Workshop on Burning Plasma Science: Exploring the Fusion Science Frontier

11-13 December 2000, Austin, TX

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Executive Summary

Stimulated by the growing interest in the science of burning plasmas coming out of discussions at the 1999 Fusion Summer Study at Snowmass, the University Fusion Association (UFA) sponsored this Workshop on Burning Plasma Science, held 11-13 December 2000, in Austin, TX, to provide a forum for in-depth community discussion of the critical scientific issues connected with burning plasmas. Discussions were focused around five questions: (1) What are the compelling scientific issues which could be addressed by a burning plasma experimental facility? (2) Identify those burning plasma scientific issues which are inaccessible for study in existing or near-term non-burning plasma experiments. (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? (4) How comprehensively can these burning plasma science issues be addressed establishing a firm basis for extrapolation in scale and magnetic configuration? (5) Are there compelling scientific issues outside of fusion energy which can be addressed by a burning plasma experimental facility?

Discussions of the first two questions seek to identify the scientific issues which would be at the frontier of fusion science and form the primary scientific basis for proceeding with a new experiment capable of studying a self-heated fusion plasma. Individually, all of the critical elements which would be advanced by a next-step burning plasma facility in the areas of energetic alpha-particles, transport, stability, and plasma boundary physics are under study in the present generation of deuterium plasma experiments in the US and abroad. While in a next-step burning plasma experiment there clearly would be advances in some of the critical scaling parameters (*e.g.* ρ^*) and for the first time a fusion self-heated deuterium-tritium plasma would be available for study, significant progress in these critical elements will also be made in the ongoing research in present deuterium plasma experimental facilities (with anticipated upgrades). A decision by the community to take a major step with a new facility will only be possible with a clear articulation of the unique contributions to fusion science that such a next-step burning plasma experiment will make possible.

Towards this end, we focused attention at this workshop on the strong, non-linear coupling that will occur in a self-heated fusion plasma between the plasma pressure profile driven bootstrap current, confinement improvement due to turbulence suppression, MHD stability, fusion alpha-particles, and boundary plasma behavior. While each of these phenomena has been discovered and/or significantly advanced in the past 10 years in our present experimental facilities, the combination of these in the environment of a burning plasma presents a qualitatively new plasma physics regime. An outstanding challenge to the field is to more clearly identify the new phenomena we can expect in this strong coupling regime, and to sharpen our picture of the behavior expected in such a system. In particular, if a burning plasma experiment were built, what flexibility and measurement capability would be essential in order to advance our understanding of the underlying plasma physics of stability and turbulent transport, as well to test our understanding of this strong coupling regime?

The importance of exploring a burning plasma for the development of fusion energy has long been recognized and extrapolation of our continually improving understanding has led over the last 15 years to a series of device designs to produce a burning plasma. In discussing the third question posed to the workshop, we focused on how recent advances in experiment and theory have affected our confidence in achieving burning plasma conditions. Based on our present level of plasma confinement understanding, there are no known show-stoppers for achieving the generic burning plasma regime in a tokamak. Numerical simulations are rapidly improving and experimental tests on existing devices continues to improve our confidence. Ideal MHD provides an upper limit to plasma stability, and forms a credible foundation for the design of next-step devices. We have a high degree of confidence in the stability boundaries predicted by ideal MHD theory. However, advanced tokamak scenarios (self-consistent stable, steady-state, bootstrap current sustained equilibria) have not yet been clearly demonstrated on existing experiments. Important further work on internal transport barriers and the edge temperature pedestal remains to be done. In particular, the low edge density required in an advanced tokamak may be incompatible with high density divertor operation.

While the most advanced fusion configuration is the tokamak, it is critical that a broad range of configurations continue to be explored in fusion research to advance plasma physics and fusion science on a broad front, and to provide information needed to ultimately optimize the design of an economic and environmentally attractive fusion power source. As a part of this broad program in the United States whose goal is to establish the scientific basis for fusion energy, it is important that advances made in fusion science with a burning plasma experiment based on the tokamak configuration, provide a firm basis for extrapolation not only for the tokamak configuration but more generally across the broad family of toroidal magnetic concepts and even to non-toroidal configurations. It is clear historically that virtually all of the theory, modeling tools, diagnostic advances, experimental techniques, and experimental discoveries made using the tokamak configuration have found application in research on other fusion configurations. Those toroidal magnetic configurations closest to the tokamak like the spherical torus, stellarator, spheromak and reversed field pinch, have been best able to build on advances made in the tokamak. Advances made in collective alpha particle effects, transport, stability, plasma control, and boundary science through the study of a burning plasma in a tokamak configuration would also be quite relevant to these configurations. However, the details of the behavior of the strong non-linearly coupled system between the plasma pressure profile driven bootstrap current, confinement improvement due to turbulence suppression, MHD stability, and boundary plasma behavior in a burning plasma in a tokamak will likely be configuration specific.

