Status of Cooperation and Collaboration Between the Alcator C-Mod, DIII-D, and NSTX Research Programs

I. Introduction and background — Presented here is a status report and review of collaborative and cooperative research between the Alcator C-Mod, DIII-D, and NSTX research programs. This report has been developed in response to a request from the Fusion Facilities Coordinating Committee (FFCC).

A substantial strength of the U.S. National Fusion Research Program is the close interaction among the three major toroidal research programs. Cooperation, collaboration, and coordination take place on several levels, from programmatic to individual experiments. Each facility provides a unique set of accessible plasma parameters, configurations, heat, current and particle sources and control methods, diagnostics, etc. Taken together, C-Mod, DIII-D and NSTX provide a diverse portfolio of complementary capabilities and resources, which are being effectively utilized to address the major issues in fusion science research.

The value of collaborative and cooperative research is multi-fold. First, performing experiments in different devices is often the only way to extract the physics underlying critical issues. The important parameters over which plasma theoretical models apply are often not available in a single device (a good example is shape/dimension) and it is only through cross machine comparisons that the models can be tested. Properly chosen, complementary experiments can challenge theoretical models at their extremes, providing substantive tests of these models not possible in any other way. This model validation is critical for developing predictive capability of future plasma characteristics, dynamics, and fusion performance. Similarly, complementary technological approaches among the facilities not only expand the available toolset for addressing the physics questions, but also provide opportunities to evaluate alternative solutions to the challenges inherent in next step fusion research. Second, toroidally confined plasmas are strongly coupled and complex systems, presenting strong challenges to theory and experiment alike. As part of the scientific process, new experimental results require duplication and validation before they are accepted and incorporated in extrapolation to next step experiments such as ITER. Confirmation of new results often requires observations in different parameter regimes and complementary experimental techniques made possible by experiments on different facilities. Third, collaboration yields more efficient operation by allowing all programs to take advantage of the unique operational and diagnostic strengths of the other programs. In this way, each program can address issues of common interest using the tools, techniques, and parameters most readily available to it, while other aspects of the problem are addressed more appropriately or efficiently elsewhere. In some cases, the physics of issues important for one program can be developed and tested within another program in a cost-effective manner. Such benefit is also found in the distribution of modeling, data management, analysis, and plasma control resources developed within the context of one research effort and now benefiting other programs on both the national laboratory and smaller university project scales. Finally, diagnostic techniques (and in some cases, actual hardware) are shared among the experimental groups, not only eliminating costly duplication of effort, but also providing a basis for comparison of results obtained under different conditions using similar or identical instrumentation, a useful feature for resolving experimental discord. In the same way, technical and engineering expertise in a variety of areas is commonly shared among the facilities.

Closely coordinated, targeted, joint experiments are carried out among the U.S. facilities, as they are in the worldwide context, to address scientific questions whose resolution requires a range of parameters or techniques beyond the scope available at a single facility. These joint experiments usually involve participation, either onsite or through remote access tools, of researchers from all the involved institutions in planning, execution and analysis of the work. Examples include questions of dependence on scale or geometry for which all parameters except those under investigation are required to be tightly controlled.

At the heart of identification and execution of successful joint experiments is the continuing high level of individual researcher initiative and creativity in identifying, developing, and executing such ideas. Various program planning activities and forums are in place to provide a programmatic means for supporting this. For example, experimental ideas are often identified, discussed, and developed in ongoing scientific forums such as the Transport Task Force and the Active Mode Control Workshop, the National Tokamak Workshop, as well as single events such as the Error Field Workshop held this fall. The three programs have extended their reach by soliciting researcher participation from within each others' programs, from other university and national laboratory programs throughout the country, and from throughout the world. A signature of such participation is seen in the broad participation in each program’s research planning forum. A number of university research programs are leading research on two or more of the facilities, providing coordination on those research activities: two examples are Columbia University and RWM research on DIII-D and NSTX, and University of Wisconsin and disruption mitigation research on C-Mod and DIII-D. In addition, the three program advisory committees have members from each other's programs, and this participation often yields adjustments aimed at further optimization of joint research activities, including maximizing efficiency. Cooperative and collaborative research is now further facilitated in the United States and internationally through participation of all three programs in the International Tokamak Physics Activity (ITPA). Program leaders consider the opportunities identified by researchers and generally have supported the development and execution of proposals that arise from these discussions. The experimental work is supported by the development and sharing of analysis and modeling codes, benefiting all three of the major U.S. programs as well as many international partners. Finally, collaborative and cooperative experiments are supported through research assignments between programs, resulting in short- and long-term stays at each others' laboratories.

