NSTX

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NSTX FY2011-12 Research Program Overview

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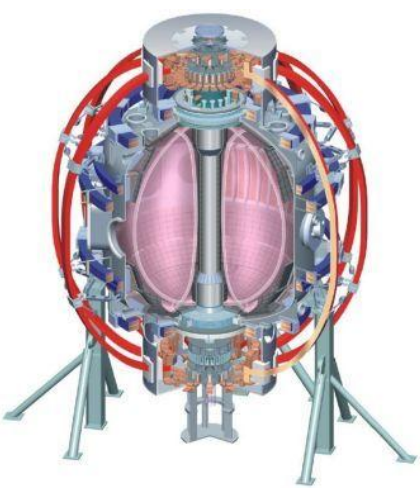
J. Menard, PPPL

For the NSTX Research Team

NSTX FY2011-12 Research Forum

Plenary Session

Tuesday March 15, 2011



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U Quebec

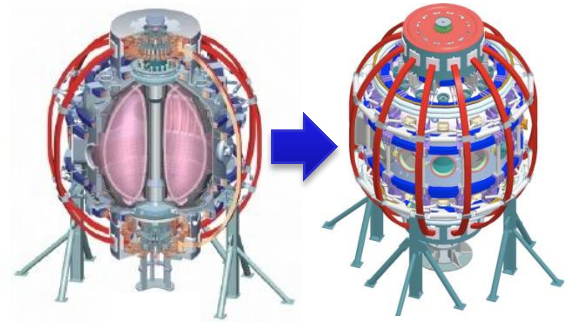
Outline

- NSTX Mission
- Organization
- Prioritization
- Run Time Guidance
- FY10 Highlights → FY11-12 Milestones and Priorities
- Forum Action Items for TSGs, Run Coordination

Forum web site: http://nstx-forum-2011.pppl.gov

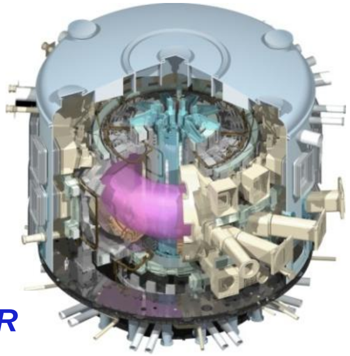
NSTX Mission Elements

- **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*

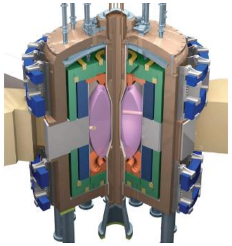
- **Extend understanding of tokamak / ITER**
  - Develop predictive capability for ITER/FNSF/Demo



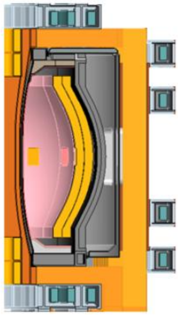
ITER

- **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

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*

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
- Consider ITER urgent needs identified directly from IO, and other unique contributions NSTX can provide to ITER
  - ITER/CC TSG can/will forward proposals to other TSGs as needed
- For NSTX and NSTX Upgrade:
  - Assess methods and coordinate experiments for particle and impurity control for NSTX and Upgrade
    - FY11-12 goal: assess *combinations* of impurity control techniques
  - Support and coordinate cryo-pumping calculations for Upgrade
  - Coordinate ELM research (have coherent program, avoid overlap – R. Maingi)
- **Dominant theme of TSG is particle and impurity control**

Some programmatic considerations for XP prioritization

(in approximate priority order)

- Viability of proposal given available NSTX capabilities
- OFES Joint Research Milestones
- NSTX Research Milestones
  - Annual milestones + other ST high priority research
  - NSTX-Upgrade design needs – expected high priority:
    - Particle and impurity control for long-pulse
    - Heat flux mitigation strategies – high flux expansion, detachment
    - Upgrade diagnostic & facility design (high-k, cryo-pumps, LLD-2, NCC, …)
    - Disruption diagnosis, characterization, forces, preliminary mitigation
- ITPA – especially where NSTX is lead/prominent experiment
- Experiments leading to high-profile publications/presentations:
  - PRL, Science, Nature / Invited talks: IAEA, APS, EPS, Sherwood, …
- Career development: PhD thesis, post-doctoral research
- Any good idea generated during run – potential 'break-thru'?

Run-time guidance for FY2011-2012 run

- Highest priority: OFES Joint Facility and NSTX Research Milestones
- TSGs should prioritize FY11 and FY12 XPs separately (into 1st, 2nd priority)
  - TSGs **NOT** guaranteed to receive full allocation - will be decided at mid-run assessment(s)
- Most important for near-term is to determine which XPs must run in FY11

Total weeks (FY11+12)	**24**
Total days	**120**
XMP - operational CC & enabling:	**(estimated)**
Days for characterizing incremental Li introduction + possible boronization	2
Control system development	3
Mo tile performance characterization	2
Calibration: magnetics, MSE, other	2
HHFW conditioning	4
Other XMP TBD	2
Program reserve	2
Total XMP + reserve	17

PCS-related commissioning XMPs
Proportional RWM controller for 6 SPAs
LQG RWM controller for 6 SPAs
Improved dZ/dt detector for vertical position control.
PCS V-nominal software upgrade for shape control.
Checking the betaN controller upgrades for correct functionality
Other new control jobs (snowflake, density control,...)

