NSTX –OFES FY2005 BPM – Attachment 4

FY03

1. Comprehensive Description of Research Plans

- **FY03-1 on Boundary Physics:** *Measure and analyze the dispersion of heat flux on plasma facing components under conditions of high heating power in NSTX.*

  Description – Intense heat flux must be dispersed safely on the chamber walls in a high performance compact fusion device. Heat flux to the plasma facing components in high power experiments will be measured and analyzed to determine the dependence on externally controllable conditions in high heating power experiments on NSTX.

  Technical Approach – The flow of heat from the hot plasma core through the cooler edge region onto the plasma facing components will be measured for plasmas heated by neutral beams, radio-frequency wave power, and resistive dissipation. While the small major radius of the scrape-off region in spherical torus is expected to concentrate the edge heat flux, the magnetic flux lines also naturally expand in the divertor region to disperse the heat flux. The strong magnetic mirror ratio of the spherical torus edge also tends to trap the collisionless ions away from the plasma facing components at smaller radius and promote plasma oscillations to disperse the plasma heat flux toward the outboard. Measurements so far have indicated much larger outboard divertor heat flux than the inboard, consistent with the above mentioned effects. Edge parameters over a wide range of conditions will be measured to assess these competing effects. Diagnostics systems on NSTX and MAST (in collaboration) include a reciprocating probe containing multiple measurements, an extensive set of Langmuir probes (> 200 in number) on the plasma facing components around the plasma, bolometer arrays, filtered fast visible cameras, 1D and 2D infra-red sensors to view the divertor region and the center column tiles. The results will enable future estimates of the required capabilities of plasma facing components on NSTX to handle high heat flux for longer pulses in future experiments.

- **FY03-2 on Physics Integration:** *Explore and characterize plasmas with high beta near the "no-wall" stability limit simultaneously with high energy confinement for durations greater than the energy confinement times.*

  Description – The spherical torus is theoretically capable of containing plasma energy efficiently at high ratios of plasma pressure to applied magnetic pressure. Experiments will be conducted in NSTX to create and characterize the conditions that improve the stability and energy containment simultaneously without active stability control, and the operation scenarios that maintain these conditions for timescales greater than the energy replacement times.

  Technical Approach – High Neutral Beam and High Harmonic Fast Wave (HHFW) power will be applied to modify the plasma pressure and current profiles, and approach the high beta and high confinement conditions for timescales greater than the energy confinement times. Increased flexibility in edge fueling and wall surface conditions and reduced field errors will assist in improving the plasma stability and confinement conditions simultaneously without active stabilization of the plasma (the so-called "no-wall limit"). Plasma operations will be improved using high-speed computers and data channels. A suite of x-ray, laser scattering, spectroscopy, visible and infrared imaging, edge probes, energetic particle, and gas injection diagnostic systems will be used to explore, measure, and characterize the conditions that simultaneously increase the plasma stability and energy containment efficiency. Substantial progress toward this milestone was achieved in FY2002 and in February 2003, when plasma β_T's of 20-25% and τ_E's greater than the H-mode scaling indications were simultaneously realized for flat-top durations $\geq \tau_E$. Further work to satisfy the milestone includes analysis during the remainder of FY03 of MHD stability, local transport properties, and the pressure-gradient effects in the H-mode pedestal. This progress will provide insights to the special techniques and conditions needed to prepare for similar investigations based on higher beta plasmas obtained using active suppression and avoidance of large scale instabilities.

- **FY03-3 on Solenoid-Free Startup and Sustainment:** *Analyze the effectiveness of using a combination of non-inductive techniques to sustain plasma pulse lengths up to 1 s.*

  Description – The spherical torus concept requires the development of techniques for sustaining plasma currents. Several techniques for this purpose will be tested on NSTX. The results will be compared with theoretical models to provide data needed for achieving NSTX plasmas with pulses substantially greater than 1 s.

  Technical approach – Techniques to generate current non-inductively to assist in the sustainment of plasma current will be tested. One method of current generation is launching into the plasma the High Harmonic Fast Wave (HHFW) with momentum input, which is predicted to accelerate electrons. The HHFW momentum will be varied as part of this studied. Another method is injecting energetic neutral beams (NBI) with a net momentum input, which deposit energetic charged particles in the plasma and generate toroidal current. Plasma heating from HHFW and NBI raises the plasma pressure, which in turn generates a significant "bootstrap" current to supplement the above externally driven current. These experiments will require the development of effective approaches for plasma control to maintain the conditions conducive to non-inductive current generation. Several relatively long pulse discharges (~ 1 s in duration) at 800-kA current have been obtained using NBI during the FY2002 campaign. Similarly long pulses were also obtained by HHFW power alone at close to 400-kA current at modest densities ($\sim 1\text{-}2\times10^{13}/\text{cm}^3$) with interesting properties. These results will be extensively analyzed during the remainder of this fiscal year to ascertain the effectiveness of the techniques used in these discharges for future applications to achieve attractive longer pulse plasma conditions in NSTX.

- **FY03-4 on MHD Stability:** *Assess interactions between plasma resonant field response and plasma rotation.*

  Description: – The maximum ratio of plasma pressure to magnetic field pressure (beta) is determined by limits set by the stability of macroscopic plasma oscillations. If the limits can be increased, more efficient plasma containment will be possible. To determine how to increase these limits, studies will be performed to assess the interactions between the resonant plasma oscillations, plasma rotation, the nearby conducting walls, and the externally applied correction magnetic fields.

