NSTX

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NSTX FY2009 Q3 Program Update

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NSTX Program / Project Director

For the NSTX Research Team

PPPL

July 15, 2009

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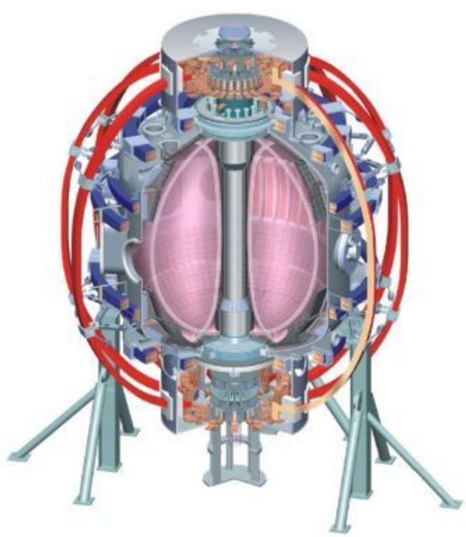

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IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

Outline

- Progress toward FY09 research milestones
  - 12 of 16 run-weeks completed
- Additional research highlights & ITER support
- Plans for remainder of FY09 run
- Summary

Synopses of NSTX FY2009 Research Milestones

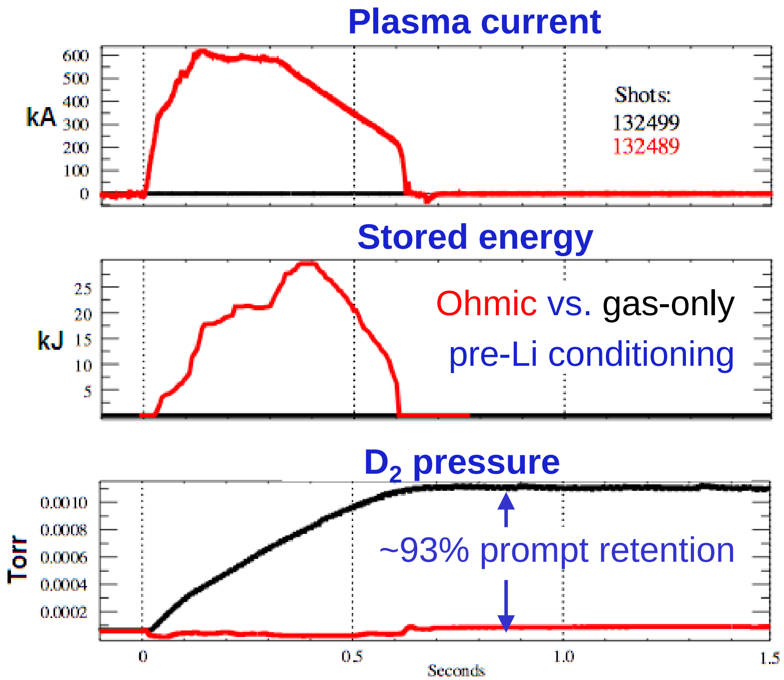
- DOE Joint milestone: *"Conduct experiments on major fusion facilities to develop understanding of particle control and hydrogenic fuel retention in tokamaks"*
  - *…identify the fundamental processes governing particle balance by systematically investigating a combination of divertor geometries, particle exhaust capabilities, and wall materials.*
  - *…NSTX is pursuing the use of lithium surfaces in the divertor…*

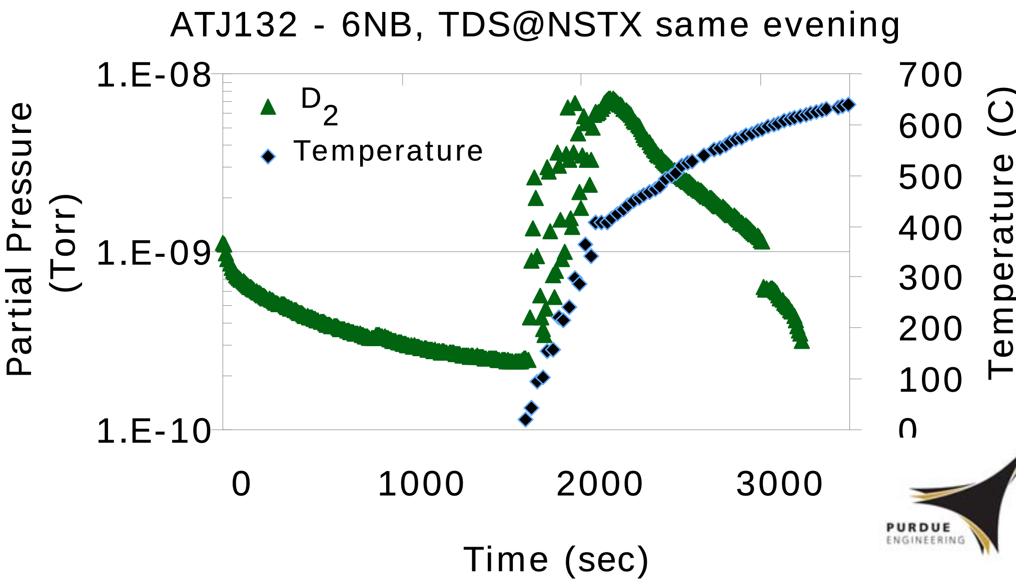
- **R(09-1) Understand RWM stabilization and control vs. rotation**
- **R(09-2) Study how j(r) is modified by super-Alfvénic ion driven modes**
- **R(09-3) Perform high-elongation wall-stabilized plasma operation**

Joint Milestone

NSTX contributing to milestone on hydrogenic retention – important for understanding T retention in ITER

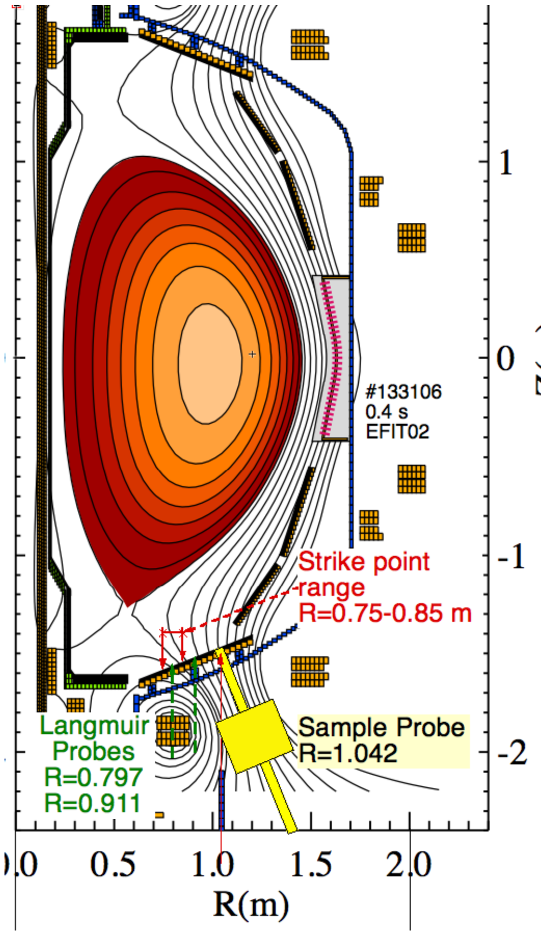
- Gas balance measurements show high (~90%) prompt retention values
  - Retention decreases due to post-shot out-gassing.
- Also studying impact of Lithium coatings on retention for C PFCs
- Performing thermal desorption spectroscopy analysis of samples of ATJ graphite, Si, Pd that were exposed to plasmas





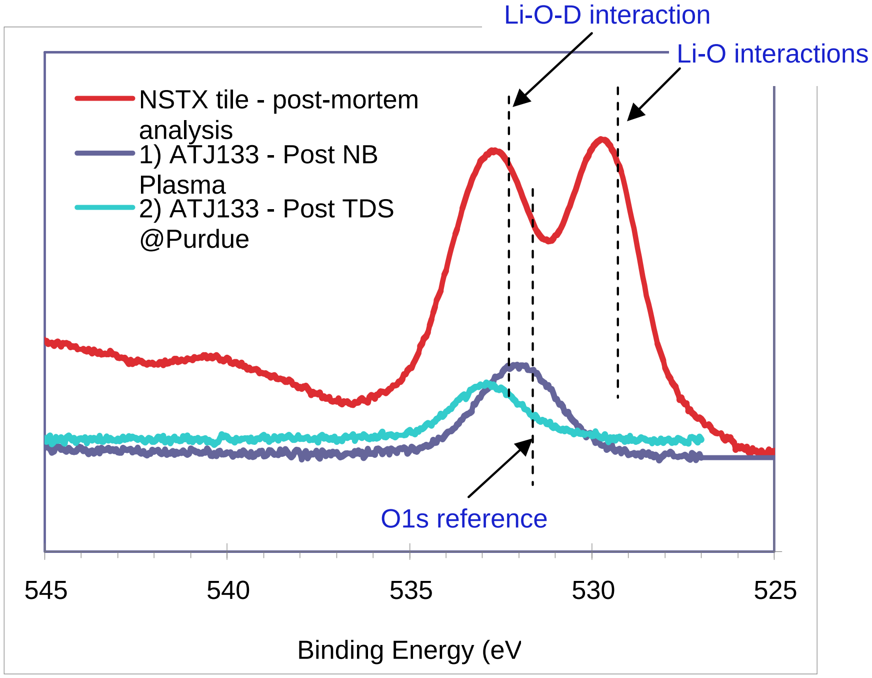
Recently installed sample probe enabling post-shot analysis of surface chemistry during normal and lithiumized operation

Discharge magnetic geometry with sample probe location



Sample probe with ATJ graphite, Si and Pd samples

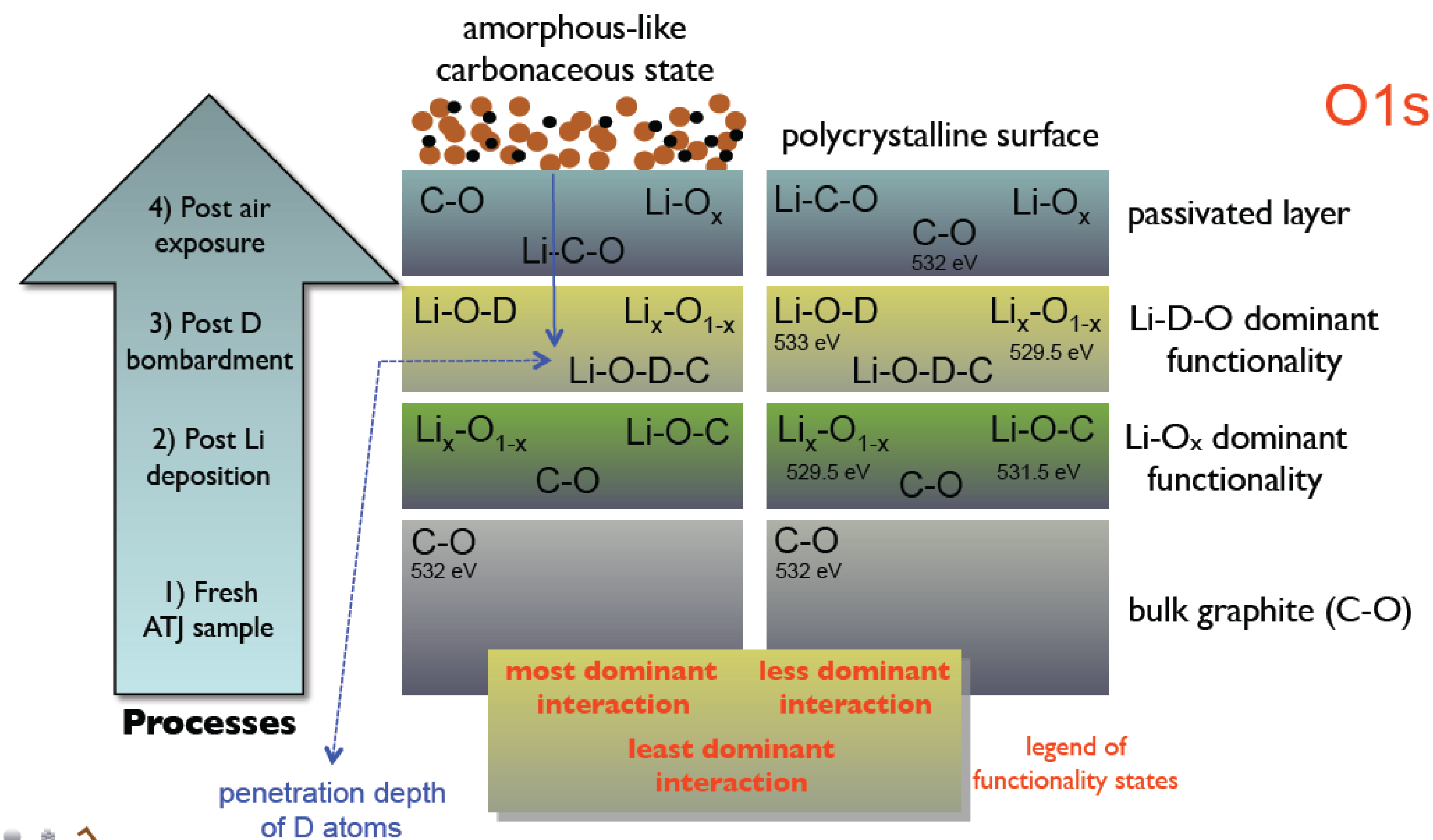
Oxygen 1s spectrum of X-ray photo-electron spectroscopy (XPS) at Purdue Univ. of ATJ graphite sample exposed to 6 NSTX neutral beam heated lithium conditioned plasmas.



