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NSTX Research Results and Plans for FY2008-2010

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For the NSTX Research Team

FY2010 OFES Budget Planning Meeting

Gaithersburg, MD

March 11-12, 2008

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The ST can contribute to all Greenwald panel "Themes"

A. Creating predictable high-performance steady-state (burning) plasmas
   - Measurement
   - Integration of high-performance, steady-state, burning plasmas
   - Validated predictive modeling
   - Control
   - Off-normal plasma events
   - Plasma modification by auxiliary systems
   - Magnets

ST offers simplified, maintainable, affordable magnets for DEMO

B. Taming the plasma material Interface (PMI)

ST offers high heat flux at small size and cost for PMI R&D

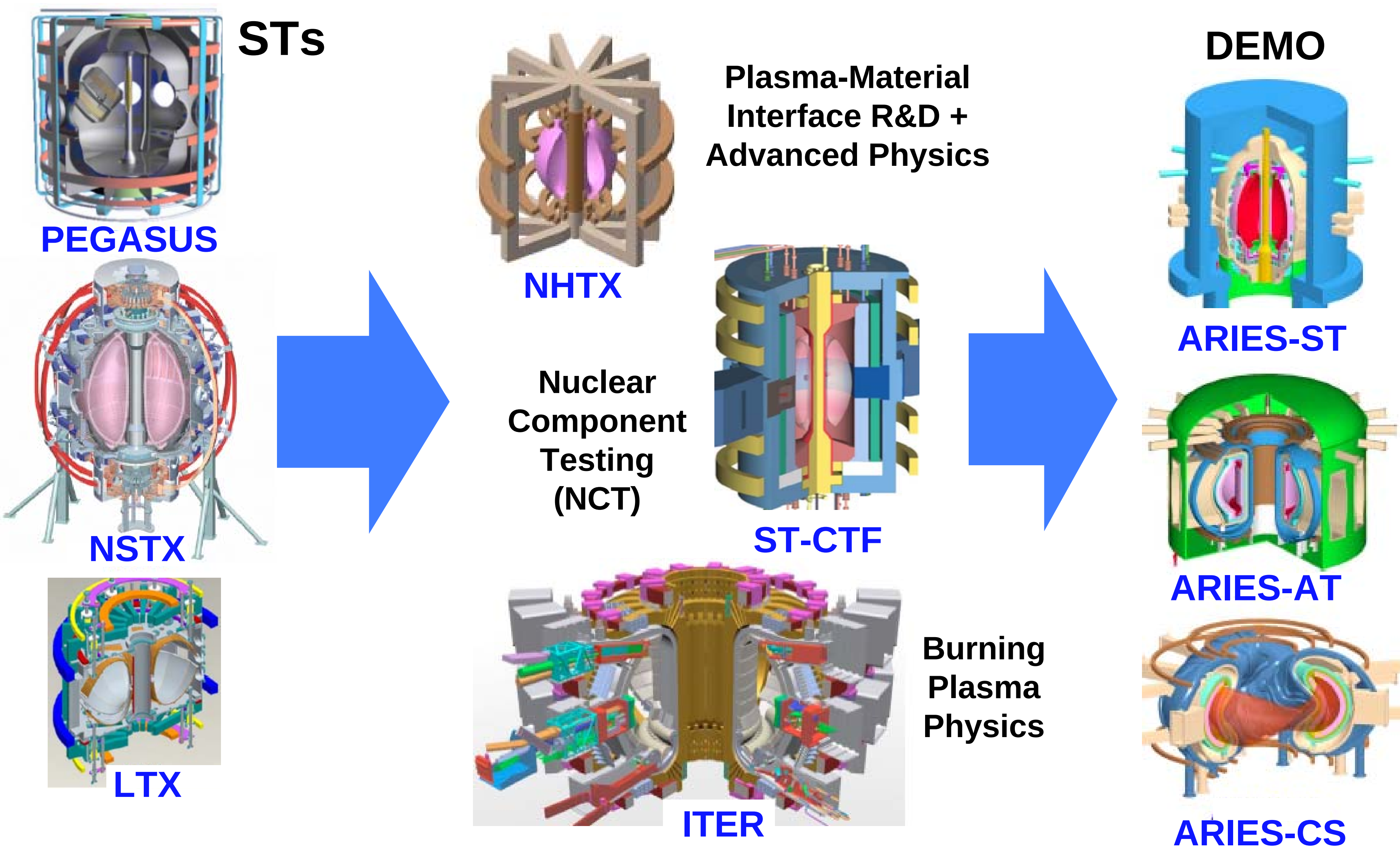
   - Plasma wall interactions
   - Plasma facing components
   - RF antennas, launching structures, and other internal structures

C. Harnessing fusion power

ST offers high neutron flux at small size and cost for testing fusion nuclear components

   - Fusion fuel cycle
   - Power extraction
   - Materials science in the fusion environment
   - Safety

Next-step STs, in combination with ITER, can complement and accelerate the development paths of all DEMO concepts



Prioritization of understanding and performance gaps

Based on input from NSTX team (5yr plan), STCC discussions, PAC-23

NSTX

Next-step ST's will have ν^* 1–2 orders of magnitude lower than present ST's
→ Impacts many topical science areas: transport, MHD, boundary physics, fast-ion modes, etc.

