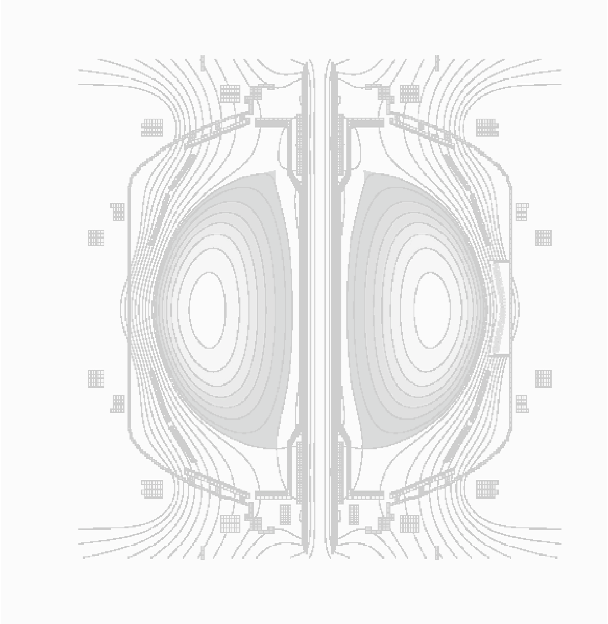

Chapter 1

The NSTX Research Plan Overview

1.1 NSTX and Fusion Energy Science Development

Research on the National Spherical Torus Experiment (NSTX) [1] began in 1999 as a leading element of the U.S. fusion energy science program's initiative to further the understanding and develop the potential of innovative confinement concepts. Committed to being a national and international research enterprise, it joins an ensemble of experiments that is broad-based and that extends across device types. By taking advantage of differences in the accessible range of plasma beta, field line geometry, stability and confinement properties, and edge conditions, they create a powerful platform from which to strengthen the scientific basis for delivering fusion energy. Together with advances in diagnostics, theory, and computation, NSTX serves as part of a vibrant test bed for optimizing magnetic confinement configurations, for addressing issues of broad importance for all of plasma science, and for furthering the understanding of plasmas outside of the laboratory through controlled studies within it.

This role for NSTX is emerging simultaneously within a new era in fusion energy research, one characterized by unprecedented diagnostic, theory, and computational capabilities. Indeed, the development of the spherical torus (ST) concept [2] represents one aspect of this new era, as its creation is grounded in theoretical expectations that the field line geometry that accompanies low aspect ratio operation should provide enhanced stability to global magnetohydrodynamic (MHD) modes, thus enabling access to beta values far in excess of those achievable on higher aspect ratio devices. In addition, microstability studies [3,4] performed years in advance of any plasma operations with high neutral beam heating power at low aspect ratio suggested that the change in field line geometry that accompanies smaller aspect ratios may yield plasmas that have low ion turbulence levels, and thus excellent confinement properties. Of course, along with this theory-based anticipation comes important research questions. First, are these theory-based predictions true? Can they be extrapolated to reactor-scale devices? What are the requirements for and viability of non-inductive sustained operations, and the manageability of edge heat fluxes? What is the role of rotation in affecting MHD and the plasma equilibria, and the scaling of non-ideal MHD instabilities properties? What are the computational requirements for assessing these issues? What are the requirements for extending the understanding obtained on NSTX and other STs to future low aspect ratio devices and other high beta innovative concepts? As a proof-of-principle device in the U.S. innovative concepts research effort, the NSTX program is structured to address these and other questions, to resolve them in an integrated manner where possible, to develop strategies for addressing in the future what cannot be resolved now, and to broaden the physics understanding of high beta plasmas more generally. It works in concert with the existing U.S. fusion program to both build upon and enhance the understanding derived from tokamak research, and also builds upon rapidly evolving ST research throughout the world [e.g. 5,6,7,8].

The rapidly evolving sophistication of fusion science, together with a deepening appreciation by policy makers and political leaders of the role that fusion can play in addressing issues of worldwide import, presents the NSTX program with unique and powerful opportunities. First, pursuit of ST research may yield a promising alternative to the moderate aspect ratio tokamak when choices are made about the first deployments of systems that will generate net electricity. Second, the compact size of the ST and the promise of high ratios of plasma pressure to magnetic pressure, or beta, suggest that the ST should be given serious consideration as the plasma configuration of a component test facility. Third, the unique field line geometry, comparatively large ratio of particle gyroradius to system size, high ratio of characteristic particle velocities to plasma wave velocities, high dielectric constants, and high betas of NSTX plasmas provide many opportunities to extend the physics understanding of topics that are broadly important to other toroidal confinement concepts. Fourth, the study of plasmas with beta values near unity, in this era of unprecedented diagnostic, theory, and computational capability, suggests that NSTX can be a high leverage tool to address fundamental plasma physics problems with applicability beyond laboratory plasmas and fusion energy.

