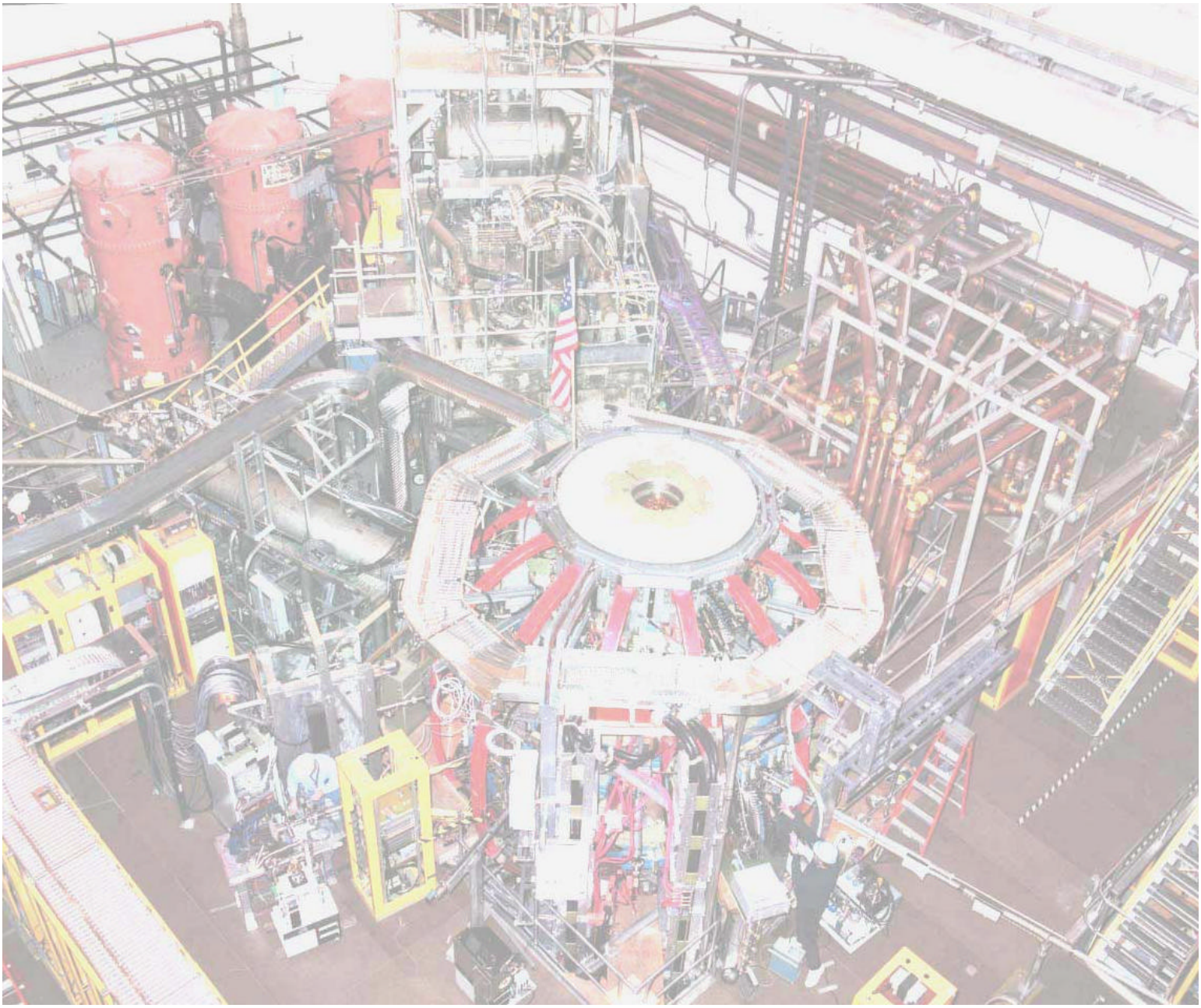
National Spherical Torus Experiment (NSTX) Program Letter – Research Program and Collaboration Opportunities for FY 2002-2005

Prepared by

NSTX National Program

April 12, 2001



National Spherical Torus Experiment (NSTX) Program Letter – Research Program and Collaboration Opportunities for FY 2002-2005

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The purposes of the NSTX Program Letter are to:

1) Articulate the overarching NSTX mission and National Research Program strategy in the context of the 1999 advice from the Fusion Energy Sciences Advisory Committee (FESAC), as expanded by the Integrated Program Planning Activity (IPPA) in 2000,
2) Describe the NSTX research plan and priorities for FY 2002-2005, and
3) Delineate the research topical areas where important benefits can be derived from a broad national participation by experts in NSTX research

The information provided by the Program Letter will further

1) Assist the present and prospective NSTX participants in the preparation of proposals to DOE for funds to conduct collaborative research on NSTX during FY 2002-2005,
2) Provide NSTX Program input to DOE for its merit review process, and
3) Indicate longer-term research elements of high-leverage deserving of attention by cooperation between other OFES programs (Theory, Technology, and Advanced Diagnostics) and the NSTX program.

NSTX is one of the leading Proof-of-Principle experiments in the U.S. Fusion Energy Sciences Program. Research in high temperature Spherical Torus (ST) plasmas invigorates scientific discovery in a new toroidal regime of very high, order unity beta (ratio of plasma to magnetic field pressure) with large variations of magnetic fields and substantial ion orbit size over the plasma size. The central volume of the ST plasma, covering roughly the inner half of the plasma minor radius, has a magnetic geometry similar to that of the Tokamak. This strong physics relationship enables rigorous extension of the robust Tokamak physics toward the outer half of the minor radius of the ST plasma. The very high beta of the ST further overlaps with or approaches the Spheromak, the Field Reversed Configuration (FRC), and the Reversed Field Pinch (RFP) in important physics properties. Understanding of the ST plasma can benefit from and contribute to the progress in these confinement configurations.

A broadly based, robust, and growing national research team is, for these reasons, an important requirement for the success of the ST research in general and the NSTX research in particular. The information provided in this document is a key component in a concerted effort by DOE, the NSTX Program, and the fusion energy sciences community to meet this requirement.

The information presented in this document has benefited from three crucial processes:

1) Annual NSTX Research Forum, when research ideas are presented and discussed among the National Research Team members and other researchers interested in participating in NSTX research,
2) Discussion among the NSTX Research Team members in arriving at recommendations of research and collaboration opportunities, and
3) Twice-annual review and advice by the NSTX Program Advisory Committee (PAC) concerning research program priorities, milestones, and research strategies.

This document particularly incorporates the input from the FY-2001 NSTX Research Forum (January 15-19, 2001) and the advice from the 10th meeting of the NSTX PAC (February 8-9, 2001).

This document contains the following sections:

1) Mission and FESAC Recommendations
2) Research Program Strategy
3) Planned Facility Capabilities
4) Research Milestones for FY 2000-2005
5) Research Emphases for FY 2001
6) Research and Collaboration Opportunities for FY 2002-2005
7) Opportunities for Cooperation with Other U.S. and International Programs

Information that supports the development of NSTX research collaboration can be viewed at:

http://nstx.pppl.gov/nstxhome/forum/collaboration.html.

1. Mission and FESAC Recommendations

The mission of NSTX is to investigate the physics principles of:

1) Confinement and transport,
2) Pressure limits, plasma stability and disruption resilience,
3) Non-inductive start-up, current sustainment and self-driven currents, and
4) Scrape-off layers and divertors,

in a low-aspect-ratio, spherical torus (ST).

These principles will be investigated in scientifically unique and interesting regimes characterized by:

1) Plasma aspect ratio $A \equiv R/a$ as low as 1.26 and elongation κ as high as 2.0 – the outer half of the minor radius represents a region for potentially new toroidal plasma physics resulting from the strong magnetic field curvature, the large fraction of toroidally non-circulating particles, the possibility for a hollow plasma current profile simultaneously with a monotonic safety factor profile, and strong field variations in the outboard plasma Scrape-off-Layer (SOL), relative to the standard $A \sim 3$ plasmas;

2) High average toroidal beta β_T (up to 40 %) and up to order-unity central beta despite high edge safety factor (~10) – the plasma sound speed can approach the plasma Alfvén speed with an enhanced pressure gradient driven plasma flow and flow shear, and potentially enhanced magnetic fluctuations;
3) A high fraction (up to 70 %) of the plasma current driven by the plasma pressure gradient – this is likely to be consistent with the hollow current density profile mentioned above; and
4) Collisionless plasmas with high temperature and densities – these lead to relatively large ratios of ion gyroradius to plasma minor radius ($\rho^* = \rho_{ci}/a$) and very large plasma frequency to electron cyclotron frequency ("over-dense" plasma density).

Several of these ST plasma features have been mentioned in the NRC FuSAC report as opportunities for potentially important scientific progress.

The NSTX Program mission is consistent with the goals and objectives of the "Report of the FESAC Panel on Priorities and Balance." In particular, a 5-year objective for FESAC Goal #2 is to "*make preliminary determination of the attractiveness of the Spherical Torus, by assessing high-beta stability, confinement, self-consistent high-bootstrap operation, and acceptable divertor heat flux, for pulse lengths much larger than the energy confinement times.*" The 1st, 2nd, and 4th mission elements, together with the new scientific features mentioned above, highlight the expected key research directions for NSTX in meeting this FESAC objective during FY 2000-2004 time scale.

