First Results of H-mode Plasmas in KSTAR

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On behalf of
KSTAR research team and domestic and international collaborators

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NFRI, KAERI, POSTECH, SNU, WCI
ORNL, PPPL, Columbia Univ, GA, JAEA

NFRI 국가핵융합연구소 National Fusion Research Institute

Introduction

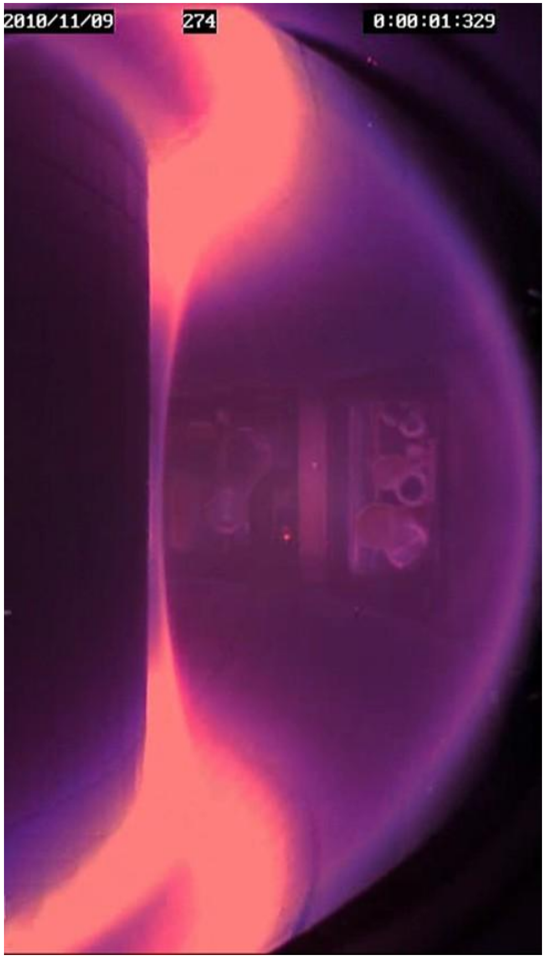
- First H-mode plasmas were produced in 2010 campaign, 1 year ahead of schedule, with only minor heating power ($P_{aux} \leq 1.6MW$)
- Major upgrades during 2009-2010 outage:
  - Full carbon PFCs and baking capability up to 200ºC
  - Installation of upper and lower divertors
  - Installation of NBI injector
  - Plasma shaping capability (DN, SN, rt-EFIT, Vertical control, etc)
  - Establishment of boronization technique with carborane
- Around 30 ELMy H-mode discharges have been achieved with combination of NBI and ECH
- KSTAR and EAST joined the new 'H-mode tokamaks club' nearly at the same time

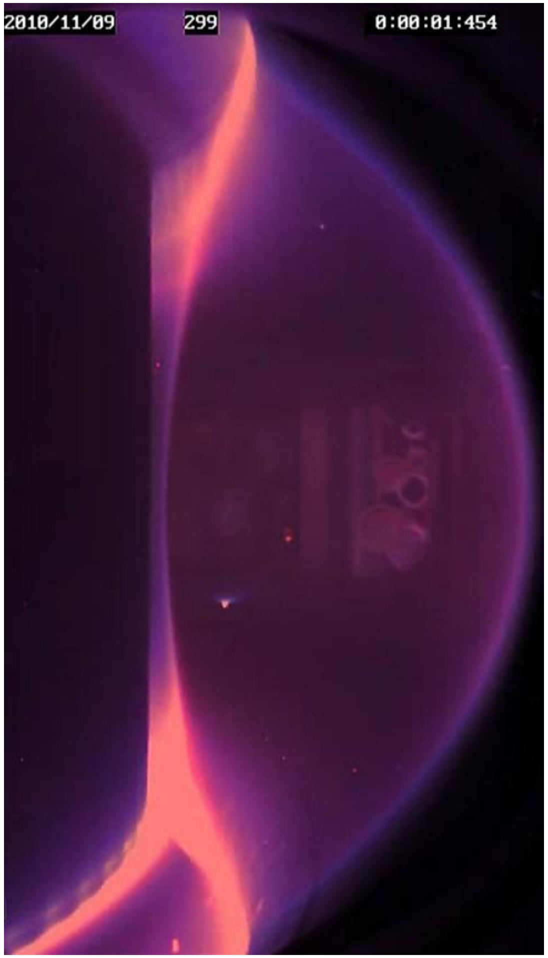
Summary of characteristics of first H-mode plasmas

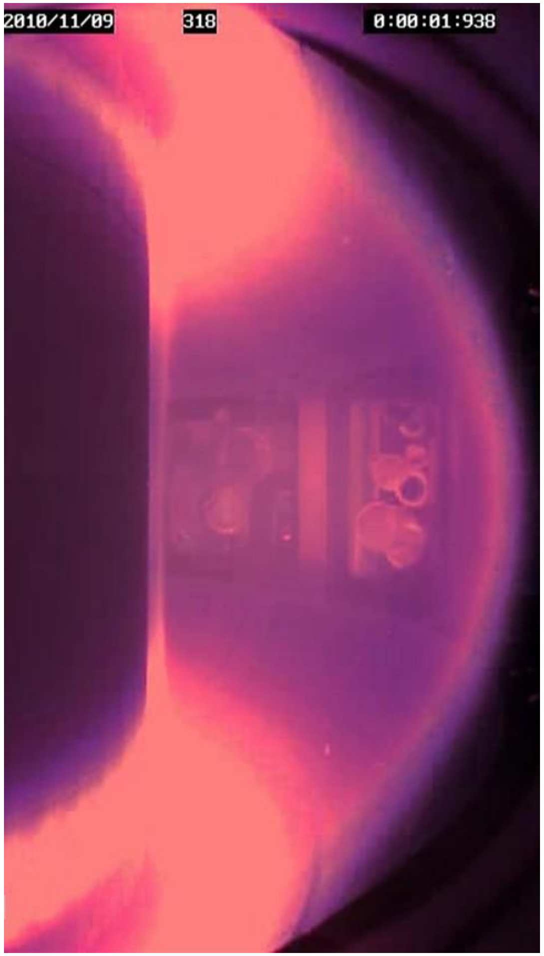
- Access to H-mode at B_T~2.0T (constrained by ECH frequency, 110GHz)
- Ip=600kA, R~1.8 m, a~0.5 m, nebar > 1.5×10^{19} m^{-3}, κ~1.8, close to DN
- Clear indication of L-H transition from D_α, W_{MHD}, XICS, ECE, CES, etc
- Many L-H transitions feature dithering or slow transition of 10-30ms
- Low threshold power, $P_{LH} < 1.5$ MW
- Many transitions appear to have been induced by a giant sawtooth crash
- Various types of ELMs observed (depending on heating method)
- ECH was found to change the sawtooth and ELM characteristics
- ELM filament dynamics revealed by 2-D ECEI measurement
- High frequency ELM precursors observed in Mirnov signal

Fast CCD images of KSTAR plasmas

Diverted L-mode (t=1.229s)	H-mode (t=1.354s)	During the ELM (t=1.838s)