PURDUE ENGINEERING

Preliminary analysis: Presence of C and O plays major role in dictating how D is bound in the lithiated graphite system

"Current" qualitative hypothesis of functionality states of lithiated-graphite surfaces in NSTX

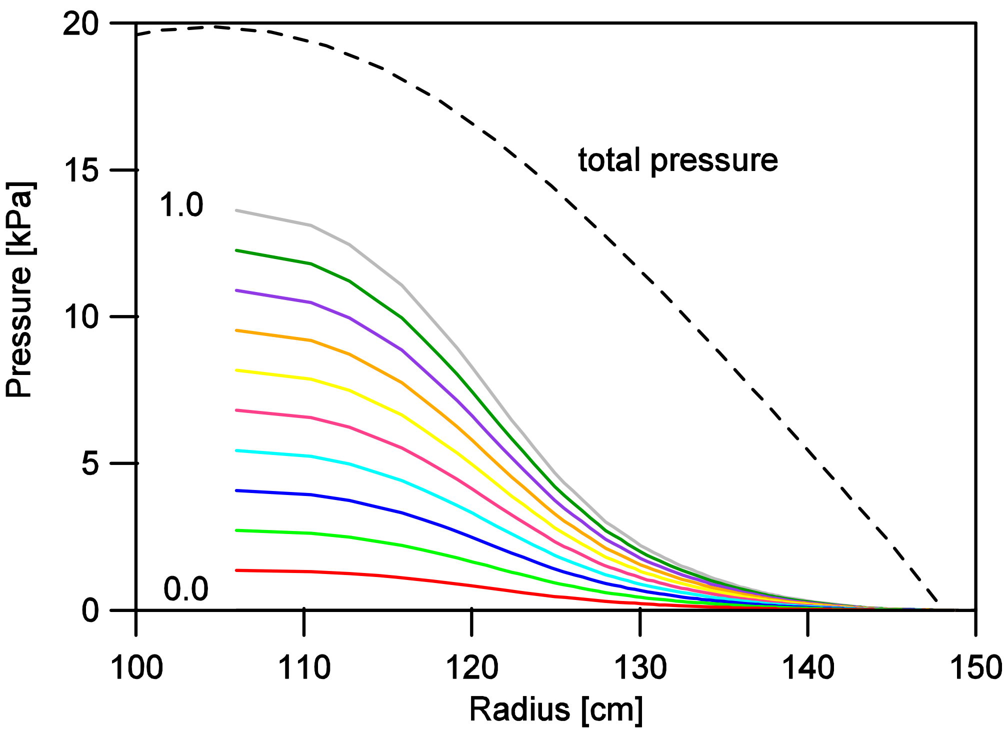


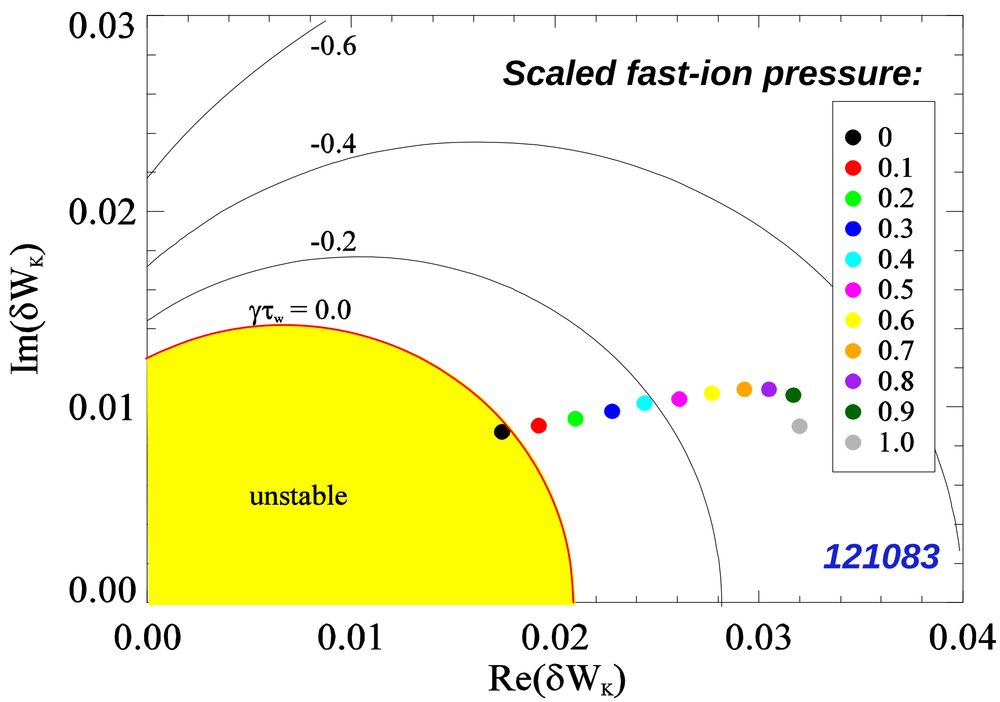
RSSEL

PURDUE ENGINEERING

FY2009 RWM stability experiments are focusing on understanding influence of NBI fast-ions on RWM stability

- Kinetic extensions of MHD energy principle for RWM indicates fast-ions are predicted to significantly modify RWM stability





$$\gamma_K \tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_b + \delta W_K}$$

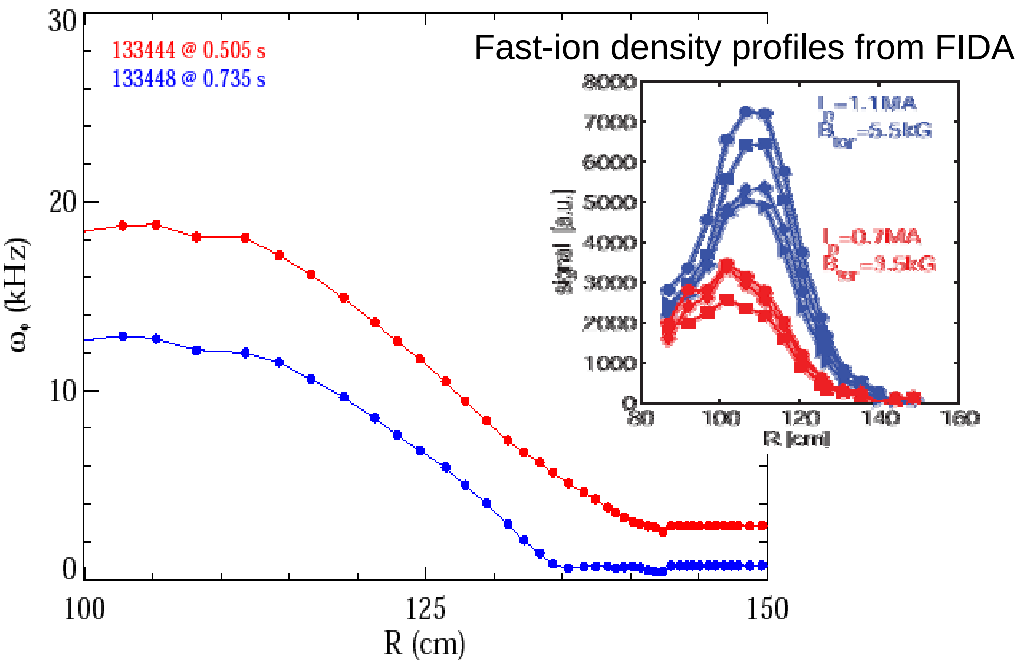
Expect $\delta W_{K\text{-fast}} \propto p_{fast}$ (approximately)

Columbia University in the City of New York   University of Rochester

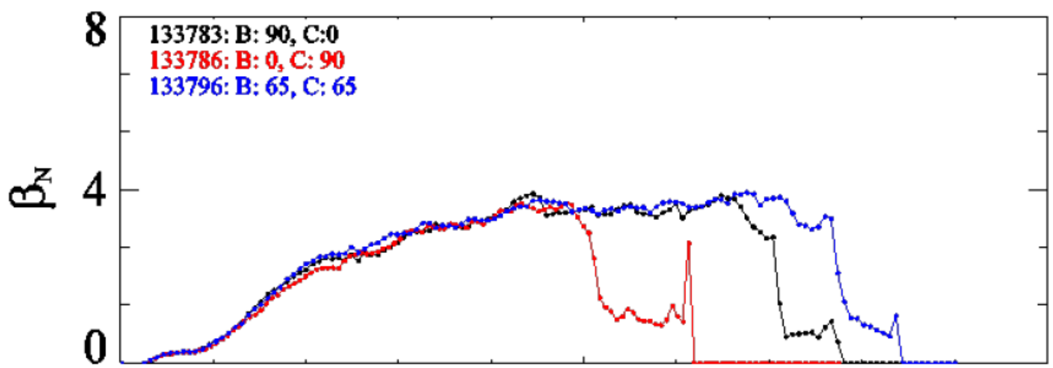
Full RWM stability data-set varying fast-ion density and source-mix obtained and under analysis

- NBI power scan at fixed q indicates lower rotation speed is required to stabilize RWM when fast-ion density is higher
  - Consistent with expectation

Rotation profiles at marginal stability



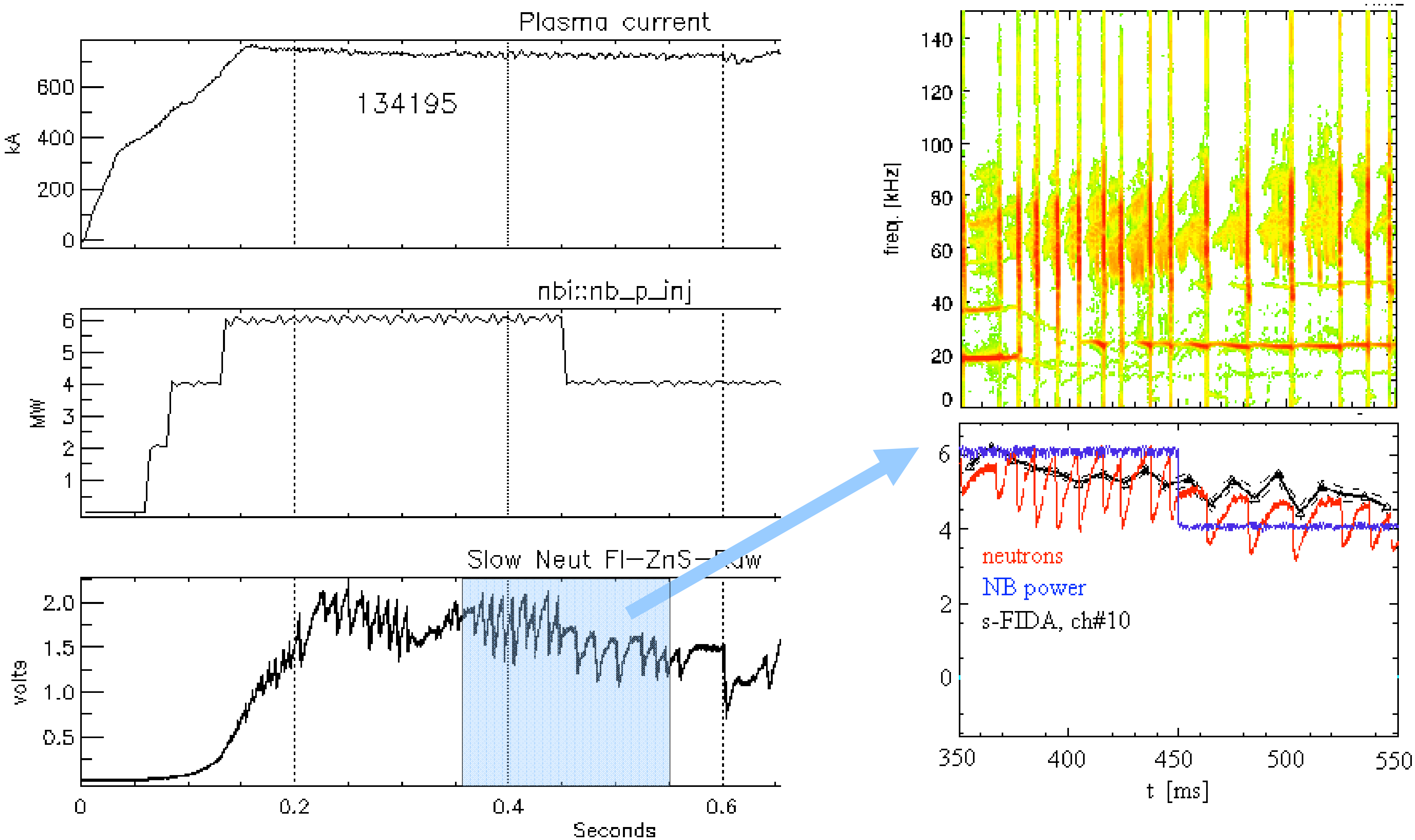
- Mix of NBI sources at fixed power also impacts RWM stability
  - Torque effect? Or fast-ion distribution function effect?



COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

Continuous BAAE/EPM bursts generated during I_P flat-top phase of discharge to assess J(r) profile modifcations

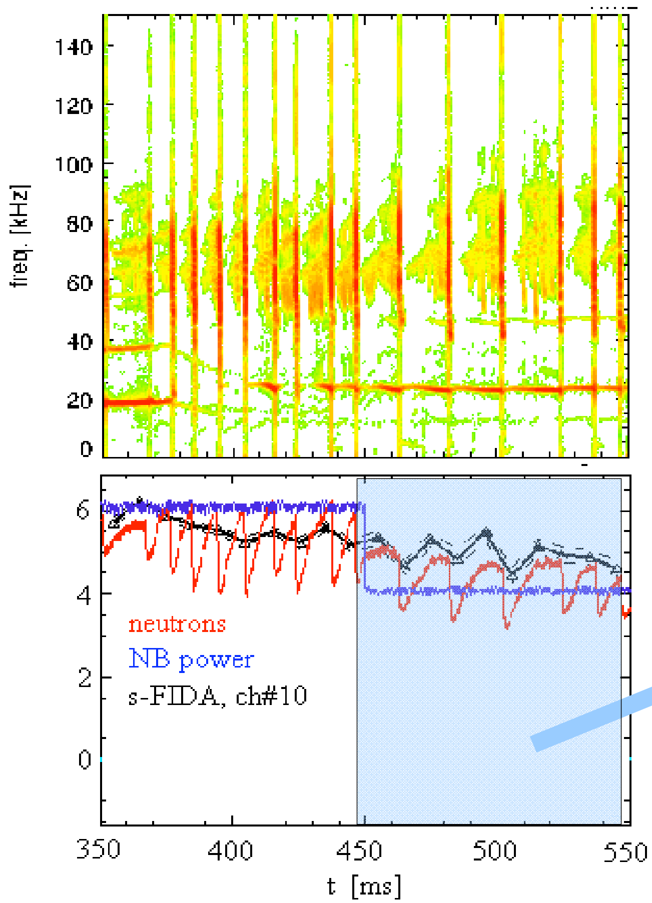
- **FIDA data shows drop in confined fast ion density coincident with bursts and fast decrease in neutron rate**

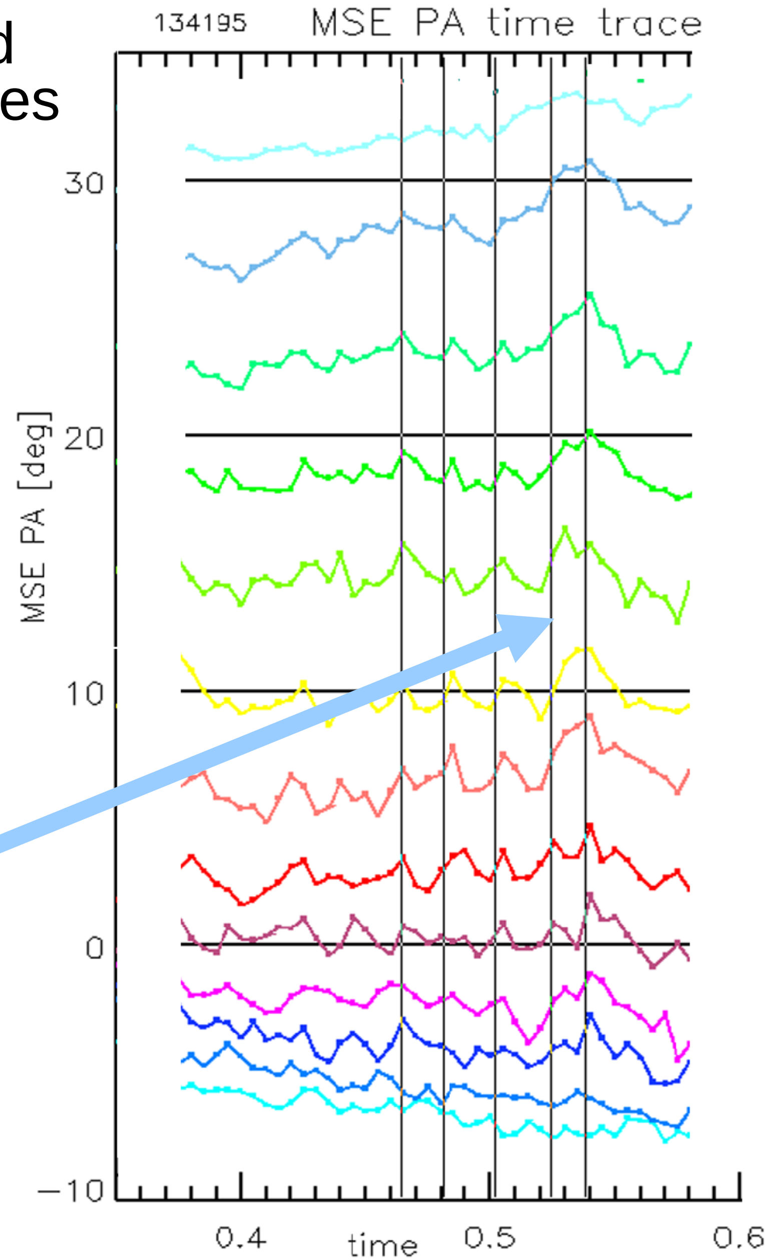


UCLA
UCIRVINE

Variations in NBI power modify BAAE/EPM burst frequency, enable time-resolved measurement of MSE → J(r,t) (in progress)