Days available **103**

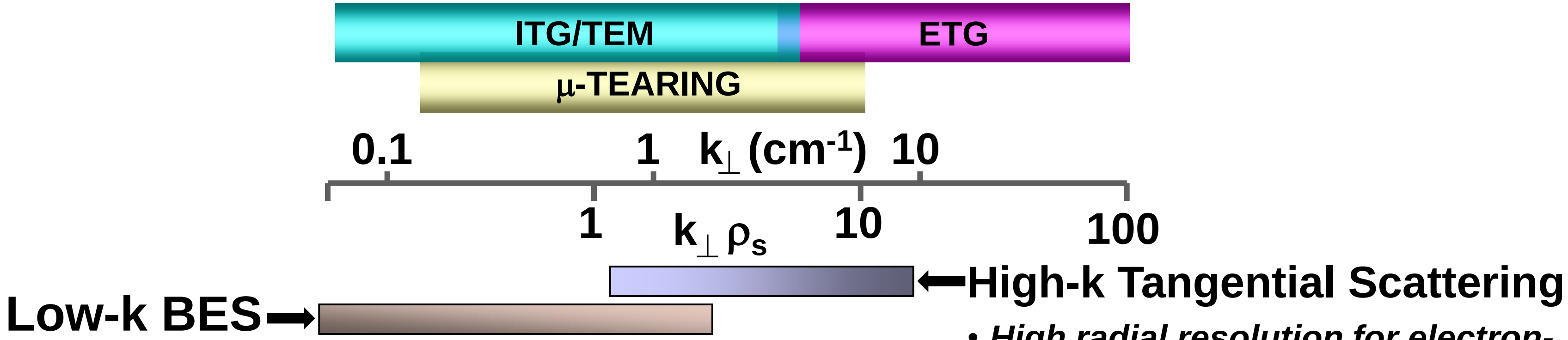
Priority 1 fraction: **0.75**

TSG	Milestones	FY11+12 1st + 2nd priority XPs (total)	FY11 run days already used	FY11 weighting (remaining run time)	FY12 weighting	FY11+12 1st + 2nd priority	FY11 1st + 2nd priority	FY12 1st + 2nd priority	FY11 1st priority	FY12 1st priority	FY11+12 1st priority
Advanced Scenarios and Control	R12-3	12	2.5	0.4	0.6	9.5	4.0	5.5	3.0	4	7
Boundary Physics	FY11 JRT, R11-3	16	2.7	0.7	0.3	13.5	9.5	4.0	7.0	3.0	10.0
ITER urgent needs & cross-cutting	R11-4	12	3.5	0.6	0.4	8.5	5.0	3.5	4.0	2.5	6.5
Lithium Research	R12-1	12	1.6	0.4	0.6	10.5	4.0	6.5	3.0	5.0	8.0
Macroscopic Stability	R11-2	12	0.6	0.6	0.4	11.5	7.0	4.5	5.5	3.5	9.0
Solenoid-free Start-up and Ramp-up	R12-2	12	2.5	0.4	0.6	9.5	4.0	5.5	3.0	4.0	7.0
Transport and Turbulence	FY12 JRT, R11-1	16	5.9	0.5	0.5	10.0	5.0	5.0	4.0	4.0	8.0
Waves and Energetic Particles	R12-2 (w/ SFSU)	11	1	0.4	0.6	10.0	4.0	6.0	3.0	4.5	7.5
Total		**103**	**20.3**			**83.0**	**42.5**	**40.5**	**32.5**	**30.5**	**63.0**

TSGs should solicit/develop XPs to support early FY2011-12 operation, obtain data for design of post-Upgrade systems

- Support and prepare for early FY2011-12 operations:
  - Assess performance of new Mo tiles – impurity influx, thermal response, melting
  - Incremental introduction of Li for wall conditioning, small ELM scenario access
  - Early HHFW operations to assess coupling/heating with minimal lithium
- Data for design of post-Upgrade systems during outage:
  - Boundary Physics, Lithium Research
    - LiTER evaporation extrapolation to 5s pulses, choice of PFCs, cryo-pumping and next-gen LLD design, divertor diagnostics, fueling requirements and systems,
  - Transport and Turbulence
    - Design of new high-k system, other turbulence diagnostics
  - Solenoid-free start-up
    - CHI capacitor bank and voltage snubbing upgrades, new diagnostics
  - Waves and Energetic Particles
    - Assess 6 or 8 strap antenna, CAE and/or EHO antenna, EP diagnostics (SSNPA?)
  - Macroscopic Stability
    - RWM/EF control, NCC for RWM/RMP/TM/EFC/NTV/TAE/EHO, disruption mitigation
  - Advanced Scenarios and Control
    - rt-rotation, rt-MSE, control algorithms for J profile, particle and power handling

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

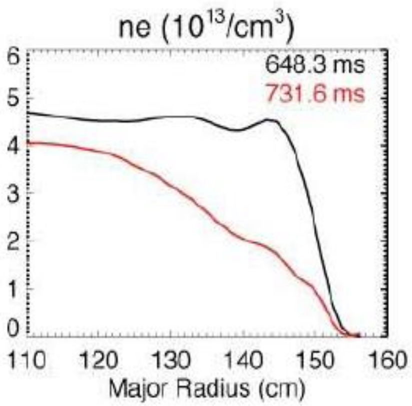


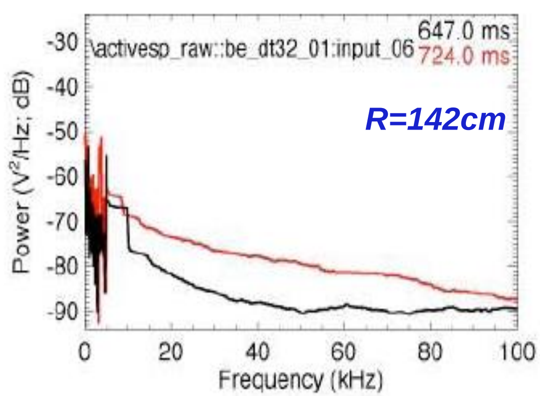
(Beam Emission Spectroscopy)

