NSTX 5-YEAR PLAN REVIEW

PPPL — JUNE 30-JULY 2, 2003

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NSTX PROGRAM ADVISORY COMMITTEE MEETING

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The panel

Bick Hooper (Chair)	LLNL
Ron Bravenec	U. Texas
Dave Hill	LLNL
Fred Jaeger	ORNL
Earl Marmar	MIT
Doug Post	LANL
Ted Strait	GA
Alan Sykes	UKAEA
Yuichi Takase	U. Tokyo

Dave Hill and Doug Post participated in the DIIID and CMOD 5-year reviews and “normalized” the process

The charge

1. Assess the i*mportance and relevance* of the proposed 5-year research program with respect to the goals of the U.S. fusion program as outlined in the Integrated Program Planning Activity (IPPA), and in particular to the second goal: "Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems by investigating a broad range of innovative magnetic confinement configurations." Is the research plan likely to accomplish the IPPA objectives? How well is the research coordinated with other national and international innovative confinement concept research activities? Also, where applicable, please comment on the importance and relevance of the proposed NSTX program to the ITPA and tokamak physics in general.

2. Assess the s*cientific and technical merit* of the ongoing and planned research. Does the research proposed address science issues at the forefront of the field? How well does the ongoing and planned research maintain a U.S. leadership position in key areas of fusion research? Are the proposed diagnostics, other facility upgrades, interactions with theory and modeling, and collaborations adequate to carry out the proposed research program?

3. Evaluate the *competency* of the proposed senior research personnel and the adequacy of the proposed resources. Assess the program's governance practices and the performance of the direct program management as well as the support provided from the host institution. How well qualified are the applicant's personnel to carry out the proposed research? Do the collaborative arrangements achieve the goal of an integrated NSTX research team?

4. Assess the reasonableness of the proposed *costs* for fusion *research* and *operations*. The cost review should be done at a summary type level, examining major items and projections from ongoing operational experience.

5. Assess the current level of *performance* of facility *operations*. Are milestones being met? Are planned operating, maintenance, repair and upgrade schedules being achieved? Are environment, safety, health and quality assurance matters being addressed appropriately?

The review procedure

The review panel met at PPPL on 6/30-7/2, 2003 to review the plan:

- **The panel members had downloaded the plan about 10 days earlier, PPPL answered some questions answered before we went to Princeton.**
- **The procedure followed much the same format as the DIII-D and CMOD reviews:**

  The panel as a whole assessed the general issues from the charge.

  Subpanels had responsibility for drafting summaries of particular issues.

  The panel reviewed, debated and modified these summaries.

  A viewgraph-based briefing summarized the consensus position of the panel and was presented to PPPL at the end of the review.
- **Individual reports were sent to Steve Eckstrand, who prepared a Summary Report. This was reviewed and accepted by the panel members as individuals. *I have not seen the individual reports*.**

The following material is based on the briefing and Eckstrand's report. (The viewgraphs are a modified version of the out-briefing.) I have added some personal comments in *"red italic."* I believe these are generally consistent with the panel but were not reviewed by it.

Importance and relevance (1)

IPPA Goal 2: Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems by investigating a broad range of innovative magnetic confinement configurations.

- **The proposed program is well matched to IPPA Goal 2**
- ➢ The outstanding scientific issues for the ST have been identified – MHD equilibria and stability, transport, and the scientific base for noninductive current drive and of startup without a central solenoid.

5-Year Objective: Make preliminary determination of the attractiveness of the spherical torus (ST), by assessing high-beta stability, confinement, self-consistent high-bootstrap operation, and acceptable divertor heat flux, for $\tau_{pulse} >> \tau_E$.

- **Progress on this objective is substantial, with $\beta_T \approx 35\%$, ion confinement ~ neoclassical, $\chi_E \sim 10\ m^2/s$, $I_{NonInducive} \sim 60\%$, and $I_{bootstrap} \sim 50\%$**
- ➢ We anticipate that NSTX will successfully address most of the IPPA objectives in this plan period
- ➢ Given likely budgets, the divertor objective may best be met by collaborations, e.g. with MAST, and other science may be advanced by collaborations
- ➢ Proposed upgrades of diagnostics, EBW, etc., will carry NSTX well beyond the 5-year IPPA objectives

We were highly impressed with the quality of the work. We made several comments and recommendations which were intended to be constructive in nature. Some addressed our expectation that the NSTX budget will be constrained, given national funding limits and priorities. <u>Planning the needed trade-offs for the next few years is critical but difficult.</u>

Importance and relevance (2)