  Technical approach – Poloidal and toroidal arrays of magnetic field sensors will be installed in the NSTX vessel to measure the plasma MHD modes and determine their interactions with the externally applied irregularities in the magnetic field. Neutral beam injection heating will be applied to create strongly rotating plasmas as the calculated stability limits are approached to determine the effects of rotation on these MHD modes. Magnetic sensor measurements are also expected to help clarify the physics of MHD mode stabilization induced by the conducting "wall" located near the plasma edge. Such stabilization should allow beta values above the theoretical "no-wall" limits to be generated for times that are long compared to the resistive wall times in NSTX. Detailed measurements of plasma profiles will also be made to enable determination of the theoretical beta limits for comparison with the observed limits. Data will be analyzed to identify the parameters that govern the critical rotation frequencies required for stabilization at high beta, and the mechanisms associated with the modes that can slow down this rotation. The results will help determine the best approaches to maintain the elevated beta values for time scales much greater than the resistive wall time, and the design of control coils for installation before the FY04 experiment campaign.

2. Research Accomplishments

- FY03-1 - Measure and analyze the dispersion of heat flux on plasma facing components under conditions of high heating power in NSTX. (September 2003)

3. Information on Physical Infrastructure Needs: none

4. Awards to Date:

FY02

Larry Grisham
Kaul Foundation Prize for Excellence
in Plasma Physics and Technology Development
Princeton University

Edmund Synakowski
Award for Excellence in Plasma Physics Research
American Physical Society

Randy Wilson
Fellow
American Physical Society

Citation of Merit Award
New Jersey Governor's Occupational Safety and Health Awards Program
for the National Spherical Torus Experiment
for Working throughout Calendar Year 2001 without Lost Time from a Work-related Injury or Illness

FY03

Stan Kaye
Fellow
American Physical Society

Division of Public Safety & Occupational Safety and Health Award
for the National Spherical Torus Experiment
for working two consecutive calendar years without a lost time injury or illness.

FY04

Decrement Budget Case (-10% with respect to the FY04 President's Request)

1. Comprehensive Description of Research Plans

- **FY04-1 on Physics Integration**: *Assess confinement and stability in NSTX by characterizing high confinement regimes with edge barriers and by obtaining initial results on the avoidance or suppression of plasma pressure limiting modes in high-pressure plasmas.*

  Description – Experiments will be conducted in operating conditions in which thermal energy is efficiently contained via strong edge barriers to heat loss and the ratio of plasma pressure to magnetic pressure is high near or above the "no-wall" MHD limit. These conditions will be maintained for durations much greater than the energy replacement times by suppressing or avoiding large scale plasma instabilities to increase the achievable pressure.

  Technical Approach – Progress and experience from the FY02-03 research and the other supporting FY04 milestones that address the Transport & Turbulence, MHD Stability, and Boundary Physics properties of the spherical torus plasma will be used to achieve this milestone. These techniques include plasma temperature, density and current profile modification via heating and current drive mechanisms, plasma shaping and current ramp variations, and plasma rotation to gain the stabilization effects of nearby conducting plates. New techniques to be tested in FY04 include multiple lithium pellets and supersonic gas injection to control plasma recycling and arrest density rise, and the external field correction to reduce the static field errors to minimal values. A broad suite of measurements will be used to quantify the effectiveness of these techniques in raising the plasma pressure, maintaining efficient energy containment, and increasing the duration of such plasmas. Multiple in-vessel magnetic sensors and ultra-soft X-ray detector arrays will be used to measure the MHD modes that may limit the plasma pressure rise under conditions of interest. These data will be used in stability analysis to determine progress toward and beyond the predicted "no-wall" beta limit while maintaining high confinement. An understanding will be obtained of the requirements for achieving the plasma profiles and edge loss barriers to extend simultaneously high beta and high confinement for durations much greater than the energy confinement times. The results will be compared with theoretical projections and contribute to a preliminary determination of the attractiveness of the spherical torus concept.

- **FY04-4 on Solenoid-free Startup and Sustainment**: *Conduct initial tests combining available techniques to achieve solenoid-free initiation to substantial plasma currents.*

  Description – A combination of radiofrequency, pressure gradient, coaxial helicity injection, and outboard poloidal field techniques will be tested for creating substantial initial plasma currents without applying induction flux from the solenoid.

Technical Approach – The first phase of solenoid-free operation in NSTX requires the initiation of a substantial plasma current (up to ~100 kA) with adequate temperature and density for the subsequent ramp up to ~500 kA. This research will focus on testing the scientific feasibility of initiating modest but substantial currents. The large toroidal currents initiated via Coaxial Helicity Injection (CHI), up to 400 kA so far, will be manipulated and converted to currents within closed flux surfaces for use in further current ramp-up. Also will be tested is the induction methods using the outboard poloidal field coils alone to assist in the initiation of the plasma current. Another technique to be tested at an initial modest level (20-30 kW, 50-100 ms) will be the use of Electron Cyclotron Wave-Electron Bernstein Wave (ECW-EBW) at very low densities, to generate pressure gradient-driven currents in plasmas of very high safety factors (~50 at edge). These techniques have been successfully used to initiate modest currents in smaller ST and tokamak devices. The results will be compared to theoretical estimates and help determine the design requirements for a fuller implementation and investigation of the physics for these techniques in the FY06-08 time scale.

