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NSTX Research Plan – FY03-05

NSTX research advances Configuration Optimization, Fundamental Understanding, and High Performance/Burning Plasmas

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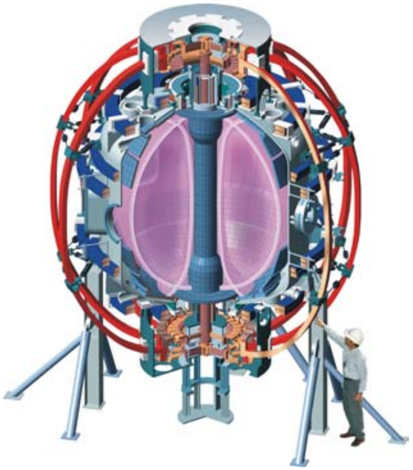
For NSTX National Research Team



Budget Planning Meeting – FY 2005
Office of Fusion Energy Sciences
Department of Energy

March 18-19, 2003
Gaithersburg, Maryland

Columbia U
Comp-X
GA
INEL
JHU
LANL
LLNL
Lodestar
MIT
Nova Photonics
NYU
ORNL
PPPL
PSI
SNL
UC Davis
UC Irvine
UCLA
UCSD
U Maryland
U New Mexico
U Wash
U Wisc
UKAEA Fusion
Hiroshima U
HIST
Kyushu Tokai U
Niigata U
Tsukuba U
U Tokyo
Frascati, ENEA
Ioffe Inst
TRINITI
KBSI
KAIST

U.S. Collaborative NSTX Team members make crucial contributions

Institution	Research Topic
Columbia U	• MHD stability & mode control • Stellar x-ray spectroscopy*
GA	• CHI equilibrium, RF physics • Plasma control
LANL	• Visible and infrared imaging • Ultra-fast turbulence imaging • CHI plasma stability modeling
Lodestar	• Edge plasma stability and turbulence
Nova Photonics	• MSE – CIF & LIF* • Ultra-fast imaging (~10^6 /s)*
NYU	• Transport & RF modeling*
PSI	• Ultrafast imaging (~10^6 /s)*
UC Davis	• FIReTIP & fluctuations
UCSD	• Fast probe, HHFW modeling • Far SOL turbulent transport
U. Washington	• CHI research
U Wisconsin	• NSTX neoclassical modeling

Institution	Research Topic
Comp-X	• CQL-3D kinetic modeling of RF heating & current drive
INEL	• Tile surface & dust analysis*
Johns Hopkins U	• USXR tomography & diagnostics
LLNL	• Edge SOL modeling • Edge plasma turbulence • Stellar x-ray spectroscopy*
MIT	• ECW-EBW modeling • HHFW modeling
ORNL	• RF launcher & experiments • ECH-EBW launcher & exp. • Edge exp.; transport modeling
SNL	• Plasma-facing material* • Material surface analysis*
UCLA	• Reflectometry & fluctuations
U Maryland	• Transport & turbulence sim.*
U New Mexico	• Fast ion-plasma interactions

* Research cooperation funded by Theory, Technology, Diagnostic Innovations, SBIR, Plasma Science Programs

NSTX has advanced far into the new PoP ST physics regime, thanks to the available tools & capabilities

Transport & Turbulence	• NBI: $H_{97L} \rightarrow 2.7$ (L and H-mode); $H_{98y,2} \rightarrow 1.5$ (sustained) • NBI: $\chi_i < \chi_{neo}$, $\chi_e >> \chi_i$, $T_i \sim 2T_e$, stiff T_e with strong V_ϕ & V_ϕ shear • HHFW: $H_{97L} \sim 1$, T_e-profile modified – electron ITB ($T_e \rightarrow 3.7$ keV)
MHD	• $\beta_T \rightarrow 35\%$; $\beta_N \rightarrow 6$; $\beta_p \rightarrow A$; $\beta_N \rightarrow 10\ell_i$ • RWM: $\beta \rightarrow 1.3\ \beta_{no\text{-}wall}$ for $> 20\tau_{wall}$, coupled to V_ϕ and nearby conductors • $V_\phi/V_{Alfvén} \sim 0.3$, n_e asymmetry measured consistent with theory • Revealing features in fast ion driven modes: TAE, CAE, etc.
Startup & Sustainment	• HIT-II converted I_{CHI} to I_{OH}; NSTX CHI absorber improved for testing • First indication consistent with HHFW current drive expectations • V_L reduced to ~ 0.1 – 0.2 V via large bootstrap current (NBI, HHFW) • $\beta_T \rightarrow 17\%$, $\beta_N \rightarrow 5$, $\beta_p \rightarrow A$, $f_{BS} \sim 0.5$, $V_L \sim 0.1$ V, for $> \tau_{skin}$ & in 1-s pulse
Boundary Physics	• Gas Puff Imaging & scanning probe: intermittent filamentary blobs • Verified inboard SOL flux tube expansion due to low A
Integrated Scenarios	• $\beta_T \sim 35\%$, $\beta_N \sim 5.4$, $H_{89P} \sim 1.5$ simultaneously sustained for $\geq \tau_E$ • TRANSP, TSC, M3D, RF codes, etc. used in NSTX research

NSTX research milestones have been organized to carry out and support 3 of the 4 IPPA MFE Thrusts

Fundamental Understanding (IPPA 3.1)

Advance understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through comparison of well-diagnosed experiments, theory and simulation.

Configuration Optimization (IPPA 3.2)

Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems by investigating a broad range of innovative magnetic confinement configurations.

