NSTX

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

Overview of Recent Results from the National Spherical Torus Experiment

S.A. Sabbagh

Columbia University

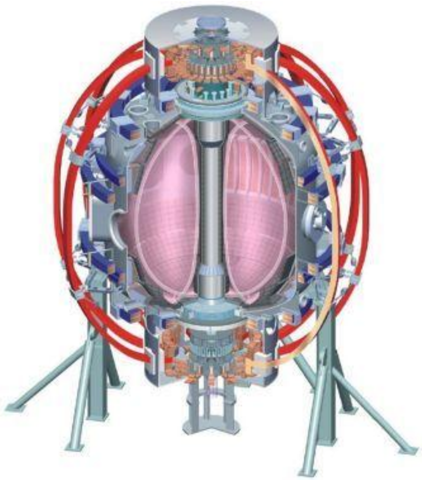
for the NSTX Research Team

53rd APS DPP Meeting

November 14th, 2011

Salt Lake City, Utah

Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
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 Washington
U Wisconsin

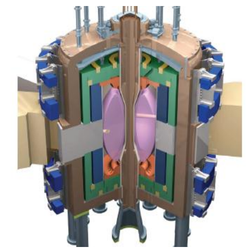


Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
NFRI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

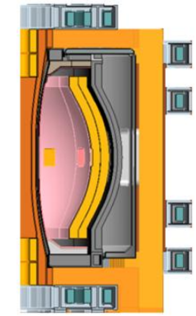
V1.7

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

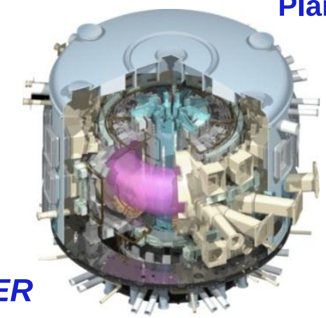
- Enable key ST applications
  - Move toward steady-state ST FNSF, pilot plant
  - Close key gaps to DEMO
- Extend understanding to tokamak / ITER
  - Leverage ST to develop predictive capability



Fusion Nuclear Science Facility (FNSF)



ST Pilot Plant

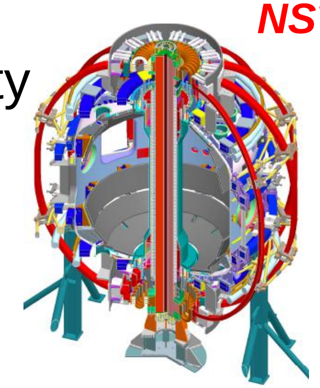


ITER

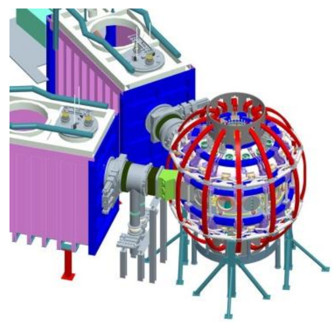
Present Research

- 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

NSTX-U



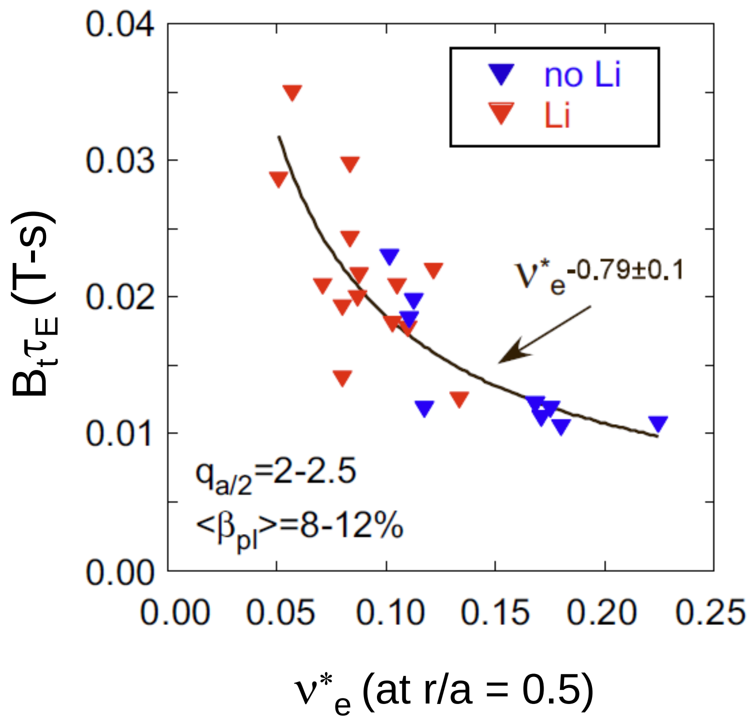
New center-stack



2nd Neutral Beam

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

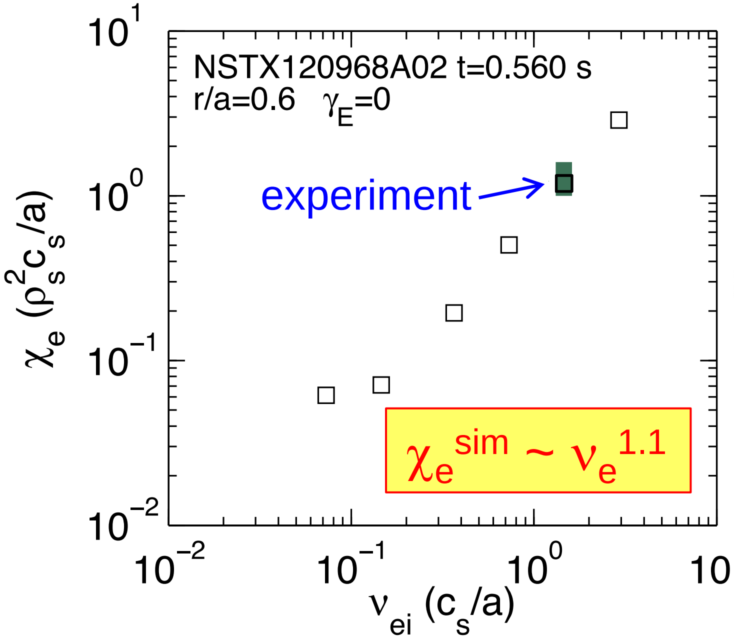
Experiment

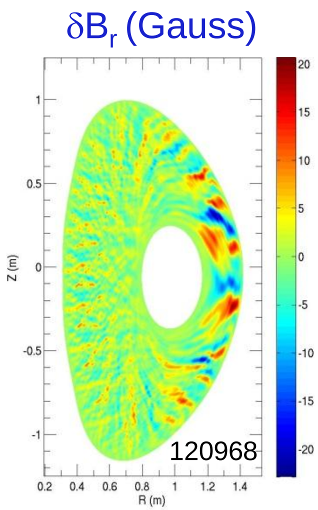


- Increase in τ_E as ν^*_e decreases
- Trend continues when lithium is used

see S. Kaye PP9.30 (Wed. PM)

Theory





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

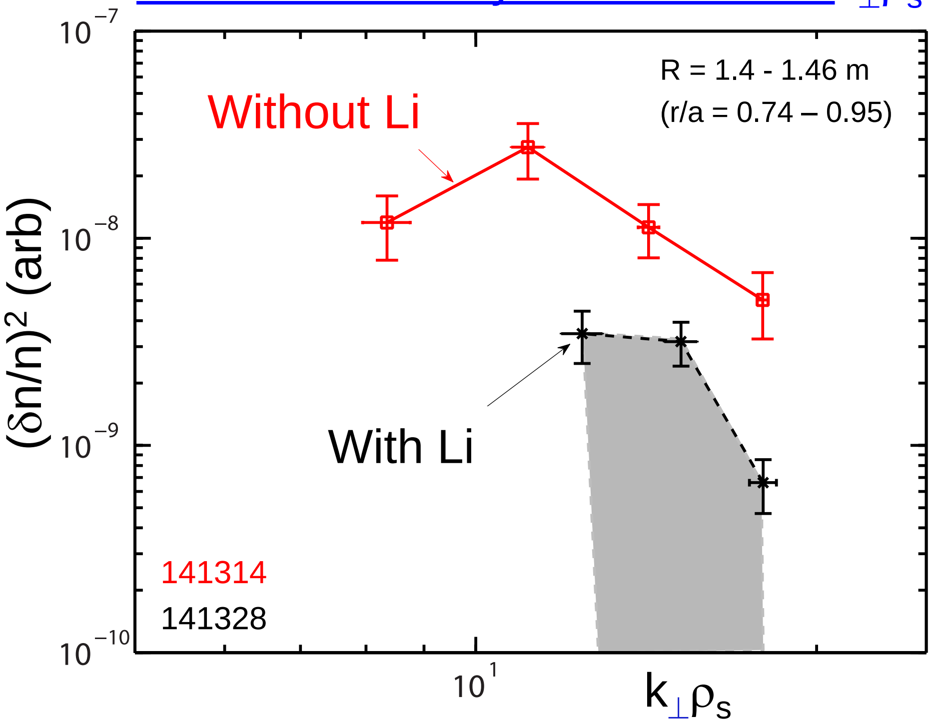
- Predicted χ_e and scaling ~ $\nu_e^{1.1}$ consistent with experiment ($\Omega\tau_E$ ~ $B_t\tau_E$ ~ $\nu^*_e{}^{-0.8}$)
- Transport dominated by magnetic “flutter”
  - $\delta B_r/B$ ~ 0.1% - possibly detectable by planned UCLA polarimetry system (J. Zhang, poster PP9.71)