1.2 Research Highlights Through 2002

With the advent of significant levels of auxiliary heating in 2000 and maturing diagnostic and operational capabilities over the last two years, the National Spherical Torus Experiment has begun intensive research aimed at establishing the physics basis for high performance, long pulse, solenoid-free operations of the spherical torus concept [9,10]. This research is directed at developing an understanding of the physics of the ST operational space, developing tools to expand this space, and contributing broadly to toroidal science. To these ends, research in the last two years has focused on high beta MHD stability, confinement, high harmonic fast wave heating and current drive, boundary physics, solenoid-free startup, and exploration of scenarios that integrate favorable confinement, stability, and non-inductive current drive properties. Some results in these efforts include the following:

- Toroidal beta values ($\beta_T \equiv \langle p \rangle/(B_{t0}2/2\mu_0)$) up to 35% with neutral beam heating have been obtained. In some plasmas at high normalized beta $\beta_N \equiv \beta_T/(I_p/aB_t)$, the no-wall stability limit is exceeded by a factor of 1.3.
- Pulse lengths have been lengthened to 1 second with the benefit of bootstrap and beam-driven non-inductive currents of up to 60 % of the total. In these plasmas, the cylindrical q as well as the total, normalized, and poloidal beta values are at the levels required for an ST-based component test facility.
- Normalized beta values β_N up to 6.5 %·m·T/MA have been achieved, with operations overall bounded by the ratio of the normalized beta to the internal inductance $\beta_N/\,l_i = 10$.

- The product $\beta_N H_{89P}$ exceeded 15 for 8 energy confinement times and over 1.5 current relaxation times. Here, H_{89P} is the energy confinement enhancement factor over the ITER89-P L-mode scaling value.

- Energy confinement times in plasmas with both L and H mode edges exceed the ITER98pby(2) scaling [11] by over 50%, and the ITER89-P L-mode scaling [12] by over a factor of two for both discharge types.

- Particle transport studies of plasmas with turbulent (L mode) edge conditions reveal impurity transport rates that are consistent with and in some cases fall below neoclassical predictions in the core.

- Signatures of resistive wall modes have been observed [13,14]. With sufficiently broad pressure profiles, their onset occurs above the calculated no-wall stability limit, pointing to the presence of passive wall stabilization.

- Tearing mode activity consistent with the expected behavior of neoclassical tearing modes has been observed. These modes can saturate beta or cause beta reduction when the central q value is near unity, but for higher q values their effect on performance is more modest.

- New classes of fast-ion-induced MHD have been observed [15,16,17]. These Compressional Alfvén eigenmodes (CAEs) exist near the ion cyclotron frequency. Bounce-precession fishbone bursts are seen near 100 kHz, and are associated with fast ion losses.

- Significant heating of electrons with high harmonic fast waves (HHFW) has been measured [18], with central temperatures reaching 3.9 keV. Interactions between fast beam ions and HHFW have been observed.

- The first indications of current driven by HHFW have been obtained [18].

- The application of coaxial helicity injection [8,19] has yielded a toroidal current of up to 400 kA, with observations of n=1 MHD activity that may be a prerequeisite for closed flux surface formation.

- Edge heat flux studies [20] using divertor infrared camera measurements indicate that 70% of the available power flows to the divertor targets in quiescent H mode discharges.

These results represent highlights of a broad research program that targets the advancement of the spherical torus concept, makes contributions to the advancement of other fusion concepts, and advances the physics understanding of high beta plasmas generally. Facility requirements, additional scientific details that motivate the particular plan, theory and modeling plans and needs, and predictive modeling of future scenarios are all outlined in subsequent chapters. What follows in this chapter is an overview of the program structure, guiding principles, and context within the world fusion research program.

1.3 Overview of the NSTX research program

1.3.1. Overarching goals - The research program of the National Spherical Torus Experiment (NSTX) is guided by two overarching goals:

1. NSTX research is directed at assessing the attractiveness of the spherical torus as a fusion energy concept, both as the centerpiece of a fusion reactor and as a neutron source for a component test facility.

2. NSTX research takes maximal advantage of its unique plasma properties, including beta values approaching unity and field line topology, to extend the knowledge base on issues of broad importance to plasma science and fusion energy development in this era of advanced theory, computation, and diagnostic capability.

The NSTX research program is guided by the implementation approaches developed by FESAC in 1999 and detailed in the Integrated Program Planning Activity (IPPA) document. The research plan for 2004 – 2008 described here addresses the primary goals pertaining to ST research, and also addresses topical goals relevant to toroidal plasma science in areas for which NSTX plasmas are particularly well suited. As a Proof-of-Principle device in the Department of Energy portfolio of fusion energy concepts, the primary IPPA goals pertaining to the spherical torus concept are:

Five year IPPA goal: Make a preliminary determination of the attractiveness of the Spherical Torus by assessing high beta stability, confinement, self consistent high bootstrap operation, and acceptable divertor heat fluxes, for pulse lengths much longer than the energy confinement time.

Ten year IPPA goal: Assess the attractiveness of extrapolable, long pulse operation of the Spherical Torus for pulse lengths much longer than the current relaxation time.