- Later bursts at lower P_{NBI} are separated widely enough in time to resolve changes in MSE signal before and after bursts





- sFLIP diagnostic indicates fast ion loss occurs within 100μs (not shown)

NOVA PHOTONICS
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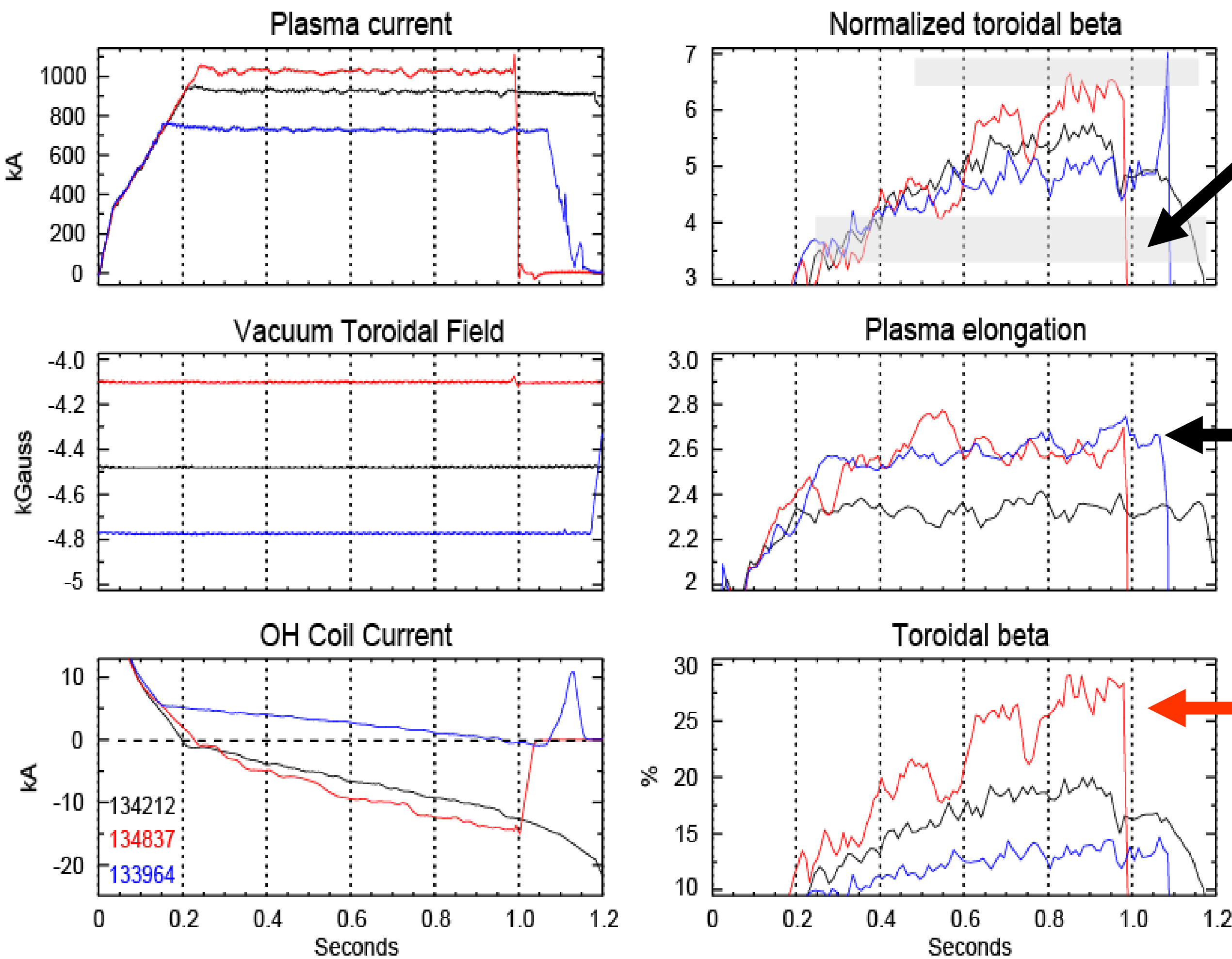
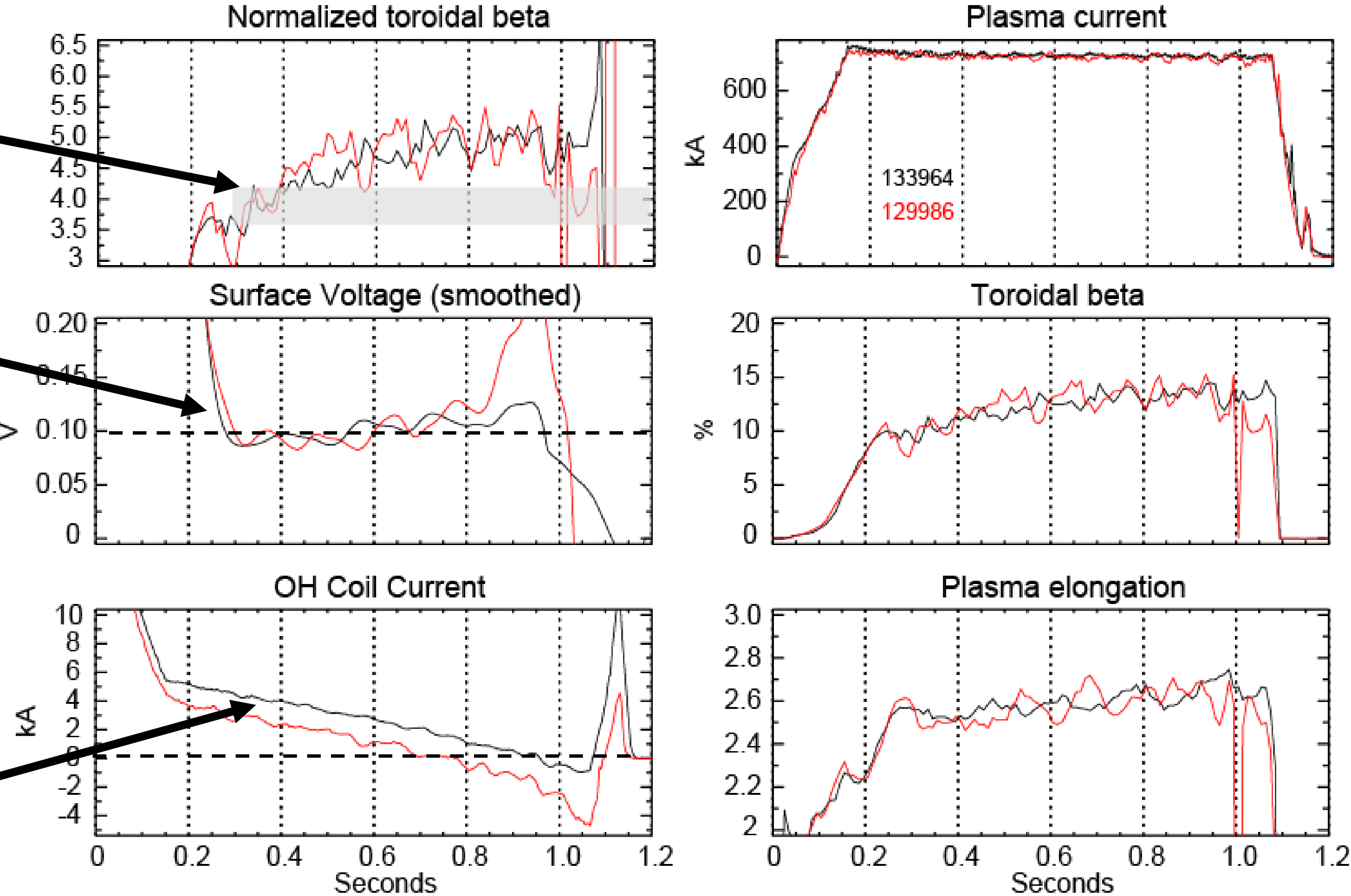
Sustained-high elongation and wall-stabilized operation has been extended from β_T = 15-20% to 20-30%



- Above n=1 no-wall limit for ~$2\tau_{CR}$
  - β_N increased ×1.2 at reduced TF, fixed power
- High elongation κ =2.6 sustained
- β up to factor of 2 higher (β_T = 25-30%)
  - I_P / aB_T increased ×1.7 at higher I_P, reduced TF
  - Pressure, density, confinement increase throughout shot

Sustained-high elongation + wall-stabilization has produced sustained low loop voltage, record low OH consumption

- Above n=1 no-wall limit for ~$2\tau_{CR}$
- Low V_{SURF} ~ 0.1V sustained for ~$2\tau_{CR}$
  - Record for NSTX
  - Increased outer gap reduced P_{RAD}
- Lowest OH flux consumption so far
  - Projects to ~2-3s pulse duration
  - ~1s limit set by TF coil heating (4.8kG)



- Non-inductive fraction = 60-65%
- But, models under-predict total I_P by ~20%
  - → Non-inductive fraction could be as high as 75%
  - Investigating data uncertainties: n_e, Z_{eff}, MSE, …

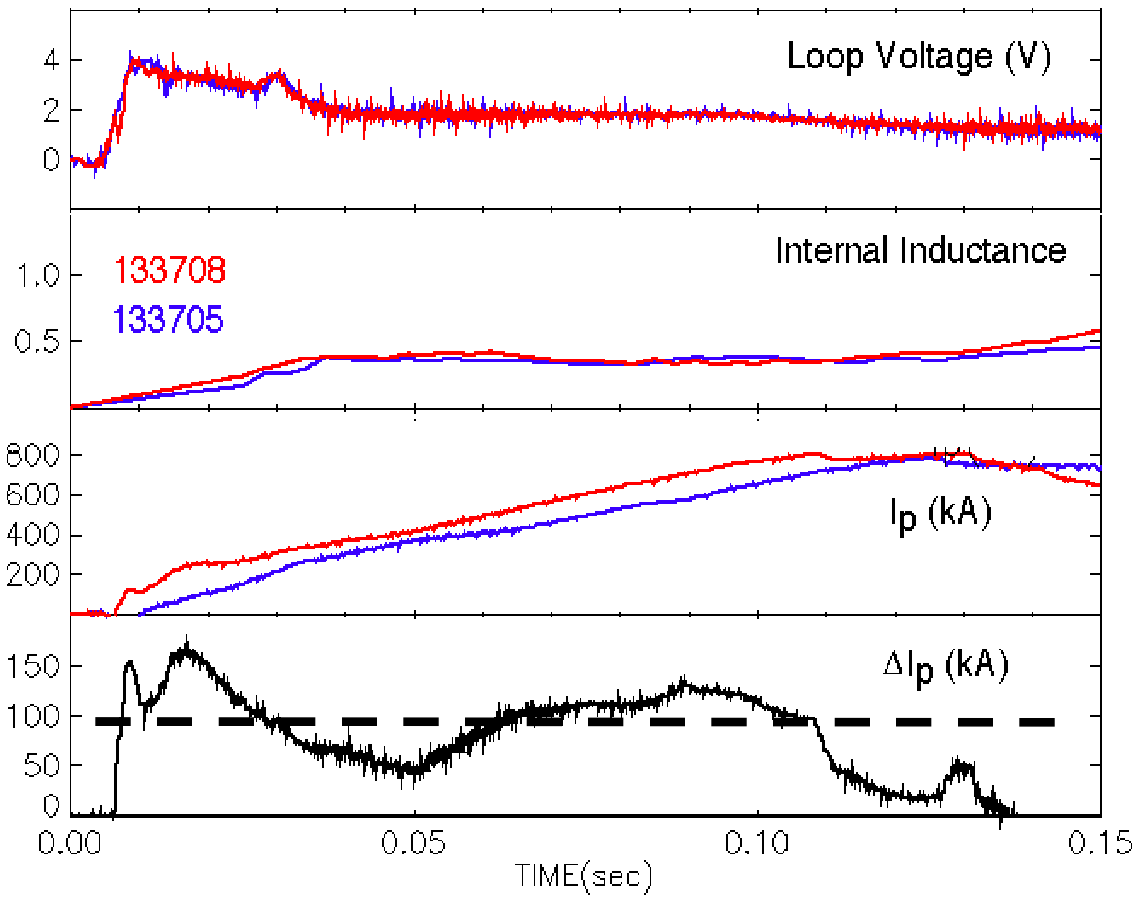
Additional research highlights

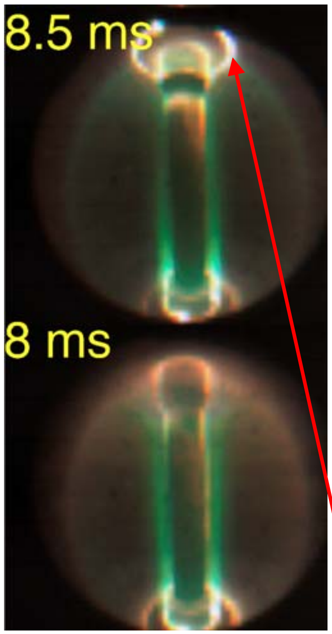
- **Solenoid-free start-up**
- **L-H threshold scaling, confinement scaling vs. β***
- **Particle control with Li, ELM stability/triggering***
- **Interactions between HHFW and NBI fast-ions**

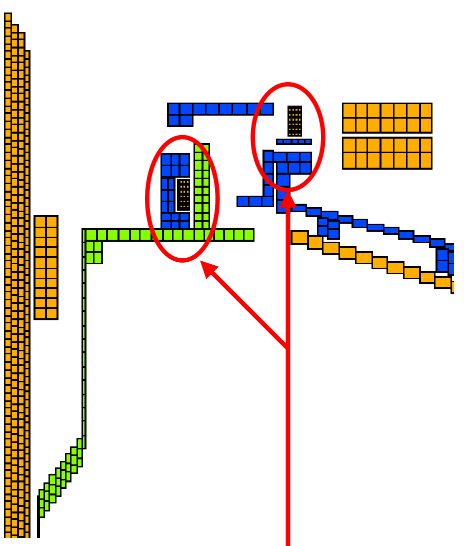
ITER high-priority research

Coaxial Helicity Injection (CHI) coupled to induction and NBI-heated H-mode with ~100kA sustained current savings

- 2× higher current savings compared to 2008, and sustained
- Result of reduction of divertor impurities and radiation

