Confinement and ELM characteristics in KSTAR H-mode plasmas

J-W. Ahn[1]

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NFRI 국가핵융합연구소 National Fusion Research Institute

Outline

- Introduction and power threshold study
- Confinement and ELM characteristics of three ELM types
- Profile measurement during the ELM cycle
- ELM characteristics of RMP ELM suppression
- Characteristics of late H-mode
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Procedure of obtaining loss power and estimation of energy confinement time

$$\frac{dW_{MHD}}{dt} = P_{ohm} + P_{NBI,inj.} - P_{NBI,shinethr.} + P_{ECH,inj} - P_{rad} - P_{loss}$$

Obtained from EFIT ($\frac{dW_{MHD}}{dt}$)

$P_{OH}=V_{SURF}\cdot I_P$

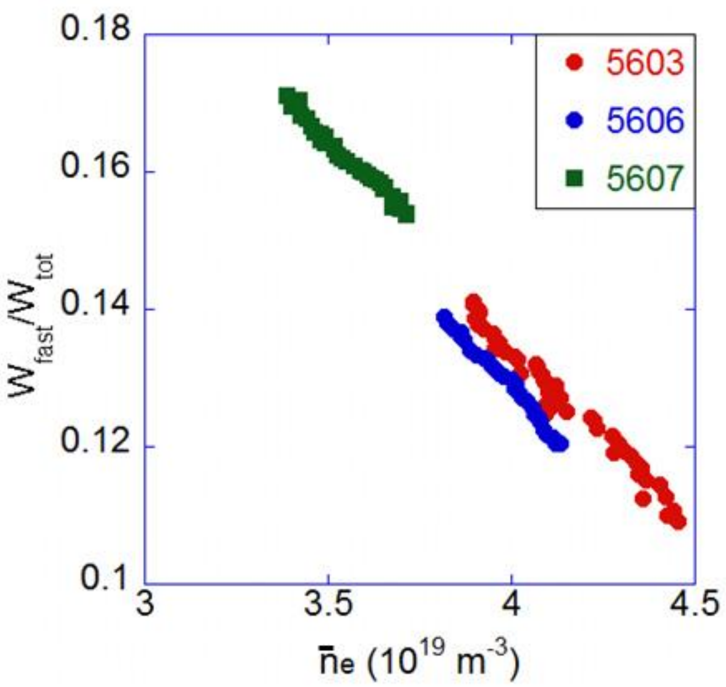
V_{SURF} is obtained from loop voltage measurement

Calculation by ASTRA code

- Global energy confinement time
  → $\tau_E = W_{stored}/P_{loss}$
- Total stored energy includes both thermal and fast ion components
  → $(W_{tot} = W_{thermal} + W_{fast})$
- W_{fast} can be obtained by ASTRA calculation
  → $\tau_{E,thermal} = W_{thermal}/P_{loss}$
- No radiation power measurement at present, therefore 10-30 % of total injected power is taken into account as the radiation power.