1. Increase and understand beam-driven current at lower n_e, ν^*
   - Next-step STs ***require*** full NICD to achieve missions, NBI-CD is largest gap
   - Need to test if decreasing n_e increases NBI-CD & non-inductive fraction as assumed
     - Test if high H_{98}, β_N, f_{BS}, and sufficient fast-ion confinement are achievable at reduced n_e

2. Increase and understand H-mode confinement at low ν^*
   - Electron energy transport (to a lesser extent ion energy transport) not sufficiently well understood to make extrapolation to next-steps with high confidence
   - Need to better understand underlying physics of scalings

3. Demonstrate and understand non-inductive start-up and ramp-up
   - Non-inductive ramp-up essential to ST-CTF and ST-DEMO, benefits AT-DEMO
   - Non-inductive start-up also beneficial

4. Sustain β_N and understand MHD near and above no-wall limit
   - Operation at no-wall limit assumed as baseline for all next-step ST designs
   - Operation near ideal-wall limit is NHTX goal, enhances NCT, required for ST-DEMO

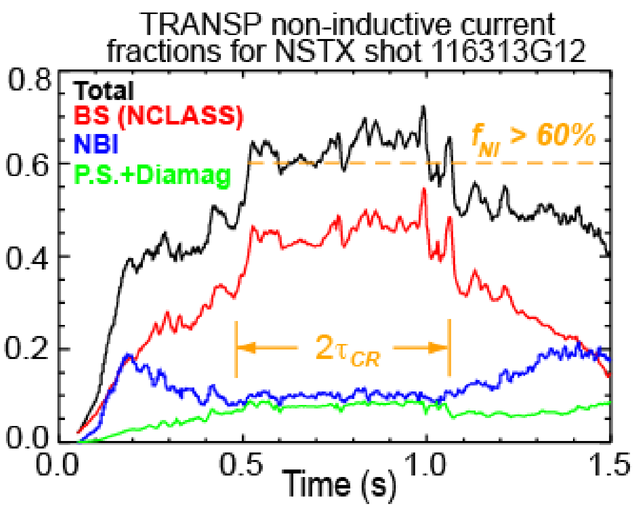
Priorities cut across FESAC-05 topical science questions and campaigns

Key scientific questions for Priority #1:

Increase & understand beam-driven current at lower n_e, ν^*

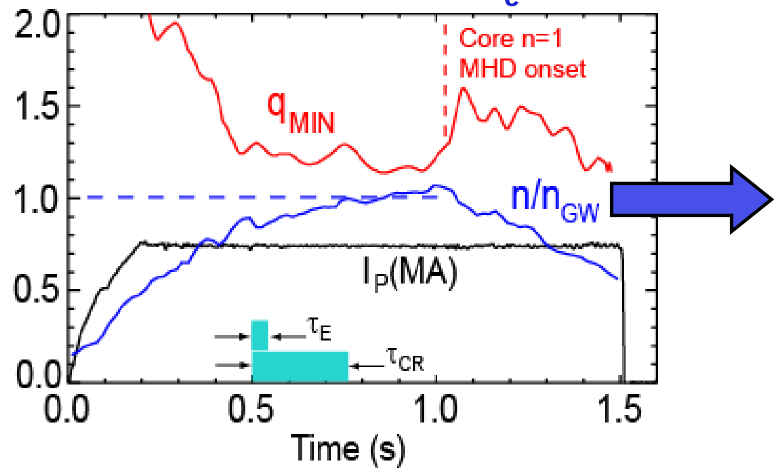
NSTX

- Next-step STs assume 25-50% f_{NBI-CD} by operating at low n_e/n_{GW} = 0.5-0.25
  - NBI-CD efficiency scales as $T_e / n_e \rightarrow 1/n_e^2$ at fixed $\beta_e \rightarrow$ favors low n_e

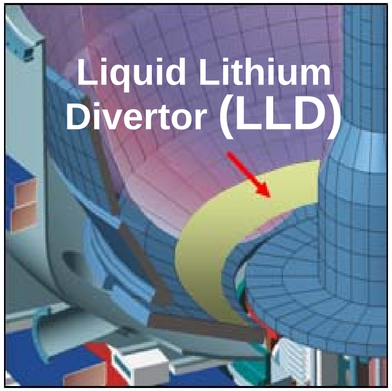


Non-inductive fraction up to 65%, but only 10-15% is from NBI-CD

NSTX needs lower n_e in H-mode to increase NBI-CD



High particle confinement + lack of pump → high n_e and low NBI-CD



LLD is estimated to reduce density 25-50% in D H-mode

- ***Key scientific questions:***
  - Does a liquid lithium divertor (LLD) pump as expected? What is impact on SOL?
  - Is NBI-CD $\propto 1/n_e^2$, or does e-transport limit ∇T_e (hence T_e) at low n_e, ν^*?
  - Will J_{NBI} be highly peaked as predicted → q_0<1, or will AEs redistribute fast ions?