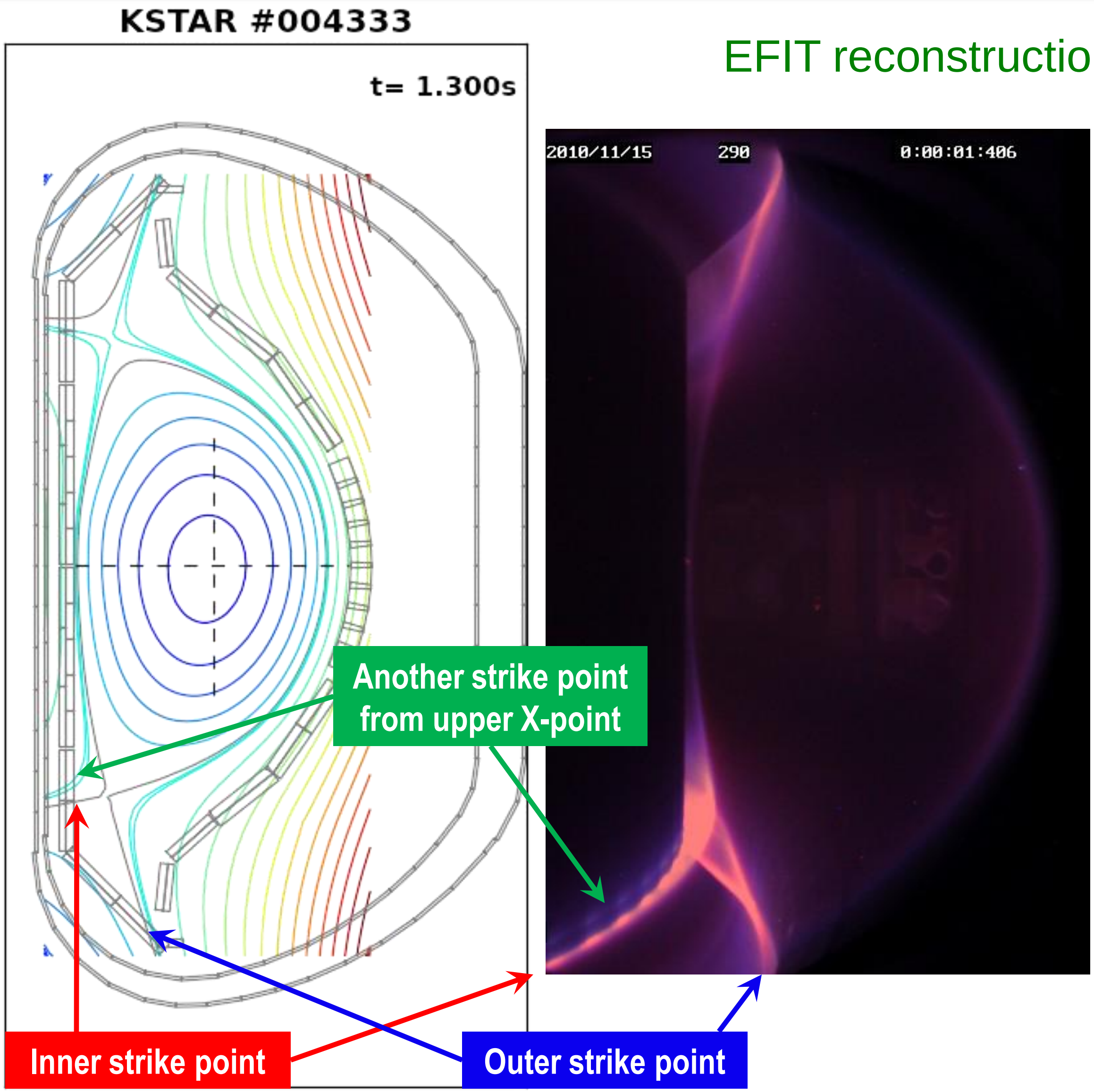




Shot 4232

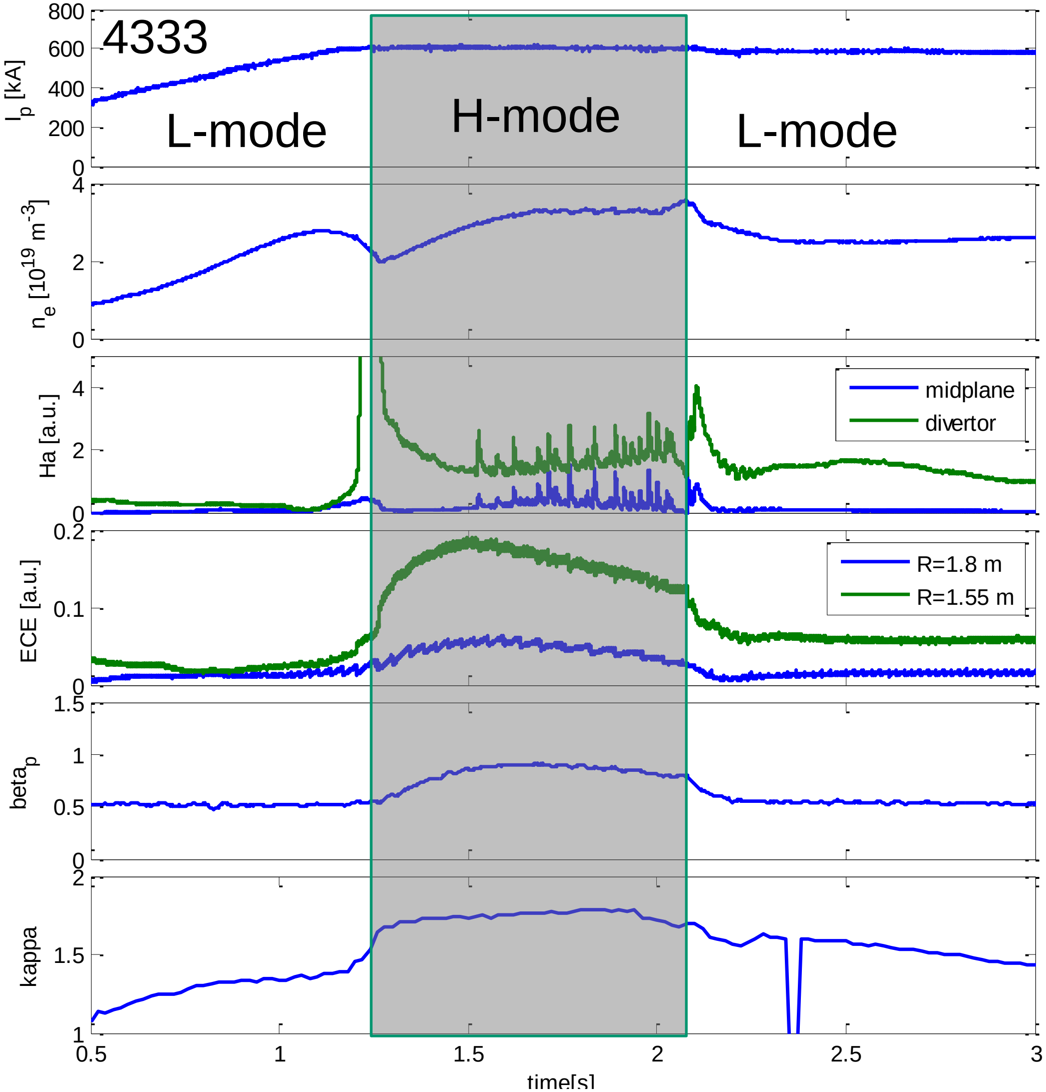
EFIT is in good agreement with CCD image

EFIT reconstruction by Y.S. Park, Columbia Univ



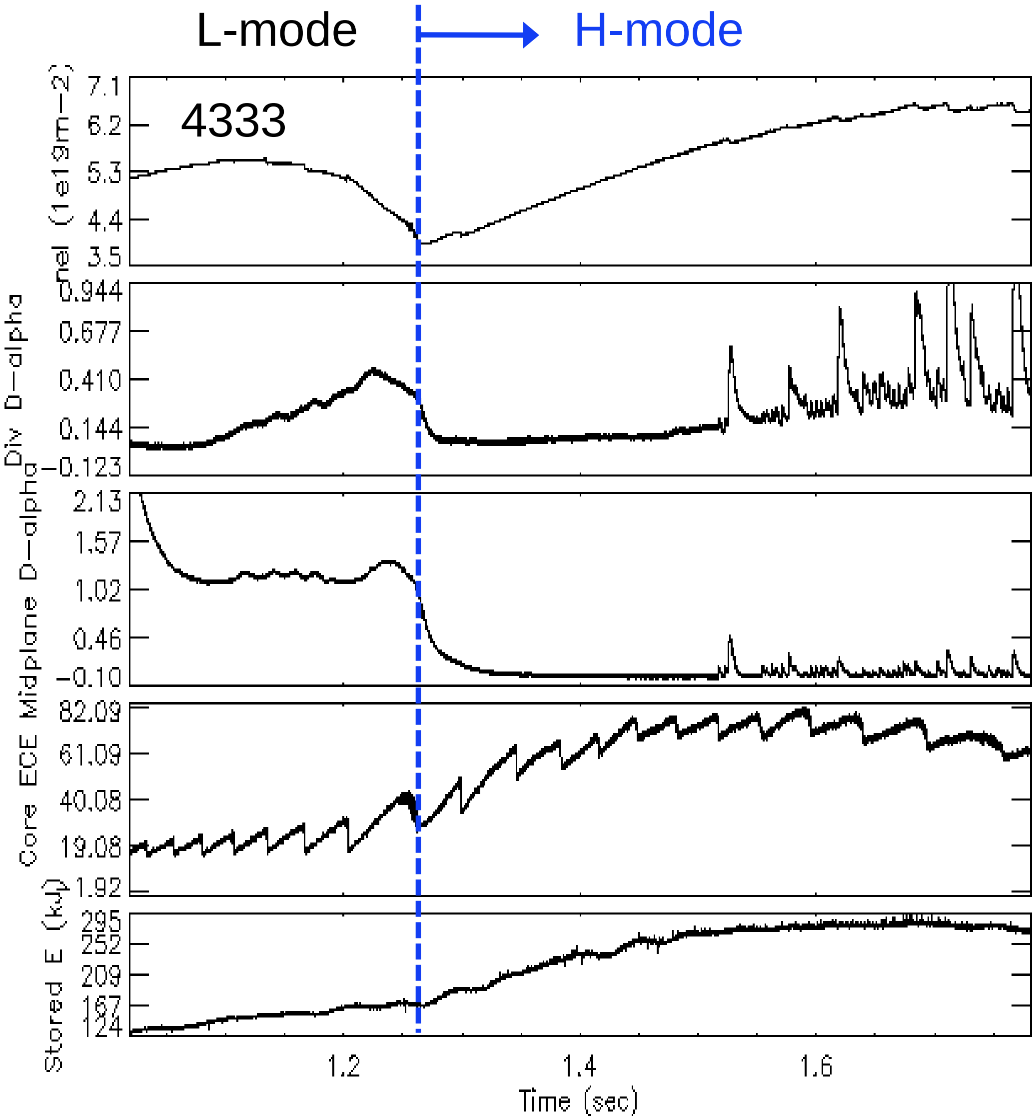
- Highly shaped plasma
  $\kappa \sim 1.7$, $\delta \sim 0.6$
  $R_{inner,gap} \sim 2cm$
  $R_{outer,gap} \sim 10cm$
- Slightly unbalanced DN (Lower Single Null)
- Primary and secondary separatrices visible
- Ion ∇B toward lower divertor

Time traces for typical H-mode in KSTAR



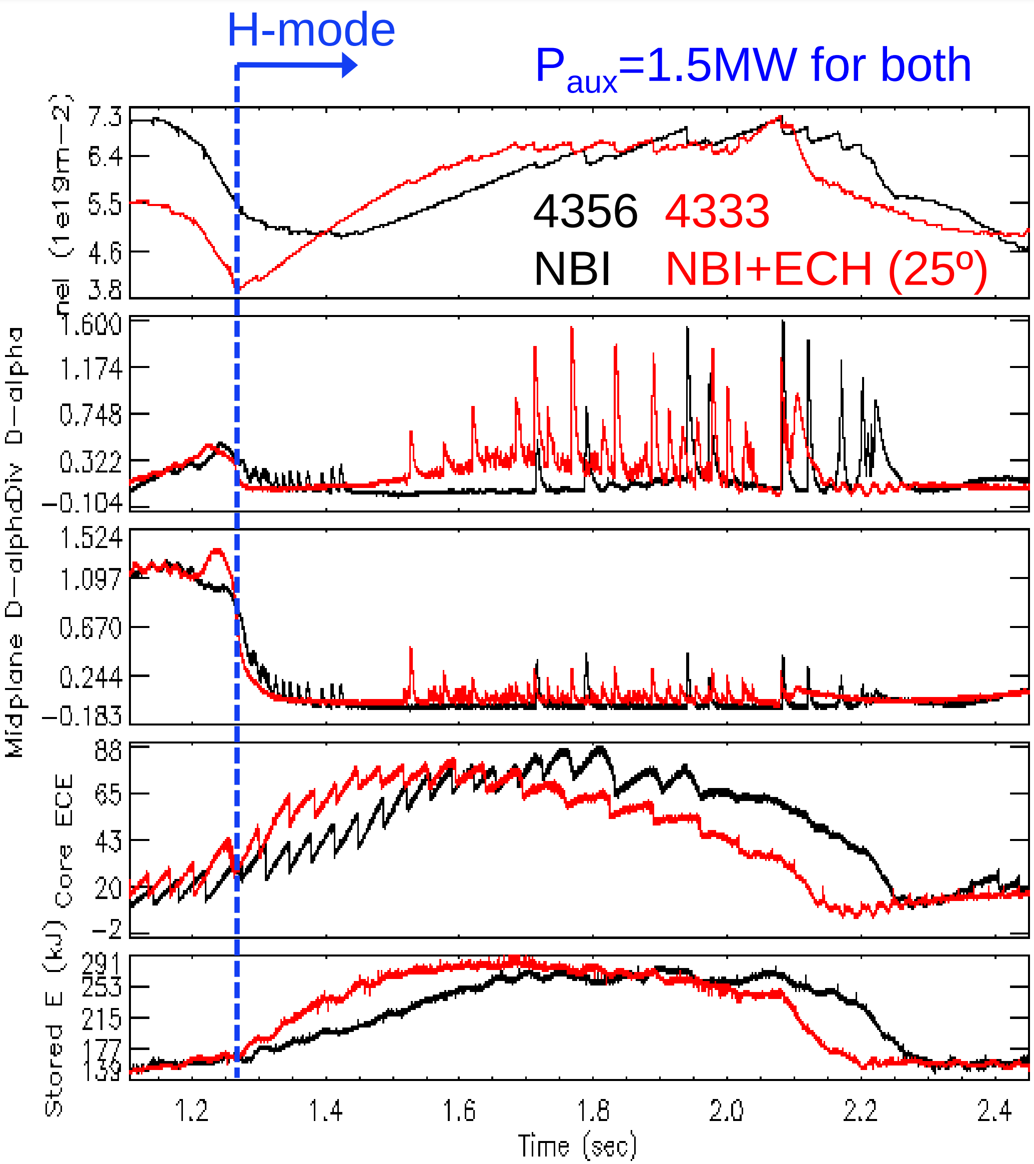
- Fresh boronization helped achieve L-H transition
- Transition immediately after Ip ramp-up phase, during rapid rise of κ (1.3→1.7) for many discharges
- Transition during steady state was also achieved
- Up to ~70-80% of increase observed for W_{MHD} and β_p
- Low threshold power
  - P_{NBI}~1.3 MW (80 keV, co-Ip)
  - P_{ECH}~0.2 MW (cntr-Ip)
  - P_{OH}~0.2 MW