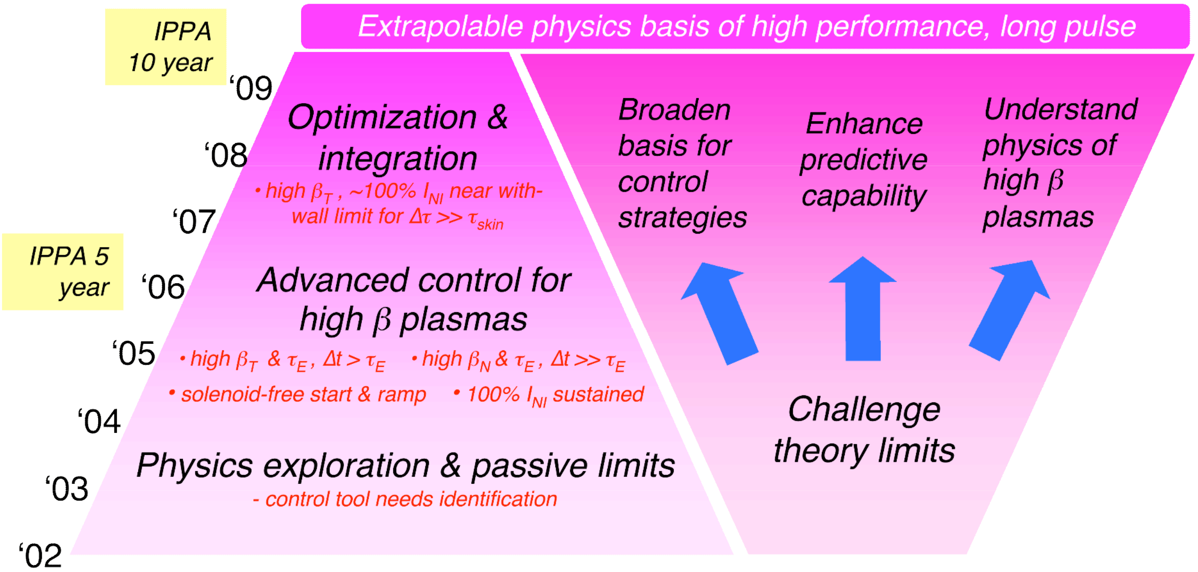

Figure 1.1 The NSTX program plan has an increasing focus with time on the demonstration of long pulse, high performance ST plasma operations. The progress is grounded in an increasing scientific understanding of the physics of high beta plasmas and the requirements for plasma control.

This document describes the research program plan for NSTX 2004 through 2008 aimed at achieving the 5 year goal midway through the plan's implementation, and at placing the program in an excellent position to strike for the 10 year goal in the near term after the end of this period.

1.3.2 Broad research themes – NSTX research is directed towards demonstration of key ST characteristics relevant to advanced ST operations, and the establishment of the required underlying physics understanding of the achievement of these regimes. While NSTX research reaches these high performance operations with time, advanced diagnostics will be implemented where key opportunities in high beta plasma science exist, and control science will be expanded as tools are developed to enable the achievement of these goals. This platform will form a broad base from which to take the next step in ST science, one that will strengthen toroidal science in many critical areas with respect to high beta effects and field line topology.

Broadly speaking, the major research phases are:

Phase I, Current Status: Exploration of passive limits - NSTX research at present is in a period where the limits of the ST operating space are being assessed under the influence of passive limits, e.g. passive wall stabilization of MHD modes with the assistance of driven rotation. Focal points in the course of this period include the identification of control tools needs and the development of plans for their implementation. This document focuses on a transition beyond the present phase of research consisting of the development and deployment of advanced control tools aimed at extending the stable operating space and duration of the pulse length of plasmas of very high beta and confinement, and for developing the basis for fully solenoid-free plasma startup and sustainment. The research effort at the end of this plan focuses on the simultaneous optimization of ST plasma performance in terms of stability, confinement, and pulse length.

Phase II: Develoment of advanced tools and physics exploration of high beta plasmas – The research described in this part of the plan will develop and take advantage of advanced control tools that maximize device flexibility and thus enable strides in optimizing plasma performance. This flexibility also forms the basis for optimizing NSTX performance, for establishing its operating limits, and for performing controlled variations that are necessary to develop a scientific basis that has theory and experiment comparisons as its cornerstone.

The advanced diagnostics will enable taking maximal scientific advantage of unique ST properties from the point of view of enabling control, of forming an extrapolable basis for ST plasmas science and contributing to issues of broad and deep importance to advancing toroidal concepts and plasma science beyond the laboratory. A maturing emphasis on detailed comparisons with high beta NSTX plasma properties with comprehensive theoretical models will develop in this phase of research.

Phase III: Optimization and integration - The sharpening focus of the program with time integrates elements of the science that contribute to enhancing NSTX performance with respect to plasma stability, confinement, and pulse length. Research elements aimed at demonstrating capabilities for solenoid-free startup and sustainment will be combined with control strategies developed for generating high beta and normalized beta plasmas to enable long pulse, high confinement, high beta operations. Advanced diagnosis will be coupled with theoretical tools to further enable broadening and deepening of the basis for physics understanding of these high beta, high confinement regimes.