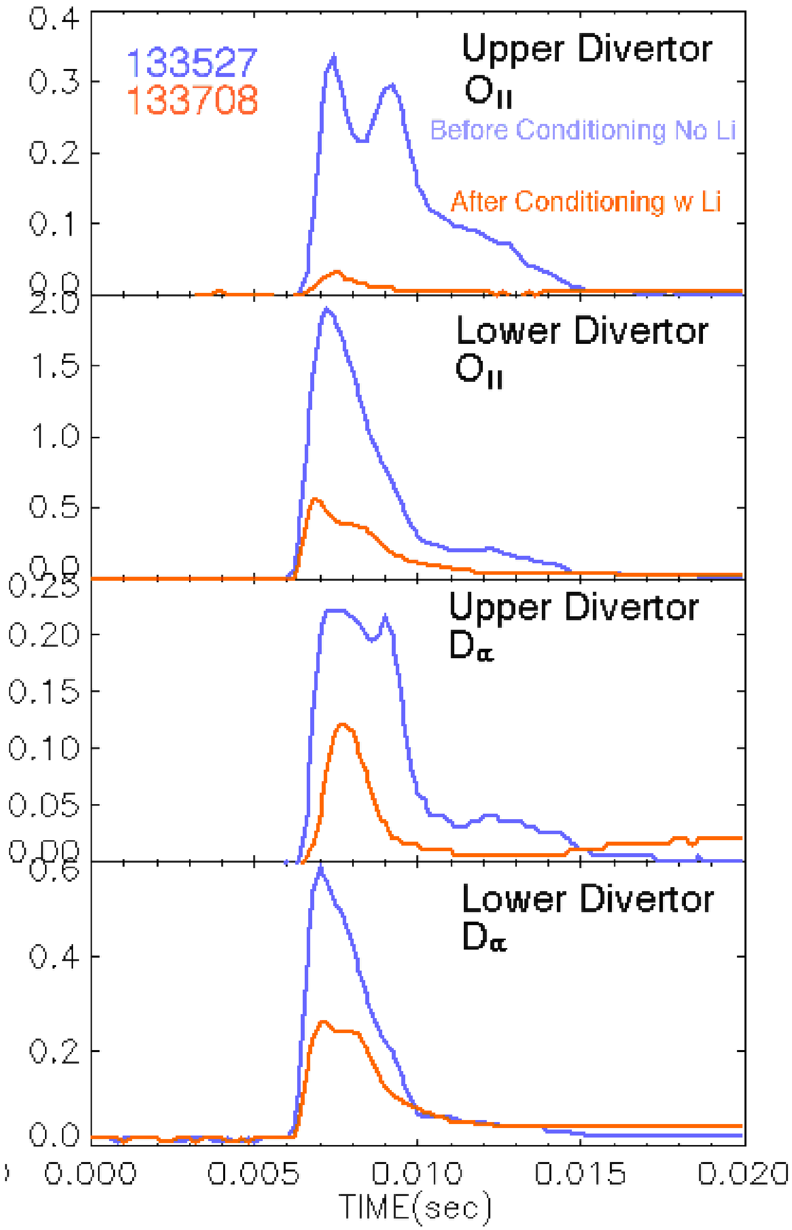






- **ΔI_P limited by absorber arcs**
- **Field nulling coils to be tested this run**

Extensive conditioning campaign improved divertor conditions for successful coupling of CHI to induction



- Upper divertor conditioned with NBI-heated USN plasmas
- Lower divertor conditioned with sustained CHI plasma
  - Rectifier power supply, 1kV, 0.4s
  - Several MW
- Li evaporation used to reduce oxygen, increase D pumping
- CHI voltage duration reduced:
  - Reduces energy striking divertor
  - Reduces absorber arcs

Additional research highlights

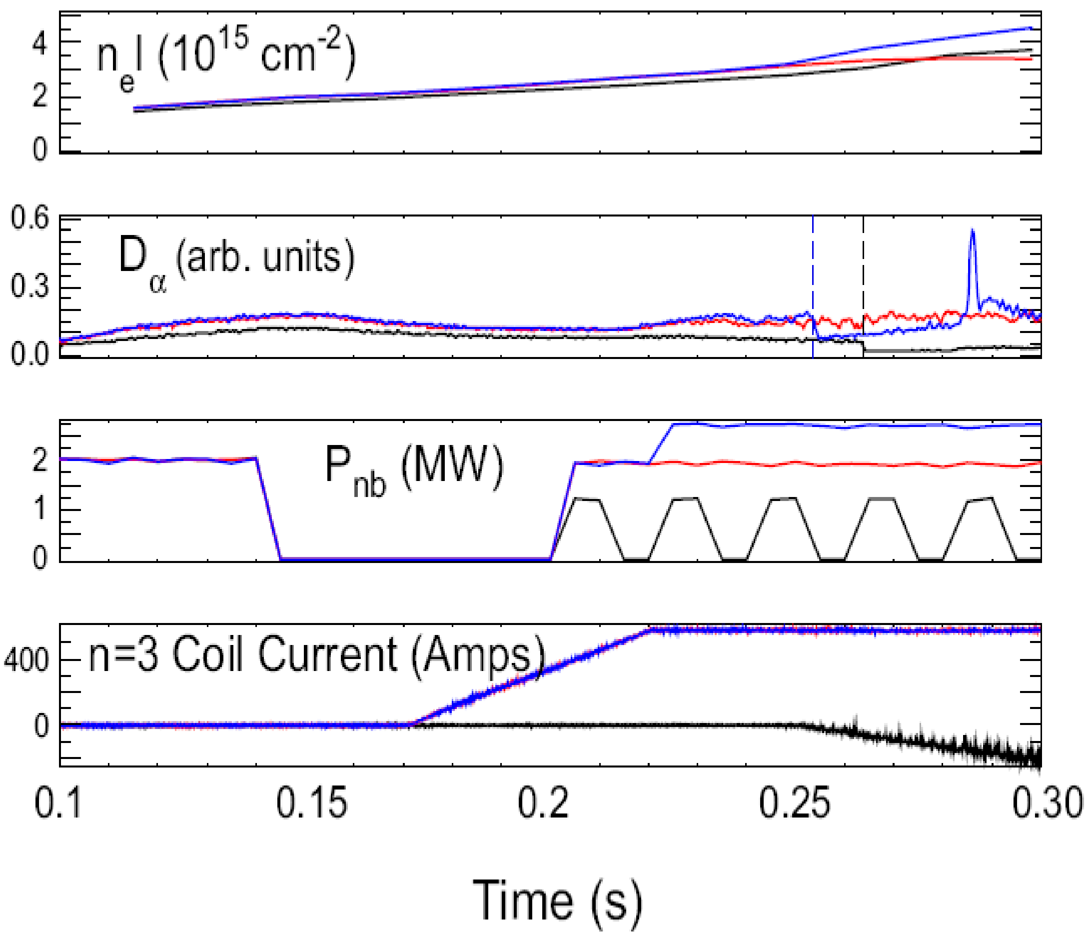
- Solenoid-free start-up
- **L-H threshold scaling, confinement scaling vs. β***
- Particle control with Li, ELM stability/triggering*
- Interactions between HHFW and NBI fast-ions

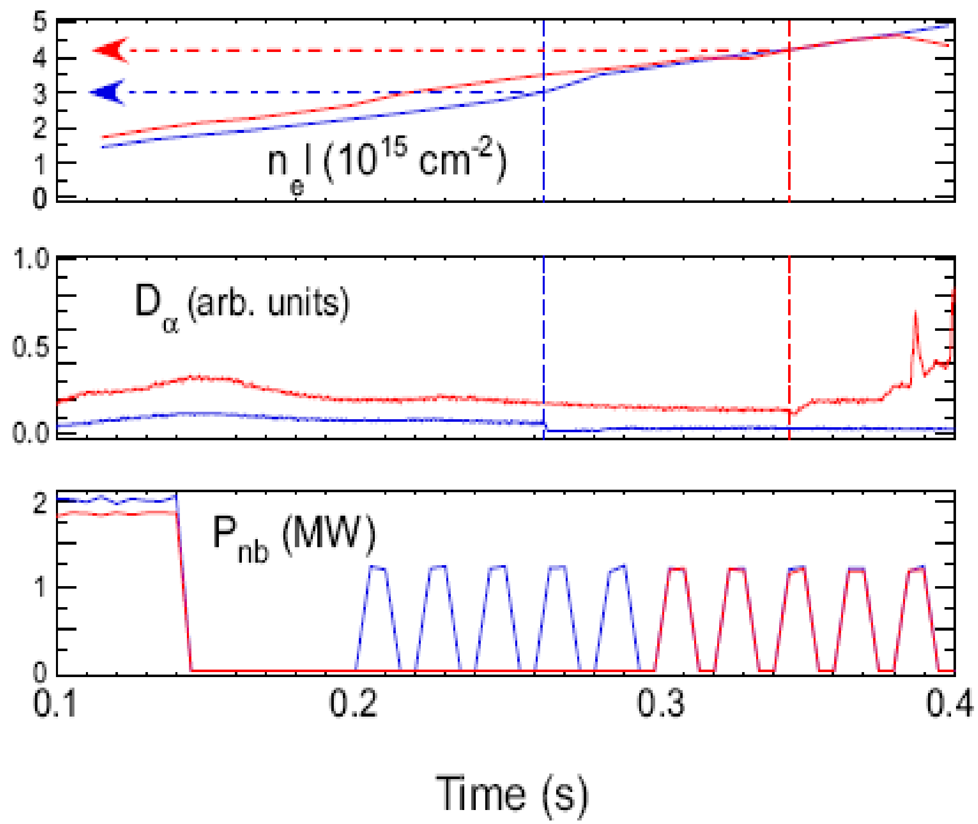
ITER high-priority research

Magnetic braking strongly influences L-H threshold, while the density dependence is weaker for n_e range tested

- $P_{L\text{-}H}$ increases from P_{NBI} ~0.6MW to 2.5MW for 2-4× higher n=3 (including intrinsic n=3 EF)

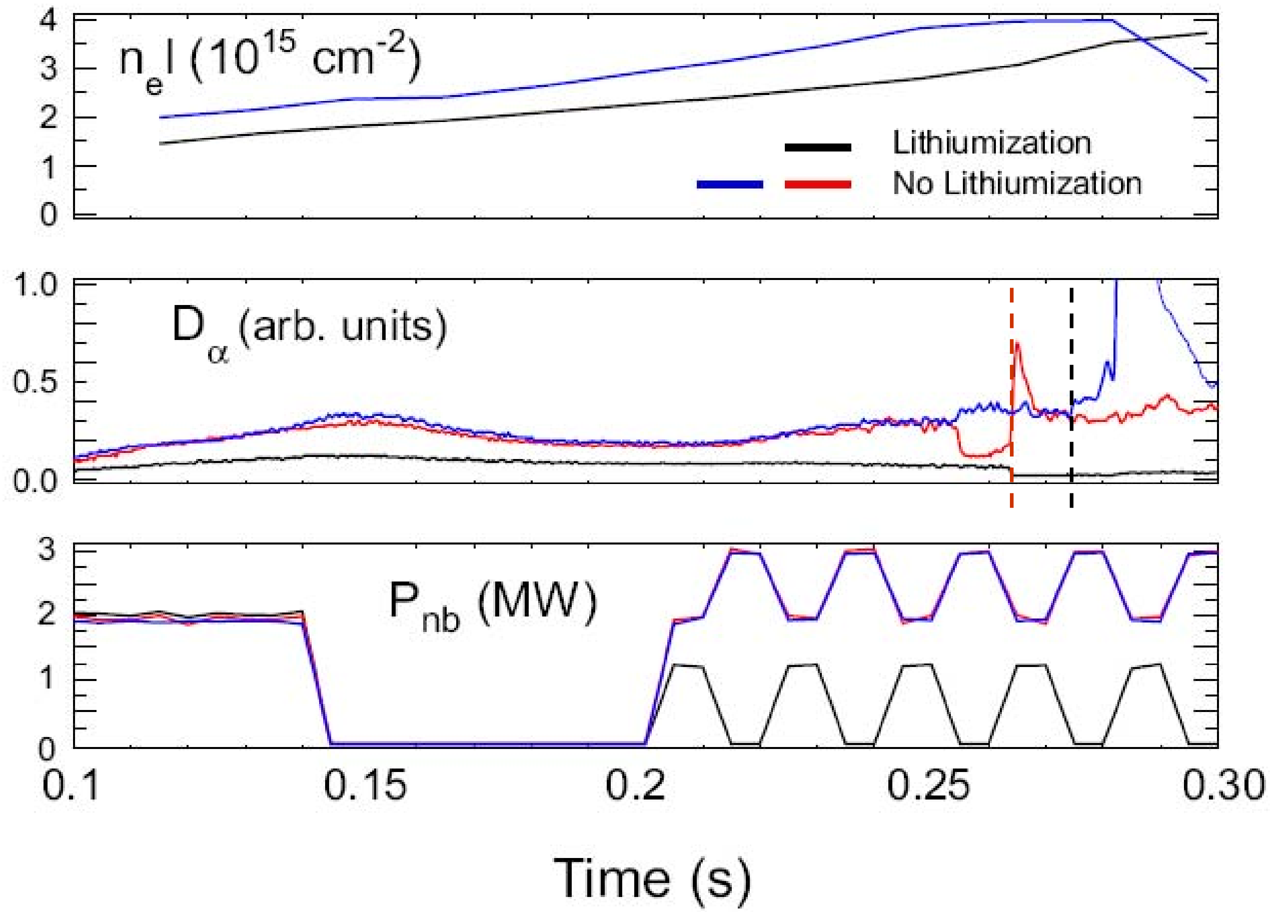
- $P_{L\text{-}H}$ similar for reference n_e and 50% higher n_e





Lithium conditioning greatly reduces L-H threshold power

P_{LH} ~ 2.5 MW NBI without Li evaporation
< 0.6 MW NBI with Li evaporation



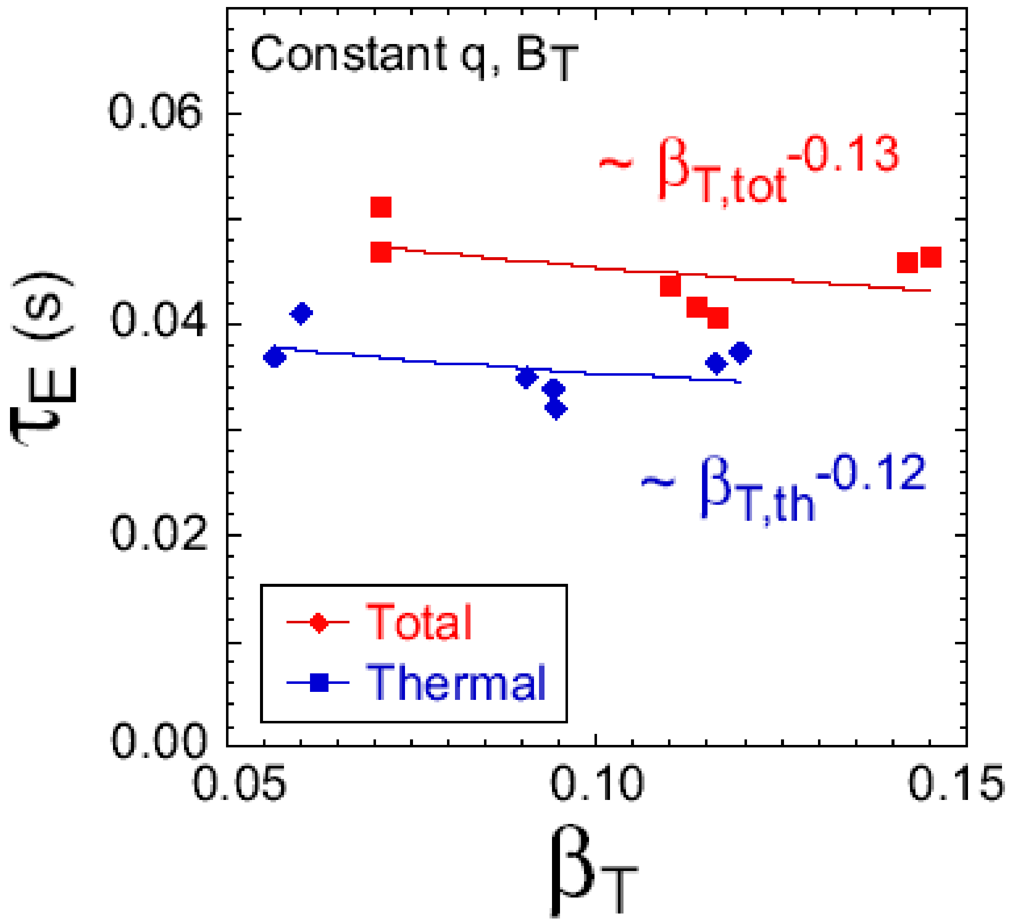
Also observe rapid increase in P_{LH} = 2 → 4MW for I_P = 0.7 → 1MA (not shown)