ASTRA simulation by H.-S. Kim

Fast ion component has strong dependence on density

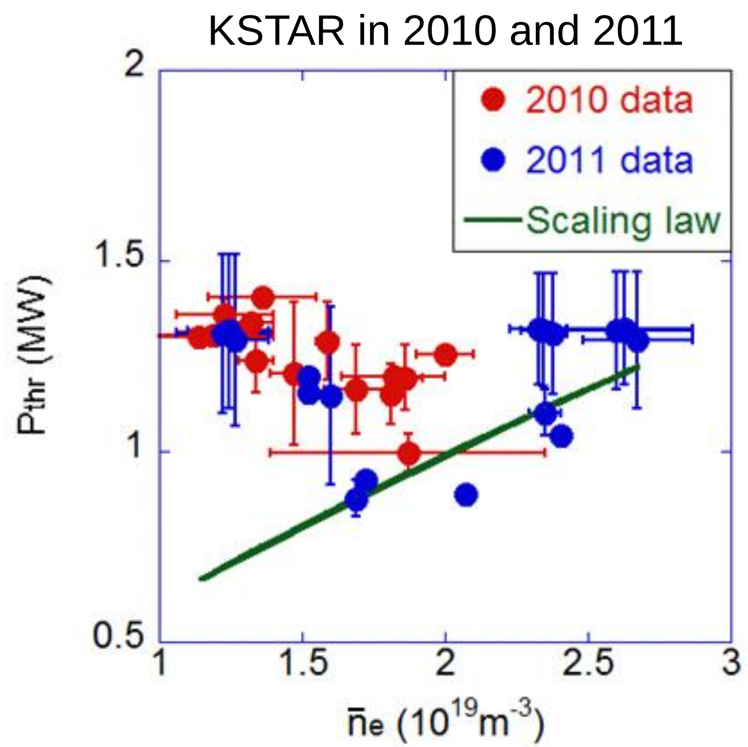


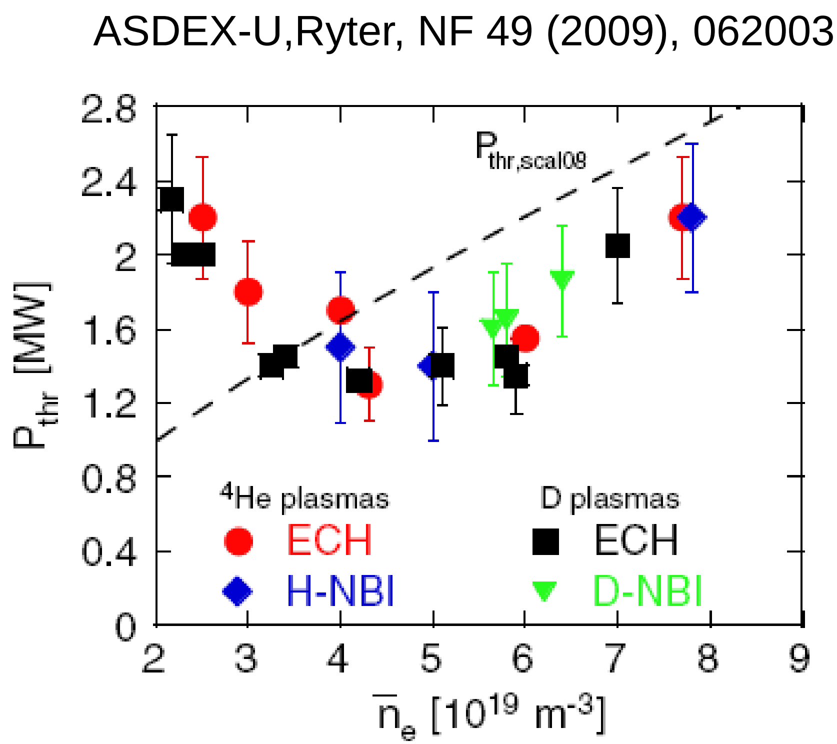
The beam module in ASTRA calculates longitudinal ($p_{||,fast}$) and perpendicular ($p_{\perp,fast}$) pressures generated by fast ions from NBI

$$W_{fast} = 0.8\times10^{-3}\int p_{\parallel,\,fast}dV + 1.6\times10^{-3}\int p_{\perp,\,fast}dV$$

- Weiland pedestal model was used to for the ASTRA calculation
  → W_{fast}~10-30% of W_{tot}
- W_{fast} is found to be a strong function of density, ie the effect of fast ion confinement becomes more important in the low density regime

Power scan yielded P_{thr} roll-over as a function of density





- Power scan by changing NBI duty cycle, ie P_{NBI}=0.7-1.5MW, in order to find the H-mode power threshold
- Good agreement with 2010 P_{thr} data for the left branch

  → 2011 data clearly shows the density roll-over and the presence of minimum power threshold at $n_e \sim 2 \times 10^{19} m^{-3}$

