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

# Overview of Physics Results from the National Spherical Torus Experiment


Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Tennessee
U Tulsa
U Washington
U Wisconsin
X Science LLC

## S. A. Sabbagh

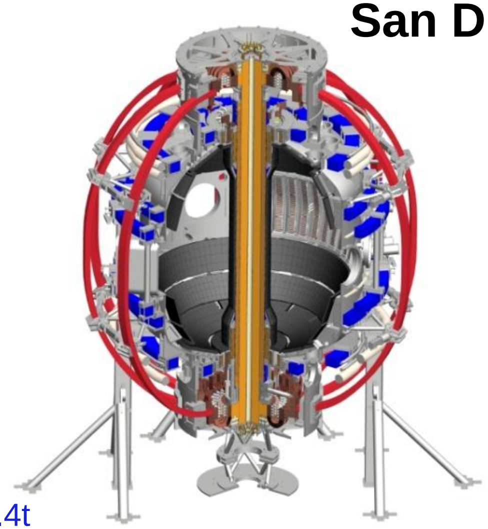
**Columbia University**

*for the NSTX-U Research Team*


**24th IAEA Energy Fusion Conference**

**October 9th, 2012**

**San Diego, California**

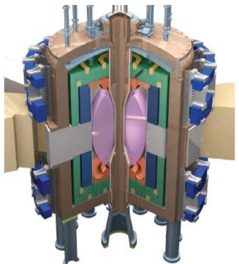



Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

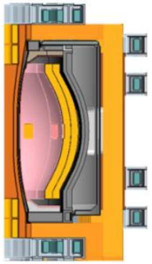

V2.4t

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

- Enable devices: ST-FNSF, ST-Pilot/DEMO, ITER
  - Leveraging unique ST plasmas provides new understanding for tokamaks, challenges theory

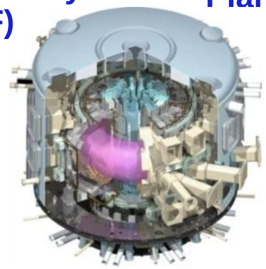


Fusion Nuclear Science Facility (FNSF)



ST Pilot Plant

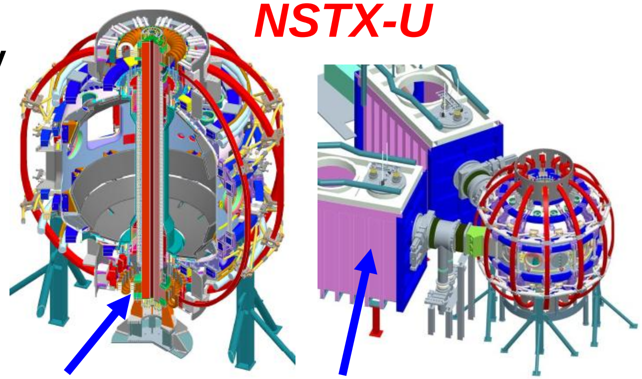
## Outline



*ITER*

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

***NSTX-U***



New center-stack

2[nd] neutral beam

| | | | |
|---|---|---|---|
| $B_T$ | 0.5 → 1 T | $P_{NBI}$ | 6 → 12 MW |
| $I_p$ | 1 → 2 MA | pulse | 1 → 5 s |

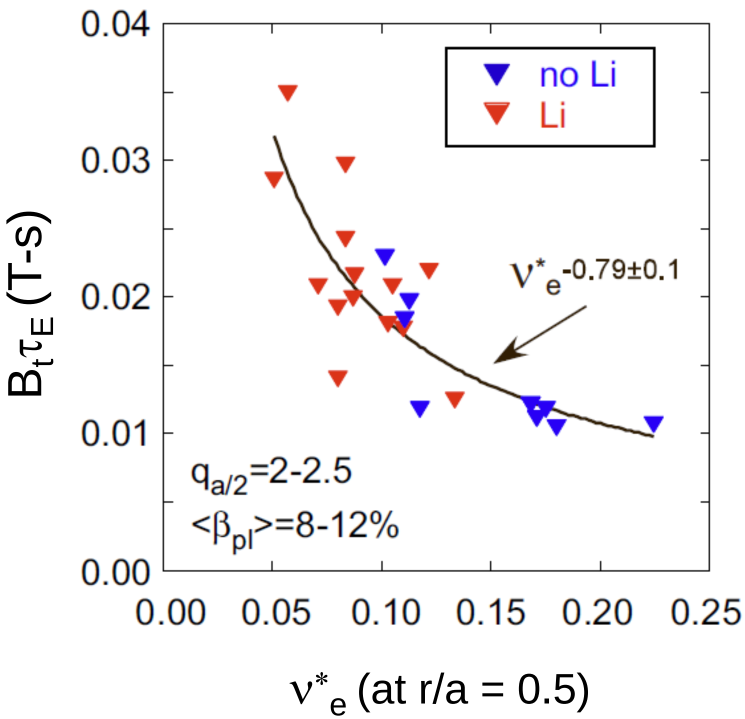
3D effects are pervasive in this research

# Outline

- Transport and stability at reduced collisionality
- Pedestal transport
- High $\beta$ pulse sustainment, disruptivity, and warning algorithms
- Energetic particles, power handling and first wall
- Non-inductive current and NSTX-Upgrade scenarios

# $\tau_E$ scalings unified by collisionality; nonlinear microtearing simulations find reduced electron heat transport at lower $\nu$

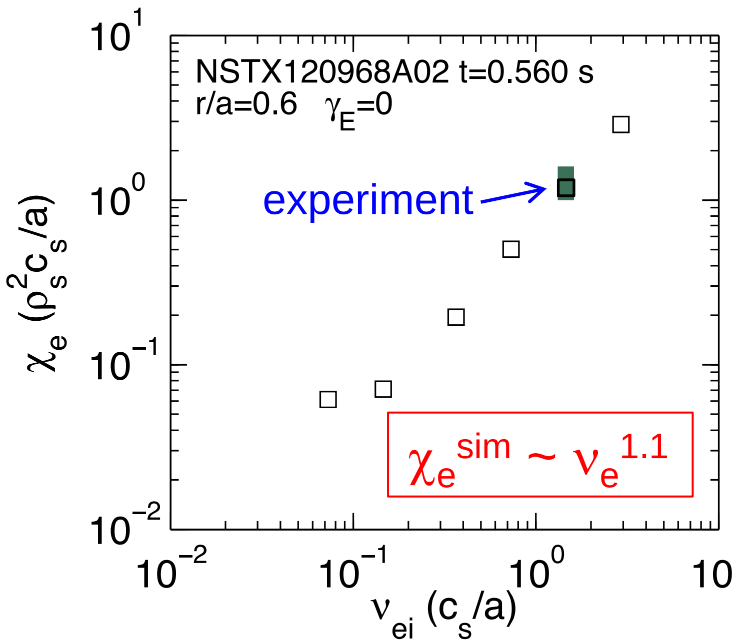
## Experiment

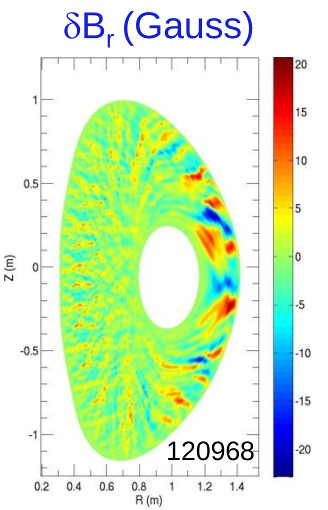



- Increase in $\tau_E$ as $\nu^*_e$ decreases
- Trend continues when lithium is used

**Kaye EX/7-1**

## Theory



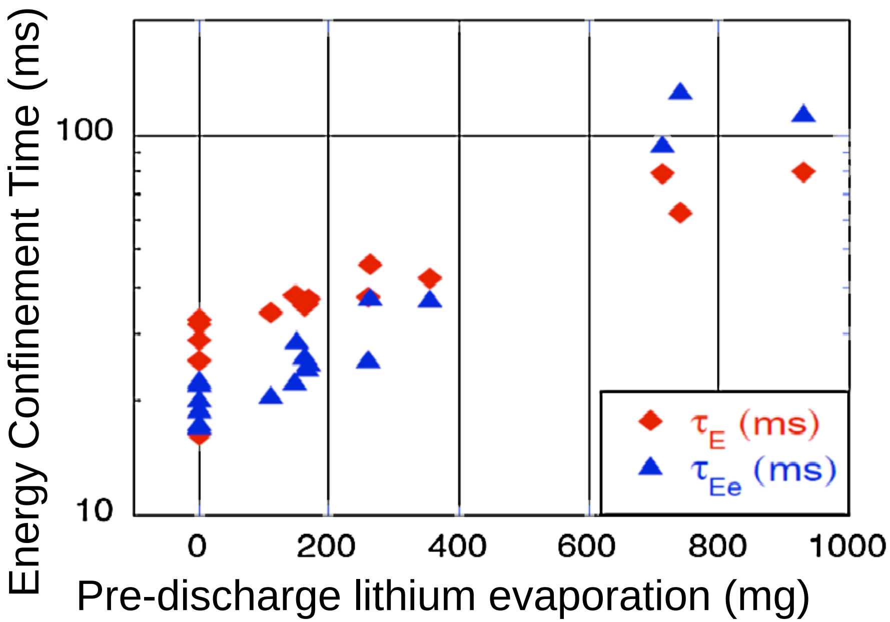

W. Guttenfelder, et al., PRL **106** (2011) 155004

- Quantitatively predicted $\chi_e$, scaling ~ $\nu_e^{1.1}$ consistent w/experiment ($\Omega\tau_E \sim B_t\tau_E \sim \nu^*_e{}^{-0.8}$)
- Transport dominated by magnetic “flutter”
  - Significant $\delta B_r/B \sim 0.1\%$

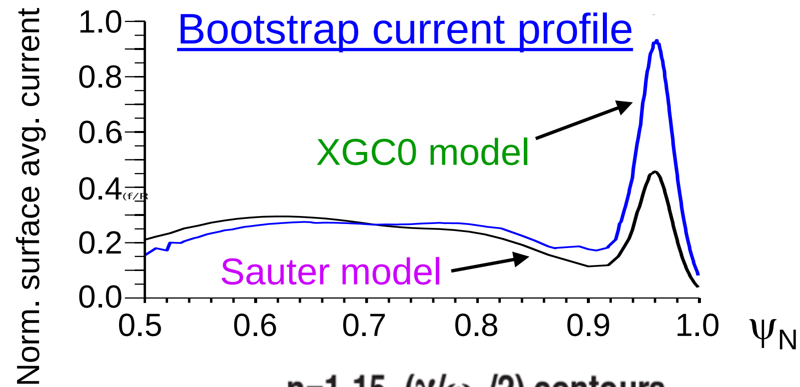
**Guttenfelder TH/6-1**

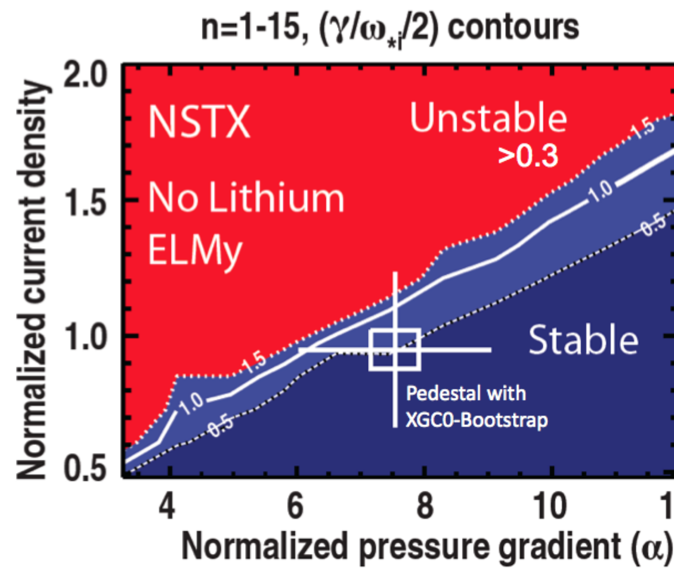
- NSTX-U computed to extend studies down to < 1/4 of present $\nu^*$