Research plan for addressing Priority #1:

Increase & understand beam-driven current at lower n_e, ν^*

NSTX

- **Does a liquid lithium divertor (LLD) pump as expected? What is impact on SOL?** **(Addresses T10, T15)**

Boundary Physics:

  - Implement, utilize, and understand Liquid Lithium Divertor (LLD) module
  - Assess particle control, H/D retention w/ Lithium divertor **(FY09 Joule milestone)**
  - Study variation and control of heat flux in SOL **(FY08 milestone)**
    - Re-assess SOL widths, SOL turbulence, divertor heat-flux & mitigation after LLD implementation

- **Is NBI-CD $\propto 1/n_e^2$, or does e-transport limit ∇T_e (hence T_e) at low n_e, ν^*?** **(Addresses T3, T4, T12)**

Transport and Turbulence:

  - Compare expt. profiles, diffusivities, k-spectra to non-linear simulation **(FY10 milestone)**

Scenario Integration and Control:

  - Perform high-elongation wall-stabilized operation at lower n_e **(FY09 milestone)**
  - Compare measured NBI-CD (total and profile) to prediction

- **Will J_{NBI} be highly peaked as predicted, or will AEs redistribute fast ions?** **(Addresses T12)**

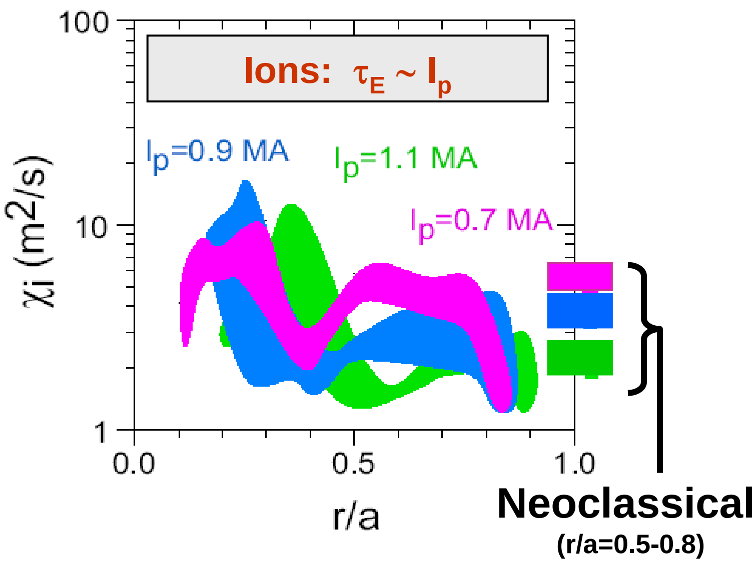
Wave-Particle Interactions:

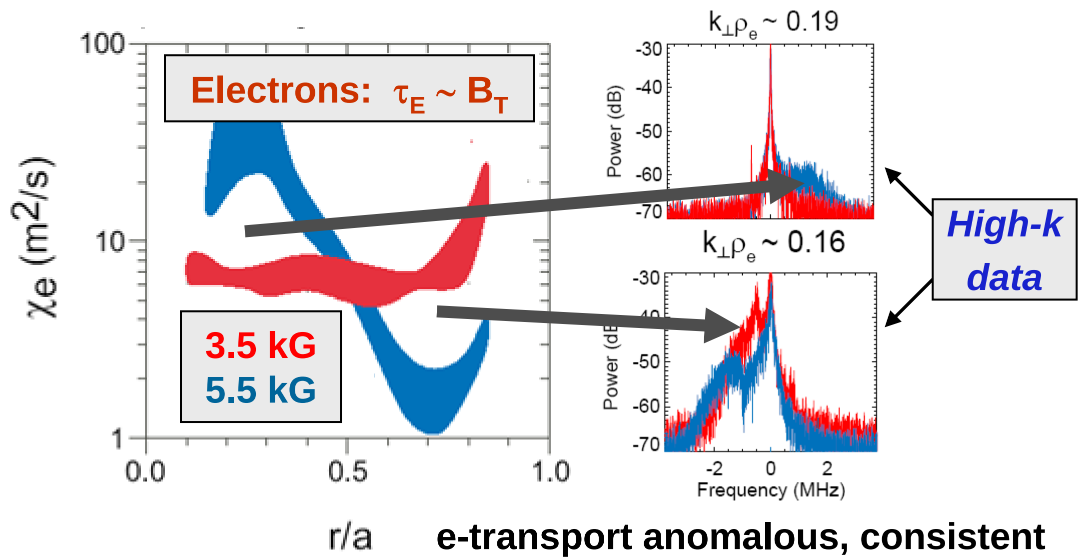
  - Study fast-ion redistribution from super-Alfvénic fast-ion modes **(FY09 milestone)**
    - NSTX: $v_{fast} / v_{Alfven} > 2$ and $\beta_{fast}(0) / \beta_{tot}(0) > 0.3$-$0.4$ can drive AE avalanches and fast-ion transport
    - Important for ST-CTF and especially ST-DEMO with alphas: $v_{fast} / v_{Alfven} \sim 3 – 6$, $\beta_{fast}(0) / \beta_{tot}(0) > 0.3$
  - Validate non-linear AE simulations for predicting next-step ST performance

Key scientific questions for Priority #2:

Increase & understand H-mode energy confinement

- Next-step ST's assume H-mode confinement with H_{98y2} = 1.3-1.5
  - NSTX has sustained $H_{98y2} \leq 1.1$, but ST scalings differ from high-A scalings





e-transport anomalous, consistent with ETG drive in many cases, but many transport mysteries remain

- ***Key scientific questions:***
  - What is low-k turbulence level? Will next-step ST ion transport be neoclassical?
  - Is e-transport driven by TEM, μ-tearing, or ETG? Implications for next-steps?
  - What are impacts of reduced collisionality and Lithium on the H-mode pedestal?