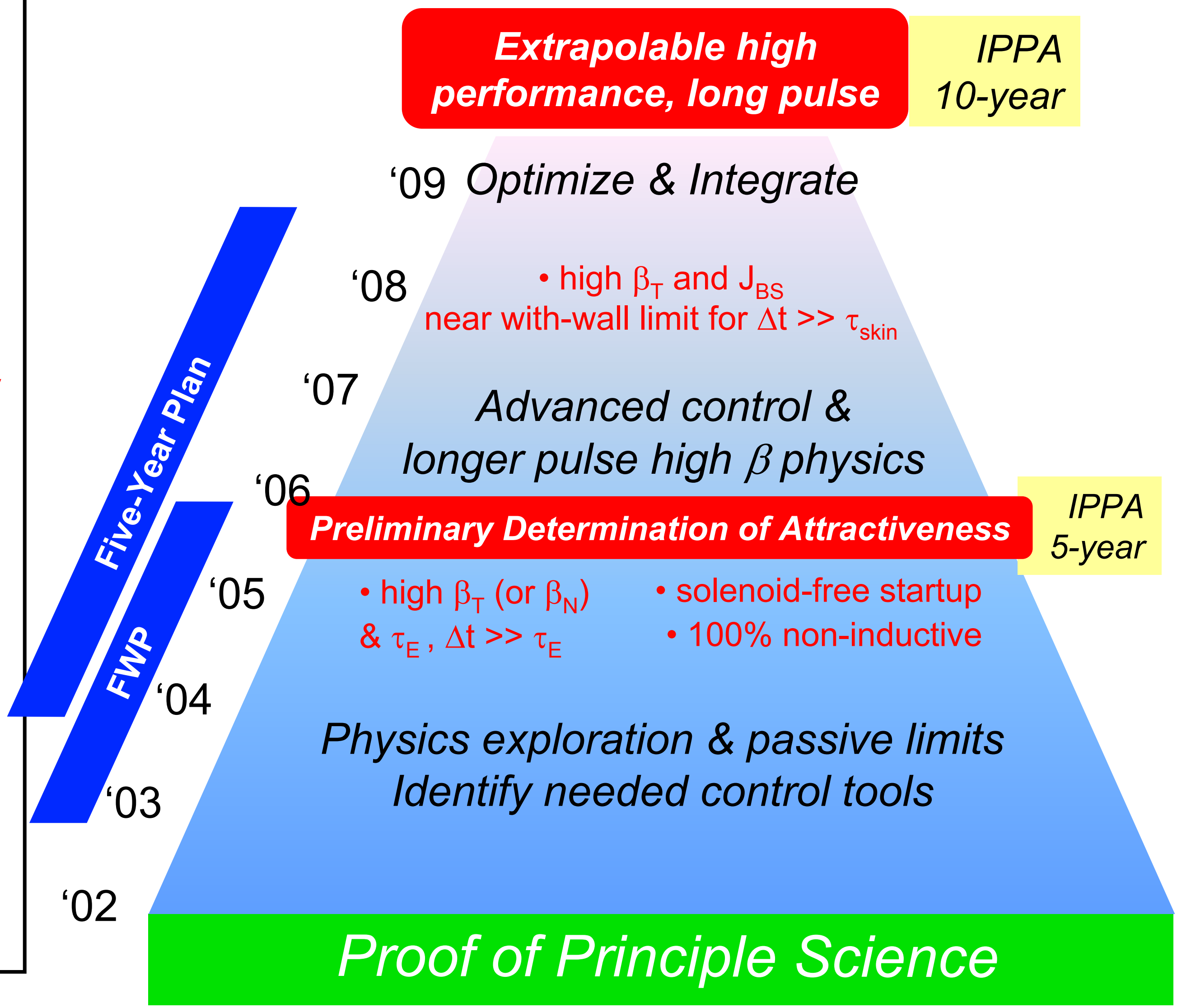
High-Performance/Burning Plasmas (IPPA 3.3)

Advance understanding and innovation in high-performance plasmas, optimizing for projected power-plant requirement; and participate in a burning plasma experiment.

- A set of ***Implementation Approaches*** was determined by the IPPA to meet the 5-year Objectives of these thrusts.
- NSTX research milestones are organized to address them.

Research planned for FY03-05 aims to achieve the initial goals of the NSTX 5-year plan

- **5-year plan (FY04-08)**
  - Establish physics basis for optimization and integration of extrapolable high performance & long pulse
- **FY03-05 plan**
  - Complete preliminary determination of ST attractiveness
- **Both**
  - Advance control tools
  - Implement key measurements
  - Carry out supporting analyses
  - Extend pulse lengths and key parameters



NSTX research address IPPA Thrust 5-year objectives through the ST Implementation Approaches (3.2.1.1–7)

	FY02	FY03	FY04	FY05	FY06
Exp. Runwks:	13	4 / Fix TFC	21	21	5-year "Checkpoint"