- NSTX-U will extend studies down to ~ 1/10 of present ν^*

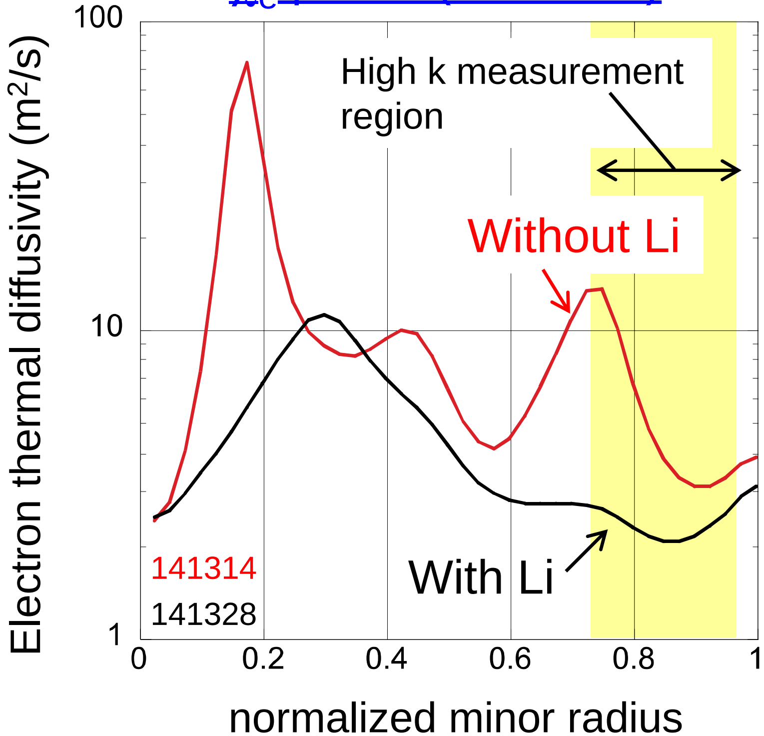
see W. Guttenfelder (invited) TI-2.6 (Thursday AM)

Measured reduction in high-k turbulence consistent with reduction in electron heat transport in outer plasma

Measured density fluctuation vs. $k_{\perp}\rho_s$



χ_e profile (TRANSP)



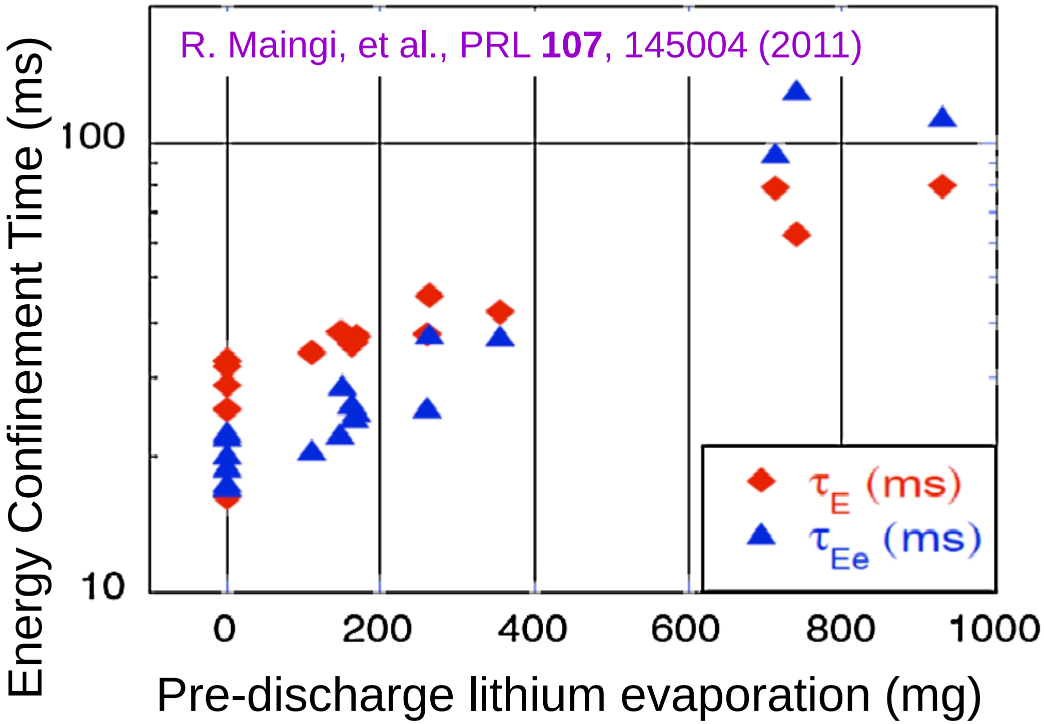
- High-k measurements at high r/a
  - spatially averaged (r/a) = 0.74 - 0.95
- Impact of collisionality and ∇n on turbulence is under investigation
  - $B_t\tau_E \sim \nu_e^{*-0.8}$ observed

see Y. Ren (invited) TI-2.2 (Thursday AM)

- Microturbulence studies using BES, O-mode reflectometry (inter-ELM)
  - spatial structure of fluctuations exhibits ion-scale microturbulence

see A. Diallo (invited) PI-2.3 (Wednesday PM)

Plasma characteristics change nearly continuously with increasing lithium evaporation inside vessel



See R. Maingi, et al., talk BO4.4 (this session)

- Role of oxygen investigated to understand deuterium retention of lithium-coated graphite
  - Threshold lithium amount, and subsequent continuous effects investigated

See J.P. Allain, et al., invited PI2.6 (Wednesday PM)

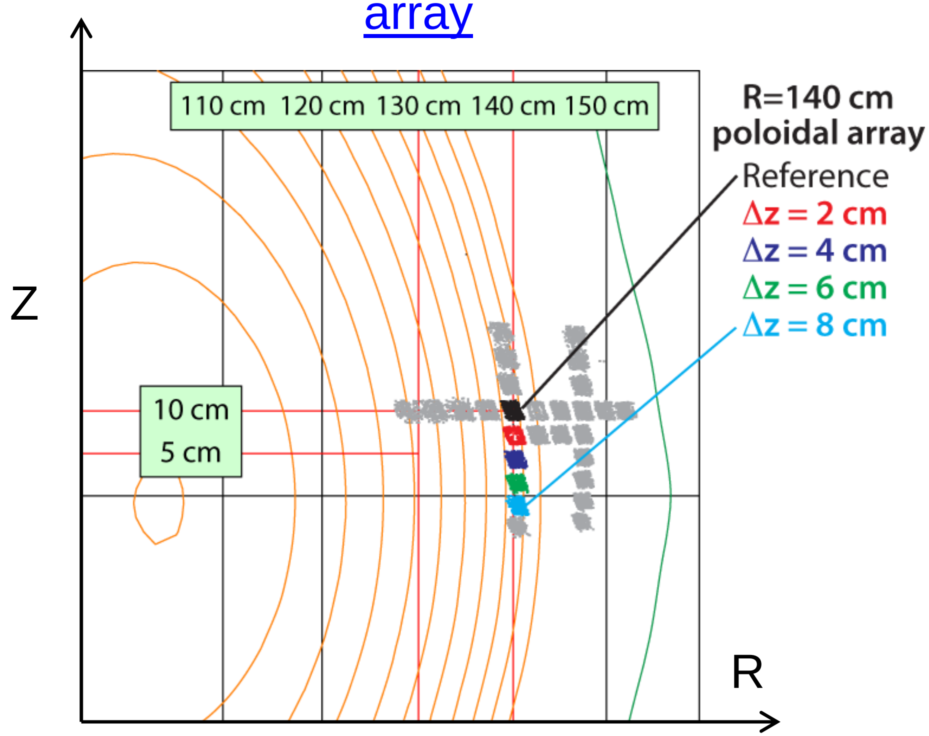
- Global parameters generally improve
  S. Kaye PP9.30 (Wed. PM)
- ELM frequency declines - to zero
  - ELMs stabilize

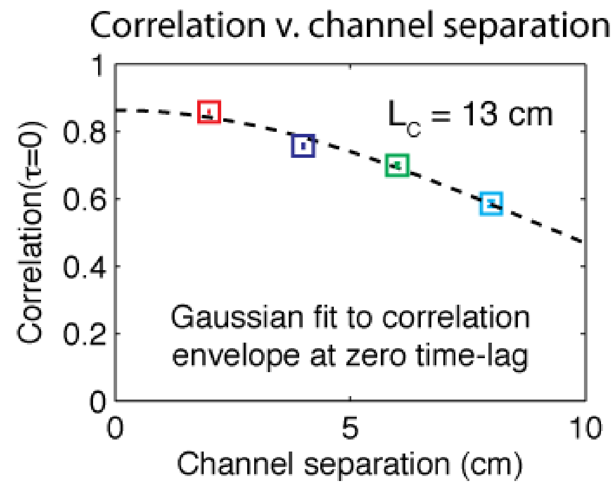
  D. Boyle, et al., talk BO4.5 (this session)
- Edge transport declines
  - As lithium evaporation increases, transport barrier widens, pedestal-top χ_e reduced