Research plan for addressing Priority #2:

Increase & understand H-mode energy confinement

NSTX

- **What is low-k turbulence level? Will next-step ST ion transport be neoclassical?**

(Addresses T4, T5)

Transport and Turbulence:

  - Evaluate generation of plasma rotation & momentum transport, and assess the impact of plasma rotation on stability and confinement **(FY08 Joule milestone)**
  - Assess role of flow shear in controlling plasma turbulence & transport using poloidal CHERS **(FY08 milestone)**
  - Study turbulence regimes (ITG,TEM) responsible for transport – χ_i and χ_ϕ **(FY10 milestone)**

  → **Accelerate BES implementation to measure low-k and complement existing high-k**

- **Is e-transport driven by TEM, μ-tearing, or ETG? Implications for next-steps?**

(Addresses T4, T6)

Transport and Turbulence:

  - Take advantage of suppressed anomalous ion transport + existing high-k + MSE + new BES
  - Test ν* dependence of e-transport w/ LLD - TEM & ETG scale differently vs. ν*
  - Compare expt. T_e profiles, diffusivities, turbulent k-spectra to simulation **(FY10 milestone)**

- **How do reduced collisionality & Lithium impact H-mode pedestal confinement?**

(Addresses T1, T4, T10)

Boundary Physics:

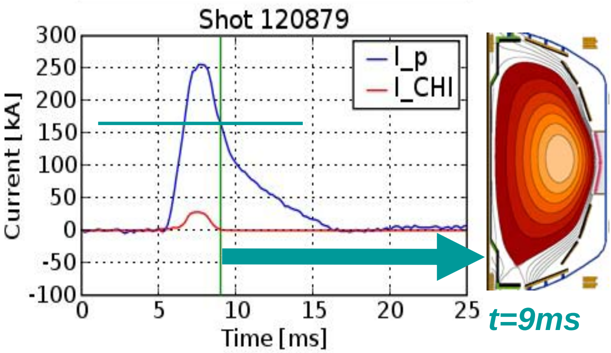
  - Assess H-mode pedestal and ELM stability as a function of ν* and Li **(FY10 milestone)**
  - Study ELM reduction and suppression, with emphasis on studying RMP physics and Li

Key scientific questions for Priority #3:

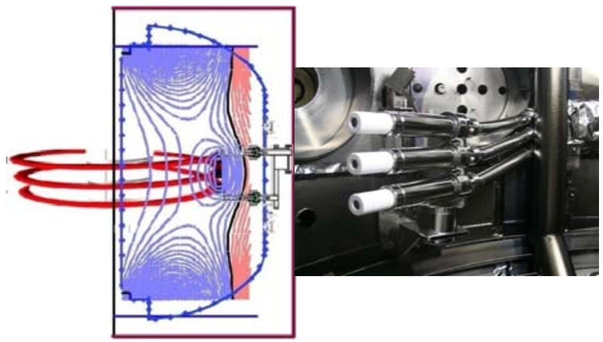
Demonstrate and understand non-inductive start-up & ramp-up

NSTX

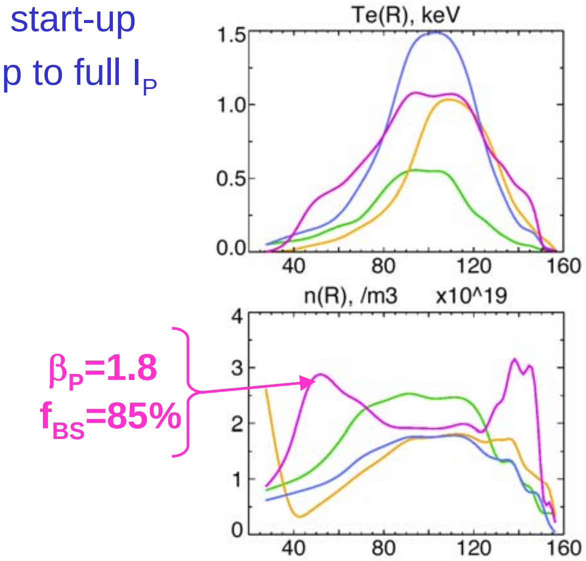
- ST-CTF requires non-solenoidal I_P ramp-up to 8-10MA
  - NHTX designed w/ solenoid for ½ swing ramp-up to full I_P, could also test start-up/ramp-up at B_T ~ CTF
- ST-CTF could have small iron core for ~1MA (estimate) of start-up current
  - Could also use CHI, plasma guns, EBW, VF ramp, or combination for start-up
  - Assume NBI-CD+BS (and maybe LHCD or EBWCD) used for ramp-up to full I_P



CHI: Record closed-flux I_P=160kA, developing coupling to induction



Pegasus: divertor guns → I_P =50kA, developing outboard midplane guns



HHFW: heats 200kA plasma to T_e=1keV, f_{BS}=85%, limited by antenna voltage stand-off, ELMs

- ***Key scientific questions:***
  - Can we demonstrate and understand non-solenoidal startup techniques?
  - What are confinement, stability, control requirements for non-inductive ramp-up?

