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NSTX Program Strategy and Research Priorities

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Martin Peng
On Behalf of the NSTX Team

NSTX PAC-19th Meeting
February 22 – 24, 2006

Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
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ENEA, Frascati
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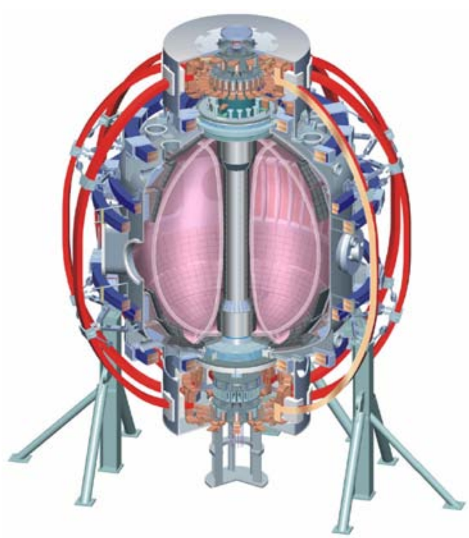
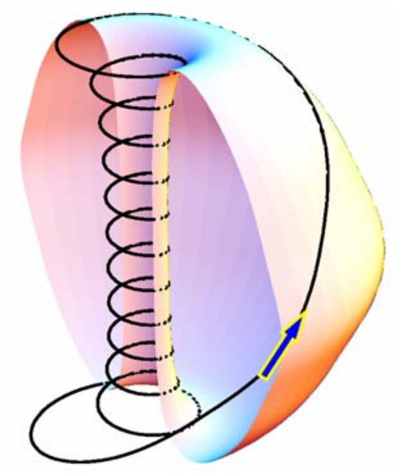


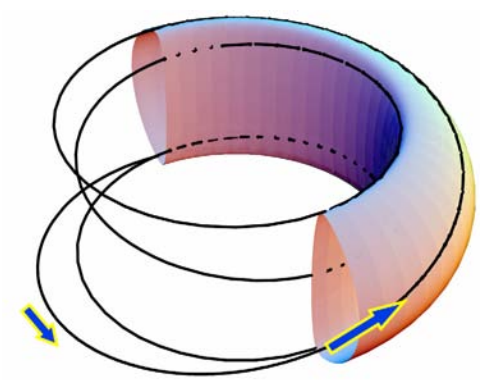
NSTX Strategy Is to Address Issues Important for Fusion Energy Sciences Using Special ST Properties

- Determine the physics principles of Spherical Torus / Spherical Tokamak, utilizing its low aspect-ratio A ~ 1.5 and very high β
- Support preparation for burning plasma research in ITER through the ITPA and benefit from it
- Complement and extends A ~ 3 and lower β 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 β Experiments in Advancing Toroidal Plasma Science



ST



Tokamak

MHD theory

- Strong plasma shaping, self fields, rotation (vertical elongation ~ 3, $B_p/B_t \sim 1$, $M_A \leq 0.4$)
- Very high β_T (~ 0.4), β_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 ($\varepsilon = \omega_{pe}^2/\omega_{ce}^2 \sim 50$)

Edge and boundary

- High divertor heat flux
- Large SOL area expansion

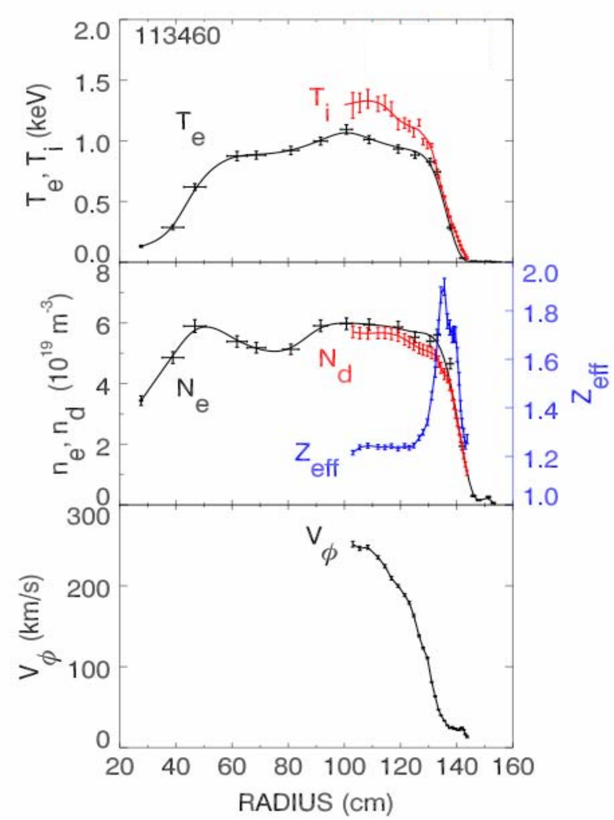
ST Research Supports, Supplements, and Benefits from ITER