# Plasma characteristics change nearly continuously with increasing lithium evaporation; reach kink/peeling limit




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



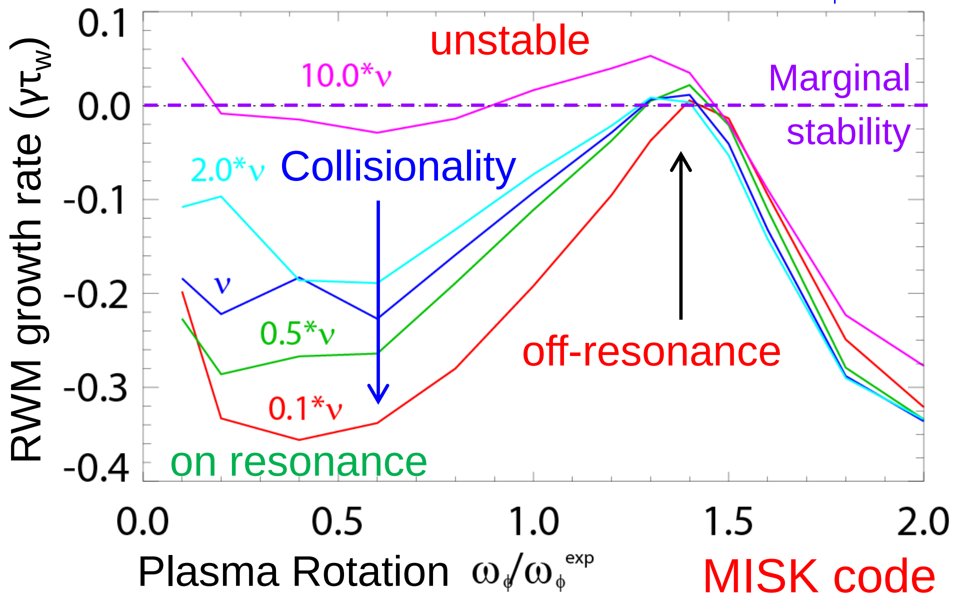




- Global parameters generally improve
  - With no core Li accumulation **Podesta EX/P3-02**
- ELM frequency declines - to zero
- Edge transport declines
  - As lithium evaporation increases, transport barrier widens, pedestal-top $\chi_e$ reduced
- New bootstrap current calculation (XGC0 code) improves agreement with profile reaching kink/peeling limit before ELM

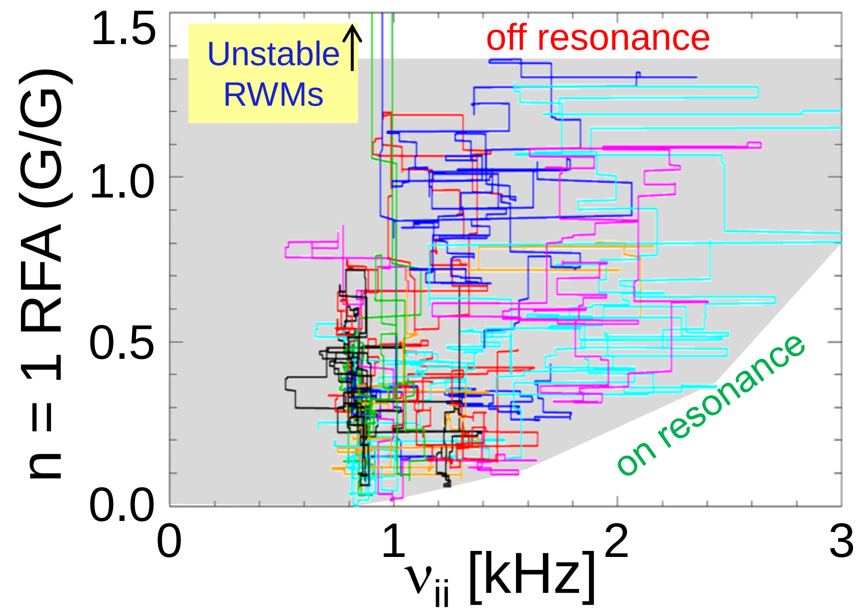
**Maingi EX/11-2** **Canik EX/P7-16** **Chang TH/P4-12** **Diallo EX/P4-04**

# Experiments measuring global stability vs. ν further support kinetic RWM stability theory, provide guidance for NSTX-U

Theory: RWM growth rate vs. ν and $\omega_\phi$




Exp: Resonant Field Amplification (RFA) vs ν




(trajectories of 20 experimental plasmas)

- Two competing effects at lower ν
  - Collisional dissipation reduced
  - Stabilizing resonant kinetic effects enhanced (contrasts early theory)
- Expectations at lower ν
  - More stabilization near $\omega_\varphi$ resonances; almost no effect off-resonance

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

- Mode stability directly measured in experiment using MHD spectroscopy
  - Decreases with ν at lower RFA ("on resonance")
  - Independent of ν at higher RFA ("off resonance")

$$RFA = \frac{B_{plasma}}{B_{applied}}$$

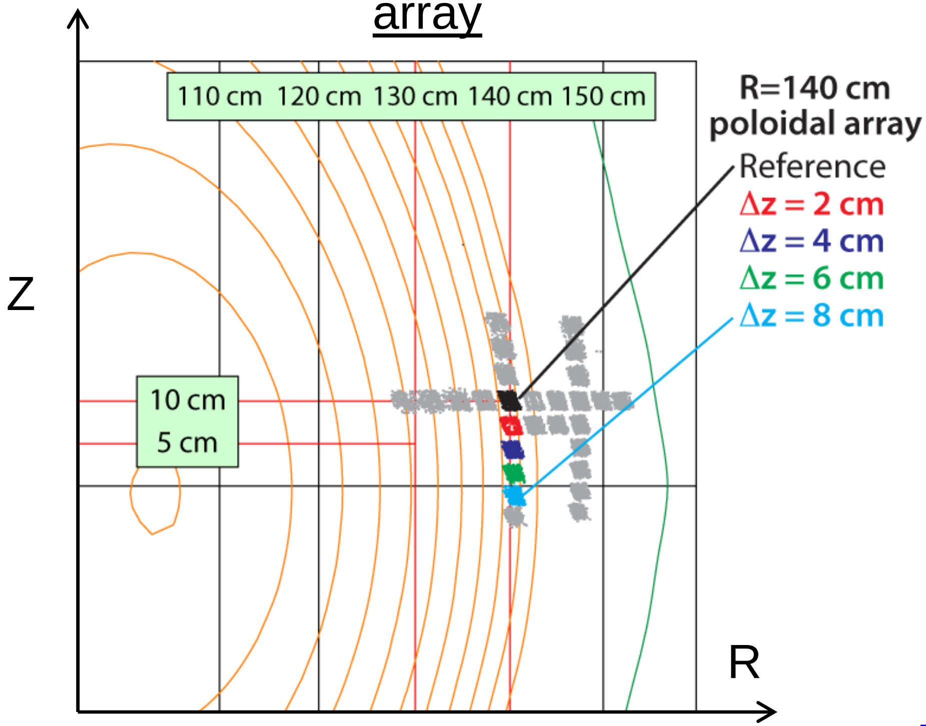
**Berkery EX/P8-07**

# Outline

- Transport and stability at reduced collisionality
- Pedestal transport
- High β pulse sustainment, disruptivity, and warning algorithms
- Energetic particles, power handling and first wall
- Non-inductive current and NSTX-Upgrade scenarios

# BES measured low-*k* turbulence in ELM-free H-mode pedestal steep gradient region is most consistent with TEMs

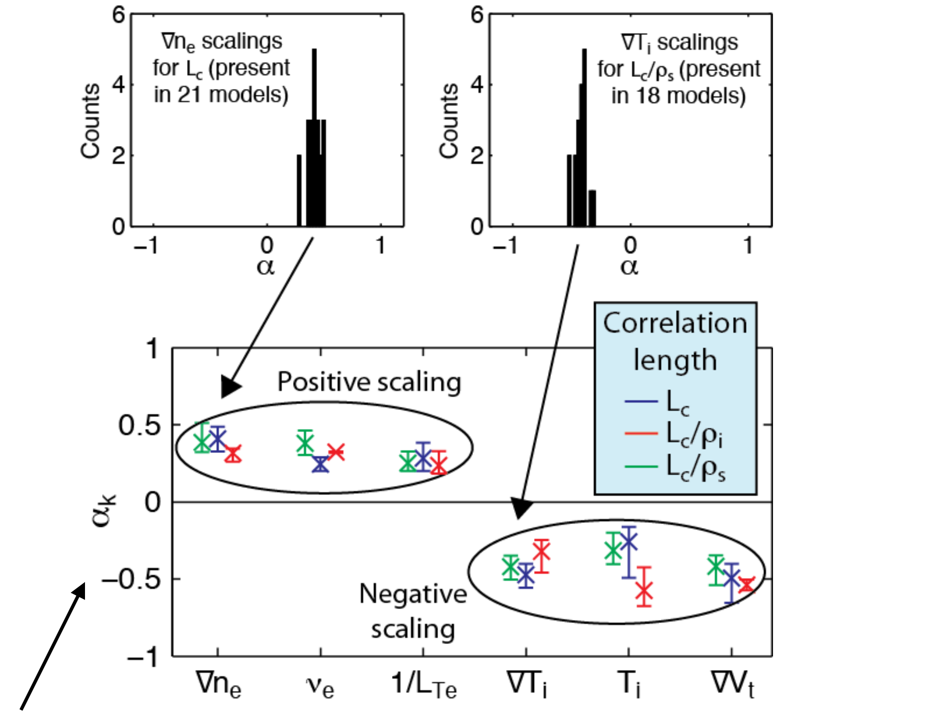
## Beam emission spectroscopy (BES) array




- Measurements during MHD quiet periods, in steep gradient region
- Large poloidal correlation lengths
  - $k_\theta \approx 0.2\text{-}0.4\ cm^{-1}$ and $k_\theta \rho_i \approx 0.2$