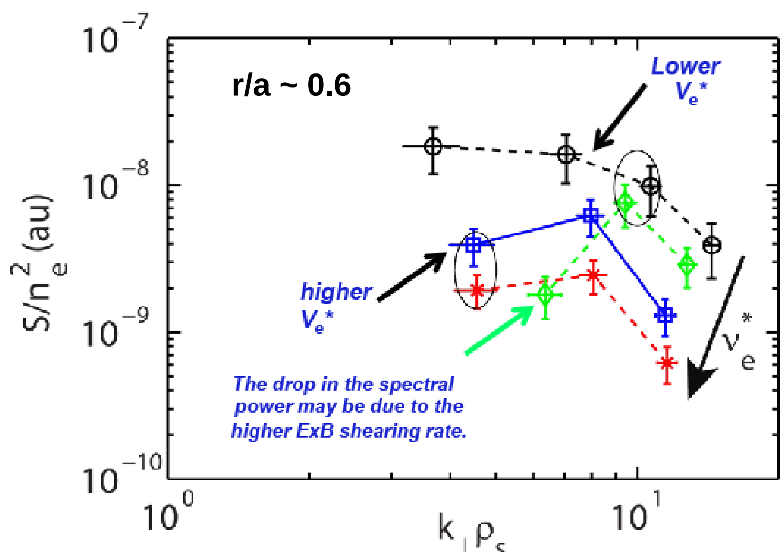
- *High radial resolution for electron-gyro-radius scale turbulence ($f \leq 3MHz$)*

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

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







- ***BES also contributing to energetic particle research***

•D. Smith, U. Wisconsin

•Y. Ren, PPPL

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

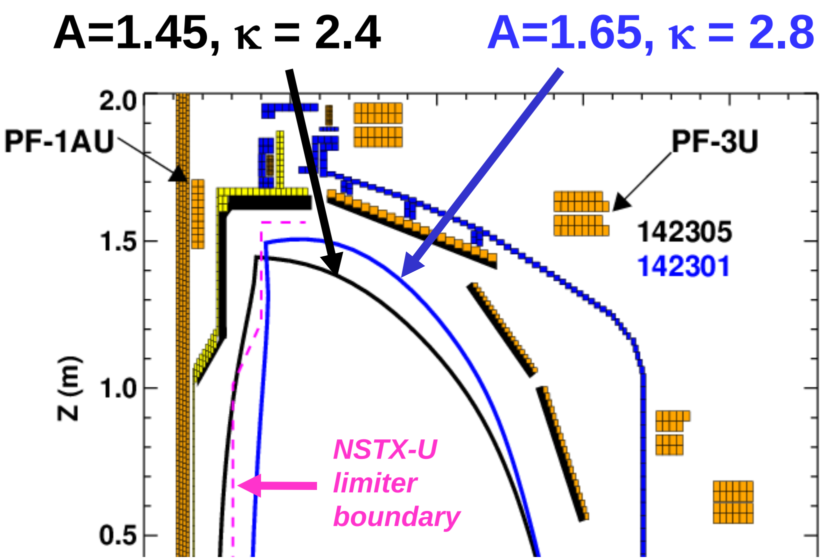
- High-k scattering measurements have identified ETG
- Low-k fluctuations (micro-tearing, ITG/TEM) and fast-ion-driven modes, e.g. GAE, may also contribute to e-transport.

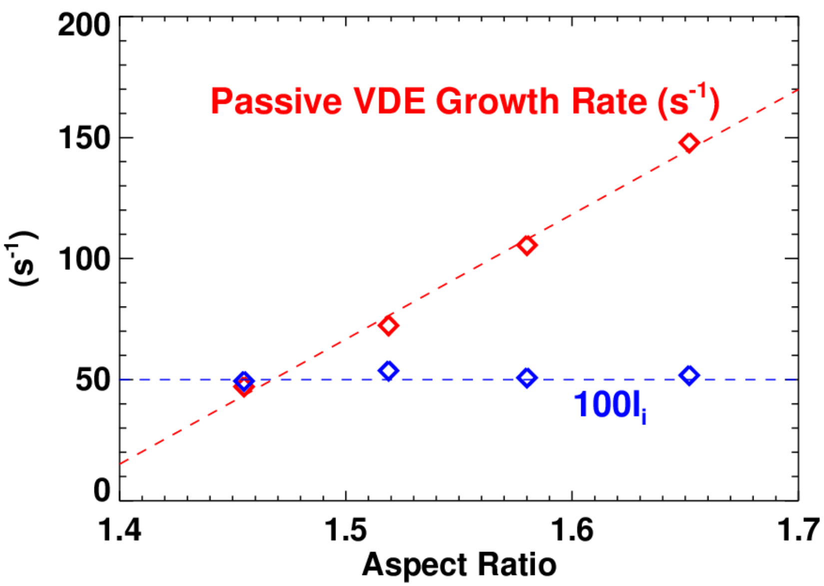
- Low-k fluctuations may also contribute significantly to momentum, ion thermal, and particle/impurity transport
  - Turbulence and *AE radial eigenfunctions will be measured with BES
  - Turbulence will also be measured w/ reflectometer, interferometer, GPI

