NSTX

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

Overview of Physics Results from the National Spherical Torus Experiment (NSTX)

Roger Raman

University of Washington

For the NSTX Research Team

College W&M
Colorado Sch Mines
Columbia U
CompX
General Atomics
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
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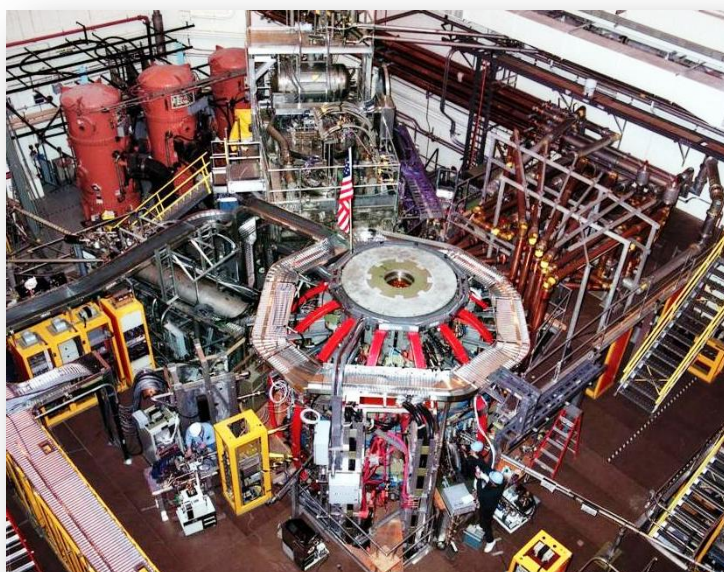
23rd IAEA Fusion Energy Conference
October 11-16, 2010
Daejeon, Korea



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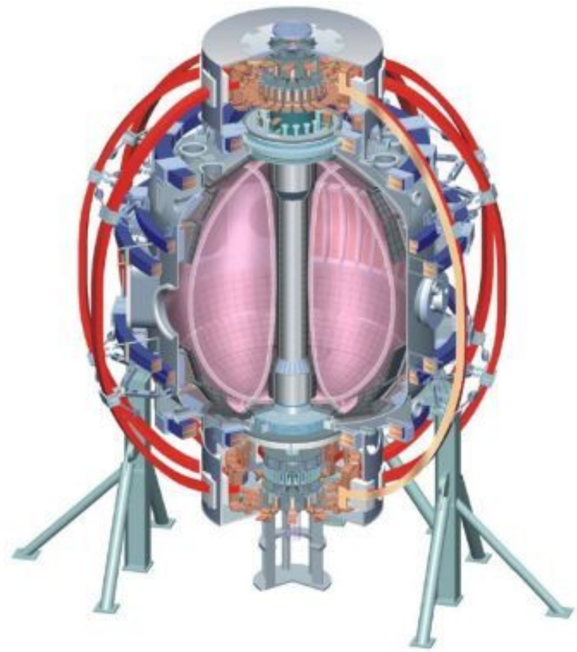
NSTX Studies Toroidal Confinement Physics at Low Aspect-Ratio & Supports ITER Research



Aspect ratio A	1.3 – 1.6
Elongation κ	1.8 – 3.0
Major radius R_0	0.85m
Plasma Current I_p	1.5MA
Toroidal Field	0.55 T
Auxiliary heating:	
NBI (100kV)	7 MW
RF (30MHz)	6 MW

Outline:

1) Lithium Research
- Confinement improvement
- ELM stability
- Liquid lithium divertor

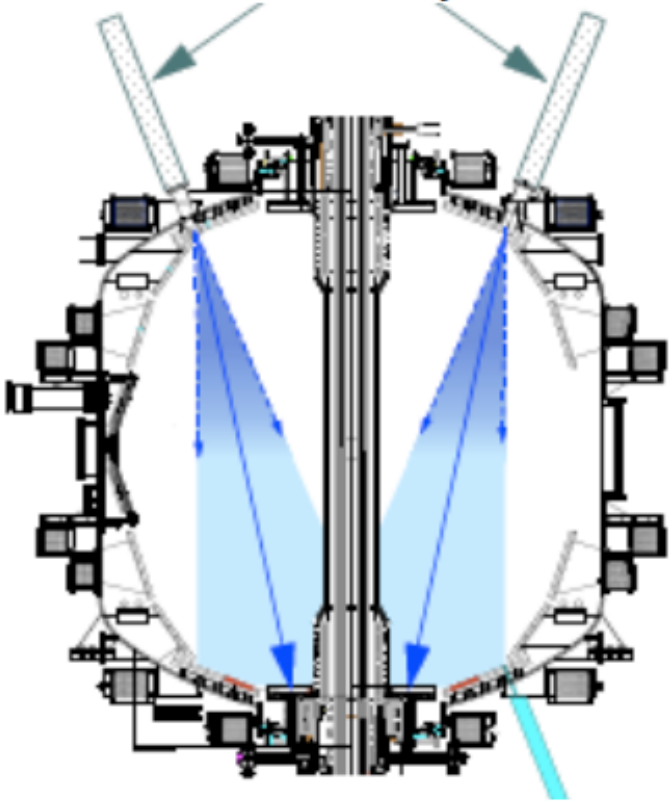
2) ITER Support
- L-H thresholds
- Error field amplification
- Resistive Wall Mode
- Fast ion instabilities & effects
- ELM pacing & divertor heat loads

3) Advanced Scenarios
- Snowflake divertor
- CHI start-up
- Partial non-inductive sustainment
- Feedback control

Lithium Research

- Confinement improvement
- ELM stability
- Liquid lithium divertor

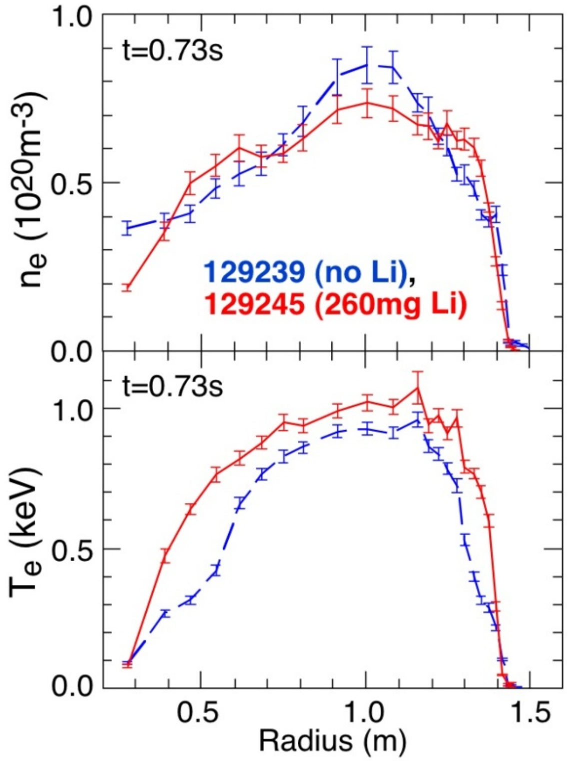
NSTX Experiments are Exploring the Benefits of Lithium to Magnetic Fusion Research

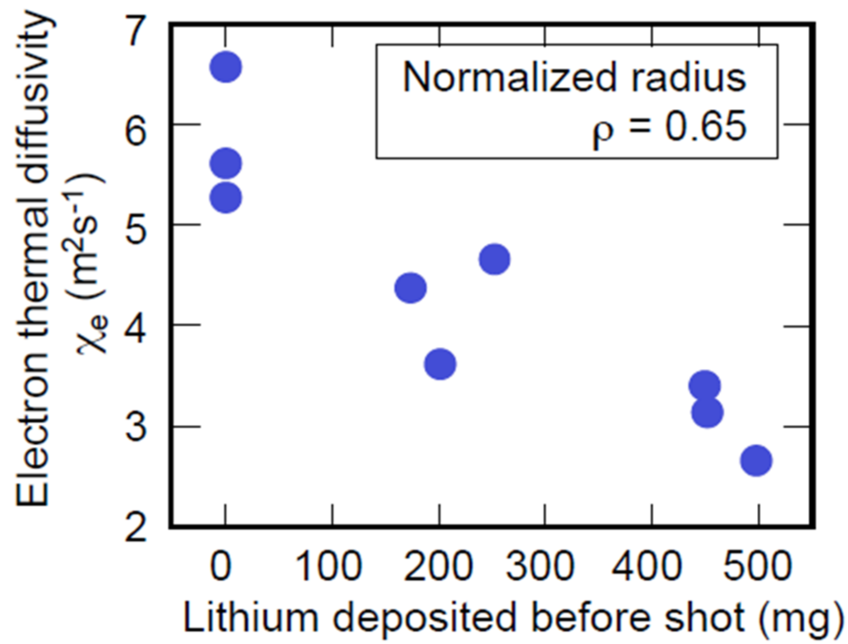


Typically 50 to 300mg lithium now deposited between shots

H.W. Kugel FTP/3-6Ra

Improved Electron Confinement With Lithium Coating Arises from Broadening of T_e Profile

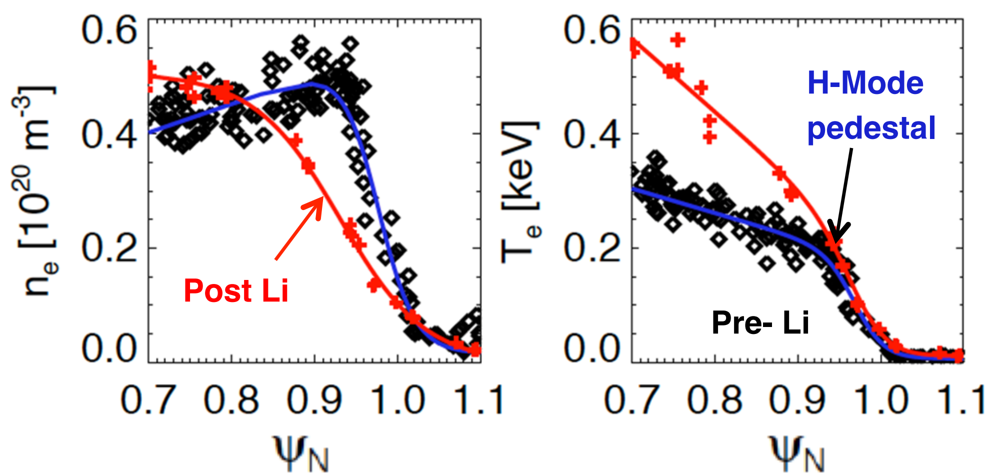




- TRANSP analysis confirms electron thermal transport in outer region progressively reduced by lithium coating. Measure reductions in high-k turbulence near edge.
- Thermal ion confinement remains close to neoclassical both with and without lithium
- New confinement mode, **Enhanced Pedestal H-mode**, found with H_{98y2}=1.8 [R. Maingi, et al., PRL 135004 (2010)]

