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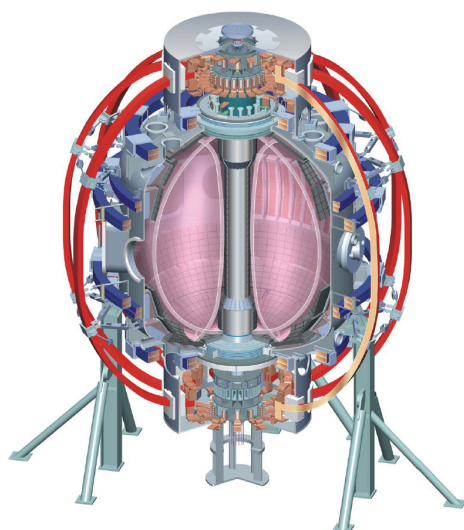


# NSTX Program Strategy and Research Priorities

**Martin Peng**  
On Behalf of the NSTX Team

**NSTX PAC-19<sup>th</sup> Meeting**  
February 22 – 24, 2006

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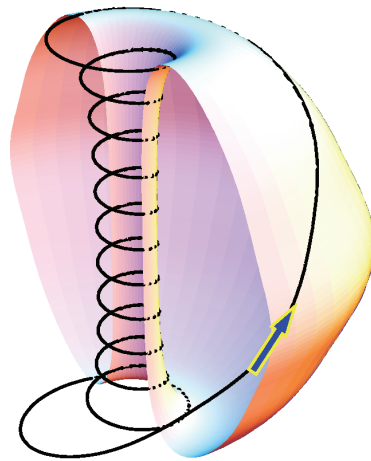
Culham Sci Ctr  
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# NSTX Strategy Is to Address Issues Important for Fusion Energy Sciences Using Special ST Properties

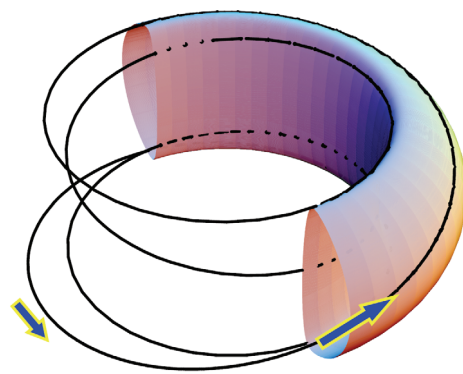


- Determine the physics principles of Spherical Torus / Spherical Tokamak, utilizing its low aspect-ratio  $A \sim 1.5$  and very high  $\beta$
- Support preparation for burning plasma research in ITER through the ITPA and benefit from it
- Complement and extends  $A \sim 3$  and lower  $\beta$  experiments in addressing key scientific issues of toroidal fusion plasmas
- Complement ITER by establishing attractive configurations for a Component Test Facility (CTF) and Demo

# ST Complements and Extends A ~ 3 and Lower $\beta$ Experiments in Advancing Toroidal Plasma Science



ST



Tokamak

## MHD theory

- Strong plasma shaping, self fields, rotation (vertical elongation  $\sim 3$ ,  $B_p/B_t \sim 1$ ,  $M_A \leq 0.4$ )
- Very high  $\beta_T$  ( $\sim 0.4$ ),  $\beta_N$  ( $\leq 7$ ) &  $f_{BS}$  ( $\leq 0.7$ )

## Turbulence and transport

- Strong electromagnetic effects ( $\beta_0 \sim 1$ )
- Small normalized plasma size ( $a/\rho_i \sim 50$ )
- Large plasma flow ( $M = V_\phi/V_S \leq 0.8$ )
- Large flow shearing rate ( $\gamma_{ExB} \leq 10^6/s$ )

## Wave-particle interactions

- Supra-Alfvénic fast ions ( $V_{fast}/V_A \sim 1-4$ )
- High dielectric constant ( $\epsilon = \omega_{pe}^2/\omega_{ce}^2 \sim 50$ )

## Edge and boundary

- High divertor heat flux
- Large SOL area expansion

# ST Research Supports, Supplements, and Benefits from ITER



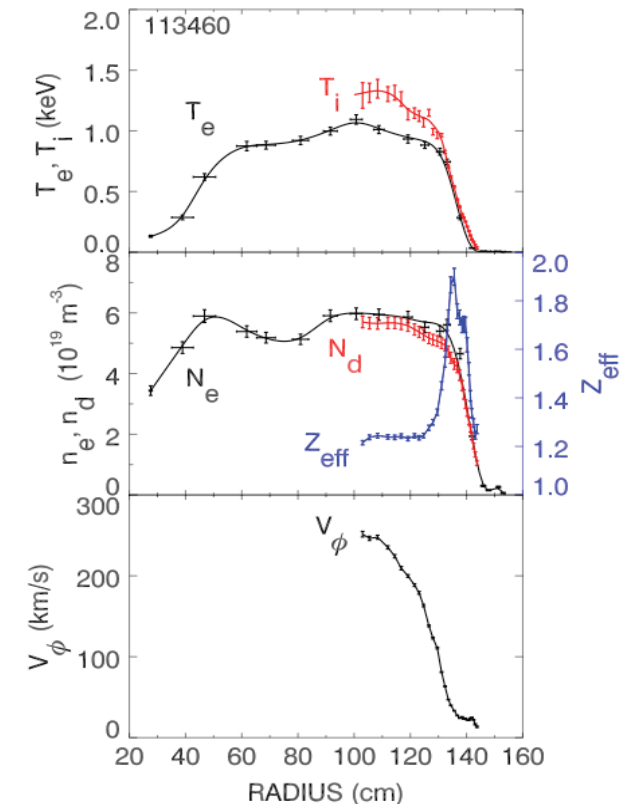
Spherical Torus	Supports	Supplements	Benefits from
<b>Stability</b>	Stabilization by active feedback & flow; physics and scaling.	Extends studies to higher beta, flow, S ( $ql/aB$ ), low aspect ratio. Current startup.	ELMs at low collisionality $\nu^*$
<b>Energetic Particles</b>	$V_f/V_A$ relevant to ITER at normal operating point – with MSE.	Extends alpha physics to higher $V_f/V_A$ . Efficient EBW current drive.	Nonlinear alpha physics, burn control.
<b>Transport</b>	Tests turbulence with powerful electron heating, unique diagnostics.	Extends transport studies to higher beta, flows.	Transport at low collisionality $\nu^*$
<b>Plasma-wall</b>	Tests very high P/R, aspect ratio effects on edge.	Tests much greater flux expansion, lithium edge.	Long pulse at high P/R.