The FESAC Panel also recommended a 10-year objective for Goal #2, which is to "*assess the attractiveness of extrapolable, long-pulse operation of the Spherical Torus for pulse lengths >> current penetration time scales.*" The 3rd mission element is uniquely important to the goal of achieving modest-size ST devices, and is particularly consistent with this objective. The NSTX research program must also address this mission element during FY 2000-2004 and prepare for meeting the 10-year objective during FY 2005-2009.

The NSTX mission is also relevant to the FESAC Goal #1, which addresses fundamental understanding of the plasma and the predictive capabilities in Turbulence and Transport, Macroscopic Stability, Wave-Particle Interactions, and Multiphase (Plasma-Wall) Interface. The ST confinement configuration possesses unique plasma science features that contribute to meeting this FESAC Goal.

Research and development using the ST configuration therefore provides new opportunities to advance the scientific foundations for an optimized confinement system and an affordable development path for practical fusion energy.

2. Research Program Strategy

In the near term, the NSTX Research Program aims to meet the FESAC ST 5-year objective of Goal #2, to contribute effectively to the FESAC Goal #1, and to prepare for the ST 10-year objective of Goal #2. The NSTX mission is consistent with meeting these goals.

A research program strategy has been developed to achieve these goals (and the NSTX mission), as summarized in Fig. 1. Three research phases have been envisioned since FY 1999: "**inductive**," "**non-inductive assisted**," and "**non-inductive sustained**," delineated according to the progression of experimental operation capabilities. A total of about 94 run-weeks are planned to complete the investigation.

Phase	I	II	III
Rnwks	13	41	40
Exp. Operation Capabilities	**Inductive**	**Non-inductive Assisted**	**Non-inductive Sustained**
• **Toroidal Beta, b_T**		• → 25%	• → 40%
• **Bootstrap Current**		• → 40%	• → 70%
• **Current**	• → 0.5 MA	• → 1 MA	• ~ 1 MA
• **Pulse**	• → 0.5 s	• → 1 s	• → 5 s
• **HHFW Power**	• → 4 MW	• → 6 MW	• ~ 6 MW
• **NBI Power**		• → 5 MW	• ~ 5 MW
• **EBW Power**	• → 30 kW	• ~ 30 kW	• → 0.4 MW
• **CHI Startup**	• → 0.2 MA	• → 0.5 MA	• ~ 0.5 MA
• **Control**	• current, R, shape	• heating, density	• flows, profiles, modes
• **Measure**	• $T_e(r)$, $n_e(r)$	• j(r), $T_i(r)$, flow, edge, modes	• turbulence

Figure 1. NSTX research program for FY 2000-2006 is composed of three research phases according to the progression of experimental operation capabilities: "inductive," "non-inductive assisted," and "non-inductive sustained," in a total of about 94 experimental run-weeks.

During FY 2000, the NSTX National Research Team demonstrated all the experimental operation capabilities of the first phase shown in Fig. 1, utilizing a total of 13 run-weeks. The results established the readiness of NSTX to proceed, beginning in FY 2001, with research using the non-inductive assisted operation. The tests included inductively produced and sustained plasma current for limited pulses, adequate plasma position and shape control, initial High Harmonic Fast Wave (HHFW) launching and plasma heating, and initial Coaxial Helicity Injection (CHI) non-inductive current startup.

For FY 2001-2003 the research program proposes to focus on plasma properties achievable via "non-inductive assisted" operation for pulse times up to 1 s ($\tau_{skin} >> \tau_{pulse} >> \tau_E$). A total of ~41 experimental run-weeks are planned to investigate the ST physics principles covering all NSTX mission elements for this pulse length. Key experimental operation capabilities are expected to include a combination of double-swing induction (solenoid magnet), non-inductive startup (CHI), and plasma heating and current drive (Neutral Beam Injection, i.e., NBI, and HHFW) to produce and sustain 1-MA plasma currents in a full pulse length of 1 s. CHI-alone startup up to 0.5 MA in plasma current and coupling with flux induction will also be tested. Plasma toroidal betas (β_T) up to 25% have been calculated to permit macroscopic stable plasmas without active feedback control of the Resistive Wall

Modes (RWM). Such calculations also indicated bootstrap current fractions (f_{BS}) up to 40%. This, together with CHI, NBI, and HHFW, are expected to assist in starting up and sustaining 1-MA current in 1-s pulses.

Transport and turbulence properties in such high β_T and f_{BS} plasmas for $\tau_{pulse} >> \tau_E$ are also important to meeting the FESAC 5-year objective for ST plasmas from Goal #2. Control of plasma heating power and density will be required. Measurements of plasma ion temperature, flow, edge parameters, current density, and macroscopic modes are planned to carry out this research. The NSTX research milestones proposed for this period is shown in Fig. 2 and will be discussed in Section 4 below. It should be noted that the research milestones show an equal emphasis in studying MHD and Transport Physics, and in studying Current Drive and Edge Physics.

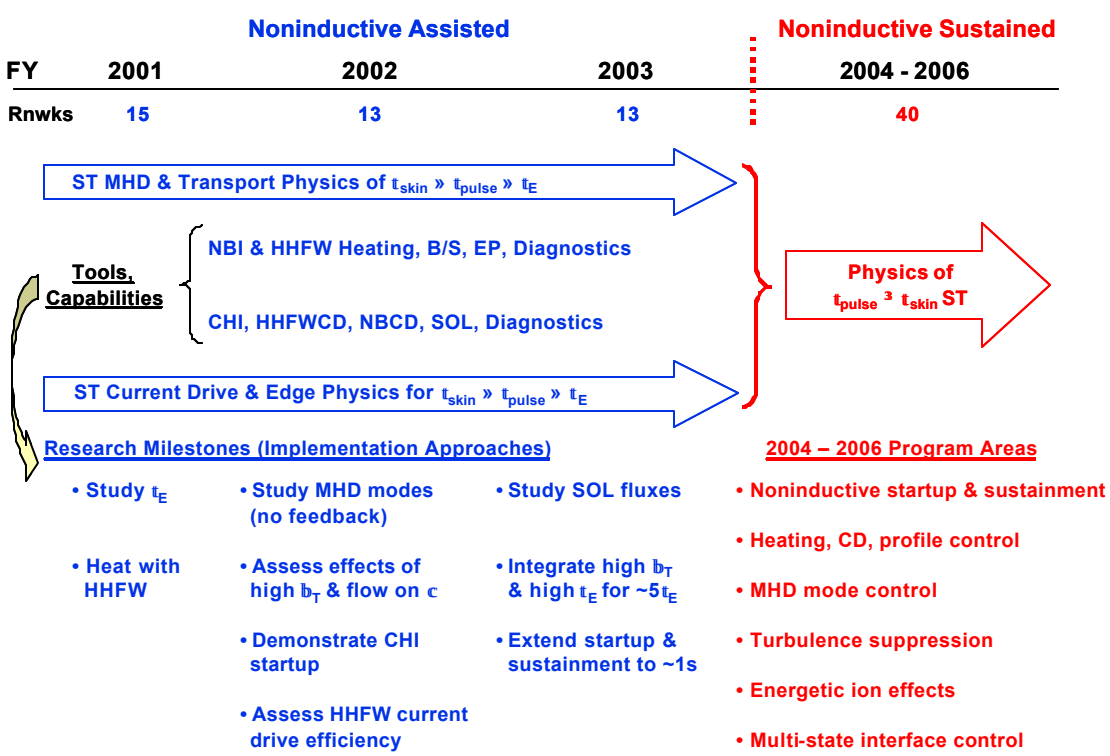

Figure 2. NSTX baseline program will focus during FY01-03 on ST Proof-of-Principle research that utilizes "non-inductive assisted" operation, before beginning research that utilizes "non-inductive sustained" operation.

The scientific questions of high importance to the ST configuration and the magnetic fusion energy sciences research, for which opportunities for discoveries are introduced by NSTX, will be discussed in Section 4 together with the research milestones. The scientific investigations on NSTX are expected to contribute to meeting the FESAC Goal #1.

For FY 2004-2006, the research program proposes to focus on plasma properties achievable via "non-inductive sustained" operation for pulse times up to 5 s at 1 MA and 3 kG toroidal field ($\tau_{pulse} \geq$

τ_{skin}), which is determined by the resistive heating limit of the center toroidal field coil legs in the present NSTX center stack design. A total of ~40 experimental run-weeks are planned to investigate the ST physics principles for this pulse durations. Key experimental operation capabilities are expected to include a combination of half-swing induction (solenoid magnet), strong non-inductive startup (CHI), and strong plasma heating and current drive (NBI, HHFW, and possibly Electron Bernstein Wave, EBW, via conversion from Electron Cyclotron Wave, ECW) to produce and sustain 1-MA plasma currents for longer pulses up to 5 s. CHI-alone startup to 0.5 MA in plasma current would be available routinely. Plasma toroidal betas (β_T) up to 40% have been calculated to permit macroscopic stable plasmas assuming successful control of RWM and the potentially damaging Neoclassical Tearing Modes (NTM). Such calculations also indicated f_{BS} up to 70%. This is expected to assist in sustaining 1-MA current in pulses up to 5 s in duration. Control of plasma flows and profiles may be required to reach this range of parameter space. Measurements of the detailed properties of plasma turbulence and the associated transport are planned to assist in this research. The NSTX research milestones proposed for this period will cover the whole spectrum of scientific topical areas, including energetic particle-plasma interactions and turbulence. Only a preliminary description of the research emphasis for this phase will be discussed in Section 4 below, as the specific activities will be affected by earlier research results.