Objective	FY02	FY03	FY04	FY05
3.2.1.1. Achieve efficient heat and particle confinement (3.1.1. Transport & Turbulence)	Assess effects of high β & flow on χ		Measure low-k turbulence	Measure hi-k turbulence
3.2.1.2. Verify stability of large-scale MHD perturbations (3.1.2. Macro Stability; 3.3.2. Hi-β Stability & Disruption)	Study MHD modes without feedback	Assess plasma & rotation interactions		Study plasmas near "with-wall" limit
3.2.1.3. Heat high-beta over-dense plasmas & *drive current* (3.1.3. Wave-Particle Interactions; 3.3.3. Burning Plasmas)	Test HHFW CD efficiency	Characterize EBW emission, est. H&CD →	Measure ΔJ from RF, NBI & ∇p	Demonstrate J_{NI} = 100%
3.2.1.4. Test plasma startup & *sustainment* with noninductive techniques (3.1.3. Wave-Particle Interactions)	Test CHI startup	Extend & analyze sustainment to 1s	Test current initiation	
3.2.1.5. Disperse edge heat flux at acceptable levels (3.1.4. Plasma Boundary Physics)		Analyze edge heat fluxes		Characterize edge of H-mode plasmas
3.2.1.6. Integrate high confinement and high beta (3.3.1. Profile Control)		Characterize high β_T & τ_E for > τ_E	Assess hi τ_E & hi β_T H-mode for >> τ_E	Assess combined RF & NBI effectiveness

3.2.1.7. Explore spherical torus issues in directed laboratory experiments (3.1.5. General Plasma Science)

Pegasus, HIT-II, CDX-U – explore new ST parameter space & technologies

MAST collaboration – EBW H&CD, boundary physics, confinement scaling, H-Mode and ELM physics

New capabilities are planned to unravel the exciting science behind transport & turbulence surprises

NSTX

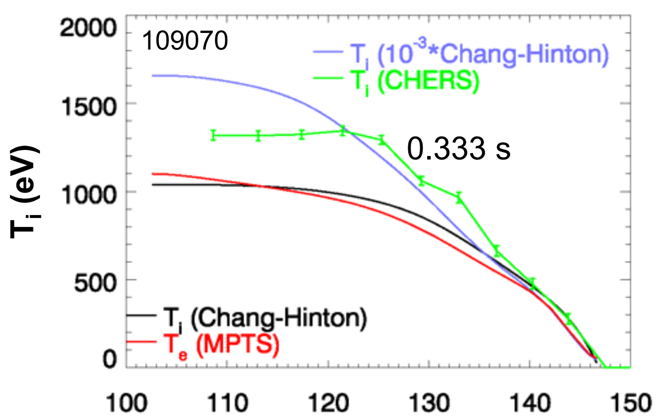
FY02	FY03	FY04	FY05

3.2.1.1. Achieve efficient heat and particle confinement (3.1.1. Transport & Turbulence)

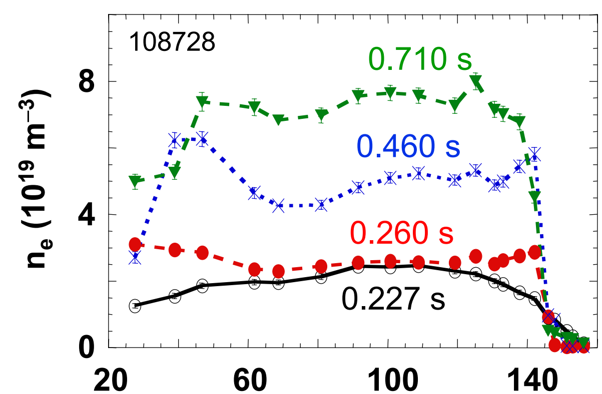
Assess effects of high β & flow on χ		Measure low-k turbulence	Measure hi-k turbulence

- **Mystery: $\chi_i < \chi_{Neo}$ in L and H-modes**
  - NBI: $\chi_e >> \chi_i$ with $T_e \sim T_i/2$
  - HHFW: $T_e \sim 2\ T_i$ with electron ITB
- **Key new effects to study**
  - Large 1/A, β, β', ρ^*, V_ϕ (~0.3$V_{Alfvén}$), V_ϕ'
  - Emerging electromagnetic turbulence
- **Measure low-k and hi-k turbulence**
  - Help solve χ_i mystery
  - Excellent lab plasma to study χ_e
- **Tooling up:**
  - Low-k: reflectometry with/without imaging, laser interferometry, probe
  - High-k: μw scattering (300, 900 GHz)
  - More & faster CHERS-spectroscopy
  - Simulation: GS2, GTC, GYRO

Observed Great Ion Confinement



in H-mode Plasma Core



MHD studies aim to develop an understanding of the physics of β limiting modes to enable very high β_T, β_N & β_p

