NSTX-U

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

NSTX Physics Results and Analysis Highlights

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Columbia University

M.G. Bell (Deputy) – (*now happily retired)*

PPPL

for the NSTX Research Team

NSTX PAC-31 meeting
PPPL B318
April 17th, 2012

Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
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Lodestar
MIT
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Nova Photonics
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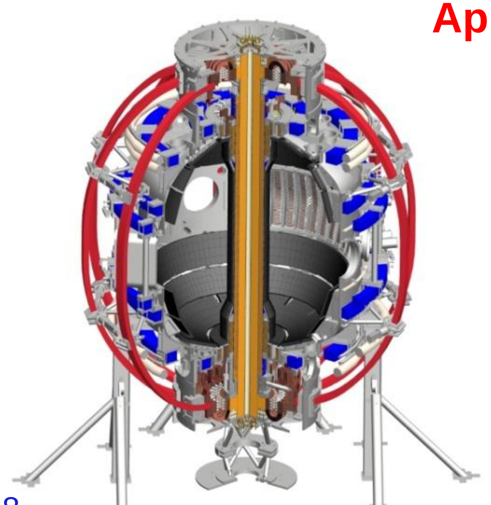
X Science LLC



V1.8

Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
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ASIPP
CIEMAT
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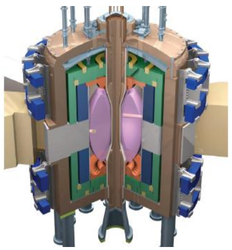
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

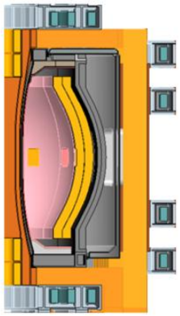
NSTX research targets predictive physics understanding needed for fusion energy development facilities

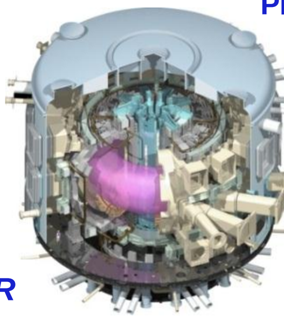
- Enable key ST applications
  - Move toward steady-state ST FNSF, pilot plant
  - Close key gaps to DEMO
- Extend understanding to tokamak / ITER
  - Leverage ST to develop predictive capability

<u>Present Research</u>

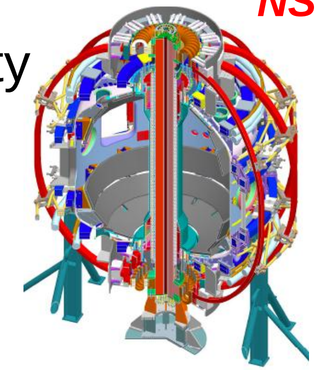
- Develop key physics understanding to be tested in unexplored, hotter ST plasmas
  - Study high beta plasma transport and stability at reduced collisionality, extended pulse
  - Prototype methods to mitigate very high heat/particle flux
  - Move toward fully non-inductive operation

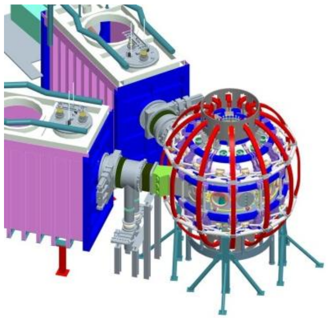

Fusion Nuclear Science Facility (FNSF)


ST Pilot Plant


ITER

NSTX-U


New center-stack


2^{nd} Neutral Beam

Following last PAC, the largest NSTX experimental program to date was planned for FY11-12

- Research Forum (March 2011): Record number of proposals
  - 193 XPs/XMPs were considered, totaling 226 days requested
    - Run time was ~3 times oversubscribed (see backup slide for detail)
  - TSG leaders + run coordination defined a full prioritized and scheduled plan for CY11-FY12 period (20 weeks)
- FY2011 run was abbreviated by TF coil fault
  - Only 4 weeks of run in FY2011 - important BES and transport data
  - NSTX-U was accelerated 6 months (upgrade began 1-Oct-2011)
- Research Milestones FY11-12 drove the run plan
  - FY11 milestones were largely addressed
  - Experiments aimed to exploit new capabilities are deferred to NSTX-U
    - e.g. Broader 3D fields studies, n > 1 control (2nd SPA); MSE-LIF; moly tiles; tangential fast ion D_{α}; more Thomson channels, real-time V_{ϕ},…

- Continued research based on NSTX data prepares needed physics hypotheses to be tested in the new, lower collisionality ST operational regime to be provided by NSTX-U

Brief summary of NSTX Milestones – key guidance for TSG XP prioritizations – FY2011

JRT-11

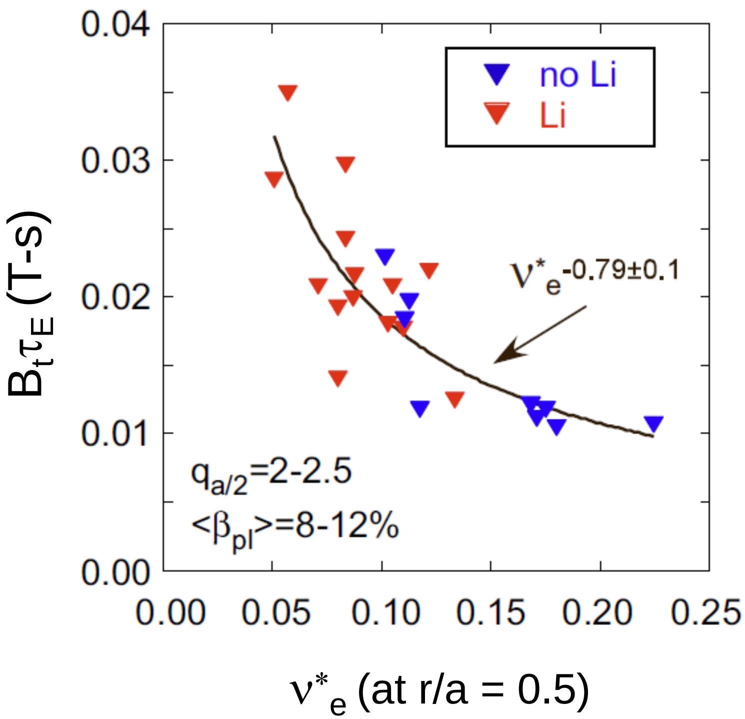
- 2011 OFES Joint Research Milestone (Boundary Physics, Transport & Turbulence)
  - *Improve understanding of physics mechanisms responsible for pedestal structure, compare with predictive models*
  - *Perform detailed measurements of the height and width of the pedestal, E_r, initial measurements of pedestal region turbulence*
  - *Perform focused analytic theory/computational effort, including large-scale simulations, on physics controlling pedestal structure, height*
- R(11-1): Measure fluctuations causing turbulent electron, ion, impurity transport
  - TSGs: Transport & Turbulence
- R(11-2): Assess ST stability dependence on plasma aspect ratio and boundary shaping
  - TSGs: Macrostability, Advanced Scenarios and Control
- R(11-3): Assess very high flux expansion divertor operation
  - TSGs: Boundary Physics, Advanced Scenarios and Control
- R(11-4): H-mode pedestal transport, turbulence, and stability response to 3D fields
  - TSGs: ITER/CC, Transport & Turbulence, Boundary Physics, Macrostability

See backup slides for original FY2012 milestones

First successful nonlinear microtearing simulations for NSTX predict reduced electron heat transport at lower collisionality

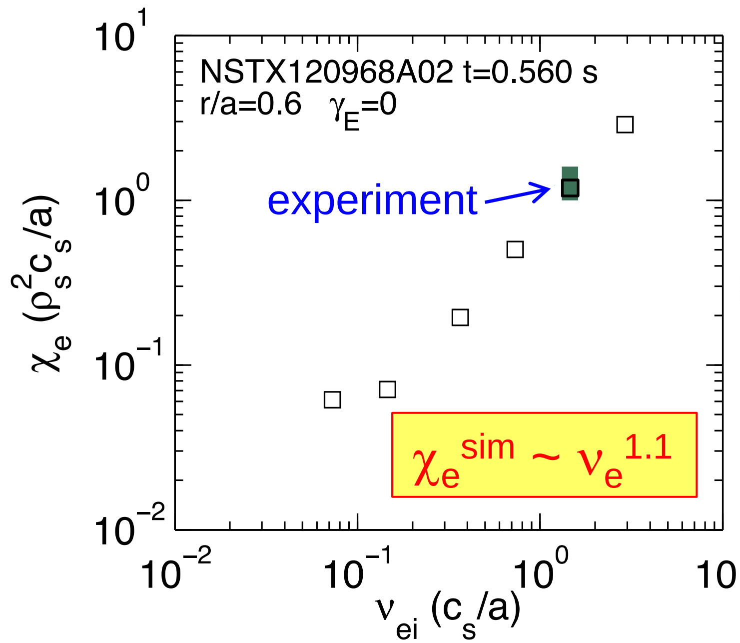
R(11-1)

