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NSTX Research Results and Plans for FY2010-12

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NSTX Program Director

For the NSTX Research Team

FY2012 OFES Budget Planning Meeting
Gaithersburg, MD
March 11-12, 2010

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Colorado Sch Mines
Columbia U
CompX
General Atomics
INL
Johns Hopkins U
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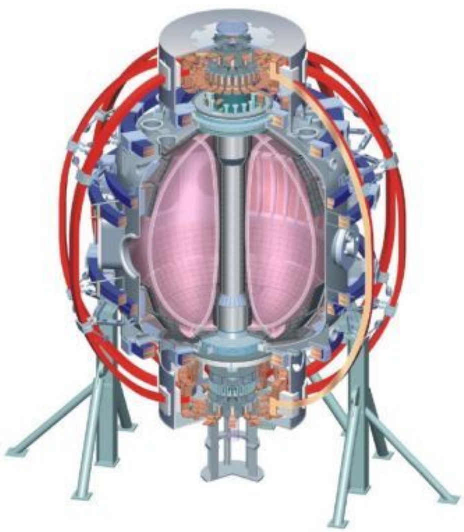

Culham Sci Ctr
U St. Andrews
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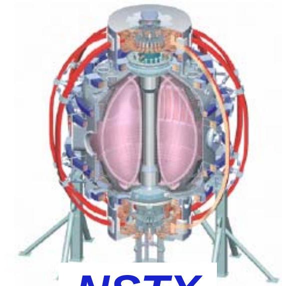
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

Outline

- NSTX Mission
- Linkages to ReNeW
- FY2010-12 Research Milestones, ITER support
- Milestone Timelines
- NSTX Upgrade Motivation
- Summary

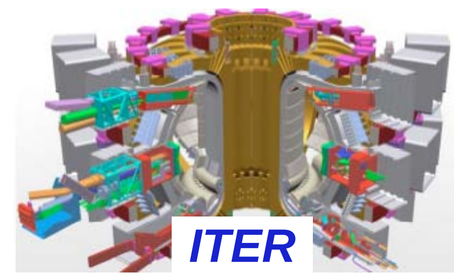
NSTX Mission Elements

- **Understand unique ST physics properties**
  - Low A, high β, v_{fast}/v_A, edge power density



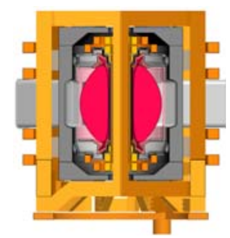
NSTX

- **Extend understanding of tokamak / ITER**

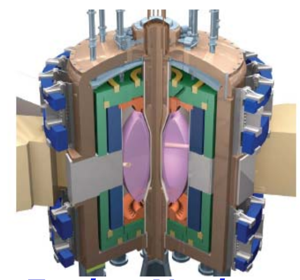


ITER

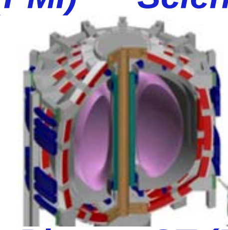
- **Establish attractive ST operating regimes**
  - Address gaps between ITER and DEMO
  - Advance ST as fusion power source



Plasma Material Interface (PMI)



Fusion Nuclear Science (FNS)



Burning Plasma ST (BPST)

ST and NSTX research strongly support all ReNeW Themes

1. ITER burning plasma

- Advancing multi-mode *AE fast-ion transport physics, diagnostics, modeling
- Developing ELM suppression and triggering understanding (lithium, 3D fields)

2. Creating and predicting high-performance/steady-state

- NSTX and Upgrade targeting 100% non-inductive, high-β_T (10-20%)
- Providing ST data to challenge wide range of theory and simulations

3. Taming the Plasma-Material Interface (PMI)

- NSTX is world leader in understanding Li PFCs + high-performance plasmas
- Also advancing radiative divertors, high flux expansion for heat flux mitigation

4. Harnessing fusion power

- ST attractive for fusion nuclear science (high neutron flux at small size, cost)

5. Configuration optimization

- ST attractive for next-steps (simplified, maintainable, affordable magnets)
- NSTX is lead US ST facility covering extensive range of ST research

NSTX research goals and milestones strongly support research actions identified in ReNeW ST Thrust 16:

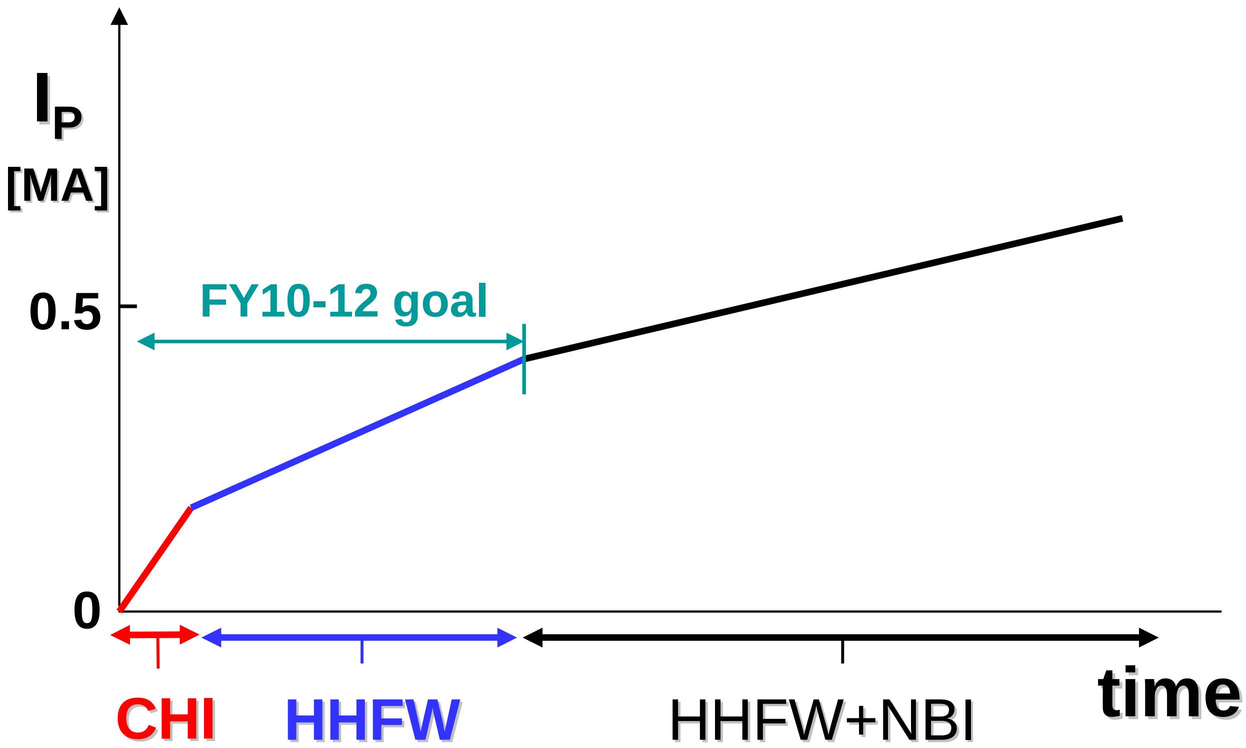
ReNeW Thrust 16: "Develop the ST to advance fusion nuclear science"
consists of 7 Thrust Elements:

1. Develop **MA-level plasma current formation and ramp-up**
2. Advance **innovative magnetic geometries, first wall solutions**
3. Understand **ST confinement and stability** at fusion-relevant parameters
4. Develop **stability control techniques** for long-pulse, disruption-free ops
5. **Sustain current, control profiles** with beams, waves, pumping, fueling
6. Develop normally-conducting radiation-tolerant **magnets** for ST applications
7. **Extend ST performance** to near-burning-plasma conditions

Thrust 16 elements provide outline for subsequent FY10-12 milestones

Initiating, ramping-up, and sustaining plasma current without reliance on central solenoid critical for nuclear applications of ST

NSTX non-inductive start-up and ramp-up approach:



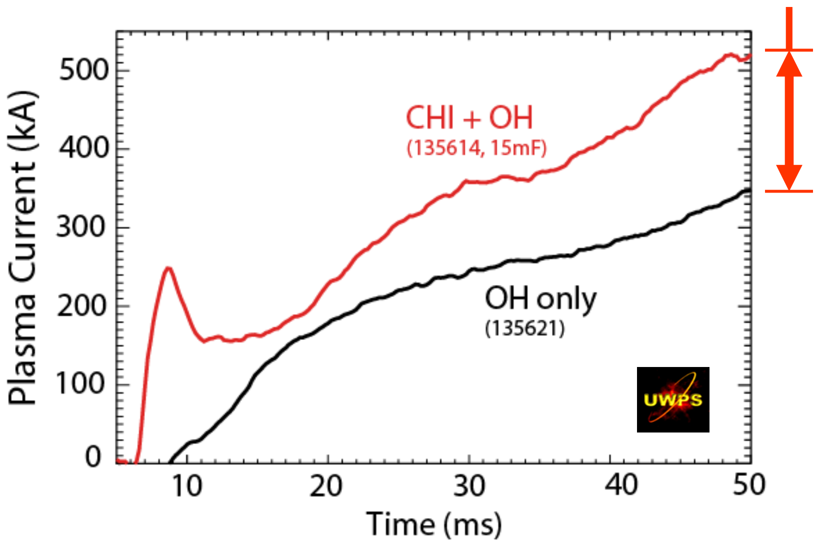
1. Co-Axial Helicity Injection (CHI) forms closed-flux ST plasma

2. High-Harmonic Fast Wave heats low I_P plasma → bootstrap ramp-up

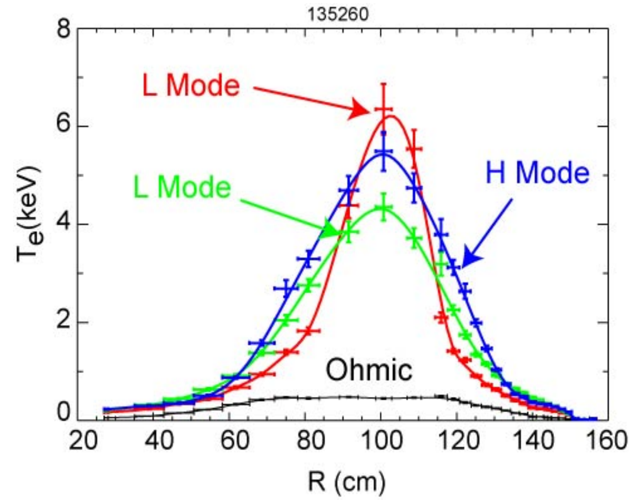
3. Neutral Beam Injection (NBI) heating & CD for ramp-up to flat-top current

Start-up goals: Non-inductively form 0.4MA plasma as target for NBI ramp-up to ~1MA in Upgrade in prep for FNSF

ΔI_P = 180kA OH flux savings achieved with CHI via low-Z impurity reduction



Upgraded HHFW has heated 100-200eV plasma to > 5keV in H-mode, maintained power during LH transition, ELMs

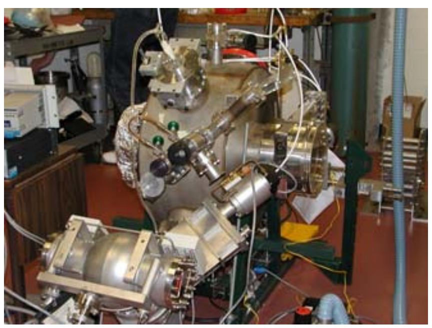


- **FY10:** Characterize HHFW heating, current drive, ramp-up in D H-mode
  - Attempt to sustain 100% non-inductive plasma (I_P = 250-400kA bootstrap CD)
  - Develop bootstrap over-drive ramp-up, also heat electrons in NBI H-modes
- **FY12:** Assess confinement, heating, ramp-up of CHI start-up plasmas
  - Use HHFW to compare confinement, heating of CHI → OH plasmas vs. OH-only
  - Apply HHFW heating progressively earlier in shot to reduce OH flux swing to 0

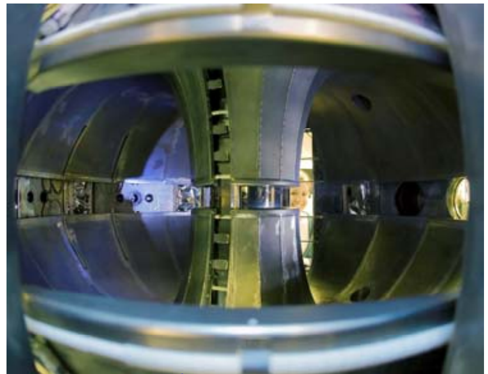
NSTX lithium research is an integral part of a program to develop lithium as a PFC concept for magnetic fusion

LTX lithium handling facility

LTX PFC test facility



Purdue surface analysis facilities



LTX operations commence 2010
- Fully non-recycling liquid lithium PFC's
- Profile control with core fueling
- No-carbon comparison to NSTX

<u>NSTX:</u>
- **Only diverted, H-mode, NBI-heated tokamak w/ Li**
- **New capability: Liquid lithium divertor (LLD)** (collaboration with SNL)

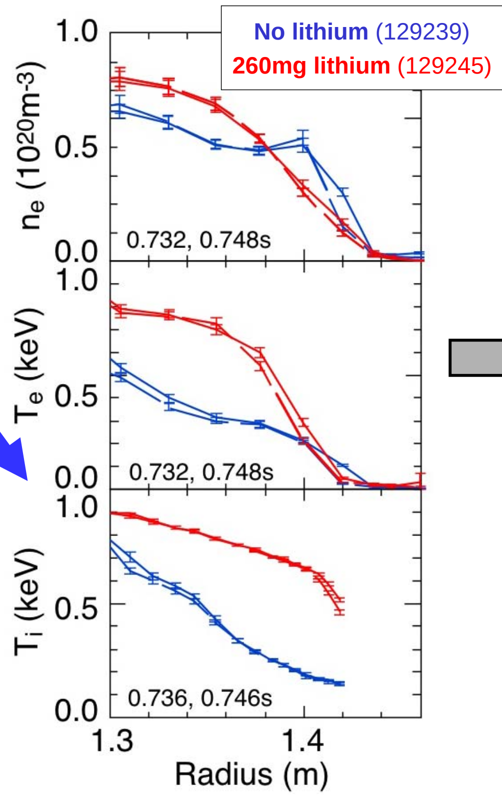
NSTX upgrade, Fusion next-steps

NSTX materials analysis probe

Understand surface physics and chemistry

Lithium goals: Assess Li divertor for pumping, impact on plasma scenarios, compatibility with high-flux expansion