- **The research is well coordinated with other ICCs and with STs in particular**
  - **There is good coordination with MAST, including a recent visit from a NSTX researcher to study Electron Bernstein Wave (EBW) heating and current drive**
  - **Collaborations are underway or being considered with CDX-U, HIT-2, Pegasus, and other STs around the world — These collaborations (a) strengthen the research in the smaller STs by supporting their work and (b) provide physics or technology guidance to NSTX**
  - **The proposed EBW research may be useful for heating and current drive in low magnetic field ICCs, e.g. the RFP and Spheromak**

- **The research is important and relevant to the ITPA and to tokamaks in general**
  - **The ST parameters, e.g. small aspect ratio, will extend tokamak confinement scalings to new regimes, thereby extending their validity**
  - **There is a good opportunity to explore electron transport physics in NSTX:**
    - **χ_E is relatively large**
    - **it may be possible to suppress long wavelength modes which would complicate the interpretation of measurements. This would be a major contribution to tokamak physics.**

Scientific and Technical Merit

- **We were very impressed by the quality of the science and the technical achievements of the NSTX team.**

- **The proposed research on the ST is world-class and makes important contributions to tokamak research in general. NSTX is clearly at the forefront of fusion research and establishes the US as a world leader in this confinement geometry.**

- **The proposed facility upgrades and diagnostics, along with the interactions with theory and with collaborators, are fully adequate to carry out the proposed research.**

  - **However, if the requested budget is not available, the rate of progress will be slowed and there will be more scientific risk. The requested funding is approximately 10% above the FY 2004 request, and other national needs are likely to limit NSTX.**
  - **The EBW heating and current drive and the MSE diagnostic are critical to the success of the proposed plan and need adequate resources to maximize their success.**

Detailed discussion of specific scientific topics is provided on the following slides.

The EBW heating and current drive and the MSE diagnostic are difficult undertakings. Program trade-offs to achieve them may require difficult decisions.

MHD Stability (1)

- **NSTX has made remarkable progress within its first 5 years of operation, culminating with the achievement of 35% toroidal beta.**
  - **Reduction of error fields has significantly improved performance**
- **The NSTX staff has proposed a comprehensive and exciting 5-year plan for MHD stability research, well-aligned with the IPPA goals.**
- **The planned MHD stability research is aimed at two broad goals:**
  - **Ensuring stable operation of a high beta, high bootstrap fraction plasma**
  - **Extending our understanding of MHD science by exploiting a unique parameter regime (beta, V/V_A, V_f/V_A, ρ_i/a, …)**
- **The planned research and the resources called for in the plan are appropriate for the first goal (high beta).**
  - **External control coils are potentially a powerful tool for enhancement of stability, through error field reduction or direct feedback control of the RWM.**
  - **Stabilization of NTMs through localized EBW current drive could be very important but remains to be tested; avoidance through tailoring of the global q-profile is an alternative.**
  - **Strong shaping (elongation and triangularity) will be an important tool for reaching the NSTX MHD goals**
  - **(*Continued on next slide*)**

MHD Stability (2)

  - **Error fields may be an important limiting factor in high performance plasmas, even after correction of the known PF coil errors. Therefore, we strongly endorse the rapid implementation of external control coils and low bandwidth feedback control for dynamic error field correction.**
  - **The planned emphasis on the effects of plasma flow, flow shear, and error field effects, in both experiment and theory, is important given the relatively high rate of rotation typical of NSTX.**

- **A broad and ambitious plan of MHD science (the second goal) has been outlined, representing many exciting opportunities (ELMs, 1/1 modes, fast-ion modes, …). The scope may need to be narrowed if requested budget is not available.**

- **Many the planned facility upgrades and new diagnostics are critical to the MHD stability portion of the plan. In particular, the current density profile is key data for MHD studies, and the MSE systems should be brought on line as quickly as possible.**

TRANSPORT AND TURBULENCE (1)

- **Global confinement times should be measured consistently with ITPA guidelines**
  - **Scalings with I_p and input powers are particularly important for scalings to reactors**
  - **Aspect-ratio scaling is a unique contribution by the ST**
- **The NSTX H-mode appears to differ from other tokamaks so their pedestal physics and edge turbulence results should be very interesting.**
- **Apparent ability to turn off low-k turbulence is impressive but remains to be verified experimentally (low-k turbulence diagnostics) and theoretically (refined neoclassical, nonlinear gyrokinetics). (These points are addressed in the plan.)**
- **Potential of microwave imaging diagnostic to provide 2-D imaging is exciting and might lead to measurements of low-k density fluctuations.**
- **Nonlinear low-k gyrokinetic simulations should proceed and results compared with experiment.**

TRANSPORT AND TURBULENCE (2)

- **Apparent "ETG-only" transport is unique in fusion research experiments. Should be verified experimentally (high-k turbulence diagnostics) and theoretically (nonlinear gyrokinetics). (These points are addressed in plan.)**

- **Nonlinear ETG simulations should proceed immediately for comparison with experimental results.**

- **Plans for experiments on minimizing transport are still evolving.**

Electron transport is a critical issue in confinement but is poorly understood. It was striking that ion transport is low but electron transport remains high — NSTX may therefore be able to make a unique contribution to understanding it. If this is judged likely after further analysis, its study should be a high priority in the research plans.