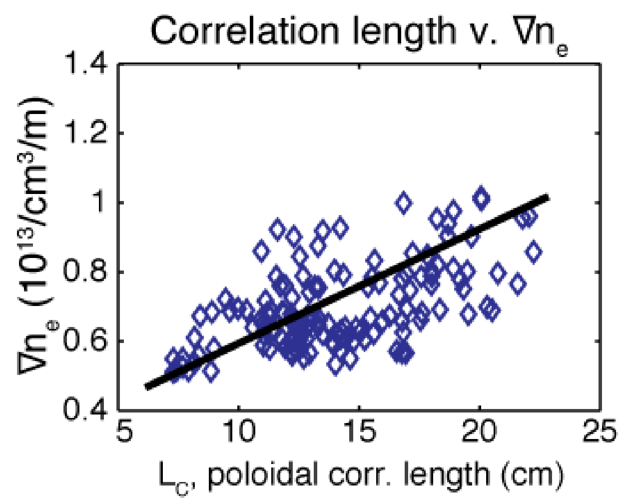
  J. Canik, et al., POP **18**, 056118 (2011)

BES measurements indicate poloidal correlation lengths in ELM-free H-mode pedestal increase at higher ∇n_e

Beam emission spectroscopy (BES) array







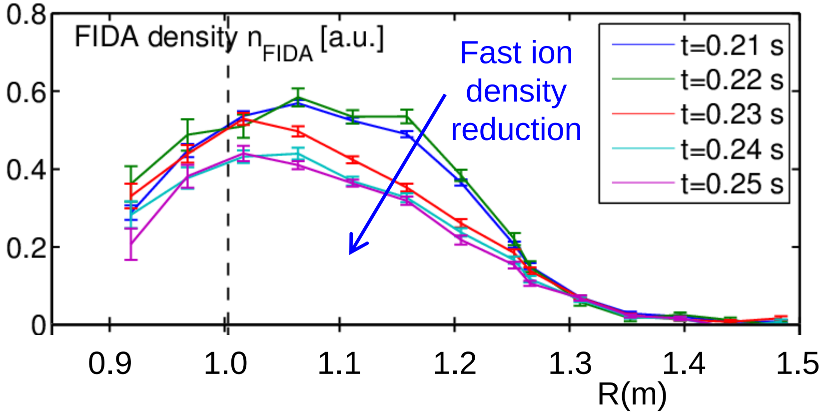
- Large poloidal correlation lengths
- Radial correlation lengths from O-mode reflectometer also large
  (A. Diallo (invited) PI-2.3)

See next talk: D. Smith, et al. BO4.2

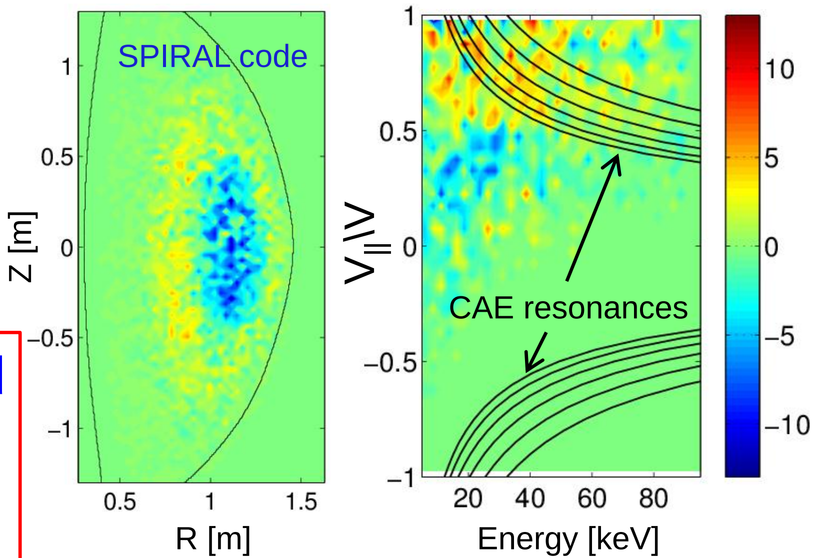
D. Smith, R. Fonck, G. McKee, D. Thompson, I. Uzun-Kaymak, UW-Madison

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 *after* onset of low frequency MHD
- Full-orbit code (SPIRAL) shows redistribution in real and velocity space
  - Radial redistribution from core plasma
  - Particles shift towards $V_{||}/V = 1$



Change in distribution due to kink mode

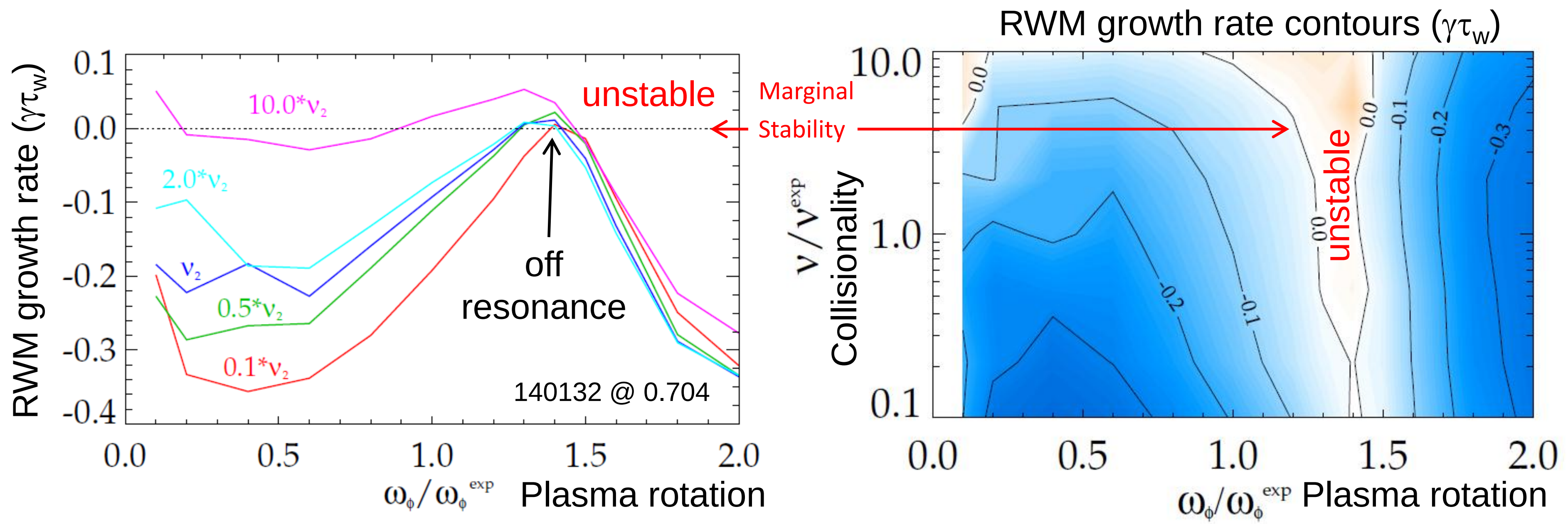


- Measured CAEs (reflectometer) examined as possible cause of enhanced core χ_e
  - mode #, frequency measured: modes peak in core, resonant with electron orbit frequencies

N. Crocker *et al*. PPCF **53**, 105001 (2011); and PP9.55 (Wed. PM)

see A. Bortolon poster PP9.56 (Wed. PM)

Reduced ν is stabilizing for resistive wall modes, but only near kinetic resonances

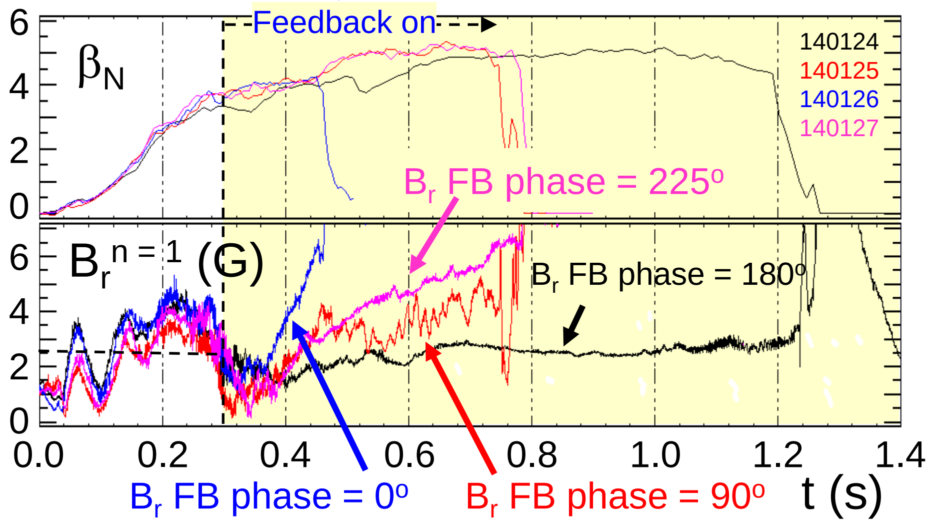


- NSTX-tested kinetic RWM stability theory: 2 competing effects at lower ν
  - Stabilizing collisional dissipation reduced (expected from early theory)
  - Stabilizing resonant kinetic effects enhanced (contrasts early RWM theory)
- Expectations in NSTX-U, tokamaks at lower ν (e.g. ITER)
  - Stronger stabilization near ω_ϕ resonances; almost no effect off-resonance
  - Plasma stability gradient with rotation increases
    - important to avoid unfavorable rotation, suppress transient RWM with active control