NSTX

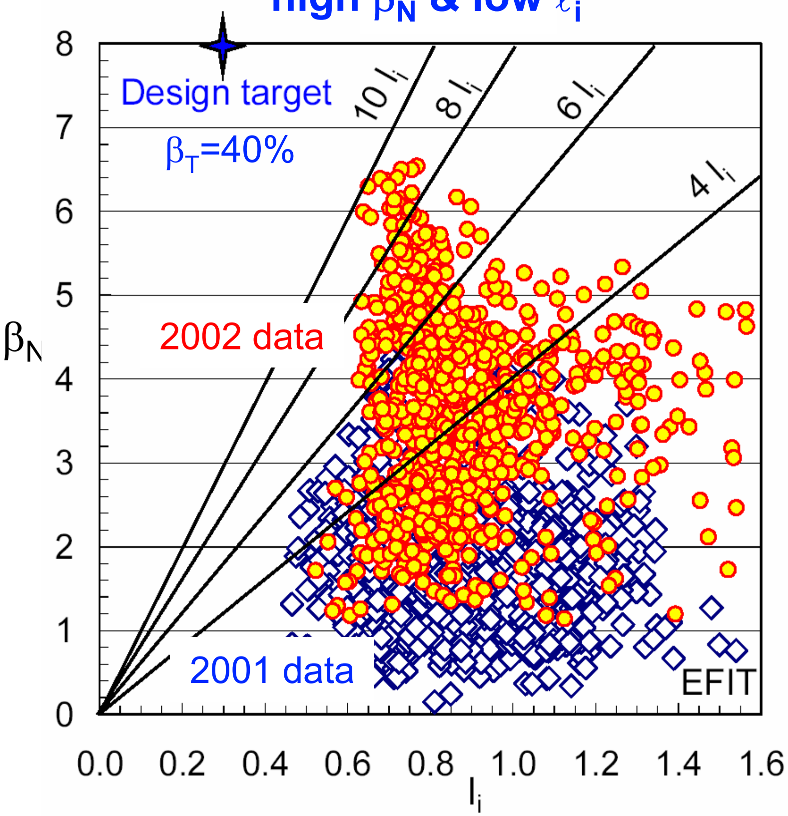
FY02	FY03	FY04	FY05

3.2.1.2. Verify stability of large-scale MHD perturbations (3.1.2. Macro Stability; 3.3.2. Hi-β Stability & Disruption; 3.3.3. Burning Plasmas)

Study MHD modes without feedback — **Assess plasma & rotation interactions** — **Study plasmas near "with-wall" limit**

- **Much expanded stability space in FY02-03**
  - >10× reduced resonant field error → ~1%
  - RWM exceeded "no-wall" limit for > τ_{wall}
  - Benefits of κ, δ, ℓ_i, V_ϕ and plasma control?
  - Field error reduced further, β_T up 15%
- **New tools for FY04**
  - Commission in-vessel mode sensors
  - Install ex-vessel RFC coils
- **Test integration with high τ_E in FY04**
  - Determine in-vessel RFC requirements
  - Prepare tests of "with-wall" limits in FY05
- **Resolve NTM, locked mode questions**
  - Avoid via high q_0 (q_{min}), κ, δ, low ℓ_i?
  - Determine RFC control requirements
- **Continue ELM, fast ion-MHD studies**

Rapid Progress toward high β_N & low ℓ_i



HHFW is being explored as a unique tool for electron heating, current drive, and confinement studies

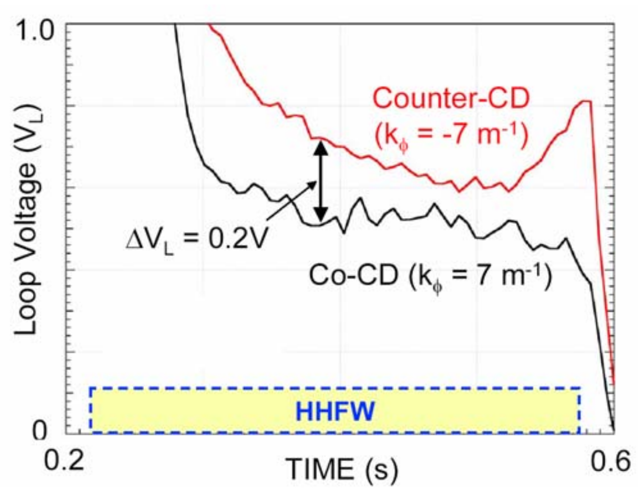
FY02	FY03	FY04	FY05

3.2.1.3. Heat high-beta over-dense plasmas & *drive current* (3.1.3. Wave-Particle Interactions; 3.3.3. Burning Plasmas)

FY02	FY03	FY04	FY05
Test HHFW CD efficiency		Measure ΔJ from RF, NBI & ∇p	Demonstrate J_{NI} = 100%
		Characterize EBW emission, est. H&CD	

- **Heats electrons effectively; CD suggested by V_L**
- **Verified predicted interactions with NBI ions**
  - Important step toward HHFW + NBI scenarios
- **Prepare for ΔJ measurements in FY04**
  - Commission multi-chord MSE CIF
  - CHERS, edge spectroscopy help resolve E_r, B_p
  - FIReTIP contributes; J_{NI} = 100% demo in FY05
- **HHFW tooling up**
  - Feed-through & reliability improved for → 6 MW
  - Fault detection, new center-fed strap in FY05
- **RF Modeling & SciDAC**
  - Improve ion heating model in ray vs. full-wave
  - Apply SciDAC full-wave 3D codes

Encouraging CD Indications



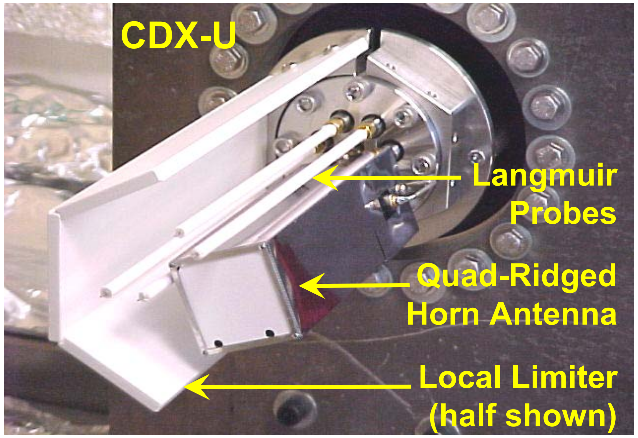
EBW studies will test the basis for local H&CD, NTM control, and initiation in over-dense ST plasmas