Plasma transport and turbulence properties with very high β_T and f_{BS} for $\tau_{pulse} \geq \tau_{skin}$ will be an important step toward meeting the FESAC 10-year objective for ST plasmas from Goal #2, the achievement of which will, however, require a new center stack capable of 10-15 s durations (so that $\tau_{pulse} >> \tau_{skin}$) for a somewhat increased applied toroidal field (~4 kG) at the magnetic axis and plasma current (in the range of 1.5 MA) to allow better containment of NBI ions with high central q.

3. Planned Facility Capabilities

The NSTX facility and diagnostics capabilities proposed for FY01-03 to support the research program are summarized in Figures 3 and 4, respectively. We plan to carry out 15 experimental run-weeks in FY01, and propose to carry out 13 run-weeks in both FY02 and FY03 in the baseline budget. As shown in Fig.4, major diagnostic upgrades on NSTX are proposed for this period, where the collaboration is proposed to play an increasingly significant role.

4. Research Milestones for FY 2000-2005 and Scientific Opportunities

The NSTX research milestones for FY 2000-2005 are organized to achieve the NSTX Proof of Principle mission, to develop the scientific basis to realize the promise of high-efficiency magnetic containment of high temperature fusion-relevant plasmas in the Spherical Torus configuration. These milestones are also relevant to the goals and objectives recommended by FESAC. The milestones are further updated in accordance with the near-term Spherical Torus Implementation Approaches suggested by the recent Integrated Program Planning Activity (IPPA), which aims to achieve the 5-year objectives of the FESAC Goals.

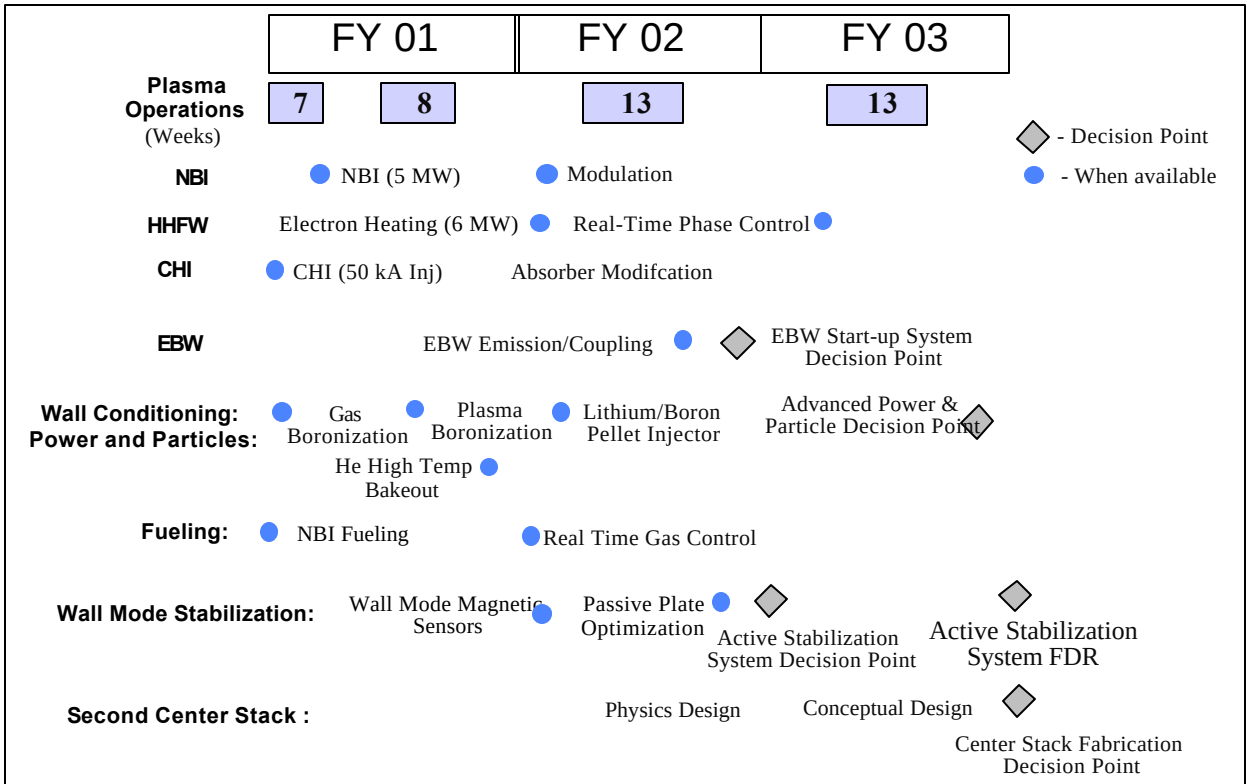

Fig. 3. NSTX Base Facility Hardware Plan

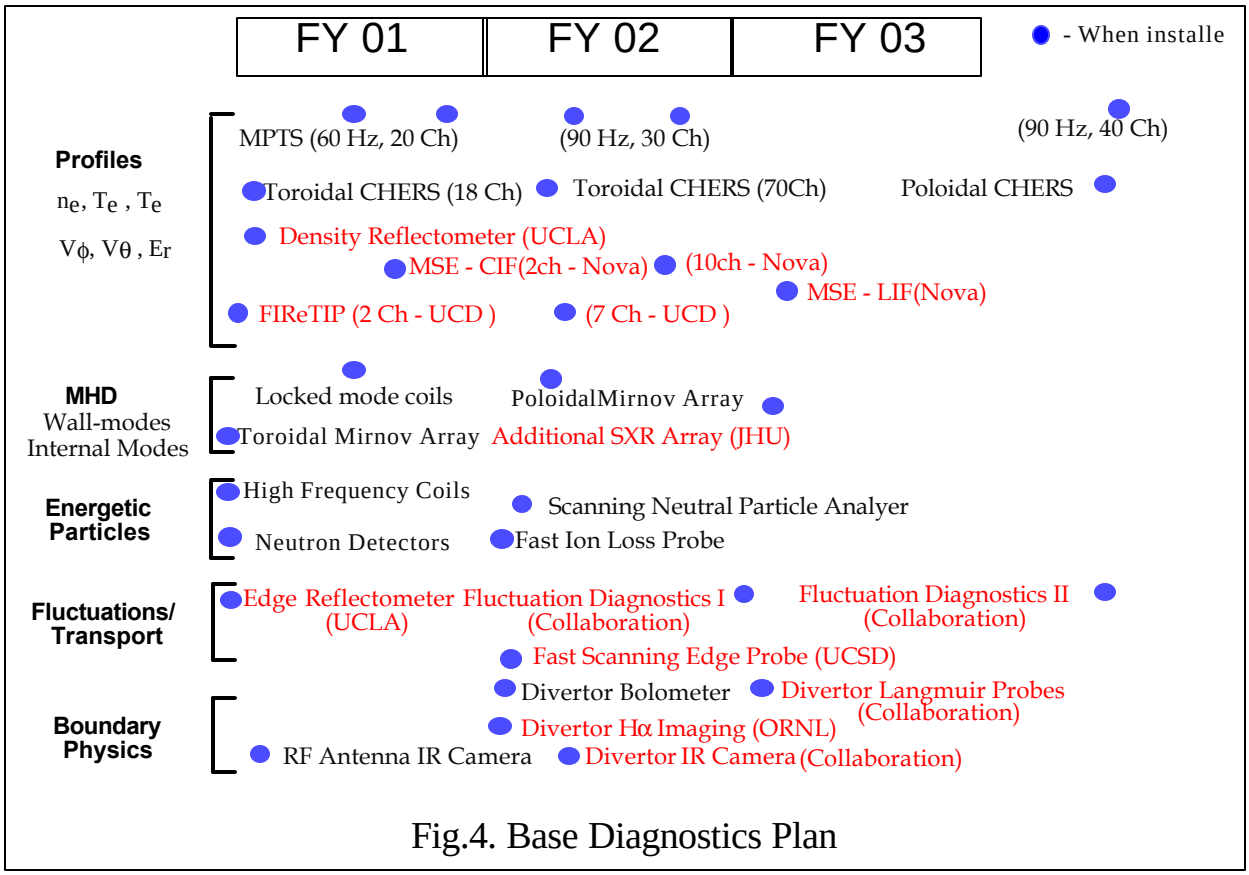

Fig.4. Base Diagnostics Plan

In the following we provide "plain-English" description of the FY 2000-2005 milestones, assuming the baseline funding for FY 2001-2003. The NSTX research milestones are paced by the proposed number of experimental run-weeks, which is in turn dictated by the available funding for the NSTX National Research and NSTX Facility Operation Teams. The speed with which the milestones are accomplished will therefore be determined by the actual run-weeks carried out in a given year.

The schedule for these milestones also accounts for the planned progress in major experimental operation and diagnostics capabilities. Preparation for achieving a milestone in subsequent years is accorded high importance in the current year. The NSTX National Research Team began research in FY 2000.

