NSTX

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# NSTX Research Program Overview for FY2009-11

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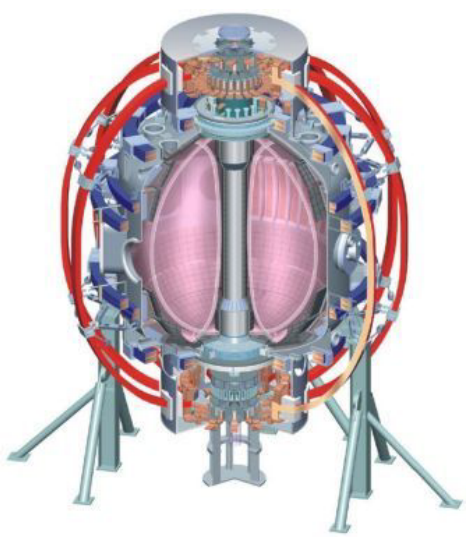
## Jon Menard, PPPL

**For the NSTX Research Team**


**FY2011 Budget Planning Meeting**
**March 31, 2009**



*Culham Sci Ctr*
*U St. Andrews*
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*Hyogo U*
*Kyoto U*
*Kyushu U*
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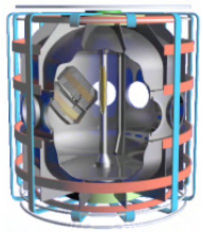
*ENEA, Frascati*
*CEA, Cadarache*
*IPP, Jülich*
*IPP, Garching*
*ASCR, Czech Rep*
*U Quebec*

# Outline:

- Role of NSTX in Fusion research
- Near-term NSTX Research Goals
- Motivation for NSTX Major Upgrades
- Contributions to ITER and Tokamak Research
- Summary

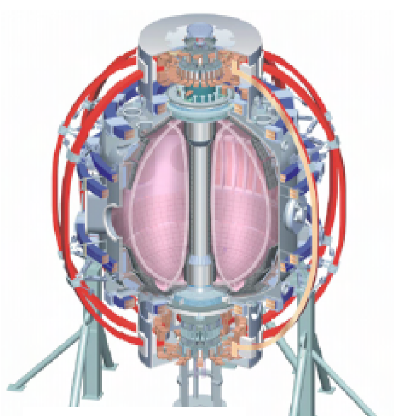
# Present and future spherical tori complement ITER and accelerate the development paths of all DEMO concepts

**STs**



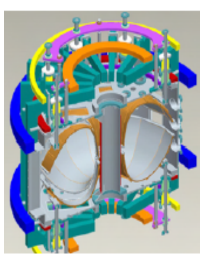
**PEGASUS**

*Plasma gun start-up, edge filaments*



**NSTX**

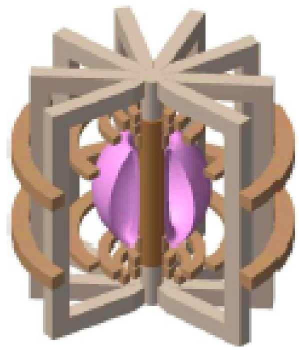
*U.S. flagship ST*



**LTX**

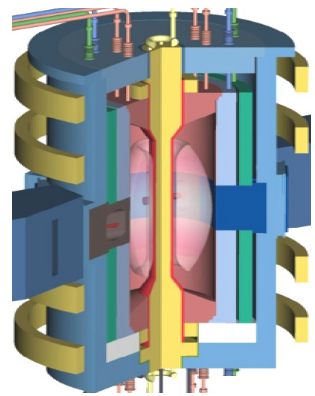
*Li PFCs - very low recycling wall*

**Plasma-Material Interface R&D + Advanced Physics**

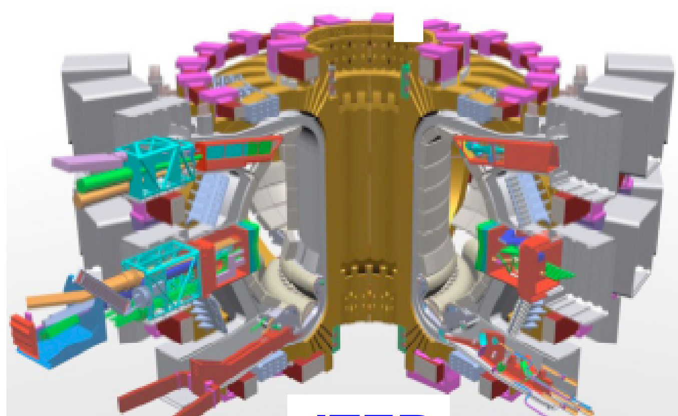


**NHTX**

**Nuclear Component Testing**



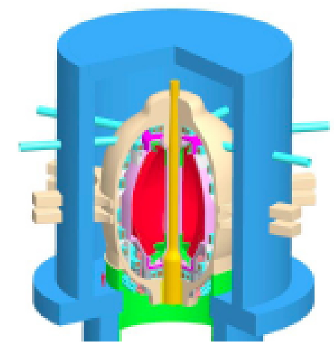
**ST-CTF**



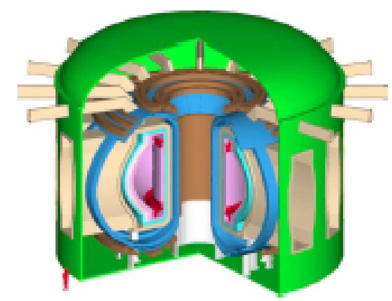
**ITER**

**Burning Plasma Physics**

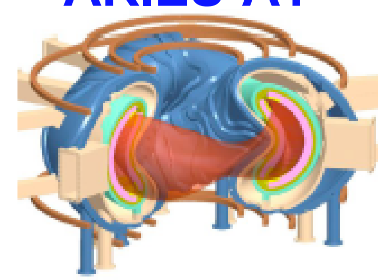
**DEMO**



**ARIES-ST**



**ARIES-AT**



**ARIES-CS**

# NSTX advances toroidal plasma science and burning plasma physics, and provides attractive near-term fusion options

***NSTX Mission Elements:***

- Understand unique physics properties of ST
  - Assess impact of low A, high $\beta$, high $v_{fast} / v_A$, etc. on all aspects of toroidal plasma science
- Complement tokamak physics, support ITER
  - Exploit unique ST features to improve tokamak understanding, while also benefiting from tokamak R&D
- Establish attractive ST scenarios for future applications
  - **Long-term goal:** Understand and utilize advantages of the ST configuration for addressing key gaps between ITER performance and that needed for DEMO

# NSTX 5 year plan review panel endorsed the NSTX mission, research priorities, and proposed major facility upgrades

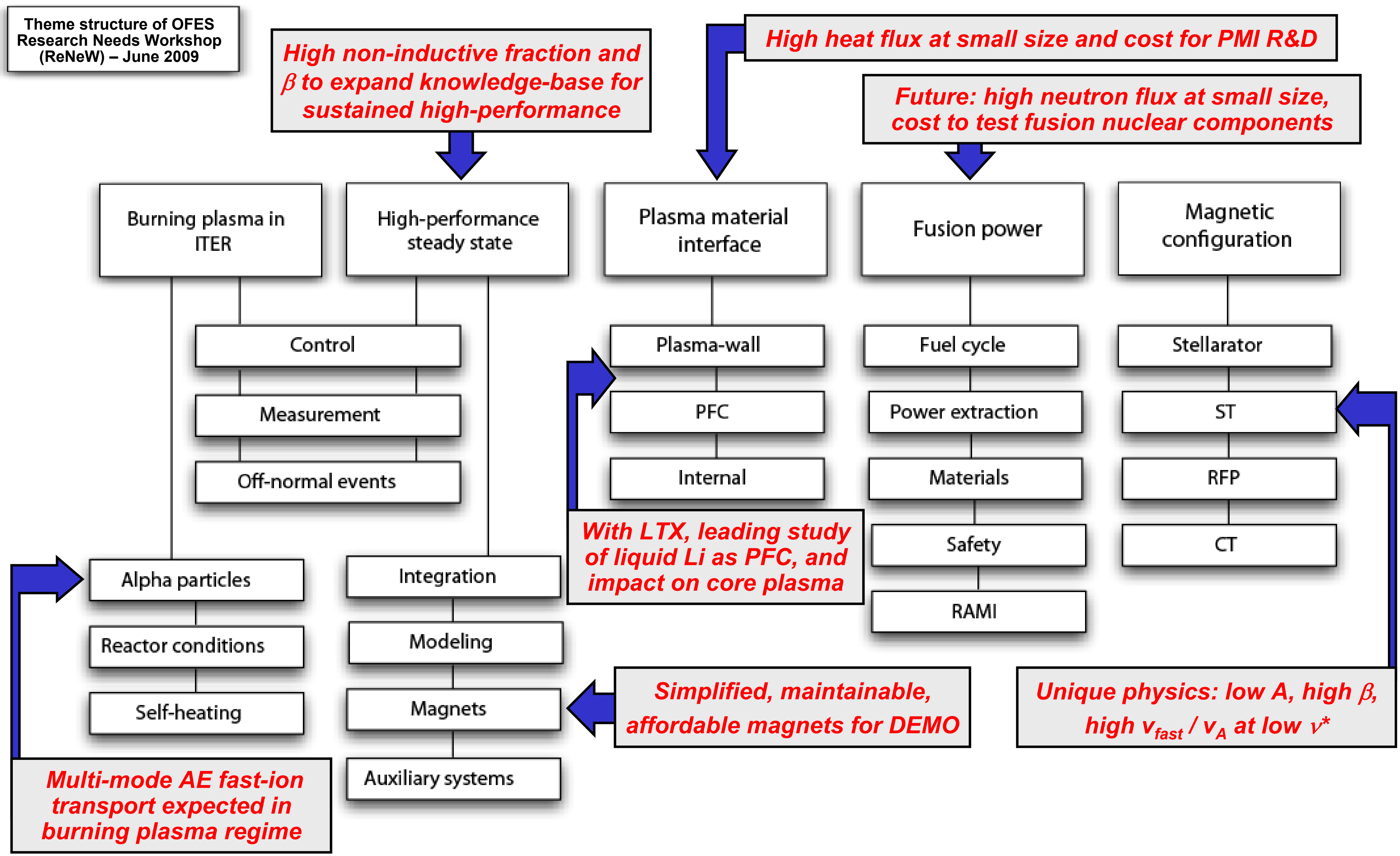
- "Proposed research clearly aims to position the ST as a candidate for future high priority US research missions, as articulated in recent FESAC reports
  - High heat flux facility for PMI research, as embodied in NHTX
  - Nuclear component testing, as embodied in ST-CTF"

- "The panel agrees that the proposed research priorities address these missions
  - 100% non inductive current drive
  - Particle and heat flux control
  - Non inductive start up and ramp up
  - Sustained high beta operation"

