

Overview of Physics Results from the National Spherical Torus Experiment

S. A. Sabbagh

Columbia University

for the NSTX-U Research Team

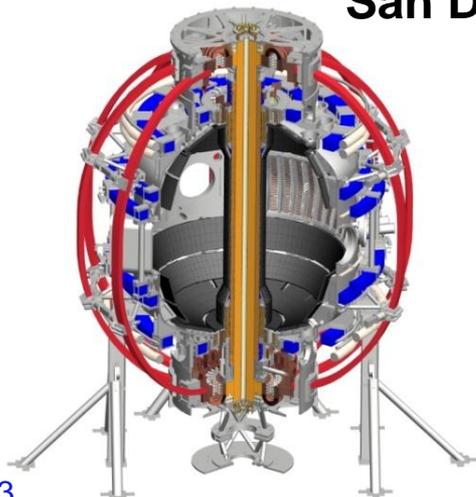
24th IAEA Energy Fusion Conference

October 9th, 2012

San Diego, California

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

V2.3

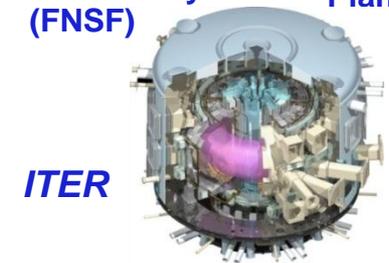
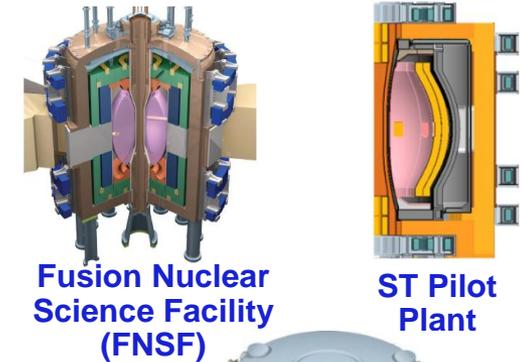


Culham Sci Ctr
 York U
 Chubu U
 Fukui U
 Hiroshima U
 Hyogo U
 Kyoto U
 Kyushu U
 Kyushu Tokai U
 NIFS
 Niigata U
 U Tokyo
 JAEA
 Inst for Nucl Res, Kiev
 Ioffe Inst
 TRINITI
 Chonbuk Natl U
 NFRI
 KAIST
 POSTECH
 Seoul Natl U
 ASIPP
 CIEMAT
 FOM Inst DIFFER
 ENEA, Frascati
 CEA, Cadarache
 IPP, Jülich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

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**

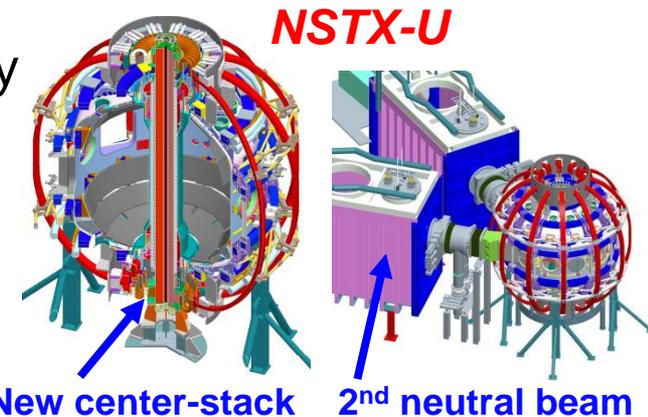


Outline

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**

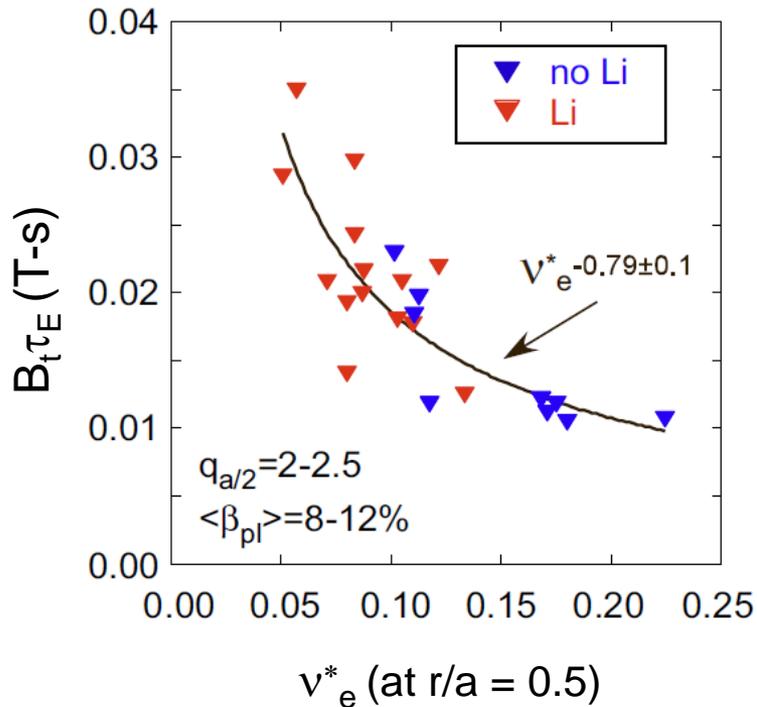
3D effects are pervasive in this research



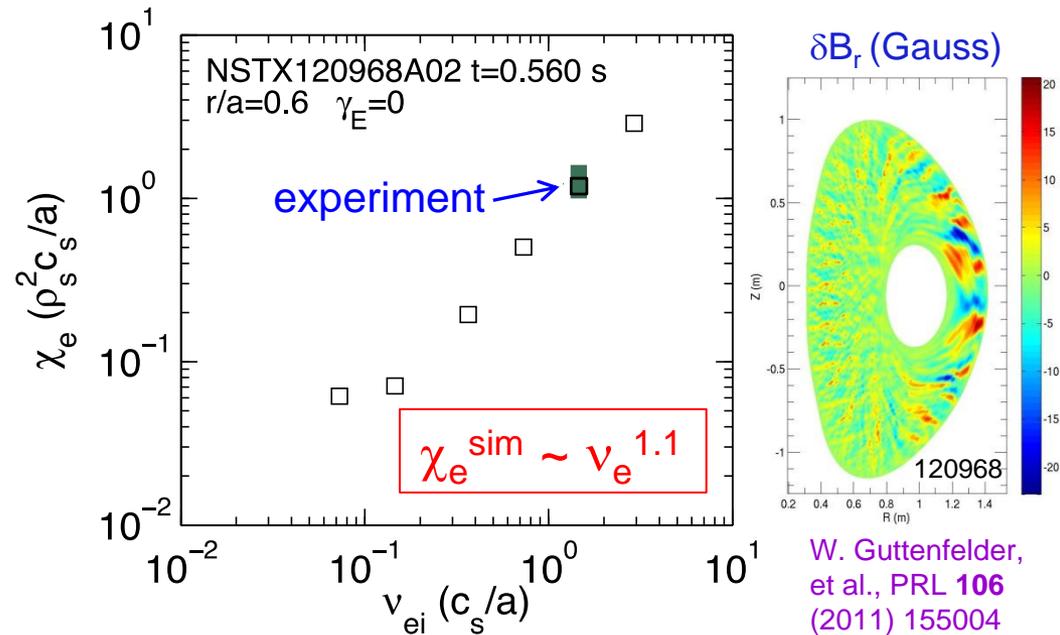
| | | | |
|-------|-----------|--------------|-----------|
| B_T | 0.5 → 1 T | P_{NBI} | 6 → 12 MW |
| I_p | 1 → 2 MA | pulse | 1 → 5 s |

τ_E scalings unified by collisionality; nonlinear microtearing simulations find reduced electron heat transport at lower ν