FY00 Research Milestones (13 run-weeks):

00-1) Operate a novel magnetic fusion confinement device, the National Spherical Torus Experiment, with 0.5 mega-ampere plasma currents approaching 0.5-second pulse lengths and 1-megampere currents for shorter pulses. (9/00)

This milestone was completed on schedule. The basic plasma operational conditions needed to achieve the NSTX FY01-03 milestones were established.

00-2) Investigate on NSTX innovative techniques for initiating plasma current, which can be utilized to simplify and reduce the cost of future spherical torus devices. (9/00)

Coaxial Helicity Injection (CHI) deposits current directly at the chamber edge. Theory suggests that this current can be transported into the chamber through the breaking and reconnecting of magnetic field lines. The intriguing physics mechanisms of this technique have been observed in the HIT and the HIT-II experiments at the University of Washington, and are similar in nature to the physics responsible for the formation of solar flares. These mechanisms will be investigated on a larger scale on NSTX using improved plasma control techniques, to initiate noninductively plasma currents approaching 200 thousand amperes. Successful noninductive startup (along with a means for current sustainment) would eliminate the need for a solenoid on the central column and thereby would simplify the spherical torus concept, leading to a major reduction in the size and complexity of a spherical torus fusion device.

This milestone was completed on schedule by producing via CHI alone plasma currents up to 260 kilo-ampere in up to 200-ms pulses in NSTX, although evidence of large scale magnetic reconnection was not observed. The basic understanding was established to enable development during FY01-03 of CHI induced plasma currents up to 500 kilo-ampere and the related investigations of noninductive startup.

00-3) Begin investigation of a new powerful radio-frequency technique to heat spherical torus plasmas to high temperature. (9/00)

Due to relatively high plasma density and low magnetic field, spherical torus plasmas in NSTX are expected to possess a large plasma dielectric constant (commonly called an "over-dense" condition). This over-dense plasma condition can often prevent plasma waves near natural resonance frequencies from propagating into the plasma core. However, radio-frequency waves at large multiples of the

natural ion rotation frequency are predicted to possess favorable wave propagation and strong wave energy absorption by electrons especially in the high temperature over-dense (i.e., high beta) plasmas expected in NSTX. The resulting electron heating and related new physics properties will be investigated at high radio-frequency heating power (up to four million watts) and at high plasma current (up to 1 million amperes) for the first time.

This milestone was completed with the delivery of up to 4 MW of HHFW power into the NSTX plasma in October 2000. Strong absorption and heating of the electrons (from about 500 eV to 1000 eV) were observed when large RF power was applied. Rapid density variations near the plasma edge have however limited the duration of RF power. These initial results provided data needed to improve the reliability of the RF system and prepare for RF-related research during FY01-03.

FY01 Research Milestones (15 run-weeks proposed):

01-1) Measure and analyze the containment properties of plasma energy within strongly heated NSTX plasmas. Good containment of energy will enable increased fusion gain in future spherical torus experiments.

Energy containment studies will be performed for the first time in spherical torus plasmas at high currents (up to one million ampere) and at high ratios of average plasma pressure over the applied toroidal magnetic pressure ($\beta_T \sim 20\%$). The investigations will begin by applying strong plasma heating via injection of neutral beams of energetic deuterium and/or of RF power, together with extensive measurements of the hot NSTX plasma core. The effects on confinement by the strongly varying, curved magnetic field lines and the high pressure gradient relative to the modest magnetic field pressure, particularly in the peripheral region unique to the spherical torus plasma, will be measured and analyzed for the first time. Modes of plasma operation showing differing properties of energy containment will also be explored and documented. The new data will also extend the existing database and understanding of energy confinement of toroidal fusion plasmas.

Deep scientific questions motivating this study include:

- Does the very high trapping fraction (approaching unity in the outer half minor radius of collisionless spherical torus plasmas) together with the large poloidal asymmetry of the magnetic field configuration materially alter the plasma transport process including the so-called "neoclassical model?" Comparison with magnetic configurations where the trapping fractions are nominally smaller will provide new opportunities for deeper understanding of this limiting plasma transport mechanisms unique to toroidal magnetic configurations.
- How does the very large beam ion gyroradius (up to about 30% of the plasma outer minor radius) affect the NBI heating efficiency, charge up the plasma potential, and induce plasma rotation? These mechanisms are expected to have a strong bearing on the ST plasma containment efficiency. Understanding of these mechanisms will contribute to plasma heating research in other configurations of high beta and modest size.
- How do the above effects combine with other mechanisms (such as edge particle recycling, radiation loss, and heat pulses from the plasma core) to influence the transition of the plasma into the so-called "High-Confinement Mode," which is characterized by a sudden decrease in plasma fluctuations, steepening of the plasma gradients, and reduction in plasma energy loss in the edge

region? How does the threshold heating power at this transition to the "H-Mode" depend on these effects and the heating technique?

01-2) Measure and analyze how high-power radio-frequency waves with slow propagation velocity interact with and heat high-temperature spherical torus plasmas.

As the spherical torus plasma in NSTX is heated to higher temperature and β_T (the ratio of plasma pressure over the applied magnetic pressure), radio-frequency wave propagation velocity in the direction of the magnetic field slows down toward the electron thermal velocity and enables strong absorption by the electrons. The wavelength perpendicular to the magnetic field shrinks to the size scale of ion gyration around the magnetic field. This enhances the rate at which the ions can absorb the wave energy. The competition between the electron and the ion interactions with the wave is therefore important to the understanding of wave interactions that are unique to very high-β_T fusion plasmas. In NSTX, waves at high multiples of the natural ion gyration frequencies will be launched to investigate how an increased interaction with the ions could reduce the wave-electron interactions and alter how the plasma can be heated and how plasma current can be driven. Very high power (up to six million watts) will be launched for the first time in NSTX with extensive measurements and analysis to clarify the relevant wave-plasma interaction properties at currents up to one million ampere.

Deep scientific questions motivating this study include:

- For HHFW propagating in the direction perpendicular to the magnetic field, how do the comparable scale of wavelength and ion gyration radius and the strong curvature and variation of the magnetic field affect the coupling of the HHFW power from the antenna to the plasma edge, and the propagation of the wave in the high beta ST plasma?
- How is the wave energy shared between the electrons and the ions in this case, and how does this sharing depend on the electron and ion temperature profiles and other plasma conditions?
- Does the strong interaction between the wave and the ions create suprathermal ion energies as part of the ion heating process?

Major research milestones in the areas of Macroscopic Stability, Non-Inductive Startup, and Edge Physics are planned for FY02-03 (see below). Important progress is made in FY01 in these areas to prepare for these upcoming milestones.

For Macroscopic Stability, it is observed that most NSTX NBI-heated high-β discharges appear to be affected by core instabilities, which under different conditions could be tearing modes (either classical and/or neoclassical) or pressure driven internal kinks. Toroidal Alfvén Eigenmodes, "fishbone-shaped" bursts, and "sawteeth-like" oscillations have also been observed routinely at lower β values. A combination of data from edge Mirnov magnetic loops and ultra-soft X-Ray, and q-profiles based on EFIT equilibrium reconstruction without constraining internal profiles, are used to estimate the mode characteristics. Plasma β is observed so far to saturate as MHD instabilities grow with additional beam power. Collapses in β associated with fast-growing edge or near-edge MHD activities have been observed more recently. Plasma conditions and parameters with which to explore and avoid different β-limiting instabilities are being identified for further investigation.

For Non-Inductive Startup, tests of Coaxial Helicity Injection (CHI) continue in FY01 to increase the toroidal current beyond 260 kA. Investigation of the effects of CHI current drive at the edge of inductively produced "Ohmic" plasmas is also planned. Data and experience from these tests, and comparison with modeling, will provide crucial information toward improvements in CHI plasma operation, control, electrical insulation (e.g., to prevent unwanted arcing across the inboard-to-outboard gaps, etc.), and measurements, in preparation for the upcoming FY02 milestone.

For Edge Physics, preparations are in progress in wall treatment (boronization, wall baking, Lithium coating, etc.), edge and impurity measurements (spectroscopy, infrared camera, reflectometry, Langmuir probes, reciprocating probes, etc.), and physics studies (fluctuations, conditions for transitions between "Low-Confinement" and "H-Confinement" modes, etc.). The results will be of crucial importance to the Edge Physics milestone in FY03 as well as to the other milestones in FY02-03 (see below).

FY02 Research Milestones (13 run-weeks proposed):

02-1) Measure and analyze the global stability of spherical torus plasmas at high ratios of plasma pressure to magnetic pressure without applying active external control.

Spherical torus plasmas in NSTX have been predicted to be stable against large-scale fluid-like perturbations at high ratios of average plasma-to-toroidal magnetic field pressure β_T up to 25% without active external stabilization. In theory, the global stability results directly from the increase in favorable magnetic curvature and shear in the unique periphery region of the spherical torus plasma, and if verified experimentally, would allow a very high efficiency of utilization of the applied magnetic field. The properties of the large-scale perturbations will be extensively measured, analyzed and compared with theoretical calculations. The new data and understanding will be crucial to decisions on the need, and if so, the best techniques for active mode stabilization in NSTX, make possible reliable projections of power density for future spherical torus devices, and extend the existing database and understanding of global stability of toroidal fusion plasmas.

