April 3, 2002

Spherical Tokamak Theory Development Panel Report*

The spherical tokamak (ST) is a promising innovative magnetic fusion concept that has just begun to be explored experimentally over the past few years. It has already achieved volume-average beta values of about 25% (ohmic) and 40% (with auxiliary), and has the prospect of attaining near unity values – with good plasma confinement. Many theory and computation areas need to be developed to facilitate further development of the ST concept and scientific understanding of the experimental results being obtained. This report briefly summarizes the present ST theory and computation challenges and opportunities.

This ST Theory Development Panel* was appointed by Professor R.J. Goldston, Director of Princeton Plasma Physics Laboratory, on September 17, 2001. The *charges to the Panel* were to:

1) Assess the status and needs for theory and computation on spherical torus (ST) confinement systems, and identify high-priority opportunities for new ST theory research and computational tools.

2) Provide a vehicle for the ST experimental projects to communicate their needs and priorities to the theory community.

3) Suggest some vehicles for drawing in researchers not traditionally associated with ST research, but with interests and expertise that could contribute to, and benefit from, such a discussion, for example, on the effects of very low-aspect-ratio and high-beta on tokamak plasmas.

4) Produce a summary document/white paper, which could aid the NSTX PAC in identifying key ST theory issues, researchers in the preparation of proposals for ST theory research, and perhaps OFES in soliciting proposals for new ST theory research.

The *Panel modalities* were as follows: The primary experimental input to the Panel was provided by the Panel participating (some remotely) in the NSTX Results review that was held September 19, 20 at Princeton Plasma Physics Laboratory (PPPL). (Electronic copies of the talks presented at the NSTX Results Review are available through the NSTX web server nstx.pppl.gov, and in particular http://nstx.pppl.gov/results_review_2001/Results_Review_Talks_Page.html). The primary theoretical input to the Panel was provided by presentations to the Panel during the morning of September 21 on: Theory and Modeling on NSTX (J. Manickam, PPPL), Theory and Modelling for the ST (H.R. Wilson, Culham Laboratory), plus some specific topics. In addition, the Panel received a document on “Theory Participation in ST Research” (http://nstx.pppl.gov/nstx/Research_Program/National_Team/). The Panel met with M. Peng (NSTX Program Director) at an informal dinner meeting on the evening of September 20, and in executive session during the afternoon of September 21. After that week of intense Panel activities, the Panel chair presented (via remote videoconferencing) a preliminary summary of the Panel’s report to the NSTX PAC-11 meeting on October 4, the Panel began drafting this report, and a lunch meeting was held at the DPP-APS meeting in Long Beach, CA to discuss the draft and the feedback received from the NSTX PAC-11 on the preliminary summary of the Panel’s work.

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To provide a context for ST theory and computation developments, the Panel sought to identify the current missions of all ST experiments in the U.S. and the major ones abroad. The *current missions of ST experiments* are apparently as follows:

NSTX (national program at PPPL**):** explore unique and interesting plasma regimes at low aspect ratio (A, ratio of torus major to minor radius), high beta (β, ratio of plasma pressure to magnetic field energy density) in which the poloidal and toroidal magnetic field strengths are comparable. Specific near-term NSTX goals are:

FY02-03: Non-inductive-assisted ST operation leading to a preliminary assessment of ST plasmas for fusion research.

FY04-06: Non-inductive-sustained ST operation to assess viability of ST fusion systems.

Other U.S. ST Experiments:

Pegasus (UW-Madison): Explore tokamak-spheromak plasma regimes with ultra low A (~1) and high ratio of plasma current to toroidal field current, and test innovative heating and current-drive schemes.

HIT-II (UW-Seattle): Develop and explore coaxial helicity injection (CHI).

CDX-U (PPPL): Test liquid lithium wall concept, EBW emission as a T_e diagnostic.

MAST (Culham, UK):

Extend international tokamak databases to low A, high beta, low magnetic field regimes.

Explore possible roles for the ST in the route to fusion.

In addition, there are other smaller international ST experiments: GLOBUS-M (Russia; innovative RF heating and current drive), TST-2, TS-3,4 and HIST (Japan; HHFW heating and current drive, FRC-like diamagnetic ST plasmas, helicity-injection physics), ETE (Brazil; spherical torus plasma physics), and SUNIST (China; RF experiments). Clearly, there is a wide range of objectives for the ST experimental research programs – as there should be for a research program.

Thus, ST theory and computation challenges and opportunities lie in many different areas. However, given the emphasis of NSTX on non-inductive current-drive and the importance of this issue for the viability of an ST fusion system, of all the ST issues this is perhaps the most important one for ST theory and computation research:

<u>*Overarching ST Issue*</u>*:* Non-inductive current-drive in low aspect ratio ST plasmas.

Approaches For Increasing Involvement Of Theorists In ST Research

Before discussing the status and needs of the various areas of ST research needs, we address the third Charge to the Panel: *Suggest mechanisms for drawing in more theorists*. Addressing this now provides a context for the organization of the subsequent discussion of ST theory and computation status and needs.

The present level of involvement of theorists in ST research is definitely sub-critical – for facilitating optimum development of both NSTX research, and other ST experimental programs. At present, the funded level of PPPL theory and computation involvement in NSTX is 1.9 FTEs plus 2.3 FTEs in computational tool development. In turn, these NSTX-specific funded involvements leverage off the much larger PPPL Theory Department activities – a total of about 14 individual PPPL scientists are involved (fractionally) in various ST theory and computation research areas. In the rest of the U.S. fusion theory community, there are a couple of small NSTX-specific theory projects (mainly on edge turbulence and EBW modeling) and about 25 scientists working on various theory projects that relate to ST theory and computation issues. Thus, in the U.S. the total theory and computation effort devoted to ST issues is apparently about 6 FTEs (specifically identified, funded), plus perhaps another 4 FTEs from fractional involvements, which represent about 6-10 % of the approximately 100 theory and computation FTEs funded by OFES/DOE.