Experiment



Theory



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

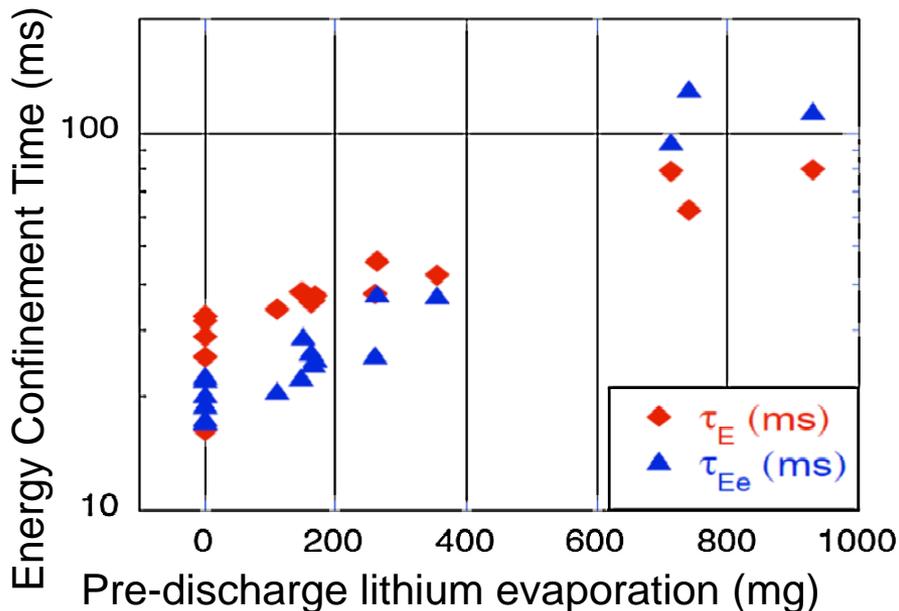
Kaye EX/7-1

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

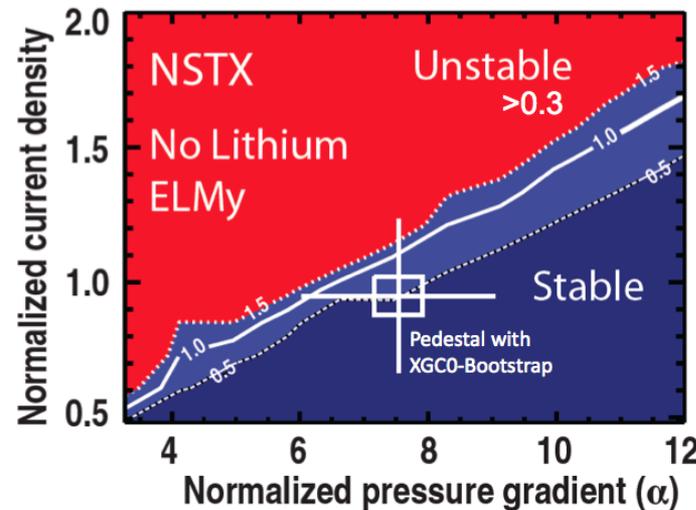
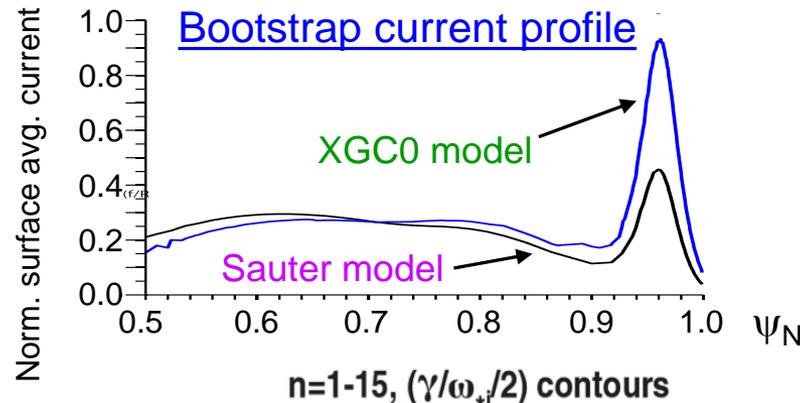
Guttenfelder TH/6-1

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

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 χ_e reduced

- New bootstrap current calculation (XGC0 code) improves agreement with profile reaching kink/peeling limit before ELM

Maingi EX/11-2

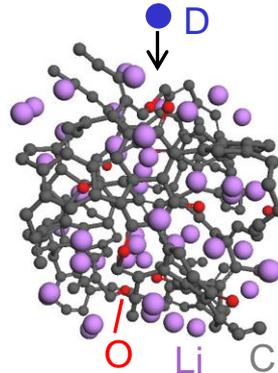
Canik EX/P7-16

Chang TH/P4-12

Diallo EX/P4-04

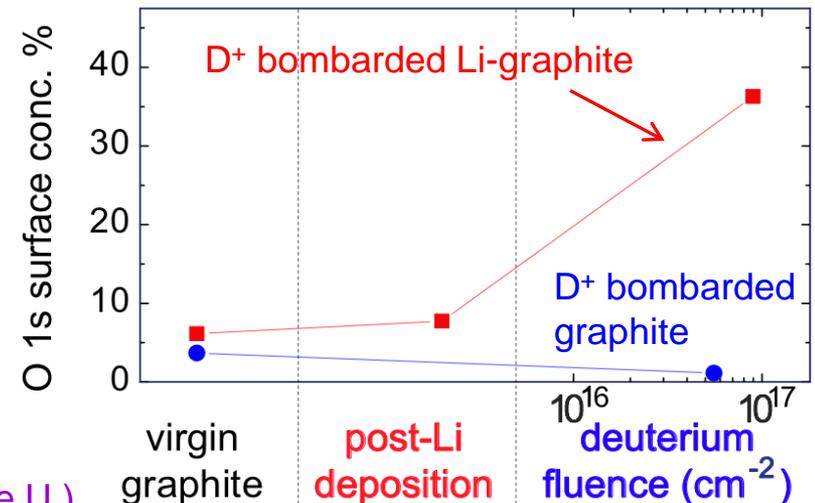
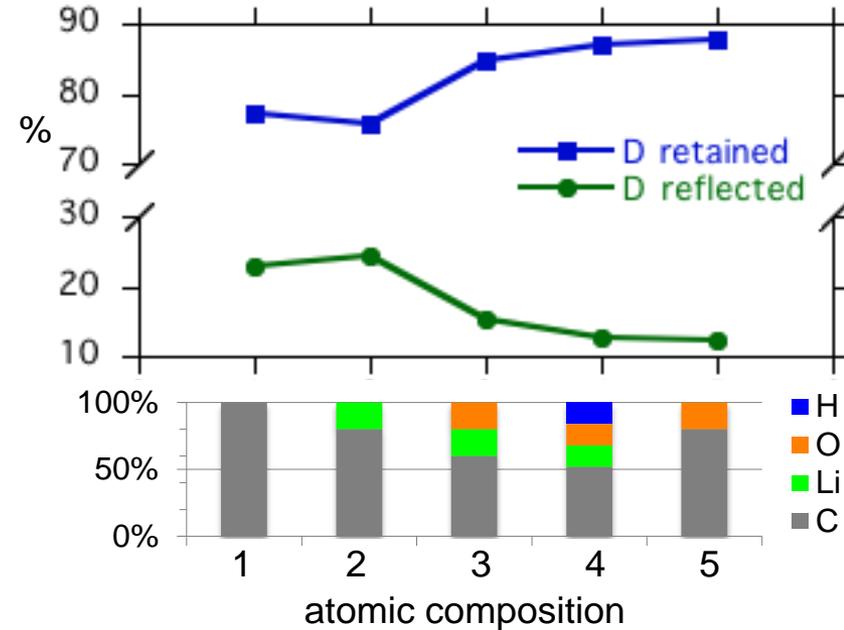
Simulations and lab results show importance of oxygen in the lithium-graphite PMI for pumping deuterium

- 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 $\sim 10\%$
 - 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

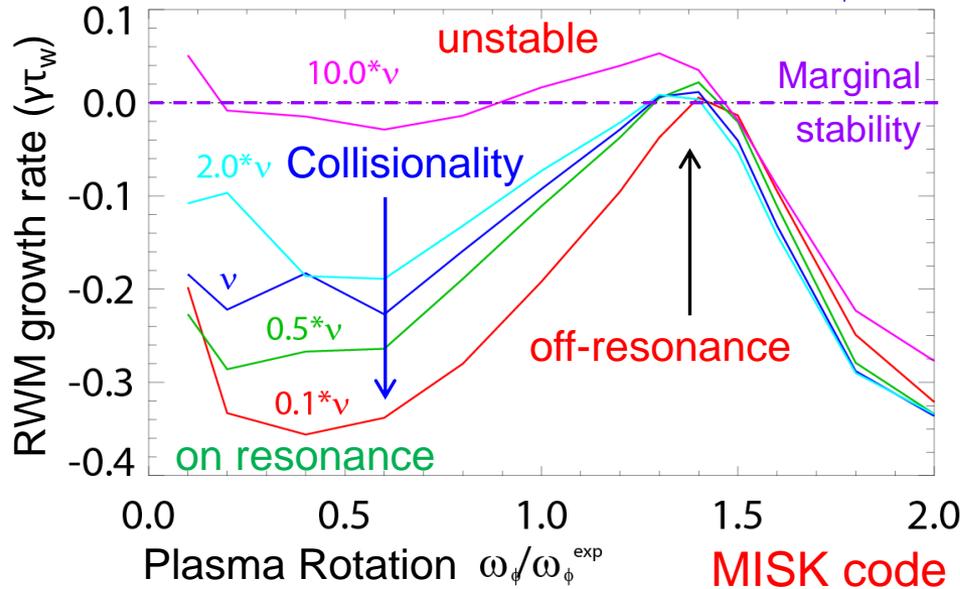


Jaworski EX/P5-31

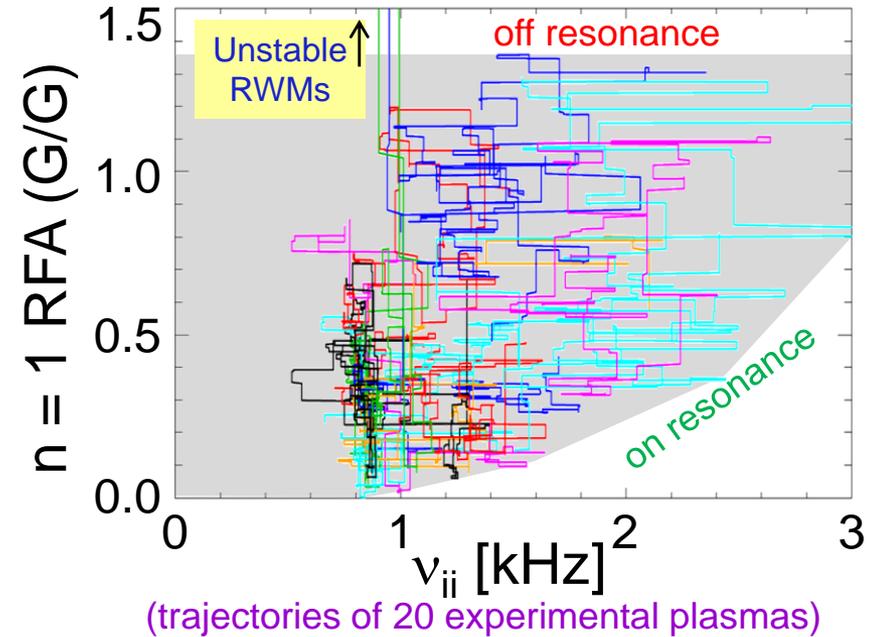
J.P. Allain, C. Taylor (Purdue U.)