1.3.3 Program Structure: Broad integration research thrusts - Two major research thrusts are targeted for from 2004 through much of this research period. These are the achievement of high beta, high confinement, high bootstrap fraction plasma conditions relevant to an ST power plant, and the development of solenoid-free operations at plasma parameters relevant to a component test facility. In 2007 - 2008, elements of each are combined as the highest level of integrated high performance, non-inductive sustained operations are pursued. The achievement of particular performance and integration targets in these thrusts will be grounded in an understanding of the topical science areas of MHD stability, transport, wave-particle interactions, boundary physics, and solenoid-free plasma current generation.

1. High beta, high confinement, high bootstrap fraction plasmas relevant to an advanced ST power plant – A major goal is improving the plasma quality as measured by simultaneously advancing the plasma toroidal beta, normalized beta, confinement time, and pulse length. At the end of the 2004 - 2008 research period, a goal is the realization of discharges approaching 40% toroidal beta, operating near the with-wall stability limits, possibly using active feedback control, with total non-inductive currents in the sustained phase of nearly 100%, and pulse durations of at least several current relaxation times. These plasmas likely will benefit from strong shaping, flexible heating and current drive tools, advanced particle control tools, and techniques that will increase savings of inductive flux that are developed in the second major thrust (below). An intermediate goal for the 2006 time period is establishing research scenarios that separately exhibit the requisite features and enable developing the tools required for the integrated high beta, long pulse goal. These scenarios include the demonstration of high β_T and high confinement for longer than an energy confinement time over as wide a range of toroidal field and current as possible. For the purposes of developing MHD mode control strategies, a parallel goal is the development of high β_N plasmas approaching the with-wall limit for time periods longer than several energy confinement times.

2. Solenoid-free operations at plasma parameters relevant to a component test facility – A major goal is developing the capability to initiate and sustain plasmas without the aid of solenoid-induced flux. In the middle third of this research period, a goal is the development of plasmas with non-inductive sustained operations for pulse lengths longer than a current relaxation time at toroidal beta values comparable to those required for a component test facility. Also, in separate plasmas, NSTX aims to demonstrate the successful development of extrapolable solenoid-free startup strategies. This will be achieved through the study of a combination of techniques, including coaxial helicity injection, poloidal field coil induction, bootstrap current, and additional current drive through the application of High Harmonic Fast Waves (HHFW), Electron Bernstein Waves (EBW), and neutral beam injection.

The research plan time line outlined in Figure 1.2 is driven in part by the following considerations. First, for the ST to be attractive, it should contain heat efficiently while maintaining high overall plasma stability. NSTX research should determine the requirements and the physics underpinning the simultaneous generation of high beta and high confinement. Second, ST attractiveness is also enhanced if the plasma pressures that can be achieved are near the theoretical maximum. NSTX research should develop the means, including advanced control tools, of realizing these limits. Third, NSTX research must assess the physics central to the issues of solenoid-free plasma startup and sustainment.

