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NSTX Research Plan – FY05-07

Contributing to Fusion Energy Science, Burning Plasma (ITER), & Concept Optimization

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ORNL

For the NSTX Team

Budget Planning Meeting – FY 2007

March 15-16, 2005
Germantown, Maryland

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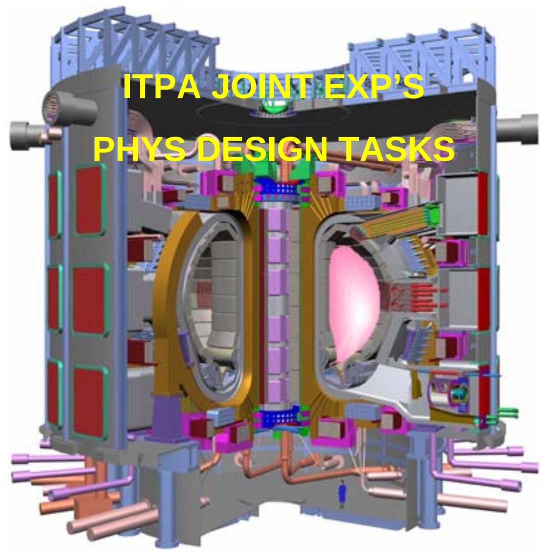
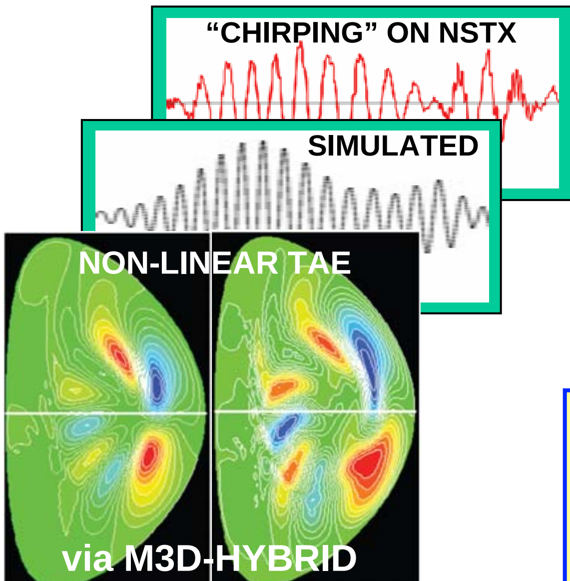
NSTX Will Advance Toroidal Plasma Science, Burning Plasma Physics, and Configuration Optimization

