NSTX/NSTX-U Global Mode Stability Research Contributions Toward High Priority Research Topics for the U.S. Magnetic Fusion Program

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The US offers unique capabilities to conduct magnetic fusion science and technology research. A key area of US leadership in the world is in sustaining operation and control of high stability and confinement performance of plasmas by leveraging the spherical torus NSTX, and its upgrade NSTX-U. Several critical topics in the area of maintaining high beta plasma stability are briefly summarized below. These topics have been established as key research areas in the US magnetic fusion program during the USDOE ReNeW process (2009). Further detailed discussion can be found in the ReNeW document and are also concisely summarized in a table in that document [1]. The summaries below are organized by the recent FESAC charge questions under the topics: A) Contributions to Burning Plasma Science, and B) Addressing Challenges for Long-Pulse/Steady-State Operation.

High performance NSTX/NSTX-U research

A) Contributions to Burning Plasma Science

1) Global mode stability physics and maintaining long pulse operation

Global MHD instabilities (such as the kink/ballooning mode, and resistive wall mode (RWM)) are critically important to avoid or control as they lead to plasma disruption, terminating the discharge and leading to large, potentially damaging electromagnetic forces and heat loads on the structure of fusion producing devices.

While many targeted performance parameters have been reached in world tokamaks, such plasmas will need to be sustained for far longer pulse lengths in machines such as FNSF, ITER, and DEMO than have been produced to date. Research has therefore changed focus to examine sustained global mode stability over long pulses and to examine profile evolution for routine long pulse operation at high beta and at high non-inductive current fraction. Common to the following studies is the unique physics understanding and control ramifications that come from such operation, and the understanding and prediction of the effect of excursions from this condition due to transient behavior. It is especially important to realize that plasma operation under marginal stability points (set, for example by plasma beta, internal inductance, rotation) is insufficient to ensure disruption-free, continuous operation in either ITER inductive or advanced scenarios due to these transients in plasma profiles. Such transients can rapidly change a stable operational point to an unstable plasma state. Therefore, understanding plasma stability gradients vs. key profiles affecting stability is essential for all operational states in ITER.

(a) RWM onset and stabilization conditions under long pulse operation

The NSTX device has produced unstable RWMs which lead to disruptions, [2] and studies of mode stability have been conducted in past years. The research has produced several key characteristics such as the toroidal mode spectrum [3,4], and conditions for mode stability. Many characteristics are important and relevant to the present FESAC charge, and future research in NSTX-U is required for further understanding. First, plasma disruptions due to RWM instability are more likely to occur closer to the n = 1 no-wall stability beta limit than at higher values of plasma beta – a positive finding for operation at higher plasma pressure. Also important is the discovery that the RWM has been found to be unstable in conditions of relatively high rotation – a negative finding that highlights the importance of active mode control [5]. These characteristics are linked, and present research shows that kinetic RWM stability theory can explain the experimental results found to date.

NSTX-U will provide key capabilities for critical physics understanding based on present research in plasma operation regimes applicable to ITER and future magnetic fusion devices. In NSTX-U, operation at up to a factor of 4 lower collisionality, with an order of magnitude variation of this quantity, will experimentally substantiate present projections of RWM stability to lower collisionality based on kinetic RWM theory (Figure 1) [6]. The device will also provide plasma rotation control by novel means (e.g. using 3D fields to change plasma rotation in closed-loop feedback) and so allow more controlled studies of the impact of plasma rotation profile on plasma stability.

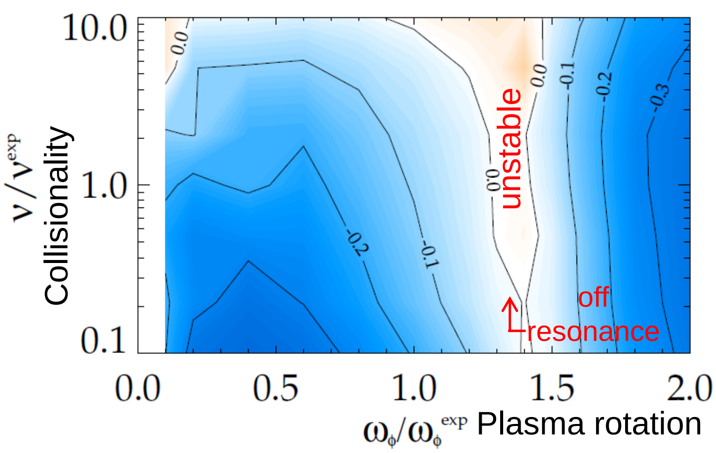

Figure 1: Computed effect of plasma collisionality on RWM stability (contours of normalized growth rate) as a function of plasma rotation, illustrating the effect of proximity to the ion-precession drift resonance.

