MHD Stability Issues and Opportunities

Report for the MHD Stability Subgroup of the Magnetic Fusion Working Group

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1. SUMMARY

MHD stability at high beta is crucial for a compact, cost-effective magnetic fusion reactor. Fusion power density varies roughly as β^2 at constant magnetic field, or as β_N^4 at constant bootstrap fraction in configurations with externally driven plasma current. (Here $\beta_N = \beta/(I/aB)$ is the normalized beta.) In many cases MHD stability represents the primary limitation on beta and thus on fusion power density. MHD stability is also closely tied to issues of creation and sustainment of certain magnetic configurations, energy confinement, and steady-state operation.

Critical issues include understanding and extending the stability limits through the use of a variety of plasma configurations, and developing active means for reliable operation near those limits. Accurate predictive capabilities are needed, which will require the addition of new physics to existing MHD models. Although a wide range of magnetic configurations exist, the underlying MHD physics is common to all. Understanding of MHD stability gained in one configuration can benefit others, by verifying analytic theories, providing benchmarks for predictive MHD stability codes, and advancing the development of active control techniques.

This report is organized into two main parts. Section 1 discusses the broad MHD stability issues for magnetic fusion. We have identified performance limitation by MHD instabilities as a key issue, and within that issue several particular instabilities that are common to most magnetic configurations. The opportunities for addressing this issue are discussed. Several additional, more specific stability issues are also mentioned. A second key issue is that the simple MHD models are not always sufficient to describe important plasma behavior, and the opportunities for advances here are described. Finally, conclusions are given, including the readiness for and need for a burning plasma experiment. Section 2 consists of a set of brief summaries of the MHD issues for specific magnetic configurations, as well as issues related to disruptions. An appendix lists the talks presented during the meetings of the MHD Stability subgroup.

1.1. Critical Issue: MHD Instabilities Limit Performance

The most fundamental and critical stability issue for magnetic fusion is simply that MHD instabilities often limit performance at high beta. In most cases the important instabilities are long wavelength, global modes, because of their ability to cause severe degradation of energy confinement or termination of the plasma. Some important examples that are common to many magnetic configurations are ideal kink modes, resistive wall modes, and neoclassical tearing modes. A possible consequence of violating stability boundaries is a disruption, a sudden loss of thermal energy often followed by termination of the discharge. The key issue thus includes understanding the nature of the beta limit in the various configurations, including the associated thermal and magnetic stresses, and finding ways to avoid the limits or mitigate the consequences. A wide range of approaches to preventing such instabilities is under investigation, including optimization of the configuration of the plasma and its confinement device, control of the internal structure of the plasma, and active control of the MHD instabilities.

Ideal Instabilities. Ideal MHD instabilities driven by current or pressure gradients represent the ultimate operational limit for most configurations. The long-wavelength kink mode and short-wavelength ballooning mode limits are generally well understood and can in principle be avoided. Intermediate-wavelength modes (n ~ 5–10 modes encountered in tokamak edge plasmas, for example) are less well understood due to the computationally intensive nature of the stability calculations. The extensive beta limit database for tokamaks is consistent with ideal MHD stability limits, yielding agreement to within about 10% in beta for cases where the internal profiles of the plasma are accurately measured. This good agreement provides confidence in ideal stability calculations for other configurations and in the design of prototype fusion reactors.

Resistive Wall Modes. Resistive wall modes (RWM) develop in plasmas that require the presence of a perfectly conducting wall for stability. RWM stability is a key issue for many magnetic configurations. Moderate beta values are possible without a nearby wall in the tokamak, stellarator, and other configurations, but a nearby conducting wall can significantly improve ideal kink mode stability in most configurations, including the tokamak, ST, RFP, spheromak, and possibly the FRC. In the advanced tokamak and ST, wall stabilization is critical for operation with a large bootstrap fraction. The spheromak requires wall stabilization to avoid the low-m,n tilt and shift modes, and possibly bending modes. However, in the presence of a non-ideal wall, the slowly growing RWM is unstable. The resistive wall mode has been a long-standing issue for the RFP, and has more recently been observed in tokamak experiments. Progress in understanding the physics of the RWM and developing the means to stabilize it could be directly applicable to all magnetic configurations. A closely related issue is to understand plasma rotation, its sources and sinks, and its role in stabilizing the RWM.

Resistive instabilities. Resistive instabilities are an issue for all magnetic configurations, since the onset can occur at beta values well below the ideal limit. The stability of neoclassical tearing modes (NTM) is a key issue for magnetic configurations with a strong bootstrap current. The neoclassical tearing mode (NTM) is a metastable mode; in certain plasma configurations, a sufficiently large deformation of the bootstrap current produced by a “seed island” can contribute to the growth of the island. The NTM is already an important performance-limiting factor in many tokamak experiments, leading to degraded confinement or disruption. Although the basic mechanism is well established, the capability to predict the onset in present and future devices requires better understanding of the damping mechanisms which determine the threshold island size, and of the mode coupling by which other instabilities (such as sawteeth in tokamaks) can generate seed islands.

1.2. Opportunities for Improving MHD Stability

Configuration. The configuration of the plasma and its confinement device represent an opportunity to improve MHD stability in a robust way. The benefits of discharge shaping and low aspect ratio for ideal MHD stability have been clearly demonstrated in tokamaks and STs, and will continue to be investigated in experiments such as DIII–D, C–Mod, NSTX, and MAST. New stellarator experiments such as NCSX (proposed) will test the prediction that addition of appropriately designed helical coils can stabilize ideal kink modes at high beta, and lower-beta tests of ballooning stability are possible in HSX. The new ST experiments provide an opportunity to test predictions that a low aspect ratio yields improved stability to tearing modes, including neoclassical, through a large stabilizing “Glasser effect” term associated with a large Pfirsch-Schlüter current. Neoclassical tearing modes can be avoided by minimizing the bootstrap current in quasi-helical and quasi-omnigenous stellarator configurations. Neoclassical tearing modes are also stabilized with the appropriate relative signs of the bootstrap current and the magnetic shear; this prediction is supported by the absence of NTMs in central negative shear regions of tokamaks. Stellarator configurations such as the proposed NCSX, a quasi-axisymmetric stellarator design, can be created with negative magnetic shear and positive bootstrap current to achieve stability to the NTM. Kink mode stabilization by a resistive wall has been demonstrated in RFPs and tokamaks, and will be investigated in other configurations including STs (NSTX) and spheromaks (SSPX). A new proposal to stabilize resistive wall modes by a flowing liquid lithium wall needs further evaluation.