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

Theory: RWM growth rate vs. ν and ω_ϕ



Exp: Resonant Field Amplification (RFA) vs ν



- 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

- 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”)

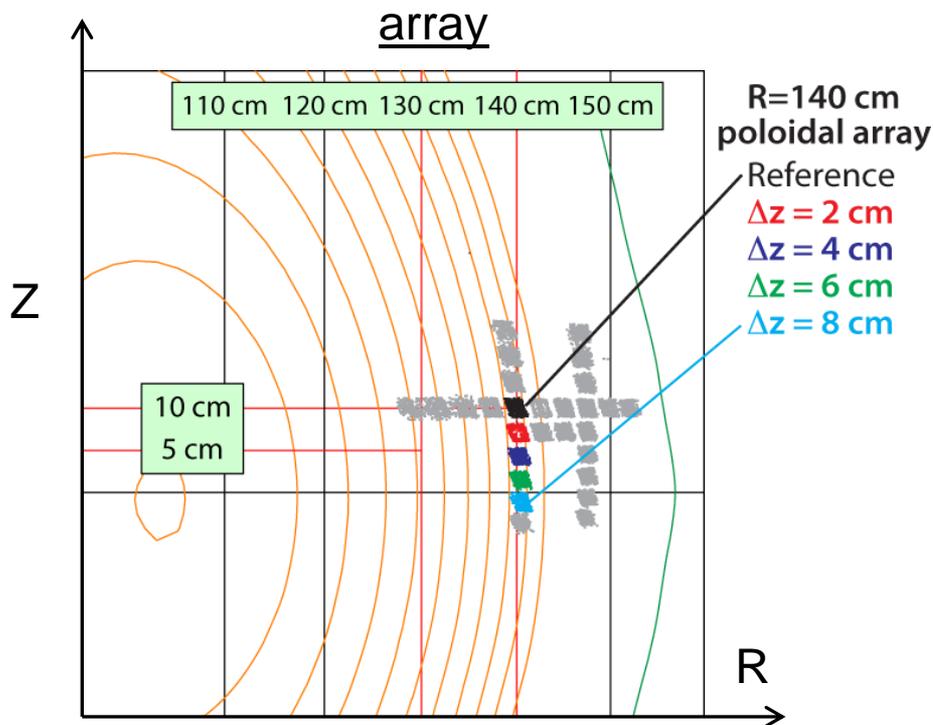
$$\text{RFA} = \frac{B_{\text{plasma}}}{B_{\text{applied}}}$$

Berkery EX/P8-07

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

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

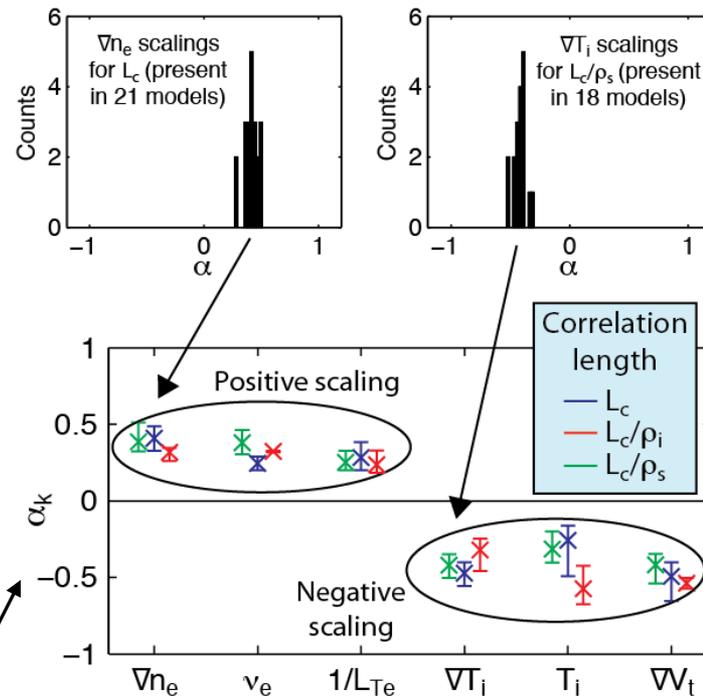
Beam emission spectroscopy (BES)



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

Smith EX/P7-18

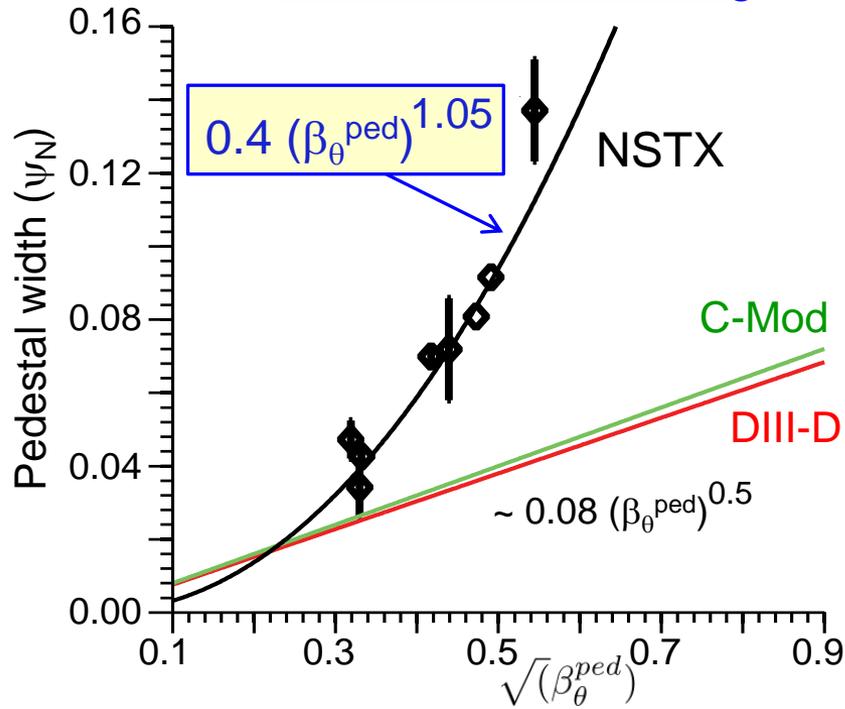
Poloidal Correlation Length vs. Parameters



- ❑ Multivariate linear scaling coefficients α_k
- ❑ Turbulence measurements in the steep gradient of the pedestal
 - ❑ Most consistent with Trapped Electron Modes
 - ❑ Partially consistent with KBM and μ -Tearing Modes
 - ❑ Least consistent with ITG Modes

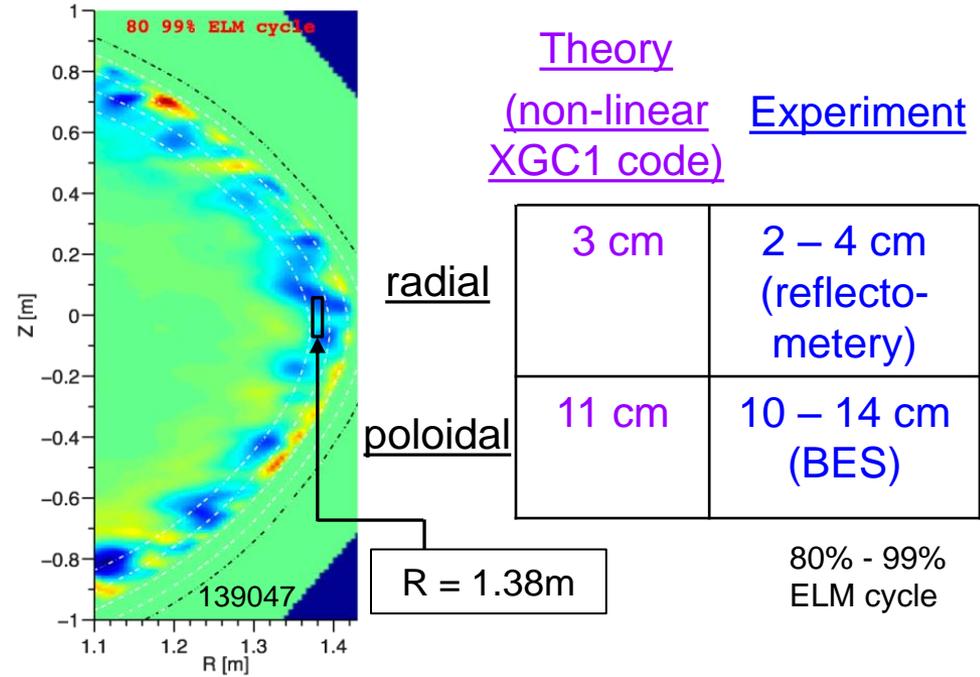
Pedestal width scaling differs from tokamaks; turbulence correlation measurements consistent with theory

Pedestal width scaling



Turbulence correlation lengths

(During inter-ELM period, at pedestal top)