Plasma shaping observed to have weak effect on β scaling of energy confinement time

Confinement remains weakly dependent on β

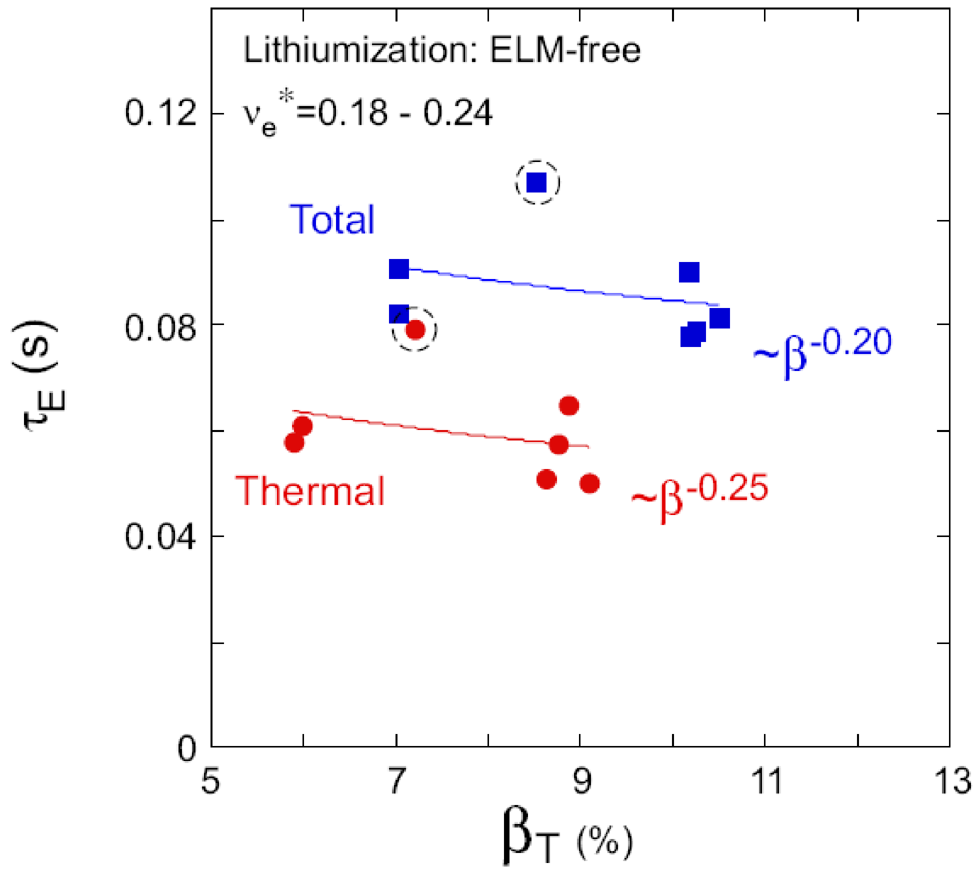
$\kappa \sim 2.1 \quad \delta \sim 0.65$

$\tau_E \sim \beta^{-0.1\text{-}0.15}$



$\kappa \sim 1.9 \quad \delta \sim 0.50$

$\tau_E \sim \beta^{-0.2\text{-}0.25}$



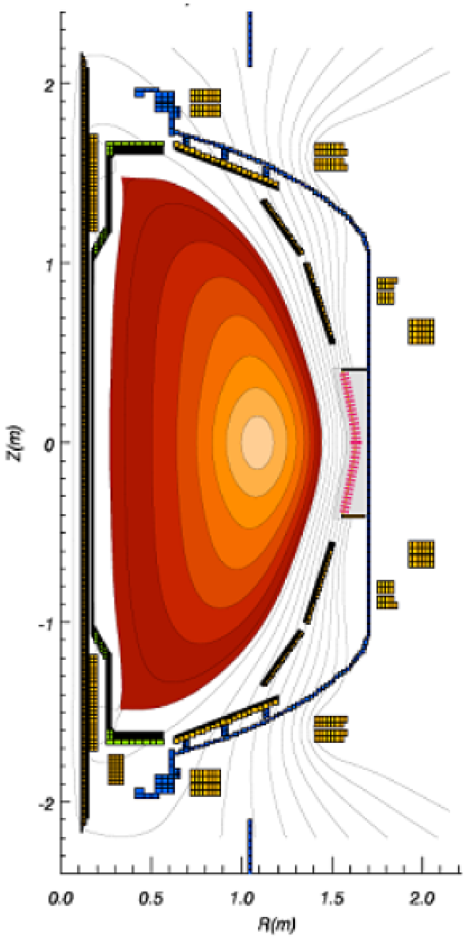
Additional research highlights

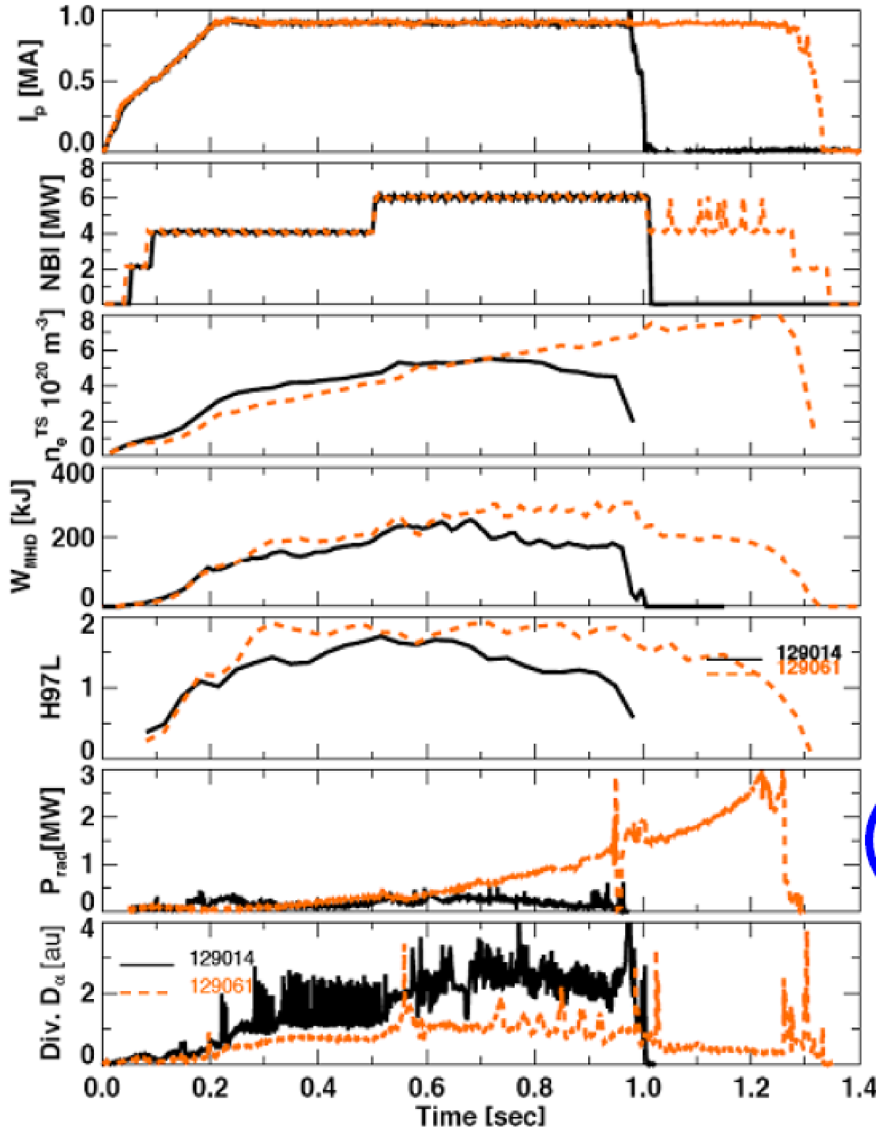
- Solenoid-free start-up
- L-H threshold scaling, confinement scaling vs. β*
- **Particle control with Li, ELM stability/triggering***
- Interactions between HHFW and NBI fast-ions

ITER high-priority research

Lithium wall conditioning improves pulse length, increases τ_E, suppresses ELMs, but shows impurity accumulation

Standard high κ~2.3, δ~0.8 shape



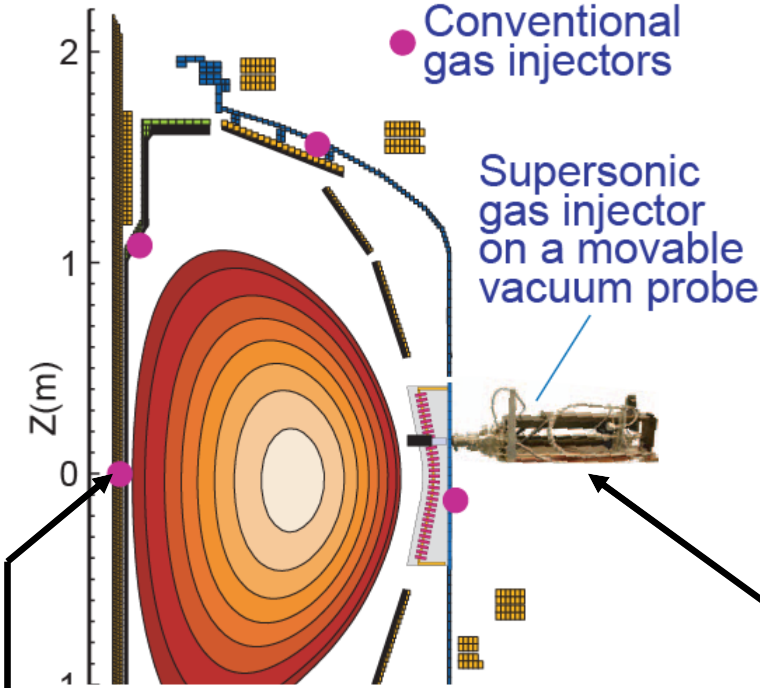


- Pre-Li, Post-Li
- Longer pulse
- Lower n_e early, higher late
- Higher stored energy
- Higher H-factor
- Higher radiated power
- ELM-free, lower recycling

Kugel PSI08

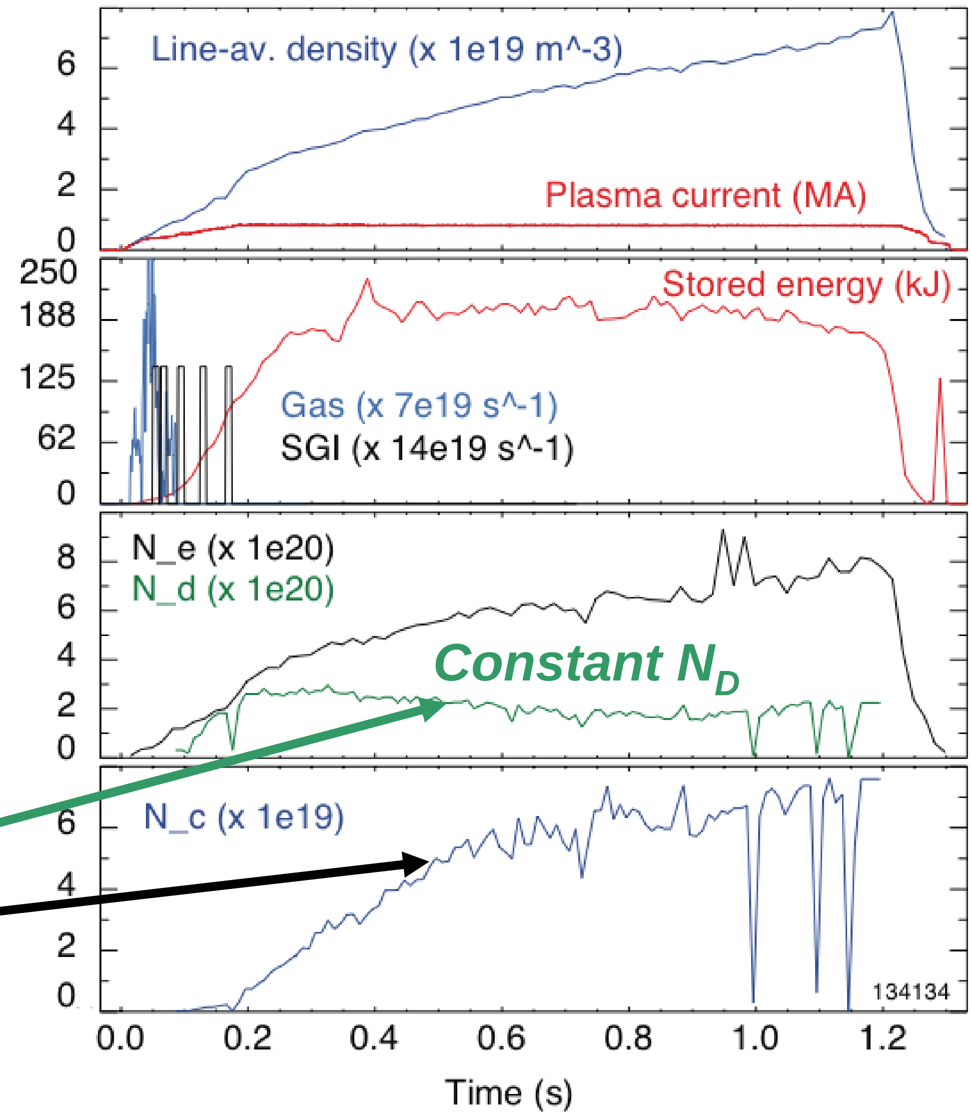
- **Now focusing on main-ion and impurity density control**

Supersonic gas injection (SGI) enables control of D^+ content in LITER ELM-free discharges, but C^{6+} dominates N_e



- Replaced high-field-side (HFS) injection with SGI-only fueling
  - HFS used for H-mode access
  - HFS long tube → slow response
- SGI only → D ion density control
- ***N_e* is rising due to carbon**
  - **C confinement too good…**