Spherical Torus	Supports	Supplements	Benefits from
Stability	Stabilization by active feedback & flow; physics and scaling.	Extends studies to higher beta, flow, S (qI/aB), low aspect ratio. Current startup.	ELMs at low collisionality ν^*
Energetic Particles	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.
Transport	Tests turbulence with powerful electron heating, unique diagnostics.	Extends transport studies to higher beta, flows.	Transport at low collisionality ν^*
Plasma-wall	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 m, a = 0.8 m, κ = 3.2, B_T = 2.5 T, I_p ~ 10 MA

Sustained Parameters	CTF ($\tau >> \tau_{skin}$)	NSTX H-mode (κ ~ 2.4, $\tau \leq 3\tau_{skin}$)
I_p/aB_T (MA/m-T)	≤6.4	≤4.4
Safety factor, q_{cyl}	≥3.0	≥2.3
β_N (%-m-T/MA)	≤3.9	≤5.5
β_T (%)	≤24	≤25
Avg. a/ρ_i (=1/ρ_i*)	~90	~60
Avg. collisionality, ν*	~0.001	~0.08
τ_{Ei} / τ_{Ee}	?	~5
n/n_{GW}	~0.2	0.3 – 0.8



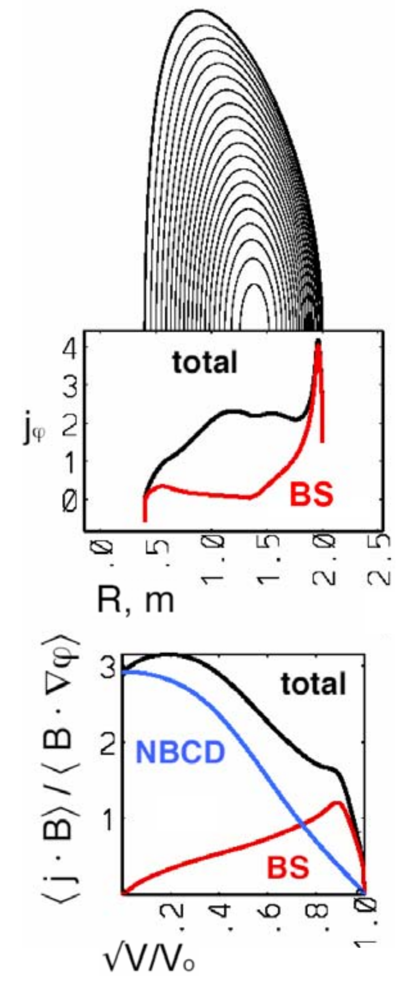
NSTX Investigations

- **Macro-stability: $\kappa \leq 2.8$ and $\tau >> \tau_{skin}$; EF / RWM control with large V_ϕ**
- **Confinement: ρ* and ν* (B, I_p, n, κ) scaling; electron-scale turbulence and transport**
- **Recycling control: lithium wall coating via evaporator → operation at low n/n_{GW}?**