J-W. Ahn, submitted to NF

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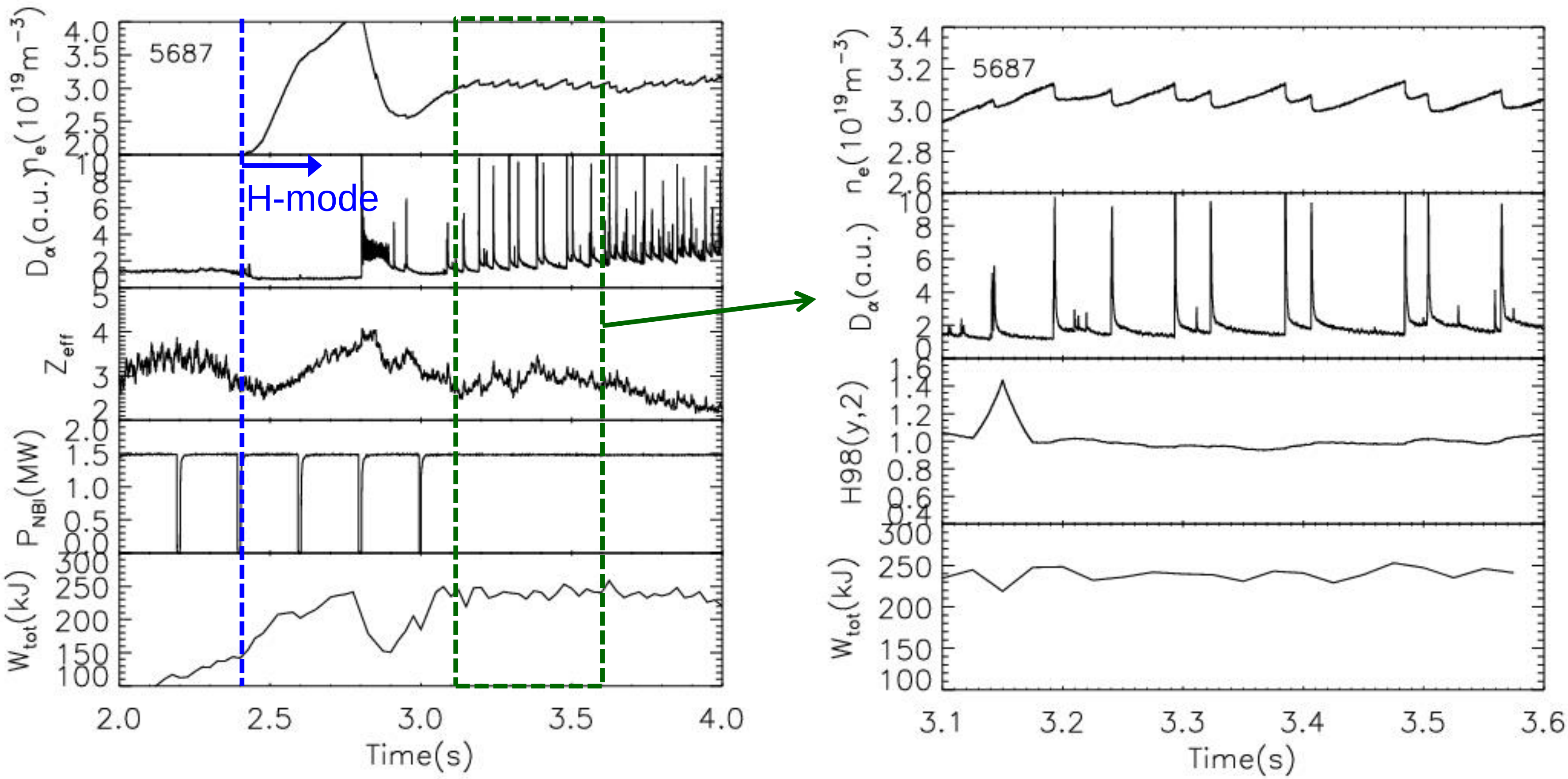
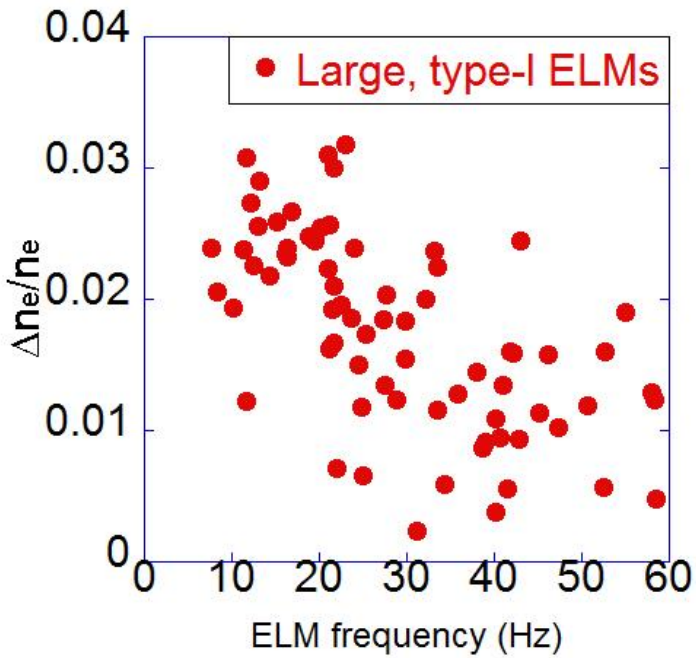
ELMs appear to be in three distinct regimes 1: Large ELMs

