NSTX FY2011-12 Program Overview

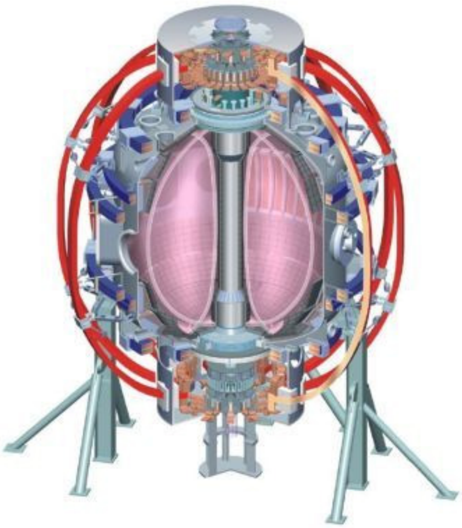
Including Research in Preparation for NSTX Upgrade

College W&M
Colorado Sch Mines
Columbia U
CompX
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Washington
U Wisconsin

J. Menard

For the NSTX Research Team

NSTX PAC-29
PPPL - B318
January 26-28, 2011



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U St. Andrews
York U
Chubu U
Fukui U
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Kyoto U
Kyushu U
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NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

Near-term NSTX programmatic schedule

- Update research milestones (completed Dec. 2010)
- Now: solicit and receive PAC-29 advice on:
  - **FY11-12 research milestones/priorities**
    - This is last run period before Upgrade outage
    - Note: PAC meeting held before Research Forum this year
    - Most / all of FY11-12 run will be finished before next PAC
  - Preparation for Upgrade
  - Consistency of Program with OFES vision
- Research Forum for FY11-12 run – Mar. 15-18, 2011
- Begin 2nd/final phase of FY11 run – summer 2011
- Finish FY12 run end of Feb. 2012 – Upgrade outage

Outline

- NSTX Mission
- OFES Vision for Fusion for Next Decade
- FY11-12 Milestone Overview and Research Plans
  - Transport & Turbulence
  - Macroscopic Stability, Advanced Scenarios and Control
  - Boundary Physics and Lithium Research
  - Advanced Scenarios and Control
  - Non-inductive Plasma Start-up (Coaxial Helicity Injection)
  - Wave-Particle Interactions
- Initial Planning for FY13
- Overview of Research in Support of Upgrade
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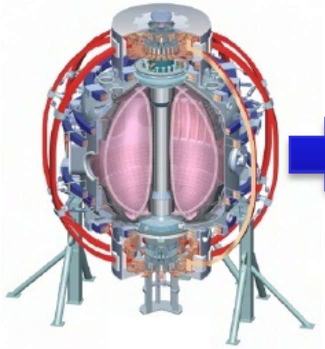
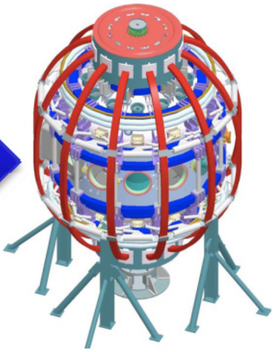
NSTX Mission Elements

- **Understand/exploit unique ST parameters**
  - High heat flux for novel divertor and PMI studies
  - Low A, l_i and high β, κ, v_{fast}/v_A for stability, transport
  - Role of NSTX Upgrade:
    - Prototype methods to mitigate very high heat/particle flux
    - Study high beta plasmas at reduced collisionality
    - Access full non-inductive operation for FNSF applications

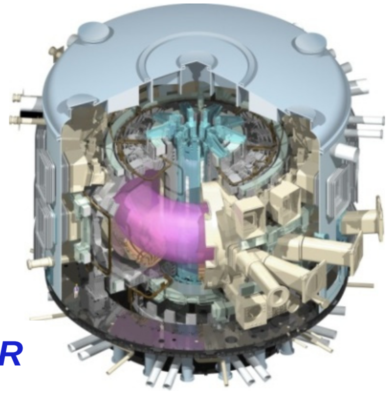


NSTX



NSTX-U

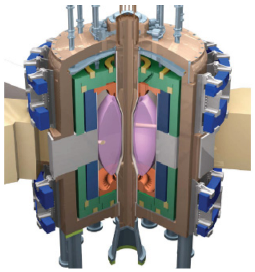
- **Extend understanding of tokamak / ITER**
  - Develop predictive capability for ITER/FNSF/Demo



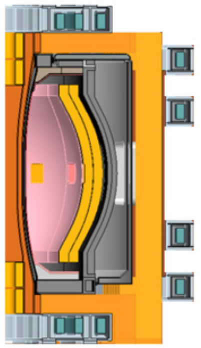
ITER

- **Establish attractive ST operation**
  - Utilize ST to close key gaps to Demo
  - Advance ST as fusion power source

Plasma Material Interface Facility (PMIF)



Fusion Nuclear Science Facility (FNSF)



Pilot Plant

A vision for U.S. fusion research in the coming decade has emerged from OFES emphasizing 4 research themes:

- **Plasma dynamics and control**
  - Perform detailed measurement of underlying processes, connect to theory, develop integrated understanding, demonstrate advanced scenarios in tokamaks
- **Materials in fusion environment, harness fusion power**
  - Understand and control processes beyond the last closed flux surface, including open field line physics, plasma-surface interactions, coupling between SOL & PSI
  - Determine the fusion nuclear science facility (FNSF) geometry
  - Determine the materials the FNSF will be made from and should test
- **Validated predictive capability**
  - Increase emphasis on validation of physics models incorporated in simulation
  - Increase confidence in extrapolating tokamak/ST in support of ITER, next-steps
- **3-D magnetic fields**
  - Determine the optimum level of 3D field in toroidal magnetic configuration accounting for both physics and engineering complexity in the optimization
    - Enhance the theory of 3-D equilibria, stability, and transport research
    - Increase emphasis in 3-D fields near-term on domestic facilities

FY2011-12 NSTX research milestones

(base and *incremental*)

	FY2010	FY2011	FY2012
Expt. Run Weeks:	15 w/ ARRA	4 10	10
1) Transport & Turbulence		R11-1 BES, High-k **Measure fluctuations responsible for turbulent electron, ion, impurity transport**	
2) Macroscopic Stability	**Assess sustainable beta and disruptivity near and above the ideal no-wall limit**	R11-2 2nd SPA, RWM state-space control **Assess ST stability dependence on aspect ratio and boundary shaping** (with ASC TSG)	IR12-1 *Real-time rotation, 2nd SPA, RWM state-space control, HHFW* *Investigate magnetic braking physics and toroidal rotation control at low ν^* (with ASC TSG)*
3) Boundary/Lithium Physics	**Assess H-mode characteristics as a function of collisionality and lithium conditioning**	R11-3 Snowflake, MPTS, Lithium **Assess very high flux expansion divertor operation** (with ASC TSG)	R12-1 MAPP, BES, High-k, Lithium **Assess relationship between lithium-conditioned surface composition and plasma behavior**
4) Wave-Particle Interaction	**Characterize HHFW heating, CD, and ramp-up in deuterium H-mode**		IR12-2 *Tangential FIDA, BES, reflectometer* *Assess predictive capability of mode-induced fast-ion transport*
5) Solenoid-free start-up, ramp-up			R12-2 CHI, NBI, HHFW **Assess confinement, heating, and ramp-up of CHI start-up plasmas** (with WPI/HHFW TSG)
6) Advanced Scenarios & Control			R12-3 SGI, Lithium, HHFW **Assess access to reduced density and ν^* in high-performance scenarios** (with MS, BP TSGs)
7) ITER urgent needs, cross-cutting		R11-4 BES, High-k, 2nd SPA **H-mode pedestal transport, turbulence, and stability response to 3D fields** (cross-cutting with T&T, BP, MS)	
Joint Research Targets (3 US facilities):	**Understanding of divertor heat flux, transport in scrape-off layer**	FY11 JRT MPTS, MSE-LIF **Characterize H-mode pedestal structure**	FY12 JRT BES, High-k **Understand core transport and enhance predictive capability**

4 of 9 FY11-12 milestones involve boundary physics:
R11-3, R11-4, R12-1, FY11 JRT

PAC27-7

NSTX Topical Science Groups (TSGs) for FY11-12

- TSG responsibilities:
  - Assist program in formulation of milestones and priorities
  - Present research plans to PAC
  - Organize Research Forum by soliciting and prioritizing experimental proposals
  - Coordinate & review experimental proposals from TSG during run

- **New TSG for FY11-12**

Run coordinator	Deputy run coordinator
S. Sabbagh*	M. Bell

TSG	Leader - experiment	Deputy - experiment	Leader - theory and modelling
Boundary Physics	V. Soukhanovskii*	A. Diallo	D. Stotler
Lithium Research	C. Skinner	M. Jaworski	D. Stotler
Transport and Turbulence	Y. Ren	H. Yuh*	G. Hammett
Macroscopic Stability	J.-K. Park	J. Berkery*	R. Betti
High-harmonic Fast Wave, Energetic Particles	G. Taylor	M. Podestà	N. Gorelenkov
Solenoid-free Start-up	R. Raman*	D. Mueller	S. Jardin
Advanced Scenarios and Control	S. Gerhardt	M. Bell	E. Kolemen
ITER Urgent Needs, Cross-cutting, Enabling	J. Menard	R. Maingi*	A. Boozer*

** indicates collaborator*

PAC27-2

PAC27-5

New ITER/CC TSG will address urgent and cross-cutting research needs for ITER and for NSTX

- For ITER: Understand transport, turbulence, stability response to 3D fields – informs decision on in-vessel coils in ITER
  - NSTX has new capabilities to address this: BES, ME-SXR, 2nd SPA
  - Research cross-cuts transport, boundary, macro-stability TSGs
  - ITER/CC TSG will coordinate research supporting ITER milestone R11-4
- For NSTX:
  - Assess methods and coordinate experiments for particle and impurity control for NSTX and Upgrade PAC27-2
    - FY11-12 goal: assess combinations of impurity control techniques
  - Support and coordinate cryo-pumping calculations for Upgrade
    - Note: this is scoping activity - cryo-pumps are not part of Upgrade project
  - Coordinate ELM research (have coherent program, avoid overlap) → R. Maingi PAC27-21
- Unifying theme of this TSG is particle and impurity control
  - See R. Maingi presentation for more detail

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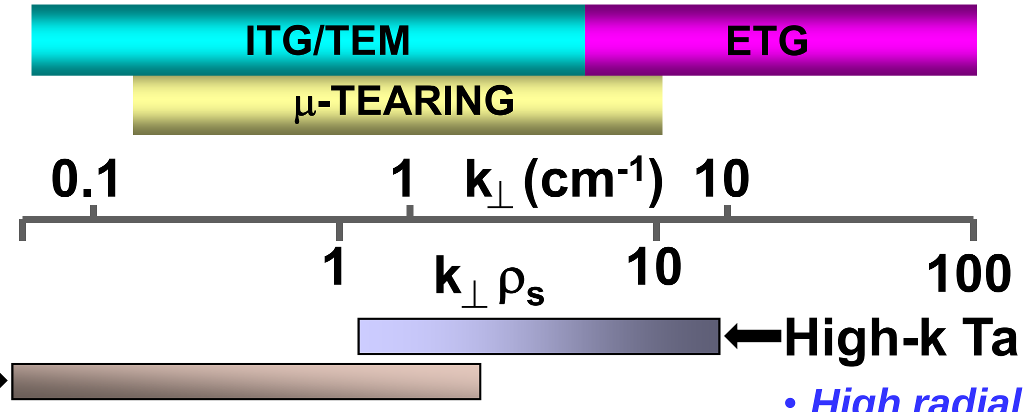
NSTX is addressing multi-scale transport issues critical to future devices – ITER and next step STs



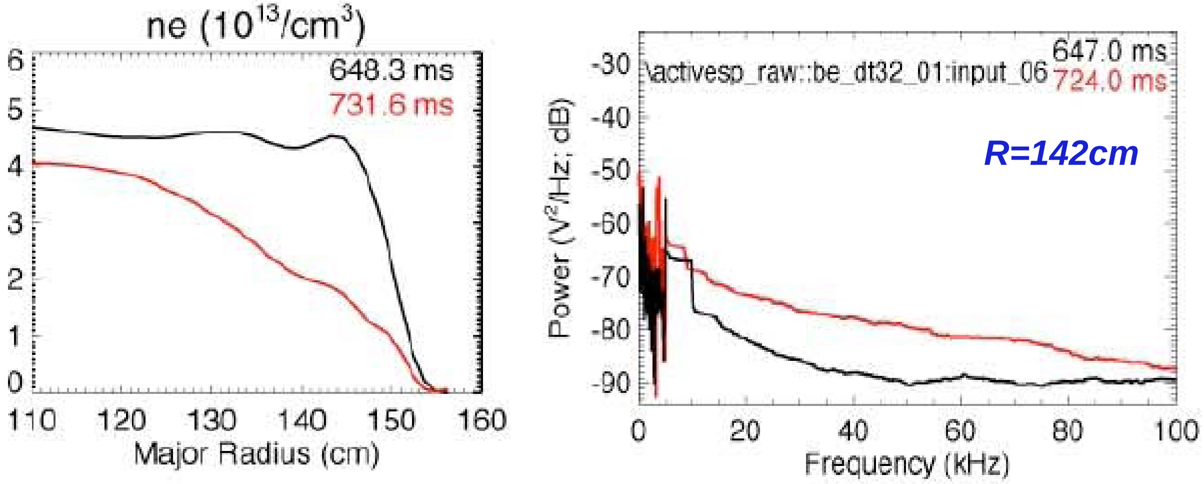
Low-k BES

(Beam Emission Spectroscopy)

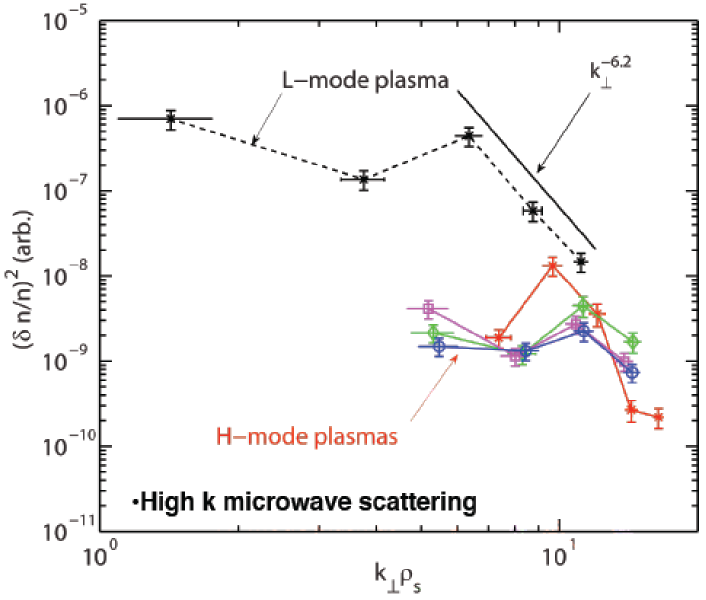
High-k Tangential Scattering

- *High radial resolution for electron-gyro-radius scale turbulence (f≤3MHz)*

- *Low-k fluctuations decrease after transition to H-Mode*
- *Fluctuations increase after H→L back-transition*



k spectra of normalized density fluctuations in beam-heated L and H-mode plasmas

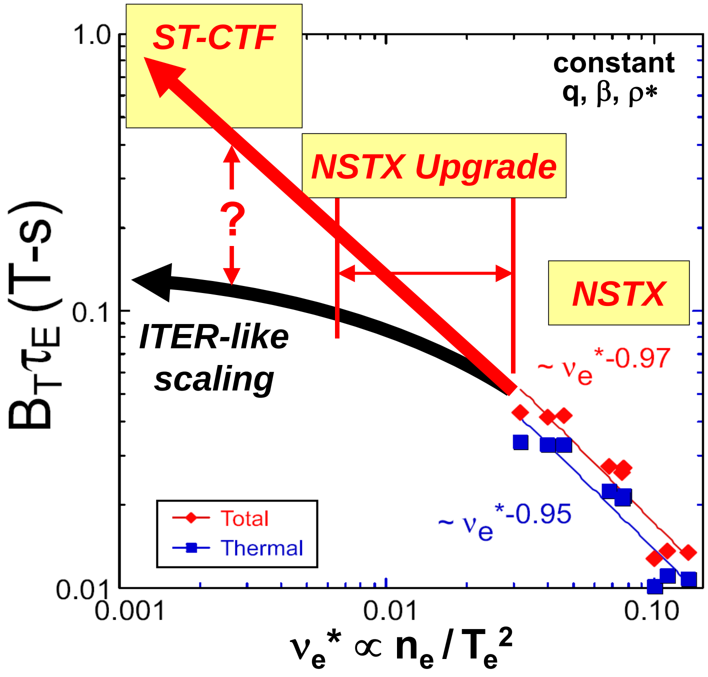


- *BES also contributing to energetic particle research*

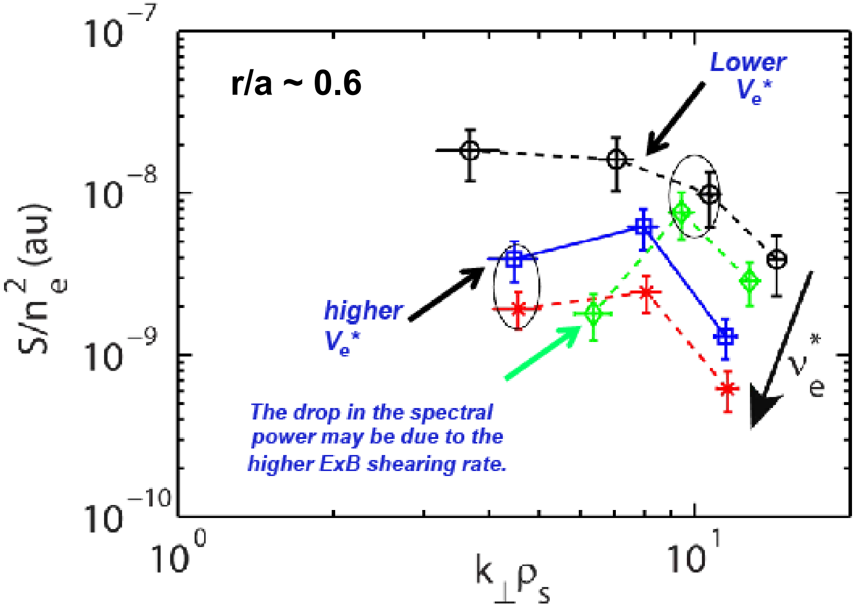
•*D. Smith, U. Wisconsin*

NSTX is beginning to unravel the mystery of the collisionality dependence of ST energy confinement