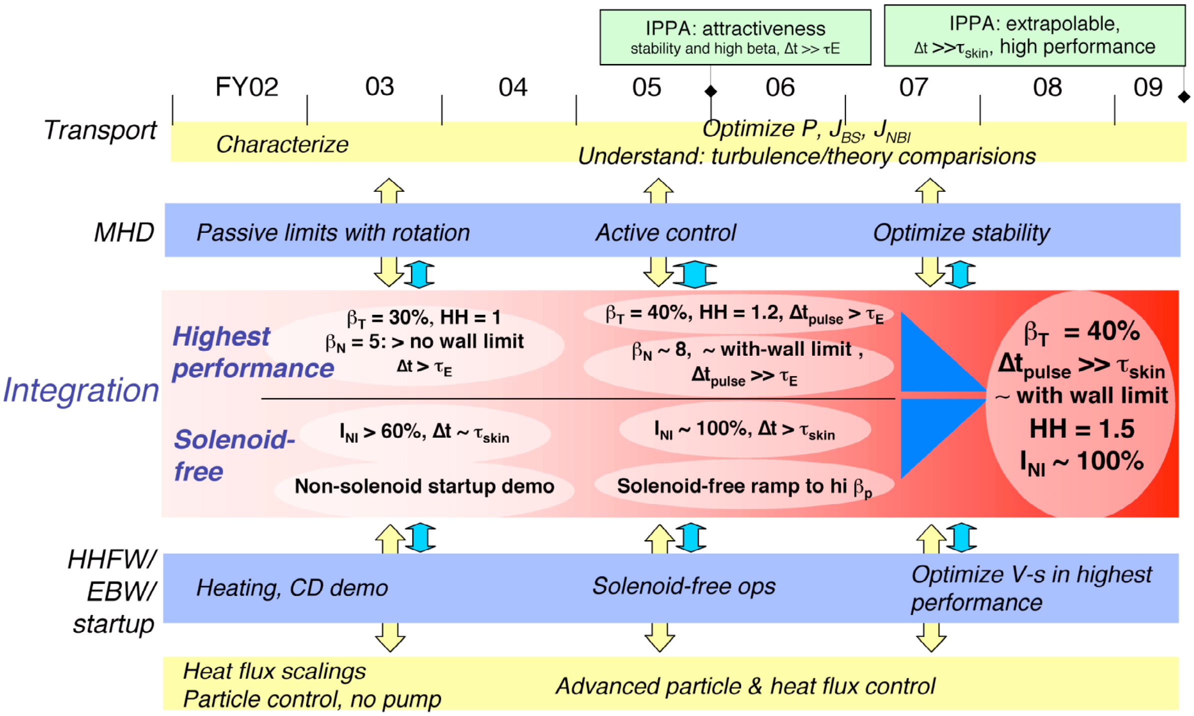

Figure 1.2 Overview of the development of the NSTX research program plan and the relations between scientific elements.

The achievement of these goals will represent major advances in demonstrating the scientific and technical attractiveness of the spherical torus. The high level goal of establishing an extrapolable basis for moving forward *demands that their achievement be grounded in a detailed understanding of the physics* *of high beta plasmas*. To enable this, the two thrusts described above are supported by topical research lines. Achieving the results outlined above and enabling these developments through plasma science is one aspect of fulfilling the obligations of NSTX has as a Proof-of-Principle experiment. Highlights of planned topical research contributions follow.

1.3.4. NSTX Topical Science Research and the IPPA Science Objectives - The performance and demonstration goals are supported by a foundation of topical science research. The research is organized along the topics of MHD, transport and turbulence, HHFW and EBW heating and current drive, solenoid-free startup and rampup, and boundary physics. These are well aligned with the five and ten year scientific objectives outlined by FESAC in 1999.

The IPPA Five Year Science Objectives and the key planned NSTX program contributions aimed at meeting these objectives follow.

IPPA Objective 1.1 - *Turbulence and Transport*: Advance the scientific understanding of turbulent transport forming the basis for a reliable predictive capability in externally controlled systems.

NSTX program contributions - Confinement results on NSTX up through 2002 reveal confinement times that exceed predictions of L- and H-mode scaling expressions developed from moderate aspect ratio tokamak experiments. Also, ion thermal and particle transport are found to be low, with transport rates at or below neoclassical predictions in some cases. A major program focus is characterizing confinement scalings for the ST and then developing a turbulence-based understanding of the role of beta and aspect ratio in governing the physics of these scalings. This is within reach of the NSTX Five Year Plan. In addition to using a rapidly maturing suite of profile diagnostics, this effort involves the development of advanced systems to measure turbulence structure in sufficient detail at both low and high wave number to allow detailed comparisons with gyrokinetic codes. The regimes realized in NSTX at high beta are predicted to be characterized by emerging electromagnetic effects in plasma turbulence, and therefore represent new physics studies that will pose challenges to existing models. They also provide a scientific connection to the regimes usually encountered in tokamaks, where electrostatic effects dominate, and other high beta innovative concepts, such as the field reversed configurations or spheromaks, where electromagnetic effects can dominate the turbulence dynamics. With these advanced diagnostics, powerful opportunities exist in testing theory predictions of the pervasive nature of turbulence suppression at low aspect ratio under the influence of high flow shear. Also, the ST geometry, with its strong field line curvature, provides opportunities for scattering measurements of turbulence that will have unprecedented spatial resolution at high wavenumber. This regime is of high relevance to understanding the physics of anomalous electron thermal transport, one of the outstanding puzzles in magnetic confinement research. These studies are important not only to tokamaks, but they are of great relevance to high beta innovative concepts as well. More broadly, the study of turbulence in plasmas with beta of order unity is of high relevance to many important astrophysical problems (see Objective 1.5, below).

IPPA Objective 1.2 - *Macroscopic Stability:* Develop detailed predictive capability of macroscopic stability, including resistive and kinetic effects.

NSTX program contributions - The research program is structured to address high beta MHD properties and limits, and MHD active stabilization to extend operations to near the with-wall limit, on a broad front. For example, this research already has been characterized by quantitative theory/experiment comparisons of global stability limits. The pursuit of active stabilization strategies to extend long pulse, high beta operations beyond the no-wall limit demands a strong coupling with experiment and theory, a coupling that already has revealed that NSTX operates routinely above the no-wall beta limit and that is guiding the design for an active mode control system. Studying the physics of the conditions for the onset of resistive wall modes, including the coupling of physics between the growing mode and external error fields, will involve detailed measurements in the presence of a controllable error field, enabling quantitative comparisons to theory. The high rotation velocities compared to the Alfvén speeds will allow tests of rotation effects on equilibria and core MHD stabilization or saturation, beyond that associated with resistive wall modes.

IPPA Objective 1.3 - *Wave Particle Interactions:* Develop predictive capability for plasma heating, flow, and current drive, as well as energetic particle driven instabilities, in a variety of magnetic confinement configurations and especially for reactor-relevant regimes.