**Smith EX/P7-18**

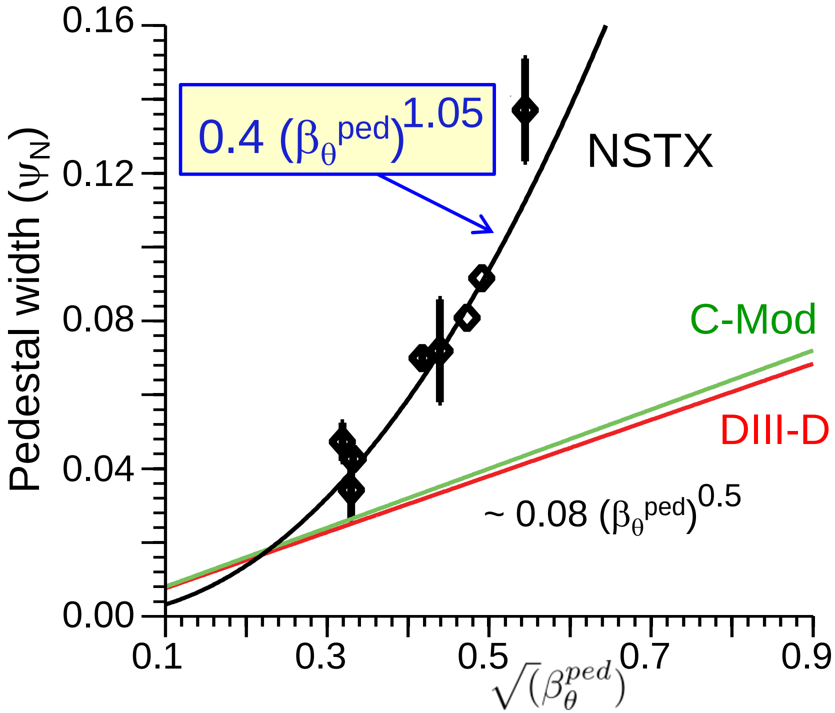
## Poloidal Correlation Length vs. Parameters




- Multivariate linear scaling coefficients $\alpha_k$
- Turbulence measurements in the steep gradient of the pedestal
  - Most consistent with Trapped Electron Modes
  - Partially consistent with KBM and $\mu$-Tearing Modes
  - Least consistent with ITG Modes

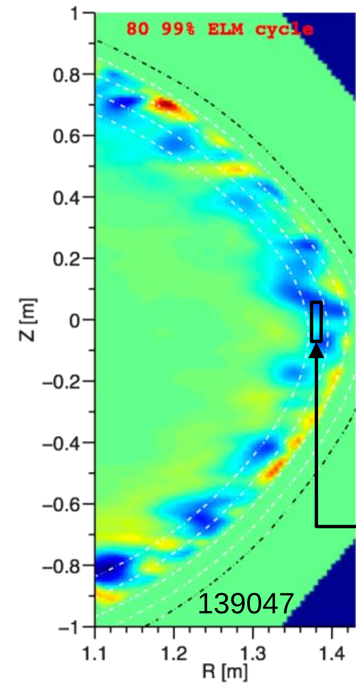
# Pedestal width scaling differs from tokamaks; turbulence correlation measurements consistent with theory

## Pedestal width scaling




## Turbulence correlation lengths

(During inter-ELM period, at pedestal top)




R = 1.38m

| | Theory (non-linear XGC1 code) | Experiment |
|---|---|---|
| radial | 3 cm | 2 – 4 cm (reflecto-metery) |
| poloidal | 11 cm | 10 – 14 cm (BES) |

80% - 99% ELM cycle

- Pedestal width scaling $\beta_\theta^\alpha$ applies to multiple machines
- In NSTX, observed ped. width is larger
  - Data indicates stronger scaling: $\beta_\theta$ vs. $\beta_\theta^{0.5}$
  - Examining possible aspect ratio effects

- Measured correlation lengths at pedestal top are consistent with theory
  - BES and reflectometry
    - spatial structure exhibits ion-scale microturbulence ($k_\perp \rho_i$ ~ 0.2 - 0.7)
    - Compatible with ITG modes and/or KBM

**Diallo EX/P4-04**

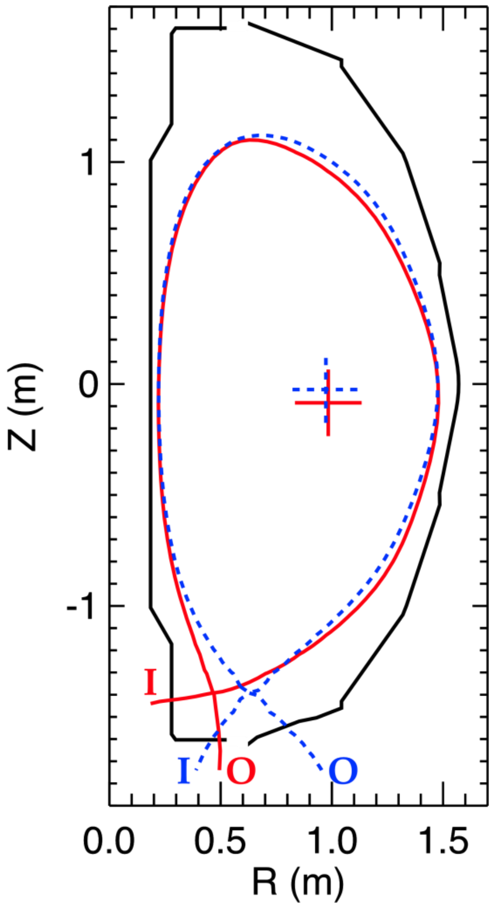
A. Diallo, C.S. Chang, S. Ku (PPPL), D. Smith (UW), S. Kubota (UCLA)

# A 30% increase in L-H power threshold is found at high vs. low triangularity, consistent with X-transport theory

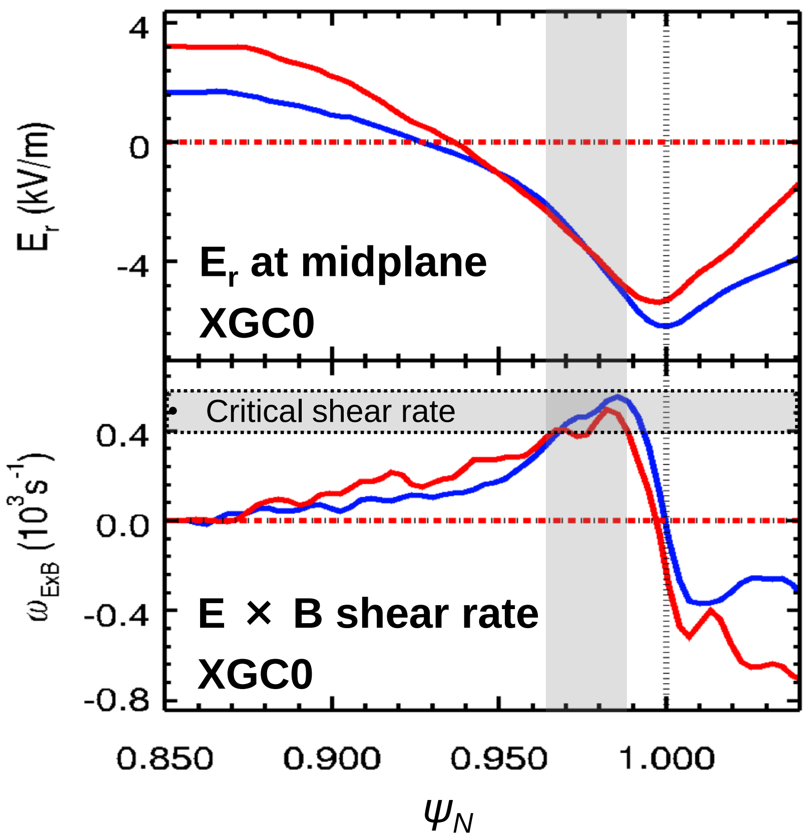
- X-point location is a hidden variable for L-H power threshold scaling ($P_{LH}$)
- $P_{LH}$ increases by 30% for high-δ vs. low-δ shape
- Consistent with predictions of X-transport theory (kinetic neo-classical transport)

High triangularity

Low triangularity




- Critical shear rate is satisfied for both shapes when core heating is 30% larger for high triangularity shape

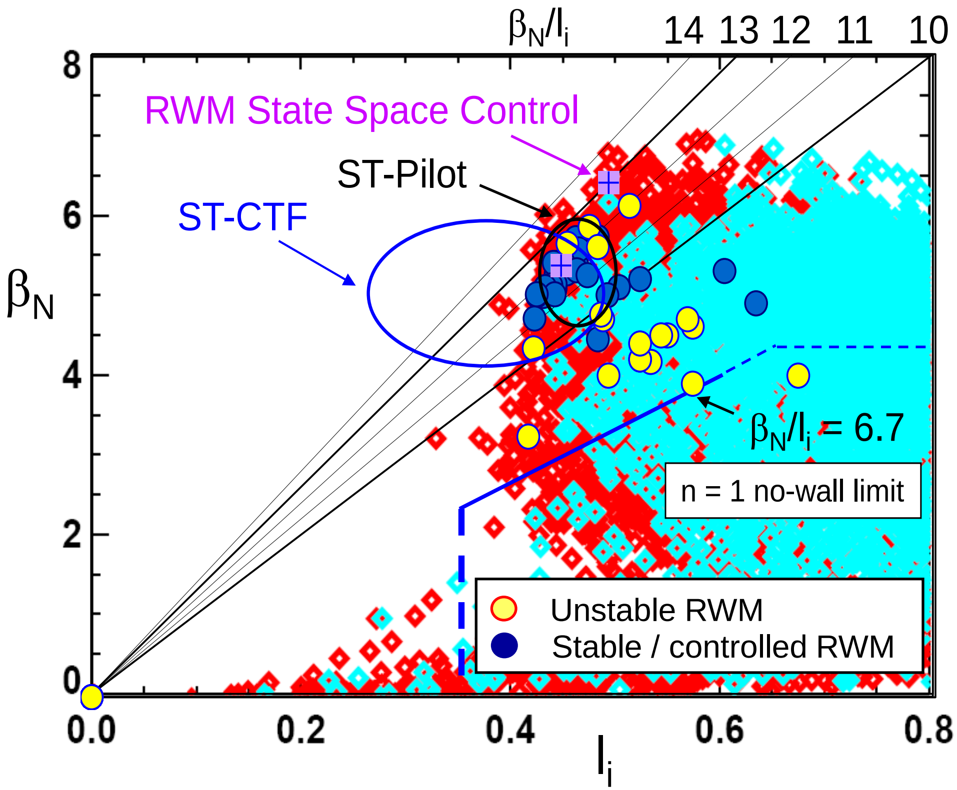



Battaglia EX/P5-28

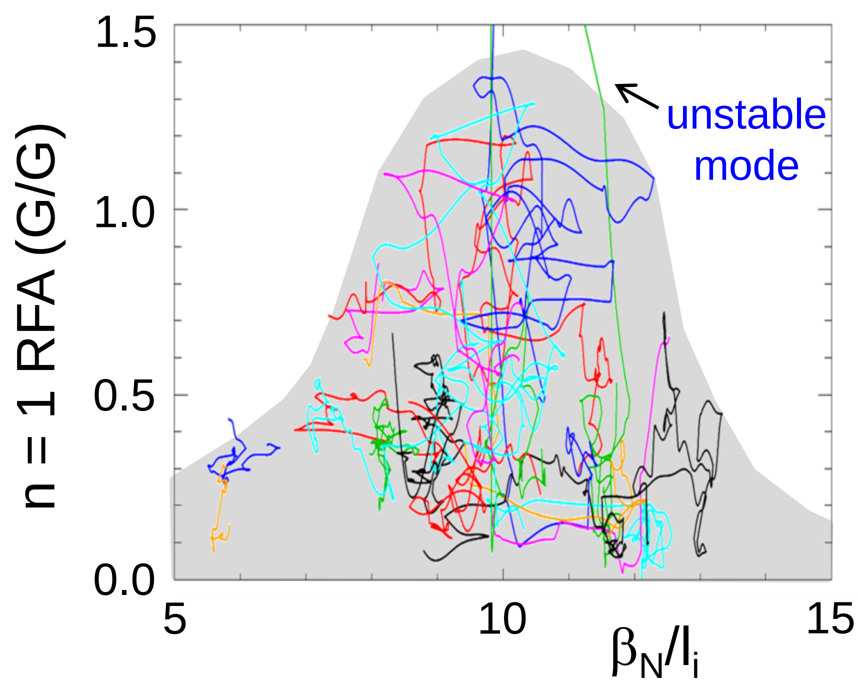
# Outline

- Transport and stability at reduced collisionality
- Pedestal transport
- High β pulse sustainment, disruptivity, and warning algorithms
- Energetic particles, power handling and first wall
- Non-inductive current and NSTX-Upgrade scenarios