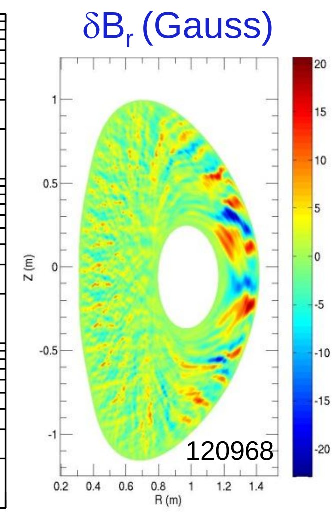
Experiment



- Increase in τ_E as ν^*_e decreases
- Trend continues when lithium is used

Theory





W. Guttenfelder, et al., PRL **106**, 155004 (2011)

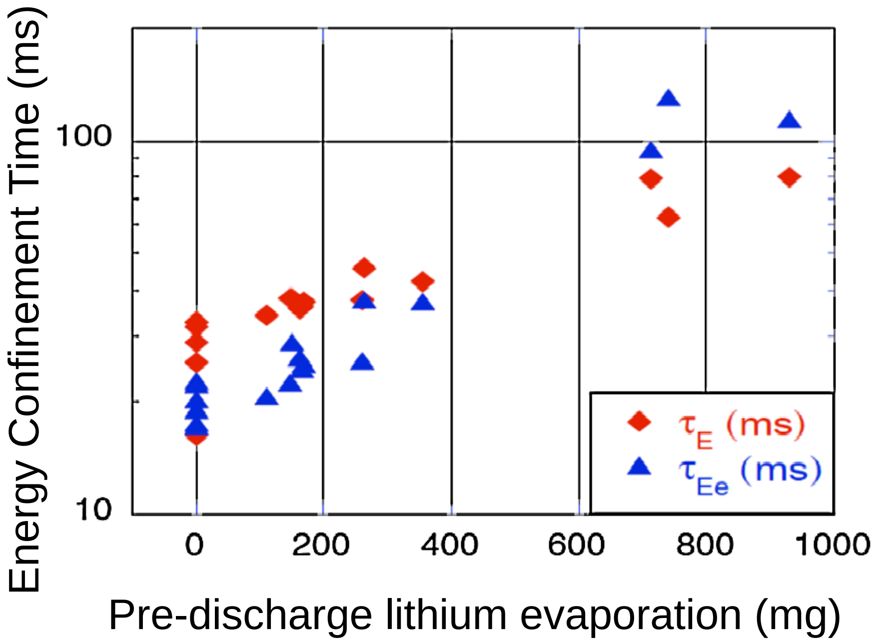
- Predicted χ_e and scaling ~ $\nu_e^{1.1}$ consistent with experiment ($\Omega\tau_E$ ~ $B_t\tau_E$ ~ $\nu^*_e{}^{-0.8}$)
- Transport dominated by magnetic "flutter"
  - $\delta B_r/B$ ~ 0.1% - possibly detectable by planned UCLA polarimetry system

- NSTX-U computed to extend studies down to ~ 1/4 of present ν^*

see Y. Ren T&T talk

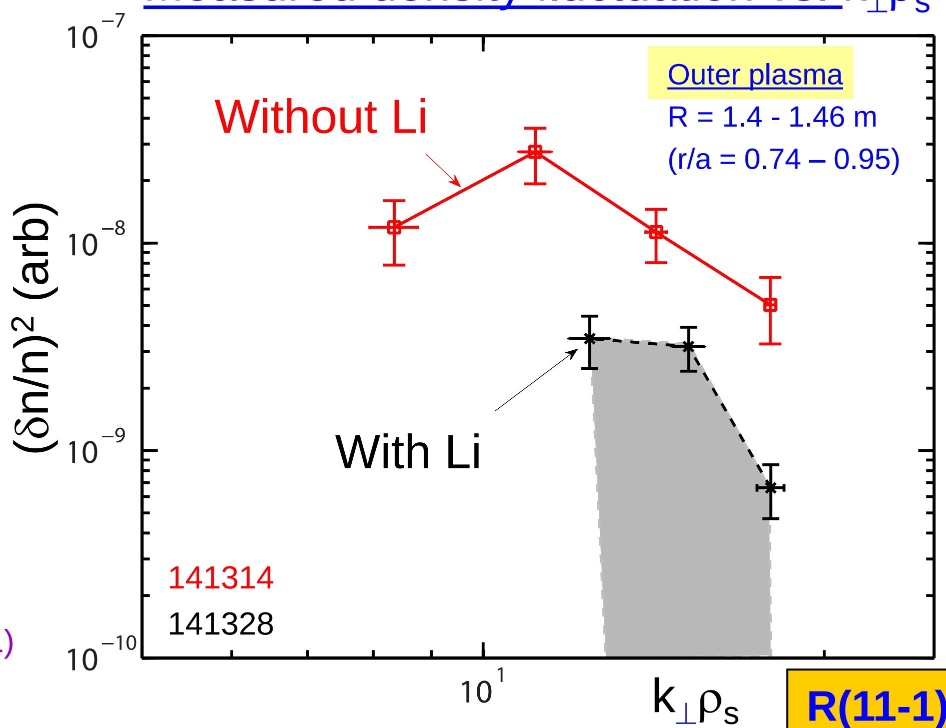
Plasma characteristics change nearly continuously with increasing lithium evaporation inside vessel

JRT-11



R(11-4)

R. Maingi, et al., PRL **107**, 145004 (2011)



R(11-1)

- Global parameters generally improve
- ELM frequency declines - to zero
  - ELMs stabilize D. Boyle, et al., PPCF (2011)
- Edge transport declines J. Canik, et al., PoP (2011)
  - As lithium evaporation increases, transport barrier widens, pedestal-top χ_e reduced

see C. Skinner Li talk

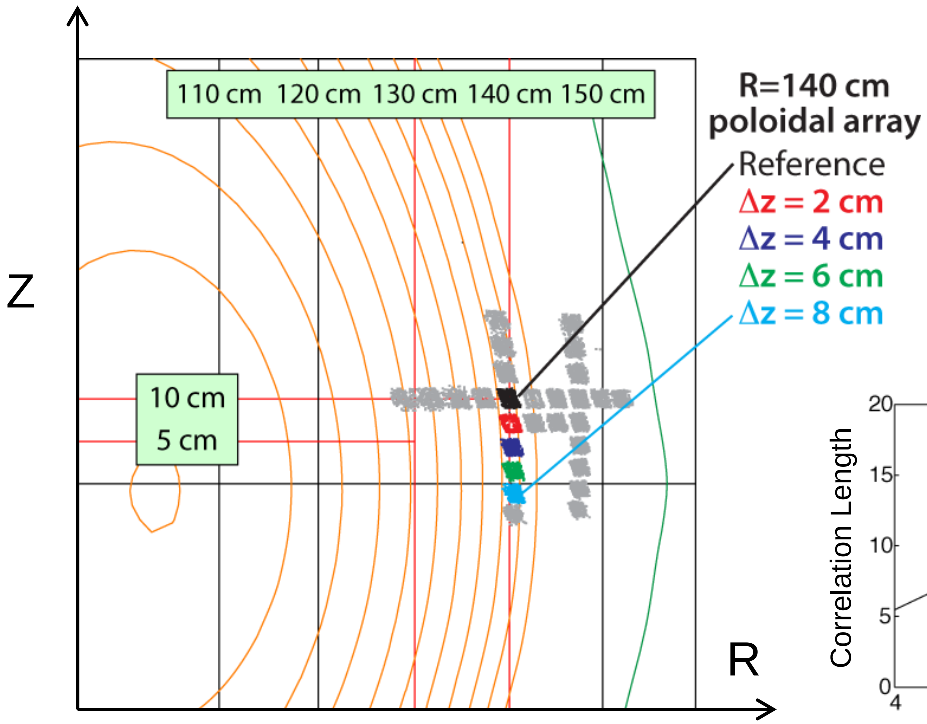
- Measured reduction in high-k turbulence consistent with reduced χ_e
- Impact of collisionality and ∇n on turbulence is under investigation
  - $B_t\tau_E \sim \nu_e^{*-0.8}$ observed