Internal Structure. Control of the internal structure of the plasma allows more active avoidance of MHD instabilities. Maintaining the proper current density profile, for example, can help to maintain stability to tearing modes. Open-loop optimization of the pressure and current density profiles with external heating and current drive sources is routinely used in many devices. Improved diagnostic measurements along with localized heating and current drive sources, now becoming available, will allow active feedback control of the internal profiles in the near future. Such work is beginning or planned in most of the large tokamaks (JET, JT–60U, DIII–D, C–Mod, and ASDEX–U) using rf heating and current drive. Real-time analysis of profile data such as MSE current profile measurements and real-time identification of stability boundaries are essential components of profile control. Strong plasma rotation can stabilize resistive wall modes, as demonstrated in tokamak experiments, and rotational shear is also predicted to stabilize resistive modes. Opportunities to test these predictions are provided by configurations such as the ST, spheromak, and FRC, which have a large natural diamagnetic rotation, as well as tokamaks with rotation driven by neutral beam injection. The Electric Tokamak experiment is intended to have a very large driven rotation, approaching Alfvénic regimes where ideal stability may also be influenced. Maintaining sufficient plasma rotation, and the possible role of the RWM in damping the rotation, are important issues that can be investigated in these experiments.

Feedback Control. Active feedback control of MHD instabilities should allow operation beyond the “passive” stability limits. Localized rf current drive at the rational surface is predicted to reduce or eliminate neoclassical tearing mode islands. Experiments have begun in ASDEX–U and COMPASS-D with promising results, and are planned for next year in DIII–D. Routine use of such a technique in generalized plasma conditions will require real-time identification of the unstable mode and its radial location. If the plasma rotation needed to stabilize the resistive wall mode cannot be maintained, feedback stabilization with external coils will be required. Feedback experiments have begun in DIII–D and HBT-EP, and feedback control should be explored for the RFP and other configurations. Physics understanding of these active control techniques will be directly applicable between configurations.

Disruption Mitigation. The techniques discussed above for improving MHD stability are the principal means of avoiding disruptions. However, in the event that these techniques do not prevent an instability, the effects of a disruption can be mitigated by various techniques. Experiments in JT–60U have demonstrated reduction of electromagnetic stresses through operation at a neutral point for vertical stability. Pre-emptive removal of the plasma energy by injection of a large gas puff or an impurity pellet has been demonstrated in tokamak experiments, and ongoing experiments in C–Mod, JT–60U, ASDEX–U, and DIII–D will improve the understanding and predictive capability. Cryogenic liquid jets of helium are another proposed technique, which may be required for larger devices. Mitigation techniques developed for tokamaks will be directly applicable to other configurations.

1.3. Additional Stability Issues

In addition to the broad issues discussed above, there are a number of key stability issues that are more specific to particular confinement configurations. In a few cases, the key issues clearly call for physical models beyond the usual ideal and resistive MHD models. Equilibrium and stability calculations for the electric tokamak, with near-sonic flow and beta near unity, must be developed. The observed stability of the FRC evidently requires effects beyond ideal MHD with static equilibria; recent calculations show that finite Larmor radius effects alone are also not sufficient. These issues will be discussed further in Section 1.4.

Important issues for the more externally controlled configurations are associated with particular ideal and resistive instabilities. The nature of the ideal MHD beta limit in stellarators, including the role of bootstrap current and the possibility of disruption-free high beta regimes, should be investigated as heating power becomes available in devices such as LHD, W-7AS, and NCSX (proposed). The relationship of ST experiments to ideal MHD stability limits, and the possible role of large natural poloidal and toroidal flows, needs to be established with improved modeling and good profile measurements in NSTX and MAST. A key issue for advanced tokamaks is the understanding and control of stability in the presence of internal and edge transport barriers with their strong gradients. Control of sawteeth is an important issue for conventional tokamaks in order to avoid neoclassical tearing modes and redistribution of alpha particles; rf current drive and rf-heated fast ions provide opportunities.

The greater degree of self-organization in configurations such as the RFP, spheromak, and FRC raises additional stability-related issues, which are closely related to issues of transport. The role of relaxation in establishing a spheromak equilibrium needs to be established, including transport to the plasma core of current driven on open field lines. Fast restructuring of FRC equilibria also needs to be investigated as a possible relaxation process. Relaxation to a minimum-energy state in which the magnetic configuration is sustained by a dynamo effect removes the need for active profile control, but ideal stability calculations indicate that the beta limit may be much smaller than for some non-relaxed profiles. Magnetic fluctuations associated with the relaxation process can also cause significant energy transport. Initial experiments on transport reduction by current profile control in MST have shown promising results. Scaling of the fluctuations and transport to reactor parameters is a critical issue requiring further modeling and experiments. Methods for stabilizing larger-scale core tearing modes in the RFP by current density profile control, and the effects on energy confinement and sustainment of the discharge, need to be developed and tested; a near-term opportunity is the use of LHCD in MST.

The compatibility of MHD stability with steady state operation is a key issue for development of any magnetic configuration into a fusion reactor. At the most primitive level, instabilities that have slow growth times or are metastable, such as the NTM and RWM, become important only with longer pulse duration. In true steady-state operation, in order to avoid large amounts of recirculating power, the current density profile must not differ greatly from the bootstrap current profile and the pressure profile must not differ greatly from the profile determined by transport and alpha heating. The helicity injection current drive techniques proposed for the spheromak, RFP, and ST must not introduce excessive turbulent transport. Self-consistent scenarios must be found through experiment and modeling which satisfy these constraints while maintaining good stability properties.