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

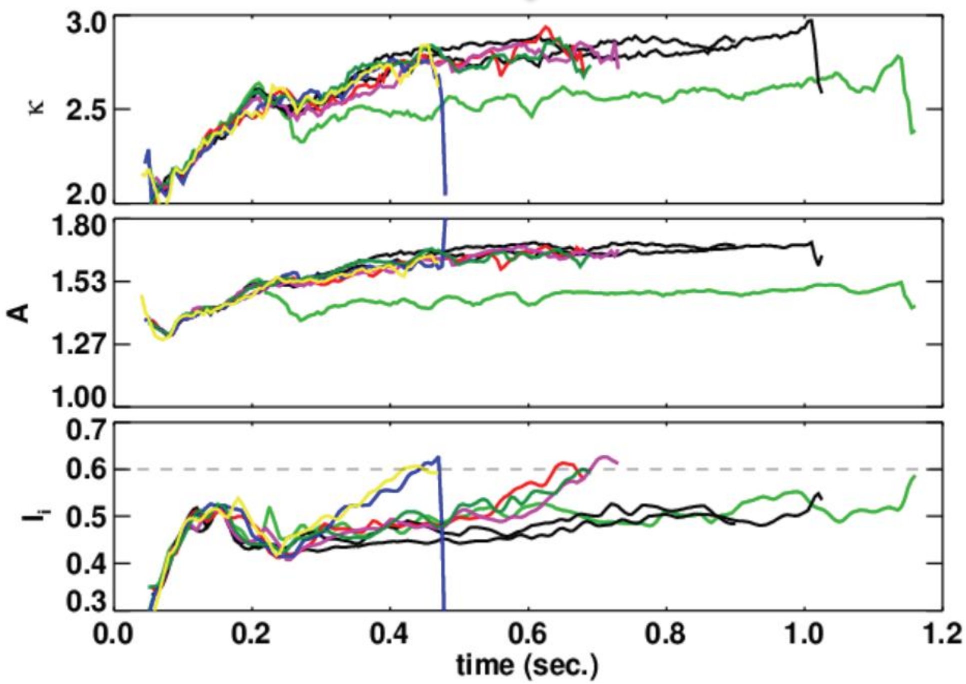
- Particle/impurity transport expts will use gas puffs, density measurements, low-to-high-k δn measurements, edge SXR

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

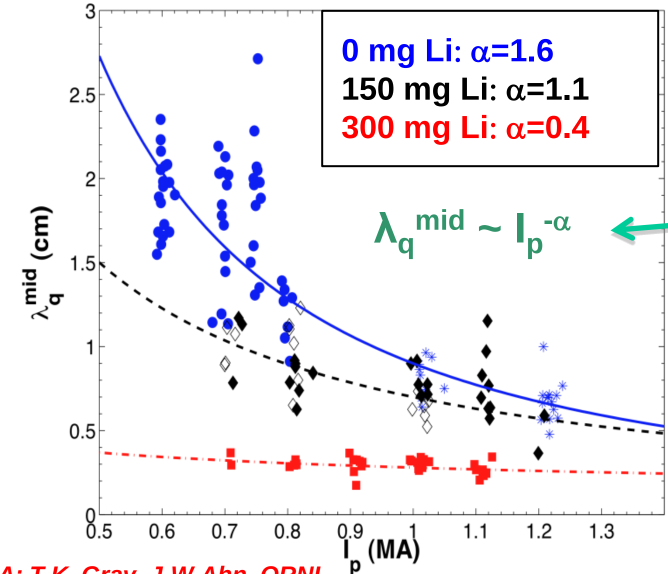


•S. Gerhardt, E. Kolemen - PPPL

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

- 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

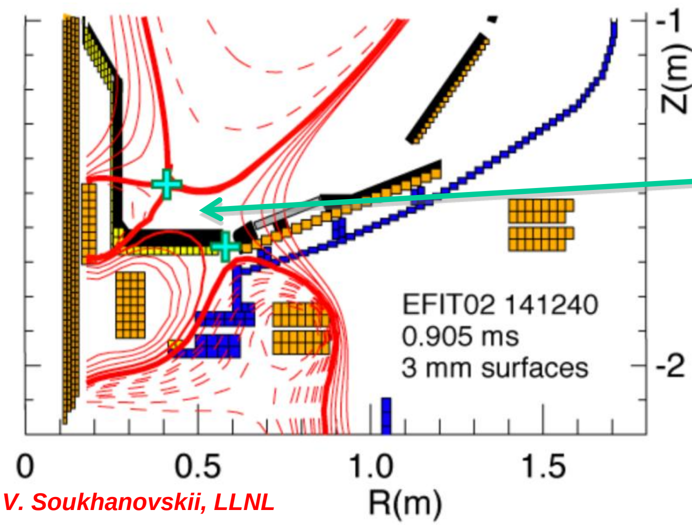


IAEA: T.K. Gray, J-W Ahn, ORNL

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

- 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/m²**



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/m² in Upgrade at highest expected I_P = 2MA, P_{AUX}=15MW**

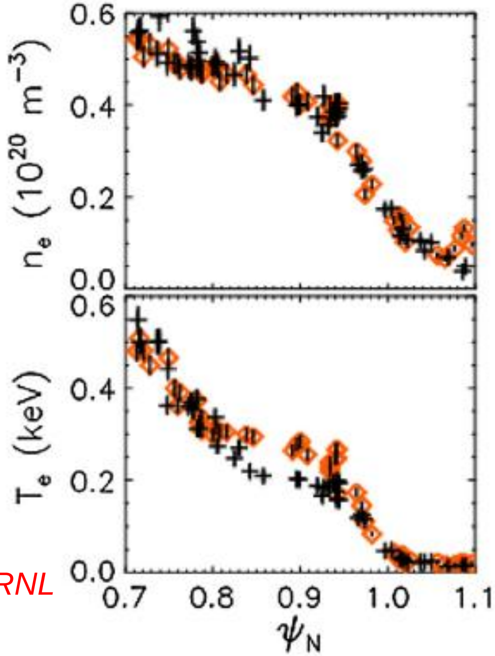
Boundary Physics Milestone R(11-3): Assess very high flux expansion divertor operation