***Motivated formation of NSTX "Lithium Research Thrust" to coordinate NSTX Li research in close collaboration with LTX***

- "The major facility upgrades are appropriately sequenced:
  1. The liquid lithium divertor (LLD) is an innovative approach to density control
     - Potential for high reward, but no guarantee LLD will provide necessary control
     - Measuring and modeling effects associated with lithium will be critical to understanding the science and projecting future applications.
     - It is not clear that there is sufficient attention paid to this in the proposal.
     - A backup strategy for density control should be better developed
  2. The center stack upgrade is very well motivated and should be installed as soon as possible
  3. The second neutral beam source is essential to take advantage of higher $B_T$ and current capability from center stack upgrade"

# NSTX is providing unique contributions to all magnetic fusion research needs – for the ITER era and beyond



# FESAC Toroidal Alternates Panel (TAP) recently prioritized issues and gaps for the Spherical Torus (ST) for the ITER era

***ST ITER-era goal:*** *"Establish the ST knowledge base to be ready to construct a low aspect-ratio fusion component testing facility …. to inform the design of a demonstration fusion power plant"*

**"Tier 1" issues and key questions from TAP, and NSTX goals:**

1. **Startup and Ramp-Up**:
   - NSTX goal: demonstrate non-inductive ramp-up and sustainment
2. **First-Wall Heat Flux**:
   - NSTX goal: assess high flux expansion, detached divertors, liquid metals
3. **Electron Transport**:
   - NSTX goal: determine modes responsible for electron turbulent transport and assess the importance of electromagnetic (high $\beta$) and collisional effects
4. **Magnets**:
   - NSTX goal: develop and utilize higher performance toroidal field magnet

# Outline:

- Role of NSTX in Fusion research
- Near-term NSTX Research Goals
- Motivation for NSTX Major Upgrades
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# Performance gaps between present and next-step STs motivate near-term research prioritization and upgrades

***Gaps to next-step STs:***

**For NHTX, ST-CTF: reduce: $n_e$ & $\nu^*_e$, increase: NBI-CD, confinement, start-up/ramp-up**
**For ARIES-ST: increase: elongation, $\beta_N$, $f_{BS}$, confinement, start-up/ramp-up**

**Near-term highest priority is to assess NHTX → ST-CTF scenarios**

| Present high $\beta_N$ and $f_{NICD}$ NSTX | | Upgraded NSTX | NHTX | ST-CTF | ARIES-ST |
|---|---|---|---|---|---|
| A | 1.53 | 1.65 | 1.8 | 1.5 | 1.6 |
| κ | 2.6-2.7 | 2.6-2.8 | 2.8 | 3.1 | 3.7 |
| $\beta_T$ [%] | 14 | 10-16 | 12-16 | 18-28 | 50 |
| $\beta_N$ [%-mT/MA] | 5.7 | 5.1-6.2 | 4.5-5 | 4-6 | 7.5 |
| $l_i(1)$ | 0.5-0.65 | 0.55-0.75 | 0.5-0.7 | 0.25-0.5 | 0.24 |
| $f_{NICD}$ | 0.65 | 1.0 | 1.0 | 1.0 | 1.0 |
| $f_{BS+PS+Diam}$ | 0.54 | 0.6-0.8 | 0.65-0.75 | 0.45-0.5 | 0.99 |
| **$f_{NBI-CD}$** | **0.11** | **0.2-0.4** | **0.25-0.35** | **0.5-0.55** | 0.01 |
| **$f_{Greenwald}$** | **0.8-1.0** | **0.6-0.8** | **0.4-0.5** | **0.25-0.3** | 0.8 |
| **$\nu^*_e$** | **0.15** | **0.04** | **0.01** | **0.002** | 0.007 |
| **$H_{98y2}$** | **1.1** | **1.15-1.25** | **1.3** | **1.5** | 1.3 |

<u>Dimensional/Device Parameters:</u>

| | | | | | |
|---|---|---|---|---|---|
| Solenoid Capability | Ramp+flat-top | Ramp+flat-top | Ramp to full $I_P$ | No/partial | No |
| $I_P$ [MA] | 0.72 | 1.0 | 3-3.5 | 8-10 | 28 |
| $B_T$ [T] | 0.52 | 0.75-1.0 | 2.0 | 2.5 | 2.1 |
| $R_0$ [m] | 0.86 | 0.92 | 1.0 | 1.2 | 3.2 |
| a [m] | 0.56 | 0.56 | 0.55 | 0.8 | 2.0 |
| $I_P$ / $aB_{T0}$ [MA/mT] | 2.5 | 1.8-2.4 | 2.7-3.2 | 4-5 | 6.7 |

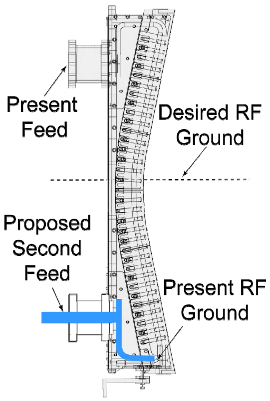
# **Near-term NSTX research prioritization** is motivated by performance gaps between **present** and **next-step STs**

1. Increase and understand non-inductive current drive at reduced collisionality
   - Next-step STs require full non-inductive CD to achieve missions, and NBI-CD is largest gap
   - Present ST experiments have achieved ~65-70% non-inductive, 50-55% bootstrap
2. Increase and understand H-mode confinement at reduced collisionality
   - Need to understand (electron) confinement to extrapolate to next-steps with high confidence
   - ST confinement scales strongly with B at low $B_T$ (~0.5T), differs from higher-A tokamaks
3. Demonstrate and understand non-inductive start-up and ramp-up
   - Non-inductive start-up/ramp-up essential to ST-CTF/DEMO (NHTX has OH for ramp-up)
   - CHI and gun plasmas coupled to induction, but ramp-up to high $I_P$ not yet demonstrated
4. Demonstrate and understand means to "tame the plasma-material interface"
   - PMI solution for very high heat/particle/neutron flux needed for ST-CTF and ST-DEMO
   - Testing flux expansion, partial detachment, liquid lithium divertor (density control for low $\nu^*$)
5. Sustain $\beta_N$ and understand MHD/disruptivity near/above no-wall stability limit
   - NHTX/ST-CTF to operate near no-wall limit, high $\beta_T$ improves CTF, essential for ST-DEMO
   - ST error field and RWM control demonstrated, but need to develop very reliable control

**NSTX near-term prioritization is compatible with FESAC-TAP ITER-era physics prioritization:**
**Start-up/ramp-up/sustainment, PMI, electron energy transport, integration, disruptions,**
RF heating and current drive, 3D fields (ELM/EF/RWM), ion scale transport, fast particle instabilities, NTMs

# NSTX major upgrades in 5 year plan (FY2009-13) will extend understanding and performance toward next-step STs

**FY2009-11**

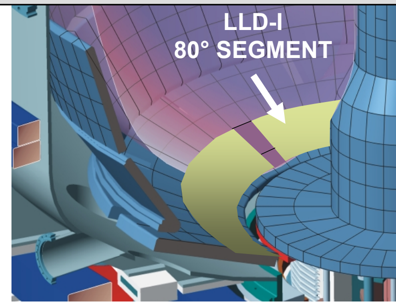



**2009-11**

Higher-power fast-wave e-heating + ELM resilience for ramp-up and sustainment of H-mode plasmas

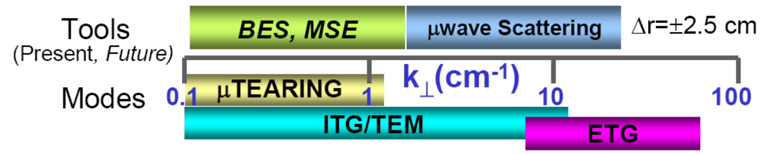
**2010-11**

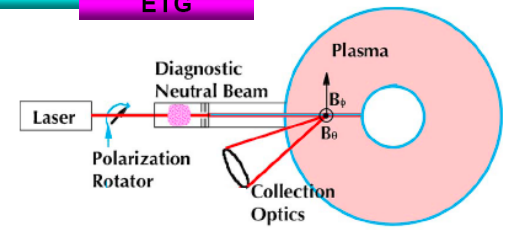
Liquid lithium divertor (LLD) for density control for higher NBI current-drive fraction




**2010-11**

BES to complement high-k scattering turbulence measurements to develop predictive capability for ST transport




**2011**

MSE-LIF for pitch angle & |B| w/o heating beam, $E_r(r)$ – especially beneficial for HHFW and energetic particle research

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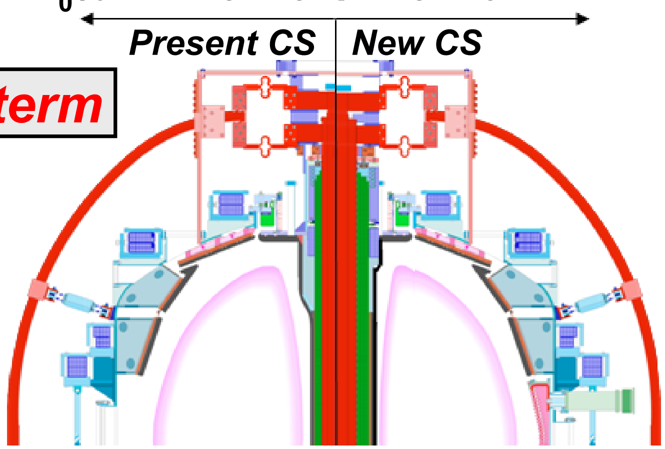
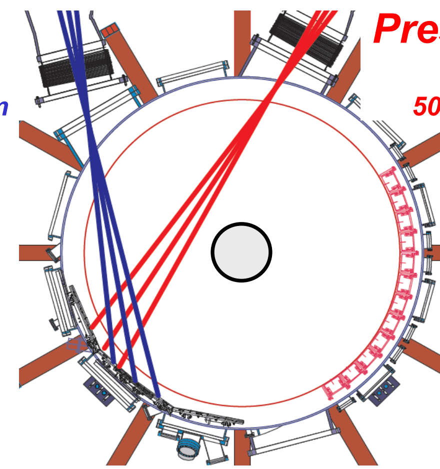
**Longer term**

New center stack for 1T, 2MA, 5s to access reduced ν*, 100% non-inductive ST plasmas

$R_0/a$ = 1.25-1.3 → 1.5-1.6




$2^{nd}$ NBI with larger $R_{tangency}$ for sustained and controllable 100% NICD + high β at low ν*



# **Near-term NSTX research priorities** motivate specific **research goals** strongly supported by **near-term upgrades/tools**