Research plan for addressing Priority #3:

Demonstrate and understand non-inductive start-up & ramp-up

- **Can we demonstrate & understand non-solenoidal startup techniques?**
  (Addresses T1, T3, T6)

  Start-up, Ramp-up, Sustainment:

  – Couple inductive ramp-up to CHI plasmas **(FY08 Milestone)**
    - Use staged cap-banks to improve control and increase current/closed poloidal flux

  – Use CHI-startup to increase pulse lengths of high-performance discharges

  – Use CHI as pre-ionization source for vertical field startup

  – Test plasma gun startup on NSTX (from Pegasus) when technically ready

  – Simulate iron-core plasma formation of ST-CTF using OH solenoid

- **What are confinement, stability, control requirements for non-inductive ramp-up?**
  (Addresses T3, T11)

  Wave-Particle Interactions:

  – Characterize High-Harmonic Fast Wave (HHFW) heating, current drive, and current ramp-up in deuterium H-mode plasmas **(FY10 milestone)**
    - Implement antenna upgrades for higher power, ELM resilience for H-mode operation

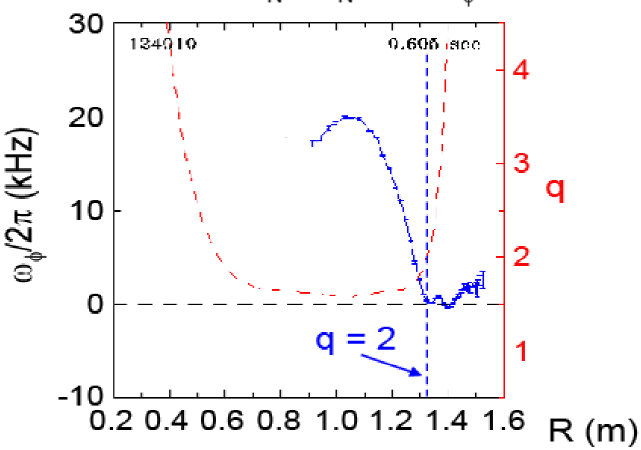
  – Use HHFW heating and CD in current ramp to reduce flux consumption

  – Use HHFW for BS+RF current overdrive and to demonstrate plasma current ramp-up

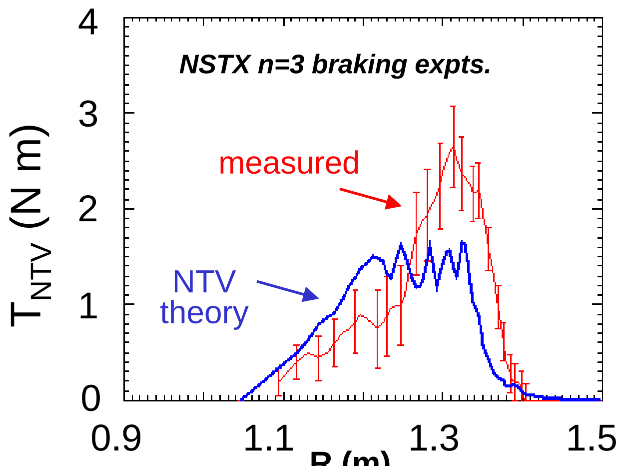
Sustain β_N and understand MHD near & above no-wall limit

- Next-step STs require stable & sustained operation near n=1 no-wall limit
  - Even near no-wall limit, likely need active control of RFA, slowly growing RWMs
  - Would greatly benefit from stable operation near ideal-wall limit

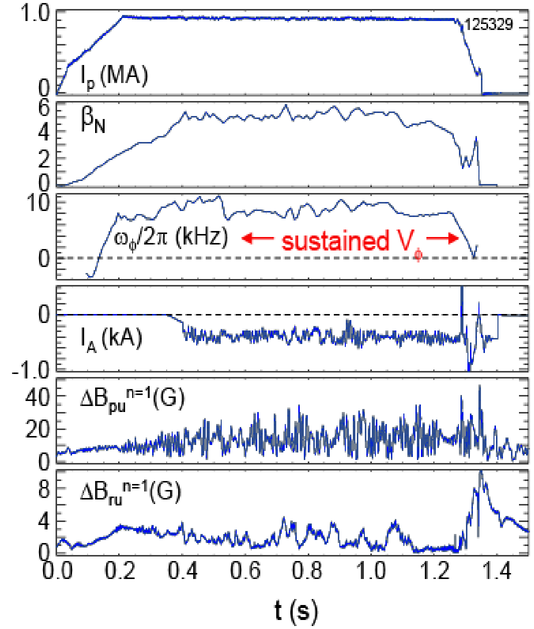
Plasma stable $\beta_N > \beta_N^{no\text{-}wall}$, $\omega_\phi^{q=2} = 0$



Scalar rotation at q=2 cannot describe RWM Ω_{crit}, and Ω_{crit} appears to depend on ν_i profile



Neoclassical toroidal viscosity (NTV) consistent w/ data, but ν_i dependence, plasma response not yet understood



High rotation & β_N = 5 sustained with n=1 feedback + n=3 EFC. Does this extrapolate to next-steps?