- Solid Li coatings can reduce pedestal ν*:
  - –Reduced edge n_e
  - –Increased edge T_e, T_i
- Other benefits:
  - –D pumping
  - –Higher τ_E
  - –Eliminate ELMs
- Issues:
  - –Impurity accumulation
  - –Pumping is transient



FY2010: Liquid Lithium Divertor (LLD) for sustained D pumping

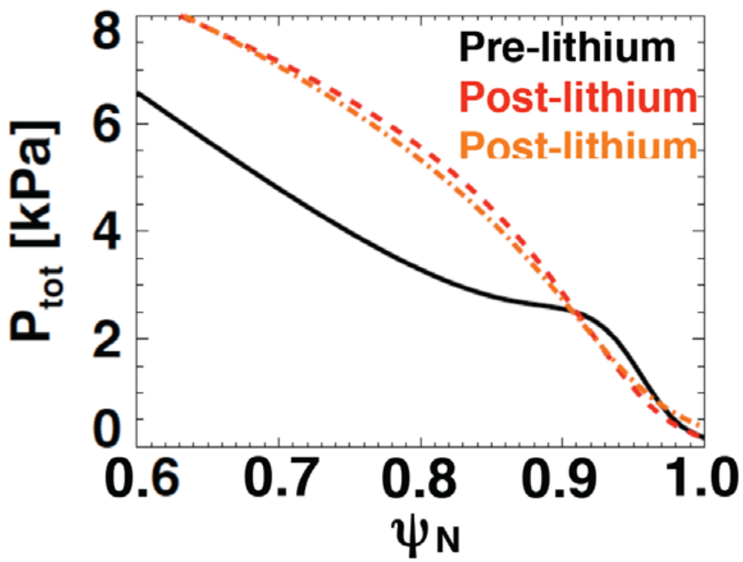
LLD = 4 heated plates with porous Mo surface
Thin film of liquid Li on plate absorbs impinging D
Li fueled/replenished from above w/ evaporators

- **FY11:** Assess the relationship between lithiated surface conditions and edge and core plasma conditions
  - – Assess pumping, retention vs. Li coverage, LLD temperature, R_{strike}, flux expansion
  - – Compare to local retention, surface composition (MAPP probe - Purdue)
  - – Measure C, Li density, transport from edge to core with toroidal, poloidal CHERS

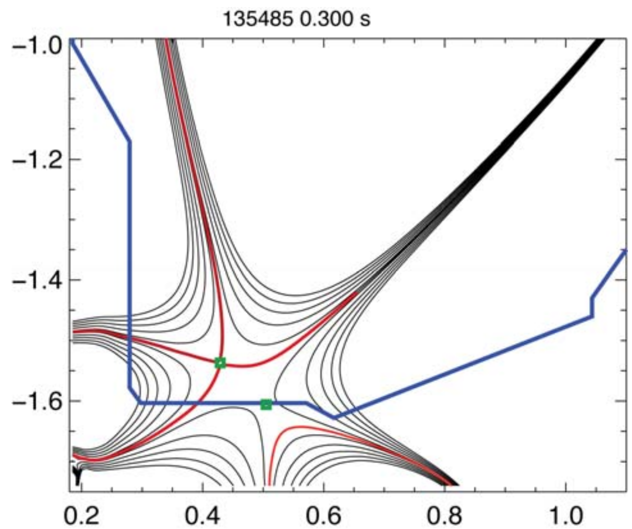
NSTX collaborator Jean Paul Allain (Purdue) awarded Early Career Award for:
"Harnessing Nanotechnology for Fusion Plasma-Material Interface Research in an in-situ Particle-Surface Interaction Facility"

Boundary goals: Improve H-mode pedestal structure/control understanding including Li, improve divertor power handling

Li suppresses ELMs via profile modification
Consistent w/ peeling-ballooning (ELITE)



Testing high flux expansion "snowflake" divertor



2009: NSTX measured reduced C influx and reduced peak heat flux with snowflake

- **FY10:** Assess H-mode pedestal, ELM stability vs. ν^*, Li conditioning
  - Determine the relative roles of n_e, ν^* vs. direct effects of Li from LiTER and LLD
  - Assess L-to-H threshold, pedestal height/width/stability, down-stream conditions
- **FY11:** Assess pedestal/SOL response to applied 3D fields *(incremental)*
- **FY12:** Characterize very high flux expansion divertor operation
  - Assess power handling, LLD pumping of "snowflake" and "x-divertor" divertors

Boundary research will support two OFES joint research milestones: divertor heat flux, H-mode pedestal structure

FY2010: "…improve understanding of the heat transport in the SOL plasma, strengthening the basis for projecting divertor conditions in ITER"

- Exploit range of SOL ν^*, β, $q_{||}$, divertor geometry spanned by 3 facilities
- **NSTX:** Liquid lithium effects, high β, lower A

FY2011 Theory-Experiment Milestone: "Understand mechanisms responsible pedestal structure, develop a predictive capability"

Experiment:

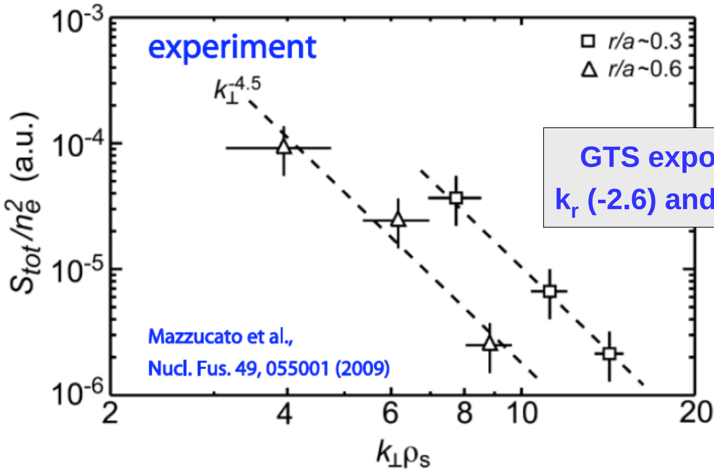
- Perform experiments to test physics models in pedestal on multiple devices
- **NSTX:** Higher-res. pedestal structure data (MPTS upgrade - ARRA), E_r
- **NSTX:** Initial measurements of turbulence in pedestal region (BES, GPI)

Theory:

- Focused analytic theory/computation effort, include large-scale simulations
- Model key physics mechanisms in experiments, compare to observations

