NSTX

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

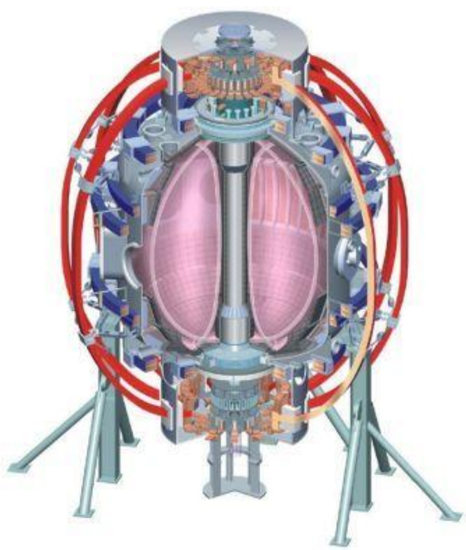
NSTX Upgrade Plans and Collaboration Discussion

Jon Menard / Masa Ono

for the NSTX Research Team

March 9, 2011
PPPL

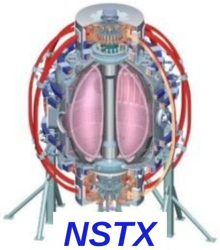
College W&M
Colorado Sch Mines
Columbia U
CompX
General Atomics
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Washington
U Wisconsin



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

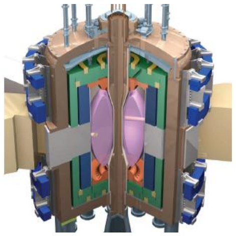
NSTX Upgrade will contribute strongly to toroidal plasma science and preparation for a fusion nuclear science (FNS) program

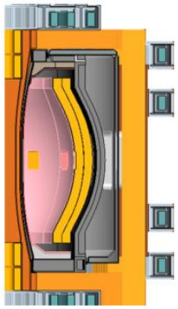
- NSTX:
  - Provide foundation for ST physics and performance and support ITER
- NSTX Upgrade:
  - Study high beta plasmas at reduced collisionality
    - Vital for understanding confinement, stability, start-up, sustainment
  - Assess full non-inductive current drive operation
    - Needed for steady-state operating scenarios in ITER and FNS facility
  - Prototype solutions for mitigating high heat, particle exhaust
    - Can access world-leading combination of P/R and P/S
    - Needed for testing integration of high-performance fusion core and edge
- NSTX Upgrade contributes strongly to possible next-step STs:
  - Plasma Material Interface Facility (PMIF)
    - Develop long-pulse PMI solutions for FNSF / Demo (low-A and high-A)
    - Further advance start-up, confinement, sustainment for ST
  - Fusion Nuclear Science Facility/Component Test Facility (FNSF/CTF)
    - Develop fusion nuclear science, test nuclear components
  - Pilot Plant usion Nuclear Science Facility
    - FSNF mission + power-plant relevant maintenance + Q_{eng} ~ 1


NSTX

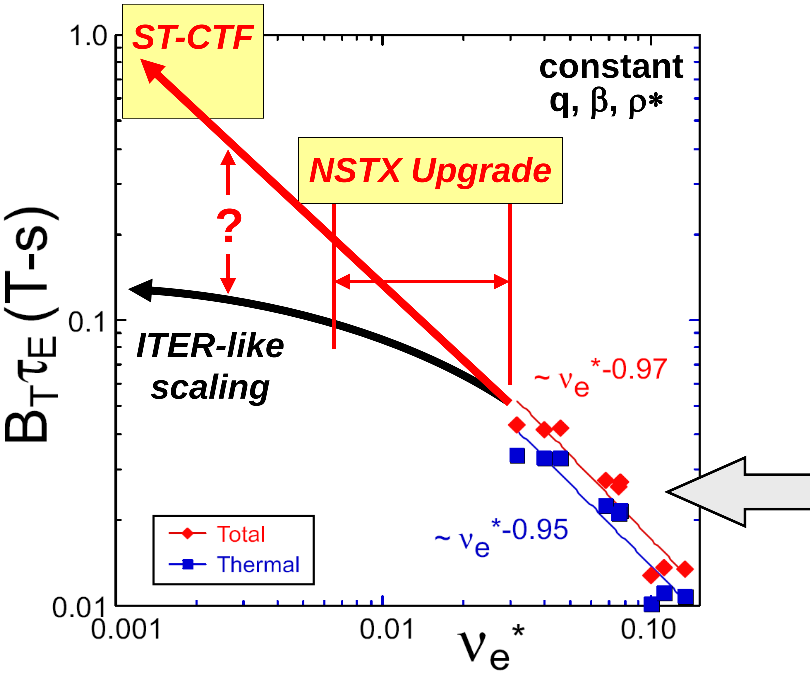

NSTX-U


PMIF (NHTX)


FNSF (ST-CTF)


Pilot Plant

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



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

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

ITER $B\tau_E$ (e-static g-Bohm) $\propto \rho_*^{-3} \beta^0$ $\nu_*^{-0.14}$ $q^{-1.7}$

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

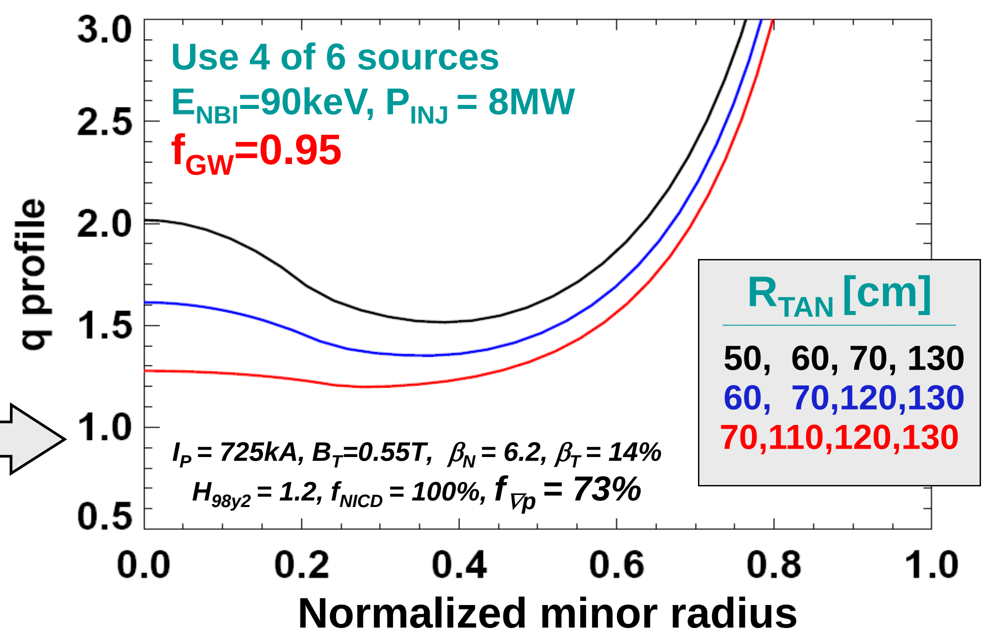
- NSTX observes much stronger scaling vs. ν*
  - Does favorable scaling extend to lower ν* ?
  - What modes dominate e-transport in ST ?
    - Electrostatic or electromagnetic?
- ν* also impacts RWM stability, rotation damping, range of other physics

- 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

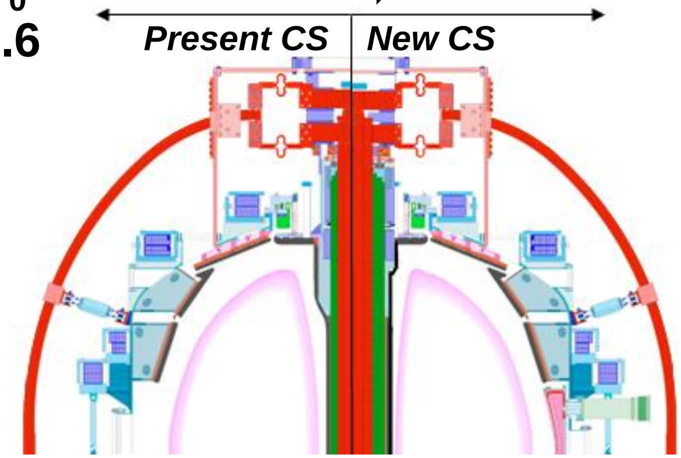
- q(r) profile very important for global stability, electron transport, Alfvénic instability behavior
  - Variation of mix of NBI tangency radii would enable core q control