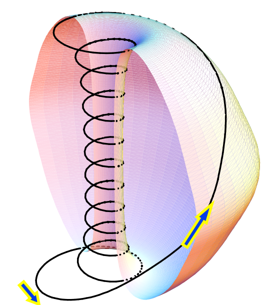
Burning Plasma



Science:
Extended Parameters



Optimization:
Unique &
Complementary

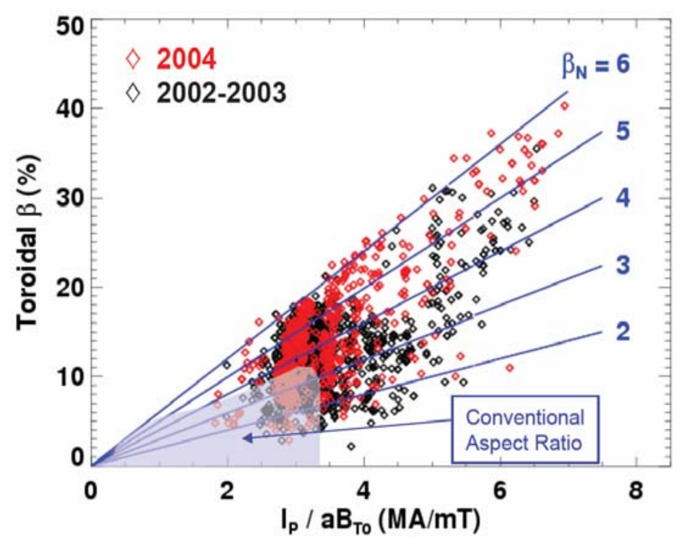


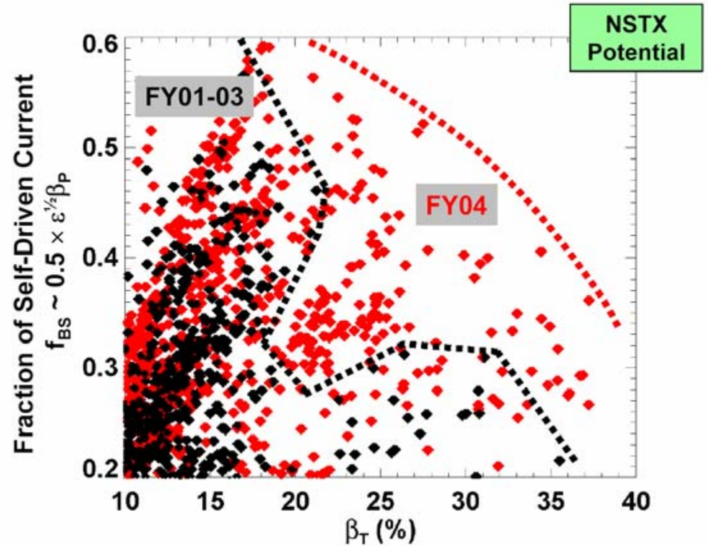
Contribute to OFES Strategic Goals by Addressing Scientific Topics:

- **Microturbulence & Transport**
- **Macroscopic Stability**
- **Waves & Energetic Particles**
- **Magnetic Flux Generation**
- **Boundary Interactions**
- **Synergy & Integrated Scenarios**

NSTX Had a Successful Year; Achieved 21 Run-Weeks; Made Key Progress on a Broad Scientific Front

- **Expanded parameter space via improved control, shaping & operation – broadening plasma science.**
- **Extended high beta-tau discharges with high B/S fraction to > tau-skin, with wall-stabilization of strongly rotating plasma.**
- **Measured RWM at substantially above no-wall limit, indicating $\omega_{crit}/\omega_A \sim 1/q^2$, consistent with neoclassical visc.**
- **Measured large radial correlation length of fluctuations in core that decreases with increasing B_T and radius.**
- **Observed increased electron energy confinement via reversed q-shear; verified ion Internal Transport Barrier.**
- **Reconstructed equilibria for strong plasma rotation, constrained by isothermal electrons and MSE field pitch.**
- **Determined via MSE & EFIT changes in core current density resulting from variations in operating scenario.**
- **Observed and modeled *AE's driven by supra-Alfvénic ions, which are anticipated in ITER burning plasma.**
- **Measured via NPA fast ion depletion due to MHD modes.**
- **Identified bursts of edge plasma filaments ("blobs") as primary characteristics of ELMs of varied severity.**
- **Measured EBW emission from core, consistent with theory.**
- **Obtained first evidence of parametric ion heating by HHFW.**





NSTX Prepared Three Plans for FY 2006-2007 to Deal with Present Uncertainties

Case	FY06 Rn-Wks	FY07 Rn-Wks	Accumulated	Upgrades
1	0	12	12	Minimal
2	12	12	24	Constrained
3	17	17	34	Optimized

- Case 2 in some detail
- Impact of Case 1
- Benefits of Case 3
- Summary charts of milestones as backup

Requested FY07 information for 0, 6, 12, 16, 20, & 25 run-weeks is supplied separately in hand-outs

Transport Studies Will Emphasize High-k Turbulence and Electron Transport, Leveraging Large β, ρ*, q-Shear

Motivation & NSTX Opportunities

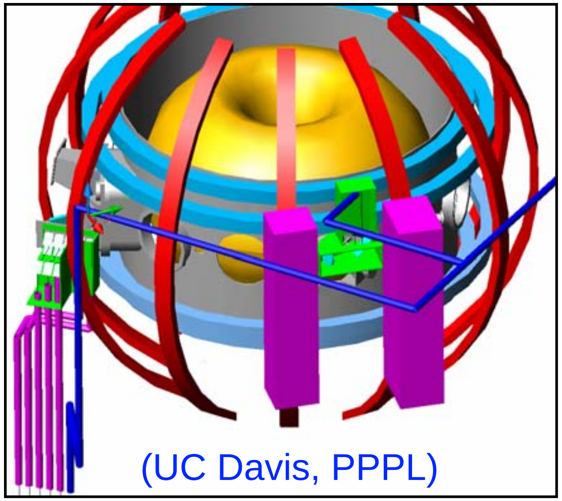
- Priority Panel (T4) & world priority; TTF initiative with emphasis on extended understanding of electron scale transport
- Key remaining scaling uncertainty for ITER – add to ITPA
- Large k (= 2 – 20 cm^{-1}), q-shear, ~ 3 cm spatial resolution
- Central β up to unity → clarify electromagnetic effects

