NSTX

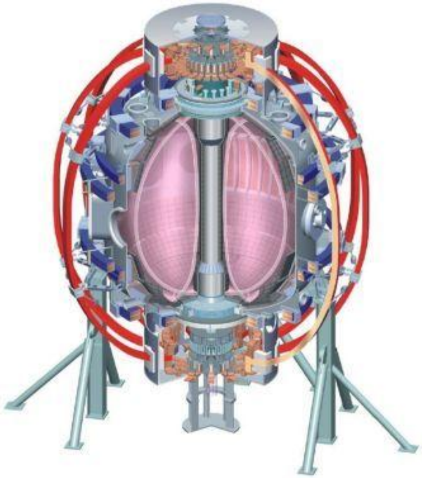
Supported by

U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX Research Plans for FY2011-13

J.E. Menard, PPPL
NSTX Program Director
For the NSTX Research Team

FY2013 FES Budget Planning Meeting
Germantown, MD
April 11, 2011



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

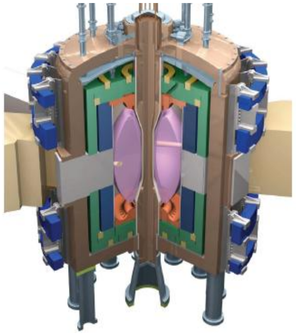
Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

Outline

- NSTX Mission
- Linkages to FNSF goals
- FY2011-12 Research Milestones
- Milestone Timelines
- FY2013 Plans
- Summary

NSTX Mission Elements

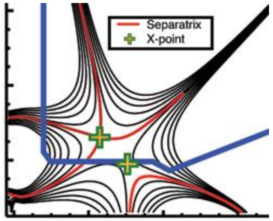
- **Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)**



ST-FNSF

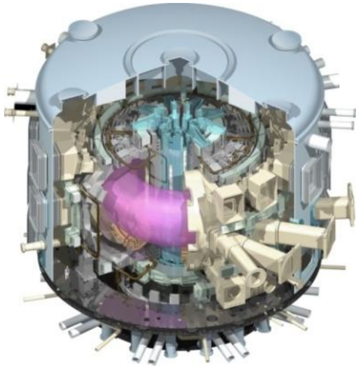
- **Develop solutions for plasma-material interface**

Lithium



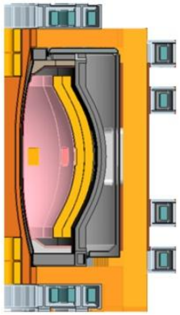
"Snowflake"

- **Advance toroidal confinement physics for ITER and beyond**



ITER

- **Develop ST as fusion energy system**



ST Pilot Plant

NSTX research goals and milestones strongly support development of basis for ST-based FNSF

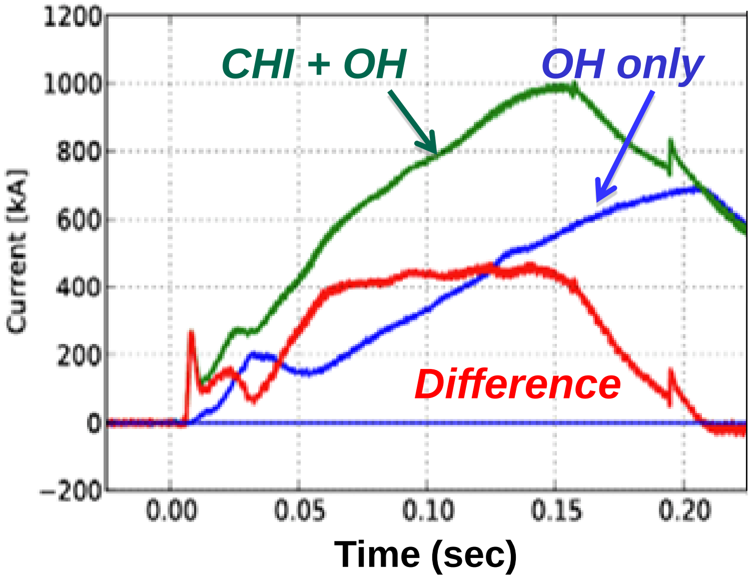
ReNeW Thrust 16: "Develop the ST to advance fusion nuclear science"
consists of 7 Thrust Elements:

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

These elements provide outline for subsequent FY11-13 plans

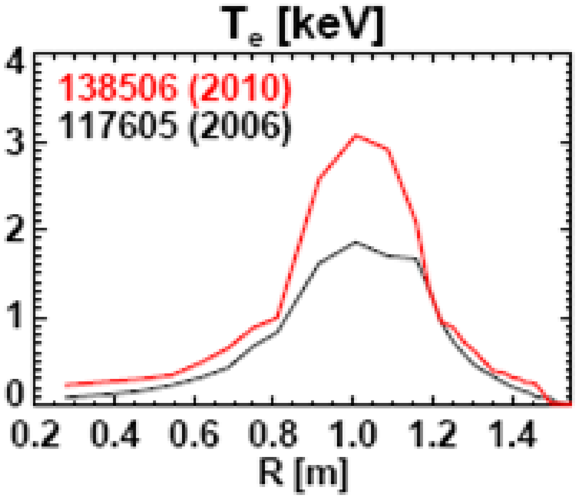
Achieved substantial progress on Coaxial Helicity Injection (CHI) and fast wave heating of low-current plasmas in 2010

- **Generated 1MA using 40% less flux than induction-only case**
  - Low internal inductance ($l_i \approx 0.35$), and high elongation > 2
  - Suitable for advanced scenarios



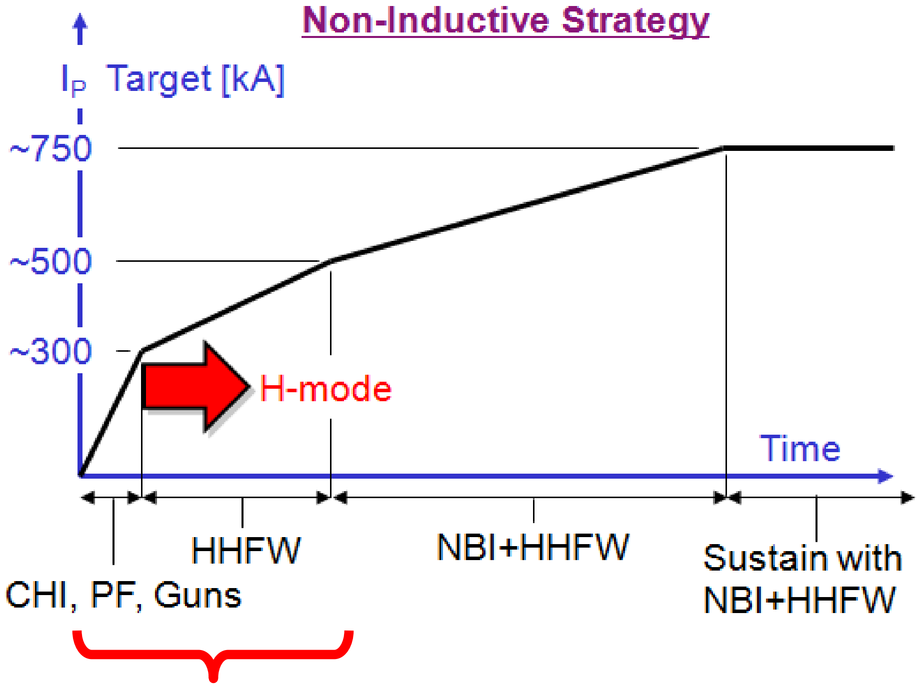
IAEA: R. Raman, B.A. Nelson U Washington

- **Achieved high $T_e(0)$ ~ 3keV at I_P=300kA w/ only 1.4MW of HHFW**
  - Previous best was $T_e(0)$ ~ 1.5keV at twice the RF power
  - Enabled by 2009 antenna upgrades



- **Non-inductive fraction ~60-70% with 25-30% from RFCD from high $T_e(0)$**
- **Projects to ~100% NI at P_{RF} = 3-4MW**
- **Will test further in 2011-12 run**

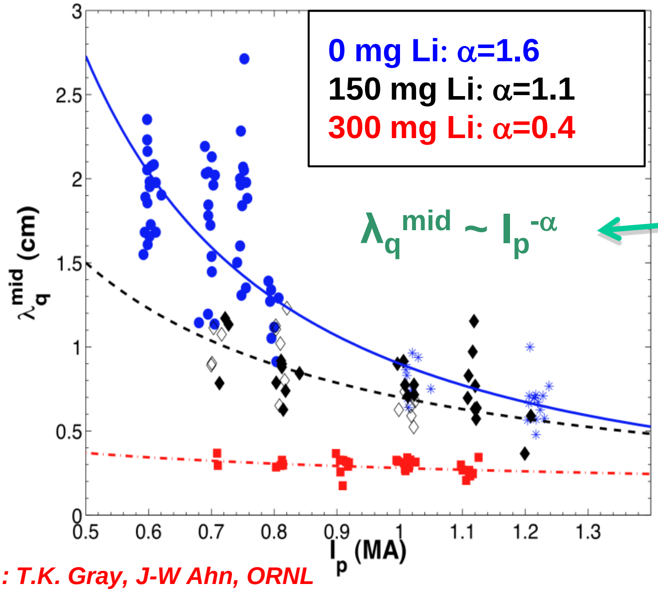
Plasma Start-up Milestone R(12-2): Assess confinement, heating, and ramp-up of CHI start-up plasmas



- **GOAL: develop ~0.3-0.4MA fully non-inductive start-up plasma for NBI-CD ramp-up to ~0.8MA in Upgrade → prototype ST-FNSF**
- FY12: HHFW & NBI heating & current drive will be used to:
  - Heat CHI → OH discharges to assess confinement vs. non-CHI
  - Heat and drive current progressively earlier in target plasma
  - Minimize/eliminate OH flux in CHI start-up, sustain with RF

NSTX has contributed strongly to divertor heat flux width studies*, and is developing new heat-flux mitigation methods

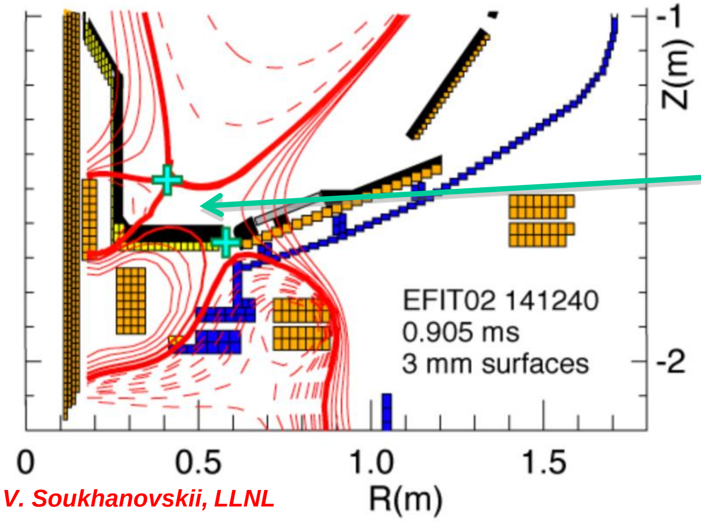
Joint Research Target (3 U.S. Facilities)



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

- Divertor heat flux width decreases with increased plasma current I_P
  - 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



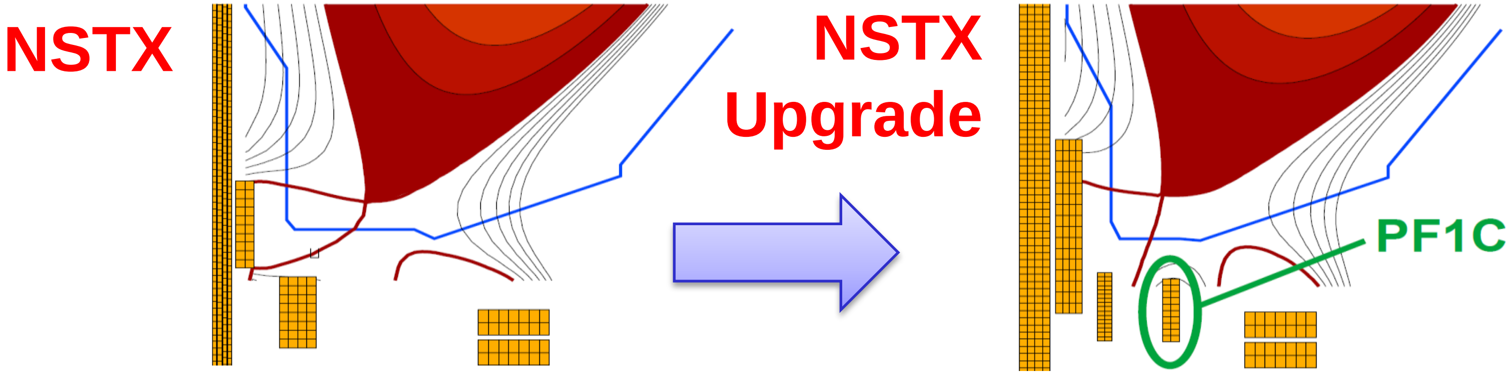
IAEA: V. Soukhanovskii, LLNL

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

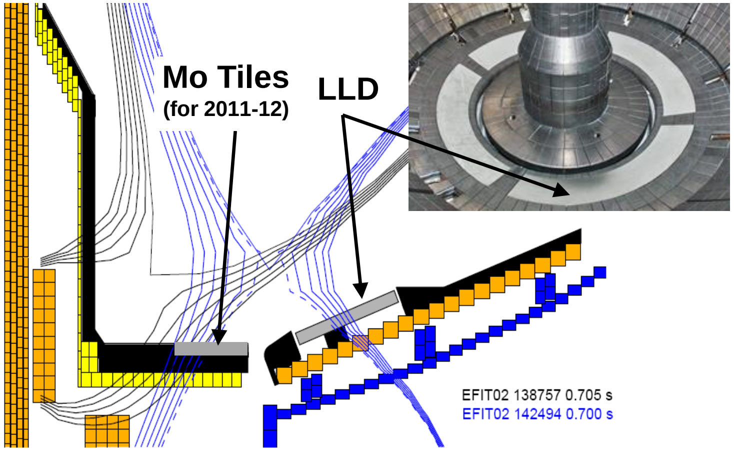
→ U/D balanced snowflake divertor projects to acceptable heat flux < 10MW/m² in Upgrade at highest expected I_P = 2MA, P_{AUX}=15MW

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

- 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
- Potential benefits of mitigation synergies will be assessed:
  - e.g. combining high flux expansion with gas-seeded radiation
- Additional PFs for U/L snowflake included in upgrade CS:
  - Provide independent control of strike-point location and flux expansion

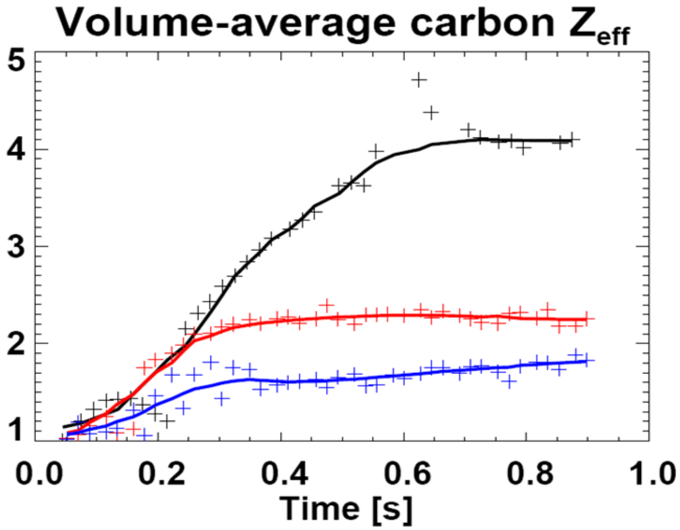


Operation with outer strike-point on Mo LLD (coated with Li) technically successful, achieved high plasma performance



LLD FY2010 results:

- LLD did not increase D pumping beyond that achieved with LiTER
  - Solid Li on C pumps D quite efficiently
  - C on LLD may have impacted D pumping
- No evidence of Mo from LLD in plasma during normal operation
- Operation with strike-point (SP) on LLD reduced core impurities



◄ SP on inner carbon divertor (no ELMs)

◄ SP on LLD, $T_{LLD} < T_{Li\text{-}melt}$

◄ SP on LLD, $T_{LLD} > T_{Li\text{-}melt}$ (+ fueling differences)

- **No ELMs, no → small, small → larger**

  → High-Z impurities also reduced, $\beta_N > 4$ sustained

Understanding roles of δ, C, Mo, Li, ELMs motivates Mo tiles on inboard divertor

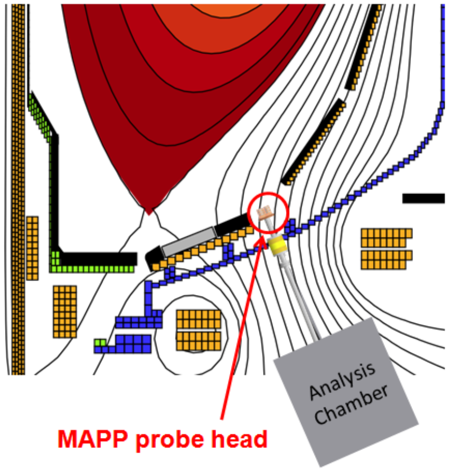
Lithium Milestone R(12-1): Investigate relationship between lithium-conditioned surface composition & plasma behavior

- Chemistry of Li on C/Mo critical, complex, under-diagnosed
- Li very chemically active → *prompt* surface analysis required to characterize the lithiated surface conditions during a shot

- An in-situ materials analysis particle probe (MAPP) being installed on NSTX to provide prompt surface analysis
  - 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 PFCs, gases
  - Correlation surface composition and plasma behavior, comparisons to lab experiments, modeling
  - Characterizations of fueling efficiency, recycling

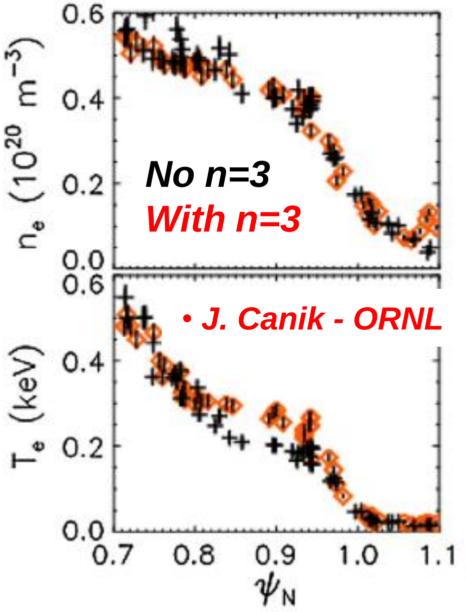
•J-P Allain, Purdue



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

NSTX provides unique data to understand response to 3D fields for ELM control:

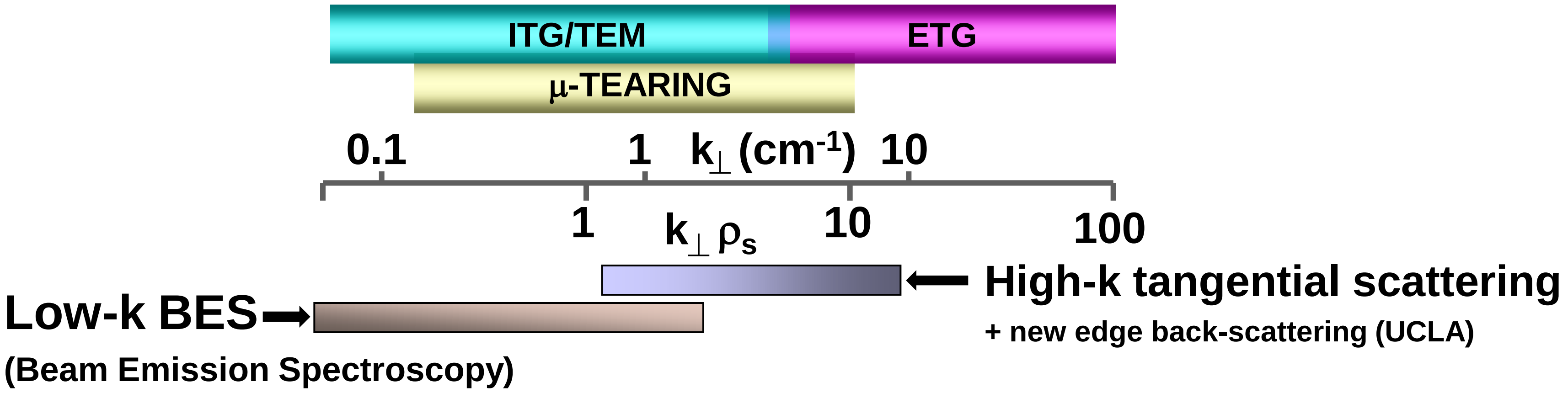
- ELMs stabilized by Li coatings
- ELMs <u>triggered</u> by 3D fields, not suppressed
  - Profile changes from 3D fields depend on Li, ν*, q_{95}