Since a next-step burning plasma facility would be a significant addition to our capability to explore new regimes of plasma physics, it is important to consider how this facility could also make a contribution to making advances important to the broader scientific community. At this workshop several possible areas of study which are inaccessible for study in existing non-burning experiments were discussed including alpha physics in the solar wind, collisionless reconnection in magnetospheric and solar plasmas, plasma effects on nuclear cross-sections important for nuclear astrophysics, and thermonuclear deflagration flame phenomena important for supernovae dynamics. Many of these areas are relatively unexplored for burning plasma regime accessible in a tokamak. Further work is needed to substantiate the possibility of significant scientific contribution as designs of candidate next-step burning plasma facilities are evaluated.

I. Energetic Alpha-Particle Physics Issues for a Burning Plasma

Kinetic-MHD phenomena due to collective effects driven by energetic alpha particles, along with their associated transport, are deep scientific challenges with important implications for reactor performance, but neither fully able to be studied in current magnetic fusion experiments nor yet adequately modeled to yield accurate predictions. There was general agreement that a burning plasma experiment would access a regime of dimensionless alpha physics parameters (Alfvénic Mach number, system size, distribution isotropy) that are difficult to achieve simultaneously in existing devices and will be an important new area for scientific investigation.

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

One category (intrinsic issues) concerns phenomena specific to alpha particle behavior—e.g., alpha-driven instabilities, anomalous loss of alphas, and alpha particle control. The second category (extrinsic issues) concerns how alpha dynamics can affect other phenomena—such as thermal confinement, MHD stability, wall loading, and helium ash accumulation. Although these two broad categories are related, intrinsic issues adopt a "reductionist" perspective in which individual phenomena are analyzed in isolation, whereas extrinsic issues emphasize the complex interaction among different phenomena.

Intrinsic issues

(a) <u>Size scaling and new transport physics</u>: The large size of a burning plasma compared to the alpha particle Larmor radius may lead to a "sea" of resonantly overlapping unstable modes, such as the various shear Alfvén eigenmodes that are known to be excited by the free expansion energy of alpha particles. Experiments to date exhibit alpha transport due to a few global modes—in contrast to the situation of multiple overlapping localized modes, where significant redistribution and transport of alpha particles could occur through resonant coupling. For instance, a subset of modes can flatten the alpha profile over the region of overlapping resonances and trigger a "domino" avalanche that sweeps particles outward. Thus, burning plasmas may exhibit fundamentally new transport dynamics for alpha loss.

(b) <u>Alpha source and energetic particle modes</u>: A significant issue is the extent to which the excitation of Alfvén instabilities will affect the alpha heating profile. For example, as the instabilities evolve nonlinearly above threshold, they could lead to a "stiff" radial distribution such that the alpha heating profile is regulated by the modes. This issue may depend on the behavior of so-called Energetic Particle Modes—resonant modes (not eigenmodes) driven by and existing only in the presence of fast particles. Their properties can change so as to remain in resonance with interacting particles, thus leading to frequency chirping, mode structure evolution, and bursts of convectively lost particles. The excitation of such modes is strongest when the magnetic shear is weak, as in advanced tokamak operation, and requires sufficiently high alpha particle pressure. An open question for a burning plasma experiment is whether the isotropy of the alphas will weaken the strong non-linear response observed in present experiments from passing-fast ion excitation of low-n global Alfvén modes. The passing-particle component of the alpha distribution is similarly expected to interact mostly with Alfvén instabilities (high-n) in a burning plasma.

(c) Phase space engineering and alpha particle control: The tailoring of phase space so as to manipulate the distribution of alpha particles in a burning plasma (e.g., bucket transport, alpha channeling) is an intriguing basic science issue for study in a burning plasma experiment, although not yet mature enough for application.

Extrinsic issues

(a) Effects of alpha particles on macro-stability: Depending on plasma parameters, energetic particles can either stabilize or destabilize ideal MHD modes—as, for example, in the case of the m=1/n=1 mode, with “sawtooth” stabilization and/or “fishbone” excitation. In a burning plasma experiment, trapped alpha particles could stabilize the m=1 mode. Eventually, however, this terminates in a monster sawtooth event, with deleterious reduction in stored energy and alpha particle heating, increase in wall loading, and even disruptions. The isotropy of alpha particles, the large ratio of alpha precessional frequency to plasma diamagnetic frequency, and the long resistive diffusion time (compared to the energy confinement time) expected in a burning plasma experiment represent a new physics regime for studying m=1 mode dynamics. Alpha particles might also affect neoclassical-type MHD modes. Higher-mode-number instabilities such as the kinetic ballooning modes are also important since they can be excited below the ideal MHD threshold by trapped alpha particles and have the potential to enhance thermal transport (“soft beta limit”) near the ballooning limit. In a large-scale burning plasma experiment, multiple high-n kinetic ballooning modes may be present, in contrast to the observation of only a few low-n modes in experiments to date. The behavior of the plasma near the ballooning limit may thus be affected by size scaling (high-n modes) and the presence of alphas.

