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NSTX Research Plan – FY04-06

Contributing to Fusion Energy Science on a Broad Front

Martin Peng

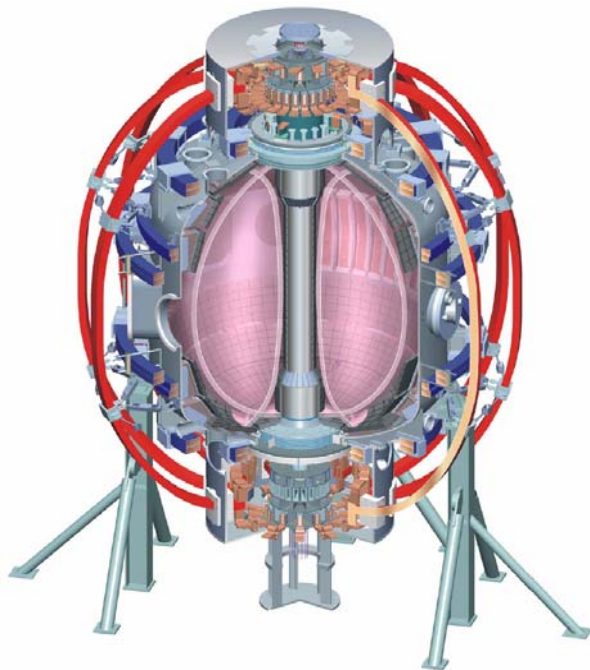
Oak Ridge National Laboratory, UT-Battelle
@ Princeton Plasma Physics Laboratory

For the NSTX Team

Budget Planning Meeting – FY 2006
Office of Fusion Energy Sciences

March 16 – 17, 2004
Germantown, Maryland

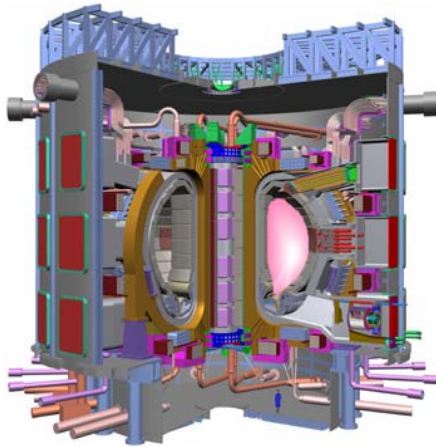
Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
NYU
ORNL
PPPL
PSI
SNL
UC Davis
UC Irvine
UCLA
UCSD
U Maryland
U New Mexico
U Rochester
U Washington
U Wisconsin
Culham Sci Ctr
Hiroshima U
HIST
Kyushu Tokai U
Niigata U
Tsukuba U
U Tokyo
JAERI
Ioffe Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
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IPP, Garching
U Quebec



NSTX Team Contributes to Fusion Energy on a Broad Front Through Scientific Investigations



Burning Plasma (ITPA)



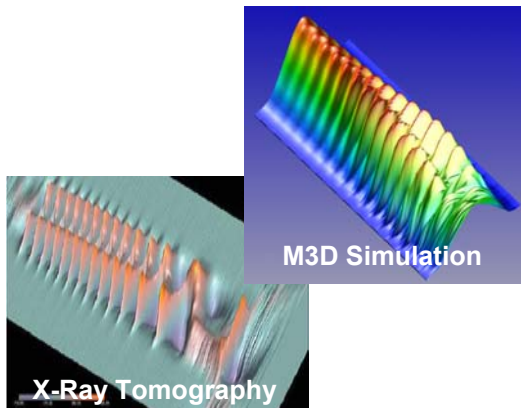
NSTX Team



Configuration Optimization



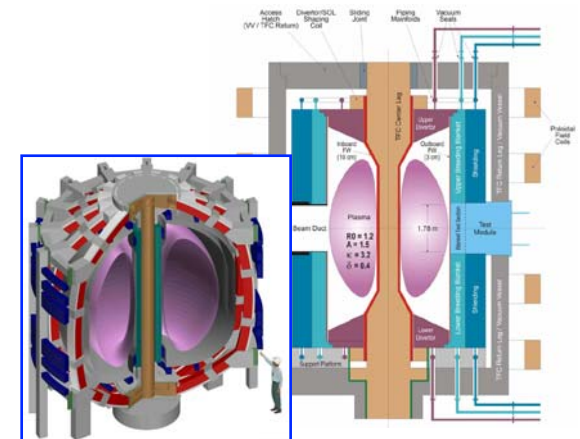
Fundamental Understanding



Scientific Topics

- Turbulence
- Stability
- Waves & Energetic Particles
- Magnetic Flux Generation
- Boundary Physics
- Integration

Materials, Components, Technologies (NSST & CTF)