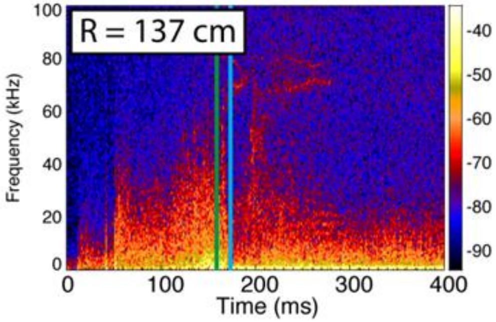
- J. Canik - ORNL

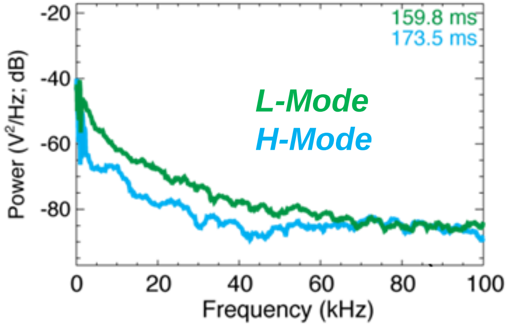
- Will study possible mechanisms for modifying transport
- Pedestal turbulence trends: BES, high-k scattering, gas-puff imaging
- Transport response: Improved Thomson, impurity injection, edge SXR
- **Supports 2011 JRT on H-mode pedestal structure**

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



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

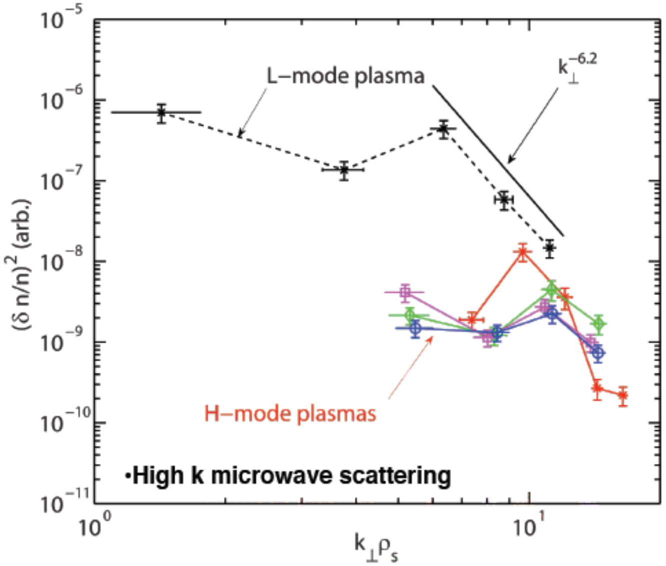




- *BES also contributing to energetic particle research*

•D. Smith, U. Wisconsin

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



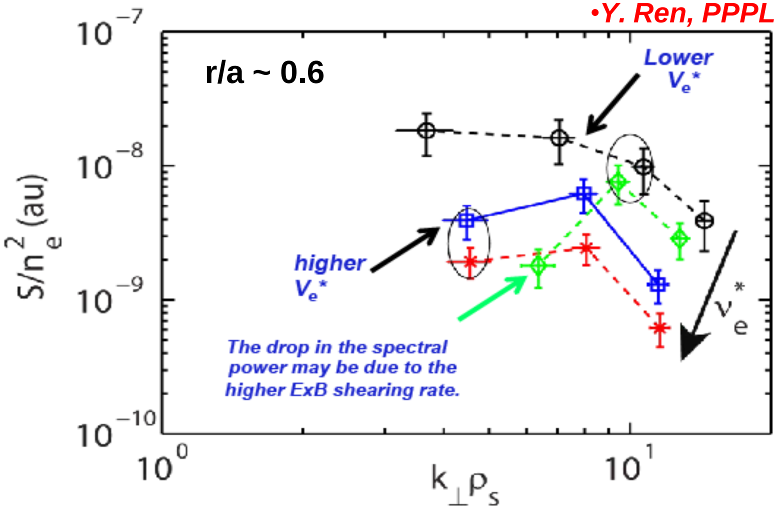
•Y. Ren, PPPL

NSTX is advancing the understanding of the collisionality scaling (i.e. 1/ν_{e*}) of ST normalized energy confinement

- New high-k scattering measurements show fluctuation levels apparently *<u>increase</u>* at lower ν*

- Inconsistent with ST global confinement scaling trends from NSTX, MAST

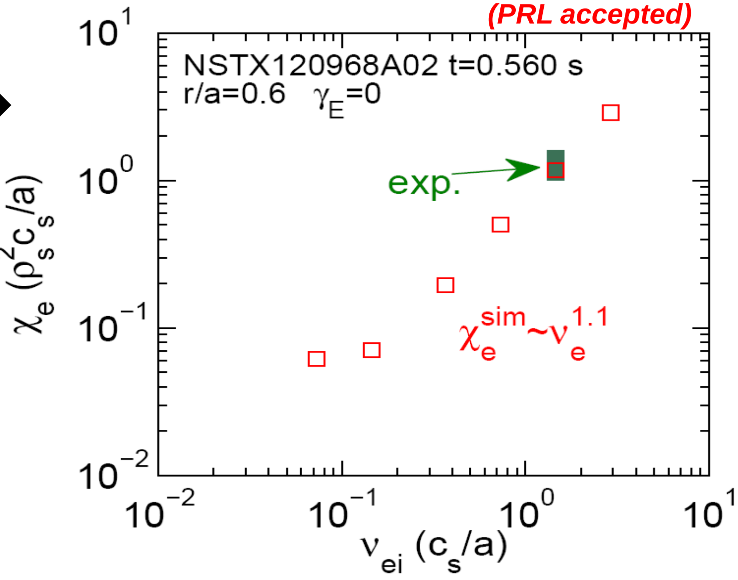
•Y. Ren, PPPL



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

- Suggests μ-tearing playing role in ST e-transport
- Predominantly EM turbulence from high plasma β

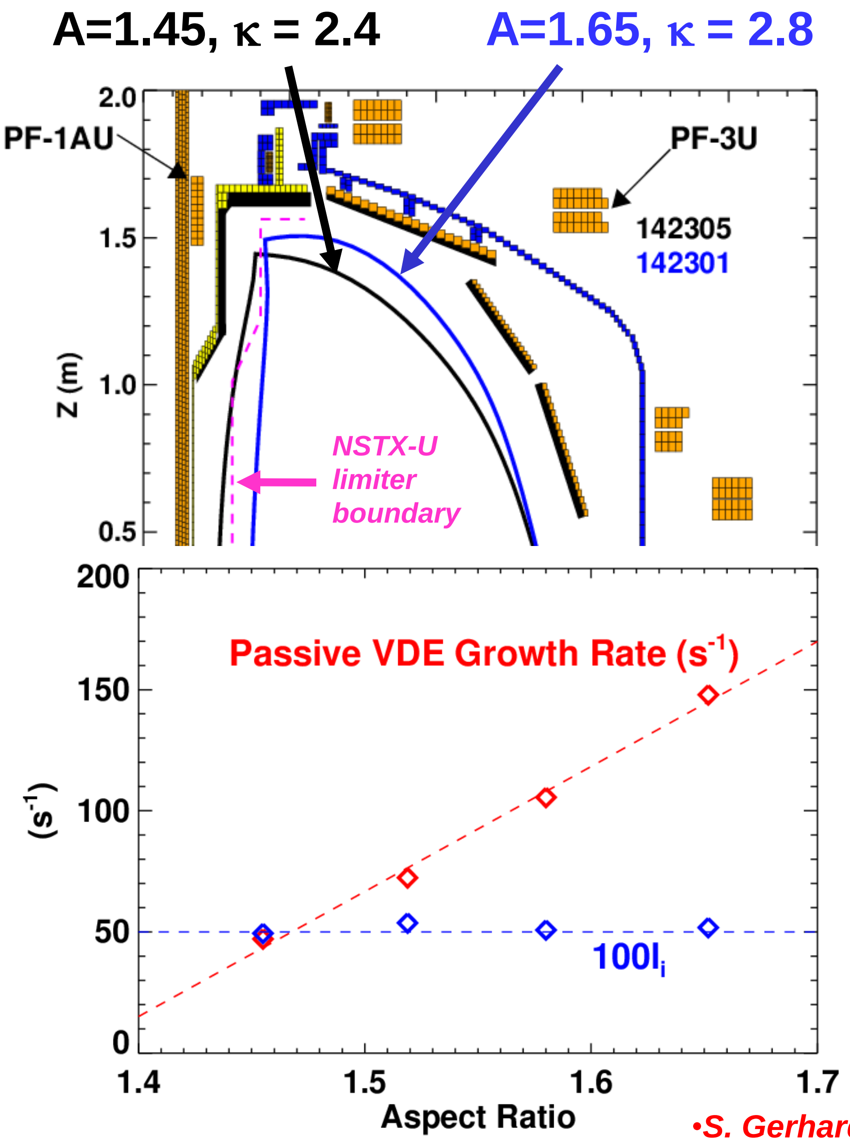
•W. Guttenfelder, PPPL (PRL accepted)



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 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
  - Measured k-spectrum will be correlated with energy diffusivities
  - Perturbative particle/impurity transport experiments will be performed
    - Gas puff imaging, density measurement, low-to-high-k δn, edge SXR
- **Supports 2012 JRT on core transport predictive capability**

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



- Next-step ST designs commonly assume increased κ = 3-3.5 and A=1.6-1.7
- NSTX has begun to explore stability of higher κ and A
- NSTX scenarios will be systematically extended toward shapes of the Upgrade and next-steps
  - Maximum κ, l_i, and sustainable β_N will be assessed
  - RWM stability and control will also be assessed, optimized

•S. Gerhardt, E. Kolemen (PPPL), S. Sabbagh (Columbia)

FY2011-12 milestones target highest priority research areas for NSTX Upgrade, ITER, and FNSF

	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)	
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**		
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, edge SXR **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, edge SXR **Characterize H-mode pedestal structure**	FY12 JRT BES, High-k **Understand core transport and enhance predictive capability**

Enhanced utilization in FY2011-12 would accelerate understanding of edge profile control using 3D fields and AE*-induced fast-ion transport

	FY2010	FY2011	FY2012
Expt. Run Weeks:	15 w/ ARRA	4 10	10 4
1) Transport & Turbulence		**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**	**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**	**Assess very high flux expansion divertor operation** (with ASC TSG)	**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			**Assess confinement, heating, and ramp-up of CHI start-up plasmas** (with WPI/HHFW TSG)
6) Advanced Scenarios & Control			**Assess access to reduced density and ν^* in high-performance scenarios** (with MS, BP TSGs)
7) ITER urgent needs, cross-cutting		**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** **Characterize H-mode pedestal structure**	**FY12 JRT** **Understand core transport and enhance predictive capability**

NSTX Participation in ITPA Joint Experiments and Activities

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)

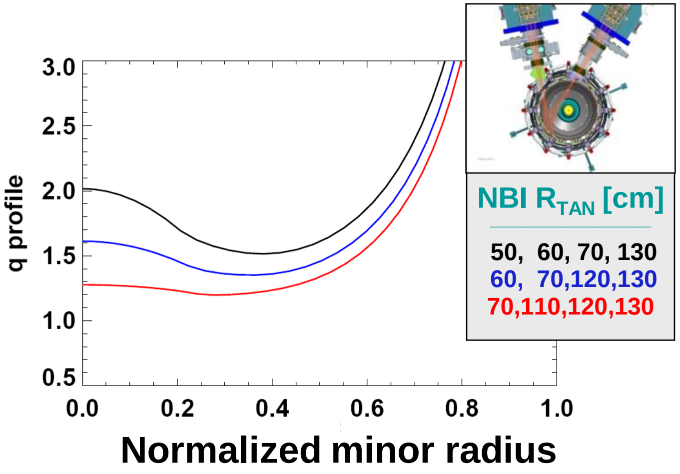
Plans for FY2012-13 analysis and research

- Complete analysis and publication of FY2011-12 data
- Research activities supporting post-Upgrade ops:
  - Start-up: Model/plan CHI upgrades and prep for plasma guns
  - Boundary: Model/plan divertor cryo-pumps, divertor diagnostics
  - Lithium: Assess/model/plan additional Mo tiles, next generation LLD
  - Transport, EP: Model/design new high-k scattering, assess SSNPA
  - MHD: 3D coil physics design for RWM/RMP/TM/EFC/NTV/TAE
  - Control: Model/plan for real-time-MSE for NBI J-profile control
- Write NSTX Upgrade 5 year plan for 2014-18
- Update/extend physics design of ST-FNSF
  - Further develop design concepts utilizing NSTX team expertise
  - Predictive modeling of start-up, sustainment, transport, stability, divertor

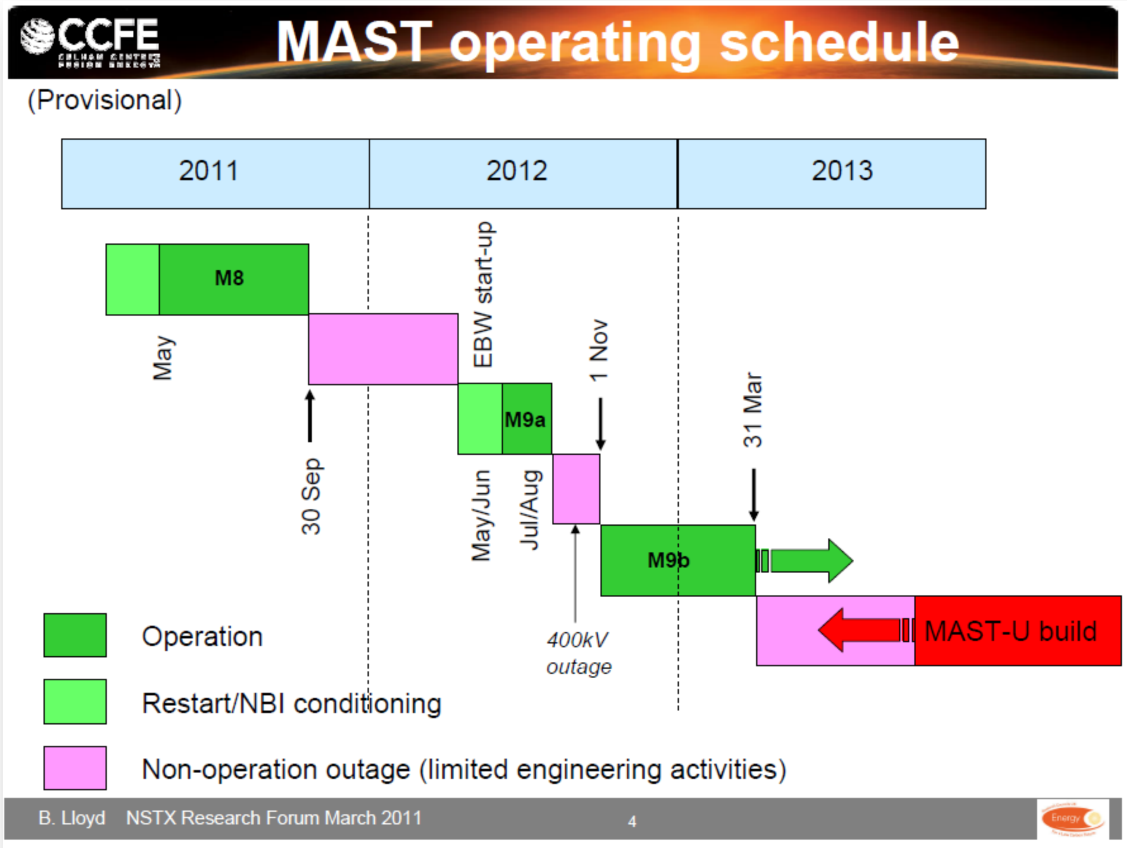
(Initial) plans for FY2013 NSTX collaboration

- Solicited/received information on collaboration opportunities
  - Enthusiastic response from: MAST, LTX, Pegasus, DIII-D, C-Mod, KSTAR, EAST
  - Also gathered info on PPPL NSTX researcher interests and skills
- ~30% time available for collaboration: ~10 FTE/yr for 2-3 yrs
- Aligning opportunities & skills with needs/goals of NSTX-U, OSR
  - **Plasma start-up:** *Pegasus, MAST*
  - **Advanced divertor, pedestal/SOL:** *MAST, EAST, C-Mod*
  - **Lithium research, high-Z PFCs:** *EAST, LTX, C-Mod, several U.S. universities*
  - **Core/edge transport:** *MAST, C-Mod, DIII-D, EAST*
  - **Stability/MHD, 3D fields/islands, disruptions, RMP:** *KSTAR, LHD, DIII-D, MAST*
  - **Energetic particles, *AE:** *MAST, JET (possible DT campaign), LHD*
  - **RF/NBI development for SS ops/control:** *EAST (ICRF/ECH/LH) , KSTAR (ICRF/ECH/NBI) , C-Mod (ICRF/LH)*
  - **Advanced scenarios development, tokamak ops:** *KSTAR, EAST, DIII-D*
  - **ST-FNSF/CTF physics design:** *MAST*

- Example: NSTX-U has goal of 100% NICD at high β + q(r) control using 1st + new 2nd NBI ⇨
  - Collaboration on advanced scenarios, profile control, energetic particle physics mutually beneficial:
    - ➢ DIII-D, EAST, KSTAR, MAST
- Issues: funding, inclusion of NSTX collaborators



MAST operation during 2012-13 provides excellent opportunity for NSTX researcher collaboration on MAST



CCFE **MAST operating schedule**

(Provisional)

- 🟩 Operation
- 🟩 Restart/NBI conditioning
- 🟪 Non-operation outage (limited engineering activities)

B. Lloyd NSTX Research Forum March 2011 4

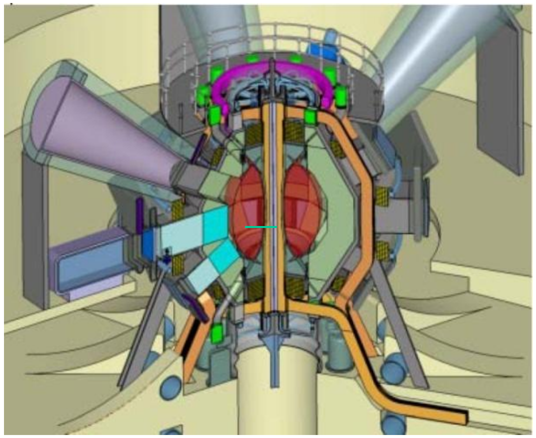
Discussions with MAST and NSTX physicists and managers Sep 2010 - Mar 2011 identified topics of mutual interest:

- Steady-state, high performance scenarios
  - Turbulent ion and electron transport
  - Pedestal physics, advanced divertors
- Energetic particle physics
  - NBI current redistribution
- 3D physics
  - Perturbed 3D equilibria

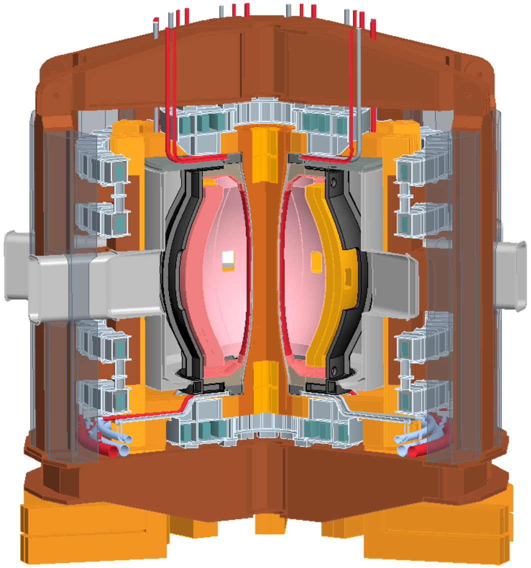
With Culham and MAST, aim to develop of common understanding, vision, design of ST-based FNSF/CTF

- Materials, fusion nuclear science, PMI major themes in U.S. fusion program
- ST can play important role in materials/PMI and FNS facility
- CCFE and PPPL are lead labs investigating, advancing ST concept
- Both labs agree it would be beneficial to work more closely
  - Developing PPPL concepts and strategy via FNSF-Pilot Plant studies
  - Challenge: both sides operating existing machines + prepping for major Upgrades