LITER at 9 mg/min, ELM-free

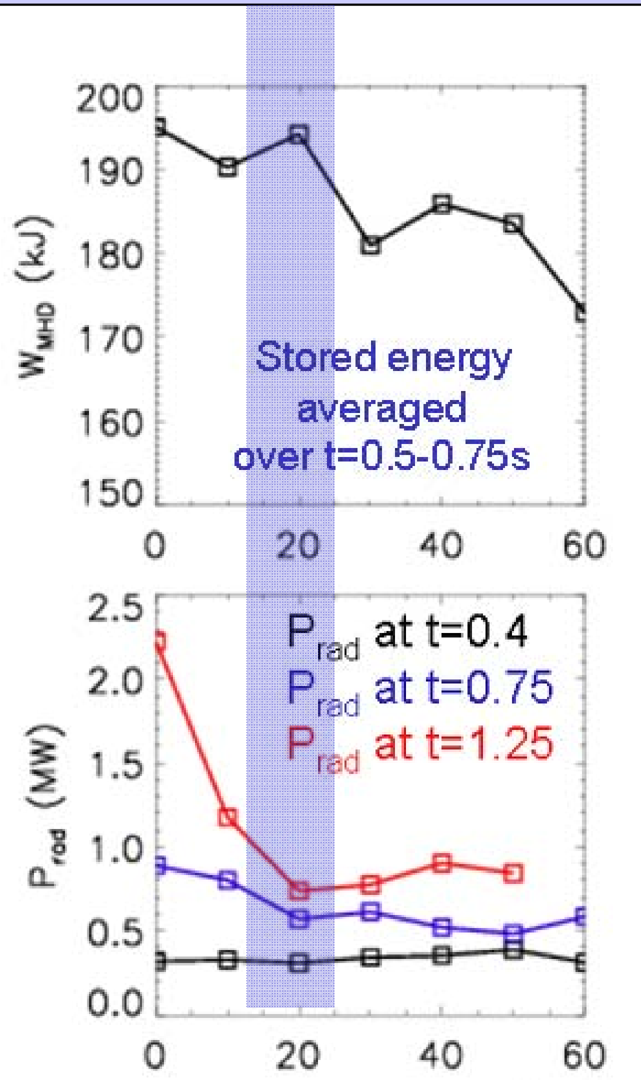


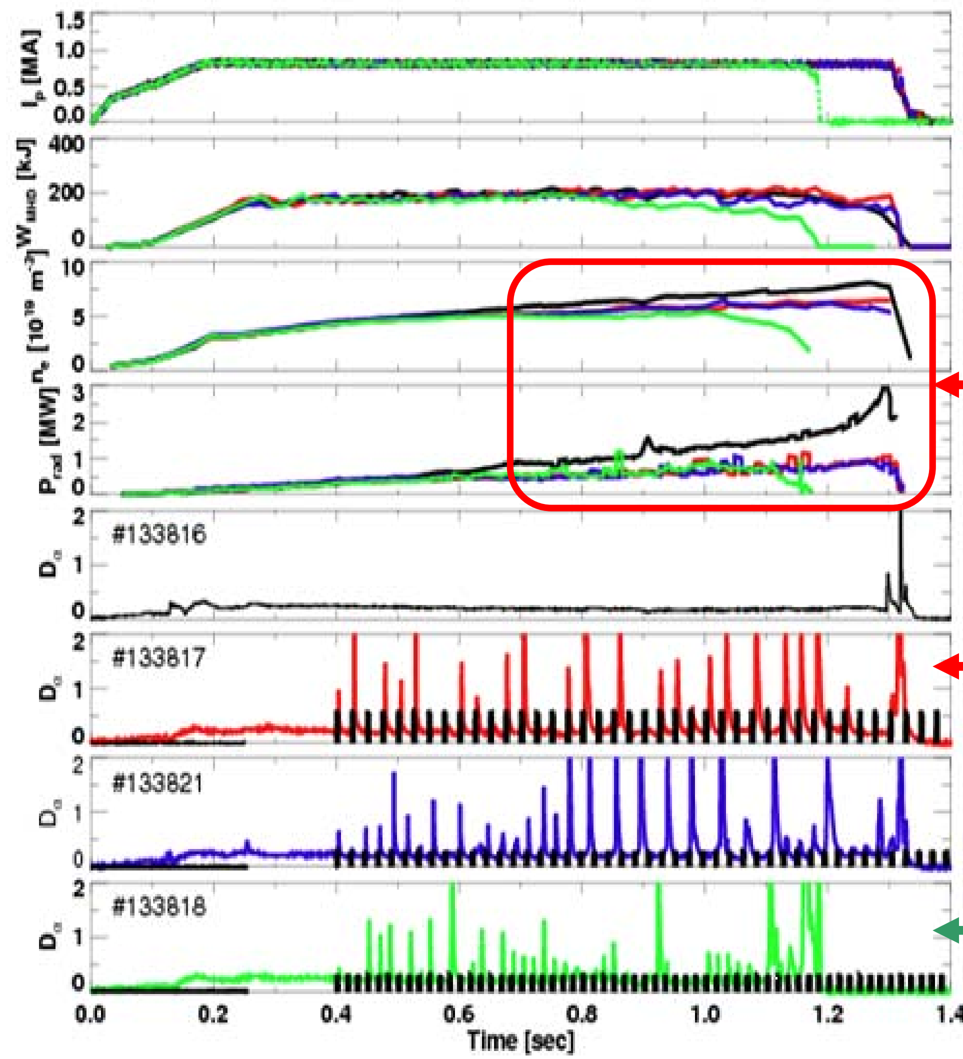
Lawrence Livermore National Laboratory

Oak Ridge National Laboratory

ELM triggering using n=3 perturbations is being optimized to control density and radiation, maintain high confinement

Favorable n=3 amplitude and triggering frequency found





n_e & radiation rise arrested

But ELM size can be large

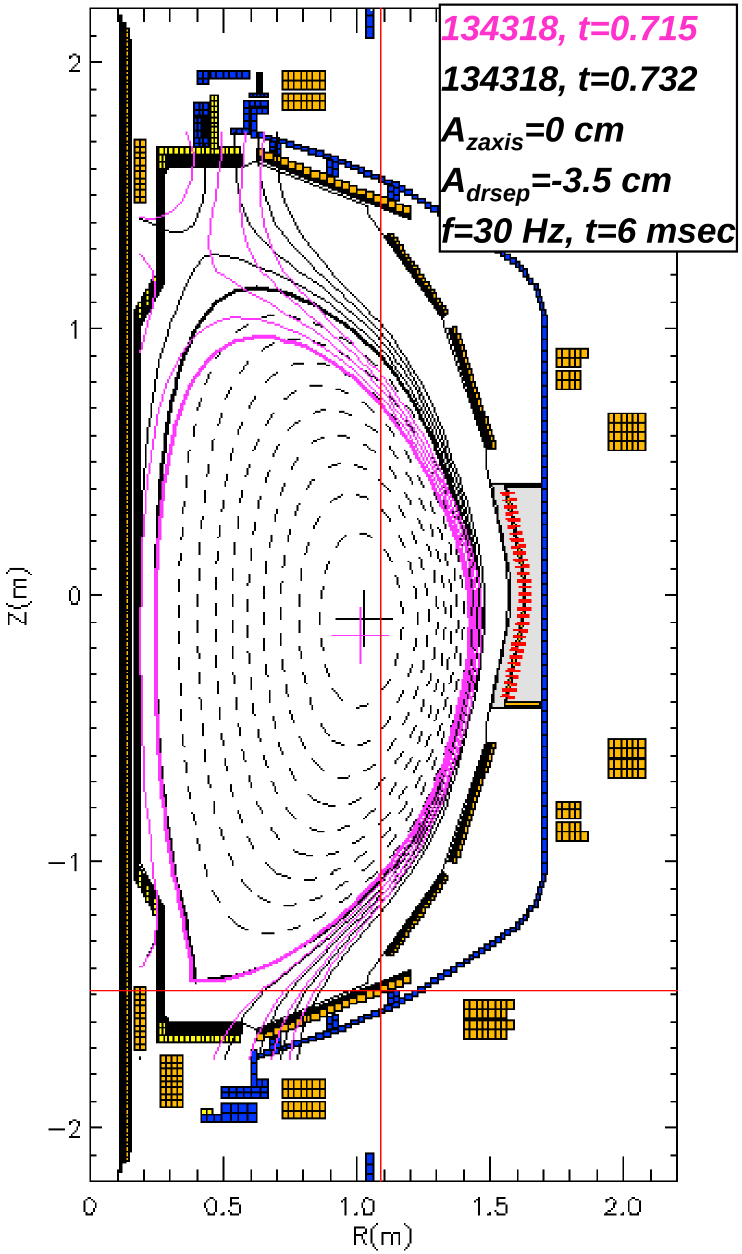
($\Delta W/W_{TOT}$= 10-15%)

Higher $f_{trigger}$ reduces size

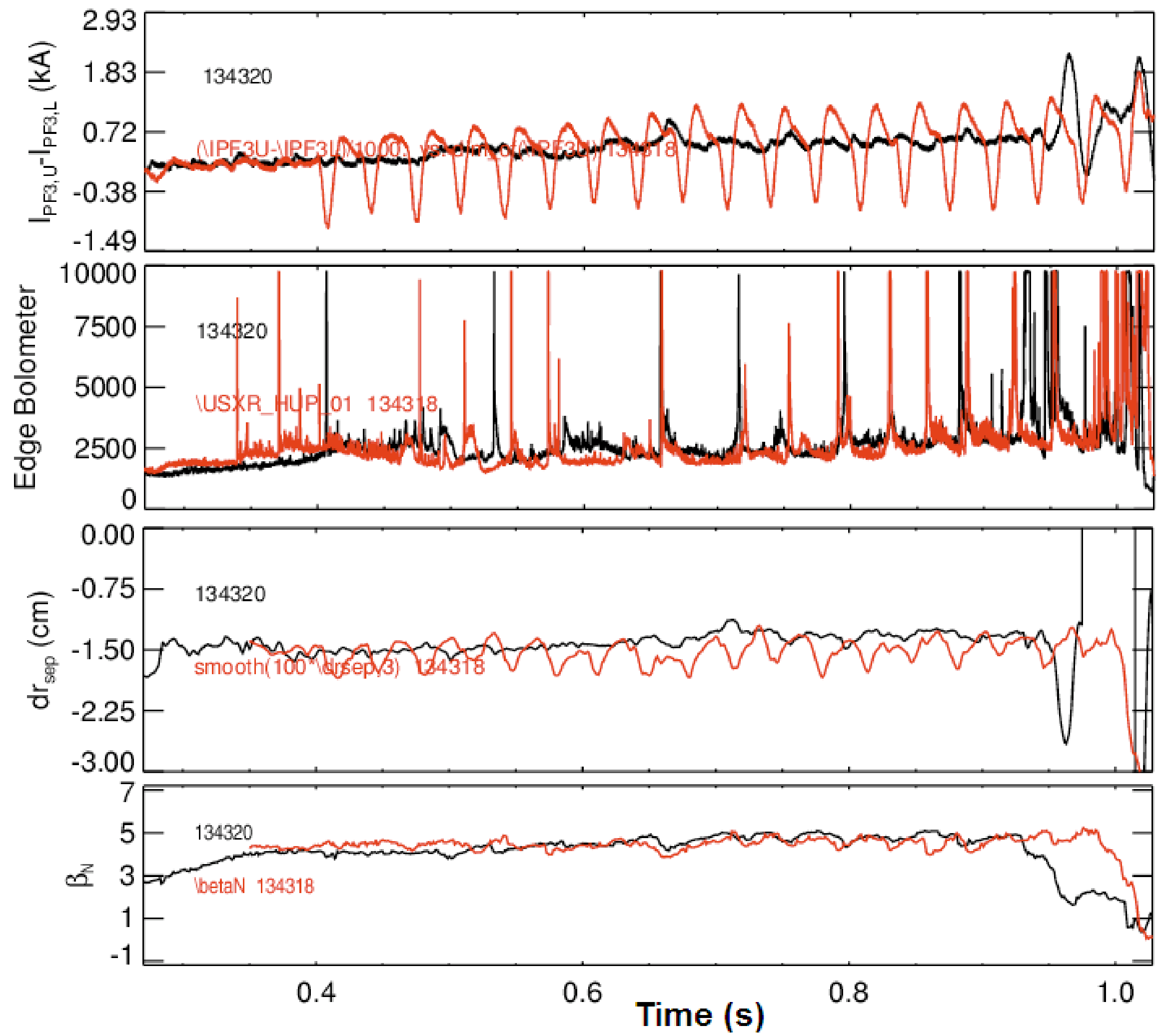
($\Delta W/W_{TOT}$ ~ 5%)

Plasma vertical position “jogs” can also trigger ELMs

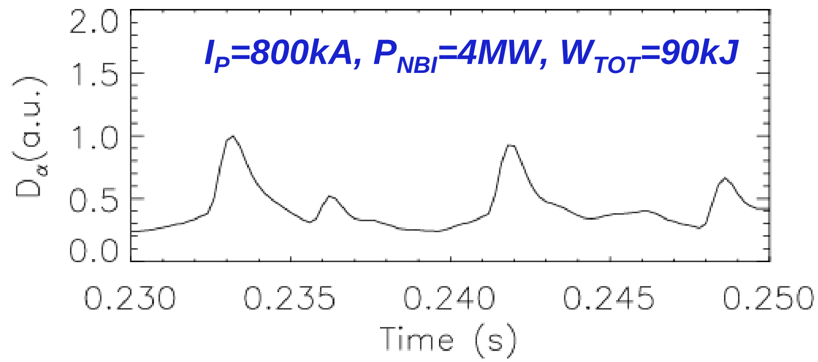
(ELM triggering with jogs observed on JET, ASDEX-U, TCV)



- Just beginning to explore this on NSTX…
- Thus far, triggering only works for $dr_{sep} < \sim -1cm$

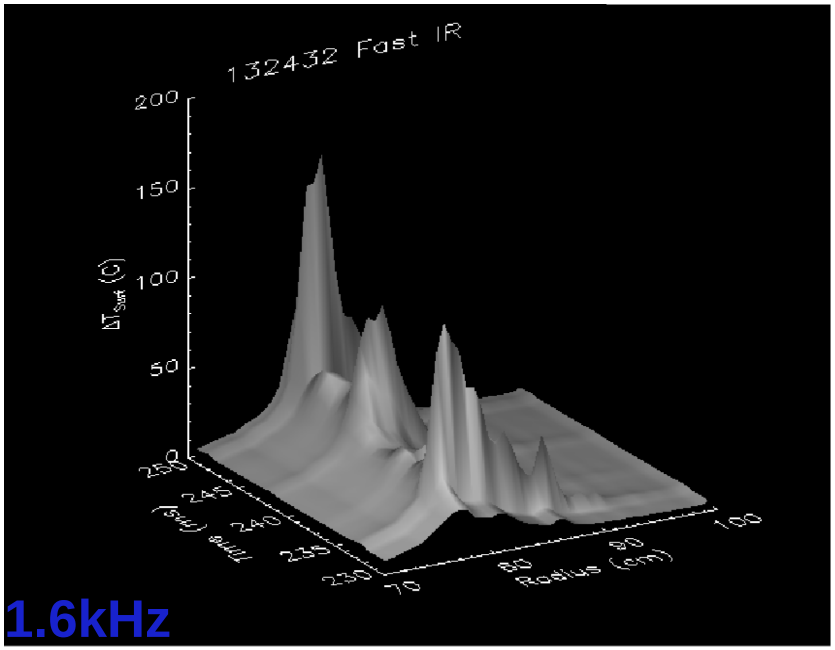


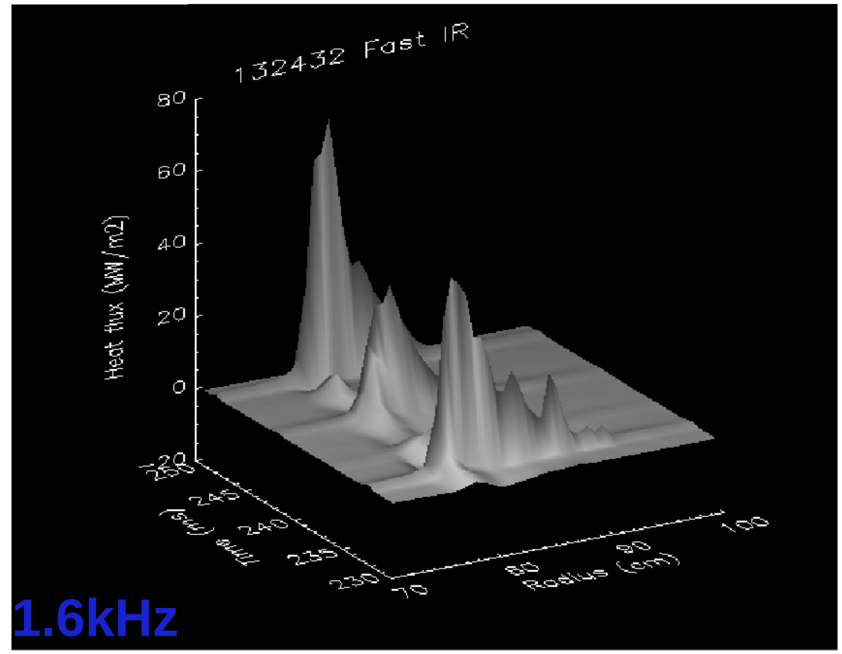
First data from fast IR camera measures ELM-resolved variation of divertor surface temperature and heat-flux