- **(FY04-5) on Wave-Particle Interactions:** *Measure Electron Bernstein Wave (EBW) emissions to assess heating and current drive requirements.*

  Description: – Maintenance of plasma current by non-inductive means is important to magnetic fusion energy sciences research. Conventional rf current drive techniques have limited applicability to high beta and high density plasmas. The viability of Electron Bernstein Waves (EBW) to heat the plasma and drive current will be explored in high beta plasmas by measuring the emission from EBW.

  Technical Approach – The EBW is a promising candidate for driving current in the ST by externally launched waves. However, this will only be effective if a strong coupling can be established between electromagnetic waves launched at the edge and the EBW, which propagates only inside the plasma. Theory suggests that this coupling is highly dependent on the plasma density profile just beyond the plasma edge in NSTX and MAST. This was confirmed by experiments in CDX-U, NSTX, and other devices where localized limiters were introduced to modify the local density gradient. An antenna with seven steerable mirrors has been installed on MAST to test the launching of EBW up to the 1 MW level at 56 GHz in frequency for a substantial duration (~0.3 s). Radiometers will be used to measure the EBW emission from the plasma and its conversion to electromagnetic waves at the plasma edge. To test theory, plasma parameters and the wave propagation angle will be varied. These results will be used to estimate the requirements for a current drive system for NSTX to supplement the CHI and HHFW schemes. In addition, the EBW radiometer already installed on NSTX could provide information on temperature changes occurring in the plasma on timescales faster than can be achieved by the Thomson scattering diagnostic, if and when NSTX operation starts in the September-October 2003 time scale. Fast temperature measurements can shed new lights on the heating and heat diffusivity properties of the plasma core. This research will be supplemented by an enhanced collaboration on the MAST device at Culham, U.K., which has extensive EBW heating and current drive capabilities at 56 GHz in frequency.

2. Research Accomplishments

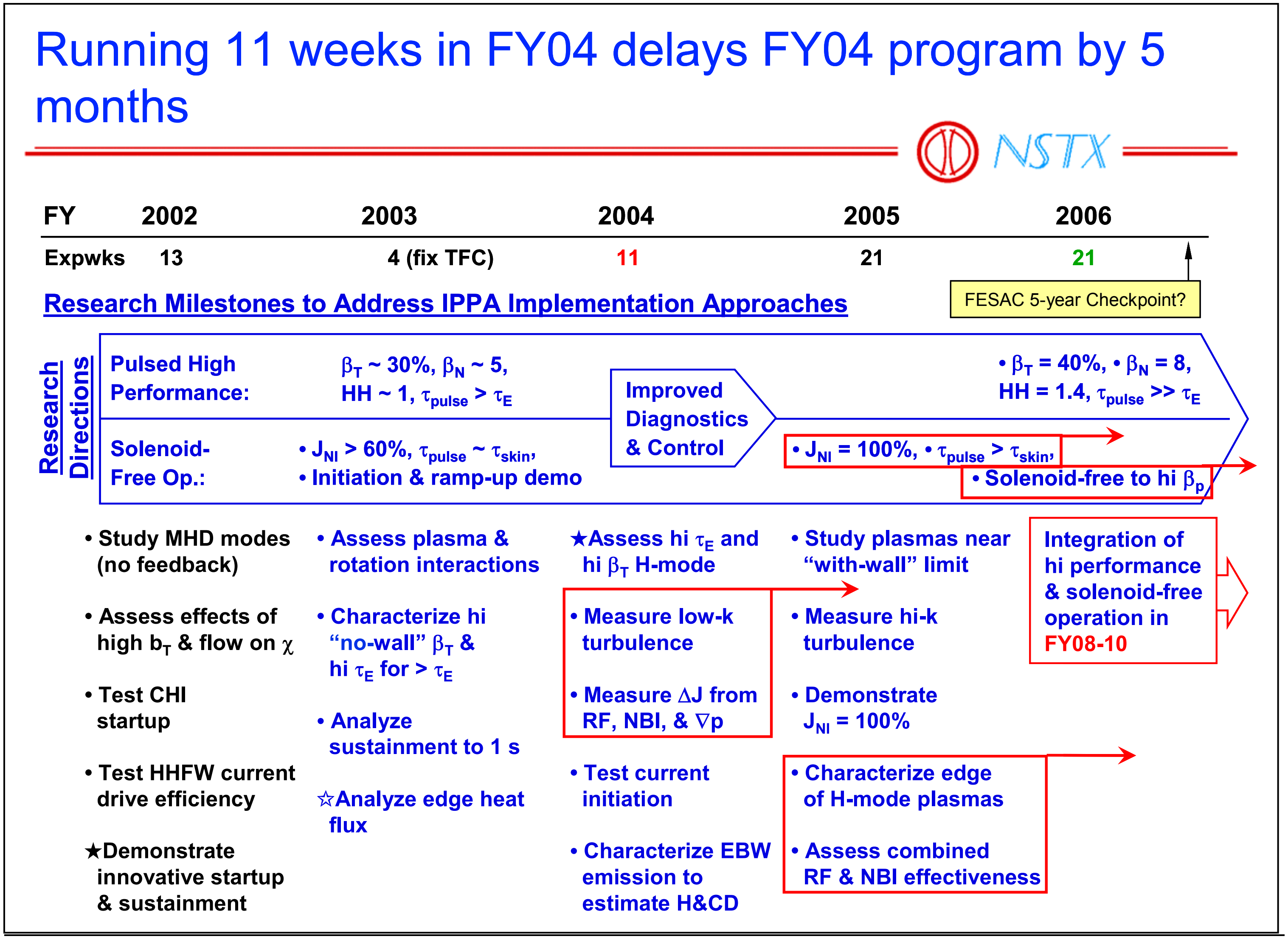
- FY04-1 Assess confinement and stability in NSTX by characterizing high confinement regimes with edge barriers and by obtaining initial results on the avoidance or suppression of plasma pressure limiting modes in high-pressure plasmas. (September 2004)