J. Menard visiting Culham/MAST in April 2011 to initiate



Culham ST-CTF



PPPL ST Pilot/FNSF

Summary: NSTX and NSTX Upgrade plans for FY2011-13 strongly support OFES vision for fusion for coming decade

- **Plasma dynamics and control**
  - Detailed measurements and simulation of turbulence, transport, core/edge stability
  - Integrating this knowledge to develop advanced high-β ST scenarios
  - Upgrade will extend scenarios to full non-inductive operation w/ advanced control
- **Materials in fusion environment, harness fusion power**
  - Providing critical data on SOL-width scaling and SOL turbulence
  - Developing novel divertors for heat-flux mitigation, Li-based PFCs
  - NSTX + Upgrade provide 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)

Upgrade outage is opportunity for enhanced collaborations

Backup

NSTX recent and upcoming program schedule

- NSTX PAC-29 – Jan 26-28, 2011
  - FY11-12 Research Milestones/Priorities
  - Preparation for Upgrade
  - Alignment of Program with FES vision

- Research Forum for FY11-12 run – Mar 15-18, 2011
  - 170+ research proposals, 210 run days (~2.5-3x available)
  - 55 team members, 17 institutions

- FES 2013 Budget Planning Meeting – Apr 11, 2011

- Begin 2nd/final phase of FY11 run – Jun/Jul 2011
  - Remaining FY11 run-time: 10 weeks
  - FY12 run (10 wks) will start in fall 2011 (no vent planned)
  - Finish FY12 run by end of Feb. 2012 → start Upgrade outage

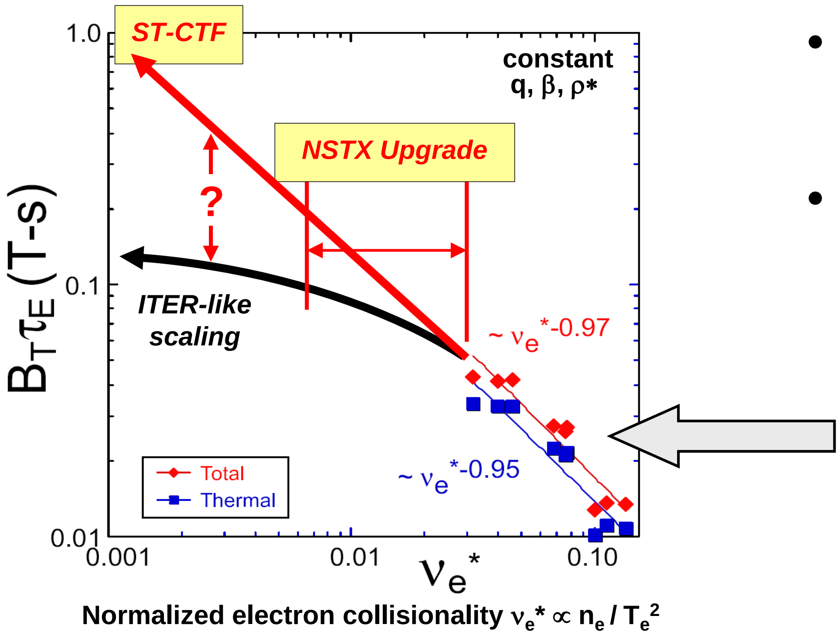
A vision for U.S. fusion research in the coming decade has emerged from OFES emphasizing 4 research themes:

- **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

Backup

NSTX Upgrade

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 10-100x 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)

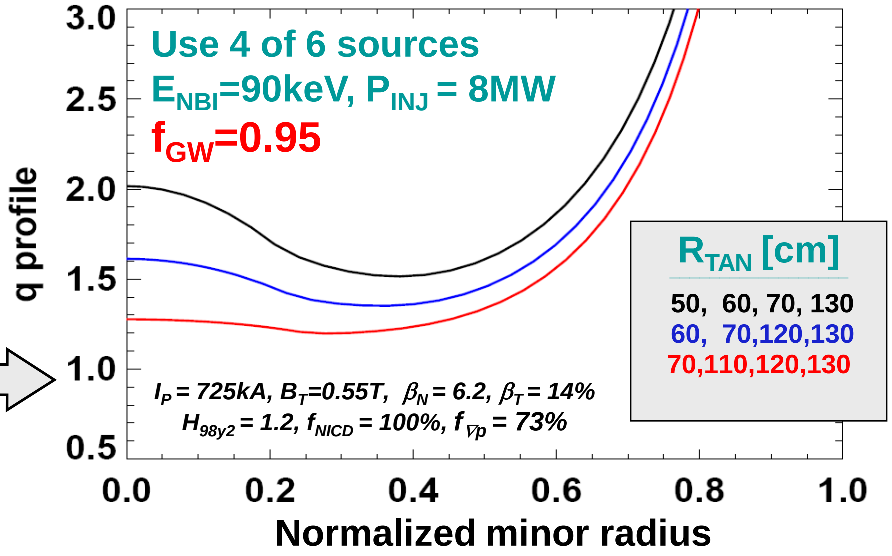
- NSTX observes much stronger scaling vs. ν*
  - Does favorable scaling extend to lower ν* ?
  - What modes dominate e-transport in ST ?
    - Electrostatic or electromagnetic?
- ν* also impacts RWM stability, rotation damping, range of other physics

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

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

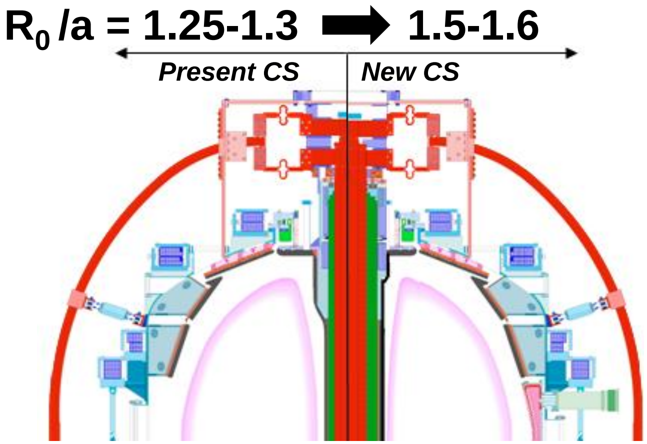
- Higher heating power to access high temperature and β at low collisionality
  - Need additional 4-10MW, depending on confinement scaling
- Increased external current drive to access and study 100% non-inductive
  - Need 0.25-0.5MA compatible with conditions of ramp-up and sustained plasmas
- Upgrade: 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

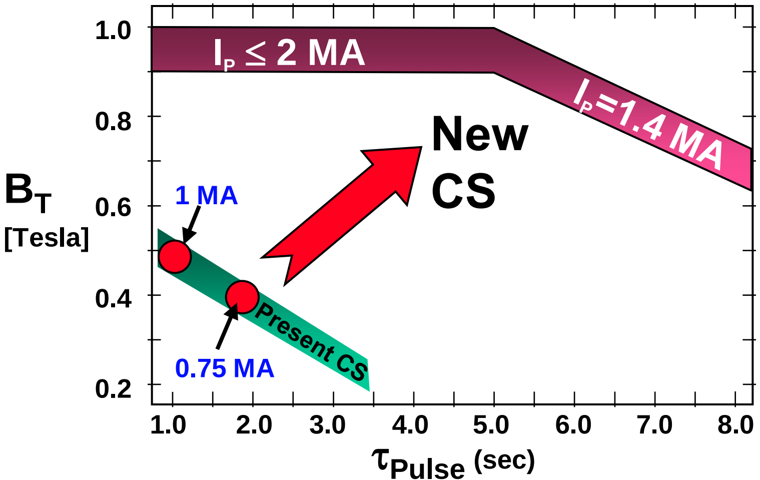
- q(r) profile very important for global stability, electron transport, Alfvénic instability behavior
  - Variation of mix of NBI tangency radii would enable core q control



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

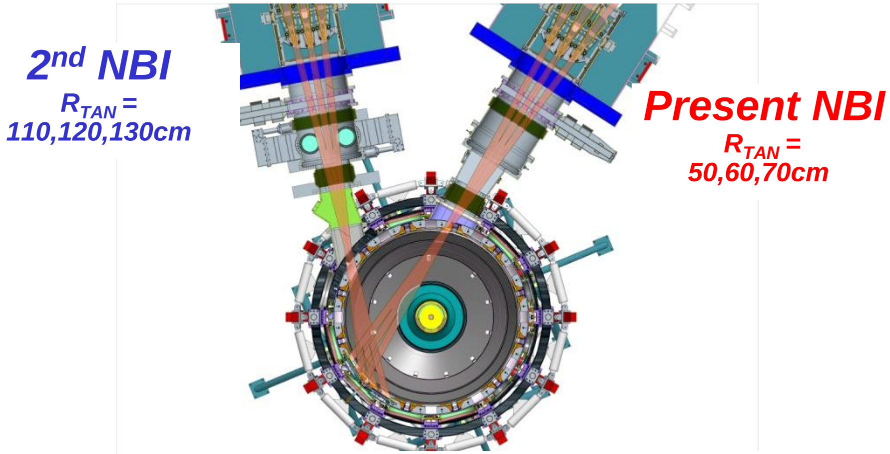
New center stack for 1T, 2MA, 5s

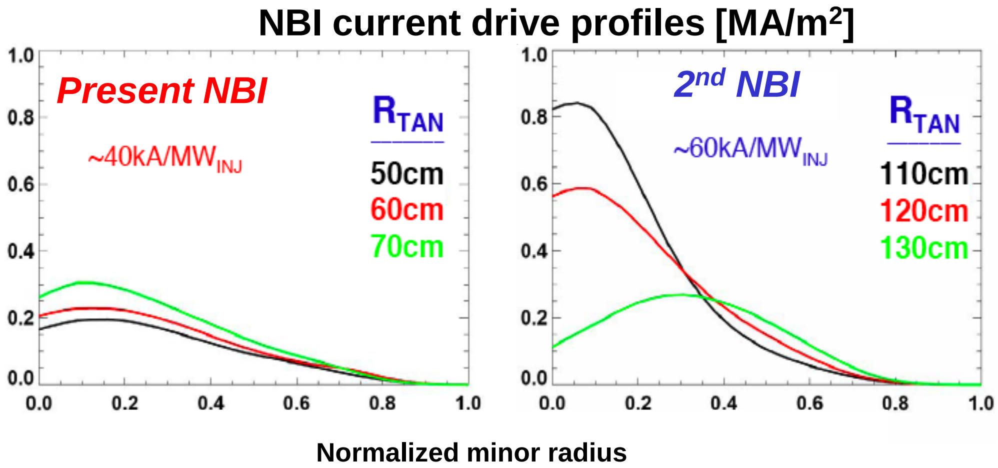




Magnet operation at ~1T (vs. 0.55T) within a factor of 2 of next-step STs

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





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

Non-inductive ramp-up to ~0.4MA possible with RF + new CS, ramp-up to ~1MA possible with new CS + more tangential 2nd NBI

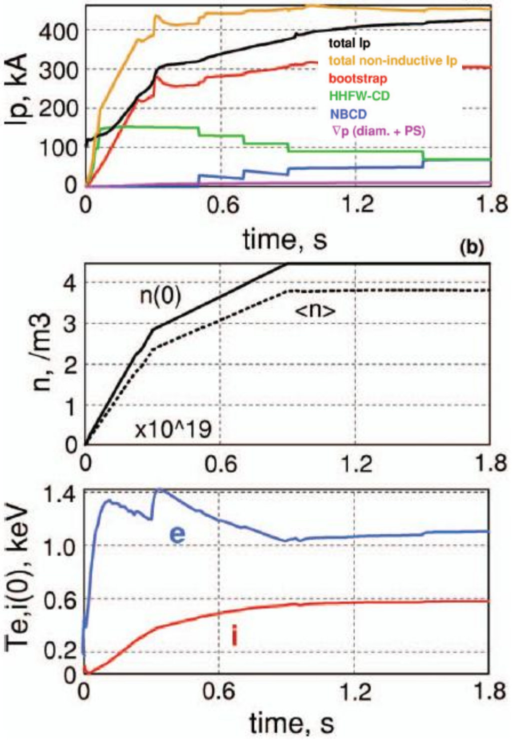
Ramp to ~0.4MA with fast wave heating:

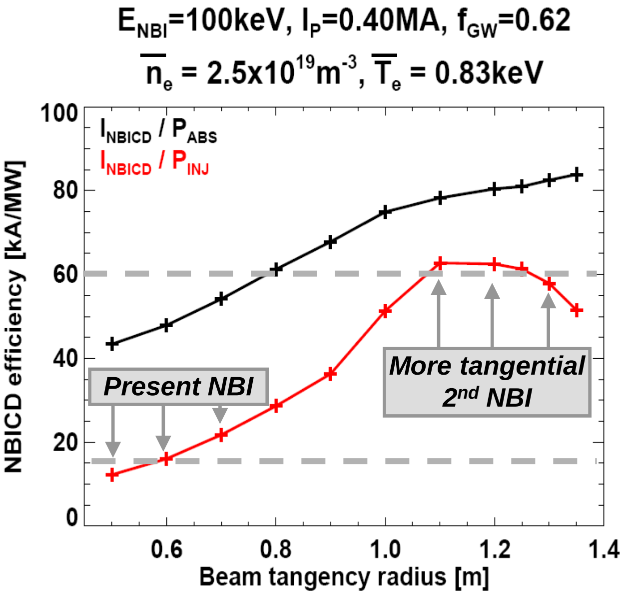
- High field ≥ 0.5T needed for efficient RF heating
- ~2s duration needed for ramp-up equilibration
- Higher field 0.5→1T projected to increase electron temperature and bootstrap current fraction

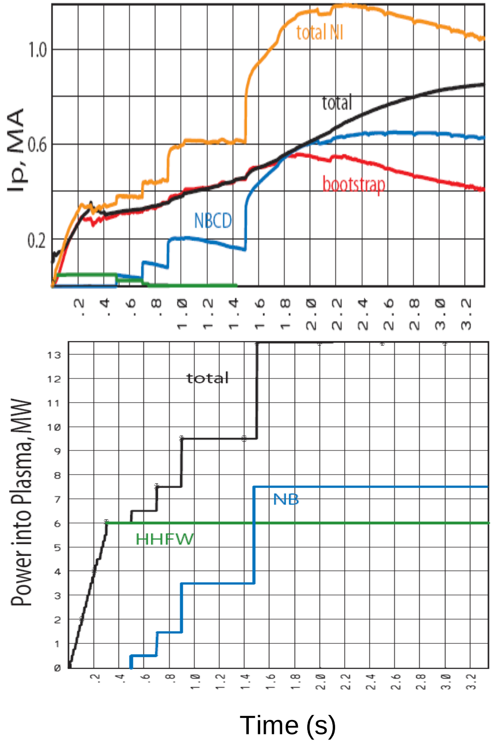
Extend ramp to 0.8-1MA with 2nd NBI:

- Benefits of more tangential injection:
  - Increased NBI absorption = 40→80% at low I_P
  - Current drive efficiency increases: x1.5-2
- New CS needed for ~3-5s for ramp-up equilibration
  - Higher field 0.5→1T also projected to increase electron temperature and NBI-CD efficiency

TSC Simulations – C. Kessel







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

- 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 ($T_{\text{carbon-tile}} \leq 1200°C$)
- 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

Backup

Additional Milestone Descriptions

Summary of Research Milestones for FY2011-12

- **FY2011 FES Joint Research Target:** *Improve understanding of physics mechanisms responsible for pedestal structure, compare with the predictive models*
- **FY2012 NSTX Research milestones:**
  - R(11-1): Measure fluctuations responsible for turbulent electron, ion, impurity transport
  - R(11-2): Assess ST stability dependence on plasma aspect ratio, boundary shaping
  - R(11-3): Assess very high flux expansion divertor operation
  - R(11-4): H-mode pedestal transport, turbulence, and stability response to 3D fields

- **FY2012 FES Joint Research Target:** *Improve understanding of core transport and enhanced capability to predict core temperature and density profiles*
- **FY2012 NSTX Research milestones:**
  - R(12-1): Investigate relationship between Li-conditioned surface composition, plasma behavior
  - R(12-2): Assess confinement, heating, and ramp-up of CHI start-up plasmas
  - R(12-3): Assess access to reduced density, ν^* in high-performance scenarios
  - *IR(12-1): Investigate magnetic braking physics and develop toroidal rotation control at low ν^**
  - *IR(12-2): Assess predictive capability of mode-induced fast-ion transport*

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

- Some next-step ST scenarios based on operating at lower Greenwald density and/or ν^* than routinely accessed in NSTX

- Reduced n_e and ν^* via Li pumping has been achieved, but additional gas fueling is typically required to avoid disruption during I_P ramp and/or in the early flat-top and high-β phase

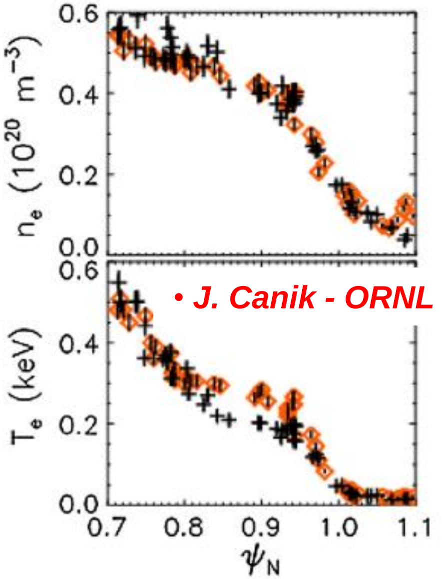
- Goal: characterize and avoid the underlying disruption causes:
  - Loss of access to H-mode, locked-modes, β limits, double tearing, …

- 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

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

NSTX provides unique data to understand response to 3D fields for ELM control:

- ELMs stabilized by Li coatings
- ELMs triggered by 3D fields, not suppressed
  - Small density change during n=3 3D fields
  - T_e and pedestal pressure increase → ELM
  - q_{95} ~ 11 optimal for ELM triggering – why?