# NSTX Research Contributes Strongly to the Physics Basis for CTF Macrostability and Confinement



$R_0 = 1.2 \text{ m}$ ,  $a = 0.8 \text{ m}$ ,  $\kappa = 3.2$ ,  $B_T = 2.5 \text{ T}$ ,  $I_p \sim 10 \text{ MA}$

Sustained Parameters	CTF ( $\tau \gg \tau_{\text{skin}}$ )	NSTX H-mode ( $\kappa \sim 2.4$ , $\tau \leq 3\tau_{\text{skin}}$ )
$I_p/aB_T$ (MA/m-T)	$\leq 6.4$	$\leq 4.4$
Safety factor, $q_{\text{cyl}}$	$\geq 3.0$	$\geq 2.3$
$\beta_N$ (%-m-T/MA)	$\leq 3.9$	$\leq 5.5$
$\beta_T$ (%)	$\leq 24$	$\leq 25$
Avg. $a/\rho_i$ ( $=1/\rho_i^*$ )	$\sim 90$	$\sim 60$
Avg. collisionality, $\nu^*$	$\sim 0.001$	$\sim 0.08$
$\tau_{Ei} / \tau_{Ee}$	?	$\sim 5$
$n/n_{\text{GW}}$	$\sim 0.2$	0.3 – 0.8



## NSTX Investigations

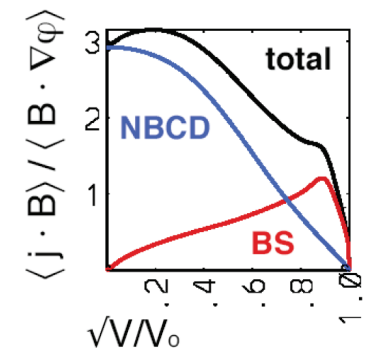
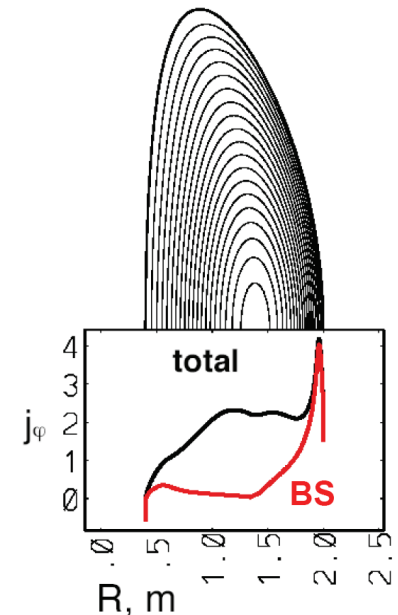
- **Macro-stability:**  $\kappa \leq 2.8$  and  $\tau \gg \tau_{\text{skin}}$ ; EF / RWM control with large  $V_\phi$
- **Confinement:**  $\rho^*$  and  $\nu^*$  ( $B$ ,  $I_p$ ,  $n$ ,  $\kappa$ ) scaling; electron-scale turbulence and transport
- **Recycling control:** lithium wall coating via evaporator  $\rightarrow$  operation at low  $n/n_{\text{GW}}$ ?