- 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

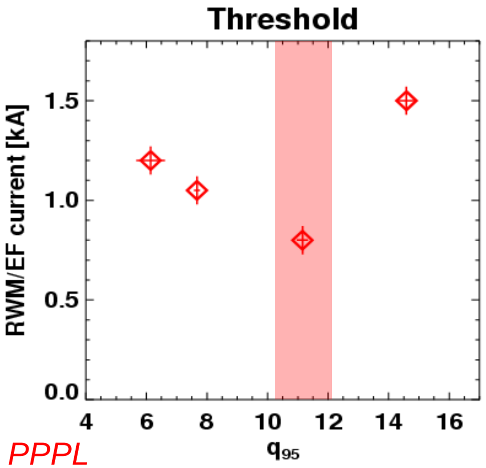
- ELMs stabilized by Li coatings
  - Edge density, pressure gradients reduced

- ELMs triggered by 3D fields, not suppressed
  - Small density change during n=3 3D fields
  - T_e and pedestal pressure increase → ELM



• J. Canik - ORNL

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



• J.-K. Park - PPPL

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

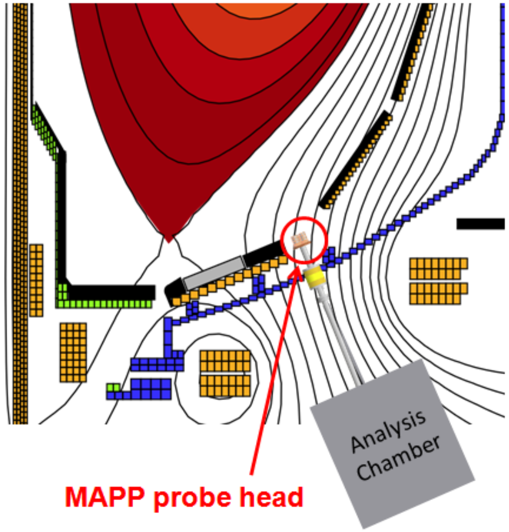
- **No evidence of Mo in plasma except from large ELMs, disruptions**
- **Chemistry of Li on C and LLD critical, complex, and under-diagnosed**

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

•J-P Allain, Purdue

- 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

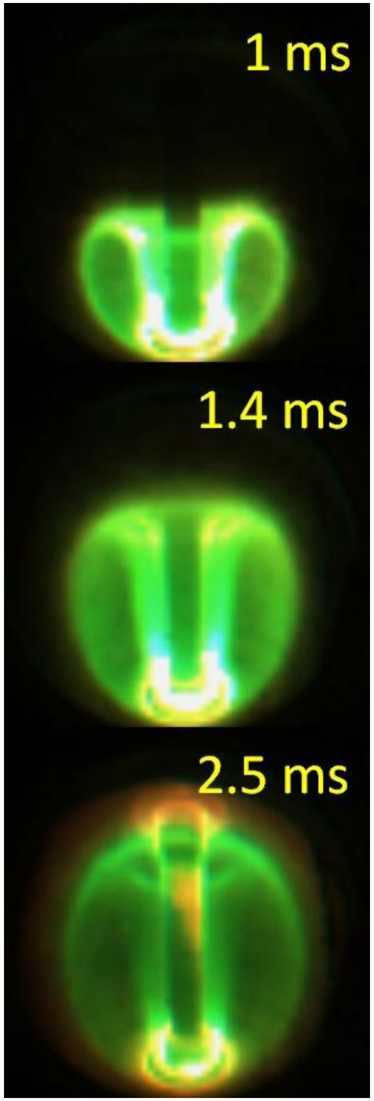


Scenarios/MHD Milestone R(12-3): Assess access to reduced density and collisionality in high-performance scenarios

- 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

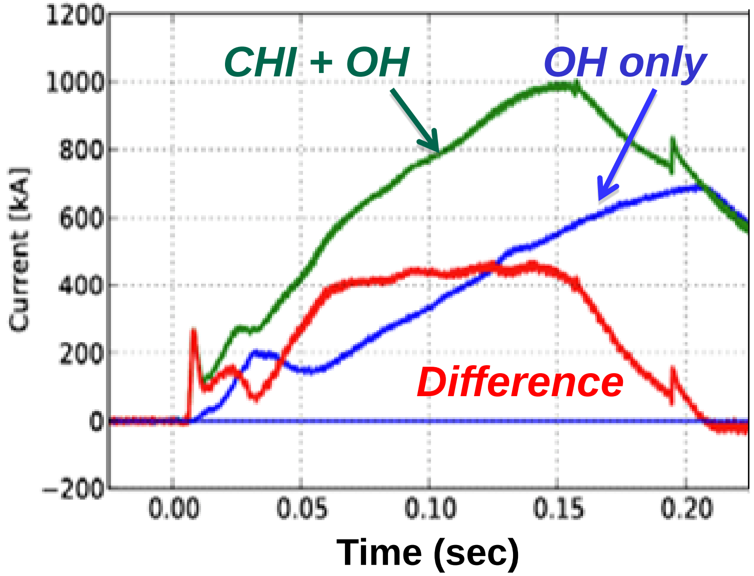
Time after CHI starts



- **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

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

- HHFW and early NBI heating will be used to:
  - Heat CHI → OH discharges to assess confinement/heating vs. non-CHI
  - Heat and drive current progressively earlier in target plasma to assess non-inductive sustainment