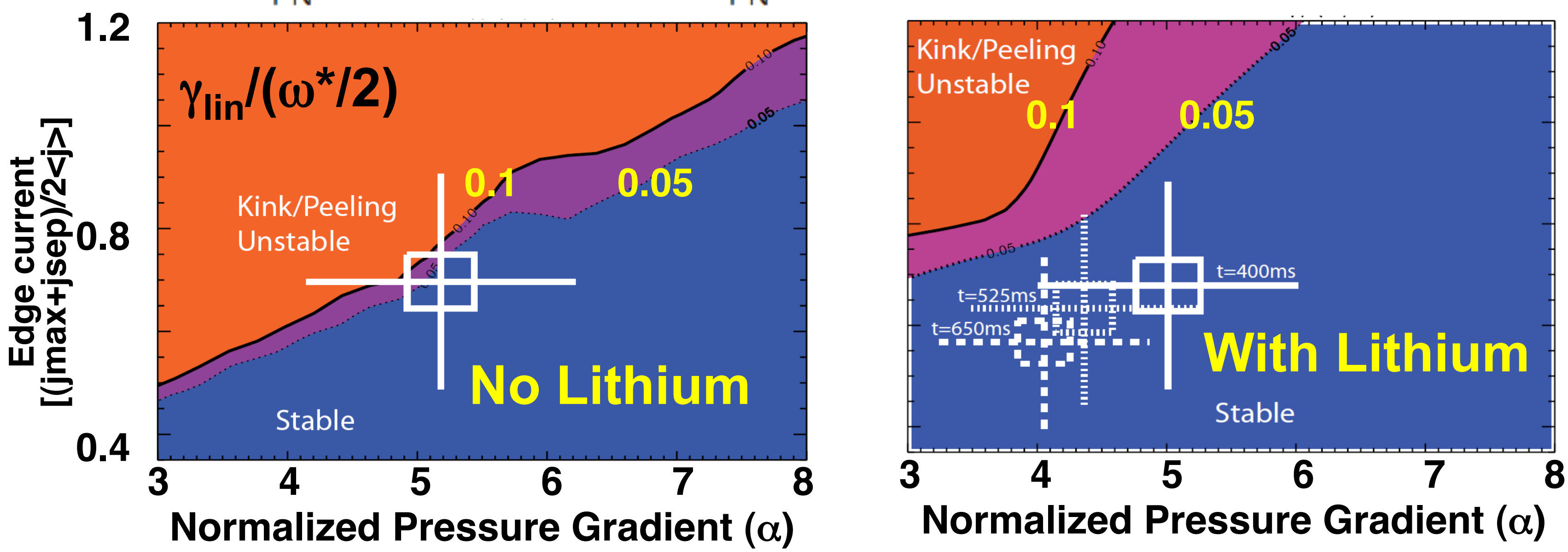
S. Ding et al., Plasma Phys. Control. Fusion 52 (1), 015001 (2010)

Pedestal Profiles Broadened and ELMs Suppressed by Lithium Wall Coatings



Edge stability calculations (ELITE)

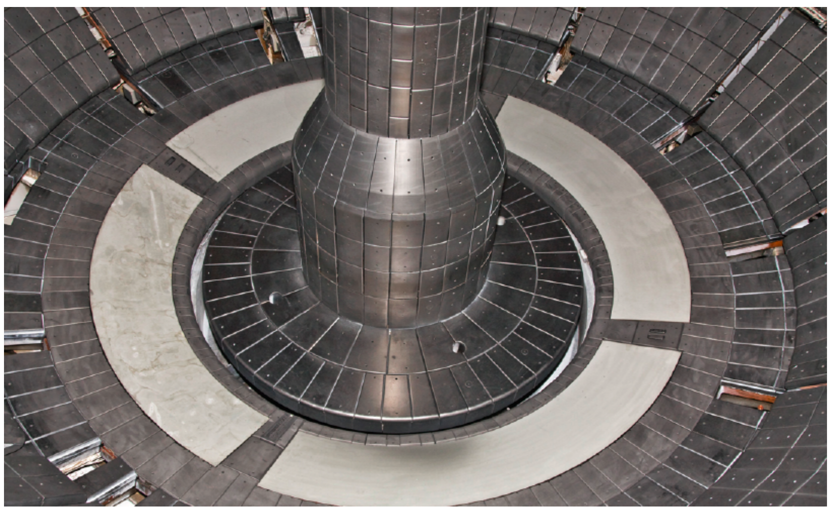
– Colors represent contours of ratio of linear mode growth rate to diamagnetic drift frequency
– Pre-Li discharges close to kink/ peeling stability boundary



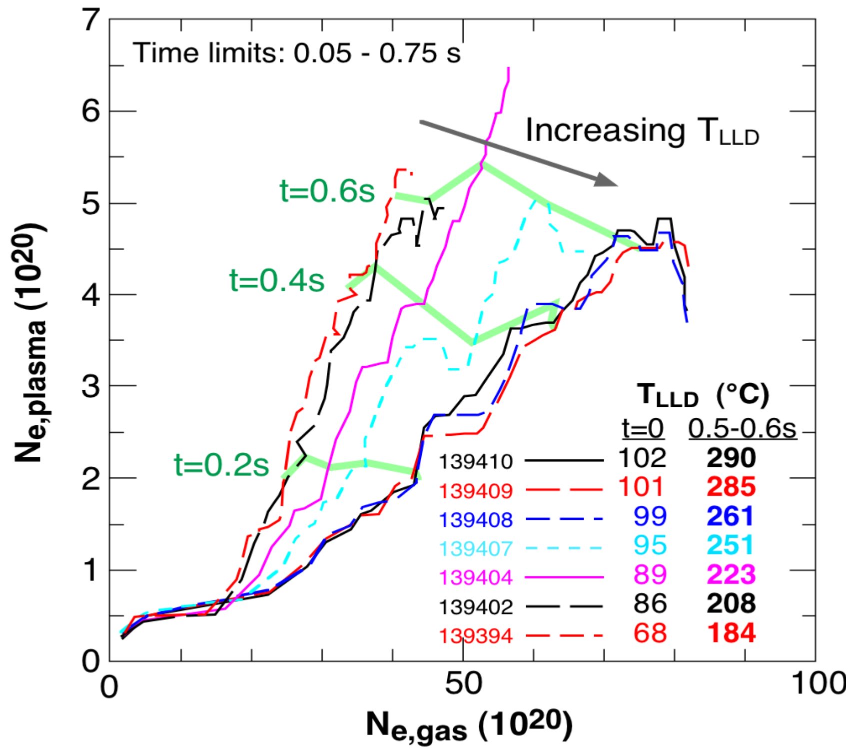
R. Maingi EXD/2-2

Now Investigating Pumping Capability and Plasma Effects of a Liquid Lithium Divertor (LLD)

- 4 LLD plates form ~20cm wide annulus in lower outboard divertor
  - Heatable surface of porous molybdenum
  - Loaded with lithium by LITER deposition



- Observed preliminary indications of D pumping when surface heating by plasma liquefies lithium coating on LLD
  - Lower single null divertor plasmas with outer strike point on LLD raise peak surface temperature to ~300°C



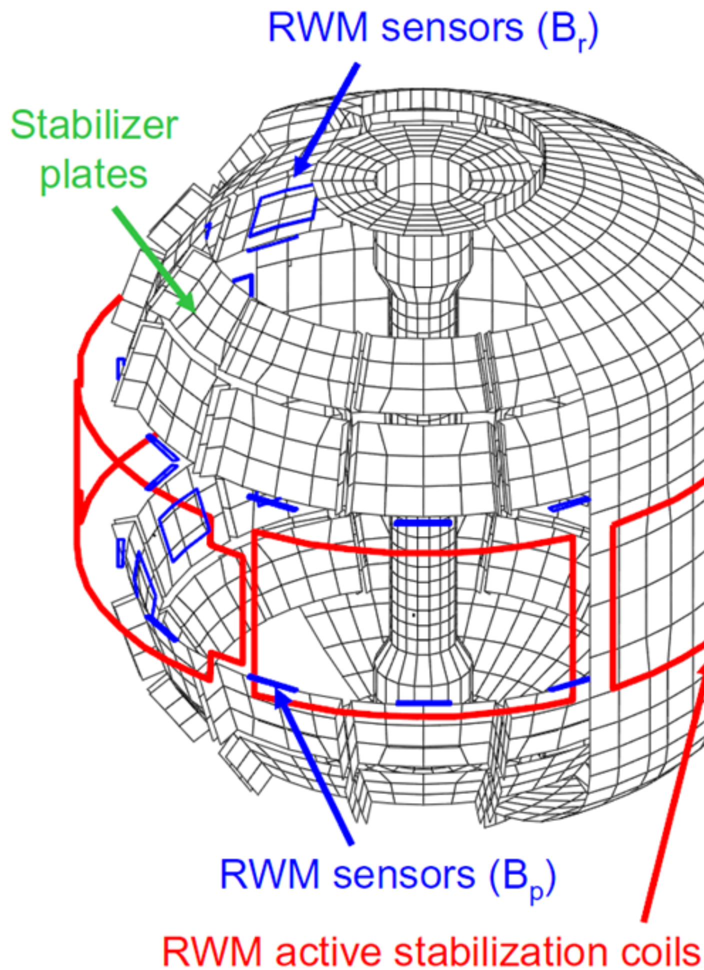
Toroidal Confinement Physics and ITER Support

- L-H thresholds
- Error field amplification
- Resistive Wall Mode
- Fast-ion instabilities and effects
- ELM pacing & divertor heat loads

