Supported by

NSTX Research Plan – FY02-04

NSTX proposes to accelerate research in FY03-04 to meet the FESAC 5-year Objective on ST

Martin Peng
Oak Ridge National Laboratory, UT-Battelle, LLC
For NSTX National Research Team

Budget Planning Meeting – FY 2004
Office of Fusion Energy Sciences
Department of Energy

March 12-13, 2002
Gaithersburg, Maryland

NSTX National Research Team & International Cooperation

Princeton Plasma Physics Laboratory: M. Ono, E. Synakowski, S. Kaye, M. Bell, R. E. Bell, S. Bernabei, M. Bitter, C. Bourdelle, R. Budny, D. Darrow, P. Efthimion, J. Foley, G. Fu, D. Gates, L. Grisham, N. Gorelenkov, R. Kaita, H. Kugel, K. Hill, J. Hosea, H. Ji, S. Jardin, D. Johnson, B. LeBlanc, Z. Lin, R. Majeski, J. Manickam, E. Mazzucato, S. Medley, J. Menard, D. Mueller, M. Okabayashi, H. Park, S. Paul, C.K. Phillips, N. Pomphrey, M. Redi, G. Rewoldt, A. Rosenberg, C. Skinner, V. Soukhanovskii, D. Stotler, B. Stratton, H. Takahashi, G. Taylor, R. White, J. Wilson, M. Yamada, S. Zweben **(CDX-U Cooperation)**

Oak Ridge National Laboratory: M. Peng, R. Maingi, C. Bush, T. Bigelow, S. Hirshman,* W. Houlberg, M. Menon,* D. Rasmussen,* P. Mioduszewski, P. Ryan, P. Strand, D. Swain, J. Wilgen

University of Washington: R. Raman, T. Jarboe, B. A. Nelson, A. Redd, D. Orvis, E. Ewig **(HIT-II Cooperation)**

Columbia University: S. Sabbagh, F. Paoletti, J. Bialek, G. Navratil, W. Zhu

General Atomics: J. Ferron, R. Pinsker, M. Schaffer, L. Lao, B. Penaflor, D. Piglowski **(DIII-D Cooperation)**

Johns Hopkins University: D. Stutman, M. Finkenthal, B. Blagojevic, R. Vero

Los Alamos National Laboratory: G. Wurden, R. Maqueda, A. Glasser*; ***Nova Photonics:*** F. Levinton

Lawrence Livermore National Laboratory: G. Porter, M. Rensink, X. Xu, P. Beiersdorfer,* G. Brown*

UC San Diego: T. Mau, J. Boedo, S. Luckhardt, A. Pigarov,* S. Krasheninnikov*

UC Davis: N. Luhmann, K. Lee, B. Deng, B. Nathan, H. Lu; ***UC Los Angeles:*** S. Kubota, T. Peebles, M. Gilmore

Massachusetts Institute of Technology: A. Bers, P. Bonoli, A. Ram, J. Egedal* **(C-Mod Cooperation)**

UC Irvine: W. Heidbrink; ***Sandia National Laboratory:*** M. Ulrickson,* R. Nygren,* W. Wampler*

Princeton Scientific Instruments: J. Lowrance,* S. von Goeler*; ***CompX:*** R. Harvey; ***Lodestar:*** J. Myra, D. D'Ippolito;

NYU: C. Cheng*; ***University of Maryland:*** W. Dorland*; ***Dartmouth University:*** B. Rogers*

U.K., Culham Fusion Center: A. Sykes, B. Lloyd, P. Carolan, R. Akers, G. Voss, H. Wilson **(MAST Cooperation)**

JAPAN, Univ. Tokyo: Y. Takase, H. Hayashiya, Y. Ono, S. Shiraiwa; ***Kyushu Tokai Univ.:*** O. Mitarai; ***Himeji Inst of Science & Technology:*** M. Nagata; ***Hiroshima Univ.***: N. Nishino; ***Niigata Univ.:*** A. Ishida; ***Tsukuba Univ.:*** T. Tamano **(TST-2, HIST, TS-3, TS-4 Cooperation)**

Russian Federation, Ioffe Inst.: V. Gusev, A. Detch, E. Mukhin, M. Petrov, Y. Petrov, N. Sakharov, S. Tolstyakov, Dyachenko, A. Alexeev; ***TRINITI:*** S. Mirnov, I. Semenov **(Globus-M Cooperation)**

Korea, KBSI: N. Na **(K-Star Cooperation)**

*In cooperation with DOE OFES Theory, OFES Technology, Astrophysics, or SBIR programs