Possible approaches for increasing involvement of theorists in ST research are as follows:

1) *Programmatic:*

   The Panel commends Manickam's efforts in his developing role in facilitating and coordinating ST theory, both for NSTX and for the ST research area as a whole. This role should be more broadly recognized, encouraged and strengthened – with the hope being that much stronger leadership for needed ST theory developments will emerge over time.

   Concentrate the NSTX-funded physics analysis efforts on a few timely issues – to concentrate the very limited NSTX funds for theory support on fewer scientists who are closely involved in current critical NSTX-specific issues, and thereby facilitate more rapid progress on these issues.

2) *Theory*. Elucidate new theory challenges for the ST fusion concept and ST plasmas by:

   Distributing this Panel's white paper and other ST-theory-issue documents.

   Discussing ST issues in terms of the deep underlying physics issues and their importance to fusion, since such issues are the ones most likely to elicit the interests of bright new students entering the field.

   Identifying and expanding common plasma physics issues between the ST and other fusion concepts, thereby facilitating better understanding and allowing more efficient exploitation of synergies between different concepts.

   Highlighting key areas where new ideas could substantially improve the ST concept.

3) *Experiment.* Highlight current ST plasma mysteries (not just what is understood), since they often provide the dominant stimuli for theorists:

   Present talks at various meetings (particularly Sherwood) and institutions highlighting current ST plasma behavior mysteries.

   Publish papers that elucidate major ST plasma enigmas.

   At annual ST Results Reviews, involve theorists and update current ST mysteries.

   Strengthen diagnostics, particularly for transport-inducing fluctuations.

In the following sections of this Panel report we discuss the status and needs for ST theory in terms of six normal fusion theory programmatic areas.

I. ST Macroscopic Stability, Behavior Issues

There are several macroscopic stability issues that can and are being addressed by the NSTX and more generally the ST theory programs. These can be divided into two categories: issues that are essentially mysteries in the sense that there is a qualitative difference in the low aspect ratio NSTX experiment from that observed at conventional aspect ratios, and issues that so far appear to be an extension of conventional tokamak behavior to the lower aspect ratio parameter regime. Both are important components of the NSTX and ST programs and need to be pursued. However, this report is intended to focus on the first category; the issues that are more conventional extensions will only be summarized below. In addition, there are a few issues that are presently not a focus of the present NSTX program that can, nevertheless, be expected to become important in the near future as the experimental program continues to mature. These will also be identified.

IA. Macroscopic theory challenges

Several features of ST experiments make them unique in the fusion program. These are: i) the inherently strong toroidal effects, and ii) the fact that the plasma flow velocities and sound speed are of roughly the same order as the Alfven speed. The strong toroidicity affects macroscopic stability in two ways – the coupling of poloidal modes is large so that the poloidal mode number m is a poor ‘quantum number’ and the Shafranov shift and corresponding distortion of poloidal flux surfaces from elliptical (or inboard-outboard asymmetry) is inherently large, even at low β. Strong coupling of poloidal modes is also inherent in most present-day conventional tokamaks with strong shaping. Thus, while important, this is not essentially a unique feature of the ST. The large inherent Shafranov shift, however, is unique in the sense that it is important at any β in contrast to conventional tokamaks. In consequence, the ST has an inherently large stabilizing magnetic well that can have an important impact on ideal macroscopic stability. A related issue is that as a result of the large Shafranov shift, ST equilibria tend to have a large core region with low shear and an edge where the shear can be very large, with high edge safety factor for moderate total current. Again, however, this is not unique to the ST since it can also be true for conventional tokamaks.

The large sound speed and flow velocities relative to the Alfven speed are expected to result in important effects on the behavior of macroscopic stability not normally included in ideal and resistive MHD theory. Flow can affect the stability through modifying the equilibrium (centrifugal effects) or by directly affecting the stability (shear flow and coriolis effects). However, the centrifugal effects are second order in the flow speed compared to the sound, Alfven speeds. Thus, one can usually neglect the equilibrium modifications, at least to a first approximation. Similarly the coriolis term is generally negligible. The effects of sheared flows can also be ignored in most conventional tokamak experiments unless the growth rates and mode frequencies are much slower than the characteristic Alfven wave frequencies. For the ST, this is not generally the case. Strong sheared flows can be stabilizing or destabilizing. In particular, sheared flows can stabilize some instabilities by essentially breaking the radial coupling. However, they also provide an additional free energy source that can destabilize otherwise stable modes or destabilize new modes. In the ST, centrifugal effects can be important as well, though they are probably less important than the direct effects of sheared flows, which are lower order. If poloidal flows are important, particularly in the centrifugal terms, a two fluid description will be needed to avoid the well-known breakdown of the single fluid ideal MHD equilibrium description when the Grad-Shafranov equation becomes hyperbolic.