NSTX Strongly Supports ITPA Joint Experiments

Transport and Confinement	
TC-1	Beta degradation of energy confinement
TC-2	Hysteresis and access to H~1
TC-4	Species dependence of L-H threshold
TC-9	Scaling of intrinsic rotation
TC-10	Exptl. identification of turbulence and comparison with codes
TC-12	Confinement at low aspect ratio
TC-14	RF rotation drive
TC-15	Dependence of momentum and particle pinch on collisionality
Macroscopic Stability	
MDC-2	RWM physics
MDC-14	Rotation effect on NTMs
MDC-15	Disruption database development
MDC-17	Active disruption avoidance
Energetic Particles	
EP-1	Measurement of damping rate of TAEs
EP-2	Fast ion loss/redistribution from localized Aes
EP-4	Effect of dynamic friction at resonance on non-linear AE evolution
Pedestal	
PEP-6	Pedestal structure and ELM stability in DN
PEP-19	Edge transport with RMP
PEP-23	ELM suppressions by magnetic perturbations
PEP-26	Critical edge parameters for achieving L-H
PEP-27	Pedestal profile evolution following L-H transition
Divertor and Scrape-Off Layer	
DSOL21	Dust transport
Integrated Operating Scenarios	
IOS-5.2	Maintaining ICRF coupling in expected ITER regimes

NSTX Equipped with Midplane Non-Axisymmetric Coils for MHD, Confinement and Pedestal Studies

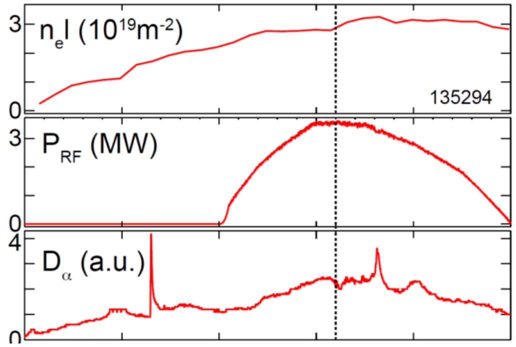


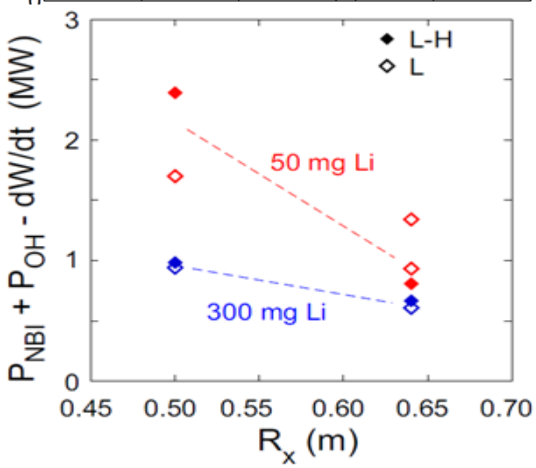
Produce n = 1, 3 or 2 (4) radial field perturbations

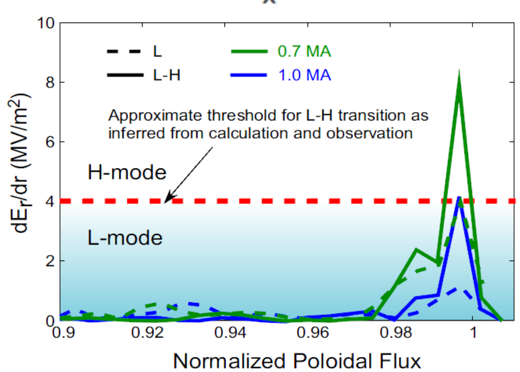
Used for studies of:

- **H-mode threshold**
- **Error field correction (EFC)**
- **Resistive Wall Mode (RWM)**
- **ELM pacing**
- **Momentum transport**

L-H Threshold Experiments in NSTX Have Explored Many ITER and ST-Relevant Issues





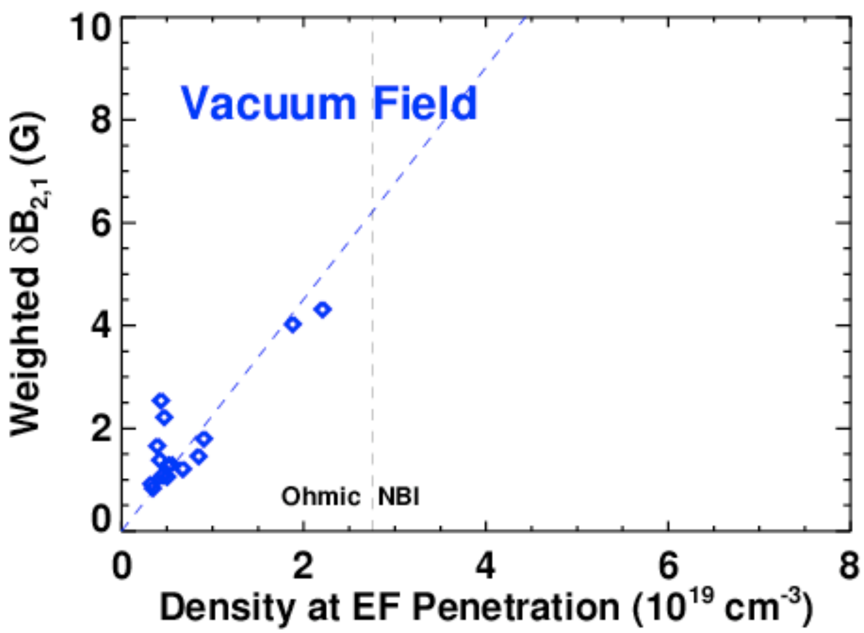


- Species dependence
  - P_{LH} (He) ~ 1.2-1.4 P_{LH} (D): RF-heated
  - $H_{98y,2}$ ~1 with no ELMs after L-H transition
- Non-axisymmetric field application
  - P_{LH} /n_e increased ~65% with several Gauss n=3 fields
- Plasma configuration
  - Lower P_{LH} at increased major radius of X-point
- Lithium coatings
  - P_{LH} /n_e decreased by ~35% with lithium coating
  - Additive influence for R_X , USN vs. LSN
- Strong I_p dependence (ST effect)
  - lower P_{LH} with lower I_p
  - XGC0 calculations show larger E_r shear at lower I_p
- Role of ion-scale turbulence
  - Beam Emission Spectroscopy now operational

S.M. Kaye EXC/2-3Rb

Inclusion of Plasma Response Important to Understanding Effects of Error Fields

- Measure dependence on the line-average density of resonant 2/1 amplitude at q = 2 surface at which mode locks
- Ohmic L-mode plasmas at low density show familiar proportional dependence



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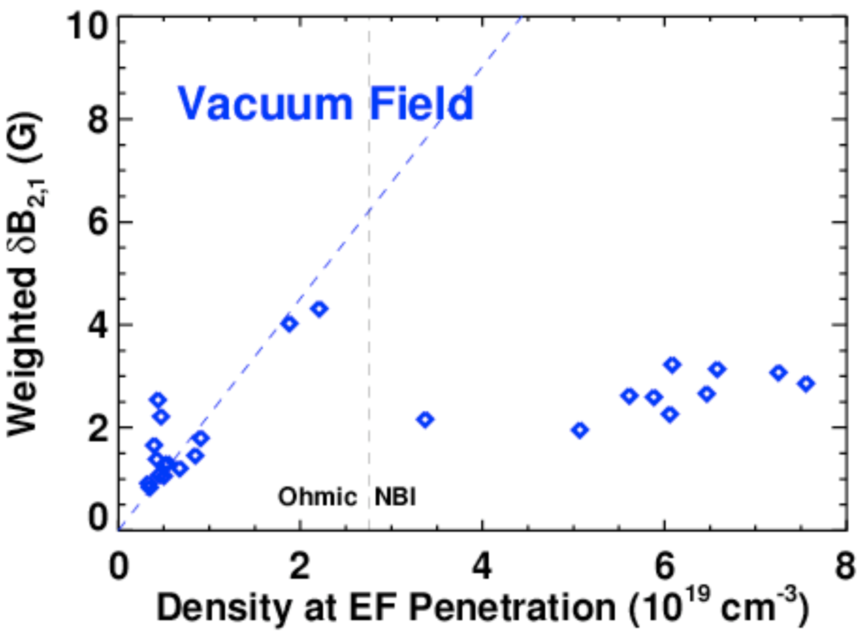
  - mode locks at anomalously low error field



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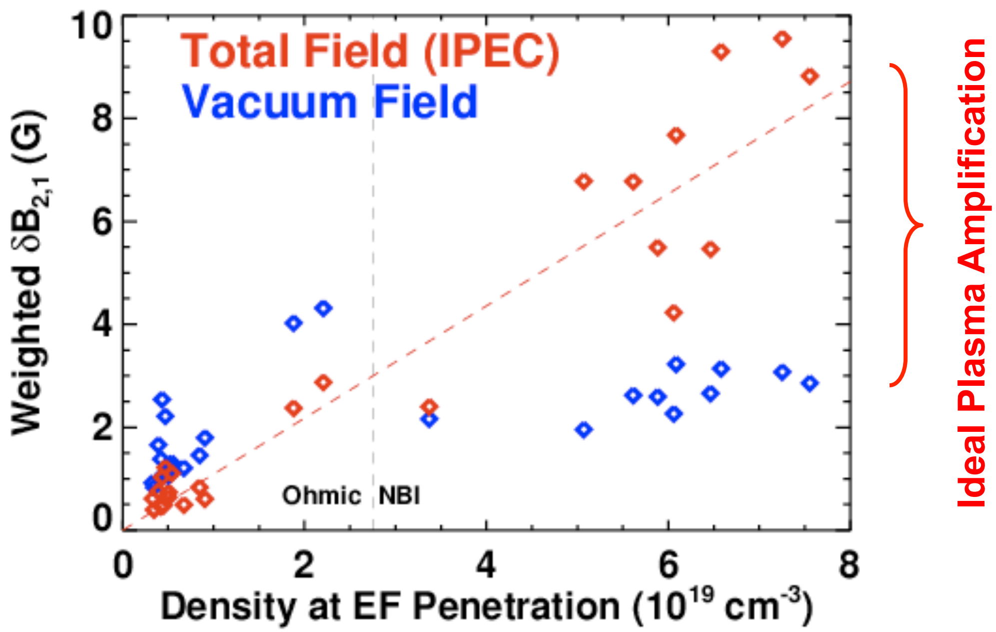
  - mode locks at anomalously low error field
- Linear scaling is restored when plasma amplification of applied field included
  - Plasma response is calculated by IPEC