(b) Current-driven kink onset and stabilization conditions under long pulse operation

Future fusion devices that operate at high non-inductive current fraction, largely produced by the bootstrap current, have low plasma internal inductance, l_i. At sufficiently low l_i, stability limits imposed by plasma pressure become substantially reduced (Figure 2). Eventually, the low l_i equilibria become unstable at *any* value of plasma pressure (beta), yielding a current-driven kink/ballooning mode, and plasma disruption. NSTX has demonstrated operation in this portion of stability space (Figure 2), with high non-inductive fractions reaching 65%. Understanding and producing long pulse operation near this purely current-driven kink limit is needed, especially as non-inductive current fractions reach 100%, and plasmas are operated without inductive drive.

NSTX-U will provide this critical operation regime, and stability research in this area is planned for the first years of operation of NSTX-U.

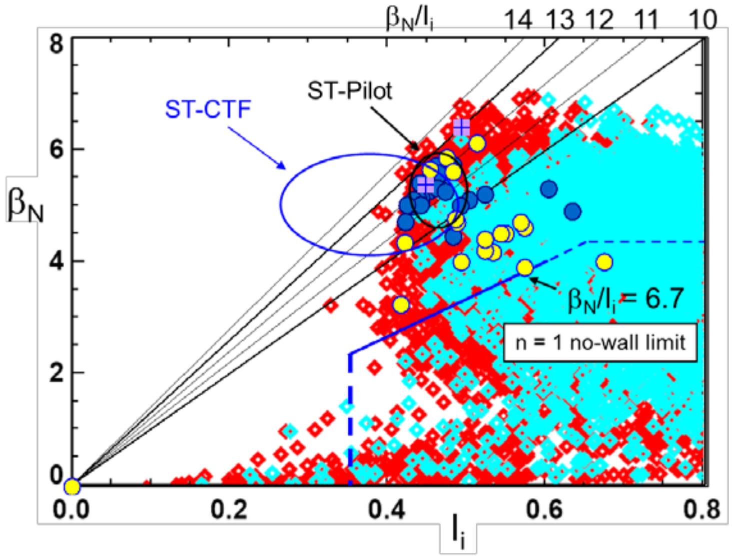

Figure 2: Operational stability space (l_i,β_N) in NSTX illustrating a higher number of disruptions (yellow circles) at intermediate values of β_N in dedicated control experiments. The sharp reduction of the n = 1 ideal no-wall stability limit as l_i is decreased is also shown, the vertical dashed line representing the approximate computed current-driven kink limit.

(c) Cause and characteristics of perturbations taking the discharge away from steady-state profiles, and ramification on mode stability

With significantly expanded profile control capabilities (e.g. q, plasma rotation), NSTX-U will allow greater ability to perturb these important profiles for investigations of how to prevent plasma disruptions excited from such excursions. Research on such disruption prevention will be conducted as a combination of active mode control and active profile control. Instability onset leading to modes growing on a relatively fast RWM growth time (milliseconds) will be actively controlled by an expanded RWM state space controller on NSTX-U, while concurrent active control of q and plasma rotation profile working on slower timescales (~50 – 100ms) will move the plasma back into a stable region. This will allow active mode control to be used transiently, which will reduce power needs, and will test the coupling of these two control techniques.

(d) The role of the fast particle profile in stabilizing beta-limiting and neutron-limiting MHD modes over long pule operation

Global modes are affected by the fast particle profile in high beta plasmas. Evidence of this has been reported in NSTX research, and continues to be an active area of research [7]. This is especially important for ITER, as a significant alpha particle fraction is expected to be required to stabilize ITER advanced scenario equilibria when utilizing the kinetic RWM stability theory tested on NSTX (Ref. [7], Fig. 5). The addition of three additional neutral beam heating sources on NSTX-U, all aimed at the plasma more tangentially than the present sources (farther from the magnetic axis), will allow a greater variation of the energetic particle profile to more fully quantify and verify its influence in the kinetic RWM stability model for further application to ITER and FNSF.

2) Three-dimensional physics effects and their use in fusion plasmas

(a) Stability-relevant plasma rotation control by non-resonant applied fields

As described above, the plasma rotation profile affects disruptive MHD instabilities. NSTX-U will build from years of experience with open-loop modification of the plasma rotation profile by non-resonant neoclassical toroidal viscosity (NTV), which is an inherently 3D field effect. The non-resonant nature of the damping force allows the plasma to be slowed in a controlled manner. Profiles with zero rotation over the outer half of the profile and very slow plasma core rotation have been produced. In NSTX-U, a greater 3D field spectrum than in NSTX will be varied in real-time to control the plasma rotation magnitude and profile. This new control system will be used to not only study and control global MHD modes and NTM stability, but also as a practical way to slow the plasma rotation to ITER-relevant levels for the most applicable physics studies for ITER.

(b) Investigation of neoclassical toroidal viscosity (NTV) physics by non-resonant applied fields

Certain key details of NTV physics, such as the magnitude and scaling of the steady-state offset rotation, differ between present devices, such as DIII-D and NSTX. NSTX-U operation will allow more definite conclusions to be made on this and other key NTV related plasma variables, including the important dependence on plasma collisionality.

B) Addressing Challenges for Sustained High Stability Performance Operation

Disruption prediction and avoidance have been two critical subjects addressed by active MHD mode detection and control for several years. NSTX research has prepared initial physics understanding and device capabilities for critical upcoming research on NSTX-U in these areas. Two important areas of research are briefly summarized below.