ΔT_{surf} = 100-150°C

ΔQ = 40-60MW/m^2



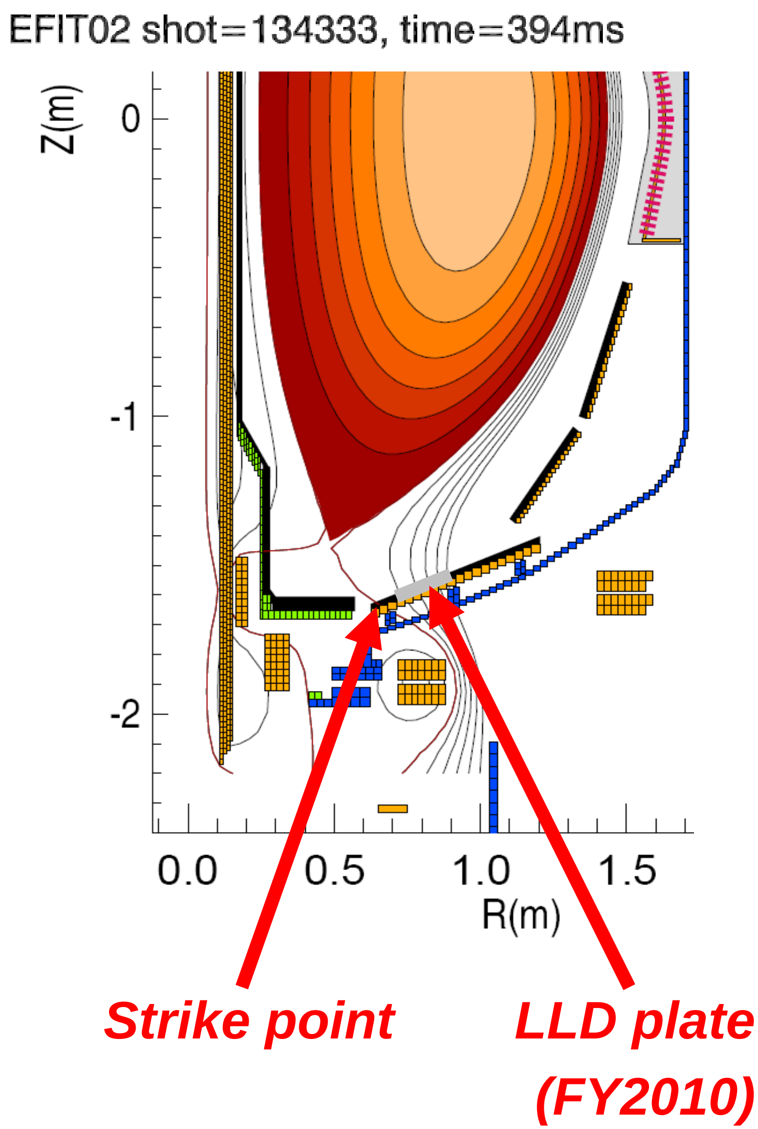


Short ELM rise time gives only one frame for a rising ELM even at 1.6kHz

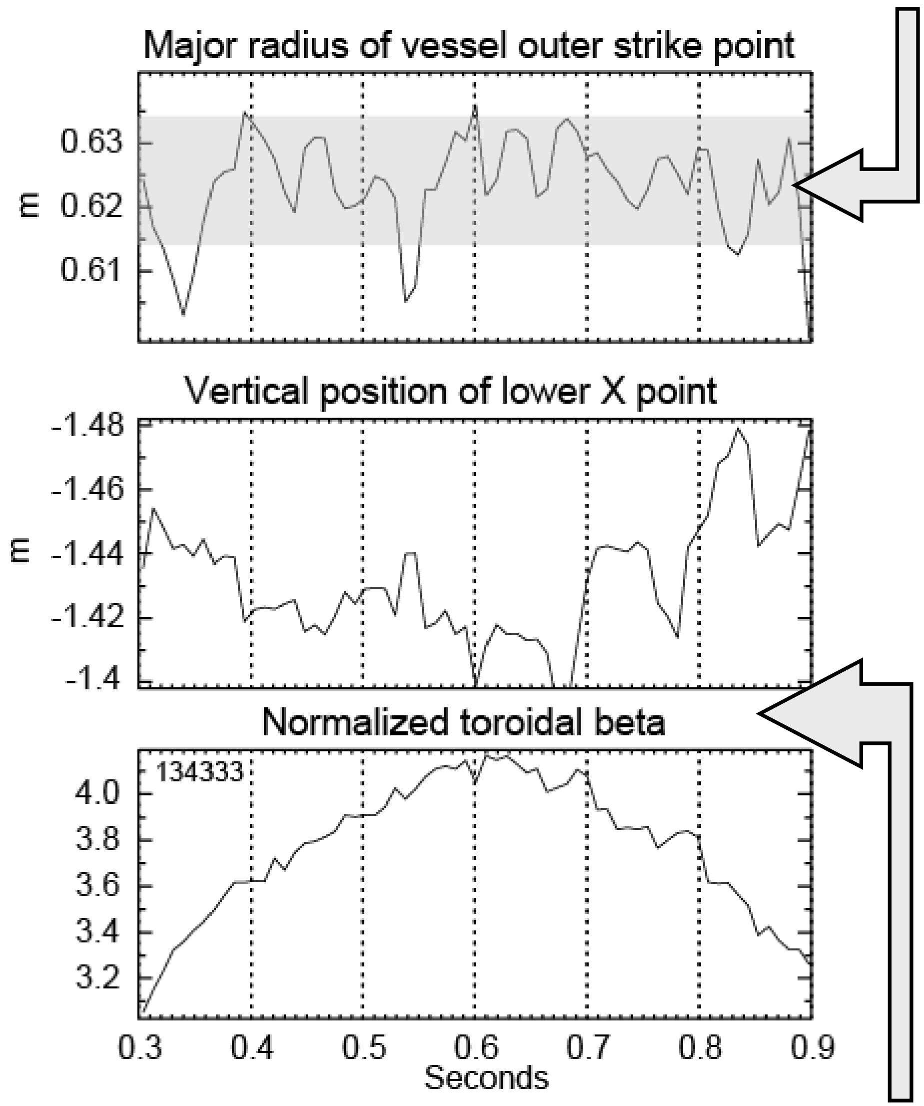
ELMs push strike point out by 2-3cm

- ***Important for understanding ELM heat loss, projecting ELM interaction with LLD***

Control of lower divertor strike-point implemented to enable and optimize operation with LLD in FY2010



R_{strike} well controlled to ~1cm variation…



PRINCETON UNIVERSITY

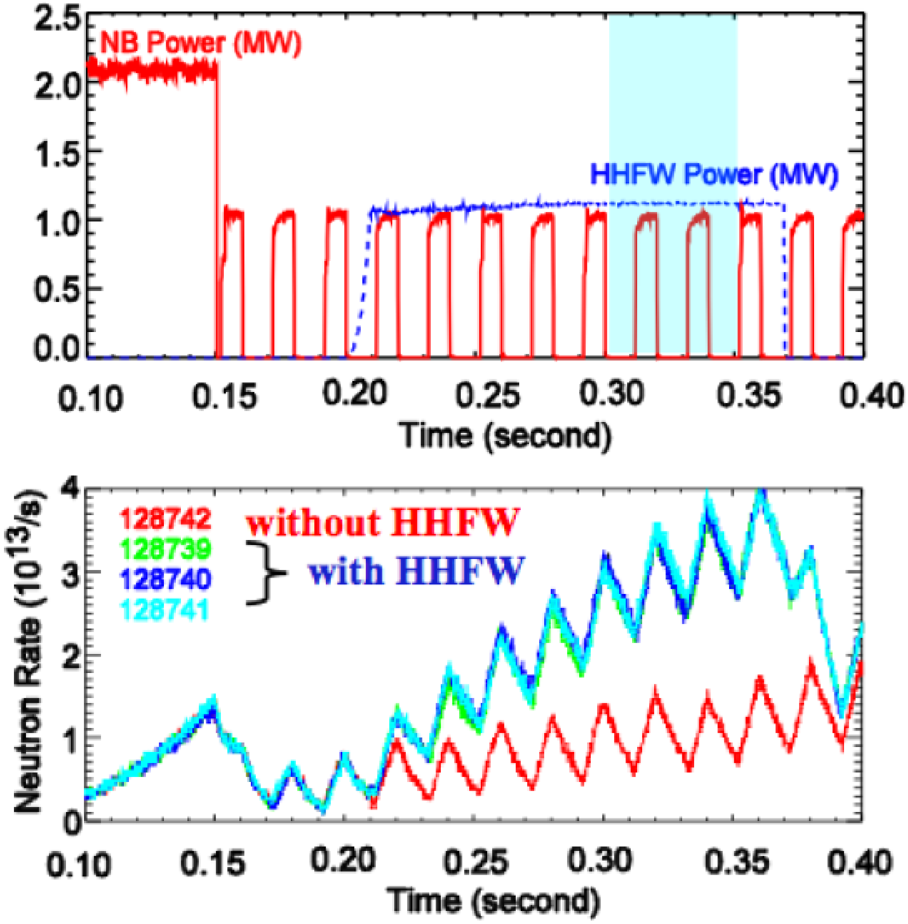
…during 8cm variation in $Z_{x\text{-point}}$ and 30% variation in β_N

Additional research highlights

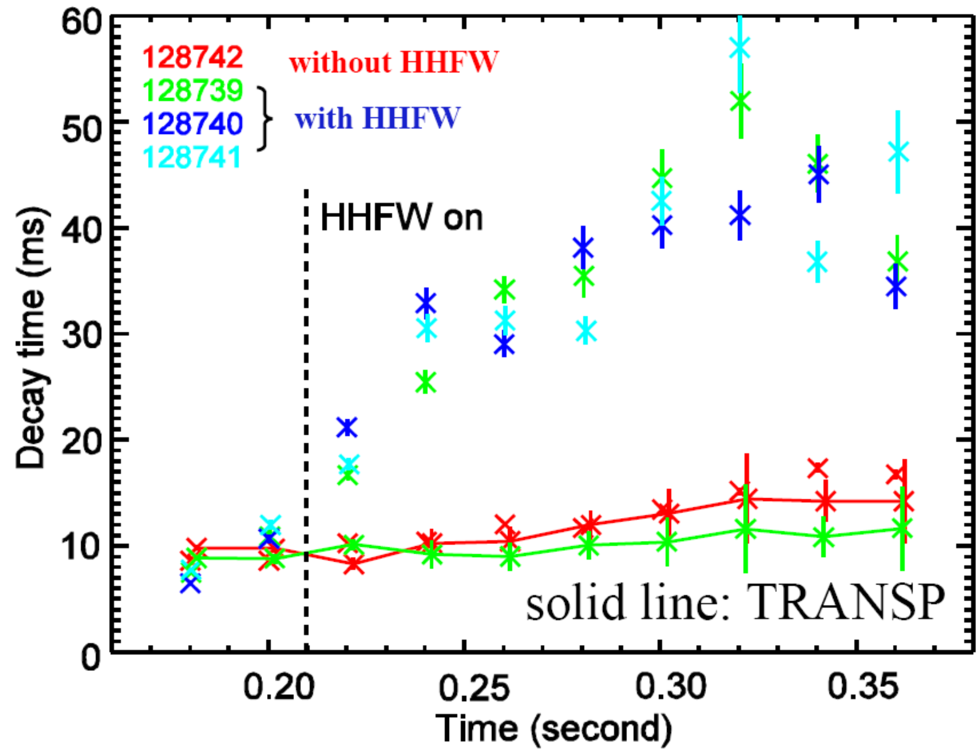
- Solenoid-free start-up
- L-H threshold scaling, confinement scaling vs. β*
- Particle control with Li, ELM stability/triggering*
- **Interactions between HHFW and NBI fast-ions**

***ITER high-priority research**

Neutron rate is enhanced during HHFW indicating acceleration of beam ions to higher energy



(Similar effects observed in Rosenberg PhD thesis 2003)

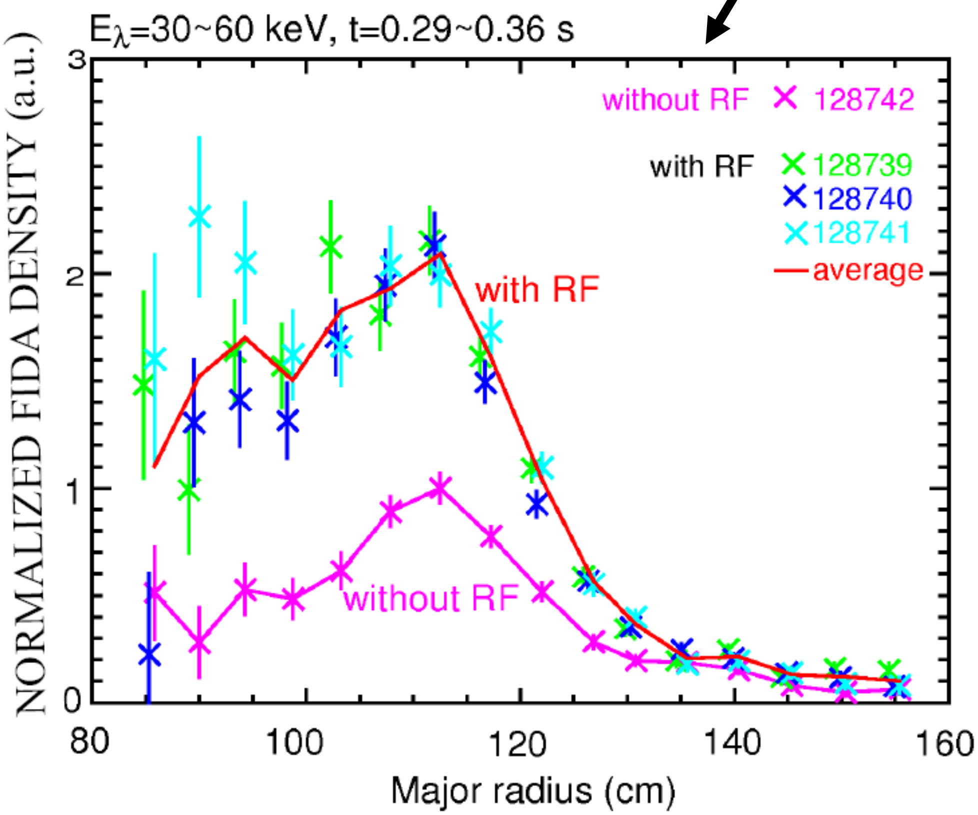


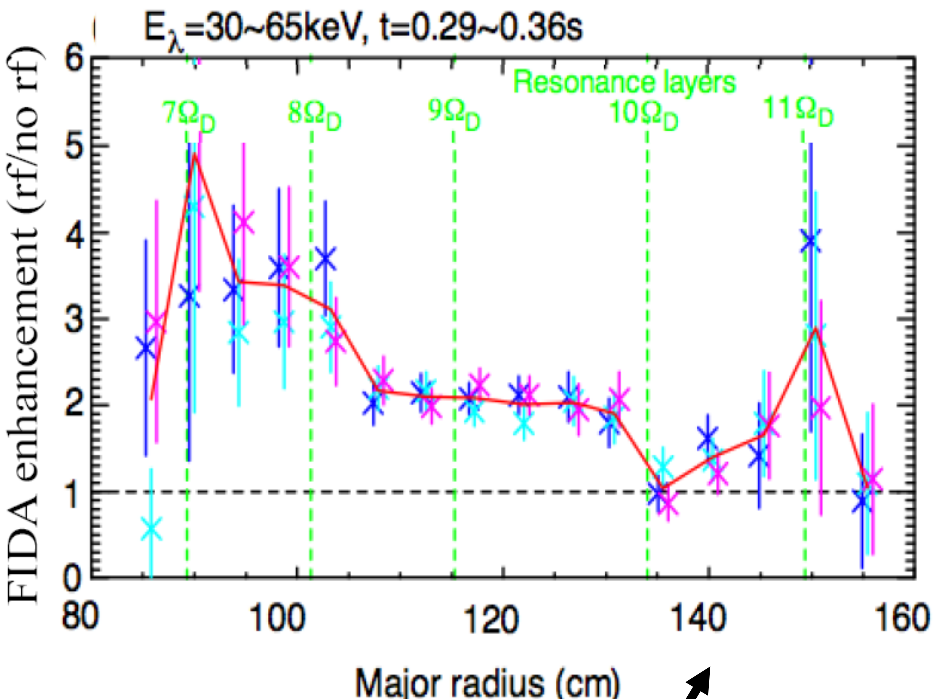
- Rise/decay rates from simple model [W.W. Heidbrink, NF **43** (2003)]
- **Larger decay time: RF acceleration counteracts Coulomb deceleration**
- No difference seen in rise time (NB ramp-up rate dominates)