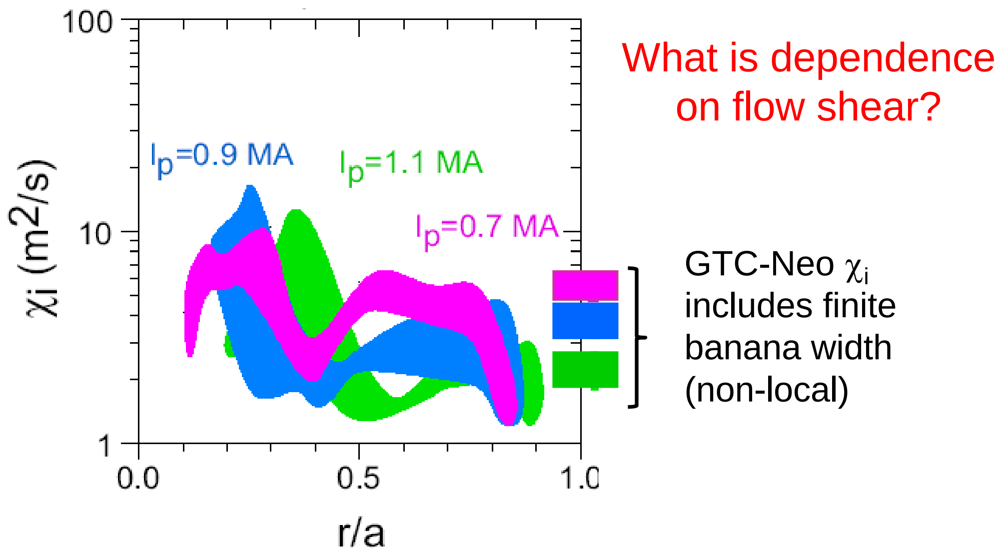
Transport goals: Exploit fluctuation diagnostics, modeling to understand turbulent transport in ST, project to next-steps

- High χ_e in ST motivates studies of e-transport
- High-k turbulence measured consistent w/ ETG
- $k_\perp$ exponent bracketed by non-linear GTS values



- Developing synthetic high-k diagnostics for GTS

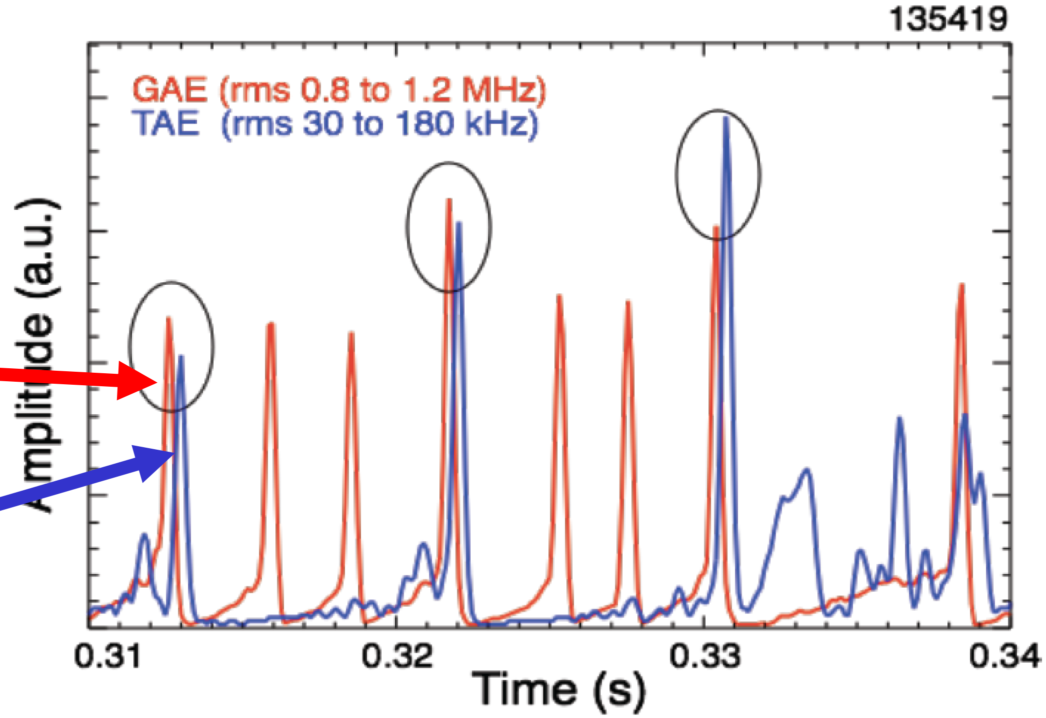
Ion thermal diffusivity previously observed to be consistent with neoclassical for outer r/a…
Is low-k turbulence stable across profile?



- **FY11:** Measure fluctuations responsible for turbulent energy transport
  - **New:** measure low-k turbulent δn/n with Beam Emission Spectroscopy (BES)
  - High-k portion will be measured with existing high-k μ-wave scattering diagnostic
  - Correlate turbulent k-spectrum w/ energy diffusivities inferred from power balance
- **FY12:** Enhance turbulent transport understanding by comparing measured fluctuations to theory and simulation
  - Compare measurements to micro-instability codes: GYRO, GTS, GS2, GTC-NEO

Energetic particle goals: Develop prediction of fast-ion transport from AE avalanches in H-mode for ST and ITER

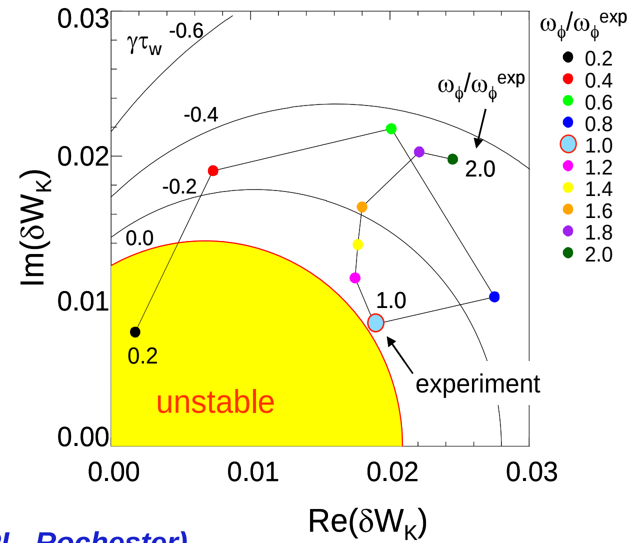
GAE avalanches can spatially redistribute fast-ions, triggering TAE avalanches