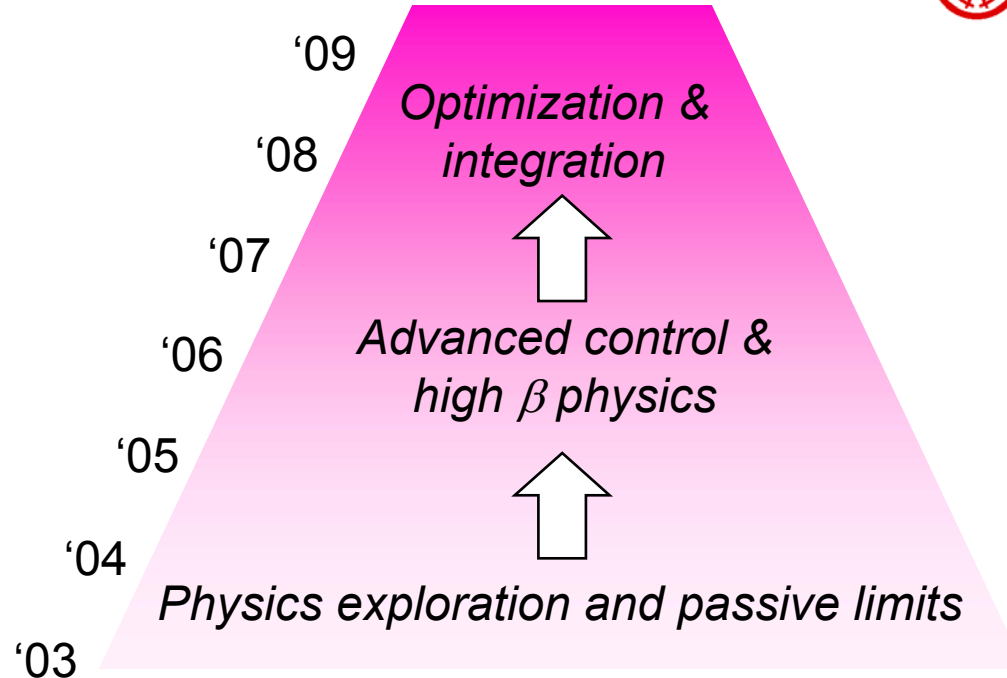
NSTX Collaborators Directly Funded by DOE Make Crucial Contributions



Institution	Research Topic	Institution	Research Topic
Columbia U	• MHD stability & mode control • Stellar x-ray spectroscopy	Nova Photonics	• MSE – CIF & LIF • Ultra-fast imaging ($\sim 10^6$ /s) • Planar LIF
Comp-X	• CQL-3D kinetic modeling of RF heating & current drive	NYU	• Transport & RF modeling
GA	• CHI equilibrium, RF physics • Plasma control • Poloidal field coil start-up	ORNL	• HHFW & EBW physics & technology • Boundary and pedestal physics • RF & transport modeling
INEL	• Tile surface & dust analysis	PSI	• Ultrafast imaging ($\sim 10^6$ /s)
Johns Hopkins U	• USXR tomography & diagnostics	SNL	• Plasma-facing material • Material surface analysis
LANL	• Visible and infrared imaging • Ultra-fast turbulence imaging • CHI plasma stability modeling	UC Davis	• FIREtIP n, B & fluctuations
LLNL	• Edge SOL physics • Edge plasma turbulence • Stellar x-ray spectroscopy	UC Irvine	• Turbulence & fluctuations
Lodestar	• Edge plasma stability and turbulence	UCLA	• Reflectometry & fluctuations
MIT	• ECW-EBW modeling • HHFW modeling	UCSD	• Fast probe, HHFW modeling • Far SOL turbulent transport
		U Maryland	• Transport & turbulence simulation
		U New Mexico	• Fast ion-plasma interactions
		U Washington	• CHI research
		U Wisconsin	• NSTX neoclassical modeling

Funded by OFES NSTX, Theory, Technology, Diagnostic Innovations, SBIR, Plasma Science Programs.

Integration of High τ_E & High β in Solenoid-Free Plasmas for $\Delta t_{\text{pulse}} \gg \tau_{\text{skin}}$ Is a Primary Goal of 5-Year Plan



- 5-Year Plan favorably reviewed by DOE Panel
- Major new tool requirements were identified:
 - *Fluctuation diagnostics* to enable detailed comparison with theory in high β plasmas
 - *Enhanced shaping* to improve stability through simultaneous high κ and δ
 - *Mode control* to allow approach toward “with-wall” limits
 - *EBW off-axis CD* to keep $q > 2$ and stabilizes NTM & internal modes
 - *Particle control* to maintain moderate n_e for CD

FY04-06 Research Milestones Aim to Advance Control and High β Physics



	FY04	FY05	FY06
Exp. Run-Weeks:	18	14	12
<u>1) Transport & Turbulence: How does turbulence cause heat, particle & momentum losses?</u>	(04-2) Measure low-k turbulence	(05-1) Measure high-k turbulence	
<u>2) Macroscopic MHD Stability: What limits maximum plasma pressure & bootstrap current?</u>		(05-2) Study plasmas near "with-wall" limit	
<u>3) Wave-Particle Interaction: How do electromagnetic waves interact with plasma?</u>	(04-3) Measure ΔJ from RF, NBI & ∇p	(05-3) Assess EBW H&CD requirements	
	(04-5) Characterize EBW emission, estimate H&CD		
<u>4) Start-up, Ramp-up and Sustainment: How is plasma magnetic flux generated?</u>	(04-4) Test current initiation		(06-1) Test solenoid-free ramp-up to high current
<u>5) Boundary Physics: How to interface fusion plasmas to surrounding materials?</u>			(06-2) Characterize edge of H-mode plasmas
<u>6) Integration: How much external control vs. self-organization is needed?</u>	(04-1) Assess high τ_E & high β_T H-mode for $\gg \tau_E$	(05-4) Assess combined RF & NBI effectiveness	(06-3) Evaluate $J_{NI} \sim 100\%$ for $\geq \tau_{skin}$