U.S. Collaborative Team members make crucial contributions

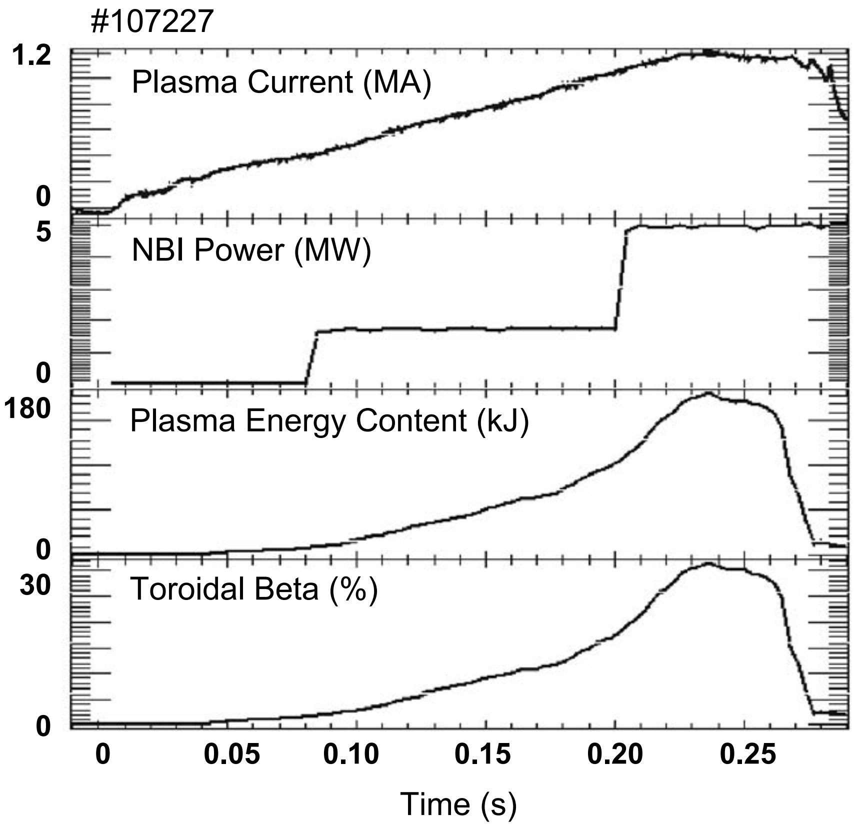
Institution	Research Topic	Institution	Research Topic
Columbia U	• MHD stability • Stellar x-ray spectroscopy*	GA	• CHI equilibrium, RF physics • Plasma control
Johns Hopkins U	• USXR diagnostics	LANL	• Visible and infrared imaging • MHD stability modeling*
LLNL	• Edge SOL modeling • Edge plasma turbulence • Stellar x-ray spectroscopy*	Lodestar	• Edge plasma stability and turbulence*
		CompX	• RF kinetic modeling
MIT	• ECW-EBW modeling • HHFW modeling	Nova Photonics	• MSE – CIF & LIF* • Ultrafast imaging (~10^6 /s)*
NYU	• Transport & RF heating modeling*	ORNL	• RF launcher & experiments • ECH-EBW launcher & exp. • Edge exp., transp. simulation
PSI	• Ultrafast imaging (~10^6 /s)*	SNL	• Plasma-facing material* • Material surface analysis*
UC Davis	• FIReTIP	UC Irvine	• Fast ion-plasma interactions
UCLA	• Reflectometry	UCSD	• Fast probe, HHFW modeling • Far SOL turbulent transport*
U. Washington	• CHI		

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

NSTX has advanced into the PoP physics regime and is developing key tools to extend it

- **High currents:**
  - Ip ≤ 1.5 MA
  - CHI ≤ 0.4 MA
- **PoP physics regime:**
  - $H_L(89) \sim 2$, $H_H(98) \sim 1.4$
  - $\beta_T \leq 31.5\%$
  - $W_p \leq 280$ kJ
  - $V_{rotation}(0) \sim 0.25\ V_{Alfven}$
- **Modest fields:**
  - 4.5 kG routine, 6 kG cap.
- **Facility capabilities:**
  - NBI (5 MW)
  - HHFW (6 MW)
  - $\kappa \leq 2.5$, IWL, DND, SND
  - Bakeout (350°C)
  - Boronization, GDC
  - Real-time plasma control

Max $\beta_T = 31.5\%$
$\beta_N = 5 = 7.4\ell_i > \beta_N$(no-wall)*



* preliminary calculations

NSTX research milestones have been organized according to FESAC IPPA plans

FESAC FES Goal 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.

5-year Objective 2.1:

Make preliminary determination of the attractiveness of the Spherical Torus, by assessing high-beta stability, confinement, self-consistent high-bootstrap operation, and acceptable divertor heat flux, for pulse lengths much greater than energy confinement times.