• *J. Canik - ORNL*

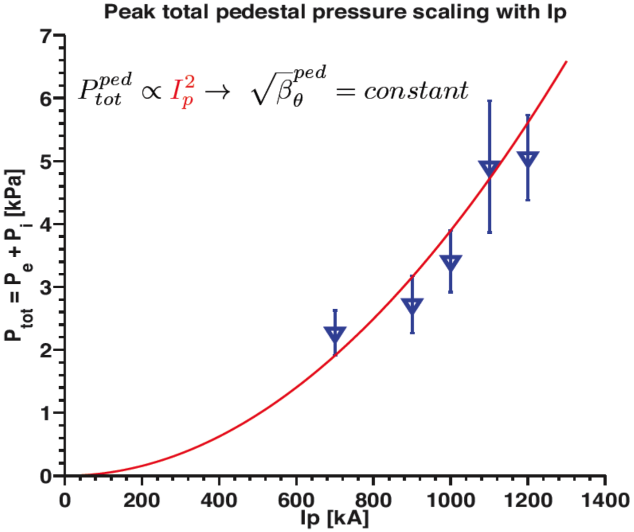
- Will study possible mechanisms for modifying transport:
  - island shielding reduction, stochastic-field ExB convective transport
  - banana diffusion and ripple loss, zonal flow damping, ExB shear mods
- Pedestal turbulence trends: BES, high-k scattering, gas-puff imaging
- Transport response: Improved Thomson, impurity injection, edge SXR
- **Supports 2011 JRT on H-mode pedestal structure**

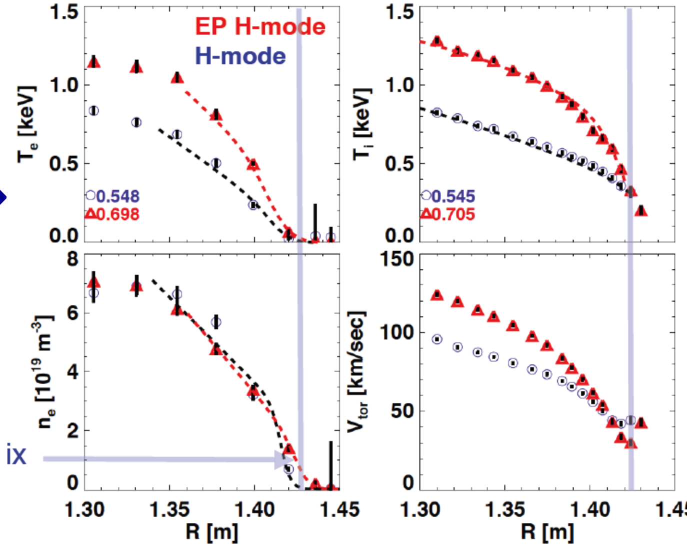
Backup

Boundary Physics

Pedestal structure and underlying MHD/transport mechanisms will be elucidated by FY 2011 JRT effort

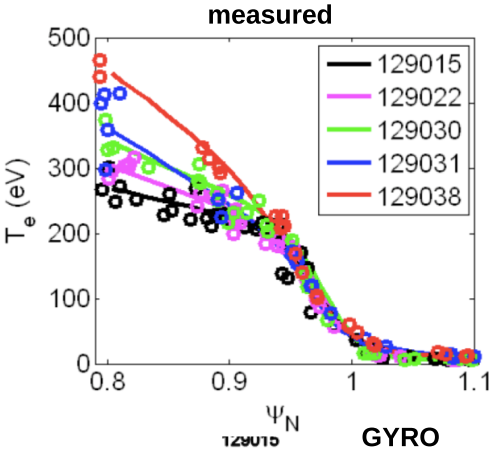
- Continuing progress in pedestal studies
  - Pedestal workshop w/ Alcator C-mod (09/2010)
  - Application of pedestal analysis tools and interface with modeling
  - FY 2010 – FY 2011 experiments
    - Pedestal pressure
      - $P_{ped} \propto I_p^2$ and increases with triangularity
      - Builds up during ELM cycle, saturates at lower I_p late in ELM cycle
      - Analysis of pedestal data with PB theory
    - Physics of EP H-mode with H98~1.7
- Planned research (R11-4)
  - Pedestal transport, turbulence, stability with 3D fields
    - Roles of particle and thermal heat transport

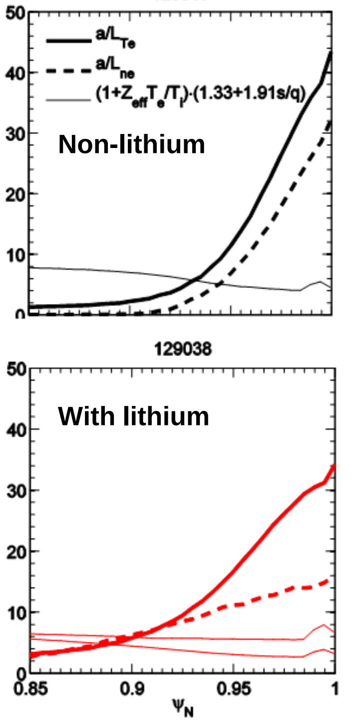




Pedestal structure and underlying MHD/transport mechanisms will be elucidated by FY 2011 JRT effort

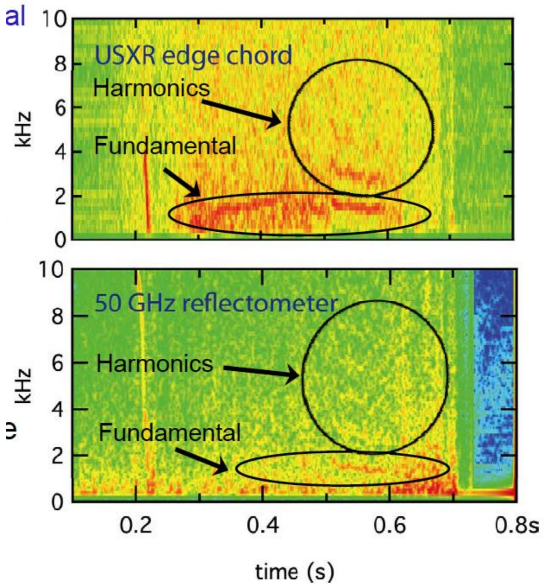
- Document dependence of pedestal structure in on I_p, B_t, δ
  - Stability analysis with ELITE, PEST; height analysis with EPED
- Evaluate edge transport rates and correlate with turbulence
  - With lithium: role of recycling and fueling (SOLPS, UEDGE)
  - In regimes with separate particle and thermal transport channels, e.g. EP H-mode and I-mode
  - Compare with paleoclassical and neoclassical (XGC) transport models
  - Evaluate role of ETG in limiting edge T_e gradient (GYRO)
    - ETG unstable in steep gradient region ($\psi_N > 0.92$)
      - threshold likely set by density gradient
    - ETG stable at top of pedestal ($\psi_N = 0.88$)
      - threshold likely sensitive to $Z_{eff}\,T_e\,/\,T_i$ and s/q
- Continue ELM stability studies
  - Role of n_e and T_e gradients, and lithium
  - Role of diamagnetic stabilization (BOUT)



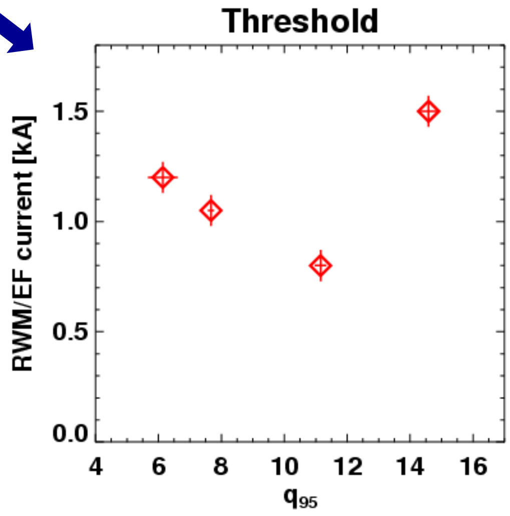


NSTX studies of ELM regimes and ELM control contribute to mitigation strategies for ITER and future STs

- ELM response to lithium, 3D fields, X-points
- Small ELM (Type V) regime
  - Type I ELMs stabilized
  - Observed EHO-like edge instability (f <10 kHz)



- Initiated ELM suppression experiment using n=3 off-midplane coils
  - Developed stable plasma shifted down by 20 cm
- With midplane n=3 coils, found threshold current and optimal q_{95} window for ELM triggering
  - ELM triggering on NSTX: weak pedestal modification, vacuum Chirikov width > 0.3, no pitch-aligned with wide q_{95} range (~9~11), ν^*_e>0.5

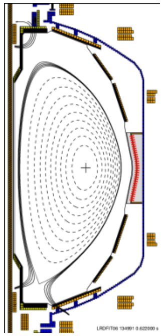


- Planned research in FY2011-2012
  - Development of small ELM regimes at low ν*, high P_{in}
  - ELM dependence on shape and magnetic balance
  - 2nd SPA for flexible spectrum (n=1,2,3) for ELM stability studies

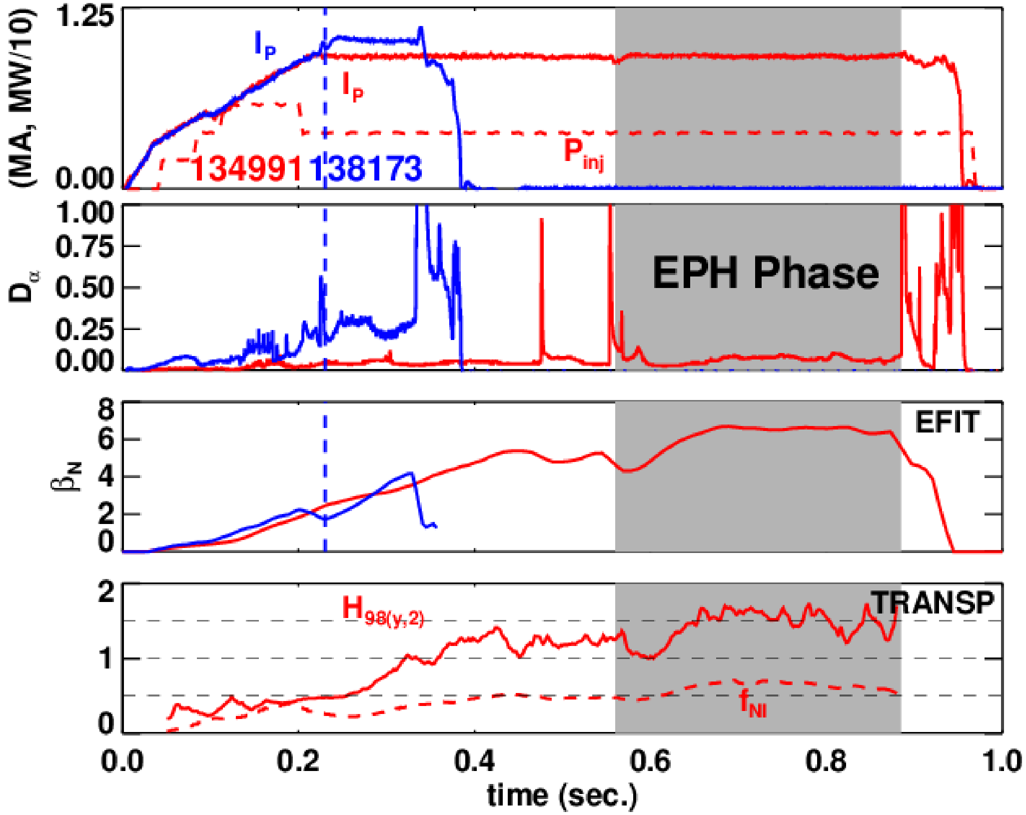
Backup

Enhanced Pedestal H-mode

ASC Experiments Tested Triggering and Control of Enhanced Pedestal H-Modes (EP-H)

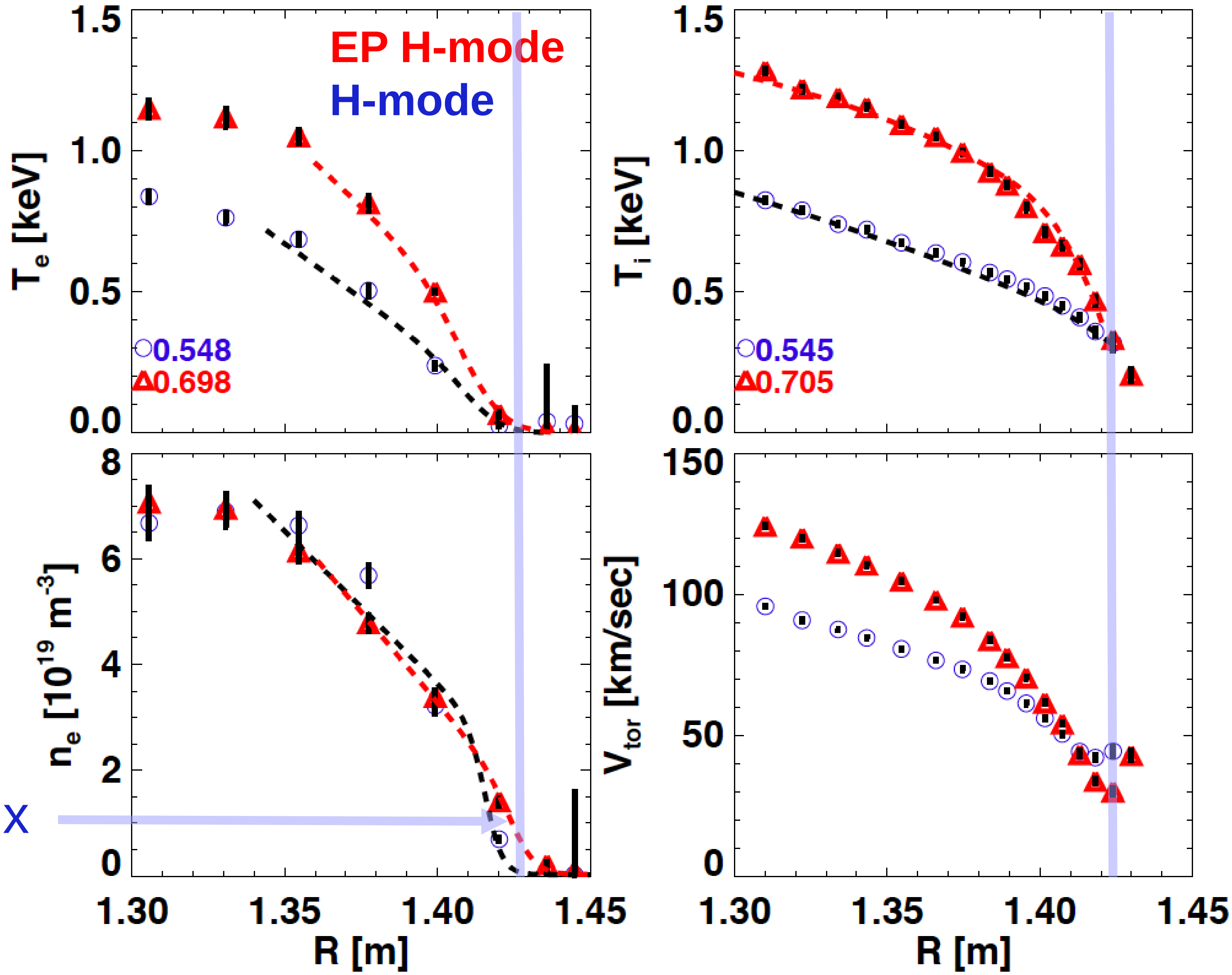


- EP-H typically triggered by an ELM
  - well after L->H transition.
- Confinement improves ~50%
  - f_{NI}~70% very high for this I_p/shape.
- Has typically resulted in β_N limit disruption.



- 2010 run goal: reliably trigger and control EP-H modes.
  - n=3 pulses for triggering
  - β_N feedback for control
- n=3 pulses which triggered ELMs not reliable in triggering EP-H.
- Developed a low-q_{95} scenario with EP-H transitions at end of I_P ramp.
  - β_N controller reduced power after EP-H transition.
  - 2nd ELM terminated EP-H
    - (single LITER that day).
- Implications for FY-11 & 12:
  - Revisit when dual LITER system is operational.
  - Understand if q_{95}, I_P or something else governs access.
  - Assess prospect for high-f_{NI} operation at reduced I_P.

Thermal barrier: Edge T_e, T_i double, with a reduction in the edge n_e gradient, and an increase in v_ϕ shear

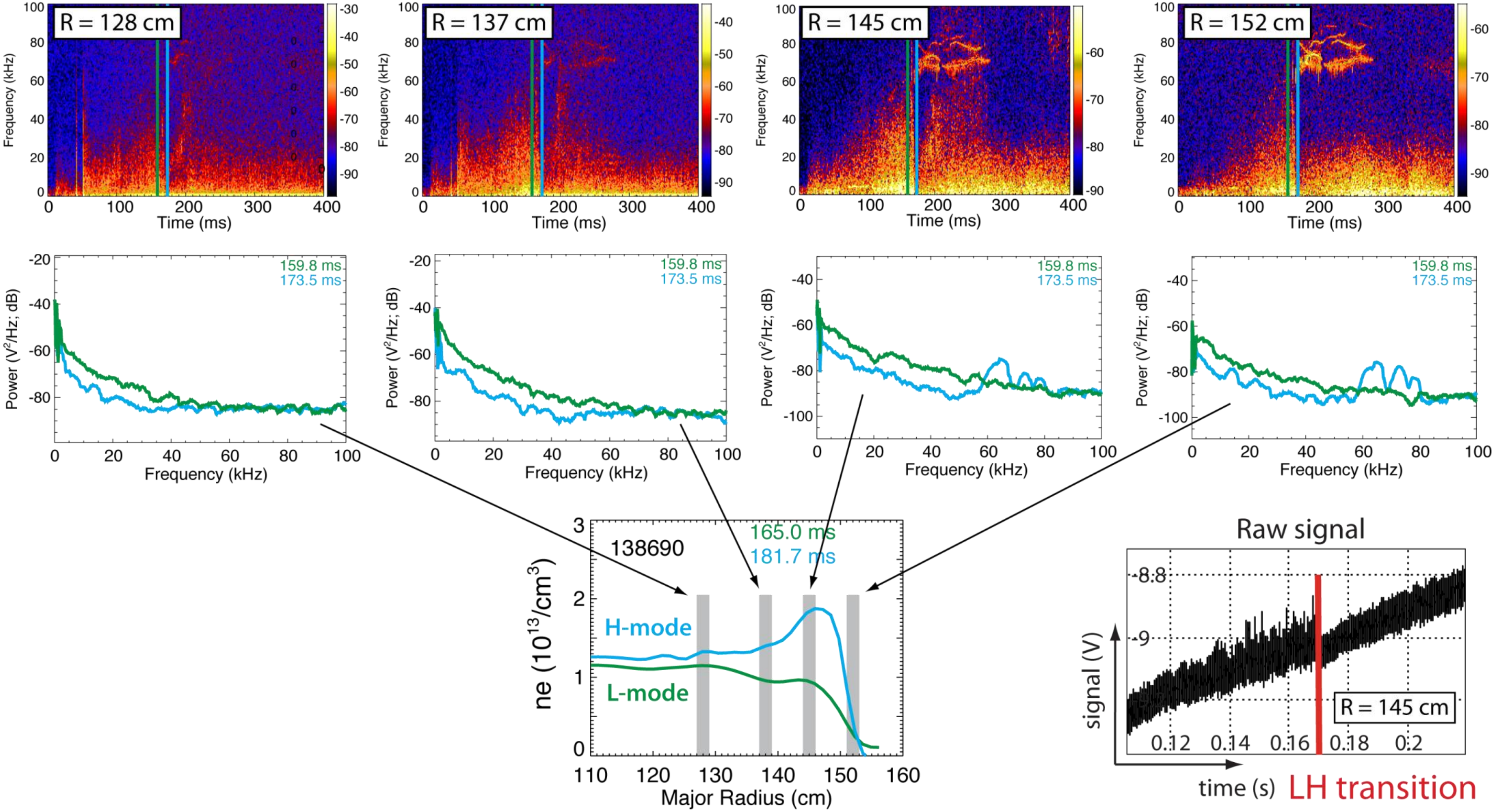


separatrix

Backup

Transport and Turbulence

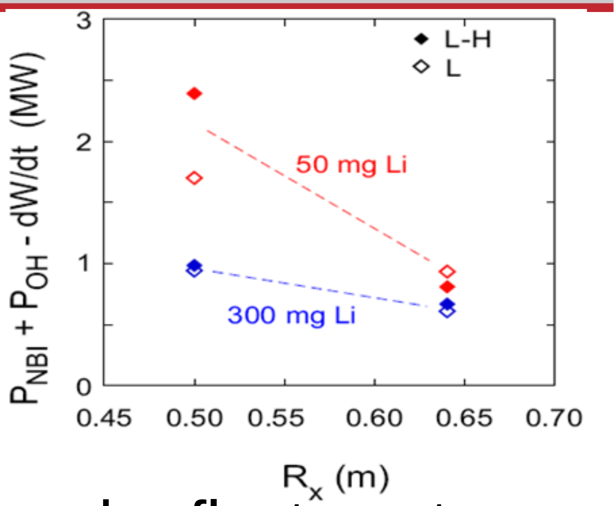
BES Observed Decrease in Fluctuations at L-H transition from Edge to Core Regions



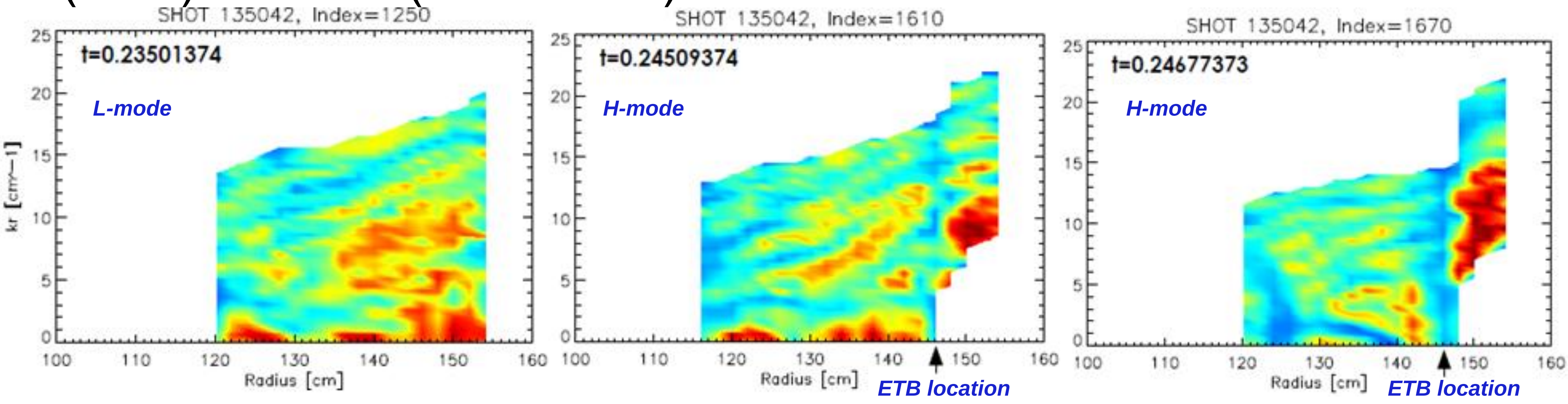
R. Fonck, G. McKee, D. Smith, and I. Uzun-Kaymak (UW-Madison) and B. Stratton (PPPL)