- ***Key scientific questions:***
  - Can we develop predictive capability for rotation & RWM stabilization threshold?
  - If NTV torque ~ $1/\nu_i$ → are next-steps (including ITER) more susceptible to EFs?
  - Do present active control techniques for RFA/RWM extrapolate to next-steps?

Research plan for addressing Priority #4:

Sustain β_N and understand MHD near & above no-wall limit

- **Can we develop predictive capability for rotation & RWM stabilization threshold?**

  Transport and Turbulence: **(Addresses T1, T2, T4, T5)**

  – Evaluate generation of plasma rotation & momentum transport, and assess the impact of plasma rotation on stability and confinement **(FY08 Joule milestone)**

  Macroscopic Stability:

  – Further understand physics of RWM stabilization and control vs. rotation **(FY09 Milestone)**

- **If NTV torque ~ $1/\nu_i$ → are next-steps (including ITER) more susceptible to EFs?**

  Macroscopic stability: **(Addresses T1)**

  – Evaluate MHD sources of plasma viscosity and assess the impact of plasma rotation on plasma stability, including NTM stability **(FY08 Joule milestone)**

  – Understand non-resonant and resonant (island) NTV, compare to computation

- **Do present active control techniques for RFA/RWM extrapolate to next-steps?**

  Scenario Integration and Control: **(Addresses T2, T3)**

  – Implement & utilize real-time β-control using rtEFIT and NBI modulation

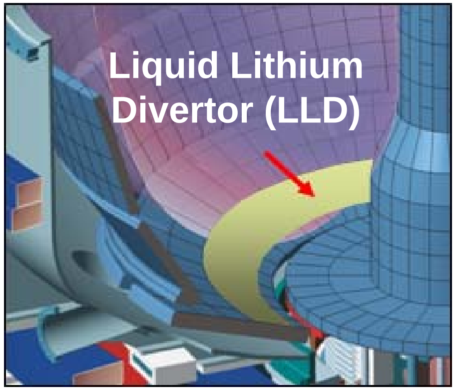
  Macroscopic stability:

  – Test fully 3D RWM control models w/ multi-mode physics and plasma rotation
    - Decrease RWM poloidal deformation & associated loss of control

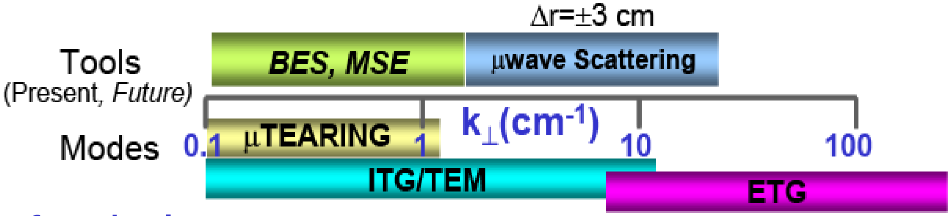
  – Characterize disruptions: Extend I_P quench data contributed to ITPA/ITER to include halo currents, thermal quench for design of next-step STs

Near-term upgrades support highest priorities for FY08-10 and enable key research thrusts:

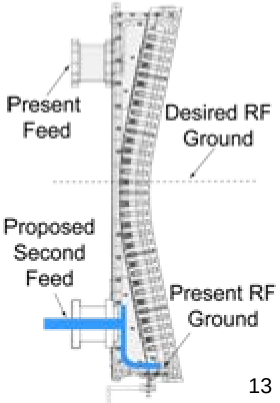
1. Implement liquid lithium divertor for pumping, and investigate other potential benefits:
   - Improved confinement
   - Reduction/elimination of ELMs
   - Compatibility of LLD with high flux expansion
   - Longer-term: steady-state high-heat-flux handling



2. Implement BES to complement existing high-k scattering diagnostic
   - Measure full wavenumber spectrum of turbulence
   - Determine modes responsible for anomalous transport of energy & momentum



3. Upgrade HHFW system for higher P_{RF} + ELM resilience
   - Determine if HHFW can ramp-up I_P in H-mode (BS+RF overdrive)
   - Determine if HHFW can heat high-β_N advanced H-mode scenarios
   - HHFW/ICRF also important for NHTX/CTF/ITER



Baseline FY2008-10 research and "Joule" milestones

(15 run weeks in FY2009/10 would enable more in-depth research of milestone topical areas)