Milestones

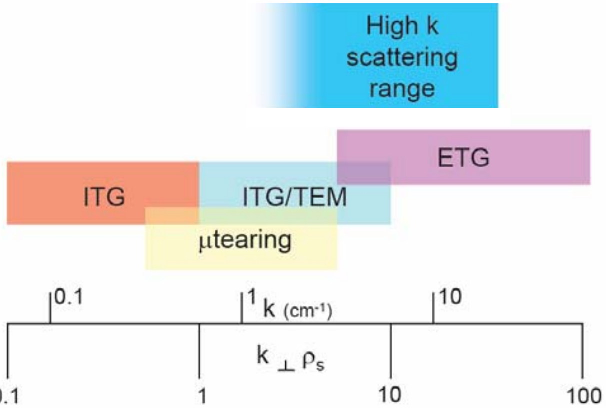
- FY05: test high-k μw scattering; extend MSE; q' & ∇T_e effects
- FY06: measure high-k turbulence in wide parameters
- FY07: correlate turbulence spectra with electron transport
- Extensive analysis: NL-GS2, GTC, FULL, GYRO, TRANSP

Additional Investigations

- Strengthen ITPA global ELMy H-mode & pedestal database
- iITB similarity experiments, momentum transport, with MAST
- H-mode aspect ratio comparison with DIII-D



(UC Davis, PPPL)



1) Transport & Turbulence: Physical processes that govern heat, particle & momentum confinement

Characterize q' & ∇T_e effects on electron transport	Measure high-k turbulence	Assess high-k turbulence spectra and electron transport
FY05 (17 wks)	**FY06 (12 wks)**	**FY07 (12 wks)**

Macroscopic Stability Studies to Advance Physics of Pressure-Limiting Modes via Feedback & Strong Shaping

NSTX

Motivation & NSTX Opportunities

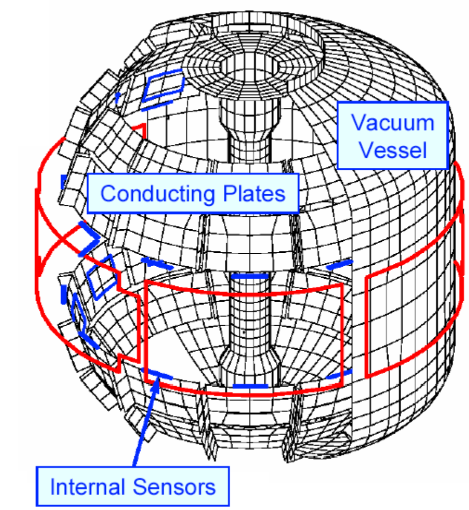
- Priority Panel (T2): what limits maximum pressure that can be achieved in laboratory plasmas? Also to enhance ITER performance
- Improved shaping ($\kappa \le 2.7$, $\delta \le 0.9$) $\Rightarrow \beta_T \le 40\%$, $\beta_N \le 6$, $I_N \le 6.5$, low ℓ_i
- New ex-vessel control coils, SPA power, internal sensors, with feedback capabilities progressively phased-in
- Resolve mode dynamics via $\beta_0 \rightarrow 1$, $V_\phi \rightarrow V_{Sound} \rightarrow V_{Alfvén}$, $V_\phi' \rightarrow \gamma_{MHD}$

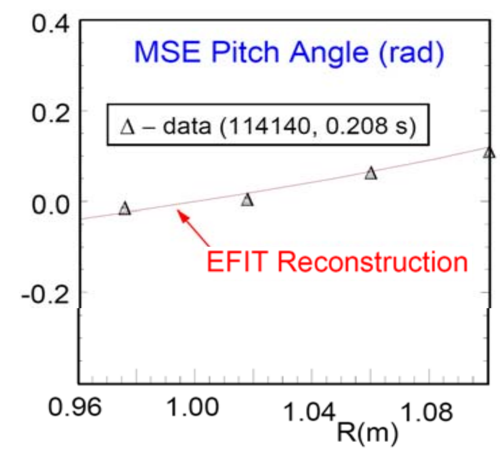
Milestones

- FY05: explore high-β plasmas via minimizing EF
- FY06: correlate resonant error field amplification, locked mode, β
- FY07: explore very high β regime close to wall-stabilized limit!
- Extensive analysis: EFIT-V_ϕ-isotherm-MSE, VALEN, MARS, M3D, …