KSTAR L-H transition is very slow



- Very slow L-H transition for most KSTAR H-mode shots
- Transition time from midplane D_α (~50ms) is longer than divertor D_α (~10ms)
- Contrary to previous explanation for DIII-D case, based on phase transition model using X-point MARFE to access marginal transition regime (P_{loss}~P_{thres})
- Sawtooth crash synchronized with the L-H transition in many cases. Sawtooth is observed to trigger fast L-H transition (<1ms) in other machines

Multiple types of ELMs observed depending on heating method



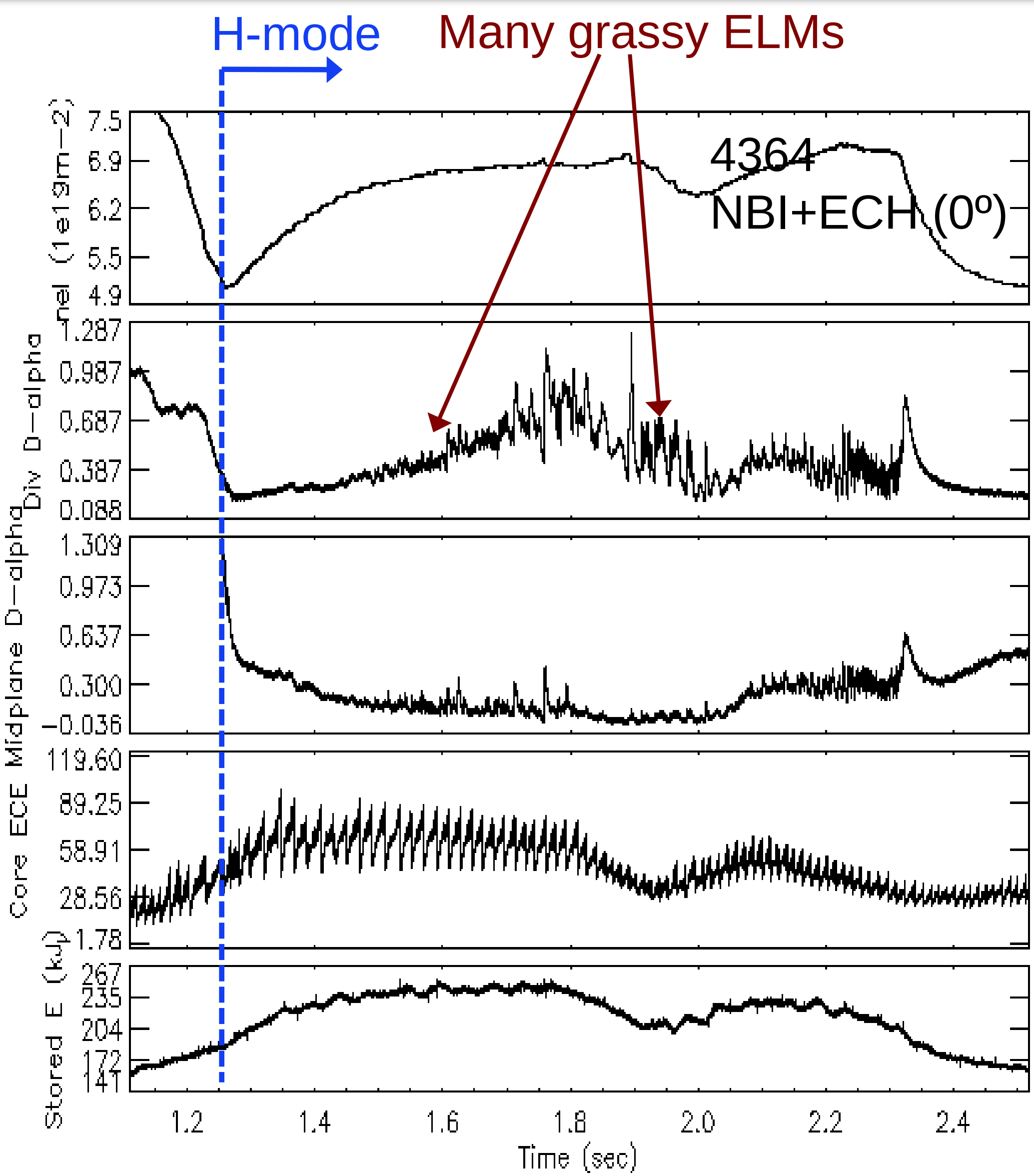
- NBI heated plasmas:

→ H-mode begins with dithers and medium amplitude and frequency (f_{ELM}=70-100Hz) ELMs occur
→ ELM-free period follows
→ Then large ELMs with long inter-ELM period

- NBI+ECH heated plasmas:

→ Initial ELM-free period
→ Low frequency (f_{ELM}=15-30Hz) and large amplitude ELMs
→ Higher frequency (f_{ELM}=200-300Hz) and very small amplitude ELMs between large ELMs

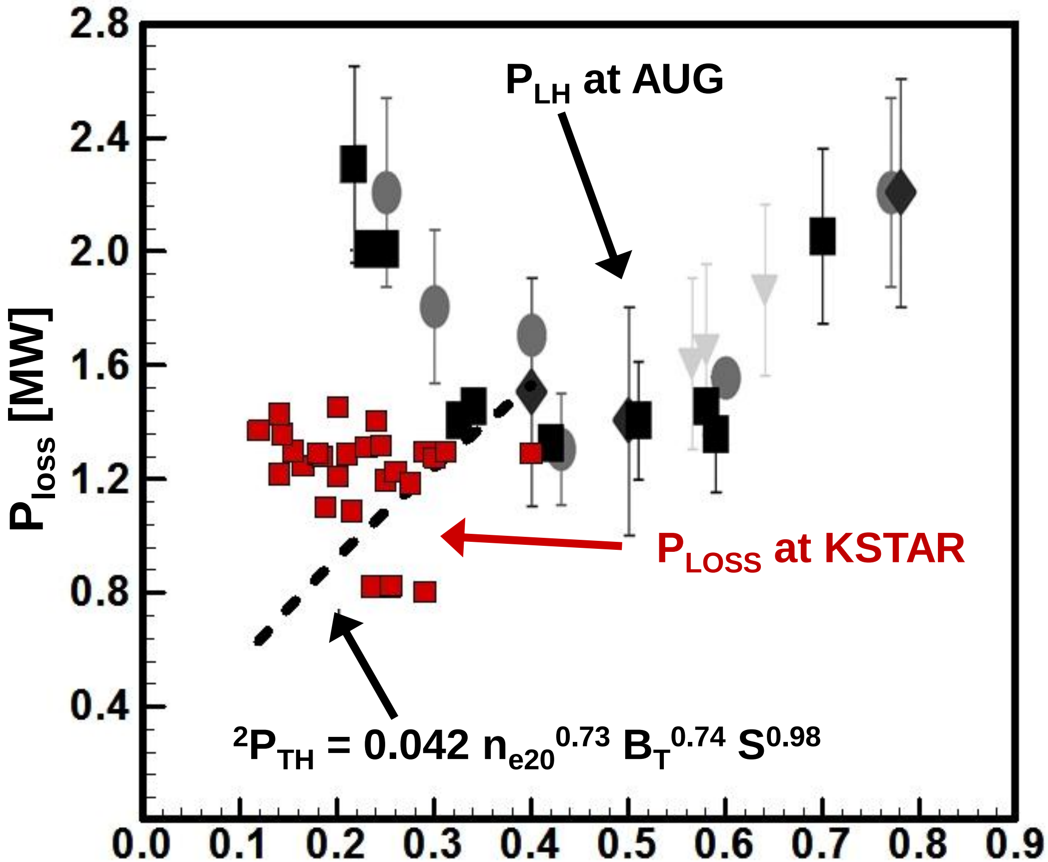
ECH injection angle changed H-mode characteristics



- Perpendicular (0º) ECH injection produced an H-mode with dominant grassy ELMs
- Raised sawtooth frequency and amplitude (ECE signal)
- Localized ECH heating may have led to a specific pedestal change necessary for grassy ELM regime???
  → ECH can be used as a means to access different ELM types?

L-H transition in low density regime and low power

Courtesy by Y-S. Na, SNU



- Asdex-U data in 2008[1] shows a minimum of P_{LH} at nebar ≈ $4.5 \times 10^{19}\ m^{-3}$, very similar for He and D
- KSTAR operation parameter similar to AUG, except Ip (600kA vs 1MA)

$P_{LOSS,KSTAR} = P_{OH}+P_{AUX}-P_{rad}-P_{fast\ ion}-dW/dt$ [MW]

$P_{LOSS,AUG} = P_{OH}+P_{AUX}-dW/dt$ [MW]

[1]Ryter, Nucl. Fusion 49 (2009) 062003
[2]Progress in ITER Physics Basis (2007)