HEATING AND CURRENT DRIVE

- **EBW-CD is potentially very important in NSTX and should be pursued aggressively.**
  - **MAST results are at a non-optimum frequency (60 GHz) to date, but are still of interest to NSTX. There should be useful information from 8.2 GHz experiments on TST-2 and several other STs.**
- **There were several HHFW issues – Does it always heat as assumed in the integrated modeling? Are there cases in which power absorption is not 100%, or the power split between electron absorption and ion absorption is inconsistent with theoretical predictions? . . . Consideration of effects such as edge absorption should be included in the work.**
- **Is the need for high power EBW going to be met in a timely way? Tube development may be delayed due to technical or financial difficulties.**

An interim scientific step should be considered to validate the predictions.

I have some personal comments on EBW-CD the next slide.

HEATING AND CURRENT DRIVE (cont.)

Some personal comments on EBW-CD:

- *It has the potential to shape the current profile to maximize beta, to form internal barriers, and to stabilize neoclassical modes.*

However:

- *Development of high-power sources is likely to be expensive and difficult, although easier than in other frequency ranges*
- *The physics is highly challenging because of its complexity, requiring successful and efficient coupling to the plasma, conversion from ordinary to extraordinary to electron Bernstein waves, and absorption at the appropriate location in the plasma*

Thus, I (and others) recommended considering source development in parallel with physics studies on other machines such as MAST and Pegasus, coordinated by NSTX. These can be done at relatively low power, and would both advance the physics and bring additional scientific expertise to bear. It is likely to be less expensive than attempting to do all the physics on NSTX.

If successful, EBW-CD is likely to be important for other confinement devices with $\omega_{ce} < \omega_{pe}$, e.g. the RFP and spheromak.

SOLENOID-FREE STARTUP (1)

- **Demonstrating solenoid-free startup should be a high priority, as recognized by the NSTX team.**

- **Despite recent advances in understanding and applying CHI, the practical realization of CHI remains uncertain.**

- **It is not clear that the short-pulse CHI method is any better than using pre-ionization and a conventional null. The proposed FY04 tests on NSTX to clarify this should be given high priority.**

I am more sanguine than some on the promise of CHI for startup. However, I was not convinced that start up experiments on HIT-II demonstrated injection of a compact torus rather than injection of plasma and current which was then "picked-up" by the ramping poloidal flux. It may not matter, however, for startup purposes.

SOLENOID-FREE STARTUP (2)

- **It is important to investigate additional approaches to non-solenoidal startup.**
- **Methods such as EBW, Compact Toroid Injection, etc are speculative — some cannot be quickly tested.**
- **Poloidal Field ramp-up (without a solenoid) is well understood and predicted to be especially effective at low A.**
- **The schemes for poloidal field ramp-up outlined by the NSTX team should be tested on NSTX as soon as feasible:**

1. ***presence and persistence of field null can be tested by direct measurement (even without TF!)***
2. ***consider using a capacitor bank to provide the initial small positive current in PF5 coil***

Boundary Physics (1)

- There was some concern that although the proposed research touches on important and challenging boundary questions, the explicit connection to advancing the concept was not articulated clearly.

- Particle control appears necessary to optimize non-inductive current drive
  - Lithium surface conditioning appears to be a cost effective way to reduce recycling. A lithium divertor is a major undertaking and careful consideration of the programmatic impact is needed.

- The study of edge-plasma transport (convective, diffusive or intermittent) is a "hot topic." The proposed expanded use of GPI and LIF will provide relevant new data to compare with edge models such as BOUT.

- ELM and pedestal physics is important for ITER – increased effort on NSTX may provide new insight due to the unique ST boundary plasma.

- High divertor heat flux is an issue for future high-power, high β plasmas with pulse lengths > few seconds. Plasma shapes compatible with heat flux reduction techniques should be explored (e.g. double null vs. single null experiments).