# Stability control improvements significantly reduce unstable RWMs at low $l_i$ and high $\beta_N$; improved stability at high $\beta_N/l_i$




Resonant Field Amplification (RFA) vs. $\beta_N/l_i$




- Disruption probability reduced by a factor of 3 on controlled experiments
  - Reached 2 times computed n = 1 no-wall limit of $\beta_N/l_i$ = 6.7
- Lower probability of unstable RWMs at high $\beta_N/l_i$

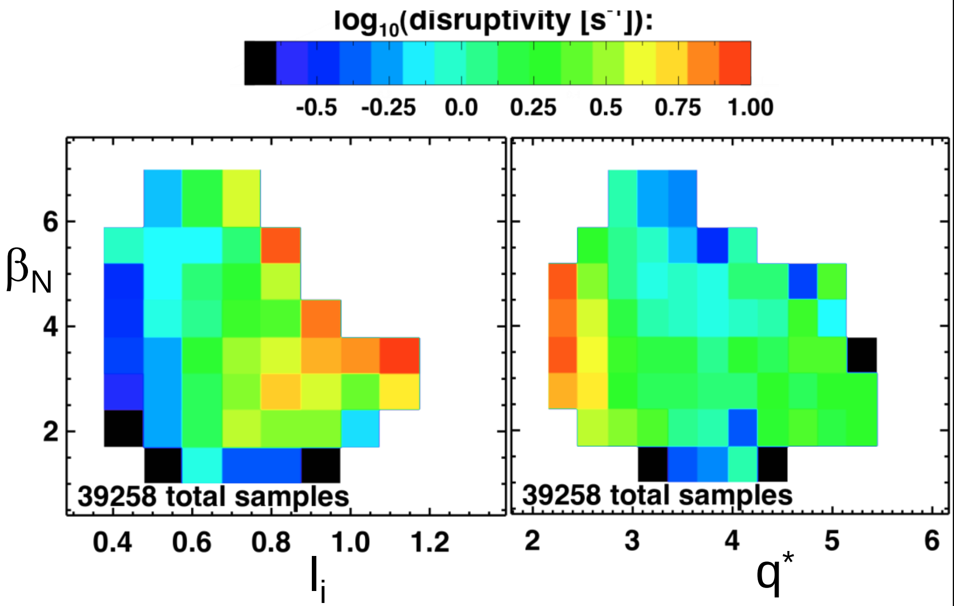
S.A. Sabbagh

- Mode stability directly measured in experiments using MHD spectroscopy
  - Stability decreases up to $\beta_N/l_i$ = 10
  - Stability increases at higher $\beta_N/l_i$
  - Presently analysis indicates consistency with kinetic resonance stabilization

Berkery EX/P8-07

# Disruptivity studies and warning analysis of NSTX database are being conducted for disruption avoidance in NSTX-U

## Disruptivity

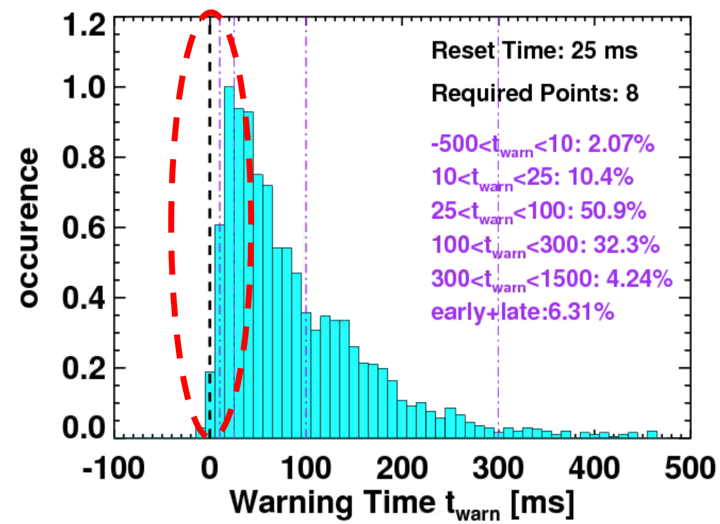



All discharges since 2006

- Physics results
  - Low disruptivity at relatively high $\beta_N \sim 6$; $\beta_N / \beta_N^{\text{no-wall}(n=1)} \sim 1.3\text{-}1.5$
    - Consistent with specific disruption control experiments, RFA analysis
  - Strong disruptivity increase for $q^* < 2.5$
  - Strong disruptivity increase for very low rotation

## Warning Algorithms

- Disruption warning algorithm shows high probability of success
  - Based on combinations of single threshold based tests

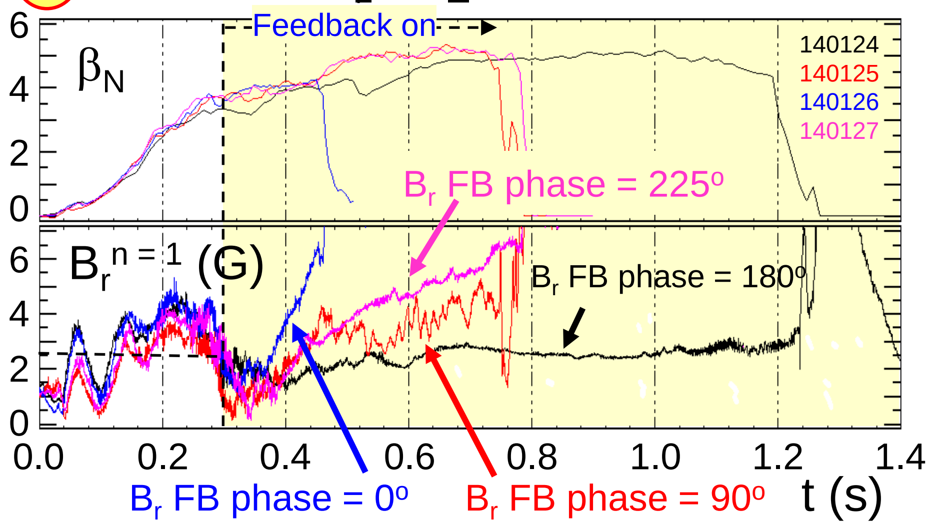



- Results
  - ~ 98% disruptions flagged with at least 10ms warning, ~ 6% false positives
  - False positive count dominated by near-disruptive events

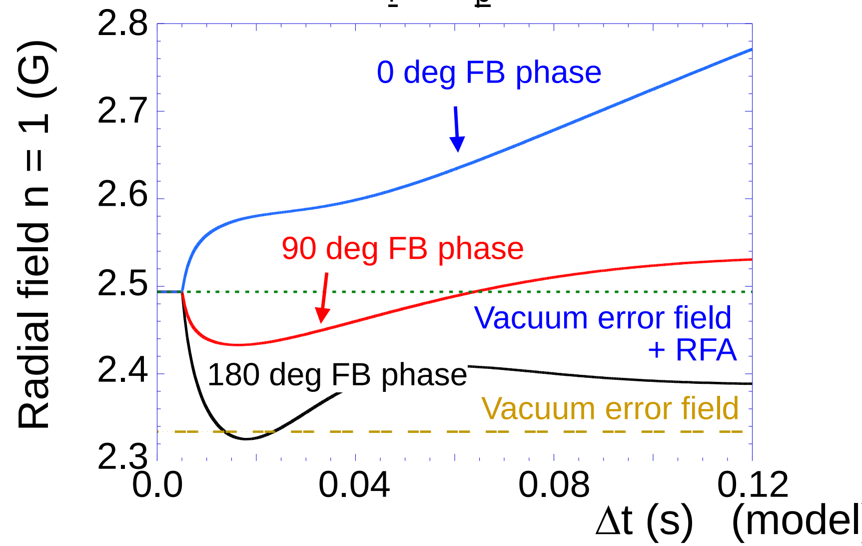
**Gerhardt EX/9-3**

# Improved stability control includes dual field component feedback and state space feedback, improved by 3D effects

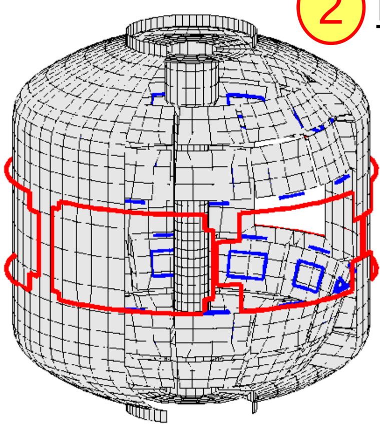
## 1 Active n = 1 $B_p$ + $B_R$ feedback (FB) control