- A set of ***Implementation Approaches*** was determined by the IPPA to meet this 5-year Objective.
- NSTX research milestones have been organized to address these **Implementation Approaches.**
- Also supports Goal 1 (understanding and predictive capability), Goal 3 (high performance tokamak innovation), and Goal 4 (technology and systems innovation)

NSTX research address IPPA implementation approaches to meet the FESAC 5-year objective on ST attractiveness

	FY01	FY02	FY03	FY04	FY05
Exp. Runwks:	6 9	12	21 4	20 5	
3.2.1.1. Achieve efficient heat and particle confinement					
	Study τ_E	Assess effects of high β & flow on χ	†Install deuterium pellet injector	Assess small-k turbulence	
3.2.1.2. Verify stability of large-scale MHD perturbations					
		Study MHD modes without feedback	Preliminary resonant field control	Suppress β-limiting global modes	
3.2.1.3. Heat high-beta over-dense plasmas *(and drive current)*					
	Heat with HHFW	Test HHFW CD efficiency	Characterize EBW emission, est. H&CD	Characterize energetic particle-wave interactions	
3.2.1.4. Test plasma startup *(& sustainment)* with noninductive techniques					
		Test CHI startup	Extend startup & sustainment to 1s	Characterize ΔJ from RF, NBI, & BS	
3.2.1.5. Disperse edge heat flux at acceptable levels					
			Study divertor heat fluxes	Characterize SOL & edge for high β	
3.2.1.6. Integrate high confinement and high beta					
			Integrate high β_T & τ_E for >> τ_E	†Integrate controlled high β_T & τ_E for >> τ_E	
3.2.1.7. Explore spherical torus issues in directed laboratory experiments					
	Pegasus, HIT-II, CDX-U – explore new ST parameter space & technologies				

Legend:
Baseline
†Incremental

5-year Checkpoint

Plain English anticipated research accomplishments on β_T & τ_E integration – FY04-6 (I)

FY01	FY02	FY03	FY04
IPPA 3.2.1.6. Integrate high confinement and high beta		Integrate high β_T & τ_E for >> τ_E	†Integrate controlled high β_T & τ_E for >> τ_E

FY04-6 (I): *Obtain plasmas with high beta beyond the "no-wall" stability limit and high energy containment efficiencies.*

Description:

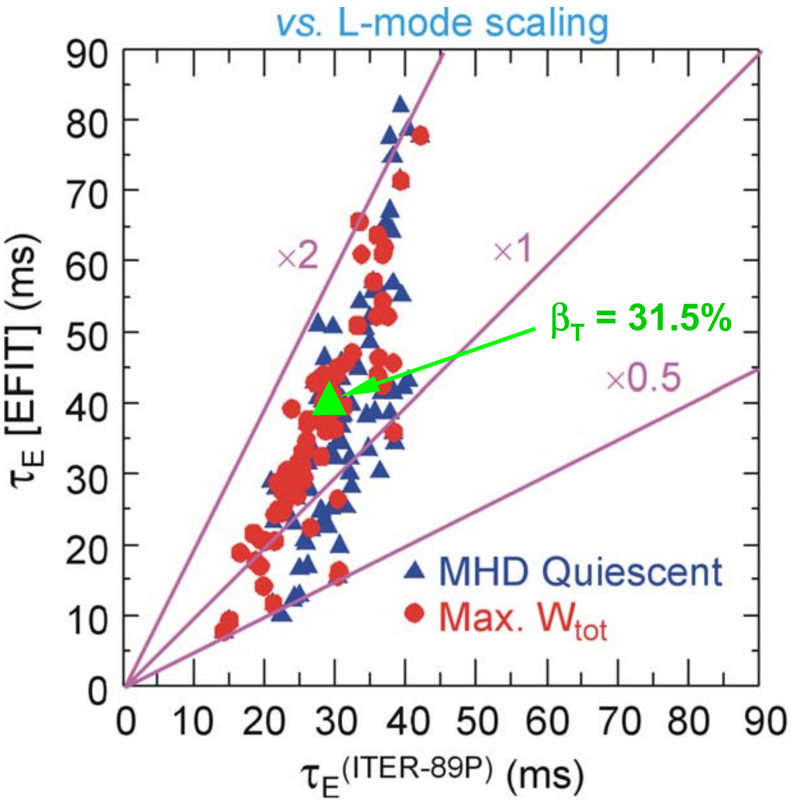
Experiments will be conducted in operating conditions in which the thermal energy is efficiently contained relative to empirical extrapolations and the ratio of plasma pressure to magnetic pressure is high. These conditions will be maintained for durations much greater than the energy replacement times by suppressing the plasma amplification of external field errors to increase the achievable pressure. The results will be compared with theoretical projections to facilitate a preliminary determination of the attractiveness of the spherical torus concept.

Transport studies aim to unravel the exciting science behind new global confinement trends

FY01	FY02	FY03	FY04
IPPA 3.2.1.1: Achieve efficient heat and particle confinement			
Study τ_E	**Assess effects of high β & flow on χ**	**†Install deuterium pellet injector**	**Assess small-k turbulence**

- **Effects of high β, strong flow, and strong curvature**
- **NBI: T_i (up to 2.5 keV) > T_e, strong flow, large τ_E in L-mode plasmas**
- **HHFW: T_e (up to 3.7 keV) >> T_i, weak flow**
- **H-mode obtained with either heating**
- **Combine H-mode & internal barrier?**
  - $\tau_E \geq 100$ ms achieved during transient H-mode rise
- **Edge control for H-mode:**
  - Bakeout, boronization, inboard gas fuel