As requested by the FFCC, the research is described here along the topical research categories of the ITPA, with some broadening of the scope of these categories to accommodate all of the major elements of the three research programs. These categories are described in Section II. Section III gives a description for the different types of collaborative and coordinated research described here. Section IV gives a brief set of examples for each topical area of collaborative research that is being pursued between the three devices. Section V gives recommendations for possible future collaborative and coordinated research opportunities, and some comments on how these efforts might be optimized further. After the written text, tables containing descriptions of the collaborative and cooperative research between Alcator C-Mod, DIII-D, and NSTX programs are presented.

II. Topical Research Categories — For the purposes of the research topics in this report, the categories used by the ITPA are used here. However, to be inclusive of the research undertaken by C-Mod, DIII-D, and NSTX, the topics within each ITPA category may be broader than typically used within the ITPA. The ITPA is organized along the following research categories:

- Pedestal and edge physics, including transport, stability, and atomic physics issues
- MHD, disruptions, and control,
- Divertor and scrape-off layer physics, including plasma facing materials issues,
- Steady-state operating scenarios and energetic particle. For this exercise, rf heating and current drive physics, other aspects of wave-particle interactions, and solenoid-free startup research are outlined here,
- Transport physics, concentrating on core plasma transport,
- Diagnostics.

The confinement database and modeling activity, which is also part of the ITPA effort, maintains a variety of databases from which semi-empirical as well as theoretically based scaling relations are derived, with a particular aim of predicting the performance of ITER or other future devices. Each of the three U.S. facilities contributes important data to this effort. Research in support of this ITPA section is included in the Transport and Pedestal and Edge tables below.

III. Descriptions of Joint Experiments and Complementary Research — Research activities are summarized in tables at the end of this document. The research described in these tables is organized by ITPA category, with one exception being a summary of shared resources developed originally within one program. The research described has the following characteristics.

1. Joint Coordinated Research Experiments — These are coordinated experiments which have been allocated run time on two or more devices. They represent areas for which precisely prescribed conditions are required to make sensible comparisons between devices. These experiments generally benefit from on-site participation from the other programs involved. Results from research on more than one device can reveal a more complete picture that may be important for testing physics models, including those relevant to ITER. These experiments are particularly useful when device, plasma, or diagnostic differences can be used to test specific physics models. One example is found in experiments designed to separate plasma physics and atomic physics effects that may govern H-mode pedestal width and height. Aimed at an issue that is critical for ITER, these experiments take advantage of similarities and differences in plasma physics and atomic-physics-related quantities between devices and demand careful matching of experimental conditions such as plasma shape. Overall, most of the activities cited are for research in 2004, and some others are preparatory activities for research to be performed in 2005. Joint research experiments are represented by a separate column in the tables.

2. Complementary and Cooperative Research Activities — These generally are experiments and campaigns which do not require precise coordination and control of plasma conditions on different devices, but for which comparative studies and frequent comparison of results and sharing of tools has high scientific leverage. Typically, broad scientific issues are studied in this manner. Examples include the challenge of developing high-bootstrap fraction sustained operation, which is needed both for ITER and for the ST configuration. A more specific example includes the development of complementary approaches to ITER steady-state scenarios on DIII-D and C-Mod. Resistive wall mode research on NSTX and DIII-D has both complementary, cooperative components as well as specific, coordinated elements. Current drive research also generally falls into this category, as each device samples differing elements of wave physics. Some specific, coordinated experiments are also being planned in this area as well and are described as such. Complementary, cooperative research is represented by a separate column in the tables.

3. Research Taking Advantage of Particular Strengths — Unique plasma characteristics, device capabilities, or diagnostic capabilities can yield important research opportunities that can be explored only or best on one device, and which may yield significant benefit and cost-effectiveness to one or both of the other programs. Such experiments and opportunities are highlighted in the text in the tables.

4. Research Activities Benefiting from Development Within One Program, Including Codes and Models — This includes the exportation of research tools developed under the umbrella of one program and now being utilized by other parts of the national program.

IV. Examples of Collaborative Research and the Complementary of Programs

A wide array of research activities are outlined in the tables that follow. Examples within each research category are given here.

