Cross-cutting Tokamak/ST Research Needs for Stability and Steady-State Control

S.A. Sabbagh[1], J.W. Berkery[1], J.M. Bialek[1], D.A. Gates[2], S.P. Gerhardt[2], R. Goldston[2], C.C. Hegna[3], O. Katsuro-Hopkins[1], R. La Haye[4], J.E. Menard[2], Y-K. M. Peng[5], H. Reimerdes[1], E.J. Strait[4]

[1]*Columbia University*
[2]*Princeton Plasma Physics Laboratory*
[3]*University of Wisconsin*
[4]*General Atomics*
[5]*Oak Ridge National Laboratory*

<u>Goal</u>:

The goal of stability and steady-state control research is to generate physics understanding of high beta plasma stability that will produce reliable high performance, continuous plasma operation with both negligible stored energy and neutron output fluctuation, and determination of optimal plasma operating conditions and control systems allowing confident extrapolation to future tokamak and ST burning plasmas (spanning from upgrades of present devices to DEMO-level plasma conditions).

<u>Knowledge gaps</u>:

The knowledge gaps can be briefly summarized as follows:

- The underlying physics of high beta ST mode stability to support future device goals is only partially known. The self-consistent effects of plasma rotation, ion pressure gradient, temperature (collisionality), current and pressure profiles, and fast particles on modes, and the role of multiple modes need to be further understood to confidently predict the robustness of stability and control needs for future ST devices. This unexplored and unique operating regime at low aspect ratio, high beta, and low collisionality amplifies neoclassical trapped particle physics, which can be favorable or detrimental to stability.

- Present ST devices that are closest in performance to future ST devices demonstrate a probability of disruption and levels of instability-induced stored energy fluctuation that remain insufficient to confidently extrapolate to continuous operation. The negative impact of instabilities on plasma rotation, pressure, current, and discharge sustainment must be sufficiently understood and characterized to attain reliable avoidance or control of the instabilities in future devices.

- Greater constraints on the positions of plasma control coils, and reduced ability to vary plasma equilibria and profiles in future high neutron producing ST devices requires that determination of optimized, yet robust plasma conditions and equilibria, as well as extrapolable control techniques, must be scoped out and developed before such devices are constructed.

(I) High beta operation and sustainment:

Stability advantages of the ST have been demonstrated in plasmas at the megampere level, and an extensive database exists with high toroidal beta, $\beta_t \equiv 2\mu_0\langle p\rangle/B_0^2$ up to 39%, high $\beta_N \equiv 10^8\langle\beta_t\rangle aB_0/I_p$ up to 7.2, high energy confinement (τ_E / $\tau_{E\ ITER\text{-}89P}$ > 2.5), and β_N to internal inductance ratio, β_N/ℓ_i exceeding 11 (ℓ_i ~ 0.5) in plasmas with relatively broad H-mode pressure profiles, favorable for high beta stability. Ratios of β_N to the ideal no-wall stability limit exceed 50% at the highest β_N values. High beta ST plasmas have been created and sustained for times greater than three plasma resistive timescales at approximately 1keV electron and ion temperatures.

It is important to appreciate that these significant results for ST plasmas created in the past decade are a necessary, but not sufficient set of results to ensure continuous operation at the plasma performance levels of an ST-CTF or ST-DEMO. Sustained operation at design parameters is uncertain for several reasons: (i) the low l_i (approximately 0.35 for ST-CTF, and lower for ST-DEMO) specified in the designs will make them more susceptible to the current-driven kink mode, which by definition is unstable at any value of β_N . It is therefore crucial to understand and characterize the robustness of low l_i stability to variations in current, pressure, and plasma rotation profiles, (ii) the low l_i yields very high ratio of β_N /l_i (exceeding 17 in ST-CTF). This operational regime should be accessible with RWM stabilization via plasma rotation and mode control, but needs to be further supported via theory and experiment, and (iii) reduction of β_N to operation below the ideal no-wall limit does not ensure robust, continuous operation. The issues include the reduction of stabilizing plasma rotation via non-resonant magnetic braking caused by resonant field amplification (RFA) by stable RWMs, resonant and/or non-resonant braking due to tearing modes, ELMs, error fields at low β, and destabilization of global MHD modes due to transient improvements in transport with related increases in β_N. Significant tearing mode (including neoclassical tearing modes or NTMs) activity (e.g. 2/1 mode) causes beta saturation, loss of V_ϕ., and locked mode-induced disruption, so it must be avoided or mitigated. This mode evolution suggests ways in which feedback control – of mode amplitude, beta, plasma rotation, and pressure and q profile – can be specifically used to reduce deleterious effects with high reliability.