NBI L-mode plasmas



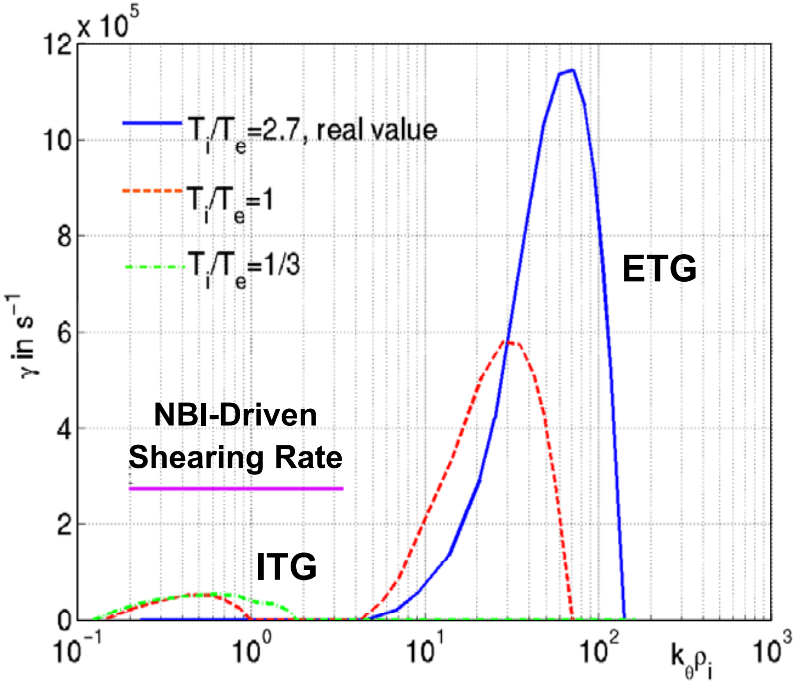
FY04 milestone offers opportunity for start of unique core turbulence studies in ST

FY01	FY02	FY03	FY04
IPPA 3.2.1.1: Achieve efficient heat and particle confinement			
Study τ_E	**Assess effects of high β & flow on χ**	**†Install deuterium pellet injector**	**Assess small-k turbulence**

- *Also supports IPPA Goal 1.1 on turbulent transport and predictive capability*

- **Commission core fluctuation diagnostics in FY03**
  - Exploring imaging options
- **Strong variations obtained in calculated growth rate**
  - High β' → substantial diamagnetic flow
  - Strong shearing & $T_i \le T_e$ → stable ITG & ETG?
- **Large-k measurements → FY05**
  - High β → strong electromagnetic effects
  - Larger ρ_e eases ETG measurement

Gyrokinetic Fluctuation Growth Rates



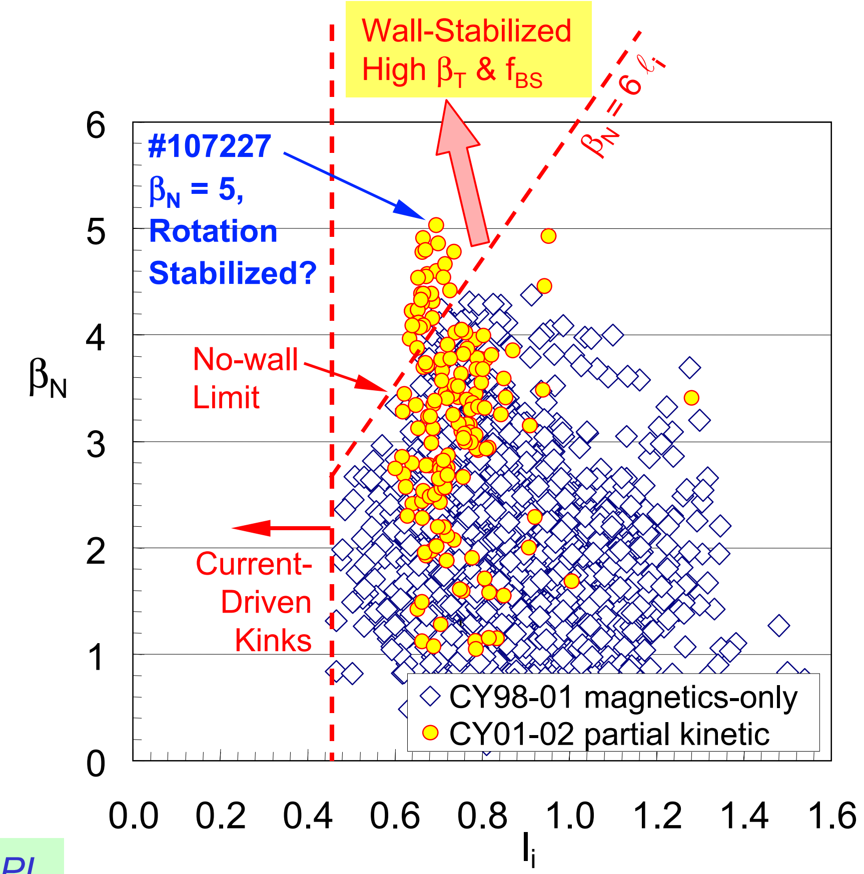
PPPL, UM

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

FY01	FY02	FY03	FY04
IPPA 3.2.1.2. Verify stability of large-scale MHD perturbations			
	Study MHD modes without feedback	**Preliminary resonant field control**	**Suppress β-limiting global modes**