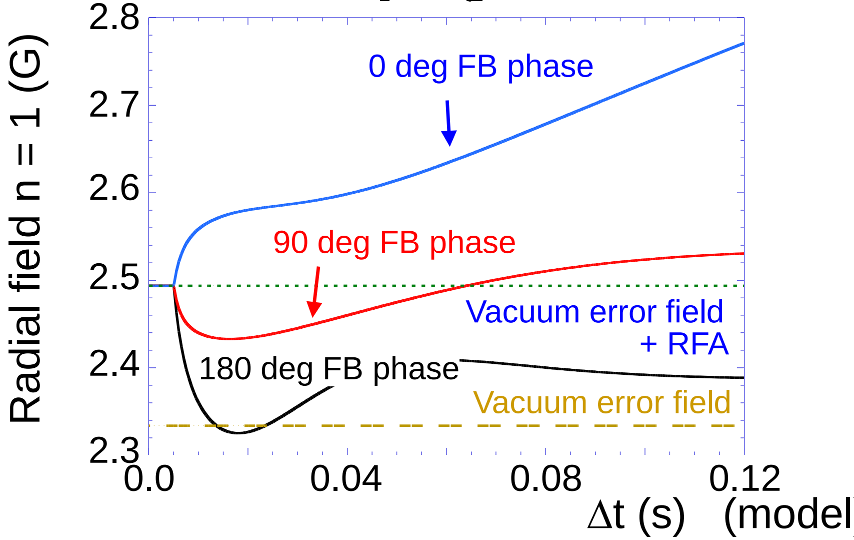
J.W. Berkery et al., PRL **106**, 075004 (2011)   See J.M. Bialek et al., poster PP9.47 (Wednesday, PM)

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

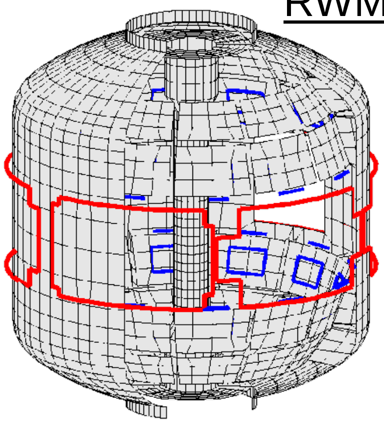
Active n = 1 B_p + B_R feedback (FB) control



Calculation of B_r + B_p control (VALEN)

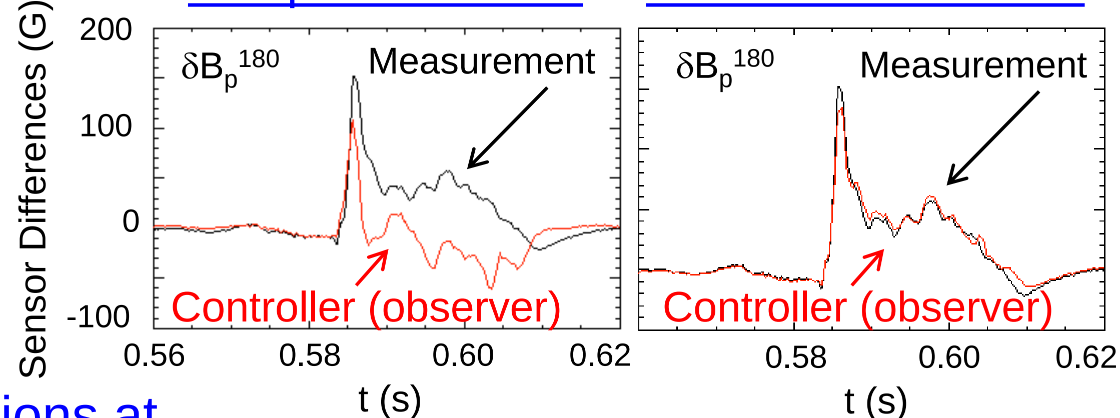


RWM State Space Controller



3D wall, ports, mode currents

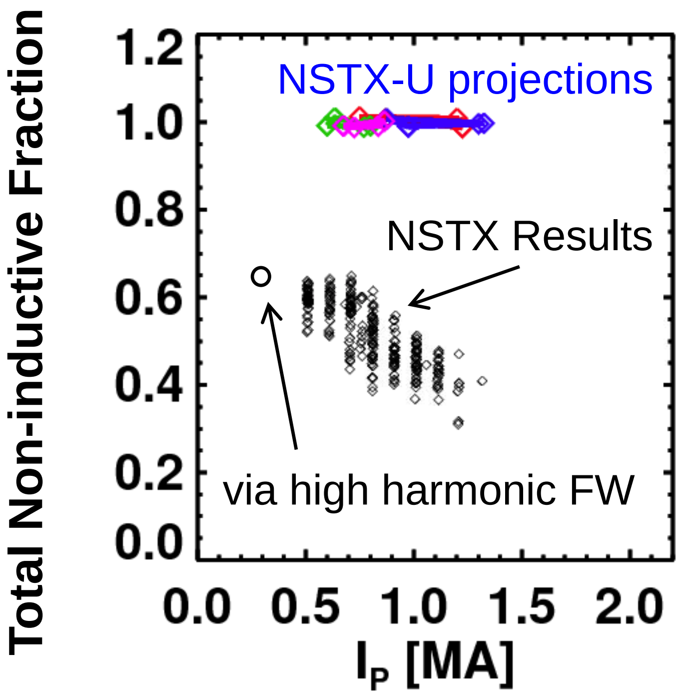
with plasma states + with 3D wall states

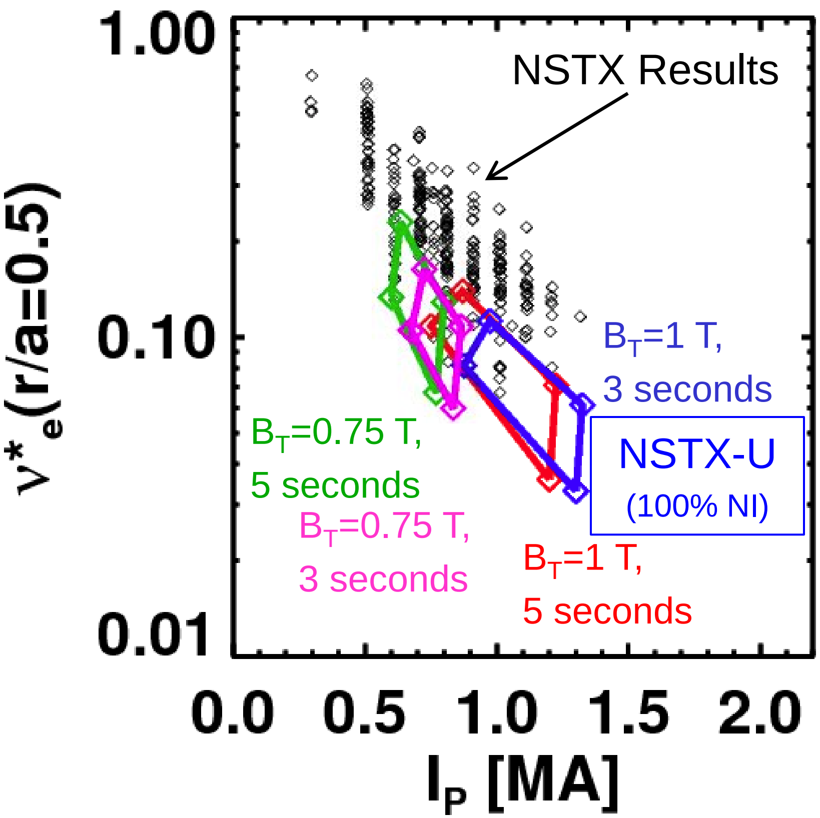


- Significantly reduced disruptions at high β_N in controlled experiments

See J.W. Berkery et al., talk BO4.6 (this session)

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





- Maximum non-inductive fractions of 65% at I_P = 0.7 MA
  - Classical beam ion diffusion < 1-1.5 m^2/s)

- 65% non-inductive also reached using high-harmonic fast wave CD

see G. Taylor poster PP-9.61 (Wednesday PM)

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

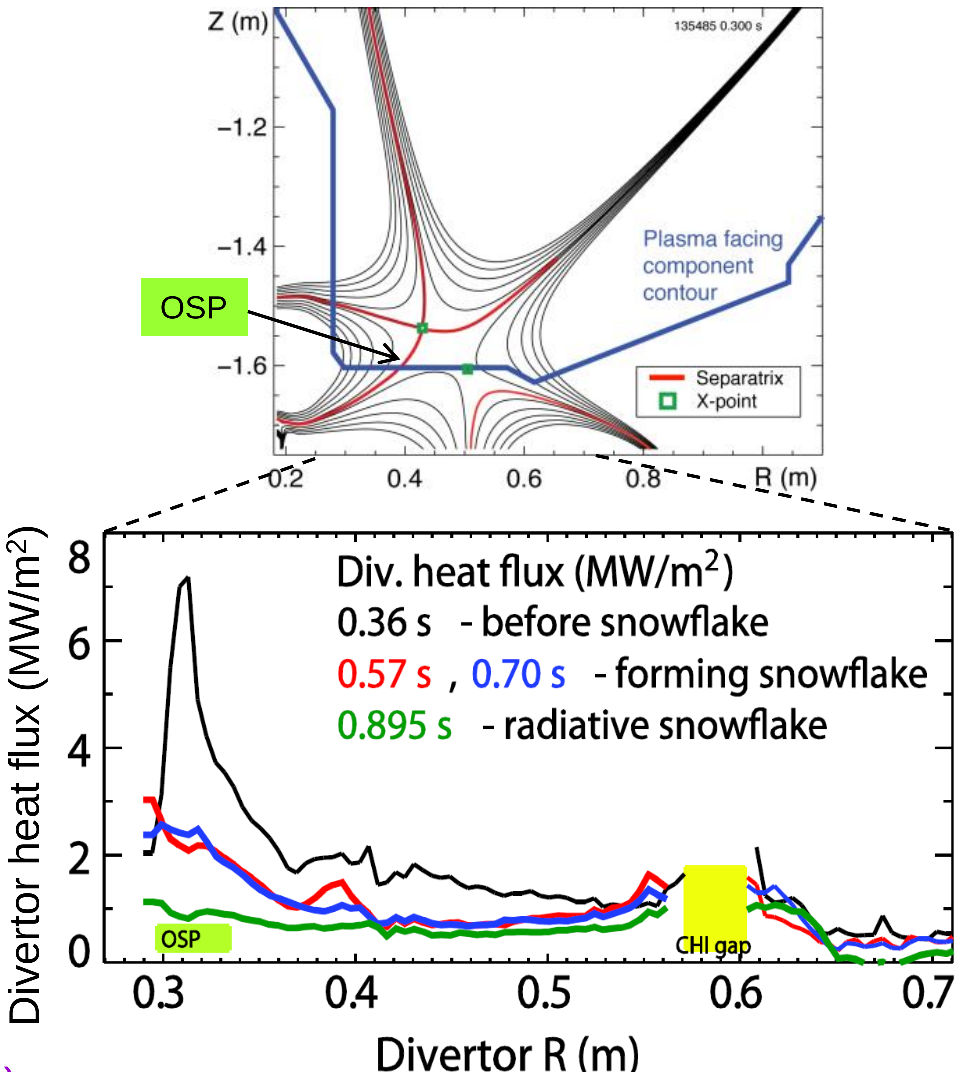
see S. Gerhardt (invited) YI-2.2 (Friday AM)