1. Pedestal and Edge Physics — The H-mode edge pedestal height is a critical factor in determining the performance of the core ITER plasma. Coordinated experiments are planned between all three devices, as well as with international partners, to take advantage of complementary plasma characteristics. A critical issue is the relative roles of atomic physics, plasma physics, and magnetic field line topology in determining the pedestal characteristics.

Plasma characteristics in a given topology and atomic physics roles are being addressed with joint C-Mod/DIII-D experiments. Experiments between DIII-D and NSTX enable the role of field line geometry are being assessed.

2. MHD, Disruptions and Control — In collaboration with Columbia University, NSTX is building on the DIII-D research program in its design and implementation of resistive wall mode research. The research on the two devices is beneficial to each program, and ultimately ITER, because the differences in Alfvén velocities and sound speed allow important tests of mode damping theory to be made. Fast ion MHD research is also complementary among the three devices. The aspect ratio difference of NSTX and DIII-D, along with their similar cross sectional shape, size, and fast ion energy, are allowing studies of the major radius dependence of Alfvén eigenmode instabilities. These studies allow tests of models used to predict characteristics of such instabilities in ITER. C-Mod's unique capability to perform high-frequency active MHD spectroscopy permits specific tests of MHD instability theory.

3. Steady-State Operating Scenarios and Energetic Particles — The challenge of developing steady-state operating scenarios with high bootstrap fraction is of critical interest to all three programs and warrants exploration within each. The ITER program, as well as future advanced tokamak reactor scenarios, is critically dependent on the development of steady-state and hybrid operating scenarios. These areas of research are central to both C-Mod and DIII-D, and the different approaches for current drive tools being used will deepen the foundation for wave physics theory needed for ITER and beyond. The NSTX program has at its heart the demonstration of high beta, non-inductively sustained operations, to be addressed under its charge of assessing the viability of the ST concept. This requires the development of electron-Bernstein-wave-based current drive tools for application in over-dense plasma conditions. Experiments using the existing DIII-D electron cyclotron capabilities may help establish the physics basis required for this.

4. Transport (Core) — An issue of central importance to ITER, and of broad scientific import, is the origin of electron thermal transport. The three devices challenge theories of electron-scale turbulence in that, in combination, a wide range of ratios of T_i/T_e is accessible. The wide range of beta that is accessible between the three devices enables the predicted turbulence to range from electrostatic to electromagnetic in character, providing a stringent test of the codes that form the basis for today's most sophisticated transport models. Diagnostics for assessing the characteristics of electron scale turbulence are in place and being deployed on both C-Mod and DIII-D, and a new diagnostic for such measurements will be installed on NSTX for use in 2005.

5. Divertor and Scrape-off Layer Physics — C-Mod, DIII-D, and NSTX research is complementary in that each is pursuing a different technological approach regarding heat and particle flux management. The issue of heat and particle flux management in a fusion environment is critical to advancing any toroidal confinement concept as a fusion device, and is of keen interest to ITER. C-Mod focuses on high Z wall materials, DIII-D research is aimed at understanding the physics of carbon mass transport in the divertor region, and NSTX research is targeted towards an assessment of and possible demonstration of lithium-based wall solutions, including a liquid lithium divertor.

V. Summary and Opportunities Identified for Improved Cooperative Research Between Alcator C-Mod, DIII-D, and NSTX — On the whole, researchers find complementary use of research capabilities and plasma differences to be integral to their addressing problems of direct value to ITER, to advancing the ST and AT, and to advancing plasma science overall. The value of further increasing the coordination among the programs is recognized by researchers and program leaders alike. When opportunities for collaboration are identified and research ideas are developed to a level that is accepted as high quality within the research community, program leaders and coordinators are highly supportive of such cooperative activity.

Several recommendations to further improve coordination emerge from this study. We propose four general and broad recommendations, and four near term specific recommendations.

1. Broad Recommendations

(a) Benefit will be derived from having presentations and discussion from program leaders to the research staffs of each facility several weeks prior to each program's research planning forum. This year, such a presentation, made by a DIII-D researcher to the NSTX team, was found to be of high value. Such sharing of program plans between researchers at all three facilities will stimulate important discussions about joint experiments and their coordination. These presentations will enable a clear and timely articulation of the research goals and run schedules of each device, and will allow for modification of the broad research programs by the program leaders in response to the feedback obtained. These presentations can be made using present remote participation tools.