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

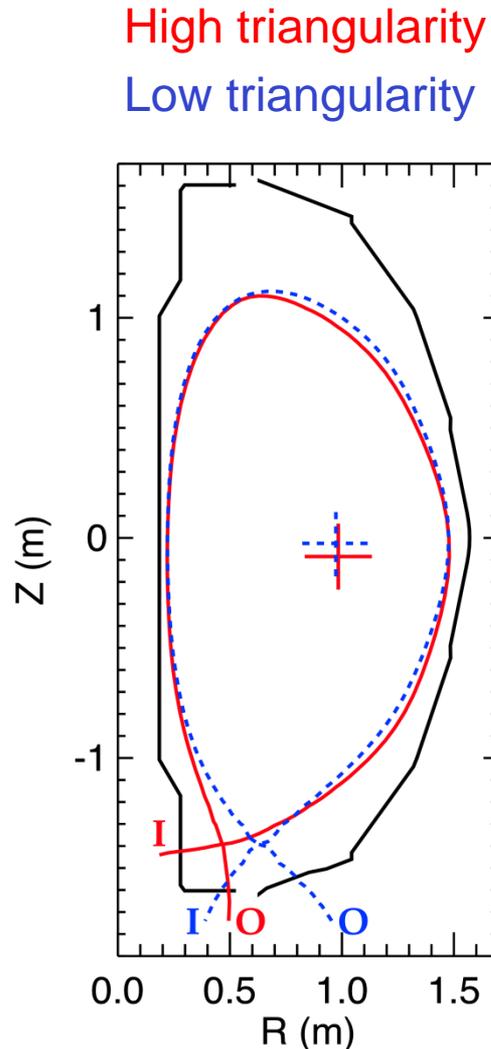
- ❑ Measured correlation lengths at pedestal top are consistent with theory
 - ❑ BES and reflectometry
 - spatial structure exhibits ion-scale microturbulence ($k_\perp \rho_i \sim 0.2 - 0.7$)
 - Compatible with ITG modes and/or KBM

Diallo EX/P4-04

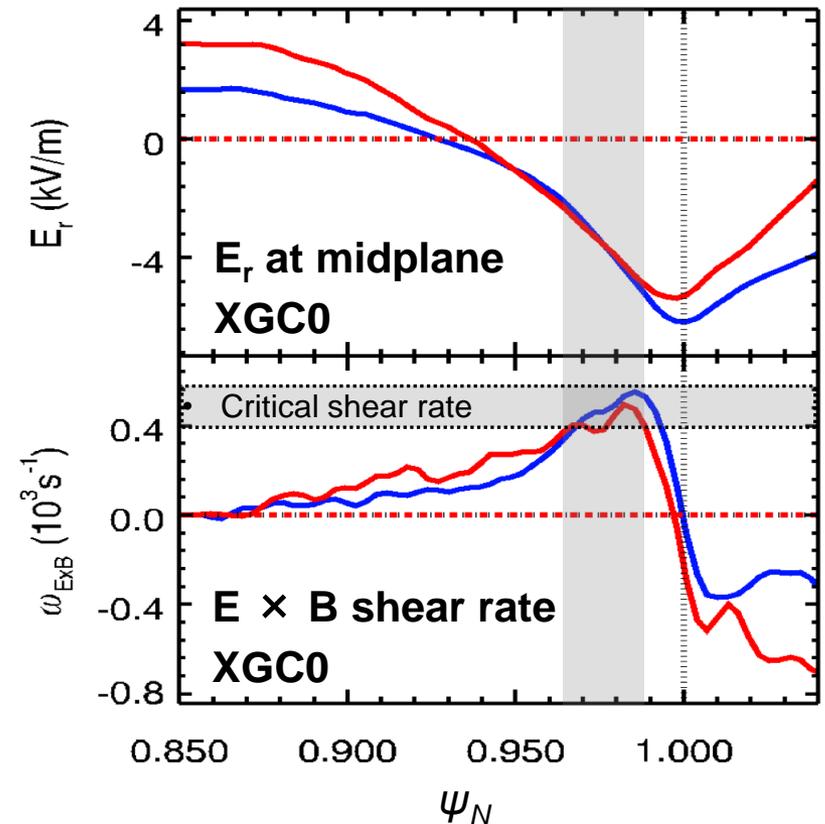
A. Diallo, C.S. Chang, S. Ku (PPPL), D. Smith (UW), S. Kubota (UCLA)

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)

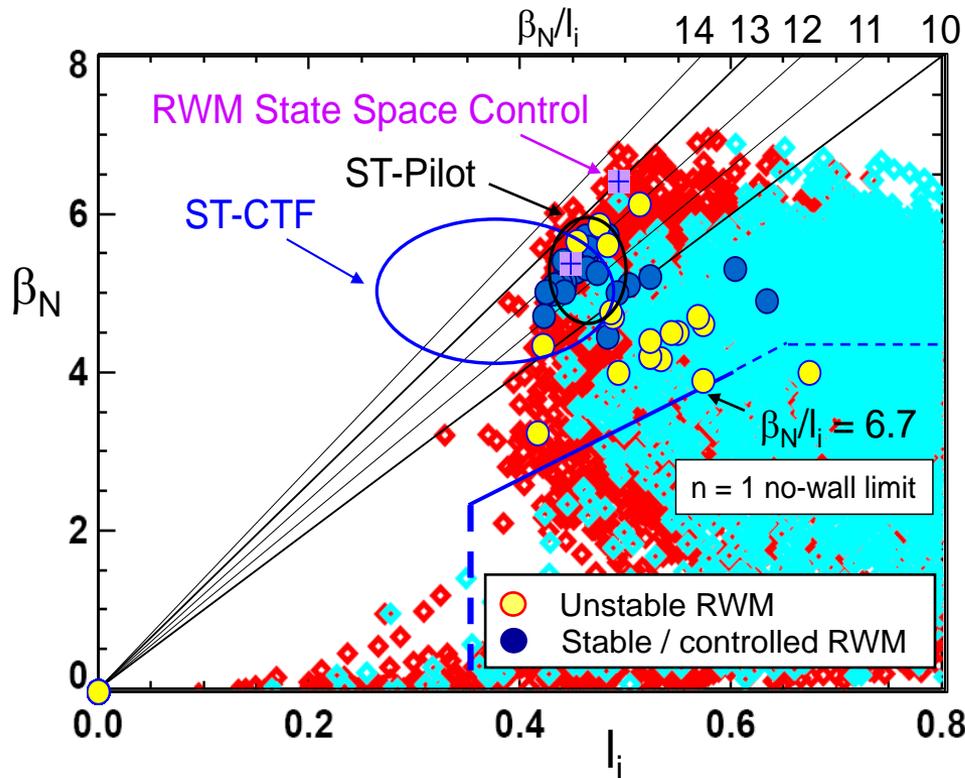


- Critical shear rate is satisfied for both shapes when core heating is 30% larger for high triangularity shape



Battaglia EX/P5-28

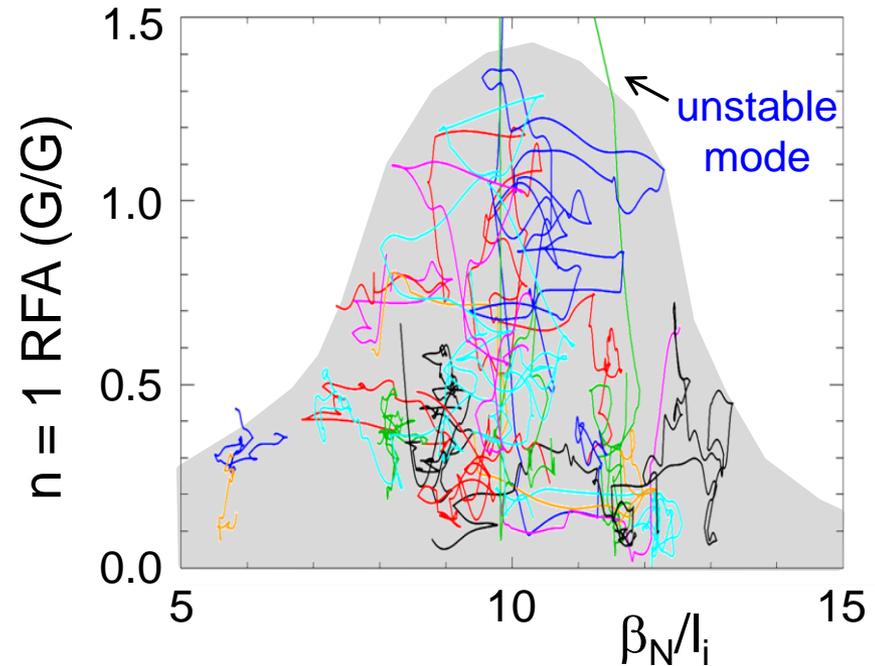
Stability control improvements significantly reduce unstable RWMs at low I_i and high β_N ; improved stability at high β_N/I_i



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

S.A. Sabbagh

Resonant Field Amplification (RFA) vs. β_N/I_i



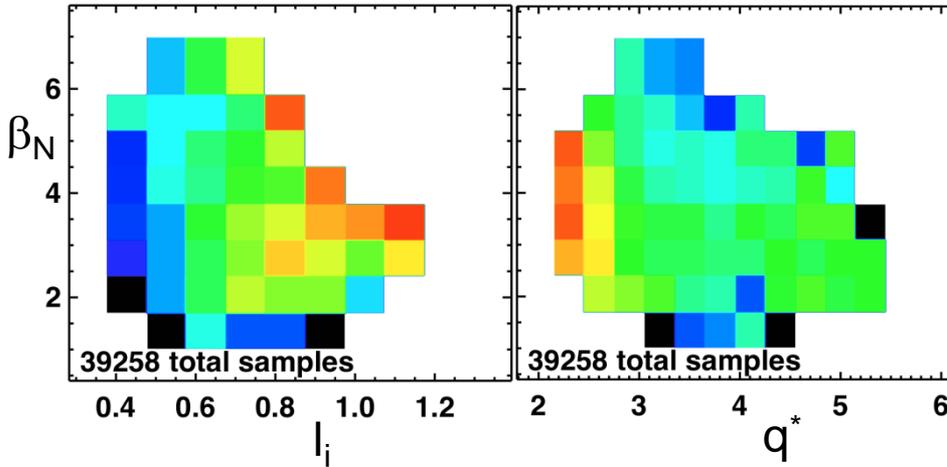
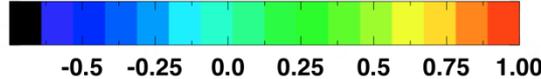
- ❑ Mode stability directly measured in experiments using MHD spectroscopy
 - ❑ Stability **decreases** up to $\beta_N/I_i = 10$
 - ❑ Stability **increases** at higher β_N/I_i
 - ❑ Presently analysis indicates consistency with kinetic resonance stabilization