The higher β_N and lower l_i levels planned for DEMO have not yet been sustained for durations on the order of the plasma resistive timescale in present ST devices. It is also envisioned that a DEMO device will not have the advantage of a significant, favorable level of stabilizing plasma rotation that an ST-CTF will have. This is significant as the present control of RWMs by conversion to a damped, rotating kink[1], or the avoidance of NTM locking leading to plasma disruption, may require an external momentum source. Since the present planned capabilities and goals for the ST-CTF do not include the capability to research variations of these equilibria, research supporting DEMO regarding the stability and control of these plasmas must be accomplished in devices that precede, or run in parallel to ST-CTF.

High plasma shaping, with record shaping factors and elongation up to 3 has been demonstrated at low l_i, which is more favorable for both passive and active mode stabilization, including n = 0 (vertical stability). Highly shaped, high β plasmas have largely avoided Type I ELM activity, however this is expected to change at the higher pedestal gradients expected in future ST devices. Understanding and either stabilizing or mitigating ELMs when they appear is vitally important. ELM mitigation with high edge confinement and V_ϕ through lithium deposition is a recent favorable result. The application of non-axisymmetric fields has shown that ELM dynamics can be altered and the mode destabilized, indicating a potential method of control.

At levels of β_N achieved in present ST devices, the excitation of multiple RWMs (with the same, or different toroidal mode number) has been theoretically shown to be an issue, with evidence from present experiments.[2] The role of multiple modes during n = 1 control is presently under investigation in ST experiments.[3] The existence and characteristics of multiple modes (stable modes leading to resonant field amplification, and/or unstable modes) must be understood to design robust feedback systems of direct mode suppression or beta control for continuous plasma operation.

Continuous operation at high β_N and low l_i will involve a self-consistent coupling of passive stabilization and active control. The physics understanding of passive stabilization, including stability to expected transients, and the control needed to sustain stable conditions are a key focus of this research, which will require plasma conditions of increased ion temperature and lower collisionality to fully investigate. Another knowledge gap, which can begin to be addressed in present devices, is a characterization of the pulsed-averaged normalized beta, $\langle\beta_N\rangle_{pulse}$, the variation from this value, $\langle\delta\beta_N\rangle_{pulse}$, the instabilities that cause this variation, and the origin of these instabilities.

(II) Physics understanding of mode stability:

Research on macroscopic modes that cause significant $\langle\delta\beta_N\rangle_{pulse}$ and disruptions (RWM, kink, kink/ballooning modes, locked tearing modes, ELMs, and their triggers) has contributed to the present success of reaching high β_N in the ST. Further understanding needs to focus on the goal of continuous plasma operation. Kink and kink/ballooning modes rotating at levels comparable to the plasma rotation speed in co-NBI plasmas, and in the presence of a conducting wall, can be successfully stabilized up to the ideal with-wall stability limit. Sustainment of this condition requires sustained plasma rotation while guarding against significant transients in pressure and q profile due to variations in transport and heating (e.g. formation of transport barriers, alpha heating in burning plasmas). The physics of stabilizing the low l_i, strongly current-driven kink mode will need to be understood and verified. Operation with $q_0 > 2$, favorable for the elimination of 2/1 tearing modes, has not yet been demonstrated for many current relaxation times.

Resistive wall modes, which are effectively locked to the stabilizing conducting structure, have a more complicated dependence on β_N, l_i, plasma rotation, V_ϕ, ion temperature, collisionality, and gradients, with initial positive comparisons of experiment to kinetic theory being performed on NSTX[1] and DIII-D[4]. For example, intermediate levels of V_ϕ can be unstable depending upon proximity to kinetic resonances. Discovery of an RWM stability model with sufficient physics to describe experiments is needed. Present models show the importance of ion collisionality and fast particle population for mode stabilization. These models need to be verified in conditions as close to future ST burning plasma devices as possible. RWM triggering by other modes[5] leading to changes in the stabilizing energetic particle population (e.g. EPMs, ELMs) needs to be understood. Present theories of multiple RWMs (multiple modes of the same n value, and multiple n values) also need to be tested to support control system design.