Additional Investigations

- Joint experiments on RWM & locked mode physics with Tokamaks
- Aspect ratio comparison on NTM physics with Tokamaks





2) Macroscopic Stability: Role of magnetic structure on plasma pressure & bootstrap current

Study rotating plasmas close to "wall-stability" with EF correction	Characterize effectiveness of closed-loop EF/LM control	Characterize effectiveness of closed-loop RWM control
FY05 (17 wks)	**FY06 (12 wks)**	**FY07 (12 wks)**

Wave-Particle Research Will Make Unique Contributions to Understanding Supra-Alfvénic Ion Driven Modes for ITER

Motivation & NSTX Opportunities

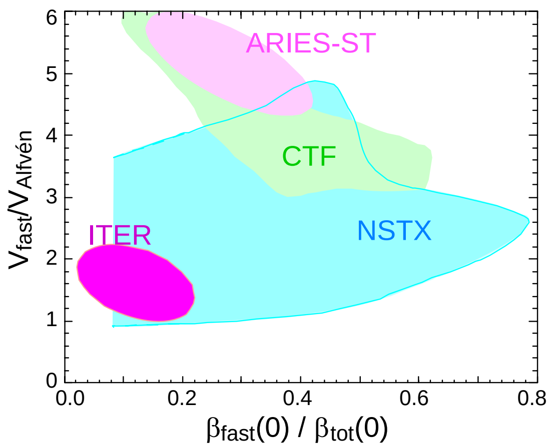
- ITER burning plasma will have supra-Alfvénic α's & beam ions
- NSTX covers the ITER regime in V_{fast}/V_A and β_{fast}/β_T; and has measured range of *AE's driven by such ions of confined orbits

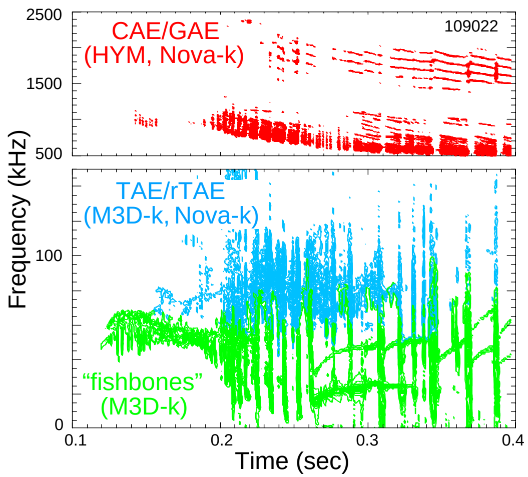
Milestones

- FY05: measure *AE's & correlate with fast ion, J_{NB} changes
- Extensive core measurements: USXR tomography for mode structure; fast tang. interferometer for amplitude; MSE for J profile
- Extensive analysis: linear & non-linear simulations
- Future: understand fast ion transport due to *AE cascades
- FY06: understand edge coupling (parametric and RF sheath effects) and optimize HHFW scenario

Additional Investigations

- EBW: B-X-O emission @ 20-40 GHz, to understand potential of Ohkawa current drive & electron phase space science
- Accumulate physics database for future high power EBW





3) Wave-Particle Interaction: Use of electromagnetic waves to sustain and control high-temperature plasmas

Assess effects of supra-Alfvénic ion driven instabilities on core J_{NB}

Characterize & optimize HHFW coupling

FY05 (17 wks)	FY06 (12 wks)	FY07 (12 wks)

Solenoid-Free Start-up Tests Will Contribute to Understanding of Flux Generation and Reconnection

NSTX

Motivation & NSTX Opportunities

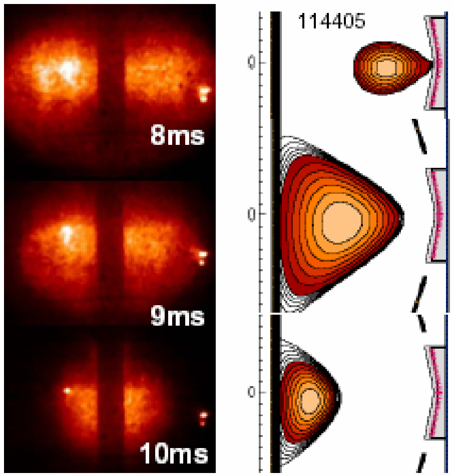
- Priority Panel (T6); important to tokamak reactor attractiveness; required for compact ST such as CTF
- Low A → low internal magnetic flux and helicity
- Large progress: **HIT-II** (CHI to 200 kA); **TST-2, LATE** (ECH + VF to 0.1 I_{TF} ~ 10 kA); **JT-60U** (ECH + VF, to >100 kA for >100 ms); **MAST** (merging-compression, to 500 kA); **NSTX** (HHFW + field null, to 20 kA); **Pegasus** (e-beam, to 10 kA)