NSTX program contributions - NSTX has a major commitment to assessing the physics of High Harmonic Fast Wave (HHFW) heating and current drive. HHFW wave physics has not been previously explored. For overdense ST plasmas, it offers the promise of current drive in conditions of modest ion temperature. Experimental tests of the theory of HHFW interactions with fast ions are being and will continue to be explored. Current drive theories associated with HHFW will be tested by measuring local changes in the current density induced by HHFW with the an MSE diagnostic that will be brought into operation at the beginning of this plan period. Additional tests of theory will come through the use of the HHFW antenna's ability to launch waves with variable phase.

The NSTX research program is also structured around an experimental and theoretical assessment of Electron Bernstein Wave (EBW) physics. EBW has the potential to be an important ST plasma control tool with respect to off-axis current drive and current profile control, neoclassical tearing mode suppression, and plasma startup assistance, EBW heating may also provide a flexible tool for electron thermal transport studies. Initial calculations suggest that the fundamental current drive efficiency of EBW current drive can be significantly great than that of electron cyclotron current drive, and can drive current efficiently near the plasma boundary, as needed for the highest performance regimes. The emission studies alone offer the prospect yielding techniques for fast time-response electron temperature measurement. Finally, the EBW research program has potential benefit for other overdense systems such as reverse field pinches and spheromaks. Fast ion MHD activity is driven by beam ions that are in a new regime compared to those injected into moderate aspect ratio tokamaks, owing to the high fast particle velocities compared to the Alfvén speed. This has already yielded significant theory/experiment interactions that include the study of the possibility that fast ion-induced MHD activity might play an important role in ion heating. Differences in gap structure in the Alfvén continuum between low and moderate aspect ratio devices and will be explored in joint experiments between NSTX and tokamaks.

IPPA Objective 1.4 - *Multiphase interfaces:* Advance the capability to predict detailed multi-phase plasma-wall interfaces at very high power and particle fluxes.

NSTX program contributions - Boundary physics has a significant role in the NSTX program with respect to creating conditions for long pulse, high beta operations. Measurements of divertor heat fluxes with spatial resolution are allowing tests of theories of the role of the expected enhancement of the divertor flux expansion as compared to that found in the moderate aspect ratio tokamak field line geometry. Detailed modeling of the NSTX divertor underpins these tests. In its research plan, NSTX is providing the option to implement a liquid lithium divertor for the management of heat and particle fluxes. Such deployment would represent a significant investigation of potentially high relevance to all toroidal confinement systems.

IPPA Objective 1.5 - *General Science:* Advance the forefront of non-fusion plasma science and plasma technology across a broad frontier, synergistically with the development of fusion science in both MFE and IFE.

NSTX program contributions - NSTX science will contribute broadly on many fronts. One of particular interest is contributing to the field of astrophysics. A connection has recently been made between the fusion community and the astrophysics community on the relevance of gyrokinetic codes developed for fusion to important astrophysical problems such as the nature and influence of the nonlinear cascade of turbulence to ion scales in plasmas with beta of order unity. An example of such a topic, one where astrophysicists are interested in laboratory tests of turbulence cascading understanding, is the puzzle of the subluminous accretion disk surrounding the supermassive black hole in our own galactic center. The test bed for these studies exists: the NSTX program is already studying plasmas with maximum local values of beta of 75% or greater. The implementation of advanced turbulence diagnostics on NSTX will enable detailed tests of gyrokinetic theory in this regime, providing a direct contribution to the study of these exotic astrophysical systems, and an opportunity of intellectual cross-fertilization.

1.3.5 High-level description of planned topical research elements

MHD

Exploration and passive MHD limits (through 2004): Beta limits will be explored and beta limiting modes will be identified. Active feedback control system needs for global mode stabilization will be identified and a system for implementation designed. Fast ion MHD modes will be characterized, and their possible effects in fast ion loss and plasma heating will be studied. In both global mode stabilization and fast-ion-induced MHD, studies will begin comparing to standard aspect ratio. Advanced MHD theory and computation will play a critical role in the development of MHD mode control tools.

Control and high beta MHD Physics (2005 – 2006): Active MHD suppression techniques and extension of NSTX operating limits through active mode control will be demonstrated in plasmas of high normalized beta (roughly, near 8), well above the no-wall limit and approaching the maximum theoretical limit. The first studies of neoclassical tearing mode stabilization studies will be performed with 1 MW of EBW heating and current drive.

MHD optimization and integration (2007 – 2008): Optimization of MHD active mode stabilization strategies developed in 2004 - 2006 will be performed. Neoclassical tearing mode active stabilization techniques will be applied with Electron Bernstein Wave current drive, if necessary. Together, active global mode and tearing mode control will be applied to NSTX plasmas to enable operating regimes at 40% toroidal beta and nearly 100% of the plasma current in steady-state generated without the benefit of the solenoid. These plasmas will benefit from the bootstrap current, pressure-gradient-driven current, neutral beam current drive, and HHFW and/or EBW current drive.