Previous NSTX (and MAST) experiments exhibit nearly inverse dependence of $B\tau_E$ on collisionality



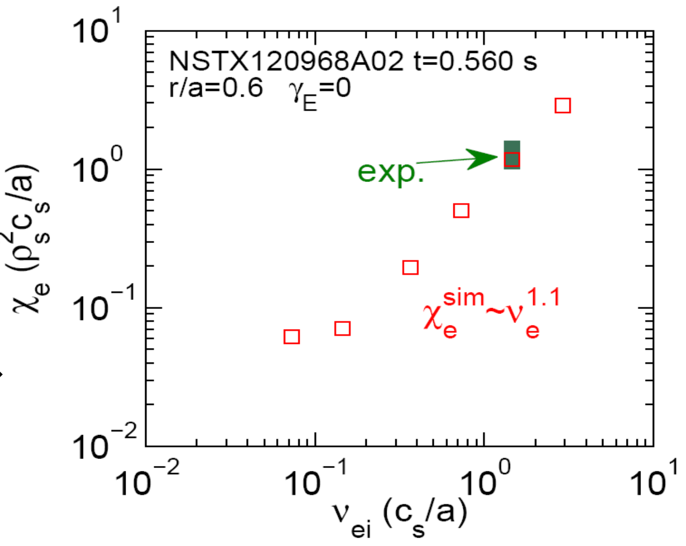
New high-k scattering measurements show fluctuation levels apparently *increase* at lower ν*



The drop in the spectral power may be due to the higher ExB shearing rate.

Non-linear GYRO simulations of lower-k μ-tearing predict χ_e proportional to ν*

Is μ-tearing playing major role in ST e-transport?



Transport Milestone R(11-1): Measure fluctuations responsible for turbulent electron, ion, and impurity transport

- High-k scattering measurements have identified ETG
- Low-k fluctuations (micro-tearing, ITG/TEM) and fast-ion-driven modes, e.g. GAE, may also contribute to e-transport.

- Low-k fluctuations may also contribute significantly to momentum, ion thermal, and particle/impurity transport
  - Turbulence and *AE radial eigenfunctions will be measured with BES
  - Turbulence will also be measured w/ reflectometer, interferometer, GPI

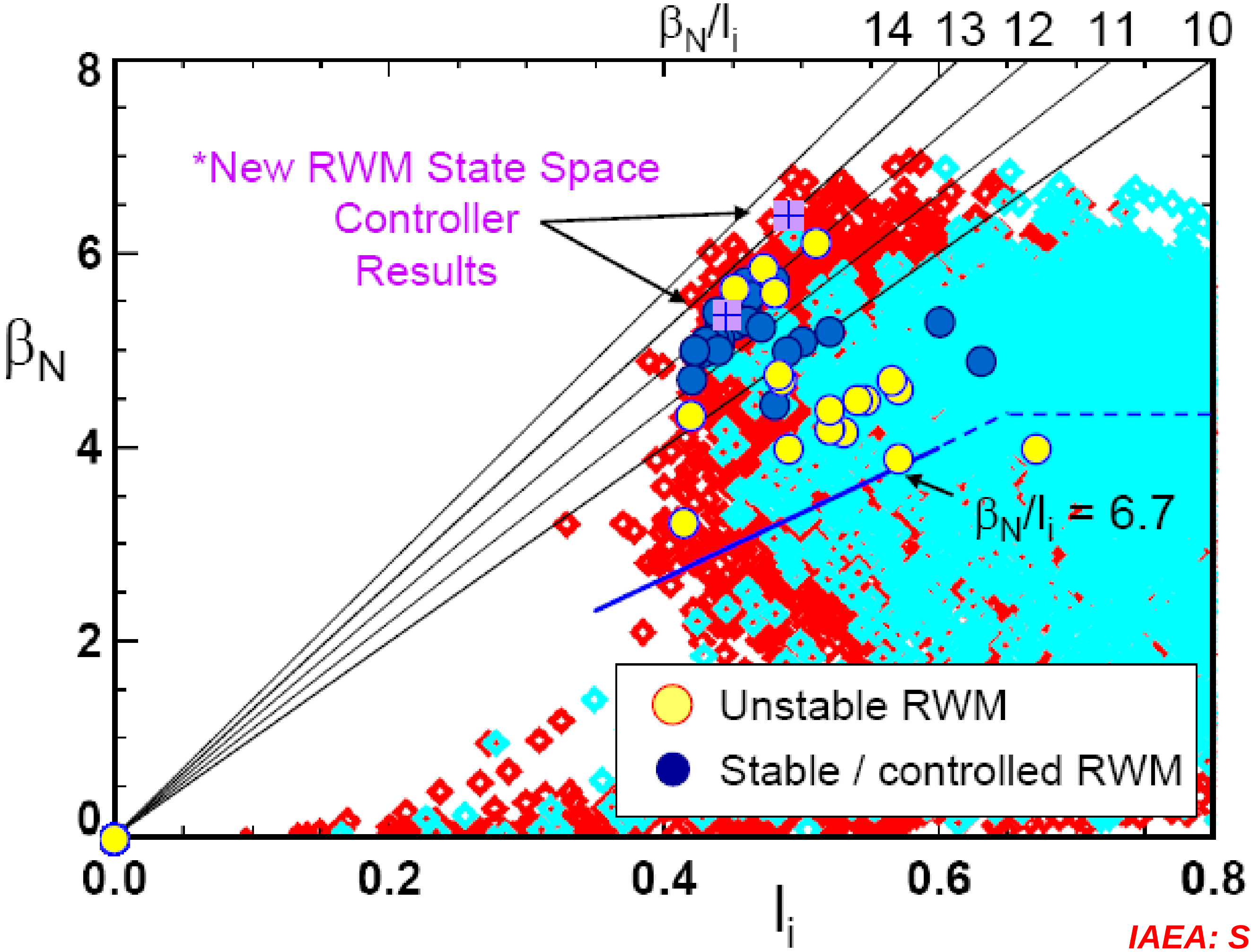
- The k spectrum of the turbulence will be measured and correlated with energy diffusivities inferred from power balance

- Particle/impurity transport expts will use gas puffs, density measurements, low-to-high-k δn measurements, edge SXR

Improvements in stability control techniques have significantly reduced RWM instability at high β_N and low l_i

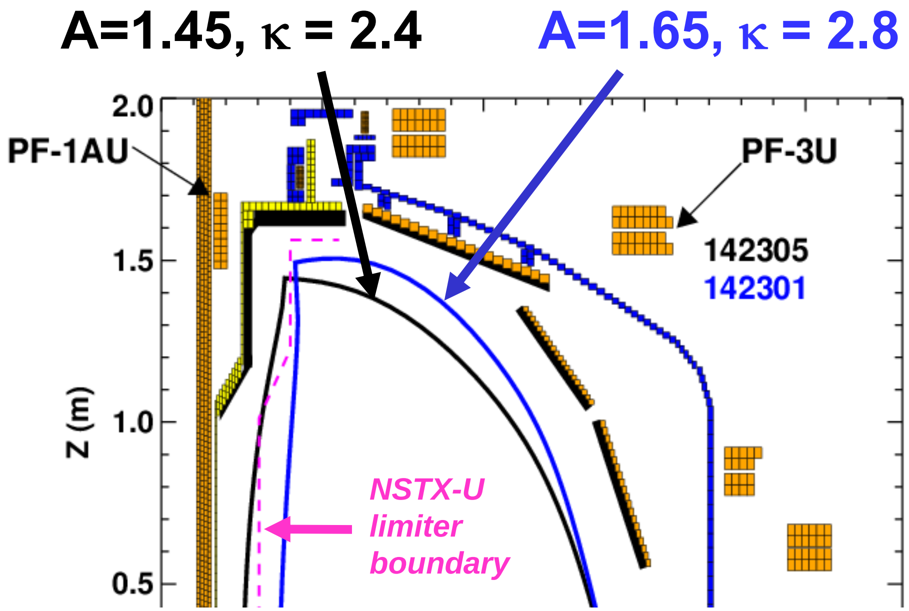
PAC27-6

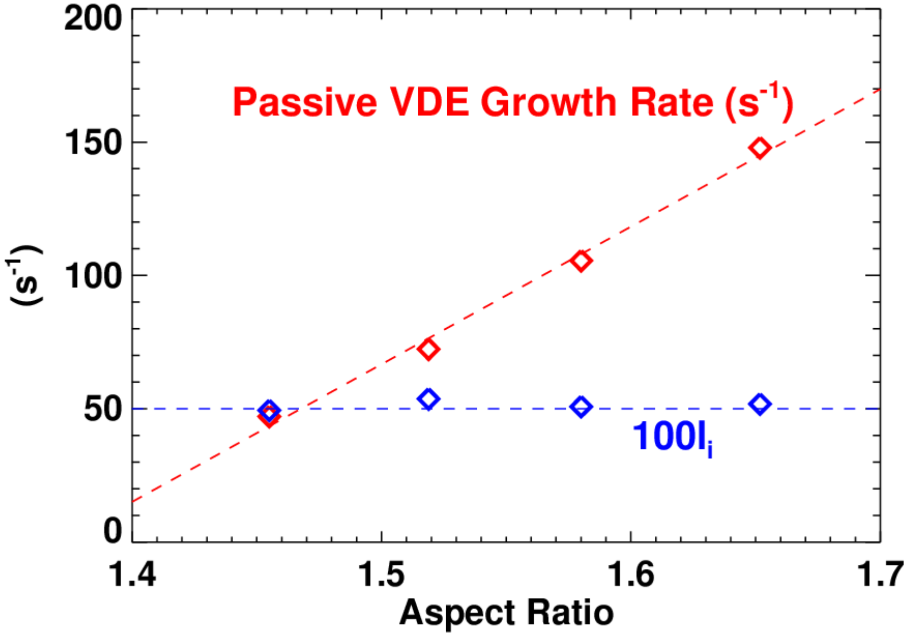
- High normalized beta β_N = 6–7 and high β_N / l_i = 10-14 routinely accessed
- Improvements: sensor AC compensation + combined B_P+B_R + state-space controller
- Disruption probability for β_N / l_i > 11 plasmas reduced from ~50% to ~14%



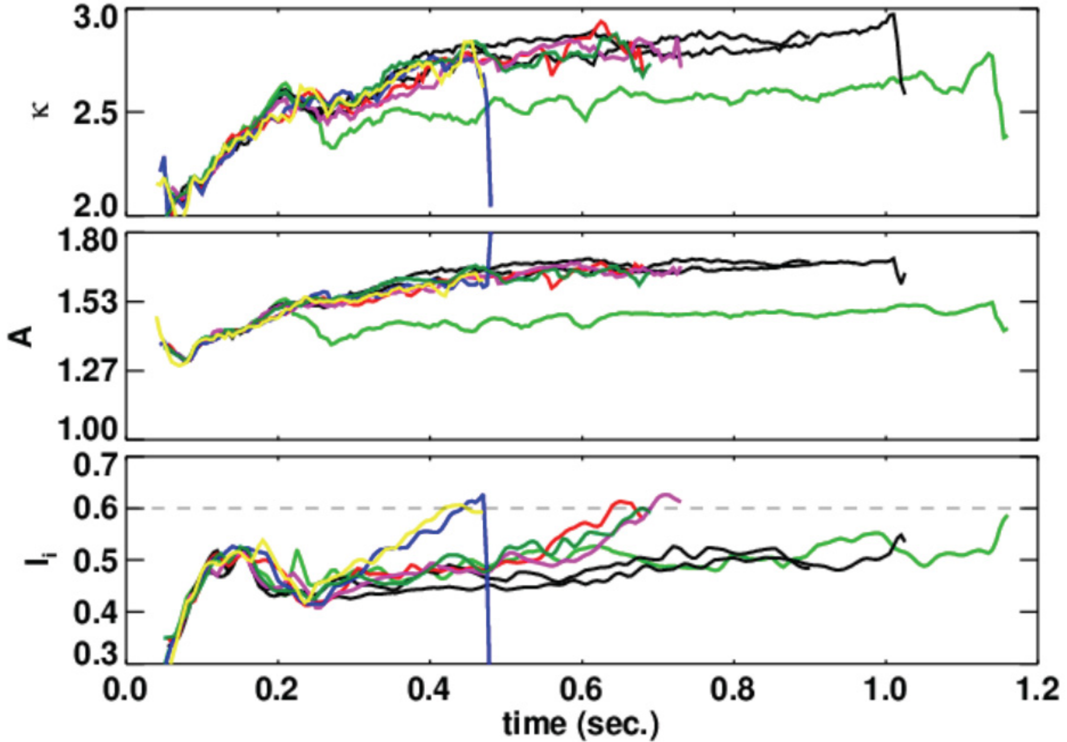
IAEA: S. Sabbagh, Columbia U

NSTX has begun to explore stability impact of higher aspect ratio and elongation in preparation for Upgrade, next-steps





- Successfully operated at $\beta_N > 4$ for several τ_{CR} at Upgrade A and κ
- Found $l_i \leq 0.6$ required to avoid VDE at higher A with present n=0 control



PAC27-6

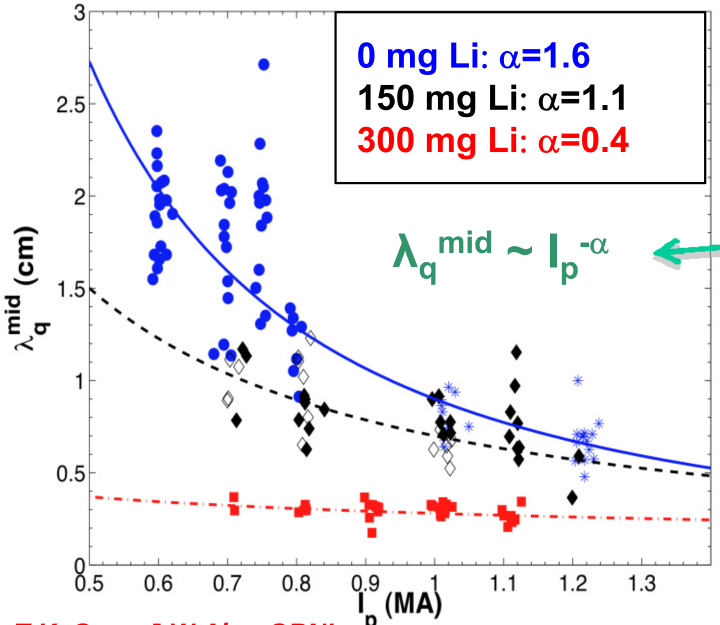
Stability/Control Milestone R(11-2): Assess ST stability dependence on aspect ratio and boundary shaping

PAC27-6

- Next-step ST designs commonly assume increased elongation (κ = 3-3.5) and aspect ratio A=1.6-1.7
  - Typical NSTX values: κ=2.4-2.8, A=1.4-1.5
  - Increased A and higher κ are projected to increase the growth rates of the n=0 vertical instability and n=1 RWM
- NSTX scenarios will be extended to plasma geometries much closer to those of the Upgrade and next-steps
- The maximum elongation, li, and sustainable β_N will be determined and optimized versus aspect ratio and elongation
- Comparisons to theory (MISK and VALEN for RWM) will be made, and the viability of present and new control techniques will be tested, and possible improvements identified

Obtained complete data-set for divertor heat flux width scaling to aid projections to ITER (FY2010 JRT*) and Upgrade