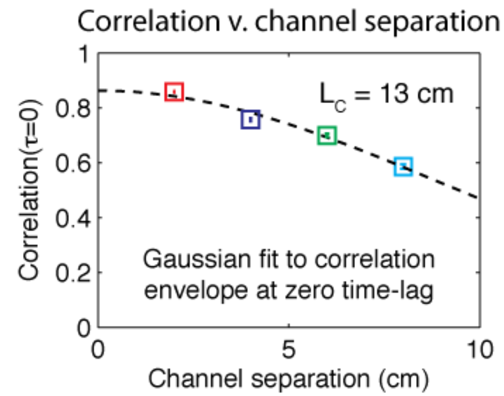
see Y. Ren transport & turbulence talk

BES provides poloidal correlation lengths of turbulence in ELM-free H-mode pedestal and parametric dependencies

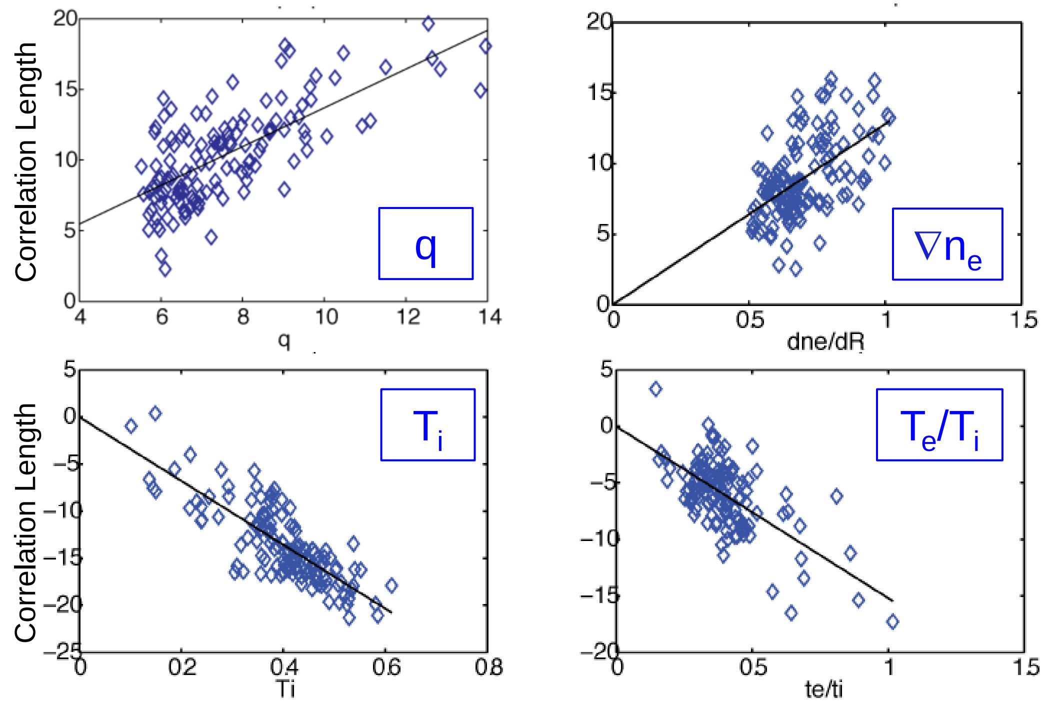
R(11-1)

Beam emission spectroscopy (BES) array





Poloidal Correlation Length vs. Parameters



- Large poloidal correlation lengths
  - $k_\theta \approx$ 0.2-0.4 cm^{-1} and $k_\theta \rho_i \approx$ 0.1-0.25
- Cross-phase, time-lags show eddy advection in ion diamagnetic direction

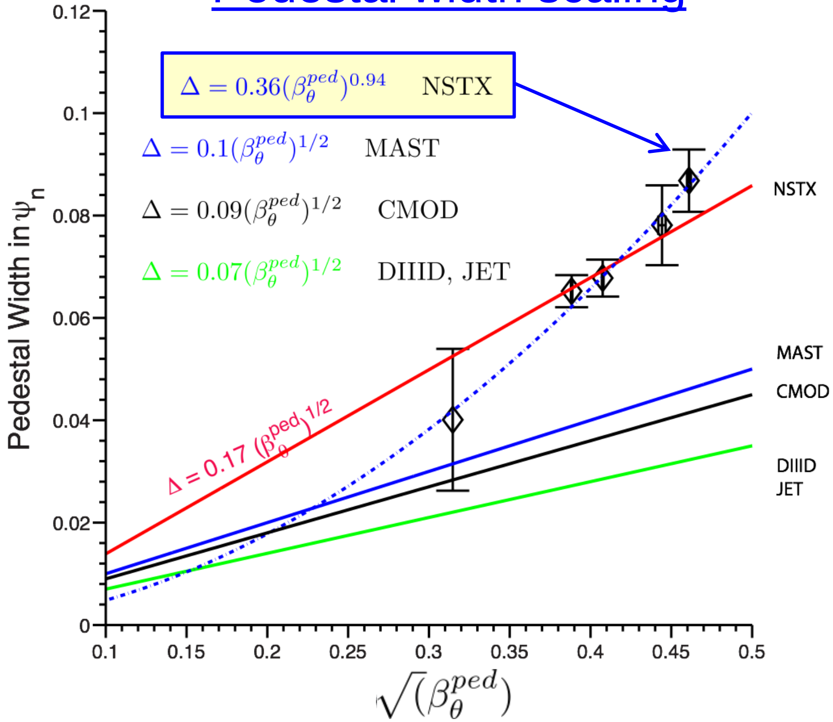
D. Smith (UW-Madison)

Pedestal scaling, structure, and dynamics studied theoretically and experimentally

JRT-11

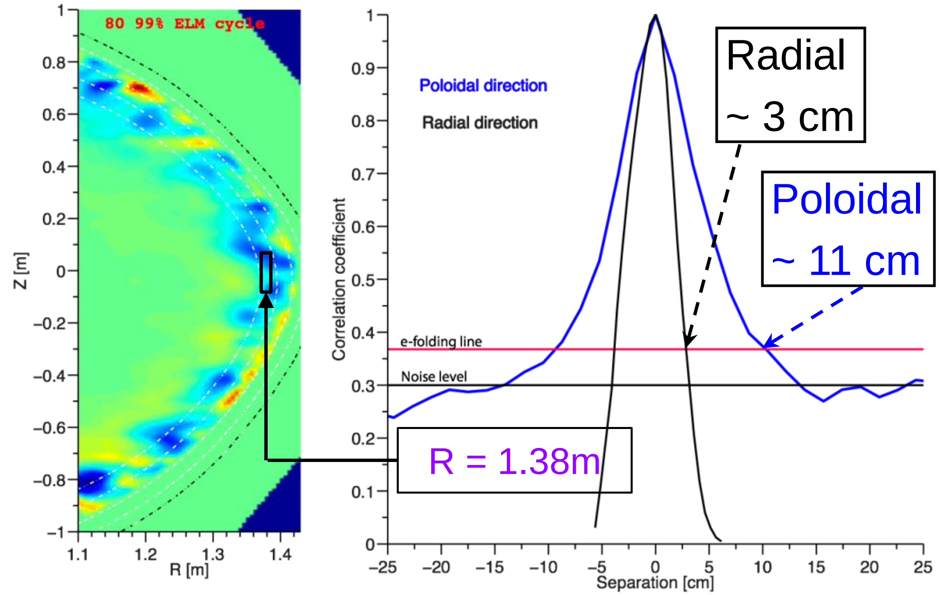
R(11-1)

Pedestal width scaling



Turbulence correlation lengths

Theory (non-linear XGC1)



- Pedestal width scaling β_θ^α applies to multiple machines
- In NSTX, observed ped. width is larger
  - 1.7 x MAST, 2.4 x DIII-D
  - Data indicates stronger for NSTX: $\beta_\theta^{0.94}$ vs. $\beta_\theta^{0.5}$

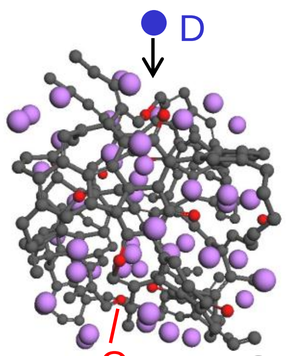
- Measured correlation lengths are consistent with theory
  - Radial (reflectometry) ~ 2 – 4 cm
  - Poloidal (BES) ~ 10 – 14 cm
    - spatial structure exhibits ion-scale microturbulence ($k_\theta \rho_i^{ped}$ ~ 0.1 - 0.2)