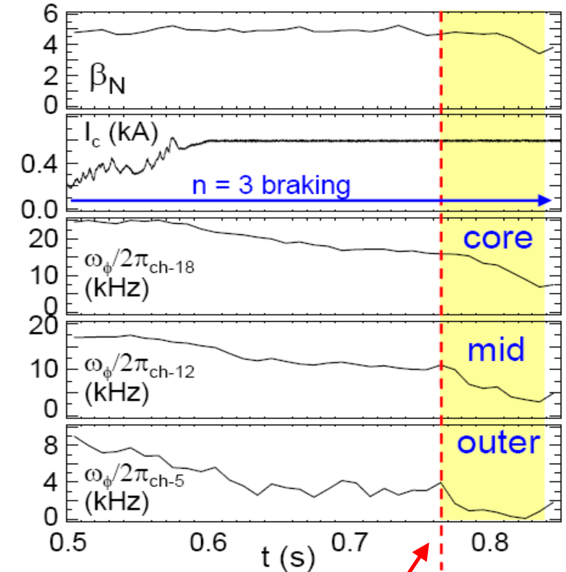
- **FY11:** Assess predictive capability of mode-induced fast-ion transport ***(incremental)***
  - Measure ξ_r(R,t) in H-mode with BES + enhanced-resolution reflectometry
  - Improve measurements of fast-ion f(v) using tangential Fast-Ion D_α (FIDA) diagnostic - extends existing perpendicular FIDA
  - Extend validation of NOVA-K/ORBIT TAE avalanche transport simulations
  - Develop multi-AE + multi-mode + fast-ion transport predictions w/ M3D-K

MHD goals: Understand kinetic effects for RWM and rotation damping to optimize RWM and rotation control for ST, ITER

RWM marginal stability depends on rotation non-monotonically due to influence of multiple kinetic resonances



MISK modeling (CU, PPPL, Rochester)



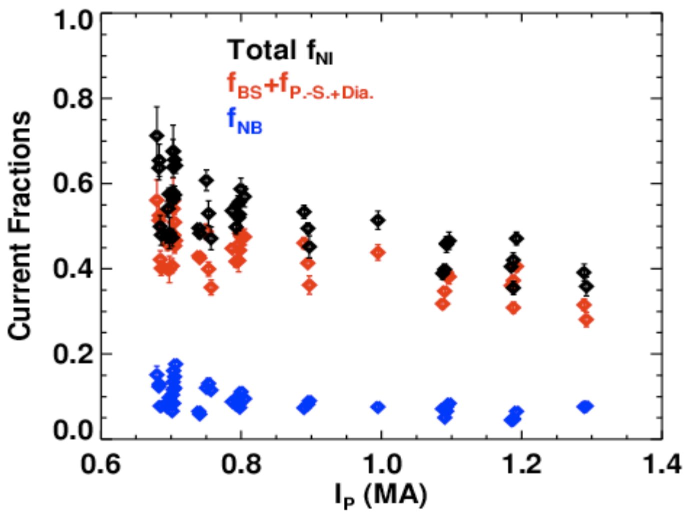
Rotation decreases non-monotonically at fixed n=3 & β_N w/o mode activity

NTV rotation damping also a sensitive function of resonances: **Stronger damping in super-banana plateau regime as $\omega_E \rightarrow 0$?**

- **FY10:** Assess sustainable β, disruptivity near/above ideal no-wall limit
  - β_N control, improved RFA/RWM detection, state-space controller, multi-mode effects
  - Characterize degree to which other instabilities (2/1 NTM) impact disruptivity
- **FY11:** Assess RWM, NTV at reduced collisionality ν* *(incremental)*
- **FY12:** Investigate physics and control of toroidal rotation at low ν*
  - Develop NTV physics understanding vs. n=1, 2, 3, ν*, β (RFA), rotation
  - MISK calculations of rotation profiles for optimized global and edge stability

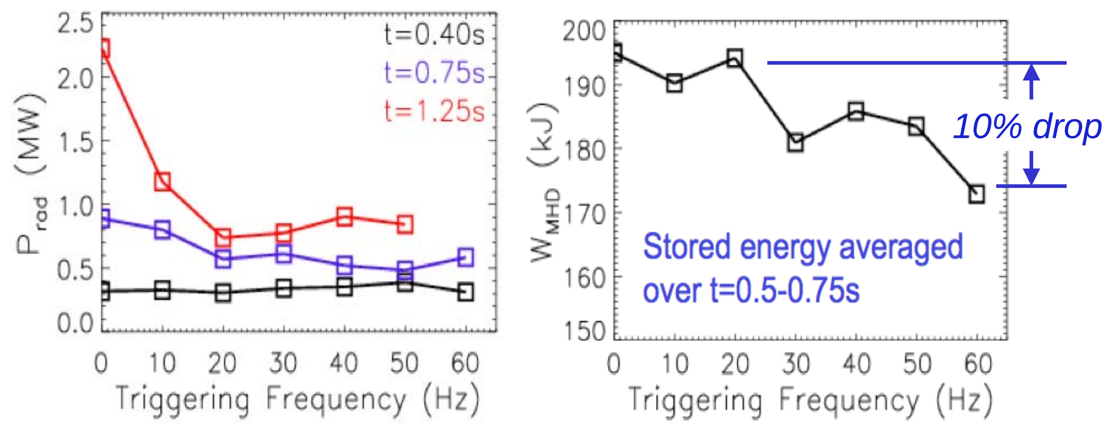
Advanced Scenario goals: Assess LLD and HHFW impact on advanced scenarios, integrate with ELM and rotation control

Goal: non-inductive CD = 70% → 80-100%



Higher NBI-CD → higher η_{CD} → higher T_e / n_e
Higher BS-CD → higher p_e thru higher T_e

Pulsed 3D fields used to trigger ELMs to control impurity content, density in Li ELM-free plasmas



New for FY11: Independent control of n=1,2,3 fields to optimize ELM pacing

- **FY11:** Assess dependence of integrated plasma performance on ν^*
  - Use LLD to reduce the density and increase τ_E, HHFW to heat electrons
  - Assess non-inductive current, confinement, core and pedestal stability, impurities
- **FY12:** Investigate physics and control of toroidal rotation at low ν^*
  - Explore role of rotation profile on transport, bootstrap current, ELMs, impurities
  - Control profile w/ independent control of n=1,2,3 NTV - utilize new 2nd SPA (ARRA)

NSTX is actively engaged in 21 ITPA joint experiments

- **Advanced Scenarios and Control**
  - IOS-5.2 Maintaining ICRH Coupling in expected ITER Regime
- **Boundary Physics and Lithium Research**
  - PEP-6 Pedestal structure and ELM stability in double null
  - PEP-19 Edge transport under the influence of resonant magnetic perturbations
  - PEP-23 Quantification of the requirements for ELM suppression by magnetic perturbations from internal off mid-plane coils
  - PEP-25 Inter-machine comparison of ELM control using mid-plane RMP coils
  - PEP-26 Critical edge parameters for achieving L-H transition
  - PEP-27 Pedestal profile evolution following L-H transition
  - DSOL-21 Introduction of pre-characterized dust for dust transport studies in divertor and SOL
- **Macroscopic Stability**
  - 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 Turbulence**
  - TC-4 H-mode transition and confinement dependence on ionic species
  - TC-9 Scaling of intrinsic plasma rotation with no external momentum input
  - TC-10 Experimental identification of ITG, TEM and ETG turbulence and comparison with codes
  - TC-12 H-mode transport and confinement at low aspect ratio
  - TC-14 RF Rotation Drive
- **Waves-Particle Interactions**
  - EP-2 Fast ion losses and redistribution from localized Alfvén Eigenmodes
  - EP-4 Effect of dynamical friction (drag) at resonance on nonlinear AE evolution