IB. Macroscopic experimental mysteries

Probably the major mystery in the ST program is the scaling of the non wall-stabilized optimum ideal MHD β limit. For conventional tokamaks, this is well described by the Troyon scaling $\beta_N = \beta/(I/aB)$, where β_N = constant (~ 3.5), or by more recent refinements, where $\beta_N = 4l_i$. For the ST, the inherently low l_i would give a low β_N limit, yet extensive theoretical calculations by several independent groups have found much higher β_N limits, even exceeding the nominal Troyon value of $\beta_N = 3.5$. Only part of the resolution of this issue comes from the arbitrariness in the toroidal magnetic field used in defining β; for conventional tokamaks one can use either the vacuum field at some nominal radius, which is the usual definition, or the average of the square of the field or the square of the average field, and the scaling remains valid since these definitions differ little. However, in the ST they can differ by up to a factor of two – still well above the $4l_i$ scaling. Experimental STs have also achieved high β_N well above the $4l_i$ scaling. Thus, the scaling of β_N with aspect ratio needs to be refined and the reasons for the additional stability needs to be identified. This may be due to the deep magnetic well, the strong coupling of poloidal modes, or the large shear typical of the optimized ST equilibria; while these are intimately related, it ought to be possible to identify the critical feature. It should be noted that even for conventional tokamaks, the optimum β_N is generally achieved with low central shear and high edge shear, with most of the pressure gradient in the high shear region; it should be verified if this is the major reason or whether it is really due mostly to the uniquely large Shafranov shift of the ST.

The role of current-driven modes in NSTX β limits is also somewhat puzzling, particularly in the wall stabilization experiments. Experiments and modeling suggest that the current-driven modes are wall stabilized and their resonant interaction with inherent error fields are causing a slowdown in plasma rotation. This apparently results in a loss of wall stabilization of the actual β limiting instability in NSTX at low q_{edge}. This is a significant operational difference from conventional aspect ratio experiments and needs to be well documented and investigated further. Several past calculations have indicated that current-driven modes at low q_{edge} are, in fact, more difficult to stabilize than at conventional aspect ratios, consistent with these observations.

More generally, there are expected to be several other significant differences in the wall stabilization of the ST compared to conventional aspect ratio. In particular, the present understanding from conventional tokamak experiments indicates that dissipation from prominent rational surfaces near the edge of the plasma and toroidal coupling of these poloidal harmonics to the core play key roles in the stabilization of the resistive wall mode (RWM) by plasma rotation. For the ST, this coupling is much larger and there are typically more edge rational surfaces that could contribute. This should be investigated further since the NSTX experiment provides a unique opportunity to study these effects. More important, however, is the effect of having the rotation speed a considerable fraction of the Alfven speed. This is expected to result in possibly qualitative differences in the behavior of the RWM in NSTX. Since wall stabilization experiments are really only just beginning in NSTX, now is probably a crucial time to systematically investigate the theory for these experiments by determining the predicted marginal wall-plasma separation and the critical rotation speeds for RWM stabilization.

Finally, the internal reconnection events that are commonly observed in STs (START, Pegasus, NSTX and MAST) remain a mystery. It is apparently still not known whether these are essentially ideal internal modes (with resistivity providing reconnection) or whether they are intrinsically resistive instabilities such as tearing modes. Also, it is not known whether they have any clear analogue in conventional tokamaks.

IC. New areas

NSTX has recently achieved H Mode operation. A critical feature of the H Mode in conventional tokamaks is the stability of Edge Localized Modes (ELMs). The current understanding from conventional tokamak experiments is that the ELMs are, in essence, ideal intermediate n kink modes driven unstable by a combination of the steep H-Mode edge pressure gradient and the local edge bootstrap current. A key question for future reactor-relevant regimes is whether the ELMs can be made small and more frequent, or even eliminated, in order to minimize their effect on the global plasma confinement and on heat loads to the divertor. In the near future, these issues will need to be addressed by the NSTX program and some initial theoretical and modeling work should be initiated.

ID. Other macroscopic stability issues

NSTX provides a unique opportunity to extend the conventional database of conventional stability phenomena to a new parameter regime. While these issues are similar to those of conventional tokamaks, it is important to utilize this facility to further our understanding in these areas. A few of these issues are identified below.

(i) ***Global kink stability:*** What are the current and q_{edge} limits in NSTX? Several past calculations have suggested that $q_{edge} < 3$ is either difficult or impossible to achieve at low aspect ratio. Is this a result of the use of conventional current profile parameterizations or is it more fundamental.

(ii) ***Sawteeth:*** NSTX experiments have shown the sawtooth inversion radius can be large due to the 'natural' low shear in the core, though some experiments have been performed in which the inversion radius was made small. Can the inversion radius be minimized in general and if not, what is the effect of the large sawtooth radius on the global plasma stability and confinement?

(iii) ***Resistive Modes:*** A number of issues arise here. Do neoclassical tearing modes (NTMs) ultimately limit β in NSTX? Nonlinear Glasser stabilization is predicted to be significant at low aspect ratio and there is a possibility that configurations could exist where it can exceed the neoclassical bootstrap destabilization. Scaling of both the seed island size and the critical seed island size of NTMs are not known and NSTX should provide unique insights on these issues. Finally, modeling for MAST has suggested that to properly model the time scale for the NTM, the resistivity used in the model needs to be increased by a factor 5 above the neoclassical value. (In contrast, neoclassical resistivity works well for conventional tokamaks). This should be investigated and confirmed or not by modeling for NSTX.

(iv) ***FLR and Finite Orbit Effects:*** While finite Larmor radius (FLR) and ion orbit effects are not unique to the ST, they are clearly more important in the relatively low magnetic field ST experiments.

IE. Summary of ST macrostability, behavior issues

Programmatic Issue:

How high a beta and low a q can be stably obtained in STs with good plasma confinement?

Theory Challenges:

Large, toroidicity-induced mode coupling (comparable to coupling from cross-section shaping) and associated large Shafranov shifts, together with large shear variation across the plasma.