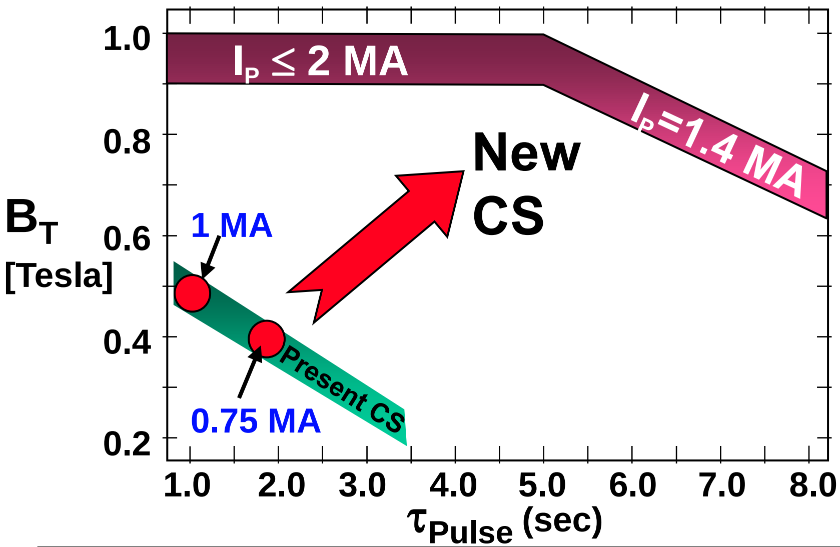


NSTX Upgrade will bridge the device and performance gap toward next-step STs

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

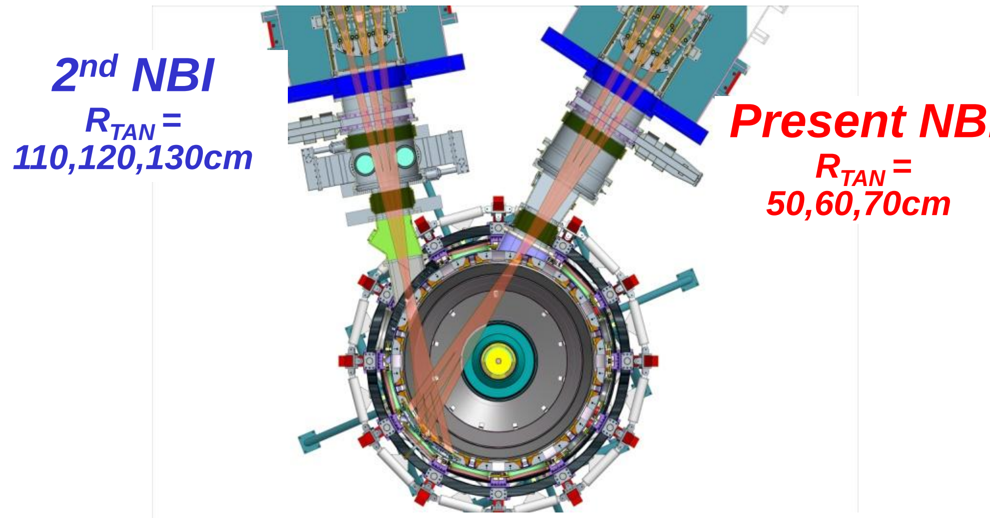
R_0/a = 1.25-1.3 ➡ 1.5-1.6

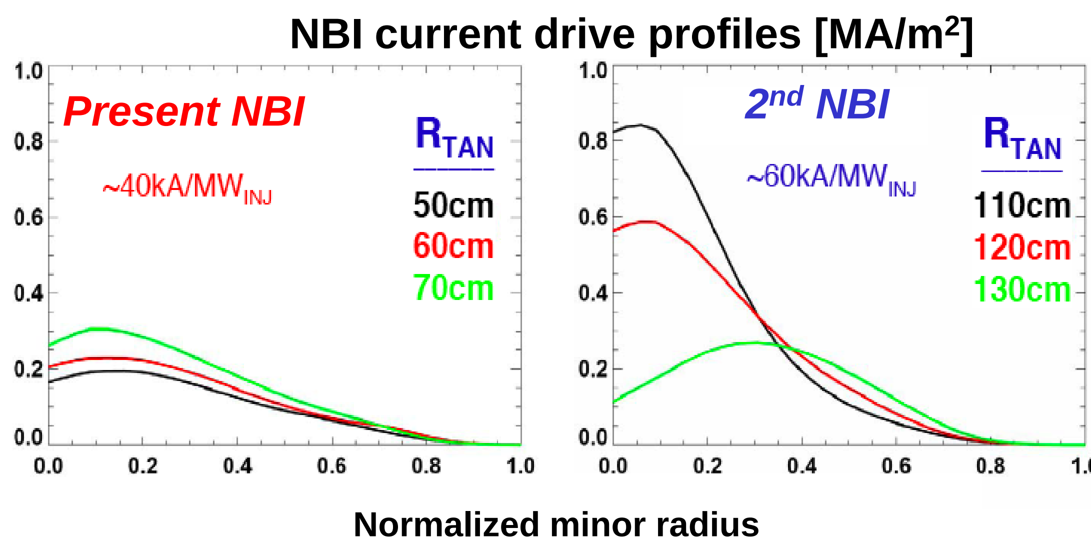




Magnet operation at ~1T (vs. 0.55T) within a factor of 2 of next-step STs

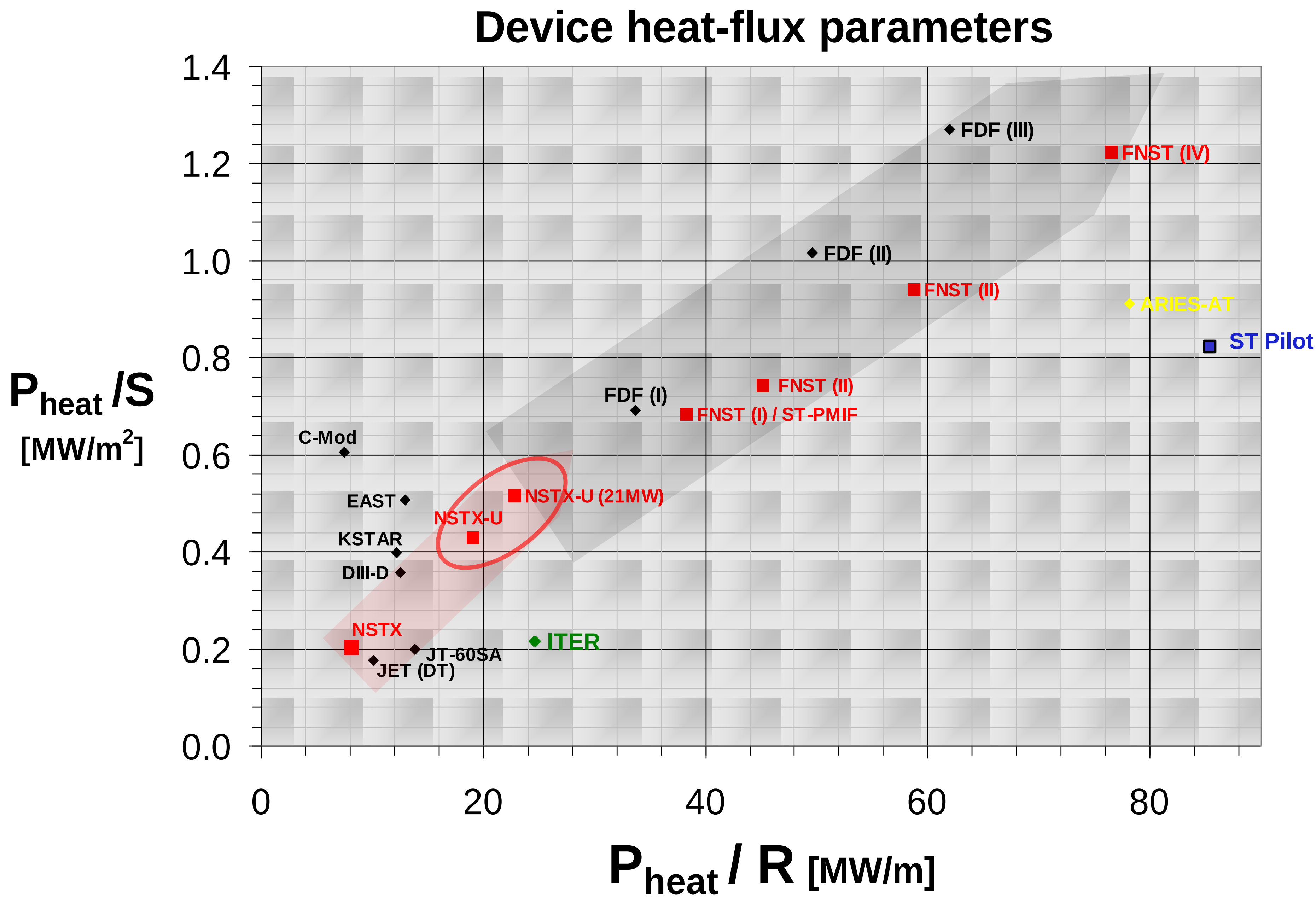
2nd NBI with 5 MW, 5s at larger R_{TAN}



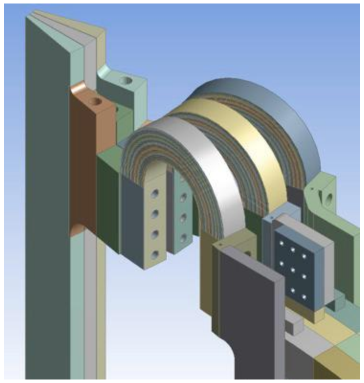


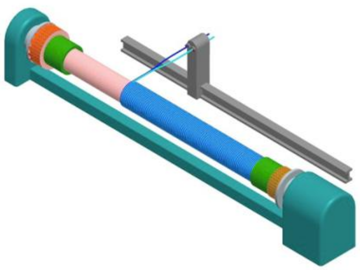
Up to 2 times higher NBI current drive efficiency, and current profile control

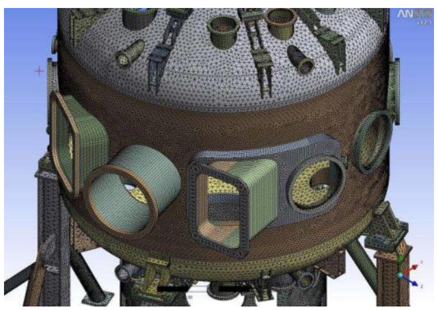
NSTX Upgrade will extend normalized divertor and first-wall heat-loads much closer to FNS, pilot regimes

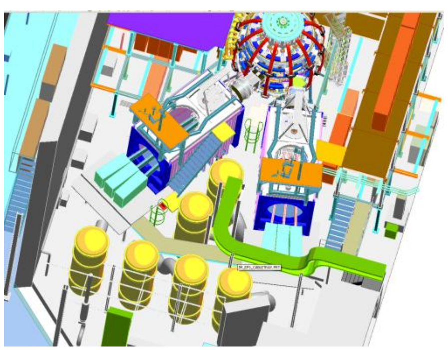


NSTX Upgrade Project
Good Progress to Date









☑ **CD-0 Approved - *February 2009***
- *Approval of mission need*
- *Begin Conceptual design*

☑ **Conceptual Design Review - *October 2009***

☑ **CD-1 Approved - *April 2010***
- *Approval of Alternate selection and cost range*
- *Begin Preliminary Design*
- *Begin Capital costing*

☑ **Preliminary Design Review - *June 2010***

☑ **CD-2 Approved - *December 2010***
- *Approval of performance baseline*
- *Technical, cost, schedule baseline frozen!*

❑ **Final Design Review - *June 2011***

❑ **Award critical and long lead procurements *- 2012***

❑ **Complete fabrication, assembly, test of TF/OH *– 2013***

❑ **Install NBI Vessel Cap, 2^{nd} NBI, new centerstack *– 2014***

❑ **Integrated system test, complete project *– 2014***

Near-term NSTX Programmatic Schedule

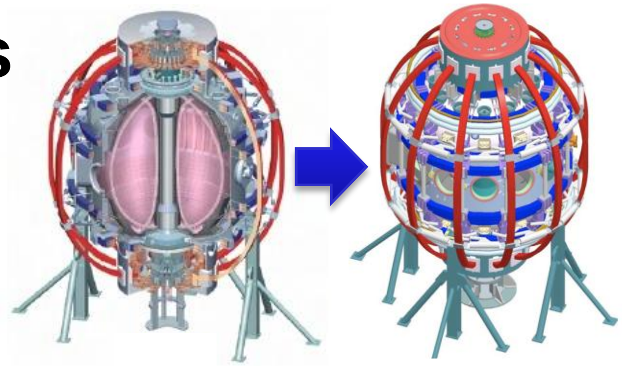
- Mar. 15-18, 2011 - Annual research forum for FY11-12 run
  - **You are invited to submit proposals!**
  - Web URL will be: http://nstx-forum-2011.pppl.gov/
- Jun. – Sep. 2011 - Finish FY2011 run (10 more run weeks)
  - Research Priorities:
    - Improve understanding of pedestal structure – joint with C-Mod, DIII-D, theory
    - Measure ion-scale (using new BES) + electron-scale turbulence
    - Optimize plasma stability and control at increased aspect ratio and elongation
    - Characterize performance of high flux expansion “snow-flake” divertor
    - Assess pedestal transport and stability response to 3D fields for ITER
- Oct. 2011 to end of Feb. 2012 - FY2012 run (10 run weeks)
  - Research Priorities:
    - Assess core transport predictive capability - joint research with C-Mod, DIII-D
    - Measure relationship between Li-conditioned surfaces and plasma behavior
    - Assess confinement, heating, and ramp-up of CHI start-up plasmas
    - Access stable high-performance scenarios with reduced density and collisionality
- April 2012 - Begin NSTX Upgrade outage

Collaboration

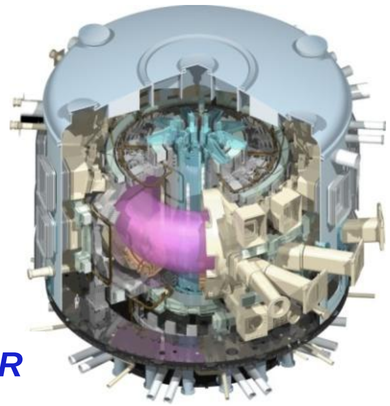
- NSTX researchers will become more available for collaboration during Upgrade outage (2012-14)
- We are working now to identify collaboration opportunities on a range of facilities:
  - DIII-D, C-Mod, KSTAR, EAST, …
- KSTAR collaboration opportunities available at:
  http://nstx.pppl.gov/DragNDrop/Program_PAC/Other_facility_plans/KSTAR_Research_Topics_2011-0302_YKOH_v2.pdf