(b) Regulation of central beta: Recent experiments have found that Alfvén eigenmodes regulate the central fast-ion beta in sawtooth-stabilized plasmas. An interesting question for a burning plasma experiment, then, is whether alpha-driven instabilities in the plasma core could effectively prevent the onset of the giant sawtooth. A related issue is whether sawtooth behavior and central alpha heating could be controlled by preferentially manipulating the excitation of the Alfven modes.

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

Of the issues mentioned in the preceding response to the first question, those that are least accessible are avalanche-enhanced transport with sea of overlapping modes, and the effect of an intense isotropic alpha particle source on growth, damping, mode structure, and saturation. The former is primarily a size scaling issue. The latter, although unique to burning plasmas, is expected to modify features, but may not introduce new phenomena (although this should be checked). The interactive coupling of alpha phenomena to self-heating, macrostability, edge physics and plasma confinement will also be a major new area for scientific investigation in a burning plasma.

Addressing the following action items would help clarify the issues that can be uniquely accessed in a burning plasma experiment:

- Develop improved theoretical and computational tools for nonlinear, self-consistent simulations of transport with a sea of resonantly overlapping Alfvén modes. Evaluate whether anticipated tritium experiments in the JET-Upgrade facility could access this regime. Explore the threshold for resonance overlap, e.g., by means of auxiliary heating experiments.
- Calculate the effect of intense auxiliary heating on the linear drive and background damping of Alfvén modes in a burning plasma for different levels of self heating in order to determine the conditions for observing instabilities excited by alpha particles.

- Evaluate the non-linear consequences of alpha driven instabilities on other plasma phenomena, by means of experiments on existing facilities and simulations, in order to elucidate clearly the alpha integration issues in a burning plasma.
- Continue to study energetic particle modes in order to improve the understanding of observations in current experiments and develop predictions for burning plasmas.

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?

In general, energetic particles have successfully heated toroidal plasmas in a variety of configurations with different heating methods and ion species. Also, alpha particles have been studied in positive-shear hot-ion-mode plasmas and these studies have confirmed the good confinement of supra-thermal particles and the efficient transfer of energy to the background plasma in the absence of collective phenomena and significant prompt loss. However, our understanding of collective alpha phenomena and associated alpha transport is far from complete, and our ability to predict the non-linear consequences of various instabilities in different burning plasma regimes needs further development.

Alpha behavior can be predicted with high confidence for classical transfer of alpha particle energy to the background plasma and for ripple loss—at least in regimes with positive magnetic shear and no Alfvén mode activity. Anomalous prompt loss of beam ions in advanced operating regimes and enhanced loss of energetic particles induced by Alfvén eigenmodes (especially in advanced operating regimes) need further study. Efficient alpha heating and low alpha particle loss to the first wall should be achievable in standard ELMy H-mode discharges.

Of moderate confidence is our ability to predict the threshold conditions for Alfvén eigenmodes in positive-shear, low-beta plasmas. Recent analysis suggests these modes may be marginally stable in a burning plasma, but subtle profile variations—e.g., density peaking or reduced magnetic shear—can readily lead to instability.

Areas where we have low predictive confidence are multi-mode collective alpha dynamics and transport; the stability and saturation of energetic particle modes; and the relative effect of these modes on alpha loss compared to that of toroidicity-induced Alfvén eigenmodes. These issues should be studied for weak and reversed magnetic shear. Also, since sawtooth dynamics and the consequences of giant sawteeth are still difficult to interpret in current experiments, extrapolation to burning plasma performance is problematic.

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

Comprehensively addressing alpha physics issues in a magnetized burning plasma will require excellent diagnostic information, device flexibility to access different operational regimes, and enhanced numerical simulation capability based on first-principles physics understanding.

- For diagnostic development, optical transmission and background noise in the presence of a significant neutron flux are severe challenges to detection. Also, shielding requirements pose constraints on the quality of obtainable diagnostic information. Work is needed now to identify and then develop diagnostics appropriate to a burning plasma environment.