Waves and Energetic Particle Research for FY2011-2012

- Understand, develop high-harmonic fast-wave for heating, CD

  2010: HHFW generated 60% NICD at low I_P ~ 300kA with P_{RF}=1.4MW

  – 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
  – Use HHFW as tool in NBI H-modes

- Develop predictive capability for fast-ion transport by *AE

  2009-10: TAE-Avalanche induced neutron rate drop modeled successfully using NOVA and ORBIT codes

  – 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

Forum action items for TSG leaders, proposers, run coordination

- ✓ Actively solicit input from the entire team – experimentalists, modelers, and theorists – to develop an extensive but goal-relevant list of ideas and proposals
- Organize, listen, question proposal presentation and plans
- Develop a prioritized XP idea lists based on run-time guidance for use in planning FY2011-12 run
- Determine XMP topics and XMP run-time required to support high-priority XPs (see run-time guidance for initial XMP list)
- Forum summary session:
  - (Deputy) TSG leaders: Present brief summary of key experiments, full list of run time requested and allocated, ID any issues/problems, and provide prioritized lists of experiments
  - Run coordinator: Recap capabilities/milestones/run-time guidance, summarize # XPs and run-days requested, sketch out initial ops and first run-month, ID which XMPs/XPs need to be reviewed first

Backup

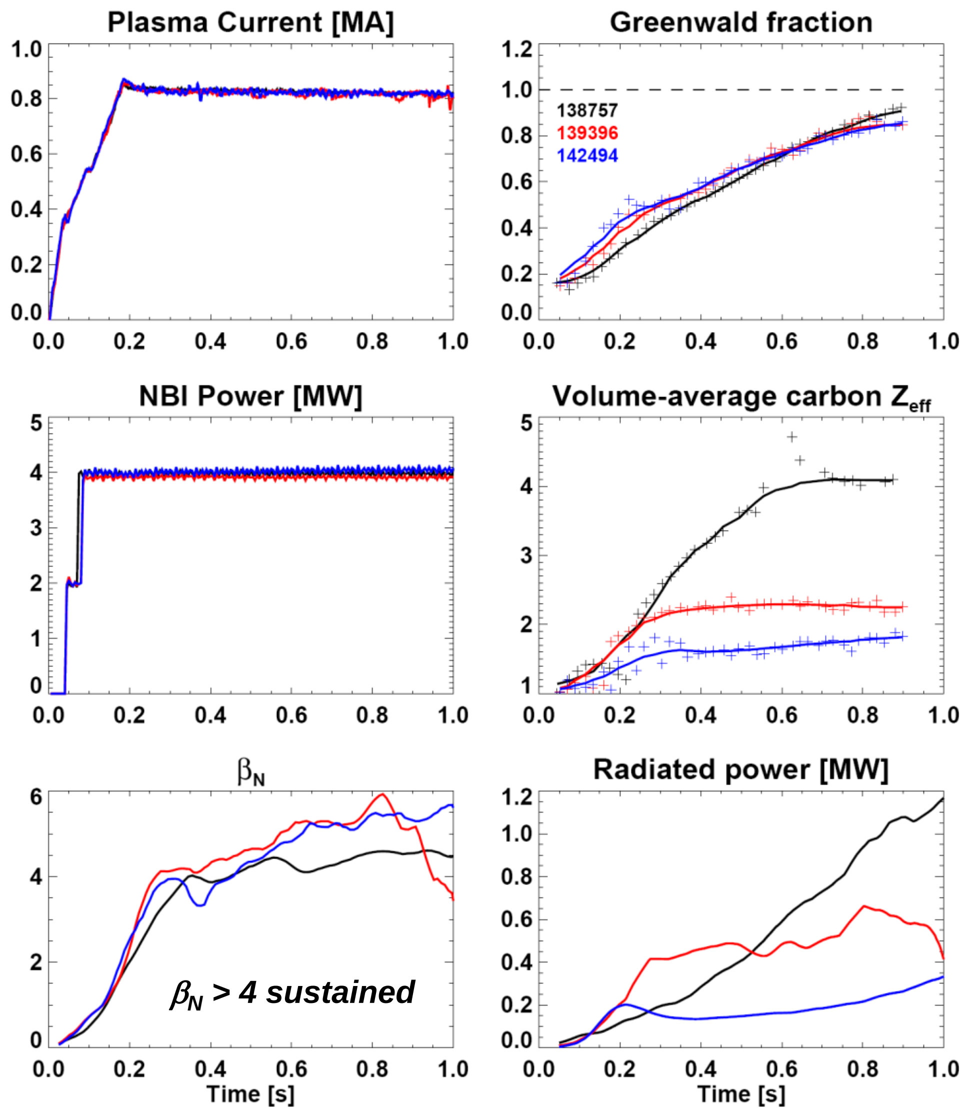
FY2011-12 NSTX research milestones
(base and *incremental*)

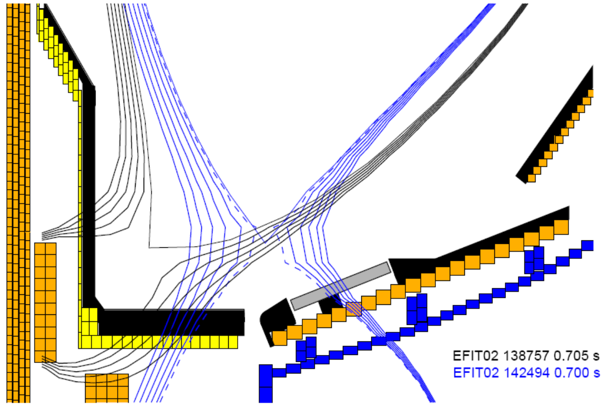
	FY2010	FY2011		FY2012
Expt. Run Weeks:	15 w/ ARRA	4	10	10