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

- Divertor heat flux width strongly decreases as I_p increases in NSTX, DIII-D, C-Mod
  M. Makowski, invited PI2.5 (Wednesday PM)

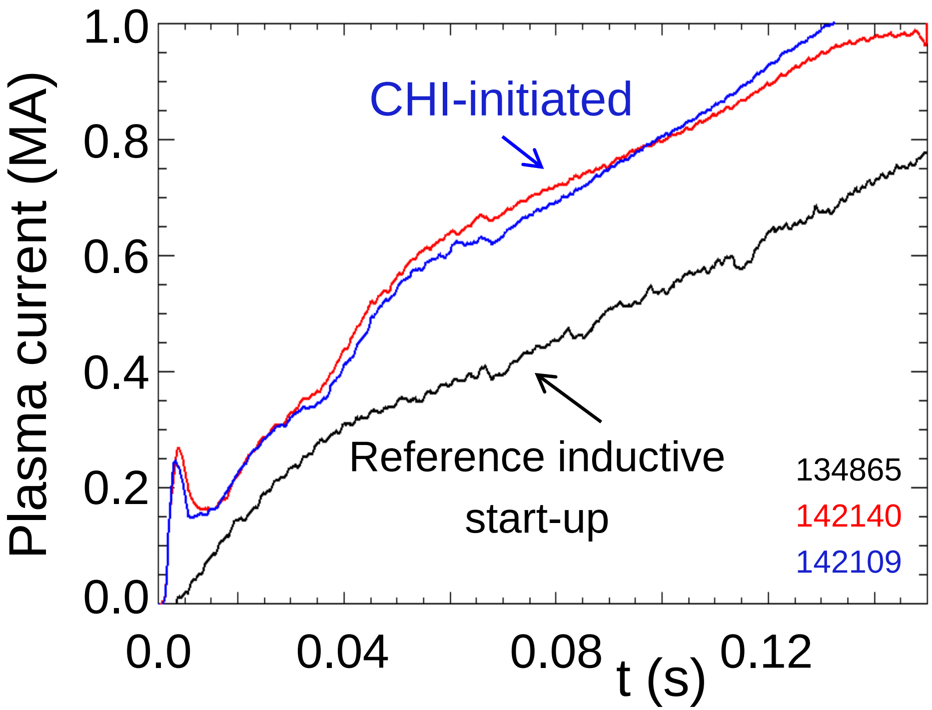
- Snowflake divertor experiments in NSTX (P_{NBI}=4 MW, P_{SOL}=3 MW)
  - Good H-mode confinement (τ_E, $T_{e,i}(0)$, β_N, H98(y,2))
  - Significant reduction in steady-state divertor heat flux (from 3-7 to 0.5-1 MW/m^2)
  - Synergistic combination of detachment + radiative snowflake divertor

Snowflake divertor in NSTX

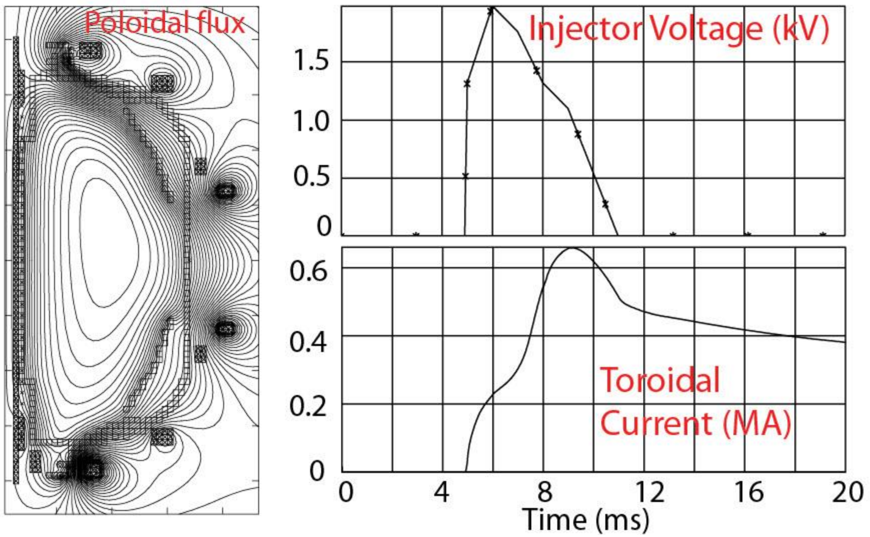


See V. Soukhanovskii, talk BO4.11 (this session)

Standard L-mode NSTX discharge ramping to 1MA requires 50% more inductive flux than a CHI-initiated Discharge



TSC simulation using 25% of full injector flux capability in NSTX-U



- Reference inductive discharge
  - Uses 396 mWb to get to 1MA
- CHI initiated discharge
  - Uses 258 mWb to get to 1MA (138 mWb less flux to get to 1MA)

- Double the closed flux current targeted for NSTX-U
  - Estimated startup current of 1 MA

R. Raman, D. Mueller T.R. Jarboe et al. PoP **18**, 092504 (2011)

see R. Raman et al., poster PP9.59 (Wednesday PM)

NSTX data and present analysis is targeting 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 Li
- Handling increased heat flux
  - Large heat flux reduction from synergistic combination of detachment + radiative snowflake divertor
- Aiming for steady-state operation / higher non-inductive start
  - Non-inductive current up to 65%, CHI yields 50% flux savings (I_p=1MA)

- DEVICE STATUS: NSTX ran for 4 weeks in FY2011 (abbreviated due to TF coil fault)
- NSTX-U is accelerated 6 months (upgrade has begun! – 1st plasma April 2014)
  - Continued research prepares needed physics hypotheses to be tested in the new, low collisionality ST operational regime provided by NSTX-U

*** Don't miss the NSTX poster session PP9 Wednesday PM ***

Supporting and Backup Slides Follow

Reflectometer array measurements indicate CAEs as possible cause of enhanced electron thermal transport

- Modes identified as CAEs and GAEs via mode number, frequency evolution
  - Mode structure measured via reflectometry (16 channels, 30 – 75 GHz)
- High frequency AE activity correlates with enhanced χ_e in plasma core

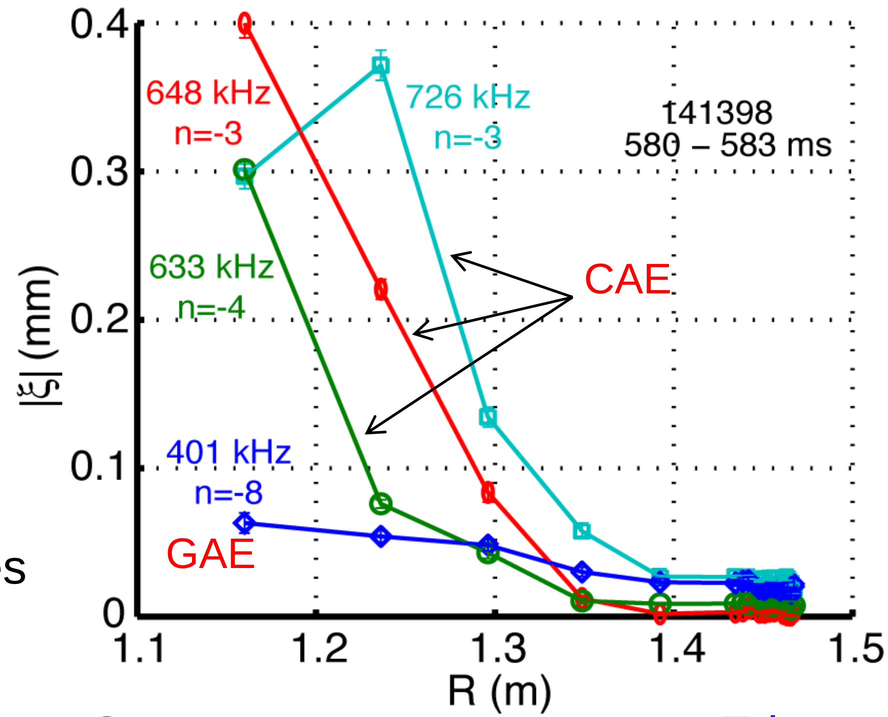
  D. Stutman *et al.*, PRL **102** 115002 (2009)