Large flow compared to the sound speed and the Alfven speed.

Edge instabilities and the need to resolve sharp gradients in pressure and current density right up to the edge.

Experimental Mysteries:

What is the appropriate scaling of the β limit instead of the $4l_i(I/aB)$ scaling that seems to describe conventional tokamak beta limits so well?

What is the role of current-driven instabilities with and without wall stabilization, and in particular, with no wall stabilization is $q_{edge} < 3$ accessible?

II. ST Microscopic Turbulence and Transport Issues

IIA. Theory challenges

There are four characteristics of the ST configuration that present exciting challenges to theorists interested in small scale turbulence and transport:

1) ST plasmas may have local beta approaching unity.
2) The fraction of trapped particles may approach unity.
3) The ratio of the ion gyroradius to the major radius is relatively large.
4) ST equilibria are naturally highly shaped.

Any one of these properties alone would make the ST configuration significantly harder to simulate and understand than a conventional tokamak. Detailed, quantitative calculations of microstability thresholds, dispersion relations, turbulence characteristics and so on cannot be undertaken without new developments in the existing simulation codes, since there is no existing code that includes all these effects.[1] Moreover, understanding the simulation results will require more sophisticated theoretical treatments than have been routinely undertaken in support of the conventional tokamak research program.

The most exciting and broadly appealing scientific, micro-physics issues for STs are related to the nature of plasma turbulence at high beta and low collisionality, for the simple reason that collisionless, turbulent, high beta plasma is found to be ubiquitous in nature. There is significant interest in the wider scientific community in understanding small-scale ($k_\perp \rho_i < 1$) Alfvenic disturbances, the coupling of electromagnetic waves with one another and with the particle populations, signatures of local plasma properties in fluctuation spectra, and so on. Because the underlying instabilities and geometric factors are very different between natural and ST plasmas, it would be desirable to develop credible, first principles turbulence simulations of high beta, small scale turbulence, which could be compared in detail with turbulence characteristics measured in ST plasmas, and then used to simulate natural systems. This will clarify the role of the ST-specific properties such as the high ExB flow shear, large ρ_i/R, high fraction of trapped particles, and strong shaping in affecting turbulence characteristics, relative to the generic features of turbulence in high beta plasmas.

IIB. Experimental mysteries

In the fusion context, NSTX in particular already has experimental results that invite careful theoretical consideration. Unlike conventional tokamaks, energy transport in NSTX is evidently dominated by (possibly quite large) electron energy losses. Ion energy transport is possibly small, and possibly radially inwards. Particle confinement is good, perhaps as low as neoclassical. Although not

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[1] Early predictions of good microstability properties for STs did not treat the possible nonlocal physics associated with relatively sharp equilibrium profile variations on the ion gyroradius scale adequately, for example.

completely unanticipated, these results are not yet understood. One would like to know why the electron losses are relatively large, and why the ratio of electron to ion energy transport is so different. On the other hand, this property offers a nice opportunity to study possible mechanisms for electron thermal transport barrier formation. There has not yet been a clear identification and correlation of microinstabilities calculated for actual NSTX equilibria and profiles with experimentally inferred transport properties and fluctuations. Given 100 ms confinement times at a toroidal field of ~ 0.45 T, the theory community should attack this problem to determine whether these results "make sense," and if so, how the ST configuration should be expected to perform at higher fields and currents. Ultimately, it would be rewarding for the theory community to help find even higher confinement ST operating regimes. Experience with other devices and configurations suggests that we are in the early stages of ST research, with better performance to be expected.

IIC. Other turbulence, transport issues

There are many other interesting theoretical issues: extensions of neoclassical theory, interaction of microscale turbulence with neoclassical tearing modes, the role of microturbulence in sawtooth oscillations, the effect of turbulence in the boundary plasma on (for example) density limits, the possible importance of microinstabilities driven by fast-ion populations, self-generated zonal flows in electromagnetic turbulence, flow dynamics in the presence of a high fraction of trapped particles, and so on. Perhaps the most interesting problems have yet to be identified.

IID. Summary of ST microscopic turbulence and transport issues

Programmatic Issue:

How can transport be made as small as possible?

Theory Challenges:

Geometry at A~1, near unity trapped fraction, beta ~1, high toroidal rotation, large ion gyroradii.

Experimental Mysteries:

What causes high electron heat transport that far exceeds ion heat transport?

How can ion heat transport be understood? – anomalous ion heating, ion heat pinch, plus residual neoclassical?

III. ST Fast Particle Issues

IIIA. Ripple losses of beam ions and alpha particles

Are they tolerable in a ST reactor? The underlying physics is robust. However, a lot of specific work needs to be done to clearly define the operational window and to examine its sensitivity to the machine parameters. Guiding center codes may not be sufficient to accurately evaluate ripple losses in ST since the guiding center orbit excursions are roughly comparable to Larmor radii. Fast ions may even have non-adiabatic orbits. In particular, magnetic moment conservation may need to be reexamined, especially for smaller machines. This calls for full orbit codes. It is highly desirable that such codes incorporate the effects of electron drag, pitch-angle scattering and equilibrium electric fields – as well as relevant atomic physics effects. Apart from ripple loss assessment, these codes should also be able to systematically map the locations of various wave-particle resonances in phase space. This would provide very important information for subsequent studies of anomalous transport produced by fast ion driven instabilities, as the latter is typically associated with resonance overlap.