Deep scientific questions motivating this study include:

- How much does the stability of the ideal kink modes benefit from the strong edge magnetic shear and in-out asymmetry of the ST (which lead to strong poloidal mode coupling and different mode structure)?
- How do the strong magnetic field variations and the increased plasma resistivity, particularly near the plasma edge, where the toroidally circulating particles are much reduced, affect the resistive kink modes and the rapid instability-driven magnetic reconnections in the ST?
- How do the plasma conditions and the gap to the conducting wall affect the so-called "Resistive Wall Modes," which are expected to occur at high β in the absence of active mode control? How do the strong variations in the magnetic field and high β affect these modes?
- How do the strong magnetic field variations affect the Resistive and Neoclassical Tearing Modes (NTM). These modes could present serious problems for long-pulse ST operation at high β that require low plasma collisionality and efficient RF, NBI, and Bootstrap current drive. Determining

the threshold for triggering the mode and determining the saturated island sizes in an ST would benefit all tokamak NTM research.

- Strong effects of large radius of gyration around the magnetic field and large fraction of toroidally trapped particle have been predicted to stabilize the small scale MHD ballooning modes at β far above the ideal limit in the ST. Can we determine experimentally if this is true?
- How do the strong variations in magnetic field and high β affect the Alfvén modes that are often energized by the energetic NBI ions?

02-2) Assess the effects of very high ratio of plasma pressure to magnetic pressure and plasma flow on plasma heat loss in spherical torus.

Theoretical calculations suggest that high plasma-to-magnetic pressure ratio (beta) can cause the magnetic field to fluctuate more with microscopic plasma turbulence than low beta, where the electric field fluctuations are expected to be more important. Strong magnetic fluctuations may increase plasma heat leakage via the electrons. Theory also suggests that strong shear in plasma flow can accompany the high beta and strong field line curvature unique to the spherical torus plasmas, and/or a large external momentum input (such as from the injection of energetic beams of deuterium in NSTX). A strong flow shear has been seen to reduce the larger-scale microscopic turbulence associated with heat leakage via the ions, but is less likely to modify the smaller-scale microscopic magnetic turbulence that may be associated with heat leakage via the electrons. Heat fluxes in NSTX plasmas will be inferred from plasma profile measurements and analyzed over a wide range of beta ($\beta_T \sim 10\text{-}20\%$) and flow shear. Trends in the ratio of ion to electron thermal heat fluxes will be compared with predictions from theoretical calculations that account for the relatively large ion orbits and the relatively small electron orbits. External heating with varied momentum input will be used to help separate the effects of externally driven flow shear from the internal high beta driven flow shear, the magnetic field fluctuations from the electric field fluctuations, and the electron heat leakage from the ion heat leakage. Understanding of the physics underpinning these mechanisms of heat loss will enable future investigations of plasmas with simultaneously high beta and high plasma containment efficiencies.

Deep scientific questions motivating this study include:

- How do large external momentum and ∇p-driven flow shears affect the nature of plasma turbulence and transport? Comparison with magnetic configurations where the flow shearing rates due to these mechanisms is nominally small and comparable to the dominant microinstability growth rates will provide new opportunities for deeper understanding of the fundamental mechanisms of turbulence and transport.
- How does high local plasma beta in the ST alter the level of magnetic fluctuations in the microturbulence and affect heat loss via the electron channel? Does strong electron temperature gradient drive microscopic magnetic fluctuations that lead to strong heat loss via the electron channel?
- Can strong shear in plasma flow stabilize such magnetic fluctuations, as in the case of electrostatic fluctuations driven by the ion temperature gradient?

02-3) Demonstrate on NSTX innovative techniques for starting up plasma currents in toroidal fusion devices that will allow these devices to be made simpler, run longer, and cost less to construct.

The initiation of plasma current by noninductive techniques is of crucial importance to the attractiveness of future spherical torus devices. The technique of Coaxial Helicity Injection (CHI) will be utilized to initiate noninductively large plasma current up to 500 kilo ampere. Improvements in control of plasma position and parameters, and insulation of the absorber region (where Coaxial Helicity Ejection can occur), will be implemented together with extensive measurements to carry out this test. Data on compatibility of CHI with magnetic induction and plasma heating via injection of radio-frequency wave and neutral beams of energetic deuterium will also be collected. The information will be crucial to future investigations on NSTX into combining this and other current drive methods to ramp up and maintain plasma currents for longer durations. Successful noninductive-assist methods for startup will help minimize the central solenoid magnets, simplify the spherical torus concept, and lead to a major reduction in the size and complexity of fusion devices.

Deep scientific questions motivating this study include:

- How do the externally applied steady toroidal magnetic field and time-dependent poloidal magnetic field affect the magnetic reconnection process when CHI current is applied to spherical torus with increasing electron temperatures?
- Can solenoid magnetic induction be applied to add toroidal current to the CHI plasma and alter the magnetic reconnection process?
- Can the CHI electric field affect the conditions of plasmas produced by other means, such as solenoid magnetic induction, and drive plasma current at the plasma edge?

02-4) Assess the effectiveness of using High Harmonic Fast Wave (HHFW) to maintain plasma current via direct interactions with the electrons and/or fast ions in high-temperature spherical torus plasmas.

Maintenance of plasma current by noninductive means represents one of the most important mission elements of the NSTX Program and is of common interest to magnetic fusion energy sciences research. High power HHFW with an increased wavelength in the direction of the magnetic field and flexible control of direction will be launched with a fast propagation velocity along the magnetic field line. This wave is expected to maximize momentum transfer to the electrons and drive plasma current noninductively. Interaction of this wave with the fast ions introduced by injection of energetic deuterium will also be investigated. The efficiency of current drive will be assessed by comparing the measurements with theory. An understanding of the underpinning physics of HHFW current drive and the techniques to ensure reliable operation at high power levels will contribute to future investigation of spherical torus plasmas sustained for longer durations in NSTX.

Deep scientific questions motivating this study include:

- For HHFW propagating close to the magnetic field, how do the comparable scale of wavelength and ion gyration radius and the strong curvature and variation of the magnetic field affect the coupling of the HHFW power from the antenna to the plasma edge, and the propagation of the wave in the high beta ST plasma?
- How is the wave energy shared between the electrons and the ions in this case, and how does this sharing depend on the electron and ion temperature profiles and other plasma conditions?
- How do a large component of energetic ions from NBI affect the propagation and absorption of the wave, in particular, its interaction with the electrons to drive current?

FY03 Research Milestones (13 run-weeks proposed):

03-1) Measure and analyze the dispersion of edge heat flux and assess the impact on plasma facing component requirements under high heating power in NSTX.

Understanding of the interaction between the plasma edge and the first wall and plasma facing components is critical to the success of containing any high-temperature plasma with high power density. The spherical torus plasma is expected to deliver increased heat flux on the plasma-facing components due to reduced device size. The plasma also introduces stronger and more favorable variations in the geometry and strength of the magnetic field in the edge region, which is expected to help disperse the plasma exhaust over a larger wall area and reduce the heat flux. Detailed investigation of the edge plasma will be carried out when large heating powers and several edge diagnostics and wall treatment techniques on NSTX are introduced. Measurements and theoretical modeling of diffusion, convection, and turbulence processes will be compared in detail to guide the investigation and help develop new techniques of heat dispersal in future experiments. Successful dispersal of plasma exhaust power over large wall areas will enable more powerful and compact spherical torus experiments and fusion devices.

Deep scientific questions motivating this study include:

- How do the strong variations in magnetic field (mirror ratio, flux tube expansion, etc.) affect the way heat and particles are exhausted from the plasma, and impurities and gas are recycled from the walls and divertors? How do these features compete with the opposite tendency by the reduced length of magnetic field lines that connects the plasma edge to the plasma-facing components?
- How do the large orbit sizes of the plasma and beam ions and large plasma flow and flow shear near the edge of the plasma, under the influence of strong variations in magnetic field, affect the mechanisms responsible for spontaneous transitions between various modes of plasma containment?
- How does the degree to which the plasma exhaust particles are retained by the wall during the plasma discharge affect the plasma edge conditions, which are in turn expected to affect the plasma containment efficiency?
- How do trace impurities (such as Lithium, Carbon, etc.) migrate from a source point to coat the walls and other components (antennas, windows, etc.) in the vessel during plasma operation?

03-2) Explore and characterize spherical torus plasmas having simultaneously good plasma containment and high plasma-to-magnetic pressure ratio for durations much larger than the energy containment time.

Simultaneously enhancing the plasma containment and raising the plasma-to-magnetic pressure ratio has been an overarching goal for magnetic fusion research and is a crucial mission element of the NSTX program. Experimental tests and extensive measurements will be carried out in NSTX to determine how to achieve the integration of high average toroidal β_T (up to 25%) without the application of active mode control, good plasma containment times, and large plasma self-driven "bootstrap" current (up to 40% in fraction of total current) for increased durations (much larger than energy containment times). Results of research during FY02 will provide information critical to the completion of this milestone. The new results of this research will provide information crucial to the subsequent investigations towards increasing plasma containment and the plasma-to-magnetic pressure ratio even further by utilizing active external stabilization or other techniques. They will also extend the existing database and understanding

of plasma containment and global stability of toroidal fusion plasmas to new regimes of plasma β_T and energy containment.