ELMs can lead to significant perturbation of the plasma stored energy. Criteria for permissible levels of fusion neutron flux excursion need to be evaluated to determine the allowable $<\delta\beta_N>_{pulse}$. If ELM mitigation is needed, the corresponding research cross-cuts with ELM mitigation studies of plasma-material interface research, and also can share magnetic control systems used for RWM stabilization. As the present incarnation of these systems run effectively DC fields, with significant $\delta B/B$, the impact of the applied non-axisymmetric field on fast particle / alpha particle confinement (including the generation of localized high energy particle losses) will need to be assessed. A physics model remains to be found that explains ELM mitigation and/or alteration in present experiments. The vacuum Chirikov condition for island overlap may be a necessary, but is not a sufficient, condition for mitigation. Theories of field line loss are presently being tested.[6] Further theories need to be tested and applied to plasma conditions most closely replicating future ST burning plasma conditions.

Variation of stability as a continuous burning ST plasma moves away from a target equilibrium needs to be evaluated for variations seen in present devices, and those envisioned for future devices. Important variations including β_N, l_i, V_ϕ, T_i, ν_i, q, and q shear, p and T_i gradients, and fast particle population, were mentioned earlier, along with possible causes. In a burning plasma, an additional potential concern is control of local pressure gradients due to alpha particle heating. Control of local transport may be needed in such cases.

(III) Constraints on stabilization and control envisioned for future ST devices:

A knowledge gap is created by constraints on stabilization and control envisioned for future ST devices with significant neutron fluence. Mode detection and application of control fields by magnetic means have been the main approaches to RWM stabilization and ELM mitigation in present experiments. However, it is presently thought that the electromagnetic coupling of the coils to the plasma will be effectively reduced by moving the coils farther from the plasma, or shielding them to a larger extent (including the presence of electrically conducting blankets). Mode detection by magnetic means may also become a greater issue as eddy currents from nearby conducting structures may reduce signal to noise, and long pulse lengths may exacerbate issues with signal drifts and offsets. Research elements exist that should be further developed and applied to future ST designs including studies of the effectiveness of magnetic control coil options available to high neutron fluence devices, advanced control algorithms that may make shielded coils more effective for mode stabilization[7], and non-magnetic mode detection to be used in real-time for instability control[8].

(IV) Physics understanding for advanced control techniques:

Several physical effects explored over the past decade in tokamaks and STs are envisioned to be used in future ST devices as key components for several control systems. Understanding the physics and practical implementation of these effects are required in the ITER era for confident extrapolation to future devices. While discrimination and feedback on multiple-n RWMs has been demonstrated in RFPs[9] (where modes are largely decoupled), discrimination of multiple modes of the same n number may be important at the high β_N values operated in STs if low frequency MHD spectroscopy[10] is to be used for mode avoidance. The advanced RWM control algorithms mentioned above, while theoretically favorable, need to be tested on magnetic fusion devices. In devices with co-NBI and plasma rotation, control of V_ϕ can be had through non-resonant magnetic braking, which has been observed in NSTX to follow the theory of neoclassical toroidal viscosity (NTV)[11] Key questions remain regarding the scaling of NTV with ion collisionality[12,13,14], and the effect of applied field amplification and/or shielding[15], which must be experimentally tested to produce a verified physical model for application in real-time V_ϕ control systems to allow extrapolation to burning plasma devices..

<u>Scientific Research Needed to Satisfy Stability / Steady-State Control Issues</u>

(I) Control methods and physics - general considerations:

Applied non-axisymmetric (3D) fields are used to mitigate or control several modes in present devices (summarized in section II below). A key general consideration for field application by metal coils in high neutron fluence devices is the coil lifetime and maintainability. Key research includes modeling of neutron damage and stability performance for a given coil set position in any particular device. Other means of producing these fields include flow control of liquid lithium in hollow shells and control of scrape-off layer currents. Control of field phase using these techniques may be difficult, but may also not be necessary. These are advanced techniques that would require experiments coupled to advanced theoretical calculations of electrically conducting fluid and/or plasma flows.