IIIB. Fast ion driven instabilities

NSTX experiments already indicate that compressional Alfven eigenmodes (CAEs) are excited by the beams in addition to shear Alfven modes. Not surprisingly, this very interesting observation has generated an enthusiastic theoretical activity. It is very important to ensure that this effort will result in an elegant and quantitatively accurate theory. The situation is very favorable and the opportunity to develop good science should not be missed in this case. The theory should ultimately provide a consistent description of CAE saturation together with a kinetic analysis of beam redistribution and plasma ion heating. A question of particular interest is whether an alpha channeling type scenario is a viable option for beam energy deposition.

It is clear that the low magnetic field in ST makes it easier for the beam to exceed the Alfven velocity, and that the large particle orbits should increase the number of possible wave-particle resonances. Linear coupling of shear Alfven modes to compressional Alfven modes and ion-acoustic modes is stronger in ST than in large aspect ratio machines. Large toroidicity creates large gaps in the Alfven continuum, which tends to broaden the family of discrete eigenmodes. On the other hand, high beta and linear coupling between the Alfven modes and the damped ion acoustic modes may help to stabilize Alfven perturbations. There is an obvious need in a systematic numerical search for weakly damped modes, since these are the best candidates for beam driven instabilities. However, it is not obvious whether one should focus very strongly on calculating the mode damping rates. It may be more productive to use the codes just to identify the mode frequencies and to combine these calculations with damping rate measurements in antenna excitation experiments. Such an approach may be particularly productive in STs since only low-to-moderate mode numbers are of primary interest and higher mode numbers are most likely stable due to FLR effects. A related thought is that linear growth rates always change significantly as instabilities reach nonlinear saturation, which happens very quickly on the plasma confinement time-scale. A really challenging goal is to develop self-consistent scenarios and predictive capabilities for the long-term nonlinear consequences of fast particle driven instabilities. This will require a very close interaction between analytic theory and simulations. The existing large codes alone are far too slow to perform broad parameter scans, not to mention that some pieces of relevant physics still need to be incorporated into these codes. Furthermore, the codes developed for conventional tokamaks are not immediately suitable for STs, and a dedicated effort is required to make proper revisions. Among specific assumptions that need to be relaxed are the ballooning approximation and the forceful elimination of compressional modes. Given the limited resources and somewhat patchy pattern of the theoretical and modeling activities related to NSTX, a stronger emphasis should be put on the relevance and internal consistency of the approximations used in both analytical theory and numerical models. This recommendation extends beyond the area of energetic particle physics. It may be helpful to pay more attention to revealing generic trends based on a first principles approach as opposed to semi-empirical data fitting.

IIIC. More ST issues involving energetic particle physics

Scalability of the energetic particle issues from present STs to a reactor.

Nonlinear description of wave-particle resonances for the needs of RF-heating and current drive. It appears that modification of the particle distribution function may affect the absorption efficiency. This should largely be an analytical work to provide a solid physics background for code development.

Can relatively large radial displacements of fast ions help to control plasma rotation by generating an equilibrium radial electric field? Recent theoretical studies indicate that this idea is worth pursuing further.

IIID. Summary of ST fast particle issues

Programmatic Issues:

Are ripple losses of beam ions and alpha particles tolerable in an ST reactor?

Do collective modes driven by fast particles degrade fast particle confinement?

Theory Challenges:

Large gyroradius and low aspect ratio (A ~ 1) properties of STs require a unified description of classical and neoclassical transport. This is especially relevant for fast particle transport.

Self-consistent description of mode saturation and fast particle transport in the presence of particle sources and multiple weakly unstable modes (steady-state turbulence versus bursty turbulence). This issue is strongly related to the general problem of anomalous transport.

Experimental Mysteries:

Are CAE modes responsible for the observed ion heating to $T_i > T_e$?

How does HHFW accelerate NBI ions above the injection energy?

IV. ST RF Wave Heating, Current-Drive Issues

IVA. Programmatic issues

Non-inductive heating and current drive are fundamental to the NSTX program and STs in general. The mission calls for understanding the physics of non-inductive start-up, current sustainment, and self-driven currents, and for machine operation with relaxed, non-inductively sustained current profiles, of which up to 70% is bootstrap current. Radio frequency (RF) waves in the plasma must play a key role in controlling the pressure profile driving the bootstrap current and in controlling the driven current profile complementing the bootstrap component. Success in these tasks is important for future development of the ST concept beyond NSTX. There are a number of challenges to meeting these goals. NSTX is in a new, comparatively unexplored parameter regime, both experimentally and theoretically, for ion cyclotron heating and current drive. There are serious questions of compatibility of high-harmonic fast waves (HHFW) with energetic neutral beam injected (NBI) ions or hot thermal ion plasmas. Electron Bernstein wave (EBW) heating and current drive, which is perhaps the best opportunity for spatially localized electron interaction in over-dense ST plasmas is even more in its infancy. To understand the physics in these new regimes and to untangle the non-linear interaction of the RF effects with transport and stability will require the capability for accurately predicting local RF power deposition, RF driven currents, formation of and interaction with energetic particle populations, and possibly plasma flow drive.

IVB. Theory issues

Calculation of RF effects in NSTX is particularly difficult compared to conventional tokamaks because many of the approximations that are presently used are of questionable validity for STs:

- Finite Larmor radius expansion – Typically $k_\perp \rho_i >> 1$, so the usual expansion to 2nd order in $k_\perp \rho_i$, particularly applied in 2D full wave codes, breaks down. This approximation also eliminates resonant particle effects from cyclotron harmonics higher than the 2nd.