# NSTX Research Addresses CTF Heating & Current Drive Physics in the Same Regime



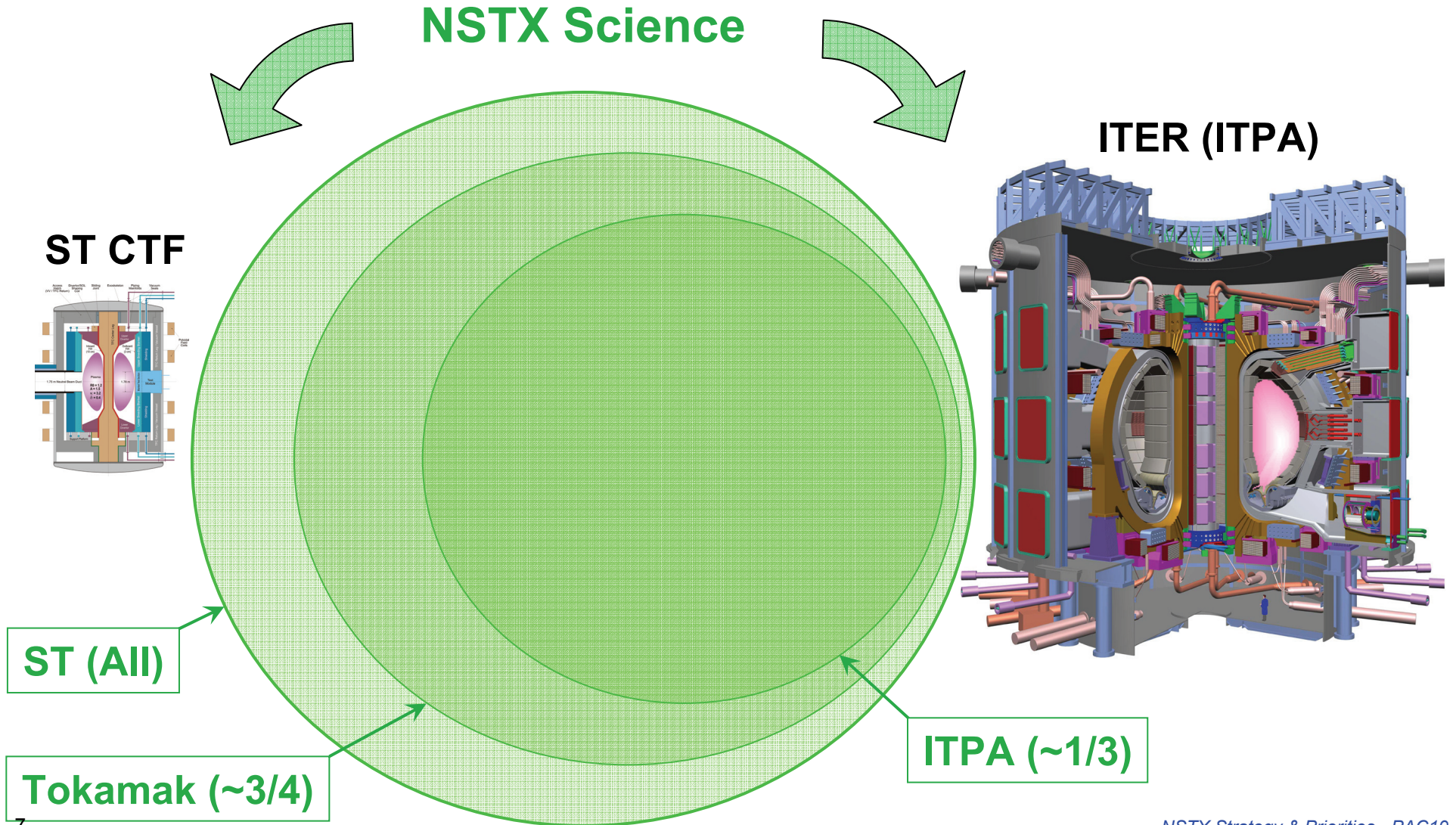
Sustained Parameters	CTF ( $\tau \gg \tau_{\text{skin}}$ )	NSTX so far ( $\kappa \leq 2.4, \tau \leq 3\tau_{\text{skin}}$ )
$V_{\text{fast}}/V_{\text{Alfvén}}$	3	1 – 4
Internal inductance, $l_i$	0.25 – 0.5	$\geq 0.7$
$I_{\text{BS}}/I_{\text{CD}}$ fractions	0.43/0.57	0.5/0.1
Start-up to $\mu_0 l_i R I_p$ (Wb)	$\geq 3.8$	$\sim 0.13$ (goal)
P/R (MW/m)	$\geq 30$	$\leq 9$
SOL area expansion	10 – 20	$\sim 5$

CTF Free-Bdry Equil;  
Stable Current Profile



- NSTX Investigations**
- **Burn physics:** super-Alfvénic ion driven modes and transport
  - **NB driven current:** high current fraction in presence of driven \*AE's
  - **Ramp-up:** minimize flux consumption via CHI, plasma gun (Pegasus), shaping, partial induction (VF; iron core in CTF), RF, NBI, and B/S
  - **Divertor physics solutions:** Tritium removal, He pumping, high heat flux handling – liquid Li divertor?