  K. Tritz, APS DPP 2010 Invited PI2.2
- CAEs candidates for causing electron transport (same as GAEs)
  - measured core localization
  - resonant with electron orbit frequencies

- Fast ion redistribution associated with low frequency MHD
  - Subsequent CAE destabilization, radial + pitch angle redistribution of core particles

  see A. Bortolon poster PP-9.56 (Wednesday PM)

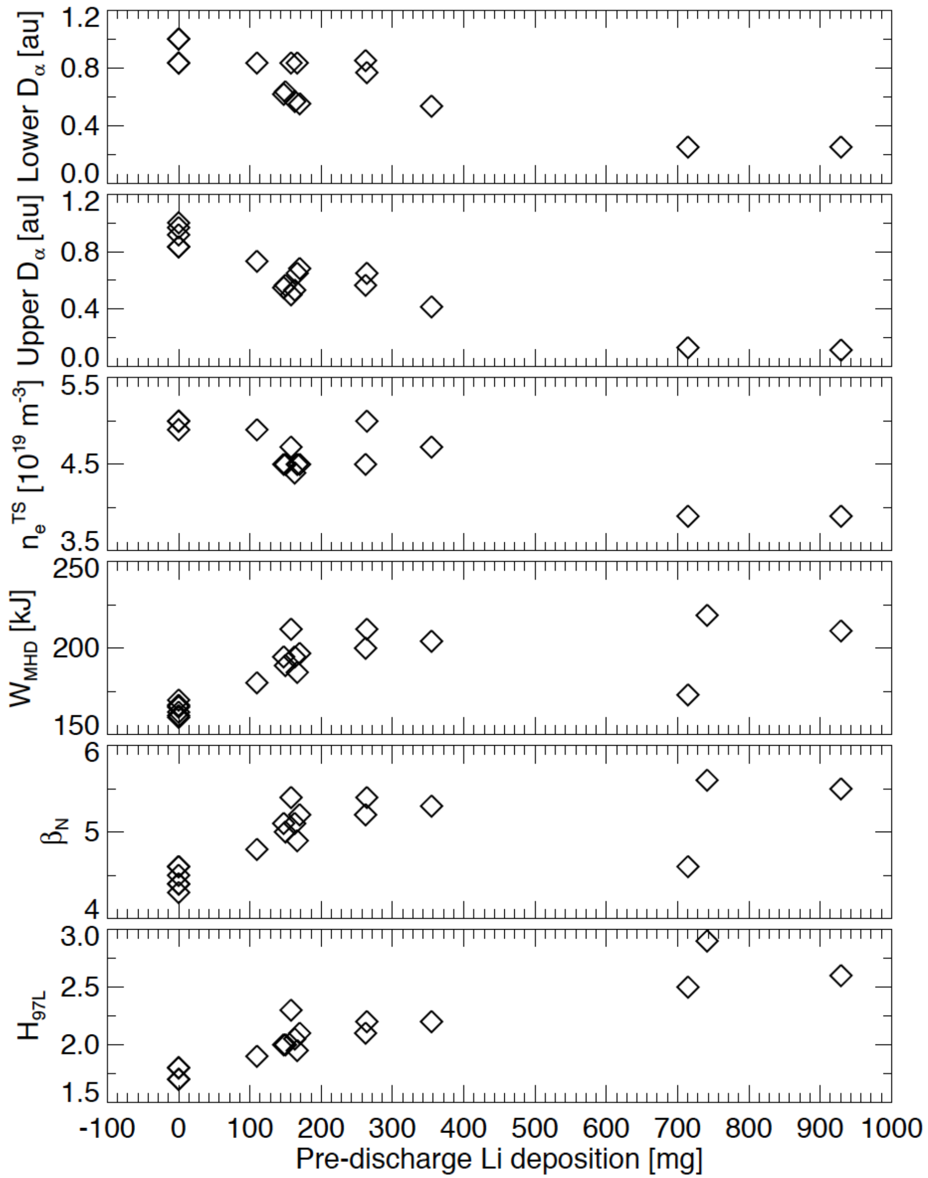
High Frequency AEs

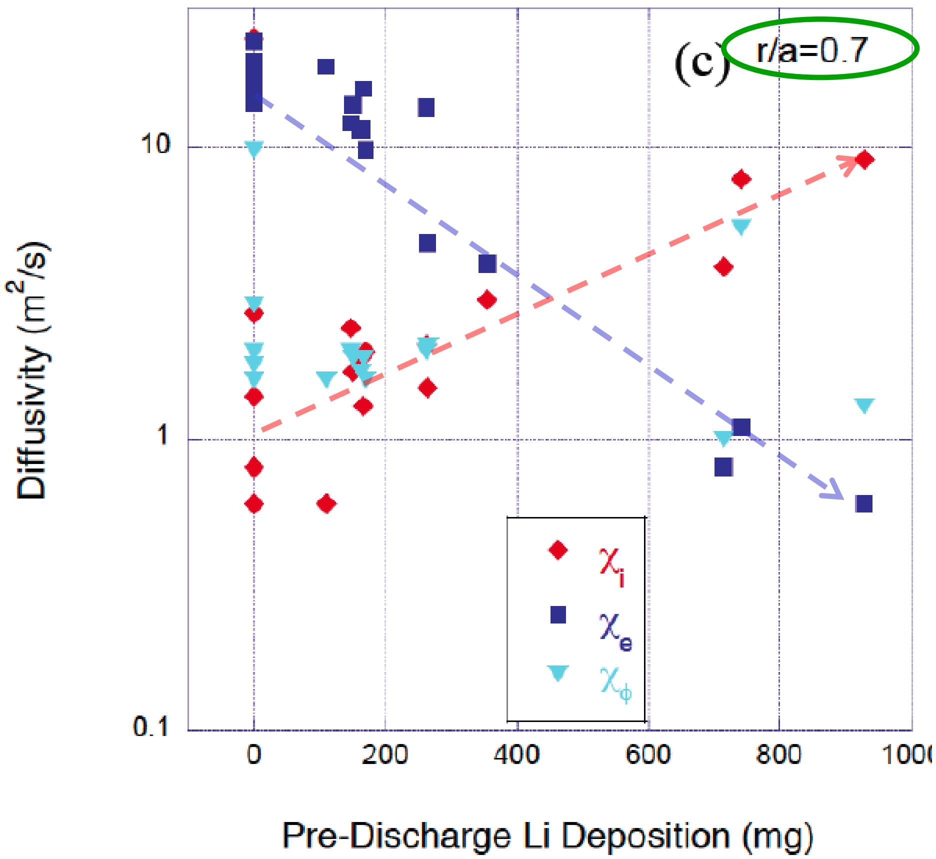


Core Edge

N A Crocker *et al*. PPCF **53** 105001 (2011)

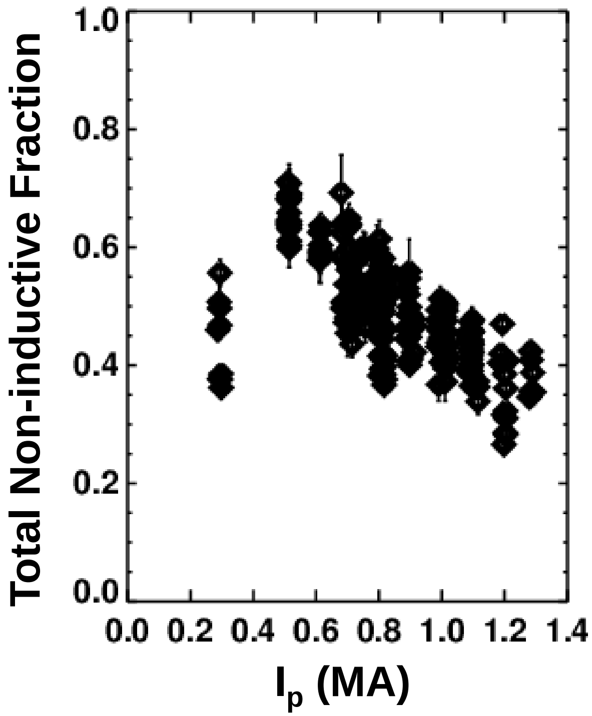
Global plasma performance improves nearly continuously with increasing lithium