3. Information on Physical Infrastructure Needs: none

Funding at this level will result in the following Impacts *(with respect to the President's request):*

- Reduce planned operation weeks from 21 weeks to 11 weeks
- Reduce Research Progress by 40% by delaying two Planned Research Milestones (FY04-2 – Transport & Turbulence and FY04-3 Wave-Particle Interaction) one year.
- Reduce planned FTE's by 15
- Delay Diagnostic Milestone to commission additional 10 channels (to 30) on MPTS one year
- Delay Facility Upgrade Designs for Double End Fed Antenna, 15 GHz EBW tube and Divertor Cryo Pumping

The impact on the research program plan is summarized in the following figure:



Running 11 weeks in FY04 delays FY04 program by 5 months

FY	2002	2003	2004	2005	2006
Expwks	13	4 (fix TFC)	11	21	21

FESAC 5-year Checkpoint?

Research Milestones to Address IPPA Implementation Approaches

Research Directions

Pulsed High Performance: $\beta_T \sim 30\%$, $\beta_N \sim 5$, HH ~ 1, $\tau_{pulse} > \tau_E$ → Improved Diagnostics & Control → • $\beta_T = 40\%$, • $\beta_N = 8$, HH = 1.4, $\tau_{pulse} >> \tau_E$

Solenoid-Free Op.: • $J_{NI} > 60\%$, $\tau_{pulse} \sim \tau_{skin}$, • Initiation & ramp-up demo → • $J_{NI} = 100\%$, • $\tau_{pulse} > \tau_{skin}$, • Solenoid-free to hi β_p

2002:
- Study MHD modes (no feedback)
- Assess effects of high b_T & flow on χ
- Test CHI startup
- Test HHFW current drive efficiency
- ★Demonstrate innovative startup & sustainment

2003:
- Assess plasma & rotation interactions
- Characterize hi "no-wall" β_T & hi τ_E for > τ_E
- Analyze sustainment to 1 s
- ☆Analyze edge heat flux

2004:
- ★Assess hi τ_E and hi β_T H-mode
- Measure low-k turbulence
- Measure ΔJ from RF, NBI, & ∇p
- Test current initiation
- Characterize EBW emission to estimate H&CD

2005:
- Study plasmas near "with-wall" limit
- Measure hi-k turbulence
- Demonstrate $J_{NI} = 100\%$
- Characterize edge of H-mode plasmas
- Assess combined RF & NBI effectiveness

2006:

Integration of hi performance & solenoid-free operation in FY08-10

FY04

Level Budget Case (i.e., flat with respect to the FY04 President's Request)

Prioritized List of Increments:
Increase Run Weeks from 11 to 21
Increase Diagnostic and Facility Upgrade Budget

1. Comprehensive Description of Research Plans ***(Increments from Decrement Case)***

- **Milestone FY04-2 on Transport and Turbulence:** *Measure long wavelength turbulence in spherical torus plasmas in a range of plasma conditions.)*

  Description – Theory suggests that the spherical torus plasmas may naturally yield conditions conducive to suppressing or reducing the turbulence in the "long wavelength" scale of a few radii of ion gyration around the magnetic field, thereby improving the plasma's heat containment. Advanced microwave and interferometer techniques will be used on NSTX to measure the turbulence properties. These measurements will be used to test predictions from state-of-the-art theory and computation.

  Technical approach – Suppression of plasma turbulence can reduce heat leakage across the magnetic field from high-temperature plasmas. Theory suggests that the spherical torus plasmas may naturally provide the conditions to reduce this turbulence. The first measurements of turbulence characteristics in a spherical torus will be carried out over a wide range of plasma flow shearing rates (up to a megahertz) and toroidal betas (up to ~30%). To diagnose the long-wavelength turbulence driven by the plasma, microwaves will be launched from the plasma edge. They are known to reflect from the "cut-off" layers in the plasma at locations uniquely determined by the plasma density and magnetic field. The amplitude and phase of the reflected wave will then be measured, enabling details of the high beta long-wavelength turbulence characteristics to be assessed. Other techniques of measurements, including high speed interferometer measurements of line-integrated electron density, will be applied. Diagnostics to measure the plasma density, ion temperature, electron temperature, ion flow velocity, and radial electric field will be used as input to theory codes. These codes will be used to predict turbulence characteristics and compare with the experimental measurements.