L-H transition in low density regime and low power

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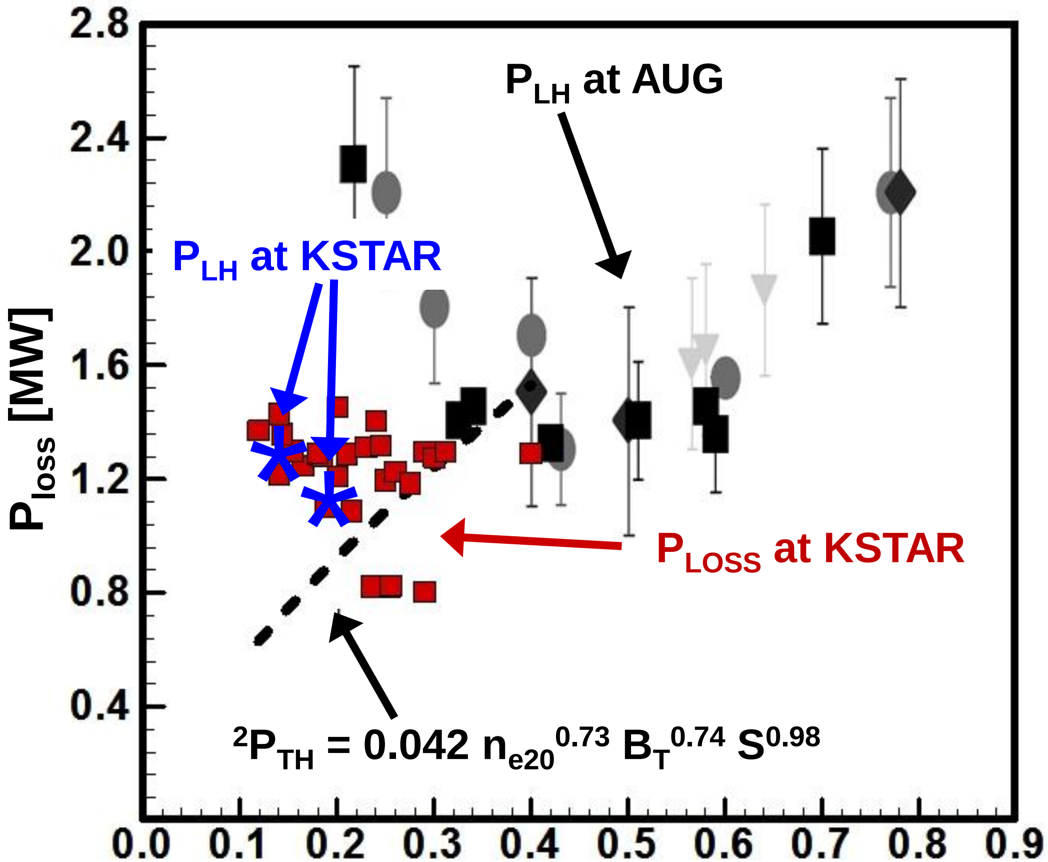

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- KSTAR operation parameter similar to AUG, except Ip (600kA vs 1MA)
- P_{LH} confirmed for two density points in KSTAR
  → Trend in very low density regime reproduced?? More data points needed

$P_{LOSS,KSTAR} = P_{OH}+P_{AUX}-P_{rad}-P_{fast\ ion}-dW/dt$ [MW]

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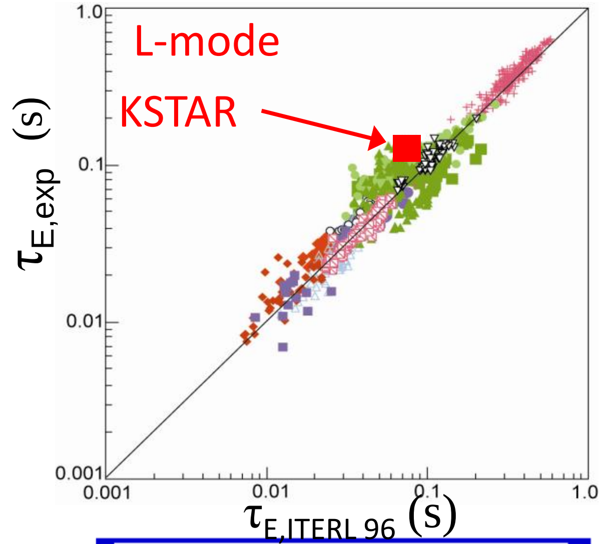
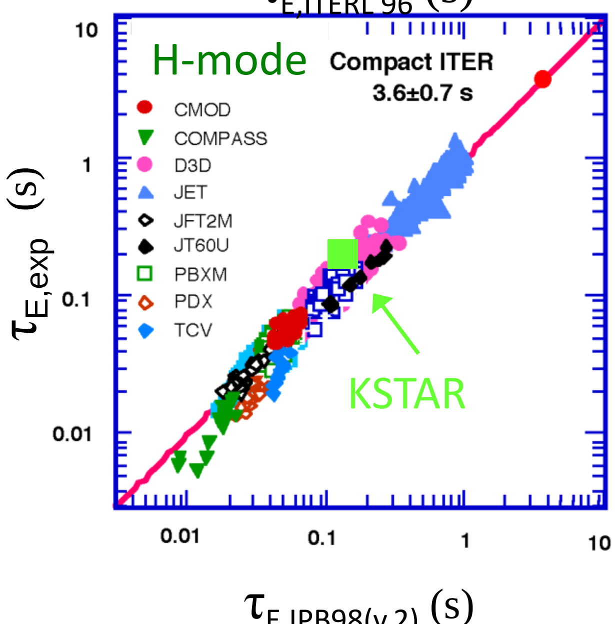
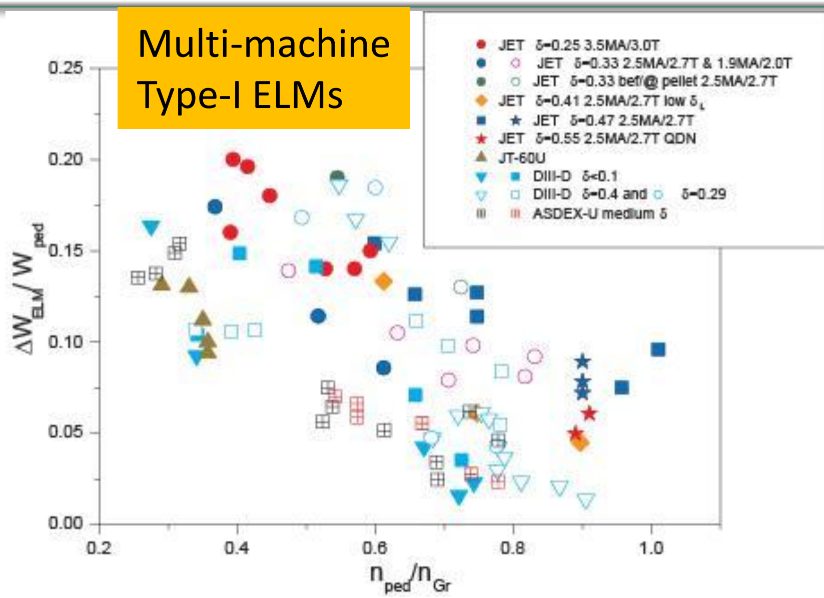
KSTAR Energy confinement time is in line with predictions of scaling law and even higher

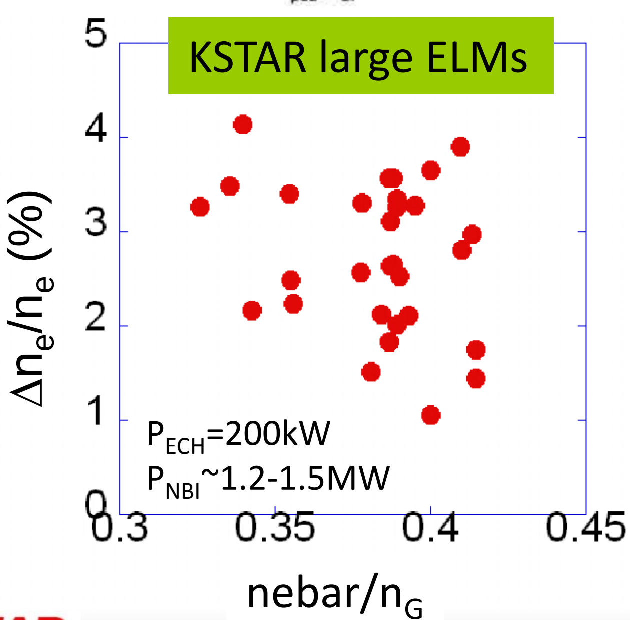




- Global energy confinement time
  → $\tau_{E,\ exp} = W_{MHD}/P_{loss}$
- Comparison with L- and H-mode scaling laws (ITER Physics Basis, 1999)
  - L-mode (7 shots)
    $\tau_{E,\ ITERL\ 96} = 0.023 I_p^{0.96} B^{0.03} P^{-0.73} n^{0.4} M^{0.2} R^{1.83} \varepsilon^{-0.06} \kappa^{0.64}$
  - H-mode (6 shots)
    $\tau_{E,\ IPB98(y,2)} = 0.0562 I_p^{0.93} B^{0.15} P^{-0.69} n^{0.41} M^{0.19} R^{1.39} \kappa_a^{0.78}$
- Maximum measured τ_E is higher than prediction from scaling law for both L- (108ms vs 69ms) and H-mode (163ms vs 115ms) plasmas
  → H factor up to ~1.42
- Accuracy relies on calculation of P_{loss} and W_p

ELM particle loss in KSTAR consistent with trend from multi-machine database for ELM energy loss



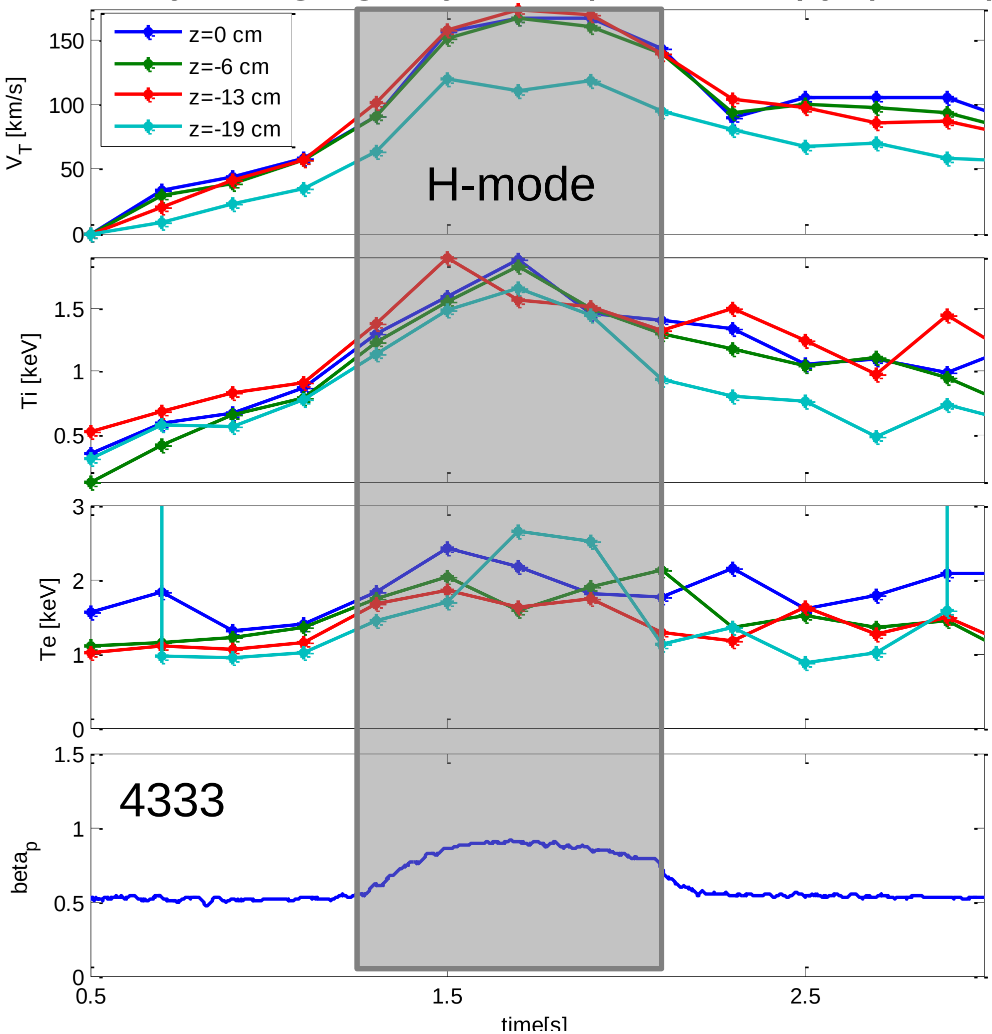


- ELM size (fraction of pedestal stored energy) decreases with increasing pedestal Greenwald fraction[1]
- No density profile available for KSTAR, but assumes nebar is strongly correlated with pedestal density in H-mode because of the broad profile shape
- nebar drop measured by interferometer indicates ELM particle loss → $\Delta n_e/n_e$ decreases with increasing Greenwald fraction even with limited variation
- Some deviation for largest ELMs