- Local approximation in conductivity tensor operator – At high harmonics the cyclotron resonances are closely spaced. Also, the large value of B_P / B_T means that particles see rapid variation of |**B**| in moving along the field lines. Therefore, the usual assumption of well separated resonances and constant $\Omega_i, \mathrm{v}_{\|}, k_{\|}$ in calculating the parallel response, $Z\left(\frac{\omega - \Omega}{k_{\|}\mathrm{v}_{\|}}\right)$, breaks down.
- Geometrical optics – Although the large dielectric constant of NSTX plasmas ensures that $\lambda/r_{\min} << 1$, as required by geometrical optics, there is presently no rigorous way to represent the fields of a spatially distributed antenna as an initial distribution of rays. The rays from spatially separated points in NSTX tend to cross and become somewhat chaotic before being absorbed, raising questions of diffraction that are not included in geometrical optics. The ray tracing codes rely on the same "local" approximation to the conductivity tensor as do the full wave codes.
- Quasi-linear response of f_0 – Present wave propagation models are based on an assumption of Maxwellian f_0 which can be violated by RF-generated tail formation or by the presence of a fast ion population produced by neutral beam injection. Also, there are indications that at high power levels with current-drive phasing the electron distribution function can deviate from Maxwellian, calling into question the use of adjoint methods for calculation of current drive. The assumptions of zero banana width and conservation of magnetic moment, commonly used in calculating the ion response, can be violated for energetic particles in NSTX.

It is important to determine which of these approximations MUST be improved upon to understand wave physics in NSTX, and to find computationally feasible ways to do so.

IVC. Experiment/theory comparison

The experimental data so far on heating profiles is sparse and the modeling results are preliminary with relevant plasma parameter profiles just becoming available. So it is perhaps premature to identify any significant discrepancies between theory and experiment. However, there are some interesting observations that deserve ongoing attention. There appears to be very strong on-axis electron heating with very peaked T_e during HHFW heating. However some models predict off-axis electron heating. Also, the physics of the apparent internal transport barrier produced is not understood. Resolution of the relative roles of heating and transport in these observations will require accurate models of heat deposition, probably including accurate representation of the launched wave spectrum. Very preliminary experimental results show no difference in the plasma with co versus counter phasing of the antenna array. If this observation persists, it will be essential to understand its cause.

IVD. Summary of ST RF wave Heating, current-drive issues

Programmatic Issue:

Need to develop the capability and experimental verification, for accurately predicting RF heating and current drive profiles and non-inductive startup in NSTX and future ST devices.

Theory Challenges:

Many approximations presently used for RF calculations are known to be of questionable validity for STs (geometrical optics, local approximation in conductivity operator, FLR expansion in full wave codes, Maxwellian f_0). Of these, identify which MUST be eliminated, and how can they be eliminated in a computationally feasible way.

What is the underlying physics of Coaxial Helicity Injection (CHI) current drive?

Experimental Mysteries:

What is the physics of the apparent RF-induced ITB seen with early application of HHFW?

How are the large n=1 oscillations during CHI related to the formation of closed flux surfaces?

V. ST Edge, Divertor Issues

VA. Programmatic issues

An important programmatic issue for STs is the anticipated higher heat load on the divertor due to the smaller plasma volume and divertor plate area. Accurate models for predicting the heat load are a key element in going beyond present day experiments. An essential step in assuring the accuracy of these models is extensive benchmarking against experimental data. Models currently used for simulating steady state edge, scrape-off layer (SOL) and divertor plasmas in conventional tokamaks are 2-D (toroidally symmetric) fluid codes. These models typically assume classical transport along field lines and "anomalous" radial transport across flux surfaces. There are two possible approaches to the anomalous radial transport: 1) the transport coefficients are regarded as parameters that are adjusted to fit detailed radial profile measurements in the edge plasma; or 2) transport coefficients are derived from more detailed 3-D turbulence simulations.

The first approach to characterizing edge radial transport requires extensive two-dimensional steady state data on edge plasma profiles that is only now beginning to appear for STs. Although existing U.S. experiments do not yet have the detailed edge measurements required for benchmarking simulation codes, the MAST experiment has produced some detailed divertor plate profile data relevant to this issue. Fitting the transport coefficients by benchmarking against the MAST data could provide a good starting point for subsequent NSTX simulations. This empirical approach to characterizing radial transport in the edge plasma has at least two drawbacks: 1) a very large data set is required in order to characterize the many different operating modes for ST devices, e.g., beam-heating versus RF-heating, ohmic versus L-mode versus H-mode, H-modes with various ELM characteristics, and perhaps CHI-sustained plasmas; and 2) extrapolation to future ST devices may be problematic.

The second approach to characterizing edge radial transport requires computationally intensive 3-D turbulence simulations, but has the advantage that it can be applied to various devices because the dependence on fundamental plasma parameters is built into the model. Ultimately, however, it also requires benchmarking against experimental measurements of edge plasma profiles. Furthermore, for complete self-consistency the 2-D "steady state" and 3-D turbulence models of the edge plasma must be iteratively coupled to follow the evolution of the edge plasma to steady state, typically for tens of milliseconds. The coupling problem is non-trivial, but for reliable simulation results the equilibrium edge plasma model must be consistent with the turbulence model.

Liquid walls and/or divertor surfaces for controlling recycling and sputtering may provide a viable alternative to conventional plasma-facing materials for high heat flux components in an ST. Present experiments such as CDX-U are already addressing some of the sputtering and evaporation problems associated with liquid walls, so near term modeling of this alternative is needed in order to understand the results and assess the long term potential. Some edge plasma modeling has already indicated the relative strengths and weaknesses of candidate materials such a lithium, FLiBe, Sn and Ga with respect to core contamination and SOL temperature collapse.