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

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

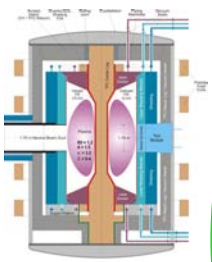
6

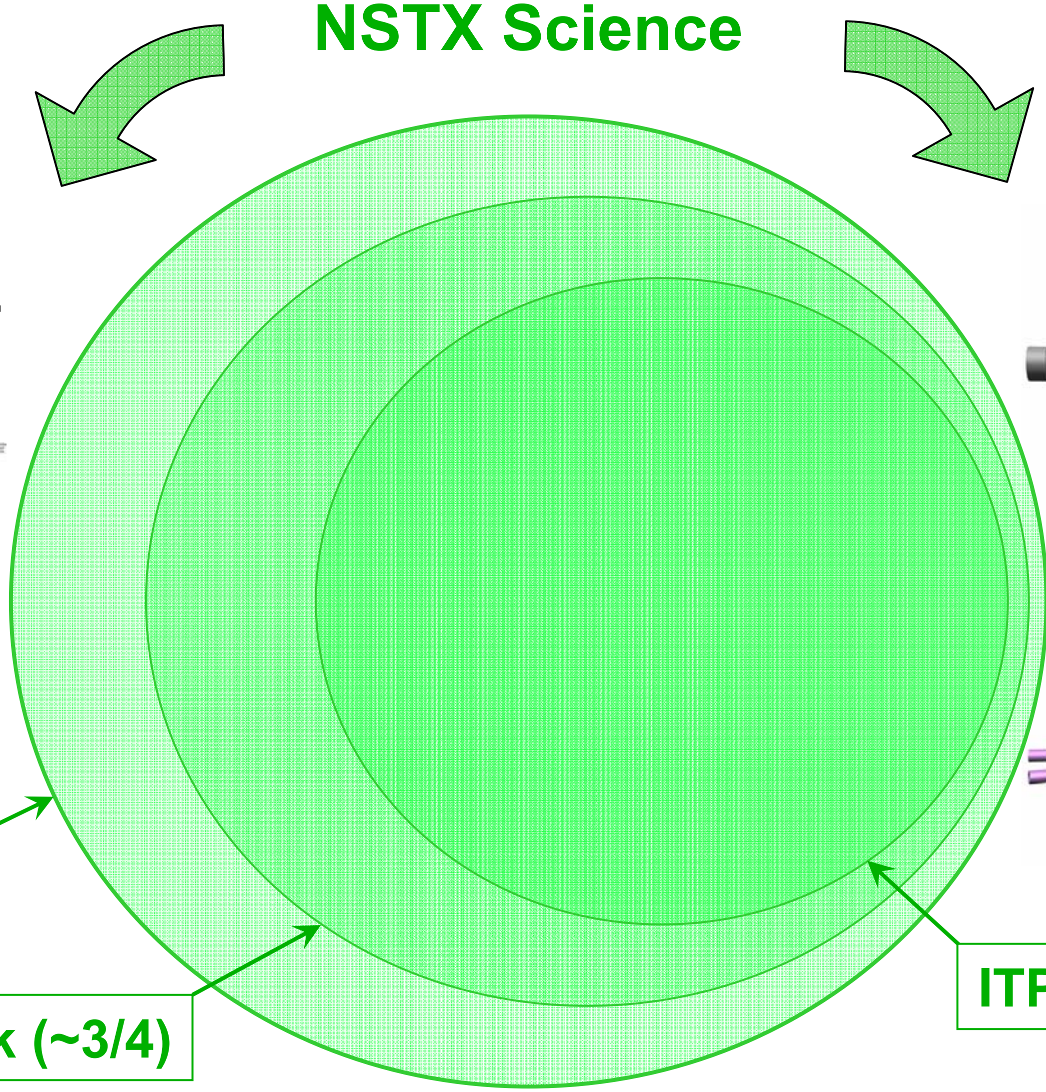
NSTX Science Naturally Supports ST Specific and Burning Plasma Needs