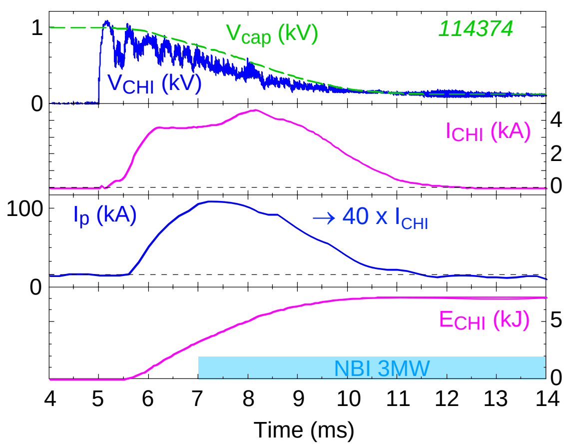
Milestones

- FY06: test & understand conditions and scenarios for flux closure via CHI injector gas puff, 2-kV, low-I_p control
- FY07: clarify low-A physics for NBI & HHFW current ramp-up
- Extensive analysis: TSC, EFIT-J_{SOL}, LRDIAG, DINA

Additional investigations

- Extend HHFW initiation with ECH preionization
- Collaborate with MAST; proposal to JET (LH-initiation)





4) Start-up, Ramp-up and Sustainment: Physical processes of magnetic flux generation and reconnection

FY05 (17 wks)	FY06 (12 wks)	FY07 (12 wks)
	Assess CHI creation of closed magnetic flux	Test solenoid-free ramp-up

Boundary Physics Studies Aim to Understand Pedestal-SOL Science of Long-Pulse High-P/R Plasmas

Motivation & NSTX Opportunities

- Priority Panel (T10); enhance progress to predict H-mode pedestal with high confidence; ITPA priority
- Low A: $B_p/B_T \sim 1$, large B_{in}/B_{out} & ρ^*, P/R $\rightarrow$ 15 MW/m
- New tools: Li pellets/coating, supersonic gas jet, better TS

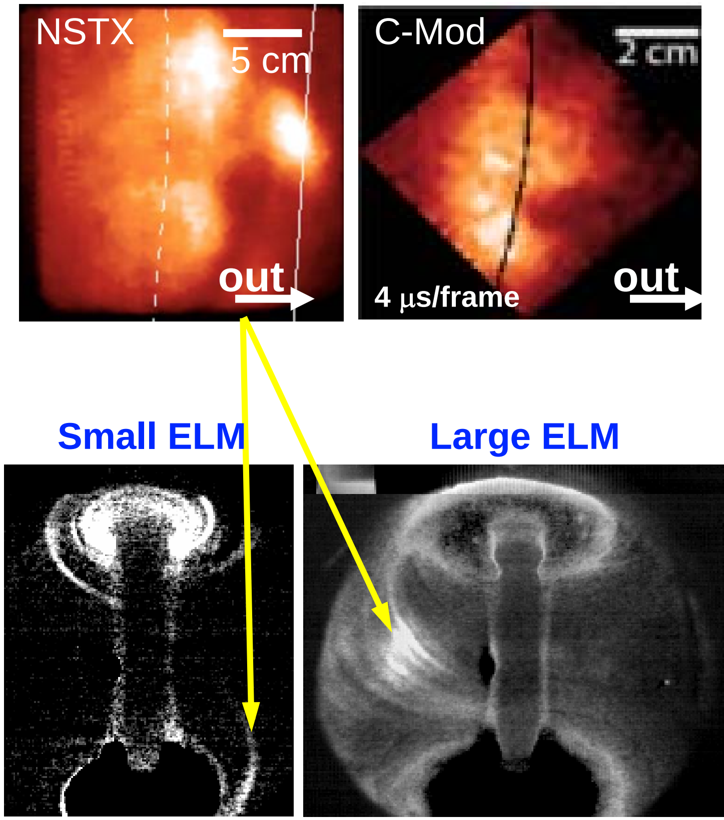
Milestones

- FY05: document detail of pedestal-SOL properties and dynamics
- Successful GPI adopted by several experiments
- "Blobs" linked to ELMs; "peeling" or shear Alfvén?
- FY07: document Li coating effects on recycling and core plasma; database for advanced particle control
- Extensive analysis: BOUT, ELITE, UEDGE, DEGAS2