FY04-06 Research Milestones under Incremental Plan Will Enable Timely Achievement of the “5-Year” Goal



	FY04	FY05	FY06
Exp. Run-Weeks:	18	14 (7)	12 (6) ← Incr. Request
1) Transport & Turbulence: How does turbulence cause heat, particle & momentum losses?	(04-2) Measure low-k turbulence	(05-1) Measure hi-k turbulence	
2) Macroscopic MHD Stability: What limits maximum plasma pressure & bootstrap current?		(05-2) Study plasmas near “with-wall” limit	(06-4-Incr) Identify tearing modes & onset conditions
3) Wave-Particle Interaction: How do electromagnetic waves interact with plasma?	(04-3) Measure ΔJ from RF, NBI & ∇p (04-5) Characterize EBW emission, est. H&CD	(05-3) Assess EBW H&CD requirements	
4) Start-up, Ramp-up and Sustainment: How is plasma magnetic flux generated?	(04-4) Test current initiation		(06-1) Test solenoid-free ramp-up to high current
5) Boundary Physics: How to interface fusion plasmas to surrounding materials?		(05-5-Incr) Characterize edge of H-mode plasmas	(06-2-Incr) Assess long-pulse heat & particle control requirements
6) Integration: How much external control vs. self-organization is needed?	(04-1) Assess hi τ_E & hi β_T H-mode for $\gg \tau_E$	(05-4) Assess combined RF & NBI effectiveness	(06-3) Evaluate $J_{NI} \sim 100\%$ for $\geq \tau_{skin}$

Transport Studies Aim to Characterize Low & High k Turbulence at High β , Low A & Strong Flow



FY04	FY05	FY06
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1) Turbulence: How does turbulence cause heat, particle & momentum losses?

(04-2) Measure
low-k turbulence

(05-1) Measure high-k
turbulence

• Opportunity: different transport conditions exist where

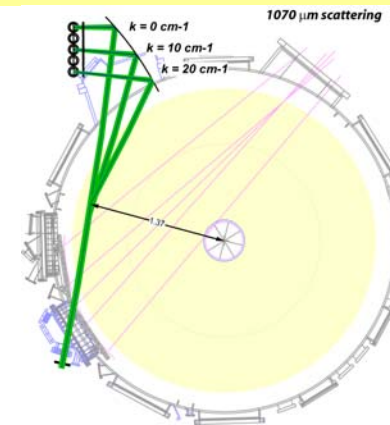
- $\chi_e \gg \chi_i$: helpful to high-k turbulence studies
- $\chi_i \sim \chi_i^{NC}$: stable low-k turbulence
- $\chi_\phi < \chi_i$: different from TFTR
- Effects of large β , ρ^* , V_ϕ ($\sim 0.3V_{\text{Alfvén}}$), V_ϕ' ; L & H-mode

• Tools, measurements and theory comparison

- FY04: μw reflectometers, FIR interferometer
- FY05: high-k μw scattering at 300 GHz
- FY07: μw imaging reflectometer (delayed from FY06)
- FULL, NLGS2, GTC, GYRO, TRANSP, NCLASS, ...

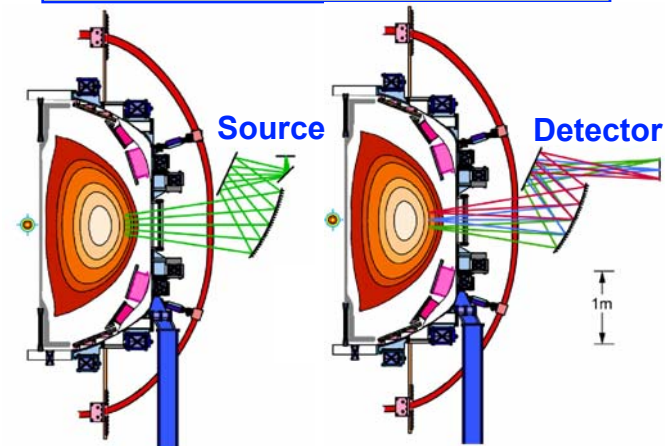
• ITPA: joint experiments with DIII-D, C-Mod, MAST

- Comparisons of A, β effects & ITB physics
- ELMy H-mode with $T_e \sim T_i$ & low input momentum
- Identity and Similarity tests of H-mode transitions & pedestal physics



High-k μw
scattering
system

μw Imaging Reflectometer



MHD Studies Aim to Understand the Physics of β Limiting Modes to Enable Very High β



FY04	FY05	FY06
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2) Stability: What limit maximum plasma pressure & bootstrap current?