1.4. Critical Issue: Simple MHD Models are Not Always Sufficient

Ideal and resistive MHD has had a great deal of quantitative success, particularly in predicting equilibrium and stability limits for tokamaks and stellarators. The predicted ideal MHD beta limits are consistent with the observed limits in tokamaks to within about 10%, given high quality profile data, and axisymmetric stability limits are routinely predicted to within a few percent. However, simple MHD models are not sufficient to describe some important magnetic configurations and observed phenomena. A critical issue for theory and modeling work is to extend the MHD model beyond its present limitations. When benchmarked against experiment, other models, and analytic theory, realistic modeling will lead to improved understanding of experiments and predictive capabilities for regimes not yet explored experimentally. Following is a list of additional physical effects that are not included in the simple MHD models, with some of the areas where these effects could be important.

Flow, Flow Shear. Large rates of plasma flow and flow shear are nearly ubiquitous features of fusion plasmas, driven by diamagnetic effects, electric fields, and external torques. Toroidal and poloidal flow may have a significant role in the equilibrium of many configurations, including the advanced tokamak, ST, RFP, spheromak, and FRC. Strong poloidal flow is a dominant element of equilibrium and stability for the electric tokamak. Flow shear may influence relaxation processes in the RFP and spheromak, and macroscopic resistive stability in the advanced tokamak, ST, and quasi-axisymmetric stellarator. Flow shear may be an important element of MHD stability in edge and internal transport barriers, while flow and flow shear are a key means of stabilizing resistive wall modes.

Neoclassical Effects. Neoclassical tearing modes are known to be significant for tokamaks. Improved modeling of their initiation and saturation is needed to understand the behavior in tokamaks, and predict with confidence their importance in STs, stellarators, and other configurations.

Two-Fluid Physics, Two-fluid (more properly known as drift-MHD) effects such as those produced from Hall terms and ω^* diamagnetic drift corrections may be needed to adequately model reconnection and some aspects of the resistive fluid evolution. Areas of particular importance include fluctuations and relaxation in the RFP and spheromak, and helicity injection current drive in the RFP, spheromak, and ST. Two-fluid physics may be key to understanding the stability of the FRC.

Finite Larmor Radius. Finite Larmor radius effects become more important in low toroidal field configurations such as the RFP and spheromak. In high toroidal field configurations, FLR effects may have an important role in the stability of regions with short gradient scale lengths, such as edge and internal transport barriers. Finite Larmor radius effects may also be key to understanding the stability of the FRC.

Kinetic Effects. Fast ions are an important feature of most present auxiliary-heated devices as well as future alpha-heated plasmas, and can be either stabilizing or destabilizing. Kinetic effects are probably needed to understand the behavior of sawteeth in tokamaks and STs, and are certainly needed to model sawtooth stabilization techniques using fast ions, as well as fast ion-driven instabilities such as fishbones. Ideal MHD does not predict all of the Alfvénic instabilities observed in tokamaks. Although Alfvén instabilities such as TAE modes have not significantly affected the performance of most experiments to date, including DT plasmas in TFTR and JET, they remain a concern for future burning plasma experiments.

Open Field Lines Current carried on open field lines is a key element of spheromak formation, and also of helicity injection current drive in the spheromak, ST, and other configurations. Current and energy transport on open field lines may play a role in tokamak ELMs. There has been some success in axisymmetric modeling of halo currents during tokamak disruptions, but the large degree of toroidal asymmetry sometimes observed and its possible relation to MHD instabilities is not yet understood.

3-D Magnetic Structure. Stellarator plasmas are explicitly three-dimensional, while nominally axisymmetric plasmas become three-dimensional with the addition of a small symmetry-breaking perturbation such as a field error or long wavelength MHD mode. The problem of a slowly growing magnetic island (such as those associated with NTMs) is essentially a 3D equilibrium problem which requires the proper evaluation of the pressure and current profiles in the island region. Three-dimensional stability calculations are also needed, for example, to calculate ballooning mode stability in the presence of a long wavelength island or kink mode. The existence of magnetic flux surfaces becomes an important issue in 3-D equilibria, and the breakup of flux surfaces into islands and chaotic regions with increasing beta can lead to an equilibrium beta limit in stellarators and may play an important role in tokamak disruptions.

1.5. Opportunity: Theory and Modeling Beyond Standard MHD

There is a strong need to develop and apply analytic theory and predictive codes with the additional features listed above. Existing 3-D nonlinear fluid-based codes such as M3D and NIMROD provide an opportunity for the most complete modeling with the addition of these features. These codes now include ideal and resistive MHD, 2-fluid physics, and neoclassical effects. A kinetic treatment of hot ions is included in M3D and soon to be included in NIMROD. Stellarator modeling is made possible by a fully 3-D mesh in M3D. Inclusion of the vacuum region and vacuum-plasma interface allows NIMROD to model external modes such as the resistive wall mode. However, there is also a strong need for smaller-scale 2-D and 3-D codes and analytic theory in order to allow study of the various additional features in isolation, to develop physical insights into their effects, and to provide benchmark tests for the large-scale codes.

A second component of this opportunity for physics understanding and predictive capability beyond simple MHD models is the need for improved experimental diagnostics. Theory and modeling can only be used with confidence when benchmarked against experiments, and such comparisons depend crucially on the quality of the experimental measurements. Accurate, high-resolution measurements of equilibrium profiles (including rotation) and mode structure are needed to reveal the regimes where simple MHD models fail, and to distinguish which additional physics effects are important. A particular challenge for the near future is the measurement of current density profiles in low field devices where MSE measurements are difficult. Two- and three-dimensional measurements of MHD mode structure must be developed for detailed comparisons with simulations.