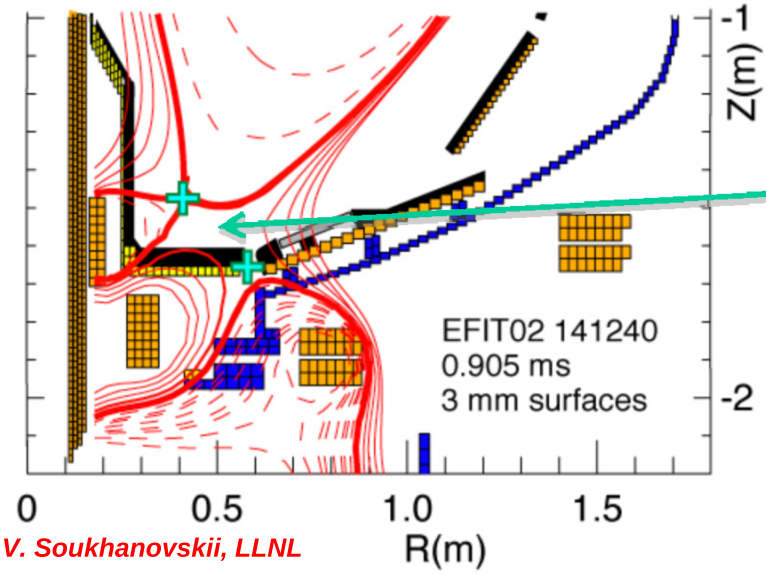
**Joint Research Target (3 U.S. Facilities)*



IAEA: T.K. Gray, J-W Ahn, ORNL

- Divertor heat flux width, magnetically mapped to the midplane, shows a strong decrease as I_P is increased
  - Potentially major implications for ITER
  - NSTX: λ_q^{mid} further decreases with Li

→ NSTX Upgrade with conventional divertor (LSN, flux expansion of 10-15) projects to very high peak heat flux up to 30-45MW/m^2



IAEA: V. Soukhanovskii, LLNL

- Divertor heat flux inversely proportional to flux expansion over a factor of five
- Snowflake→ high flux expansion 40–60, larger divertor volume and radiation

→ U/D balanced snowflake divertor projects to acceptable heat flux < 10MW/m^2 in Upgrade at highest expected I_P = 2MA, P_{AUX}=15MW

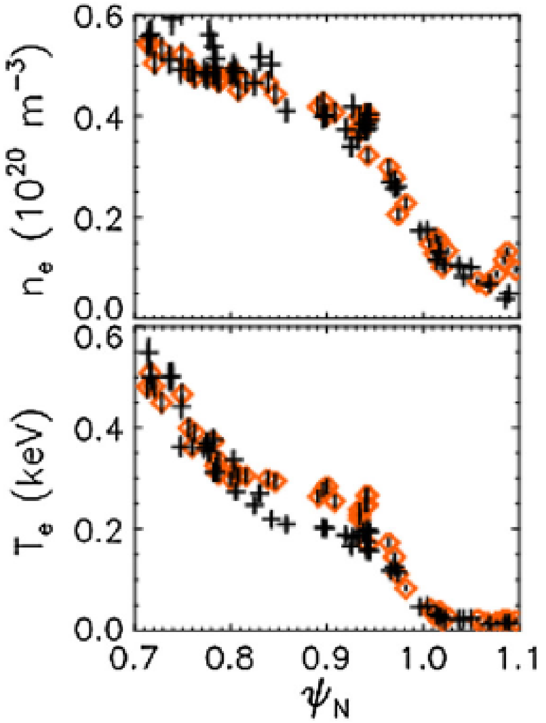
PAC27-2

Boundary Physics Milestone R(11-3): Assess very high flux expansion divertor operation

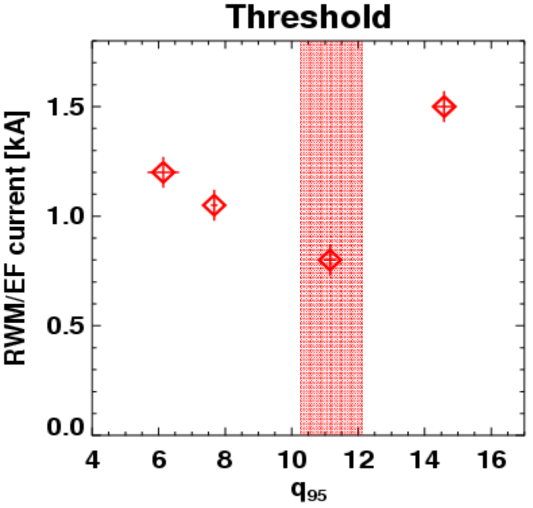
- The exploration of high flux expansion divertors for mitigation of high power exhaust is important for
  - NSTX Upgrade, ST/AT fusion nuclear science facilities, Pilot, Demo
- High flux expansion “snowflake” divertor will be assessed:
  - Magnetic controllability – especially up/down-balanced snowflake
  - Divertor heat flux handling and power accountability
  - Pumping with lithium coatings
  - Impurity production
  - Trends versus global parameters
- Potential benefits of combining high flux expansion with gas-seeded radiation will also be explored

NSTX provides a unique environment to better understand the H-mode pedestal response to 3D fields for ELM control

- ELMs stabilized by Li coatings
  - Edge density, pressure gradients reduced
    - Maingi et al, PRL 103, 075001 (2009)
- ELMs triggered by 3D fields, not suppressed
  - Small density change during n=3 3D fields
  - T_e and pedestal pressure increase → ELM
    - Canik et al, PRL 104, 045001 (2010)



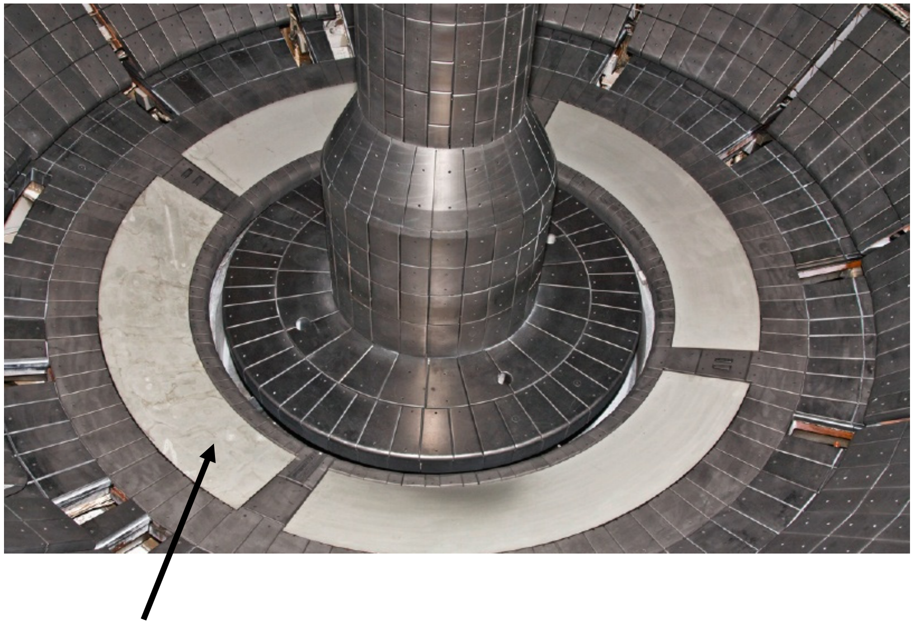
- Optimal q_{95} ~ 11 for ELM triggering
  - Vacuum Chirikov > 1 width ~ 0.3 for all cases
  - What is underlying physics of this dependence?



ITER/cross-cutting Milestone R(11-4): H-mode pedestal transport, turbulence, and stability response to 3D fields

- The use of three-dimensional (3D) magnetic fields is proposed to control the H-mode pedestal to suppress ELMs in ITER
  - However, the mechanisms for particle and thermal transport modification by 3D fields are not understood
- Study possible mechanisms for modifying transport:
  - zonal flow damping
  - stochastic-field-induced ExB convective transport
  - island shielding reduction as $\omega_{e-\perp} = \omega_e^* + \omega_{ExB} \rightarrow 0$ (XGC0)
  - banana diffusion or ripple loss
- Measure pedestal turbulence trends vs. applied 3D field
  - BES, high-k scattering, gas-puff imaging
  - Independent control of n=1,2,3 applied 3D fields - 2nd SPA (ARRA)
- Measure pedestal profile response, edge particle transport
  - Improved Thomson scattering, impurity injection, edge SXR

NSTX is a world leader in investigating pumping capability & plasma effects of Li - including Liquid Lithium Divertor (LLD)



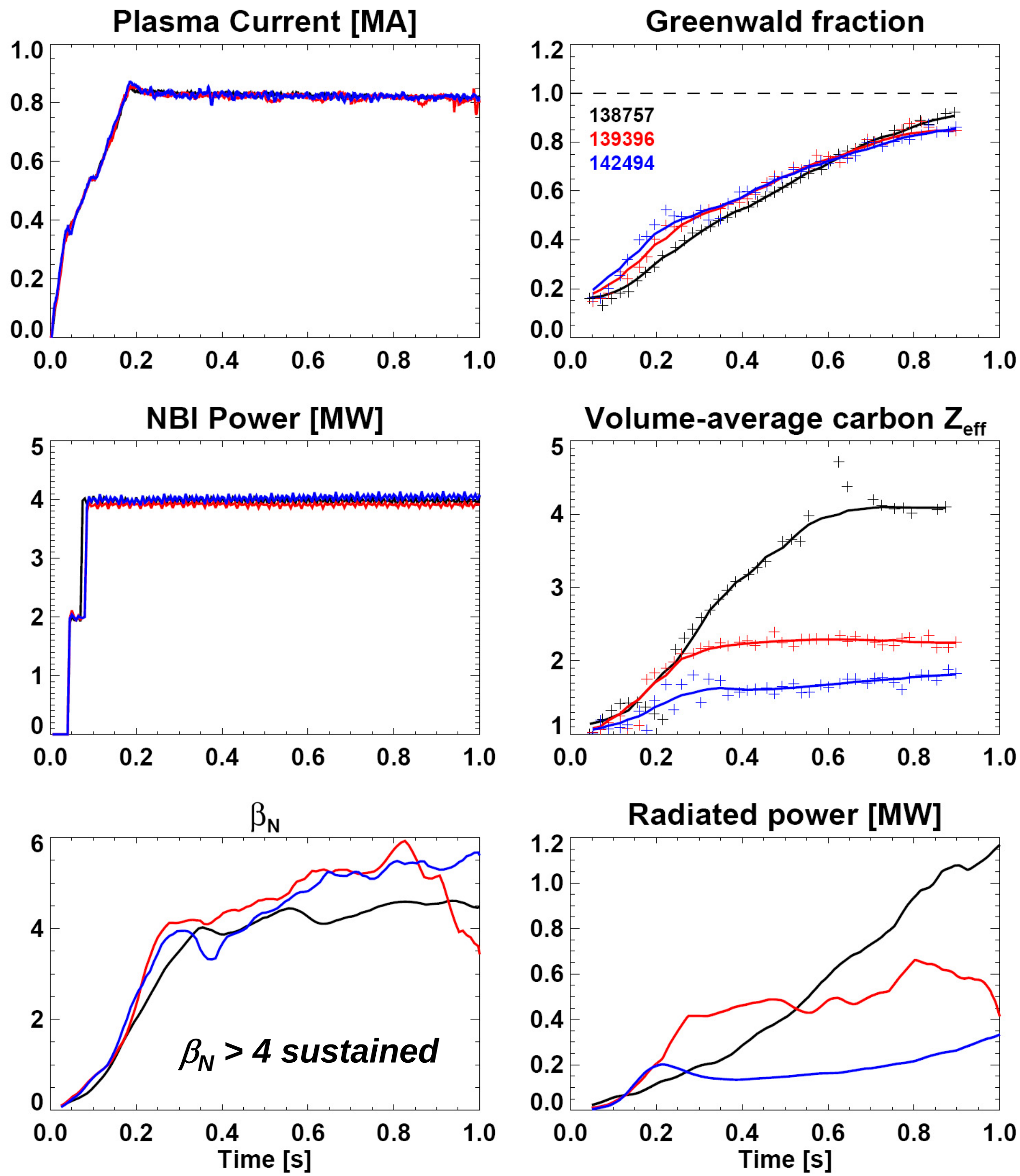
- 4 LLD plates formed ~20cm wide annulus in lower outboard divertor
  - Heatable surface of porous molybdenum (Mo)
  - Loaded with Li by LiTER evaporation from above

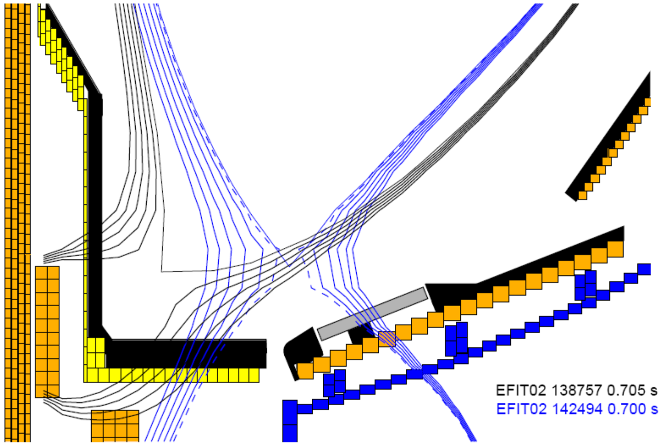
LLD Impact on Plasma Performance:

- LLD did not increase D pumping beyond that achieved with LiTER
  - Assessing if LLD provides more sustained pumping than LiTER
  - Data indicates C present on LLD, which may have impacted pumping performance
- Operating w/ strike-point on LLD may decrease core C content
  - Strongest effect observed when plasma heats LLD surface above Li melting temperature
  - Interpretation complicated by ELMs in lower-δ shape

- **No evidence of Mo in plasma except from large ELMs, disruptions**
- **Chemistry of Li on C and LLD critical, complex, and under-diagnosed**

Operation with outer strike-point on Mo LLD (coated with Li) compatible with achievement of high-performance plasmas





◀ **Strike-point (SP) on inner divertor**

- **Carbon Z_{eff} = 3-4 typical of LiTER ELM-free H-mode**

◀ **SP on LLD – $T_{LLD} < T_{Li\text{-}melt}$**

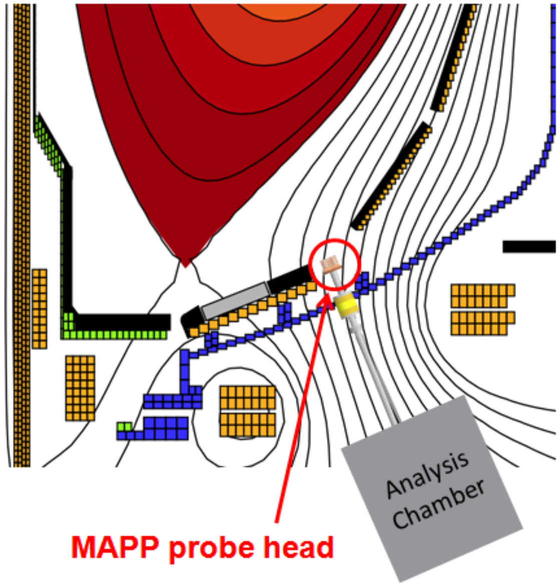
◀ **SP on LLD – $T_{LLD} > T_{Li\text{-}melt}$ (+ other differences)**

- **Shots have different fueling, LiTER conditions, ELM characteristics:**
  - **No ELMs, no → small, small → larger**
- **LSN with SP on LLD reduces δ, κ, *q***
  - **Reduces ELM and global stability** **PAC27-2**
- **Yet, can achieve high β_N, low Z_{eff}, P_{rad}**
  - **Would like to revisit operation on LLD in FY11**
  - **Supports consideration of inboard Mo tiles**

Lithium Milestone R(12-1): Investigate relationship between lithium-conditioned surface composition & plasma behavior

- With very chemically active elements such as lithium, prompt surface analysis is required to characterize the lithiated surface conditions during a plasma discharge
- In support of prompt surface analysis, an in-situ materials analysis particle probe (MAPP) will be installed on NSTX
  - MAPP probe will enable the exposure of various samples to the SOL plasma followed by ex-vessel but in-vacuo surface analysis **within minutes** of plasma exposure using state of the art tools

- Li experiments will utilize MAPP to study:
  - Reactions between evaporated Li and plasma facing materials, residual gases
  - Correlations between the surface composition and plasma behavior, comparisons to lab experiments and modeling
  - Characterizations of fueling efficiency, recycling