Deep scientific questions motivating this study include:

- How do large thermal ion orbits and strong magnetic field variations (curvature, in-out asymmetry, magnetic shear) affect the threshold heating power and the thickness and pressure gradient of the pedestal at the edge of the H-mode plasmas?
- How do this pressure gradient and the associated edge bootstrap current affect the macroscopic stability of the plasma?
- How do large ion orbits and strong magnetic well (minimum in the strength of B) affect the thickness and pressure gradient of transport barrier in the plasma core region?
- How do this pressure gradient and the associated bootstrap current in the plasma core affect the macroscopic stability of the plasma?
- If substantial suppression of plasma turbulence occurs, does neoclassical transport due to relatively large ion orbits lead to a broadened pressure profile in the plasma core that is calculated to be more favorable to macroscopic stability at increased plasma beta?

03-3) Measure and analyze the effectiveness of using a combination of noninductive techniques to assist in startup and sustainment of plasma pulse lengths up to 1 s.

The investigation of the spherical torus plasma properties appropriate for enabling plasma pulse durations up to 1 s using noninductive assist is a crucial mission element of the NSTX program. The experience and understanding in current startup and maintenance using Coaxial Helicity Injection, radio-frequency wave, pressure gradient (bootstrap current), and magnetic induction will be combined to create the plasma conditions that minimize the dissipation of the solenoid magnet flux while permitting increased plasma pulse duration. Extensive measurements and analysis of the interactions among these current drive techniques will be carried out over a range of plasma parameters and conditions to establish a basis to begin the development of the plasma conditions that enable the extension of the plasma pulse toward 5 s during FY04-06.

Deep scientific questions motivating this study include:

- How does the magnetic flux linked to the CHI plasma interact with the magnetic flux introduced externally by solenoid induction and internally by HHFW current drive?
- How does the combination of NBI and HHFW heating and current drive, and substantial bootstrap current affect the plasma containment efficiency and macroscopic stability (without active external control of large scale modes) for timescales much larger than τ_E?
- How does the total amount of solenoid induction required for 1-s plasma pulses depend on the plasma startup and sustainment methods and plasma operation scenarios?

<u>FY04-06 Research Milestones (40 run-weeks assumed):</u>

As shown in Figs.1 and 2, NSTX research for FY 2004-2006 plans to focus on ST plasma properties that can be achieved via "non-inductive sustained" operation for pulses up to 5 s in duration ($\tau_{pulse} \geq \tau_{skin}$). Major topical areas for research milestones are presently anticipated to include:

1) Noninductive startup and sustainment
2) Heating, current drive, and profile control
3) MHD mode control and avoidance
4) Turbulence suppression
5) Energetic ion effects
6) Multiphase interface control

Relative to the FY01-03 research, the FY04-06 research will aim to test and understand the underlying physics mechanisms that

1) Reduce, minimize, and eliminate if possible, reliance on solenoid induction during current startup to full current, which would reduce the size and complexity of near-term ST devices that utilize "non-inductive sustained" operation. A combination of CHI, HHFW, NBI, EBW, and bootstrap current will be used to test the plasma conditions (including the plasma internal magnetic flux) best suited for this purpose. Increasing the plasma duration beyond 1 s and up to 5 s may be used during this study.
2) Improve the efficiency of plasma heating and current drive methods for increasingly sustained plasma durations, which also heightens the need for density control via control of sustained fuel sources from edge and in the core. A combination of CHI, HHFW, NBI, EBW, and bootstrap current will be used to test the plasma conditions (including the plasma internal magnetic flux) best suited for this purpose. Plasma durations up to 5 s may be used during this study. The target plasma could be produced by a fast half-swing of solenoid flux with the noninductive assist methods to be tested during FY01-03.
3) Raise the macroscopic stability beta limit beyond the limits observed without using active feedback control, accounting for the effects of increasingly large ratios of plasma flow speed and sound speed over the plasma Alfvén speed. Techniques of instability avoidance (such as current profile and flow shear control) and mode stabilization (such as active feedback to stabilize the Resistive Wall Modes and the possibility of precise EBW-suture of magnetic field lines torn by the Neoclassical Tearing Modes) will most likely be used in this study.
4) Lower the level of or even suppress electrostatic and magnetic turbulence in high beta plasmas with strong flow and flow shear, in such a way as to be increasingly compatible with the plasma pressure profile (by influencing plasma heat diffusivity) and the current profile (by applying current drive and modifying the pressure gradient that modifies the bootstrap current) needed to achieve higher beta. The effects of large ion orbits, essentially absent circulating ions in the outer plasma volume, and large flow shear with flow speeds comparable to the sound and Alfvén velocities, on the limiting neoclassical diffusion mechanisms will be measured and analyzed.
5) Understand the special interactions between energetic ions of supra-Alfvén velocities and the ST plasma with large Mach (and Alfvén Mach) numbers. Measure how these interactions could alter the confinement and stability properties of the high beta ST plasmas, and how energy is transferred from these ions to the plasma. This study is crucial to projections of the next-level tests of the fusion ST physics in the same energetic-particle parameter regime.
6) Test and utilize the large mirror ratio and magnetic flux expansion of SOL to develop new methods for sustaining desirable plasma edge conditions, controlling plasma-wall interaction, and overcoming the effects of reduced field line lengths from plasma to wall, in support of the preceding research with increased durations and higher heat fluxes.

Research during FY06 is further expected to focus on the physics of integrating these potentially new ST properties into long pulse plasmas (up to 5 s in total duration) separately for ramp-up to full current and sustainment at full current.

Crosscutting diagnostics and enabling capabilities are expected to command a major effort of preparation during FY01-03 to support these research milestones during FY04-05 (see Section 6). Cooperation with the OFES Advanced Diagnostics and the Enabling Technology Programs will be crucial to the success of this preparation.

5. Research Emphasis for FY01

The relative emphases among the major scientific Experimental Task (ET) areas for FY01 research, consistent with the NSTX PAC advice, are given below.

Scientific Areas	Emphasis (%)
ET1: Macroscopic Stability	18
ET2: Transport and Turbulence	18
ET3: High-Harmonic Fast Wave (& Electron Bernstein Wave)	13
ET4: Coaxial Helicity Injection	13
ET5: Boundary Physics Preparation	8
Multipurpose Experiments (NBI, plasma control, etc., commissioning)	12
Contingency	20
Total	100

This distribution of effort accounts for the needs of the FY01 milestones and preparation for the FY02-03 milestones.

6. Research and Collaboration Opportunities for FY 2002-2005

The information provided in this section is organized in seven "Scientific Topical Areas" for research during FY 2002-2005. Since this duration spans large fractions of the "non-inductive assisted" (FY02-03) and the "non-inductive sustained" (FY04-05) research, the relative research emphasis among these topical areas is expected to evolve. The research during this time will address the FESAC 5-year objective for the spherical torus, prepare for the FESAC 5-year assessment point, develop a scientific understanding that forms a foundation for the next-level spherical torus experiments, and prepare for future research to meet the FESAC 10-year objective for the spherical torus. For these reasons, the 7 topical areas are assigned approximately equal relative programmatic emphasis.

Scientific Topical Areas
1) Noninductive Startup
2) Heating, Current Drive, and Profile Control

3)	Macroscopic Stability
4)	Turbulence and Transport
5)	Energetic Particle Physics
6)	Multi-Phase Interface (Edge Physics)
7)	Crosscutting Diagnostics and Enabling Capabilities

In the tables below, important “Research Elements” are identified within each of the above "Scientific Topical Areas.” “Relative Programmatic Emphases” (H or M, for High or Medium, respectively) are chosen among these research elements effectively to meet the key research milestones planned for NSTX, to take advantage of the new scientific opportunities (Section 4), and to utilize the growing capabilities of the NSTX facility (Section 3). Input of the participants of the FY 2001 NSTX Research Forum and discussion within the National NSTX Research Team led to the selection of these Research Elements.

The "Relative Collaboration Opportunity" (H or M) for each of the "Research Elements" indicates where the capabilities and expertise of the NSTX National Research Team can be maximized through collaboration in achieving the research milestones and taking advantage of the scientific opportunities. Results of the FY 2001 NSTX Research Forum, the “Letter of Interest to Participate in NSTX Research during FY 2002-2005,” and discussion within the NSTX Research Team contributed to an estimate of the opportunities for collaboration research on NSTX. For this estimate, “H” denotes encouragement for a strong collaboration effort, while “M” denotes encouragement for a significant collaboration effort.

A large number of “Research Ideas” were presented and discussed during the FY 2001 NSTX Research Forum. These are organized according to the Research Elements in the tables below. The NSTX Research Team reviewed these research ideas and expressed an opinion on the desirability, feasibility, and timeliness for their possible implementation in NSTX research during FY 2002-2005. Included in the tables are examples of research ideas presently judged to be desirable, timely, and feasible, as well as consistent in direction with the research milestones and scientific opportunities identified for FY 2002-2005 (Section 4).

