NSTX RESEARCH PROGRAM 2000-2003

(Draft, December 1999)

The NSTX program **mission** is to prove the broad scientific principles of the Spherical Torus (ST) plasma toward an optimized confinement system and an affordable energy development path. The ST promises very large increases in the efficiencies of magnetic field shaping and utilization, leading to plasmas of higher pressure and confinement using reduced size and magnetic field. The NSTX research aims to advance the fusion science of magnetically confined plasmas of order-unity beta (where the plasma pressure is comparable to the magnetic pressure) and contribute to progress in the science of magnetic fusion energy in general.

The NSTX project was completed in FY 1999, as a national research team was formed to begin research. A major **near term objective** for the NSTX research program, together with other ST experiments in U.S. and other countries, is to make a preliminary determination of the attractiveness of the Spherical Torus concept in 5 years. The capabilities of the national research team as well as the national facility are expected to expand to produce high-quality scientific results and excellent plasma performance in achieving this objective.

Phase-I research on NSTX will be carried out in FY 2000 to investigate properties of resistively heated plasmas, test high-harmonic fast wave (HHFW) heating at substantial power, and develop coaxial helicity injection (CHI) physics in forming substantial plasma current without relying on solenoid induction. Modern diagnostics and a powerful neutral beam injection (NBI) system will be installed and commissioned during this time to establish the basic operational and diagnostic capabilities of NSTX. A schematic summary of the near term NSTX research program is provided in the next page.

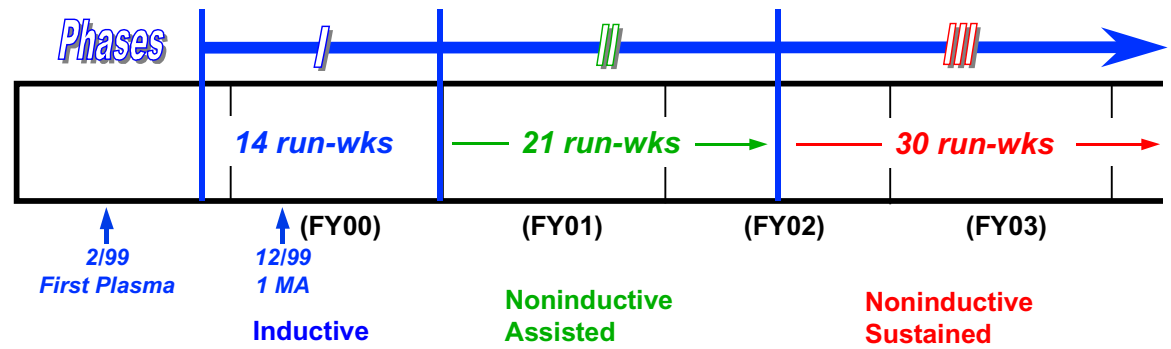
Phase-II research will begin in FY 2001 to investigate plasma stability, confinement, heating and current drive, and scrape-off layer physics under intense rf and NBI heating and at high plasma beta. Advanced techniques to measure plasma profiles will be implemented, some of which will rely on energetic ions produced by intense NBI and rf powers. Phase-II research is expected to continue into FY 2002, when current startup experiments will be conducted using CHI, HHFW, NBI, and possibly Electron Bernstein Wave (EBW) to assist the operation of high performance plasmas for substantial pulses (~1 s). Techniques to make high confinement and stability compatible at high plasma pressure will be tested. Investigations of new scientific possibilities for sustaining Spherical Torus plasmas at high temperature and high current without magnetic induction are expected also to begin during FY 2002.

The FY 1999 NSTX achievement and the planned FY 2000–2002 NSTX scientific goals are provided in the succeeding pages.

Phase-III research is expected to begin during the second half of FY 2002, and investigate the scientific issues of very high beta, bootstrap current fraction, confinement, and divertor heat flux, for long pulse lengths (~5 s) to allow the plasma current profiles to evolve toward steady state shapes. Noninductive startup to full plasma current will also be tested over this time scale utilizing the full plasma pulse length. Advanced diagnostics for plasma turbulence and modern techniques of MHD mode control will be implemented to support this research. Phase-III

research is expected to continue through FY 2003, when a new center stack would be installed to maximize NSTX's capability for magnetic field shaping and utilization. Such a capability is expected to enable the investigation of fully self-sustained ST plasmas, which are of high interest to viable even attractive applications to fusion energy.