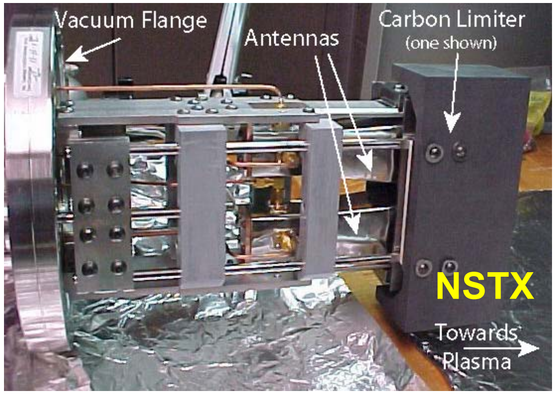
NSTX

FY02	FY03	FY04	FY05
3.2.1.3. Heat high-beta over-dense plasmas & *drive current* (3.1.3. Wave-Particle Interactions; 3.3.3. Burning Plasmas)			
Test HHFW CD efficiency	Characterize EBW emission, est. H&CD →	Measure ΔJ from RF, NBI & ∇p	Demonstrate J_{NI} = 100%

- **Encouraging EBW results**
  - Emission measured in CDX-U, NSTX, MAST, etc., consistent with theory
  - H&CD: W-7AS, COMPASS-D successful
  - Localized H&CD profiles predicted
  - Fast $T_e(R,t)$ measurement (Adv. Diag.)
- **Much preparation needed**
  - Collaboration on MAST (60 GHz, 1 MW)
  - Complete GENRAY-CQL3D scoping
  - Emission studies on NSTX in early FY04
  - Develop launch and H&CD scenarios
- **1-MW EBW at ~ 15 GHz in FY06!**
  - Working with VLT to procure in FY05

EBW Receivers: CDX-U → NSTX





Innovative noninductive startup and sustainment has made progress – very important to ST development

NSTX

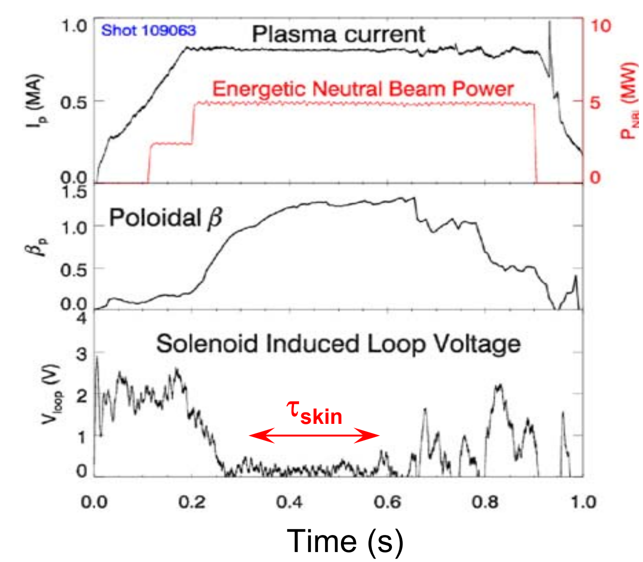
FY02	FY03	FY04	FY05

3.2.1.4. Test plasma startup & *sustainment* with noninductive techniques (3.1.3. Wave-Particle Interactions)

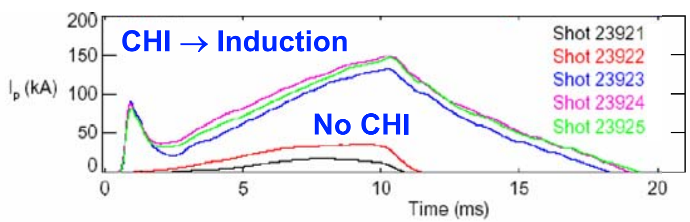
Test CHI startup	Extend & analyze sustainment to 1s	Test current initiation	

- **Long-pulse (~1s) H-mode results so far**
  - NBI (5-6 MW): 0.8 MA, $\varepsilon\beta_p \leq 1$, $V_L \sim 0.1$ V
  - HHFW (3 MW): 0.4 MA, $\beta_p \leq 1$, $V_L \sim 0.2$ V
  - Extensive analysis in FY03; startup delayed
- **Test solenoid-free initiation in FY04-05**
  - Encouraged by existing results
  - **HIT-II**: CHI → Induction → add HHFW
  - **MAST, JT-60U**: VF flux
  - **CDX-U, TST-2**: tested ECH-EBW initiation
  - **MAST**: collaboration (~1MW, 60 GHz)
- **Analysis:**
  - TSC, P-TRANSP, EFIT-J_{SOL}, 3D MHD
- **Full EBW tests planned**
  - 1 MW in FY06; up to 3 MW by FY08