1. Increase and understand non-inductive current drive at reduced collisionality
   - → ***Goals:*** ***Assess NBI-CD and bootstrap vs. reduced $n_e$, higher $T_e$, $P_{Heat}$***
   - → ***Tools:*** ***LLD, HHFW, MSE-LIF, new CS, $2^{nd}$ NBI***

2. Increase and understand H-mode confinement at reduced collisionality
   - → ***Goals:*** ***Determine ST transport mechanisms + $B_T$, $I_P$, $P_{Heat}$ scaling***
   - → ***Tools:*** ***BES, HHFW, MSE-LIF, new CS, $2^{nd}$ NBI***

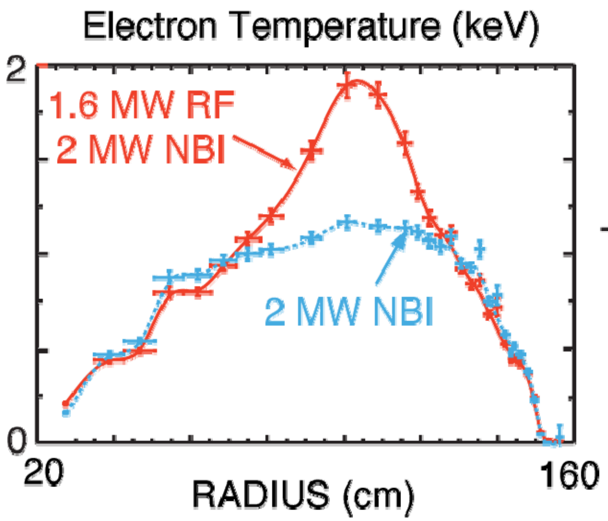
3. Demonstrate and understand non-inductive start-up and ramp-up
   - → ***Goals:*** ***Increase ramp-up heating & current drive – especially with RF and NBI***
   - → ***Tools:*** ***HHFW, MSE-LIF, new CS, $2^{nd}$ NBI***

4. Demonstrate and understand means to "tame the plasma-material interface"
   - → ***Goals:*** ***Near-term: Short-pulse pumping → long-pulse + heat-flux mitigation***
   - → ***Tools:*** ***LLD, $2^{nd}$ SPA, new CS, $2^{nd}$ NBI***

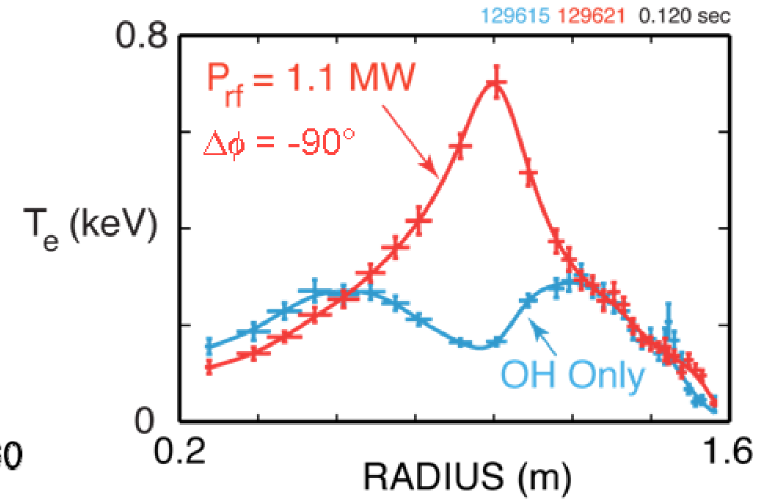
5. Sustain $\beta_N$ and understand MHD/disruptivity near/above no-wall stability limit
   - → ***Goals:*** ***Improve RWM/EF/ELM, $\Omega_\phi(r)$, q(r) control***
   - → ***Tools:*** ***$2^{nd}$ SPA, MSE-LIF, $2^{nd}$ NBI, off-midplane coils (incremental)***

# Lithium coating has improved HHFW heating efficiency in deuterium NBI H-modes, and at low $k_{||}$ for current drive

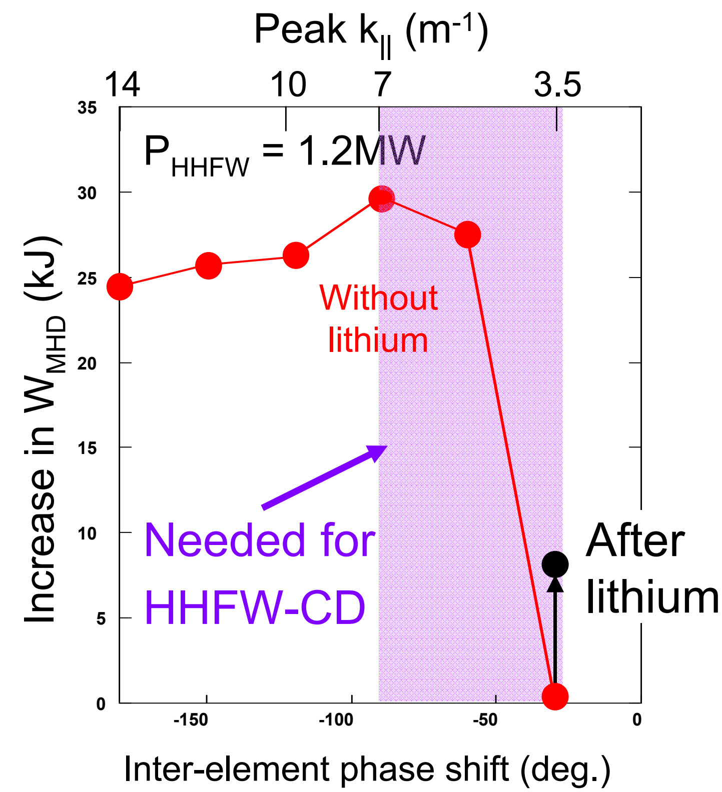
First strong core electron heating in NBI H-Mode




Heating at low $I_P$ = 300kA, 90° CD phasing (L-mode)




First electron heating with 30° CD phasing (L-mode)

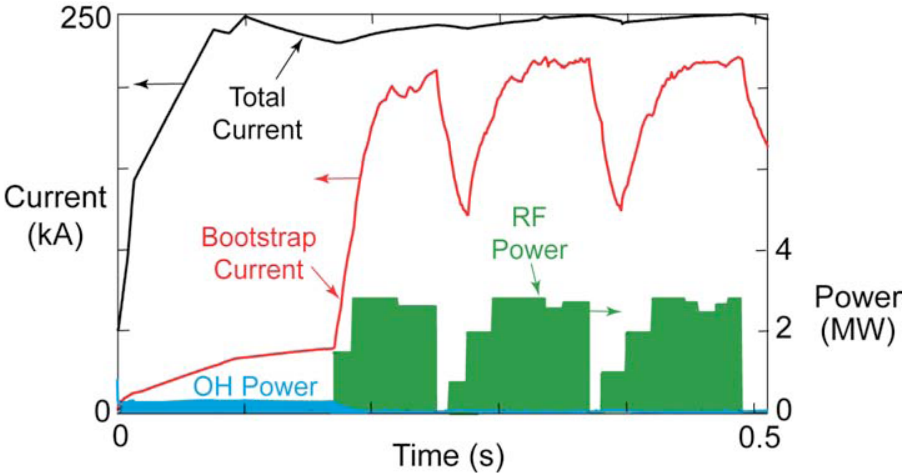



- Reflectometer measures reduced SOL density in front of antenna with lithium
  - Consistent with suppression of parasitic surface wave excitation

**2009-11**

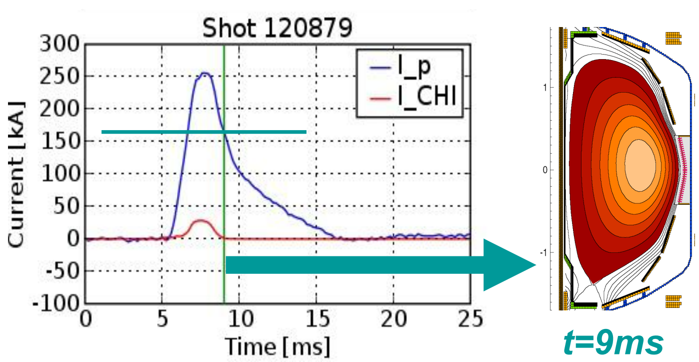
***Higher-power fast-wave electron heating + ELM resilience*** *will be tested for* ***increasing $T_e$ and NBI-CD efficiency*** *in NBI-heated H-mode plasmas,* ***full non-inductive sustainment*** *of H-mode plasmas (300-400kA) using BS + RF-CD, and for* ***non-inductive ramp-up***

# Near-term upgrades and collaboration strongly support ST start-up and ramp-up research – the highest priority issue for ST-CTF



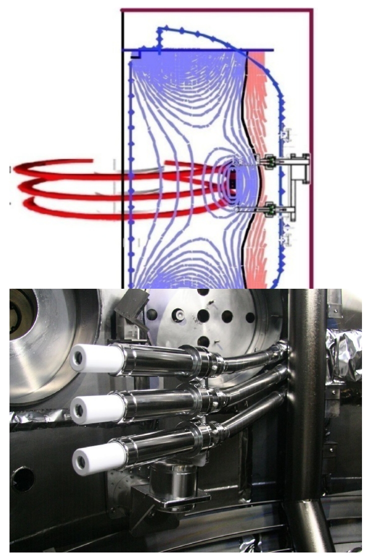

**NSTX HHFW:** heated 250kA H-mode plasma to $T_e$=1keV, $f_{BS}$=85%, limited by antenna voltage stand-off, ELMs

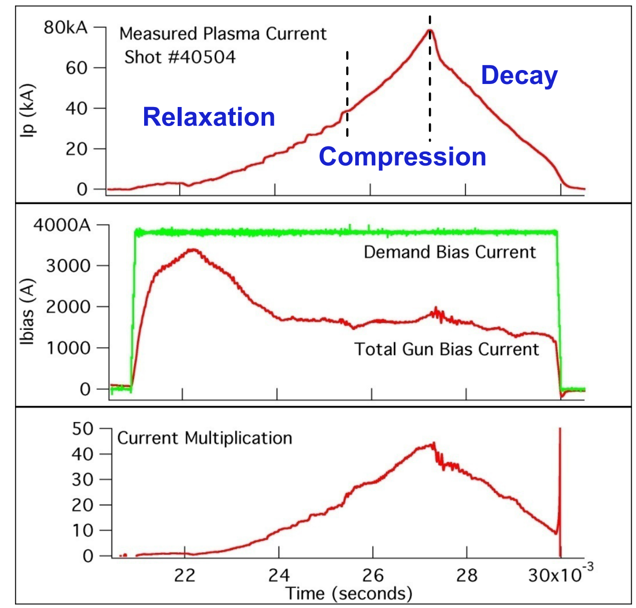
- **Results strongly motivate increased HHFW power and ELM resilience → test HHFW for BS overdrive ramp-up**