- For device flexibility, the two most critical parameters for alpha-driven instabilities are magnetic shear (since weak shear lowers instability threshold) and the alpha particle pressure gradient. Varying the alpha drive would allow the instability threshold and non-linear behavior of unstable modes to be scanned. Such flexibility would require some density control; an issue is whether sufficient density control can be achieved in a burning plasma experiment.

The general physics understanding of Alfvén instabilities (including advanced simulation techniques and alpha diagnostics) is certainly transferable to the family of toroidal, low-beta configurations, even though specific new phenomena may be expected.

- In stellarators, the spectrum and structure of Alfvén eigenmodes are similar to those in tokamaks, but only when the non-axisymmetry (toroidal coupling) can be ignored to lowest order. The interaction of the energetic particles with the modes may be different, given the different classes of orbits. Also, continuum damping cannot be ignored; the development of more comprehensive codes benchmarked to tokamak physics experiments will contribute to understanding the role of the continuum in stellarators.
- For spherical tori (low and high beta), the wide continuum gap structure implies that multiple same-n modes may occur, leading to multi-mode interactions, although preferentially these will involve low-n global modes. A significant physics difference is the large Alfvénic Mach number for energetic particles in spherical tori, which can lead to the excitation of instabilities such as compressional Alfvén eigenmodes. Also, the possibility of a thermal ion resonance will require a fully kinetic, nonperturbative treatment of mode damping.

The transferability of physics learned from a tokamak burning plasma to high-beta configurations in general is less clear, since global low-n modes may be preferentially excited in this case, as opposed to the high-n modes expected in a low-beta burning plasma. Also, the presence of a magnetic well in a variety of high-beta configurations could alter particle orbits and affect linear stability and nonlinear saturation.

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

The understanding of wave-particle interactions and linear and nonlinear dynamics of supra-thermal populations has been successfully exported to applications in magnetospheric and solar physics (e.g., substorm trigger, coronal loops, solar wind), although this scientific interconnectedness could be further strengthened. Burning plasma experiments would deepen the understanding of wave-particle dynamics, which could then be applied in other fields (see the summary report of Breakout Group 5).

II. Confinement, Transport, and Self-Heating in a Burning Plasma

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

Achieving a controlled plasma burn is in itself a "grand challenge" scale scientific effort, requiring success on many different axes simultaneously. In particular, the scientific challenges that underlie the laboratory demonstration of sufficient energy confinement and plasma purity by magnetic fields to allow significant self-heating at thermonuclear pressures in a stable configuration despite the presence of turbulence are significant. Strong coupling among these elements constrain the solution space, implying likely need for continued development of external control, especially with respect to density, current, electric field, and pressure.

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

A number of important scientific elements are accessible without a burning plasma. Existing experiments can simulate and test most issues related to confinement and transport more than has been undertaken so far. Numerical simulations provide significant guidance with respect to many issues <u>individually</u> (*e.g.* turbulence, MHD, atomic physics, *etc*.). However, with a burning plasma experiment, new scientific issues inaccessible in a non-burning plasma environment could be explored. These include issues related to the strong coupling which is already a very challenging problem in present Advanced Tokamak experiments. At several levels, turbulence and nonlinearity mediates these strong couplings and experiments in this burning plasma regime are needed to improve our understanding. Another issue is the coupling between atomic physics at the plasma edge and in the divertor and the core plasma physics. An critically important near-term research goal is to identify specific important nonlinearities expected in a burning plasma. For example, the fusion power is proportional to the confinement enhancement factor, H, to the 7th power and with H observed to be strongly dependent upon edge density and electric field, new challenges emerge in the burning plasma regime.

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?

Based on our present level of understanding, there are no known showstoppers for achieving the generic burning plasma regime in a tokamak. Numerical simulations are rapidly improving and experimental tests on existing devices continues to improve our confidence. As our knowledge base continues to expand, specific design approaches to burning plasma experiments needs to be re-evaluated. Overall, the more recent burning plasma conceptual designs fare better than the ITER-FDR design, but existing transport models have not yet converged in extrapolation exercises. However, for most theory based models, stronger plasma cross-section shaping with a wider operating window relative to the empirical density limit, improves expected confinement properties and empirical H-mode power thresholds are not difficult to achieve in conceptual burning plasma experiment designs presently being evaluated.

Advanced tokamak scenarios (self-consistent stable, steady-state, bootstrap current sustained equilibria) have not yet been clearly demonstrated on existing experiments. Important further work on internal transport barriers and the edge temperature pedestal remains to be done.