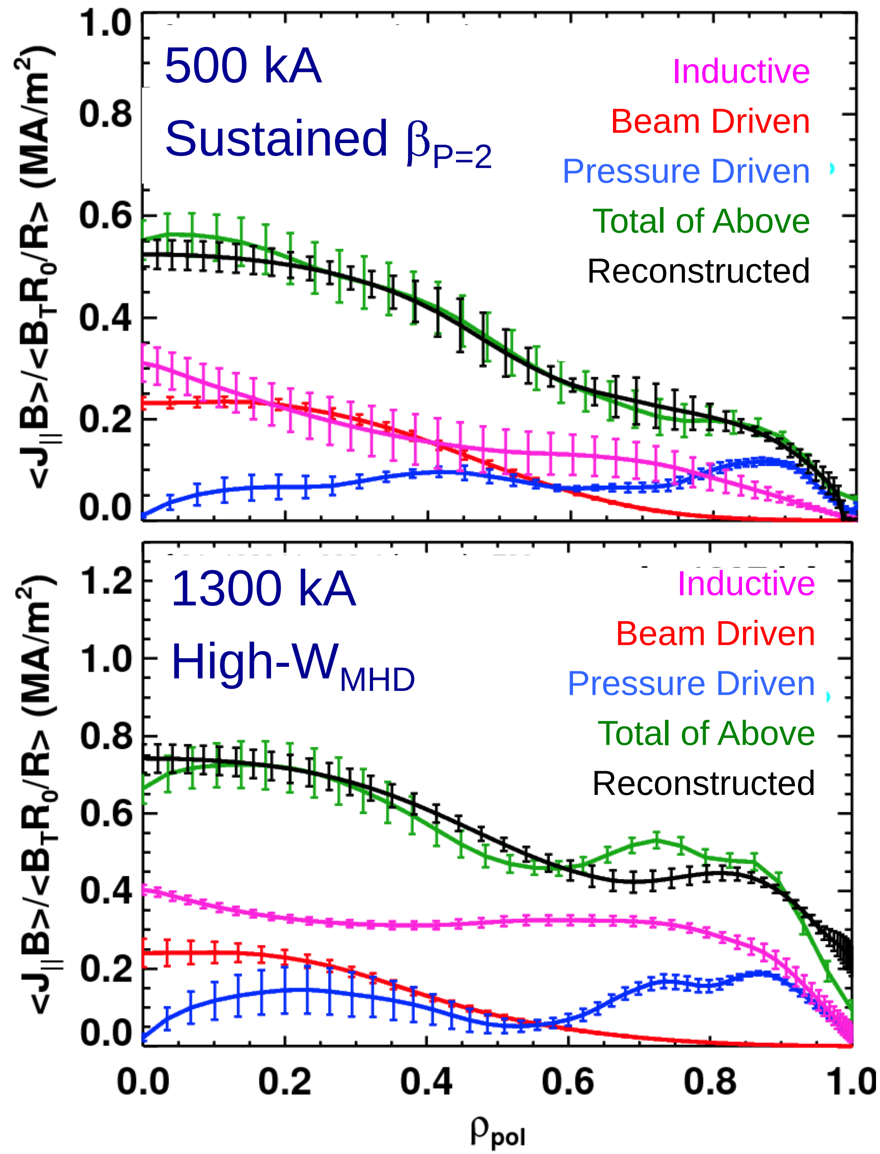




R. Maingi – PRL 107, 145004 (2011)

Non-inductive current fractions of up to 65% sustained



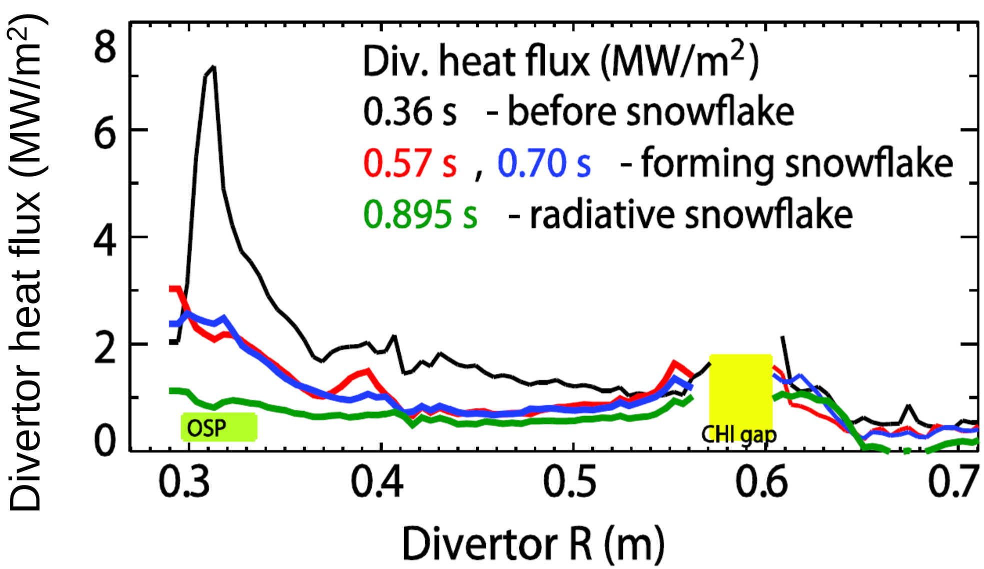


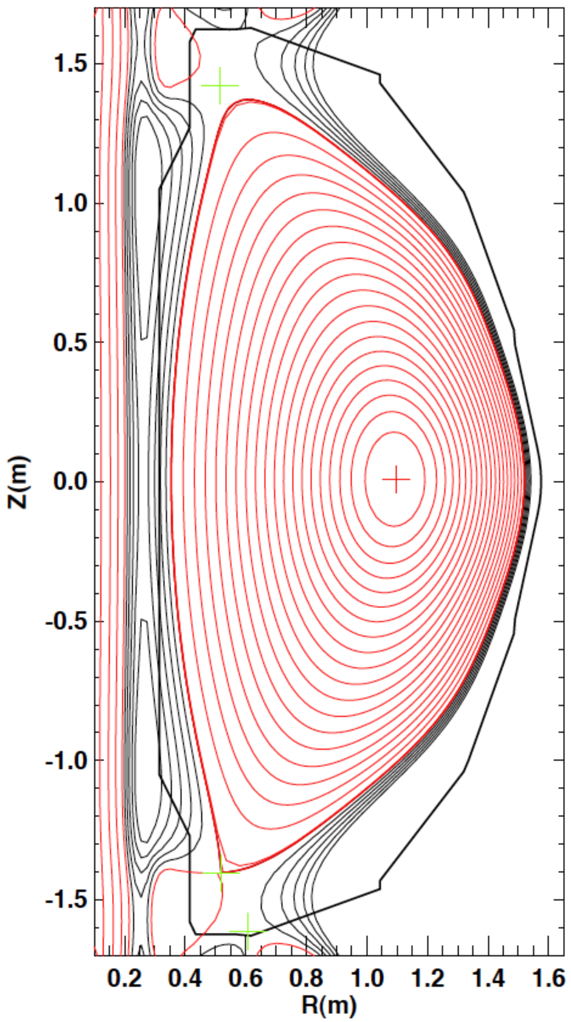
- Maximum non-inductive fractions of 65%, with I_P=500-800 kA
  - Classical beam ion diffusion (D_{FI} < 1-1.5 m^2/s)
    see S. Gerhardt (invited) YI-2.2 (Friday AM)

- 65% non-inductive also reached using high-harmonic fast wave CD
  see G. Taylor poster PP-9.61 (Wednesday PM)

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

- Divertor heat flux width strongly decreases as I_p increases in NSTX
- 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



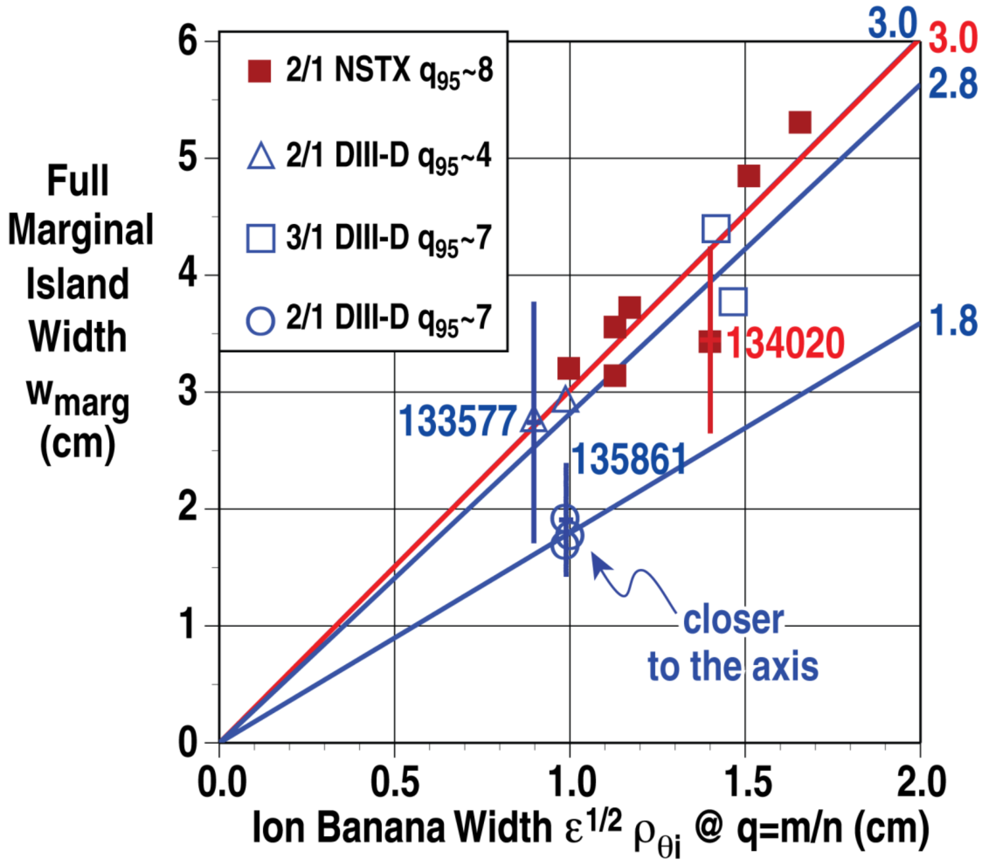


Planned upper and lower snowflake-minus configuration (NSTX-U)

See V. Soukhanovskii, talk BO4.11 (this session)