Berkery EX/P8-07

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

Disruptivity

$\log_{10}(\text{disruptivity [s}^{-1}\text{)}):$



All discharges since 2006

Physics results

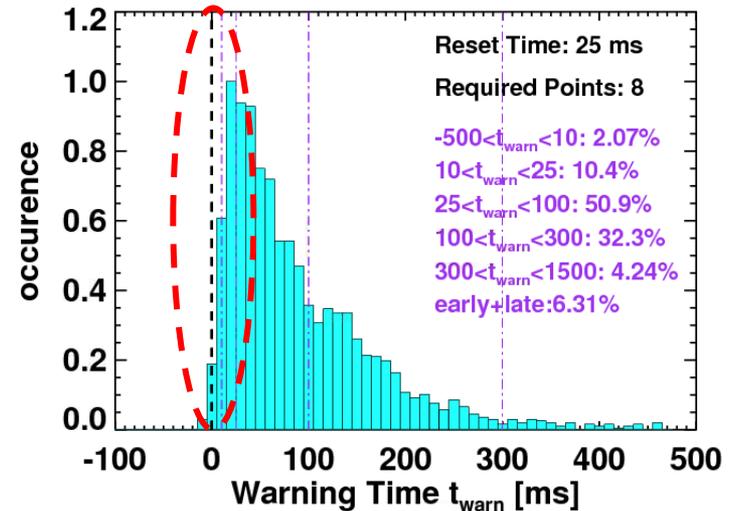
- Low disruptivity at relatively high $\beta_N \sim 6$; $\beta_N / \beta_N^{\text{no-wall}(n=1)} \sim 1.3-1.5$
 - Consistent with specific disruption control experiments, RFA analysis
- Strong disruptivity increase for $q^* < 2.5$
- Strong disruptivity increase for very low rotation

Gerhardt EX/9-3

Warning Algorithms

- Disruption warning algorithm shows high probability of success

- Based on combinations of single threshold based tests

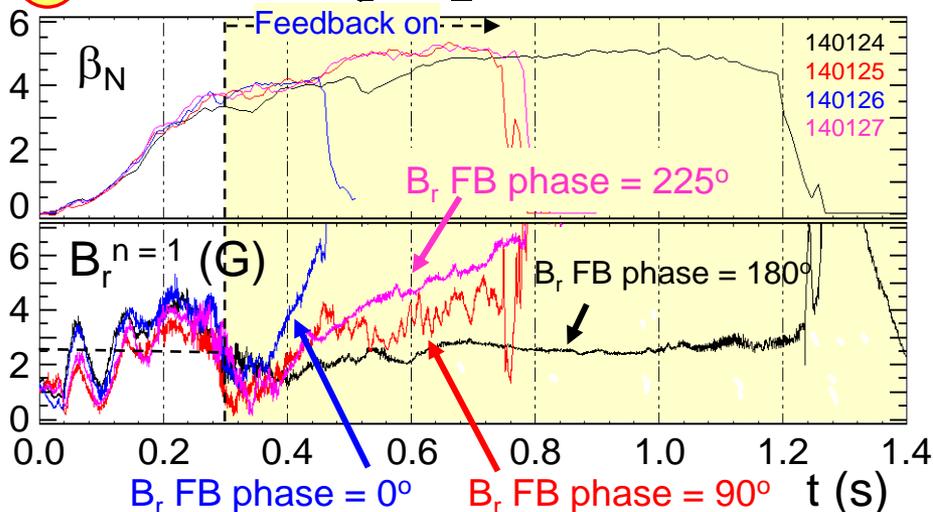


Results

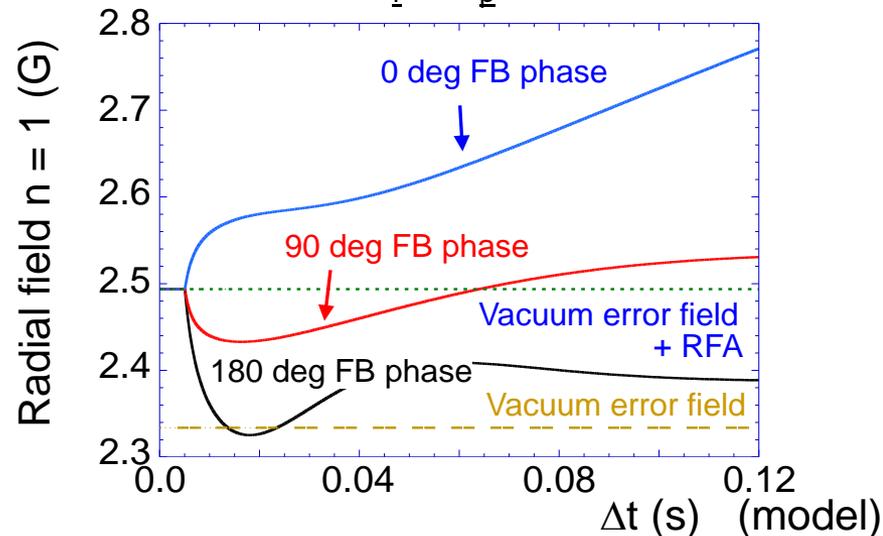
- $\sim 98\%$ disruptions flagged with at least 10ms warning, $\sim 6\%$ false positives
- False positive count dominated by near-disruptive events

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

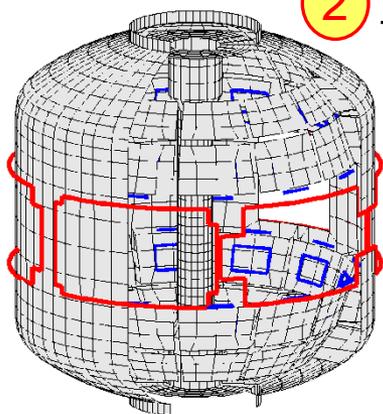
1 Active $n = 1$ $B_p + B_R$ feedback (FB) control



Calculation of $B_r + B_p$ control (VALEN)



2 RWM State Space Controller

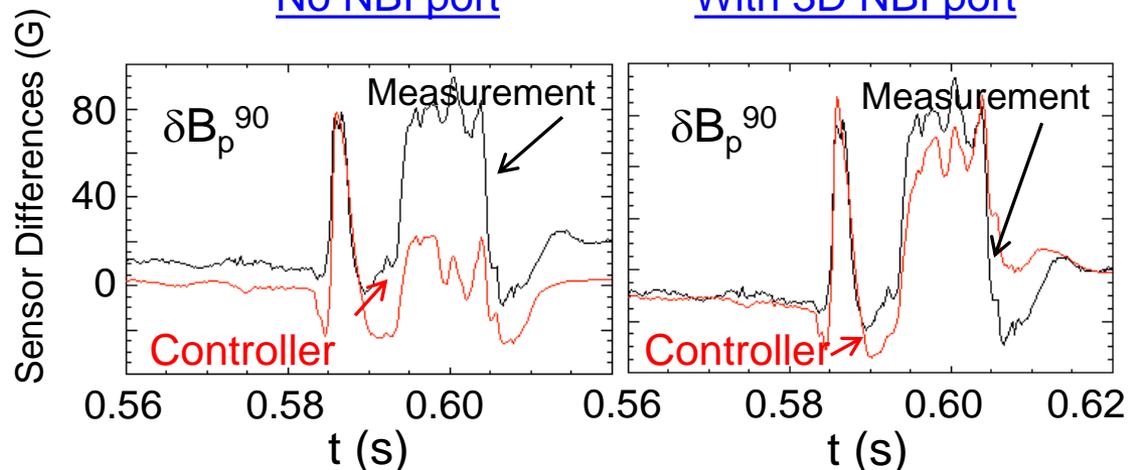


3D wall,
ports,
mode
currents

□ Inclusion of 3D mode and wall detail improves control

No NBI port

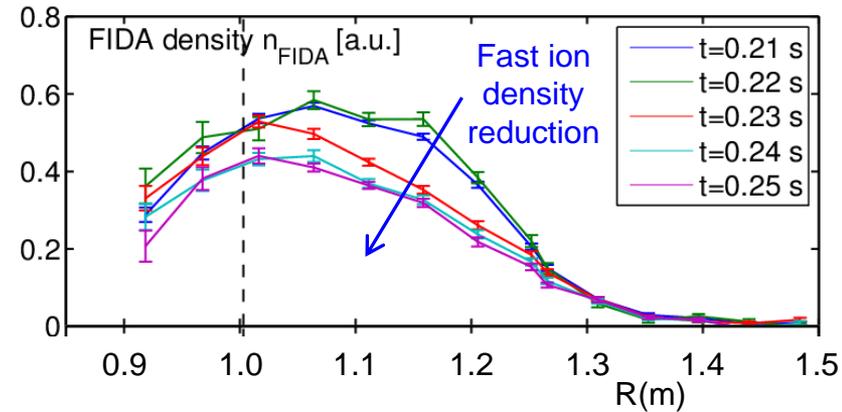
With 3D NBI port



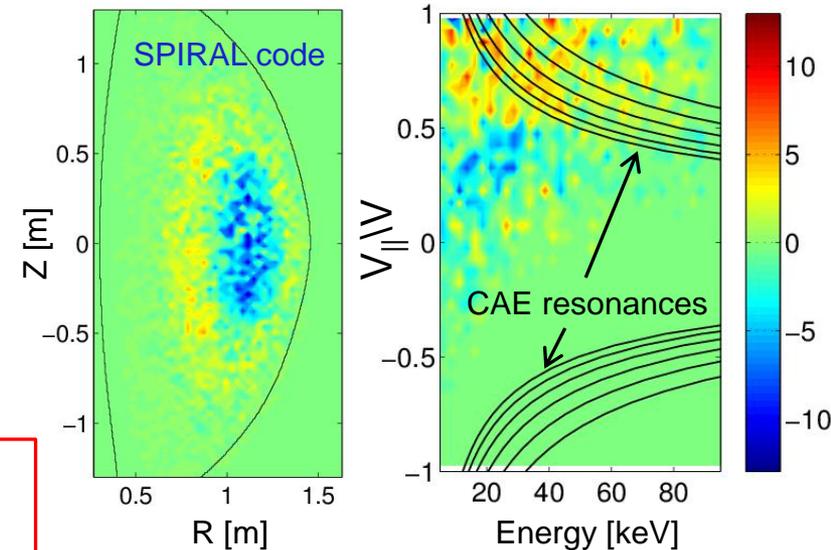
S.A. Sabbagh, O. Katsuro-Hopkins, J.M. Bialek, S.P. Gerhardt