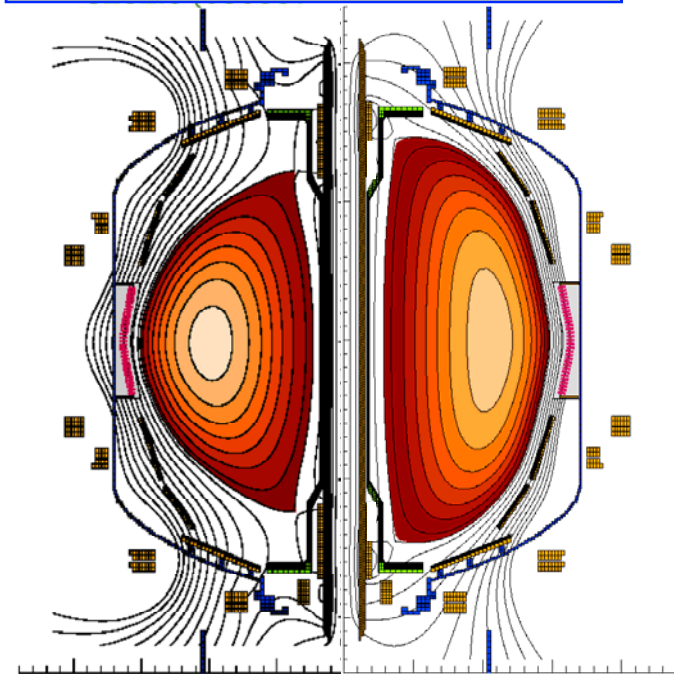
(05-2) Study plasmas near
“with-wall” limit

(06-4-Incr) Identify tearing
modes & onset conditions

- **Opportunity:** $\beta_0 \sim 1$, $V_{\text{Alfvén}} \sim V_{\text{Thermal}} \sim 3V_\phi$, $V_\phi' \sim \gamma_{\text{MHD}}$
 - Reached $\beta_T = 35\%$ at $\kappa = 2$, $\delta = 0.8$
 - Study RWM, internal mode rotation damping physics
 - Can reach $\kappa=2.55$, $\delta=0.8$ with PF1A modification
- **Tools, measurements, control & theory comparison**
 - FY04: install ex-vessel control coils; test rotation damping via error field reduction
 - FY05: commission & apply active field & RWM control
 - FY06-Incr: identify pressure-limiting tearing mode conditions
 - EFIT- V_ϕ , VALEN, MARS, M3D, GATO, PEST, DCON
- **ITPA: DIII-D, MAST, AUG, JET, JT-60U, C-Mod**
 - Compare RWM varying $V_{\text{Alfvén}}/V_{\text{Thermal}}$; compare NTM varying A ; error field sideband effects
- **ICC: relevant to MST, SSPX, FRC high β stability**

Calculated Equilibria:

κ :	2.0	2.55
PF1A:	Present	Modified



HHFW Aims to Test Current Drive in FY04 and Prepares for $J_{NI} = 100\%$ Demonstration in FY06



FY04	FY05	FY06
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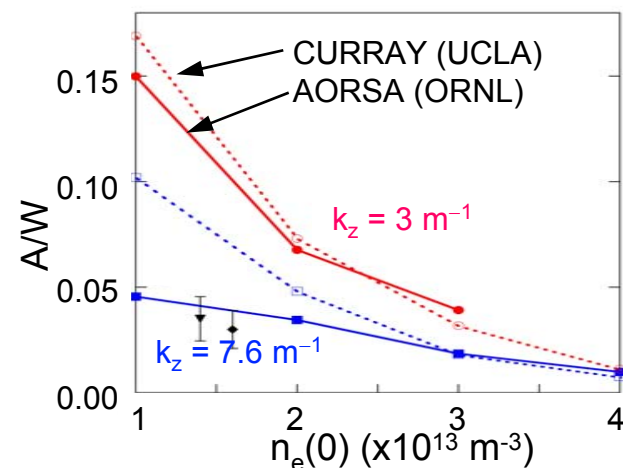
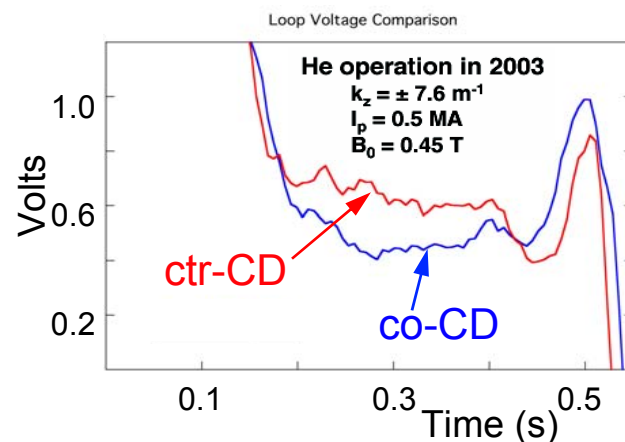
3) Wave-Particle Interaction: How do electromagnetic waves interact with plasma?

(04-3) Measure ΔJ
from RF, NBI & ∇p

(05-4) Assess combined
RF & NBI effectiveness

(06-3) Evaluate J_{NI}
~ 100% for $\geq \tau_{skin}$

- **Opportunity: HHFW in overdense plasmas (ST, RFP)**
 - Observed effective electron heating
 - Observed CD @ $k_z = 7.6 \text{ m}^{-1}$
 - Modeling indicates 3 m^{-1} should drive more current
 - Assess fast & thermal ion coupling
- **Tools, measurements & theory comparison**
 - FY04: commission multi-chord MSE C1F
 - CHERS & edge spectroscopy resolve E_r effect
 - Tangential polarimetry & X-Ray imaging contribute
 - Prepare for RF+NBI (FY05) & $J_{NI} = 100\%$ evaluation (FY06)
 - RF modeling, 1D & full-wave comparison, scenario simulation: CURRAY, HPRT, TORIC, AORSA, METS
- **ICC applications**
 - MST, Pegasus, CDX-U (LTX)