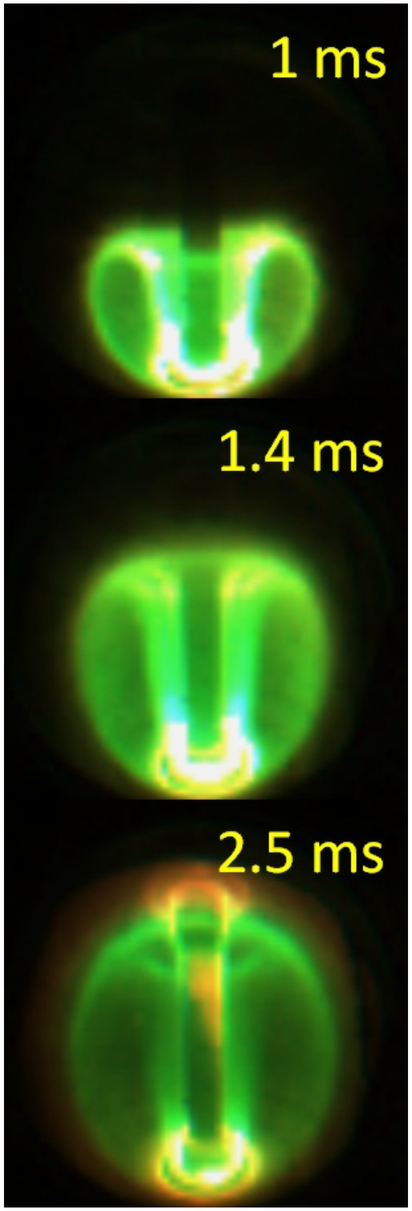
Scenarios/MHD Milestone R(12-3): Assess access to reduced density and collisionality in high-performance scenarios

- The high performance scenarios targeted in NSTX Upgrade and next-step STs are based on operating at lower Greenwald density and lower ν^* than routinely accessed in NSTX.
- Strong D pumping via Li has been observed, but additional gas fueling is typically required to avoid plasma disruption during the current ramp and/or in the early flat-top and high-β phase

- Goal: characterize and avoid the underlying causes responsible for disruption at reduced density, including:
  - Loss of access to H-mode, locked-modes, β limits, double tearing, …
- Possible methods for stability improvement include:
  - Changes in current ramp-rate (l_i and q(r) evolution), H-mode timing
  - Shape evolution, heating/beta evolution and control
  - Improved fueling control, and varied pumping

Coaxial Helicity Injection (CHI) has produced substantial current, and demonstrated significant ohmic flux savings

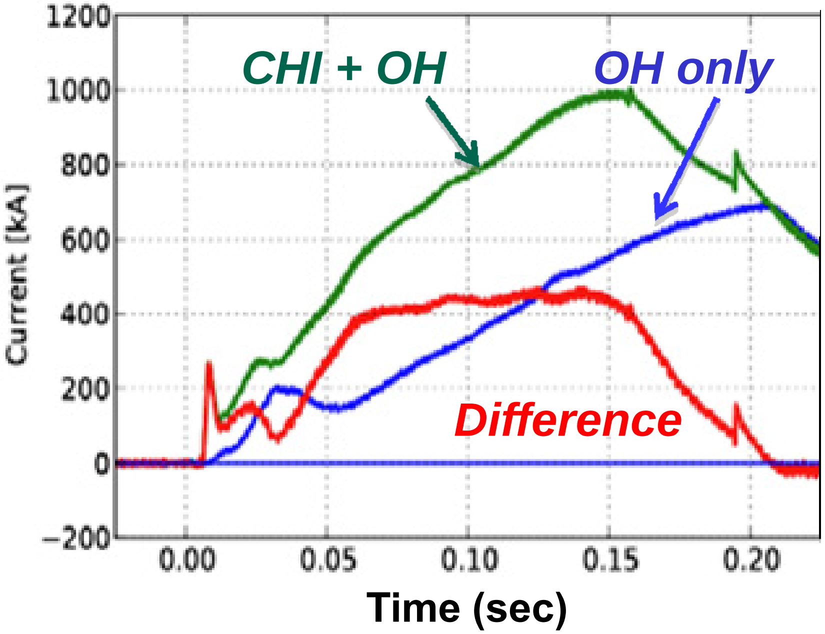
Time after CHI starts



- **Impurity Control Success**
  - Elimination of arcs in absorber region at top of vacuum vessel
  - Conditioning of lower divertor
    - Inboard Mo tiles could aid CHI

- **CHI synergy with OH extended in 2010 run:**
  - Generated 1MA using 40% less flux than induction-only case
  - Low internal inductance ($l_i \approx 0.35$), and high elongation
  - Suitable for advanced scenarios

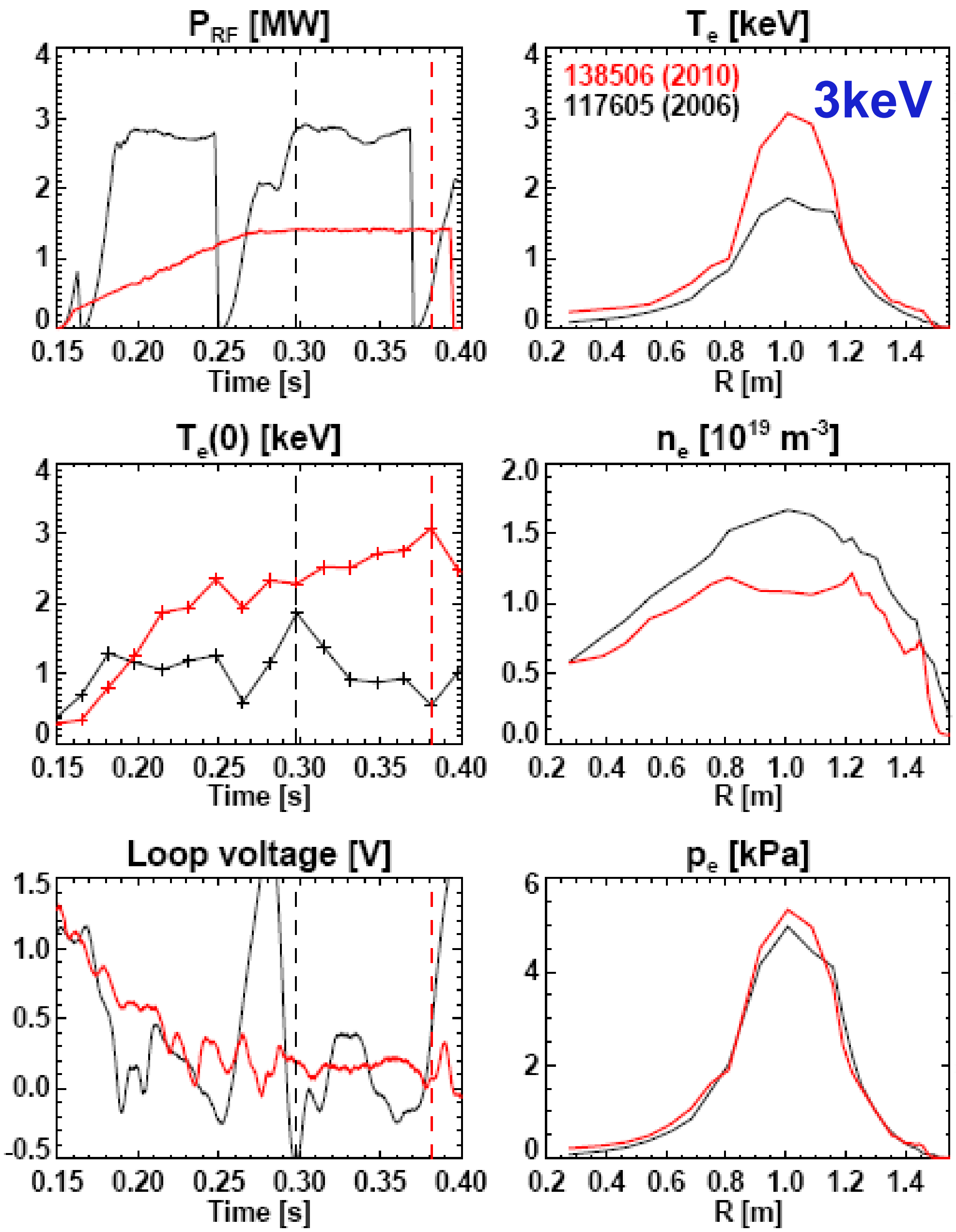
- **Also obtained new record 370 kA peak current by CHI alone**



IAEA: R. Raman, B.A. Nelson U Washington

Progress in sustaining HHFW heating and current drive at low I_P ~ 300kA

(Use low I_P ohmic target to prototype heating solenoid-free start-up plasma)



High $T_e(0)$ ~ 3keV with only 1.4MW

- Previous best at low I_P ~250kA was ~1.5keV at twice the power

- **P_{RF} and high T_e sustained longer**
  - But, max power was limited in FY2010 by arcing attributed to Li dust formation near/on antenna

- **Non-inductive fraction 60-70% sustained (25-30% RF, 35-40% BS)**
  - FY11: Will re-try for ~100% non-inductive at P_{RF} = 3-4MW

Pressure profiles are similar in both cases - profile stiffness?

Plasma Start-up Milestone R(12-2): Assess confinement, heating, and ramp-up of CHI start-up plasmas

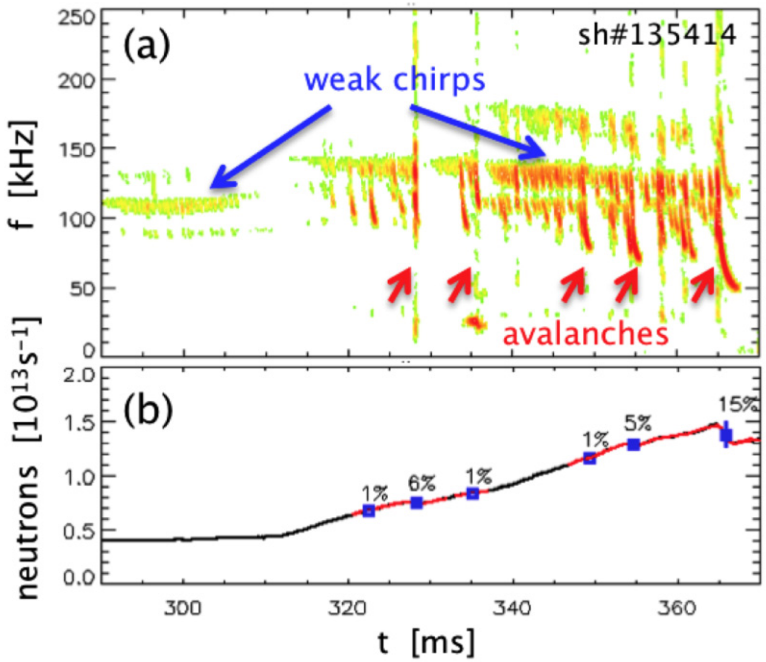
- CHI initiated plasmas have been successfully coupled to induction and NBI-heated H-mode.
  - While these results are favorable, **the confinement properties of CHI start-up plasmas have not been characterized.**
  - CHI-initiated plasma equilibrium, confinement, and stability information is needed for projecting to Upgrade, next-steps

- HHFW and recently NBI heating of low-current ohmic targets was demonstrated in 2008 and 2010

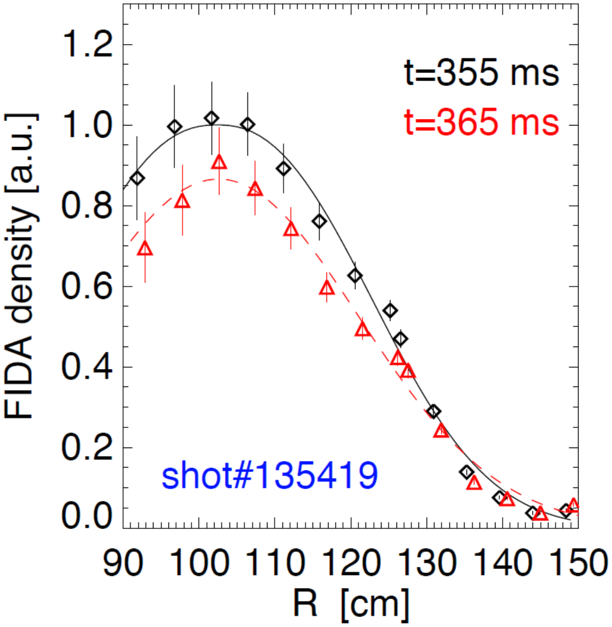
- HHFW and early NBI heating will be applied to CHI → OH discharges to assess confinement/heating vs. non-CHI

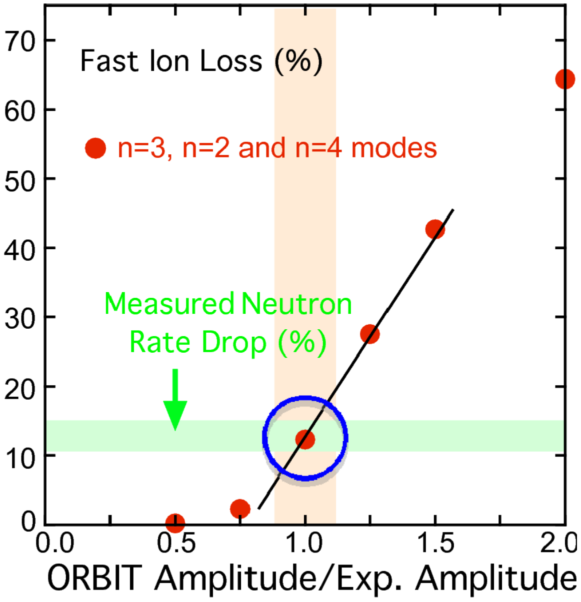
- NBI and HHFW heating and CD will be applied progressively earlier in target plasma to assess non-inductive sustainment

TAE-Avalanche induced neutron rate drop modeled successfully using NOVA and ORBIT codes



Fast Ion Profile
(E_λ = 30-60keV)





- **Toroidal Alfvén Eigenmode (TAE) avalanches in NBI-heated plasmas associated with transient reductions in DD neutron rate - “sea” of TAEs expected in ITER and future STs**
- **Change in beam-ion profile measured with Fast-ion D-alpha (FIDA)**
- **Modeled using NOVA and ORBIT codes**
  - **Mode structure obtained by comparing NOVA calculations with reflectometer data**
  - **Fast ion dynamics in the presence of TAEs calculated by guiding-center code ORBIT**

IAEA: E. Fredrickson ***IAEA: M. Podestà UCI*** ***IAEA:G-Y. Fu***

Waves and Energetic Particle Research for FY2011-2012

- Understand, develop high-harmonic fast-wave for heating, CD
  - Utilize antenna upgrade as tool for start-up, ramp-up, sustainment of advanced scenarios - e.g. HHFW heating of CHI+OH and CHI plasmas
  - Overcome/avoid problem of Li-compounds/dust on antenna
  - Improve resilience to edge transients (ELMs), understand edge power losses (surface waves, PDI) and NBI fast-ion interactions

- Develop predictive capability for fast-ion transport by *AE
  - Extend *AE avalanche results obtained in L-mode to H-mode scenarios/profiles (BES + improved reflectometry + tangential FIDA)
  - Compare measured to predicted fast-ion transport – M3D-K validation in support of ITER, NSTX Upgrade, next-steps

Initial planning for FY13 analysis and research:

- Complete analysis, publication of FY11-12 data in FY2013
- Activities supporting post-Upgrade operations – examples:
  - Design new high-k scattering system
  - Update equilibrium magnetics, reconstructions, plasma control system
  - Begin modifications to Multi-pulse Thomson Scattering (MPTS)
  - Design new particle pumping systems – new LLD and/or cryo-pump(s)
  - Scope/design new divertor/PMI/LLD diagnostics
  - Scoping studies for real-time-MSE for eventual NBI J-profile control

See TSG presentations for more complete list

- NSTX 5 year plan for 2014-18 will be written in 2013
- FY2013 is best period of opportunity for NSTX researchers to collaborate at other facilities:
  - Contribute to other research programs, bring back knowledge to NSTX
- Beginning to identify leading collaboration opportunities
  - Culham/MAST (CTF design, transport, *AE, divertor, RMP), EAST, DIII-D, …

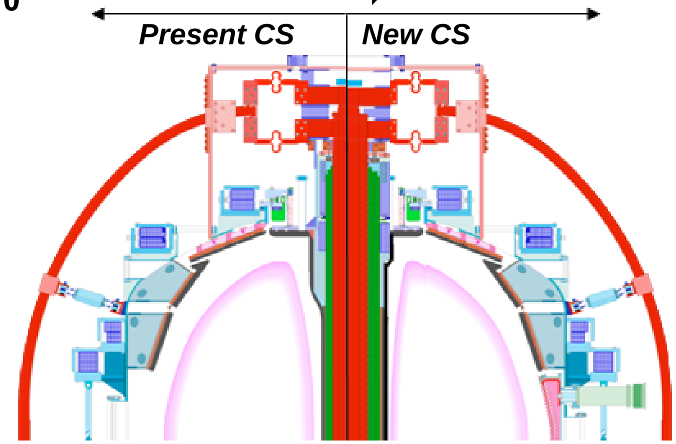
Outline

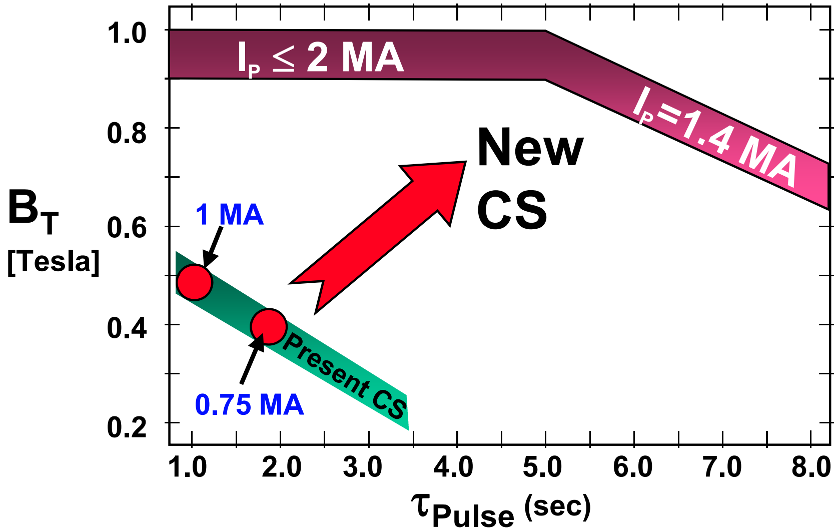
- NSTX Mission
- OFES Vision for Fusion for Next Decade
- FY11-12 Milestone Overview and Research Plans
  - Transport & Turbulence
  - Macroscopic Stability, Advanced Scenarios and Control
  - Boundary Physics and Lithium Research
  - Advanced Scenarios and Control
  - Non-inductive Plasma Start-up (Coaxial Helicity Injection)
  - Wave-Particle Interactions
- Initial Planning for FY13
- Overview of Research in Support of Upgrade
- Summary