# NSTX Science Naturally Supports ST Specific and Burning Plasma Needs



# Research Milestones for FY06-08 Are Selected to Address Key Scientific Topics & Utilize Unique Capabilities



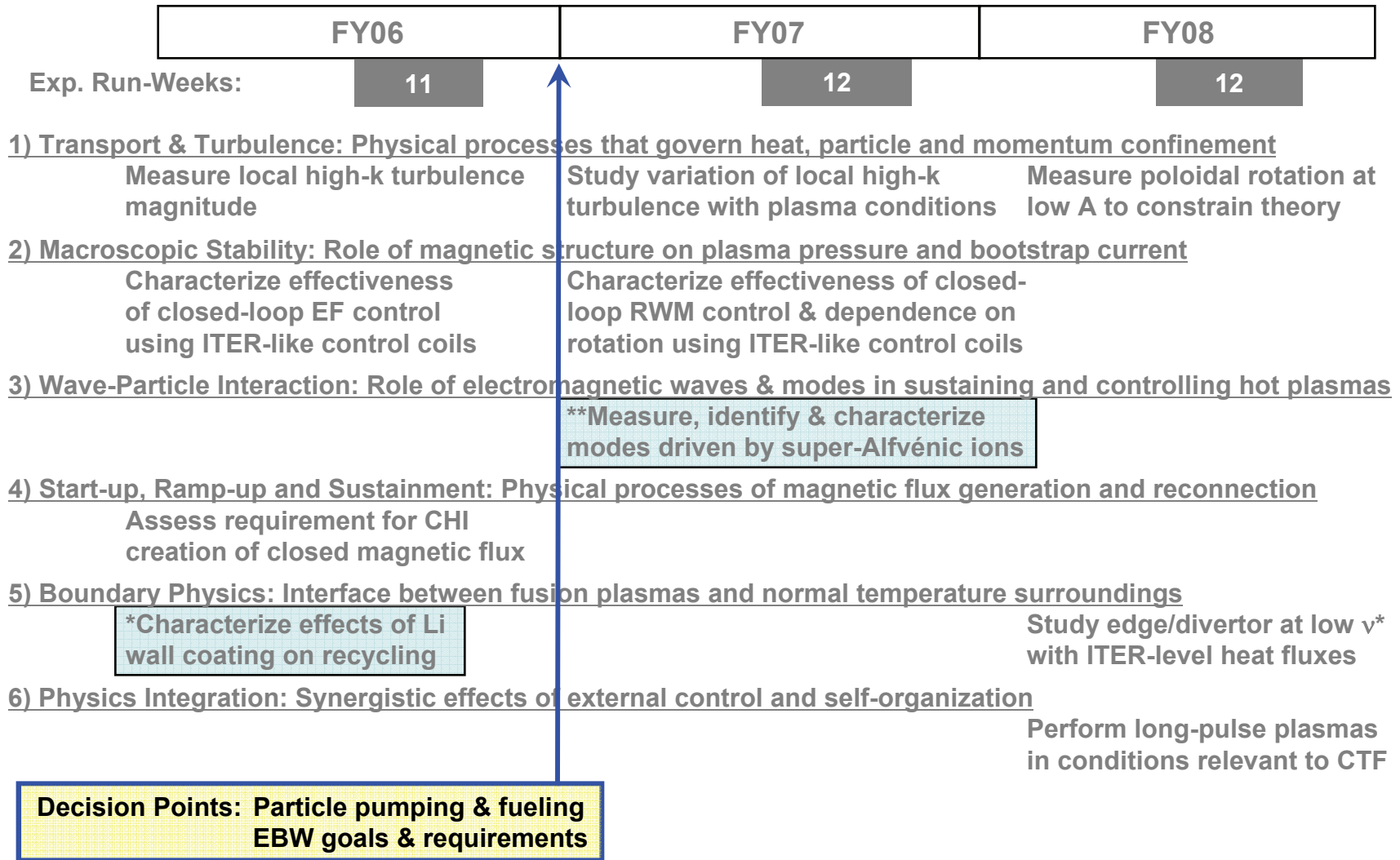
	FY06	FY07	FY08
Exp. Run-Weeks:	11	12	12
<b>1) Transport &amp; Turbulence: Physical processes that govern heat, particle and momentum confinement</b>	Measure local high-k turbulence magnitude	Study variation of local high-k turbulence with plasma conditions	Measure poloidal rotation at low A to constrain theory
<b>2) Macroscopic Stability: Role of magnetic structure on plasma pressure and bootstrap current</b>	Characterize effectiveness of closed-loop EF control using ITER-like control coils	Characterize effectiveness of closed-loop RWM control & dependence on rotation using ITER-like control coils	
<b>3) Wave-Particle Interaction: Role of electromagnetic waves &amp; modes in sustaining and controlling hot plasmas</b>		**Measure, identify & characterize modes driven by super-Alfvénic ions	
<b>4) Start-up, Ramp-up and Sustainment: Physical processes of magnetic flux generation and reconnection</b>	Assess requirement for CHI creation of closed magnetic flux		
<b>5) Boundary Physics: Interface between fusion plasmas and normal temperature surroundings</b>	*Characterize effects of Li wall coating on recycling		Study edge/divertor at low $v^*$ with ITER-level heat fluxes
<b>6) Physics Integration: Synergistic effects of external control and self-organization</b>			Perform long-pulse plasmas in conditions relevant to CTF

\*OFES "Tracked" Milestone

\*\*DOE "JOULE" Milestone



# Decisions on Particle Control and EBW Aims to Set Major Direction for Future Research & Capabilities



\*OFES "Tracked" Milestone

\*\*DOE "JOULE" Milestone

# Transport Studies Emphasizes High-k Turbulence and Transport, Leveraging Large $\beta$ , $\rho^*$ , q-Shear, MSE



## Motivation

- Extend understanding of electron scale transport, a key remaining scaling uncertainty – needed by ITER and CTF

## Milestones

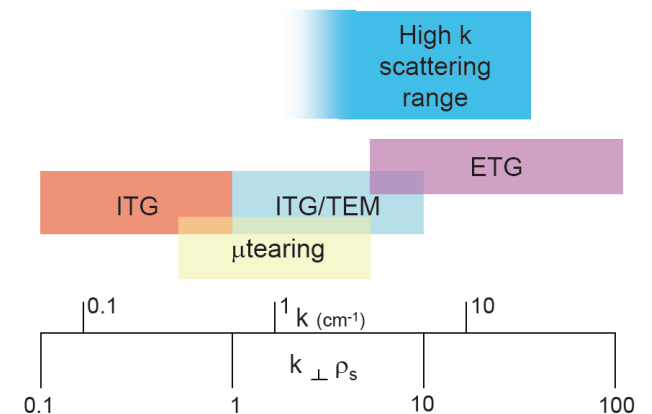
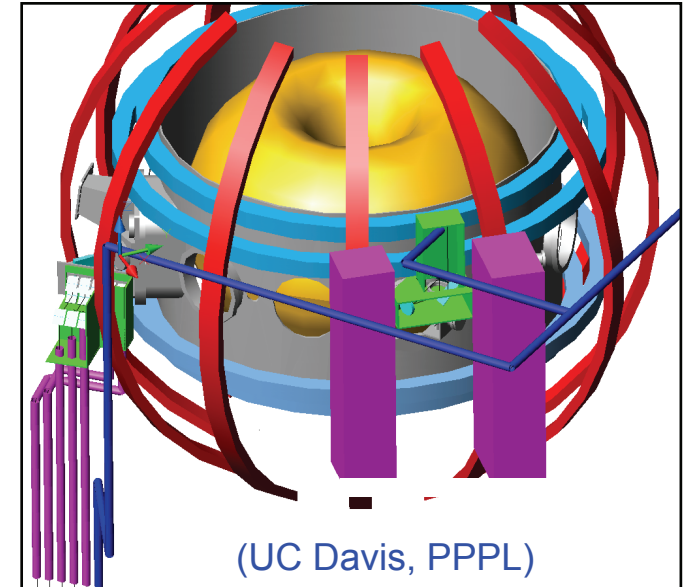
- FY06: measure local high-k turbulence over wide conditions
- FY07: correlate turbulence spectra with electron transport
- FY08: measure poloidal rotation, constrain theory at low A