L-H Transition Study on NSTX Characterizes both Power Threshold and Turbulence

- P_{LH} decreases with R_X and Li deposition
  - Consistent with XGC-0 predicted E_r well depth
  - B_T at X-point location is important in determining P_{LH}
  - Plan to study the effect of X-point height and to investigate P_{LH} dependence on B_{TX} with XGC-0



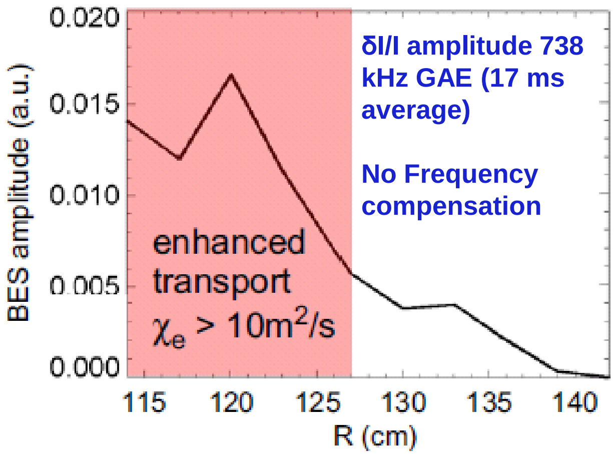
- k_r backscattering measurements from improved reflectometer show turbulence suppression at the Electron Transport Barrier (ETB) location (R≈146 cm) after L-H transition



NSTX is also Exploring Other Mechanisms of Electron Thermal Transport (R11-1, TC-10, 2012 JRT)

- BES measured Global Alfvén Eigenmode (GAE) peak amplitudes consistent with numerically simulated electron thermal transport
  - – BES calibrated mode structures and amplitudes for future ORBIT simulations
  - – To investigate robustness of physics with constant-q B field scan and P_{NBI} scan

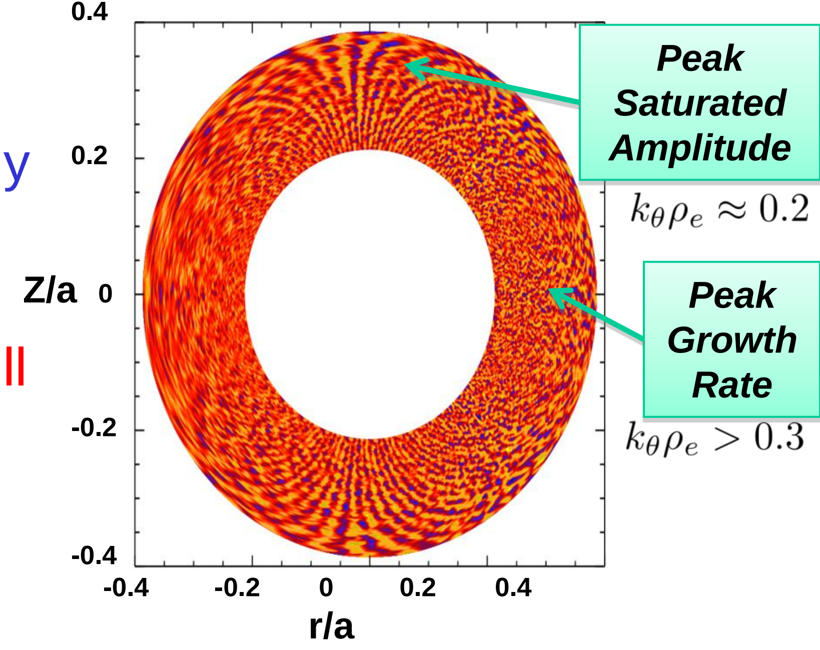
Relative mode profile



δI/I amplitude 738 kHz GAE (17 ms average)

No Frequency compensation

- ETG is identified in NSTX reversed shear plasmas
  - – Off-mid-plane ETG streamers nonlinearly driven by mid-plane unstable ETG with steep T_e profile (nonlinear GYRO)
  - – High-k measurement at off-mid-plane will be conducted
    - High-k scattering at Z/a≈-0.3 possible
    - Shifting magnetic axis will be tried.



Peak Saturated Amplitude

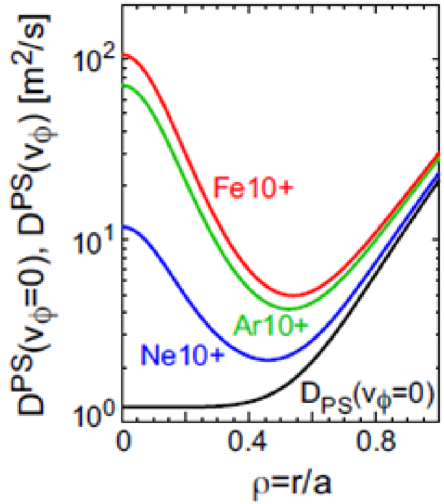
$k_\theta \rho_e \approx 0.2$

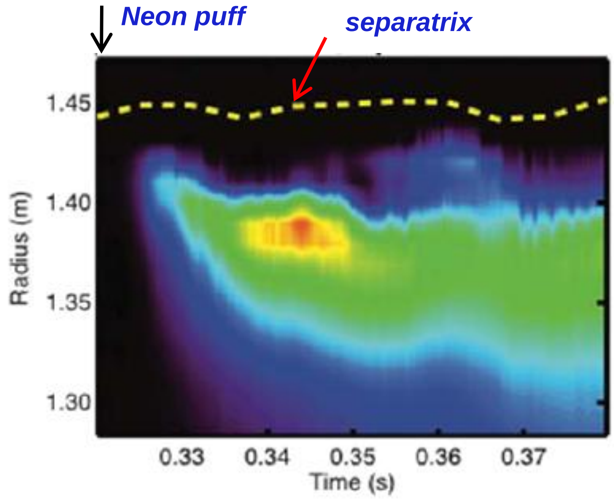
Peak Growth Rate

$k_\theta \rho_e > 0.3$

Impurity Transport Studies will Exploit New Diagnostics and Modeling Capabilities (R11-1, 2012 JRT)

- Neon diffusivity neoclassical in the core accompanied by some anomalous convection
  - Under-resolved at the edge and suffered from low signal
- Plasma rotation enhancing core impurity transport without invoking low-k turbulence
- New Multi-Energy Soft X-Ray diagnostic in 2010
  - ~1 cm resolution; <100 μs response; high SNR; r/a>0.65
- STRAHL transport code being used
  - Neoclassical calculation embedded; Up-to-date atomic data
- Impurity transport study at plasma edge
  - Carbon build up in ELM-free discharges
  - Z dependence of impurity transport
  - Measure edge turbulence and its relation to impurity transport (BES, High-k, reflectometer etc.)

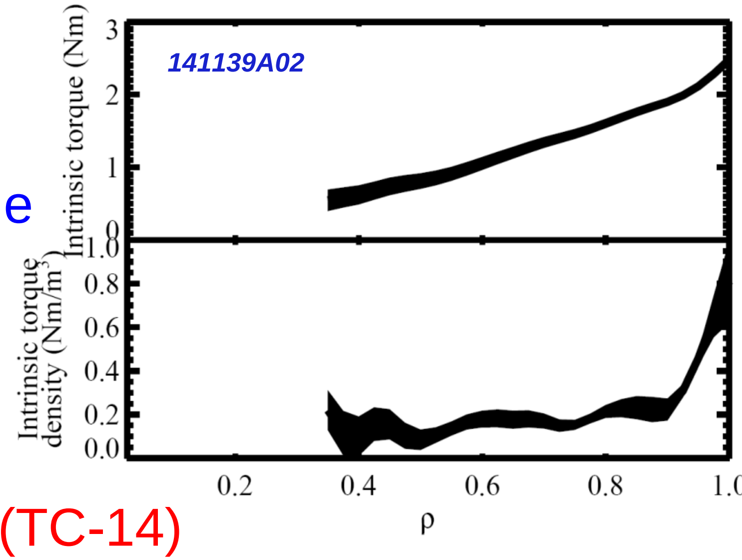




H-, He-like Neon

NSTX is Participating in ITPA JEX Studying Intrinsic Torque

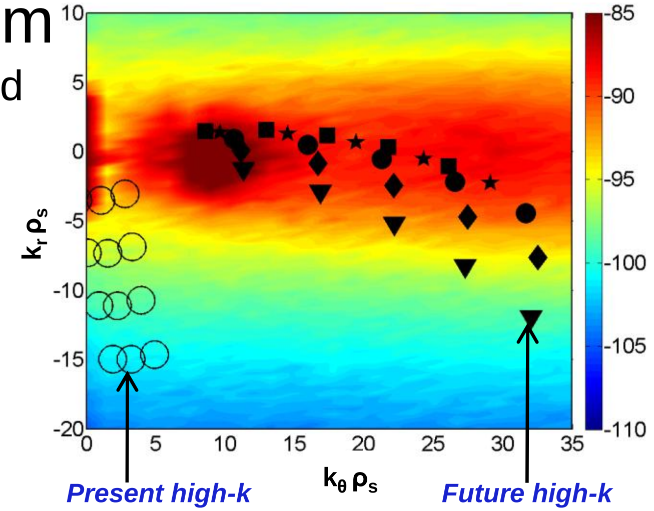
- Preliminary results indicating higher and more edge-localized intrinsic torque in NSTX than in DIII-D (TC-9)
  - Qualitatively similar torque profile as observed on DIII-D
- Understanding the mechanism of intrinsic torque is important for ITER
  - Projection and optimization of rotation profile



- Plans for FY11 and FY 12:
  - Characterize role of turbulence in driving intrinsic rotation (R11-1)
  - Modification to intrinsic drive by RF/HHFW (TC-14)
  - Interaction of intrinsic drive with other torques (*e.g.* NTV)
  - Contribute data to ρ* scaling experiment (TC-17)
  - Look for signature of thermal ion orbit loss

T&T TSG Activities for FY13 and FY14

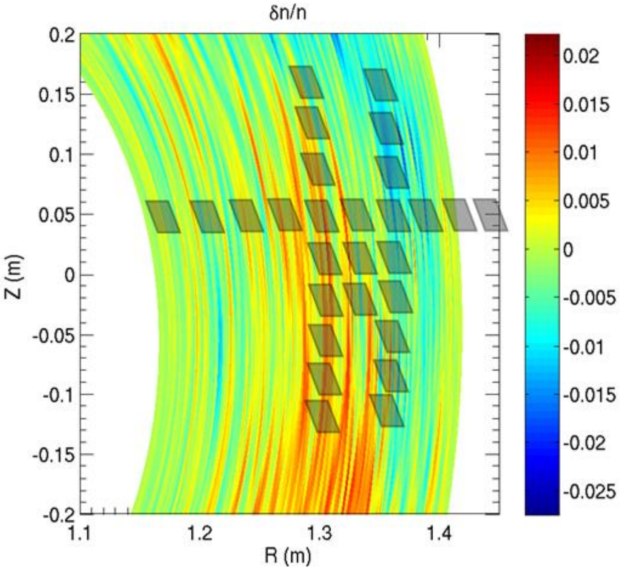
- Current high-k_r scattering system will be removed to install the 2nd NB during upgrade
  - Design of a new high-k scattering system is in progress and will be completed during FY13 and FY14
- Extensive comparison between measurements and micro-instability calculations including GYRO, GTS, GS2, GTC-NEO
  - Use synthetic diagnostics to compare simulated and measured fluctuating quantities and their spectral characteristics



Present high-k

Future high-k

k space coverage for the present and future high-k scattering systems with ETG k spectrum (non-linear GYRO, NSTX L-mode)

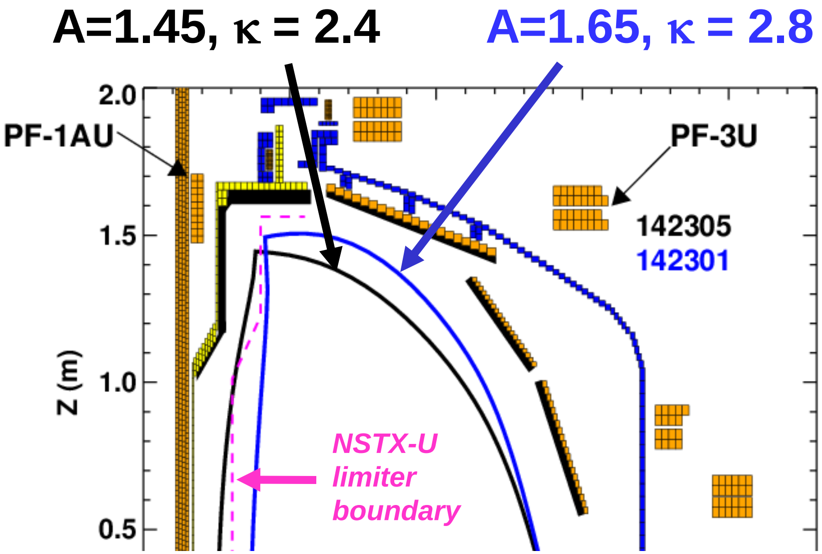


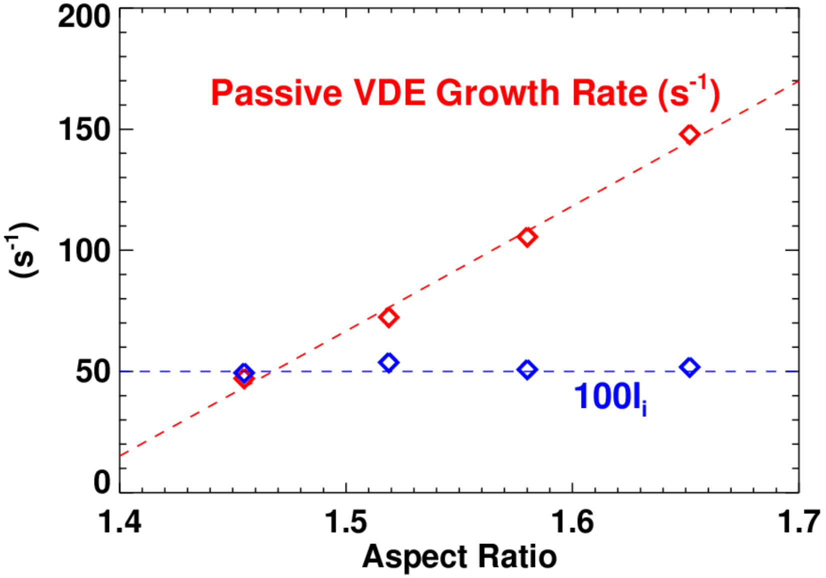
BES views with micro-tearing density fluctuations (nonlinear GYRO NSTX H-mode)

Backup

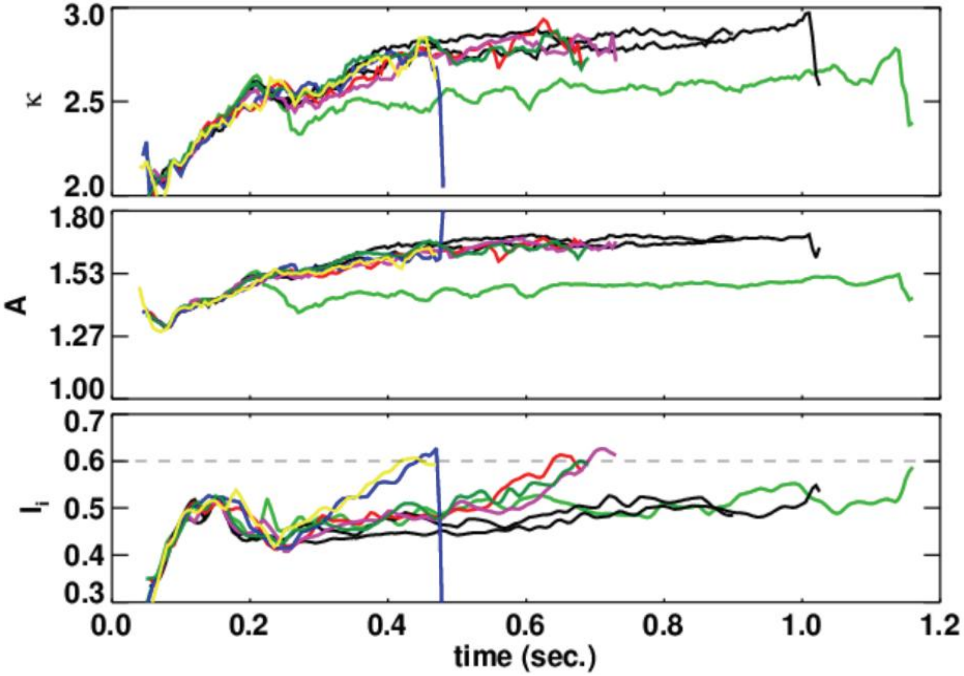
Macroscopic Stability

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

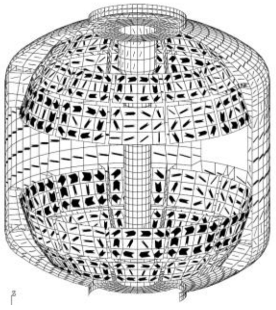


•S. Gerhardt, E. Kolemen - PPPL

NSTX is first tokamak to implement advanced RWM state-space controller, and has utilized it to sustain high β_N

Full 3-D model

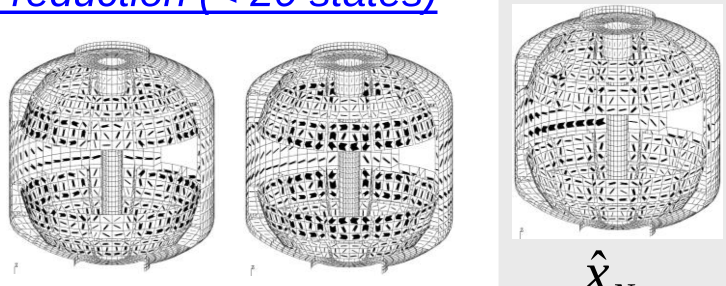
~3000+ states



State reduction (< 20 states)

RWM eigenfunction(2 phases, 2 states)

$(\hat{x}_1, \hat{x}_2)$



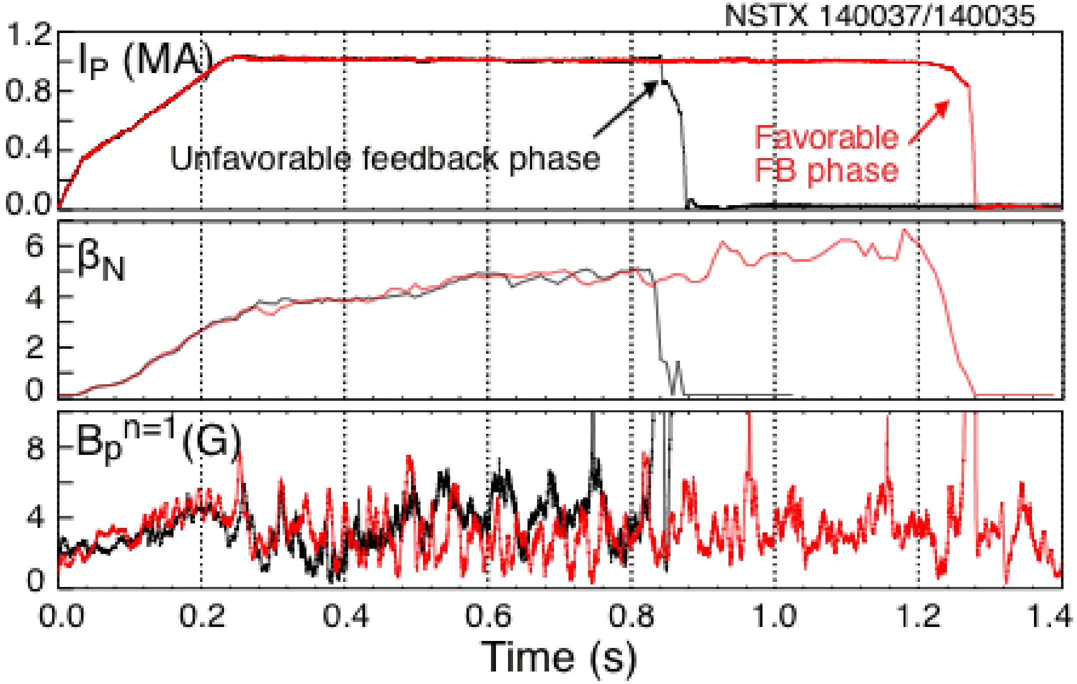
$\hat{x}_3$ $\hat{x}_4$ $\hat{x}_N$

truncate

- device R, L, mutual inductances
- instability B field / plasma response
- modeled sensor response

