily a burning plasma. Qualitatively new physics results will be obtained from the investigation of neoclassical tearing modes (NTM) in a burning plasma-scale device. Present experiments are consistent with a predicted unfavorable scaling of the NTM threshold island size with the normalized ion gyroradius $\rho_i^*=\rho_i/a$. 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 burning plasma difficult to predict with confidence. At constant plasma temperature and density, S scales with plasma minor radius a and magnetic field strength B as S~aB, while $\rho_i^*\sim(aB)^{-1}$. A burning plasma experiment should bridge the gap between existing tokamaks (aB~1-4 m-T) and a reactor prototype such as ITER-EDA (aB~16).

New physics may also be observed during disruptions as the plasma size increases. For example, the theoretically predicted knock-on avalanche process for runaway electrons during a disruption has not been clearly observed to date, but could become important in larger plasmas. It is predicted to produce a runaway current gain of about 10^2 in present 2 MA tokamaks, but 10^6-10^7 in a 5 MA burning plasma. Disruption issues are discussed in more detail in the summary of the Boundary Science group.

3) What is the present physics basis and confidence level in achieving burning plasma conditions? In particular, how have recent developments in theory and experiment affected our confidence in achieving burning plasma conditions?

The present understanding of MHD stability limits is sufficient to design a burning plasma experiment. Ideal MHD provides a well-characterized upper limit to plasma stability. We have a high degree of confidence in the stability boundaries predicted by ideal MHD theory (given the pressure and current density profiles), and these form a credible foundation for the design of next-step devices. The nonlinear evolution of the instabilities is not as well understood, but often this is less important since the aim is to avoid the linear instability threshold. A notable exception to the success of ideal MHD in predicting stability limits is the m=1 internal kink. However, the fundamental MHD stability limits are understood well enough to avoid them at least transiently in achieving a burning plasma state. For example, the m=1 kink can be avoided transiently by creating plasmas with central safety factor q(0)>1, and for longer pulses through current profile control to maintain the elevated central q.

The greatest uncertainty regarding stability limits lies in the threshold for neoclassical tearing modes, as discussed above. However, experiment and theory suggest that NTMs with higher mode numbers ($n \geq 3$ and perhaps even $n=2$) can be tolerated with only a small degradation of energy confinement. The larger-scale $n=1$ NTMs should be avoidable through current profile control or direct stabilization with localized current drive.

Recent advances in profile control and active control of MHD instabilities add to the confidence in avoiding or suppressing instabilities for longer pulses. Current profile modification with localized non-inductive current drive (electron cyclotron current drive and lower hybrid current drive) has been demonstrated on many tokamaks including DIII-D, Tore Supra, and Asdex-Upgrade. Theoretical foundations have been developed for active control of NTMs through localized current drive, and for the suppression of resistive wall modes above the no-wall beta limit using feedback-controlled coils. Although still at an early stage of development, there have been promising experimental demonstrations of active stabilization of NTMs in Asdex-Upgrade, DIII-D, and JT-60U, and of RWMs in HBT-EP and DIII-D.

Other recent experimental and theoretical developments support the expectation that MHD instabilities can be avoided in achieving a burning plasma state. Operation for several seconds very near stability limits has been demonstrated in DIII-D through the use of feedback control of plasma pressure. Although much more work is needed, initial calculations of self-consistent burning plasma scenarios for devices such as FIRE add confidence in the feasibility of a burning plasma experiment. Nonlinear 3D fluid-based codes such as M3D and NIMROD incorporate much stability physics beyond ideal MHD and will provide guidance in predicting the actual stability limits in future devices; benchmarking of these codes against experiments is beginning. Hybrid codes including both MHD and energetic particle effects have improved our understanding of alpha particle interactions with MHD instabilities.

4) How comprehensively can these burning plasma science issues be addressed establishing a firm basis for extrapolation in scale and magnetic configuration?

In terms of the new physics arising from self-heating and collective alpha particle effects, a burning plasma experiment can address most or all of the macroscopic stability issues that will be present in a reactor-size plasma. An experiment that lies between existing and reactor-size plasmas, as measured by size scaling parameters such as aB or $BR^{5/4}$, will provide a very strong basis for extrapolation in scale of stability limits, alpha-particle effects, and integration issues. A burning plasma tokamak experiment will also, to a lesser extent, allow extrapolation to burning plasma physics in other magnetic configurations such as the ST and stellarator – although details will differ, much of the underlying physics should transfer. In configurations such as the RFP, which differ more from the tokamak in q-profile, degree of self-organization by MHD relaxation, etc., extrapolation is more difficult but “first principles” understanding should still be transferable.

Extrapolations in scale and especially in configuration require a well-diagnosed burning plasma experiment, at least at the level of diagnostic measurements in today’s large tokamaks. Detailed experimental validation of theoretical and numerical models is needed in order to have confidence in any extrapolation based on those models.

5) Are there compelling scientific issues outside of fusion energy which can be addressed by a burning plasma experimental facility?

A burning-plasma tokamak experiment 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.). Modeling of extraterrestrial plasmas frequently relies on resistive MHD models. It has become apparent that in order to completely understand the macroscopic properties of magnetized plasmas, the inclusion of non-ideal and kinetic effects is crucial. The magnetic confinement community can play a leading role in developing deeper physics understanding of the role of non-ideal MHD effects in the macroscopic fluid properties of plasmas. Validation of the underlying physics in laboratory experiments will increase the confidence in applying these models in settings where controlled experiments and detailed internal measurements are more difficult. As discussed above, a burning plasma experiment will extend the validation of non-ideal MHD physics to regimes with isotropic fast ions, low ρ_i*, and large S, that are not available in present experiments.