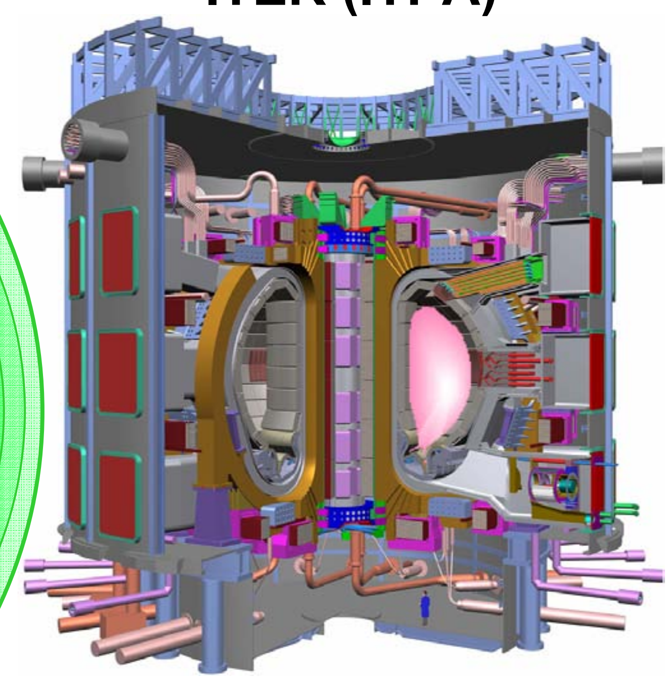
NSTX Science

ITER (ITPA)

ST CTF







ST (All)

Tokamak (~3/4)

ITPA (~1/3)

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

	FY06	FY07	FY08
Exp. Run-Weeks:	11	12	10
1) Transport & Turbulence: Physical processes that govern heat, particle and momentum confinement			
	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
2) Macroscopic Stability: Role of magnetic structure on plasma pressure and bootstrap current			
	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	
3) Wave-Particle Interaction: Role of electromagnetic waves & modes in sustaining and controlling hot plasmas			
		**Measure, identify & characterize modes driven by super-Alfvénic ions	
4) Start-up, Ramp-up and Sustainment: Physical processes of magnetic flux generation and reconnection			
	Assess requirement for CHI creation of closed magnetic flux		
5) Boundary Physics: Interface between fusion plasmas and normal temperature surroundings			
	*Characterize effects of Li wall coating on recycling		Study edge/divertor at low ν^* with ITER-level heat fluxes
6) Physics Integration: Synergistic effects of external control and self-organization			
			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

NSTX

	FY06	FY07	FY08
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	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
2) Macroscopic Stability: Role of magnetic structure on plasma pressure and bootstrap current			
	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	
3) Wave-Particle Interaction: Role of electromagnetic waves & modes in sustaining and controlling hot plasmas			
		**Measure, identify & characterize modes driven by super-Alfvénic ions	
4) Start-up, Ramp-up and Sustainment: Physical processes of magnetic flux generation and reconnection			
	Assess requirement for CHI creation of closed magnetic flux		
5) Boundary Physics: Interface between fusion plasmas and normal temperature surroundings			
	*Characterize effects of Li wall coating on recycling		Study edge/divertor at low ν^* with ITER-level heat fluxes
6) Physics Integration: Synergistic effects of external control and self-organization			
			Perform long-pulse plasmas in conditions relevant to CTF

Decision Points: Particle pumping & fueling
EBW, pre-ionization source

**OFES "Tracked" Milestone* ***DOE "JOULE" Milestone*

Transport Studies Emphasizes High-k Turbulence and Transport, Leveraging Large β, ρ^*, 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**; **β-degradation**; **ρ^*-effect**; ITB; momentum transport