IPEC:

Ideal Perturbed Equilibrium Code

Calculates

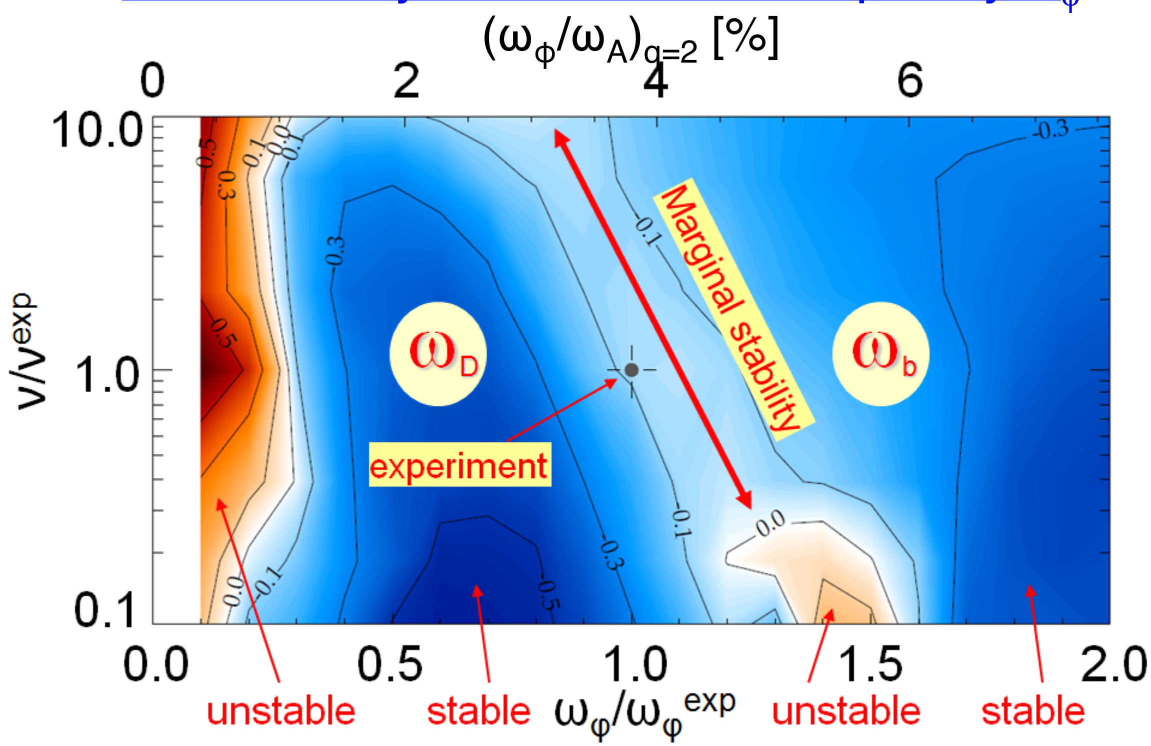
- **Ideal plasma response**
- **Shielding currents**
- **Total resonant field at q=m/n**

J-K. Park EXS/P5-12

Resistive Wall Mode (RWM) Stability Depends on Thermal Kinetic Resonances and Fast-ion Content

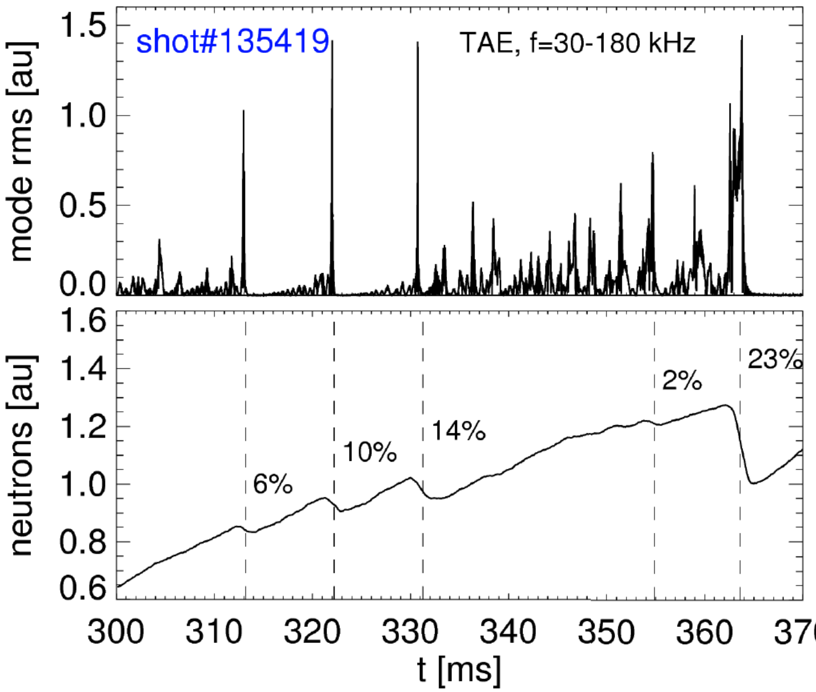
- Observe that RWM can be unstable despite significant plasma rotation
- **MISK code** predicts stabilization of RWM from:
  - precession drift resonance ω_D at low rotation
  - bounce resonance ω_b at high rotation
- Plasma marginally unstable at intermediate rotation

Calculated growth rate $\gamma\tau_w$ contours *vs* collisionality ν and rotation frequency ω_ϕ

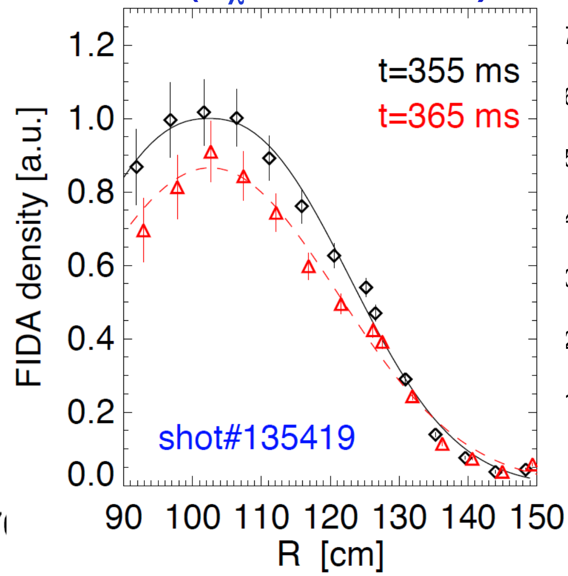


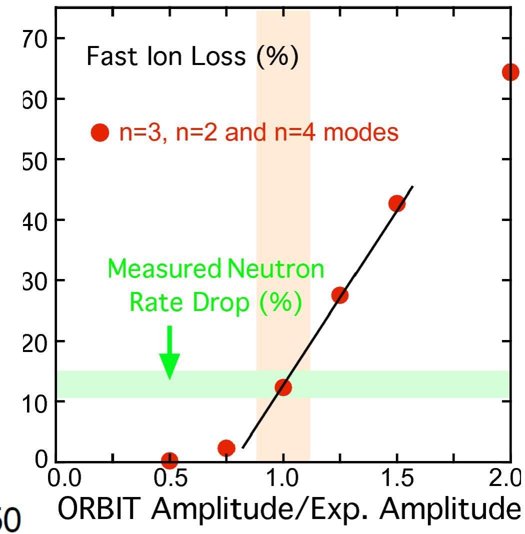
- Stability to RWM predicted to improve with fast ion content
  - Lower rotation speed required to stabilize RWM for higher fast-ion density
  - Important for high-beta ST-FNSF and ITER advanced scenarios

TAE-Avalanche Induced Neutron Rate Drop Modeled Successfully Using NOVA and ORBIT Codes



Fast Ion Profile
(E_λ = 30-60keV)



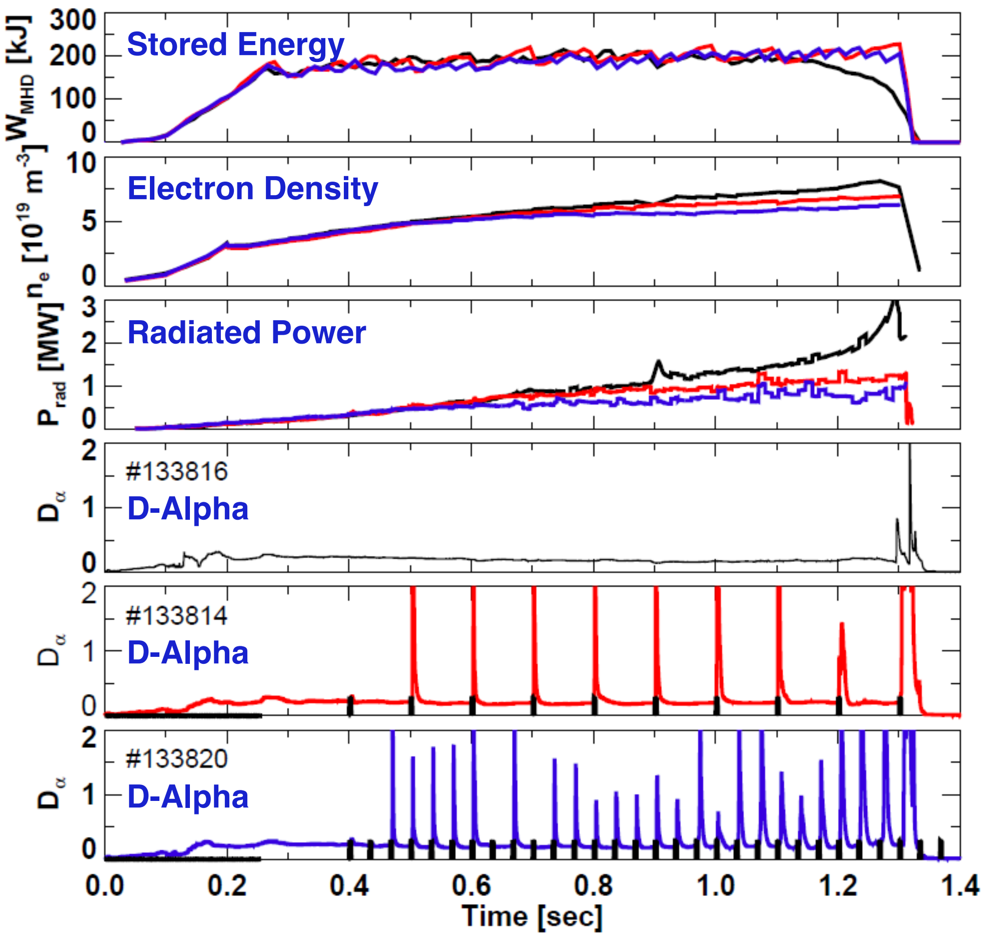


- Toroidal Alfvén Eigenmode (TAE) avalanches in NBI-heated plasmas associated with transient reductions in D-D (beam-target) neutron rate
- Change in beam-ion profile measured with Fast-ion D-alpha (FIDA)
- Modeled using NOVA and ORBIT codes
  - Mode structure obtained by comparing NOVA calculations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