## ITPA

- **A-dependence**;  **$\beta$ -degradation**;  $\rho^*$ -effect; ITB; momentum transport

## Capabilities and Opportunities

- Scattering of mm wave by large  $k_r$  ( $= 2 - 20 \text{ cm}^{-1}$ ) fluctuations,  $\sim 4 \text{ cm}$  spatial resolution in large q shear
- Central  $\beta$  up to unity  $\rightarrow$  clarify electromagnetic effects
- Analyses: EFIT, NL-GS2, GTC, FULL, GYRO, TRANSP
- **Counter injection?** expanding confinement parameter space



# Macroscopic Stability Studies Advance Control of Pressure-Limiting Modes via ITER-Like Control Coils



## Motivation

- Determine maximum pressure that can be achieved in laboratory plasmas – benefits ITER and CTF

## Milestones

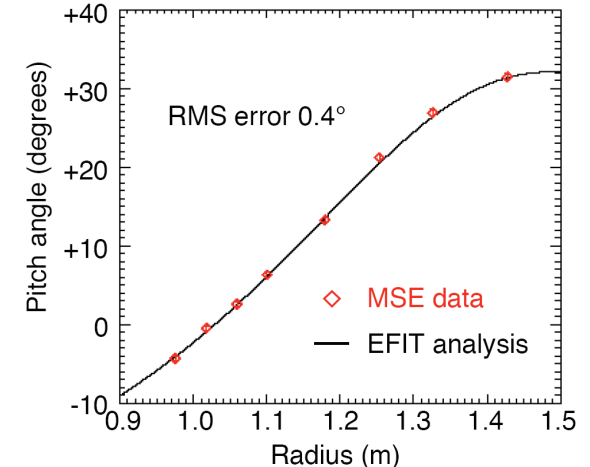
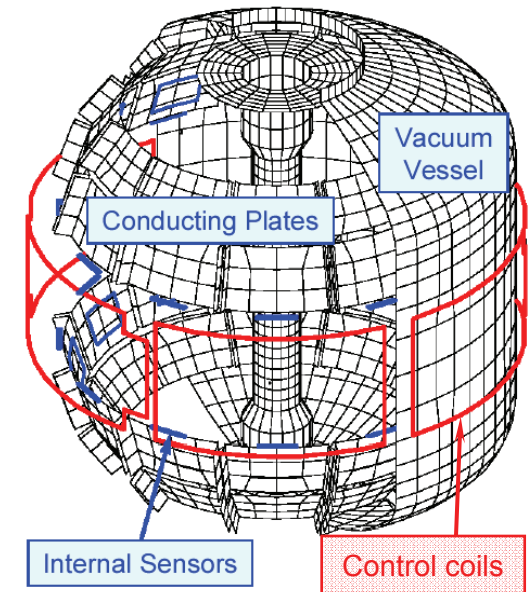
- FY06: correlate resonant error field amplification, locked mode,  $\beta$
- FY07: explore very high  $\beta$  regime close to wall-stabilized limit!

## ITPA

- RWM control; NTM; **Super-Alfvénic ions**; disruption physics; sawtooth physics; low- $\beta$  error field

## Capabilities and Opportunities

- Ex-vessel control coils, SPA power, internal sensors, with feedback capabilities → U.S. proposed coil set on ITER
- Improved shaping ( $\kappa \leq 2.8$ ,  $\delta \leq 0.8$ )  $\Rightarrow \beta_T \leq 40\%$ ,  $\beta_N \leq 7$ ,  $I_N \leq 7$ , low  $l_i (\geq 0.7)$
- Resolve mode dynamics via  $\beta_0 \rightarrow 1$ ,  $V_\phi/V_S \leq 0.8$ ,  $V_\phi/V_A \leq 0.4$ ,  $V_\phi' \sim 10^5/s \rightarrow \gamma_{MHD}$
- Analysis: EFIT- $V_\phi$ -isotherm-MSE, VALEN, MARS, M3D, ...



# Wave-Particle Research Will Make Unique Contributions to Supra-Alfvénic Ion Driven Modes Expected in ITER



## Motivation

- Establish physics basis for super-Alfvénic fusion  $\alpha$ 's in burning plasmas – needed by ITER and CTF

## Milestone

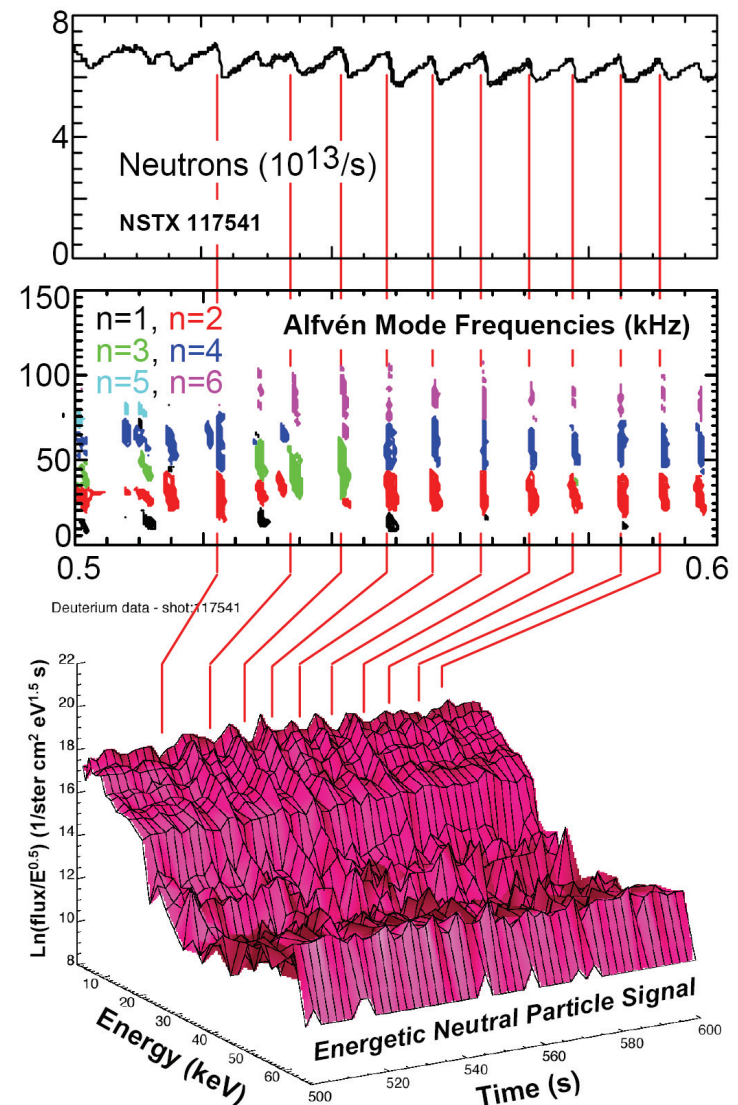
- FY07 **DOE JOULE milestone**: measure, identify & characterize modes driven super-Alfvénic ions