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

Based on our present understanding of tokamak performance in a burning plasma, an experiment to explore this new plasma physics regime the key to maximizing discovery and advances in our understanding is experimental flexibility. Examples of possible criteria for maximizing the potential for advancing understanding (subject always to cost constraints) include:

1) Sufficient stable margin in β to reduce impact of MHD limits.
2) Sufficient sheared plasma flows to increase confinement margin.
3) High density operation relative to empirical scaling to increase fusion reactivity (self-heating) margin.
4) A high degree of cross-section shaping to increase flexibility.
5) A high degree of target equilibria self-consistency to reduce overall control requirements.
6) Long pulse length relative to important plasma time scales (*e.g.* current penetration skin-time).
7) Capability for a large number of discharges to facilitate broad exploration.

III. Macrostability in a Burning Plasma

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 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 may 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 an upper limit to plasma stability, with the possible exception of the fast ion-stabilized m=1 internal kink, as discussed earlier under question (2). 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. The fundamental MHD stability limits are understood well enough to avoid them at least transiently in achieving a burning plasma state. For example, sawteeth 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≥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. A firm theoretical foundation has been developed for active control of MHD instabilities through localized current drive (NTMs) or feedback-controlled coils (resistive wall modes). Recent experimental demonstrations of active stabilization on Asdex-Upgrade, DIII-D, and HBT-EP, althugh still at an early stage of development, are promising.

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.

IV. Boundary Science

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

Burning core - plasma boundary integration

Detached divertor operation has been proposed as a method of power dispersal, ensuring an acceptable operating life for the divertor targets. Aspects of its integration with core operation include perpendicular plasma transport, both inside and outside the separatrix, as well as impurity generation, transport, and radiation.

The character of the burning core - plasma boundary interaction is expected to be qualitatively different than that in existing experiments. Dimensionless parameters quantifying this difference need to be determined. For example, the ion-neutral friction and volume recombination processes underlying a detached divertor become important when divertor temperatures fall below a few eV. A critical upstream density can be inferred that scales with the scrape-off layer power per unit area. One potential dimensionless parameter can be obtained by dividing that density by the minimum central density obtained from core power balance. Other relations could be developed involving the density limit phenomenon, core confinement requirements for the pedestal temperature, and MHD behavior (ELMs, tearing modes). Additional scientific understanding, such as a scaling for the pedestal to separatrix density ratio, is required for the creation of these dimensionless parameters.

Perturbations in the boundary plasma that result in an improvement in core confinement will result in an increase in the power flowing into the scrape-off layer (through the increased fusion power). This additional feedback linkage between the core plasma and the boundary may change the nature of their interaction. The power handling capability of the plasma boundary must have sufficient margin as to be robust to such perturbations.

Disruption damage effects.

Disruption energy densities in all burning plasma experiments will be high enough to cross the vaporization threshold for divertor targets (˘ 1 MJ/m^2; a corresponding dimensionless parameter needs to be de-rived), permitting observation of the “vapor shielding” phenomenon predicted by simulations. The same may even be true of type I ELMs. Also, for plasma currents above ˘ 10 MA, runaway electron conversion is expected to result in runaway currents comparable to the plasma current.

Tritium retention, Erosion / PFC lifetime, Dust Generation.

The most aggressive burning plasma experiments contemplated would involve long pulse lengths and / or high duty factors, permitting study of erosion and plasma-facing component lifetime issues, as well as those of dust generation and tritium retention. Moreover, new regimes of plasma-wall interaction and erosion would likely arise as a result of such experiments.

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

Burning core - plasma boundary integration.

This issue could be studied to some extent on existing devices and from a theoretical point of view by further perfecting models for the physics components. Dimensionless parameters of the sort described in response to Question (1) need to be developed to permit the establishment of quantitative requirements for studying the various aspects of core - boundary integration.

Disruption damage effects, disruption avoidance and mitigation.

Only in a burning plasma experiment will the vaporization threshold be crossed and the runaway electron conversion effect be large enough for them to be studied. Because the consequences of disruptions in an DEMO-class device are severe, thoroughly understanding them at a smaller scale is advisable. Avoidance and mitigation studies are of equal importance.

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?**

Recent developments in theory and experiment have led to operating scenarios featuring simultaneous good core confinement without type I ELMs and satisfactory power and particle control. Additional experience with these regimes will increase confidence in being able to achieve them in a burning plasma experiment. Stability of the core-boundary interaction, including the stability of radiating regions, has not been addressed.

The low edge density required in an advanced tokamak may be incompatible with high density divertor operation. Furthermore, modeling a low edge density may require a (more problematic) kinetic description of the edge plasma.

Existing experiments have demonstrated high confinement operation at densities near and above the Greenwald density limit with no deterioration in particle transport. Additional experience with these operating modes will be required to obtain confidence in their applicability to burning plasma experiments.