In FY2010-12, NSTX will support confinement, pedestal, and ELM research identified as high priority by the ITER Organization

NSTX will dedicate 5 run-days in FY2010 specifically to ITER high-priority:

From ITER Physics Work Programme 2009-2011 - Sections 2.1 - ITER Short term activities (2008-2010) and 2.2 - ITER Medium term activities (2011 and beyond)

2.1.1 Transport and Confinement during transient phases
2.1.2 Access to high confinement regimes in ITER during steady/state and ramp-up/down H, D and DT phases
2.1.3 Characterization of proposed schemes for active ELM control, compatibility with scenario requirements

- **Assess NSTX confinement, H-mode threshold, etc. during ramp-up/down**
- **Complete/extend NSTX L-H, H-L threshold experiments from FY2009 in FY2010-11**
- **Contribute NSTX understanding of RMP ELM pacing results**

2.2.1 Pedestal width, pedestal energy and uncontrolled ELM energy loss in ITER
2.2.2 Development of alternative regimes providing high fusion performance in ITER without or with small ELMs compatible with overall scenario requirements
2.2.3 Develop alternative methods for ELM control/suppression in ITER & integration w/ scenario requirements
2.2.6 Momentum transport in ITER reference scenarios & expected plasma rotation in ITER

- **Contribute to OFES 3 facility joint research milestone on pedestal structure in FY2011**
- **Attempt to extrapolate NSTX Type V ELMs to low ν^*, explore access to QH mode**
- **Extend NSTX vertical jogs and RMP fields for ELM pacing to smaller ELM size**
- **Develop NSTX Li ELM-free H-mode with reduced/halted impurity accumulation**
- **Use NSTX HHFW to reduce input torque, use NB pulses + CHERS for T_i and rotation**

Jong-Kyu Park (PPPL) awarded DOE-SC Early Career Award for: “Self-consistent Calculations of Pedestal Structure Modification by 3D Fields in Tokamaks”

FY2010-12 milestones exploit new liquid lithium divertor (LLD), upgraded fast-wave, and BES for boundary physics, transport, start-up, integration

	FY2010	FY2011	FY2012
Expt. Run Weeks:	15 w/ ARRA	14	14
1) Transport & Turbulence		*BES, LLD, HHFW* Measure fluctuations responsible for turbulent ion and electron energy transport	*BES* Compare measured turbulence fluctuations to theory & simulation
2) Macroscopic Stability	*LLD* Assess sustainable beta and disruptivity near and above the ideal no-wall limit		
3) Boundary/Lithium Physics	*LLD* Assess H-mode characteristics as a function of collisionality and lithium conditioning	*LLD, BES* Assess relationship between lithiated surface conditions and edge and core plasma conditions	*LLD* Assess very high flux expansion divertor operation
4) Wave-Particle Interaction	*HHFW* Characterize HHFW heating, CD, and ramp-up in deuterium H-mode (joint with solenoid-free start-up TSG)		
5) Solenoid-free start-up, ramp-up			*LLD, HHFW* Assess confinement, heating, and ramp-up of CHI start-up plasmas (joint with WPI-HHFW TSG)
6) Advanced Scenarios & Control		*LLD, HHFW* Assess integrated plasma performance versus collisionality	*LLD* Investigate physics and control of toroidal rotation at low collisionality (joint with MS TSG)
Joint Research Targets (3 US facilities):	*LLD, HHFW* Understanding of divertor heat flux, transport in scrape-off layer	*LLD* Characterize H-mode pedestal structure	Not yet decided

Enhanced utilization in FY2011-12 would accelerate understanding of transport response to 3D fields, RWM stability, fast-ion confinement

	FY2010	FY2011	FY2012
Expt. Run Weeks:	15 w/ ARRA	20	20
1) Transport & Turbulence		Measure fluctuations responsible for turbulent ion and electron energy transport	Compare measured turbulence fluctuations to theory & simulation
2) Macroscopic Stability	Assess sustainable beta and disruptivity near and above the ideal no-wall limit	Assess RWM, rotation damping physics at reduced collisionality	
3) Boundary/Lithium Physics	Assess H-mode characteristics as a function of collisionality and lithium conditioning	Assess relationship between lithiated surface conditions and edge and core plasma conditions Assess pedestal & SOL response to externally applied 3D fields	Assess very high flux expansion divertor operation
4) Wave-Particle Interaction	Characterize HHFW heating, CD, and ramp-up in deuterium H-mode (joint with solenoid-free start-up TSG)		Assess predictive capability of mode-induced fast-ion transport
5) Solenoid-free start-up, ramp-up			Assess confinement, heating, and ramp-up of CHI start-up plasmas (joint with WPI-HHFW TSG)
6) Advanced Scenarios & Control		Assess integrated plasma performance versus collisionality	Investigate physics and control of toroidal rotation at low collisionality (joint with MS TSG)
Joint Research Targets (3 US facilities):	Understanding of divertor heat flux, transport in scrape-off layer	Characterize H-mode pedestal structure	Not yet decided

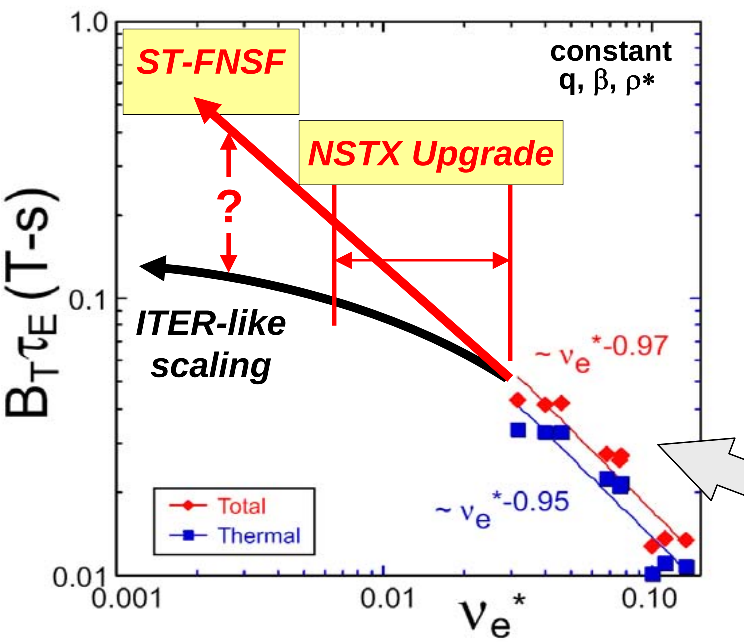
Reduced utilization (-10% case) in FY2011-12 would significantly delay progress on scenario integration, plasma start-up, and profile control

	FY2010	FY2011	FY2012
Expt. Run Weeks:	15 w/ ARRA	9	9
1) Transport & Turbulence		Measure fluctuations responsible for turbulent ion and electron energy transport	Compare measured turbulence fluctuations to theory & simulation
2) Macroscopic Stability	Assess sustainable beta and disruptivity near and above the ideal no-wall limit		
3) Boundary/Lithium Physics	Assess H-mode characteristics as a function of collisionality and lithium conditioning	Assess relationship between lithiated surface conditions and edge and core plasma conditions	Assess very high flux expansion divertor operation
4) Wave-Particle Interaction	Characterize HHFW heating, CD, and ramp-up in deuterium H-mode (joint with solenoid-free start-up TSG)		
5) Solenoid-free start-up, ramp-up			~~Assess confinement, heating, and ramp-up of CHI start-up plasmas (joint with WPI-HHFW TSG)~~
6) Advanced Scenarios & Control		~~Assess integrated plasma performance versus collisionality~~	~~Investigate physics and control of toroidal rotation at low collisionality (joint with MS TSG)~~