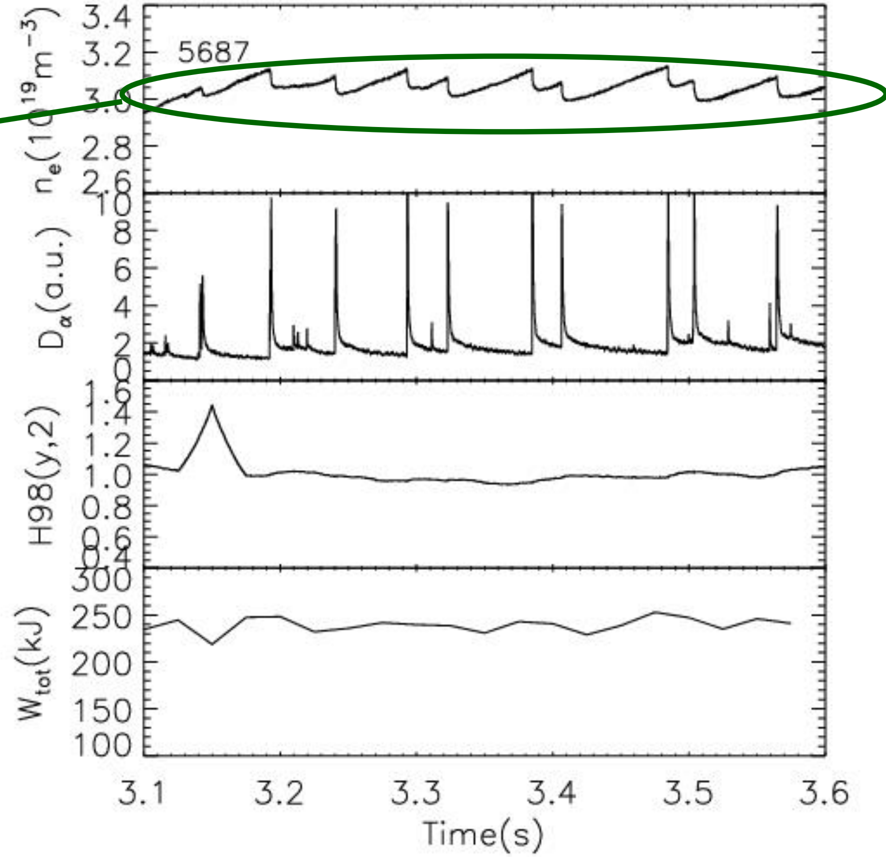
- Large, type-I ELMs
  - Low ELM frequency (f_{ELM}=10-50Hz), large ELM size ($\Delta n_e/n_e$=1-4%), good confinement quality ($H_{98(y,2)}$ ~1)