A. Diallo, et al., NF **51**, 103031 (2011) A. Diallo, C.S. Chang, S. Ku (PPPL), D. Smith (UW), S. Kubota (UCLA)

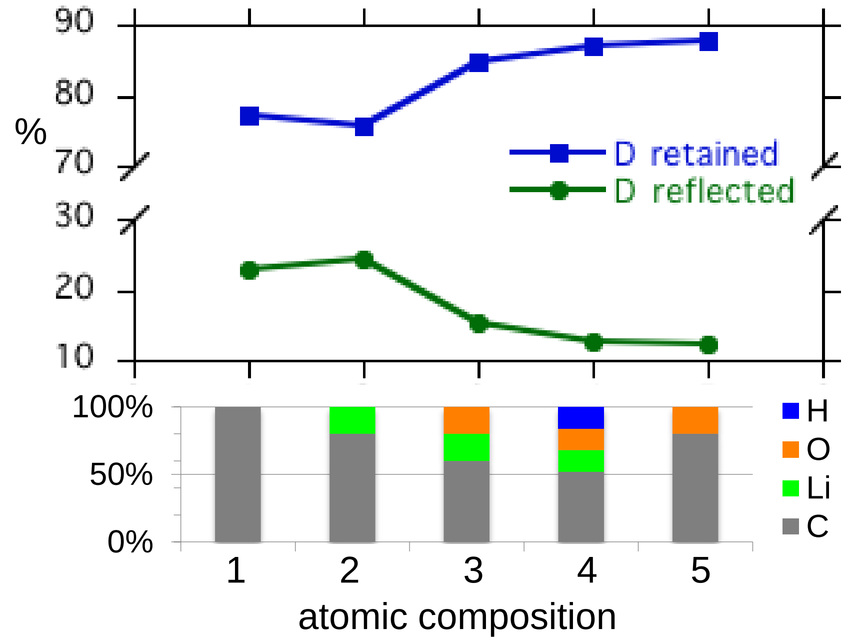
Simulations and lab results show importance of oxygen in lithium-graphite PMI for pumping deuterium

PAC29-18

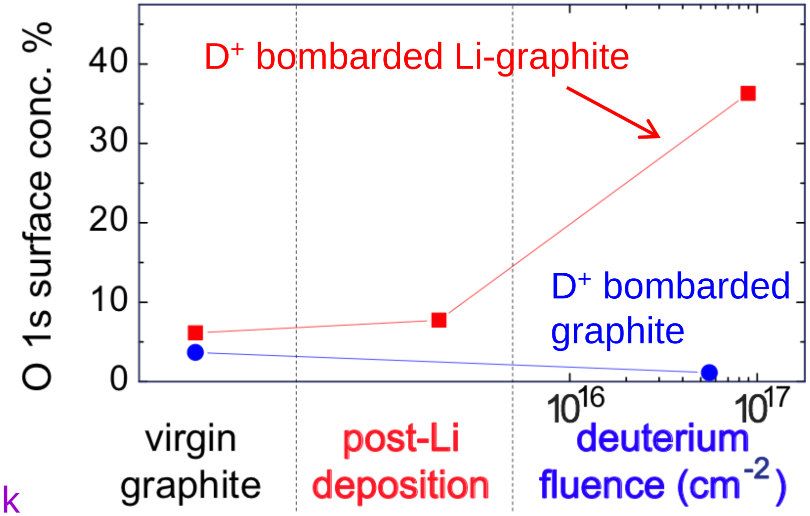
- Quantum-classical atomistic simulations show surface oxygen plays key role in the retention of deuterium in graphite



P. Krstic, sub. to Nature Comm.



- Accordingly, lab results support that Li on graphite can pump D effectively due to O
  - XPS measurements *(Purdue)* show 2 μm of Li increases surface oxygen content of lithiated graphite to ~10%
  - deuterium ion irradiation of lithiated graphite greatly enhances oxygen content to 20%-40%
    - In stark contrast, D irradiation of graphite ***without*** Li *decreases* amount of surface O
  - Li acts as an O getter, and the O retains D



J.P. Allain, Taylor (Purdue U.)

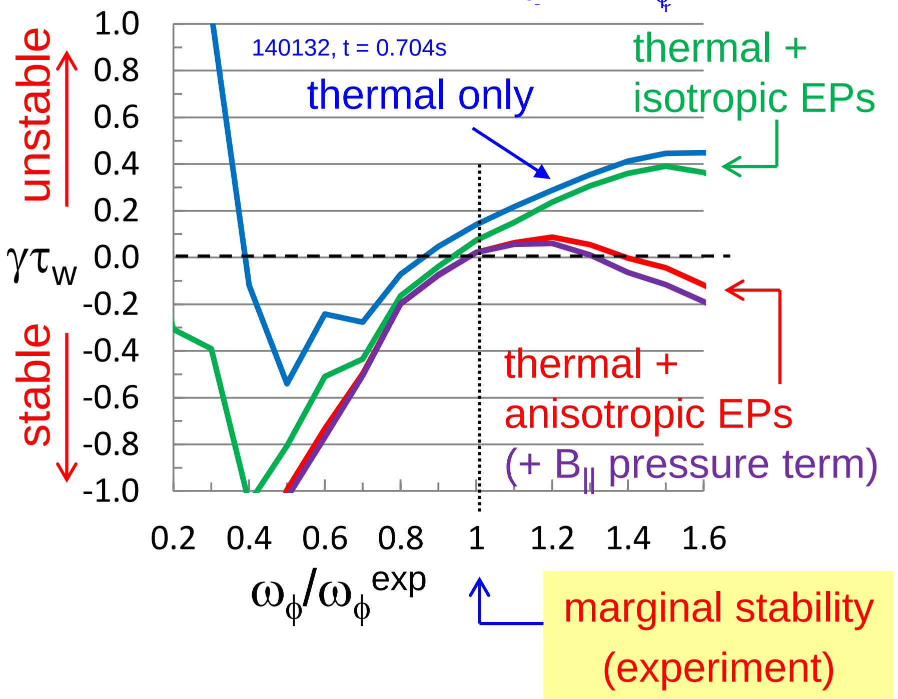
see C. Skinner Li talk

Kinetic RWM stability theory further tested against NSTX experiments, provides guidance for NSTX-U

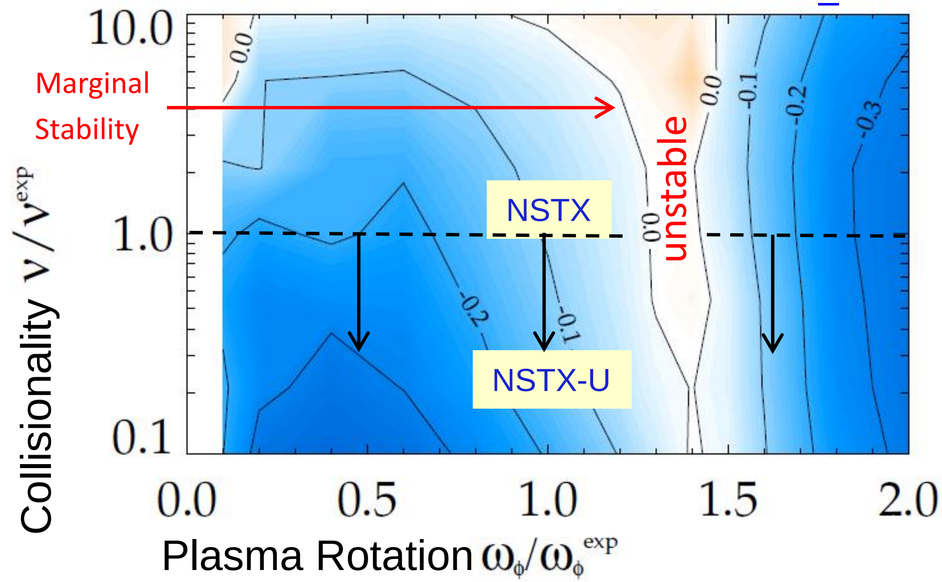
R(11-2)

MISK code

RWM stability vs. ω_ϕ



RWM growth rate contours ($\gamma\tau_w$)



- Improvements to physics model
  - Anisotropy effects
  - Testing terms thought small
    - Already good agreement between theory and experiment of marginal stability point improved

Part of ITPA MDC-2 benchmarking task

(S. Sabbagh, leader)