(a) Real-time stability detection for MHD modes to avoid crossing marginal stability boundaries under long pulse operation

The plasma response to applied 3D fields has been used to diagnose the stability of global, low-frequency MHD modes. Resonant field amplification (RFA) by the plasma of the 3D field has shown changes of the stable MHD mode growth rates as the plasma pressure increases and marginal stability points are approached [8]. The technique has been used in NSTX [3] and has recently been applied in real-time in DIII-D [9]. While research has been performed using this technique, it has not been extensively used and verified against marginal stability points of key global MHD instabilities. The use of this technique will be applied further in NSTX-U in the unique operational space (described above) which (in NSTX) has shown non-monotonic dependence of global mode stability limits on plasma beta and rotation. This technique will also be of great importance for diagnosing purely current-driven kink stability at low plasma internal inductance in plasmas with high non-inductive fraction (near, or at 100%). Additionally, the use of non-magnetic sensors to further expand this research is especially important for devices producing high neutron fluence, and is envisioned for NSTX-U as the sensors become available.

(b) Model-based advanced active feedback control of global MHD with multi-mode and real-time mode spectrum control

Computation of the multi-mode spectrum of ITER advanced scenarios (Figure 3) has shown that these plasmas exhibit a broader mode spectrum beyond the standard "single-mode" analysis that is typically conducted and that is used in tokamak mode control systems. Operation of NSTX-U plasmas in the high beta operational space accessible by the device will allow testing of the importance of this expanded mode spectrum to further improve active mode control.

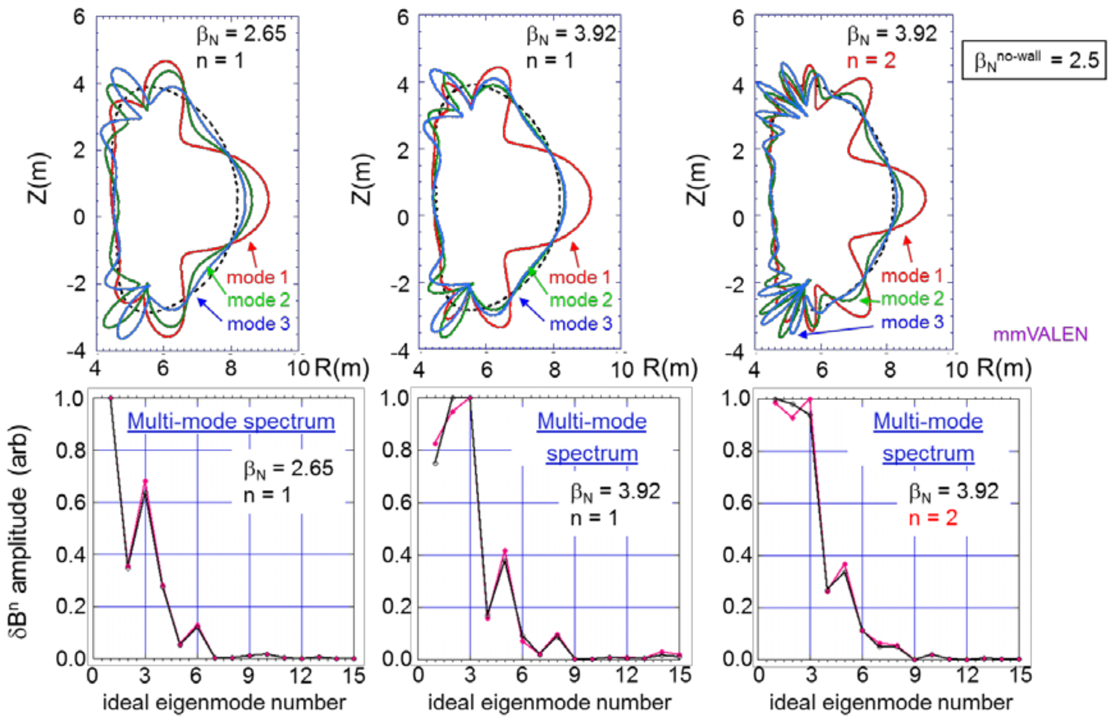

Figure 3: Multi-mode RWM analysis of ITER advanced scenario discharges, demonstrating a significant eigenmode spectrum in addition to the standard single ideal eigenmode typically assumed in control calculations.

In addition to the off-line multi-mode analysis capabilities used on NSTX, which is directly applicable to NSTX-U, the present model-based RWM state space control system initially used on NSTX (in plasmas that reached very high values of key stability parameters $\beta_N > 6.4$, $\beta_N / l_i > 13$) [4], enables the use of the multi-mode spectrum in real-time global mode control. The new NSTX-U capability of independent RWM coil actuator control combined with an expanded RWM state-space controller will allow multi-mode spectrum control enabling needed research to determine how varied details of the mode spectrum (including 3D mode effects), and 3D detail of the device conducting structure can improve disruption avoidance by improved mode control.

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