Large ELMs show clear inverse proportionality between ELM size and frequency

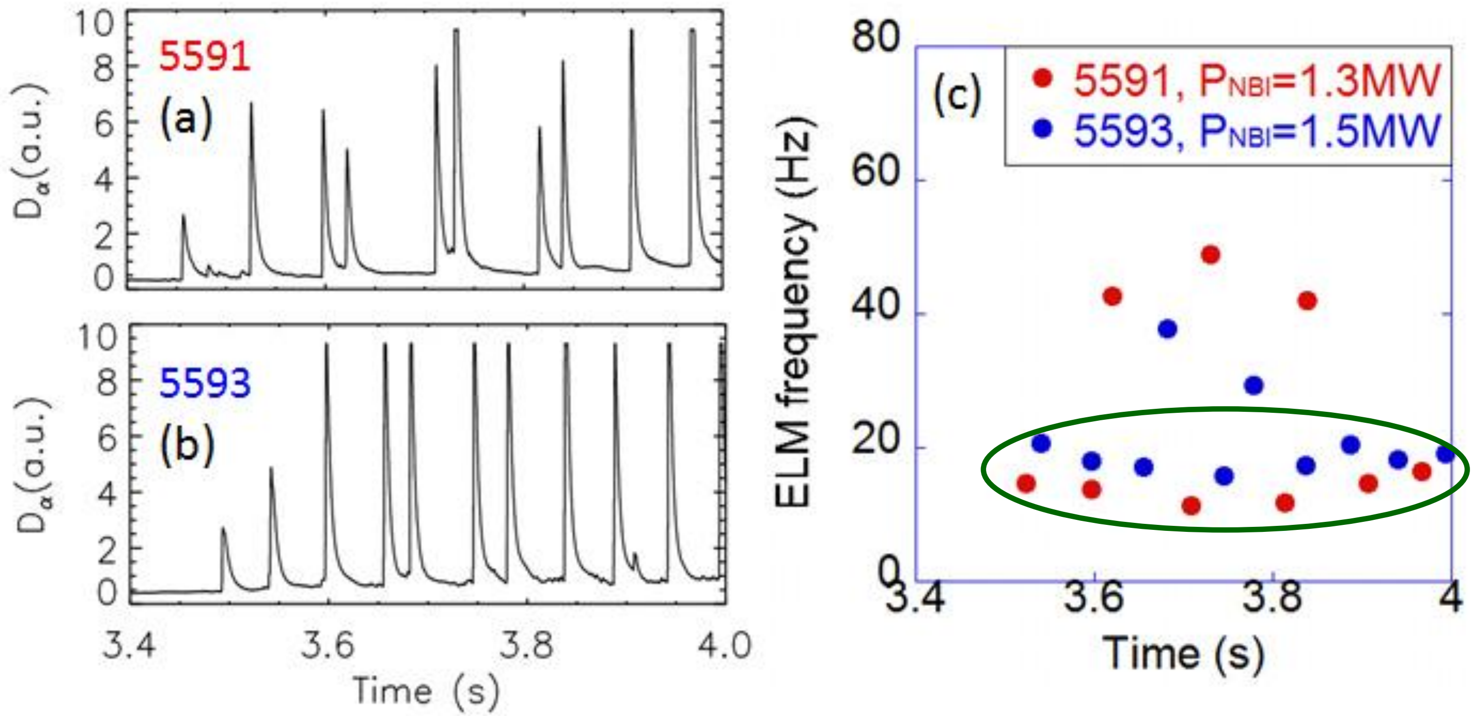
- Large, type-I ELMs
  - Low ELM frequency (f_{ELM}=10-50Hz), large ELM size ($\Delta n_e/n_e$=1-4%), good confinement quality ($H_{98(y,2)}$ ~1)





- Density drop due to an ELM burst ($\Delta n_e/n_e$) used as ELM size
- ELM size is inversely related to the ELM frequency

Large ELMs: ELM frequency increases with increasing heating power, a behavior of type-I ELMs