EBW Studies Will Establish Physics Basis in FY04-05 for Design of High-Power System in FY06



FY04	FY05	FY06
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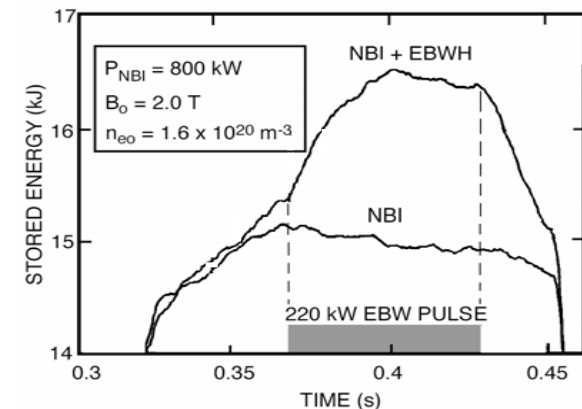
3) Wave-Particle Interaction: How do electromagnetic waves interact with plasma?

(04-5) Characterize EBW emission, estimate H&CD

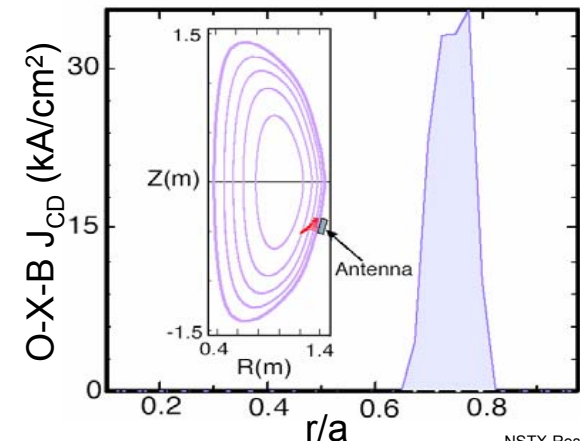
(05-3) Assess EBW H&CD requirements

W7-AS: O-X-B Data @ 140GHz

- **Opportunity: EBW in overdense plasmas (ST, RFP)**
 - Measured thermal emission in CDX-U, NSTX, MAST
 - Successful H&CD on W-7AS, COMPASS-D
 - Predicted large & localized H&CD profiles in NSTX
- **Tools, measurements, theory comparison, design**
 - FY04: X-B & O-X-B emission studies
 - FY05: collaborative H&CD tests on MAST @ 28 & 60 GHz and 200 & 700 kW level, respectively
 - FY05: EBW test on DIII-D, pending analysis results
 - GENRAY, CQL3D (NSTX); OPTPOL, GLOSI (MAST)
 - FY06: model H&CD scenarios and begin launcher design
- **ICC applications**
 - Pegasus, TST-2, MST, SSPX
 - New ST experiments: LATE (Japan), SUNIST (PRC)



NSTX: 135kA @ 28GHz, 3MW, 40% β_T



Solenoid-Free Start-up Will Be Tested Extensively in FY04-06 Towards Future ST and AT Devices



FY04	FY05	FY06
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4) Start-up, Ramp-up and Sustainment: How is plasma magnetic flux generated?

(04-4) Test current initiation

(06-1) Test solenoid-free ramp-up to high current

• Opportunity: solenoid-free startup shows promise

- **CHI:** 100kA on HIT-II; 390kA on NSTX
- **Merging-compression:** 500 kA on MAST
- **ECH, LHCD & NBI:** 200→600 kA on JT60-U
- **ECH:** 20 kA, 8 kA on DIII-D, TST-2
- EBW solenoid-free startup to high β_p

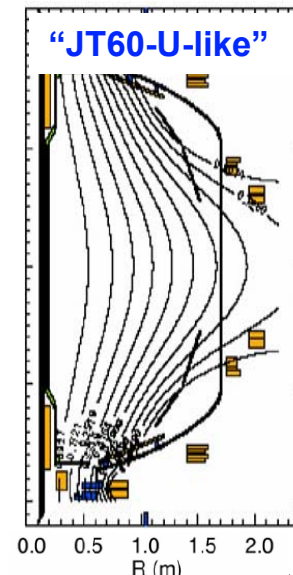
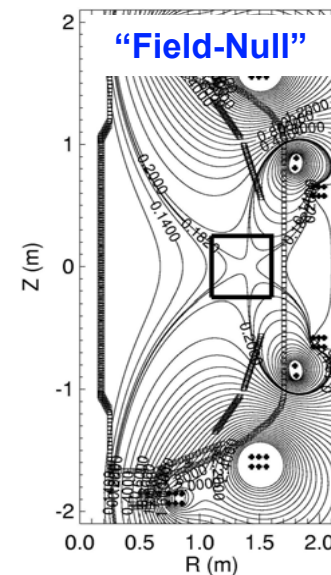
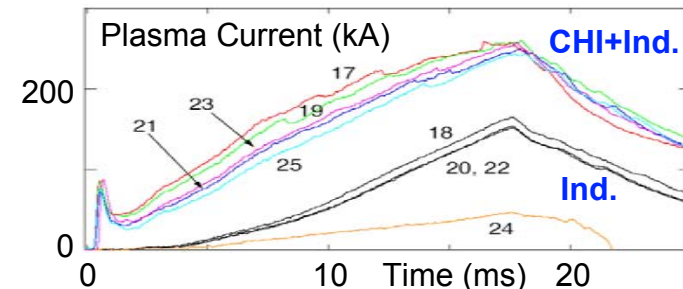
• Tools, measurements & theory comparison