(b) Broader participation in the research planning forums, especially by the leaders of the topical research areas from each program, should be encouraged. Scheduling of the three planning forums should, to the extent permitted by other constraints, be coordinated to allow maximum cross-program participation.

(c) There is broad participation in the International Tokamak Physics Activity (ITPA) by the three U.S. facilities, C-Mod, DIII-D, and NSTX. Presently this group provides suggestions for joint experiments on worldwide tokamak facilities, including C-Mod, DIII-D, and NSTX. It is recommended that the U.S. participants provide suggestions to the FFCC for specific coordinated experiments among the U.S. facilities. The U.S. group leader would be responsible for providing these suggested joint experiments to the FFCC chair, presumably following the ITPA fall meetings. These joint experiment suggestions would be compiled and made available for the research planning activities of each program, and would be reviewed by the FFCC.

(d) After the run planning is completed the tables in this document should be updated and reviewed by the FFCC to obtain agreement on the coordinated experiments and update the research plans on complementary experiments.

2. Specific Recommendations

(a) The several planned coordinated experiments between NSTX and DIII-D on the aspect ratio dependence of confinement, the major radius dependence on fast ion MHD characteristics, and on the aspect ratio dependence of H-mode pedestal characteristics may benefit from additional coordination so as to optimize the run time used on each device. It is suggested that the program leaders of DIII-D and NSTX discuss further to facilitate completion of these experiments.

(b) During this exercise, it has come to our attention that a significant opportunity for joint ECH/EBW research exists between DIII-D and NSTX. This idea was initiated by scientific staff from DIII-D and PPPL, and would take significant advantage of the ECH facilities on the DIII-D device, including the high power 110 GHz gyrotrons, and the steerable launchers provided by PPPL. Off-axis EBW current drive has been identified as a highly valuable tool for the achievement of the NSTX long-term research goals, but the physics of EBW wave coupling, mode conversion, and deposition remains in many respects untested. The technical feasibility of performing experiments with over-dense DIII-D plasmas to enable the physics of EBW coupling, deposition, heating, and current drive to be explored on DIII-D is being pursued. This feasibility assessment includes modeling of EBW conversion, wave propagation, and damping for over-dense DIII-D plasmas. If technically attractive, this will provide a means of assessing the EBW physics that needs to be validated prior to the development and deployment of an EBW current drive system for NSTX.

(c) Significant plasma rotation has been observed on both C-Mod and DIII-D without external momentum input; in C-Mod discharges with Ohmic heating and ion cyclotron heating, and in DIII-D discharges with Ohmic heating and electron cyclotron heating. Plasma rotation and sheared rotation are generally favorable for confinement and MHD stability, and are potentially useful for stability and transport control appropriate for larger facilities such as ITER. It is therefore important to understand the source of the rotation, the momentum transport and their scaling to larger size. The fact that such rotation is observed under significantly different plasma conditions and with different heating techniques in the two devices could greatly benefit the effort to understand the underlying physics. We therefore encourage exploration of the opportunities for coordinated experiments and analysis on rotation in ICRF and EC heated plasmas in C-Mod and DIII-D to facilitate progress in this important research area.

(d) It is recommended that researchers from C-Mod and NSTX investigate the possibility of developing a comparative study on the role of aspect ratio in determining H mode pedestal characteristics and relaxation mechanisms. Such studies are important because pedestal height is critical to H-mode performance and fusion power output on ITER, and identifying benign edge relaxation mechanisms are important for developing a viable divertor scenario. The possibility will be pursued that C-Mod can represent a bridging point in studies that would include NSTX low aspect ratio H-mode plasmas and JFT2-M discharges. The JFT2-M plasmas have an aspect ratio approaching 5 and have already been documented as part of a study with the C-Mod Program.