E. Fredrickson EXW/P7-06 **M. Podestà EXW/P7-23** **G-Y. Fu THW/2-2Rb**

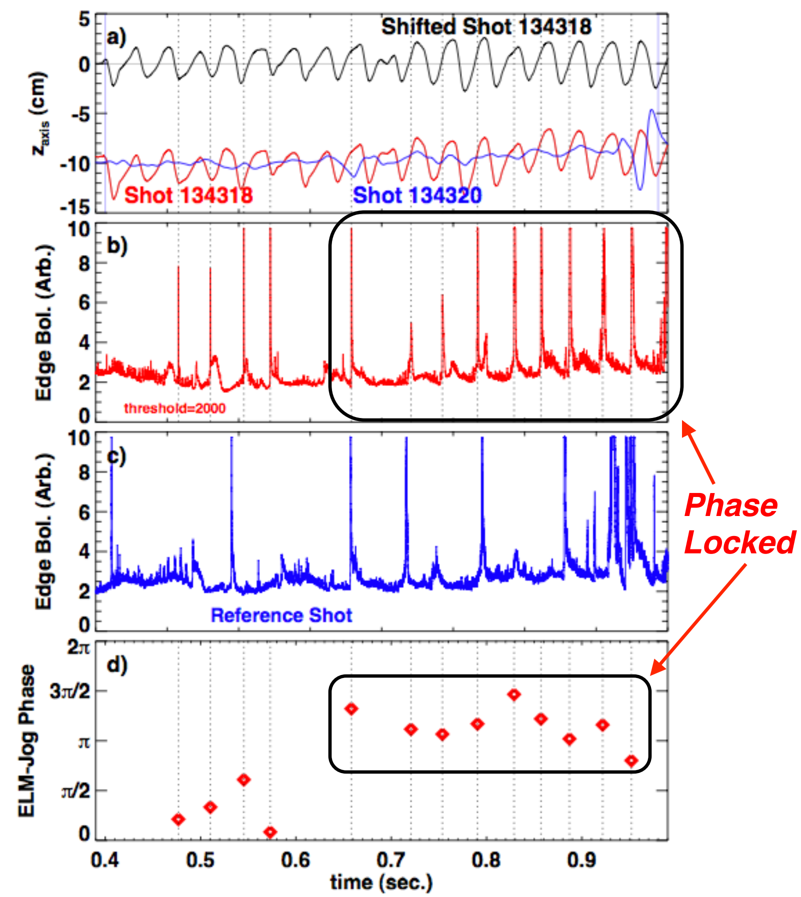
ELM Pacing Developed With Pulsed Non-Resonant Fields and Vertical Jogs

Rapid, Reliable Triggering with Pulsed 3-D Fields



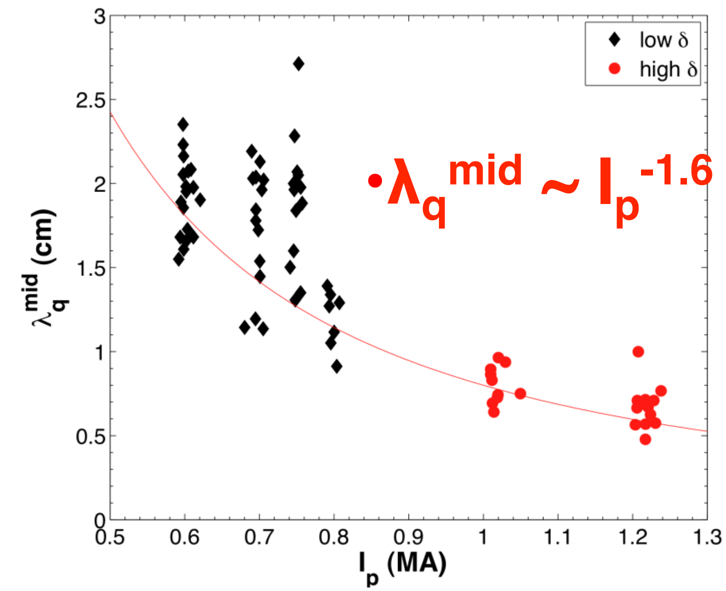
- Reduction in radiated power
- Rapid ELMs lead to smaller per-ELM energy loss

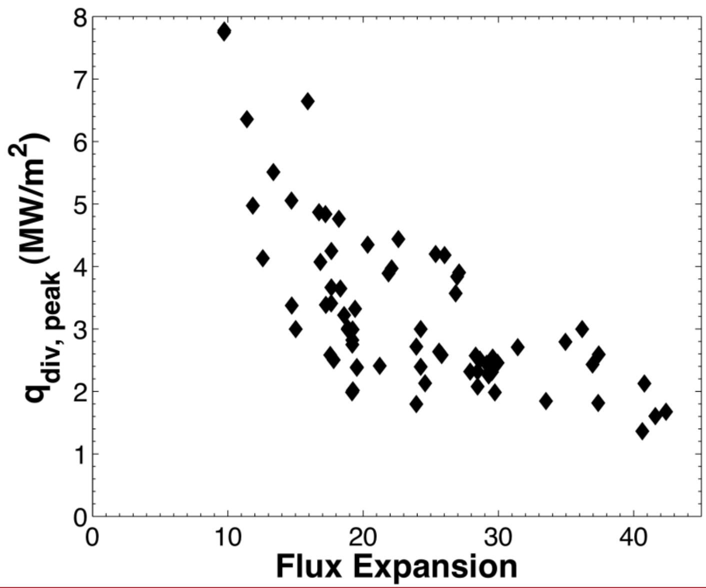
ELM Pacing Via Vertical Jogs



- Vertical jogging successful despite thick continuous vacuum vessel.
- ELMs become phase locked to upward motion

Heat Flux Profile Width Decreases Strongly with I_p in NSTX, Largely Independent of P_{loss}, Flux Expansion, and B_T





- Divertor heat flux width, magnetically mapped to the midplane, shows a strong decrease as I_p is increased
  - λ_q^{mid} further decreases in ELM-free Li conditioned discharges
  - Research continuing to determine if adverse Ip scaling is offset by favorable size scaling to future devices.

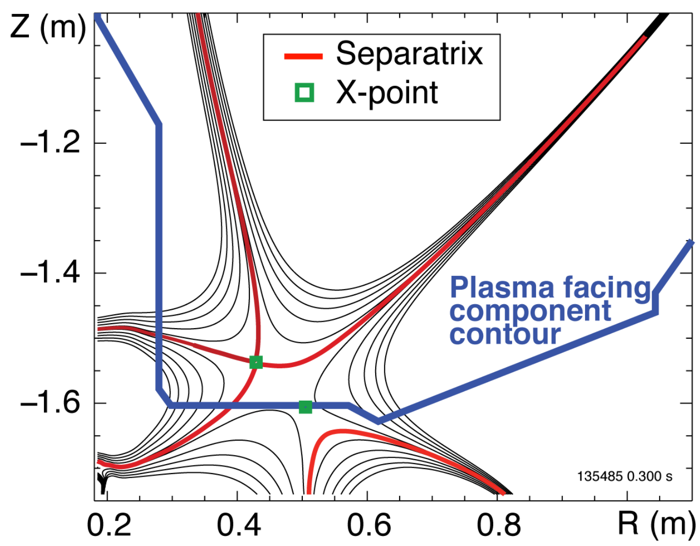
- Divertor heat flux inversely proportional to flux expansion over a factor of five