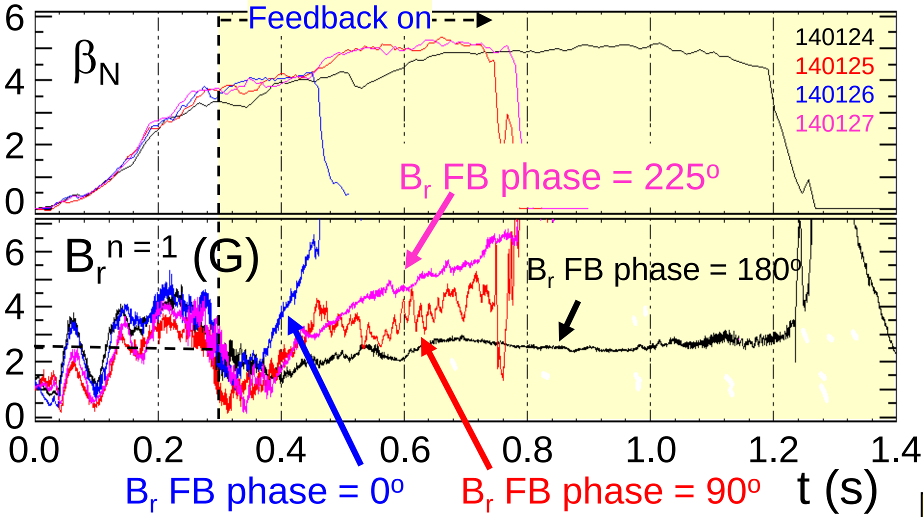
- Two competing effects at lower ν
  - Collisional dissipation reduced
  - Stabilizing resonant kinetic effects enhanced (contrasts early theory)
- Expectations at lower ν
  - More stabilization near ω_φ resonances; almost no effect off-resonance
    - Active RWM control important

J. Berkery et al., PRL **106**, 075004 (2011)

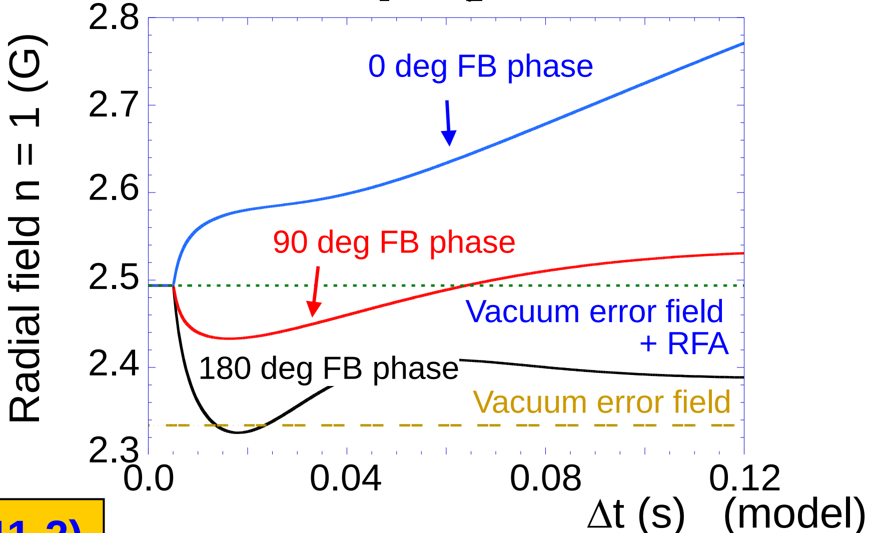
see J.-K. Park talk

Improved RWM control includes radial and poloidal field, and state space feedback with a 3D conducting structure model

Active n = 1 $B_p + B_R$ feedback (FB) control

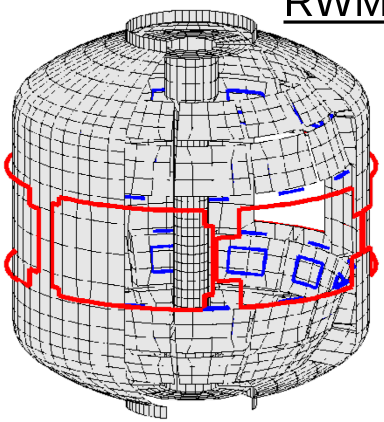


Calculation of $B_r + B_p$ control (VALEN)



R(11-2)

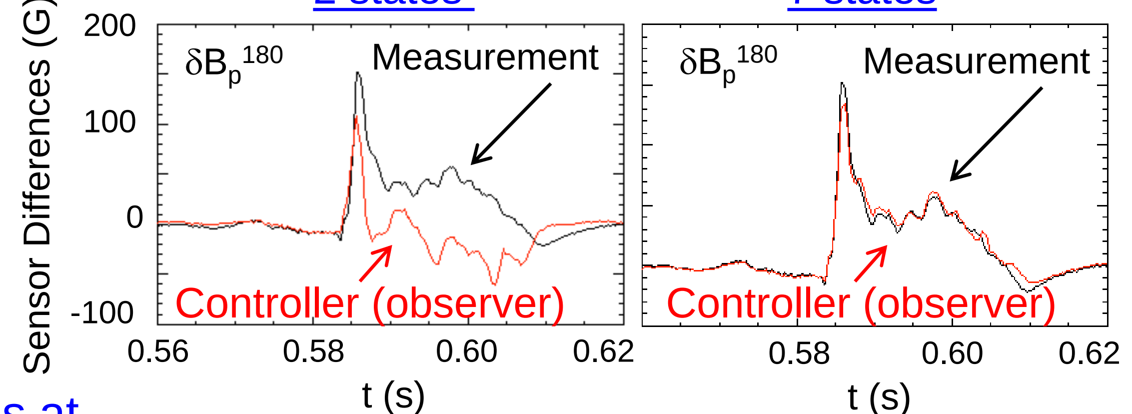
RWM State Space Controller



3D wall, ports, mode currents

2 states

7 states



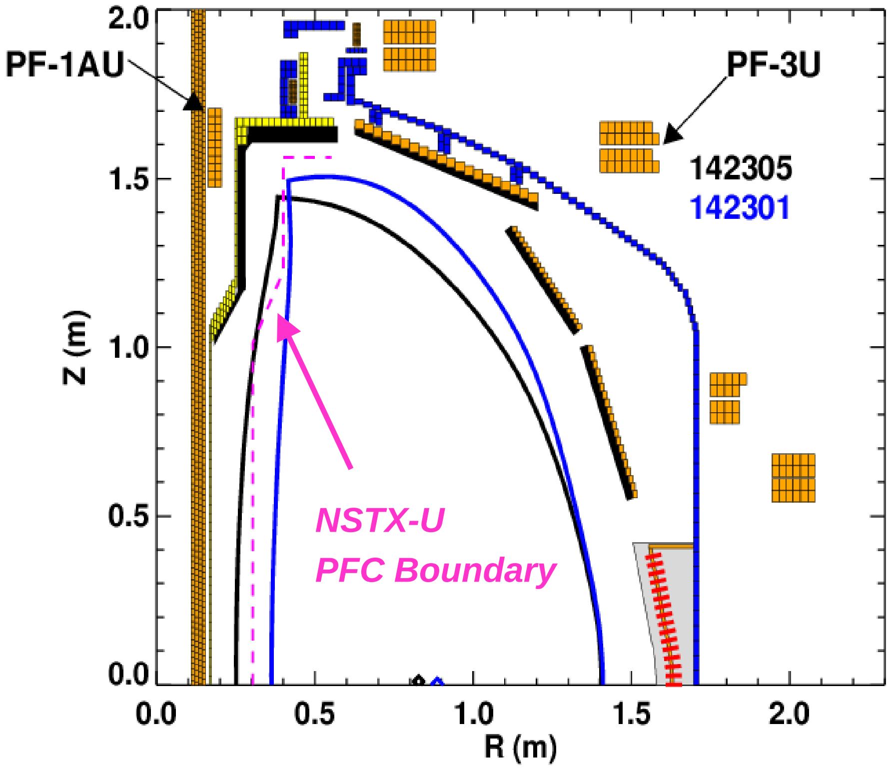
- Significantly reduced disruptions at high β_N in controlled experiments