VB. Theory challenges

Although fluid models of the edge plasma have been successful in simulating conventional tokamaks, new or modified models may be required for STs. Two characteristics of the edge plasma in an ST that distinguish it from the edge plasma in a conventional tokamak are: a) large ion gyroradius and b) low collisionality, especially near the outboard mid-plane.

Large ion gyroradius can impact edge plasma stability by changing the spatial characteristics of edge plasma turbulence and may require that simple diffusive models of radial transport in fluid codes be replaced by non-local transport models. Conventional fluid models for turbulence and SOL transport will need kinetic corrections and validation with respect to fully kinetic models and experimental data. Neutral particle transport near the outboard midplane may also require a kinetic treatment, especially if the dominant fueling source turns out to be recycling of energetic charge-exchange neutrals from the walls rather than divertor recycling. Monte Carlo models are an obvious choice for simulating the neutral gas component of equilibrium edge plasmas. The coupling of fluid and Monte Carlo models for plasma and neutral components has been demonstrated, but there may be new complications in the low collisionality, large gyroradius regime.

Low collisionality can result in a significant population of mirror-trapped (non-Maxwellian) ions near the separatrix. Ions escaping from the core plasma can lead to significant parallel heat transport in the SOL by energetic particles. The relatively short SOL connection length in an ST means cross-field transport will be less competitive with parallel transport, so SOL widths will be affected. Most likely this will lead to narrower heat flux profiles. The peak heat flux might scale differently with input power, depending on the core heating method and loss mechanisms for energetic particles. Energetic tail electrons can modify the parallel heat transport, sheath characteristics and SOL currents. Extensive SOL data and modeling will be required to sort this out. A three-way comparison of fluid models, kinetic models and experimental data is essential. Sputtering is also an issue if there is a significant population of energetic ions in the SOL; energetic electrons might modify sheath characteristics and hence the sputtering energy of incident ions.

Stability considerations, both macroscopic and microscopic, play a significant role in defining the equilibrium edge plasma characteristics such as the H-mode pedestal height and width. There is some evidence in conventional tokamaks that the width of the pedestal is determined by the neutral particle penetration depth near the outboard midplane while the height of the pedestal is set by ballooning or peeling mode stability. If the neutral penetration depth and stability limits are different in STs than in conventional tokamaks, one can expect different pedestal characteristics and perhaps different power thresholds for the L-H transition. Similarly, the transient heat and particle loads on the divertor due to ELMs may be different in the low-collisionality, large-ion-gyroradius regime of an ST. The magnitude, duration and frequency of the ELMs could be affected.

STs and spheromaks have similar requirements for sustaining a steady state discharge via CHI, so perhaps a joint effort with the spheromak community on the physics and modeling of CHI would be beneficial to both. Edge plasma and CHI issues are coupled in the sense that for sustaining a discharge the edge/divertor plasma is the interface between the injector electrodes and the core plasma where the toroidal current is to be driven. Some edge plasma models already incorporate plasma currents on open flux surfaces between divertor plates; identifying and characterizing the "diffusion" (via a hyper-resistivity model) of this SOL current into the core could be a step toward a self-consistent edge plasma and CHI model for both spheromaks and STs.

VC. Experimental mysteries

Global power and particle accountability in NSTX is a mystery at the present time, mainly due to inadequate diagnostics. Some important questions that eventually need to be answered are: Is the plasma fueled by recycling from the divertor plates or gas released from the walls? Is this different in NSTX and MAST and other STs? Are sputtered impurities radiating a significant fraction of the input power? Are energetic particles depositing power on the walls and producing enhanced sputtering sources? Do the impurities originate from the walls or divertor plates? An understanding of hydrogenic particle fueling, impurity sources and radiative losses is an essential part of global particle and power balance, which ultimately defines the heat load on the divertor plates. Plasma density and impurity control are also critical for auxiliary heating and current drive and probably CHI. The edge plasma is the medium that provides this control, so it needs to be understood at an early stage of ST development.

VD. Summary of ST edge, divertor issues

Programmatic Issues:

Smaller volume results in higher power loadings in divertor regions than conventional and advanced tokamaks. Benchmarked models for the SOL plasma are essential for current understanding and extrapolation to future devices.

Theory Challenges:

The ion gyroradius can be comparable to the radial gradient scale length of the outboard edge plasma. Conventional fluid models for turbulence and SOL transport will need kinetic corrections and validation with respect to fully kinetic models and experimental data.

Low collisionality in the edge plasma changes the pedestal and SOL region parameters of an ST relative to conventional or advanced tokamaks. Turbulent radial transport, the L-H power threshold, ELM characteristics and divertor plate heat loads may be affected.

Experimental Mysteries:

Global power and particle accountability in NSTX is a mystery at the present time, mainly due to inadequate diagnostics. An understanding of particle and energy transport in the edge plasma could lead to more effective plasma control in auxiliary heating and current drive experiments.

VI. ST Integrated System Issues

The success of the ST concept depends on developing high performance operational scenarios in which the plasma current is generated and sustained non-inductively. This requirement is predicated on not having an inductive capability in an ST power plant because of the lack of inboard space and because of potential neutron damage to a thinly shielded center stack.

Co-axial Helicity Injection (CHI) is one non-inductive discharge startup technique presently being developed on NSTX and HIT-II. The present belief is that large amplitude n=1 mode oscillations are necessary for the poloidal flux generated by CHI to form closed flux surfaces, although the precise underlying mechanism is not understood. Without sufficient knowledge of this mechanism, confidence in extrapolating CHI to larger devices and to an ST power plant will not be high. The importance of non-inductive startup to the success of the ST necessitates a high priority to developing an understanding various techniques:

- What is the underlying physics of CHI current drive? What conditions are required for flux surface closure?