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



Change in distribution due to kink mode



A. Bortolon

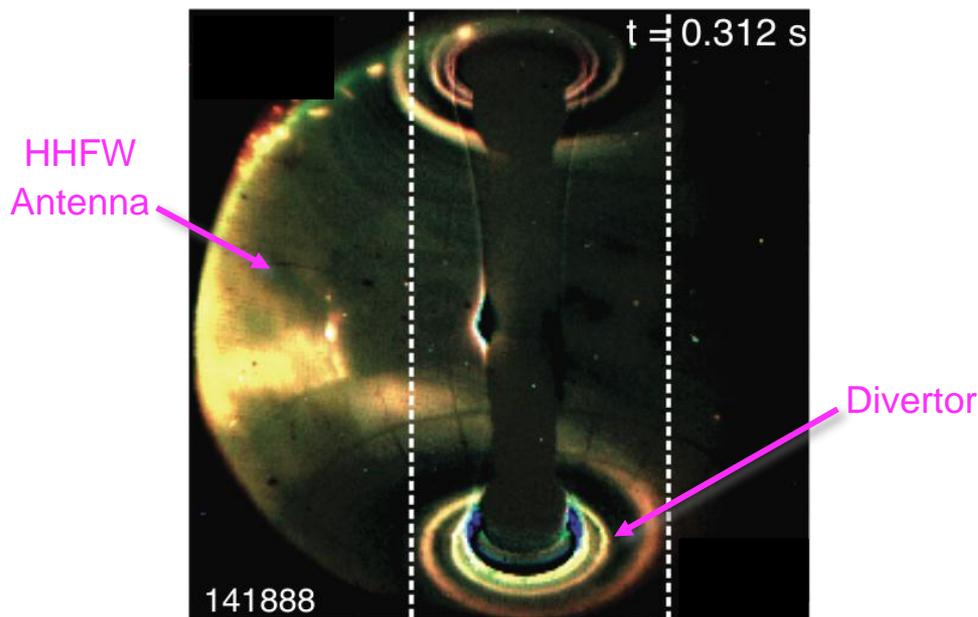
❑ Fast ion energy redistribution accounts for neutron rate decrease in H-mode TAE avalanches Fredrickson EX/P6-05

❑ Core localized CAE/GAEs measured in H-mode plasmas (reflectometer)

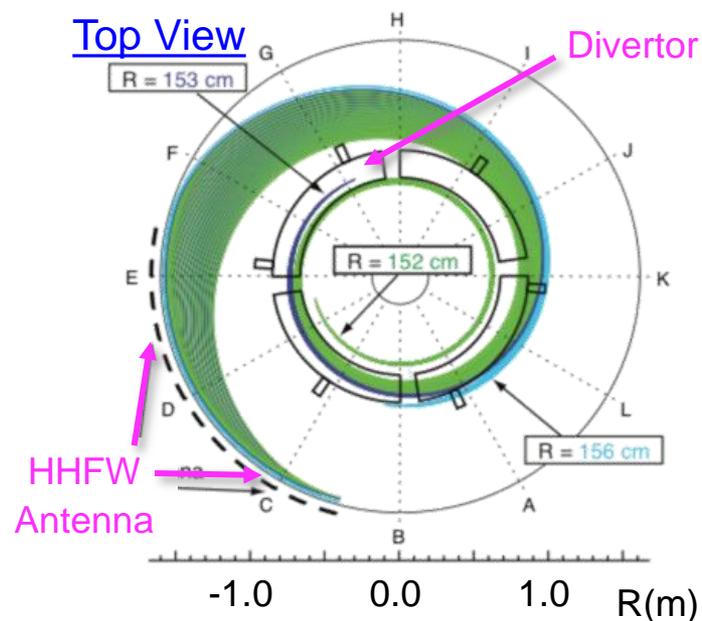
Crocker EX/P6-02

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

Visible camera image of edge RF power flow to divertor



SPIRAL modeling of field lines from antenna to divertor



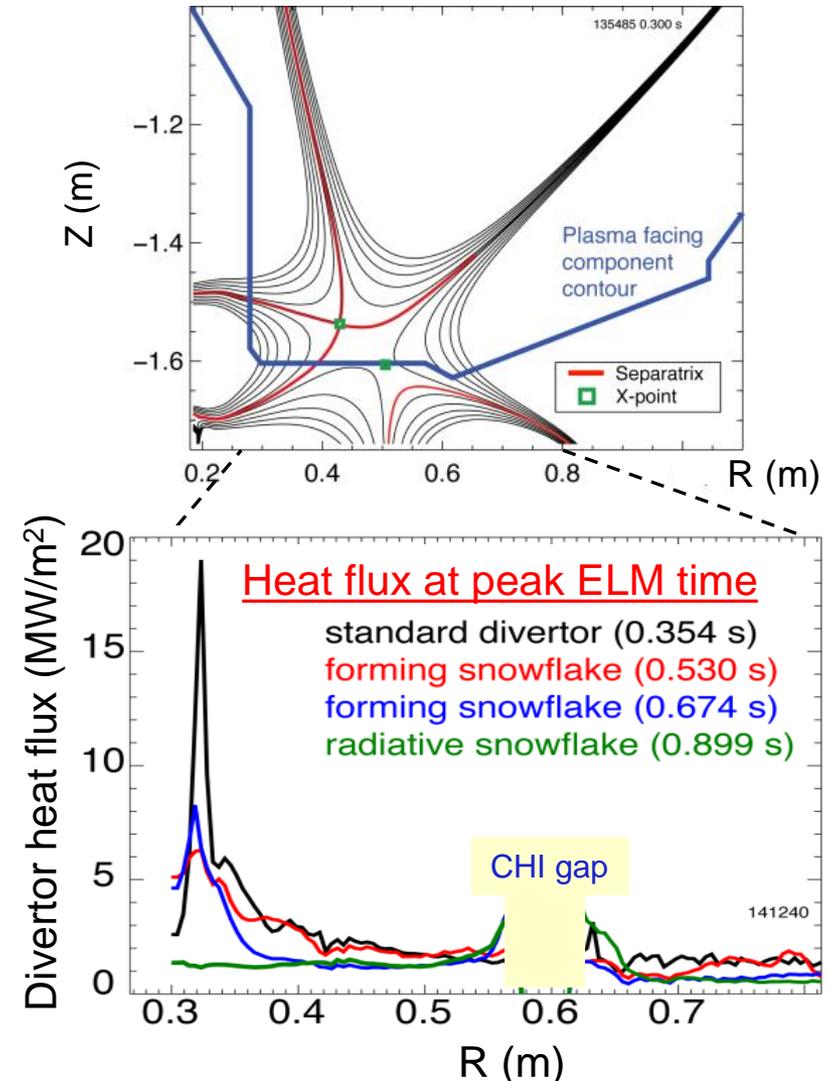
- RF power couples to field lines across entire SOL width, not just to field lines connected to antenna components
- Shows importance of quantitatively understanding RF power coupling to the SOL for prediction to future devices