S.A. Sabbagh, O. Katsuro-Hopkins, J.M. Bialek

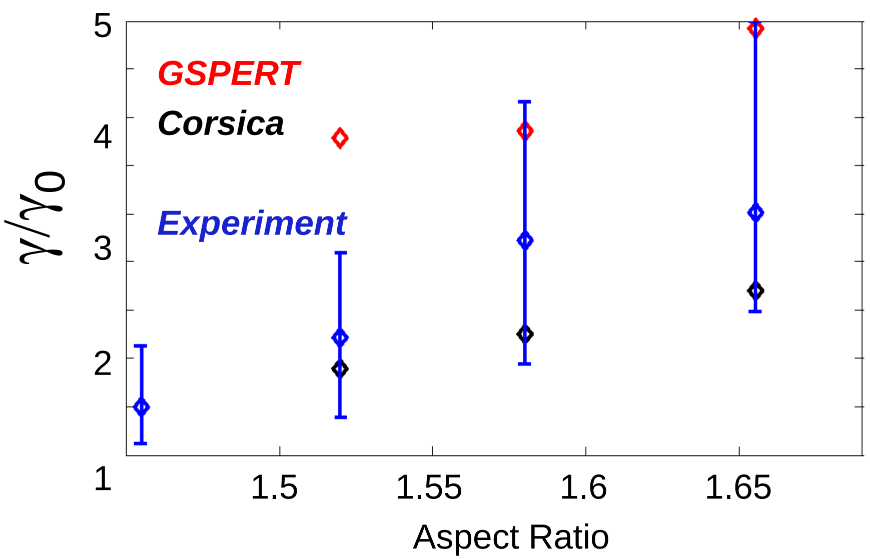
see J.-K. Park talk

Higher aspect ratio of NSTX-U tested in NSTX, vertical stability growth rate data obtained, compared to simulation

R(11-2)



Vertical Stability Growth Rates vs. A



- NSTX Discharges have matched aspect ratio and elongation of NSTX-U without performance degradation

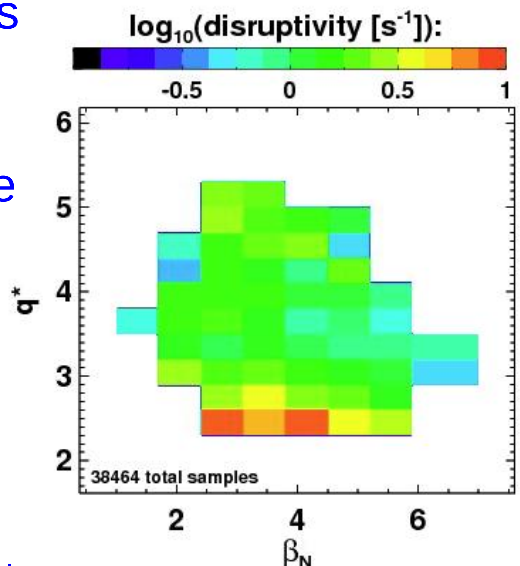
- Improvements to vertical control capability and understanding
  - Begun to compare measured growth rates to theoretical predictions (Corsica, GSPERT)
  - Improved plasma position observer
  - Modeled use of RWM coils for n=0 control

see S.P. Gerhardt ASC talk

Disruption Detection and Warning Analysis is Being Developed for Disruption Avoidance

Disruptivity

- All discharges since 2005 with 1/3 ms sampling time
  - Recorded equilibrium and kinetic parameters, disruption statistics

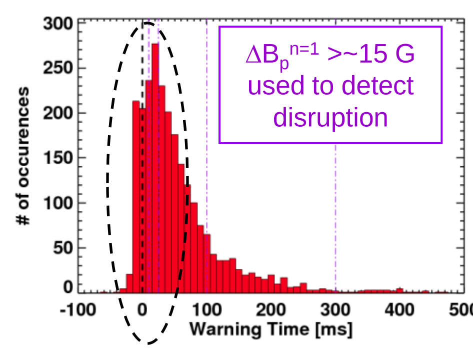


- Physics results
  - Minimal disruptivity at relatively high β_N ~ 6; β_N / $\beta_N^{no-wall(n=1)}$ ~ 1.3-1.5
    - Consistent with past specific disruption control experiments
  - Strong disruptivity increase for q* < 2.5
  - Strong disruptivity increase for lowest rotation

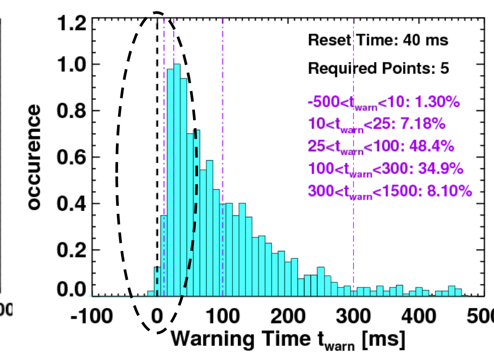
Warning Algorithms

- Disruption warning algorithm shows high probability of success
  - Based on combinations of threshold based tests; no machine learning

Statistics for a single threshold test



Statistics of full warning algorithm



- Results & Physics implications
  - ~99% disruptions flagged with at least 10ms warning, ~8% false positives
  - Most false positives are due to "near disruptive" events
    - Early MHD slows ω_ϕ
    - recoverable Z motion

see S.P. Gerhardt ASC talk

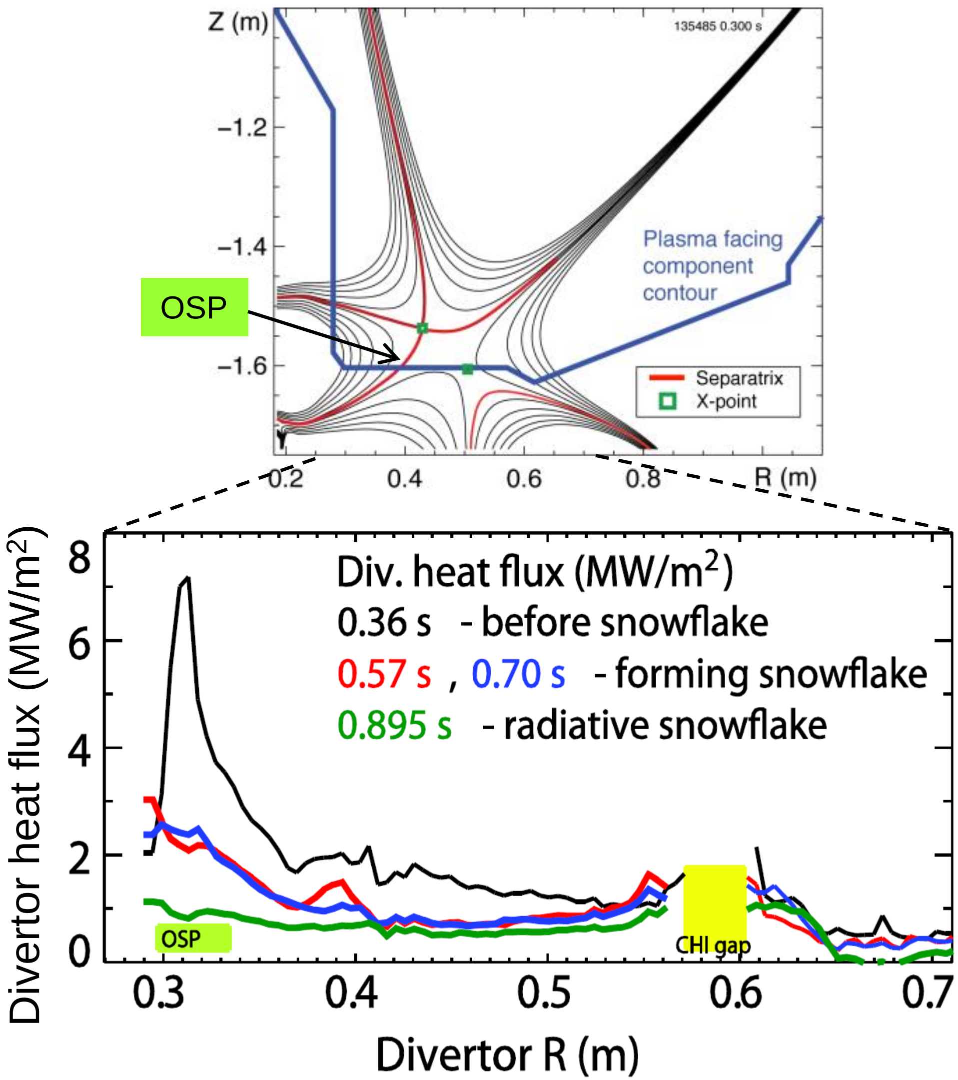
Snowflake divertor experiments provide basis for required divertor heat flux mitigation in NSTX-U

R(11-3)