1) Noninductive Startup

Relative Programmatic Emphasis	Research Elements • Research Ideas for Collaboration	Relative Collaboration Opportunity
H	CHI plasma formation and combination with other startup techniques • Reconnection mechanisms and flux surface closure under CHI conditions • Inductive and other methods to promote flux surface closure • Interactions with other heating and current drive mechanisms (HHFW, NBI, ECH/EBW, etc.)	H
H	CHI startup capabilities • Absorber insulator configuration • Active control • Absorber poloidal field control coil	M
M	ECH conversion to EBW startup • Tests at 0.2-0.4 MW (2003)* • Tests at >1 MW (2005)	H
M	Ramp-up via bootstrap current overdrive	M
M	Alternative methods for plasma formation and sustainment • Tests of plasma solenoid • Tests of merging-compression	M
H	Theory and Modeling for Comparison with Data • Reconstruction of axisymmetric equilibrium with open flux surface force-free current • Reconnection mechanisms (Sweet-Parker, Hall MHD, two-fluid MHD, etc.) • ECH/EBW current initiation • Bootstrap current ramp up	H

* Incremental budget proposal

2) Heating, Current Drive, and Profile Control

Relative Programmatic Emphasis	Research Elements • Research Ideas for Collaboration	Relative Collaboration Opportunity
H	HHFW heating and current drive • RF coupling, launcher-sheath-edge interactions, power deposition, etc. • HHFW effects during current ramp-up • Profile control	H
H	NBI heating and current drive • NBI ion orbit losses, slowing down, power deposition, etc. • Profile control	M
H	Bootstrap current drive during sustainment	M
M	CHI edge current drive during sustainment	H
M	EBW heating and current drive • EBW emission, launching, mode conversion, localized power deposition, current drive, etc. • Profile control	H
M	Core Fueling • Pellet injection • CT injection	H
H	Modeling for heating and current drive • HHFW modeling tools and integration into transport analysis codes (absorption by ions, RF-driven current, RF-driven plasma rotation, RF/NBI interaction, etc.) • 2D integral wave • EBW conversion and propagation, and control • Advanced HHFW antenna • Fast ion transport under strong RF heating	H

3) Macroscopic Stability

Relative Programmatic Emphasis	Research Elements • Research Ideas for Collaboration	Relative Collaboration Opportunity
H	MHD operation and stability limits, and parametric dependence • Ideal modes and passive wall effects • Resistive wall modes (RWM) • Neoclassical tearing modes (NTM) • Edge localized modes, reconnection effects, sawteeth • Locked modes (non-axisymmetric field error) • Disruptions and halo currents	H
H	Active and passive mode control options • Active feedback • Plasma rotation • Passive eddy current path • Elimination of error fields • Localized current drive to control profile/suppress tearing modes	H
M	Tests of effects of large sheared plasma flow (toroidal and poloidal) on equilibrium and macroscopic stability	M
H	Modeling and fast reconstruction of high beta equilibrium (including large plasma sheared flow) and macroscopic instabilities (such as DCON, EFIT, GATO, M3D, PEST, two-fluid MHD, VALEN, etc.)	H

4) Turbulence and Transport

Relative Programmatic Emphasis	Research Elements • Research Ideas for Collaboration	Relative Collaboration Opportunity
H	Local transport investigations: • Electron vs. ion thermal losses • Particle diffusion • Relation between particle, momentum, and energy transport	M
H	Core fluctuation investigations: • Investigate low-k and high-k fluctuations • Core transport barriers • Suppression via velocity and zonal flow shear • Interplay of ∇p- and neutral beam-driven $E\times B$ shear	H
H	Edge-SOL plasma turbulence & transport and barrier studies • Fluctuation, scale length characterization • Pedestal characteristics • Suppression via velocity and zonal flow shear • Intermittent fast convective transport • High beta effects on H-mode transition • High edge rotation physics	H
M	Characterization of global confinement • $\langle ne \rangle$, Ip, heating power, plasma shape (A, κ, etc.) dependencies • Dimensionless dependencies • Confinement modes	M
M	Parallel transport and resistivity for RF and NBI heated plasmas	M
H	Comparison with transport theory and modeling, and predictive simulation • Gyrokinetic simulation on local particle and energy fluxes • Neoclassical transport • MHD stability of pressure gradient with neoclassical ions • Gyrofluid and gyrokinetic models with T, n dependence on fluxes • Edge and core transport, including edge-SOL turbulence, and barrier formation • Predictive transport simulation of temperature profiles assuming temperature at edge	H

5) Energetic Particle Physics

Relative Programmatic Emphasis	Research Elements • Research Ideas for Collaboration	Relative Collaboration Opportunity
H	Orbit confinement • Orbit loss • Collisional effects • Non-adiabaticity effects • Large drift orbit width effects • Momentum source/E_r generation	M
H	Macroscopic (MHD) mode interactions • Toroidal Alfven modes and turbulence • Energetic particle driven MHD instabilities • Fishbone modes due to passing fast ions • Fast ion transport due to macroscopic modes	M
M	Fast ion-HHFW interactions • Energetic tail formation from bulk • HHFW damping on NB ions	M
H	Modeling tools and comparison with theory • Fast NB ion orbit and power deposition models for incorporation into transport simulation code • Large gyroradius collisional orbit code (LOCUST) • Constant of motion NB ion loss (non-adiabatic effects) code • Collisional and field ripple loss • Alfvén eigenmode modeling • Macroscopic mode induced fast ion transport • Fishbone modes • Energetic particle energy channeling to thermal ions	H

6) Multi-Phase Interface (Edge Physics)

Relative Programmatic Emphasis	Research Elements • Research Ideas for Collaboration	Relative Collaboration Opportunity
H	Heat Flux and Power Balance • Particle and heat fluxes to plasma facing components • Particle and heat fluxes in SOL and divertor channels • Relationship of edge plasma parameters with these quantities and fluctuations	H
H	Edge and SOL Characterization • Database for comparison with theoretical models • Edge transport barrier mechanisms • Edge and SOL turbulence • Asymmetries and plasma & neutral flow patterns	H
H	Wall Conditioning, Recycling and Impurity Control (e.g., boronization, Lithium surface) • Methods and regimes of reliable operation • Methods for density control • Material measurements & advanced wall testing • Edge particle & impurity sources and sinks (migration within vessel) • Liquid Lithium module	M
M	Modeling • Diffusion based plasma edge modeling (UEDGE b2.5, EIRENE, DEGAS 2, etc.) • Turbulence based plasma edge modeling (BOUT, etc.) • Kinetic 2D modeling to correct non-local transport in SOL and divertor channels	H

7) Crosscutting Diagnostics and Enabling Capabilities

Relative Programmatic Emphasis	Research Elements • Research Ideas for Collaboration	Relative Collaboration Opportunity
H	Plasma control (multiple input and output)	H
H	Diagnostics for CHI plasma	H
H	Current Profile & Er • MSE via CIF and LIF • Enhanced FIReTIP channels • Dual-mode reflectometry, local |B|	H
M	HHFW • B-dot probes for edge HHFW fields	M
H	Macroscopic MHD mode • SXR imaging • Fast Mirnov array • Fast tangential X-ray camera • EBW radiometer	H
H	Transport & Turbulence • Fluctuations via 2D reflectometry • Radial polarimetry/interferometry for B and n fluctuations • Collective scattering high “k” fluctuations • Edge fluctuations via probes, magnetic loops, and edge spectroscopy: electrostatic (n, φ, Te), magnetic, convective cells • Tunable CHERS for multiple impurity flow measurements • Fast tangential X-ray imaging (gas electron multiplier) • Ultra fast visible imaging • Flexible pellet injector to trigger ITB/PEP modes • Laser blow-off system for impurity transport	H
M	Energetic Particle • Horizontal and vertical scanning NPA • Energy and angle resolved fast ion loss measurements • Natural diamond detectors as NPA • Alfven mode spectroscopy • Fusion source profile monitor	M

M	<u>Multi-Phase Interface</u> • Wall conditioning: coating, heat loads, electrical path, fast IR imaging, liquid Li surface • Neutral and impurity fluxes: 3D Da emission, 3D visible light emission of impurities, 2D bolometry for edge power balance • Edge plasma parameters: electron, ion and impurity densities, temperatures, current density, plasma flow, magnetic surfaces, electrostatic potential • Edge fluctuations (see Turbulence & Transport diagnostics)	H

7. Opportunities of Cooperation with Other U.S. and International Programs

The NSTX National Research Team has developed and benefited greatly from extensive cooperation with other programs within the Office and Fusion Energy Sciences (OFES) and cooperation with ST research programs in other countries. This cooperation (where the research participations are funded by different DOE managers or by other countries) has a growing importance to the success of the NSTX Research Program, and will be available for participation by the Research Team members. The summary below provides information useful in considering NSTX collaboration research proposals to DOE.

Whereas this document emphasizes information regarding the development of NSTX collaboration research (where the research participants are funded by the same DOE managers), the NSTX program will also work to enhance cooperation with other OFES programs (such as Theory, Enabling Technology, and Advanced Diagnostics) in developing advanced tools and capabilities needed to meet the special challenges and new scientific and technological opportunities offered by the ST experiments, which are described in this Program Letter.

Theory: NSTX research has benefited substantially from cooperation with experts in the Theory Program of OFES in areas of Boundary Plasma Stability and Turbulence, Core Transport and Turbulence, RF Heating, and energetic particle driven Compressional Alfven Wave Instabilities. The new plasma regimes already evident from recent encouraging results from NSTX have introduced several new scientific opportunities of high importance to Fusion Energy Sciences Program that can benefit greatly from a fresh look by Theory experts in the field.