**NSTX CHI:** Record closed-flux $I_P$=160kA, coupled CHI to induction and high-performance H-mode

- Will test metallic divertor (LLD) and improved absorber null to reduce impurity influx at high $I_{CHI}$

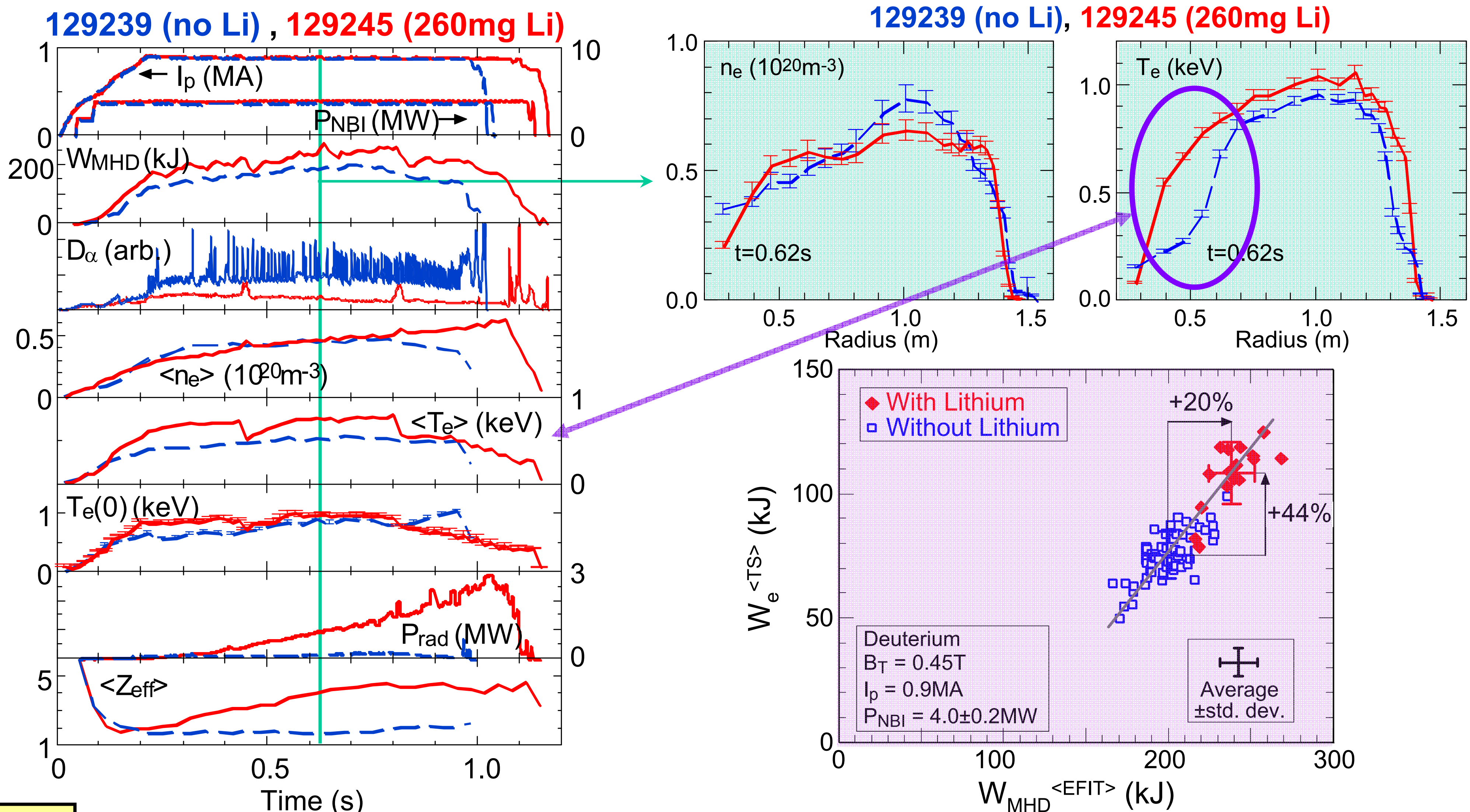





**Pegasus:** Developing outboard mid-plane gun current injection start=up, $I_P$ ramped-up to ~80kA so far

- Will test on NSTX when technically ready (≥ FY2011)

# Solid lithium coatings have demonstrated favorable results: reduced D recycling, ELM suppression, improved confinement

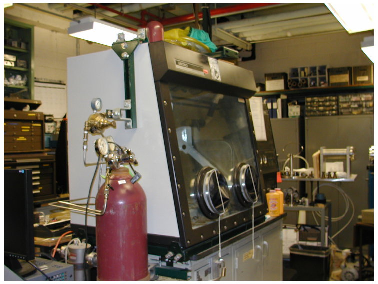



**2010-11**

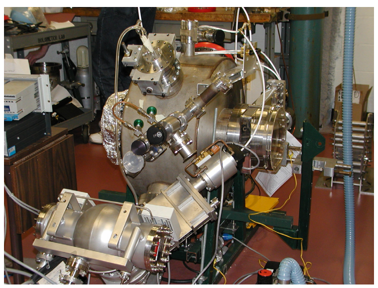
***Liquid Lithium Divertor (LLD)*** *will test impact of liquid Li PFCs on high-performance diverted H-mode plasmas for first time, with goal of providing* ***$n_e$ control for higher NBI-CD fraction***

# NSTX lithium research is integral part of broad approach to develop lithium as PFC concept for magnetic fusion

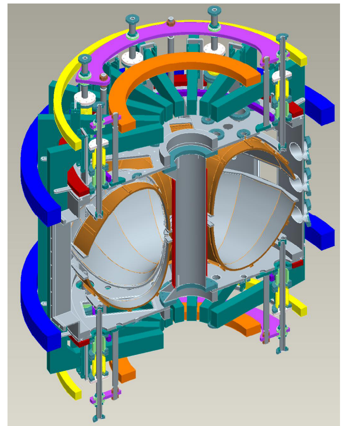
LTX lithium handling facility



LTX PFC test facility

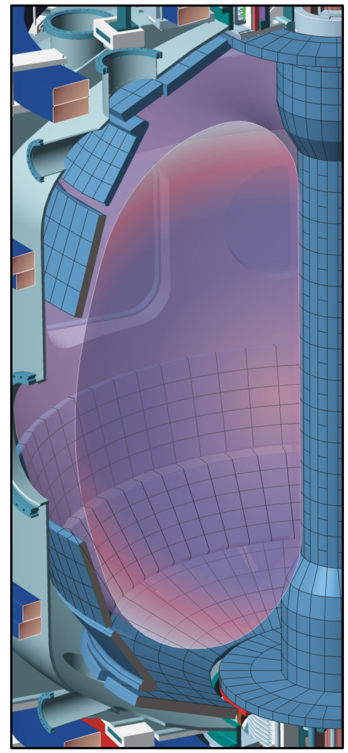


Purdue surface analysis facilities

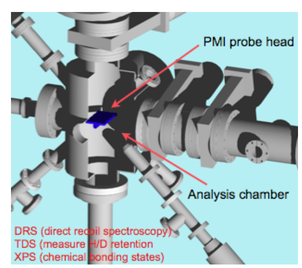


LTX
- Fully non-recycling liquid lithium PFCs
- Profile control with core fueling

NSTX
- Lithium evaporator
- Liquid lithium divertor
- High performance plasma



NSTX materials analysis probe

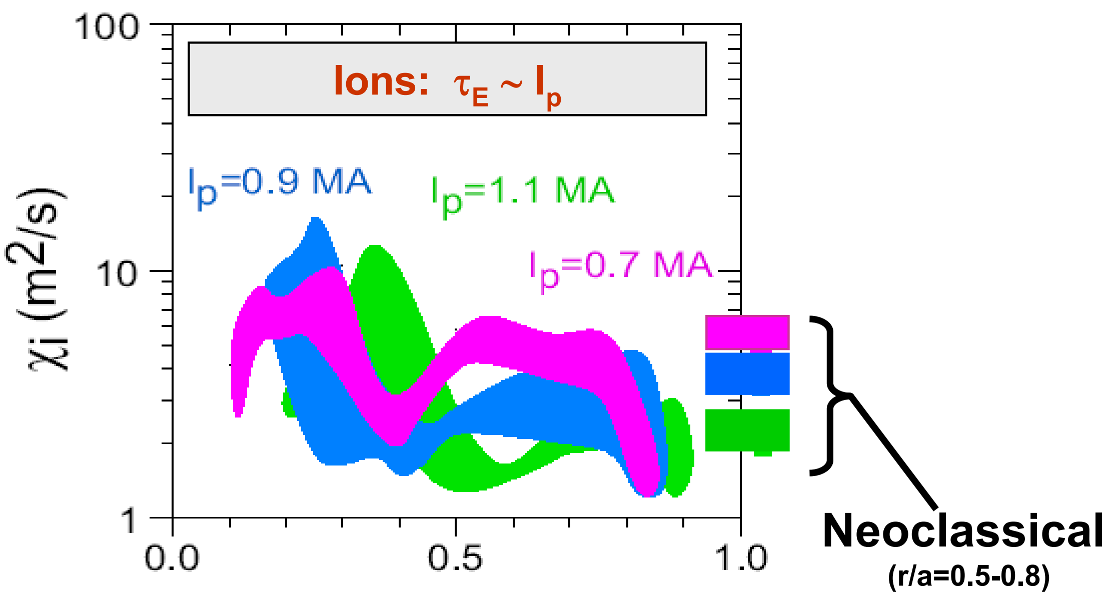



**Possible PMI solution for next steps**

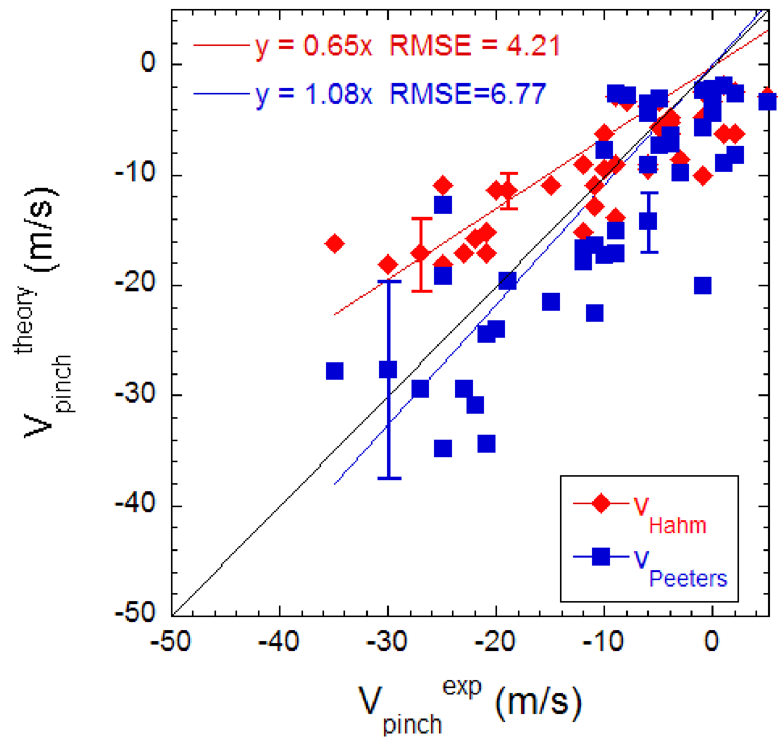
Erosion/deposition
H retention modeling

# NSTX plasmas providing strong tests of leading theories of ion thermal and momentum diffusivity

- In H-modes with large E×B shear, ion thermal transport is neoclassical (for r/a > 0.5), consistent with the suppression of low-k turbulence, but angular momentum diffusivity remains anomalous (not shown)