UCIRVINE

FIDA diagnostic measures broad HHFW-fast-ion absorption profile likely due to presence of multiple resonances

- Fast-ion density profile broadens over most of minor radius
  - Central region (R=80-120 cm) shows more pronounced effects

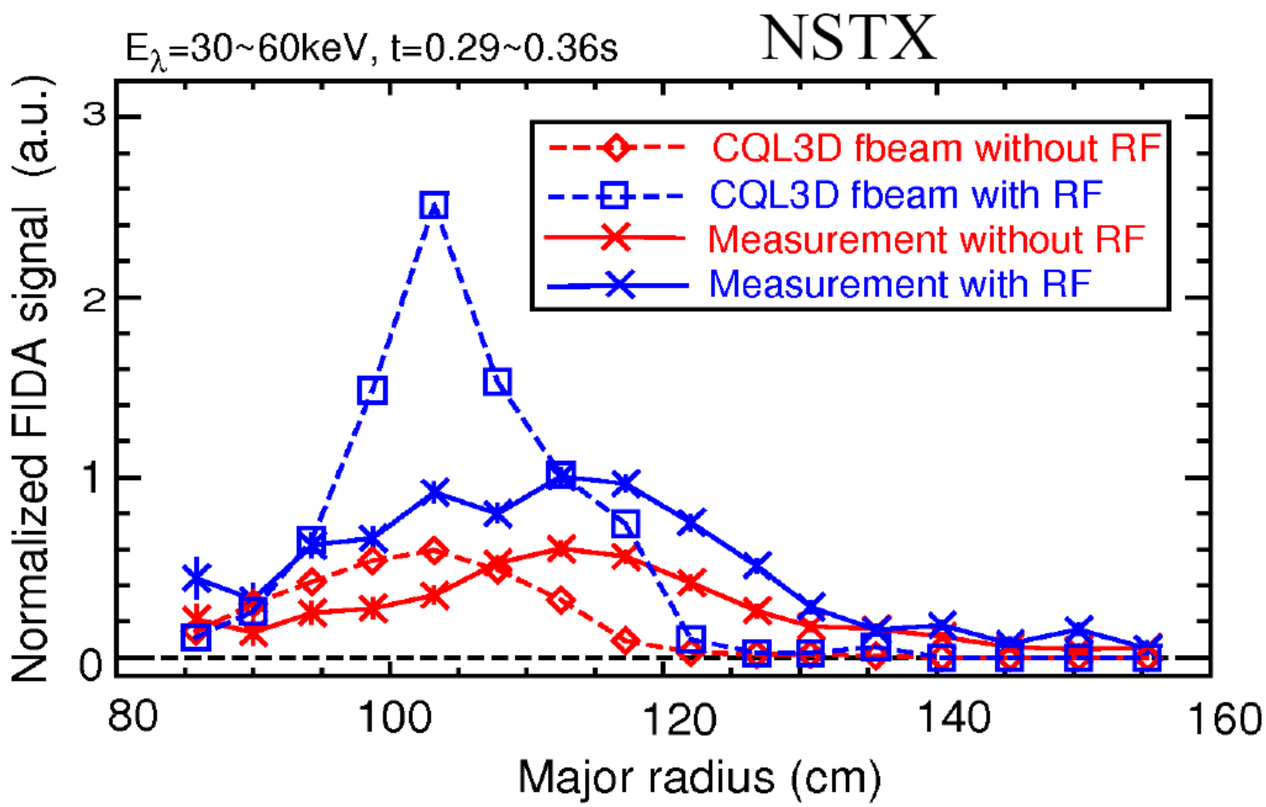




- Multiple resonances lead to broad HHFW absorption

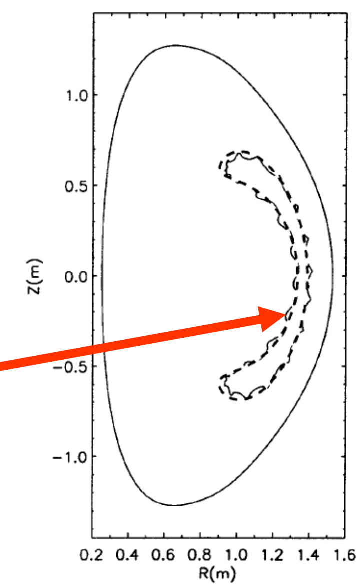
UCIRVINE

Discrepancy between FIDA data and CQL3D simulation of fast-ion diffusion from HHFW acceleration



- CQL3D profile more peaked than expt.
- CQL3D assumes zero-banana width
  - Not good approximation for NSTX beam ions
  - Need AORSA finite-banana diffusion coefficients for CQL3D Fokker-Planck (Harvey)

CompX℠ UCIrvine



coinjected 80 keV deuterium ion injected with initial $v_\parallel/v$=0.20

Plans for remainder of FY2009 run

- Assess HHFW upgrade for higher power, high T_e, D H-mode
- Obtain high-k scattering data measuring GAE mode $\delta n/n$
  - Important for understanding core e-transport
- First test of CHI absorber nulling coils for higher start-up I_P
- First test of beta feedback control algorithm using NBI
- Reversed toroidal field (time permitting, 4-6 run days)
  - L-H power threshold physics
  - SOL and divertor transport and turbulence changes
  - HHFW coupling physics, and FIDA calibration/discrepancy
  - Compare confinement, density evolution for long-pulse shots
    - "Improved L-mode" (C-Mod) w/ good thermal confinement, C impurity control?

Summary

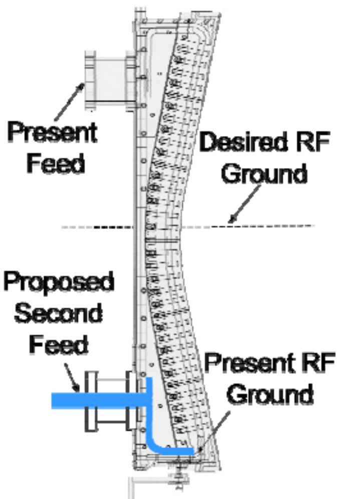
- Joint Research Milestone data collection completed
  - Developing detailed understanding of retention with C and C+Li walls
  - Will be critical for understanding LLD performance in 2010
- Research Milestones
  1. Good data set obtained for fast-ion impact on RWM (APS invited)
  2. Good *AE conditions developed to measure MSE and J(r,t) variations
  3. High β + non-inductive fraction sustained above no-wall limit at high κ
- CHI has doubled I_P savings to 100kA, try for 200kA this run
- Obtained good first data set for L-H scaling for ST, and ITER
  - Rotation and Li (and I_P) strongly influence threshold values
- Improved fueling, ELM triggering with 2D,3D fields, control, are improving impurity issues in high-performance Li shots
- New progress in understanding fast-ion acceleration by HHFW

Backup

NSTX Research Priorities

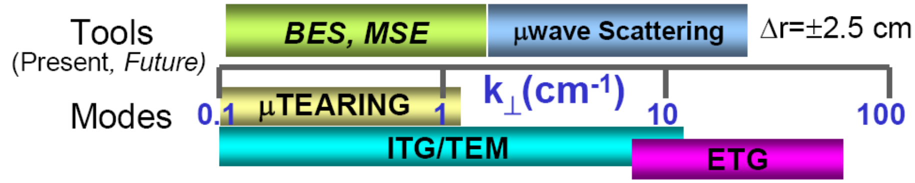
- Full non-inductive current sustainment (i.e. without central solenoid)
  - ST/tokamak requires full non-inductive current drive for steady-state
  - NSTX: Neutral beam current drive may be strongly influenced by Alfvénic instabilities in ST
- Electron and ion transport in high-confinement regimes
  - Need predictive capability to confidently extrapolate to next-steps
  - Electron energy transport increases in operating regimes of ST (i.e. high β, ρ^*, ν^*)
  - NSTX: energy, momentum, particle transport; relation to neoclassical theory, L-H threshold
- Non-inductive start-up and ramp-up
  - Essential for ST applications without solenoid: CTF, DEMO
  - NSTX: CHI, HHFW
- "Taming the plasma-material interface (PMI)"
  - Solutions for very high particle/heat/neutron flux needed for CTF and DEMO
  - NSTX: liquid metals, pedestal studies, tritium retention (2009 U.S. joint research milestone)
- High β, MHD control near stability limits, disruption physics
  - Higher β would accelerate component testing in CTF, essential for DEMO
  - NSTX: ELM/RWM control, NTM, disruption studies

NSTX FY09-11 upgrades support research goals to extend understanding and performance toward next-step STs



2009-11

Higher-power fast-wave e-heating + ELM resilience for ramp-up and sustainment of H-mode plasmas

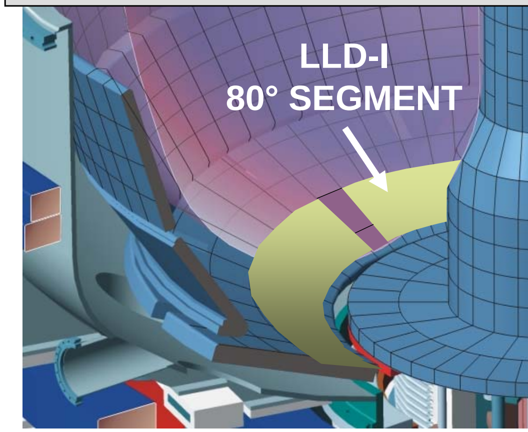


2010-11

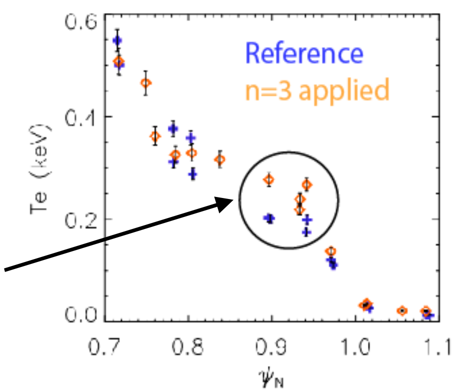
BES to complement high-k scattering e-turbulence measurements to develop predictive capability for ST transport, measure Alfvén eigenmode ξ(r, t)

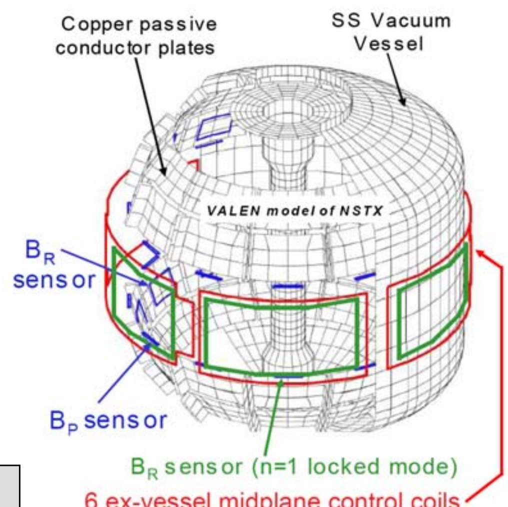
2010-11

Liquid lithium divertor (LLD) for particle control for higher NBI current-drive fraction, assess impact of liquid Li on edge transport and ELMs



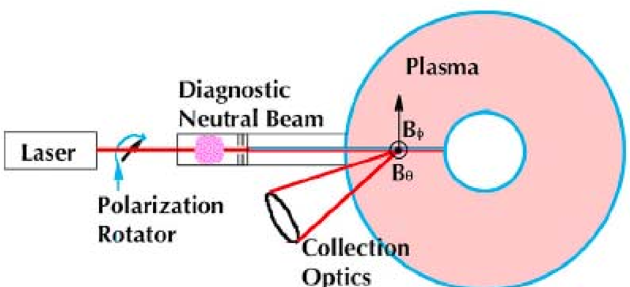
Pedestal change during n=3 RMP ELM triggering





2011

Higher resolution edge Thomson + independent control of all 3D field coils for improved edge diagnosis and control



2011

MSE-LIF for pitch angle & |B| w/o heating beam, E_r(r) – especially beneficial for HHFW and energetic particle research

In FY2009-10, NSTX Will Support Several High Priority Research Tasks Identified by ITER

- ELM modification, suppression, control
  - Important for ITER divertor survivability at high fusion gain
  - NSTX: Understand ELM stabilization with Li, destabilization with RMP, also RMP ELM control at lower q_{95}, reduced ν^* (HHFW, LLD)

- Impact of He (and possibly H) operation on H-mode
  - Important for commissioning phase of ITER operation
  - NSTX: Examine L→H threshold, global confinement, ELM stability

- ITER error field analysis using Ideal Perturbed Equilibrium Code (IPEC)
  - NSTX + DIII-D + CU proposal in response to ITER task agreement solicitation

- Validate neoclassical toroidal viscosity (NTV) flow damping theory
  - Important for minimizing mode locking during ITER RMP ELM control
  - NSTX: Additional expt/theory comparisons at varied ν^*, rotation, RMP spectrum

- Simulation of ITER test blanket module impact on plasma
  - Important for understanding impact of large predicted error fields
  - NSTX: Assess use of EF/RWM coils to approximate TBM spectrum

NSTX Participation in International Tokamak Physics Activity (ITPA) Benefits Both ST and Tokamak/ITER Research

Actively involved in 21 joint experiments – contribute/participate in 33 total

MHD, Disruption Control

• MDC-2	Joint experiments on resistive wall mode physics
• MDC-4	Neoclassical tearing mode physics – aspect ratio comparison
• MDC-12	Non-resonant magnetic braking
• MDC-14	Rotation effects on neoclassical tearing modes
• MDC-15	Disruption database development
• MDC-17	Physics-based disruption avoidance

Transport and Confinement

• TC-1 (was CDB-2)	Confinement scaling in ELMy H-modes: beta degradation
• TC-2 (was CDB-10)	Power ratio – Hysteresis and access to H-mode with H~1
• TC-4 (was CDB-12)	H-mode transition and confinement dependence on ionic species
• TC-6	Effect of Rotation on Plasma Performance
• TC-10 (was TP-7)	Experimental ID of ITG, TEM and ETG turbulence + comparison w/ codes
• TC-15	Dependence of momentum and particle pinch on collisionality

Energetic Particles

• EP-2	Fast ion losses and redistribution from localized *AE

Pedestal and Edge Physics, Divertor, Scrape-off Layer

• PEP-6	Pedestal structure and ELM stability in DN
• PEP-19	Edge transport under the influence of resonant magnetic perturbations
• PEP-25	Inter-machine comparison of ELM control by magnetic field perturbations from midplane RMP coils
• DSOL-17	Cross machine comparisons of pulse-by-pulse deposition
• DSOL-21	Introduction of pre-characterized dust for dust transport studies in divertor and SOL

Integrated Operation Scenarios

• IOS-4.1	Access conditions for hybrid with ITER-relevant restrictions
• IOS-5.1	Ability to obtain and predict off-axis NBCD
• IOS-5.2	Maintaining ICRH coupling in expected ITER Regime