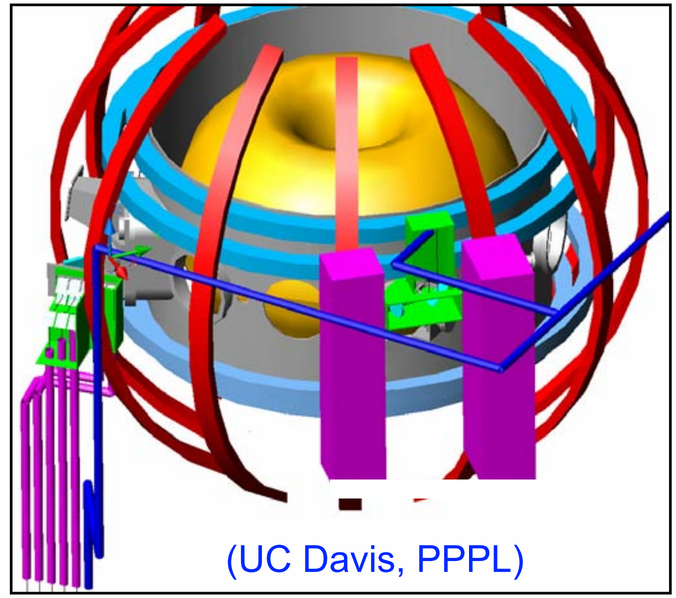
Capabilities and Opportunities

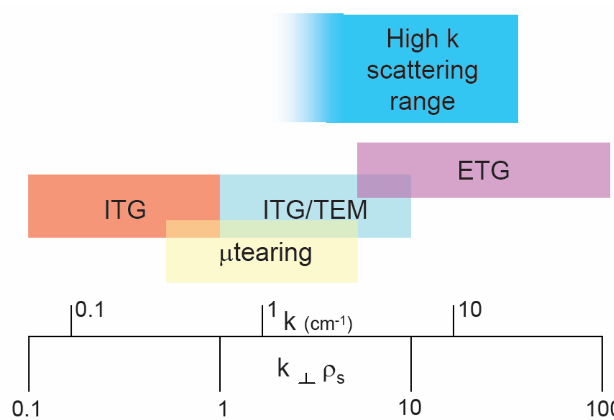
– Scattering of mm wave by large k_r (= 2 – 20 cm^{-1}) fluctuations, ~ 4 cm spatial resolution in large q shear

– Central β 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

NSTX

Motivation

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

Milestones

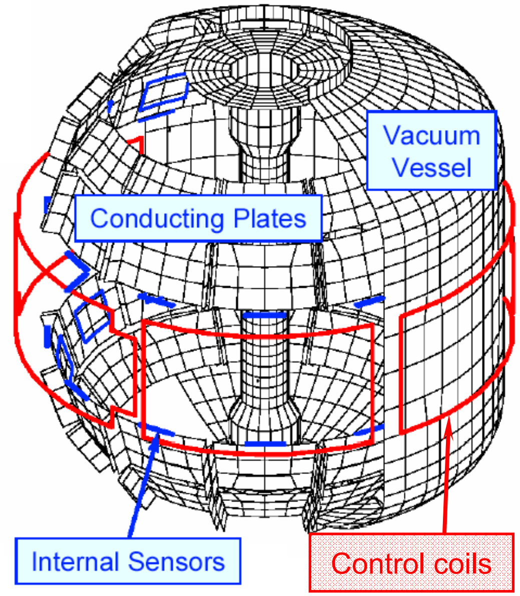
- FY06: correlate resonant error field amplification, locked mode, β
- FY07: explore very high β regime close to wall-stabilized limit!

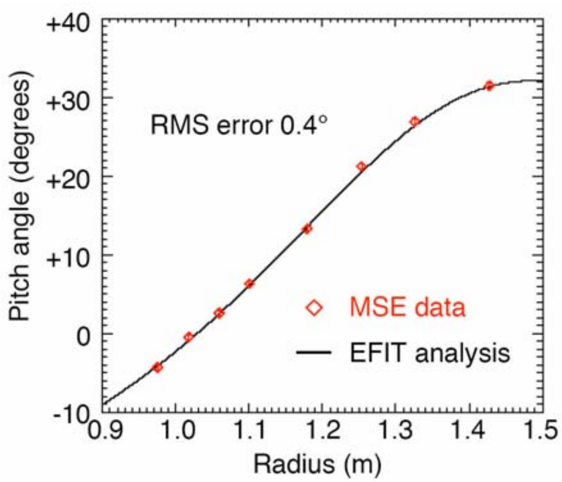
ITPA

- RWM control; NTM; **Super-Alfvénic ions**; disruption physics; sawtooth physics; low-β error field

Capabilities and Opportunities

- Ex-vessel control coils, SPA power, internal sensors, with feedback capabilities $\rightarrow$ 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 (≥ 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_ϕ-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 α's in burning plasmas – needed by ITER and CTF

Milestone

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

ITPA

– **Super-Alfvénic ions: driven *AE's and redistribution**

Capabilities and Opportunities

– NSTX measured, in the ITER the super-Alfvénic regime, range of *AE's driven by super-Alfvénic ions