- Inferred momentum pinch velocities in outer region agree reasonably well with theories based on low-k turbulence




Peeters *et al.* (PRL, 2007), Hahm *et al.* (PoP, 2007)

**2010-11**

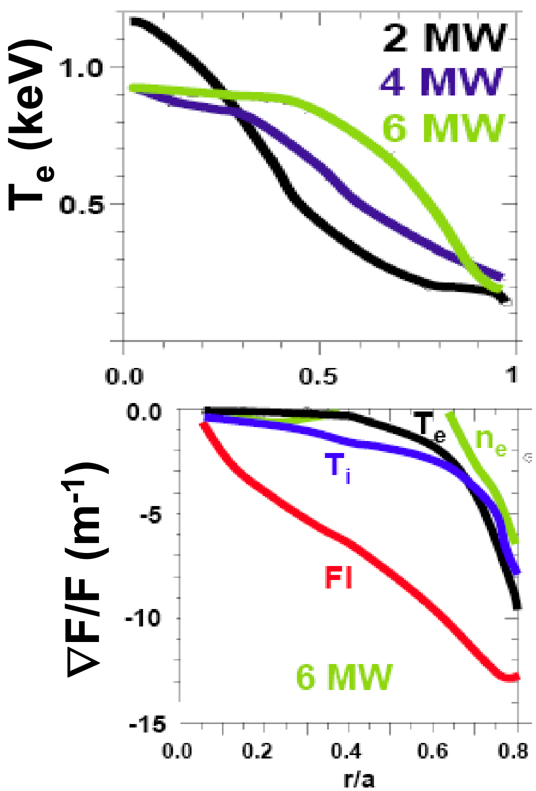
***Beam Emission Spectroscopy (BES) diagnostic** will enable unique measurements and comparisons to theory/simulation for understanding the relationship between **low-k turbulence and energy and momentum transport** in the ST and tokamak*

# NSTX investigating newly discovered link between high-frequency Alfvénic instabilities and core electron transport

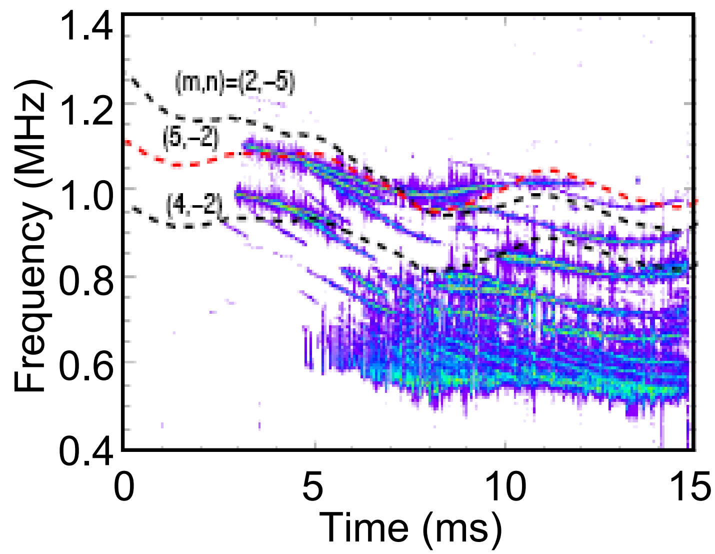
- Observe “flat $T_e$” region in core of plasmas with high NBI power

⇒ Implies mechanism for electron transport *not* driven by $T_e$ gradient

- Global Alfvén Eigenmodes (GAEs) driven by fast-ion pressure gradient a possible source



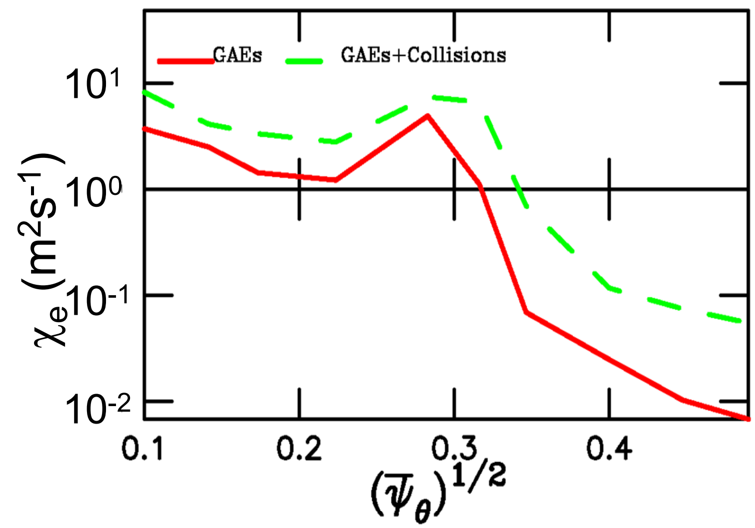

$$\omega_{GAE} \simeq v_{A0}(m - nq_0)/q_0 R.$$




- GAEs localized near center
- Radial width ∝ $m^{-1}$
- $f_{GAE}$ ~ $f_{be}$ trapped electron bounce frequency

## Modeling with ORBIT code

- Used 14 GAEs n = 1–8; m so f = 0.4–0.6 MHz
- Peak amplitude $\xi_r/R \sim 4\times10^{-4}$ consistent with reflectometry




**2009-11**

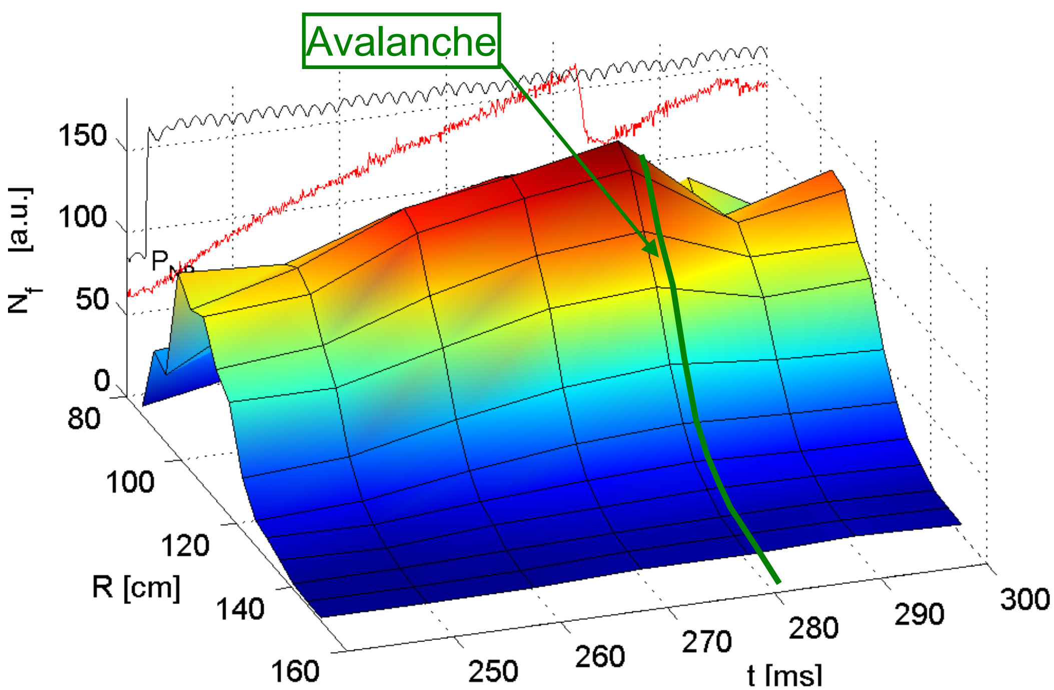
*Existing **high-k scattering + new BES** + tangential FIDA + MSE-LIF will significantly aid identification of modes responsible for **anomalous electron transport***

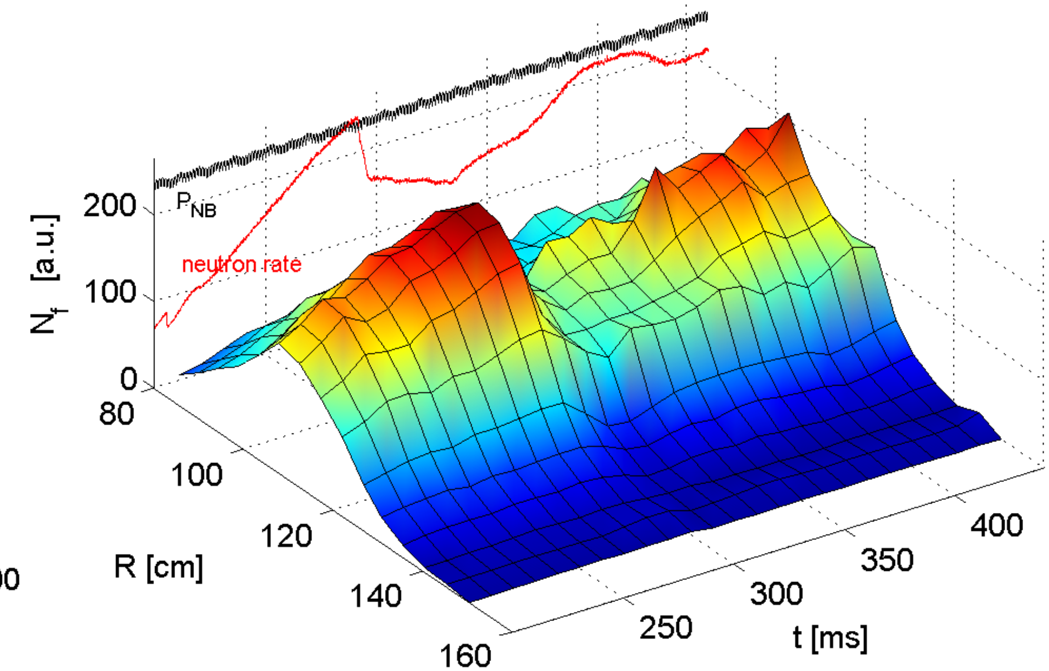
# New Fast-Ion Deuterium-Alpha (FIDA) diagnostic measured response of fast Ions to MHD modes