C-Mod, DIII-D, and NSTX Coordinated and Complementary Research Activities

Pedestal and Edge Physics

Research Topic	**Coordinated Joint Experiments**	**Complementary Research Activities**	**Additional Comments**
Pedestal height and width, and the role of plasma physics vs. atomic physics	Joint experiments with DIII-D, NSTX, and MAST. Builds on recent results of joint dimensional identity experiment with DIII-D and C-Mod assessing the role of atomic physics in determining pedestal characteristics **International element**: In conjunction with C-Mod/JET and C-Mod identity experiments and DIII-D/JET ρ_* scaling experiment	Each program contributes to this research, coordinated with ITPA **C-Mod:** Additional 2004 research aimed at dependence of pedestal parameters on configuration (SNL, DN, SNU) **NSTX**: Pedestal parameters, esp. in ion channel, to be studied in 2004 with improved diagnostics, control, and shaping capability **DIII-D:** Measure edge current density, and pedestal characteristics in highest pedestal pressure, VH-mode	**High, immediate ITER relevance**. - Core performance is proportional to pedestal height, thereby having a strong impact on ITER performance - Strong multi-program international effort **Physics complementarity of devices**: - Differing proximities to walls, wide range of gyroradii between devices gives information on the role of plasma vs. atomic physics
ELM-free and small ELM H-mode operations with good particle exhaust and enhanced confinement	**International element**: Recent successful DIII-D/JT-60U and DIII-D/JET quiescent H-mode experiments. Follows successful DIII-D/ASDEX-U studies, where QH-mode was found on ASDEX-U following DIII-D. C-Mod/JFT2M experiments are under way to evaluate EDA and HRS	**C-Mod:** EDA H mode research on C-Mod; quasi-coherent mode. **DIII-D:** Quiescent H-mode found with counter NBI-only; EHO.	**High, immediate ITER relevance** - Pulsive heat and particle flux from ELMs could limit the lifetime of the ITER divertor. These ELM-free regimes eliminate the transient heat and particle loads to the divertor while maintaining good performance. Range of collisionality, shaping effects may determine nature of relaxation mechanism

Pedestal and Edge Physics II

Research Topic	Coordinated Joint Experiments	Complementary Research Activities	Additional Comments
L-H transition	Comparative experiment planned between C-Mod and ASDEX-U. NSTX and MAST recently completed first stage of joint experiment utilizing similar shapes but very different wall proximity.	**C-Mod:** Studying role of edge and core rotation in setting threshold difference with respect to ion ∇B direction (SNL, SNU, DN); also limiter configurations **NSTX:** Aspect ratio and fueling dependence of threshold **DIII-D:** High time resolution turbulence and profile measurements across transition	**High ITER relevance** Prediction of threshold is crucial issue for ITER **Physics complementary of devices**: - Differing proximities to walls, wide range of gyroradii, large difference in field line pitch between the devices gives information on the role of plasma vs. atomic physics.

MHD, Disruptions, and Control

Research Topic	**Coordinated Joint Experiments**	**Complementary Research Activities**	**Additional Comments**
Active mode control (RWM) (ITPA)	Joint experiments between NSTX and DIII-D to assess physics of mode damping. **International element:** Coordinated experiments on JET and ASDEX-U.	**Take advantage of device complementary:** Test physics of mode damping. Tests enabled by different aspect ratios, different Alfvén speeds, yet similar sound speeds.	**ITER and AT relevance is high.** - Stabilization of RWMs will provide added margin for steady state high performance ITER operation **Importance to ST program is high.** - Active wall mode stabilization is the leading strategy for enabling operation near the with-wall limit on NSTX. Builds on DIII-D research program. DIII-D RWM thrust leader is PPPL staff. Columbia University staff are program leaders on DIII-D and NSTX, building on their own research on HBT-EP.
Non-axisymmetric error field effects	**C-Mod, DIII-D:** Joint experiment with JET to clarify size and B_T scaling of locked mode threshold.	**C-Mod:** External non-axisymmetric control coils increase operational range; study sideband effects **DIII-D:** Internal and external compensation coils; large variation in poloidal spectrum and unique capability to study stochastic edge effects **NSTX:** First tests of error field modification with new coils late in '04 will enable direct comparisons to earlier DIII-D observations.	**ITER relevance high**. - Goal is to predict locked mode threshold for ITER - Active area of research in all programs; cooperation facilitated by Error Field Workshop at last APS-DPP
NTM aspect ratio comparison (ITPA)		DIII-D, NSTX progress and plans updated through ITPA	Use aspect ratio differences to test role of toroidicity in NTM onset

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MHD, Disruptions, and Control II