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*

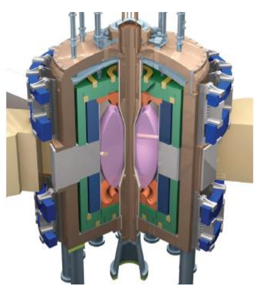


ITER

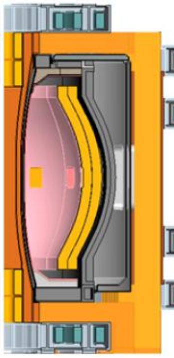
- **Extend understanding of tokamak / ITER**
  - Develop predictive capability for ITER/FNSF/Demo

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

Plasma Material Interface Facility (PMIF)

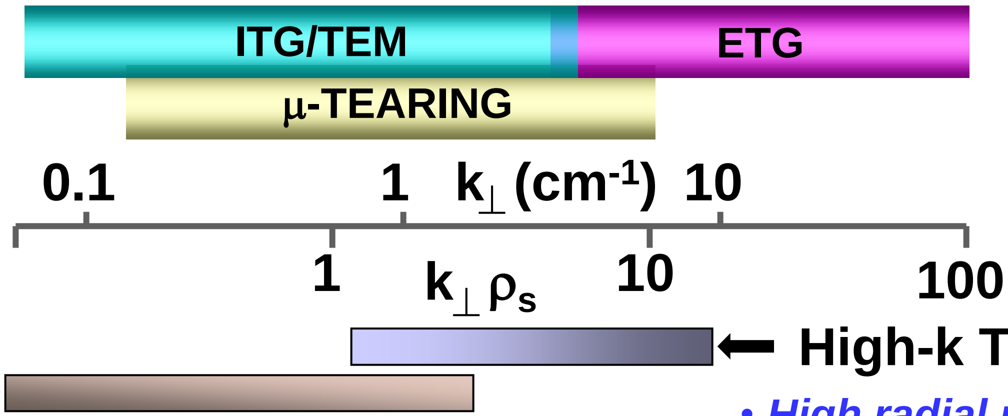


Fusion Nuclear Science Facility (FNSF)



Pilot Plant

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



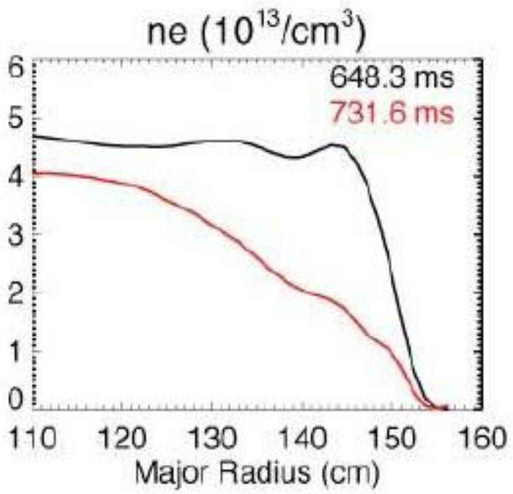
High-k Tangential Scattering

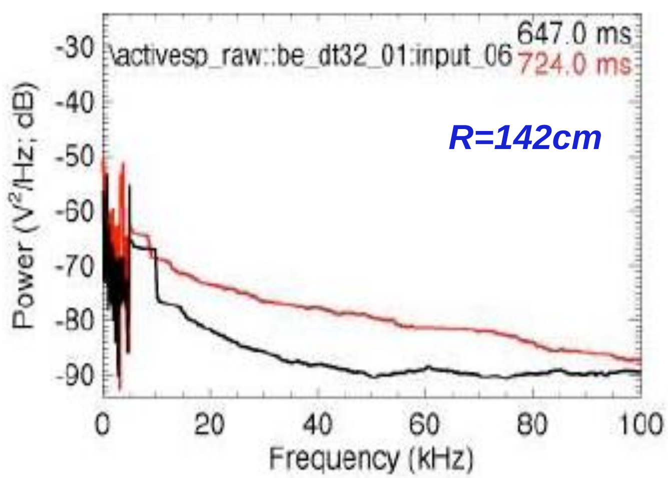
- *High radial resolution for electron-gyro-radius scale turbulence (f≲3MHz)*

Low-k BES

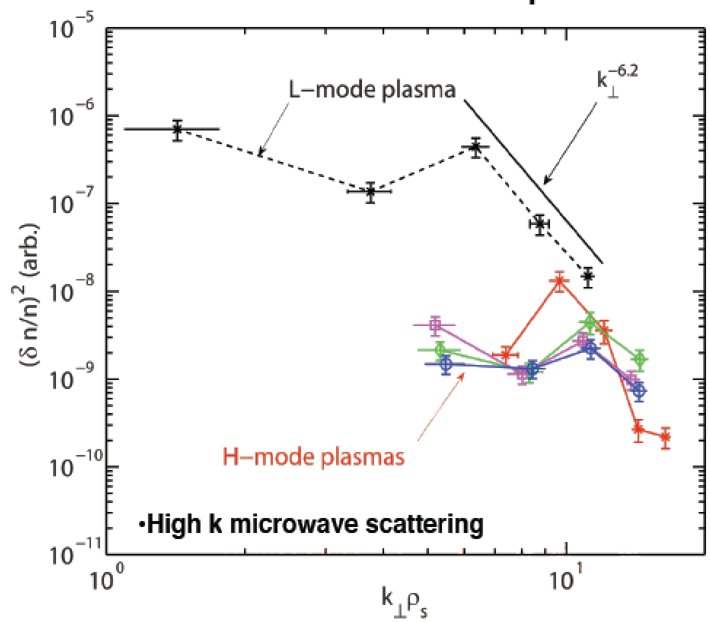
(Beam Emission Spectroscopy)

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





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

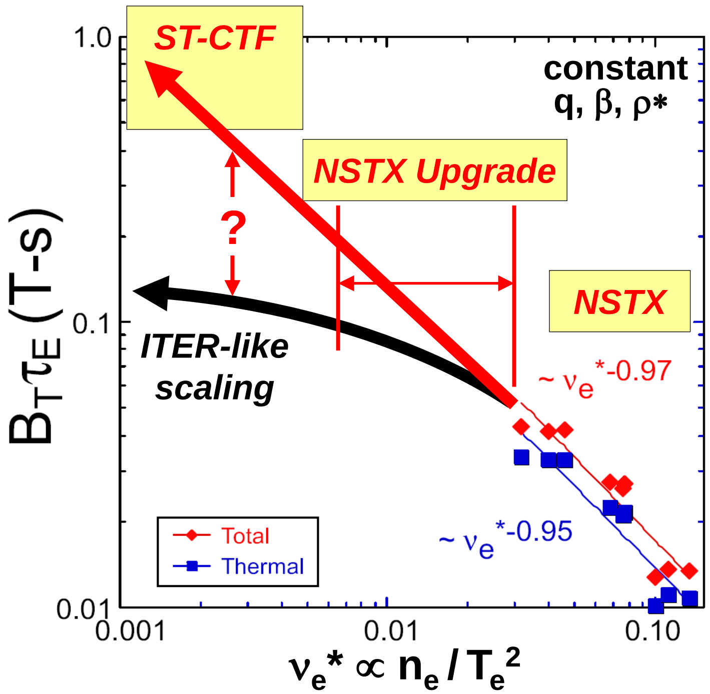


- ***BES also contributing to energetic particle research***

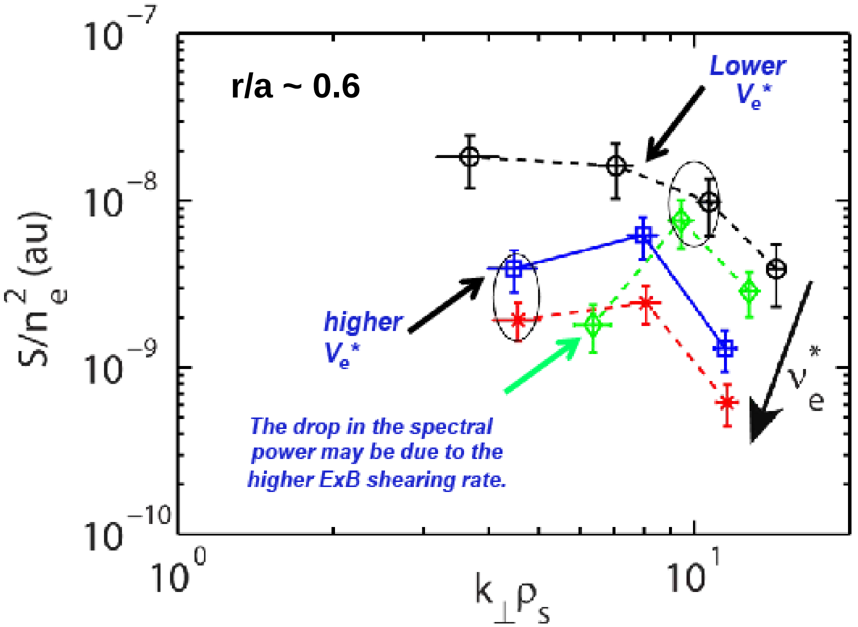
•*D. Smith, U. Wisconsin*

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

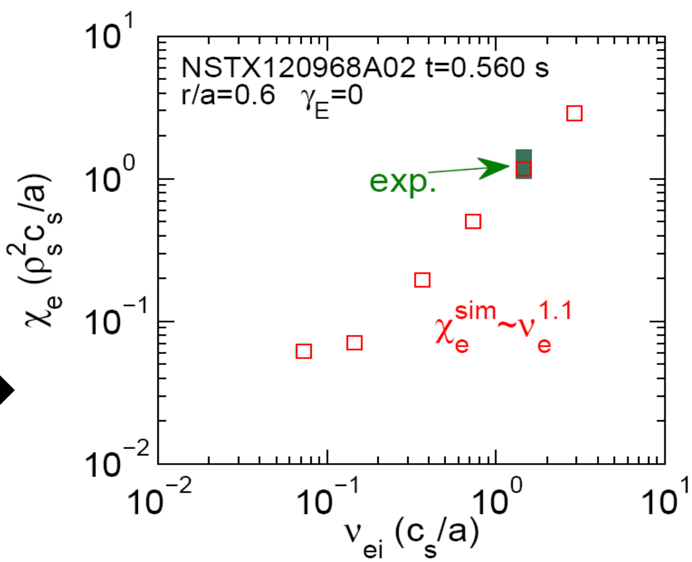
Previous NSTX (and MAST) experiments exhibit nearly inverse dependence of $B\tau_E$ on collisionality