[1]Loarte, PPCF (2003), 1560

Time trace of Te, Ti & V_T shows clear increase after L-H transition

X-Ray Imaging Crystal Spectroscopy (XICS)

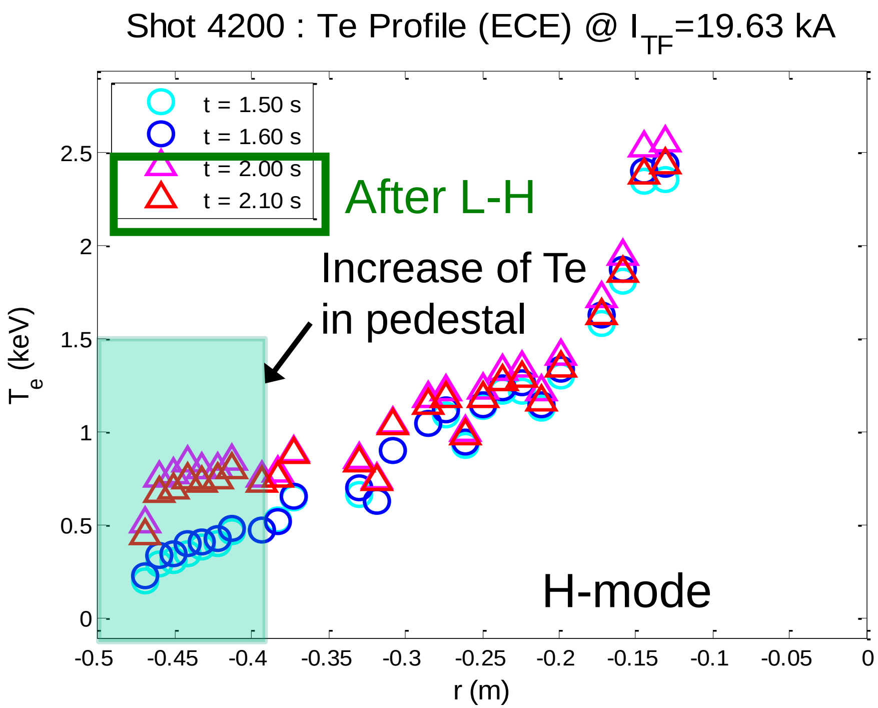


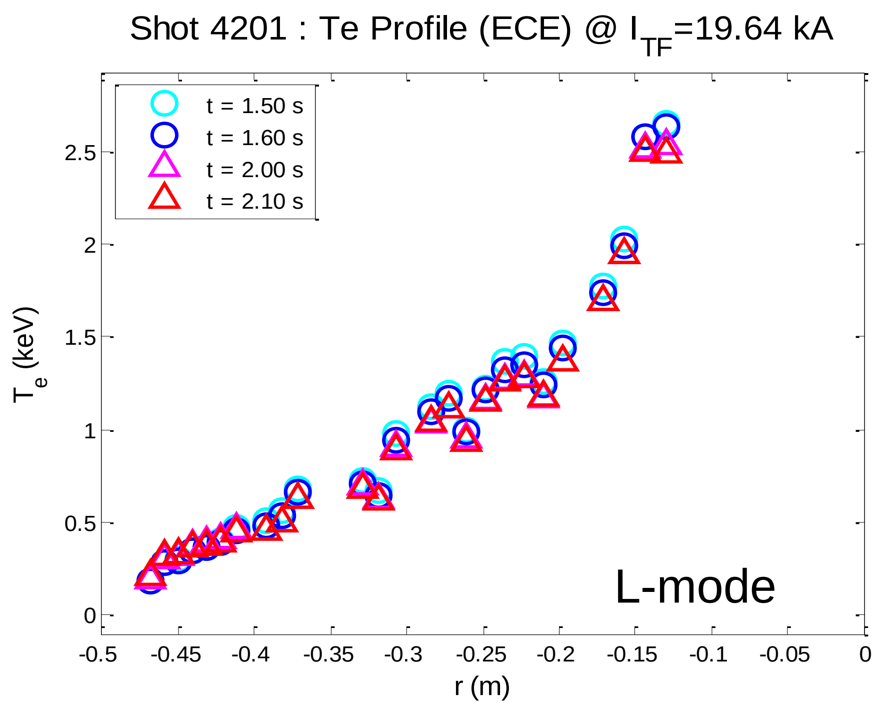
XICS data by S.G. Lee, NFRI

- Vertical profiles from the midplane (z=0, -6, -13, -19 cm)
- Factor of ~2 increase of Ti & V_T After the transition
- Relatively smaller increase of Te

Clear Te increase in the pedestal region

ECE data by K-D. Lee, NFRI



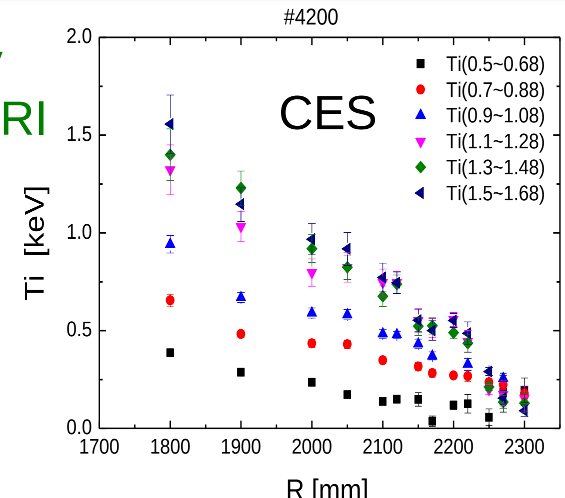


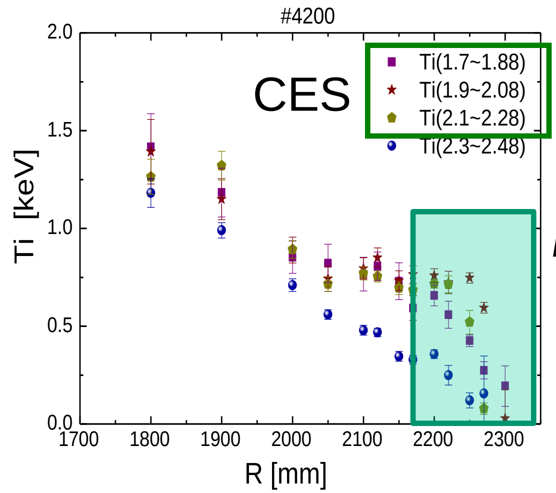
- Large uncertainty on 3rd harmonics components on ECE intensity near pedestal due to overlap with 2nd harmonics
- However, relative increase of pedestal Te in H-mode appears robust
- No discernable increase of Te in the core region (similar to XICS data)