The neutral densities associated with detached operation are great enough that pumping of helium should not be an issue. Furthermore, the helium ash removal criterion scales favorably with device size. If the scrape-off layer is operated at low densities, helium ash removal may resurface as an issue.

Recent efforts to develop disruption avoidance and mitigation techniques show encouraging progress, but confidence in their applicability to a burning plasma experiment is not high. Design of the device consistent with the quick and cost-effective replacement of the divertor hardware is advisable.

Confidence in the predictions of disruption damage effects based on model and disruption simulator results is fair. Additional testing of them would be prudent.

The ITER and FIRE design efforts have resulted in improvements in erosion lifetime and fatigue effects and have led to the development of promising new refractory materials that may provide viable solutions to materials-related issues. Materials-related issues should not directly affect the ability to achieve burning plasma conditions. However, they could control the duration of experimental operations. Due to the primitive understanding of these issues and lack of appropriate diagnostics, confidence in predicting their severity is not high. The situation is exacerbated by the fact that graphite, the most widely tested and robust material in existing experiments, will give rise to the highest levels of tritium retention.

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

Additional progress is required in the development of turbulent transport theories, both in the core plasma and the scrape-off layer before they can be extrapolated to reactor-scale devices with confidence. The boundary conditions at the materials surfaces are currently based on relatively unsophisticated models that cannot be extrapolated.

A first burning plasma experiment will be able to validate disruption vapor shielding models. To do the same for the runaway electron conversion, a plasma current in excess of roughly 10 MA is needed.

Materials-related issues can only be understood fully by doing long-pulse experiments with good diagnostic coverage. Because of access and cost concerns, such experiments would be best carried out independently of a burning plasma experiment. Corresponding new theoretical models would have to follow along.

One virtue of boundary science issues is that they are in many ways applicable to all magnetic configurations. This is particularly true of plasma-materials interaction concerns. To some extent, knowledge in this area can even be applied to inertial confinement fusion devices.

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

Materials science problems are pervasive in today’s technology. Fundamental materials science research carried out in search of improved power handling capability will have applicability in a number of areas.

The 14 MeV neutrons generated in a burning plasma experiment will provide a higher rate of displacements per atom (DPA) per neutron and a higher number of helium atoms per DPA than any other radiation source. The resulting data will constitute a valuable data point for neutron irradiation models used in fission reactors and other neutron irradiation environments.

V. Relationship of Burning Plasma Science to Other Fields

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

In Marshall Rosenbluth's words, "the point at which science and fusion energy goals converge is in a burning plasma experiment." With this convergence, we are sure to learn plasma science in a new regime that has significant implications for compelling issues outside of fusion energy. In what follows we discuss some of these issues.

ALPHA PHYSICS IN THE SOLAR WIND

Alfven and cyclotron waves are widely believed to play an important role in the heating of protons, alpha particles and heavy ions in the solar corona and solar wind. Although the energy of alpha particles in the solar wind is typically much smaller than the 3.5 MeV produced in a fusion reaction, the linear and nonlinear physics of kinetic waves and instabilities mediated by self-organized alpha-particle distribution functions is relevant to our understanding of analogous processes in the solar wind. We give below examples of outstanding questions involving alpha physics in the solar wind that do not have definitive answers yet:

(iv) Why is $|v_{0\alpha} - v_{0p}|/v_A \leq 1$ throughout the solar wind although $|v_{0\alpha} - v_{0p}|/v_A << 1$ in the solar corona? Here $v_{0\alpha}$ and v_{op} are the mean alpha and proton speeds, and v_A is the Alfven speed, measured locally.

(v) Why is $T_{\|\alpha} \geq T_{\perp\alpha}$ and $T_\alpha / m_\alpha \cong T_p / m_p$ in the solar wind?

(vi) Why do energetic Helium ions in impulsive solar flares show an isotopic ratio of $^3He/^4He \sim 1$ whereas the isotopic ratio in the solar corona, where flares originate, is $^3He/^4He \leq 5 \times 10^{-4}$?

There are theoretical models attempting to answer question (i) that rely on Alfven/cyclotron instabilities excited by alpha/proton relative flows as a possible mechanism. The enhanced magnetic fluctuations scatter alphas and constrain $|v_{0\alpha} - v_{0p}|$, maintaining the ratio $|v_{0\alpha} - v_{0p}|/v_A \approx 1$, with v_A decreasing with increasing distance from the Sun. The same scattering process tends to reduce $T_{\|\alpha} / T_{\perp\alpha}$ and increase T_α relative to T_p, providing a possible answer to question (ii).