- Controller can compensate for wall currents
  - Including mode-induced current
  - Examined for ITER
- Successful initial experiments
  - Suppressed disruption due to n = 1 applied error field
  - Best feedback phase produced long pulse, $\beta_N = 6.4$, $\beta_N / l_i = 13$

State space feedback with 12 states



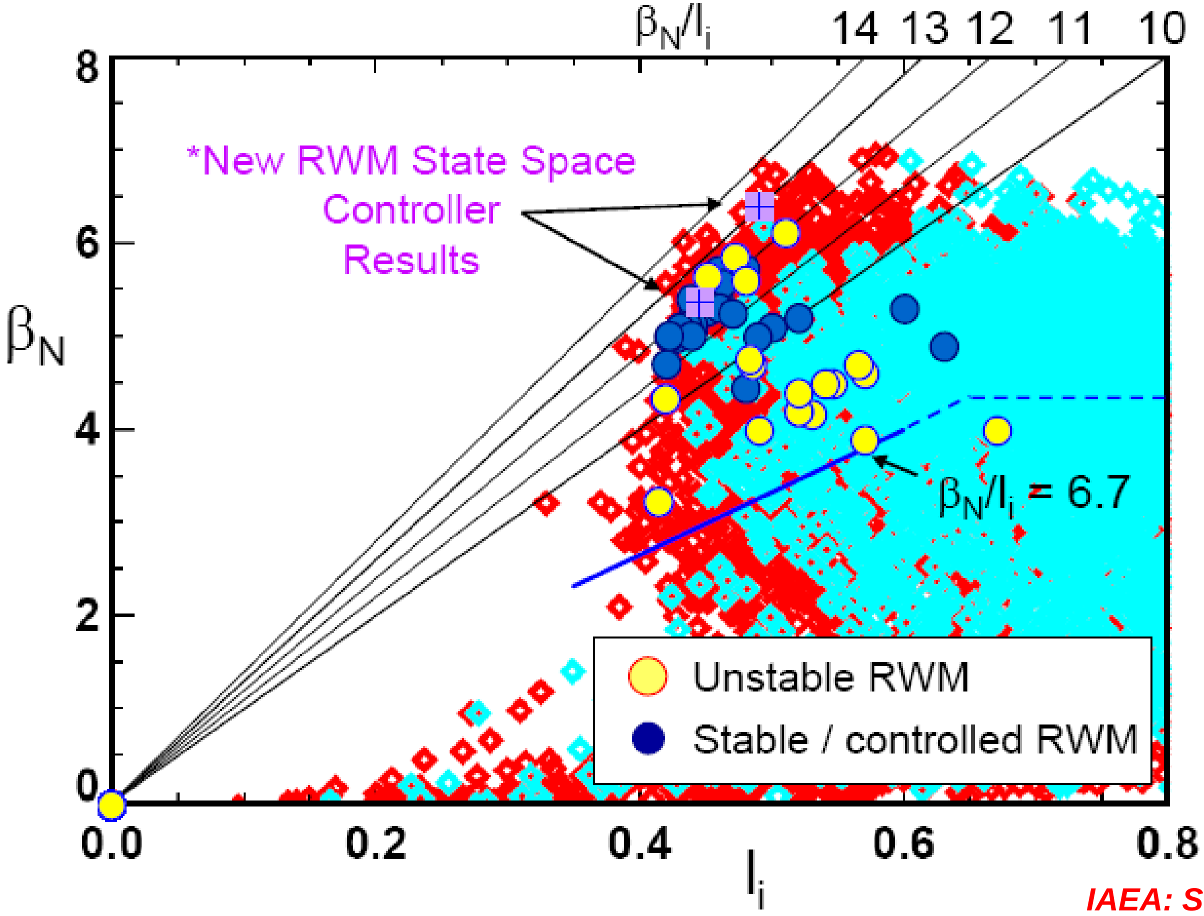
IAEA: S. Sabbagh, Columbia U

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

- High normalized beta β_N = 6–7 and high β_N / l_i = 10-14 routinely accessed

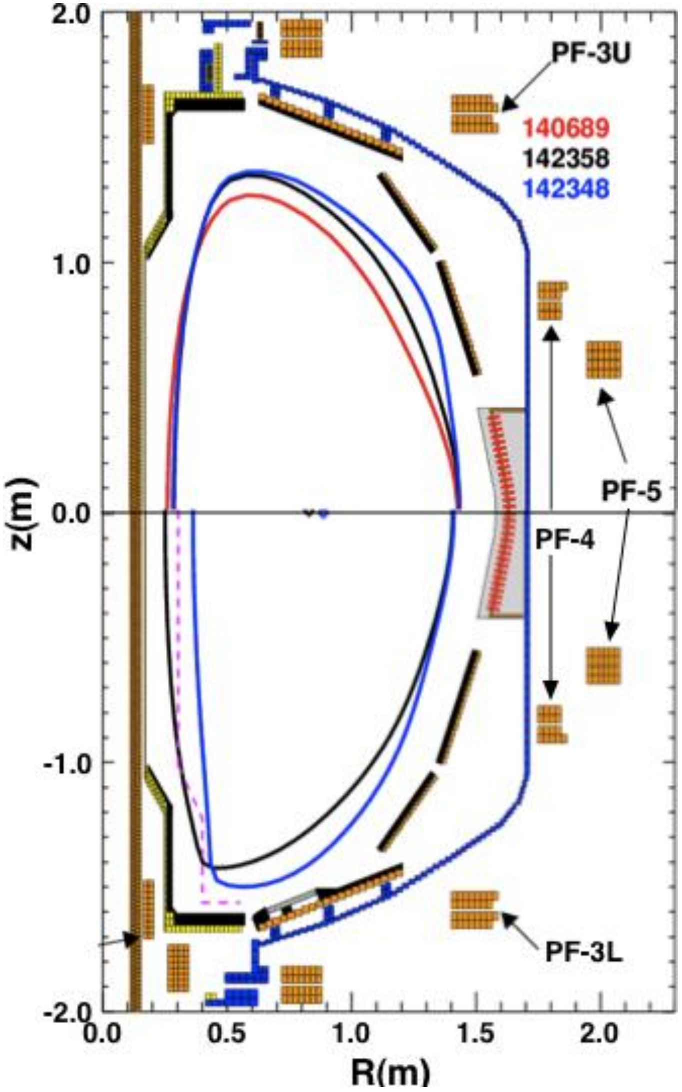
PAC27-6

- 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

PCS upgrades & PF4 coil commissioned to support NSTX-U operations, provide shape control flexibility



- PF-4 coil used in both senses, relative to PF-5.
  - In same sense, gives more vertical field, needed for high current.
  - In opposite sense can increase squareness.
- Coil used in pre-programmed mode, and in shape control loop.
  - With PF-4/PF-5 ratios far larger than required for NSTX-Upgrade

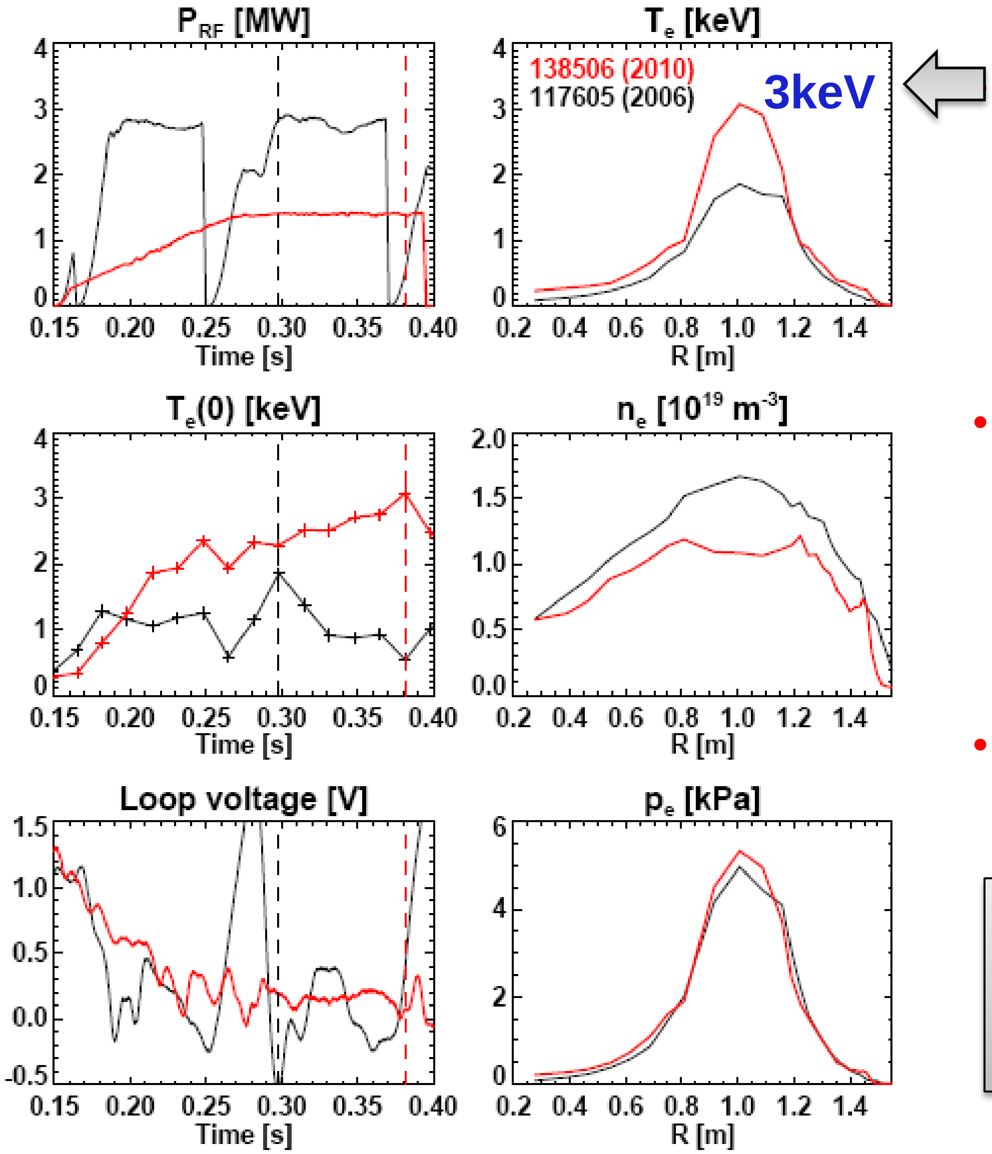
- Higher aspect ratio (NSTX-U) discharges demonstrated simultaneous high β_n (≥ 5) and high κ (≥ 2.6)
- Compare new, higher aspect-ratio boundary, consistent with NSTX-U centerstack, with current high performance plasma shape.

Backup

Waves and Energetic Particles

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

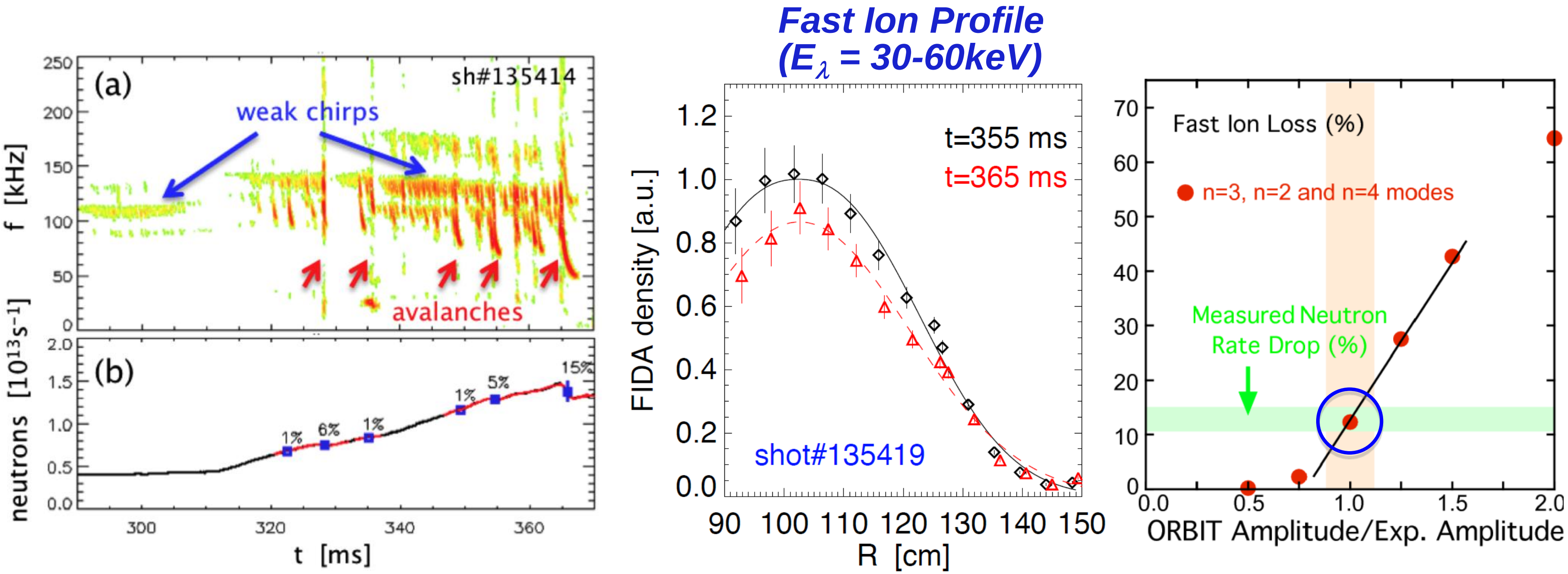
  - Previous best at low I_P ~250kA was ~1.5keV at twice the power

- **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)**

Results project to ~100% non-inductive at P_{RF} = 3-4MW (will test further in 2011-12 run)

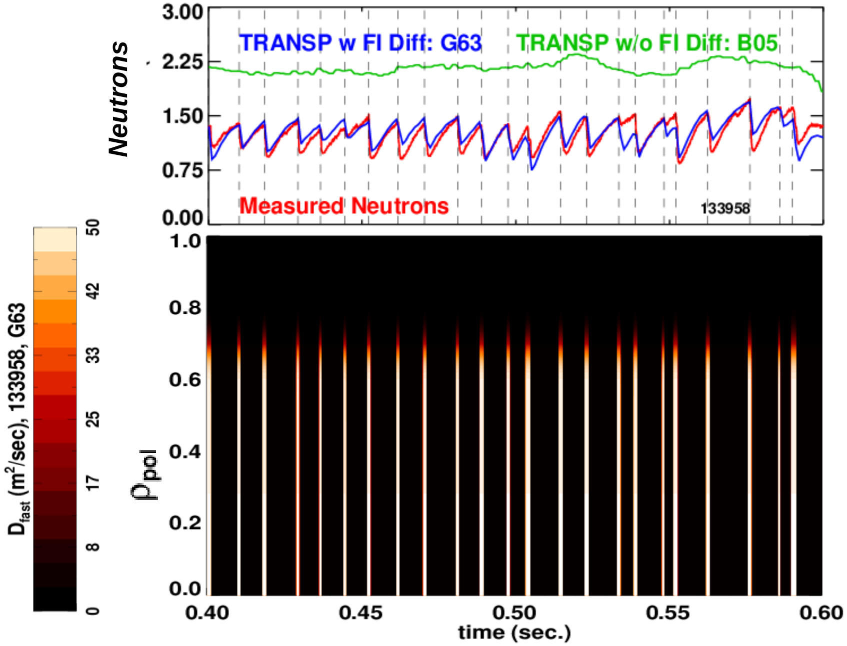
TAE-Avalanche induced neutron rate drop modeled successfully using NOVA and ORBIT codes



- **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**

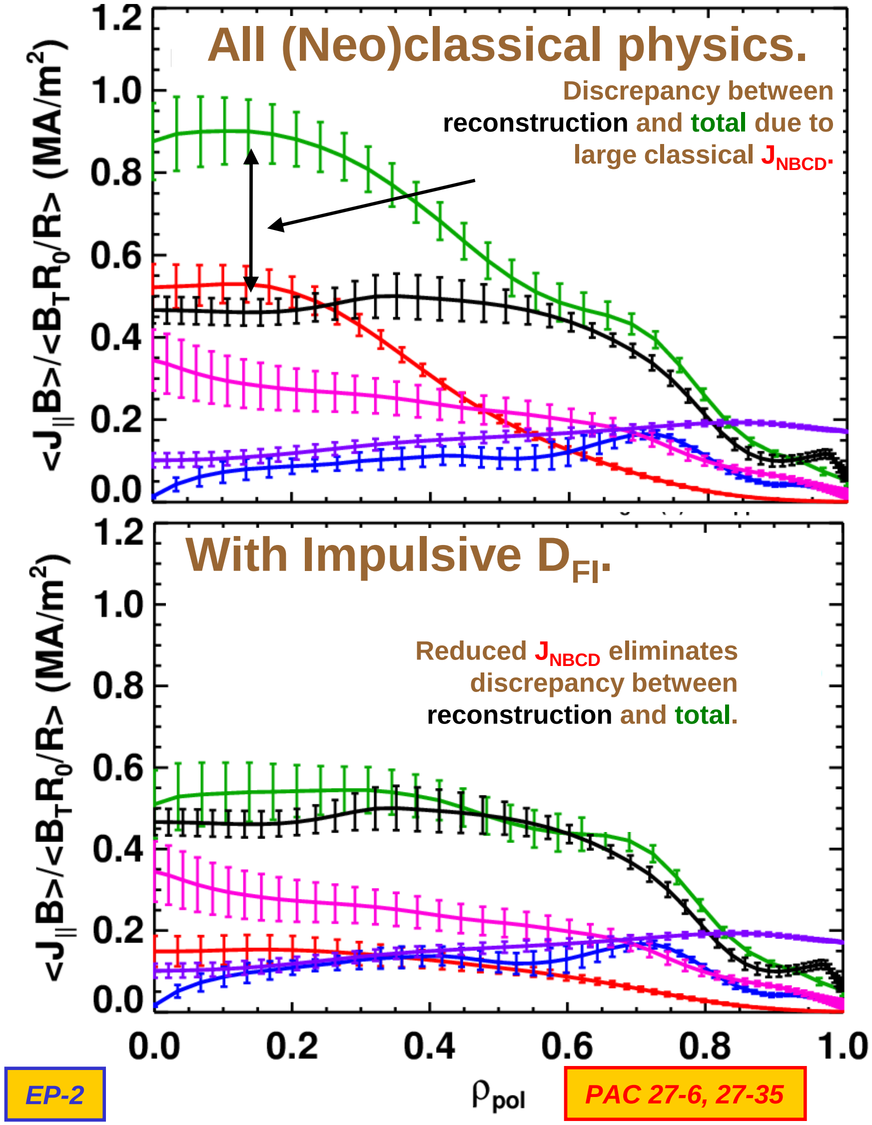
IAEA: E. Fredrickson ***IAEA: M. Podestà UCI*** ***IAEA:G-Y. Fu***

TAE Avalanches Lead to Major Modifications of the Beam Driven Current Profile



- Modeled TAE avalanches using spatially and temporally localized fast-ion diffusivity $D_{FI}(\psi,t)$.
  - Use S_n drops to determine $D_{FI}(\psi,t)$ details.
  - Reinforces need for predictive modeling of avalanche transport.
- FY-11 & 12 scenario modeling plans
  - Examine NSTX-U scenario results with various D_{FI} profiles, improved equilibrium solvers.
  - Interface with transport TSG to identify plausible transport models.

700 kA High-β_P with Rapid TAE Avalanches



All (Neo)classical physics.

Discrepancy between **reconstruction** and **total** due to large classical J_{NBCD}.

With Impulsive D_{FI}.

Reduced J_{NBCD} eliminates discrepancy between **reconstruction** and **total**.