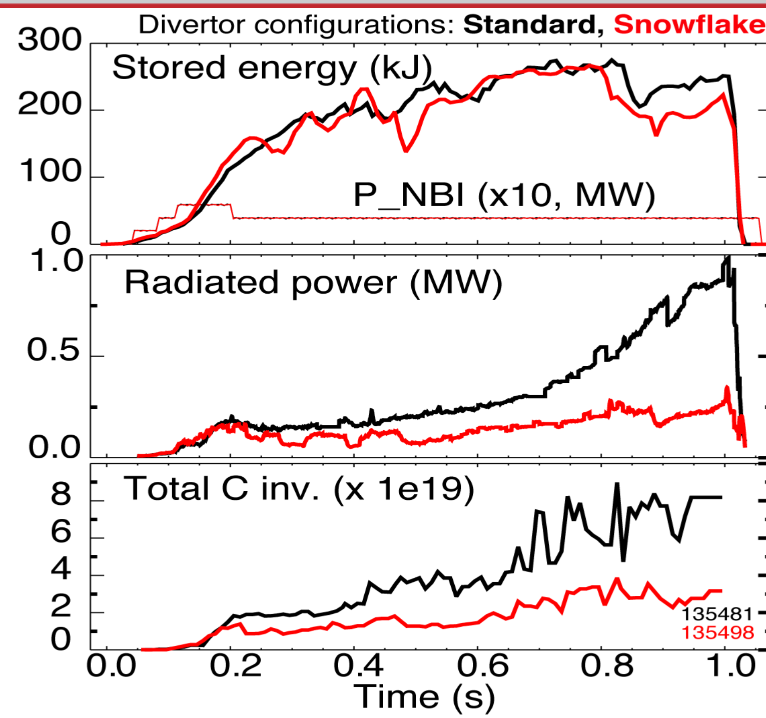
T.K. Gray, EXD/P3-13

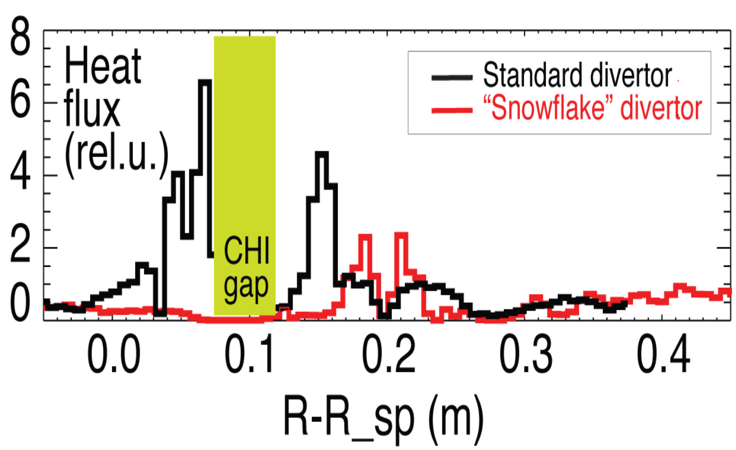
Advanced Scenarios

- Snowflake divertor
- CHI start-up
- Partial non-inductive sustainment
- Feedback control

"Snowflake" Divertor Configuration Resulted in Significant Divertor Heat Flux Reduction and Impurity Screening





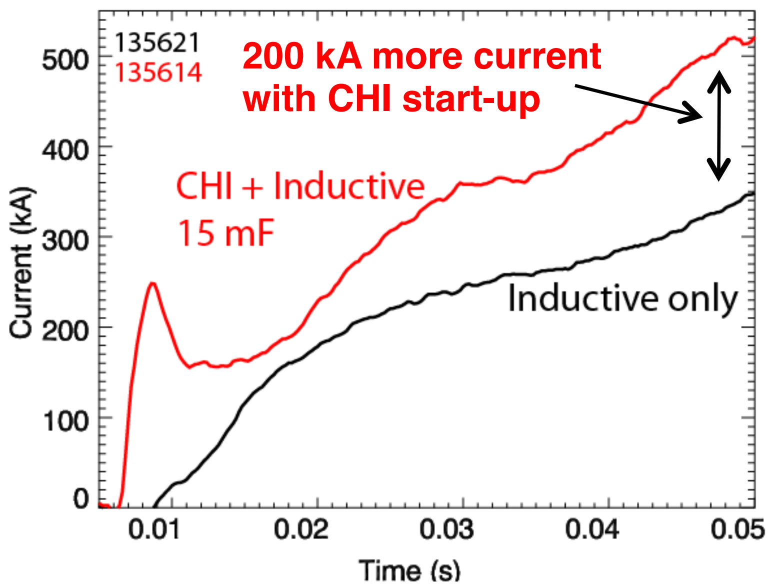


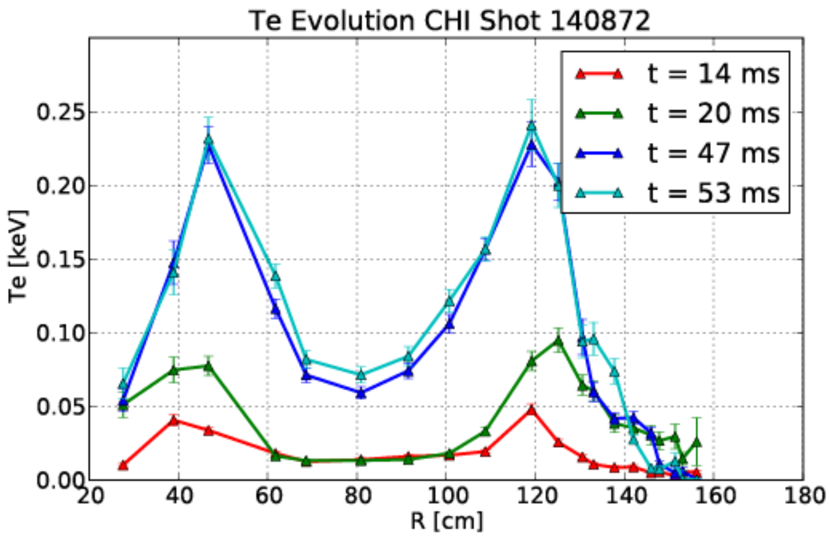
Higher flux expansion (increased div wetted area)
Higher divertor volume (increased div. losses)

- Maintained "snowflake"-like configuration for 100-600 ms
- Maintained H-mode confinement with core carbon reduction by 50%

V. Soukhanovskii EXD/P3-32

Coaxial Helicity Injection (CHI) has Produced Substantial Flux Savings and Scales Favorably with Size and B_T





Enabling capabilities

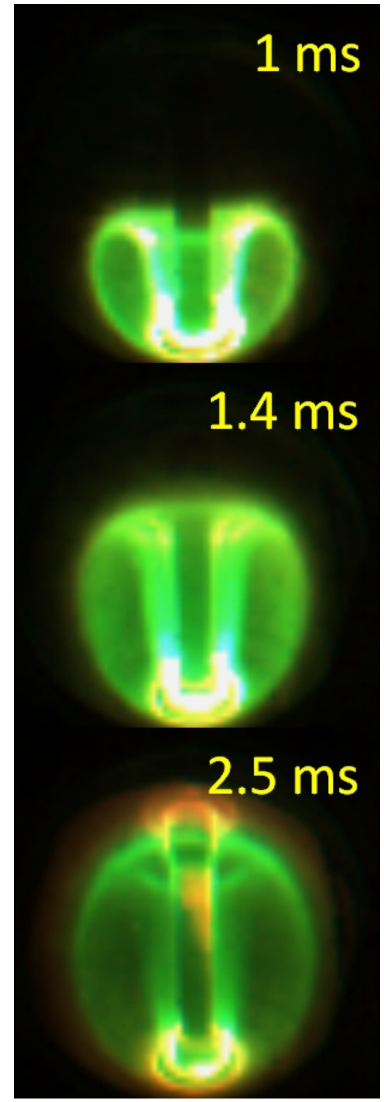
- Elimination of arcs in absorber region
- Conditioning of lower divertor

Generated 1MA using 40% less flux than induction-only case

- Hollow T_e maintained during ramp
- Low internal inductance ($l_i \approx 0.35$)
- High elongation
- Suitable startup for advanced scenarios

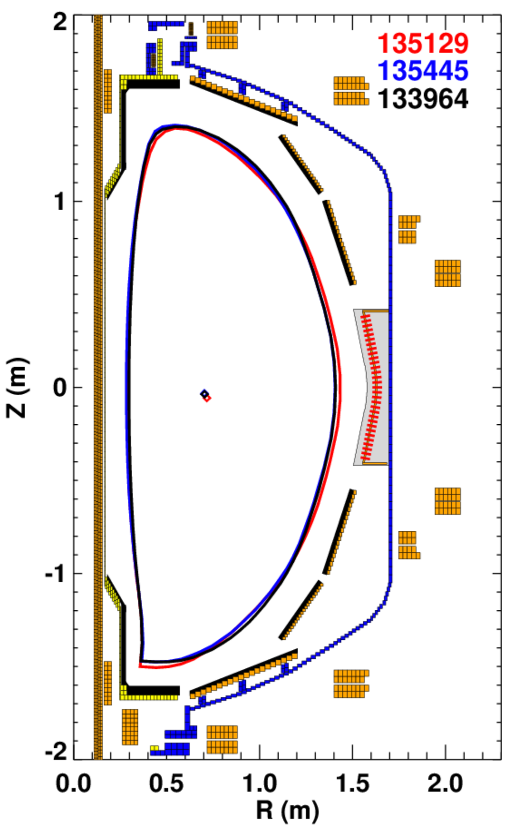
B.A. Nelson EXW/P2-8

Time after CHI starts



Developed Sustained High-Elongation Configurations Over a Range of Currents and Fields

High-β_T	***Long Pulse***	***High-β_P***
q*=2.8	***q*=3.9***	***q*=4.7***
B_T=0.44 T	***B_T=0.38 T***	***B_T=0.48 T***
I_P=1100 kA	***I_P=700 kA***	***I_P=700 kA***



