Response to Question 4b) from FESAC Panel Feedback to the ST Community

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Question 4b):

Macrostability: Are presently achievable and sustainable beta values sufficient to meet the requirements for the ITER-era goal? Are the scenarios for which these sustained beta values are achieved extrapolable to the ST goal? Are NTMs a concern for the ST goal, and if so, what control tools are needed to avoid or stabilize these modes? More generally, which instabilities have to be tamed, and which primarily will be studied to improve the broader knowledge base?

Response:

(i) Achievable vs. sustainable beta values

When compared simply as numerical values, transiently achieved beta values meet design points for the ITER-era ST goal (systems codes estimate β_N ~ 3.8 - 5.9 for 1 - 2 MW/m^2 wall loading, respectively). This is sufficient as an existence test, but insufficient as a criterion to judge sustainment. There are two critical details that must be addressed. First, the community has not yet agreed upon a specific design for a device that will fulfill the ITER-era ST goal. As suggested by DOE, attention has first been placed on determining the required science understanding needed in the ITER era. (it is expected that specific device designs and operating parameters will be proposed and reviewed as a next-step by the ST Community.) Second is the crucial distinction between transient achievement and sustained beta sufficient to meet the ITER-era goal.

With these important considerations in mind, beta values sufficient to produce high heat flux and neutron fluence for the ITER-era ST goal have most likely already been established transiently in one mega-Ampere class plasmas at less than 0.5 MJ plasma stored energy, with normalized beta, β_N, reaching 1.5 times the ideal n = 1 no-wall limit at the highest β_N values in the device and central safety factor $q_0 > 1$. While this is a significant experimental accomplishment, results are most likely insufficient to claim that sufficient beta values have been reliably sustained to meet the ITER-era ST goal with high confidence, as various elements conspire to significantly reduce plasma performance within a few current relaxation times in the longest pulse experiments to date.

Because of this, ST research began to advance several years ago to address high beta sustainment through avoidance and/or control of instabilities leading to significant degradation of neutron production, plasma beta, or elements causing plasma disruption, such as significant loss of plasma rotation. Key elements of this present research involve the understanding of stability and control of :

- Modes leading to disruptions: Global kink/ballooning, RWM (mode growth), NTM (mode locking)

- Modes leading to significant beta collapse/decay: internal kink, NTM, large ELMs
- Modes leading to significant loss of stabilizing plasma rotation: stable RWM (resonant field amplification (RFA)), NTM
- Modes potentially leading to reduction in fusion production efficiency: broad spectrum of Alfven eigenmodes

Without making reference to a specific design, ST plasmas used to fulfill the ITER-era ST goal will most likely need to operate near or above the ideal no-wall beta limit, and perhaps significantly above it if desired operation at further reduced plasma internal inductance, l_i, and elevated q_0 (see below) is used. RFA has been observed in high beta ST plasmas and in the JET tokamak (Gryazenvich, EPS 2008) significantly below (~ 0.5 times) the ideal no-wall beta limit, and the probability of kink/ballooning mode and RWM destabilization greatly increases as this value is approached.

Research planned in these areas will yield science understanding to determine the simplest techniques to curtail the deleterious effects on the plasma and allow the sustained high beta required to meet the ST goal with high reliability. This research is also a crucial test-bed for sustained high beta operation envisioned for operation of an ST power reactor.

(ii) <u>Extrapolation of scenarios for sustained beta</u>

The key to confident extrapolation of present operational scenarios for the ST goal of sustained high beta operation will come from on-going research addressing the physics of mode stabilization and control, and the effects of modes on key plasma characteristics determining stability, such as rotation.

When considering the most basic aspects of the high beta equilibrium, nature has fortunately provided a high beta ST operating scenario that extrapolates to the ST goal. The equilibrium is highly shaped for improved global stability, with low l_i that allows favorable bootstrap current alignment and is naturally amenable to passive kink/ballooning and RWM mode stabilization and RWM control. Low l_i is consistent with increased q_0 operation which is generally favorable for low and high-n kink/ballooning modes, RWM, and NTM stabilization. Also of primary importance for access to high beta operation is the broad pressure profile afforded by H-mode operation.

Extrapolability is therefore more a question of how mode behavior – stable, saturated, or unstable including secondary effects such as non-axisymmetric field-induced plasma torques including neoclassical toroidal viscosity – extrapolates to the ST goal. As one example, significant progress over past years has very recently produced controlled high beta plasmas through the combination of lithium deposition on plasma facing components, static $n > 1$ error field correction, and combined passive and active RWM control. Discharge pulse lengths are constrained by technical considerations of the magnet systems. Key to confident extrapolation of this result regarding stability considerations includes:

- Underlying physics understanding of NTM mitigation due to the application of lithium
- RWM destabilization physics at intermediate levels of plasma rotation
- Effect of reduced ion collisionality (stronger neoclassical effects) on RWM and NTM stabilization, and non-axisymmetric field-induced plasma viscosity (e.g. neoclassical toroidal viscosity)
- Physics understanding of RWM control, conversion to kink modes and subsequently to tearing modes
- Physics understanding of global mode destabilization in the absence of significant saturated NTMs
- Role of n > 1 fields, associated modes, and RFA

(iii) Role of NTMs, and potential control tools

As mentioned in greater detail above and in the FESAC ST document input to the FESAC TAP, NTMs are an important concern for the ST goal due to their negative effects. The modes might also play a positive role if sufficiently controlled. To summarize: (i) high amplitude NTMs cause significant plasma viscosity, mode locking, and plasma disruption, (ii) rotating NTMs reduce plasma beta. At sufficiently high amplitude, the rotating NTM typically causes a soft beta limit. While this is detrimental to maximizing plasma beta, the energy dissipation due to the mode has been shown to stabilize RWMs. In this way, low amplitude saturated NTMs could play a positive role if mode amplitude can be controlled. Key characteristics of the mode such as onset conditions as a function of beta and rotation are presently being examined, and the dependence on ρ^* can be compared to present tokamak experiments and investigated more fully in ITER-era ST devices operating at lower ρ^*.

Due to the natural high beta, low l_i equilibria envisioned for the ST goal, a potentially simple technique for NTM stabilization is to raise q_0 (e.g., $q_0 > 2$), thereby eliminating key rational surfaces for the most dangerous instabilities. Sustained ST operation with $q_0 > 2$ has not yet been demonstrated, but is possible through combined bootstrap and other non-inductively (NBI and RF) driven currents. At present, this approach is thought to be easier than successful NTM control demonstrated in tokamaks using RF waves targeted at particular rational surfaces, due to the overdense ST plasma. However, this consideration may change depending on the specific design of the next-step ST device and further investigation of using EBW for mode control in that design (ECCD is not thought to be a viable option).

(iv) Instabilities required to be tamed, and instabilities to be studied to improve the broader knowledge base

See the bulletized list in section (i) above for the instabilities that need to be tamed. Nearly all present ST research on macrostability is devoted to taming crucial instabilities and their deleterious effects, with basically no time given to study modes solely to improve the broader knowledge base. As the important characteristics of these crucial modes depend on high beta and geometry (high shaping, and low aspect ratio), this research additionally provides tests of key theory needed for confident extrapolation to future high beta devices and thereby improves the knowledge base - an additional benefit to the wider community.