	FY2008	FY2009	FY2010
Expt. Run Weeks:	15	11 (15)	11 (15)
1) Transport & Turbulence	Measure poloidal rotation at low A and compare w/ theory		Study turbulence regimes responsible for ion and electron energy transport
2) Macroscopic Stability		Understand physics of RWM stabilization & control as a function of rotation	
3) Boundary Physics	Study variation and control of heat flux in SOL		Assess H-mode characteristics as a function of collisionality and lithium conditioning
4) Wave-Particle Interaction		Study how j(r) is modified by super-Alfvénic ion-driven modes	Characterize HHFW heating, CD, and ramp-up in deuterium H-mode
5) Start-up, Ramp-up, Sustainment	Couple inductive ramp-up to CHI plasma		
6) Scenario Integration & Control		Perform high-elongation wall-stabilized operation at lower n_e	
"JOULE" Milestones:	Rotation and momentum transport & stability physics	Particle control and hydrogenic fuel retention	TBD

Full utilization in FY2009-10 would enable critical research on fast-ion redistribution, start-up and ramp-up, HHFW, and high β

NSTX

	FY2008	FY2009	FY2010
Expt. Run Weeks:	15	25	25
1) Transport & Turbulence	Measure poloidal rotation at low A and compare w/ theory		Study turbulence regimes responsible for ion and electron energy transport
2) Macroscopic Stability		Understand physics of RWM stabilization & control as a function of rotation	Assess sustained operation above the no-wall limit at reduced collisionality
3) Boundary Physics	Study variation and control of heat flux in SOL		Assess H-mode characteristics as a function of collisionality and lithium conditioning
4) Wave-Particle Interaction		Study how j(r) is modified by super-Alfvénic ion-driven modes Accelerate high-power HHFW 1yr Integrate MHD mode modification of j(r) into optimized operation	Characterize HHFW heating, CD, and ramp-up in deuterium H-mode Test predictive capability of mode-induced fast-ion redistribution/loss
5) Start-up, Ramp-up, Sustainment	Couple inductive ramp-up to CHI plasma	Investigate methods for solenoid-free current initiation using induction from the outer poloidal field coils	Test non-inductive current generation using plasma guns
6) Scenario Integration & Control		Perform high-elongation wall-stabilized operation at lower n_e	
"JOULE" Milestones:	Rotation and momentum transport & stability physics	Particle control and hydrogenic fuel retention	TBD

NSTX participation in ITER design activities and ITPA benefits both ST and tokamak/ITER research

- Near-term (March 08) NSTX experiments support critical ITER design activities:
  - **ELM suppression: test single row of midplane coils for ELM mitigation, multiple n's, NTV braking**
  - **Vertical control: quantify controllable ΔZ, compare across devices, compare to ITER**
  - **RWM control: simulate proposed ITER port-plug design to assess toroidal asymmetry of coil layout**

Actively involved in 17 ITPA joint experiments – contribute/participate in 24 total

Boundary Physics
- PEP-6 Pedestal structure and ELM stability in DN
- PEP-9 NSTX/MAST/DIII-D pedestal similarity
- PEP-16 C-MOD/NSTX/MAST small ELM regime comparison
- DSOL-15 Inter-machine comparison of blob characteristics
- DSOL-17 Cross-machine comparison of pulse-by-pulse deposition

Macroscopic stability
- MDC-2 Joint experiments on resistive wall mode physics
- MDC-3 Joint experiments on neoclassical tearing modes including error field effects
- MDC-12 Non-resonant magnetic braking
- MDC-13: NTM stability at low rotation

Transport and Turbulence
- CDB-2 Confinement scaling in ELMy H-modes: β degradation
- CDB-6 Improving the condition of global ELMy H-mode and pedestal databases: Low A
- CDB-9 Density profiles at low collisionality
- TP-6.3 NBI-driven momentum transport study
- TP-9 H-mode aspect ratio comparison

Wave Particle Interactions
- MDC-11 Fast ion losses and redistribution from localized Alfvén Eigenmodes

Scenario Integration and Control
- SSO-2.2 MHD in hybrid scenarios and effects on q-profile
- MDC-14: Vertical Stability Physics and Performance Limits in Tokamaks with Highly Elongated Plasmas

Significant research milestones needed for extrapolation to next-step ST's would be unmet without operation in FY2010

NSTX

FY2010 Milestones:

- Lose understanding of modes responsible for anomalous transport
  - Need time to exploit BES system in a variety of plasma conditions/experiments
- Lose demonstration and understanding of I_P ramp-up needed for ST-CTF
  - Cannot reliably utilize HHFW in H-mode plasmas w/o ELM resilience upgrade
- Lose understanding of impact of low ν^* and Li on H-mode pedestal, ELMs
  - Need time to separate roles of low ν^* and Li on H-mode characteristics

- More broadly, not operating in FY2010 severely impacts low-ν^* research:
  - Cannot implement long-pulse LLD and n_e control for advanced operations
  - Impacts research on: NBI-CD, transport, high-β, AE avalanches, SOL, etc.

The NSTX PAC strongly endorses the NSTX prioritized plan through FY2010:

"The PAC agrees that achieving all (four) of these research goals would fill knowledge gaps and greatly improve confidence in the extrapolation to next-step ST devices."

"The PAC believes a 'full three-year' research program extending through the end of FY 2010 is fully warranted."

"A shorter period of operation would be a tremendous waste of a valuable resource."