Research Topic	Coordinated Joint Experiments	Complementary Research Activities	Additional Comments
Stabilization of NTMs and NTM threshold (ITPA)	C-Mod, DIII-D joint experiment to test theory by comparing mode onset conditions **International element:** - Builds on international joint experiments with ASDEX-U, JET, and JT-60U	DIII-D has demonstrated stabilization using ECCD. C-Mod plans to investigate the use of LHCD and MCCD.	**ITER relevance high:** Because theory predicts NTMs on ITER at lower beta. An element of C-Mod's longer term effort is to assess stabilization using LHCD by Δ' modification, and using MCCD for bootstrap current replacement.
Disruption mitigation Scaling of gas jet penetration	Coordinated activity between C-Mod, DIII-D, and led by the University of Wisconsin. Experiments on C-Mod are designed to follow-up on DIII-D experiments performed in 2003. Coordinated research with JET as well.		**High ITER relevance:** - Disruption mitigation on ITER can significantly increase the reliability of components and device availability. Disruption mitigation using high pressure gas injection has been shown highly effective on DIII-D. The key question on its applicability to ITER is the penetration of the gas jet at high plasma pressures and larger size. ITER-relevant plasma pressures on C-Mod Increase of gas jet pressure on DIII-D by factor of 10 in 2004

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Steady-State Operating Scenarios and Energetic Particles

Research Topic	**Specific Coordinated Joint Experiments**	**Complementary Research Activities**	**Additional Comments**
Steady-state, high bootstrap fraction scenario development	Coordinated international activity between DIII-D and JT-60U (experiment performed this year), ASDEX-U and JET (to be performed later this year), on both hybrid and steady state scenarios.	**Preparation of ITER steady-state scenarios (ITPA):** C-Mod, DIII-D using complementary tools. **Preparation of ITER hybrid scenarios (ITPA):** C-Mod, DIII-D using complementary tools. **NSTX long pulse, high beta scenario development**	**High ITER relevance:** - Steady-state scenario research aims to develop a solid basis for steady-state operation, extrapolable to ITER - Hybrid scenarios important for fusion testing using longer pulses. May eliminate or significantly reduce sawteeth. **High relevance to ST development:** - ST-based CTF and reactor scenarios require developing a solid basis for fully non-inductive, moderate and high beta scenarios **Complementary physics and tools on all three devices**: - **C-Mod:** current profile control with LHCD and MCCD - **DIII-D:** current profile control with ECCD, NBCD, and FWCD (under-dense plasmas) - **NSTX:** current profile control with NBCD, HHFW, and ultimately EBW (over-dense plasmas) - Enhance understanding of bootstrap current by validations of bootstrap current models at extremes of aspect ratio. - Validate wave-particle interaction models in over-dense and under-dense plasmas

Steady-State Operating Scenarios and Energetic Particles II

Research Topic	**Specific Coordinated Joint Experiments**	**Complementary Research Activities**	**Additional Comments**
Current profile optimization in plasma startup	**DIII-D and NSTX:** Early H-mode development to yield lower internal inductance. Extend early discharge evolution scenarios developed on DIII-D to NSTX current ramps, taking advantage of rtEFIT on both devices	C-Mod current profile optimization includes developing scenarios for early ITB formation using ICRF to increase core T_e, reducing current diffusion. DIII-D uses EC to increase T_e, change q profile evolution	Experiments were performed on DIII-D in 2003, planned on NSTX in 2004
Fast ion MHD	DIII-D/NSTX joint experiments in 2004 builds on first experiments in 2003.	Additional fast ion MHD studies part of all three programs. DIII-D/NSTX complementary includes differing aspect ratio with similar cross sectional shape and size. $V_{\text{fast ion}}/V_{\text{Alfvén}}$ can be matched or made to be different. **C-Mod:** active spectroscopy to probe damping of stable modes to test theories; collaboration with JET Observation of Alfvén Cascades in AT regimes in DIII-D and C-Mod (also JET, TFTR)	**ITER relevant:** specific AE theory predictions are being directly tested: **DIII-D/NSTX:** major radius dependence of AE mode structure **C-Mod:** test theory predictions of mode damping.