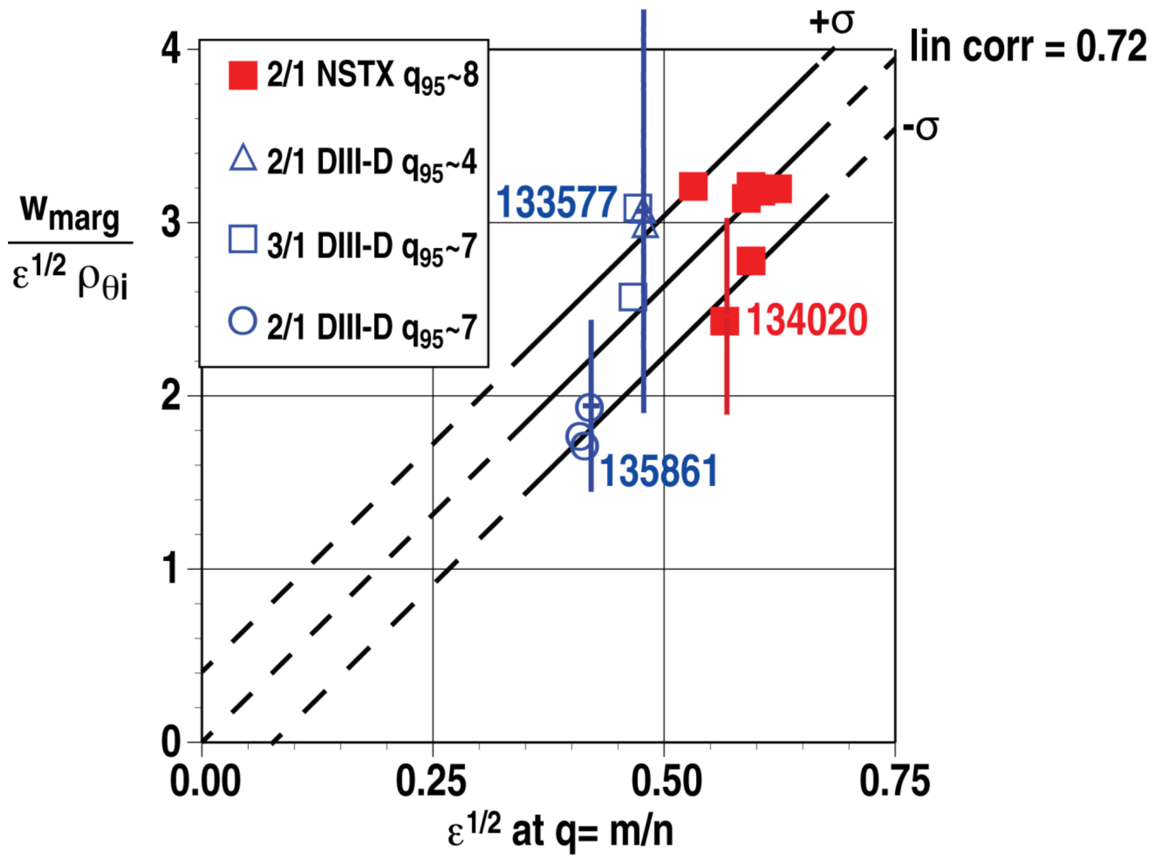
Measure of the Marginal Island Width Gives Information on Small Island Stabilizing Physics that in Part Governs Onset

- **Empirically, marginal island width 2~3 times ion banana width**
  - ★ **outlier is DIII-D 2/1 mode closer to axis at higher q95**



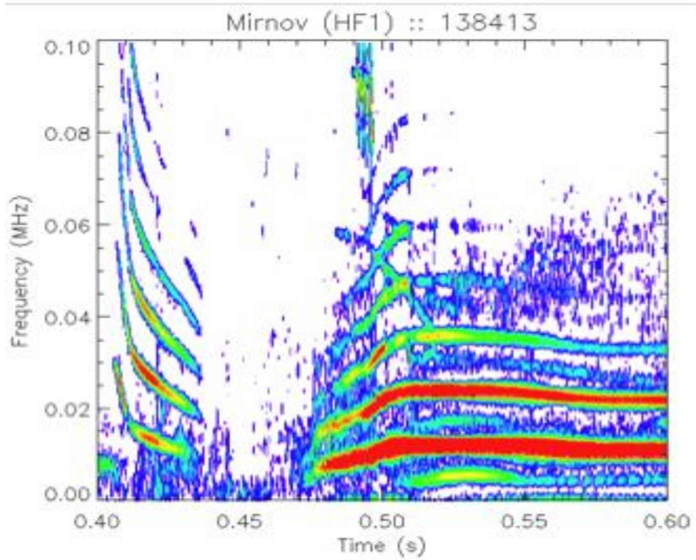
Ratio of Marginal Island Width to Ion Banana Width Correlated with Square Root of Inverse Aspect Ratio

- $\varepsilon \equiv (B_{in} - B_{out})/(B_{in} + B_{out}) \approx r/R_o$ on q=m/n surface



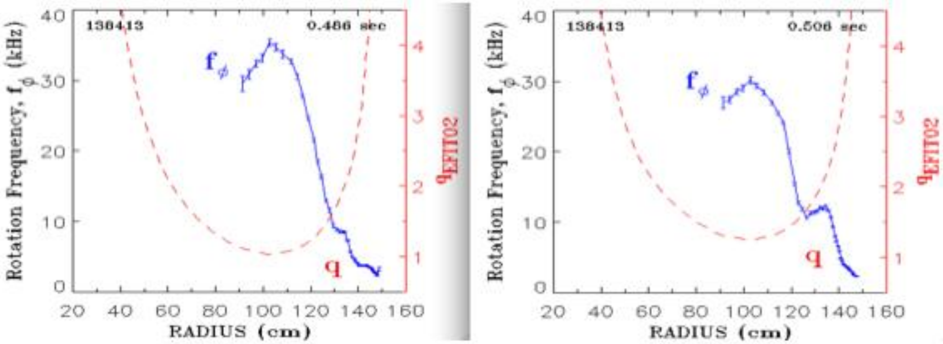
Multiple harmonic oscillations in NSTX

1. In NSTX, multiple harmonic oscillations with $f = nf_\phi$ are found to associate with *magnetic islands rotating at* f_ϕ.
2. The islands can be anywhere from the plasma core to the plasma edge.
3. The islands enhance transport for plasma energy, particle and momentum.



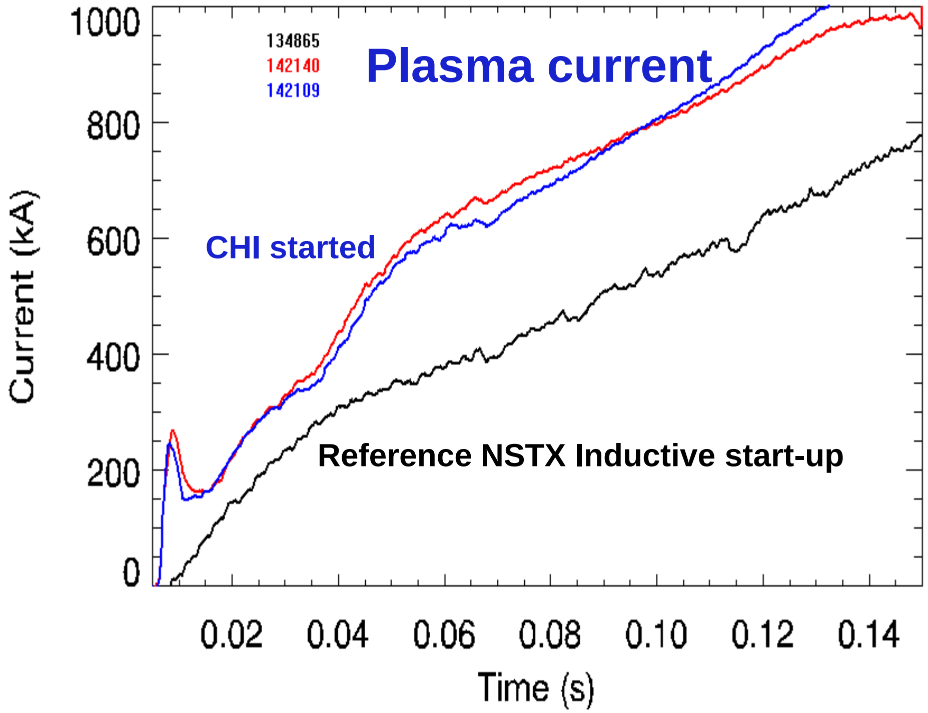
Magnetic islands in NSTX are identified by a flat region in the toroidal rotation profile determined by CHERS

When the islands are at the plasma edge, the stochastic magnetic fields near the island separatrix can suppress ELMs like the RMP coils do, and provide a transport mechanism that peeling modes don't. This may be an alternative interpretation for the EHOs in D3D QH-mode plasmas



K-L Wong

Standard L-mode NSTX discharge ramping to 1MA requires 50% more inductive flux than a CHI initiated Discharge



- Reference inductive discharge
  - Uses 396 mWb to get to 1MA
- CHI initiated discharge
  - Uses 258 mWb to get to 1MA (138 mWb less flux to get to 1MA)

Parameters	NSTX
Toroidal Field (T)	0.55
Planned Non-Inductive sustained Current (MA)	0.7
Plasma Poloidal flux (mWb)	132
Maximum available injector flux (mWb)	80
Maximum startup current potential (MA)	0.4

- Double the closed flux current targeted for NSTX-U
  - Estimated startup current of 1 MA

see R. Raman et al., poster PP9.59 (Wednesday PM)

R. Raman, D. Mueller T.R. Jarboe et al. PoP **18**, 092504 (2011)