Additional Investigations

- Pedestal similarity, small ELM comparison, "blob" characteristics comparison, with MAST, DIII-D, C-Mod

Gas Puff Imagnig (GPI)



5) Boundary Physics: Interface between fusion plasmas and normal temperature surroundings

Characterize pedestal and SOL of low-A, H-mode, high P/R plasmas

Characterize Li pellet & evaporator coating effectiveness

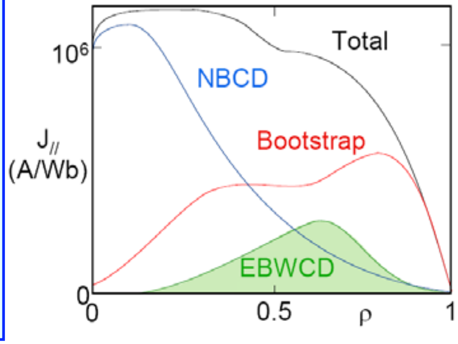
FY05 (17 wks)	FY06 (12 wks)	FY07 (12 wks)

Integrated Scenario Studies Contribute to Understanding of Self-Organization and External Control

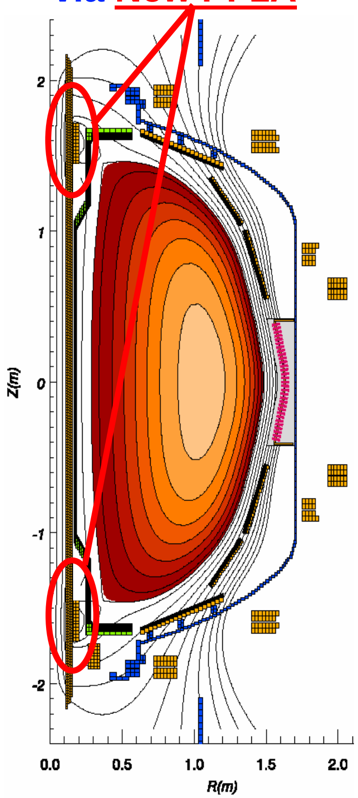
NSTX

- **Motivation & NSTX Opportunities**
  - Priority Panel (T3): integrated understanding of self-organization & external control, enabling high-pressure sustained plasmas; ITER "hybrid" mode
  - High β & low A: clarify B/S vs. CD
  - Clarify future EBW and particle control needs
- **Milestones**
  - FY05: document and understand physics interplay of attractive, low-V_L, NBI plasmas
  - FY06: benchmark simulation models & codes
  - Identify needed "actuators" & model improvements
  - Future: determine conditions for surface $V_L = 0$ long-pulse operation, though q_0 may evolve
- **Additional Investigations**
  - Contribute to mapping of ITER/NSTX hybrid scenario, accounting for *AE effects

I_p = 1 MA
$\kappa = 2.7$; $\delta = 0.9$
P_{NBI} = 4 MW
P_{HHFW} = 3 MW
P_{EBW} = 3 MW
$\langle n_e \rangle = 2.7 \times 10^{19} m^{-3}$
$H_{98y2} = 1.5$
$\beta_T = 41\%$; $\beta_N = 8.9$
Stable n = 1,2,3 & ∞



High-Performance Sustained Plasma via New PF1A



6) Physics Integration: Synergistic effects of external control and self-organization

Characterize high-B/S & low-V_L plasmas for > τ_{skin}

Benchmark time-dependent scenario simulation with data

FY05 (17 wks)	FY06 (12 wks)	FY07 (12 wks)

NSTX Participates Strongly in ITPA Topical Groups and is Committed to Important 2005 Joint Experiments