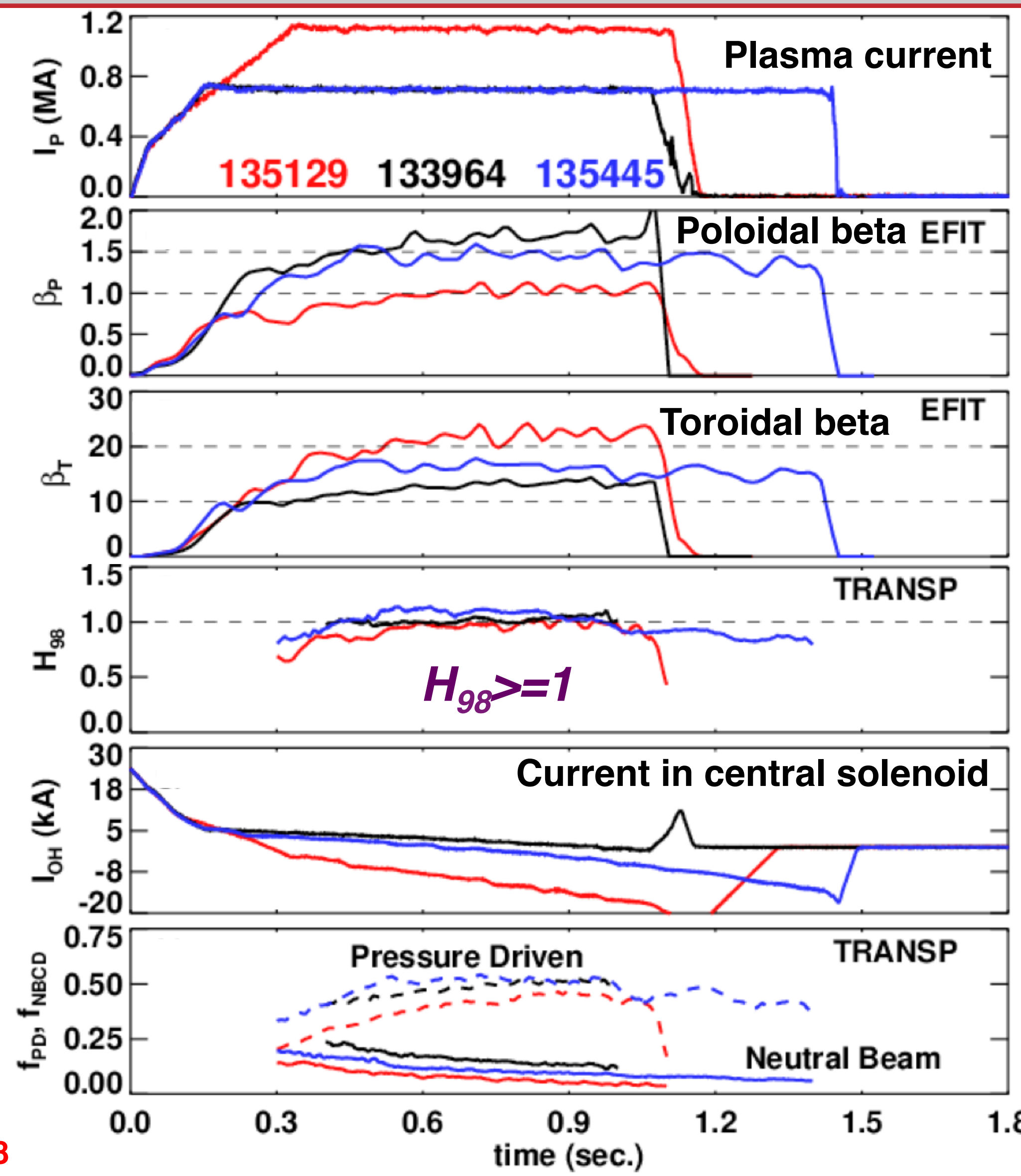
$$q^* = \frac{\varepsilon\left(1+\kappa^2\right)\pi a B_{T0}}{\mu_0 I_P}$$

κ~2.6-2.7

δ~0.8

Double Null

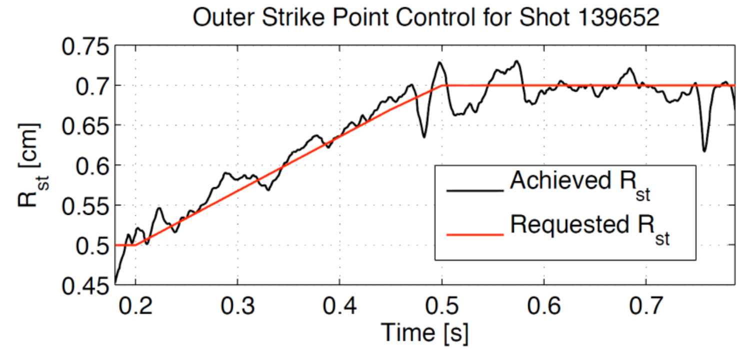
S. Gerhardt EXS/P2-8



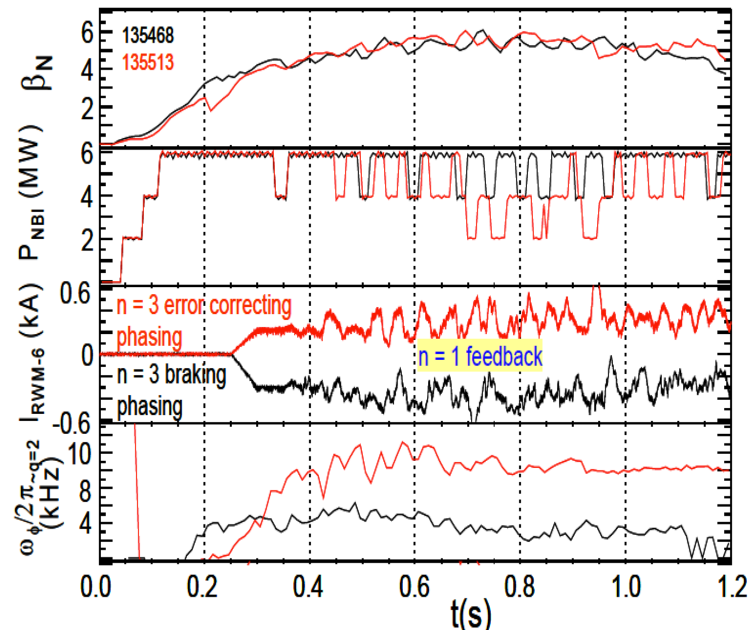
NSTX is Developing Shape and Stability Control Techniques Relevant to ITER and Next-Step STs

- New inner & outer strike-point control
  - In-line system ID for single-shot optimal gain identification
  - Used for LLD experiments and snowflake divertor control
- Feedback-based n=1 error field correction and RWM control.
  - Routine with PID controller + first state-space RWM controller in high-β tokamak.
- Control β_N using NBI power modulation
- Combined controllers result in improved performance.
  - Example: simultaneous RWM + β_N control w/ different levels of rotation.

Controlled Strike-Point Motion



Simultaneous Control of β_N and n=1 RWMs



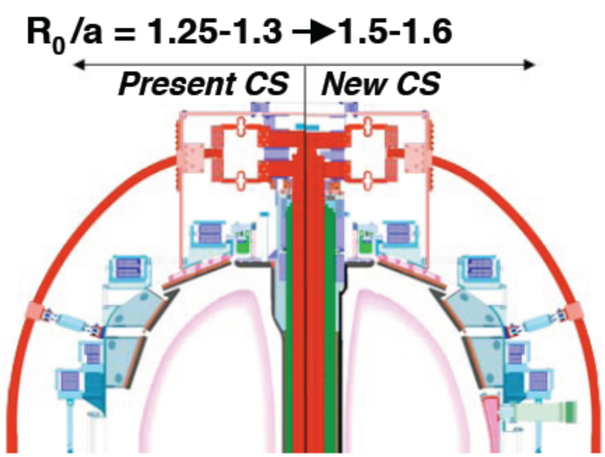
E. Kolemen EXD/P3-18 S. Gerhardt EXS/P2-8 S.A. Sabbagh EXS/5-5

Summary: Considerable Progress Made in NSTX Towards Sustained Operation in Support of STs and ITER

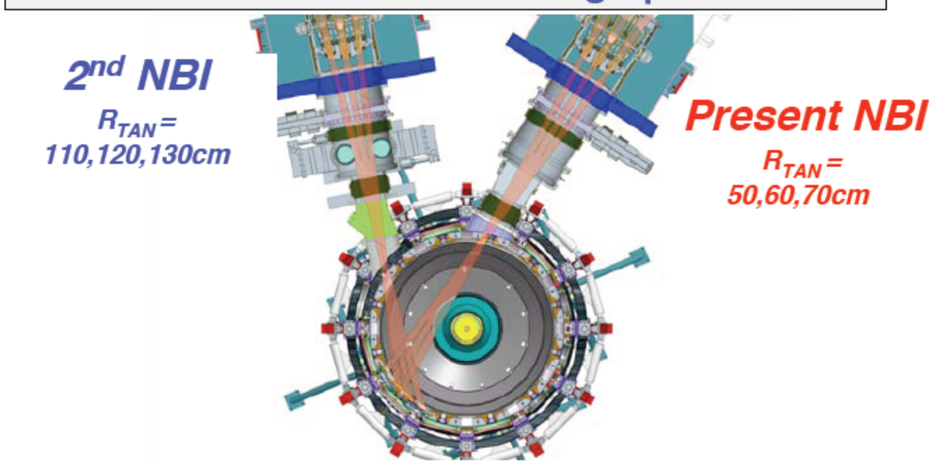
- Developing understanding of transport and stability changes from Li
- Strongly supporting ITER (LH threshold, ELM triggering, SOL width scaling)
- Using CHI to initiate ST plasmas, advanced control to sustain ST plasmas

FUTURE: Major upgrade of NSTX to occur 2012-2014 with 2 elements:

New center stack for 1T, 2MA, 5s to access reduced ν^*, 100% non-inductive ST plasmas



2nd NBI with larger $R_{tangency}$ for sustained and controllable 100% NICD + high β at low ν^*



NSTX related papers at this conference

Talks

Tuesday

"Modification of edge profiles, edge transport and ELM stability with lithium in NSTX " **R. Maingi** **EXD/2-2**

"L-H Threshold Studies on NSTX" **H. Meyer / S. Kaye** **EXC/2-3R**

Wednesday

"Simulation of Energetic Particle-driven Alfven Instabilities with Source and Sink" **G. Fu** **THW/2-2Rb**

Thursday

"Resistive wall mode stabilization and plasma rotation damping considerations for maintaining high beta plasmas in NSTX" **S. Sabbagh** **EXS/5-5**

Friday

"Optimization of Density and Radiated Power Evolution Control using Magnetic ELM Pace-making in NSTX " **J.M. Canik** **EXC/8-1**