Ti and V_T pedestal profile shows large increase after L-H transition

CES data by W.H. Ko, NFRI

Ti profile

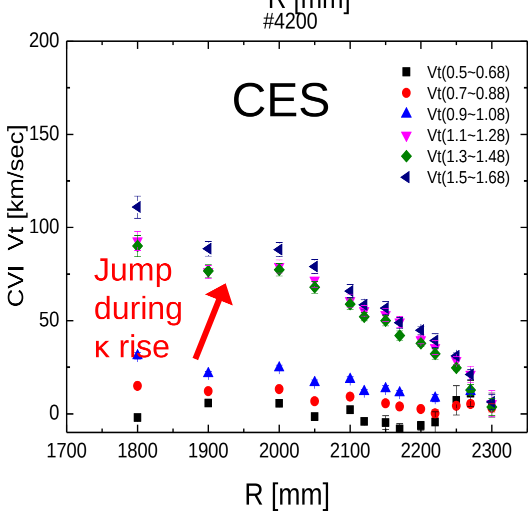


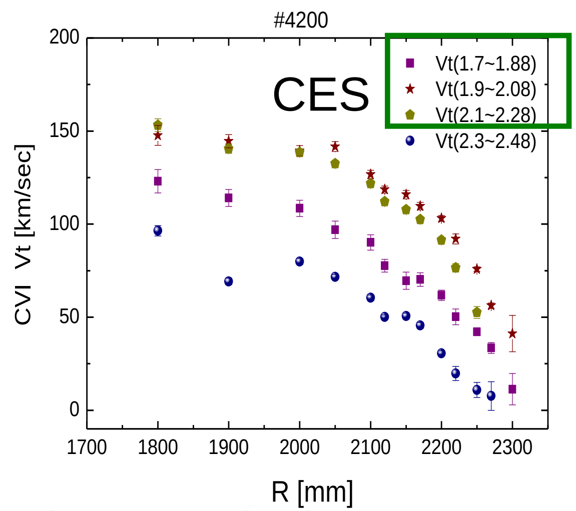


H-mode

Large increase of Ti mainly in pedestal

V_T profile





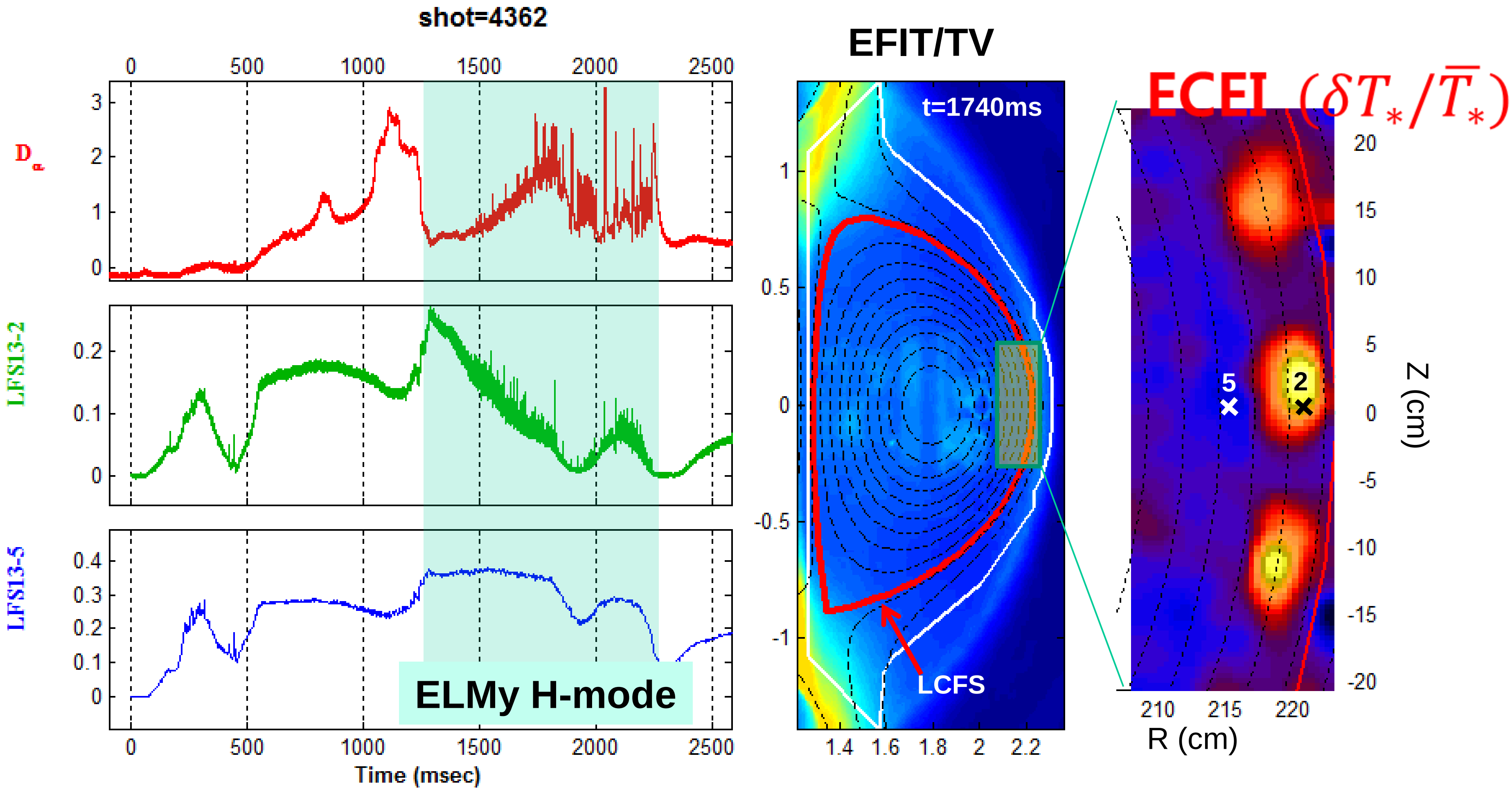
H-mode

- Ti increase mainly at R=2~2.25m (pedestal region)
- Overall V_T profile rises rapidly during the κ rise even in L-mode
- Increase of V_T due to H-mode observed in both core and pedestal regions

Clear Evidence of Filaments during ELMs by ECEI

Courtesy by G.S. Yun, Postech

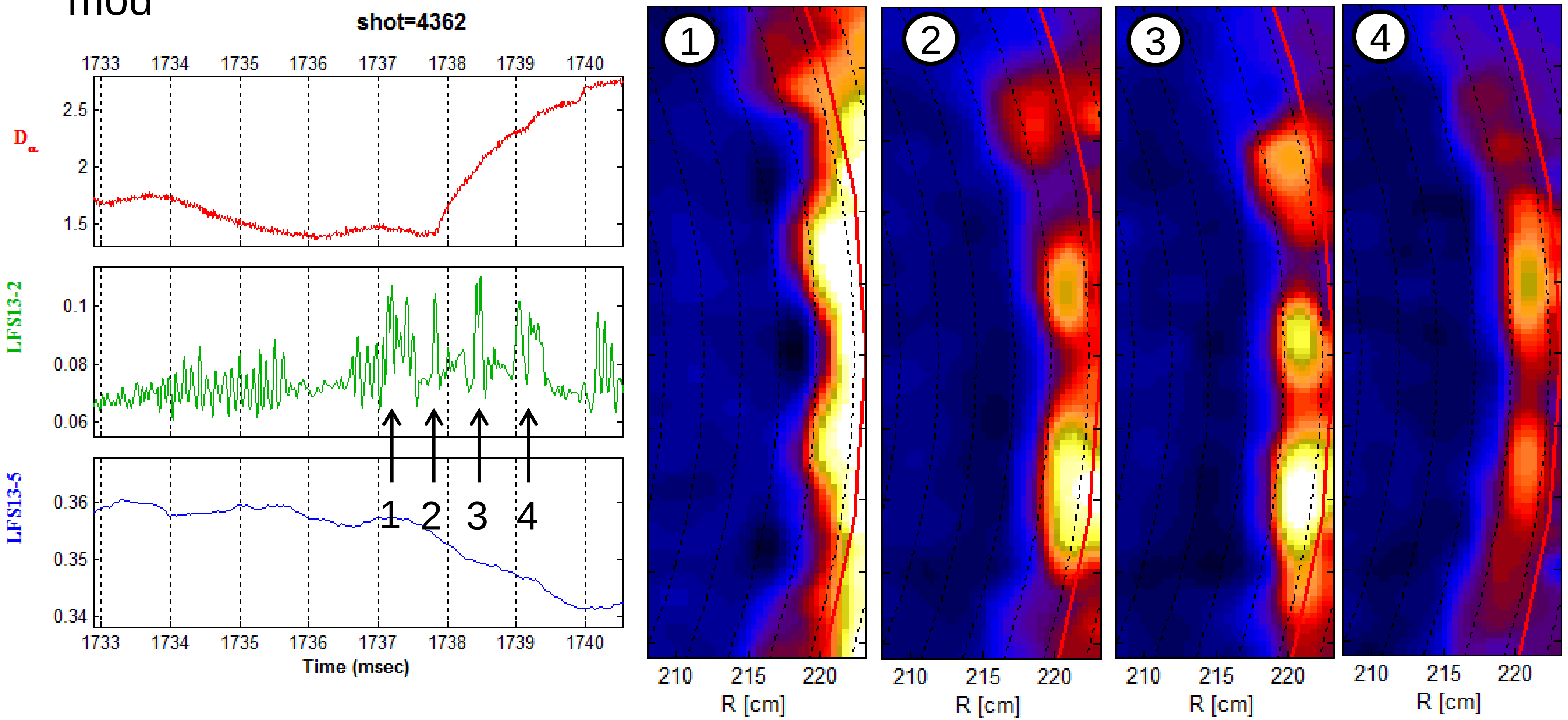
- Growth, interim steady phase, and bursts of edge localized filaments



Large ELM event consists of multiple crashes

Courtesy by G.S. Yun, Postech

- Initial large crash followed by multiple small bursts (~0.5 msec apart)
- Similar to the primary and secondary filaments observed in NSTX* and C-mod**



* Maqueda, Maingi, and NSTX team, PoP **16** (2009), ** Terry et al, J. Nucl. Mat. **363-365** (2007)

Summary

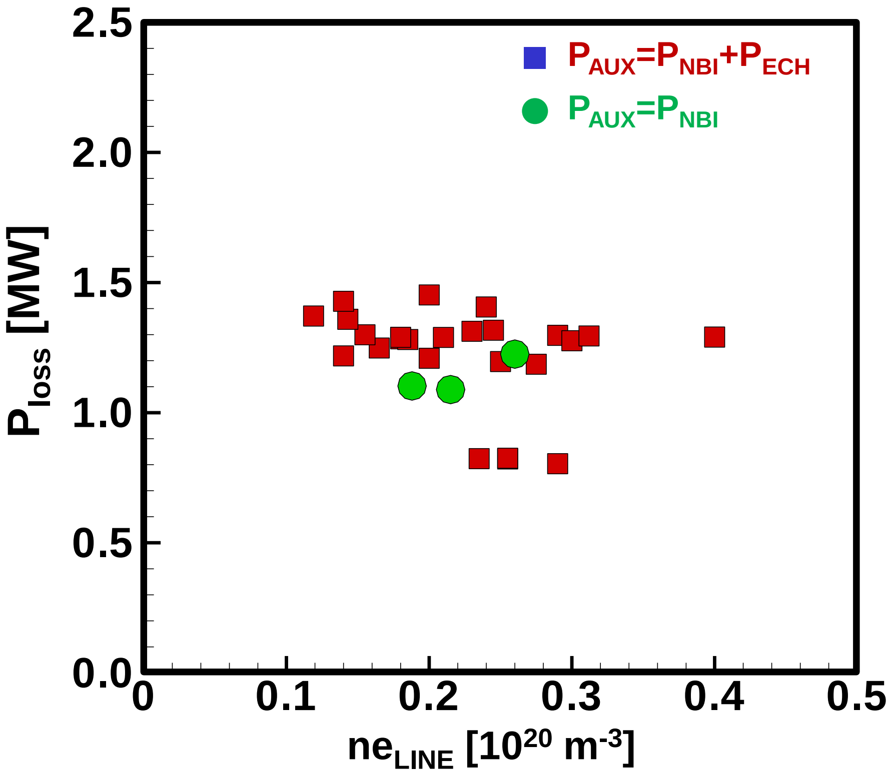
- First KSTAR H-mode plasmas feature low power threshold, slow L-H transition, and various ELM types
- ECH injection strongly affected characteristics of ELM and sawtooth
- P_{LH} at low density indicates diverge from the P_{th} scaling law and is consistent with results from other tokamaks
- Estimated energy confinement time is in line with the H98 scaling and H factor of up to ~1.4 was achieved
- The measured Te, Ti, and V_T profiles show strong increase in pedestal, but no significant change in the core except for V_T