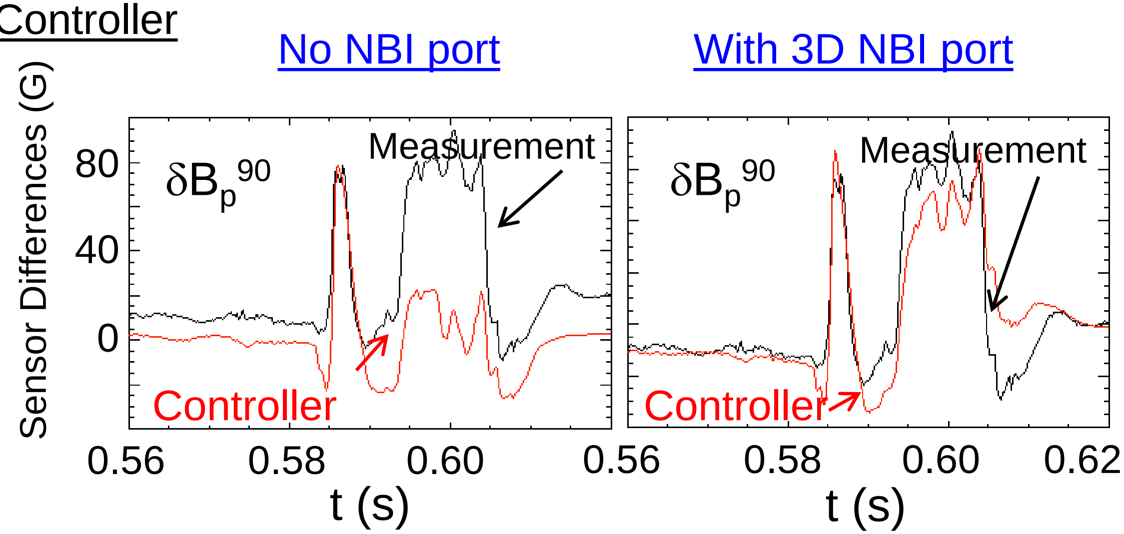

## Calculation of $B_r$ + $B_p$ control (VALEN)




## 2 RWM State Space Controller



3D wall, ports, mode currents




- Inclusion of 3D mode and wall detail improves control

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

# Outline

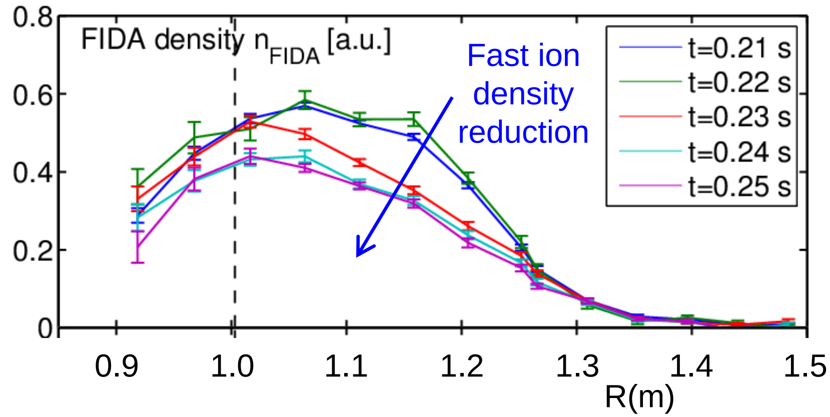
- Transport and stability at reduced collisionality
- Pedestal transport
- High β pulse sustainment, disruptivity, and warning algorithms
- Energetic particles, power handling and first wall
- Non-inductive current and NSTX-Upgrade scenarios

# Fast ion redistribution associated with low frequency MHD measured by fast ion $D_\alpha$ (FIDA) diagnostic

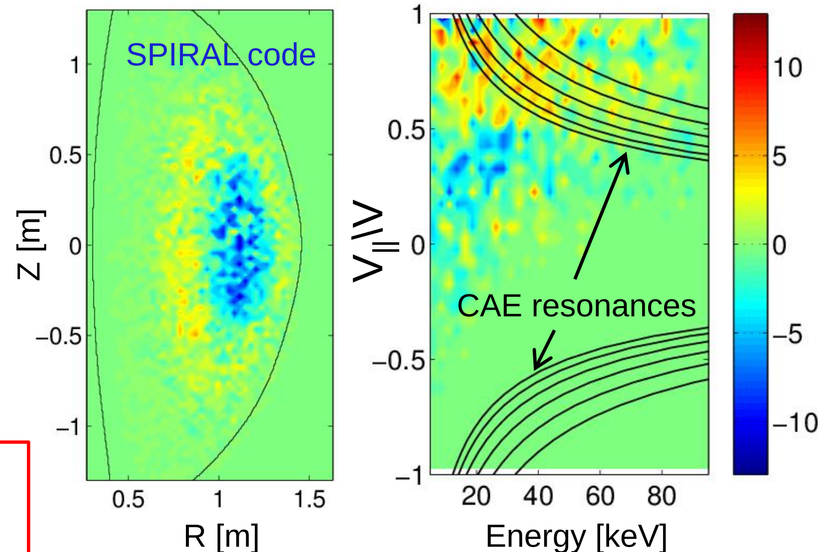
- Caused by n = 1 global kink instabilities
- Redistribution can affect stability of *AE, RWMs, other MHD
- Full-orbit code (SPIRAL) shows redistribution in real and velocity space
  - Radial redistribution from core plasma
  - Particles shift towards $V_{||}/V = 1$
- Applied 3D fields alter GAE stability
  - By altered fast ion distribution (SPIRAL)

- Fast ion energy redistribution accounts for neutron rate decrease in H-mode TAE avalanches **Fredrickson EX/P6-05**

- Core localized CAE/GAEs measured in H-mode plasmas (reflectometer) **Crocker EX/P6-02**



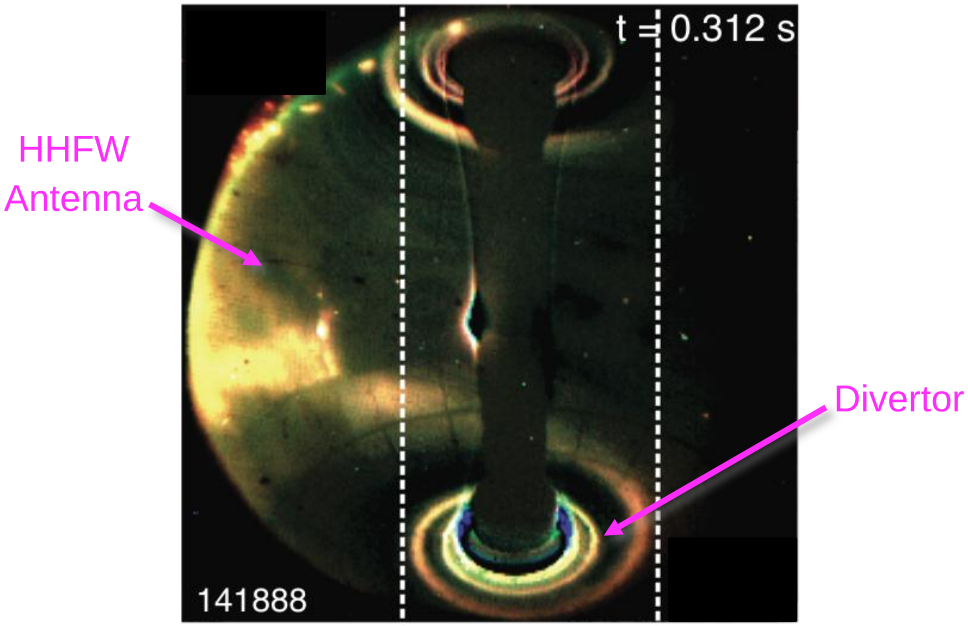

Change in distribution due to kink mode



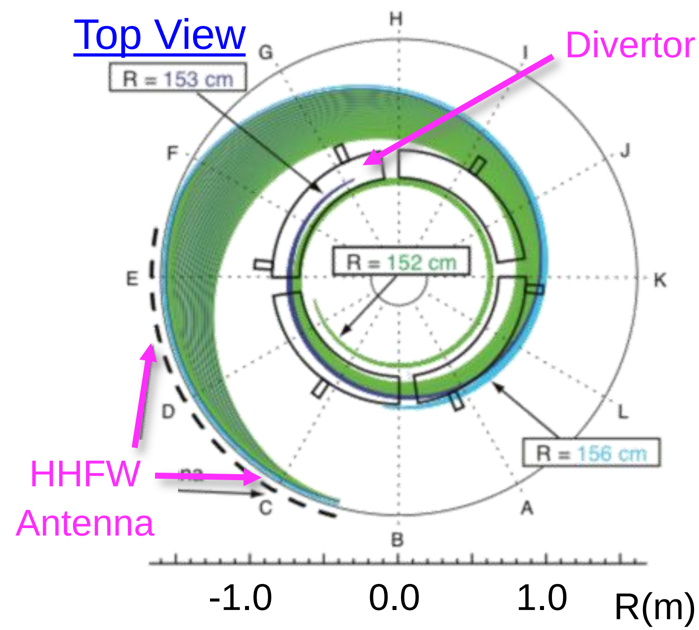

A. Bortolon

# Significant fraction of the HHFW power lost in the SOL in front of antenna flows to the divertor region

<u>Visible camera image of edge RF power flow to divertor</u>




<u>SPIRAL modeling of field lines from antenna to divertor</u>




- RF power couples to field lines across entire SOL width, not just to field lines connected to antenna components
- Shows importance of quantitatively understanding RF power coupling to the SOL for prediction to future devices

R. Perkins, et al., PRL **109** (2012) 045001

**Perkins EX/P5-40**

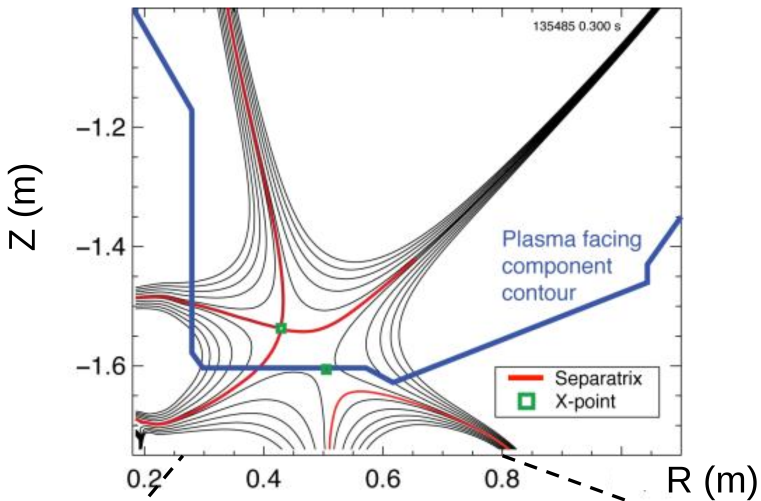
# Snowflake divertor experiments provide basis for required divertor heat flux mitigation in NSTX-U

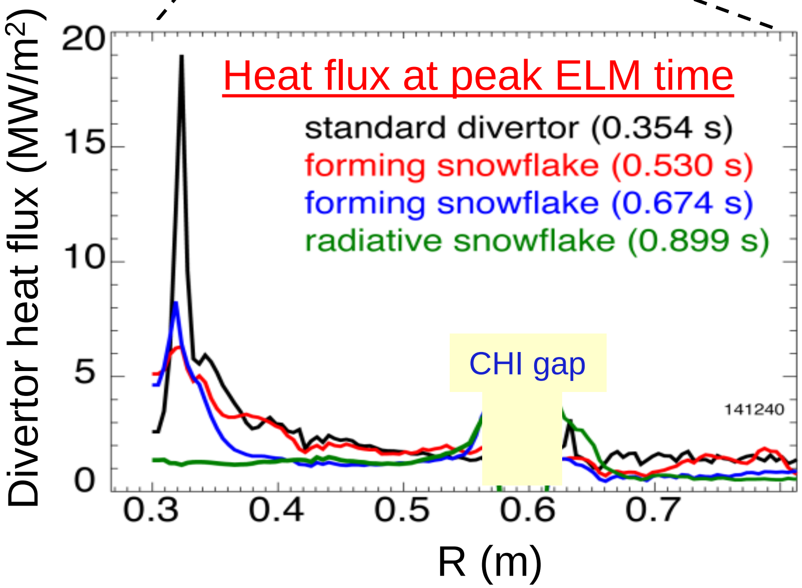
- Needed, as divertor heat flux width strongly decreases as $I_p$ increases

- Snowflake divertor experiments ($P_{NBI}$ = 4 MW, $P_{SOL}$ = 3 MW)
  - Good H-mode $\tau_E$, $\beta_N$, sustained during snowflake operation
  - Divertor heat flux significantly reduced both during and between ELMs
    - during ELMs: 19 to ~ 1.5 MW/m$^2$
    - steady-state: 5-7 to ~ 1 MW/m$^2$
  - Achieved by a synergistic combination of detachment + radiative snowflake divertor