- *Also supports IPPA Goal 3.1.2 on detailed predictive capability on macroscopic stability*

- **Effects of strong rotation & low R/a**
  - Building on DIII-D, HBT-EP experience
- **RWM, NTM identification in FY02**
  - Passive RWM stabilization via strong rotation (already observed?)
- **Preliminary RWM control in FY03**
  - Suppression of plasma amplification of external field errors
  - Critical plasma rotation
- **Phase-II control methods in FY04**
- **NTM investigations**
  - Seeding mechanisms
  - Avoidance and control (J-profile)



Wall-Stabilized High β_T & f_{BS}

#107227 β_N = 5, Rotation Stabilized?

No-wall Limit

Current-Driven Kinks

CU, PPPL

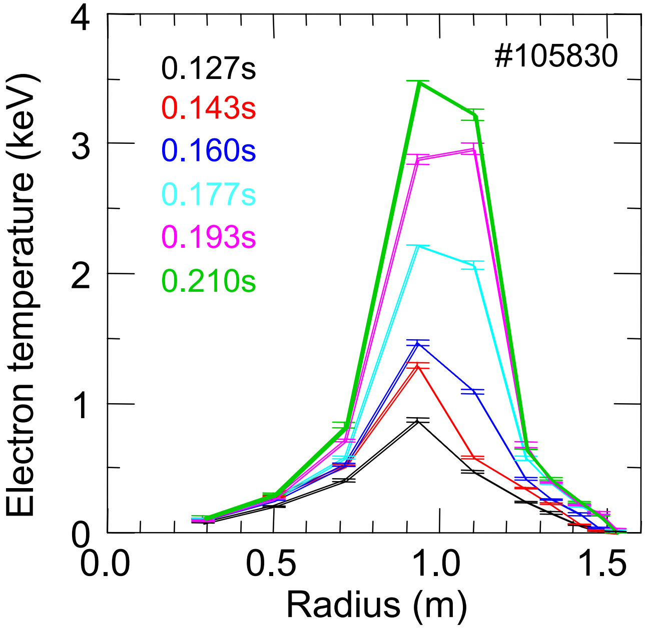
HHFW studies aim to achieve predictive capability based on measurement and theory comparisons

FY01	FY02	FY03	FY04
IPPA 3.2.1.3. Heat high-beta over-dense plasmas *(and drive current)*			
Heat with HHFW	**Test HHFW CD efficiency**	**Characterize EBW emission, est. H&CD**	**Characterize energetic particle-wave interactions**

- *Also supports IPPA Goal 3.1.3 on wave-particle interactions, and relevant to Goal 3.2.2 on Reversed Field Pinch*

- **Strong electron heating in over-dense plasma achieved by RF**
  - T_e up to 3.5 keV at 3 MW power
- **Antenna phasing capability at full power in FY02**
  - Test fast wave current drive (k = 7 /m)
- **Fast ion physics in FY04**
  - 80-keV beam ions accelerated to 140 keV!
- **(P)TRANSP (heating and current drive) analysis**
  - Infer RF power, current drive profiles
- **RF Modeling & SciDAC**
  - Ray tracing: GENRAY, CURRAY, HPRT
  - Full wave: TORIC, METS
  - Complete wave theory: AORSA-2D

HHFW Heating of Electrons



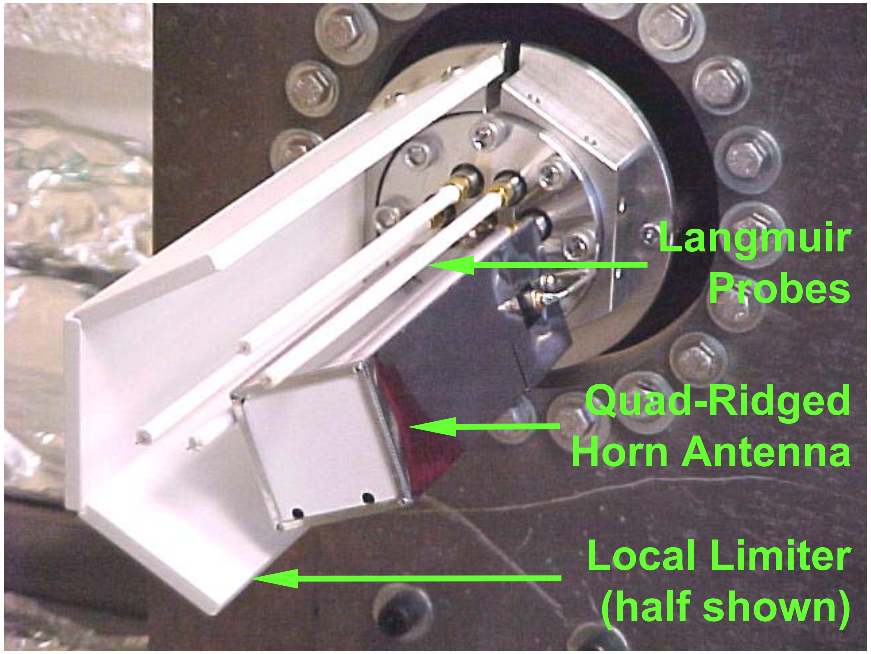
CompX, MIT, ORNL, PPPL, UCSD

EBW studies aim to establish basis for current drive, NTM control, and startup of high-β plasmas