- Density profile of fast ions (15 – 65 keV) deduced from Doppler-shifted $D_\alpha$ emission by energetic neutrals created by charge-exchange with NBI neutrals

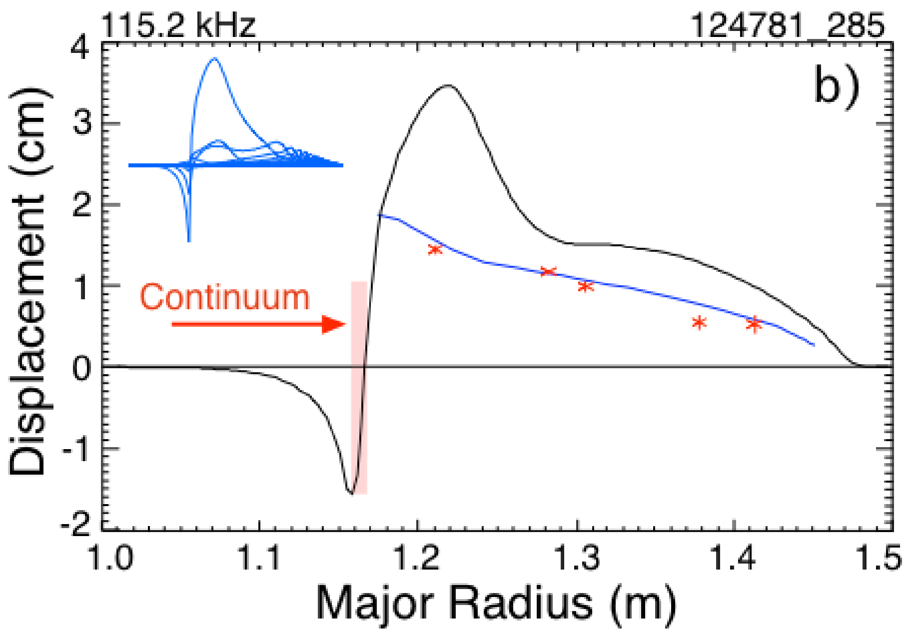
- During TAE avalanches, measured fast-ion losses up to 30%
  - Consistent with neutron rate drop
  - Profile remains peaked

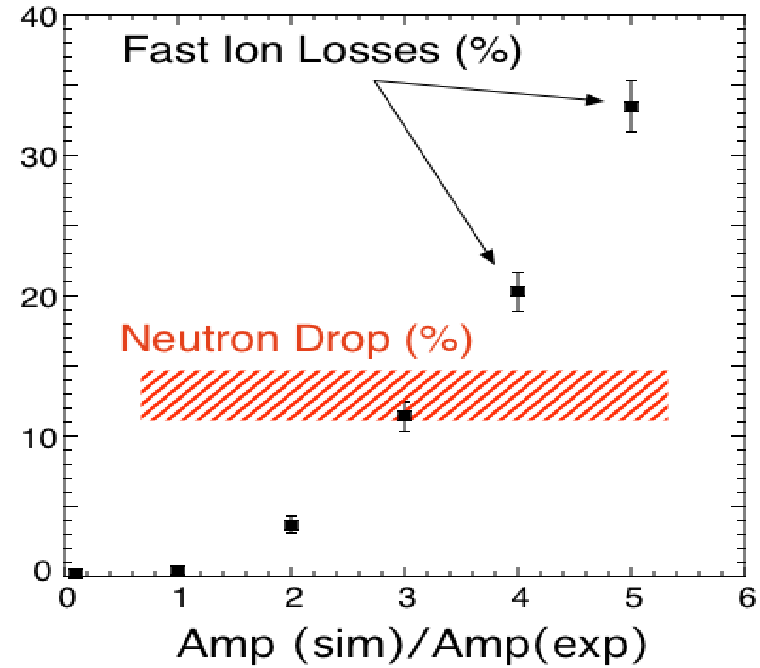
- Low-frequency (kink) activity redistributes fast ions outwards
  - Can destabilize Compressional Alfvén Eigenmodes (CAEs) in outboard midplane region



# Present simulations cannot explain measured NBI fast ion losses, highlighting need for improved predictive capability for *AE




- NOVA eigenmode (black curve) fit with "synthetic reflectometer" (blue curve) to reflectometer array data (red points).
- Present studies limited to L-mode - need monotonic & low $n_e(r)$ for reflectometer $\xi(r)$

- Presently, a factor of roughly 3 enhancement in mode amplitude is needed for ORBIT to reproduce experimental losses.

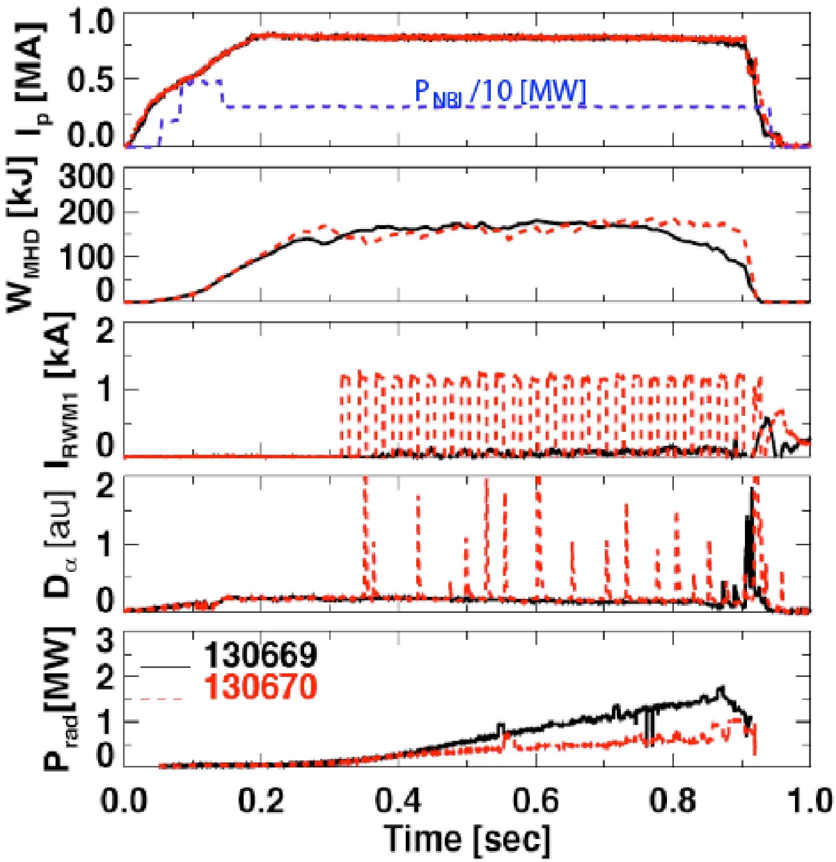
***2010-11***

***Beam Emission Spectroscopy (BES) diagnostic** will be used for higher spatial resolution *AE eigenfunction measurements (30 chan) in H and L-mode + non-linear M3D-K simulations = predictive capability for fast-ion transport and **NBI-CD redistribution.***

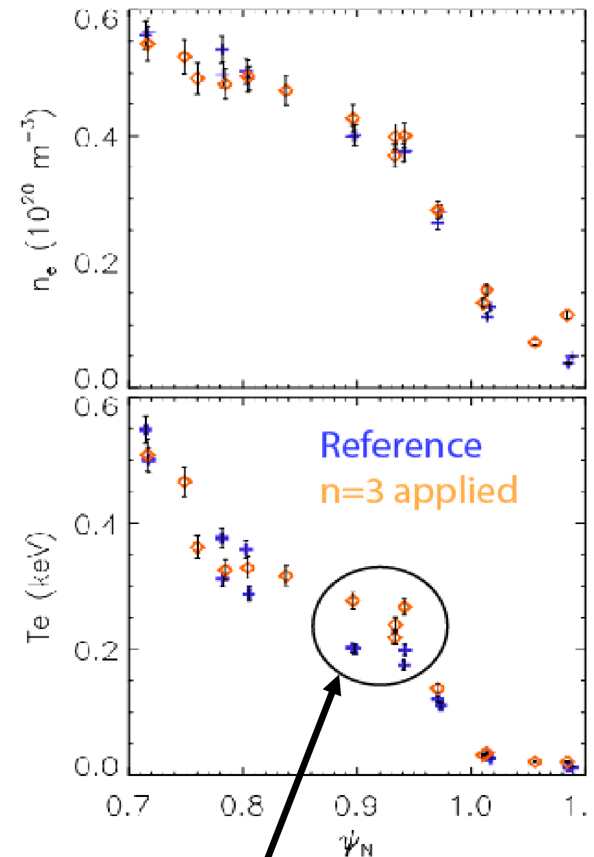
***MSE-LIF will complement FIDA $n_{fast}(r)$ and provide q(r) for arbitrary NBI conditions***

# 3-D fields used to alter ELM behavior - provides a possible scenario for impurity and radiation control of ELM-free Lithium discharges

**Type I ELMs triggered for impurity control (post-Li, n=3)**




**Edge $T_e$ and $dT_e/dr$ increased with RMP → n=3 more unstable (PEST)**




**2011**

*2nd SPA needed for arbitrary mix of odd and even-n RMP pulses for optimal ELM control simultaneous with n=1-3 RWM/EF control*

**2011**

*Additional edge Thomson needed to improve pedestal $T_e$, $n_e(\psi)$ resolution, support FY11 joint research milestone*

# NSTX FY2009-11 Research Milestones

## (base and incremental)

| | FY2009 | FY2010 | FY2011 |
|---|---|---|---|
| Expt. Run Weeks: | 16 w/ ARRA | 17 (20) | 14 (20) |
| **1) Transport & Turbulence** | | | Study turbulence regimes responsible for ion and electron energy transport (formerly FY2010) |
| **2) Macroscopic Stability** | Understand physics of RWM stabilization & control vs. rotation | Assess sustainable beta and disruptivity near and above the ideal no-wall limit | Assess sustained operation above the no-wall limit at reduced collisionality |
| **3) Boundary Physics** | | Assess H-mode characteristics as a function of collisionality and lithium conditioning | Relationship between lithiated surface conditions and edge and core plasma conditions |
| **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 *Joint milestone w/ solenoid-free TSG* | Assess predictive capability of mode-induced fast-ion transport |
| **5) Solenoid-free start-up, ramp-up** | | | |
| **6) Advanced Scenarios & Control** | Perform high-elongation wall-stabilized operation at lower $n_e$ | | Dependence of integrated plasma performance on collisionality *(FY2010 incremental accelerates this by 1yr if LLD and/or HHFW achieve FY2010 goals)* |