Steady-State Operating Scenarios and Energetic Particles III

Research Topic	Coordinated Joint Experiments	Complementary research activities	Additional comments
Plasma current startup without a solenoid	**Important NSTX program element:** Aided by DIII-D control tools and modeling. Strong NSTX collaboration with HIT-II device on this topic [coaxial helicity injection (CHI)]. - Transient CHI developed on HIT-II being tested on NSTX.	DIII-D researchers participating in PF induction experiments on NSTX Modeling underway for collaborative NSTX/DIII-D experiments to assess EBW physics for ST startup and sustainment Researchers from JT-60U will perform experiments on NSTX to test JT-60U I_p rampup approach	**High relevance for the ST, significant benefit to vision of an AT as well:** - Major focus of the NSTX program. CHI, PF induction, EBW. Success would also benefit plans for future AT reactors - Plasma startup modeling tools for PF induction studies being shared between NSTX and DIII-D.
Current drive physics	Modeling underway for collaborative NSTX/DIII-D experiments to assess EBW physics for ST startup and sustainment	**C-Mod:** Lower hybrid and mode-conversion CD being studied on C-Mod **DIII-D:** ECCD. FWCD, NBCD **NSTX:** HHFW, EBW being developed. EBW a unique program need for NSTX.	**Complementarity of wave physics between devices** - Wave-particle interactions and current drive in low and high density, as well as over-dense conditions. **EBW physics for NSTX and the ST may be tested on DIII-D:** - Modeling underway to assess the viability of using over-dense plasma operations on DIII-D with gyrotron tube and launcher capability to enable important tests of EBW physics for NSTX.
RF flow drive physics		**C-Mod:** Generation of local poloidal flows using mode-converted IBW, ICW. **Unique** emphasis of C-Mod program, supported by ICRF capability, wave and rotation diagnostics, low external torque.	Generation of localized flow and flow shear by rf waves offers potential for control of transport. High importance for ITER and Reactor AT scenarios.

Transport Physics (Core)

Research Topic	Specific Coordinated Joint Experiments	Complementary Research Activities	Additional Comments
Thermal transport: underlying physics (turbulence)		**C-Mod:** Upgraded diagnostics (phase contrast imaging) emphasize high k turbulence measurements. Study with direct electron heating (LH) and indirect (ICRF and ion-electron coupling). **DIII-D:** Initial high k turbulence diagnostics deployed for 2004. ECH a tool for ECE for time-dependent analysis. Several run days planned. **NSTX:** Low k turbulence measurements in 2004 into confinement zone. Theory indicates controllable low and high k with NBI and HHFW. High k scattering for 2005	**High relevance to ITER and for predicting beyond it:** Confinement a determining factor in device size requirements. Electron thermal transport identified as a community-wide issue that requires a broad attack. **Complementary physics:** Three devices span electrostatic (DIII-D, C-Mod, NSTX) to electromagnetic (NSTX, $\beta \sim 1$) turbulence realms, allowing tests of gyrokinetic turbulence theory. - NSTX: Merger of thermal and Alfvén velocities with high beta, low B. Theory suggests possible AE damping on ions.
Thermal transport: ITER-like conditions: High performance with $T_e \sim T_i$ (ITPA)		A C-Mod programmatic focus. DIII-D is planning two experiments this year with $T_e \sim T_i$, one in the hybrid scenario, the other in the steady-state scenario.	**Immediate ITER relevance:** Due to high density conditions in C-Mod and expected in ITER. DIII-D, NSTX approach this with combined NBI and wave heating of electrons
Aspect ratio dependence of core confinement (ITPA)	Run time allotted for joint experiment with NSTX and DIII-D in 2004		**NSTX, DIII-D devices ideally suited for cross-comparison:** Poloidal cross sectional shape and size can be matched. Match β_p, but with varying total beta. Same beam heating configuration.
Beta dependence of core confinement (ITPA)		All three programs contribute to database to assess beta dependence of confinement scalings. Of note are recent JET-DIII-D beta scaling experiments.	**ITER relevance high:** Work is aimed at clarifying apparent beta degradation of confinement implicit in some scaling expressions.

Transport Physics (Core) II

Research Topic	**Specific Coordinated Joint Experiments**	**Complementary Research Activities**	**Additional Comments**
Momentum transport and the origin of plasma-generated flows		**C-Mod:** Observations of rotation without NBI motivate much of the ongoing C-Mod program. Collaboration with NSTX regarding enhanced core rotation measurements - ITPA topic of broad research interest **DIII-D:** Recent observations of radial electric field and flows associated with ECH leading to experiments this campaign. Core measurements of poloidal rotation being developed in collaboration with PPPL. **NSTX:** Studies beginning using NBI and HHFW with enhanced core toroidal rotation diagnostics and new edge poloidal rotation measurements	**High ITER relevance:** - Torques from beams will be less effective on ITER than on present devices. Rotation from other sources may have a profound effect on ITER confinement and MHD stability. - An outstanding scientific issue identified by the transport community as requiring additional attention and requiring a broad approach. **Major facility upgrades:** DIII-D will reorient a neutral beam to allow co-counter mix in 2005 **Complementary physics:** - Can driven waves be used to modify turbulence and control the pressure and bootstrap current? - C-Mod: Rotation in the absence of an obvious torque; observed with ohmic as well as ICRF heating. ICRF can also trigger ITBs, which may be related to flow generation. - DIII-D observation of ECH-related radial electric field is also unexpected, may be connected with wave-generated flows.