1.6. Burning Plasma Issues and Opportunities

From the perspective of MHD stability, the tokamak is ready to proceed with a burning plasma experiment, at least in a pulsed, inductively driven configuration. Experiment and modeling show that conventional H-mode plasmas with strong shaping have ideal MHD no-wall stability limits in the range β~3-4(I/aB), eliminating the issue of resistive wall modes. Inductive techniques for current profile modification can be and have been developed for transiently stable operation.

For longer pulses, neoclassical tearing modes may become an issue. While the basic physical mechanism is understood theoretically, a number of open issues remain, including accurate predictions of the scaling of the nonlinear island width threshold and seed island formation. In particular, a potential issue for burning plasma experiments is the scaling of the nonlinear island width threshold with ρ^* (normalized ion gyroradius). Theoretical calculations and preliminary experiments in ASDEX-U suggest that a small amount of localized current, driven by electron cyclotron current drive for example, is sufficient to reduce the island width to acceptable levels. However, additional work is needed to assess the scaling of neoclassical tearing mode thresholds to burning-plasma parameters and the feasibility of stabilization by localized current drive.

A burning plasma experiment can uniquely address several of the MHD stability issues discussed above. Operation in a new regime of low ρ^* and high Lundquist number will provide valuable data for the scaling of neoclassical tearing mode thresholds, as well as for FLR effects on other instabilities. Energetic particle effects may alter MHD modes and their associated stability limits through FLR effects and introduce fishbone and Alfven instabilities; these may be crucial issues in a burning plasma with a significant alpha particle population. A burning plasma experiment can also provide a first look at MHD stability when the core pressure profile and bootstrap current profile are determined largely by alpha heating.

1.7. Conclusions

Despite the wide variation in magnetic configurations, a small number of critical MHD issues have been identified: avoidance of neoclassical tearing modes, stabilization of resistive wall modes, compatibility of relaxed profiles with MHD stability and of the relaxation process with energy confinement, and a general need for analytic and numerical modeling including physics beyond simple ideal and resistive MHD. As identified above, many of these issues can and will be addressed in existing facilities, given sufficient resources. Certain other issues are difficult to address in existing facilities, including the scaling of neoclassical tearing modes to reactor-like parameters, and the effects on MHD stability of a significant alpha-particle population. A burning plasma experiment would offer the opportunity to address these issues.

2. ISSUES AND OPPORTUNITIES FOR SPECIFIC CONFIGURATIONS

2.1. MHD Issues for the Stellarator (S. Knowlton)

The physics of current and pressure driven MHD instabilities is common to all toroidal confinement concepts, including stellarators. Of all presently envisaged toroidal devices, the stellarator generally provides the greatest amount of external control over the 3-D magnetic configuration, which can be tailored to reduce the susceptibility to MHD instability. Therefore, the application of externally generated non-axisymmetric stellarator magnetic fields offers good opportunities for passively stabilizing or suppressing MHD instabilities that could lead to degraded confinement and disruptions in high beta toroidal plasmas.

In stellarators, current-driven instabilities may be controlled by either reducing the plasma currents, and/or tailoring the externally generated shear and corrugation of the plasma edge. In the W7-X stellarator, the bootstrap and Pfirsch-Schlüter currents are minimized by design of the helical and toroidal curvature; the quasi-helical configuration embodied in HSX also exhibits greatly reduced pressure-driven currents in comparison to an equivalent tokamak. On the other hand, the quasi-axisymmetric stellarator (QAS) has a predicted bootstrap current comparable to that of a tokamak, and low-aspect ratio configurations generally do not minimize the Pfirsch-Schlüter current. Nonetheless, 3-D stability calculations indicate that compact stellarator configurations such as NCSX can be made stable to external kinks at beta levels of 4% to 5% by external control of the shear and 3-D shape. This may be achieved even in the absence of a close-fitting wall. The externally applied helical field also provides improved vertical stability, allowing expanded possibilities for plasma shaping for further optimization of beta limits. Furthermore, stellarators can be made passively stable to neoclassical tearing modes by proper choice of the sign of the shear of the rotational transform profile with respect to the direction of the bootstrap current. These opportunities for suppression of current-driven instabilities should make high performance stellarators more resistant to disruption than comparable tokamaks. Most operating stellarators have a relatively small toroidal current and therefore do not experience current disruptions, but a number of low-beta current-carrying stellarators have operated disruption-free at q(a) as low as 1.7, with toroidal current providing over 75% of the rotational transform — a regime which is quite kink-unstable and prone to disruptions in tokamaks. On the other hand, a very low-shear stellarator plasma operating near q = 2 can be made to disrupt with modest plasma currents. Clearly, there is a need for a more complete understanding of the stellarator disruption, particularly near predicted beta limits, to ensure that disruptions can be effectively eliminated in stellarators before continuing to the proof-of-performance level. The extent to which current-driven modes can be stabilized in finite beta current-carrying stellarator plasmas is an issue of key importance to be resolved in upcoming experiments.

While stellarators have operated above the Mercier beta limit with no MHD-induced degradation of confinement, most do not yet have sufficient heating power to exceed ballooning and kink beta limits. There is a critical need at this juncture to determine the experimental beta limits of stellarator configurations, and also to explore the nature of the MHD beta limit. For example, is the ballooning mode limit relatively mild, as is the case for the plasma behavior at the stellarator density limit? Or can the ballooning instability couple to a kink mode and lead to a disruption, as in a tokamak? This might improve the attractiveness of the stellarator as a reactor while hopefully keeping its natural advantages of low disruptivity and low recirculating power.

2.2. MHD Issues for the Tokamak (E.J. Strait)

Tokamaks represent the best current candidate for a burning plasma experiment. Steady-state, advanced tokamak configurations present additional challenges for MHD stability, but also additional opportunities through a greater degree of active control of the plasma. The most important issues for both conventional and advanced tokamaks are the large-scale n = 1 ideal and resistive instabilities which can lead to disruptions if not controlled.