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



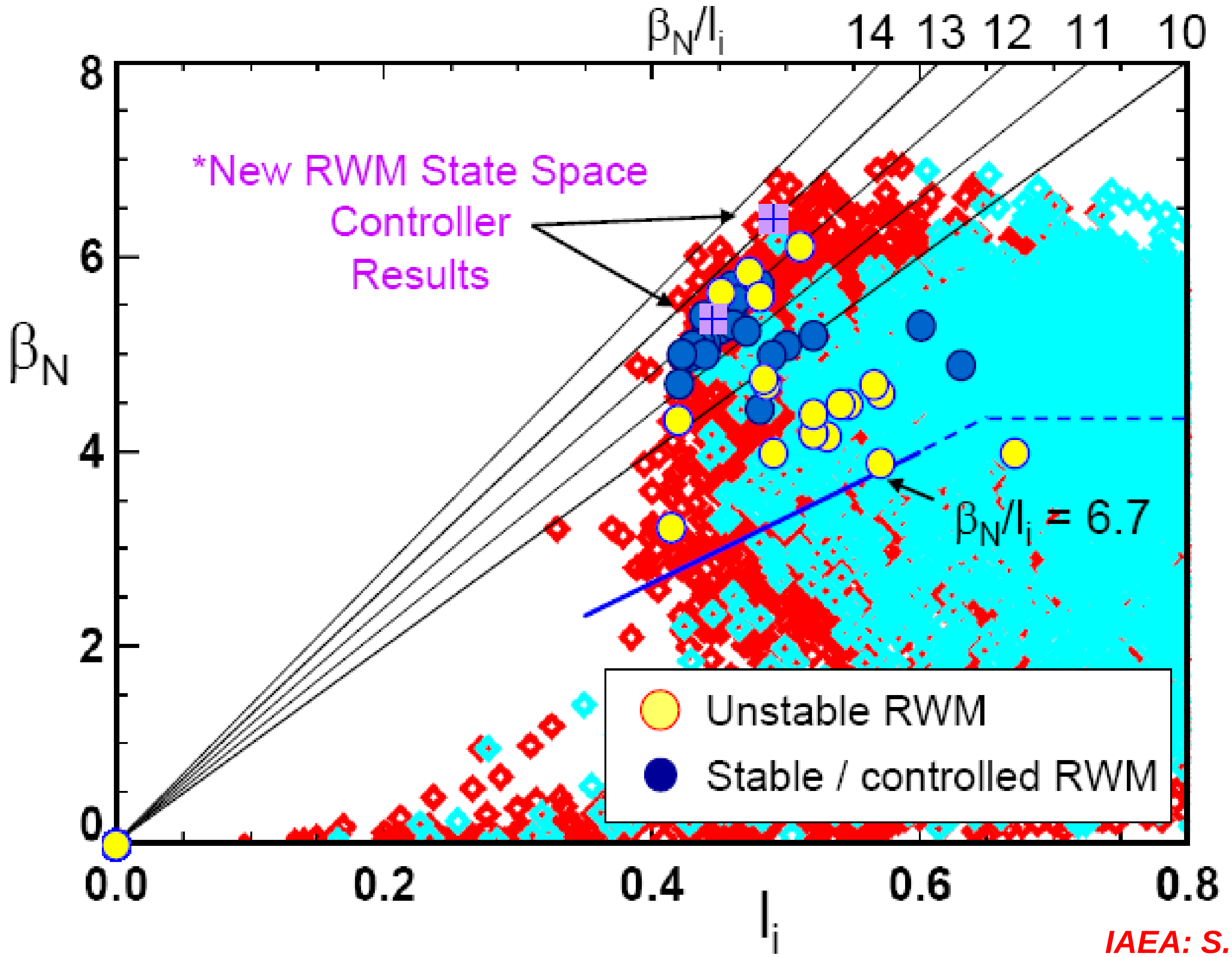
Non-linear GYRO simulations of lower-k μ-tearing predict χ_e proportional to ν*



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

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

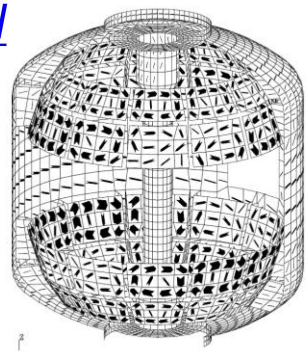
- High normalized beta β_N = 6–7 and high β_N / l_i = 10-14 routinely accessed
- Improvements: sensor AC compensation + combined B_P+B_R + state-space controller
- Disruption probability for β_N / l_i > 11 plasmas reduced from ~50% to ~14%



IAEA: S. Sabbagh, Columbia U

New RWM state space controller sustains high β_N

Full 3-D model

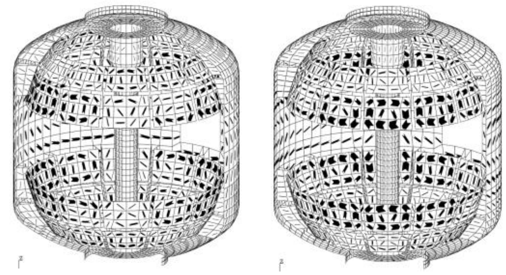


~3000+ states

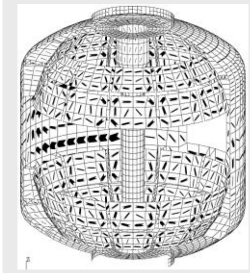
State reduction (< 20 states)

RWM eigenfunction (2 phases, 2 states)

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



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



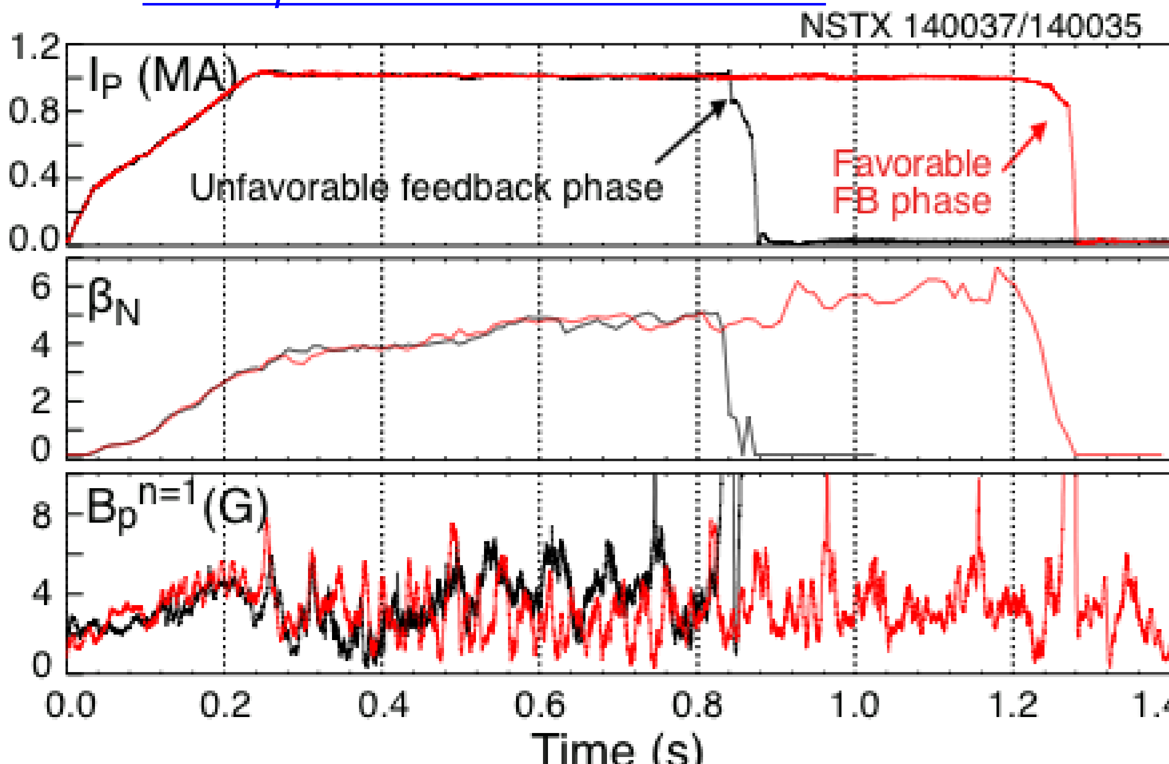
$\hat{x}_N$

truncate

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

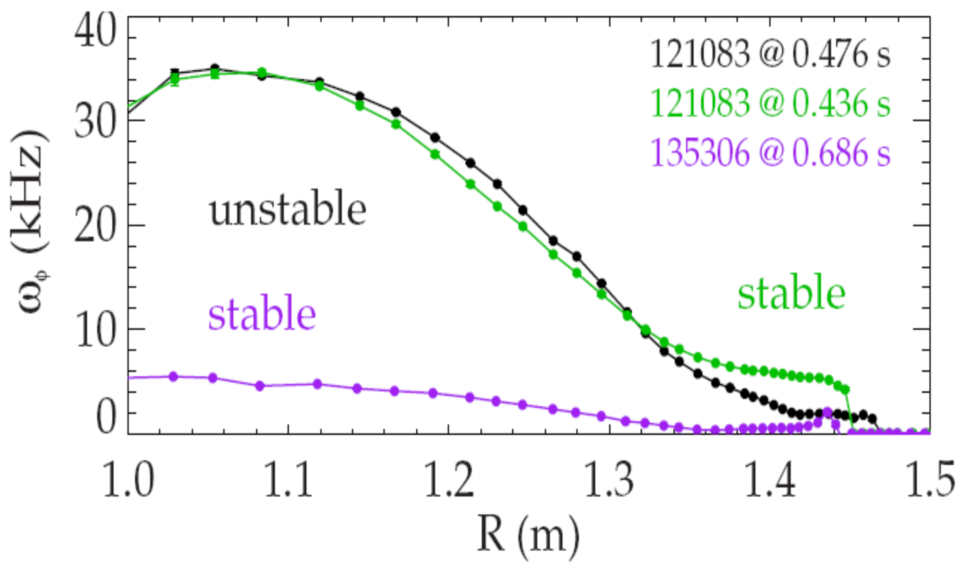
- *Controller can compensate for wall currents*
  - *Including mode-induced current*
  - *Examined for ITER*
- *Successful initial experiments*
  - *Suppressed disruption due to n = 1 applied error field*
  - *Best feedback phase produced long pulse, β_N = 6.4, β_N/l_i = 13*

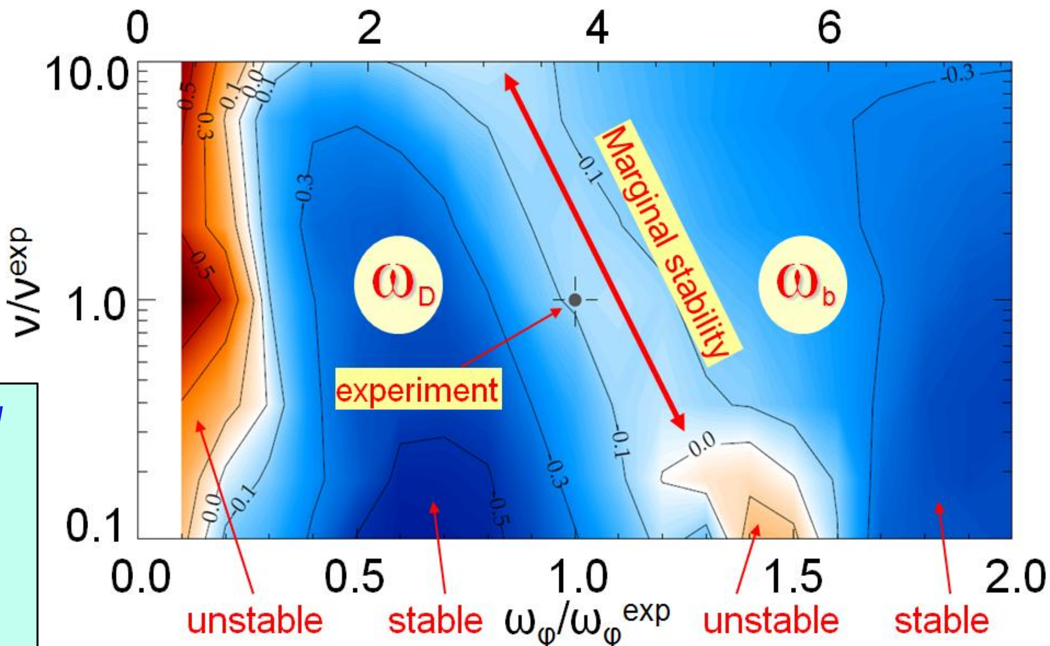
State space feedback with 12 states



Kinetic high beta RWM stability model tested
Resolved some RWM (Resistive Wall Mode) stability puzzles

- ***Observed that RWM can be unstable despite significant plasma rotation contrary to fluid-based theory***
- ***Obtained detailed measurements of RWM stability dependence on toroidal rotation to validate kinetic stability MISK models****
- *MISK code predicts stabilization of RWM from*
  - *precession drift resonance (ω_D) at low rotation*
  - *bounce resonance (ω_b) at high rotation*
- *Plasma is marginally unstable at intermediate rotation*