Rotation control in rotating plasmas requires continued theoretical and experimental research of plasmas bridging ion collisionality between present devices and burning plasmas. Closed-loop control of rotation itself remains an advanced technique, with initial studies conducted in DIII-D, and only open-loop studies conducted in STs. A key experimental goal is to determine if non-resonant magnetic braking saturates, or continues to increase at significantly decreased ion collisionality (about an order of magnitude below presently achieved levels). The unfavorable scaling $\delta B^2 \varepsilon^{1.5}/\nu_i$ of non-resonant field torques on the plasma with decreased ν_i is theoretically expected to saturate as high E_r is generated by these torques. The uncertainly in the scaling of mode stability and torque balance for steady-state V_ϕ as a function of ν_i show the critical importance of producing lower plasma collisionality. Inducing plasma rotation in devices expected to have small rotation, such as ST-DEMO, is another key consideration and should be investigated in present devices and their upgrades (e.g. potential intrinsic rotation, NTV-induced rotation). Since 3-D fields are a primary source of rotation control, research considerations of 3-D field application may be needed for this research as well.

Pressure profile control is critical for continuous β_N operation. Core pressure gradient modification due to alpha heating can be modeled, formation of transport barriers, and transport reduction due to excited modes or 3-D fields can be modeled but will require experimental verification. Edge gradient modifications by 3-D fields and liquid metal walls will require both theoretical and experimental research.

Current profile control has greater considerations, which are covered in the section on RF heating and Current Drive. A consideration is that elevated $q_0 > 2$ still needs to be demonstrated for several current relaxation times along with a self-consistent pressure profile in a stable equilibrium. Strong shear reversal is a further consideration if desired, as it has also not been stably sustained.

(II) Research needed to tame instabilities for future ST devices:

All modes:

- Maintain β_N, expressed as an average over pulse lengths significantly greater than the current relaxation time (or the longest time of interest for maintaining parameters influencing stability), and minimize fluctuation from this value.

Kink/ballooning modes:

- Model self-consistent transport and equilibrium, and create experimental conditions determining the robustness of low $l_i < 0.35$ (below present ST experiments), high $q_0 > 2$ with high and low shear reveral, experimental ST pressure profiles (both L and H-mode) and departures from them, including the effect of low recycling walls (e.g. liquid lithium) on both pressure and q profiles.

- Create modeled optimal and robust equilibria using pressure, q, and rotation control techniques in experiments approaching ST-CTF levels of ion collisionality.

Demonstrate maintenance of stability through induced profile transients by passive or active profile and rotation control.

RWMs:

- Determine optimal 3-D field spectrum for control for future low l_i, high β_N ST devices. This should include modeling and experimental verification of error field control, resonant field amplification and dependence on β_N and ν_i in these conditions.
- Determine the robustly stable range of plasma rotation profiles to avoid unstable RWM bands of rotation found in present kinetic theory. Improve theoretical understanding of stability dependence on ν_i, and experimentally verify.
- Experimentally verify theoretical expectation of fast particle stabilization of RWMs at low ν_i.
- Determine the physics of EPMs as triggering mechanisms for unstable RWMs, in order to eliminate triggering.
- Multi-mode stabilization and control needs to be tested, experimentally verified, and diagnosed at high β_N, especially under active RWM feedback control, thereby eliminating loss of stability due to mode deformation (due to $n > 1$ and/or eigenfunctions with various poloidal mode number spectra) at low aspect ratio. This must be understood to optimize sensor, actuator, and feedback algorithm design.
- Determine requirements for control sensors (e.g. non-magnetic sensors) needed in steady-state, nuclear environment.

ELMs:

- Determine necessary and sufficient conditions for ELM mitigation and excitation in present devices. Once established, extend to pedestal pressure gradients and current profiles modeled for future burning STs, and in experiments that produce these profile conditions most closely.
- Determine optimal 3-D field spectra for ELM mitigation based on experimentally tested models and subsequent requirements for producing these fields (e.g. multi-purpose coils systems, or more advanced means)
- Determine methods of ELM mitigation or triggering to relax edge pressure gradients and current, or generally regulate confinement, without exciting other disruptive instabilities.