Transport and turbulence

Transport and turbulence exploration (through 2004): Global confinement characteristics will be identified, including parametric scalings. Edge turbulence measurements will be continue. Profile measurements and the first ion and electron heat fluxes, assessed in experiments through 2002, will be compared in detail to gyrokinetic microstability calculations of heat fluxes and profile scale lengths. Core impurity ion transport studies will extend to both L- and H-mode plasmas. In 2004, a system for making initial measurements of high k turbulence will be deployed. Edge turbulence studies, begun in 2001 and 2002, will be extended, and data from multiple turbulence diagnostics will be compared. Theoretical microturbulence studies, including nonlinear simulations,\ will be performed to identify the expected drives, amplitudes, spectral ranges, and electrostatic vs. electromagnetic character of turbulence.

High beta transport physics and pressure profile optimization (2004 – 2006): Advanced turbulence diagnostics for measuring low and high k turbulence will be developed and deployed to advance the physics understanding of ion and electron thermal heat transport in high beta plasmas. Transport modification in H mode and with core barriers, and neutral beam and high harmonic fast wave heating will be used to optimize the pressure profiles for long pulse, stable operations. Particle influx control techniques, including lithium deposition, will be applied to modify edge influxes and thus the transport. The initial EBW system will be used for local electron heating studies, including the study of electron thermal barrier formation and the study of local electron heating on short- and long-wavelength turbulence characteristics.

Transport and turbulence: optimization and integration (2007 – 2008): Turbulence studies will be extended. Wavenumber spectra measurements will be compared with detailed gyrokinetic theory that includes electromagnetic effects and full electron dynamics. Studies will be extended to plasmas with core betas in excess of unity. Tools that modify the transport, including off-axis and radially localized heating, H mode and core barrier, edge influx control, and pellet injection, will be used to optimize the pressure profile and bootstrap current in long pulse plasmas with toroidal beta values approaching 40%.

HHFW and EBW studies: understanding heating and developing solenoid-free operations

Heating and current drive exploration (through 2004): High harmonic fast wave heating and current drive operations will be extended to the 6 MW level, with active phase feedback control demonstrated. Studies of wave-particle interactions through the analysis of the lost fast particles will be undertaken. Studies of Electron Bernstein Wave emission, as well as theoretical studies of EBW propagation and damping, will be used to identify the system needs for an EBW antenna and launch system.

Control with heating and current drive (2004 – 2006): HHFW current drive will be used in conjunction with the bootstrap current in HHFW heated plasmas to generate solenoid-free current ramps from an initially low (~ 100 kA) level to a high poloidal beta current flattop. HHFW heating will be applied to support 100% fully non-inductive operations for longer than a current penetration time at parameters relevant to a component test facility plasma in terms of beta, shape, and q. Active feedback of launched wave phase with real-time measurements of current drive effects will be deployed. HHFW will be applied as part demonstration of capability for solenoid-free startup to high poloidal beta plasmas, in conjunction with coaxial helicity injection and neutral beam injection. The first 1 MW EBW CD tests will be performed for current drive and neoclassical tearing mode control. The prospects of driving edge current with coaxial helicity injection will be explored.

Heating and current drive: integration and optimization (2007 – 2008): Flux savings techniques developed with HHFW and EBW will be applied towards the demonstration of plasmas approaching 40% toroidal beta for times much longer than a current penetration time. EBW at powers of up to 3 MW will be applied towards the active suppression of neoclassical tearing modes, if necessary, as well as for off-axis current drive to increase central q values. Localization of EBW will be explored with the aim of demonstrating the control of neoclassical tearing mode activity. Up to 6 MW of HHFW will be used for heating to increase the bootstrap current as well as to provide current drive. If necessary, the development of edge current drive from CHI to support solenoid-free sustained operations will be pursued.

Solenoid-free startup research

Solenoid-free startup research (through 2004): Develop the required plasma control techniques and demonstrate the generation of toroidal plasma currents using coaxial helicity injection without a solenoid. Assess flux closure. Demonstrate in 2004 the coupling of plasmas initiated only with CHI to plasmas sustained with ohmic induction, and begin exploration of requirements for coupling to HHFW-only plasmas. Perform initial studies of solenoid-free startup using poloidal field induction. New tools for this include the activation of a presently unused outboard poloidal field coil. In conjunction with two coils that are presently used for plasma control, modeling suggests that a poloidal field null with substantial volt-second capacity can be generated.

Solenoid-free start and coupling to solenoid-free current ramp-up (2004 - 2006): Assess the control requirements for handoff from solenoid-free startup to current rampup and demonstrate the initiation and current ramp without a solenoid from zero to several hundred kA of current. Tools for startup to be studied are PF induction and CHI for plasma initiation. For plasma current rampup to a high poloidal beta plasma target, HHFW heating and current drive will be used, as will bootstrap current drive. Neutral beam current drive is also a likely tool for the extension of this scenario to higher plasma currents. The utility of EBW as a plasma initiation tool, as well as for current drive and heating in assisting the current ramp, will be explored.

Optimization of solenoid-free operations and utilization of V-s savings (2007 - 2008): Optimize the scenarios for solenoid-free plasma initiation and current ramp-up using the tools identified above. Use techniques that demonstrate savings in volt-seconds consumption in current ramp-up to help establish conditions for solenoid-free sustained phase of high beta, long pulse scenarios.