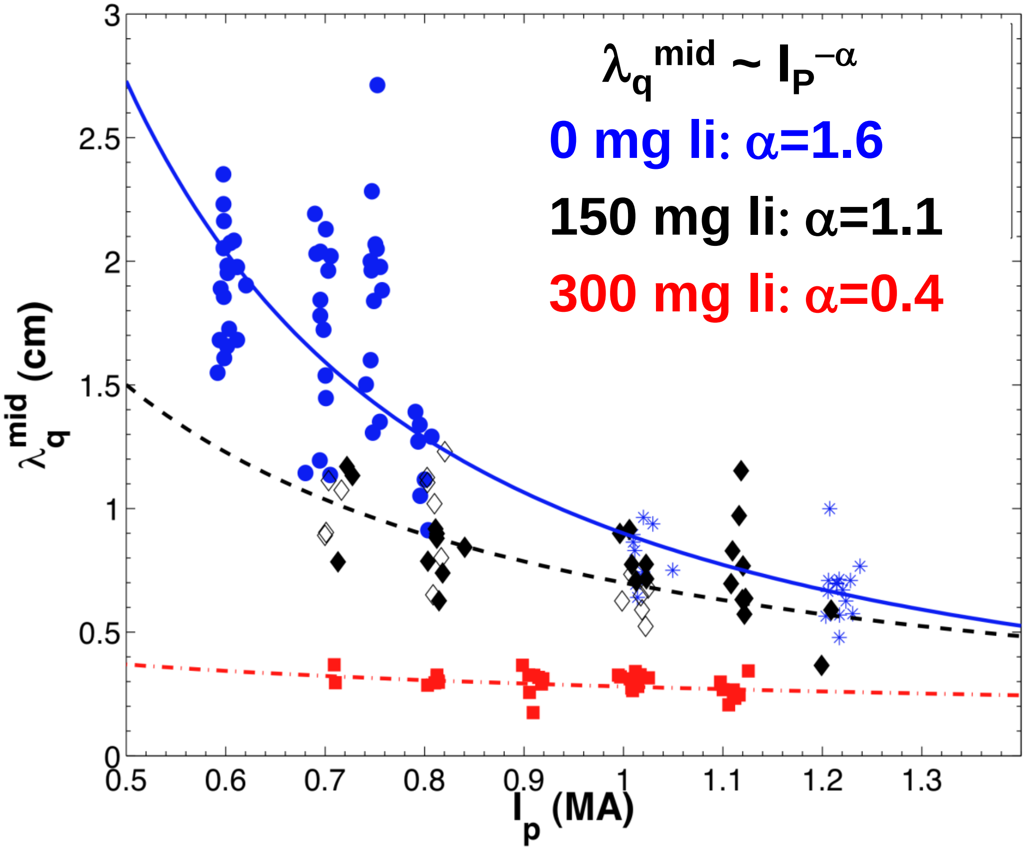




•Theory enhancements may lead to a unified model explaining NSTX / DIII-D observations having important implications for ITER: RWM can be unstable at expected rotation (advanced scenario 4)

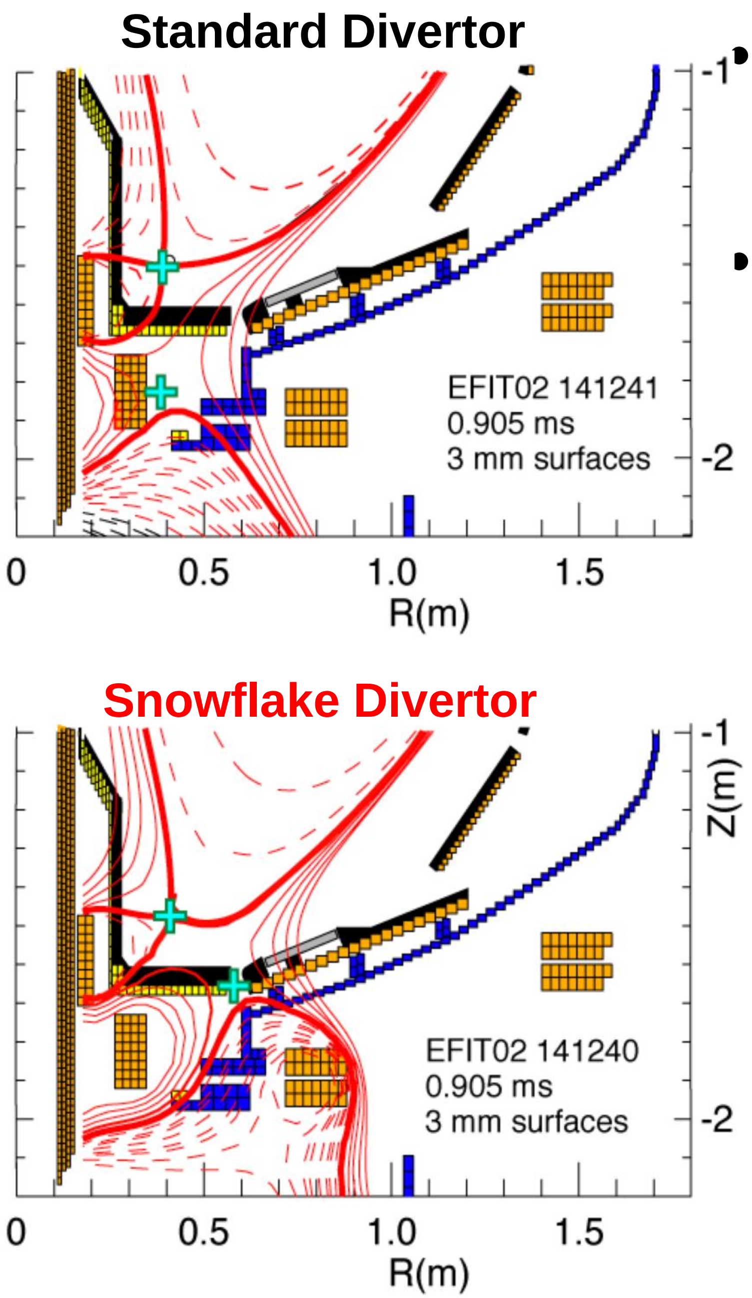
J. Berkery, PRL (2010)

λ_q^{mid} found to vary strongly with I_p, independent of B_t and P_{loss} as part of FY 2010 Joint Research Target

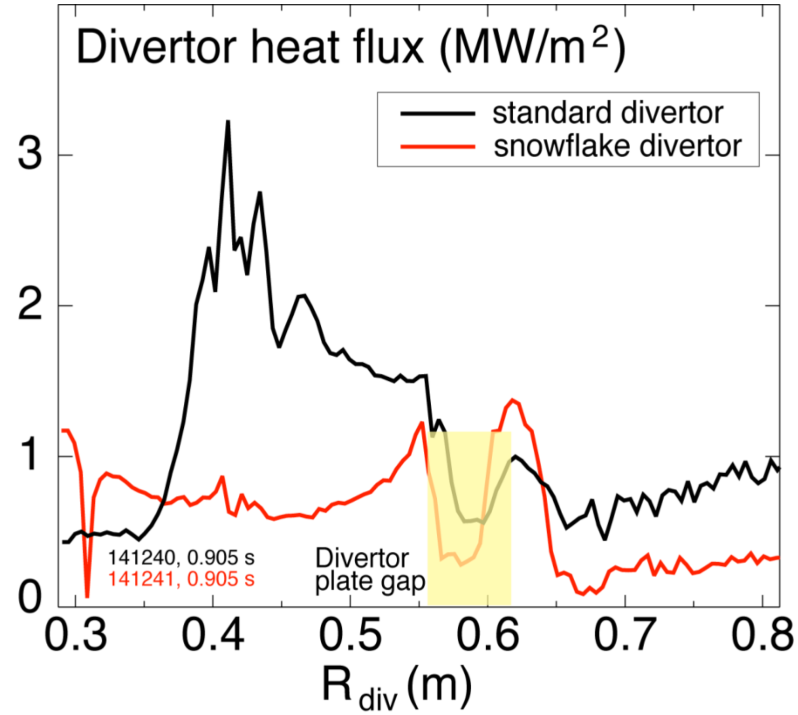


- α depends on level of lithium conditioning, as does leading constant (Gray, IAEA 2010)
  - Data includes slow IR + fast two-color IR cameras
- SOLT modeling reproduces P_{loss} trend, but not I_p dependence (Myra, PoP 2011)
- XGC-0 modeling reproduces ~ $1/I_p$ dependence in tokamaks, from neoclassical physics (Pankin, IAEA 2010)

"Snowflake" divertor configurations obtained in NSTX have significantly reduced peak heat flux



- High-δ divertor configuration is transformed into "Snowflake" divertor.
- Significant reduction of peak heat flux observed in "snowflake" divertor.
  - Potential divertor solution for NSTX-U.



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

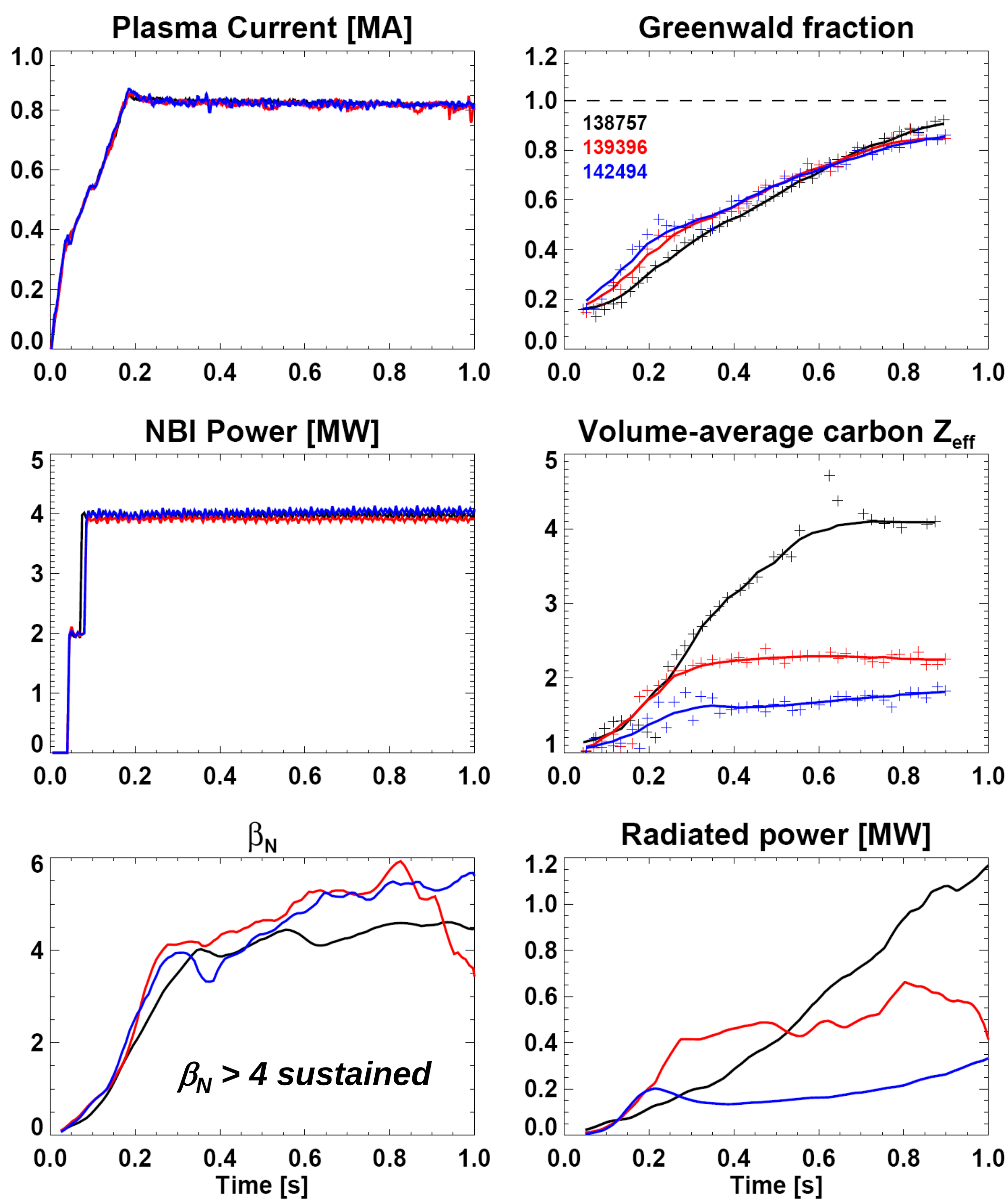
- 4 LLD plates formed ~20cm wide annulus in lower outboard divertor
  - Heatable surface of porous molybdenum (Mo)
  - Loaded with Li by LiTER evaporation from above