NBI Nearly Enabled Full Sustainment

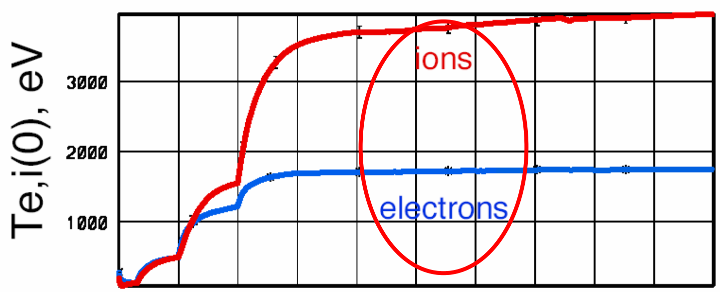


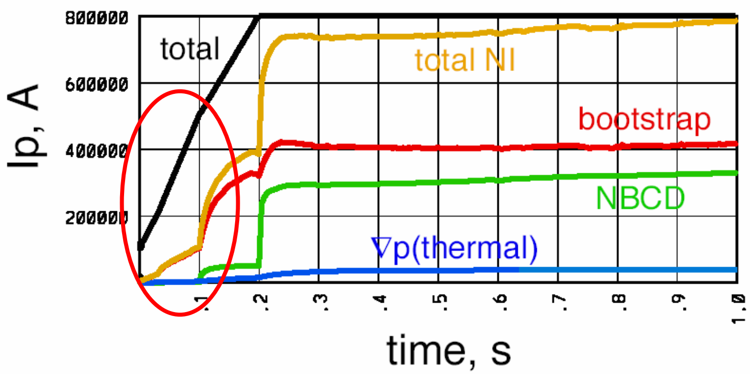
CHI Plasma Was "Captured" in HIT-II

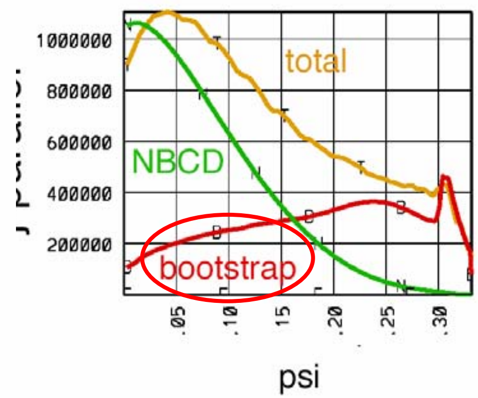


Simulations of J_{NI} = 100% plasmas identify scenarios and motivate important NSTX research topics

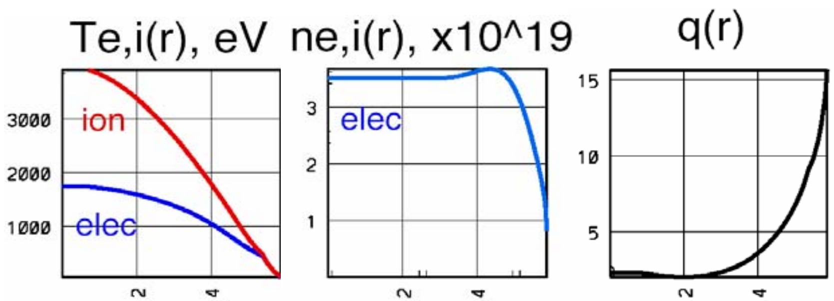
Identified Scenarios to Achieve Long Pulse Sustainment







Assume #109070 plus χ_e, $\chi_i \propto P^{-0.5}$:
κ = 2.6, $H_{98(y,2)}$ = 1.1,
β_N = 7.0, β_T = 20%,
Stable to n = 1 & ∞

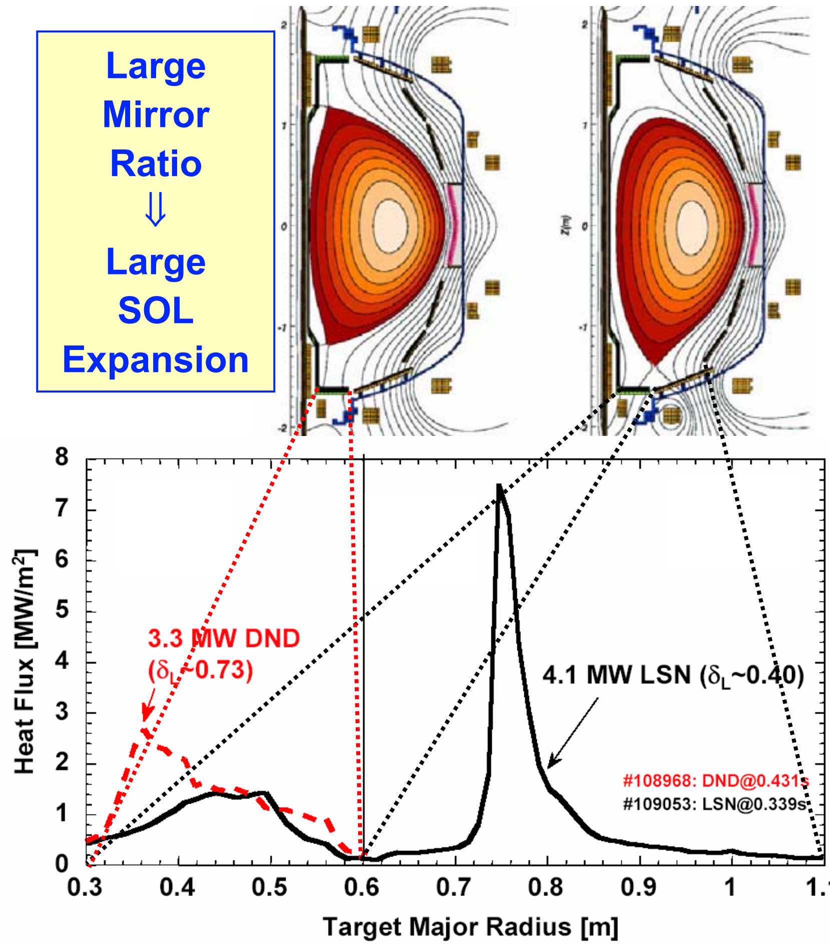


- **ST research topics**
  - Bootstrap J at low A
  - HHFW heating in presence of NBI
  - Scaling of χ_e, χ_i with $T_i >> T_e$
  - Effects of large V_ϕ and V_ϕ shear on stability & transport
- **Scenario elements**
  - CHI or EBW I_p initiation
  - Non-inductive I_p ramp-up
  - Active particle control
- **Relevance: sustained D-T ST plasmas**