## ITPA

- Beam ion-driven \*AE's and fast ion redistribution

## Capabilities and Opportunities

- NSTX measured, in the ITER the super-Alfvénic regime, range of \*AE's driven by super-Alfvénic ions
- Multi-mode bursts correlated with loss of these ions
- Extensive measurements of modes, fast ions, profiles planned
- **EBW**: B-X-O emission @ 20-40 GHz, potential of Ohkawa current drive & electron phase space science – CTF, Demo
- Decisions on EBW requirements and plan: end of FY06
- **HHFW**: Understand edge coupling (parametric and RF sheath effects) and optimize HHFW scenario – relevant to ITER ICRF



# Solenoid-Free Start-up Tests Are Uniquely Important to ST-CTF Development



## Motivation

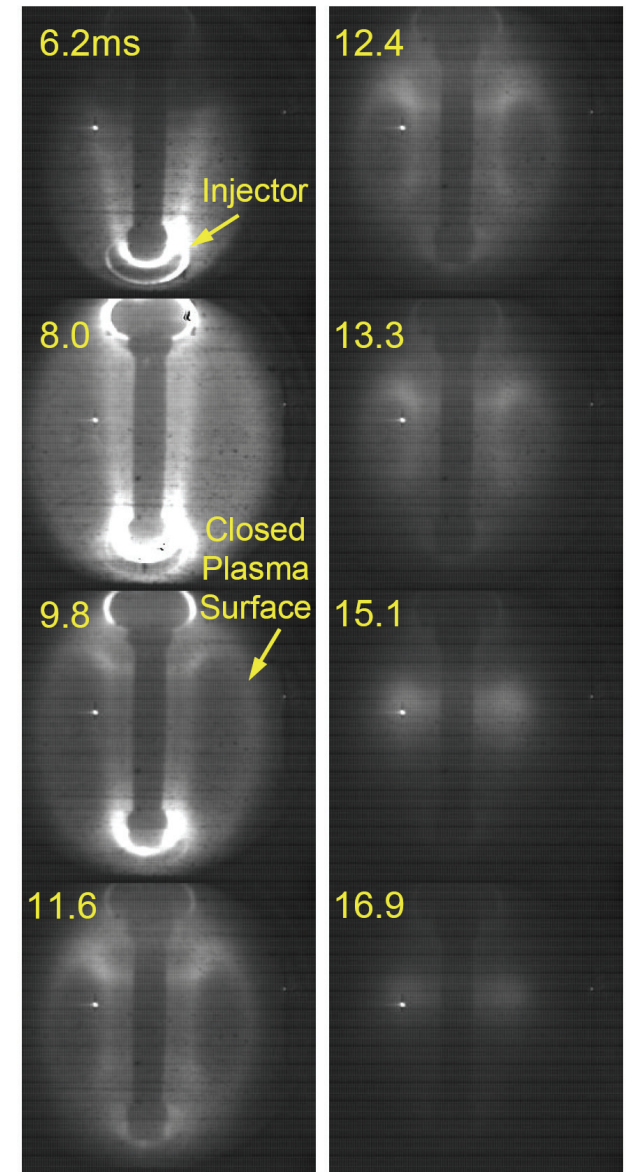
- Required for compact ST such as CTF ; Low A  $\rightarrow$  low internal magnetic flux and helicity helps
- Potentially important to tokamak reactor attractiveness

## Milestones

- FY06: assess requirement for CHI creation of closed magnetic flux
- **NSTX** (transient CHI to 60 kA); **HIT-II** (CHI to 200 kA)
- Determine conditions for “hand-off”

## Capabilities and Opportunities

- Collaboration:
  - **TST-2, LATE** (ECH,  $I_p = 10$  kA =  $0.15 I_{TF}$ , sustained)
  - **Pegasus** (plasma gun,  $I_p = 26$  kA =  $2I_{TF}$ , sustained)
  - **JT-60U** (EC+VF ramp to  $I_p = 180$  kA; EC+NB ramp to  $I_p = 310$  kA; NBI B/S over-drive @  $I_p = 600$  kA sustained for 0.5 s)
  - **MAST** (merging-compression, to 500 kA)
- Continue study of HHFW heating at low density and current



# Boundary Physics Studies Aim to Understand Pedestal-SOL Science of High-P/R Plasmas Relevant to ITER



## Motivation

- Predict SOL and H-mode pedestal properties with high confidence; develop solutions for high P/R operation – needed by ITER and CTF

## Milestones

- FY06: characterize effects of Li wall coating on recycling
- FY08: Study edge/divertor plasmas with ITER-level heat fluxes