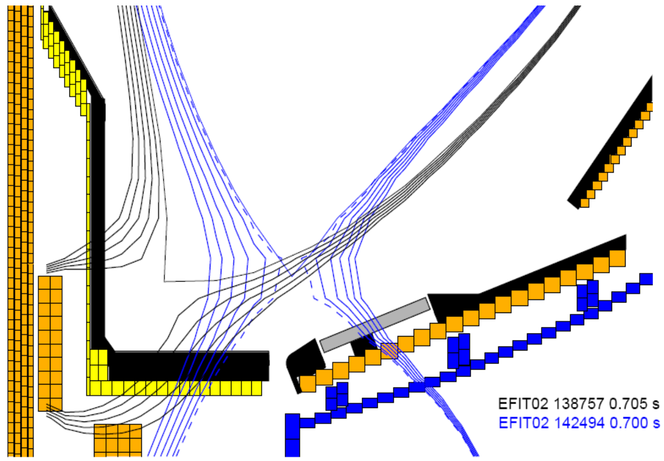
LLD Impact on Plasma Performance:

- 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**

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





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

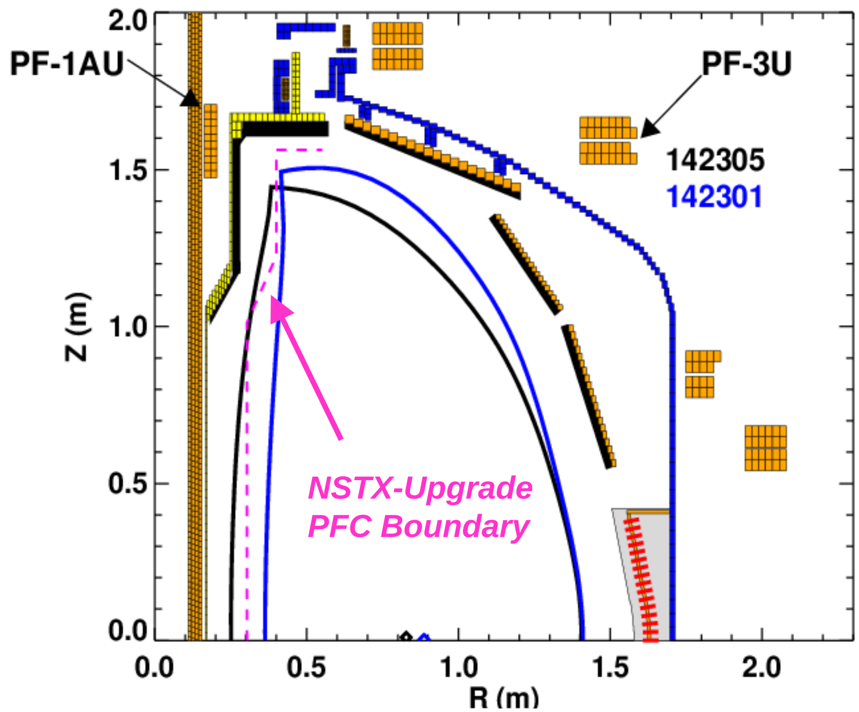
- **Carbon Z_{eff} = 3-4 typical of LiTER ELM-free H-mode**

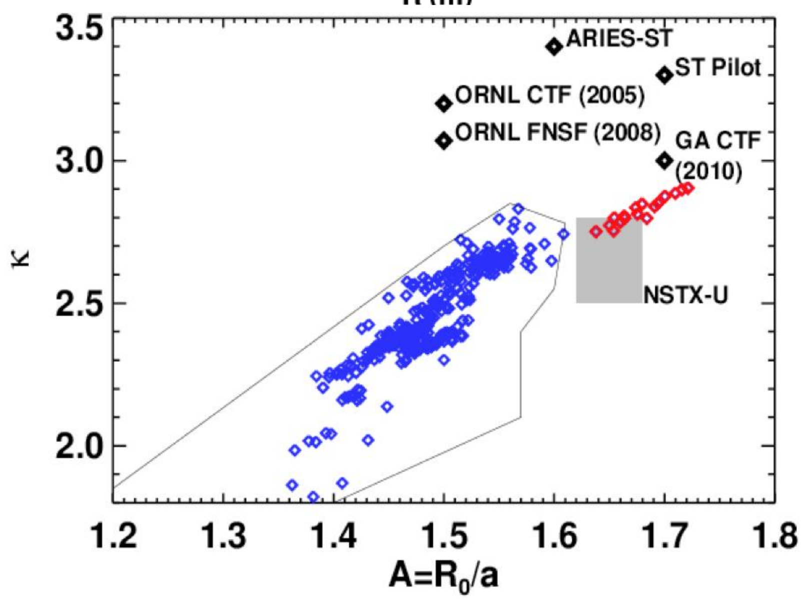
◀ **SP on LLD – T_{LLD} < $T_{Li\text{-}melt}$**

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

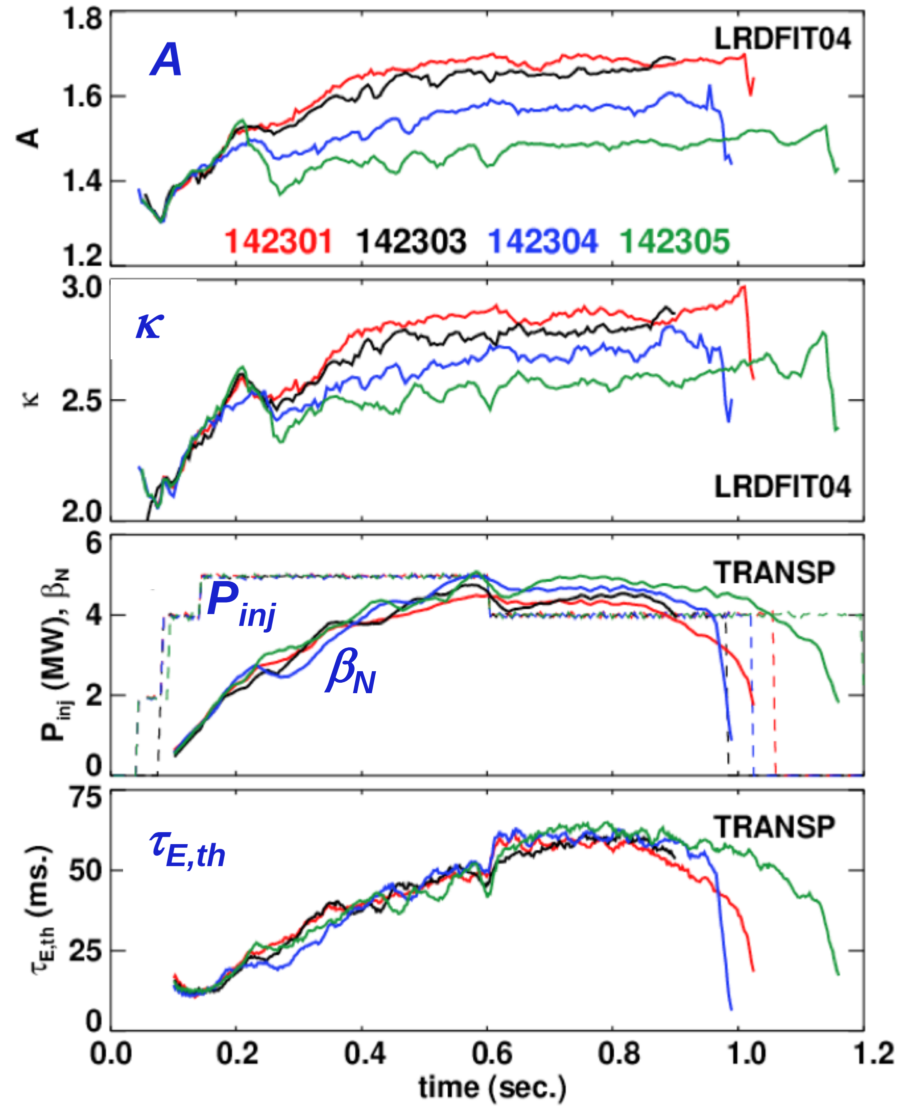
- **Shots have different fueling, LiTER conditions, ELM characteristics:**
  - **No ELMs, no → small, small → larger**
- **LSN with SP on LLD reduces δ, κ, q**
  - **Reduces ELM and global stability**
- **Yet, can achieve high β_N, low Z_{eff}, P_{rad}**
  - **Would like to revisit operation on LLD in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

Discharges With NSTX-Upgrade Aspect Ratio and Elongation Produced for Long Pulse at High-β





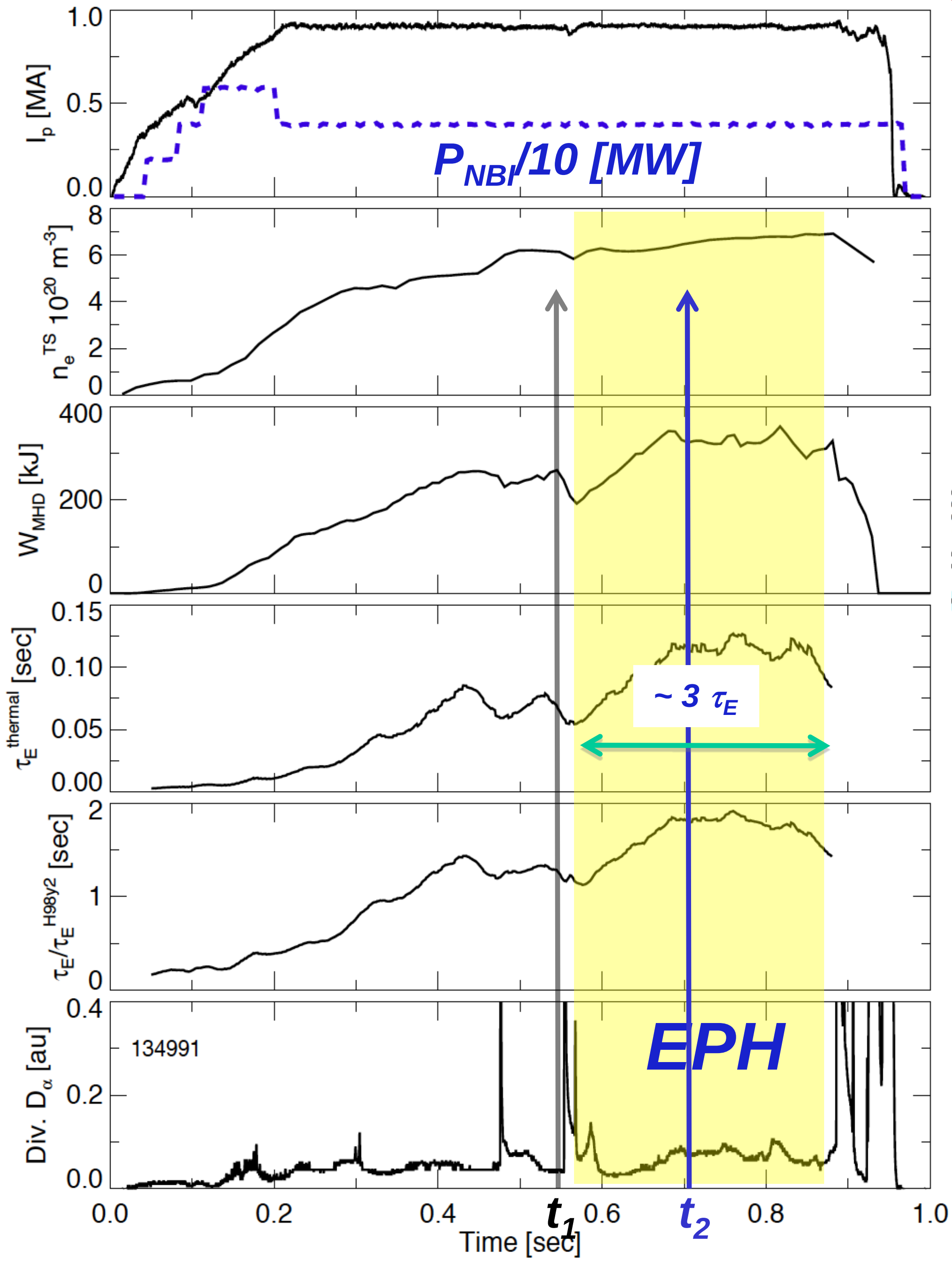
Performance Characteristics vs. Aspect Ratio