- FY04: Capture CHI plasma by induction, HHFW
- FY04: Test outer PF-coil start-up scenarios, using ECH pre-ionization and HHFW heating
- Collaborative tests with MAST, DIII-D, TST-2
- FY06: test start-up scenarios to high current
- TSC, DINA (DIII-D), EFIT-J_{SOL}, LRDIAG

• ITPA & ICC applications

- Save V-s on ITER? $\Rightarrow$ increase inductive I_p , t_{pulse}
- Pegasus, TST-2, LATE, SUNIST

HIT-II captured CHI plasma by induction



Boundary Physics Studies Aim to Develop and Test Solutions for Long-Pulse High-Performance Plasmas



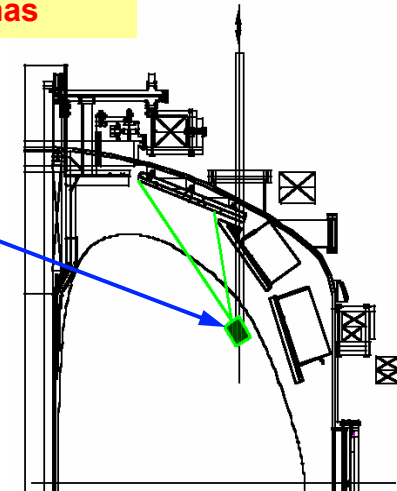
FY04	FY05	FY06
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5) Boundary Physics: How to interface fusion plasmas to surrounding materials?

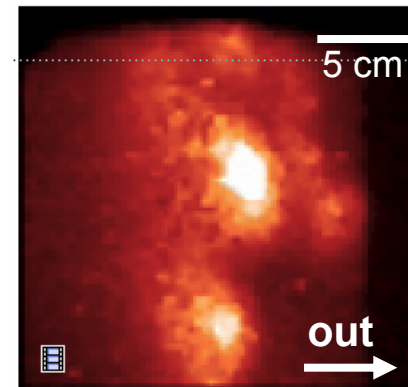
(06-2) Characterize edge of H-mode plasmas

- **Opportunity:** $B_p/B_T \sim 1 \Rightarrow >10$ SOL expansion, large B_{in}/B_{out} ratio & ρ^*
 - Divertor footprint larger than R-ratio $\Rightarrow$ favorable SOL at low A and high δ
 - Li: Cost-effective way to control recycling
- **Tools, measurements & theory comparison**
 - FY04: lithium pellets, supersonic gas jet, fast imaging
 - FY05: lithium coating; more edge TS points
 - FY06: fast IR camera; poloidal CHERS
 - Study ELM & “blob” fluxes
 - **Decision: cryo-pump or lithium module**
- **ITPA: DIII-D, C-Mod, AUG comparisons**
 - H-mode, pedestal, edge turbulence
 - Type-I ELM energy flux, $\chi_\perp$, n_{sep} , SOL profiles

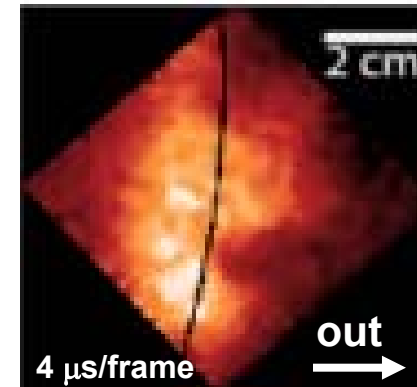
E-beam
Deposition
System



Edge Turbulence
NSTX



C-Mod



Integration Studies Will Assess Compatibility of Requirements for Stability, Transport, Heating & Current Drive



FY04	FY05	FY06
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6) Integration: How much external control vs. self-organization is needed?

(04-1) Assess high τ_E & high β_T H-mode for $\gg \tau_E$

(05-4) Assess combined RF & NBI effectiveness

(06-3) Evaluate J_{NI} ~ 100% for $\geq \tau_{skin}$

- **Opportunity: High β , low A & low B change the balance of external & internal influences**

- FY04: assess high τ_E at high β
- FY05: assess combined RF & NBI effectiveness in H&CD
- FY06: evaluate conditions for 100% non-inductive operation using **NBI & HHFW only**

- **Tools, modeling & scenario simulation**

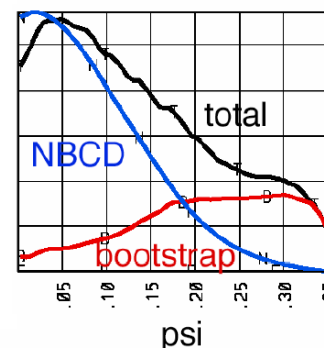
- Guide experiment with extensive modeling & scenario simulation
- Decisions: multi-MW EBW (FY05); active particle control (FY06)