The first question involves theoretical development in understanding the underlying physics. The second question can be addressed through modeling (e.g., nonlinear M3D, NIMROD type initial value codes, TSC simulations with anomalous resistivity).

- What are other possible techniques that can provide non-inductive startup?

This can be addressed by theory/modeling efforts to develop RF, NBI, or bootstrap current based techniques.

Once the ST discharge is established, the plasma current will have to be maintained non-inductively also through RF, NBI or bootstrap current based techniques. In order to generate significant current through RF or bootstrap drive, the plasma electron temperature and total beta need to be high. This requires the non-inductively driven plasma to also have good plasma confinement and stability properties. Furthermore, it is necessary to understand and be able to predict the interplay and symbiosis of these facets of plasma behavior in order to develop operational scenarios to achieve this goal.

- What is the effect of the current profile generated by bootstrap drive on the macrostability and transport properties of the core plasma? Can the bootstrap drive be sustained and be self-regulating?

Addressing this question will help determine whether plasma profiles can be produced that will drive sufficient bootstrap current (>70%), but at the same time not drive internal pressure or current-driven kinks and NTMs.

- What is the effect of low aspect ratio and large gyroradius (fast ion and thermal ion) on ideal and resistive/neoclassical MHD instabilities consistent with a current profile formed partially by non-inductive means?

This may be especially important for edge plasmas where even the thermal ion Larmor radii are of order or greater than the gradient scale lengths there. The importance of understanding the processes controlling edge stability also has ramifications in terms of being able to operate in steady state, since FLR effects may impact the ability to produce the “grassy” ELMs associated with stationary conditions. The Larmor radii of either the fast or thermal ions at the edge may be of order the wavelength of the mode responsible for the ELMs.

- It is necessary to develop a self-consistent treatment of the effect of RF on both electron and fast ion distribution functions, and to be able to determine the effect of these modified distributions on macro- and micro-stability, including fast ion driven modes

It is known that HHFW will interact with electrons, and both thermal and fast ions. Experimental measurements show that the HHFW can pull the tail of the neutral-beam-induced fast ion population out to almost twice the beam injection energy. Modifications of the distributions will impact the stability properties of the plasmas, especially the fast ion and current-driven modes, the equilibrium properties of the plasma through changes in stored energy and driven current profiles, and, therefore, the subsequent RF wave propagation and absorption profiles. It is essential to develop a self-consistent description of this physics in order to understand present day experiments and to be able to predict with confidence the performance of next step devices.

- Do the processes controlling transport (i.e., microinstabilities) limit the electron and thermal ion temperature and density gradients, and thus the ability to drive bootstrap current?

If the plasma profiles are near a marginal stability condition for microinstability, and if the profiles are stiff, the amount of bootstrap current that is driven can be limited. It is therefore important not only to understand the underlying processes controlling transport but also to determine self-consistently how the bootstrap current drive, as well as the plasma microstability, is affected.

VIA. Summary of ST integrated system issues

Programmatic Issue:

Need noninductive-sustained ST plasmas at low A, high beta, high bootstrap current.

Theory Challenges:

Effect of low A and large gyroradius (fast ion and edge thermal ion) on ideal MHD instabilities consistent with a current profile formed partially by non-inductive means (i.e., bootstrap and RF).

Self-consistent treatment of effect of RF on both electron and fast ion distribution functions, and the effect of these modified distributions on macro- and micro-stability, including fast ion-driven modes.

Experimental Mysteries:

Since ST devices such as NSTX and MAST are just beginning to explore integrated system issues, the experimental mysteries exclusive to this area have yet to be uncovered. This is particularly true in the area of non-inductive current sustainment where RF and high bootstrap-driven-current experiments are first being planned for upcoming experimental runs. Experiments using CHI for non-inductive current generation have been conducted on NSTX with the goal of driving up to 500 kA of toroidal current on closed flux surfaces. While it has not yet been determined if the flux surfaces are closed, n=1 oscillations, which have been associated with the formation of closed flux surfaces in CHI experiments on other devices, have been observed.

What causes the development of n=1 oscillations in CHI-driven plasmas, and what is the relation of these oscillations to the formation of closed flux surfaces?

Other integrated system questions so far raised by experimental results:

What is the interplay and causal relationships among various MHD instabilities (NTMs, RWMs, locked modes,…) as well as with error fields, in determining the stability limits in STs?

What is the relationship between the fast ion or plasma electron, ion distribution functions in driving waves that can then cause anomalous plasma heating?

Of the many issues that have been discussed in this white paper, the overall most important ones are those that contribute to making progress on an integrated ST confinement system sustained by non-inductive current drive.

VII. Summary

In summary, the Panel's responses to its Charges are:

1) *Assess ST theory status and needs:* The core of this document provides a brief summary of the status and needs for ST theory and computation in six major areas of fusion science research.

2) *Provide vehicle for experiment-theory communication:* An initial vehicle was provided by the Panel participating (vigorously) in the NSTX Results Review meeting. Additional venues and mechanisms should continually be sought to encourage theorists and experimentalists to become aware of each other's ST issues and challenges, and work toward their solution.

3) *Suggest mechanisms for drawing in more theorists*: This has been addressed specifically in a Section above. The main suggestion is that experimentalists (and program leaders) highlight not just their successes in understanding and performance of ST plasmas, but also what limits development of the ST fusion concept and what are the current experimental mysteries in STs.

4) *Produce "white paper" identifying key ST issues:* This document is the Panel's response.