NSTX Upgrade will bridge the device and performance gap toward next-step STs

New center stack for 1T, 2MA, 5s

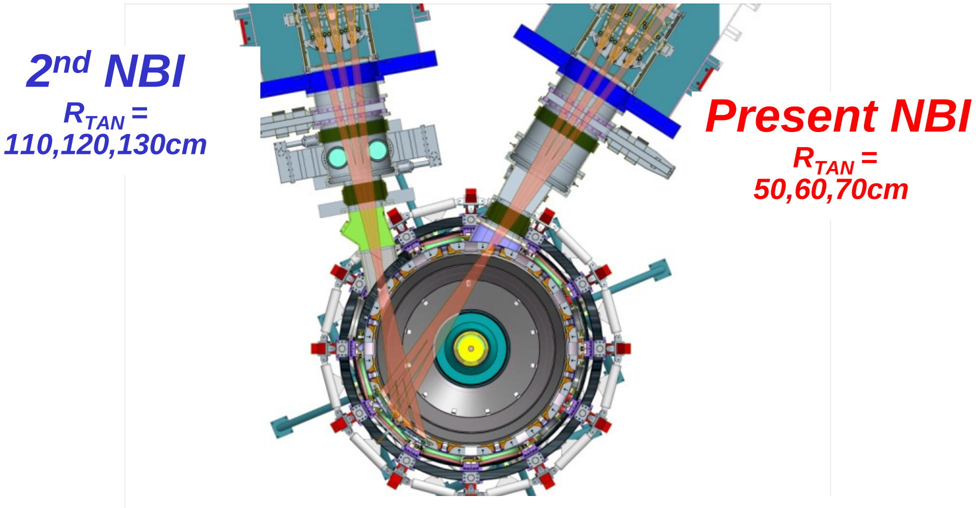
R_0/a = 1.25-1.3 ➡ 1.5-1.6

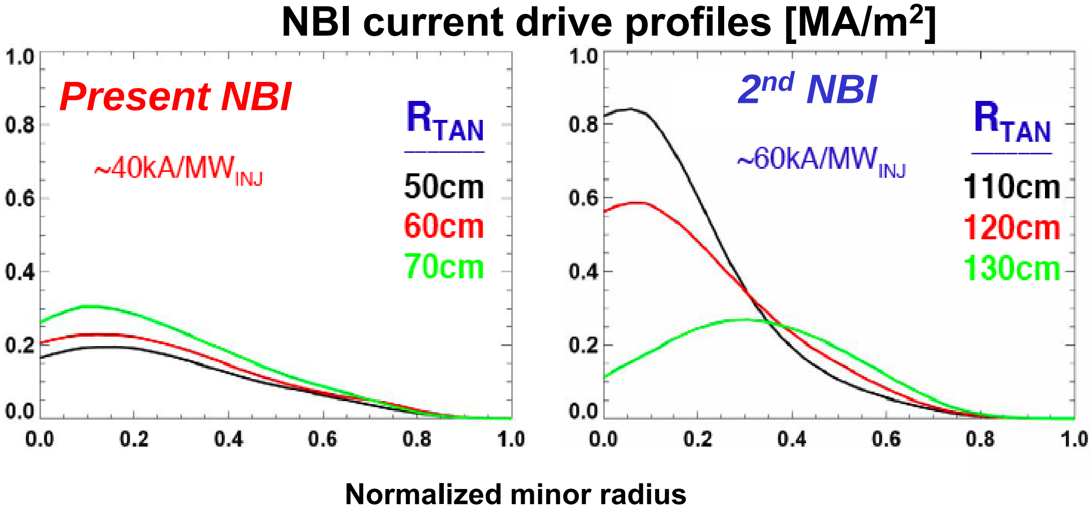




Magnet operation at ~1T (vs. 0.55T) within a factor of 2 of next-step STs

2^{nd} NBI with 5 MW, 5s at larger R_{TAN}





Up to 2 times higher NBI current drive efficiency, and current profile control

NSTX Upgrade reference operating scenarios highlight major research capabilities and needs of Upgrade

PAC27-2

PAC27-6

- Dual NBI capability (P/Δt): 15MW/1.5s, 10MW/5s, 5MW/10s
- TF flat-top capability: 1T for 6s, 0.75T for 10s, total OH flux = 2.1Wb
- Divertor peak heat flux limit = 10MW/m^2 for 5s ($T_{carbon\text{-}tile} \leq 1200°C$)
- Plasma carbon $Z_{eff} \leq 2.5$ (goal)

$\beta_N \leq 5.5$, τ_E = ITER-98y2 H-mode scaling, SOL width scaling $\propto I_P^{-1.6}$

Reference Scenario	B_T [T]	I_P [MA]	Δt_{flat} [s]	NICD [%]	n_e / $n_{Greenwald}$	P_{NBI} [MW]	P_{RF} [MW]	P_{TOT} [MW]	Unmitigated divertor peak heat flux [MW/m^2] (f_{exp} = 20)	Unmitigated divertor peak heat flux [MW/m^2] (f_{exp} = 60)	D pumping required (NBI fueling only) [10^{21} s^{-1}]
Long pulse	0.8	1	7	50-70	≤ 1	6	0	6	5	2	0.7
High non-inductive	1	0.8	5	80-100	≤ 1	8	0	8	5	2	1.0
High I_P	1	1.5	5	50-70	≤ 1	8	0	8	13	4	1.0
Max I_P	1	2	4-5	40-60	0.7-1	10	0	10	25	8	1.2
Max I_P & power	1	2	4-5	40-60	≤ 1	10	5	15	38	13	1.2

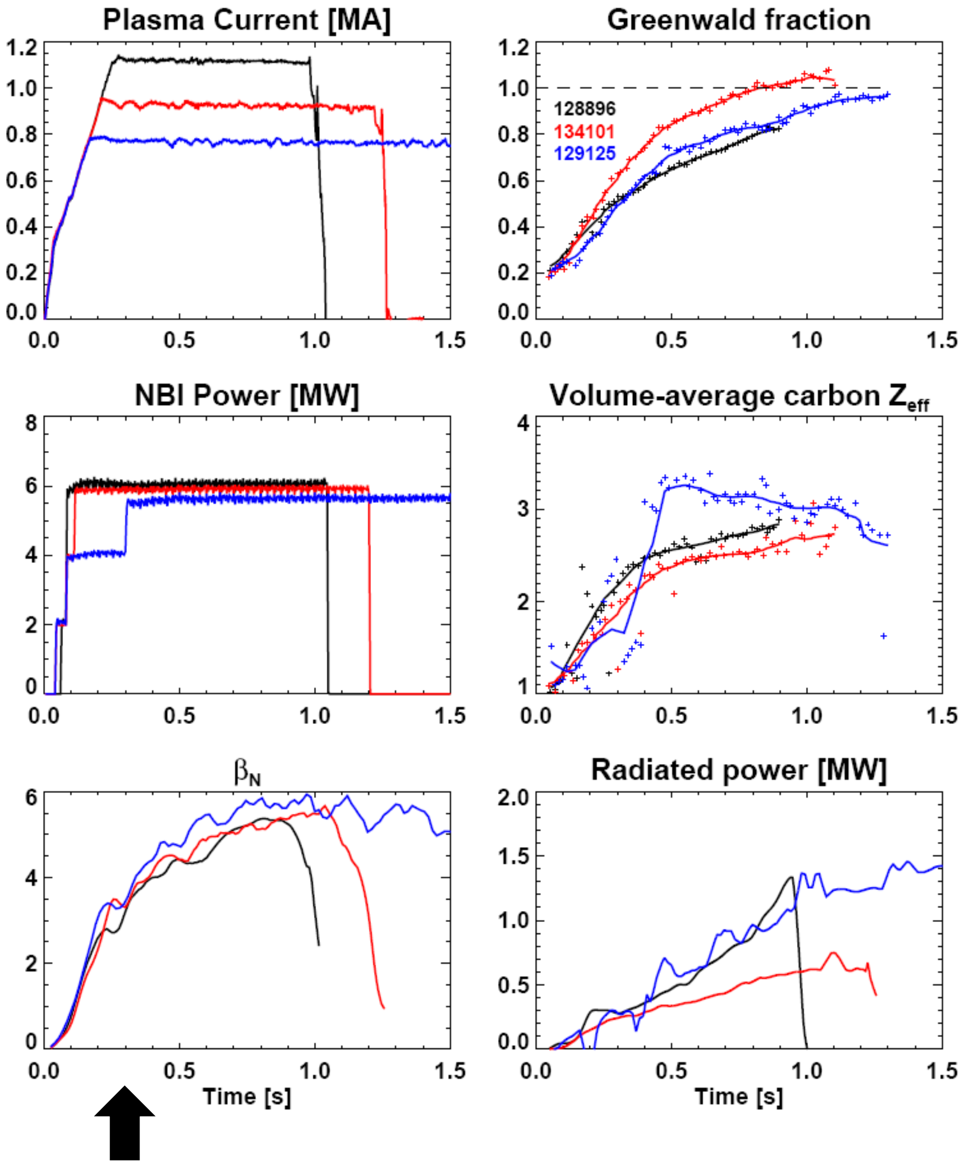
2MA operation may require n_e / $n_{Greenwald}$ = 0.7 to aid achievement of sufficiently high T_e to reduce loop voltage to 0.25V for 5s flat-top

1.5-2MA operation for 5s will require heat-flux mitigation utilizing: U/L power sharing, detachment, and/or snowflake (possibly all three)

This is major goal of Upgrade research program

ELMy H-mode combined with modest Li-wall conditioning can provide sufficient particle control for initial Upgrade ops

PAC27-2



β_N = 5-6 sustained for ~1s – ready to assess stability at longer pulse-lengths in Upgrade

- NSTX long-pulse plasmas with ELMs approach density flat-top by t ~1s with n_e / $n_{Greenwald}$ → 1
  - Modeling indicates n_e / $n_{Greenwald}$ = 0.7-0.9 likely required for 100% NICD
- Carbon Z_{eff} = 2.5-3 acceptable, and will attempt to reduce further in FY11-12 research
- Radiated power < 25% of NBI power, which is acceptable

Improved D pumping required to access n_e / $n_{Greenwald}$ < 1 operating scenarios – will be part of longer-term Upgrade research program

NSTX FY11-12 research plan addresses key issues anticipated for NSTX Upgrade operation (1)

- Diagnostic impact
  - – Issue: High-k scattering system will be displaced by Upgrade 2nd NBI
  - – Plan: Gather complete high-k dataset for R11-1, FY12 JRT, and to support design of new high-k system during Upgrade outage period
- Achievability of stable, high-performance operating scenarios
  - – Issue: Plasma stability, control (n=0, 1) will be impacted by higher A, κ
  - – Plan: Assess stability impact in R11-2, modify/improve controllers as needed during FY11-12 run and during Upgrade outage period

PAC27-6

- Power exhaust and PFC thermal limits
  - – Issue: Highest I_P & power Upgrade plasmas require heat flux mitigation
  - – Plan: Assess performance and controllability of SN and DN snowflake divertors + synergy with other mitigation techniques in R11-3

PAC27-2

NSTX FY11-12 research plan addresses key issues anticipated for NSTX Upgrade operation (2)

- Particle and impurity control, role of Lithium

  PAC27-2

  - Issue: Li evaporation will be only D pumping tool during initial post-Upgrade operation (cryos and/or LLD not included in Upgrade Project),
    - Present NSTX particle and impurity control may not extrapolate to longer pulses (2-5s) and/or reduced density for 100% non-inductive ops
  - Plan: Assess evaporated Li and LLD performance in R12-1, impurity control methods and cryo-pumping scoping studies in ITER/CC TSG
  - Plan: Develop stable scenarios w/ less fueling, more Li in R12-3

- Achievement of non-inductive start-up and ramp-up
  - Issue: Confinement, stability of low-I_P target plasmas not fully characterized for projecting to non-inductive ramp-up in Upgrade
  - Plan: Achieve ~100% non-inductive low-I_P plasmas with HHFW & NBI, assess confinement and stability of start-up plasmas in R12-2.

Summary: NSTX and NSTX Upgrade strongly support OFES vision for fusion for coming decade

- **Plasma dynamics and control**
  - NSTX is performing detailed measurements of turbulence, transport, core/edge stability, and integrating this knowledge to develop advanced high-β ST scenarios
  - NSTX Upgrade will extend these scenarios to full non-inductive operation with current profile control + advanced stability control
- **Materials in fusion environment, harness fusion power**
  - NSTX is providing critical data on SOL-width scaling and SOL turbulence, novel divertors for heat-flux mitigation, and lithium-based plasma facing components
  - NSTX + Upgrade providing critical data for assessing the ST as potential FNSF
- **Validated predictive capability**
  - Performing leading validation efforts for ST turbulent transport, tokamak/ST RWM stability and 3D MHD effects, edge turbulence, fast-ion transport from *AE
  - Upgrade will substantially extend range of collisionality, rotation, fast-ion drive, …
- **3-D magnetic fields**
  - Research to understand transport/stability response to 3D fields for ITER, beyond
  - A leader in 3D perturbed equilibrium analysis/R&D, 3D perturbed transport (NTV)

Table of PAC-27 recommendations and comments, and NSTX and response (1)