- **FY04-3 on Wave-Particle Interactions**: *Measure plasma current profile modifications produced by radiofrequency, neutral beam injection, and pressure-gradient techniques.*

  Description – Like tokamaks, spherical torus plasmas carry large currents that are essential for confining the plasma. Learning how to sustain these currents efficiently is a major research goal for NSTX. New techniques to measure the light emitted from beams of energetic atoms will be employed to measure changes in the profile of the plasma current induced by radiofrequency waves, fast ions born from the injected energetic neutral particles, and changes in the plasma pressure profile, to determine how best to sustain large currents in spherical torus.

Technical Approach – This research will focus on determining the plasma current profile with a number of new diagnostics, in conjunction with an extensive set of magnetic diagnostics and equilibrium reconstruction codes. The first measures the polarization properties of light emitted from energetic neutral atoms injected into the plasma and influenced by the Motional Stark Effect. These properties provide information on the details of the magnetic field in the plasma, which is in turn related to the distribution of plasma current. Determination of the plasma electric field via spectral measurements of carbon ion pressure and flow will provide valuable information, together with the MSE measurements, to determine the current profile (via supporting neoclassical analysis and equilibrium reconstruction). Separately, measurements of the effect of magnetic field on the polarization of externally applied laser lights will provide addition useful information. Finally, 2-dimensional X-ray images of the hot plasma core can be used to constrain the shape of internal plasma cross sections in calculations of the plasma equilibria and current profiles. The measurements will be performed when various techniques that may drive current in the plasma are applied, including radiofrequency waves and injection of energetic neutral atoms. Current driven by gradients in the plasma pressure will also be tested and measured for the first time. The results will be compared with theory to establish a physics basis for application of effective current drive techniques in future NSTX research and in future spherical torus devices of compact size and high performance.

2. Research Accomplishments ***(Increments from Decrement Case)***

- FY04-2 Measure long wavelength turbulence in spherical torus plasmas in a range of plasma conditions. (September 2004)

3. Information on Physical Infrastructure Needs: none

FY04

Program Planning Budget ($1M increment above the level budget case)

Prioritized List of Increments:
Increase Diagnostic and Facility Upgrade Budget to support experimental progress towards the FESAC objectives.

- The FY 04 incremental budget includes one significant facility capability: the addition of an injector for frozen deuterium pellets for core plasma fueling, improving the energy containment efficiency, changing the pressure profile, and controlling the edge condition and impurity flux in spherical torus plasmas characterized by large in-out asymmetries.

- The FY 04 incremental budget includes one significant diagnostic upgrade to install and commission a high-speed infrared camera viewing the divertor tiles. NSTX is currently equipped with two infrared cameras which have a frame rate of 30 Hz. These cameras which measure the temperature of the plasma facing surfaces have been used to make measurements of the power flux to the divertor plates during quiescent periods of the discharge. However, the design of plasma facing components is usually driven by peak power fluxes during transient events, which the present cameras are not capable of resolving. We propose to install a fast, high-resolution infrared camera with a suitable image transport system to enable the camera to be mounted outside the region of high magnetic field near the observation windows. This will be used to measure the power flux and its spatial structure during transient plasma events.

1. Comprehensive Description of Research Plans ***(Increments from Level Budget Case)***

There will be no incremental research milestones for FY04

2. Research Accomplishments ***(Increments from Level Budget Case)***

There will be no incremental research milestones for FY04

3. Information on Physical Infrastructure Needs: none

FY05

Decrement Budget Case (-10% with respect to the FY04 President's Request)

1. Comprehensive Description of Research Plans

- **FY05-1 for MHD Stability**: *Produce and characterize ST plasmas near the "wall-stabilized" limits.*

  Description – Large-scale, pressure driven plasma instabilities will be controlled by the combined effects of the conducting wall surrounding the plasma, field correction coils and plasma rotation to permit pressures near the ideal "wall-stabilized" limits in NSTX. The properties of such plasmas will be studied as they are maintained for periods longer than the timescale for the stabilizing eddy currents in the walls to decay naturally.

  Technical Approach – The beneficial effects of a conducting wall surrounding the plasma in stabilizing pressure-driven MHD instabilities are well known and have been confirmed in NSTX. However, unless the wall is superconducting or the plasma is rotating toroidally sufficiently rapidly, this benefit will be lost due to resistive decay of the eddy currents flowing in the wall which provide the stabilization. The necessary toroidal rotation has been produced in NSTX by neutral beam injection. However, as the plasma beta rises above the point where the wall stabilization becomes necessary, the interaction of the MHD mode with the wall damps the rotation and the stabilizing effect is lost, leading to the growth of so-called "resistive wall modes" (RWMs). The rotation damping accompanying growth of the RWM can be reduced by applying small correction fields with the appropriate periodicity to reduce the mode-induced drag on the plasma. Correction field coils and power supplies are being designed and installed in NSTX to stabilize the RWMs at higher beta and for longer timescales beyond the levels to be achieved for Milestone FY03-5. Neutral beam injection heating will be applied to create strongly rotating plasmas that approach the wall-stabilized stability limit. Detailed measurements of plasma profiles will be made to enable calculations of the theoretical beta limits for comparison with the observed mode behavior. The data from poloidal and toroidal arrays of poloidal magnetic field sensors will continue to be analyzed to determine the critical rotation frequency for growth of the RWM and the structure of the resonant field response from the plasma interacting with the wall. If the RWM has a simple and reproducible structure, it may be possible to counteract it by applying a preprogrammed correction field. However, if the mode spectrum is complicated and changes dynamically, active feedback control of the correction field will be required. The requirements for such feedback will be analyzed to design a suitable system for maintaining wall-stabilized high-beta plasmas, if necessary.