Neoclassical tearing modes (NTM) are metastable in many high beta tokamak configurations, becoming unstable when a "seed island" provides a helical perturbation of the bootstrap current. Degradation of confinement can result, or disruption if the saturated islands become too large. A predictive capability for the onset in future devices requires improved understanding of the threshold island size for destabilization and its relation to the normalized gyroradius, and of the mode coupling which generates seed islands and its dependence on collisionality, Lundquist number, and shear flow. These represent opportunities for improved theory and modeling, and for inter-device databases. Avoidance requires active current profile control to improve the stability of NTMs and of instabilities which could trigger the NTM, sawteeth in particular. Experiments are beginning to investigate suppression by localized current drive at the rational surface. The slow growth of the NTM allows time for corrective action to avoid a disruption.

Instabilities can arise from the steep pressure gradients associated with transport barriers, and may damage the transport barrier, or even cause disruption. Ideal n = 1 kink instabilities at advanced tokamak internal transport barriers are well understood and avoidable, but work is needed to optimize and control internal barriers for compatibility with stable operation. H–mode edge-driven instabilities (ELMs) are often associated with intermediate-n modes; ideal stability calculations for n ~ 5–10 are needed. An important issue is whether the apparent violation of ideal high-n ballooning stability at the edge results from second regime access provided by bootstrap current, or from some other mechanism such as diamagnetic shear flow. Approaches to controlling edge gradients and stability include impurity radiation and discharge shaping.

Advanced tokamak configurations generally need broad current density profiles for good bootstrap alignment, and must rely on wall stabilization of kink modes at high beta; thus the resistive wall mode (RWM) becomes an important issue. Rotational stabilization has been demonstrated experimentally, but a quantitative theoretical prediction is needed for the critical rotation frequency, and rotation drive is an issue for large plasmas. Experiments suggest that the RWM can exist at a small, saturated amplitude which causes slowing of the plasma rotation; this conjecture needs support of theory and modeling. Experimental development of active feedback control is beginning, and realistic modeling including plasma rotation is needed. Stabilization by flowing liquid metal walls is a recent proposal that requires further investigation.

Tokamak disruptions can be minimized through avoidance or stabilization of modes such as those discussed above, by means of open-loop profile modification, real-time profile analysis and feedback control, or active suppression of MHD instabilities. Consequences of a disruption can be minimized by operation at a neutral point for vertical stability, and by mitigation techniques such as injection of solid pellets or gas and liquid jets.

2.3. MHD Issues for the Electric Tokamak (M.W. Kissick)

The eventual goal of the electric tokamak (ET) which has a high aspect ratio (>5), large volume (~180 m^3), and low magnetic field (~0.25 T) is the achievement of a stable near unity beta plasma. Rotation both poloidal: $M_\theta = (V_\theta B_T)/(B_\theta C_S) > 1\text{–}2$ and toroidal: $M_T = V_T/C_S < 1$ and $V_T < V_{\mathrm{Alfv\acute{e}n}}$ will be employed to bifurcate[1] the plasma into a "global H–mode." Note that $V_\theta < C_S$ and $V_\theta < V_{\mathrm{Alfv\acute{e}n}} B_\theta/B_T$ (but close to it) as well, even though it rotates *poloidally* supersonic. Therefore, bulk rotation, its associated shear, as well as near unity beta effects should be included for an accurate stability analysis of ET. Some work on bulk toroidal[2] and sheared poloidal[3] rotational stabilization of kink modes has been done for tokamaks that produced promising implications for ET. In addition, sheared toroidal rotation[4] on ballooning and unity beta[5] effects on equilibrium, interchange, and ballooning have also been done which again produced encouraging implications for ET.

The issues of fast rotation, especially poloidal rotation, and very high beta are very active areas of research and a complete understanding of these effects is still forthcoming. For instance, with flow the self-adjointness property of the energy principle fails. Also, at beta ~1 and near sonic poloidal flow, the Grad-Shafranov equation becomes hyperbolic. With possibly increased pressure non-uniformity along field lines (poloidal shocks[6]), an MHD treatment may fail as well. More advanced numerical treatments such as NIMROD[7] are being employed and may provide useful results.

The experiment will proceed ahead of these needed advances in theory (not an atypical situation). We anticipate that the experimental results from ET will aid the active theory pursuits in these new high rotation and high beta regimes that other experiments will also require.

2.4. MHD Issues for the ST (S. Sabbagh)

MHD stability of the spherical torus (ST) configuration is one of the key issues that will determine the viability of the ST as a fusion energy reactor. The requirement of both high fusion power and high bootstrap current fraction in the ST yields a dependence of the fusion power, $P_f \sim \beta_N$.[8] This scaling provides a strong motivation to demonstrate stable ST operation at high β_N in proof-of-principle (PoP) scale experiments (NSTX and MAST) over the next 5 years. These two machines represent the key experimental opportunities to address the key issues that were discussed by the group.

The talk and discussion of ST issues and opportunities in the MFCWG session focused on beta-limiting issues for the ST — both experimental and theoretical. Additional topics not specifically related to physical modes included the importance of the successful operation of current drive sources for ST startup and sustainment consistent with MHD stability, the validity of assumptions being made in the present modeling (including the uncertainty of bootstrap current magnitude and profile shape), the application of standard tokamak performance parameters (such as β) as figures-of-merit for the ST, and the importance of internal field measurements for both stability analysis and mode identification.

The physical instabilities discussed during the session were loosely ranked by order of importance by the group. The following is a summary of the talk and discussion on these instabilities, addressing the modes according to the ranked priority (high to low):

1. Low-*n* Kink/Ballooning Mode

   Violation of the ideal instability threshold for low-*n* modes has been associated with the onset of disruptions in standard tokamaks. The global nature and fast onset (Alfvén time scale) of the mode makes it basically impossible to suppress once triggered. Therefore, the ideal no-wall β limit is assumed to be an upper limit to β. Theoretical and experimental research in standard tokamaks over the past 10 years has shown that the ideal β limits can be predicted to within 10%–15%; useful knowledge for mode avoidance.