PAC Recommendation Response Number	PAC Report Section	Issue	PAC Recommendations and Comments.	NSTX Response	Action for Speaker	Response (talk)	VG #
PAC27-1	1	NSTX Upgrade status, impact on NSTX program	We do urge continuing focus/planning on minimizing the upgrade related downtime, and maximizing staff research activities during the upgrade process.	Agree	Describe status and schedule for review and completion of NSTX Upgrade project	Ono (Facility)	21
PAC27-2	2.1	Divertor, impurity, and particle control issues	(a) The PAC recommends that both the near- and mid-term research plans be modified to give increased emphasis to activities that build confidence that NSTX has a viable divertor boundary solution that (i) controls particle and impurity influx, (ii) manages divertor heat flux (peak and integrated), and (iii) meets performance targets. (b) With regard to impurity control, quantitative goals could include the divertor heat flux limits, quantification of the level of core impurities and impurity sources as well as source mechanisms.	Agree	Outline research plans, milestones, and groups, to address these issues (Menard). Outline upgrade performance targets in overview (Menard). BP talk to cover progress/plans for heat flux mitigation and reduced impurity influx using snowflake. ASC talk to cover performance targets and integration in more detail, and how targets will be met.	Menard (Program), Soukhanovskii (BP), Gerhardt (ASC)	8,17, 21, 32-35 6,8 15, 16
PAC27-3	2.1	Divertor diagnostics	Because there will be only limited opportunities for hardware modifications during the next two years, the PAC encourages you to plan ahead for the need for possible minor modifications to address critical divertor physics needs. Consider additional ways to supplement divertor diagnostics (e.g., additional camera coverage and impurity source diagnostics).	Agree	Discuss additional camera coverage and diagnostics implemented for LLD (funded via ARRA) that can be used	Ono (Facility)	8,17
PAC27-4	2.1	Density and impurity control	Additionally, since the LLD/Li systems are your primary option for density and impurity control, more effort and planning is needed to develop an alternative if the LLD fails to perform as expected. As part of this effort, to control impurities the PAC supports the plans to install sample molybdenum divertor tiles to gain experience with Li-coated Mo tiles and its effect on carbon impurities in NSTX.	Agree	Discuss status of Mo tile design, fabrication, likelihood of installation before next run campaign (Ono). Presentation on initial calculations of cryo-pumping.	Maingi (P&I Control), Ono (Facility)	2, 3-9 12
PAC27-5	2.1	Density and impurity control	The PAC urges the NSTX Team to demonstrate density and impurity control, within the next two years, in discharges characteristic of your post-upgrade operation. We suggest you consider combining the forces of several physics tasks groups to address these critical divertor and boundary issues.	Agree these research areas are high priority	Discuss CC&E TSG high priority task for density and impurity control techniques (Menard or Maingi).	Menard (Program), Maingi (P&I control)	8 2
PAC27-6	2.1	Physics targets	The PAC also suggests that the NSTX team identify other discharge and physics targets that will optimize operation of NSTX past the Upgrade. These include control metrics related to shaping, low internal inductance, and RWM control	Agree - will be addressed in TSG presentations	Discuss Upgrade targets in program overview talk (Menard), control of shaping and low li access in ASC talk (Gerhardt), and low li stability impact and RWM control in MS talk (Sabbagh)	Menard (Program), Gerhardt (ASC), Sabbagh (Macro)	13-15, 32, 34, 6, 9-13, 15 4-6
PAC27-7	2.1	ReNeW emphasis	Consequently, the PAC suggests that those ReNeW theme areas related to divertor and boundary physics should be strengthened even if this results in some delay to your progress addressing core-specific research theme areas.	Agree, but also recognize that the Upgrade and future STs need integrated core/boundary	Discuss research milestones and priorities in Program talk	Menard (Program)	6
PAC27-8	3.1	Boundary Physics	Get more people involved, perhaps by having some redirection/merging of effort from other NSTX topical areas (such as scenarios and control) or possibly from outside of NSTX. This area is sufficiently critical to the success of NSTX-Upgrade that additional effort is justified	Agree - several additional young researchers now working on boundary physics	In NSTX facility talk, note new grad-students (Scotti advised by Vlad/LLNL) and post-docs/researchers from ORNL (McClean, Gray, Ahn, …) and PPPL (Diallo, Jaworski) working on boundary physics	Ono (Facility)	8
PAC27-9	3.1	Boundary Physics	Deploy the new Thomson channels as soon as practical to shed further light on SOL profiles.	Agree	Discuss status and schedule of additional MPTS channels	Ono (Facility)	22, 23
PAC27-10	3.1	Boundary Physics	Develop a means to diagnose the width in the main SOL to check its currently assumed relationship to the measured width at the divertor.	Agree	Discuss existing MPTS data for SOL width, reciprocating probe data and related publications, and new MPTS channels	Soukhanovskii (BP)	4
PAC27-11	3.1	Boundary Physics	Look for correlations of SOL width with turbulence levels and other SOL characteristics.	Agree	Discuss GPI data and comparison to SOLT code, also discuss new BES data obtained in pedestal/edge region	Soukhanovskii (BP)	4, 5
PAC27-12	3.1	Boundary Physics	For discharges with blobby edge transport, further quantify where the particles and power go, and what is the resultant surface response. It would be best if this were a coordinated effort between experiment and modeling, for example, BOUT simulation coupled with post-processing of the fluxes onto the walls with a wall code. More generally, determine the fraction of power and particles that go to the main wall versus plasma parameters.	Agree	Discuss GPI data and comparison to SOLT code, also discuss related progress/results with WallPSI code modelling, and any other calculations of power and particle flux into the wall and liberation of impurities from the wall.	Soukhanovskii (BP)	5

Table of PAC-27 recommendations and comments, and NSTX and response (2)

PAC Recommendation Response Number	PAC Report Section	Issue	PAC Recommendations and Comments.	NSTX Response	Action for Speaker	Response (talk)	VG #
PAC27-13	3.2	Lithium Research	A clear plan to measure the pumping by the LLD separately from the rest of the chamber has not been delineated but should be done as soon as possible. One could consider experiments where first fiducial discharges are well characterized with the LLD well coated. Then the LLD is heated (Li removed) and the fiducial discharges repeated - the difference in pumping corresponding to the loss of LLD pumping. Perhaps the group could also derive a measure of the pumping from planned measurements (Ly-alpha and probes).	Agree	Discuss results from Kugel and Soukhanovski 2010 LLD experiments and analysis from M. Bell, R. Bell, Soukhanovskii, Scotti, and Jaworski	Skinner (Lithium)	6
PAC27-14	3.2	Lithium Research	For example, what is the thickness of the Li on the surface? Is it 10s of nm, several times the depth of the implanting ions as assumed for the pumping predictions? Or, does most of the Li wick into the Mo mesh?	Agree on need to quantify this	Discuss Li thicknesses used during LLD experiments, and any observed dependences on this thickness	Skinner (Lithium)	9
PAC27-15	3.2	Lithium Research	Do Li wetting experiments on Mo, as done, e.g., by UIUC and by SNL and collaborators, reliably apply to NSTX? The answers to these questions affect the understanding of how to use the LLD in NSTX and should be remedied by offline experiments (if the information does not already exist). An additional question is how multiple Li depositions change the surface – does it build up in thickness or does it wick into the Mo leaving the same thickness.	Agree need to answer	Discuss wetting experiments performed thus far at PPPL, and UIUC surface analysis results	Skinner (Lithium)	7, 9
PAC27-16	3.2	Lithium Research	We are concerned that the diagnosis of heat load uniformity and impurity sources is below that needed to develop strategies for impurity control and reduce hot spots before the machine is upgraded.	Agree need to address	Discuss camera results showing hot-spots from leading edges, and cameras added in 2010 using LLD ARRA funding to image entire lower divertor	Soukhanovskii (BP), Ono (Facility)	6, 8 8
PAC27-17	3.2	Lithium Research	The Mo surface can reach higher temperatures than C without causing problems for the core. At the same time, the Mo is potentially more dangerous in terms of effect on the core plasma even with lower sputtering yields than carbon, under plasma conditions of high Te and low ne, which could be obtained at the inner divertor due to high D pumping by the LLD. Such plasma conditions would lower the sputtered particle re-deposition and allow a higher fraction of sputtered material to reach the core plasma. Also, melting of Mo tiles can be a problem. Also, modeling of sputtered Mo transport, prior to installation, would seem highly feasible and desirable.	Agree need to address	Discuss REDEP/WBC Mo tile analysis of J. Brooks for NSTX	Maingi (P&I Control)	10
PAC27-18	3.2	Lithium Research	If Mo tiles are used, they should be installed as soon as possible, probably on a small scale (small fraction of the toroidal circumference) to gain experience. The tiles should be installed where there is proper spectroscopic coverage to determine Mo influxes to be correlated with core Mo levels. In parallel, an improved set of camera views of the 360-degree circumference of the vessel should be installed and followed to determine any hot spots and correlate with C and other impurity measurements in the core plasma. Utilizing the IR camera in 2D mode to evaluate leading edges and peaking factors should be pursued as this will base the extrapolation to doubling the power and 5x longer pulse lengths more on reality as opposed to assuming uniform temperature rises. Additional IR cameras would help in that effort as well.	Agree	Discuss Mo tile design, fabrication, installation status and schedule in facility presentation. Mo tile options include: 1 full toroidal row of tiles, a subset/several tiles, or no tiles (if cost or schedule is problematic). Also discuss visible and IR cameras added to NSTX in 2010 that can be used in 2011-12	Ono (Facility)	11, 12
PAC27-19	3.3	Macrostability	In considering the first charge question, the PAC believes the improved physics understanding of high-beta and MHD phenomena on NSTX should be used to assess RWM stability in the planned NSTX-U scenarios. Experiments towards lower li and Vphi should be foreseen in 2011/12 in preparation.	Agree	Discuss progress in achieving elevated betan/li results from 2009 and 2010, reductions in no-wall limit at low li, milestone for exploring stability/control limits at higher A and varied shaping, and (incremental) milestone plans for rotation damping physics and rotation control in FY2012.	Sabbagh (Macro)	3, 5, 8, 10, 12
PAC27-20	3.3	Macrostability	Work in the areas relating to other ITER high-priority areas (e.g. disruptions, NTMs) is focused on NSTX specific needs. The team is encouraged to assess even better the area(s) in which they can make unique contributions towards ITER needs in MHD, such as NTM thresholds, NTM excitation, and similar physics areas.	Agree	Describe disruption results (halo-currents, heat loads, etc), and NTM-onset threshold reduction vs. error field (Park/LaHaye/Buttery) results, and also Delgado-Aparicio/Volpe results of impurity/radiation driven islands (if info available)	Sabbagh (Macro)	3, 7, 11-13
PAC27-21	3.3	ELMs	The PAC observes that ELM research is spread over at least three groups (boundary, MHD and integrated scenarios). Because of the central importance of ELM research, the PAC suggests that the NSTX Team should make sure ELM studies are well coordinated, possibly by appointing a "research organizer" for ELM research.	Agree ELM research - like all research areas on NSTX - should be well coordinated	Will consider/discuss appointment of research organizer or another mechanism for ensuring good coordination of ELM research in Program talk	Menard (Program)	8
PAC27-22	3.4	Transport and Turbulence	It has been shown that the improvement of confinement with Lithium operation is due to a local decrease of the electron heat diffusivity. This clearly answers a PAC recommendation, though it would be interesting to know more about the reasons why this local improvement occurs.	Agree	Show reflectometer data and high-k data (both from Canik APS 2010 presentation) indicating density fluctuation reduction in edge region with Li	Soukhanovskii (BP), Ren (T&T)	5 15 (in backup)

Table of PAC-27 recommendations and comments, and NSTX and response (3)

PAC Recommendation Response Number	PAC Report Section	Issue	PAC Recommendations and Comments.	NSTX Response	Action for Speaker	Response (talk)	VG #
PAC27-23	3.4	Transport and Turbulence	The near-term program will continue to investigate the respective role of different candidates (ETG, micro-tearing modes, and GAEs) to explain electron turbulent transport. With respect to the planned upgrade, it would be interesting to see the parametric dependence of the observed ETGs and GAEs on Bt and Ip to see if the different confinement scaling can be related to the proposed transport mechanisms.	Agree	Describe dependence of high-k fluctuations on collisionality from FY201011 run. Also discuss recent non-linear micro-tearing analysis of Guttenfelder and dependence on collisionality. Briefly review Yuh's FY2008-10 RS L-mode results and discuss recent analysis by L. Petersen for nonlinear gyrokinetic simulations of reversed-shear NSTX plasmas.	Ren (T&T)	7, 8
PAC27-24	3.4	Transport and Turbulence	The work that has been done on the L-H transition is interesting, in particular regarding hysteresis and the parametric dependences of the power threshold. The experiments that are planned should bring more information, and the PAC looks forward seeing these results. It is of particular importance to go beyond threshold scaling experiments and characterize also the fluctuations in order to understand the triggering mechanism for the transport barrier.	Agree	Describe results on L-H transition obtained in FY2010 including threshold vs. x-point radius (Battaglia) and XGC0 Er/orbit-loss predictions, BES and/or GPI data surrounding H-mode transition, and anything from recent OH H-mode studies using improved reflectometer.	Ren (T&T)	5, 6
PAC27-25	3.4	Transport and Turbulence	Overall, it is certainly important to clarify the issues related to edge turbulence and its interplay with core turbulence, in view of the operation of NSTX with Li-coated PFCs. Regarding this point and the possible implementation of Molybdenum tiles, the PAC recommends intensifying the study of impurity transport and investigating possible solutions (e.g., external coils, RF heating) to prevent impurity accumulation.	Agree	Much of this will be covered in other talks, but should discuss results from NF paper by Delgado-Aparicio investigating impurity transport coefficients compared to neoclassical, and impact of rotation on NC diffusion rates.	Ren (T&T)	9
PAC27-26	3.5	Energetic Particles	An important preparation for post-Upgrade operation is to work further on improving predictive capability, especially by validating the linear and nonlinear energetic particle simulation codes. The NSTX Upgrade, with its new center stack and additional neutral beam, will extend parameter capabilities for fast particle studies. A quantitative assessment should be made of Alfvén eigen-mode physics for NSTX-U including linear thresholds and fast ion losses. The PPPL linear codes could be used to explore whether stability regime(s) are modified significantly. The M3D-K code could be used to explore nonlinear behavior, since it is self-consistent, whereas the ORBIT code is not.	Agree this is important longer-term goal - but emphasis for FY11-12 will be on obtaining best AE experimental results and analysis from NSTX for analysis/predictive modeling during outage for Upgrade	(1) Discuss Podesta AE experimental results, Darrow SSNPA measurements, Crocker reflectometer upgrade results, improved measurements of eigenfunctions. Include any updated/improved AE simulations from Gorelenkov/Fu/White/or other. (2) Also discuss Gerhardts TRANSP modelling of avalanche transport, and need for improved predictive model. (3) Finally, discuss incremental milestone for FY12 for validation.	Podesta (EP), Gerhardt (ASC)	9 6
PAC27-27	3.6	HHFW	The PAC recommends that NSTX continue to push the antennas to find the new limits to antenna performance and develop plasma scenarios that can be used for HHFW heating in current ramp-up and start-up plasmas. These might include: (i) investigating impurity puffing to reduce high power arcing, and (ii) studying trade-off between outer gap and pulse length with NBI in order to assess options for optimization.	Agree	Discuss results from low-Ip experiments where HHFW heating and HHFW+2MW NBI was used to reduce loop voltage and increase NI fraction. Provide estimates of the maximum non-inductive fraction achieved, and expectations for FY11-12 runs. Discuss challenges to increasing power above 2-3MW experienced in FY2010. Discuss any possible plans for impurity puffing, and results from gap and NBI power scans.	Taylor (HHFW)	4-7
PAC27-28	3.6	HHFW	The PAC also suggests that NSTX (i) revisit the absorption and propagation physics of HHFW in NSTX-U in light of the fact that the harmonic resonances will be lower with the 1 Tesla magnetic field for the upgrade, (ii) continue to assess the level of parasitic losses in combined HHFW+NBI experiments, especially now that combined HHFW+NBI heating has been demonstrated, (iii) continue to interact with the Boundary Physics Group to quantify RF sheath losses in NSTX and to aid in developing mitigation techniques if needed, and (iv) evaluate the effectiveness of ELM/arc discriminating electronics to maintain antenna protection in the presence of ELM-induced transients in the antenna loading.	Agree this is important longer-term goal - but emphasis for FY11-12 will be on validating NSTX HHFW+NBI fast-ion interaction models with CQL-3D, AORSA, and TORIC	Discuss in HHFW presentation the modelling results on HHFW fast-ion absorption from Choi, Green, Harvey, and Petrov. Also discuss expected scaling of other parasitic losses (surface waves, PDI, and sheaths) with higher TF and plasma current. Discuss any plans for implementation of arc reduction/ELM avoidance/discrimination.	Taylor (HHFW), Ono (Facility)	5, 8-10 29
PAC27-29	3.6	HHFW	We also strongly endorse the experimental plan to heat lower current target plasmas with HHFW to demonstrate full non-inductive current sustainment. This is likely to greatly simplify issues associated with RF coupling, equilibrium control, and stability. It will also begin to quantify power requirements for the more challenging step of current ramp-up.	Agree	Discuss results from FY2010 HHFW experiments using of low-Ip ohmic and OH+NBI target plasmas.	Taylor (HHFW)	6, 7
PAC27-30	3.7	Current Start-up and Ramp-up	The PAC notes that the planned experiments to optimize arc mitigation using the absorber coils are high leverage in informing the expected performance of CHI post-upgrade of the centerstack. Since there are no equivalent coils planned in the new center-stack, the effects of local field shaping in the absorber region need to be understood, and an assessment made on whether CHI will be negatively impacted by the absence of these coils.	Agree	Present analysis of CHI absorber nulling capabilities with additional upper (and lower) PF coils included in CS upgrade.	Raman (SFSU)	8

Table of PAC-27 recommendations and comments, and NSTX and response (4)

PAC Recommendation Response Number	PAC Report Section	Issue	PAC Recommendations and Comments.	NSTX Response	Action for Speaker	Response (talk)	VG #
PAC27-31	3.7	Current Start-up and Ramp-up	We also strongly urge the use of the LLD in CHI experiment in 2010, even if experiments with reversed toroidal field are not available. The impact of LLD on impurity and particle control could be very significant.	Agree	Present any noteworthy results of impact of LLD on CHI during FY10 run. Also note any expected impact of inboard Mo tiles on CHI in FY2011-12 if such tiles are installed.	Raman (SFSU)	5
PAC27-32	3.7	Current Start-up and Ramp-up	The PAC recommends maintaining a close collaboration with DIII-D (and other facilities, as relevant) on outer-PF start-up. The PAC continues to encourage revisiting start-up and ramp-up scenario modeling using realistic inputs from achieved plasma conditions, taking into account transport and stability considerations.	Agree	Describe TSC modeling of CHI start-up, and Gerhardt/Taylor TRANSP analysis of HHFW heating and current-drive at low Ip	Raman (SFSU)	2, 6
PAC27-33	3.8	Advanced Scenarios and Control	For density and impurity control, the NSTX Team should consider (i) increased emphasis on integration of ELM pacing and high-beta operation and (ii) reduction of uncertainties in expectations for density/impurity control in high-performance plasmas, through systematic experiments and improved diagnostics.	Agree	Discuss results from using early DRSEP variation to trigger ELM and reduce C impurities, and n=3 ELM pacing attempts in high beta-poloidal shots, and jog+n=3 results	Maingi (P&I Control)	2-9
PAC27-34	3.8	Advanced Scenarios and Control	For HHFW, the NSTX Team should consider increased emphasis on determining compatibility of HHFW (in particular plasma-antenna gap) and long-pulse, high-power NBI.	Agree	Discuss attempts at these experiments in FY2010, prospects this in FY2011-12.	Gerhardt (ASC)	16
PAC27-35	3.8	Advanced Scenarios and Control	For modeling, the NSTX Team should reinvigorate efforts to model discharge scenarios through improvements in transport modeling and benchmarking with experiment.	Agree	Describe TRANSP modelling of AFID for AE avalanches, and wide range of scenario scoping studies using TRANSP with varied confinement, temperature, Zeff, etc.	Gerhardt (ASC)	3, 6
PAC27-36	3.8	Advanced Scenarios and Control	The PAC suggests the plans for advanced scenarios be expanded to incorporate the performance capabilities of the NSTX upgrade. For example, present plans use only four of six NBI sources, and reach targets of only 0.725 MA at a toroidal field of 0.55 T.	Agree	Discuss modeling performed for 0.55T scenarios (may be representative of maximum TF capabilities immediately after upgrade if cannot afford power supply upgrade). Also discuss 1T/1MA scenario modeling (done since 5yr plan) in ASC presentation.	Gerhardt (ASC)	2
PAC27-37	3.8	Advanced Scenarios and Control	Finally, the NSTX Team should investigate and develop backup options for density control if LLD is found to be incompatible with long-pulse, high-beta operation.	Agree	Discuss density/impurity control needs for advanced scenarios. Techniques for providing this control will be covered in others presentations/groups	Gerhardt (ASC), Maingi (P&I Control)	2 17-22