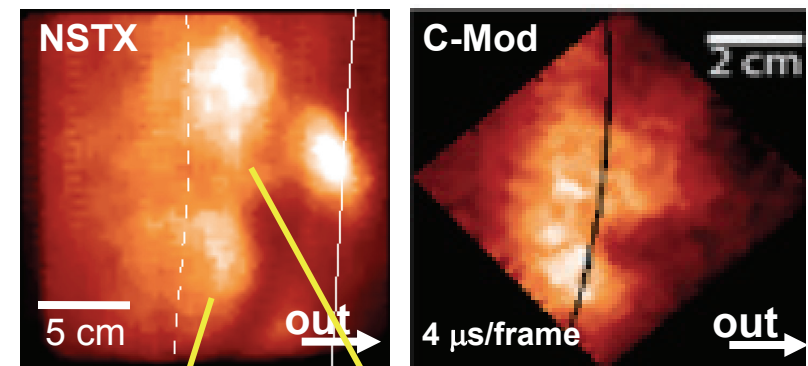
## ITPA

- Pedestal similarity; small ELM comparison; “blob” characteristics comparison; radial flux from ELMs; impurity migration and deposition

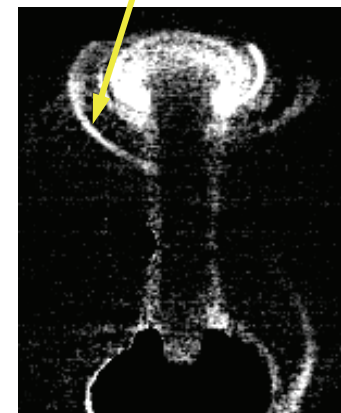
## Capabilities and Opportunities

- Li evaporator coating → CTF relevant low  $n/n_{GW}$  and low  $v^*$
- Short SOL connection, large P/R → ITER-relevant divertor heat flux  $\sim 10 \text{ MW/m}^2$
- Supersonic gas jet, edge TS, PGI, movable probe
- Analysis: BOUT, ELITE, UEDGE, DEGAS2

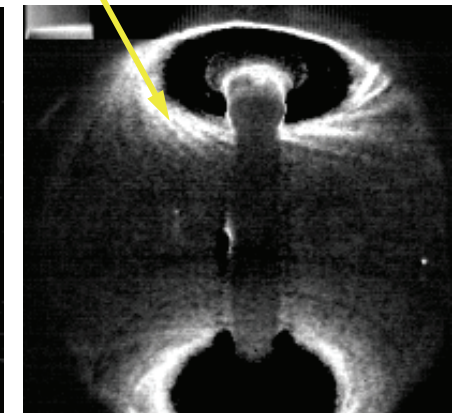
## Gas Puff Magnig (GPI)



## Small ELM



## Large ELM



# Integrated Scenario Studies Contribute to ITER Hybrid Mode and Future ST-CTF



High-Performance Sustained Plasma via PF1A Mod

## Motivation

- Understand self-organization & external control, enabling high-pressure sustained plasmas – relevant to ITER “hybrid” mode and CTF

## Milestones

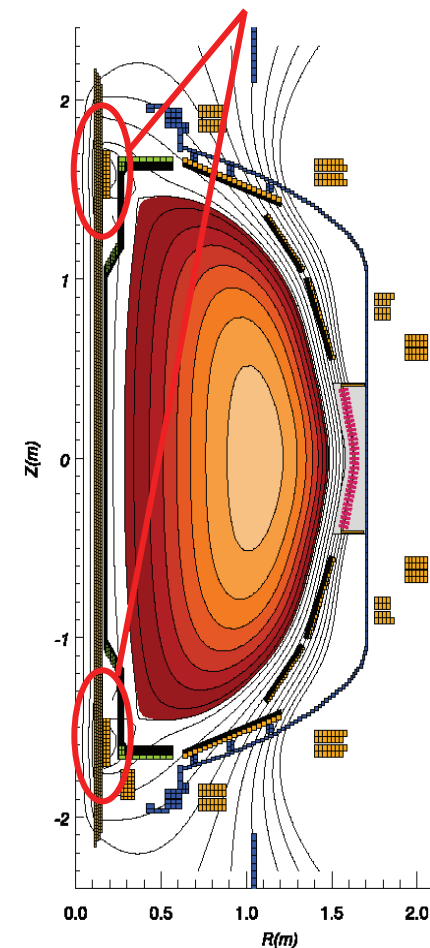
- FY08: perform long-pulse plasmas in conditions relevant to ST-CTF

## ITPA

- Mapping of ITER hybrid scenario; MHD effects on  $q$  profile and confinement;  $\rho^*$  effects

## Capabilities and Opportunities

- Substantial progress during 2005
- Determine conditions for surface  $V_L = 0$  long-pulse operation, though  $q_0$  may evolve
- Minimize magnetic flux consumption during ramp-up
- Benchmark simulation models & codes



# FY06 Run Will Maximize Relevance of Run Days Simultaneously to ST, ITPA, and Tokamak



1. FY06 research milestones (49%)
  - Lithium evaporator coating effects first
2. Present ITPA goals (38%)
3. Uniquely ST driven (26%)
4. Additional goals (36%)
  - Enabling tokamak-relevant
  - FY06 decisions
  - FY07-08 research milestones
  - Future ITPA goals
5. Contingency – mid-term assessment (25%, 14 days)

**Relevance of 41 allocated days :**  
100% → ST  
49% → Milestones  
38% → ITPA  
74% → Tokamak  
26% → Uniquely ST driven