NTMs:

- Determine a comprehensive theory describing NTM physics to allow confident extrapolation to future tokamak and ST devices. An extensive database is available in the tokamak literature describing NTM threshold, seeding and saturation processes through a combination of analytic modeling and experimental investigation. Largely, different elements of the theory can be parameterized by a set of dimensionless numbers, normalized gyro-radius, measures of toroidal flow and toroidal flow shear, collisionality, etc. from which extrapolations and predictions of future devices are predicted. Present ST operation feeds into this physics program and helps firmly establish the relevant physics. Since STs operate in the extremes of normalized flow shear, plasma shaping,etc., it may be possible to identify a desirable operational region that makes STs somewhat less sensitive to the deleterious effects of NTMs. Of particular note to the ST, is the scaling with ρ* and with large flow/flow shear. As such, enhanced emphasis on ST relevant theory and computation in this area needs to be made. Coupled with this advance is the need to develop diagnostics that can probe the detailed structure of magnetic island physics in STs.

- Tools to address NTM physics and stabilization need to be developed. Upgrading present STs to higher magnetic field and current may provide a mechanism to viable scenarios that avoid NTMs. Additionally, detailed methods to control current and flow profiles need to be developed. Assessments of the use of localized current drive sources for active control of NTMS in STs need to be addressed. In particular, is localized ECCD a possibility at higher magnetic field? The ability to develop localized EBW current drive in STs may provide another mechanism to stabilize NTMs. In tokamak operation, there are principally two classes of mechanisms for dealing with NTMs. The first is NTM avoidance by operating with q profiles that avoid low order resonances. The second is to use active feedback by using localized ECCD current drive to stabilize the slowly growing NTMs. In present STs, NTM avoidance by operating with elevated q_{min} is the preferred method. However, present experiments are largely unable to sustain high performance discharges with elevated q_{min} and hence, NTM instabilities remain a prominent issue. Active feedback with ECCD is not available in present day STs due to relatively low magnetic field strengths.

Externally produced field transform to effect plasma stability:

- Determine requirements for vertical stability, kink/ballooning stability, RWM stability, and disruption avoidance and compare to experiments using 3-D field coils.

---

[1] S.A. Sabbagh, J.W. Berkery, R.E. Bell, *et al.*, *22nd IAEA Fusion Energy Conference*, Geneva, Switzerland, 13-18 October 2008, paper EX/5-1.

[2] S.A. Sabbagh, A.C. Sontag, J.M. Bialek, et al., *Nucl. Fusion* **46** (2006) 635.

[3] S.A. Sabbagh, R.E. Bell, J.E. Menard, et al., *Phys. Rev. Lett.* **97** (2006) 045004.

[4] J.W. Berkery, et al., U.S.-Japan Mode Control Meeting, Austin, TX, 2008.

[5] G. Matsunaga, Y. Skamoto, N. Aiba, et al., *et al.*, *22nd IAEA Fusion Energy Conference*, Geneva, Switzerland, 13-18 October 2008, paper EX/5-2.

[6] T. E. Evans, K. H. Burrell, M. E. Fenstermacher, et al., Phys. of Plasmas **13** (2006) 056121.

[7] O. Katsuro-Hopkins, et al., Nucl. Fusion **47** (2007) 1157.

[8] D. Stutman, M. Finkenthal, K. Tritz, “Multi-energy USXR array for the ITER Pedestal”, (1st USBPO Workshop on Diagnostic Development for Burning Plasmas, 2007)

http://physics-astronomy.jhu.edu/research/plasma_physics/ITER_pedestal_ME-SXR.pdf.

[9]L. Grando, G. Manduchi, L. Marrelli, *et al.*, *22nd IAEA Fusion Energy Conference*, Geneva, Switzerland, 13-18 October 2008, paper EX/P9-8.

[10]H. Reimerdes, M.S. Chu, A.M. Garofalo, et al., *Phys. Rev. Lett.* **93** (2004) 135002.

[11]W. Zhu, S.A. Sabbagh, R.E. Bell, et al., *Phys. Rev. Lett.* **96** (2006) 225002.

[12]K.C. Shaing, S.A. Sabbagh, M.S. Chu, *Plasma Phys. Control. Fusion* **51** (2009) 035004.

[13]K.C. Shaing, S.A. Sabbagh, M.S. Chu, *Plasma Phys. Control. Fusion* **51** (2009) 035009.

[14]A.M. Garofalo, et al., APS DPP Invited Talk 2008.

[15]J-K. Park, J.E. Menard, A.H. Boozer et al., ""Importance of Plasma Response to Non-axisymmetric Perturbations in Tokamaks", submitted to *Phys. Plasmas* 2009.