Soukhanovskii EX/P5-21

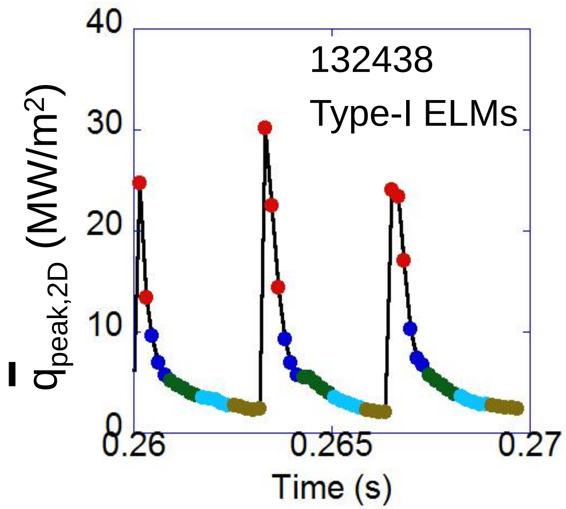
Snowflake divertor in NSTX



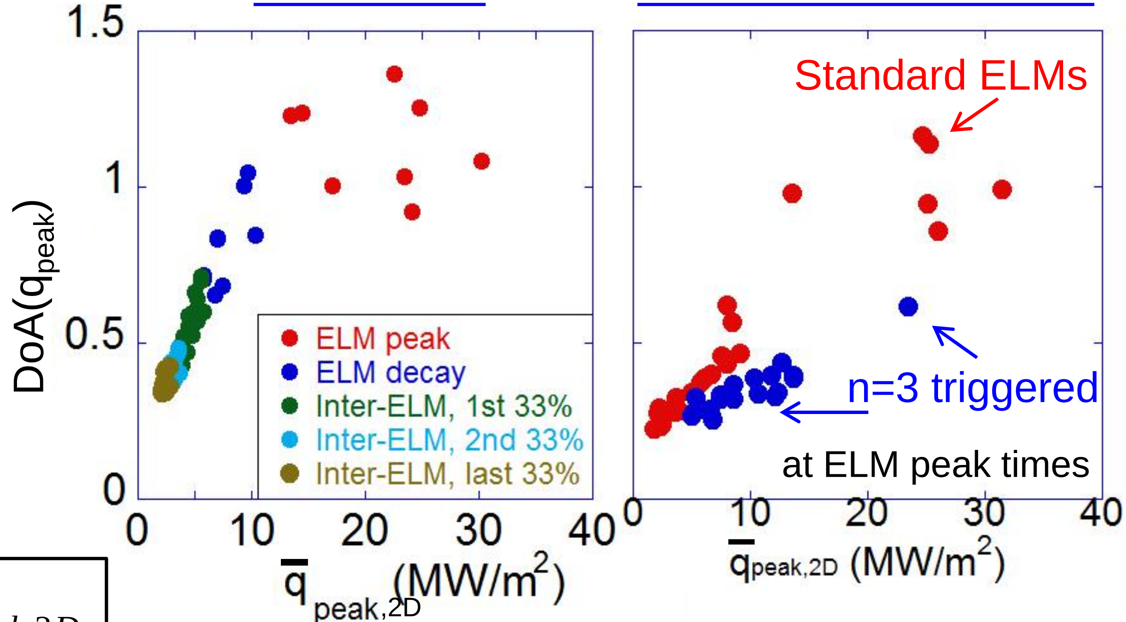
# Toroidal asymmetry of heat deposition measured during standard ELMs, but decreases for 3D field-triggered ELMs

Mean Peak 2D Heat Flux During ELMs vs. t




$$DoA(q_{peak}) = \sigma_{qpeak} / \bar{q}_{peak,2D}$$

Toroidal Degree of Asymmetry vs. $q_{peak}$




- 2D fast IR camera measurement (6.3kHz), heat flux from TACO code
- Toroidal asymmetry
  - Becomes largest at the peak heat flux for usual Type-I ELMs
  - Reduced by up to 50% in ELMs triggered by n = 3 applied fields

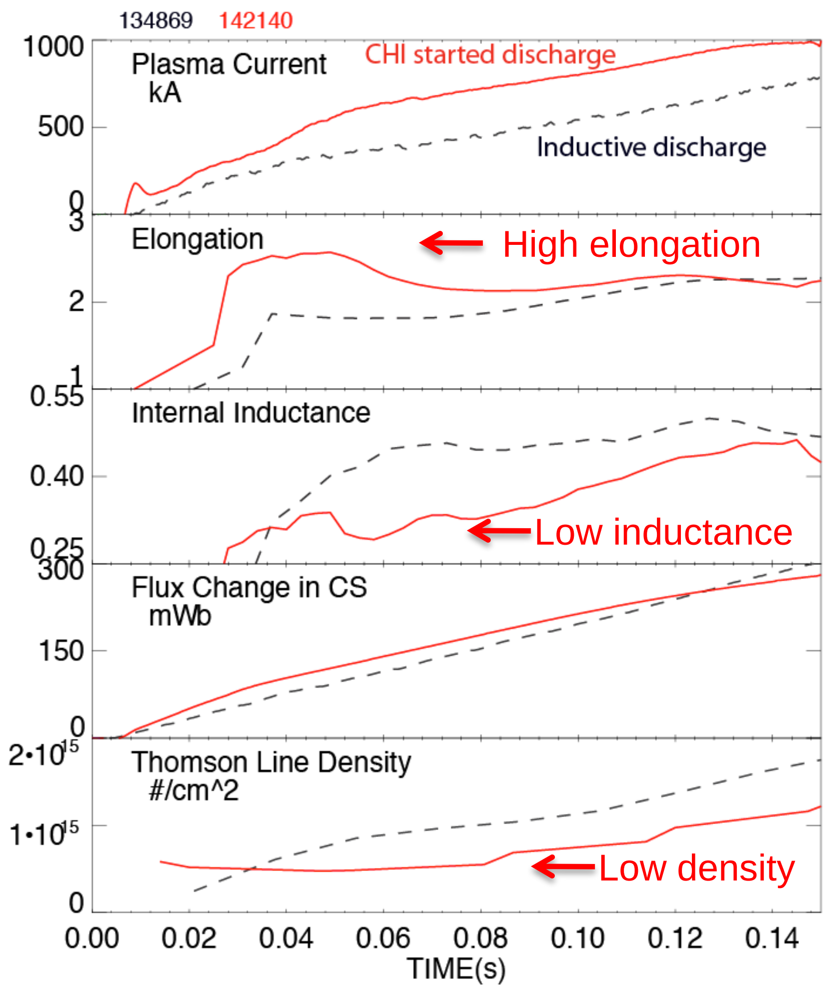
Ahn EX/P5-33

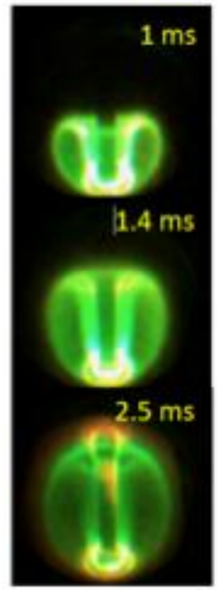
# Outline

- Transport and stability at reduced collisionality
- Pedestal transport
- High β pulse sustainment, disruptivity, and warning algorithms
- Energetic particles, power handling and first wall
- Non-inductive current and NSTX-Upgrade scenarios

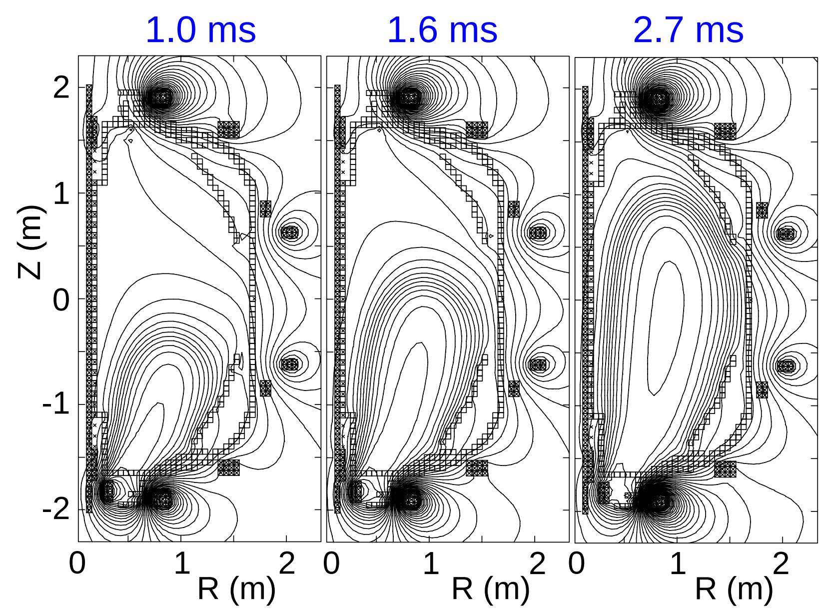
# Plasma discharge ramping to 1MA requires 35% less inductive flux when coaxial helicity injection (CHI) is used