# Remaining Presentations Will Show How We Achieve These Research Priorities



- **M Ono**                      **Facility Plans**
- **M Bell**                      **Turbulence & Transport**
- **S Kaye**                      **Confinement Scaling & ITER Relevance**
- **A Sontag**                      **Macro-stability**
- **E Fredrickson**              **Super-Alfvénic Ion Driven Instabilities and Transport**
- **G Taylor**                      **EBW & HHFW (including Pegasus)**
- **D Mueller**                      **Transient CHI**
- **H Kugel**                      **Li Wall Coating & Recycling Control**
- **R Maingi**                      **Boundary Physics**
- **D Gates**                      **Toward Stable Steady State Operation & Rampup**
- **R Raman**                      **Run Plan for FY06**

# Handout: NSTX Makes Important Contributions to ITPA Leveraging Special Properties and Capabilities



ID No	Topical Group	2006 Proposal Title	Devices	NSTX Lead	C-Mod	DIII-D
CDB-2	Conf DB & Mod	Confinement scaling in ELMy H-modes: $\beta$ degradation	AUG, DIII-D, JET, JT-60U, Tore-Supra(L), MAST, NSTX	<b>Kaye</b> skaye@pppl.gov		<b>2007</b>
CDB-6	Conf DB & Mod	Improving the condition of Global ELMy H-mode and Pedestal databases: Low A	MAST, NSTX, DIII-D	<b>Kaye</b>		<b>2007</b>
CDB-8	Conf DB & Mod	$\rho^*$ scaling along an ITER relevant path at both high and low beta	JET, DIII-D, C-mod, AUG, NSTX	<b>Kaye</b>	Y	<b>2006</b>
CDB-9	Conf DB & Mod	Density profiles at low collisionality	JET, DIII-D, C-mod, AUG, JT-60U, TCV, Tore-Supra, MAST, FTU, NSTX, T-10	<b>Lee (piggyback)</b> klee@pppl.gov	Y	<b>2007</b>
TP-6.3	Transport Physics	NBI-driven momentum transport study	DIII-D, JT-60U, NSTX, MAST, JET	<b>Peng</b> mpeng@pppl.gov		<b>2006</b>
TP-8.1	Transport Physics	ITB Similarity Experiments	MAST, NSTX	<b>Peng (p, complete)</b>		
TP-9	Transport Physics	H-mode aspect ratio comparison	NSTX, DIII-D, MAST, T-10	<b>Kaye</b>		<b>2007</b>
PEP-9	Pedestal and Edge	Pedestal similarity study	DIII-D, MAST, NSTX	<b>Maingi</b> rmaingi@pppl.gov		<b>2005, 2007</b>
PEP-10	Pedestal and Edge	The radial efflux at the mid-plane and the structure of ELMs	AUG, MAST, NSTX, C-mod	<b>Maingi</b>	Y	
PEP-16	Pedestal and Edge	Small ELM regime comparison	NSTX, MAST, C-mod	<b>Maingi</b>	Y	
DSOL-15	Divertor & SOL	Inter-machine comparison of blob characteristics	C-Mod, NSTX, TJ-II, JET, TCV, HT 7, Tore-Supra, AUG, JT-60U	<b>Zweben (p)</b> szweben@pppl.gov	Y	
DSOL-18	Divertor & SOL	Impurity migration and deposition study	NSTX, AUG, JET	<b>Skinner</b> cskinner@pppl.gov		

# Handout: NSTX Makes Important Contributions to ITPA Leveraging Special Properties and Capabilities



MDC-2	MHD, Disruptions & Control	Joint experiments on resistive wall mode physics	DIII-D, JET (experiments scheduled Feb 06), NSTX, JT-60U, AUG and TEXTOR	<b>Sabbagh</b> ssabbagh@pppl.gov		<b>2007</b>
MDC-4	MHD, Disruptions & Control	Neoclassical tearing mode physics - aspect ratio comparison	AUG, MAST, NSTX, DIII-D	<b>Fredrickson</b> efredrickson@pppl.gov		<b>2007</b>
MDC-5	MHD, Disruptions & Control	Comparison of sawtooth control methods for neoclassical tearing mode suppression	AUG, DIII-D, JET, NSTX, TCV and HL2A, C-mod, FTU	<b>Menard (p)</b> jmenard@pppl.gov	Y	<b>2007</b>
MDC-6	MHD, Disruptions & Control	Low beta error field experiments	C-mod, TEXTOR, MAST, DIII-D, NSTX, JET(done)	<b>Menard</b>	Y	<b>2006</b>
MDC-9	MHD, Disruptions & Control	Fast ion redistribution by beam driven Alfvén modes and excitation threshold for Alfvén cascades	JT-60U, JET, DIII-D, NSTX, MAST, AUG	<b>Fredrickson</b>		<b>2006</b>
SSO-2.1	Steady-State Operation	Complete mapping of hybrid scenario	JET, JT-60U, DIII-D, AUG, NSTX, C-mod	<b>Kessel (p)</b> ckessel@pppl.gov	Y	<b>2006</b>
SSO-2.2	Steady-State Operation	MHD effects on q-profile and confinement for hybrid scenarios	AUG, JET, DIII-D, JT-60U, NSTX, C-mod	<b>Menard</b>	Y	<b>2006</b>
SSO-2.3	Steady-State Operation	$\rho^*$ dependence on confinement, transport and stability in hybrid scenarios	DIII-D, JET, AUG, JT-60U, C-mod, NSTX	<b>Kaye (p)</b>	Y	<b>2006</b>
DIAG-1	Diagnostics	Assessment of the effect of noise on vertical velocity measurement	JET, JT-60U, TCV, NSTX, AUG, C-mod	<b>Gates (p)</b> dgates@pppl.gov		<b>2007</b>
DIAG-2	Diagnostics	Environmental tests on Diagnostic First Mirrors (FMs)	T-10, TEXTOR, Tore-Supra, JET, DIII-D, TCV, AUG, LHD, FTU, NSTX, C-mod, JT-60U	<b>Skinner</b>	Y	<b>2007</b>