   Several important physics effects, related to the lower aspect ratio, *A*, and B_t need to be investigated in the evaluation of ST β limits. These include toroidal and poloidal flows (which are expected to be a significant fraction of the Alfvén speed at high β) and FLR effects. The former might lead to a significant reduction of the β limits calculated for static equilibria. Assumptions of proximity to the separatrix and the constraint of bootstrap current are also important in determining the ST β limit. These issues, in addition to lack of internal magnetic field profile data, led to significant uncertainties in β-limit calculations for START.

2. Resistive Wall Mode

   The attraction of operating at the highest β_N compels us to operate above the no-wall β limit and consider active stabilization of the resistive wall mode. The approach to stabilization in the PoP devices will depend on present research being conducted on DIII–D. A physical argument (i.e. bootstrap fraction) should be made to determine how far over the no-wall β-limit the ST should operate. Greater poloidal and toroidal mode coupling at low *A* might require more complex sensor and feedback coils in an ST.

3. Resistive/Neoclassical Tearing Mode

The NTM has been shown to lead to β collapse and disruption. At low *A*, the stabilizing "Glasser term" (due to Pfirsch-Schlüter current) can balance the instability drive term depending on the local *q* and *p* profile shapes. This gives the ST increased capability to stabilize the mode through profile control.[9]

4. High-*n* Ballooning Mode

   The destabilizing effect of the poloidal field curvature (small in a standard tokamak) becomes important at low aspect ratio.[10] Experimental verification of this effect can be performed in the PoP devices. This effect is reduced at high *q.* Robust stability to high-*n* modes is easier at low *A* and high *q* and does not require global shear reversal, which can lead to infernal modes when coincident with high pressure gradient.

5. Edge Localized Mode

   Large perturbations to p' from ELMs might significantly perturb the bootstrap current and hence stability at high β. Control of these modes might be required to maintain a high-β ST equilibrium.

6. Alfvén Eigenmode and Non-Axisymmetric Ballooning Mode

   At low A, the TAE gap increases, which will reduce continuum damping. At the reduced B_t of the ST, one might expect that the non-axisymmetric ballooning mode could lead to reduced β limits.

2.5. MHD Issues for the RFP (R. Nebel)

Reversed Field Pinch (RFP) behavior is believed to be dominated by MHD activity. Indeed, MHD modes are responsible for the sustainment of the discharge itself. The major issue faced by RFPs is whether these MHD modes limit confinement to the point that the device is unable to scale to a reactor.

Kinks and Tearing Modes. These modes require wall stabilization and are driven unstable by gradients in J_{par}/B. Resistive diffusion will lead to profiles that are unstable to these modes. These modes then nonlinearly provide the sustainment mechanism that counteracts the diffusion and maintains the plasma. They also undergo global reconnection resulting in stochasticity and rapid transport in the plasma core.

The major issue is whether the transport these modes induce is tolerable at reactor conditions. Definitive scaling studies (i.e. expanded parameter ranges) of δB/B with the Lundquist number (S) along with careful comparisons with experimental data need to be done. It is also likely that fluctuations will scale with other parameters such as viscosity and the Hall parameter. These possibilities should also be explored.

If these fluctuations do not scale adequately in the MHD model, a number of mitigation schemes exist. One is flow stabilization coupled with two fluid effects. A second is poloidal current drive with rf. MST has shown improved confinement with inductively driven poloidal current drive and has plans to consider rf drive experimentally. A third is pulsed operation, which does not require relaxation and can allow maintenance of profiles that are stable to these modes.

Resistive g Modes. RFPs have bad curvature everywhere ($q < 1$) and thus are MHD unstable to resistive g (interchange) modes for all modes which are resonant in the plasma. Detailed studies of these modes with large spectra, extended S values, and non-ideal effects are needed.

Locked Modes. There are two types of locked modes: those locked to the shell and those locked to the field errors. The MHD model predicts that instabilities will lock to the conducting shell and grow on the resistive wall penetration time. Field errors also provide a seed that allows the plasma to lock to the errors. Thick shells can mitigate the resistive wall modes, but they impair vertical field control and can lead to mode conversion and field errors. Thin shells allow for adequate vertical field control, but can lead to wall modes. The major issue is whether plasma flow allows for an operation window that eliminates both resistive wall modes and field error locking. The opportunity is to study this with extended MHD models including flow and two fluid effects. If locked modes cannot be mitigated by rotation, an opportunity exists to investigate a number of other schemes such as feedback stabilization, “smart” shells (which simultaneously control multiple modes), and shear flow liquid metal walls.

At present the resistive wall mode data base in RFPs has only two data points, one from HBTX-1C and one from OHTE. Both of these experiments were done 10 years ago and no systematic studies (varying shell thicknesses, etc.) were possible. A small experiment with easily changeable shell resistance would be useful to study wall stabilization schemes.

Current Drive. Current drive schemes can be divided into two categories: profile control (discussed in Section 2.1) and current sustainment. Lower hybrid current drive is a possibility for profile control and has been proposed for the MST device. Theoretical as well as experimental studies need to be conducted in this area.

The primary proposed scheme for current sustainment is oscillating field current drive (OFCD) which involves helicity injection via properly phased ac fields. The MHD mechanisms involve an interplay of the kinks and tearing modes discussed in Section 2.1 along with a current penetration mode (global Kadomtsev reconnection) which yields poloidal flux generation. The modes necessary for OFCD to work have been identified, but the self-consistent interplay required for current drive has not been demonstrated. The opportunity is to address these issues at high S with MHD/Extended MHD models.

2.6. MHD Issues for the Spheromak (L. LoDestro)

Among the attractive features the spheromak offers as a fusion reactor are its ideal MHD stability at high engineering beta, without the need for active radial profile control. It has been demonstrated experimentally that the core (closed surfaces) plasma current can be maintained by driving an edge (open field-line) current, which is transported to the interior by magnetic fluctuations. The fluctuations also cause energy transport. The challenge is then to maintain the favorable configurational advantages of the spheromak while also maintaining adequate confinement and macroscopic stability. The MHD model should well extend to a cold, collisional edge plasma. The main research directions and needs are summarized as follows.