NSTX will make world-leading contributions to ST development, and contribute strongly to ITER and fundamental toroidal science

- The FY08-10 plan:
  - Focuses research to address key gaps in extrapolating to next-step STs
    - Increase and understand beam-driven current at lower n_e, ν^* (also assess integration)
    - Increase and understand H-mode confinement at low ν^*
    - Demonstrate and understand non-inductive start-up and ramp-up
    - Sustain β_N and understand MHD near & above no-wall limit
  - Contains targeted upgrades:
    - FY09 – Liquid Lithium Divertor for lower n_e, ν^*
    - FY10 – BES for transport & AE, improved HHFW for ramp-up & sustainment

- These plans and upgrades enable exciting new science in all topical science areas:
  - Measure & understand underlying instabilities that cause **anomalous energy transport**
  - Understand **RWM critical rotation and viscous torques** and dependence on lower ν_i
  - Understand role of ν^* and **Lithium on pedestal transport/stability** and divertor physics
  - Develop predictive capability for **fast-ion redistribution from multi-mode AE** for ST, ITER
  - Integrate CHI into normal ops, develop/understand I_P **ramp-up w/ HHFW BS overdrive**
  - **Push toward 100% non-inductive operation** by increasing NBI-CD with reduced density

Backup Slides

Gaps between present and next-step STs motivate NSTX research goals and associated upgrades and milestones

GOALS: reduce n_e, increase NBI-CD & H-mode confinement, demonstrate start-up/ramp-up

Present high-f_{NICD}	NSTX	NHTX	ST-CTF
A	1.53	1.8	1.5
κ	2.6-2.7	2.8	3.1
β_T	14%	12-16%	18-28%
β_N [%-mT/MA]	5.7	4.5-5	4-6
f_{NICD}	0.65	1.0	1.0
$f_{BS+PS+Diam}$	0.54	0.65-0.75	0.45-0.5
f_{NBI-CD}	0.11	0.25-0.35	0.5-0.55
f_{GW}	0.8-1.0	0.4-0.5	0.25-0.5
H_{98y2}	1.1	1.3	1.5
Dimensional/Device Parameters:			
Solenoid Capability	Ramp-up + flat-top	Ramp-up to full I_P	No/partial ramp-up
I_P [MA]	0.72	3-3.5	8-10
B_T [T]	0.52	2.0	2.5
R_0 [m]	0.86	1.0	1.2
a [m]	0.56	0.55	0.8
I_P / aB_{T0} [MA/mT]	2.5	2.7-3.2	4-5

Reduced normalized density/collisionality represents the largest gap between present and next-step ST operating scenarios

- Next-step STs rely on lower n_e/n_{GW} to increase NBI-CD for full non-inductive operation
  - **Next-steps: n_e / n_{GW} = 0.25-0.5, versus 0.7-1 of high non-inductive fraction NSTX**

Reduced density/collisionality impacts all topical science areas:

- Transport & Turbulence
  - Underlying instabilities (micro-tearing, TEM, and ETG) scale differently versus ν^*
  - If $T_e(r)$ is determined by critical ∇T_e, H-mode confinement may be reduced at reduced n_e
- Macroscopic Stability
  - RWM critical rotation and viscous torques may increase at lower ν_i
- Boundary Physics
  - ELM ΔW increases with reduced ν^*_e - could impact confinement, plasma purity, divertor
  - Detachment schemes for heat flux reduction more challenging with reduced SOL ν
- Wave-Particle Interaction
  - AE avalanches more easily triggered at reduced n_e – possible fast-ion redistribution/loss
- Start-up, Ramp-up, Sustainment
  - NBI-CD and RF-CD efficiency for ramp-up are increased at reduced n_e, increased T_e
- Scenario Integration and Control
  - Steady-state scenarios rely on reduced n_e to increase NBI-CD to achieve 100% NI-CD

NSTX contributes to near-term and long-term issues for ITER

- Near-term (Mar. 08) experiments in support of critical design activities:
  - ELM suppression
    - Any demonstration of ELM suppression using a single row of coils would provide very valuable data for improved RMP understanding
    - n=2, or combination of n=1 and n=3 yet to be tried on NSTX
    - Does braking from RMP vary w/ T_i, ν_i, n, ε as NTV theory predicts?
  - Vertical control
    - Is ITER n=0 control model valid, and/or consistent w/ experiments?
    - Allow plasma to drift vertically, then try to regain control
    - Quantify controllable ΔZ, compare across devices, compare to ITER
    - Could impact ITER PF coils, power supplies, l_i operating range
  - RWM control
    - Simulate proposed ITER port-plug coil design to assess impact of toroidal asymmetry of coil layout (due to NBI interferences) on RWM control capability
- Longer-term ST research benefiting ITER & fundamental toroidal science:
  - Understanding of electron thermal transport, β scaling of confinement
  - RWM feedback at low rotation with mid-plane coils, RWM damping physics
  - RMP physics understanding, heat flux mitigation, pedestal physics
  - Unique multi-AE “avalanche” studies with full diagnostics + non-linear modeling
  - HHFW coupling physics - surface-wave excitation relevant to ITER ICRF