- Divertor heat flux width strongly decreases as I_p increases in NSTX, DIII-D, C-Mod

- Snowflake divertor experiments in NSTX (P_{NBI}=4 MW, P_{SOL}=3 MW)
  - Good H-mode confinement (τ_E, $T_{e,i}(0)$, β_N, H98(y,2))
  - Significant reduction in steady-state divertor heat flux (from 3-7 to 0.5-1 MW/m^2)
  - Synergistic combination of detachment + radiative snowflake divertor

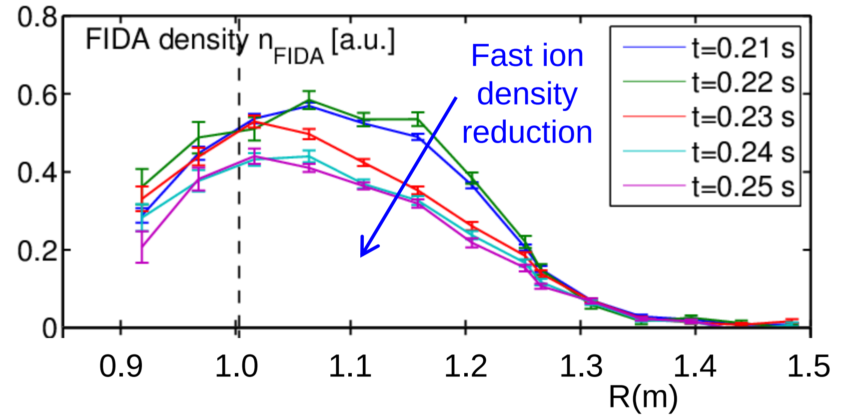
Snowflake divertor in NSTX



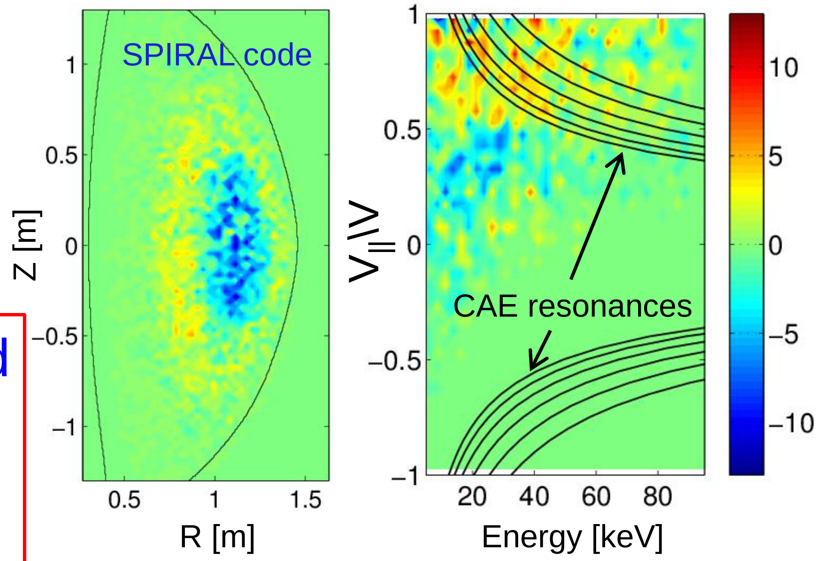
See V. Soukhanovskii, boundary physics talk

Fast ion redistribution associated with low frequency MHD measured by fast ion D_α (FIDA) diagnostic

- Caused by kink-like, global instabilities
  - Primarily n = 1, weaker n = 2 present
- Redistribution can affect stability of *AE, RWMs, other MHD
  - CAE activity observed <u>*after*</u> onset of low frequency MHD
- Full-orbit code (SPIRAL) shows redistribution in real and velocity space
  - Radial redistribution from core plasma
  - Particles shift towards $V_{||}/V = 1$



<u>Change in distribution due to kink mode</u>

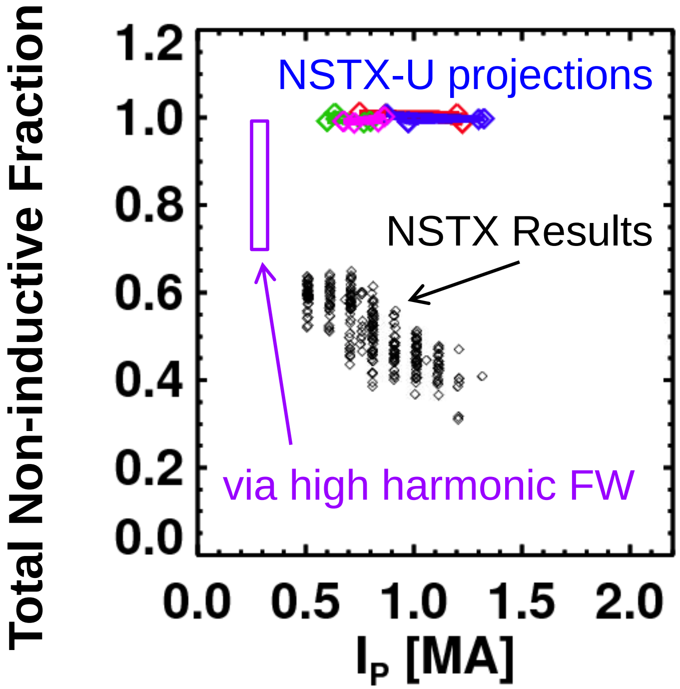


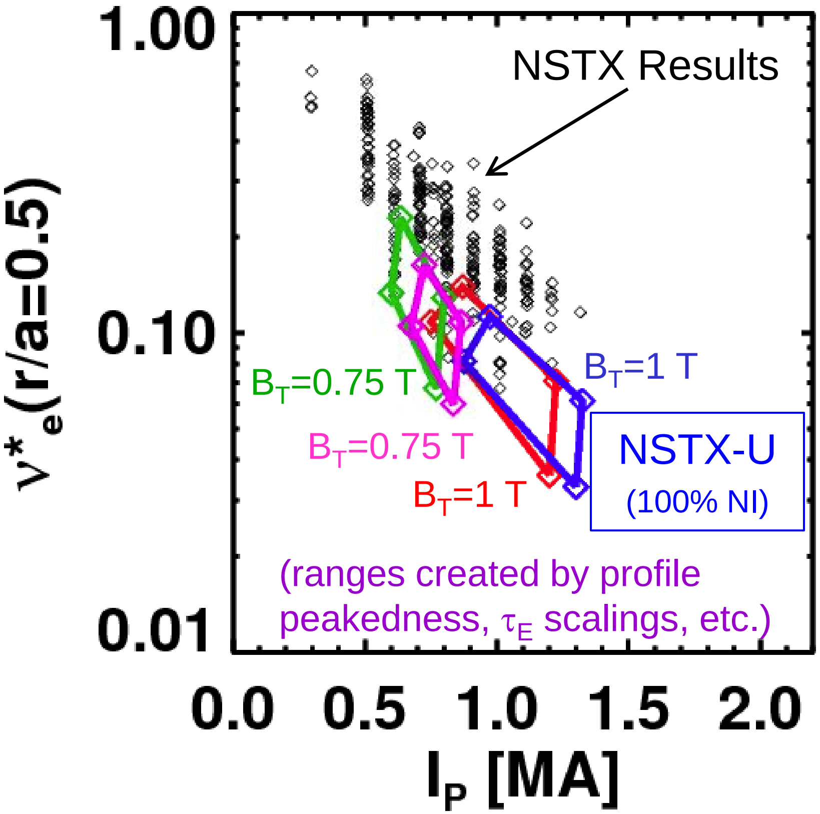
- Measured CAEs (reflectometer) examined as possible cause of enhanced core χ_e
  - mode #, frequency measured: modes peak in core, resonant with electron orbit frequencies

N. Crocker *et al*. PPCF **53**, 105001 (2011) FEATURED article

A. Bortolon

Non-inductive current fractions of up to 65% sustained in NSTX, >70% transiently; Upgrade projected to achieve 100%





- Maximum sustained non-inductive fractions of 65% w/NBI at I_P = 0.7 MA
- 70- 100% non-inductive reached transiently using HHFW CD