**Joint Research Targets (3 US facilities):**

| | FY2009 | FY2010 | FY2011 |
|---|---|---|---|
| | Particle control and hydrogenic fuel retention | Understanding of divertor heat flux, transport in scrape-off layer | Characterize H-mode pedestal structure |

# Run time/schedule priority will be given to milestones

## List below is prioritized based on relative importance of gaps to next-steps

- Key tools (existing + upgrades) utilized for milestones are shown in **red**
- Note that all milestones below are "high priority", since milestones are allocated as much run-time as is needed (within reason) to achieve their goal

| | **FY2009 Milestones** | **Tools** |
|---|---|---|
| **Joint** | Particle control and hydrogenic fuel retention in tokamaks | Li evap. (LiTER), sample probe |
| 1. | Perform high-elongation wall-stabilized operation at reduced $n_e$ | LiTER, NBI control |
| 2. | Study how j(r) is modified by super-Alfvénic ion-driven modes | Fast-ion D-alpha (FIDA) |
| 3. | Understand physics of RWM stabilization and control vs. rotation | NBI control, NTV braking |
| | **FY2010 Milestones** | |
| **Joint** | Understanding of divertor heat flux, transport in scrape-off layer | Div. bolom & fast IR, LLD |
| 1. | Characterize HHFW heating, CD, and $I_P$ ramp-up in H-mode plasmas | Upgraded HHFW |
| 2. | Assess pedestal characteristics and ELM stability as a function of $\nu^*$ & Li | LLD, Li CHERs, sample probe |
| 3. | Assess sustainable $\beta$ and disruptivity near and above ideal no-wall limit | Improved $\beta$ & mode control |
| *Inc-1* | *Dependence of integrated plasma performance on collisionality* | *LLD, HHFW* |
| | **FY2011 Milestones** | |
| **Joint** | (TBD) Improve understanding of H-mode pedestal structure | Higher-resolution MPTS |
| 1. | Dependence of integrated plasma performance on collisionality | LLD, HHFW, MSE-LIF |
| 2. | Study turbulence regimes responsible for ion, electron energy transport | BES, HHFW, LLD |
| 3. | Relationship between lithiated surface & edge/core plasma conditions | LLD, MAPP, div. spectrosc. |
| *Inc-1* | *Assess sustained operation above the no-wall limit at reduced collisionality* | *LLD, HHFW, 2nd SPA, MSE-LIF* |
| *Inc-2* | *Assess predictive capability of mode-induced fast-ion transport* | *BES, MSE-LIF, tang-FIDA* |

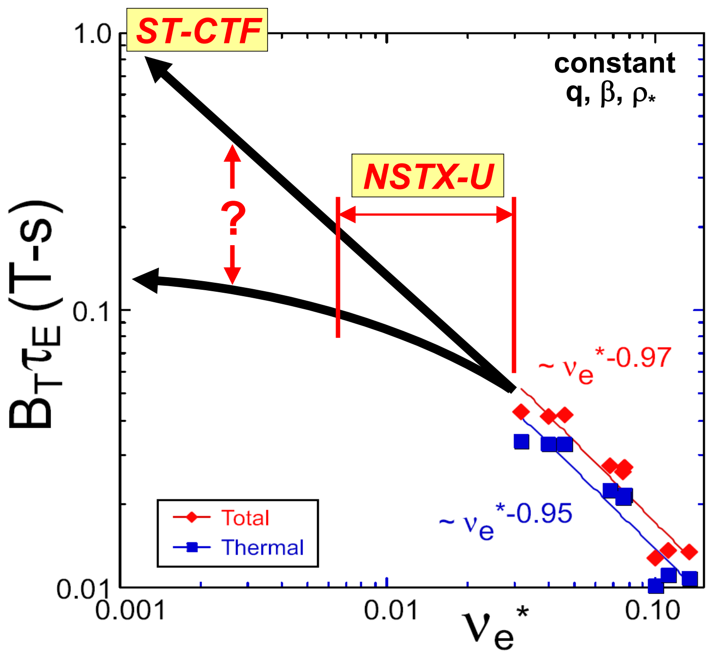
# Outline:

- Role of NSTX in Fusion research
- Near-term NSTX Research Goals
- Motivation for NSTX Major Upgrades
- Contributions to ITER and Tokamak Research
- Summary

# Li research is elucidating how collisionality impacts ST physics and performance across all topical science areas

- Macroscopic Stability
  - RWM critical rotation and neoclassical viscous torques may increase at lower $\nu_i$
- Transport & Turbulence
  - Underlying instabilities (micro-tearing, CTEM, and ETG) scale differently versus $\nu^*$
  - If $T_e(r)$ is set by a critical $\nabla T_e$, H-mode confinement may be reduced at reduced $n_e$
- Boundary Physics
  - ELM $\Delta$W increases at lower $\nu_e$ * - could impact confinement, plasma purity, divertor
  - ELM stability may improve at lower $\nu_e$* - through transport, second-stability access?
  - Detachment for heat flux reduction more challenging at reduced SOL density
- Wave-Particle Interactions
  - AE avalanches may be more easily triggered at reduced collisionality due to increased fast-ion pressure fraction → possible fast-ion redistribution and/or loss
- Plasma Start-up, Ramp-up, Sustainment
  - NBI-CD and RF-CD efficiency for ramp-up are increased at reduced $n_e$, increased $T_e$
  - ST-CTF scenarios rely on reduced $n_e$ and increased $T_e$ to increase NBI current drive efficiency to achieve 100% non-inductive current fraction.

# Increased temperature and duration needed to address key issues for toroidal plasma science, ITER, and next-step STs



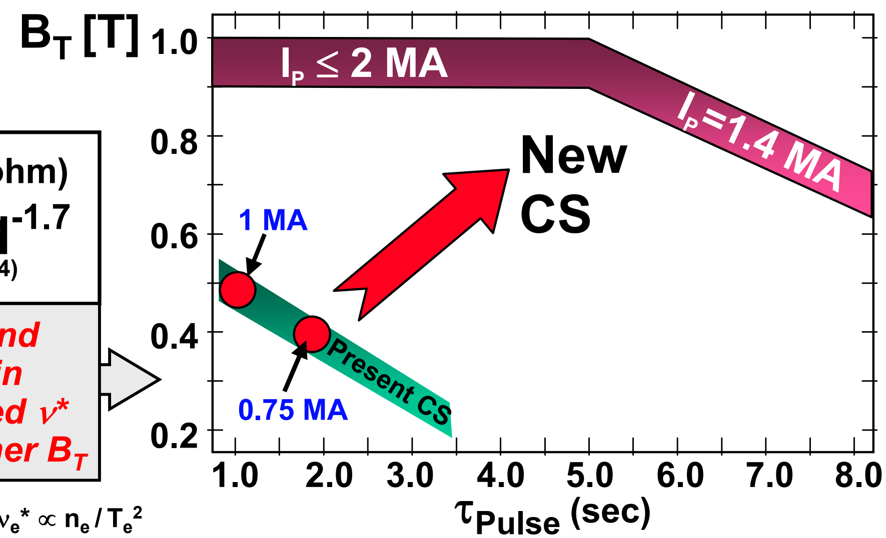

ITER $B\tau_E$ (e-static g-Bohm)

$\propto \rho_*^{-3}\,\beta^0\,\nu_*^{-0.14}\,q^{-1.7}$

Petty et al., PoP, Vol. 11 (2004)

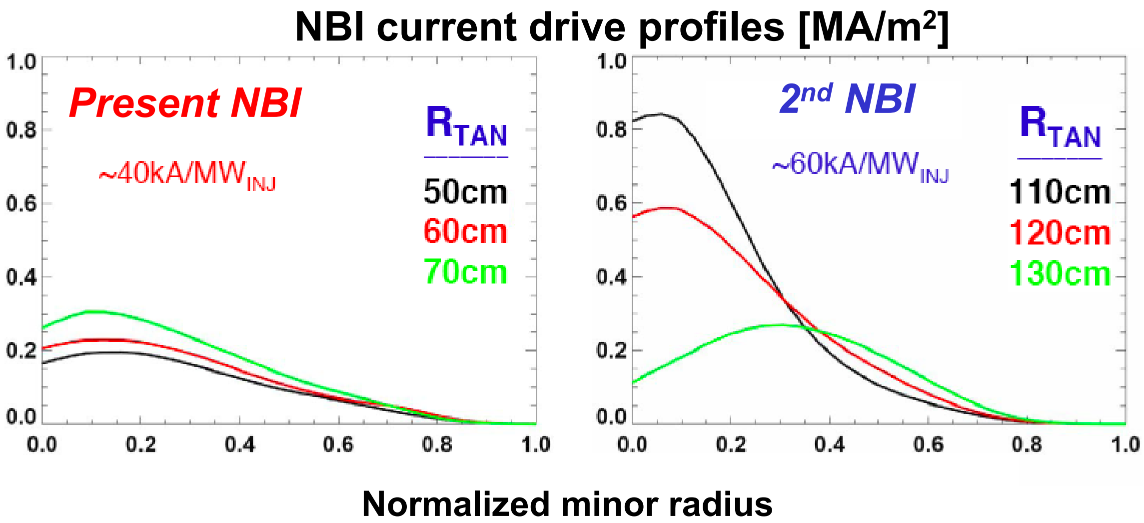
*Does NSTX strong and favorable increase in confinement at reduced $\nu^*$ persist at lower $\nu^*$, higher $B_T$*

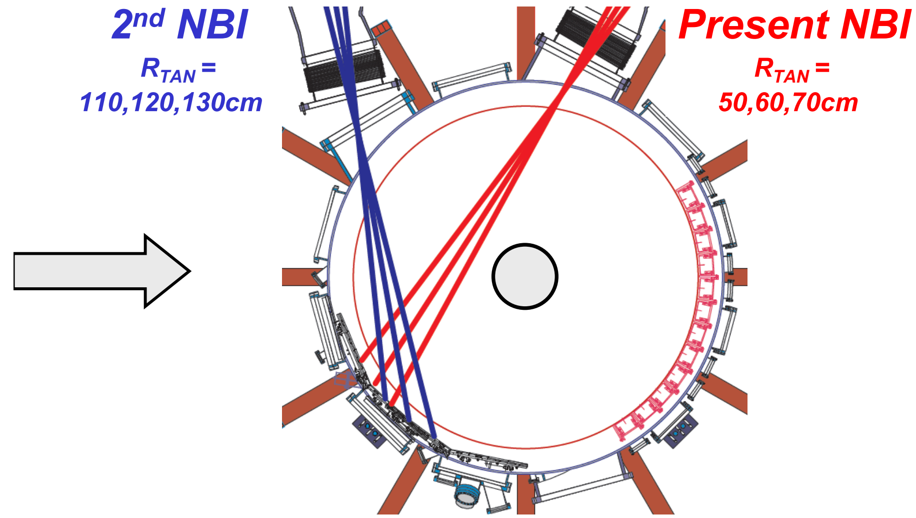
Normalized electron collisionality $\nu_e^* \propto n_e / T_e^2$