Topical Groups	ID#	Burning Plasma Issues	Participating Programs
Confinement Database & Modeling	CDB-2	β degradation in confinement scaling of ELMy H-modes	AUG, DIII-D, JET, JT-60U, MAST, NSTX, Tore-Supra
	CDB-6	Improving condition of global ELMy H-mode and pedestal database: low A	DIII-D, MAST, NSTX
Transport Physics	TP-8.1	ITB similarity experiments	MAST, NSTX
	TP-9	H-mode aspect ratio comparison	DIII-D, MAST, NSTX
Pedestal & Edge Physics	PEP-9	Pedestal similarity experiments	DIII-D, MAST, NSTX
	PEP-16	Small ELM regime comparison	C-Mod, MAST, NSTX
Divertor, SOL	DSOL-9	Carbon migration and deposition	AUG, DIII-D, JET, JT-60U, NSTX, TEXTOR
	DSOL-15	Comparison of edge “blob” characteristics	C-Mod, JT-60U, NSTX, TJ-II, Tore-Supra
MHD, Disruption Control	MDC-2	Resistive Wall Mode physics	AUG, DIII-D, JET, JT-60U, NSTX, TEXTOR
	MDC-4	Neoclassical Tearing Mode – A comparison	AUG, DIII-D, MAST, NSTX
	MDC-6	Error field physics comparison	C-Mod, DIII-D, JET, MAST NSTX, TEXTOR
	MDC-9	Fast-ion redistribution by *AE & cascade	AUG, DIII-D, JET, JT-60U, NSTX
Steady-State Op	SSO-2.1	Complete mapping of hybrid scenario	AUG, DIII-D, JET, JT-60U, NSTX

Case-1 Impact Will Be Severe – National Research Team will Strive to Make Important Contributions

NSTX

- FY06 milestones delayed to FY07 (12 run-weeks).
- Three code and tool benchmark milestones for FY06:
  - *Compare EF/LM/RWM data with models of stability conditions.*
  - *Compare fast ion driven mode data with non-linear simulation.*
  - *Benchmark time-dependent scenario simulation with high-B/S, low-V_L data.*
- Hold results review early in FY06; analyze data; present and publish FY05 results, expected to be extensive and important.
- Carry out ITER Physics Design Tasks using appropriate expertise.
- Enhance collaboration with MAST, DIII-D, C-Mod, etc. in critical topical areas, utilizing remote experimental participation.
- Install diagnostics and facility improvements (minimal non-labor funds) to prepare for early FY07 run.
- Hold FY07 NSTX Research Forum in FY06.

NSTX Case-3 Plan will Advance OFES Strategic Goals Effectively in Science, Burning Plasma, and Optimization

- Exciting NSTX science can be accelerated.
  - *Combine EF & RWM active feedback control earlier; perform intensive tearing mode studies.*
  - *Measure fast-ion transport due to fast-ion driven modes.*
  - *Accelerate Li coating milestone; assess long-pulse heat & particle control requirements of low-A, H-mode, high P/R plasmas.*
  - *Characterize surface $V_L = 0$ plasmas for > τ_{skin}.*
  - *Make decision on advanced particle control.*
- Can enhance participation in ITPA on critical topics.
- Rapid progress in science will be made in a broad front.
- Begin high-power EBW preparation, a key to advancing performance of high-β, high-B/S, high-confinement plasmas.

NSTX Will Advance Toroidal Plasma Science, Burning Plasma Physics, and Optimization

- Prepared three plans with progressive levels of research.
- Case-2 plan, assuming 12 run-weeks for FY06 and FY07, will
  - *Emphasize high-k turbulence and electron transport;*
  - *Advance physics of pressure-limiting modes via feedback & very strong shaping;*
  - *Make unique contributions to understanding supra-Alfvénic ion driven mode;*
  - *Contribute to understanding of magnetic flux generation and reconnection;*
  - *Understand pedestal-SOL science of long-pulse high-performance plasmas.*
- NSTX addresses key Priority Panel topics and participates strongly in ITPA 2005 Joint Experiments.
- Case-1 impact will be severe – National Team will strive to make important contributions.
- Case-3 will advance OFES Strategic Plan Effectively.

Next talk addresses Facility, Diagnostics, Budget.

Case-1 Plan (No Run in FY06, 12 Run-Weeks in FY07) Research Milestones

NSTX

	FY05	FY06	FY07	FY09
Exp. Run-Weeks:	17	0*	12*	
1) Transport & Turbulence: Physical processes that govern heat, particle and momentum confinement				
	Characterize q' & ∇T_e effects on electron transport		(1) Measure high-k turbulence	
2) Macroscopic Stability: Role of magnetic structure on plasma pressure and bootstrap current				
	Study rotating plasmas close to "wall-stability" with EF correction	(1) Compare EF/RWM/LM data with theoretical models of stability conditions	(1) Characterize effectiveness of closed-loop EF/LM control	
3) Wave-Particle Interaction: Role of electromagnetic waves & modes in sustaining and controlling hot plasmas				
	Assess effects of supra-Alfvénic ion driven instabilities on core J_{NB}	(1) Compare fast ion driven mode data with non-linear simulation	(1) Characterize & optimize HHFW coupling	
4) Start-up, Ramp-up and Sustainment: Physical processes of magnetic flux generation and reconnection				
			(1) Assess CHI creation of closed magnetic flux	
5) Boundary Physics: Interface between fusion plasmas and normal temperature surroundings				
	Characterize pedestal and SOL of low-A, H-mode, high P/R plasmas			
6) Physics Integration: Synergistic effects of external control and self-organization				
	Characterize high-B/S & low-V_L plasmas for > τ_{skin}	(1) Benchmark time-dependent scenario simulation with high-B/S & low-V_L data		