Boundary physics studies aim to test and develop solutions for high performance NSTX plasmas

FY02	FY03	FY04	FY05
3.2.1.5. Disperse edge heat flux at acceptable levels (3.1.4. Plasma Boundary Physics)			
	Analyze edge heat fluxes		Characterize edge of H-mode plasmas

- **Study low A effects on SOL in FY03**
  - Mirror ratio increases flux expansion
  - Edge turbulence minimal in H-mode
  - Analyze and compare with modeling
  - Design impact assessment delayed
- **Support integrated high performance plasma tests in FY04**
- **Characterize H-mode edge in FY05**
  - Several types of H-mode observed
  - L-H threshold results to shed new light
- **New tools**
  - Supersonic gas jet, lithium pellets
  - New fast probe head for kinetics & fluctuations
  - D2 pellets, cryo-pump?



Confinement and stability integration studies aim to test synergy among special ST properties

NSTX

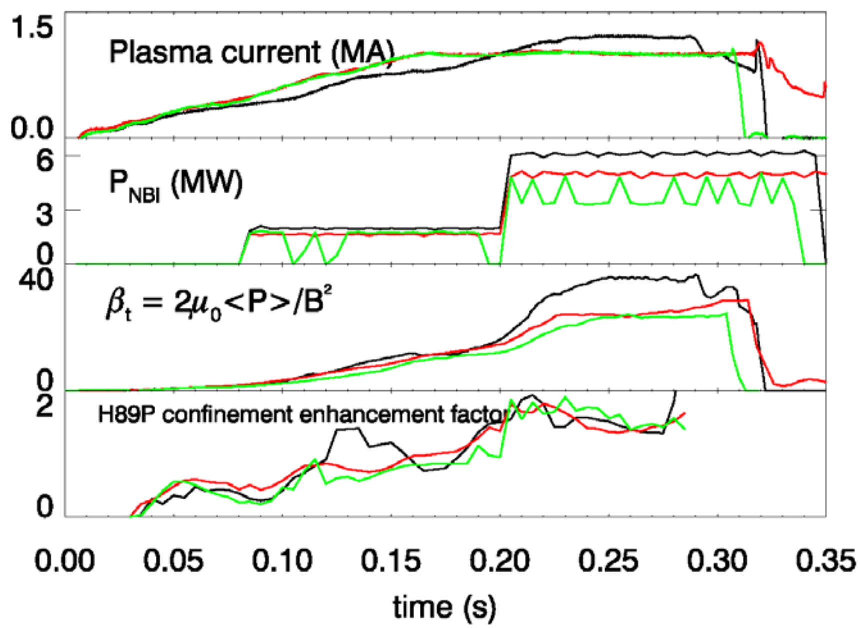
	FY02	FY03	FY04	FY05
3.2.1.6. Integrate high confinement and high beta (3.3.1. Profile Control)		Characterize high β_T & τ_E for > τ_E	Assess hi τ_E & hi β_T H-mode for >> τ_E	Assess combined RF & NBI effectiveness

- **Achieved simultaneous high τ_E and β_T <u>without feedback</u> for > τ_E in FY02-03**
- **Extended test in FY04**
  - H-mode for $\Delta\tau$ >> τ_E
  - Improved density source and sinks
  - Ex-vessel RFC-coils and large V_ϕ to avoid or suppress RWM
- **Extensive tools & measurements**
  - NBI, HHFW, wall, plasma control
  - Mode δ**B** sensors, USXR arrays
  - Fast calculation of β vs. $\beta_{no\text{-}wall}$
  - Feedback on ($\beta - \beta_{no\text{-}wall}$)
- **Test HHFW-NBI integration in FY05**
  - Required for further flat-top extension
  - Test HHFW as reliable tool

Important Progress in β-τ Integration

I_p = 1 – 1.2 MA, P_{NBI} = 4 – 6 MW,

β_T = 25 – 35%, H_{89P} ~ 1.5, $\Delta\tau \geq \tau_E$

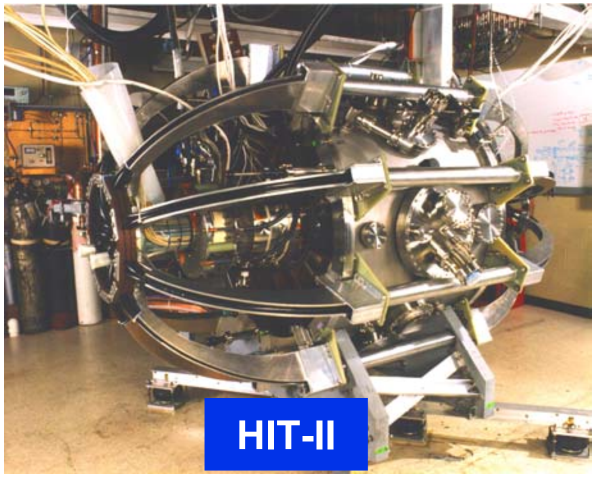


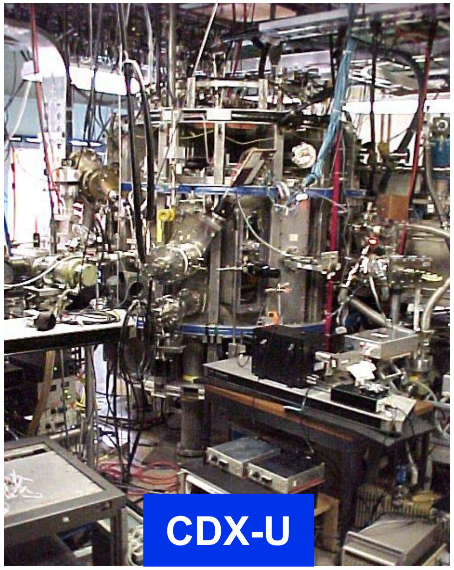
Pegasus, HIT-II (HIT-SI) and CDX-U plans to explore new ST parameter space and technologies