A possible answer to question (iii) lies in identifying a physical mechanism that accelerates ^3He very efficiently preferentially selecting this isotope over ^4He. A currently favored model suggests that electron beams (inferred to exist from *X*-ray observations) excite Alfven/cyclotron instabilities propagating obliquely with respect to the background magnetic field $\mathbf{B_0}$. The excited magnetic fluctuations interact preferentially with ^3He via a cyclotron resonance. As the mirror force due to an inhomogeneous $\mathbf{B_0}$ slows $v_\|$, the resonance of ^3He persists and ions are accelerated to MeV energies.

These are just a few examples of how enhanced magnetic fluctuations produced by instabilities in the solar corona and wind can, via wave-particle scattering accelerate (or slow down) and isotropize (or anisotropize) alpha particles (or heavier ions). Although there are theoretical models for most observed phenomena of the solar wind, few of these can quantitatively predict the broad range of observations. Many of the limitations in predictive capability can be attributed to uncertainties in our understanding of the nonlinear evolution of Alfven instabilities, also identified as a challenge in the summary from Breakout Group 1. A better understanding of the nonlinear evolution of resonant energetic particle modes when they remain in resonance with interacting particles, thus leading to frequency-chirping, modifications in the mode-structure and rapid convective transport can lead to better understanding of similar energetic particle interactions with the solar wind plasma. Furthermore, decades of *in situ* observations from Voyager to Helios spacecrafts suggest that the solar wind plasma is a large natural laboratory of Alfvenic turbulence. If a burning plasma is a "sea" of resonantly overlapping unstable shear Alfven eigenmodes (excited by alpha particles), then understanding the characteristics of the anisotropic shear Alfven turbulence in a burning plasma can probably yield valuable insights into the physics of kinetic or collisionless Alfvenic turbulence in the solar wind.

COLLISIONLESS RECONNECTION IN MAGNETOSPHERIC AND SOLAR PLASMAS

Although the plasma parameters in a burning fusion plasma, the Earth's magnetotail and the solar corona are quite different, they have one important feature in common: the Lundquist numbers of all these plasmas is very high ($>10^{10}$). We describe such plasmas as "collisionless." Recent developments in the theory and simulation of nonlinear collisionless reconnection hold the promise for providing solutions to some outstanding problems in fusion and space plasma physics. Examples of such problems are: the sawtooth instability in tokamaks, magnetotail substorms, and impulsive solar flares. In each of these problems, a key issue is the identification of fast reconnection rates that are insensitive to the plasma resistivity. The classical models of Sweet-Parker and Petschek sought to resolve this issue in the realm of resistive MHD. However, the plasmas mentioned above are collisionless, and hence obey a generalized Ohm's law in which the Hall current and electron pressure gradient terms play a crucial role. Recent work on triggered as well as quasi-steady reconnection governed by a generalized Ohm's law show that the reconnection rate, to leading order, is independent of the mechanism that breaks field lines. In the triggered reconnection problem, not only is the growth rate fast but the time-derivative of the growth rate changes rapidly. Quantitative comparisons of theory with sawtooth oscillation data from TFTR and JET as well as multi-satellite data from the Earth's magnetotail show a remarkable degree of quantitative agreement. (It does not appear to be widely known that some of the crucial insights of recent collisionless reconnection theory, developed in the space physics community, had their antecedents in two-fluid studies of the sawtooth instability in the early 1990s.)

As discussed in the summaries from Breakout Group 3 as well as Breakout Group 1, one of the important physics issues in a burning plasma is the interaction of the sawtooth instability with alpha particles and energetic ions. Previous fusion experiments have shown that fast ions can have a strong stabilizing effect on the sawtooth instability. These results have interesting implications for space plasmas. While reconnection appears to be ubiquitous in the magnetosphere and the solar corona, it does not always occur even if the magnetic configuration is favorable. For example, there is clear observational evidence that as the Earth's magnetotail is driven by the solar wind, it does not always undergo violent current disruption and diploarization characteristic of a substorm. Two magnetotail configurations with very similar field profiles can often show very different dynamical behavior, with one profile erupting into a substorm while the other settles into a quiescent convection bay. Might it be that the kinetic effects of energetic particles cause suppression of reconnection and halt the progress of a substorm in its slow growth phase?

Reconnection can also play an important role in causing major disruptions in burning plasmas. It has been shown theoretically that runaway electrons can be produced in very high numbers by a knock-on avalanche process in high-current and large burning plasmas. (See narrative from Breakout Group 4.) This mechanism, which has been verified by careful Fokker-Planck calculations in the context of ITER physics studies, needs to be tested in burning plasma experiments. The implications of this mechanism for the problem of high-energy electron acceleration (inferred from *X*-ray emission) during impulsive solar flares need to be explored. Unlike a toroidal fusion device, the magnetic geometry of a solar coronal arcade has contiguous regions of closed and open magnetic field lines, and it remains to be seen whether the knock-on avalanche mechanism, believed to be very efficient in a toroidal device, is equally so in coronal geometry.