Boundary physics

Characterization and operational limits (through 2004): Heat flux scaling will be measured, and the plasma facing component requirements for high power operations for times longer than a skin time will be identified. Studies of the divertor power balance will be performed. Particle control needs will be identified. A flexible edge particle fueling system with various fueling locations will be deployed that includes the capability of supersonic gas puffing to increase fueling efficiency. Heat flux modeling will be carried out in support of these studies. A lithium pellet injector will be implemented to provide a preliminary assessment of the benefits of lithium wall coatings on particle influxes and plasma performance.

Boundary control (2004 – 2006): Active particle control tools will be deployed,. Cryopumping will be implemented. Also deployed will be a lithium coating system that utilizes evaporation of lithium between discharges on plasma facing components. At the end of this period, results from these lithium coatings studies will serve as input on a decision to design and implement a liquid lithium divertor. The decision to proceed with such a system will rely in part on the success of liquid lithium research being performed on the CDX-U device. Compact toroid injection will be considered for particle fueling. Deuterium pellet fueling will be implemented.

Boundary physics integration optimization (2007 – 2008): Particle fueling and pumping and heat fluxes will be optimized to enable 40% toroidal beta, high bootstrap fraction operations for time scales longer than the current penetration time. If a decision to move forward with a liquid lithium divertor was made at the end of 2006, design, construction, and installation of this system will take place.

1.4 Building a Strong Foundation for Fusion Energy Science

The rapid progress of NSTX research has generated a sense of optimism within the program. This optimism pertains to the possibilities of generating deep and lasting contributions to plasma science, and of the possibilities of making substantial progress towards making fusion power a reality. Scenarios have already been experimentally achieved that are close to major programmatic goals in terms of plasma beta and relation to stability limits, enabling the science program to focus on the unique aspects of high beta, low aspect ratio operations. Long pulse operations with significant fractions of non-inductive currents have been obtained in plasmas with dimensionless parameters in the range of those necessary for component test facility operations. The rapid development of heating and control systems and wall preparation techniques have enabled the maturation of operating scenarios that are allowing entry into new regimes of plasma science.

Importantly, the excitement in the program centers on the recognition that the unique parameters associated with high beta and low aspect ratio pose new and important challenges to our fundamental theory understanding, and enable a vital dialogue with the entirety of the toroidal confinement research program. For example, while ion thermal transport and turbulence is widely regarded as being a tremendous success story born out of the tokamak experience, the power of exploring alternative concepts is revealed in a striking fashion on NSTX. This simple change of aspect ratio and beta has yielded a plasma system that seems to naturally have low ion thermal transport, without an observable bifurcation in the plasma core. A new science is emerging with respect to Electron Bernstein Waves in the ST community, motivated by requirements for current drive and new temperature diagnostics. H mode plasmas, a phenomena identified in 1982 [21] that still presents puzzles to all in the toroidal confinement community, are being explored on NSTX [22] and MAST [23] in part because of the importance that high ion gyroradius and strong poloidal damping may have in determining pedestal widths and power thresholds. Already the research program is confronting the challenges of three-dimensional resistive MHD theory, required for the understanding of coaxial helicity injection. The inclusion of plasma flows in MHD theory [24,25] is particularly important to low-field, rotating ST plasmas. Detailed comparisons of predictions from this research to observations of equilibrium asymmetries, enabled by Thomson scattering measurements with unprecedented photon statistics, are already emboldening theory efforts to address details of nonlinear effects of flows on kink stability. Both of these branches of MHD science find applications relevant to the emerging optimized stellarator development, RFP research, and the study of spheromaks. Plasmas with beta of order unity have already been achieved on NSTX. Therefore, this device can be used to explore the emergence of important electromagnetic effects in plasma dynamics, enabling stringent tests of the extremes of existing theories of turbulence, waves, and MHD, and enabling controlled laboratory tests of physics models relevant to high beta plasmas outside the fusion laboratory. Further examples can be cited, and the list grows as the research matures.

The optimism in the program is based on the science that has been produced with the NSTX facility, whose status and proposed upgrades are outlined in Chapter 2. Chapter 3 describes the details of experimental research proposed in various areas. Chapter 4 outlines the results of integrated modeling studies aimed at clarifying the range of operating scenarios achievable on NSTX, and the needs for device flexibility and targeted theoretical research. Chapter 5 captures the theory and modeling needs described in Chapter 3, expands on them and outlines the plans for developing further needed theory tools. Chapter 6 describes the connetions of NSTX research to possible next-steps in ST research. Chapter 7 describes the program structure and how the NSTX team research program is developed and managed. This includes a description of the Experimental Task Forces and the role of researchers from throughout the country who partake in the development and execution of the NSTX research run plan. Finally, and importantly, an appendix provides a compendium of the planned and proposed contributions of research partners who collaborate with the Princeton Plasma Physics Laboratory in this national and international program. In the appendix, connections are explicitly made to the experiment and theory research discussions.

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