NSTX

3.2.1.7. Explore spherical torus issues in directed laboratory experiments (3.1.5. General Plasma Science)
Pegasus, HIT-II, CDX-U – explore new ST parameter space & enabling technologies

- **Pegasus plans**
  - MHD stability as R/a $\rightarrow$ 1
  - EBW physics in very over-dense plasmas
  - Physics connections with Spheromak
- **HIT-II (HIT-SI) plans**
  - Steady helicity injection
  - Explore NSTX CHI improvements ideas
- **CDX-U plans**
  - Lithium surface-plasma interactions
  - Support development of Liquid-Surface Module for NSTX in collaboration with VLT

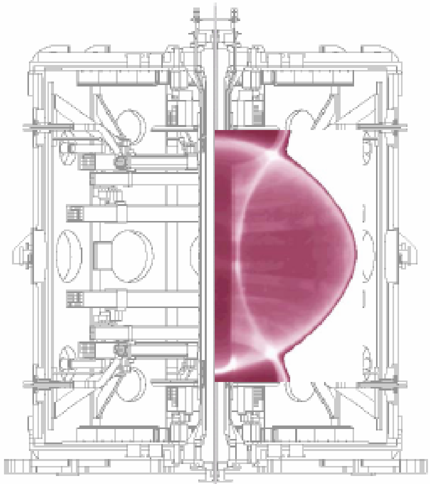




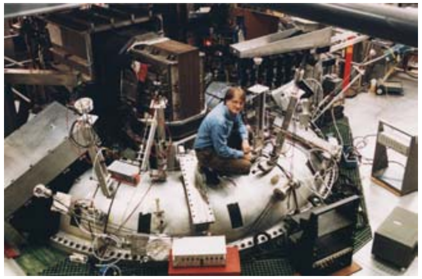
ST physics relevance to IPPA thrusts (including Burning Plasmas) has led to broadened collaborations

- **Merging database with MAST, U.K.**
  – NBI H-mode, transport, τ_E
  – EBW H&CD (1 MW, 60 GHz), FY03
  – Divertor heat flux studies, FY03-04
  – NTM, ELM characterization
- **Exploratory ST's in Japan**
  – **TST-2**: ECW-EBW initiation
  – **TS-3,4**: FRC-like β~1 ST plasmas
  – **HIST**: helicity injection physics
  – **LATE**: solenoid-free physics
- **MST:** electromagnetic turbulence, EBW
- **Began participation in ITPA (ITER)**
  – A and β effects: H-mode, ITB, ELM's & pedestal, SOL, RWM, and NTM
- **DIII-D & C-Mod collaboration**
  – Joint experiments on RWM, Fast ion MHD, pedestal, core confinement, edge turbulence

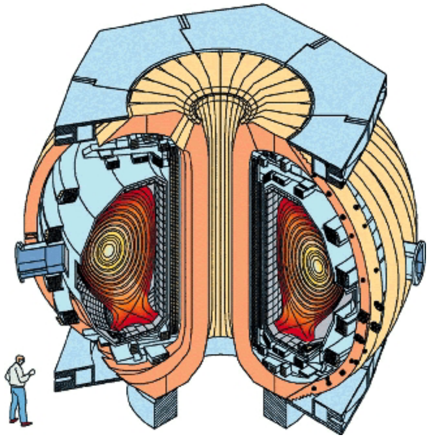
MAST (U.K.)



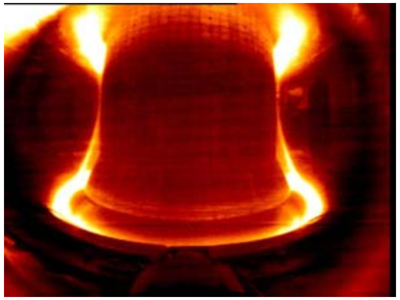
MST (U.S.)



DIII-D (U.S.)



C-Mod (U.S.)



NSTX research advances Configuration Optimization, Fundamental Understanding, and High Performance/Burning Plasmas

- Growing contributions by National Research Team to
  - Configuration Optimization
  - Fundamental Science
  - Through ITPA - High-Performance/Burning Plasmas
- Results advanced far into new PoP physics regimes
  - Max β_T = 35%; β_N = 6.7 %•m•T/MA (~ $10\ell_i$)
  - High H-factors relative to ITER confinement scalings
  - $V_\phi/V_{Alfvén}$ ~ 0.3 and large V_ϕ shear
  - Progress toward J_{NI} = 100%, V_L ~ 0.1 V for > τ_{skin}
- Organized to address IPPA Implementation Approaches & objectives; milestones determined for FY03-05.
- Growing international ST & Tokamak research cooperation

Next: Ono – NSTX Operation and Upgrade Plans