NSTX Participation in ITPA Joint Experiments and Activities

Proposals under consideration awaiting NSTX Research Forum discussion and/or further definition from respective ITPA groups

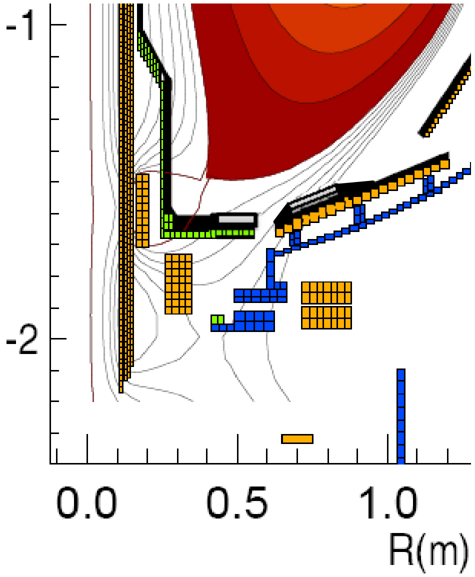
NSTX typically actively participates in ~25 Joint Experiments/Activities

- **Advanced Scenarios and Control (5)**
  - IOS-1.2 Study seeding effects on ITER baseline discharges
  - IOS-4.1 Access conditions for advanced inductive scenario with ITER-relevant restrictions
  - IOS-4.3 Collisionality scaling of confinement in advanced inductive plasmas
  - IOS-5.2 Maintaining ICRH coupling in expected ITER regime
  - IOS-6.2 li controller (Ip ramp) with primary voltage/additional heating
- **Boundary Physics and Lithium Research (16)**
  - PEP-6 Pedestal structure and ELM stability in DN
  - PEP-19 Basic mechanisms of edge transport with resonant magnetic perturbations in toroidal plasma confinement devices
  - PEP-23 Quantification of the requirements for ELM suppression by magnetic perturbations from off-midplane coils
  - PEP-24 Minimum pellet size for ELM pacing
  - PEP-25 Inter-machine comparison of ELM control by magnetic field perturbations from midplane RMP coils
  - PEP-26 Critical parameters for achieving L-H transitions
  - PEP-27 Pedestal profile evolution following L-H/H-L transition
  - PEP-28 Physics of H-mode access with different X-point height
  - PEP-29 Vertical jolts/kicks for ELM triggering and control
  - PEP-31 Pedestal structure and edge relaxation mechanisms in I-mode
  - PEP-32 Access to and exit from H-mode with ELM mitigation at low input power above PLH
  - PEP-33 Effects of current ramps on the L-H transition and on the stability and confinement of H-modes at low power above the threshold
  - PEP-34 Non-resonant magnetic field driven QH-mode
  - DSOL-20 Transient divertor reattachment
  - DSOL-21 Introduction of pre-characterized dust for dust transport studies in divertor and SOL
  - DSOL-24 Disruption heat loads
- **Macroscopic Stability (7)**
  - MDC-1 Disruption mitigation by massive gas jets
  - 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 Active disruption avoidance
- **Transport and Turbulence (11)**
  - TC-1 Confinement scaling in ELMy H-modes: beta degradation
  - TC-2 Hysteresis and access to H-mode with H~1
  - TC-4 H-mode transition and confinement dependence on ionic species
  - TC-9 Scaling of intrinsic rotation with no external momentum input
  - TC-10 Experimental identification of ITG, TEM and ETG turbulence and comparison with codes
  - TC-11 He and impurity profiles and transport coefficients
  - TC-12 H-mode transport and confinement at low aspect ratio
  - TC-14 RF rotation drive
  - TC-15 Dependence of momentum and particle pinch on collisionality
  - TC-17 rho-star scaling of intrinsic torque
  - TC-19 Characteristics of I-mode plasmas
- **Wave-Particle Interactions (5)**
  - EP-1 Measurements of damping rate of intermediate toroidal mode number Alfven eigenmodes
  - EP-2 Fast ion losses and redistribution from localized AEs
  - EP-3 Fast ion transport by small scale turbulence
  - EP-4 Effect of dynamical friction (drag) at resonance on nonlinear AE evolution
  - EP-6 Fast ion losses and associated heat load from edge perturbations (ELMs and RMPs)

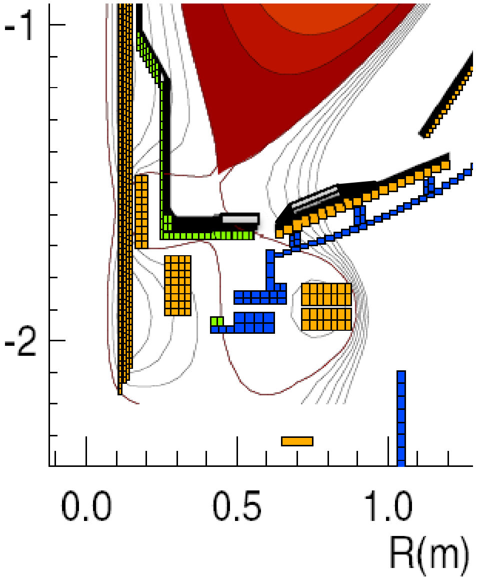
Backup

Addition of IBD Mo tiles would enable important divertor studies

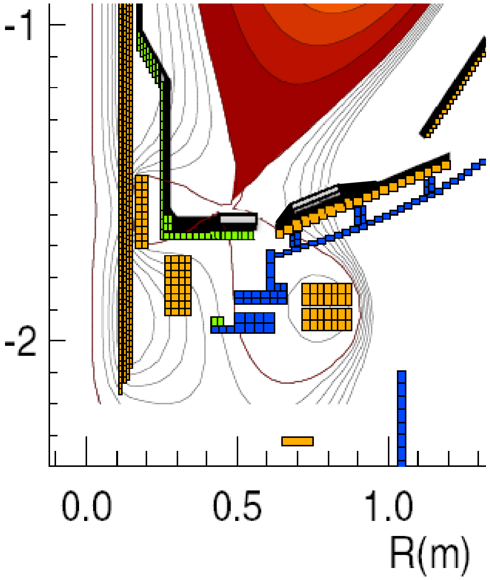
- Help quantify fraction of core C coming from lower divertor for high-δ shapes
- Potentially reduce C content of Li ELM-free scenarios
- Characterize Mo performance to inform choice of div/CS PFC in Upgrade
- Apply Li (LiTER) to IBD/OBD Mo for partial/full LLD
- If LLD present, LSN with both strike-points on Mo (how different than C?)



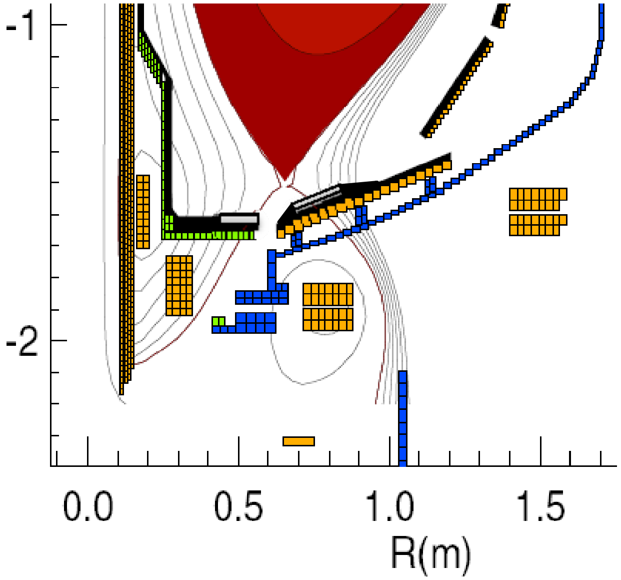
Standard divertor on C



Standard divertor on Mo



Snowflake on Mo (also possible on C, not shown)



LSN strike-pts on Mo, Mo + Li, or C (IBD) + Mo (OBD) (not shown)

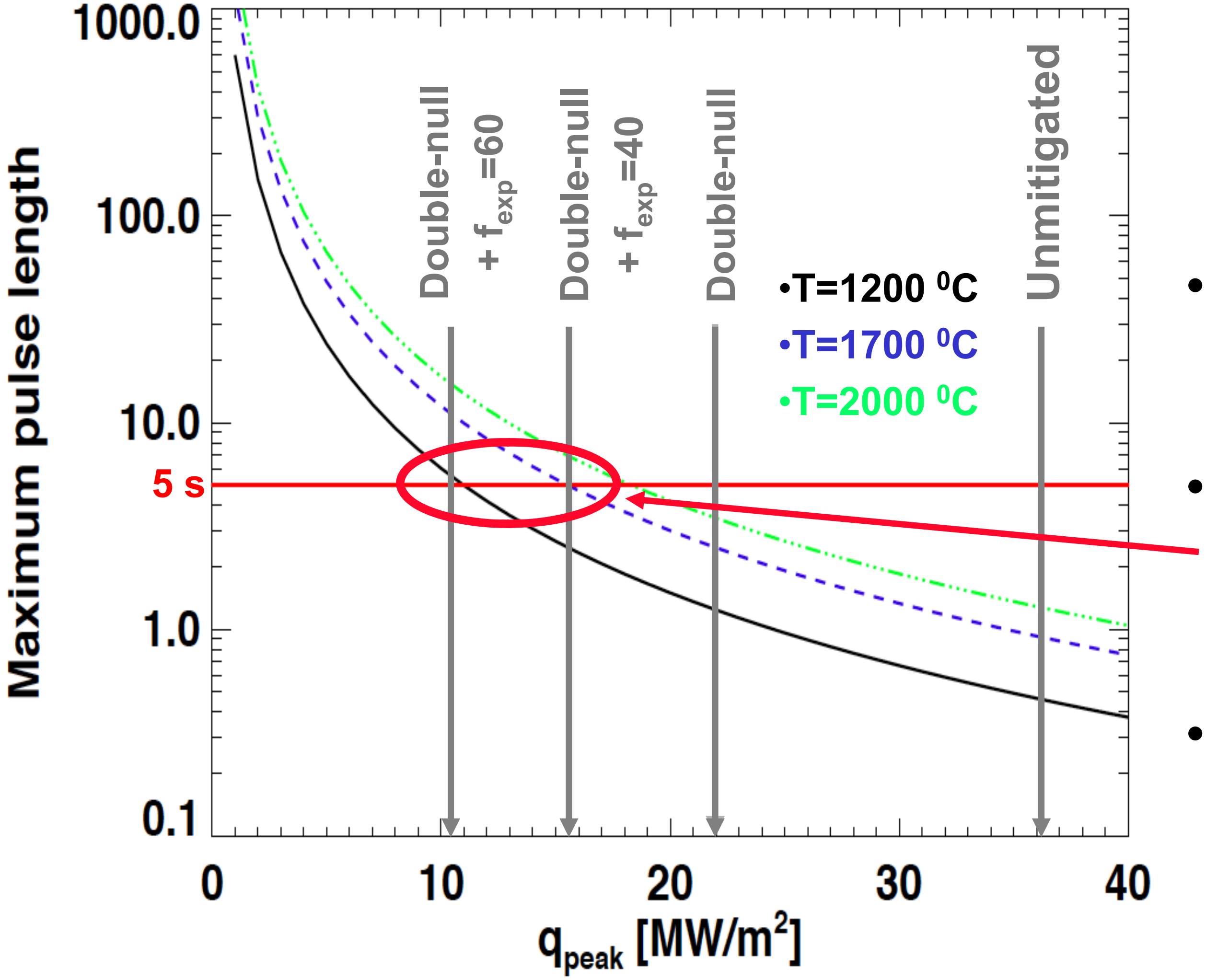
Success of Mo as PFC during LLD experiments supports usage of Mo inboard divertor tiles during FY2011-12 runs

- Motivation, potential benefits of inboard Mo tiles:
  - Reduce C impurity influx from divertor
    - Carbon dominates Z_{eff} in NSTX long-pulse ELM-free Li-conditioned shots
  - Informs choice of C or metallic divertor in NSTX Upgrade
    - Baseline CS upgrade design has all C PFCs – Mo may be advantageous
  - First test of inboard LLD – benefit from higher LiTER replenishment
  - Expected to improve CHI via reduction in C, O impurity content

- Risks, issues:
  - High-Z accumulation/radiation possibly worse, especially if ELM-free
    - May need to use central RF heating, ELM pacing, PDD, snow-flake
  - May need to eliminate all C PFCs to eliminate C from plasma (AUG)
  - Tile alignment critical (plan to improve C tile alignment for FY11-12)

- Design: replace outer-most row of inboard C divertor tiles with Mo

High current 2 MA, high P_{NBI} scenario requires extra flux expansion for full pulse length with existing tiles

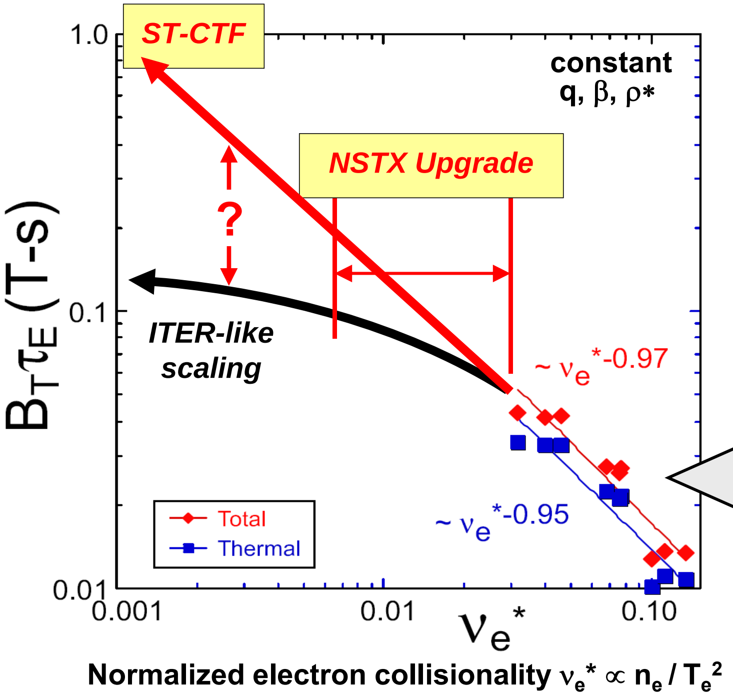


$f_{div}=0.5$, $\lambda_q^{mid} = 3$ mm

- **High-current 2 MA LSN,**

  P =15 MW (10MW NBI + 5 MW RF)
- **Using DN and increasing flux expansion (e.g. SFD) would just manage for 5s**
- **Molybdenum tile for higher temperature being pursued for 2011-2012**

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



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

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?