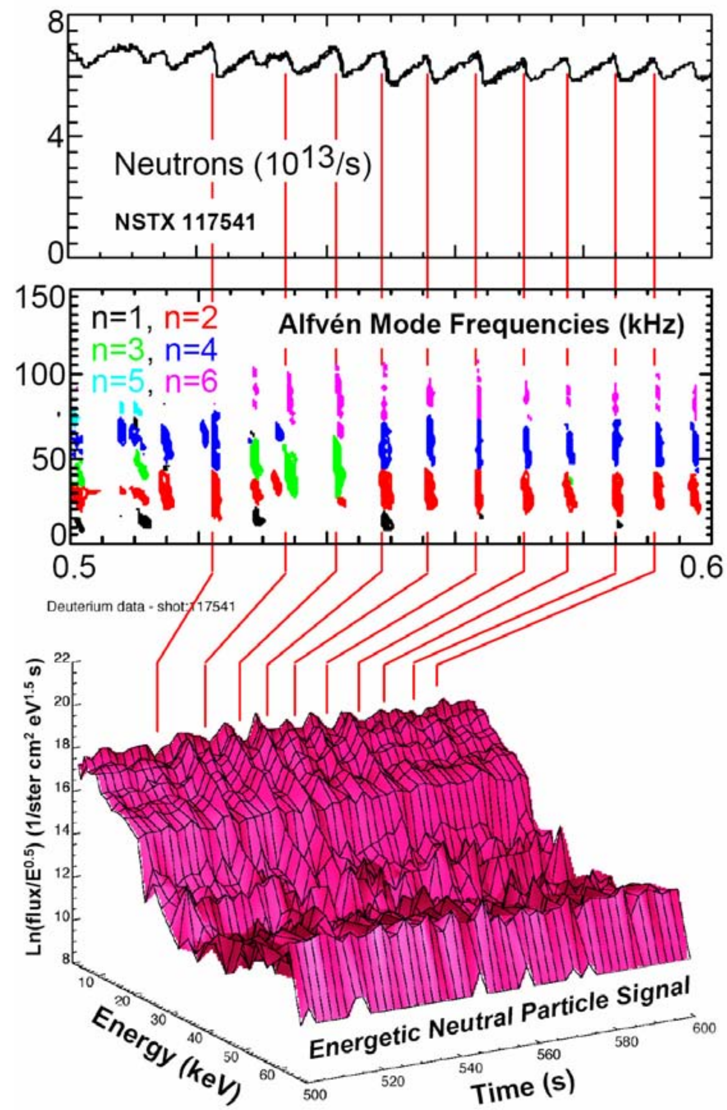
– Multi-mode bursts correlated with loss of these ions

– 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

NSTX

Motivation

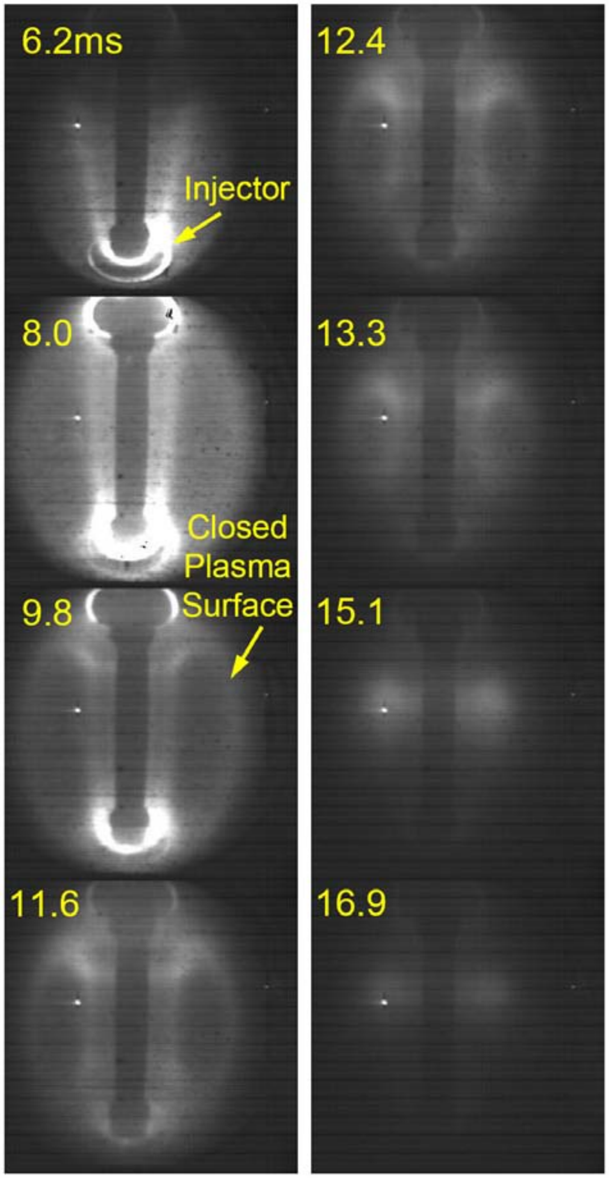
- Required for compact ST such as CTF ; Low A → low internal magnetic flux and helicity helps
- Potentially important to tokamak reactor attractiveness