## CHI assisted startup in NSTX



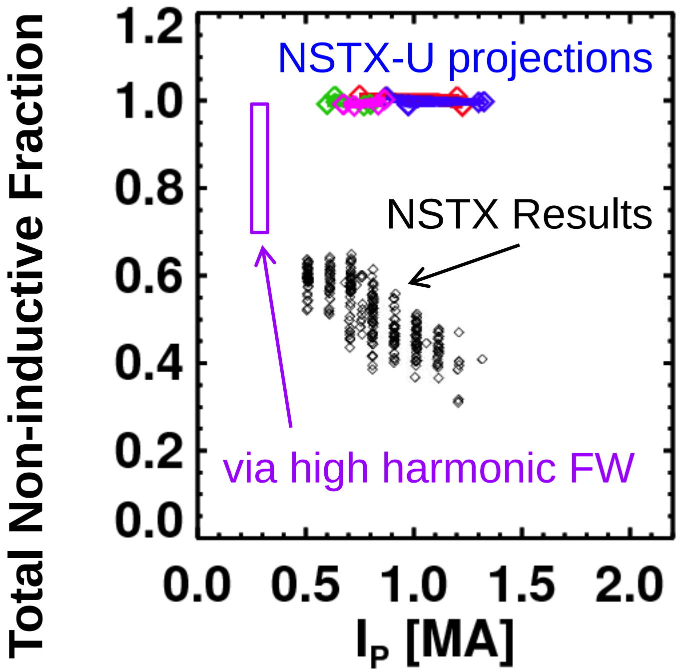

## TSC simulation of CHI startup

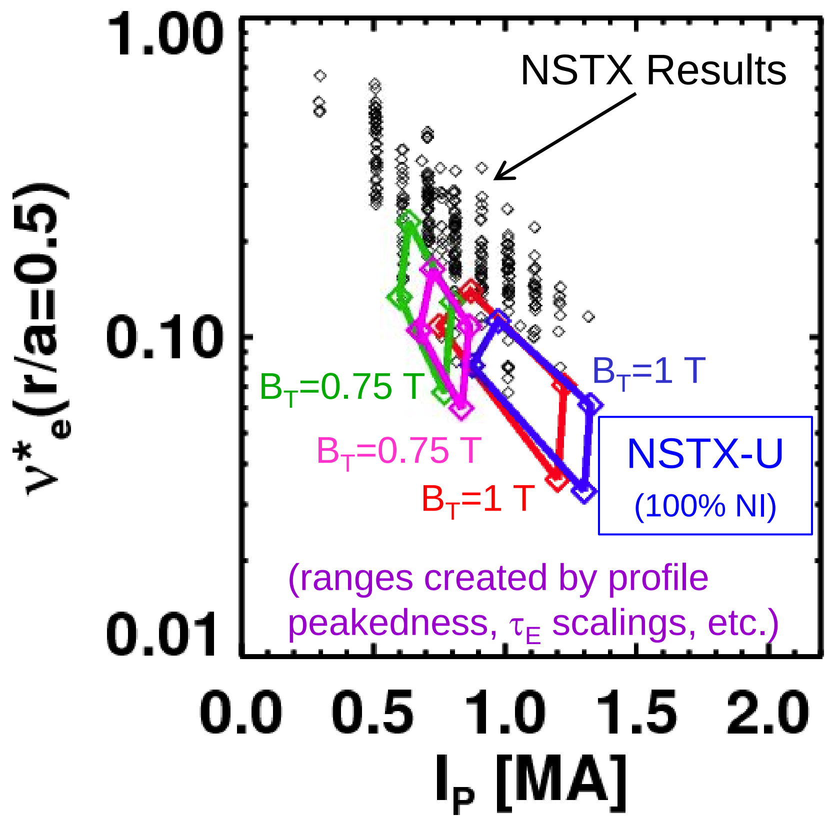



- CHI generates plasmas with high elongation, low $l_i$ and $n_e$
- TSC now used for full discharge modeling to 1MA
  - CHI start-up + NBI current ramp-up
- Results imply a doubling of closed flux current > 400kA in NSTX-U

**Raman EX/P2-10**

# 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

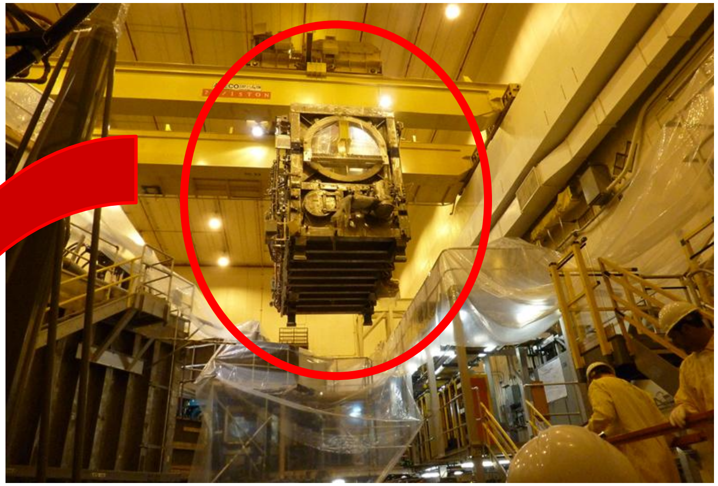
G. Taylor (Phys. Plasmas **19** (2012) 042501)

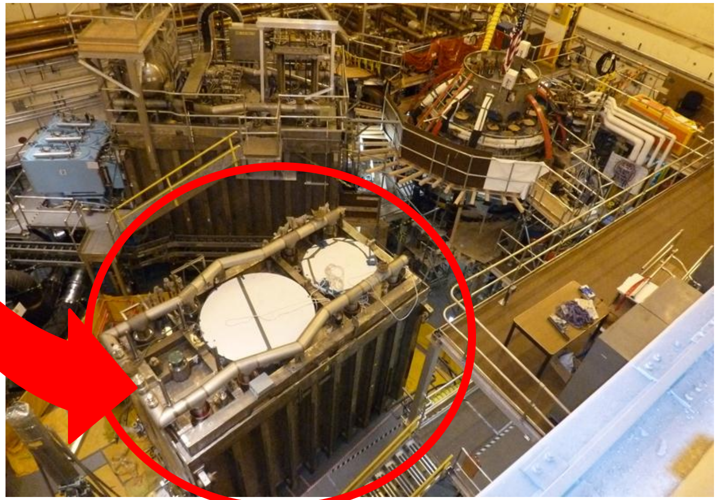
S. Gerhardt, et al., Nucl. Fusion **52** (2012) 083020

- 100% non-inductive scenarios found over wide operation range
  - Higher A ~ 1.65 of NSTX-U created in NSTX, vertical stability tested

**Menard FTP/3-4** **Kolemen EX/P4-28**

# Rapid Progress is Being Made on NSTX Upgrade

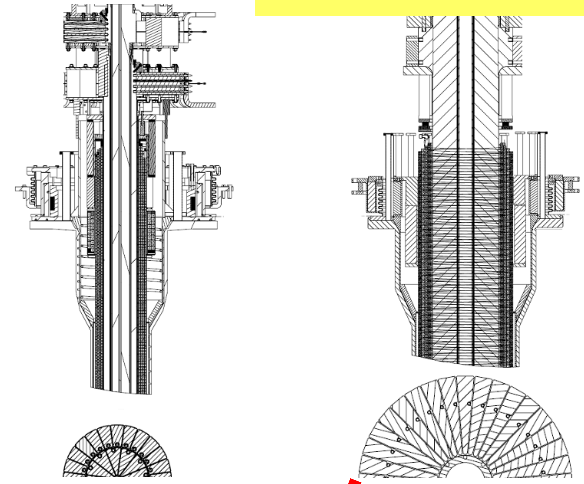




- 2nd neutral beam moved into place

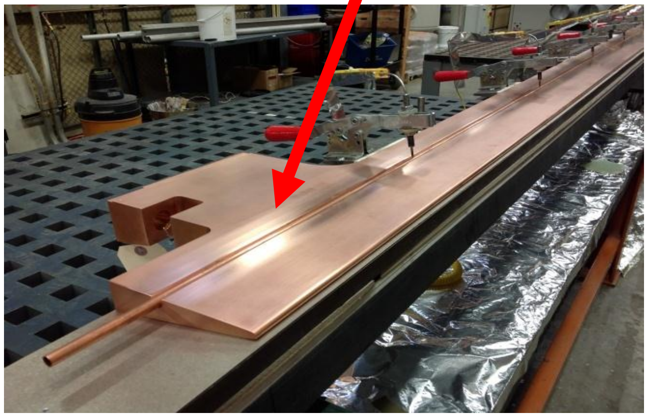
Old center stack

NEW Center Stack



TF OD = 20cm

TF OD = 40cm



- TF conductors being made

(first plasma anticipated June 2014)

Menard FTP/3-4

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

- Transport and stability at reduced collisionality
  - $\tau_E$ scalings unified by collisionality; non-linear microtearing simulations match experimental $\chi_e$, predict lower $\chi_e$ at lower $\nu_e^*$ shown in experiment
  - Nearly continuous increase of favorable confinement with increased lithium
  - Stabilizing kinetic RWM effects enhanced at lower $\nu$ when near resonances
- Pedestal
  - Width scaling stronger than usual $(\beta_p^{ped})^{0.5}$; measured $\delta n_e$ correlation lengths consistent w/TEMs in ped. steep gradient, non-linear gyrokinetics at ped. top
- Pulse sustainment / disruption avoidance
  - Global stability increased + low disruptivity at high $\beta_N/l_i$, advanced mode control
  - Disruption detection algorithm shows high (98%) success rate
- Power handling and first wall
  - Large heat flux reduction from combination of radiative snowflake divertor + detachment; heat asymmetry from ELMs reduced when triggered by n = 3 field
- Significant upgrade underway (NSTX-U)
  - Doubled $B_T$, $I_p$, NBI power; 5x pulse length, projected 100% non-inductive sustainment over broad operating range

# NSTX Presentations at the 2012 IAEA FEC

## Talks

### Thursday

- Progress in Simulating Turbulent Electron Thermal Transport in NSTX — **Guttenfelder** — TH/6-1
- The Dependence of H-mode Energy Confinement and Transport on Collisionality in NSTX — **Kaye** — EX/7-1

### Friday

- Disruptions in the High Beta Spherical Torus NSTX — **Gerhardt** — EX/9-3
- Progress on Developing the Spherical Tokamak for Fusion Applications — **Menard** — FTP/3-4

### Saturday

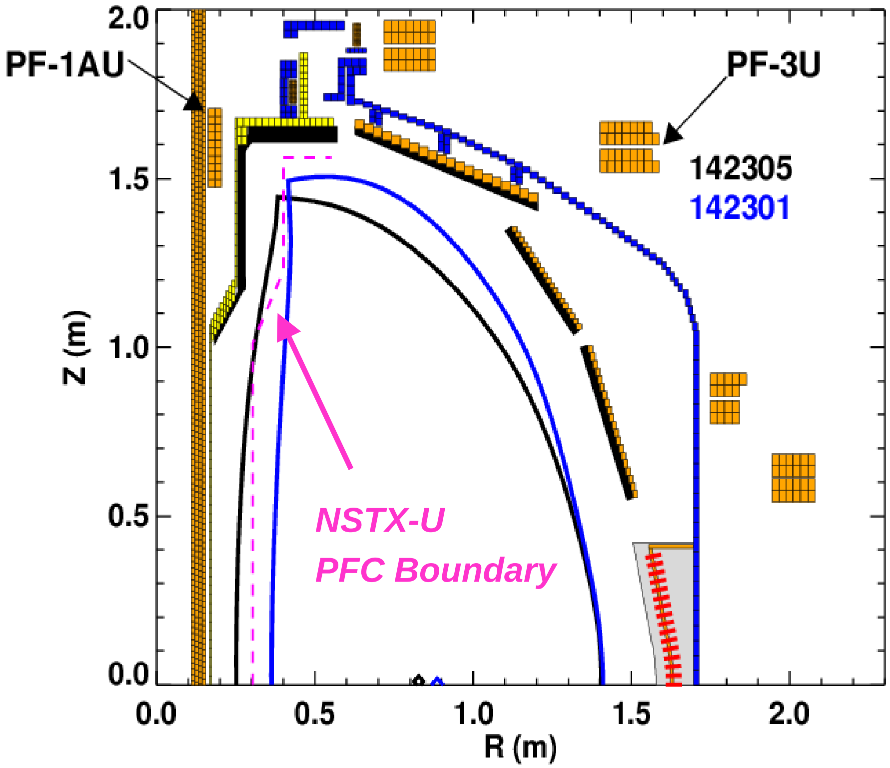
- The Nearly Continuous Improvement of Discharge Characteristics and Edge Stability with Increasing Lithium Coatings in NSTX — **Maingi** — EX/11-2