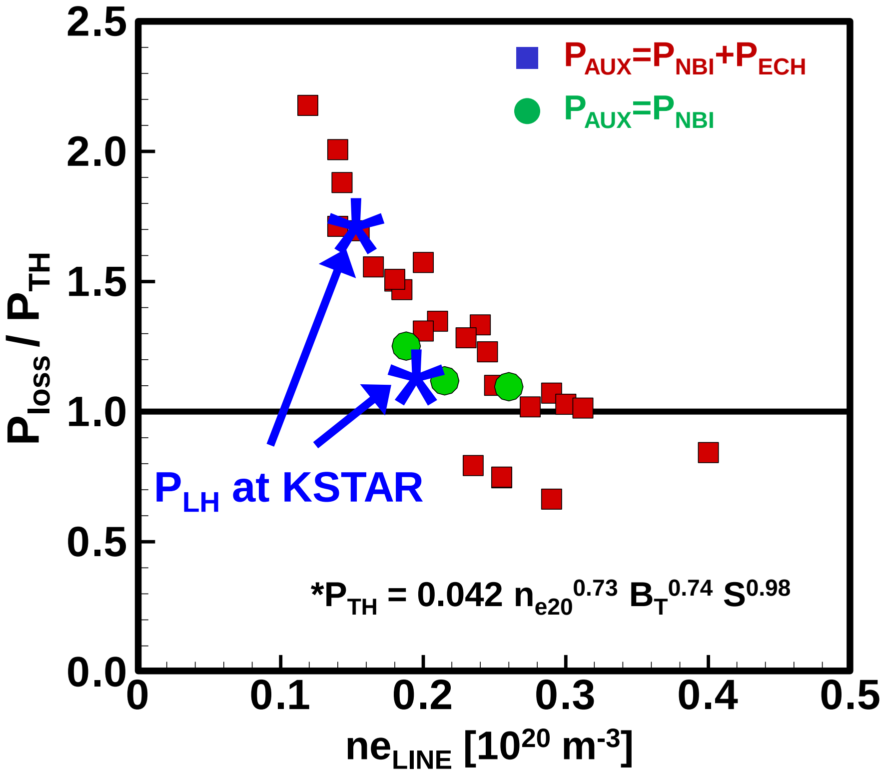
Detailed characterization of KSTAR H-mode is planned for the 2011 campaign, focusing on the profile measurements and parameter scans

Backup slides

Power Loss Phase Diagrams

Courtesy by Y.S. Na, SNU





- Estimated P_{Loss} for H-mode shots in replacement of P_{LH}
- Initial data suggests P_{loss} is diverging in the region of low density from the scaling law as reported in other tokamaks, assuming that estimated P_{Loss} is similar to P_{LH}

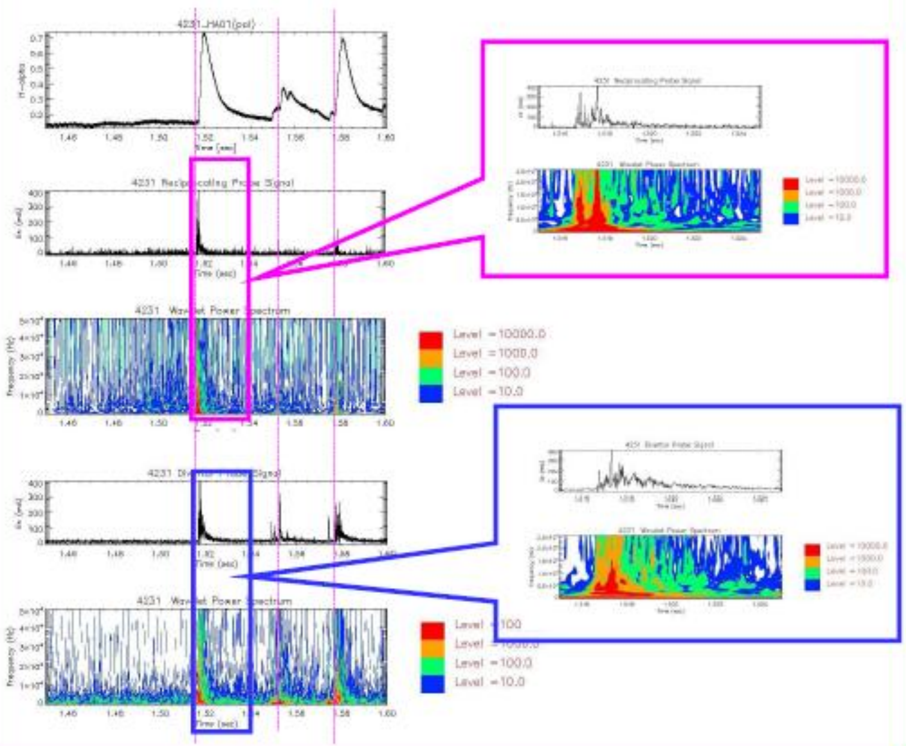
*Progress in ITER Physics Basis (2007)

High frequency precursor for ELMs

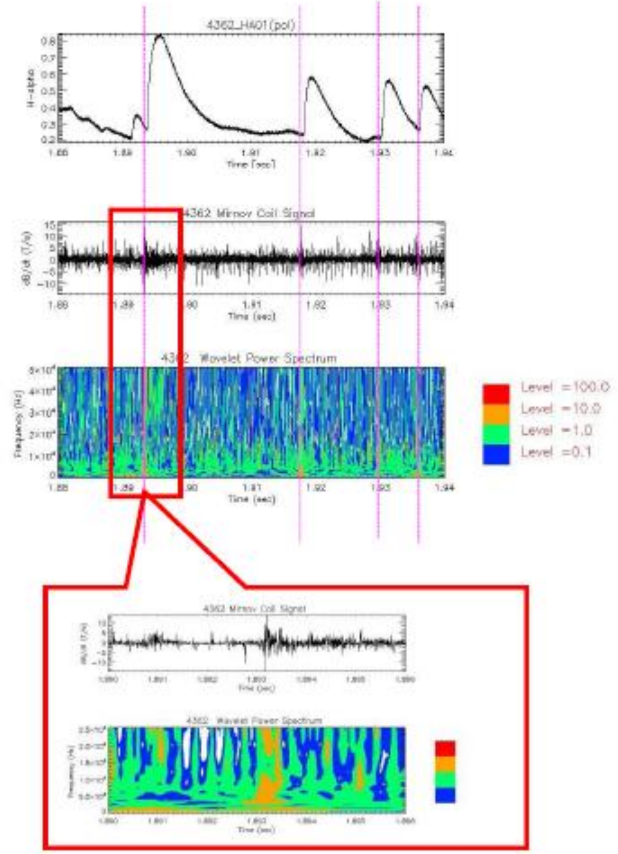
Frequency spectra during ELM

Probe and Magnetics data by J.G. Bak, NFRI

Electrostatic fluctuations by Langmuir probes during ELM

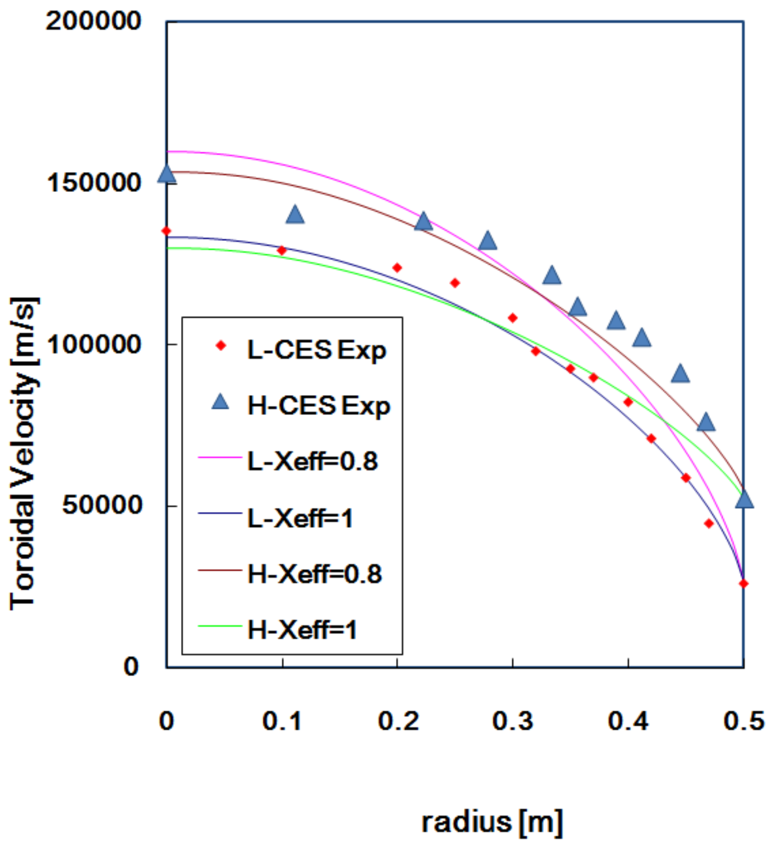


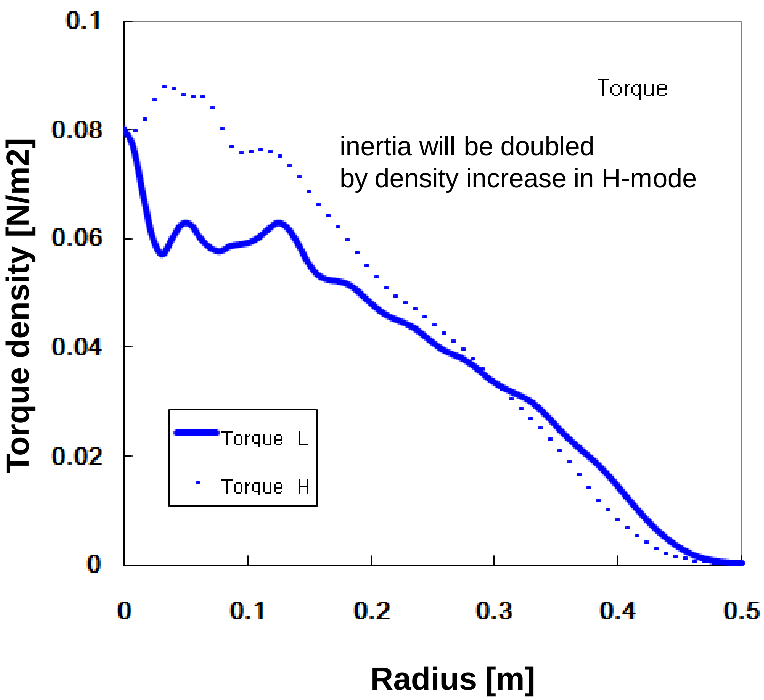
Up to 50 kHz ELM precursors were observed in Mirnov coil



Rotation profiles are self-similar for L- & H-modes

Change of NBI torque is not sufficient to explain the increase of VT in H-mode
Simple diffusion model predicts lower toroidal viscosity for H-mode (0.8 vs 1.0 m^2/s)