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/EBW**, 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 Ip = 180kA; EC+NB ramp to Ip = 310 kA; NBI B/S over-drive @ Ip = 600 kA sustained for 0.5 s)
  - MAST (merging-compression, to 500 kA)
- Continue study of early HHFW heating at low n and current; **higher $k_{||}$ antenna**?



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

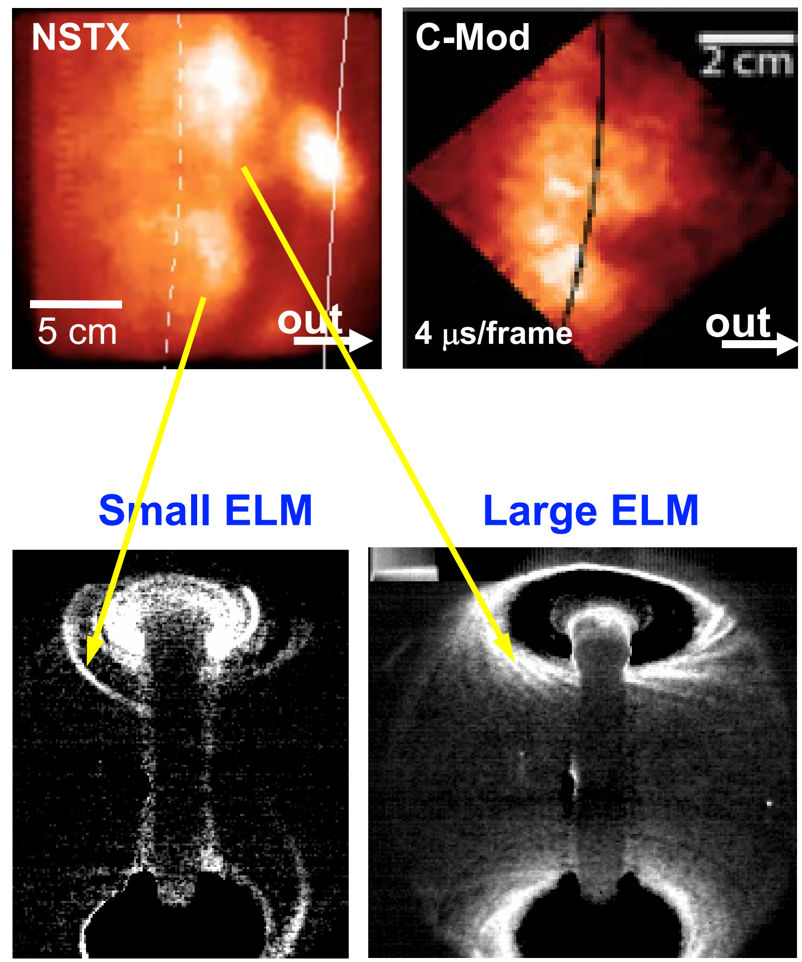
– Li evaporator coating → CTF relevant low n/n_{GW} and low ν^*

– Short SOL connection, large P/R → ITER-relevant divertor heat flux ~ 10 MW/m^2

– Supersonic gas jet, edge TS, PGI, movable probe

– Analysis: BOUT, ELITE, UEDGE, DEGAS2

Gas Puff Imagnig (GPI)