Global External Instabilities of the Plasma Core.

- Ideal, non-resonant, current-driven modes, primarily $m = 1$: the tilt/shift ($n = 1$), bending ($n = 2$), etc., modes. In a sufficiently oblate plasma, a moderately close conducting wall stabilizes the modes. Remaining issues: reassessment with an edge plasma; RWMs.
- Ideal and resistive resonant $m = 1$ modes. In RFPs, these extend from the magnetic axis to the wall and are thought to cause the large transport inside the reversal surface.

Central-Column Kink(s). Screw-pinch like instability of the edge plasma is associated with the current-drive mechanism. Coupling to core harmonics could be significant (tight aspect ratio; mode-rational surfaces, including a 1/1, packed near the separatrix).

Transport-Relevant Modes. Since $q < 1$ and q' is weak and often negative, both ideal and resistive p'-driven instability is expected (although the bootstrap is stabilizing).

Ideal MHD beta limits have been found; for particular profiles (not near relaxed), these can reach 30%–40%. Other results indicate that operating at beta values up to 2–3 times the Mercier limit might be possible. Such values have been found to be stable in experiment; in simulations at these beta's, the most unstable modes were at moderate n and m, were highly localized around the resonant surfaces and had extremely small growth-rates.

Resistive modes in the core will transport both current and energy, driving the plasma towards a relaxed state. Scaling arguments for a continuous dynamo indicate a magnetic-fluctuation energy $\tilde{W} \propto 1/S$, where $S \equiv \tau_{\text{Alfvén}}/\tau_{\text{res}}$; if islands overlap across the plasma, then $\tilde{W} \propto S^0$. With

1/S scaling, energy is confined well enough for a steady-state reactor. However, sustained spheromaks in the past, which had $q \geq 1$ at the magnetic axis, showed no clear S-scaling and had poor confinement. The crucial transport problem might then be stated: to design equilibria such that the fully evolved MHD spectra yield a core $\tilde{W} \propto 1/S$. Consistent with the picture of a continuous dynamo with low-amplitude, fine-scale fluctuations is a system with small free energy, i.e., a nearly relaxed state, at least within the closed surfaces. At low beta, the problem is then to find axisymmetric equilibria with

- Nearly flat $J_{||}/B$ while $1 > q > 0.5$ over most of the core, eliminating resonant $m = 1$ modes;
- Few and well-separated low-order $m \geq 2$ resonant surfaces;
- Sharply decreasing (inside ψ_{sep}) unstable eigenfunction(s) of the driven edge plasma;

and to understand the low-order island widths, including effects of the fine-scale fluctuations. The external control variables (apart from active profile control) include S; the shape of the vessel; the PF coil set; and the edge-current distribution and boundary conditions.

We think resistive MHD should be explored first. When considerable understanding has been built up and promising avenues identified, self-consistent inclusion of the full array of two-fluid effects would be warranted, both for improved quantitative analysis and for the possible performance gains to be realized by exploiting the additional physics, e.g., the ratio ν/η. Possible exception: if toroidal rotation significantly exceeds ω_*, as there is some experimental evidence it does, then it should be included at a relatively early stage.

Major Cross-Cutting Need. Three-dimensional MHD codes with current on the open field-lines. At present, NIMROD is the only such tool. Both ideal and resistive linear codes are needed for benchmarking NIMROD and for more convenient and rapid general use.

2.7. MHD Issues for the FRC (L. Steinhauer)

Non-MHD Stability. The stability of FRCs is the result of effects outside the standard paradigm of ideal MHD with static equilibria. This stability is achieved despite a vanishing safety factor and without the benefit of magnetic shear. The likely explanation is a combination of finite ion orbit effects (FLR), two-fluid effects, flow shear, and a “charge uncovering” effect related to the precession of trapped particles. Each of these is a correction on the basic MHD model, and should weaken as the size parameter ρ_i/a (Larmor radius / minor radius) becomes somewhat less than unity. Even so FRCs have been generated with ρ_i/a as low as 1/5 without evidence of instability. This is not explained by the best available FLR theory. The possibility arises that the non-standard effects may produce stability for ρ_i/a somewhat lower than expected. Since these nonstandard phenomena are present in all magnetic fusion concepts, FRCs offer a unique testbed for exploring them and their stabilizing potential.

Flowing Equilibrium. A flexible algorithm for computing flowing equilibria needs to be developed in order for stability computations to proceed. These equilibria have a bewildering complexity: they are defined by six arbitrary surface functions compared with two for Grad-Shafranov equilibria. An important clue that may simplify this arises from the equilibrium states of minimum energy, which are specified by only three arbitrary parameters. These states arise because of the existence of magnetofluid invariants for each species (the self helicities) plus an angular momentum constraint (if the boundary is axisymmetric).

Nonstandard Stability. Once an effective equilibrium solver is in hand, the broad enterprise of stability analysis and computation can proceed. At present, only a variational principle exists for a flowing two-fluid, and a separate FLR theory for a static one-fluid. These theories, still in their infancy, must be brought to maturity. Hopefully, intuitive paradigms are in the offing once the implications of the two-fluid invariants are better understood. In addition, two-fluid simulations need to be given broad use to allow them to mature as well.

FRCs as a Testbed for Peculiar Phenomena. Little detail is known about the inner structure of FRCs. However, the two-fluid theory predicts several peculiar phenomena connected with the relaxation to a stable state. (1) *Rapid restructuring process*. Without a stabilizing toroidal field, this takes place in a few Alfvén times. (2) *Spontaneous flow shear generation*. The relaxation toward the state of minimum energy generates counterflows through nonlinear mode-mode interactions. (3) *Continuous "metabolism" of quiescent FRCs*. The same relaxing processes should counteract influences that evolve the equilibrium (resistivity, viscosity) and maintain the FRC very near a state of minimum energy. (4) *Edge-core coupling*. Rapid outflow of plasma in the scrape-off layer should cause the edge plasma to depart from the state of minimum energy. The resulting "local instability drive" will couple to the relatively stable core plasma in ways that need to be understood. The presence of these phenomena, the result of theoretical predictions, needs to be verified by detailed measurements of the magnetic and flow structure of FRCs.