EP-2

PAC 27-6, 27-35

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

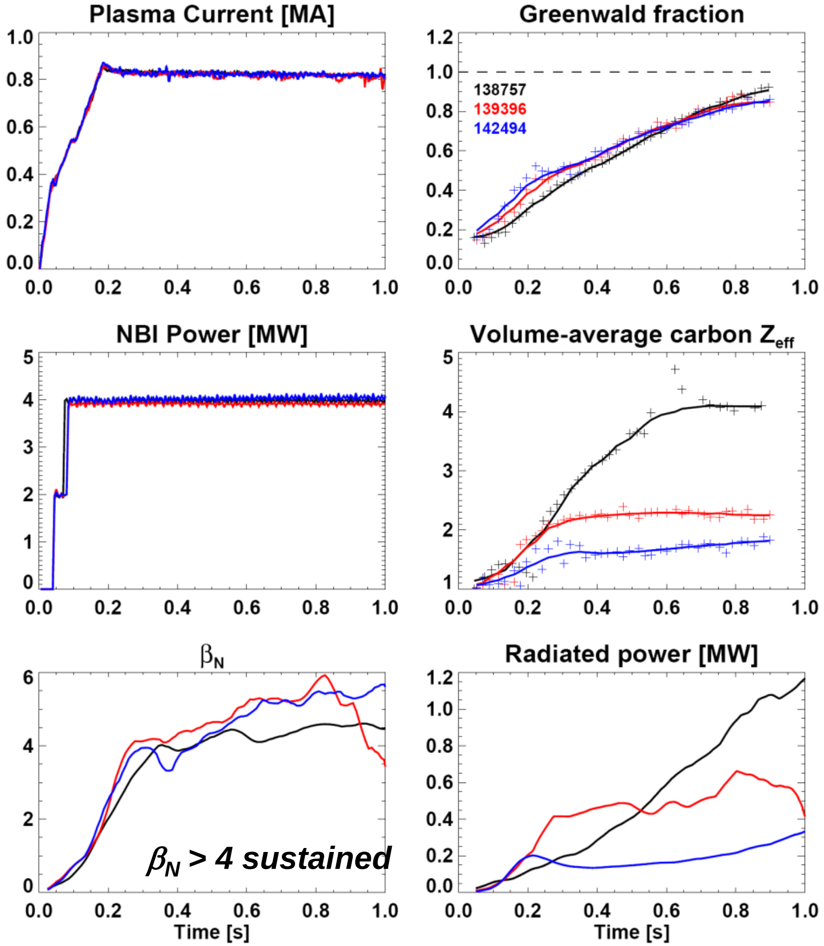
  - Extend *AE avalanche results obtained in L-mode to H-mode scenarios/profiles (BES + improved reflectometry + tangential FIDA)
  - Compare measured to predicted fast-ion transport – M3D-K validation in support of ITER, NSTX Upgrade, next-steps

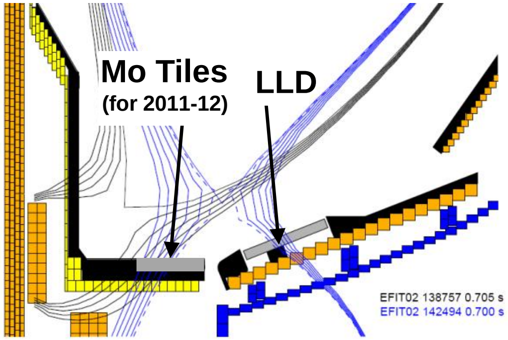
Backup

Lithium Research

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

- **No evidence of Mo in plasma except from large ELMs, disruptions**





◀ Strike-point (SP) on inner carbon 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)

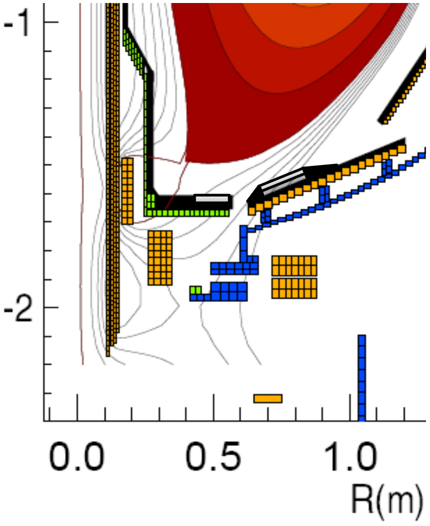
- ELM characteristics:
  - No ELMs, no → small, small → larger
- Impurities reduced, high β_N sustained

- **Understanding roles of δ/Li/Mo/ELMs motivates Mo tiles on inboard divertor**

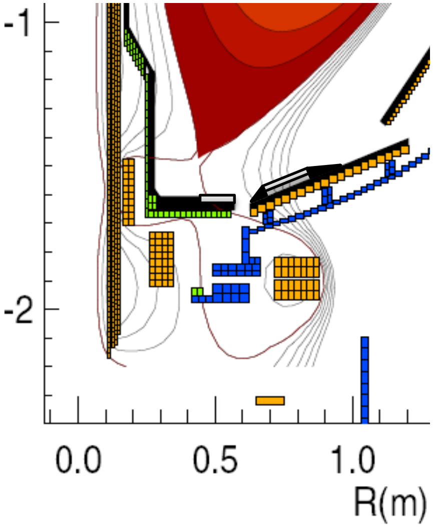
- **Chemistry of Li on C and Mo/LLD critical, complex, under-diagnosed**

Addition of IBD Mo tiles would enable important divertor studies

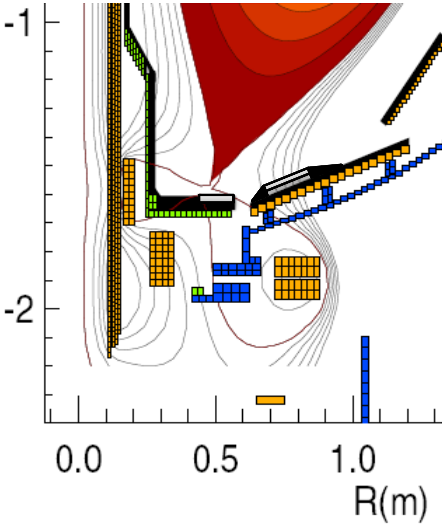
- Help quantify fraction of core C coming from lower divertor for high-δ shapes
- Potentially reduce C content of Li ELM-free scenarios
- Characterize Mo performance to inform choice of div/CS PFC in Upgrade
- Apply Li (LiTER) to IBD/OBD Mo for partial/full LLD
- If LLD present, LSN with both strike-points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



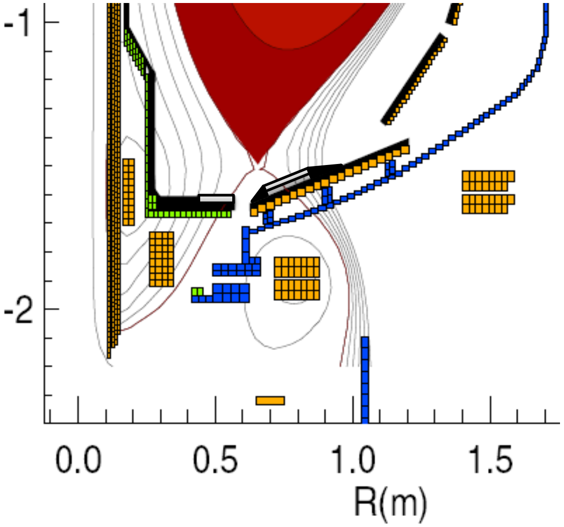
Standard divertor on C



Standard divertor on Mo

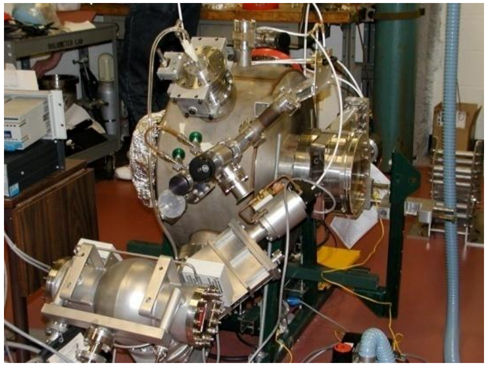


Snowflake on Mo (also possible on C, not shown)



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

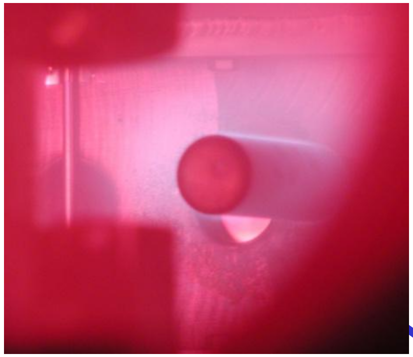
NSTX lithium research is an integral part of a program to assess viability of Li as a PFC concept for magnetic fusion



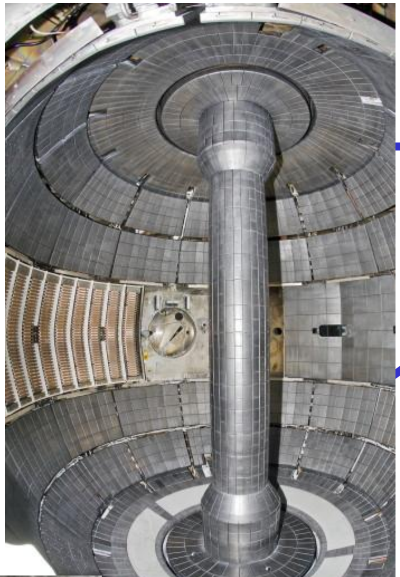
PFC test facility.

NSTX probe, Purdue collaboration, modeling…

LTX now operating:
Li evaporated into helium glow ->
All-metal walled comparison to NSTX.



NSTX: Only diverted, NBI-heated tokamak studying Li at present. LLD installed FY10.



EAST / NSTX: Li collab. achieved H-mode !

NSTX Upgrade, Fusion next-steps.

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

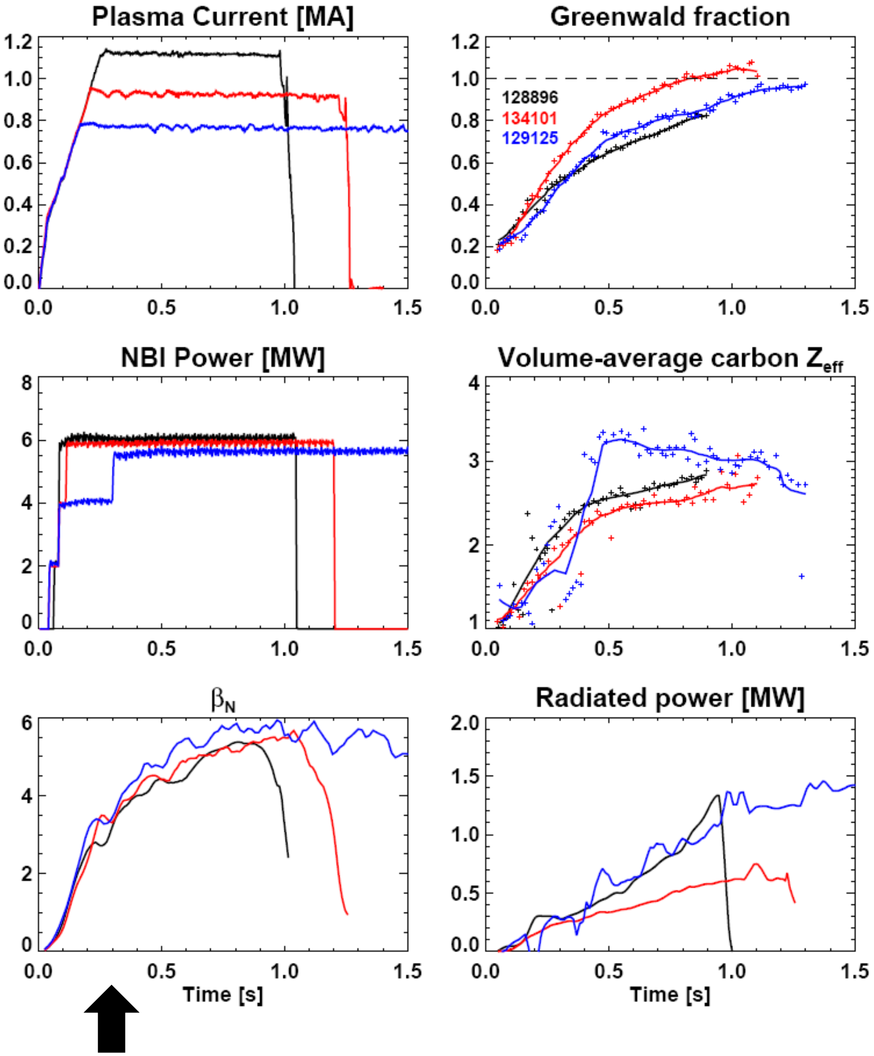
- 4 LLD plates formed ~20cm wide annulus in lower outboard divertor
  - Heatable surface of porous molybdenum (Mo)
  - Loaded with Li by LiTER evaporation from above

LLD Impact on Plasma Performance:

- LLD did not increase D pumping beyond that achieved with LiTER
  - C present on LLD 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**

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 / $n_{Greenwald}$ → 1

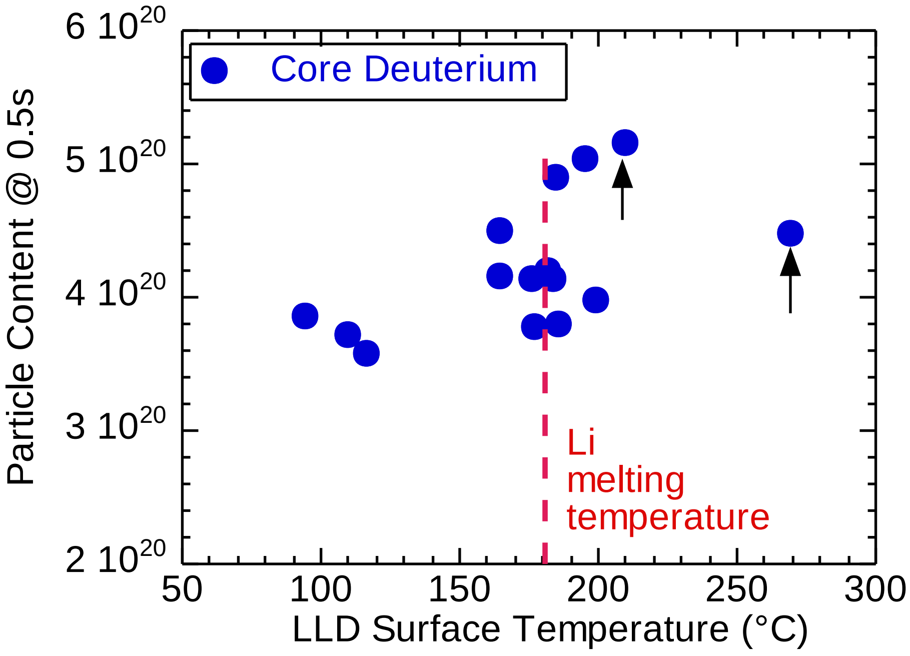
- Modeling indicates n_e / $n_{Greenwald}$ = 0.7-0.9 likely required for 100% NICD

◀ Carbon Z_{eff} = 2.5-3 acceptable, and will attempt to reduce further in FY11-12 research

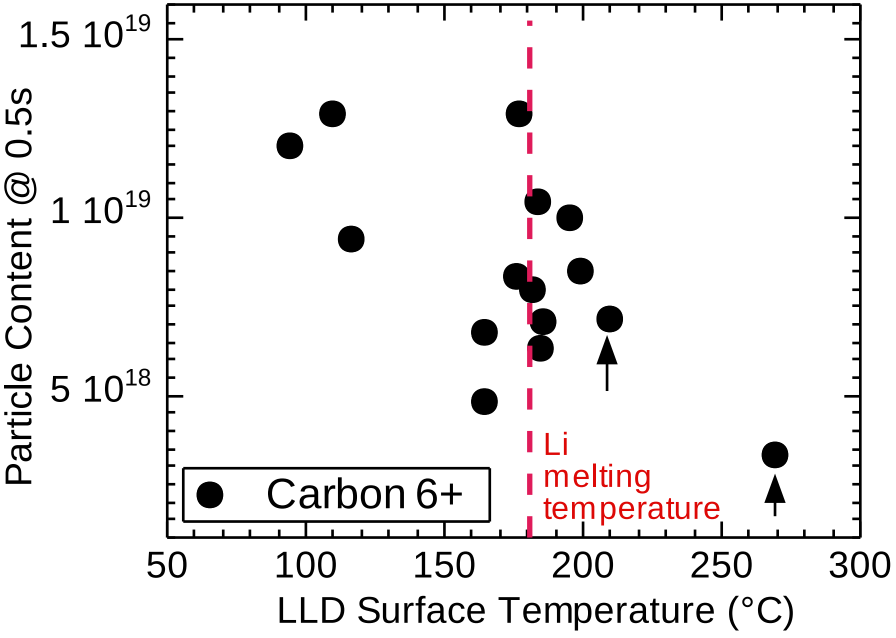
◀ Radiated power < 25% of NBI power, which is acceptable

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

LLD pumping similar above or below Li melting temperature



(for ▲ points one plate 80°C lower.)



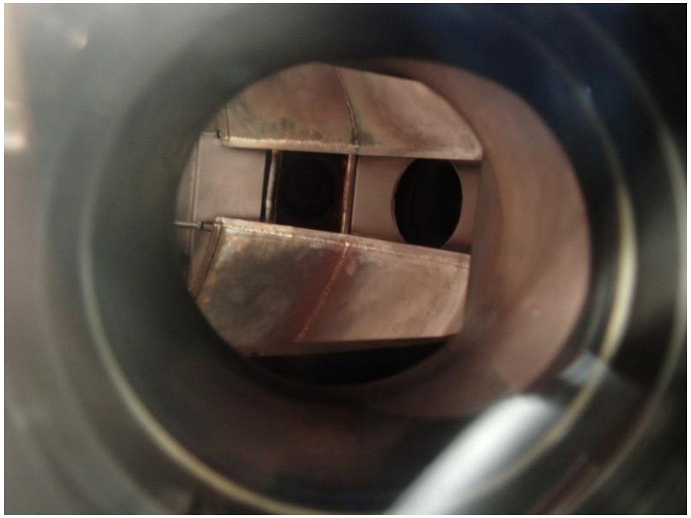
(for ▲ points one plate 80°C lower.)

- Constant deuterium fueling for LLD 100% Li fill conditions, 4 plates air heated.
- As LLD surface temperature transitioned from solid temperatures to the liquid regime, the plasma electron and deuterium content remain relatively constant.
- Core carbon C6+ content decreased - may be due in part to increased ELMing and edge turbulence.

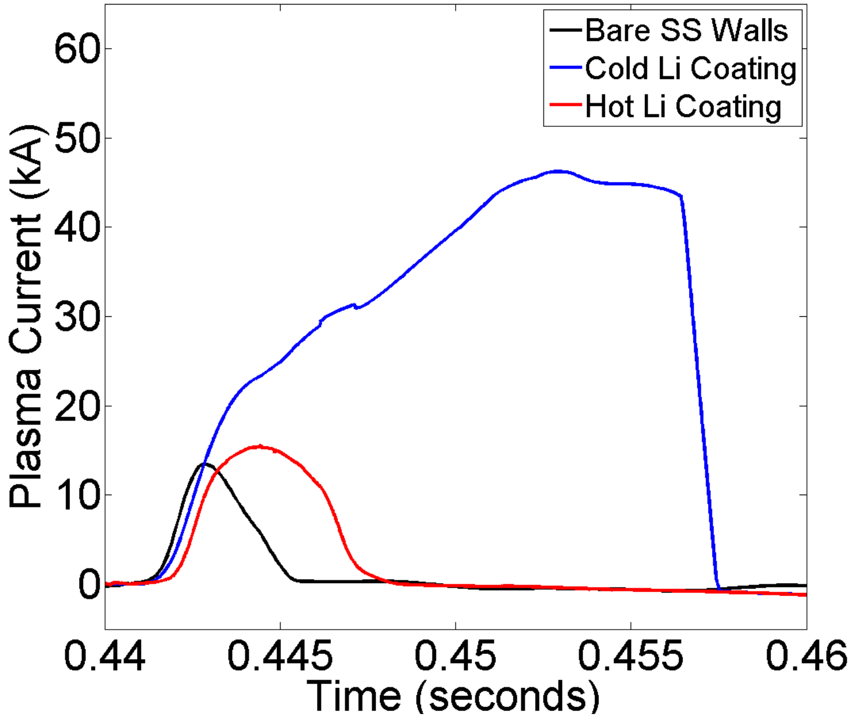
- No systematic trend in D-alpha, wall inventory, or ion pumping with a transition above the Li melting temperature.

Full metal wall data from LTX shows thin liquid film reacts rapidly with residual/background gasses

- LTX is a full high temperature, high Z wall operation of a tokamak
  - lithium evaporated into 5 mTorr helium fill to disperse coating.