A schematic summary of the near term NSTX research program is provided below:



• **Toroidal Beta, β_T**		• → 25% (no-wall limit)	• → 40% (wall stabilized)
• **Bootstrap Current**		• → 40% (no-wall limit)	• → 70% (wall stabilized)
• **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	• → 0.4 MW (incremental)	• ~ 0.4 MW
• **CHI Startup**	• → 0.2 MA	• → 0.5 MA	• ~ 0.5 MA
• **Measure**	• $T_e(r)$, $n_e(r)$	• j(r), $T_i(r)$, flow, edge	• turbulence, mode control

Three initial phases of NSTX Research Program, aimed at determining the attractiveness of the Spherical Torus concept in the FY 2004 time scale.

NSTX Accomplishment and Major Scientific Research Goals for FY 1999 - 2002
(Draft, December 1999)

FY 1999 Accomplishment

- **A New Proof of Principle Facility Began Operation with a Newly Formed National Research Team.**

  The National Spherical Torus Experimental (NSTX) project at the Princeton Plasma Physics Laboratory (PPPL) was completed in FY 1999 at cost, and exceeded its first major operational milestone of first plasma ahead of schedule. A national research team was organized and the facility began experimental operations in FY 1999 and achieved its second major operational milestone (500 thousand ampere current) on schedule. The team is preparing to carry out a full research schedule in FY 2000.

FY 2000 Goals

- **Achieve High Plasma Current for High-temperature Spherical Torus Plasmas Investigations** (9/30/00)

  Operate a novel magnetic fusion confinement device, the National Spherical Torus Experiment, with 0.5 megampere plasma currents approaching 0.5 second pulse lengths and 1 megampere currents for shorter pulses.

- **Explore the Application of Noninductive Startup Current via Magnetic Reconnection to Larger Spherical Torus Plasmas of Lower Collisionality** (9/00)

  Coaxial Helicity Injection (CHI) uses dc radial electric field within the plasma chamber to start up the toroidal plasma current through magnetic reconnection. The intriguing physics properties of this innovative noninductive technique have been observed in the HIT and the HIT-II experiments. The same mechanisms will be investigated in the larger NSTX using improved control technique to initiate plasma currents up to 200 thousand amperes in low-collisionality plasmas.

- **Begin Investigation of New High-Power Radio Frequency Method to Heat High-Temperature Spherical Torus Plasmas** (9/00)

  Spherical Torus plasmas possess a dielectric constant approaching 100. Radio frequency waves at large multiples of the ion magnetic resonance frequencies are calculated to heat such plasmas and drive current effectively. Efficient heating and current drive will reduce the operating cost of future Spherical Torus power plants. Up to four million watts of radio frequency power will be launched in NSTX into high-current Spherical Torus plasmas for the first time to investigate the relevant physics properties.

- **Installation and Commissioning High-Power Neutral Beam Injection (NBI) System** (10/00)

  An NBI system from the Tokamak Fusion Test Reactor Project will be refurbished and commissioned to deliver to the NSTX plasmas up to 5 million watts of neutral particle power at 80 kilo-volts of energy for up to 5 seconds, to support the scientific goals of the NSTX research program.

FY 2001 Goals

- **Evaluation of Spherical Torus Plasma Heating to High Temperature and Pressure**

  Intense heating from NBI and rf will be applied to MA-level Spherical Torus plasmas. This will enable the investigation of the physics of large ion gyroradius (the size of ion orbits which is only one order of magnitude or so smaller than the plasma size) and dielectric constant (~100, which is about two orders of magnitude larger than low-beta configurations) for plasma temperatures of 10–20 million degrees Celsius. This advance would establish the conditions of relevance to future energy producing Spherical Torus plasmas.

- **Exploration of Collisionless Plasmas at High-Temperature and Pressure That are Stable to Large-Scale Perturbations**

  Spherical Torus plasmas in NSTX have been calculated to be stable against large-scale fluid-like perturbations simultaneously for high ratios of plasma to magnetic pressure (up to 25%) and self-driven current fraction (up to 40% of total current). Active feedback control of such perturbations is expected not to be required. Intense heating and extensive measurements will be applied in NSTX to create high-temperature collisionless Spherical Torus plasmas for plasma currents up to one million amperes for stability investigations. The new data will substantially expand the existing stability database for lower plasma-to-magnetic pressure ratios and high plasma temperatures, and develop the understanding needed for future, more powerful Spherical Torus experiments.