Boundary Physics (2)

- **The group has focused its boundary physics efforts on learning to operate in optimal parameter ranges. Minimal resources have been available for more extensive, traditional boundary physics studies. The proposed effort increase in this area is encouraged. They should also strengthen their interaction with MAST.**
- **Edge-pedestal studies will require increased spatial resolution for edge diagnostics, e.g. the Thomson scattering system (as planned). Differences in pedestal behavior may be linked to differences in ST confinement scaling.**
- **H-mode ELM studies should be strengthened. Their measurements of edge fluctuations via Gas Puffing Imaging (and LIF in the future) are world class.**
- **Numerical studies showing how various fueling profiles might optimize high β non-inductive CD scenarios should be strengthened to decide what sorts of new fueling methods to pursue. The physics basis for the strategy needs clarification.**

This is an area in which collaborations might be particularly productive.

INTEGRATION AND PLASMA CONTROL

- **Committee recognized that NSTX integration goals are ambitious**
- **Descriptions of requirements need to be more quantitative.**
- **Modeling to design controllers is at an early stage and needs further effort. (Especially for the non-solenoid startup scenarios.)**
- **Consider use of diamagnetic flux (as on DIII-D) rather than rtEFIT as a first step for control of β; this is not as powerful as the profile approach, but should be much easier to implement.**

INTEGRATED SCENARIO MODELING

Committee endorses the NSTX team vision that integrated scenario modeling can greatly improve operational efficiency and optimize the selection of experiments

- **The NSTX team has begun a serious effort to utilize integrated scenario simulation**
- **Their approach of constraining many of the unknowns with experimental data is reasonable**
- **Free-boundary calculations that include the interaction with PF system are important for CD scenario selection**
- **Team has made a good start with their TSC/TRANSP modeling effort**
  - **Self-consistent integration of CD calculations with TSC will improve the efficiency of scenario simulation**
- **Recommend that rotation effects be included in the MHD equilibrium.**
- **More help to speedup the calculations would be productive; a more intense effort would be useful**

Theory and Modeling

- **Theory and modeling is doing a good job in beginning to address the unique scientific issues in NSTX.**
- **High toroidal rotation velocity, flow shear, and rotational damping seem very important in NSTX and should be given highest priority for inclusion in models.**
- **Present modeling of EBW (GENRAY) does not account for mode conversion. One option might be an all-orders, full-wave model in 1-D with with a poloidal field and parallel magnetic field gradient (SciDAC).**
- **Next step ST's may not be in the HHFW regime. So in modeling these devices, we might look at conventional mode conversion from the fast wave to IBW. This could give off-axis heating (C-mod) and possibly off-axis current drive.**
- **Incorporating transport coefficients derived from gyrokinetic simulations into predictive analysis codes (TRANSP) in FY03-04 need to be planned carefully, otherwise the computer time needed for first results will be prohibitive.**

Proposed Costs and Budget

- **The proposed total costs (a 10% increase over the President's request) represent a reasonable request for additional funding to carry out the NSTX research program.**

- **The balance between hardware and diagnostic upgrades seems reasonable – the scope of the boundary physics diagnostic upgrades looks to be very ambitious given the size of the group.**

- **While proposing an expanded program with increased funding, the NSTX team clearly recognizes budget realities and have tentatively identified a strategy to move forward – but at a reduced pace with increased scientific risks due to necessary focusing of efforts.**

- **Proposed trade-offs between run time, upgrades to the facility, and diagnostics seem reasonable at the Presidential request level.**

- **If further reductions are mandated (below the President's budget), it is recommended that the impact on EBW physics and non-solenoidal startup be minimized, possibly through expanded collaborations and modeling. These research topics are unique to the ST and critical to the application of the concept.**

Personnel and Organization

- **The senior PPPL and NSTX management personnel are highly competent.**
  - **The PPPL personnel participating on the experiment are highly competent and are doing a good job of carrying out the research.**
- **A sign of health for the program:**
  - **Many presentations were given by "the next generation." Future leaders are being prepared.**
- **NSTX should continue outreach to increase the number of graduate students involved in the experiment.**
- **The NSTX team has built a successful national and international collaboration program**
  - **The core group of collaborators who spend a large fraction of their time at PPPL are well integrated into NSTX.**
  - **Numerous off-site collaborators are effective and significant contributors.**
  - **Collaborations with MAST and other experiments in US and abroad have been successful and valuable**

I have heard concerns from some collaborators that the available funding is spread too thin, constraining their ability to contribute as fully as they would like.

Conclusion

The Committee was very impressed with the quality of the people and of the work. NSTX has achieved a great deal, understanding and advancing the concept. The science has been excellent.

I was surprised at how seriously the toroidal field accident was viewed at the DOE Office of Science. It is extremely important that the machine be up and running successfully as soon as possible.

The 5-Year Plan Review Committee had considerable advice for NSTX

- ***This should not be construed negatively but as an attempt to be constructive***

As with most of the fusion community, there are more good ideas than resources can support. Perhaps the most important thing, now, is to determine how to proceed within limited resources. This will require difficult decisions.