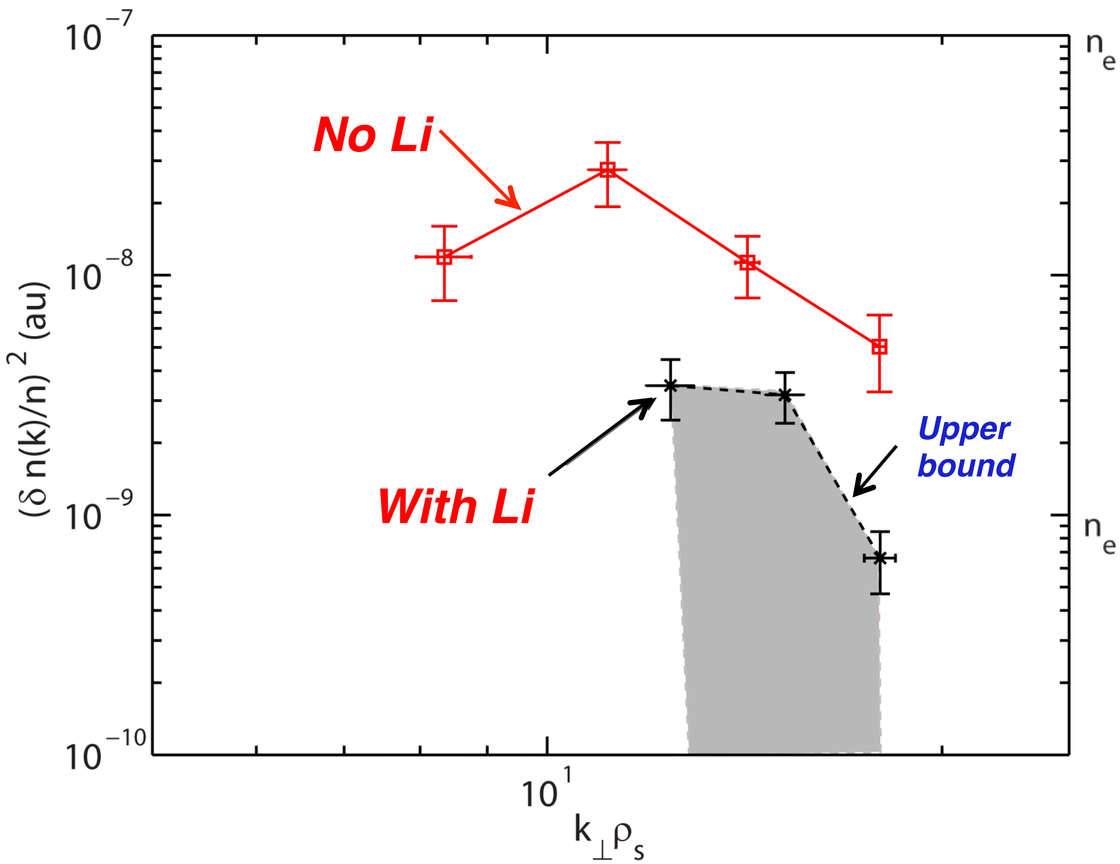
"Prospects for pilot plants based on the tokamak, ST and stellarator" **J. Menard** **FTP/2-2**

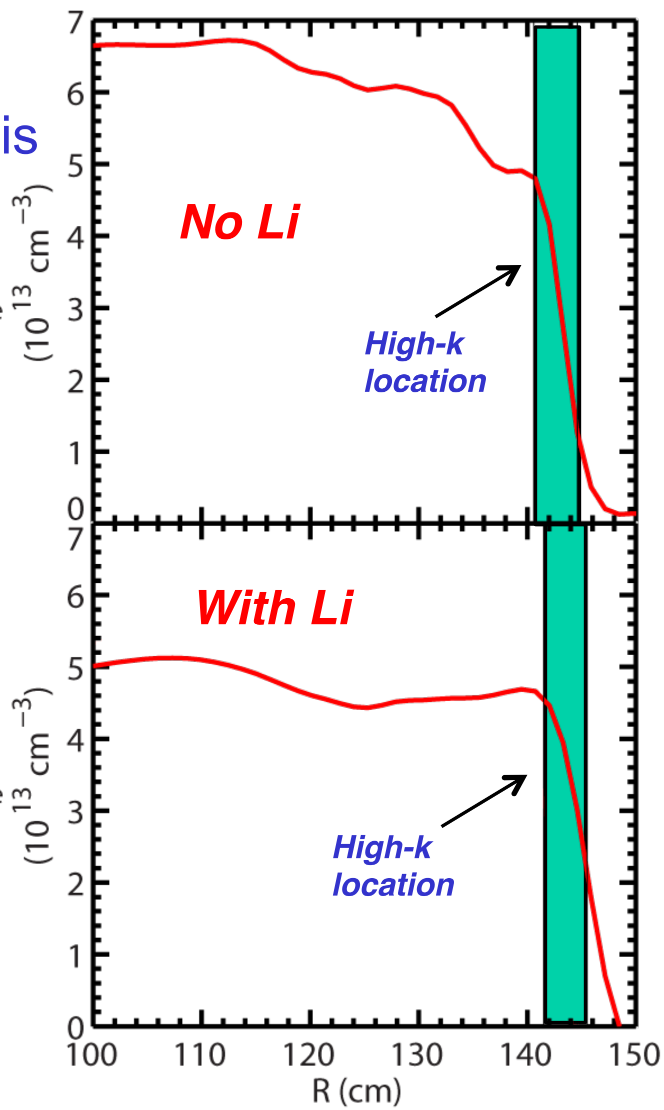
"Lithium Technologies and Their Impact on Boundary Control, Core Plasma Performance, and Operations" **H.W. Kugel** **FTP/3-6R**

Tuesday	**POSTERS**	
Advanced scenarios	S.P. Gerhardt	EXS/P2-8
Solenoid-free startup	B.A. Nelson	EXWP2-8
Internal Modes	J.A. Breslau	THS/P2-3
Wednesday		
L-H Threshold	S. Kaye	EXC/2-3Rb
Particle Transport	L. Delgado-Aparicio	EXC/P4-4
Divertor profile mod.	J-W. Ahn	EXD/P3-1
Divertor heat flux	T.K. Gray	EXD/P3-13
Plasma Control	E. Kolemen	EXD/P3-18
ELM pedestal	A. Sontag	EXD/P3-31
Snowflake divertor	V. Soukhanovskii	EXD/P3-32
H-Mode formation	K.C. Lee	THC/P3-4
Gyro kinetic simul.	S. Ethier	THC/P4-08
Transport	W.X. Wang	THC/P4-30
Thursday		
NTMs	R. Buttery	EXS/P5-3
3D Error Fields	J-K. Park	EXS/P5-12
Lithium Technology	H.W. Kugel	FTP/3-6Ra
Friday		
GAE	E. Fredrickson	EXW/P7-06
HHFW physics	B.P. LeBlanc	EXW/P7-12
TAE avalanches	M. Podesta	EXW/P7-23

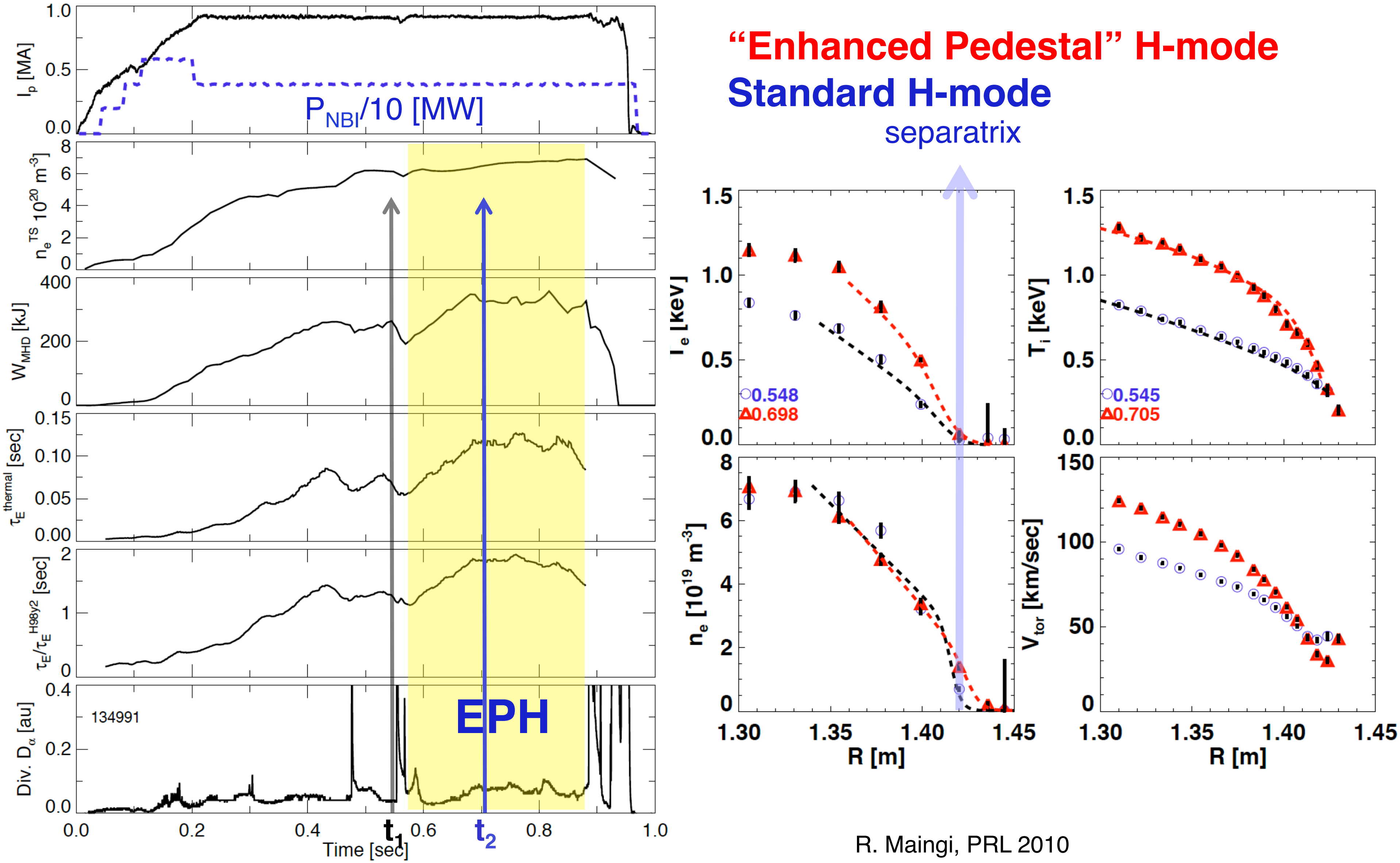
Electron Gyro-scale Turbulence in Edge Reduced with Lithium

- k spectra of normalized density fluctuations
- Reduction of high-k turbulence power is observed in the pedestal region as Lithium is added.





New high confinement regime with HH98y2 ≤ 1.8 observed in NSTX



R. Maingi, PRL 2010