- **FY05-2 on Transport and Turbulence**: *Measure short wavelength turbulence in the plasma core in a range of plasma conditions. (September 2005)*

Description – Short wavelength turbulence, on the scale of a few radii of the electron gyration around the magnetic field, is an important issue for future toroidal plasmas at fusion-grade temperatures. Theory suggests that spherical torus plasmas may naturally yield conditions conducive to suppressing or reducing this turbulence, thereby improving the plasma's heat containment. Advanced microwave techniques will be used on NSTX to measure the short-wavelength turbulence properties over a wide range of conditions. These measurements will be used to test predictions from state-of-the-art theory and computation, especially as they pertain to heat loss by the electrons.

Technical approach – Suppression of plasma turbulence can reduce heat leakage across the magnetic field from high-temperature plasmas. Theory suggests that the spherical torus plasmas may naturally provide the conditions to reduce this turbulence. These measurements of turbulence characteristics in a spherical torus will be carried out over a wide range of plasma flow shearing rates (up to a megahertz) and high toroidal betas (up to ~30%). To diagnose the short-wavelength turbulence driven by plasma electrons, microwaves will be launched from the plasma edge. The scattering of these microwaves off of the density fluctuations of the turbulence will yield key information of the short-wavelength turbulence characteristics of the high beta plasma. Diagnostics to measure the plasma density, ion temperature, electron temperature, ion flow velocity, and radial electric field will be used as input to theory codes. These codes will be used to predict turbulence characteristics and compare with the experimental measurements.

2. Research Accomplishments

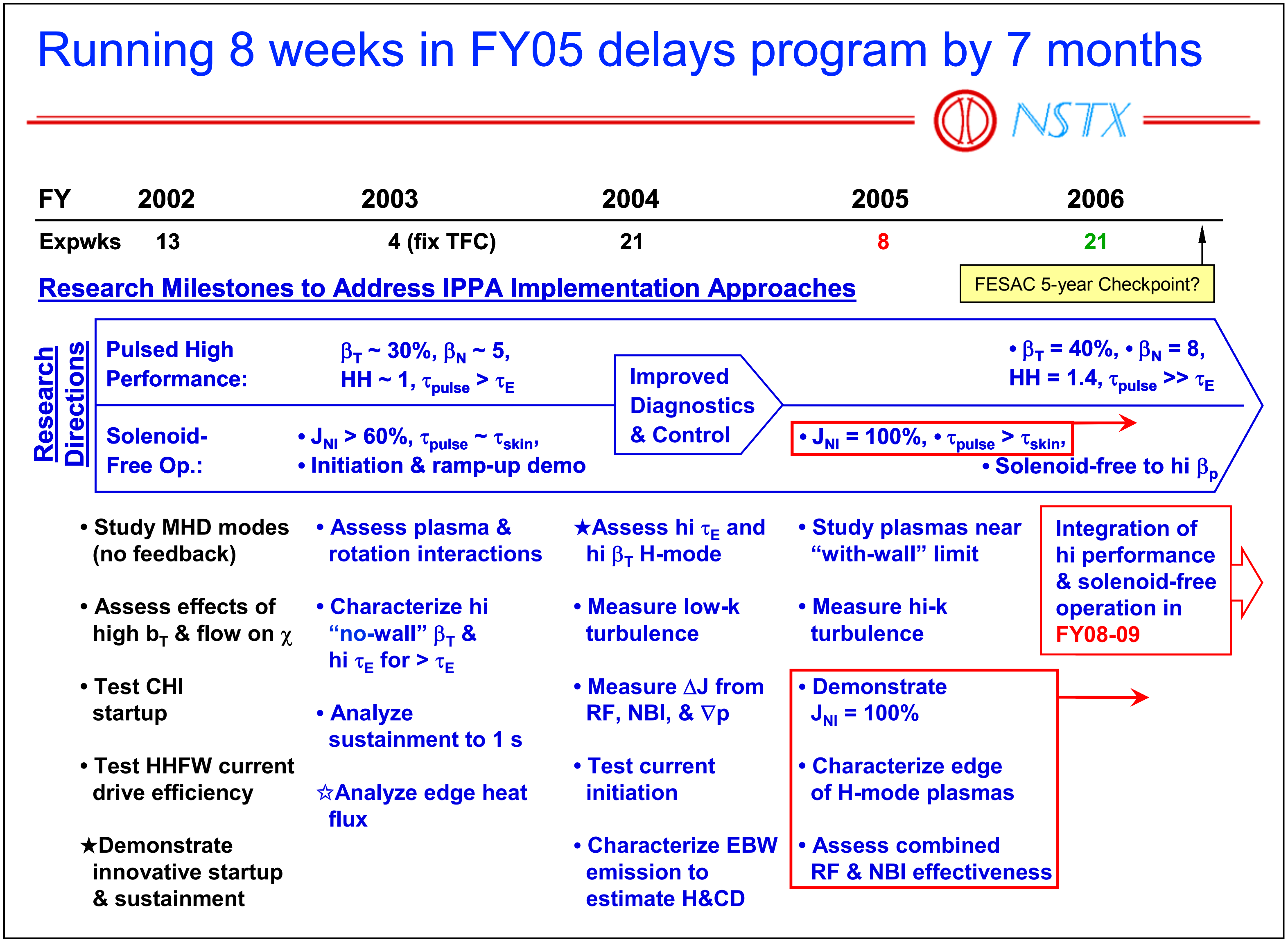
- FY05-1 Produce and characterize ST plasmas near the "wall-stabilized" limits. (September 2005)