2.8. Issues and Opportunities in Disruption Research (A.G. Kellman)

Disruptions represent a potential obstacle to the achievement of an attractive magnetic fusion reactor. There are two main challenges to the fusion research program: either to eliminate disruptions or when that is not possible to reduce/mitigate the effects of disruptions. The most desirable approach to the disruption problem is to eliminate disruptions entirely. Three approaches include: (1) disruption avoidance via passive techniques, (2) avoidance via active profile regulation while maintaining passive stability, and (3) avoidance utilizing active feedback control of the instability.

In the simplest approach, the plasma is passively stable, the profiles are unregulated and the research has focused on identifying the causes of disruptions and the stability boundaries. Our understanding of the ideal stability boundaries in a tokamak is extremely good, but theoretical calculations of the resistive stability boundaries and island evolution are less advanced. Answers to these questions require experimental studies of 3-D magnetic structure and improved measurements of the details of the plasma state. Non-ideal and kinetic effects are needed to adequately model the threshold and the non-linear evolution to disruption. A more promising, short-term goal using the NIMROD or M3D codes is the prediction of the marginal saturated island size above which the plasma evolves to a disruption.

Profile optimization via active regulation of the profiles permits higher performance levels to be obtained while maintaining passive stability. Theoretical effort is required to calculate the optimized profiles. The major experimental issues involve the development of actuators for profile control (e.g. ECCD), and of real-time profile measurement. Real-time stability boundary identification is needed to trigger a secondary disruption avoidance feedback loop or to initiate a pre-emptive termination sequence. The proposed QAS stellarator represents an alternate opportunity to achieve high performance without disruptions by using external coils to provide shear and shaping while maintaining passive stability.

Further improvements in plasma performance can be achieved by exceeding the limits of passive stability through active feedback control of the instability. Feedback control of the axisymmetric instability is in routine use in all shaped tokamaks. This approach requires the development of the theory of stability control, including the plasma response model, development of the control actuators, and real-time measurement of control parameters. Feedback stabilization of the resistive wall mode using external coil systems and of the neoclassical tearing mode using ECCD are areas of active research.

Even with successful implementation of an active feedback system, any device must be able to survive the worst case disruption resulting from a failure of the feedback system. To achieve this, one must be able to predict the disruption forces and heat loads in future devices. Considerable progress has been made in the prediction of axisymmetric halo currents and current decay rates. However, significant issues remain in the understanding and prediction of non-axisymmetric halo currents, thermal quench times, the spatial deposition of the heat flux, and runaway electron generation. For the last topic the major issues involve the structure of the field lines during the disruption and their influence on runaway generation, and the role of plasma instabilities or plasma-beam instabilities.

Techniques for mitigation of disruption effects include solid or gas injection and operation at the neutral point of the vertical instability. On present devices the injection of impurity pellets or massive gas puffing has successfully reduced halo currents by more than 50%, almost eliminated the toroidal asymmetry of the halo currents, and significantly reduced the heat flux to the divertor by radiating most of the energy. Runaway electrons have resulted from impurity pellet injection but not from gas puffing. Simulation of impurity pellets in ITER indicates the generation of energetic runaway components, so proposals for mitigation in reactors have focused on liquid D_2 jet injection or massive gas puffing. Issues of liquid jet transport and stability, runaway generation, and anomalous penetration of the massive gas puffs must be understood and evaluated for large devices. Finally, all the methods studied to date are pre-emptive, requiring either precursor signals or development of real time disruption boundary identification. No system has yet been developed to provide mitigation once the disruption begins.

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APPENDIX: TALKS PRESENTED TO THE MHD STABILITY SUBGROUP

MHD Issues for Magnetic Confinement Configurations

S. Sabbagh (Columbia Univ.), *Key MHD Issues for the Spherical Torus*
S. Knowlton (Auburn Univ.), *MHD Stability Issues for Stellarators*
A. Reiman (PPPL), *Stabilization of MHD and Neoclassical Tearing Modes by 3-D Shaping**
E.J. Strait (General Atomics), *MHD Stability Issues for Advanced Tokamak Plasmas*
M. Kissick (UCLA), *MHD Stability Issues for the Electric Tokamak*
L. LoDestro (LLNL), *MHD Questions and Tasks for Spheromaks*
L. Steinhauer (Univ. of Washington), *MHD Issues for the FRC*
R. Nebel (LANL), *MHD Stability Issues for the RFP*
D. Garnier (Columbia Univ.), *MHD Issues for the Levitated Dipole **

Other MHD Issues

A.G. Kellman (General Atomics), *Issues and Opportunities for the Disruption Research Program*
A. Reiman (PPPL), *Are Neoclassical Tearing Modes Responsible for Many of the Disruptions Observed on DIII-D?**
G. Navratil (Columbia Univ.) *Active Mode Control: RWM Control on DIII-D*
D. Gates (PPPL), *MHD Issues for Profile Control **
R.J. La Haye (General Atomics), *Need for Real-Time Current Profile Control to Avoid Neoclassical Tearing Modes **
L. Zakharov (PPPL), *A Tokamak Reactor with Lithium Walls **
M. Kotschenreuther (IFS), *Synergism between Liquid Metal Walls, Tokamak Physics Performance, and Reactor Attractiveness**
J. Drake (Univ. of Maryland), *Diamagnetic Stabilization of Edge Pedestal **
H. Berk (IFS), *Nonlinear Wave-Particle Interactions: Universal Structure, Applications, Opportunities **
A.D. Turnbull (General Atomics), *MHD Issues for a Burning Plasma **

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[*] Contributed talk.