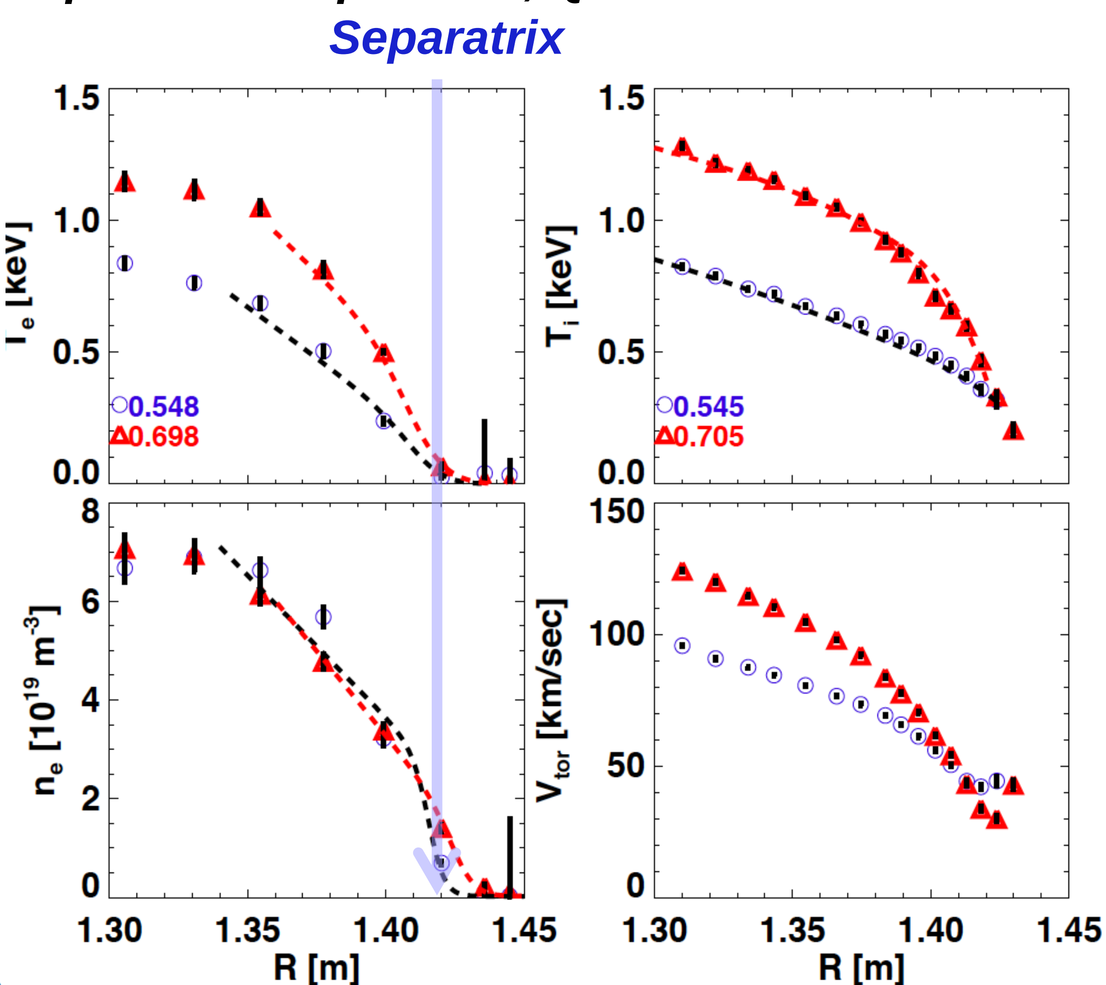
Plans in 2011 & 12

- n=0 control at high-A (boundary and VDE)
- Integrated performance, including transport and divertors

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



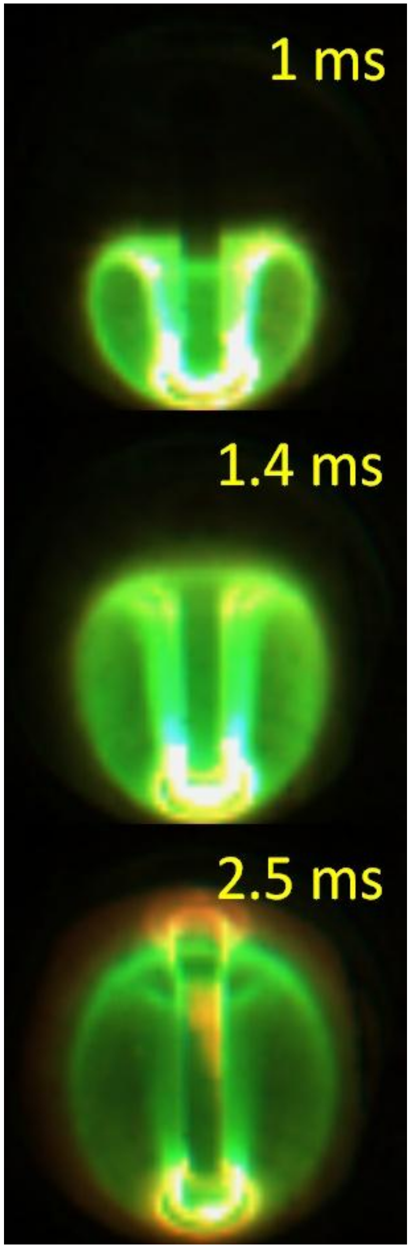
- ***Specially high H98y2 ≤ 1.7 is a combination of lithium confinement improvement and higher pedestal temperatures / pressure***
- ***ITER performance is highly pedestal pressure dependent, Q ~ P^2***



IAEA: R. Maingi, PRL 2010

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

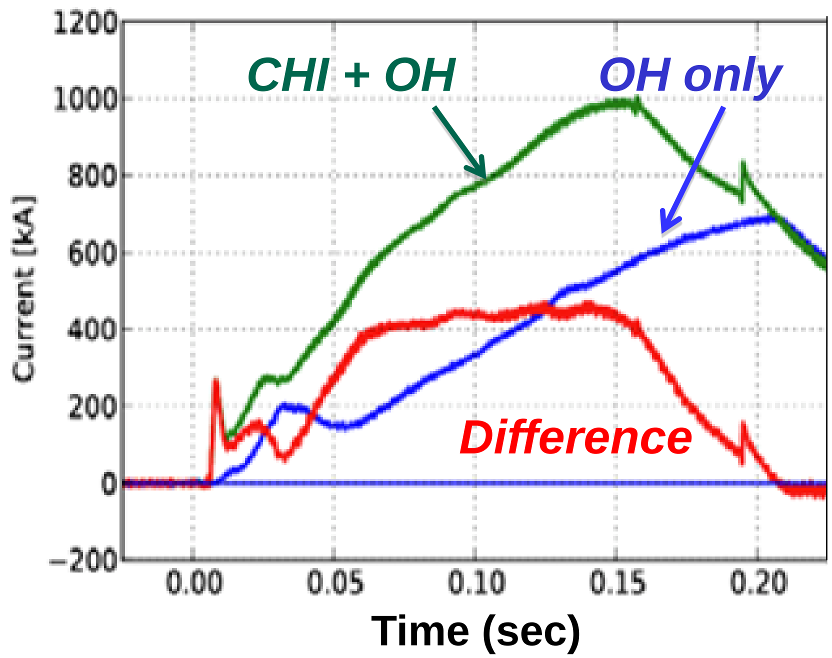
Time after CHI starts



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

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

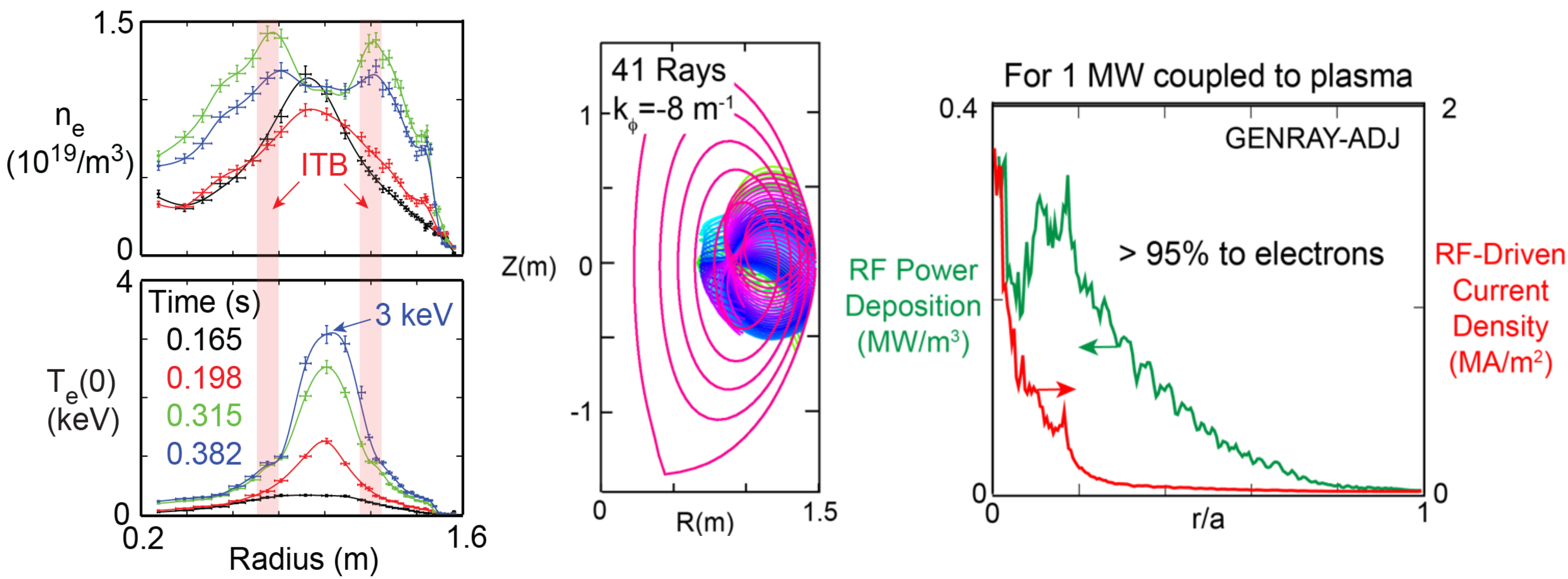
- **Also obtained new record 370 kA peak current by CHI alone**