- Higher field and current enable access to higher temperature
- Higher temperature reduces collisionality and increases efficiency of non-inductive current-drive sources, and increases equilibration time
- New CS with $B_T$ = 1T, $I_P$ = 2MA (with induction), $t_{flat\text{-}top}$ = 5s would provide:
  - Longer pulse to assess RF ramp-up, 100% non-inductive sustainment at ~1MA
  - Higher field to stably accept high power for edge heat/particle transport studies
  - Extended range of field, current, β, collisionality to obtain unique data to aid development of first-principles understanding of turbulent transport
  - Magnet operation at ~1T (vs. 0.55T), within factor of 2 of next-step STs

# More tangential 2nd NBI would enhance heating & current-drive for start-up, sustainment, heat-flux, transport studies




- More tangential 2nd NBI would provide:
  - Up to 2 times higher current-drive efficiency, and current profile control
  - Tests of NBI ramp-up to ~1MA
  - World-leading capabilities for plasma boundary physics at high heat flux
    - Double NBI power: P/R = 12 → 20 MW/m (includes 4MW RF)
    - ITER / CTF / DEMO = 19 / 40-50 / 40-130 MW/m
  - Increased heating power to access very high $\beta$ at low collisionality – important for fundamental studies of transport and global stability
  - Overall, a highly flexible tool for toroidal physics research by varying current, heating, and torque profiles, and fast-ion distribution function $f(v_{||},v_{\perp})$

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# NSTX participation in International Tokamak Physics Activity (ITPA) benefits both ST and tokamak/ITER research

## Actively involved in 21 joint experiments – contribute/participate in 33 total

**MHD, Disruption Control**

| | |
|---|---|
| • MDC-2 | Joint experiments on resistive wall mode physics |
| • MDC-4 | Neoclassical tearing mode physics – aspect ratio comparison |
| • MDC-12 | Non-resonant magnetic braking |
| • MDC-14 | Rotation effects on neoclassical tearing modes |
| • MDC-15 | Disruption database development |
| • MDC-17 | Physics-based disruption avoidance |

**Transport and Confinement**

| | |
|---|---|
| • TC-1 (was CDB-2) | Confinement scaling in ELMy H-modes: beta degradation |
| • TC-2 (was CDB-10) | Power ratio – Hysteresis and access to H-mode with H~1 |
| • TC-4 (was CDB-12) | H-mode transition and confinement dependence on ionic species |
| • TC-6 | Effect of Rotation on Plasma Performance |
| • TC-10 (was TP-7) | Experimental ID of ITG, TEM and ETG turbulence + comparison w/ codes |
| • TC-15 | Dependence of momentum and particle pinch on collisionality |

**Energetic Particles**

| | |
|---|---|
| • EP-2 | Fast ion losses and redistribution from localized *AE |

**Pedestal and Edge Physics, Divertor, Scrape-off Layer**

| | |
|---|---|
| • PEP-6 | Pedestal structure and ELM stability in DN |
| • PEP-19 | Edge transport under the influence of resonant magnetic perturbations |
| • PEP-25 | Inter-machine comparison of ELM control by magnetic field perturbations from midplane RMP coils |
| • DSOL-17 | Cross machine comparisons of pulse-by-pulse deposition |
| • DSOL-21 | Introduction of pre-characterized dust for dust transport studies in divertor and SOL |

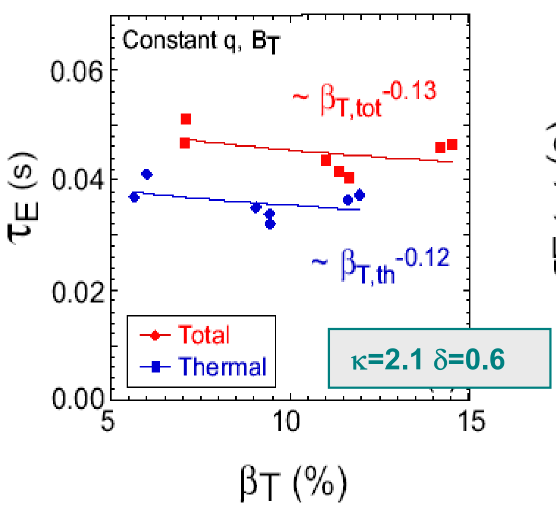
**Integrated Operation Scenarios**

| | |
|---|---|
| • IOS-4.1 | Access conditions for hybrid with ITER-relevant restrictions |
| • IOS-5.1 | Ability to obtain and predict off-axis NBCD |
| • IOS-5.2 | Maintaining ICRH coupling in expected ITER Regime |

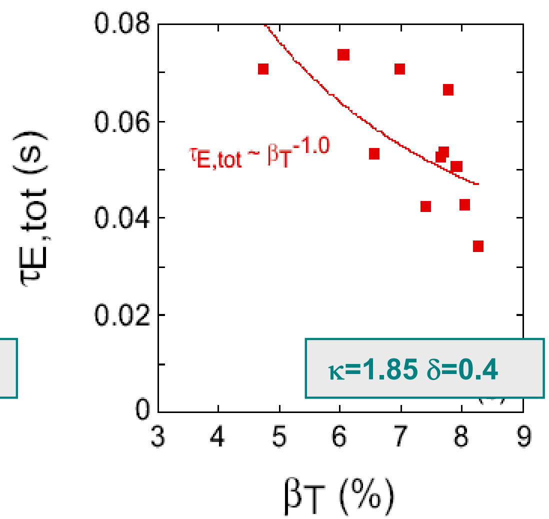
# Previous examples of NSTX contributions to ITPA for ITER:

- **Transport:** $\beta$-dependence of H-mode confinement important to ITER advanced scenarios ($B\tau_{98y2} \sim \beta^{-0.9}$)
  - NSTX performed $\beta$-scan (factor of 2-2.5) at fixed q, $B_T$
  - Degradation of $\tau_E$ with $\beta$ weak on NSTX for strongly shaped plasmas, stronger for more weakly shaped plasmas
  - Implies shape and/or ELM-type influences $\beta$ dependence of H-mode confinement scaling

**Small Type V ELMs**

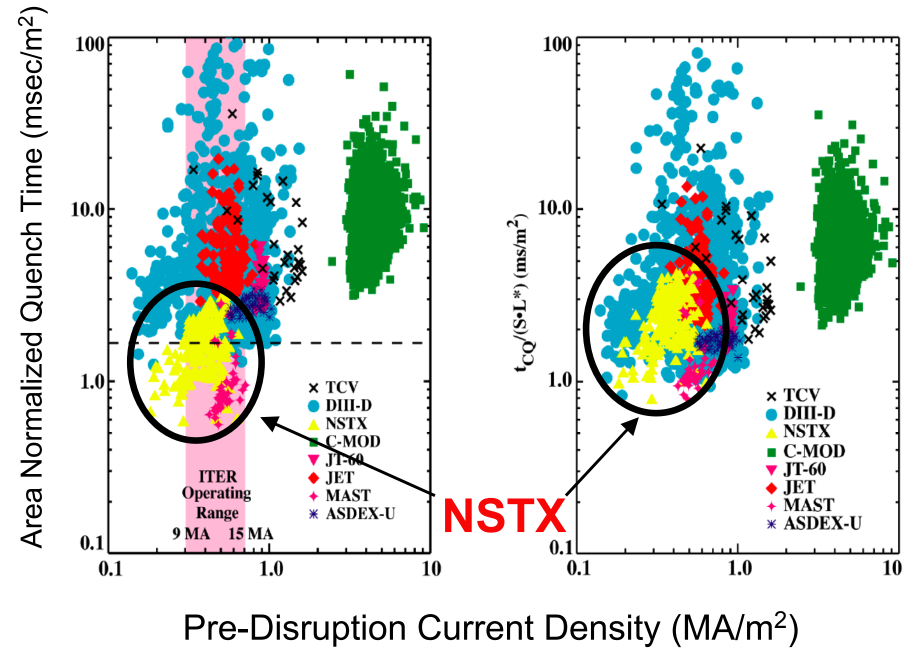



**Type III/No → Type I ELMs**




- **MHD:** Reduced normalized external inductance of low-A explains difference in $I_P$ quench-rate
  - Implies tokamaks & STs have similar $T_e$ during $I_P$ quench phase (impurity radiation dominates dissipation of plasma inductive energy)

Area-normalized (left), Area and $L_{ext}$-normalized (right) $I_p$ quench time vs. toroidal $J_p$ (ITER DB)



# In FY2009-10, NSTX will support several high priority research tasks identified by ITER Organization

- Impact of He (and possibly H) operation on H-mode
  - Important for commissioning phase of ITER operation
  - **NSTX**: Examine L→H threshold, global confinement, ELM stability
- ELM modification, suppression, control
  - Important for ITER divertor survivability at high fusion gain
  - **NSTX**: Understand ELM modification results:
    - ELM stabilization with Lithium
    - ELM destabilization of with resonant magnetic perturbations (RMP)
  - **NSTX**: RMP ELM control at lower $q_{95}$, reduced $\nu^*$ (HHFW, LLD), vertical jogs(?)
- Validate neoclassical toroidal viscosity (NTV) flow damping theory
  - Important for minimizing mode locking during ITER RMP ELM control
  - **NSTX**: Additional expt/theory comparisons at varied $\nu^*$, rotation, RMP spectrum
- Simulation of ITER test blanket module impact on plasma
  - Important for understanding impact of large predicted error fields
  - **NSTX**: Assess use of EF/RWM coils to approximate TBM spectrum

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

- The FY09-11 plan:
  - Focuses research to address key gaps in extrapolating to next-step STs
    - Increased beam-driven current and higher non-inductive fraction at reduced $\nu^*$
    - Electron and ion H-mode confinement
    - Non-inductive start-up and ramp-up
    - Density control and novel means to "tame the plasma-material interface"
    - Sustaining high normalized beta plasmas to maximize future fusion performance
  - Plan is well aligned with FESAC-TAP, and is responsive to ITER high priorities

- 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 $\nu_i$
  - Understand role of $\nu^*$ 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 w/ reduced collisionality