- **ITPA, future ST & ICC application**

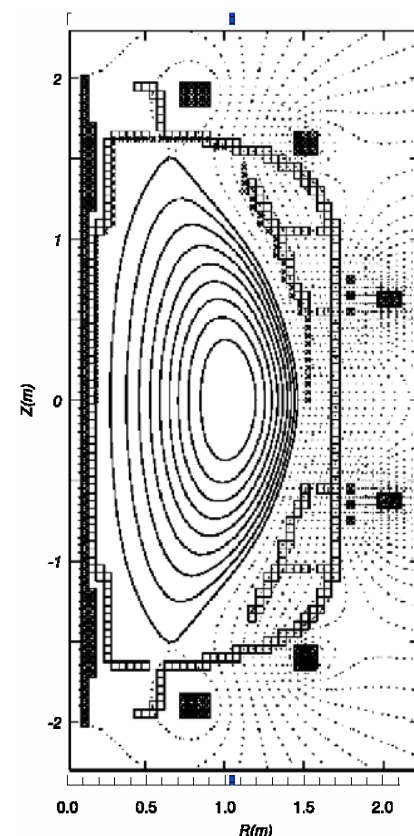
- ITER hybrid scenario
- Larger ST physics requirements

$I_p = 0.8$ MA
 $\kappa = 2.6$; $\delta = 0.38$
 $P_{NBI} = 6$ MW
 $P_{HHFW} = 6$ MW
 $P_{EBW} = 0$
 $\langle n_e \rangle = 3 \times 10^{19} \text{m}^{-3}$
 $H_{98y2} = 1.2$
 $\beta_T = 19\%$; $\beta_N = 6.8$
 Stable $n = 1$ & ∞

$J_{||}$ profiles



TSC: NBI+HHFW



“Five-Year” Plan Goal Drives Major NSTX Decisions on EBW and Particle Control Capabilities



FY04	FY05	FY06
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6) Integration: How much external control vs. self-organization is needed?

(04-1) Assess high τ_E & high β_T H-mode for $\gg \tau_E$

(05-4) Assess combined RF & NBI effectiveness

(06-3) Evaluate J_{NI} ~ 100% for $\geq \tau_{skin}$

- **Opportunity: High β , low A & low B change the balance of external & internal influences**

- FY04: assess high τ_E at high β
- FY05: assess combined RF & NBI effectiveness in H&CD
- FY06: evaluate conditions for 100% non-inductive operation using NBI & HHFW only

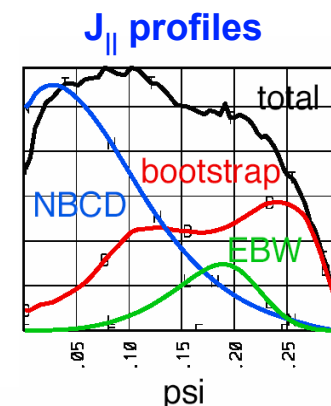
- **Tools, modeling & scenario simulation**

- Guide experiment with extensive modeling & scenario simulation
- **Decisions: multi-MW EBW (FY05); active particle control (FY06)**

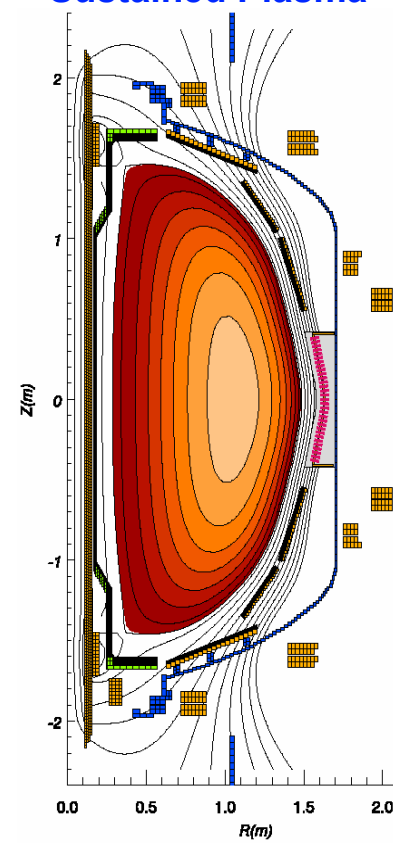
- **ITPA, future ST & ICC application**

- ITER hybrid scenario
- Larger ST physics requirements

$I_p = 1$ MA
 $\kappa = 2.55$; $\delta = 0.8$
 $P_{NBI} = 4$ MW
 $P_{HHFW} = 3$ MW
 $P_{EBW} = 3$ MW
 $\langle n_e \rangle = 2.7 \times 10^{19} \text{m}^{-3}$
 $H_{98y2} = 1.5$
 $\beta_T = 41\%$; $\beta_N = 8.9$
 Stable $n = 1$ & ∞