FY01	FY02	FY03	FY04
IPPA 3.2.1.3. Heat high-beta over-dense plasmas *(and drive current)*			
Heat with HHFW	**Test HHFW CD efficiency**	**Characterize EBW emission, est. H&CD**	**Characterize energetic particle-wave interactions**

- **EBW emission (10-28 GHz)**
  - T_e and heat pulse studies on CDX-U (Munsat, PU)
  - T_e diagnostic (Diagnostic Innovations, *PPPL*)
  - Existing horn and limiter in FY02
  - Steerable horn in FY03
- **→ Heating & current drive**
  - Off-axis local heating and current drive for NTM stabilization
  - Non-inductive startup
  - Definition of high-power system by end of FY03

Innovative EBW Receiver-Launcher System Developed on CDX-U



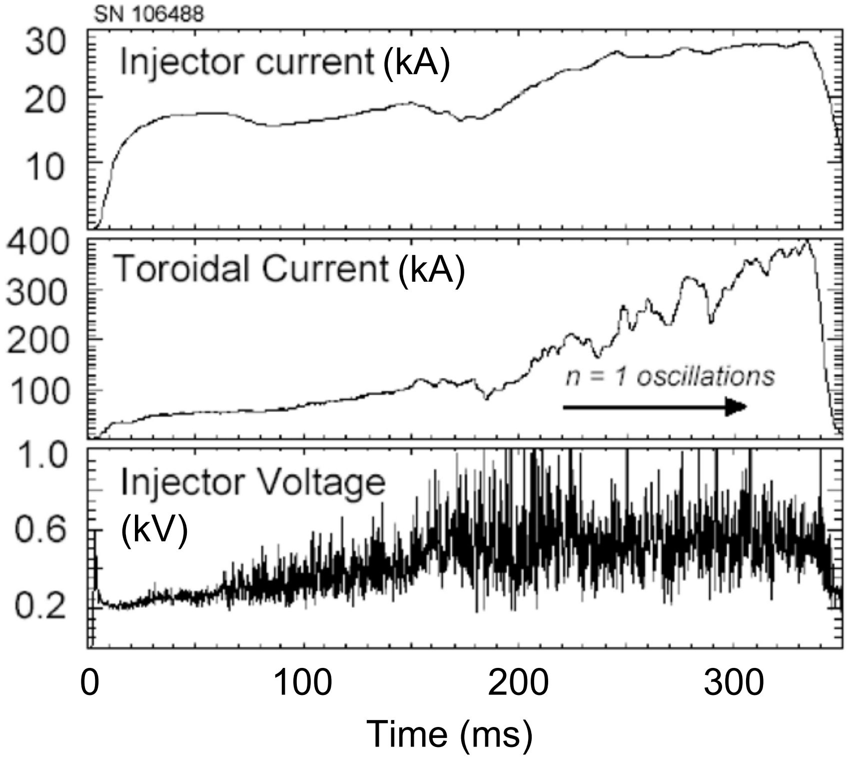
CompX, MIT, ORNL, PPPL

Innovative noninductive startup and sustainment is important to ST development

FY01	FY02	FY03	FY04
<u>IPPA 3.2.1.4. Test plasma startup *(& sustainment)* with noninductive techniques</u>			
	Test CHI startup	Extend startup & sustainment to 1s	Characterize ΔJ from RF, NBI, & BS

- **Tested CHI current to 400 kA in FY01; sustain for ~100 ms in FY02**
  - n=1 oscillations associated with reconnection on HIT-II
  - Improved CHI plasma control in FY02
- **Contribute to 1-s plasma pulse in FY03**
  - Improve CHI absorber design (insulator, field-null coils) in FY02
  - HHFW, NBI, B/S
- **Measure non-inductive current profile**
  - J-profile: MSE (CIF, LIF) in FY03-04; FIReTIP in FY02-03
  - "Current hole" to permit faster rampup?
- **Analysis in addition to (P)TRANSP**
  - EFIT with SOL currents
  - 3D MHD: magnetic reconnection

CHI Startup on NSTX, 2001



UW, GA, LANL, Nova Photonics, PPPL

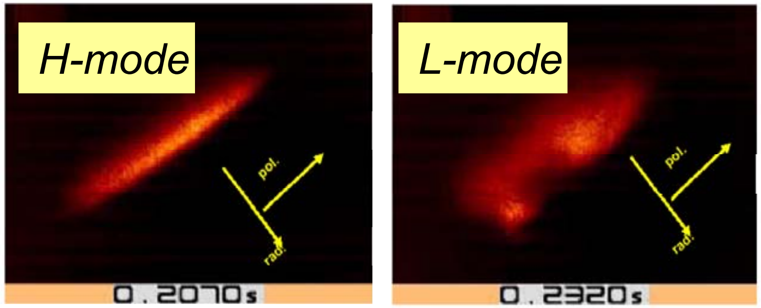
Boundary physics studies aim to test and develop solutions for high performance ST devices