Research area	FY2011	FY2012
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 — 2^{nd} SPA, RWM state-space control **Assess ST stability dependence on aspect ratio and boundary shaping** (with ASC TSG)	IR12-1 — *Real-time rotation, 2^{nd} 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, 2^{nd} 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):	FY11 JRT — MPTS, MSE-LIF	FY12 JRT — BES, High-k
Understanding of divertor heat flux, transport in scrape-off layer	**Characterize H-mode pedestal structure**	**Understand core transport and enhance predictive capability**

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





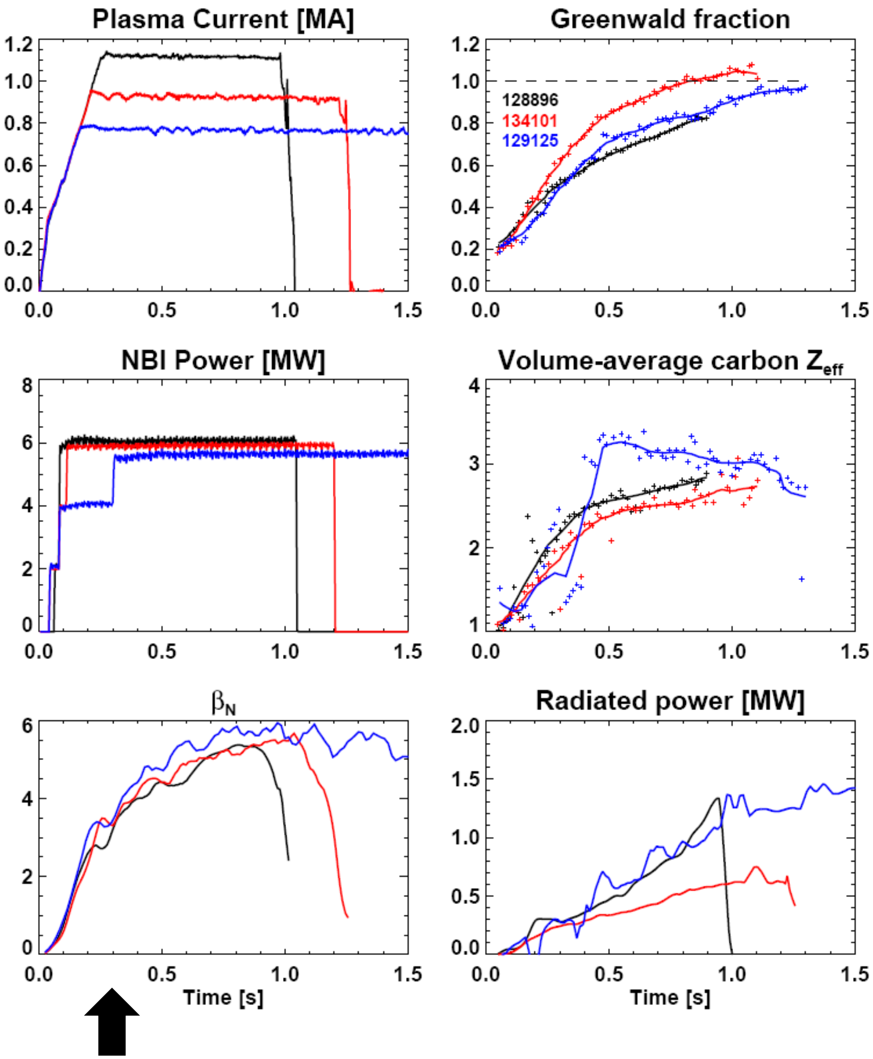
◀ **Strike-point (SP) on inner divertor**

- **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**
- **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**

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



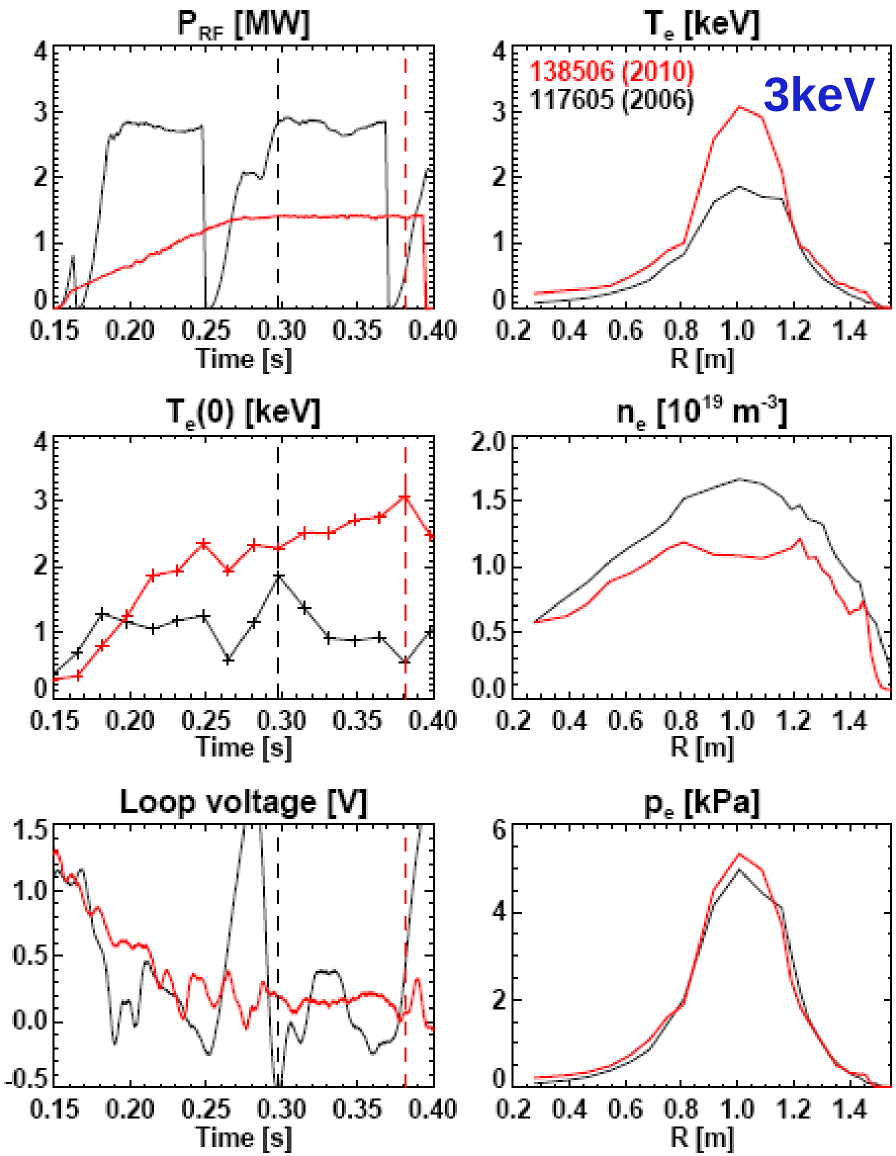
β_N = 5-6 sustained for ~1s – ready to assess stability at longer pulse-lengths in Upgrade