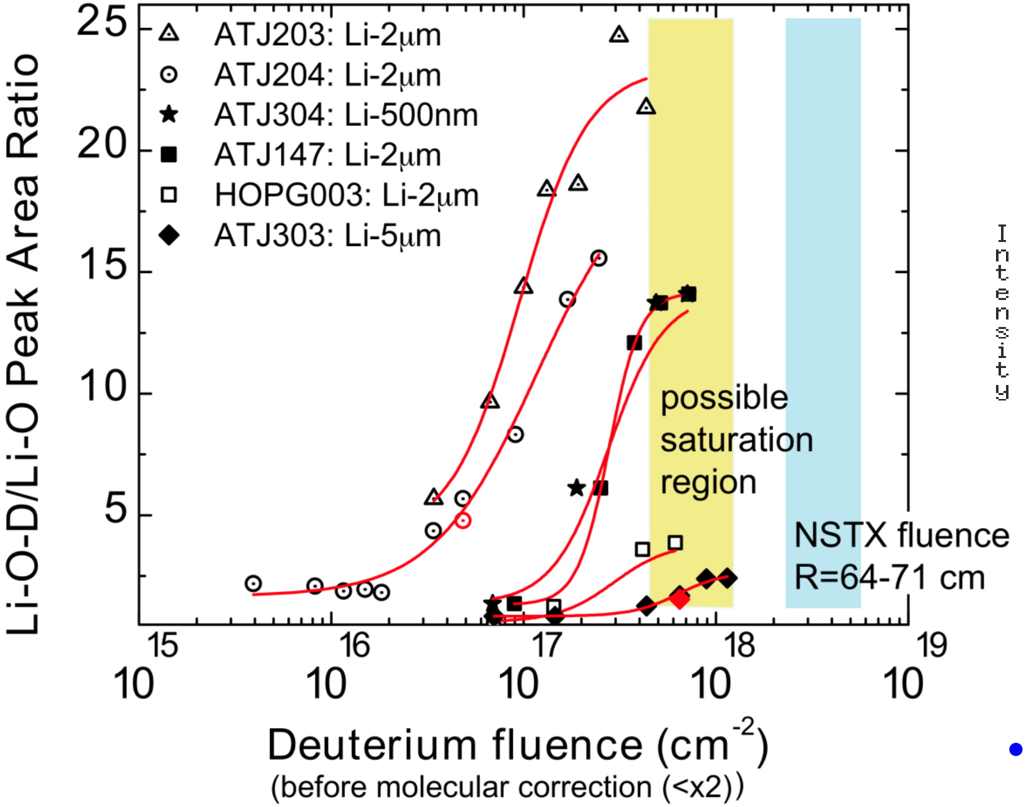
- Deposition rate ~0.75 g/hour/evaporator
  - 3 hour duration
  - est. 1.6 micron average thickness.
- Thin liquid lithium coating darkened rapidly
  - indicative of reactions with background gases or oxidized substrate
  - no visual evidence of metallic surface.



- Hot (300 °C) shell with thin lithium coatings does *not* exhibit reduced recycling
  - but strong lithium emission observed
  - relevant to NSTX LLD operation.

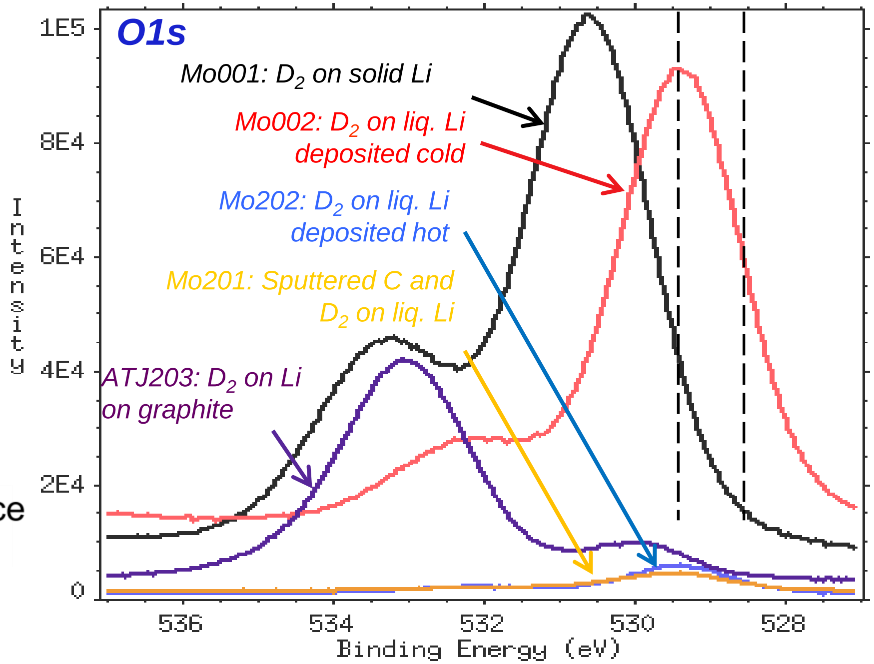
Lab analysis of NSTX exposed samples (Purdue U.)

Deuterium saturation of Li



- Modeling by the TBDFT code showed the probability for D to bond to a Li-C complex is 3 x larger than to C

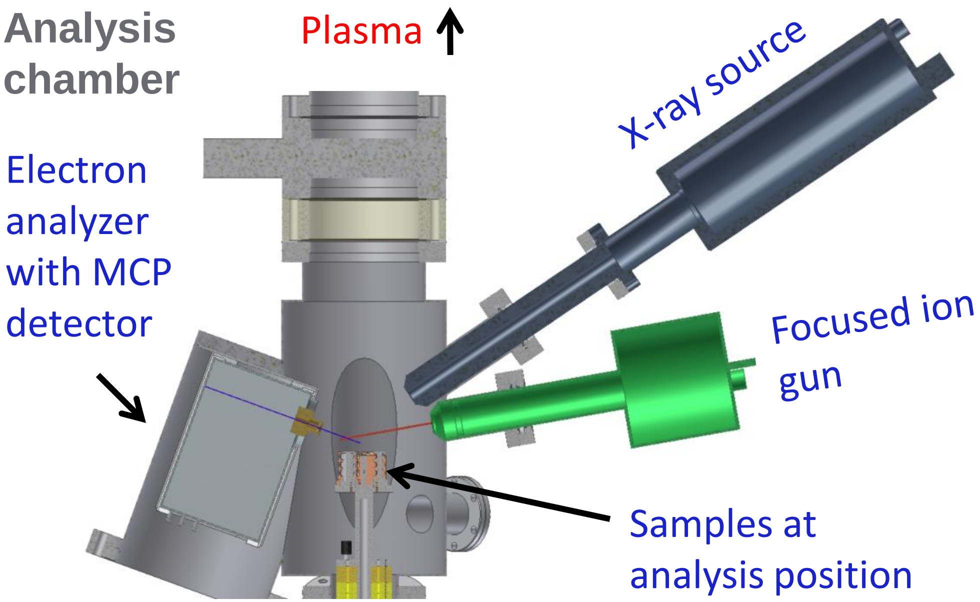
XPS O1 spectra for the LLD samples 30 mins D_2 irradiation of Li on:

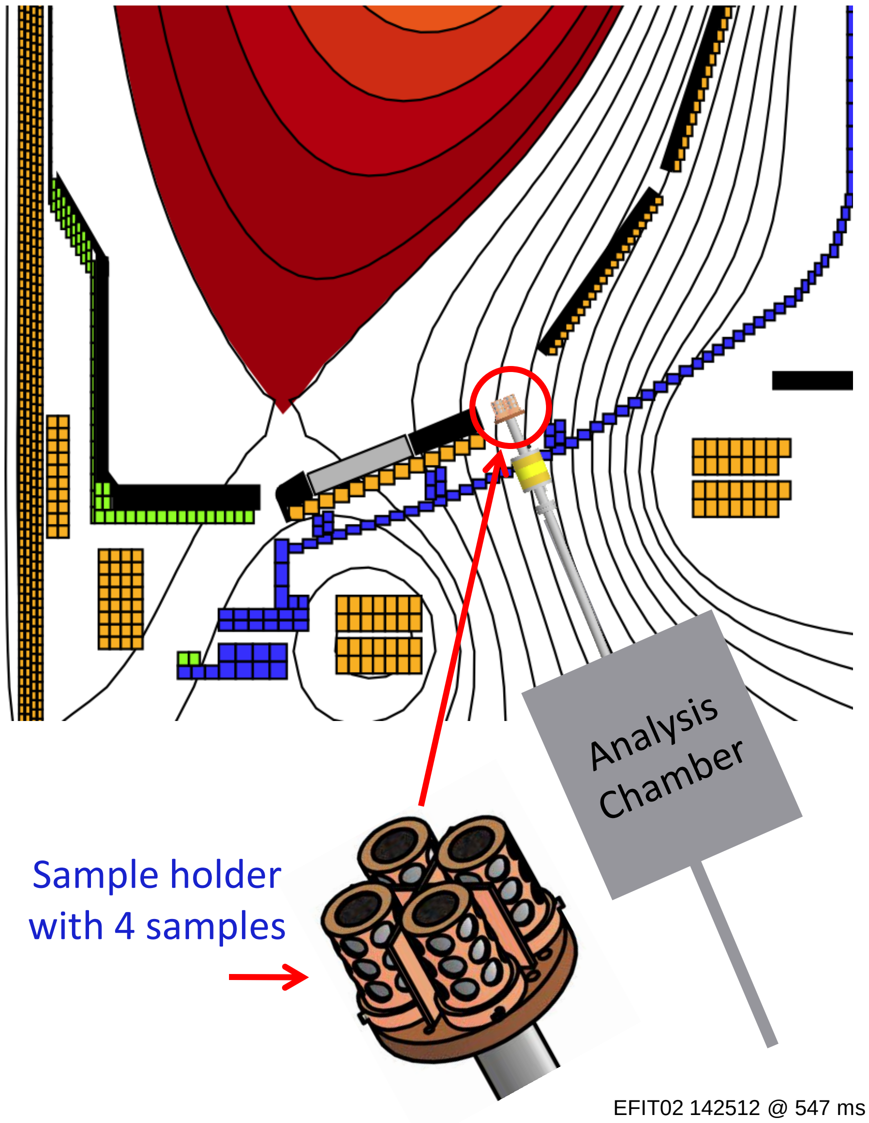


- XPS O1s spectra show changes in surface chemistry with D irradiation of Li deposited on cold / hot / C contaminated Mo and graphite.
- Suggests Li on Mo is interacting with D and diffusing into Li.

MAPP probe will be installed for FY11-12

- MAPP is the first in-vacuo surface analysis diagnostic directly attached to a tokamak, capable of shot-to-shot chemical surface analysis of material samples (solid Li, liquid Li, Mo etc).
- MAPP will enable the correlation of PFC surface chemistry with plasma conditions and point the way to improved plasma performance. (R12-1)





Backup

NSTX-MAST
Collaboration Opportunities

1. Develop common understanding, vision, design of ST-based FNSF/CTF

- What is mission scope?
  - Limited to test modules with small total surface area?
  - Try for TBR = 1?
  - Aim for net electricity production?

- What are wall loading requirements, assumptions?
  - How does this drive assumed physics scenarios?
  - How does this impact ongoing research on NSTX and MAST?

- What are best design, maintenance approaches?
  - Sharing of engineering and design expertise most valuable
  - Could be good project as Upgrade design activities reach closure

Resources needed: ~1-2 FTE total: design, mechanical engineering, physics input

J. Menard visiting Culham/MAST in April 2011 to share PPPL ideas, begin discussions

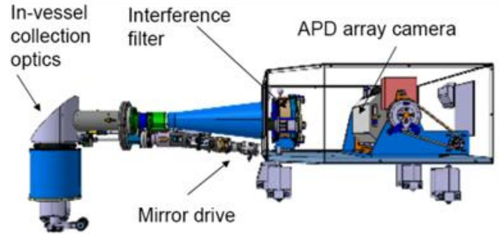
2. Collaborate on physics topics important to ST, FNSF, also ITER & Demo

Discussions with MAST and NSTX physicists and managers Sep 2010 - Mar 2011 identified topics of mutual interest:

- Steady-state, high performance scenarios
  - Turbulent ion and electron transport
  - Longer term – advanced divertors
- Energetic particle physics
  - NBI current redistribution
- 3D physics
  - Perturbed 3D equilibria

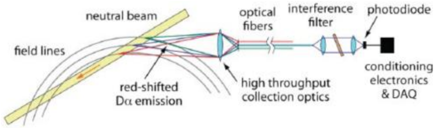
Turbulent transport has important implications for size/design of ST as FNSF, and for ITER, Demo

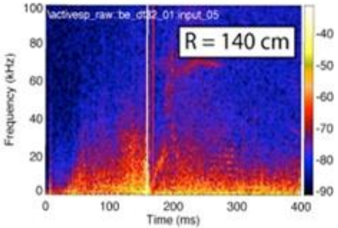
MAST



2D BES to be used 2011

NSTX





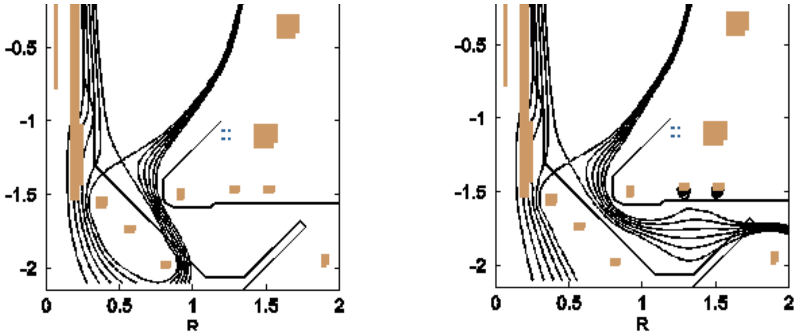
Initial 2D BES data obtained 2010
(+ existing high-k scattering)

- NSTX, MAST observe similar confinement scaling that differs from conventional A – strong ~ 1/ν* scaling – what is underlying physics?
- Both devices now have similar ion turbulence diagnostics – 2D BES
- MAST expressed particular interest in PPPL/NSTX experiment-theory comparison expertise
- Potential collaborators:
  - NSTX: S. Kaye, D. Smith, Y. Ren, W. Guttenfelder
  - MAST: A. Field, C. Roach, M. Valovic
  - GK theory: G. Hammett, W. Dorland, C. Roach, A. Schekochihin, H. Wilson

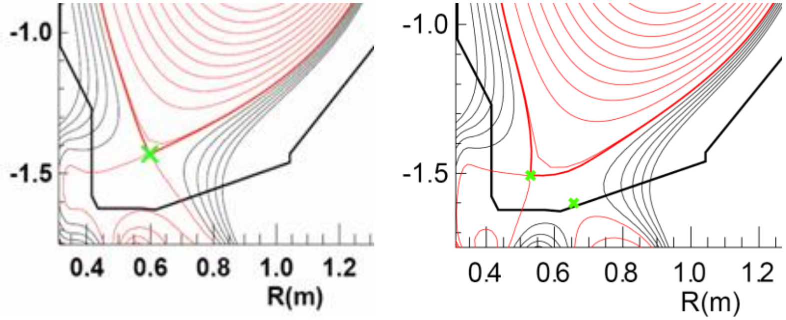
A. Field visited NSTX in February 2011 to collaborate with D. Smith, S. Kaye on BES

Advanced divertors will be needed for heat flux mitigation in Upgrades, FNSF, Demo

MAST Upgrade


Conventional *Super-X*

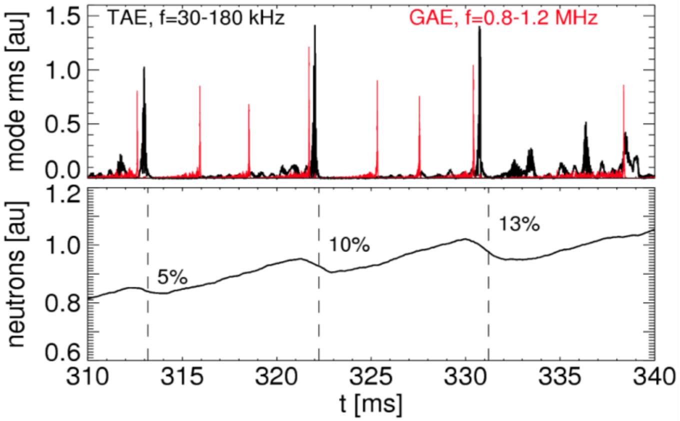
NSTX, NSTX Upgrade


Conventional *Snowflake*

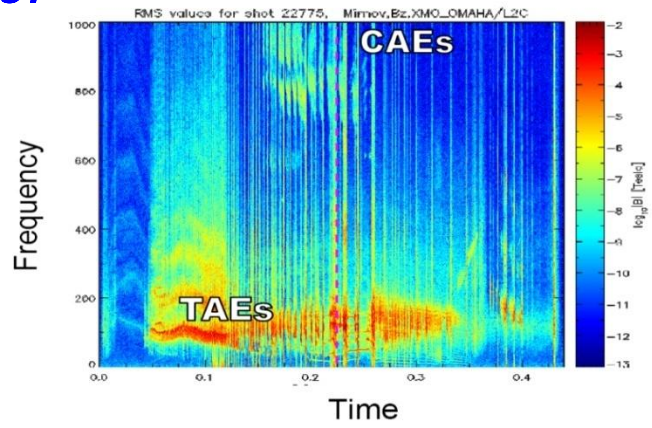
- MAST: effect of line-length on H-mode, NSTX: snowflake, LLD
- MAST-U: Super-X + cryos, NSTX-U: snowflake + Li pumping
  - Both will access substantial flux expansion, variation of line-length, pumping
  - Complementary: open vs. closed divertor, different pumping techniques
  - Will need advanced boundary control (example: control of multiple X-points)
- Potential collaborators:
  - NSTX: V. Soukhanovskii, R. Maingi, J. Canik, A. Diallo, D. Stotler, E. Kolemen
  - MAST: G. Fishpool, A. Kirk, H. Meyer, G. Cunningham

Energetic particle transport has important implications for NBI-CD, alphas for FNSF, ITER BP

NSTX



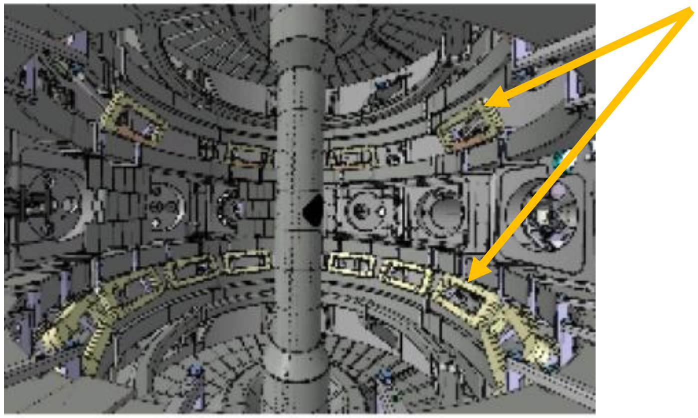
MAST



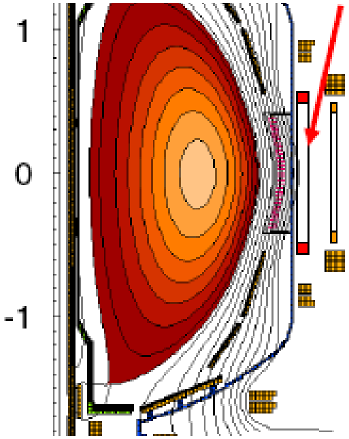
- NSTX, MAST observe multi-mode *AE, fast-ion transport
- NSTX has FIDA, NPA, … MAST has neutron collimator
  - Both also have BES for *AE eigen-function measurement
- MAST expressed particular interest in improving models for “anomalous diffusion” from *AE (for TRANSP analysis)
- Potential collaborators:
  - NSTX: E. Fredrickson, M. Podesta, G. Kramer, G. Fu, A. Bortolon
  - MAST: R. Akers, S. Pinches, M. Turnyanskiy

Improved 3D plasma response models needed to understand RMP ELM suppression for ITER, FNSF

MAST – in-vessel off-midplane RMP coils



NSTX – ex-vessel mid-plane RMP coils



- MAST, NSTX modify edge transport and ELMs with 3D fields
  - Have not yet suppressed ELMs with 3D fields
  - Both observe transport/plasma response to 3D fields sensitive to q_{95}
- MAST, NSTX have complementary 3D coil capabilities
- Collaboration initiated on perturbed equilibria, NTV rotation damping
  - US: DCON, IPEC codes → resistive DCON, GPEC code, UK: MARS, T7
- Collaborators:
  - U.S.: J.-K. Park + A. Glasser, A. Boozer, S. Sabbagh
  - Culham/UK: I. Chapman, Y. Liu, C. Gimblett, H. Wilson

Park and Glasser visited Culham in September 2010 to collaborate on plasma response models