## Posters

| | | |
|---|---|---|
| **Tuesday** | | |
| Lithium program | **Ono** | FTP/P1-14 |
| Co-axial helicity injection | **Raman** | EX/P2-10 |
| Particle code NTV simulation | **Kim** | TH/P2-27 |
| **Wednesday** | | |
| Bootstrap current XGC | **Chang** | TH/P4-12 |
| Pedestal transport | **Diallo** | EX/P4-04 |
| Power scrape-off width | **Goldston** | TH/P4-19 |
| Vertical stability at low A | **Kolemen** | EX/P4-28 |
| Blob dynamics / edge V shear | **Myra** | TH/P4-23 |
| EHOs | **Park** | EX/P4-33 |
| Core lithium levels | **Podesta** | EX/P3-02 |
| C, Li impurity transport | **Scotti** | EX/P3-34 |
| Snowflake divertor theory | **Ryutov** | TH/P4-18 |
| **Thursday** | | |
| Divertor heat asymmetry | **Ahn** | EX/P5-33 |
| L-H power threshold vs. X pt. | **Battaglia** | EX/P5-28 |
| NBI-driven GAE simulations | **Belova** | TH/P6-16 |
| CAE/GAE structure | **Crocker** | EX/P6-02 |
| TAE avalanches in H-mode | **Fredrickson** | EX/P6-05 |
| Li deposition / power exhaust | **Gray** | EX/P5-27 |
| Liquid lithium divertor results | **Jaworski** | EX/P5-31 |
| RF power flow in SOL | **Perkins** | EX/P5-40 |
| Snowflake divertor | **Soukhanovksii** | EX/P5-21 |
| **Friday** | | |
| Global mode control / physics | **Berkery** | EX/P8-07 |
| Edge transport with Li PFCs | **Canik** | EX/P7-16 |
| Turbulence near OH L-H trans. | **Kubota** | EX/P7-21 |
| ELM triggering by Li in EAST | **Mansfield** | PD |
| Electron-scale turbulence | **Ren** | EX/P7-02 |
| Low-k turbulence vs. params. | **Smith** | EX/P7-18 |

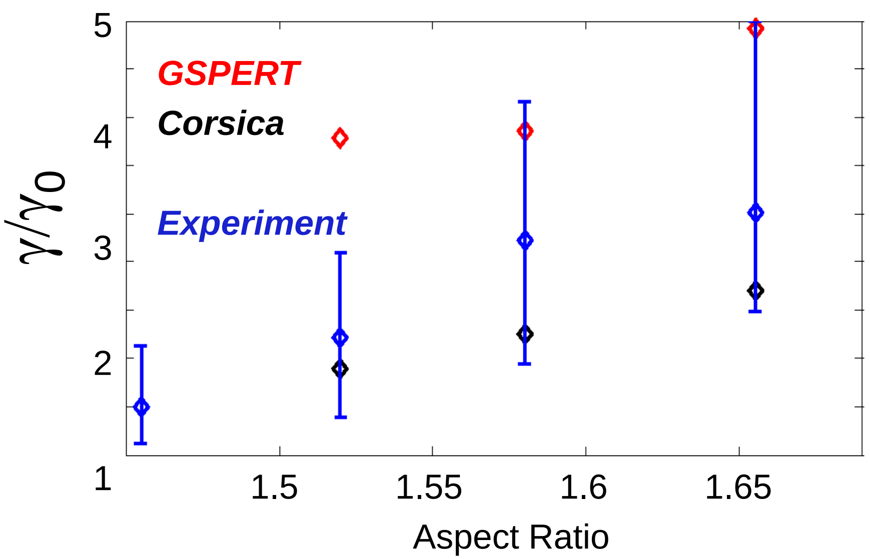
# Supporting slides follow

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




- NSTX Discharges have matched aspect ratio and elongation of NSTX-U (A = 1.65) without performance degradation

Vertical Stability Growth Rates vs. A

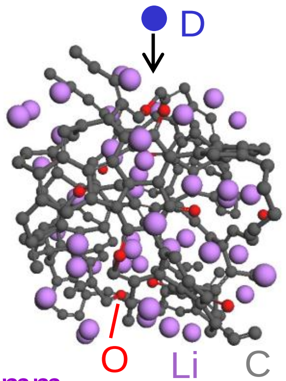



- Improvements to vertical control capability and understanding
  - Begun to compare measured growth rates to theoretical predictions (Corsica, GSPERT)
  - Improved plasma position observer
  - Modeled use of RWM coils for n=0 control

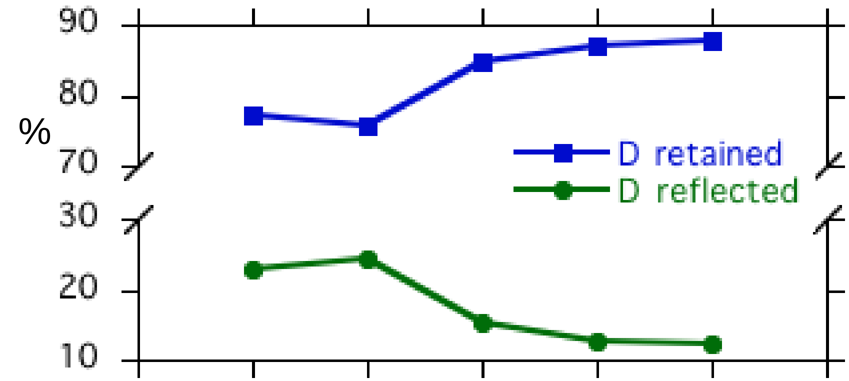
**Kolemen EX/P4-28**

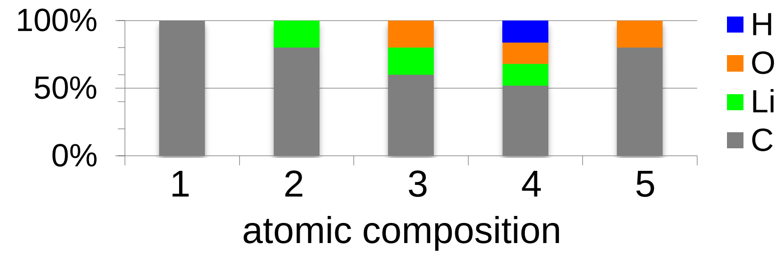
# Simulations and lab results show importance of oxygen in the lithium-graphite PMI for pumping deuterium

- Quantum-classical atomistic simulations show surface oxygen plays key role in D retention in graphite

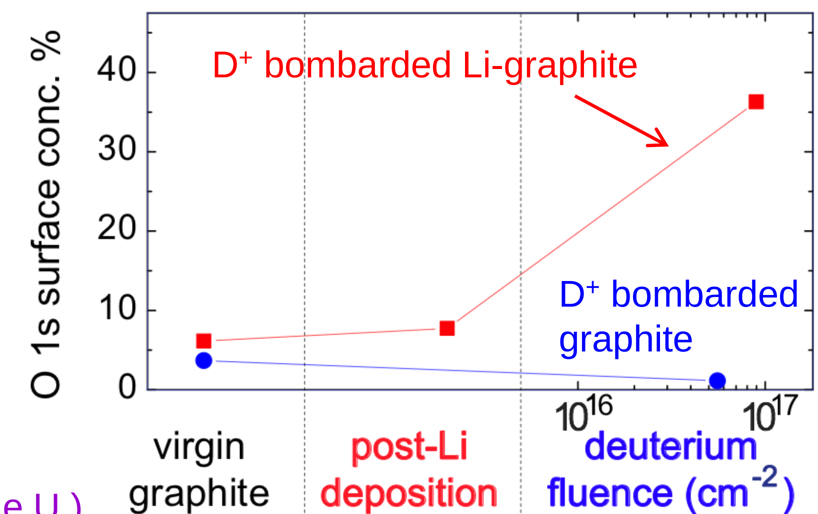



P. Krstic, sub. to Nature Comm.




- Accordingly, lab results support that Li on graphite can pump D effectively due to O
  - Measurements 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



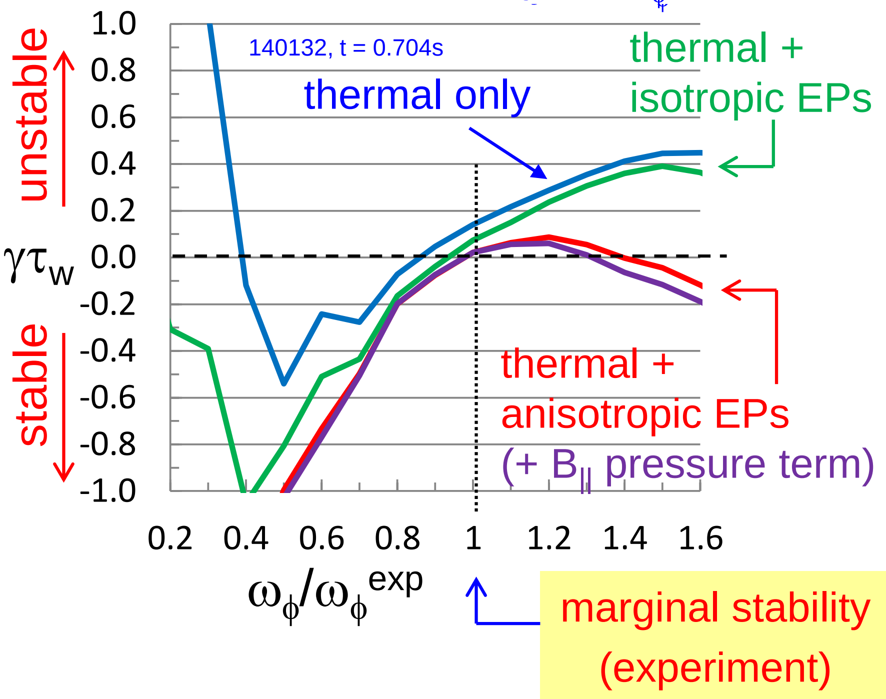

**Jaworski EX/P5-31**

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

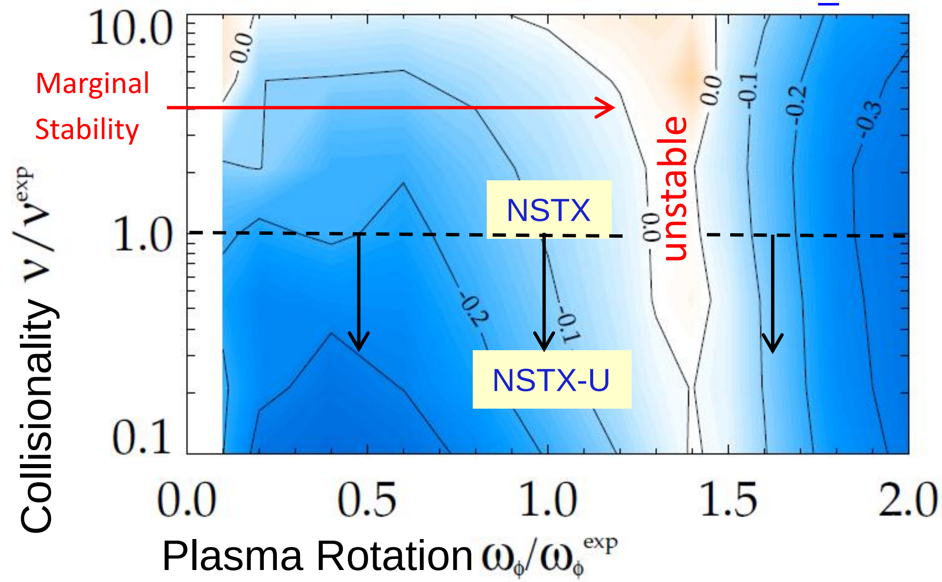
# Kinetic RWM stability theory further tested against NSTX experiments, provides guidance for NSTX-U

MISK code

RWM stability vs. $\omega_\phi$




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

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

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

**Berkery EX/P8-07**