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

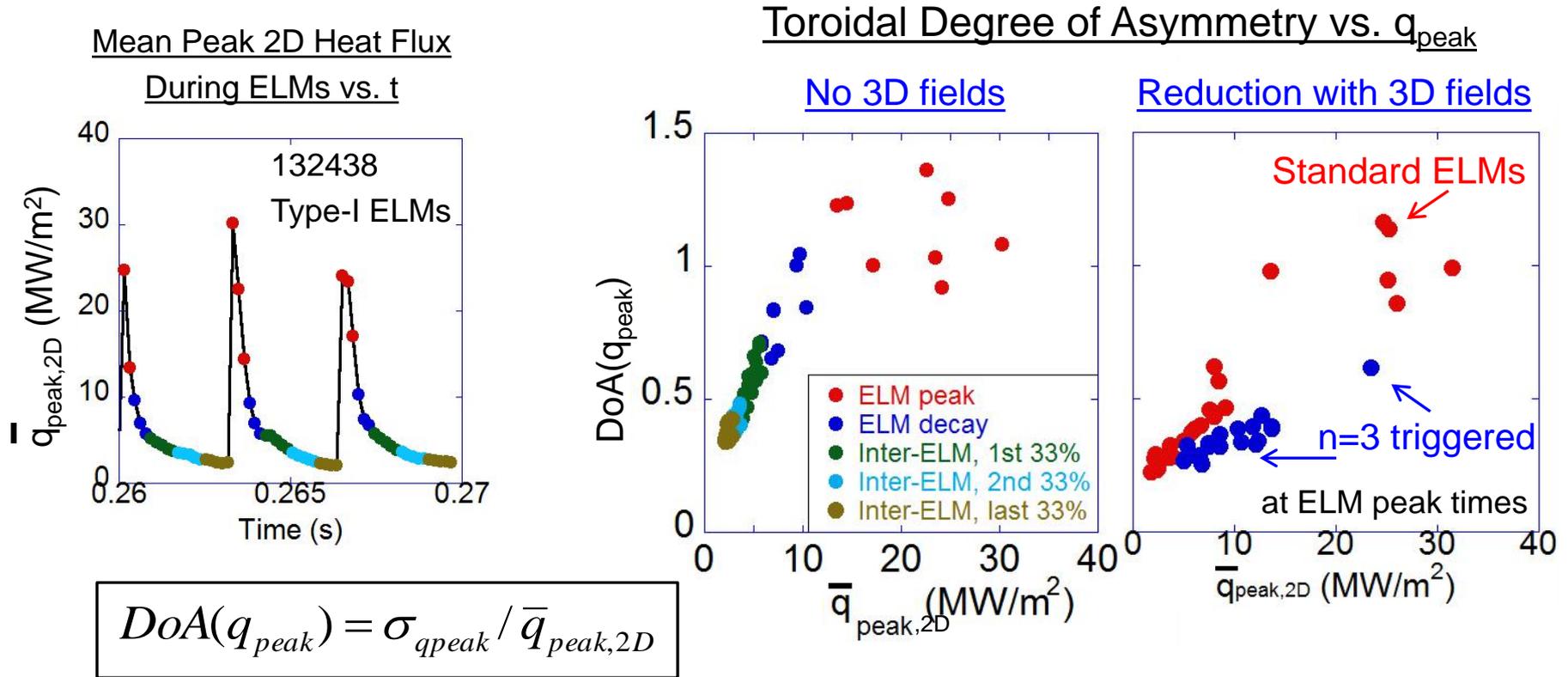
- ❑ Needed, as divertor heat flux width strongly decreases as I_p increases
- ❑ Snowflake divertor experiments ($P_{NBI} = 4$ MW, $P_{SOL} = 3$ MW)
 - ❑ Good H-mode τ_E , β_N , sustained during snowflake operation
 - ❑ Divertor heat flux significantly reduced **both** during and between ELMs
 - during ELMs: 19 to ~ 1.5 MW/m²
 - steady-state: 5-7 to ~ 1 MW/m²
 - ❑ 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

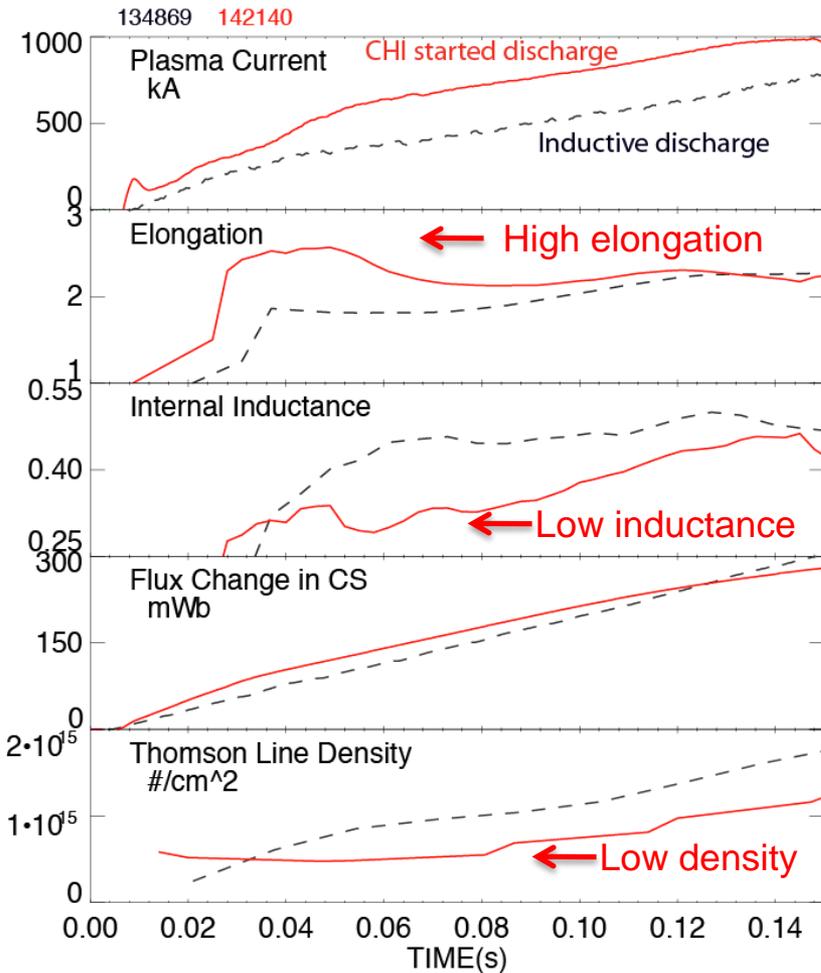


- ❑ 2D fast IR camera measurement (6.3kHz), heat flux from TACO code
- ❑ Toroidal asymmetry
 - ❑ Becomes **largest** at the peak heat flux for usual Type-I ELMs
 - ❑ **Reduced by up to 50%** in ELMs triggered by n = 3 applied fields

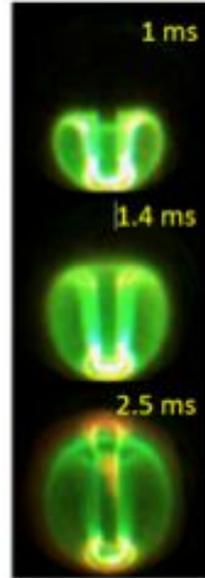
Ahn EX/P5-33

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

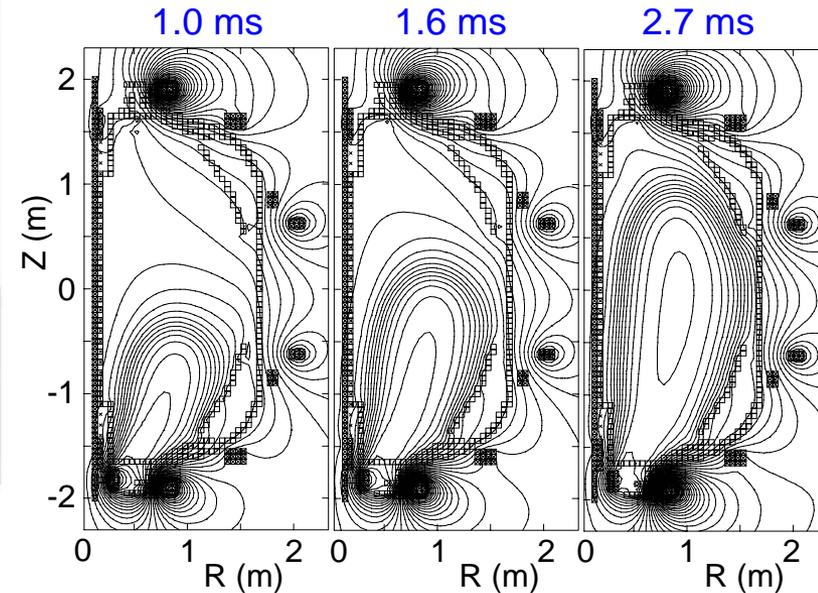
CHI assisted startup in NSTX



Raman EX/P2-10

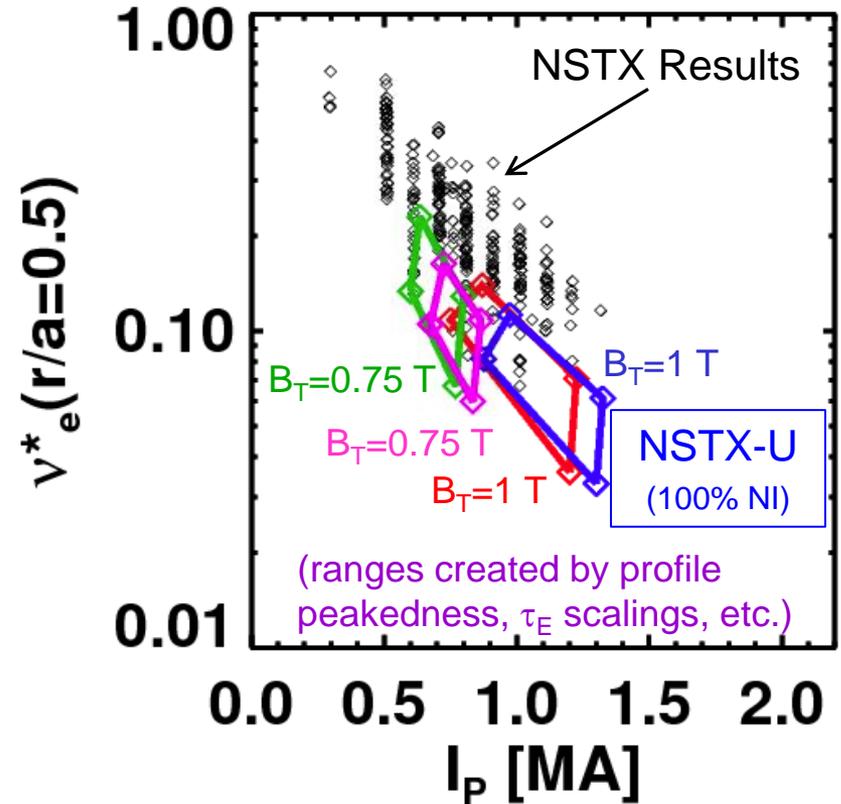
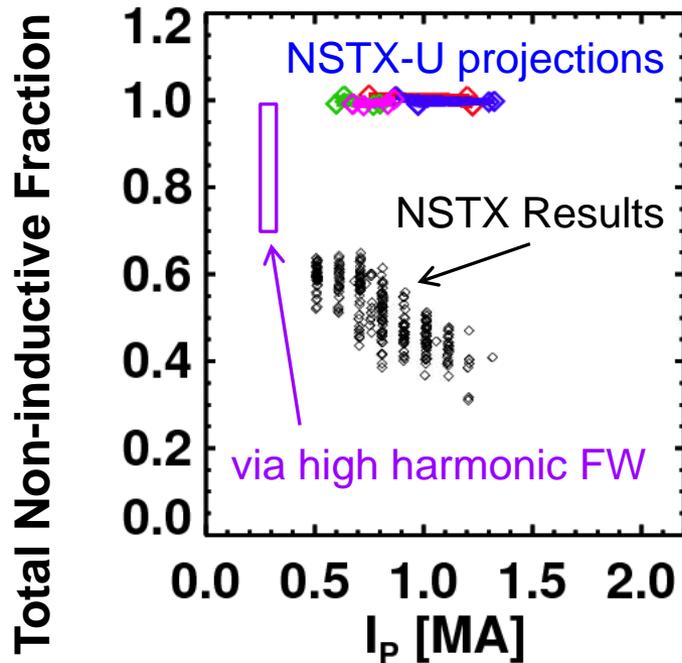