3. Information on Physical Infrastructure Needs: none

Funding at this level will result in the following Impacts *(with respect to Level budget case @ FY04 President's request):*

- Reduce planned operation weeks from 21 weeks to 8 weeks
- Reduce Research Progress by 60% by delaying three Planned Research Milestones (FY05-3 Wave-Particle Interactions, FY05-4 Boundary Physics, and FY05-5 Integration) one year.
- Reduce planned FTE's by 12
- Delay Diagnostic Milestone to commission an additional laser on the MPTS system.

The impact on the research program plan is shown in the following figure.



Running 8 weeks in FY05 delays program by 7 months

NSTX

FY	2002	2003	2004	2005	2006
Expwks	13	4 (fix TFC)	21	8	21

FESAC 5-year Checkpoint?

Research Milestones to Address IPPA Implementation Approaches

Research Directions

Pulsed High Performance: β_T ~ 30%, β_N ~ 5, HH ~ 1, $\tau_{pulse} > \tau_E$

Solenoid-Free Op.:
- J_{NI} > 60%, τ_{pulse} ~ τ_{skin},
- Initiation & ramp-up demo

Improved Diagnostics & Control

- β_T = 40%, • β_N = 8, HH = 1.4, $\tau_{pulse} >> \tau_E$
- J_{NI} = 100%, • $\tau_{pulse} > \tau_{skin}$,
- Solenoid-free to hi β_p

• Study MHD modes (no feedback)	• Assess plasma & rotation interactions	★Assess hi τ_E and hi β_T H-mode	• Study plasmas near “with-wall” limit	Integration of hi performance & solenoid-free operation in FY08-09
• Assess effects of high b_T & flow on χ	• Characterize hi “no-wall” β_T & hi τ_E for > τ_E	• Measure low-k turbulence	• Measure hi-k turbulence	
• Test CHI startup	• Analyze sustainment to 1 s	• Measure ΔJ from RF, NBI, & ∇p	• Demonstrate J_{NI} = 100%	
• Test HHFW current drive efficiency	☆Analyze edge heat flux	• Test current initiation	• Characterize edge of H-mode plasmas	
★Demonstrate innovative startup & sustainment		• Characterize EBW emission to estimate H&CD	• Assess combined RF & NBI effectiveness	

FY05

Level Budget Case (i.e., flat with respect to the FY04 President's Request)

Prioritized List of Increments:
Increase Run Weeks from 8 to 21
Increase Diagnostic Upgrade Budget

1. Comprehensive Description of Research Plans ***(Increments from Decrement Case)***

- **FY05-3 on Wave-Particle Interactions:** *Demonstrate full non-inductive current via combinations of radiofrequency wave, neutral beam injection, and pressure-gradient driven currents in a spherical torus.*

  Description – Discharge conditions will be produced in which the toroidal plasma current necessary for confinement is maintained without electromagnetic induction from the central solenoid, for a period beyond the plasma current redistribution time. To achieve this, combinations of neutral-beam and radio-frequency wave power will be applied to supplement the self-generated current resulting from the pressure gradient.

  Technical Approach – The "bootstrap" current, *i.e.* the current resulting from the radial pressure gradient in collisionless toroidal plasma, is particularly important in a spherical torus. Discharges have been produced in NSTX in which up to 60% of the toroidal current has been sustained by a combination of the bootstrap effect and the current driven by the tangentially injected neutral beams (NBI). In addition, the solenoid-induced loop voltage has been reduced to the range of 0.1-0.2 V for durations greater than the current redistribution times, suggesting that the plasma is being sustained with little inductive current. High-Harmonic Fast-Wave (HHFW) heating also has separately demonstrated the capability for driving current when the waves are launched with a toroidally directed spectrum. Experiments to develop and characterize the HHFW current drive scheme will be conducted in FY'04, in particular using the capability in NSTX for real-time control of the wave spectrum to maintain the current drive while plasma conditions evolve and to control the profile of the driven current. The interaction between HHFW and NBI ions will also be investigated during this time (see, Milestone FY05-5). This will permit validation of HHFW current drive theory and predictive modeling to develop discharge sustainment scenarios. In FY'05, experiments will be conducted to combine the non-inductive current drive methods, NBI, HHFW and bootstrap, to sustain the whole plasma current without the need for electromagnetic induction from the central solenoid beyond the startup phase. Optimization of the plasma profiles will be needed to match the profile of the total driven current with that required for MHD stability at the high beta needed (see, milestones FY04-1 and FY04-3). Possible synergistic effects between the current drive mechanisms will be investigated to determine the optimal plasma operation scenarios.