FY01	FY02	FY03	FY04
IPPA 3.2.1.5. Disperse edge heat flux at acceptable levels		Study divertor heat fluxes	Characterize SOL & edge for high β

- *Also supports IPPA Goal 3.1.4 on plasma boundary physics and material surfaces interactions*

- **Effects of large SOL mirror ratio in FY03**
  - Heat and particle fluxes, fluctuations
  - Edge Localized Modes (ELM's)
  - Intermittent bursts
- **Edge, SOL conditions for high core performance in FY04**
- **Measurements**
  - Edge reciprocating probe, fixed probes, bolometer arrays, infrared and CCD cameras, faster edge imaging in FY02-03
- **Comparison with theory**
  - Diffusive and turbulence transport models
  - Edge simulation codes

He Gas Puff Imaging of H-L Transition



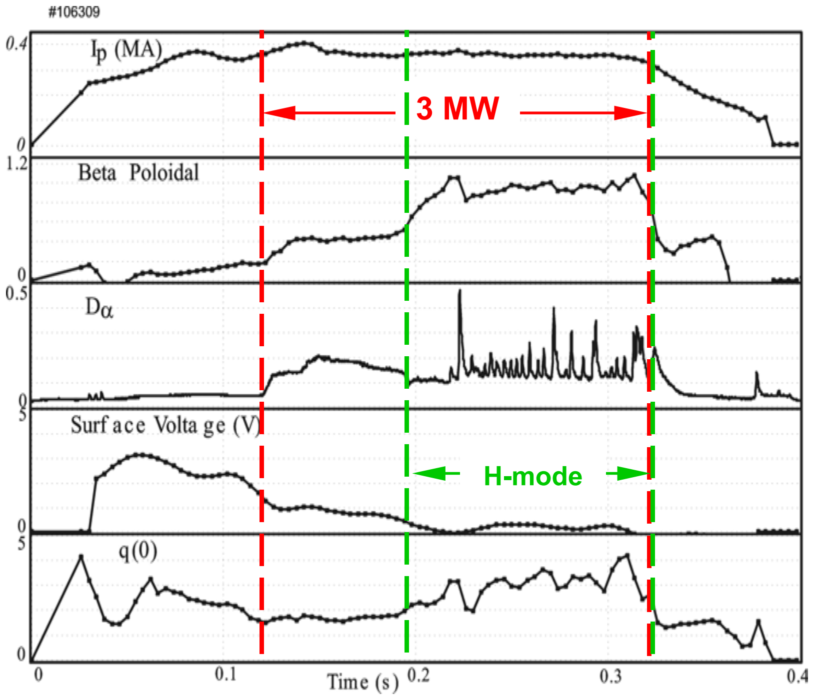
LANL, LLNL, ORNL, PPPL, UCSD

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

FY01	FY02	FY03	FY04
IPPA 3.2.1.6. Integrate high confinement and high beta		Integrate high β_T & τ_E for >> τ_E	†Integrate controlled high β_T & τ_E for >> τ_E

- **Test the conditions for high τ_E and β_T <u>without feedback</u> for >> τ_E in FY03**
- **(Incremental) Test for higher τ_E and β_T <u>with feedback</u> (as needed) for >> τ_E in FY04**
- **Utilize tools for controlling heating, current drive, stability, turbulence, and edge properties**
  - Feedback on plasma amplified modes
  - Avoid or reduce NTM's by adjusting profiles
  - Search over large ranges of β_p, q_0, L vs. H-modes, NBI vs. HHFW, edge conditions

HHFW-heated H-mode with high β_p & q_0



3 MW

H-mode

Carrying out the FY04 incremental milestone in FY04 will maintain the "5-year check-point" timetable in FY05

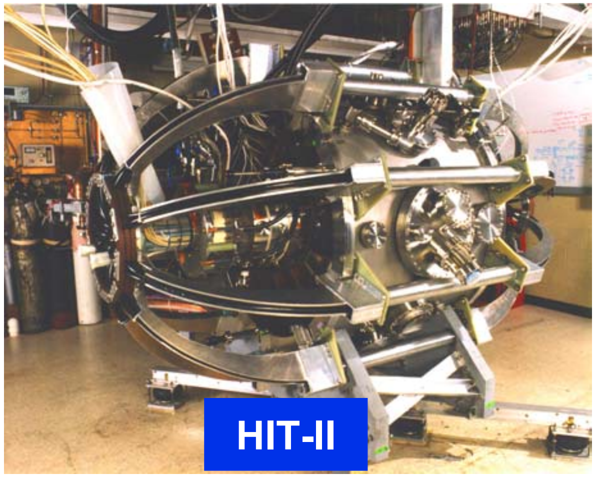
Pegasus, HIT-II (HIT-SI) and CDX-U plans to explore new ST parameter space and technologies