TSC simulation of CHI startup



- CHI generates plasmas with high elongation, low I_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

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
 - Higher A ~ 1.65 of NSTX-U created in NSTX, vertical stability tested

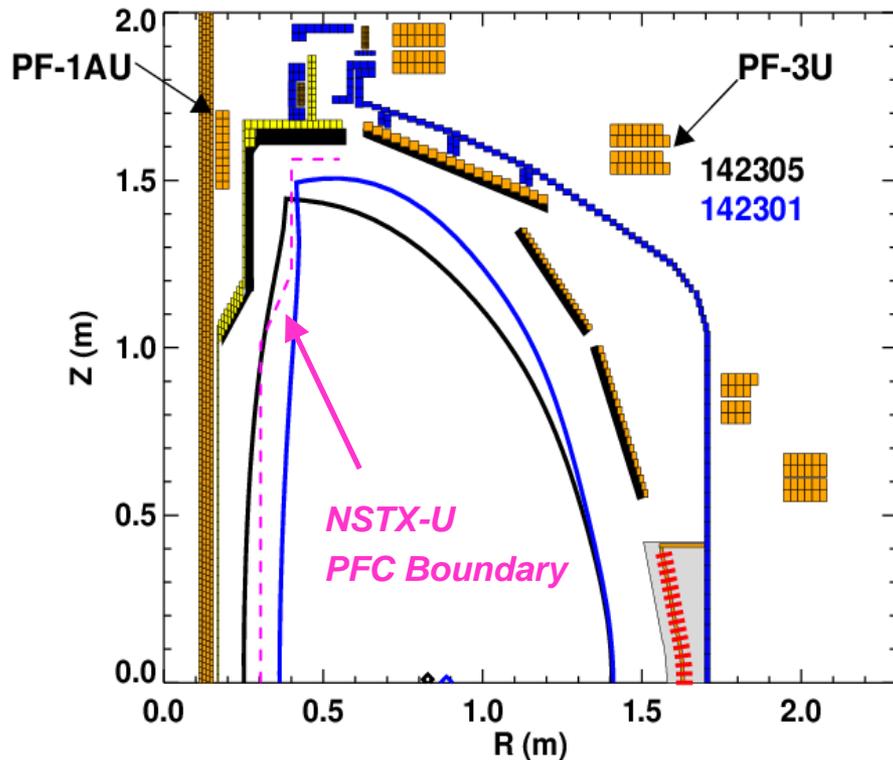
G. Taylor (Phys. Plasmas **19** (2012) 042501)

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

Menard FTP/3-4

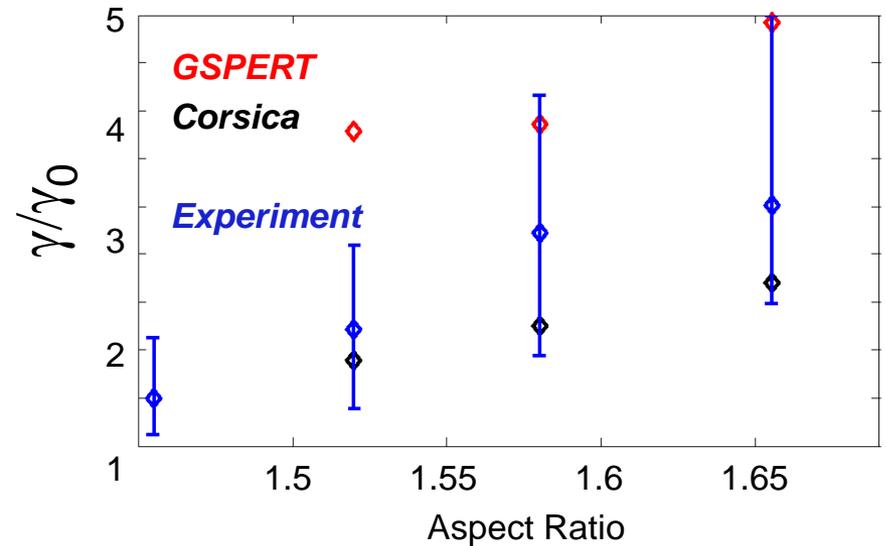
Kolemen EX/P4-28

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

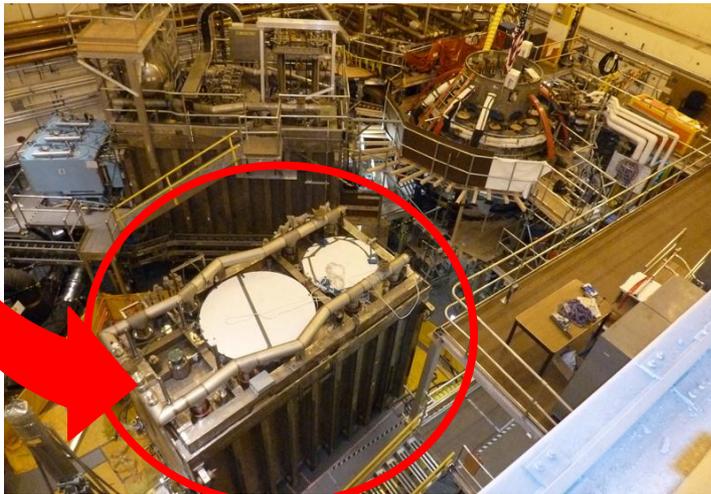
Vertical Stability Growth Rates vs. A



- 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

Rapid Progress is Being Made on NSTX Upgrade

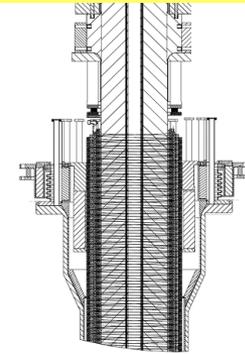
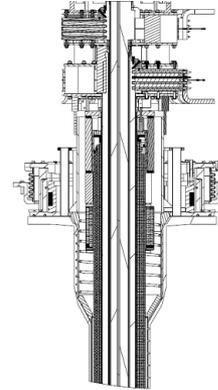


- 2nd neutral beam moved into place

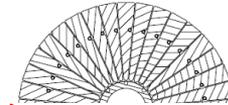
(first plasma anticipated June 2014)

Old center stack

NEW Center Stack



TF OD = 20cm



TF OD = 40cm



- TF conductors being made

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
 - ❑ τ_E scalings **unified** by collisionality; non-linear microtearing simulations match experimental χ_e , predict lower χ_e at lower v_e^* shown in experiment
 - ❑ Nearly continuous increase of favorable confinement with increased lithium
 - ❑ Stabilizing kinetic RWM effects **enhanced at lower v when near resonances**
- ❑ Pedestal
 - ❑ Width scaling **stronger than usual** ($\beta_p^{\text{ped}})^{0.5}$; measured δn_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 β_N/I_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
Co-axial helicity injection
Particle code NTV simulation

Ono FTP/P1-14
Raman EX/P2-10
Kim TH/P2-27

Wednesday

Bootstrap current XGC
Pedestal transport
Power scrape-off width
Vertical stability at low A
Blob dynamics / edge V shear
EHOs
Core lithium levels
C, Li impurity transport
Snowflake divertor theory

Chang TH/P4-12
Diallo EX/P4-04
Goldston TH/P4-19
Kolemen EX/P4-28
Myra TH/P4-23
Park EX/P4-33
Podesta EX/P3-02
Scotti EX/P3-34
Ryutov TH/P4-18

Thursday

Divertor heat asymmetry
L-H power threshold vs. X pt.
NBI-driven GAE simulations
CAE/GAE structure
TAE avalanches in H-mode
Li deposition / power exhaust
Liquid lithium divertor results
RF power flow in SOL
Snowflake divertor

Ahn EX/P5-33
Battaglia EX/P5-28
Belova TH/P6-16
Crocker EX/P6-02
Fredrickson EX/P6-05
Gray EX/P5-27
Jaworski EX/P5-31
Perkins EX/P5-40
Soukhanovskii EX/P5-21

Friday

Global mode control / physics
Edge transport with Li PFCs
Turbulence near OH L-H trans.
ELM triggering by Li in EAST
Electron-scale turbulence
Low-k turbulence vs. params.

Berkery EX/P8-07
Canik EX/P7-16
Kubota EX/P7-21
Mansfield PD
Ren EX/P7-02
Smith EX/P7-18