Joint Research Targets (3 US facilities):

FY2010	FY2011	FY2012
Understanding of divertor heat flux, transport in scrape-off layer	Characterize H-mode pedestal structure	Not yet decided

Access to reduced collisionality is needed to understand underlying causes of ST transport, scaling to next-steps



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

- Future ST's are projected to operate at 10-100× lower normalized collisionality ν*
- Conventional tokamaks observe weak inverse dependence of confinement on ν*

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)

- NSTX observes much stronger scaling vs. ν*
  - Does favorable scaling extend to lower ν* ?
  - What modes dominate e-transport in ST ?
    - Electrostatic or electromagnetic?

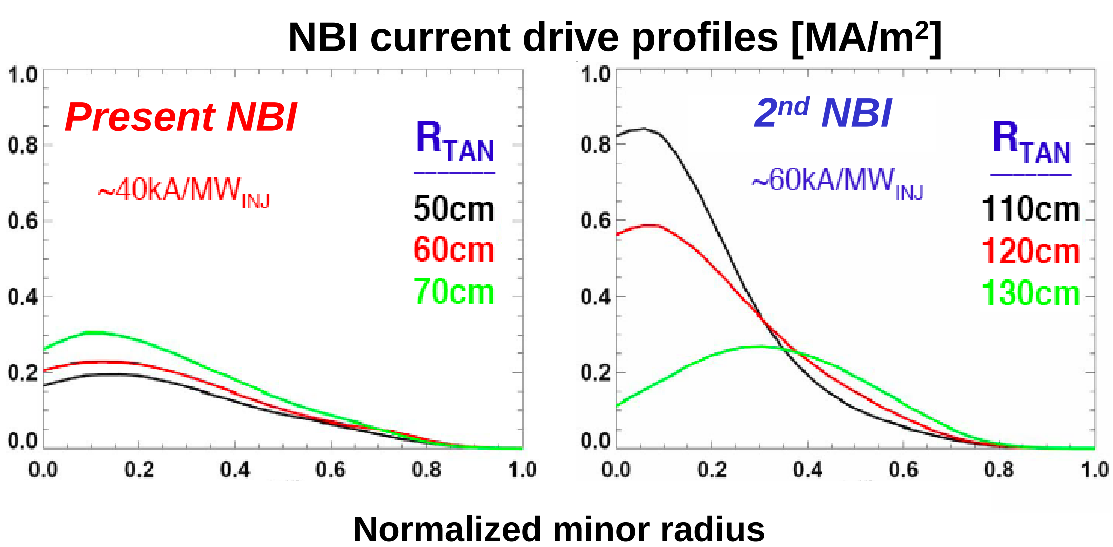
- Higher toroidal field & plasma current enable access to higher temperature
- Higher temperature reduces collisionality, but increases equilibration time

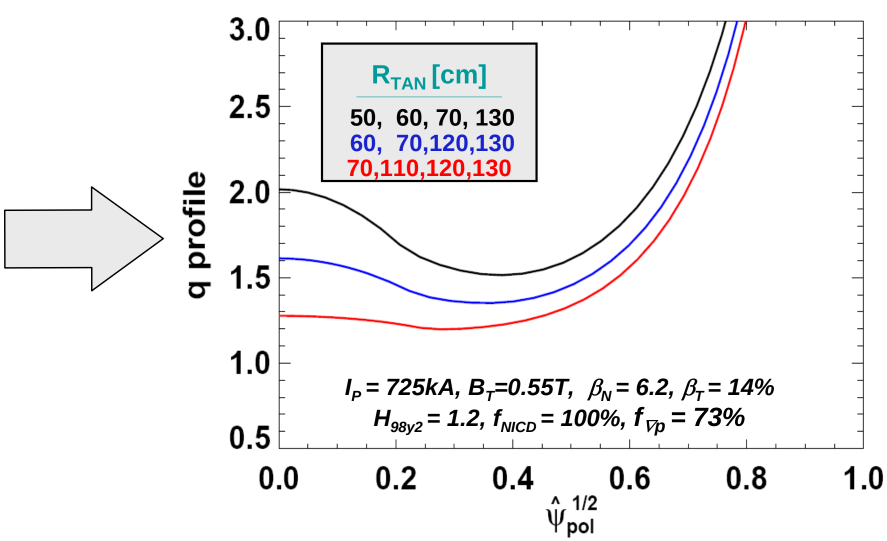
- **Upgrade: Double field and current for 3-6× decrease in collisionality → require 3-5× increase in pulse duration for profile equilibration**

Increased auxiliary heating and current drive are needed to address ST start-up, sustainment, and boundary issues