Reconnection theories have not been able to account yet for the problem of incomplete reconnection ($q(0) < 1$) in tokamaks, and have, similarly, left open questions in the problem of magnetospheric substorm onset. Kinetic ballooning instabilities are presently viewed favorably as a possible mechanism for substorm onset. Here too a burning plasma experiment can shed valuable light, especially in regard to the potential of such an instability to cause current disruption and dipolarization in a nonlinear growth phase.

OTHER COLLATERAL SCIENCE ISSUES

In addition to the issues discussed above, we identified a number of other issues of a more exploratory nature. Some of these issues can be possibly addressed in smaller and less expensive collateral experiments in parallel with a burning plasma facility.

(i) Nuclear Astrophysics

In precision cosmology (big-bang nucleosynthesis), accurate knowledge of nuclear reaction cross-sections have significant implications for the baryonic density problem. The production rate of light elements places bounds on the baryonic density. While these production rates are presently known with an accuracy of approximately 10%, the target precision in the nuclear astrophysics community is about 1%. A number of important cross-sections are uncertain at the 5-25% level, and there are significant gaps at high energies. Can a burning plasma experiment provide incentive for accurate experimental determination of some of the relevant cross-sections for reactions such as $p(n,\gamma)d$; $d(d,n)^3He$; $^3He(d,p)^4He$? It could be that the large size and high density of kilovolt plasmas that can be just obtained with Ohmic heating in a burning plasma might make access to some of the lower reaction rates possible.

There is a current controversy in the solar astrophysics community regarding plasma screening effects and whether they alter significantly the commonly used reaction cross-sections. (Such calculations have significance for theoretical estimates of the solar neutrino flux.) While one probably cannot use a burning plasma to measure the screening effects directly, can one design a relevant, scaled experiment to test theoretical predictions?

(ii) Collisionless Shocks and Particle Acceleration

Particle acceleration to relativistic energies remains one of the outstanding problems of plasma astrophysics. The exhaust from a burning plasma facility might itself be a unique plasma source that can be possibly useful for studies of particle acceleration by collisionless shocks. Simple estimates of the energy content and flows in such a diverted plasma suggest that it can be possibly used to produce collisionless shocks and substantial particle acceleration in a pre-formed magnetized plasma several cubic meters in volume. An important question is whether it is possible to set up suitable diagnostic capabilities for such an experiment in a burning plasma environment.

(iii) Thermonuclear Deflagration Flame Physics

Astrophysical nuclear flames, which propagate at subsonic speeds (and are deflagrations, not detonations), are of great interest, for instance, in the interior of a white dwarf of nearly the Chandrasekhar mass. Assuming that energy transport is dominated by electron heat conduction, such physics has been explored theoretically in the early 1990s and more recently, simulated in high-resolution numerical experiments (in the presence of vortical fluid flows) for astrophysical applications. The possibility that a radial flames can be produced and sustained in a magnetically confined D-T plasma in the laboratory has been studied in an idealized one-dimensional time-dependent numerical calculation, and the results are interesting. One needs to assess the feasibility of such a scenario in a burning plasma experiment by incorporating more realistic geometry and transport physics.

Identify those scientific issues that are inaccessible for study in existing or near-term non-burning plasma experiments

Of the issues discussed above, the ones that are least accessible are :
(i) the self-consistent interaction of intense alpha particle distributions (isotropic and anisotropic) with Alfven/cyclotron modes,
(ii) the physics of shear-Alfven turbulence generated by a “sea” of resonantly overlapping eigenmodes,
(iii) the knock-on avalanche process as a mechanism for electron acceleration,
(iv) nuclear cross-sections for light elements and the efficacy of plasma screening,
(v) thermonuclear deflagration flame physics.

The following issues, which are of great relevance to a burning plasma facility *and* have potentially significant implications for space and astrophysical plasma physics, should be pursued in existing and near-term fusion experiments:
(i) the nonlinear interaction of alpha particles with Alfven/cyclotron waves, leading to frequency-chirping, modifications in the mode-structure and rapid convective transport,
(ii) investigation of the stabilization of the $m = 1$ mode by energetic particles and the effect of ballooning instabilities on the electron pressure gradient which controls the nonlinear reconnection dynamics of the collisionless $m = 1$ instability. These investigations may lead to a conclusive resolution of the $q(0) < 1$ problem.

In all of the above, a broad research effort in theory and simulation can provide fertile common ground between burning plasma science and other fields.

VI. Workshop Organization

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