Enabling Technology of VLT: NSTX has substantial cooperation with the Enabling Technology program under the VLT. These include the High Harmonic Fast Wave rf technology (ORNL), the collaboration of which has led to early success in electron heating and a robust research plan on rf heating and current drive on NSTX. A cooperation of a similar nature is proposed on the Electron Bernstein Wave (EBW) technology to enable research into the unique physics features of the EBW conversion heating and current drive in high beta low field configurations such as the ST. This application is unencumbered by density limits that handicap the application of ECH to the over-dense ST plasmas of very high dielectric constants, and is of high relevance to other high beta fusion configurations. The NSTX program has further benefited from the expert participation's of VLT researchers on the important topics of plasma facing material and particle deposition (SNL) and laser ranging measurements of the wall (ORNL). In addition, the NSTX and the ALPS/APEX programs have cooperated in developing concept exploration level tests of liquid wall interactions on CDX-U. These programs are working together to establish the scientific and technical requirements and the database needed for a possible liquid Lithium wall module in the near future to enable strong control of deuterium recycling from the wall. Strong reduction in edge particle recycling has been shown in tokamaks to lead to important improvements in plasma properties. Controlled fueling that is relatively independent of edge recycling is expected to be a key element of this improvement. Such likely benefits should be particularly important to NSTX for longer pulse operations under higher edge heat and particle fluxes, to be encountered during the "noninductive sustained" operation planned to begin in FY 04. Discussions with these programs in the near future are scheduled to develop coordinated plans to carry out these important R&D activities.

Advanced Diagnostics: NSTX research has also benefited substantially from cooperation with experts in the Advanced Diagnostics Program of OFES in areas of Reflectometry, Polarimetry, X-ray Spectroscopy, and Motional Stark Effect Polarimetry, to name a few. The new plasma regimes already evident from recent encouraging results from NSTX have introduced several new scientific opportunities and challenges of high importance to Fusion Energy Sciences Program that can benefit greatly from a fresh look also by Diagnostics experts in the field.

CDX-U, HIT-II, START: NSTX is the Proof-of-Principle ST experiment based on the successful Concept Exploration tests such as the CDX-U (Current Drive Experiment-Upgrade, PPPL), HIT and HIT-II (Helicity Injected Torus-II, U. Washington), and START (Small Tight Aspect Ratio Tokamak, U.K.). CDX-U and START have investigated the operational Ohmic edge q limit and related MHD activities. HIT has proven the feasibility of ST plasma start-up and current maintenance using Coaxial Helicity Injection (CHI) in the presence of a close-fitting conducting shell. HIT-II has been successful in demonstrating the feasibility of CHI start-up relying primarily on PF coils to control plasma position and the NSTX-like "open" CHI configuration. As for auxiliary heating, CDX-U has tested the launching, propagation and heating of HHFW successfully. START has successfully proven the high efficacy of NBI heating (with the NBI system on loan from the U.S.), producing low-q (~3) H-mode-like ST plasmas with toroidal average betas β_T as high as 40% in the absence of nearby conducting shell. These pioneering tests of ST plasmas have produced exceptionally encouraging and valuable data for the NSTX design and Research Program plan.

PEGASUS: The PEGASUS device at the University of Wisconsin started operation during 1999 and began to explore the ST plasma regime approaching the extreme low limit of R/a ~ 1.1. Plasma currents more than 100 kA and toroidal average betas more than 20% have already been obtained in PEGASUS with resistive heating alone, indicating the potential physics benefits of the extreme low aspect ratio. PEGASUS further plans to explore new methods for rf heating (such as via conversion of Electron Cyclotron Wave to Electron Bernstein Wave) and for making a physics connection to a very low aspect ratio Spheromak plasma. The NSTX Research Program will benefit greatly from the exploratory research carried out in this and other smaller ST devices.

DIII-D and HBT-ET: In order to attain very high betas (β_T up to 40%) and high bootstrap current fractions (up to 70%) in NSTX, it is likely that the potentially unstable Resistive Wall Modes (RWM) and Neoclassical Tearing Modes (NTM) will need to be stabilized. The experimental data and physics understanding from the on-going effort on DIII-D and HBT-ET (and other tokamaks) in FY01-03 will therefore be a strong complement to macroscopic stability research on NSTX. These will provide valuable information on the necessity, approach, design, construction and operation of active feedback control system for these modes on NSTX in the FY03 time frame. Furthermore comparison between NSTX and DIII-D plasmas of equal minor radius, cross section, and applied toroidal field (~ 6 kG) at different major radii could reveal the distinguishing aspect ratio and beta effects on plasma turbulence and transport. NSTX research during FY01-2 will aim to produce data at 6 kG applied toroidal field to enable this comparison.

ARIES-ST Study: The ARIES Team study of ST-based power plant under the organization of Virtual Laboratory for Technology (VLT) is of high interest to the NSTX Research Program, particularly in

identifying ST physics assumptions with large uncertainty at present that could strongly influence the attractiveness of the power plant. The bootstrap sustained mode of ST plasma operation with elongation comparable to or greater than 3 has so far been identified in the ARIES-ST study as having high leverage to ensure the attractiveness of future ST power plants. Experimental tests of ST plasmas with elongations between 2 and 3 on NSTX are therefore highly desired and should be part of future research plans, included in the longer pulse upgrade to the NSTX center stack.

In the international arena, the ST research has recently been marked by a rapidly growing research community and cooperation.

Cooperation with MAST (U.K.): The new Mega-Ampere Spherical Tokamak (MAST, U.K.) started operation in late 1999. It has design features and research capabilities highly complementary to those of NSTX. At present there is no conducting shell close to the plasma edge in MAST, owing to the unique merging-compression start-up scenario that reduces the requirements of the central solenoid. The combination of large vacuum chamber and internal PF coils further give MAST added flexibility in divertor configuration. MAST emphasizes initial operation with NBI heating and Electron Cyclotron Heating (ECH), since the compression start-up scenario excludes the possibility of fixed outboard Fast Wave launchers. During its first 3-month experimental campaign in 2000, MAST produced H-mode plasmas and >1 keV ion temperatures at currents up to 800 kA using a moderate NBI power of up to 700 kW. Plasma densities were found to exceed the "Greenwald" limit often without apparent loss of confinement. (The NBI system and a Neutral Particle Analyzer on loan from ORNL and PPPL, respectively, have been instrumental in these rapid successes on MAST.) The low-cost Trimethalboron technique was used to "boronize" the MAST wall, prior to its use on NSTX, providing important improvements to plasma conditions during the first campaigns with auxiliary heating. NSTX research during 2000 benefited almost immediately from these new experiences and results in making rapid progress in its own research. A substantial number of collaborations and exchanges on a broad number of topics are planned for FY01-03 to derive mutual benefits to the NSTX and MAST research programs.

US-Russia Exchange on ST: The new **GLOBUS-M** recently reached over 150 kA in plasma current and plans to explore various improved rf heating and current drive techniques, such as the poloidal launch of lower hybrid waves. A formal collaboration is in place to cooperate in areas of Ohmic plasmas and advanced diagnostics. Other fusion research exchanges will continue to involve researchers from Ioffe Institute, Kurchatov Institute, Efremov Institute, and TRINITI at Troitsk, covering a range of topics in ST physics and diagnostics.

US-Japan Cooperation on ST: Six fusion researchers from universities in Japan (Himeji Institute of Technology, Hiroshima University, Kyoto-Tokai University, University of Tokyo) participated in the NSTX research during the summer of 2000. Topics of cooperative research covered divertor spectroscopy, ion Doppler spectroscopy of CHI plasmas, rf heating, electron Bernstein wave, and plasma operation scenarios. Proposals for the 2001 US-Japan cooperation on ST have been increased to include possibly 4 more researchers from Niigata University, University of Tokyo, and possibly National Institute for Fusion Studies and Tsukuba University to cover the additional topics of the effects of large flow on equilibrium and stability, ultrahigh beta ST plasma scenario, microwave reflectometry, and possibly momentum transport effects on confinement. These cooperative research activities are

expected to contribute to the success of research on NSTX as well as to enhancing the already substantial research interest in Japan in ST plasmas.

IAEA Coordinated Research Project (CRP) on Comparison of Compact Toroid (CT) Configurations: NSTX participated in and provided key contributions to an IAEA-sponsored CPR to compare the CT configurations covering the Spheromak, the Field Reversed Configuration (FRC) and the ST. In its second research coordination meeting, sixteen researchers from eight countries (Brazil, Italy, Japan, RPC, Russia, UK, Ukraine, and USA) reviewed the relevant research activities and made recommendations on research topics of common interest to the high beta modest field CT plasmas for possible future research cooperation. An example of such cooperation stems from the apparently close physics relationship between a strongly diamagnetic ST plasma of very high beta and bootstrap current fraction and FRC plasmas of order unity average beta stabilized by a weak externally applied toroidal magnetic field recently produced in TS-3 (University of Tokyo, Japan). This has contributed to an active discussion between the NSTX and TS-3 researchers and the inclusion of this topic for conceptual studies in the proposed US-Japan cooperation summarized above. Final report of this CRP is expected in 2002.

IEA Implementing Agreement on ST Research: Progress was made recently by DOE official in advancing a new IEA Implementing Agreement on ST Research, initially involving ST research activities in Brazil, U.K., U.S., and possibly Japan. This agreement provides a vehicle for effectively coordinating and integrating the already diverse international research cooperation currently conducted by the NSTX National Research Team, and will enable the application of the best capabilities and expertise available in the world to bear on the challenging and exciting ST research, with potential high payoff to the U.S. Fusion Energy Sciences Program.