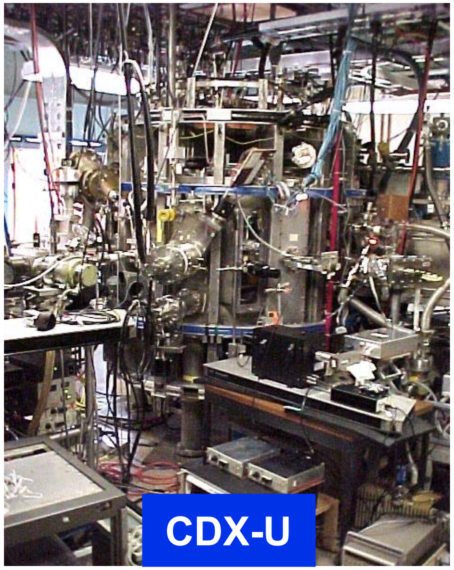
IPPA 3.2.1.7. Explore spherical torus issues in directed laboratory experiments

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

- **Pegasus plans**
  - MHD stability as R/a → 1
  - Physics connections with Spheromak
- **HIT-II (HIT-SI) plans**
  - Verification of NSTX CHI improvements ideas
  - Magnetic reconnection mechanisms (n=1 mode)
  - Steady helicity injection
- **CDX-U plans**
  - Lithium surface-plasma interactions
  - EBW emission as Te diagnostic


PEGASUS

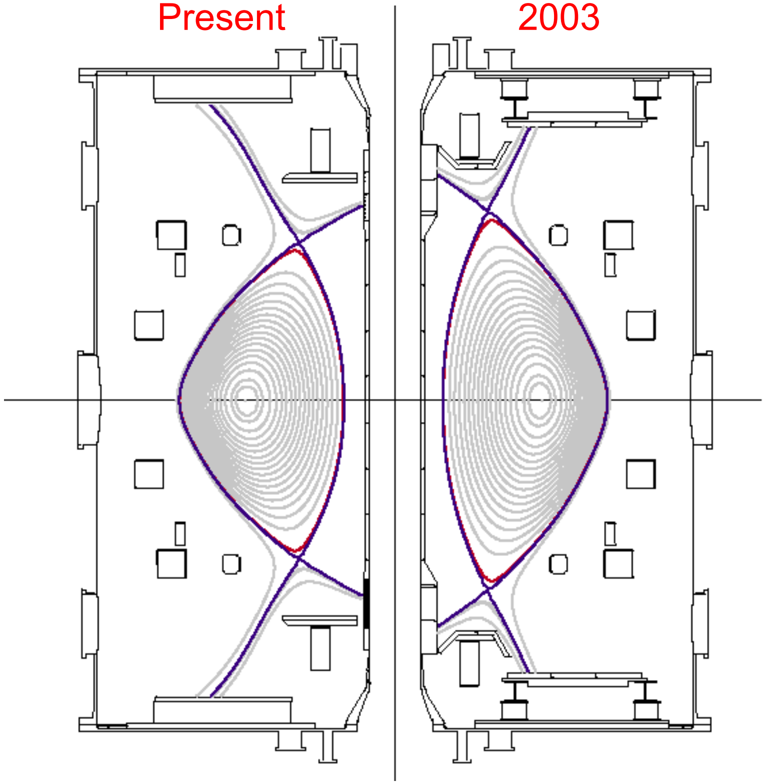

HIT-II


CDX-U

NSTX collaborates actively with world ST programs to derive large complementary mutual benefits

- **MAST, U.K.**
  - Highly complementary to NSTX in capabilities (in-vessel coils, far wall, compression-merging startup)
  - H-mode access/thresholds
  - NTM, ELM characterization
  - EBW H&CD (1 MW, **60 GHz**) in ‘02
  - Divertor heat flux amelioration in ‘03
  - Disruptions & halo currents
- **Globus-M, R.F.**
  - Innovative RF H&CD (low harmonic fast wave, poloidal launch lower hybrid wave)
- **ST’s in Japan**
  - **TST-2**: “Combline” HHFW antenna
  - **TS-3,4**: FRC-like diamagnetic ST plasmas
  - **HIST**: helicity injection physics

MAST



NSTX proposes to accelerate research in FY03-04 to meet the FESAC 5-year Objective for ST

- Successful National Research Team
- Strong international ST research cooperation
- Already entered PoP physics regimes
  - Max β_T = 31.5%, β_N = 5 %•m•T/MA (= $7.4\ell_{\mathbf{i}}$)
  - High H-factors relative to ITER confinement scaling
  - $V_{rotation}/V_{alfven} \sim 0.25$
- Milestones organized according to IPPA Implementation Approaches
- Physics integration milestone in FY05 → FY04 with incremental budget meets 5-year FESAC objective

Next: Ono – NSTX Facility Plan, Budget, and Issues