Transport Physics (Core) III

Research Topic	Specific Coordinated Joint Experiments	Complementary Research Activities	Additional Comments
Particle transport (core)		**C-Mod:** Particle transport control in ICRF-generated AT regimes with transport barriers being studied. **DIII-D:** Impurity transport studies with charge exchange recombination spectroscopy planned for 2004, targeted for ITER scenarios and NSTX/DIII-D aspect ratio/beta comparison. On DIII-D, outside, vertical, and inside pellet launch available (ORNL). **NSTX:** neon gas puffing and soft x-ray measurements planned for NSTX/DIII-D aspect ratio/beta confinement comparison.	**High ITER relevance:** - An outstanding issue recently identified by the transport community as requiring additional attention and a broad approach. Diagnosis of gyrokinetic codes developed under SCiDAC will enable predicted relations between particle and thermal fluxes to be compared to experiment.

Divertor and SOL Physics

Research Topic	Specific Coordinated Joint Experiments	Complementary Research Activities	Additional Comments
Edge turbulence imaging research: scaling of radial transport (ITPA)		C-Mod/NSTX (developed with LANL). Focus on convective transport and toroidicity effects. Both devices participating through ITPA in studies of the scaling of radial SOL transport. C-Mod/DIII-D coordinated research effort on divertor and main chamber recycling.	Role of convective cross-field transport events in particle balance important for ITER particle handling
Multi-machine study on separatrix density and edge profiles		C-Mod and DIII-D progress and plans updated through ITPA.	Comparative studies motivated by differences in particle balance. Understanding required for ITER.
Particle/power handling, including co-deposition and impurity behavior		**C-Mod:** High Z metallic facing components. Major programmatic focus. **DIII-D:** Mass transport in the boundary is one of the program's major focal points. Experiments to understand C13 transport, deposition, and removal are very collaborative, with many international participants. **NSTX:** Lithium coatings (pellets) investigated in 2004. Developing database for possible advanced liquid lithium divertor, in collaboration with LTX.	**High ITER relevance:** Complementary approaches being investigated. Successful Liquid Li divertor would have high impact on both ST and AT

Collaborative Development of Diagnostics

Diagnostic Approach	**Research Activities**	**Additional Comments**
Phase contrast imaging	C-Mod/DIII-D collaborative development	
Edge turbulence imaging	C-Mod/NSTX collaborative development	Comparative studies enable turbulence theory tests at different extremes of density, temperature, and toroidicity
X-ray crystal spectroscopy	**C-Mod/NSTX:** Development of ion temperature/rotation diagnostic. Detector development performed in collaboration with the Korean Basic Sciences Institute	
Reflectometry	UCLA researchers lead efforts for these reflectometry-based turbulence measurements on both NSTX and DIII-D. Also lead efforts to develop backscattering on these two devices. PPPL involved in reflectometry systems on C-Mod and DIII-D	
Edge probes	UCSD leads efforts on both DIII-D and NSTX.	

Shared Resources

Resource	**Comments**
Plasma control	**rtEFIT**, developed at DIII-D, being implemented this run period on NSTX. Explicit run time is dedicated for this implementation. Discussions underway for implementation on C-Mod in 2005
Analysis	TRANSP, developed at PPPL. Now used community-wide EFIT, developed by DIII-D program, now used community-wide.
Modeling	**RF:** Current drive, heating. Development of heating and current drive packages supported by SCiDAC effort benefits all programs. **Transport and turbulence:** SCiDAC support of microturbulence project enabling wide distribution of gyrokinetic codes that are now applied within all three programs.
Data management	MDSplus developed by the C-Mod program in collaboration with LANL and RFX (Padova), is now central to DIII-D and NSTX research Now used community-wide. Establishes a common data structure essential for joint experimentation
Fusion Grid	All three programs participate. For the researcher: allows easier and swifter access to resources, creating a more efficient scientific environment For the service provider, it becomes relatively easy to make their resource available to a large audience without having to support a large number of duplicate yet geographically distributed installations.