- NSTX long-pulse plasmas with ELMs approach density flat-top by t ~1s with $n_e / n_{Greenwald} \rightarrow 1$
  - 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

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

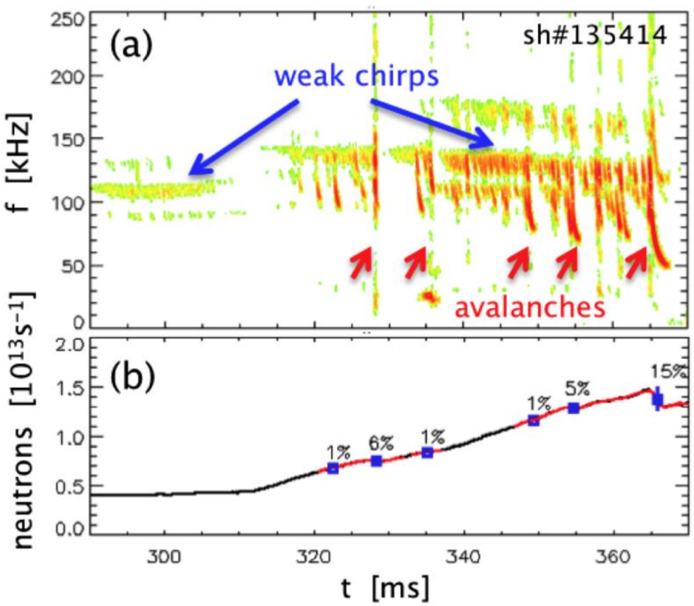
- Previous best at low I_P ~250kA was ~1.5keV at twice the power

- **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

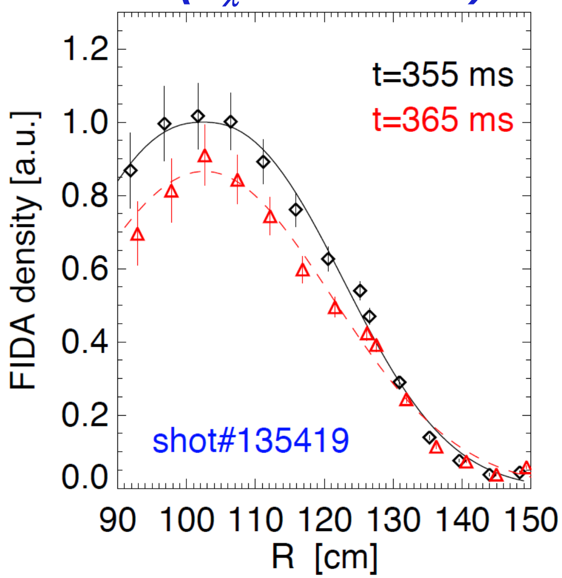
- **Non-inductive fraction 60-70% sustained (25-30% RF, 35-40% BS)**
  - FY11: Will re-try for ~100% non-inductive at P_{RF} = 3-4MW

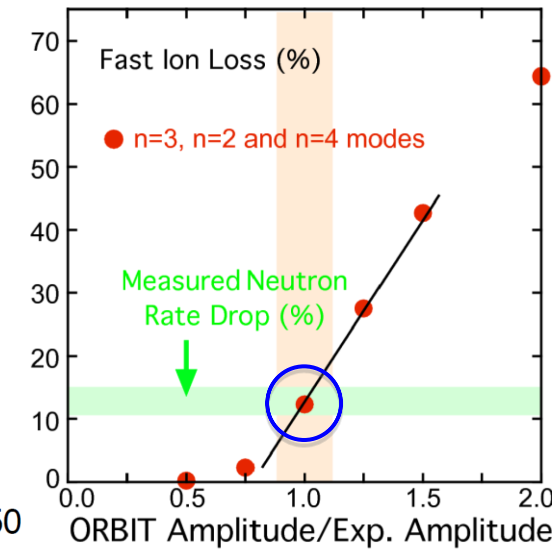
Pressure profiles are similar in both cases - profile stiffness?

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**

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