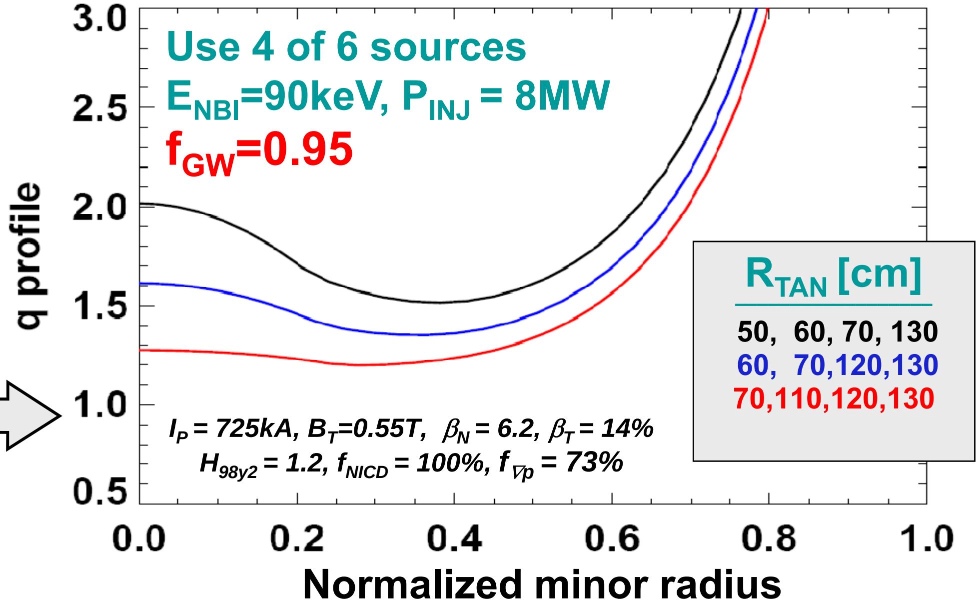
- ν^* also impacts RWM stability, rotation damping, range of other physics

- Higher toroidal field & plasma current enable access to higher temperature
- Higher temperature reduces collisionality, but increases equilibration time
- Upgrade: Double field and current + 3-5× increase in pulse duration to substantially narrow capability gap → 3-6× decrease in collisionality

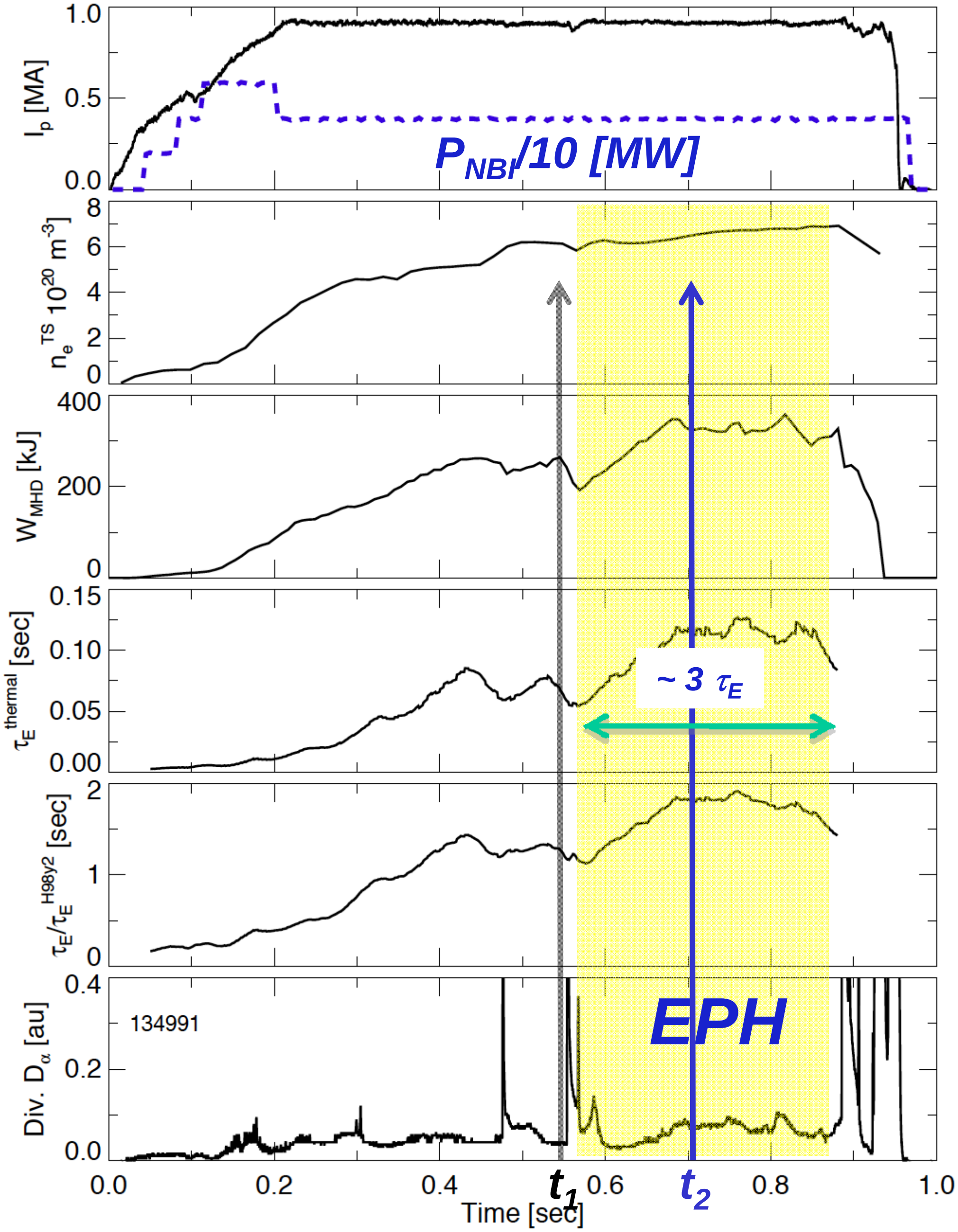
Increased auxiliary heating and current drive are needed to fully exploit increased field, current, and pulse duration

- Higher heating power to access high temperature and β at low collisionality
  - Need additional 4-10MW, depending on confinement scaling
- Increased external current drive to access and study 100% non-inductive
  - Need 0.25-0.5MA compatible with conditions of ramp-up and sustained plasmas
- Upgrade: double neutral beam power + more tangential injection
  - More tangential injection → up to 2 times higher efficiency, current profile control
  - ITER-level high-heat-flux plasma boundary physics capabilities & challenges

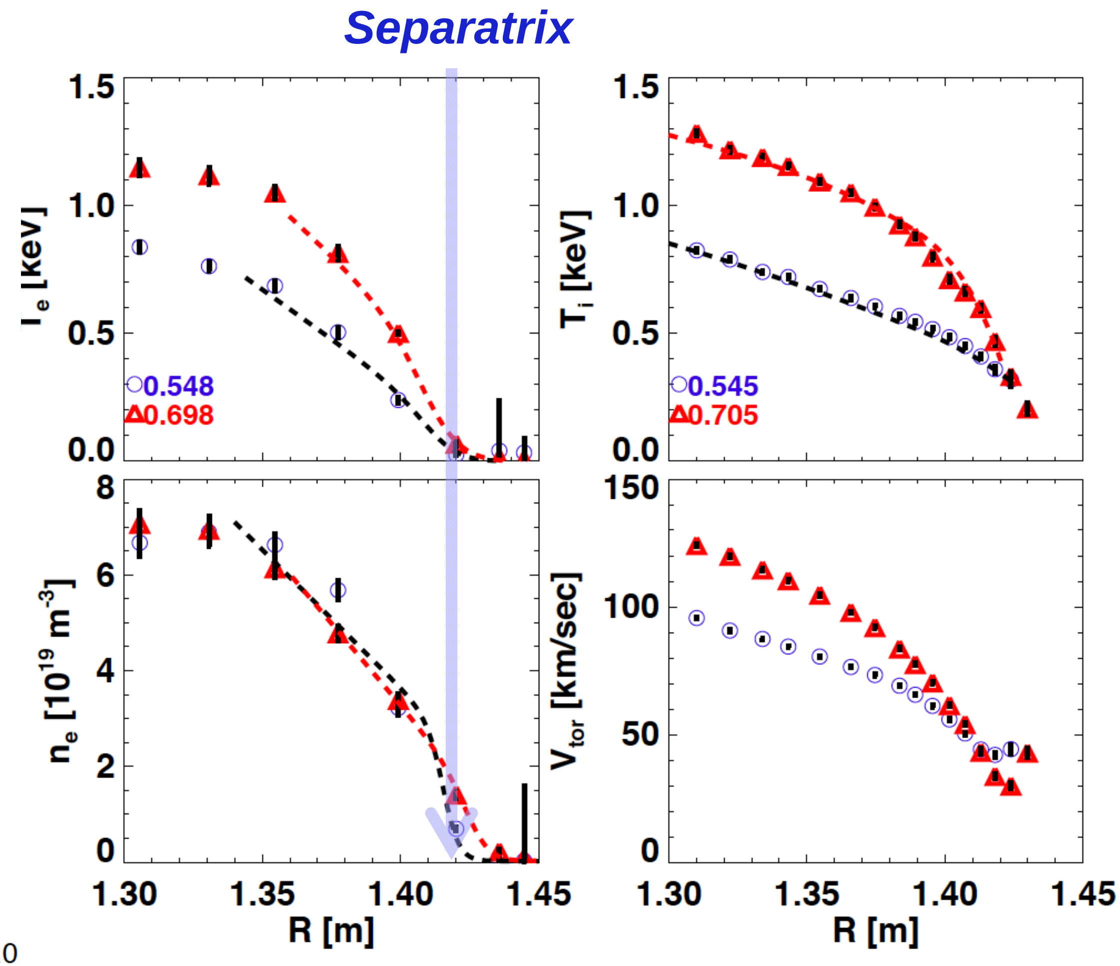
- q(r) profile very important for global stability, electron transport, Alfvénic instability behavior
  - Variation of mix of NBI tangency radii would enable core q control



High Confinement H-Mode Regime Obtained with Lithium
~ High Performance ST Pilot Plant level Confinement of H98y2 $\leq$ 1.7



- *Specially high* ***H98y2 $\leq$ 1.7*** *is a combination of lithium confinement improvement and higher pedestal temperatures / pressure*
- *ITER performance is highly pedestal pressure dependent, Q ~ P^2*



IAEA: R. Maingi, PRL 2010

Kinetic high beta RWM stability model tested

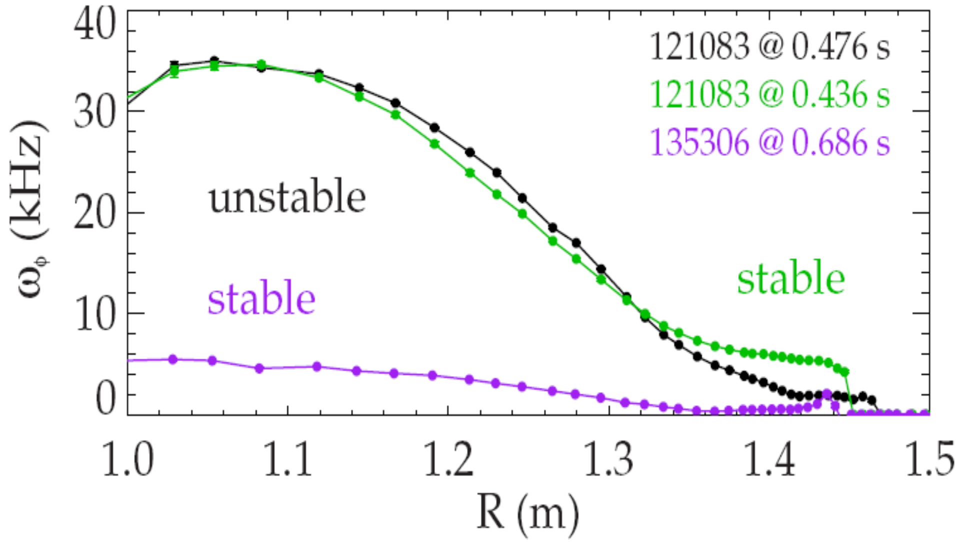
Resolved some RWM (Resistive Wall Mode) stability puzzles

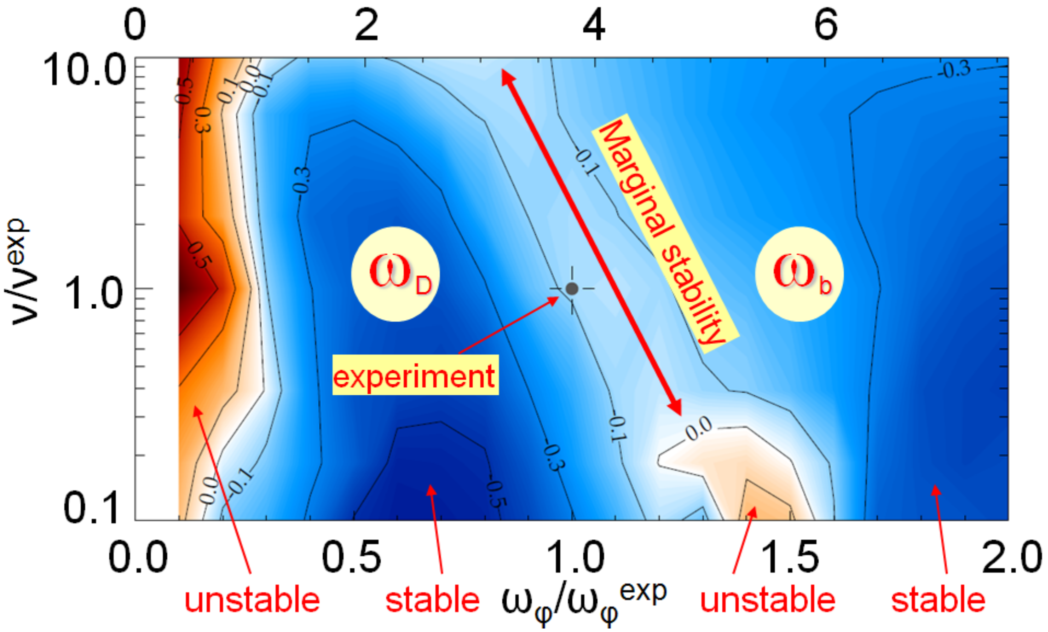
- ***Observed that RWM can be unstable despite significant plasma rotation contrary to fluid-based theory***

- ***Obtained detailed measurements of RWM stability dependence on toroidal rotation to validate kinetic stability MISK models****

- ***MISK code predicts stabilization of RWM from***
  - ***precession drift resonance (ω_D) at low rotation***
  - ***bounce resonance (ω_b) at high rotation***
- ***Plasma is marginally unstable at intermediate rotation***

•Theory enhancements may lead to a unified model explaining NSTX / DIII-D observations having important implications for ITER: RWM can be unstable at expected rotation (advanced scenario 4)

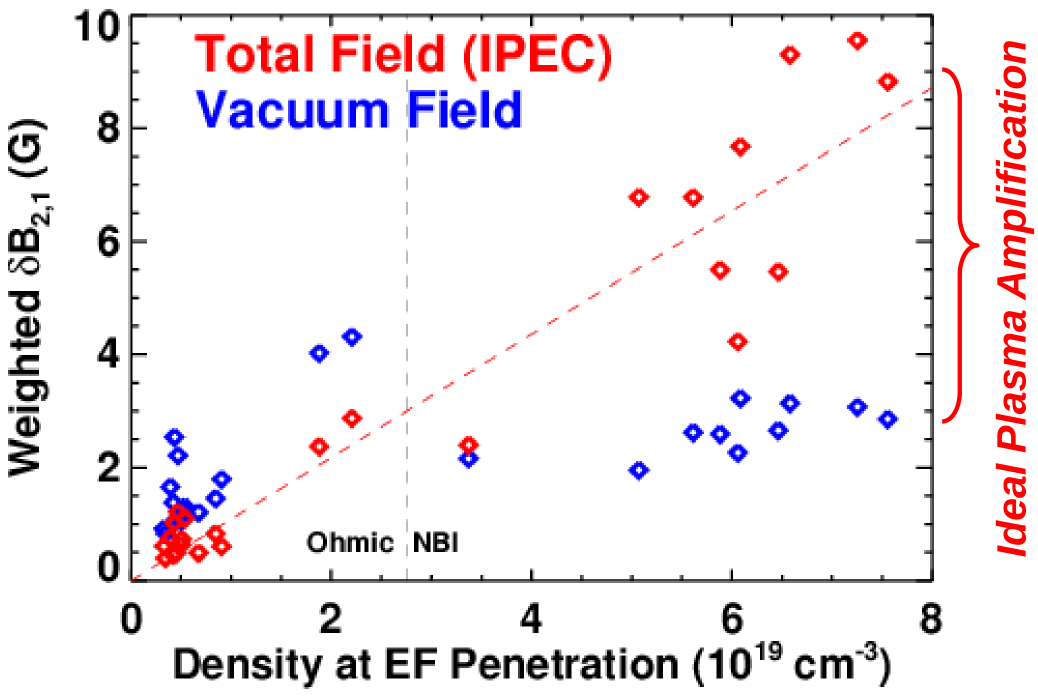




J. Berkery, PRL (2010)

Inclusion of Plasma Response Important to Understanding Effects of Error Fields

- Measure dependence on the line-average density of resonant 2/1 amplitude at q = 2 surface at which mode locks
- Ohmic L-mode plasmas at low density show familiar proportional dependence
- Linear scaling with density breaks down in high-density, high-β NBI-heated plasmas
  - mode locks at anomalously low error field
- Linear scaling is restored when plasma amplification of applied field included
  - Plasma response is calculated by IPEC



- ***IPEC: Ideal Perturbed Equilibrium Code***
  - ***Computes tokamak ideal plasma response to 3D perturbed magnetic fields***

- ***IPEC being utilized for***
  - ***RMP coil design for ITER, DIII-D, JET***
  - ***Error-field correction for ITER***

•IAEA: J-K. Park, A. Boozer, J. Menard