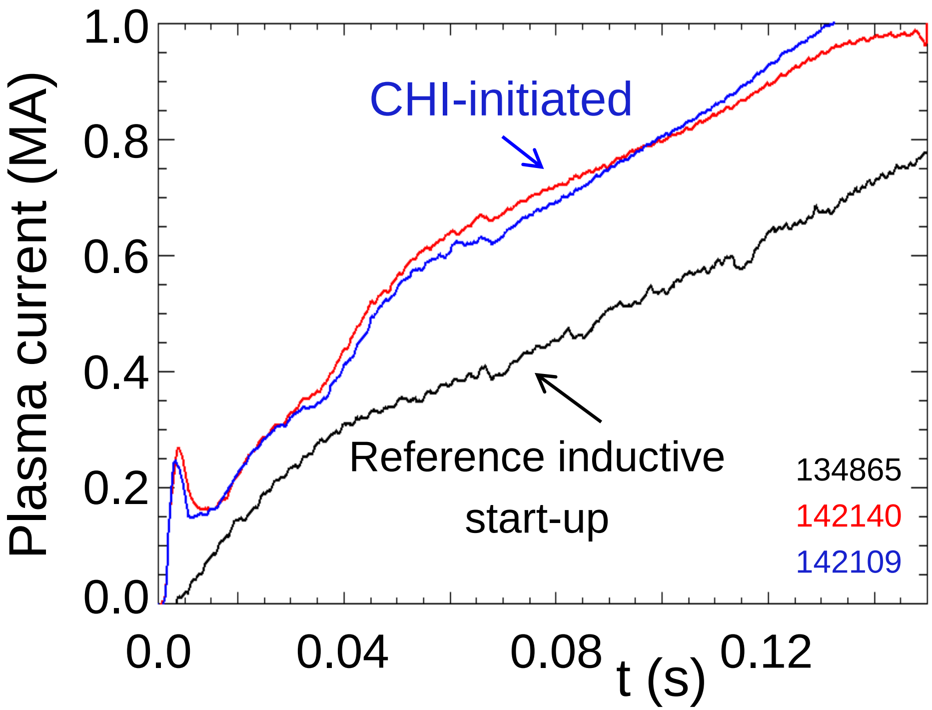
- 100% non-inductive scenarios found over wide operation range
  - Scenarios at 74% Greenwald density

see G. Taylor W&EP talk

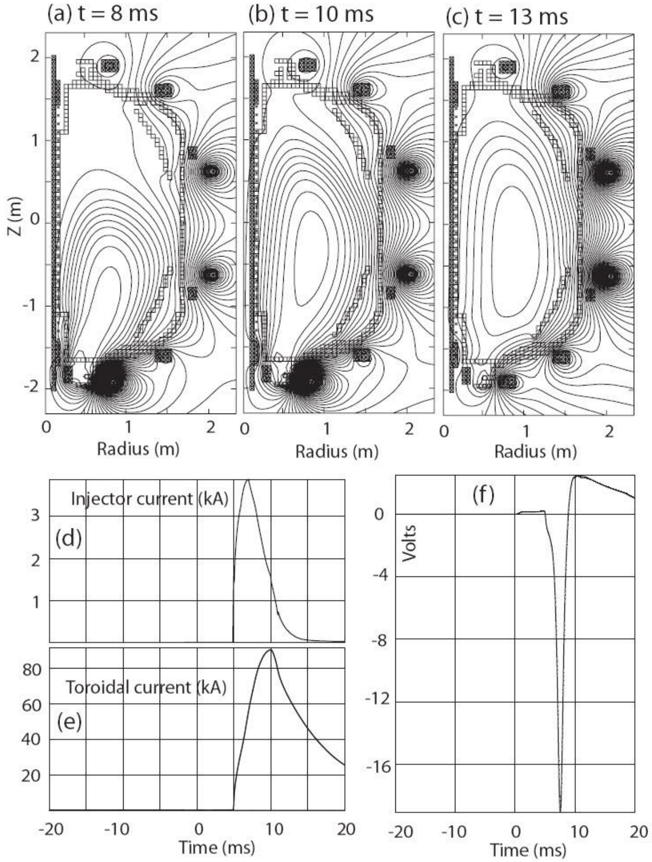
(S. Gerhardt, submitted to NF)

see S. Gerhardt ASC talk

L-mode discharge ramping to 1MA requires 35% less inductive flux when coaxial helicity injection (CHI) is used



TSC simulation of NSTX CHI startup



- Reference inductive discharge
  - Uses 396 mWb to get to 1MA
- CHI initiated discharge
  - Uses 258 mWb to get to 1MA (35% less inductive flux)
- Estimated startup current of 0.4 MA - 0.6 MA for NSTX-U

- Decaying poloidal flux induces positive loop voltage, causes flux closure

R. Raman, et al. Nucl. Fusion **51**, 113018 (2011)

Continuing analysis of NSTX data targets a predictive physics understanding required for future fusion devices

- Operating at reduced collisionality
  - Nonlinear microtearing simulations predict reduced χ_e of experiment
  - Measured high-k turbulence reduction consistent with lower edge χ_e
  - Reduced ν can be stabilizing for resistive wall modes, but only near kinetic resonances (requires control)
  - Nearly continuous increase of favorable effects with increased lithium
  - ELM stabilization through density profile modification by lithium
- Handling increased heat flux
  - Large heat flux reduction from synergistic combination of detachment + radiative snowflake divertor
- Detecting & avoiding disruptions
  - Initial success in disruption detection and avoidance algorithms
  - Expansion of physics model for RWM state space active control; determine favorable stability at ω_ϕ targets accessible by rotation control
- Developing non-inductive start-up and sustainment
  - Non-inductive current up to 65%, CHI yields 35% flux savings (I_p=1MA), NSTX-U scenarios computed to access 100% NICD in broad operational range

Supporting slides follow

CY2011-FY2012 prioritized run plan met run-time guidance

Run time guidance for experiments and proposal stats (CY2011 & FY2012)

Topical Science Group	Milestones	FY11 1st priority XPs	FY11 2nd priority XPs	FY12 1st priority XPs	FY12 2nd priority XPs	FY11+12 total run days	XPs (+XMPs) submitted	Run days requested
Advanced Scenarios and Control	R12-3	3.0	1.0	4.0	1.5	9.5	23	22.0
Boundary Physics	Y11 JRT, R11	7.0	2.5	3.0	1.0	13.5	28	35.5
ITER urgent needs & cross-cutting	R11-4	4.0	1.0	2.5	1.0	8.5	42	52.5
Lithium Research	R12-1	3.0	1.0	5.0	1.5	10.5	17	19.0
Macroscopic Stability	R11-2	5.5	1.5	3.5	1.0	11.5	22	23.5
Solenoid-free Start-up & Ramp-up	R12-2	3.0	1.0	4.0	1.5	9.5	8	17.5
Transport and Turbulence	Y12 JRT, R11	4.0	1.0	4.0	1.0	10.0	24	29.0
Waves and Energetic Particles	12-2 (w/ SFSU	3.0	1.0	4.5	1.5	10.0	29	27.0
Total		**32.5**	**10.0**	**30.5**	**10.0**	**83.0**	**193**	**226.0**

- Record number of proposals (193 XPs/XMPs were considered)
- Requested run days outpaced available days by factor of 2.8
- TSGs were either very close to meeting, or met run time guidance
  - Slight (up to 0.5 day) mis-alignment of FY12 1st and 2nd priority not an issue – some shuffling may be required at mid-run assessment
  - WEP TSG is +0.5 days on their FY11 1st priority XPs (but total # days ok)

Brief summary of NSTX Milestones – key guidance for TSG XP prioritizations – FY2011

- 2011 OFES Joint Research Milestone (Boundary Physics, Transport & Turbulence) JRT-11
  - *Improve understanding of physics mechanisms responsible for pedestal structure, compare with the predictive models.*
  - *Perform detailed measurements of the height and width of the pedestal, E_r, initial measurements of pedestal region turbulence.*
  - *Perform focused analytic theory/computational effort, including large-scale simulations, on physics controlling pedestal structure, height.*
- R(11-1): Measure fluctuations causing turbulent electron, ion and impurity transport
- R(11-2): Assess ST stability dependence on plasma aspect ratio and 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

Original FY12 Milestones

- 2012 OFES Joint Research Milestone (Transport & Turbulence)
  - *Improve understanding of core transport and enhanced capability to predict core temperature and density profiles.*
  - *Assess the level of agreement between theoretical / computational transport models and available experimental measurements of core profiles, fluxes and fluctuations.*
  - *Emphasize simultaneous comparison of model predictions with experimental energy, particle and impurity transport levels/fluctuations in various regimes, including with electron modes.*
- R(12-1): Investigate relationship between Li-conditioned surface comp. and plasma behavior
- R(12-2): Assess confinement, heating, and ramp-up of CHI start-up plasmas
- R(12-3): Assess access to reduced density and collisionality in high-performance scenarios