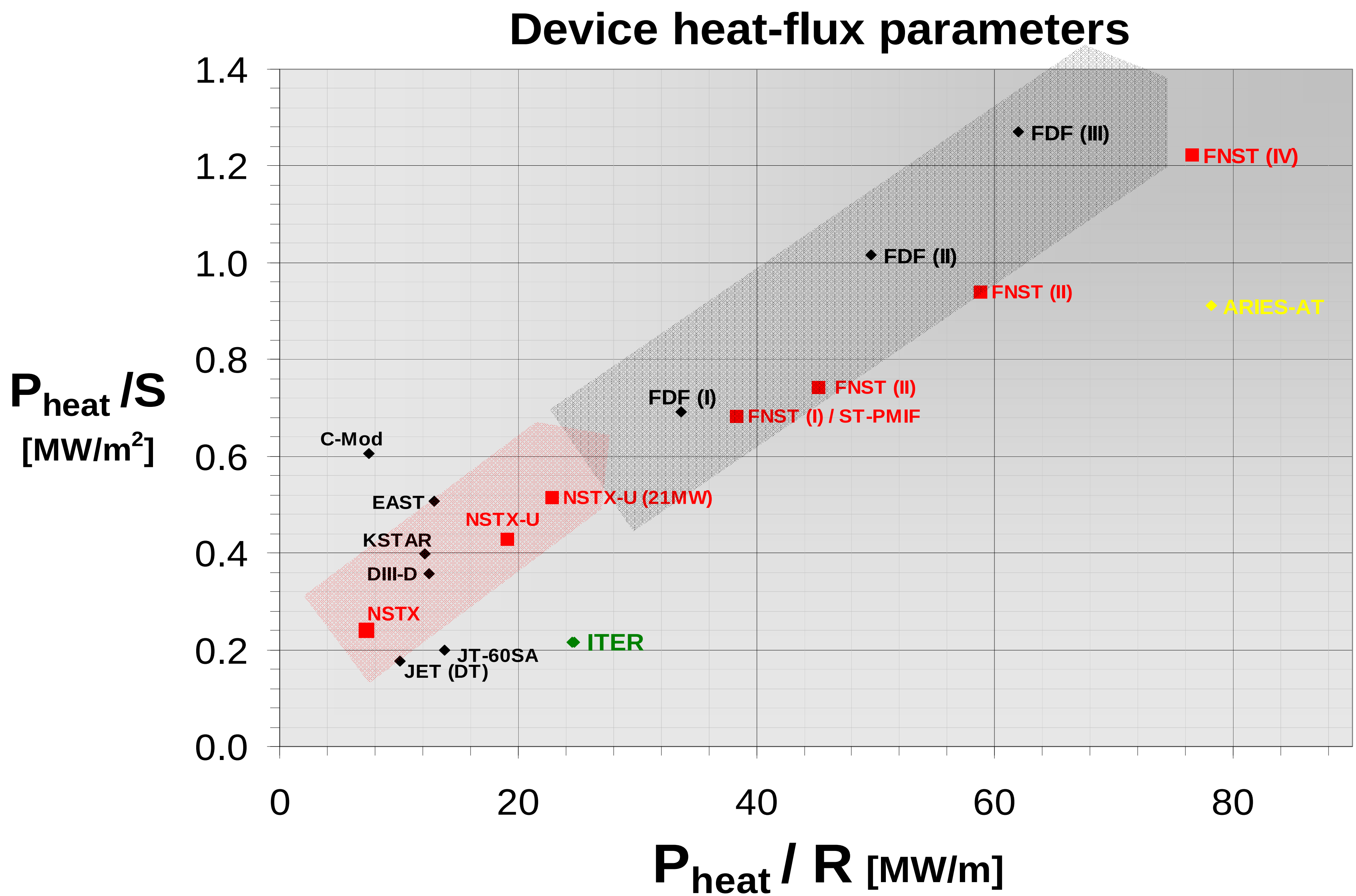
- Need additional heating power to access high temperature and β at low ν^*
  - → 4-10MW more heating, depending on confinement scaling
- Need increased <u>current drive</u> to access and study 100% non-inductive
  - → 0.25-0.5MA more current drive compatible with ramp-up, sustainment plasmas
- Need to learn to manage ≥ ITER→FNSF-level high-heat-flux challenge
  - → high divertor power density (P/R ≤ 20MW/m) + flexible divertor PF coil set

- **Upgrade: Double neutral beam power + more tangential injection**
  - More tangential injection → up to 2 times higher efficiency, current profile control



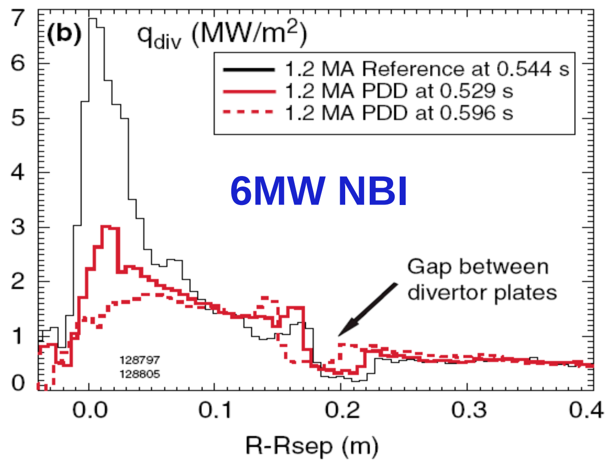


NSTX Upgrade will enable access to normalized divertor and first-wall heat-loads much closer to FNS and Demo regimes

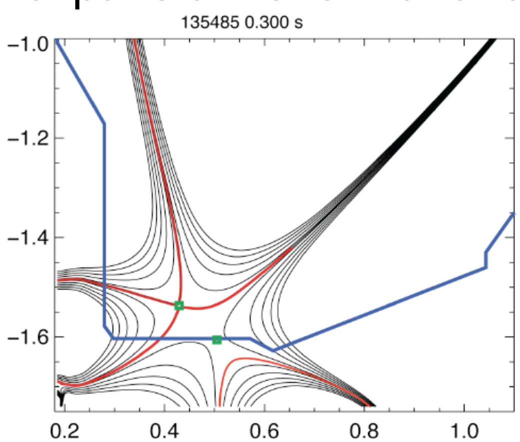


Combinations of advanced PMI solutions will be assessed in NSTX and NSTX Upgrade in support of next-steps, Demo

- High divertor heat flux can be reduced in NSTX with partially detached divertor (PDD)



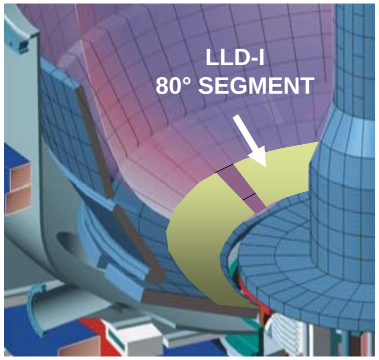
- NSTX has demonstrated the formation of high flux-expansion “snowflake” divertor



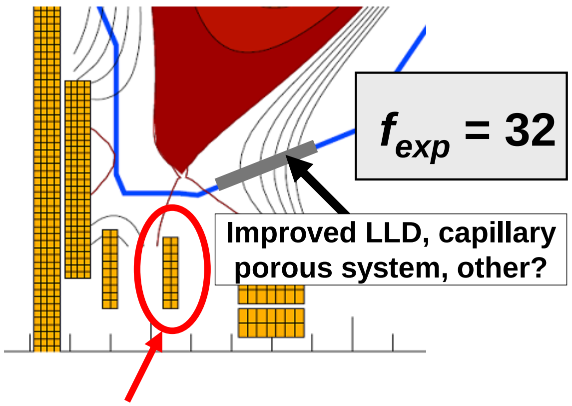
- The PDD operating regime + other PMI solutions will be challenged in NSTX-U:
  - 2-3× higher input power
  - 30-50% reduction in n / $n_{Greenwald}$
  - 3-5× longer pulse duration, leading to substantial increase in $T_{divertor}$

- NSTX and NSTX-U will test the compatibility of high flux expansion, PDD, and a liquid lithium divertor (LLD)

- **NSTX LLD**



- **NSTX-U high flux expansion example:**



- Additional coil added to control flux expansion and R_{strike}

Vlad Soukhanovskii (LLNL) received DOE-SC Early Career Award for proposal to study “Advanced High Heat Flux Divertor Program on the NSTX”

Summary

- **NSTX FY2010-12 research plan contributes strongly to ST and ITER, and to all OFES ReNeW themes and most thrusts**
- **Plan and upgrades enable exciting new understanding and ST performance across all topical science areas:**
  - CHI start-up and HHFW BS-overdrive non-inductive ramp-up
  - Lithium effects on transport, stability, boundary and divertor physics
  - Advanced power and particle exhaust solutions for ST, FNSF, Demo
  - Micro-instabilities causing anomalous energy transport
  - Fast-ion transport from multi-mode AE for ST, ITER
  - RWM critical rotation, torques from 3D fields, dependence on lower ν_i
  - Push to 100% non-inductive ops with increased bootstrap and NBI-CD