TSC: High-Performance Sustained Plasma

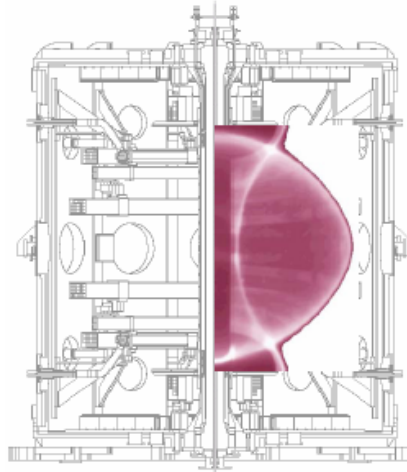


Worldwide NSTX Collaborations are Enhancing Contributions to ITPA-ITER

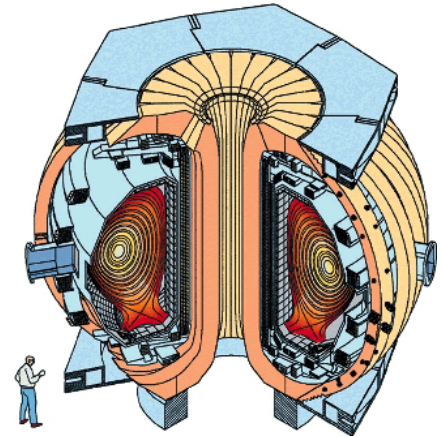


- **Extensive collaboration with MAST**
 - NBI H-mode, ITB, τ_E scaling
 - EBW H&CD, start-up (28, 60 GHz)
 - Fueling, SOL pedestal studies
 - Energetic particle characterization
- **Strong participation in ITPA**
 - **DIII-D, C-Mod**: RWM, Fast ion MHD, pedestal, core confinement, edge turbulence, x-ray crystal spectrometry, EBW
 - **A and β effects**: H-mode, ITB, ELM's & pedestal, SOL, RWM, NTM
- **Exploratory ST experiments**
 - **Pegasus**: Extreme low A, EBW
 - **CDX-U/LTX**: Li-plasma
 - **TST-2, LATE, SUNIST**: RF start-up, H&CD
 - **TS-3,4**: FRC-like $\beta \sim 1$ ST plasmas
 - **HIT-II/HIT-SI, HIST**: CHI physics

MAST (U.K.)



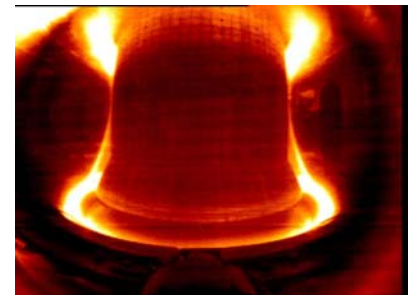
DIII-D (U.S.)



Pegasus (U.S.)



C-Mod (U.S.)



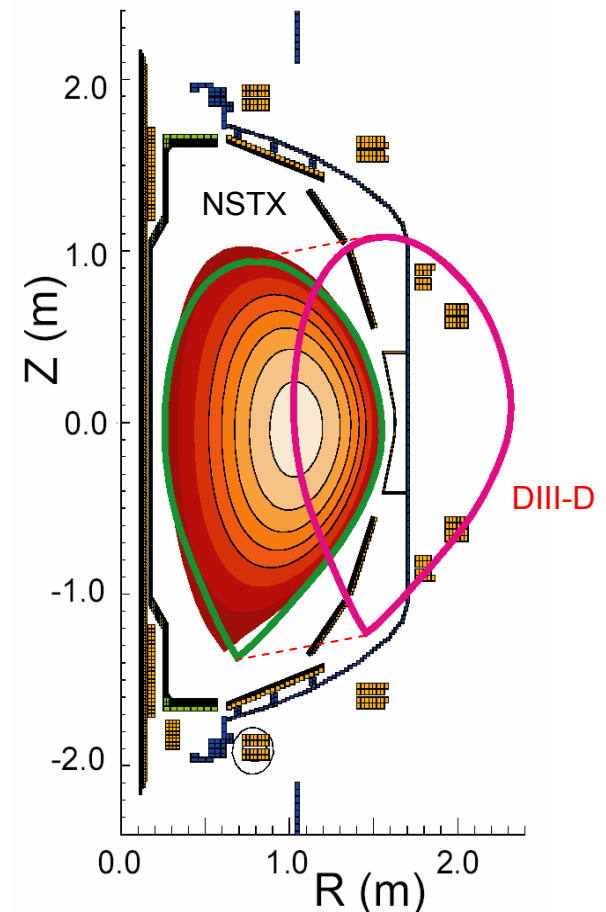
Collaborative Research with DIII-D and C-Mod is a Key Element of the NSTX program



Ongoing Coordinated Research:

- **MHD: active mode control; fast ion modes**
 - DIII-D: physics of different $V_{\text{Alfvén}}$
- **Transport: core confinement & H-mode pedestal**
 - DIII-D: similarity studies, with MAST researchers
- **Solenoid-free startup**
 - DIII-D: PF-only startup tests, with JT-60U researchers
- **EBW: mode conversion and deposition – off-axis current drive & NTM stabilization**
 - DIII-D: Operate with overdense conditions, using 110 GHz gyrotrons & PPPL launcher?
 - Modeling study underway.
- **Core measurement, SOL/edge transport & turbulence**
 - C-Mod: Fast camera gas puff imaging studies
 - C-Mod: X-ray crystal spectrometer for T_i & T_e

Various Plasma Shapes Available for Physics Comparison



NSTX National Team Contributes to Fusion Energy Sciences Along A Broad Front



- NSTX research addresses key scientific issues and supports
 - Fundamental understanding
 - Configuration optimization
 - Burning plasmas through ITPA
 - Physics database toward future ST's
- FY04-06 research aims to advance control and high β physics, the near-term goal of the NSTX 5-Year Research Plan
 - How does turbulence cause heat, particle & momentum losses?
 - What limits maximum plasma pressure & bootstrap current?
 - How do electromagnetic waves interact with plasma?
 - How is plasma magnetic flux generated?
 - How to interface fusion plasmas to surrounding materials?
 - How much external control vs. self-organization is needed?
- Additional investment in EBW and particle control required to develop high β long pulse discharges
- Strong contributions to ITPA, and broad collaborations worldwide