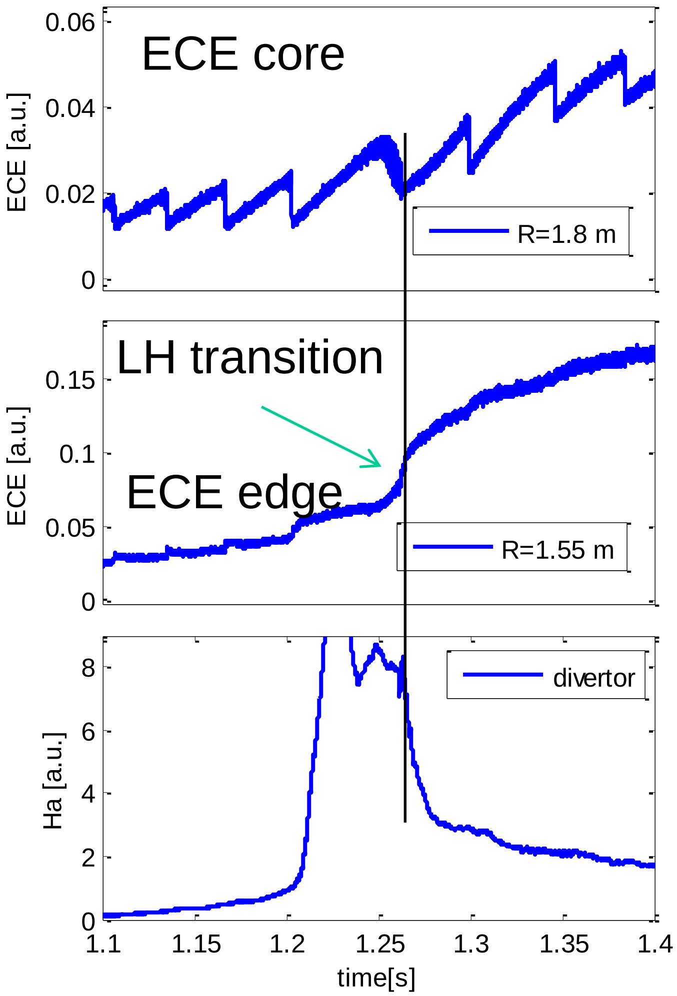




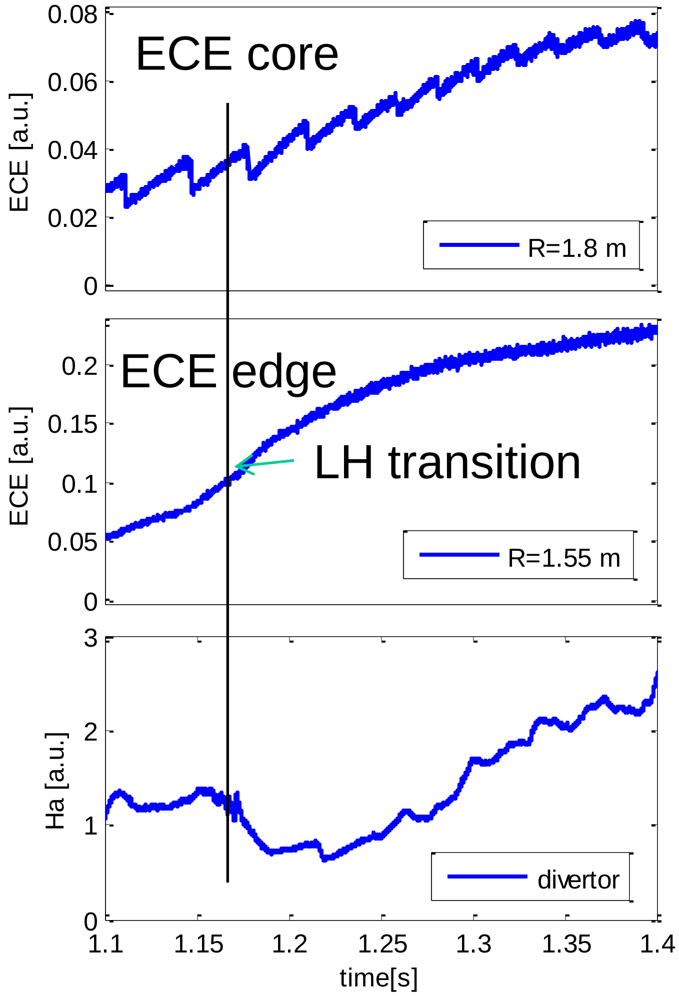
Estimations of rotation based on the NBI torque
Assumption : no pinch, no intrinsic torque, constant viscosity

Transition is synchronized for Giant Sawtooth Crash

Shot # 4333



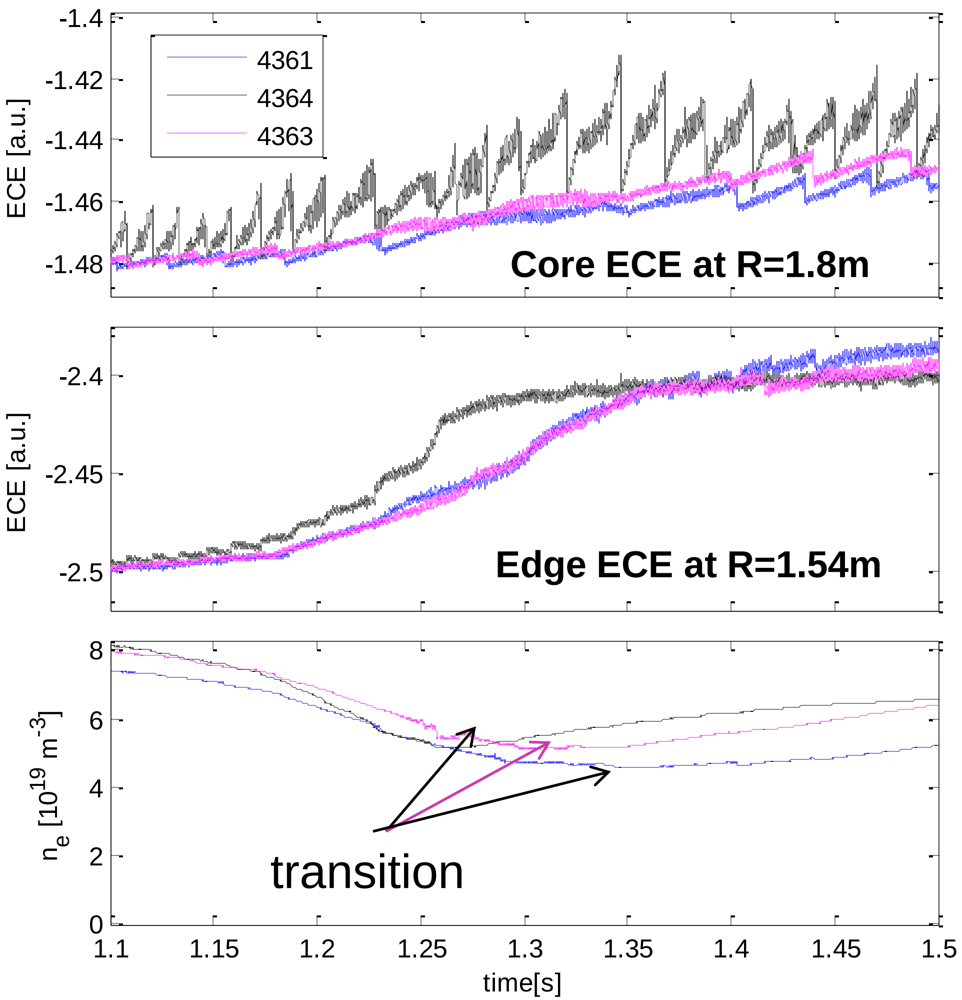
Shot # 4202



Bigger sawtooth
Synchronized with ST

Smaller sawtooth
Not synchronized with ST

Effect of ECCD on sawtooth at transition



4361 : central cntr-ECCD
4364 : central perpendicular
4363 : central co-ECCD

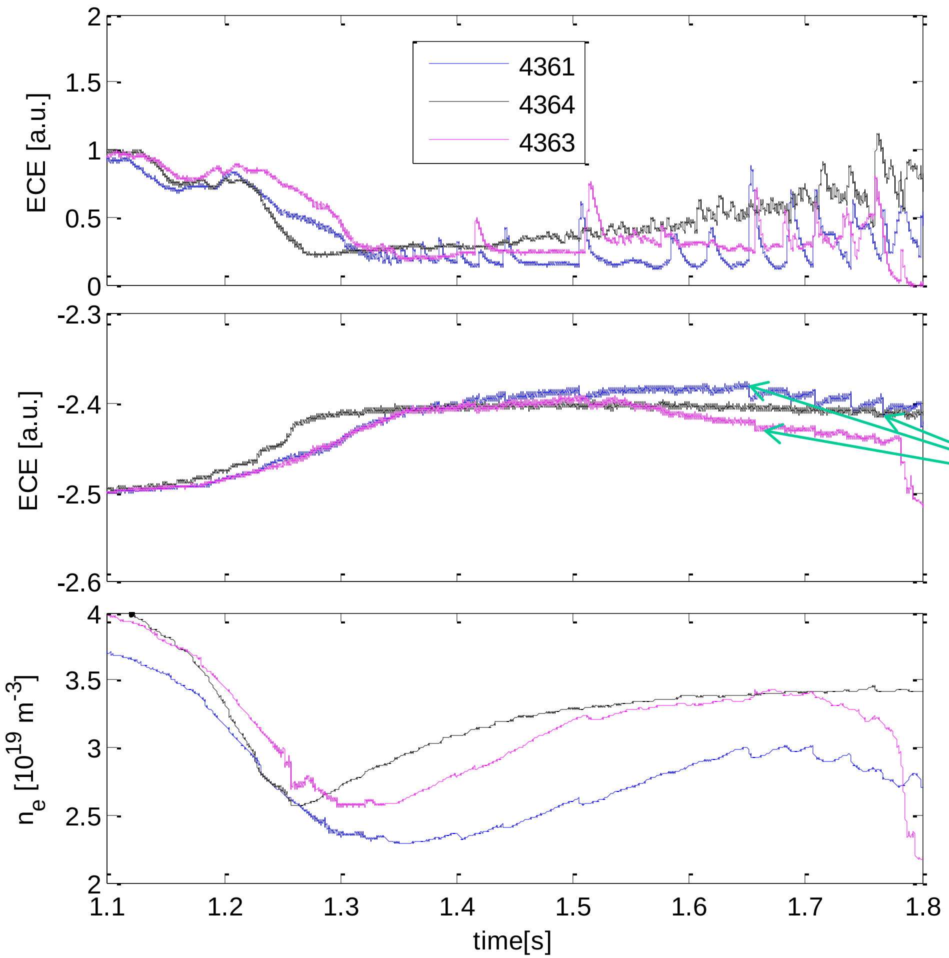
With 70keV co-NBI (~0.8 MW)
(ST period increased as reported)
A. Mux, EPS 2003

-Larger ST peroid & smaller amplitudes for Cntr- & co- ECCD
Stabilizing!

-smaller ST period & larger amplitude for perp- ECRH
Destabilizing!

-Stabilizing effect for Cntr- & co- ECCD (different from reported)
A. Manini, EPS 2005

Effect of ECCD on ELMs (effect of density?)



4361 : central cntr-ECCD
4364 : central perpendicular
4363 : central co-ECCD

Perpendicular ECRH has low amplitude & grassy ELMs

Small drop of ECE for perpendicular injection

However, it might be due to the different density level also.