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

NSTX

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

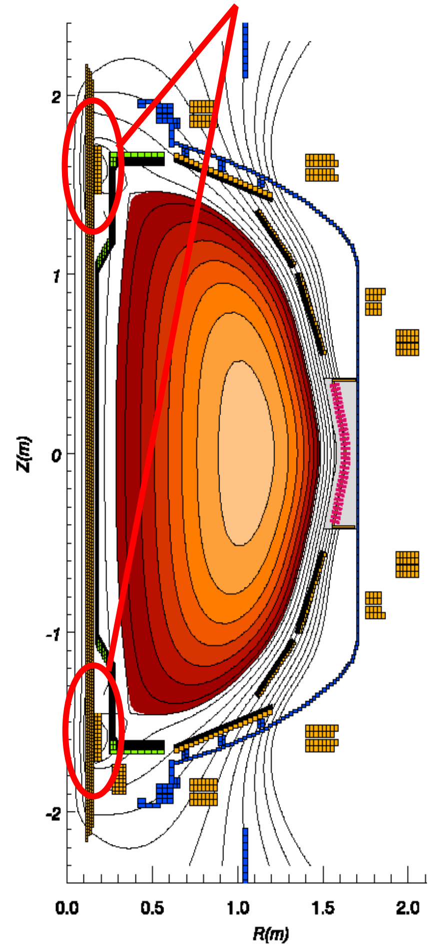
ITPA

- Mapping of ITER hybrid scenario; MHD effects on q profile and confinement; ρ* **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

High-Performance Sustained Plasma via PF1A Mod



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	Macrostability
• 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: β degradation	AUG, DIII-D, JET, JT-60U, Tore-Supra(L), MAST, NSTX	**Kaye**		**2007**
CDB-6	Conf DB & Mod	Improving the condition of Global ELMy H-mode and Pedestal databases: Low A	MAST, NSTX, DIII-D	**Kaye**		**2007**
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	**Kaye**	**Greenwald**	**Petty**
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	**Lee (piggyback)**	**Ernst Snipes**	**2007**
TP-6.3	Transport Physics	NBI-driven momentum transport study	DIII-D, JT-60U, NSTX, MAST, JET	**Peng**		**Gohil**
TP-8.1	Transport Physics	ITB Similarity Experiments	MAST, NSTX	**Peng (p, complete)**		
TP-9	Transport Phsyics	H-mode aspect ratio comparison	NSTX, DIII-D, MAST,T-10	**Kaye**		**2007**
PEP-9	Pedestal and Edge	Pedestal similarity study	DIII-D, MAST, NSTX	**Maingi**		**2005, 2007**
PEP-10	Pedestal and Edge	The radial efflux at the mid-plane and the structure of ELMs	AUG, MAST, NSTX, C-mod	**Maingi**	**Terry**	
PEP-13	Pedestal and Edge	Comparison of small ELM regimes in JT-60U and AUG and JET	AUG, JT-60U, JET, NSTX	**Maingi**		
PEP-16	Pedestal and Edge	Small ELM regime comparison	NSTX, MAST, C-mod	**Maingi**	**Hubbard**	
DSOL-15	Divertor & SOL	Inter-machine comparison of blob characteristics	C-Mod, NSTX, TJ-II,JET, TCV, HT-7, Tore-Supra, AUG, JT-60U	**Zweben**	**Terry**	

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

DSOL-18	Divertor & SOL	Impurity migration and deposition study	NSTX, AUG, JET	**Skinner**		
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	**Sabbagh**		**2007**
MDC-4	MHD, Disruptions & Control	Neoclassical tearing mode physics - aspect ratio comparison	AUG, MAST, NSTX, DIII-D	**Fredrickson**		**2007**
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	**Menard (p)**	**Y**	**2007**
MDC-6	MHD, Disruptions & Control	Low beta error field experiments	C-mod, TEXTOR, MAST, DIII-D, NSTX, JET(done)	**Menard**	**Wolfe**	**Scoville**
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	**Fredrickson**		**Heidbrink Nazikian**
SSO-2.1	Steady-State Operation	Complete mapping of hybrid scenario	JET, JT-60U, DIII-D, AUG, NSTX	**Kessel**		**Wade**
SSO-2.2	Steady-State Operation	MHD effects on q-profile and confinement for hybrid scenarios	AUG, JET, DIII-D, JT-60U, NSTX	**Menard**		**Wade**
SSO-2.3	Steady-State Operation	ρ^* dependence on confinement, transport and stability in hybrid scenarios	DIII-D, JET, AUG, JT-60U, NSTX	**Kaye**		**Petty**
DIAG-1	Diagnostics	Assessment of the effect of noise on vertical velocity measurement	JET, JT-60U, TCV, NSTX, AUG	**Gates** dgates@pppl.gov		**2007**
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	**Skinner**		**2007**