Advanced Particle Control Decision Point

***CASE-1**

Case-2 Plan (12 Run-Weeks for FY06 & FY07) Research Milestones

NSTX

	FY05	FY06	FY07	FY08
Exp. Run-Weeks:	17	+12*	12	

1) Transport & Turbulence: Physical processes that govern heat, particle and momentum confinement

FY05	FY06	FY07
Characterize q' & ∇T_e effects on electron transport	(2) Measure high-k turbulence	(2) Assess high-k turbulence spectra and electron transport

2) Macroscopic Stability: Role of magnetic structure on plasma pressure and bootstrap current

FY05	FY06	FY07
Study rotating plasmas close to "wall-stability" with EF correction	(2) Characterize effectiveness of closed-loop EF/LM control	(2) Characterize effectiveness of closed-loop RWM control

3) Wave-Particle Interaction: Role of electromagnetic waves & mdoes in sustaining and controlling hot plasmas

FY05	FY06	FY07
Assess effects of supra-Alfvénic ion driven instabilities on core J_{NB}	(2) Characterize & optimize HHFW coupling	

4) Start-up, Ramp-up and Sustainment: Physical processes of magnetic flux generation and reconnection

FY05	FY06	FY07
	(2) Assess CHI creation of closed magnetic flux	(2) Test solenoid-free ramp-up

5) Boundary Physics: Interface between fusion plasmas and normal temperature surroundings

FY05	FY06	FY07
Characterize pedestal and SOL of low-A, H-mode, high P/R plasmas		(2) Characterize Li pellet & evaporator coating effectiveness

6) Physics Integration: Synergistic effects of external control and self-organization

FY05	FY06	FY07
Characterize high-B/S & low-V_L plasmas for > τ_{skin}		

*CASE-2

(2) Advanced Particle Control Decision Point (FY08)

Case-3 Plan (17 Run-Weeks in FY06 and FY07)
Research Milestones

NSTX

	FY05	FY06	FY07	FY08
Exp. Run-Weeks:	17	12 + 5*	12 + 5*	

1) Transport & Turbulence: Physical processes that govern heat, particle & momentum confinement

FY05	FY06	FY07
Characterize q' & ∇T_e effects on electron transport	(2) Measure high-k turbulence	(2) Assess high-k turbulence spectra and electron transport

2) Macroscopic Stability: Role of magnetic structure on plasma pressure & bootstrap current

FY05	FY06	FY07
Study rotating plasmas close to "wall-stability" with EF correction	(3) Characterize effectiveness of closed-loop EF/RWM control	(3) Characterize tearing mode onset conditions & impact

3) Wave-Particle Interaction: Use of electromagnetic waves to sustain and control high-temperature plasmas

FY05	FY06	FY07
Assess effects of beam-Alfvénic ion driven instabilities on core J_{NB}	(2) Characterize & optimize HHFW coupling	(3) Measure fast-ion transport due to fast-ion driven modes

4) Start-up, Ramp-up and Sustainment: Physical processes of magnetic flux generation and reconnection

FY05	FY06	FY07
	(2) Assess CHI creation of closed magnetic flux	(2) Test solenoid-free ramp-up

5) Boundary Physics: Interface between fusion plasmas and normal temperature surroundings

FY05	FY06	FY07
Characterize pedestal and SOL of low-A, H-mode, high P/R plasmas	(3) Characterize Li pellet & evaporator coating effectiveness	(3) Assess long-pulse heat & particle control requirements of low-A, H-mode, high P/R plasmas

6) Physics Integration: Synergistic effects of external control and self-organization

FY05	FY06	FY07
Characterize high-B/S & low-surface V_L plasmas for > τ_{skin}		(3) Characterize surface V_L = 0 plasmas for > τ_{skin}

(3) Advanced Particle Control Decision Point

***CASE-3**