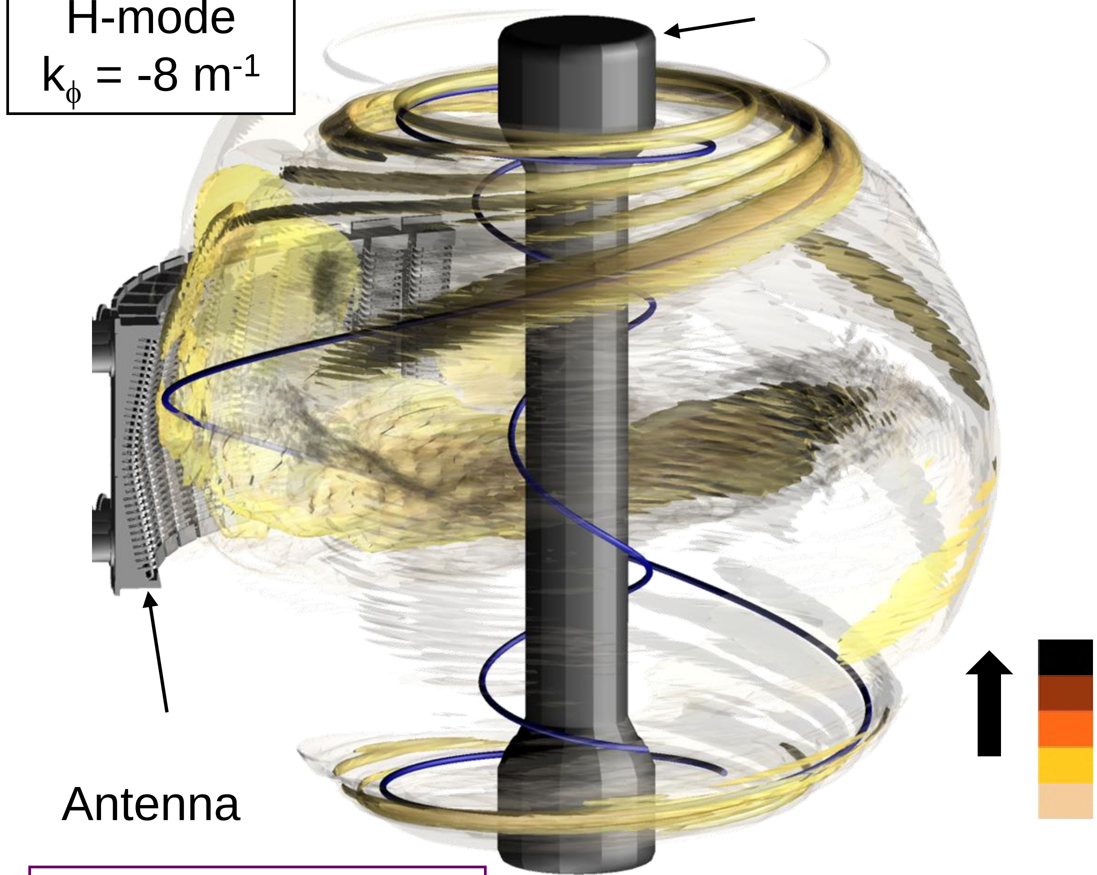
IAEA: R. Raman, B.A. Nelson U Washington

Progress made in sustaining HHFW heating during I_p=300 kA RF-only H-mode plasma; $T_e(0)$ = 3keV with only 1.4 MW

- Low I_p HHFW experiments in 2005 could not maintain P_{RF} during H-mode
- Produced sustained RF-only H-mode in 2010:
  - Better plasma-antenna gap control than in 2005, due to reduced PCS latency
  - Modeling predicts I_{RFCD} ~ 85 kA, $I_{Bootstrap}$~ 100 kA → f_{NI} ~ 60%
  - High f_{NI} enabled by positive feedback between ITB, high $T_e(0)$ and RF CD
  - f_{NI} ~ 100% requires P_{RF} ~ 3 MW, well below arc-free P_{RF} available in 2009
  - No q-profiles for these RF-only plasmas – MSE-LIF will enable this in FY11-12

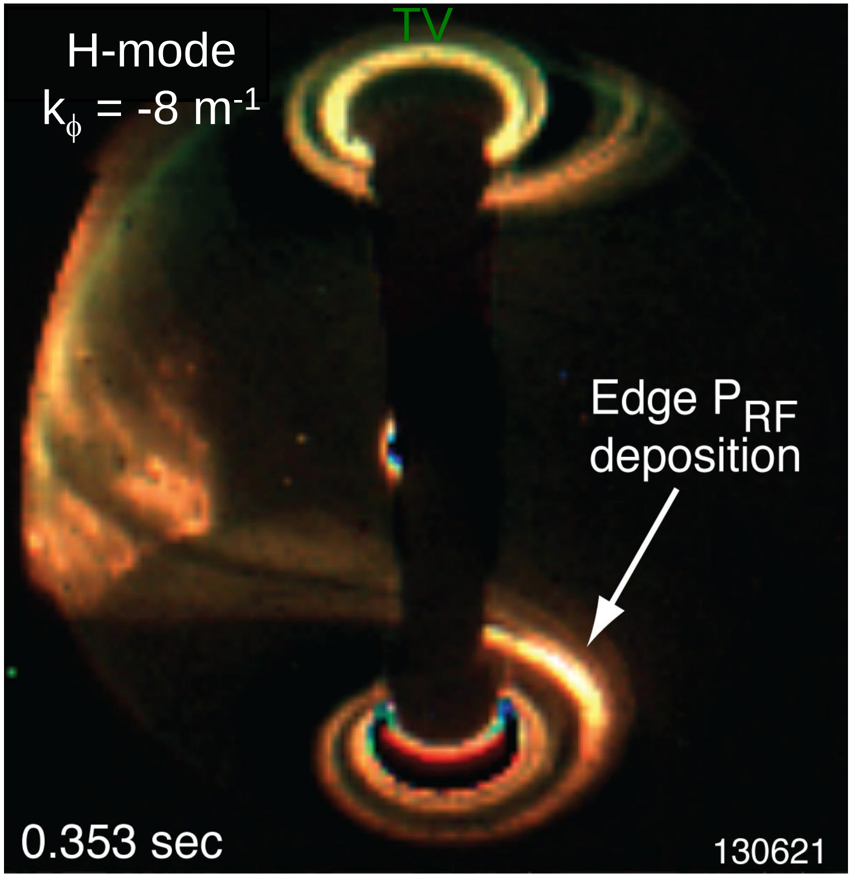


3-D AORSA full-wave model with 2-D wall boundary predicts large E_{RF} following magnetic field near top & bottom of NSTX



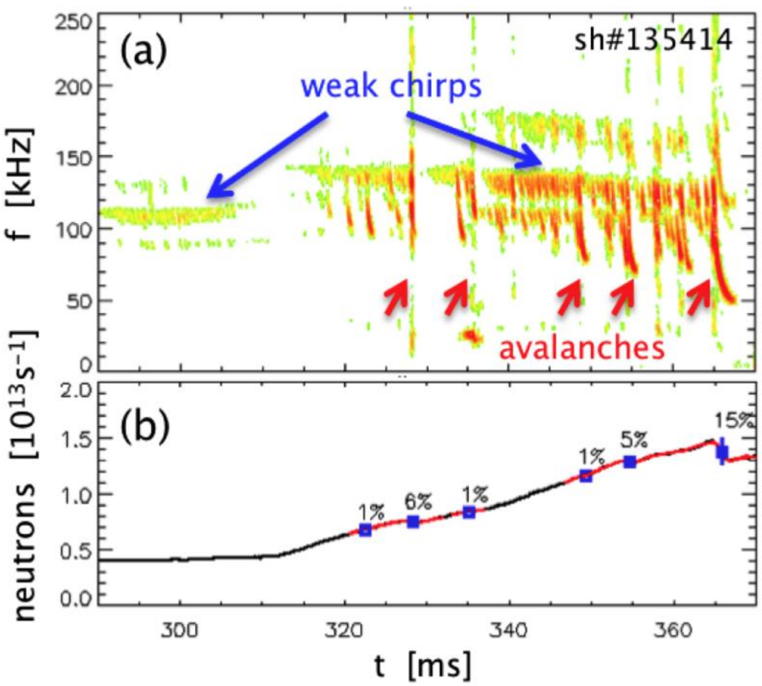
D. L. Green, ORNL

Edge RF eigenmode looks similar to striated structures imaged by visible plasma TV

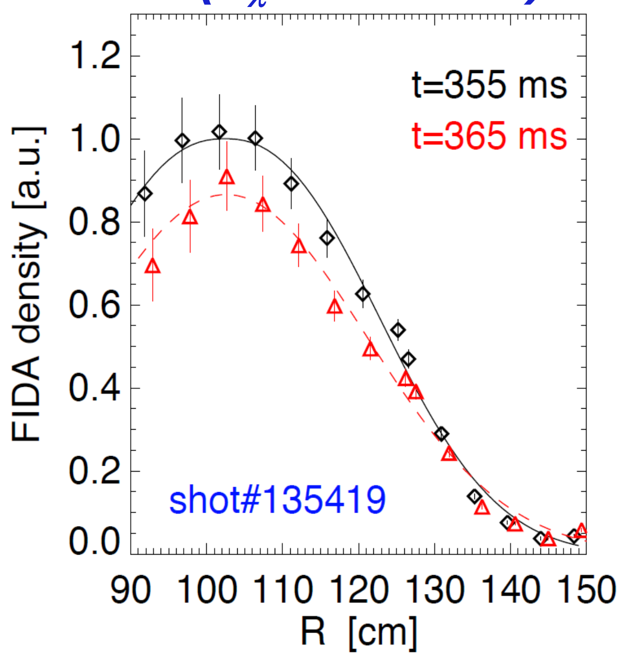


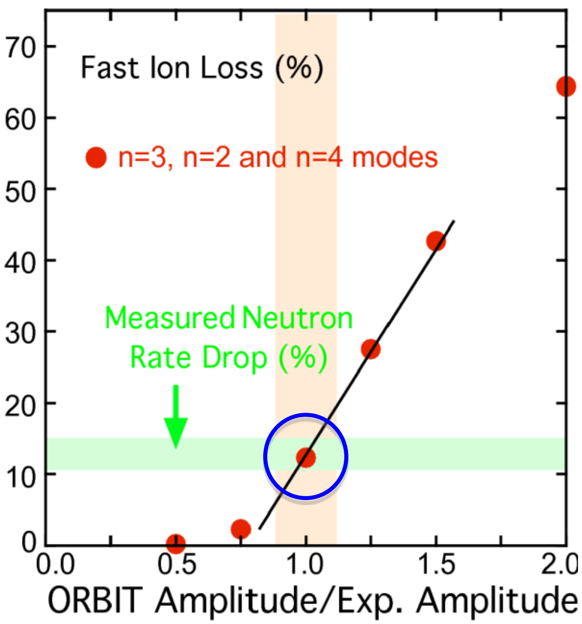
- In addition to RF power coupling to core, AORSA predicts some RF power propagates just inside LCFS as an edge localized RF eigenmode
- Beginning to make divertor tile current measurements to compare to theory

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



Fast Ion Profile
(E_λ = 30-60keV)





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

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