- **FY05-4 on Boundary Physics**: *Characterize the plasma edge pedestals and scrape-off layer fluxes in high performance spherical torus plasmas.*

  Description – High performance toroidal plasmas in the spherical torus and tokamak are expected to set stringent requirements on the plasma edge conditions and introduce high heat fluxes that require increased control. Plasma edge parameters and configurations in NSTX will be varied to obtain the optimal dispersal of edge heat flux in conditions that have favorable performance characteristics in the core. Progress in impact assessment on future plasma facing component requirements will be reported.

  Technical Approach – The plasma edge efflux will be characterized under the conditions where high beta and high confinement core plasmas are obtained. Variations in parameters such as the plasma shape, density, and magnetic configuration will be studied using different plasma heating methods to optimize the edge particle and heat dispersal. The relationship of the edge pedestal height, width, and gradient to the plasma edge fluxes, parameters, and configurations will be studied with improved spatial resolution in measurements using such as laser Thomson scattering, edge impurity spectroscopy, and reflectometry of rf pulses. In addition, the balance between diffusive and convective cross-field transport will be studied with improved edge turbulence diagnostics. Also, a one-dimensional charge-coupled device (CCD) camera, an array of fixed divertor Langmuir probes, a divertor bolometer, and an infrared camera will be implemented for more detailed measurements. The results will be compared with theoretical calculations of the edge pedestal and SOL regions based on a collection of MHD stability, fluid, and turbulent transport models.

- **FY05-5 on Physics Integration**: *Explore scenarios for combining neutral beam injection and radiofrequency heating and current drive to achieve high plasma pressure and high energy containment efficiency for time scales much larger than the energy replacement times.*

  Description – Strong interactions between the High Harmonic Fast Wave (HHFW) power and the fast ions injected by the neutral beams (NBI) have been observed in NSTX. Experiments will be conducted on NSTX in which large powers of HHFW and NBI will be combined to optimize the current and pressure profiles for long pulse, high pressure, and stable plasmas. Successful combined application of these techniques will establish the basis for achieving high performance plasmas in future longer pulse tests of the spherical torus plasmas in NSTX.

  Technical Approach – Preliminary experiments in FY04 to test the interactions between large HHFW and NBI powers will have afforded opportunities to investigate the nature of strong interactions between the wave and the fast ions. Comparison with theoretical analysis is expected to introduce an improved understanding of how to take advantage of these interactions. A series of experiments will be conducted in which the relative timing and power of the HHFW and NBI will be varied to develop optimized scenarios to achieve high beta and high confinement for long pulse lengths in NSTX. The launched HHFW momentum will be adjusted for varied plasma conditions and level of current drive as part of the study. Time-dependent measurements of the plasma current evolution using the MSE diagnostic, as well as NPA measurements of the fast ion distributions, will be crucial to the success of these studies. The results of this study will provide the physics springboard for tests of the combined HHFW and NBI scenarios to extend the plasma durations toward and beyond the current redistribution time scales during FY06-08.

2. Research Accomplishments ***(Increments from Decrement Case)***

- FY05-2 - Measure short wavelength turbulence in the plasma core in a range of plasma conditions. (September 2005)

3. Information on Physical Infrastructure Needs: none

FY05

Program Planning Budget ($2.6M increment above the level budget case)

Prioritized List of Increments:
Increase Diagnostic and Facility Upgrade Budget to support experimental progress towards the FESAC objectives.
Increase spare parts and support off-hour activities such as diagnostic installation by PPPL and collaborators

- Implement Facility Upgrade Plan - The possible upgrade activities under consideration are 1) Implement EBW tube development and 2) Install the proposed Power and Particle Control System. The choice of the path to follow will be made on the basis of ongoing technical assessments by PPPL and collaborating institutions and the results from NSTX in fulfilling its research milestones. The EBW system development will require an experimental demonstration on NSTX of a high EBW emission coefficient (which is an inverse of the coupling of injected power to the EBW). Previously in CDX-U, with suitable plasma edge density conditions, an emission coefficient near 100 % has been measured. The EBW antenna installed in FY 03 will explore this coupling in NSTX. In parallel, ray-tracing calculations of EBW propagation will be performed to assess the viability of externally launched EBW waves for NTM stabilization. Since the desired high-power 15GHz EBW tube is not available, an R&D effort to develop the tube will be initiated (with the MIT group supported under the VLT program) in FY 04 - FY 05 if the research results are favorable. The power and particle handling system requirements will be assessed on the basis of the results obtained early in FY 04 with high-power NB and RF heating using the complement of edge diagnostics expected then to be available on NSTX. In particular, the requirement for going to higher power and longer discharge duration will be modeled to determine the need and system requirements for active power and particle handling. If the scientific and technical assessments indicate that such a system is needed to meet NSTX research goals, fabrication and installation will be accomplished in FY 05.

- The FY 05 incremental budget includes the design and fabrication of a divertor Thomson scattering system for installation on NSTX. A multi-point, multi-pulse Thomson scattering system optimized for the conditions expected in the divertor will be designed and fabricated ready for installation on NSTX. When installed and commissioned the data from this diagnostic will be used to test and calibrate divertor modeling codes.

1. Comprehensive Description of Research Plans ***(Increments from Level Budget Case)***

There will be no incremental research milestones for FY04

2. Research Accomplishments ***(Increments from Level Budget Case)***

There will be no incremental research milestones for FY04

3. Information on Physical Infrastructure Needs: none