- **Evaluation of Self-Suppression of Micro-Turbulence in Collisionless Spherical Torus Plasmas at High Pressure**

  Spherical Torus plasmas with high plasma-to-magnetic pressure ratios have been calculated to possess physics features such as the strong self-driven flow shear that may suppress plasma micro-turbulence and reduce plasma loss rates toward the irreducible minimum due to collisions between charge particles. Intense heating and extensive measurements will be applied in NSTX to investigate these properties in collisionless plasmas of high pressure, for plasma currents up to one-million amperes. The new data will substantially expand the existing toroidal database of lower plasma-to-magnetic pressure ratios, and develop the confinement physics understanding needed for future, more powerful Spherical Torus experiments.

- **Study of New Mechanisms for Dispersing Intense Plasma Heat and Particle Fluxes**

  Understanding of plasma properties just beyond the plasma edge is critical to the success of small-size Spherical Torus plasmas with high power densities. The naturally shaped and elongated Spherical Torus plasma introduces the new features of much stronger variations in the geometry and strength of the magnetic field in such plasmas. Also calculated is an increased expansion of the cross section of the field line bundle that exhausts the plasma fluxes to the walls. These properties are expected to introduce localized instabilities there and help disperse the plasma exhaust fluxes over much larger wall areas. Detailed investigation of these plasma properties will begin when intense heating powers and several edge diagnostics on NSTX are introduced. Successful dispersal of plasma exhaust power over large wall areas will be needed for future, more powerful compact Spherical Torus experiments.

FY 2002 Goals

- **Study of New Methods for Starting up Plasmas**

  By combining edge current drive such as the CHI (see FY 2000 Goals) with the core currents driven by radio frequency waves, neutral beam injection, and bootstrap current generated by plasma pressure itself, calculations have shown that it should be possible to create plasmas with currents up to one-half million amperes without using a solenoid magnet to induce the plasma current in the conventional way. Successful noninductive startup would help dispensing with the central solenoid magnets, and simplify the Spherical Torus concept enormously. These new methods for starting up plasmas will be tested in NSTX.

- **Evaluation of Compatibility of High Confinement and Stability at High Pressure**

  Controlling the plasma profiles to render good confinement and improved stability (i.e., high performance) compatible has been an overarching goal for the Advanced Tokamak research, and is expected to be similarly so for the Spherical Torus research. Calculations have shown that hallow current profiles and broad pressure profiles are simultaneously needed to achieve this goal. Recent calculations have indicated that such profiles may be naturally achievable for Spherical Torus plasmas. In the Spherical Torus, the combination of strong toroidal transformation and large vertical height of the plasma cross section leads to a stable hollow current profile. The hollow current profile is further expected to increase the irreducible plasma diffusion near the plasma center of low current density while reduce it toward the plasma edge of high current density. This promotes a broad pressure profile under the condition of good plasma confinement (or substantially reduced micro-turbulence). Experiments will be carried out in NSTX to clarify the underlying science of these special properties and develop techniques to improve compatibility of these optimized profiles in Spherical Torus plasmas.

- **Evaluation of Noninductive Maintenance and High Performance for Long Pulses**

  Calculations have shown that the hollow current profiles needed for stable high-pressure Spherical Torus plasmas are also more nearly compatible with the hollow bootstrap current generated by plasma pressure itself. This increases the possibility for the self-generated bootstrap current profiles to stay aligned and below the full plasma current profile, and more easily allow other methods of current drive (see preceding goals) to make up the balance. Successful noninductive current maintenance in Spherical Torus, together with noninductive startup, will enable dispensing with the solenoid and permit compact high-performance devices suitable high-gain fusion experiments. High-gain fusion experiments would in turn establish the database for energy producing plasma physics needed by the technology-intensive volume neutron source that is appropriate for fusion energy development. These new possibilities of noninductive maintained Spherical Torus plasmas will be investigated in NSTX for currents up to one million amperes.