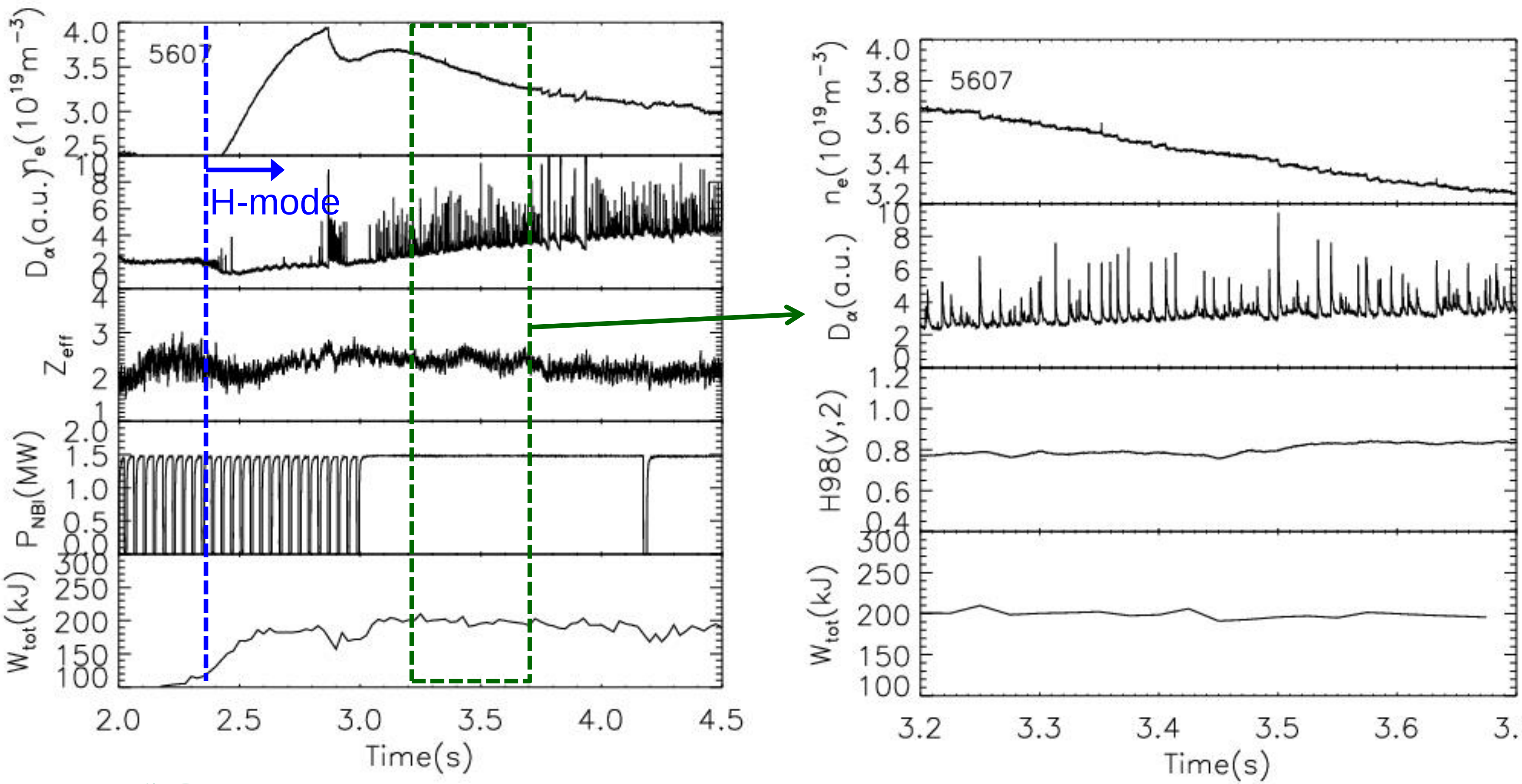


- P_{NBI} increase of 0.2MW raises the ELM frequency
  → behavior of Type-I ELMs

- However, the apparent ELM type often changes later during a shot and also during a run day (ie, type-I → type-III). Wall condition matters?

ELMs appear to be in three distinct regimes 2: Intermediate ELMs

- Intermediate ELMs (type-III?)
  - High ELM frequency (f_{ELM}=50-250Hz), small ELM size ($\Delta n_e/n_e$ below 1%, normally ≤ 0.5%), poorer confinement quality ($H_{98(y,2)}$ = 0.7-0.8)



Intermediate ELMs do not show clear size and frequency correlation

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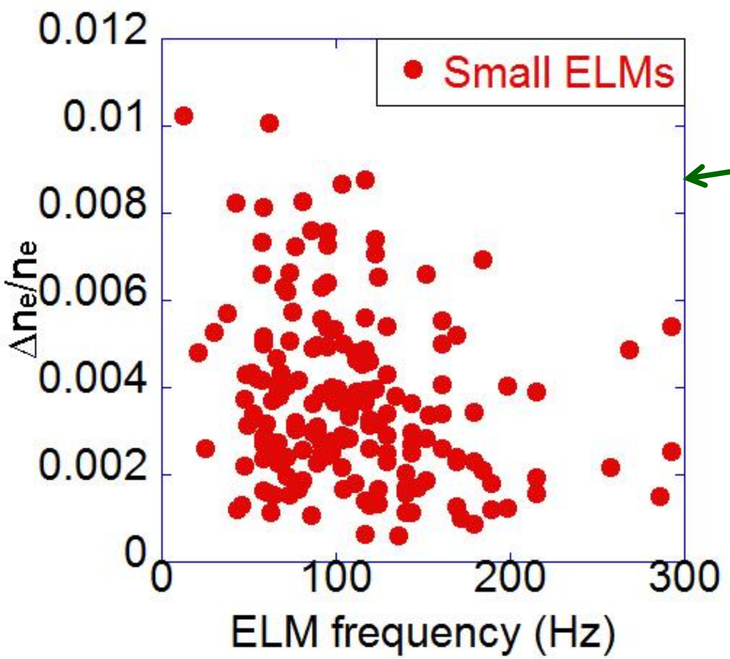
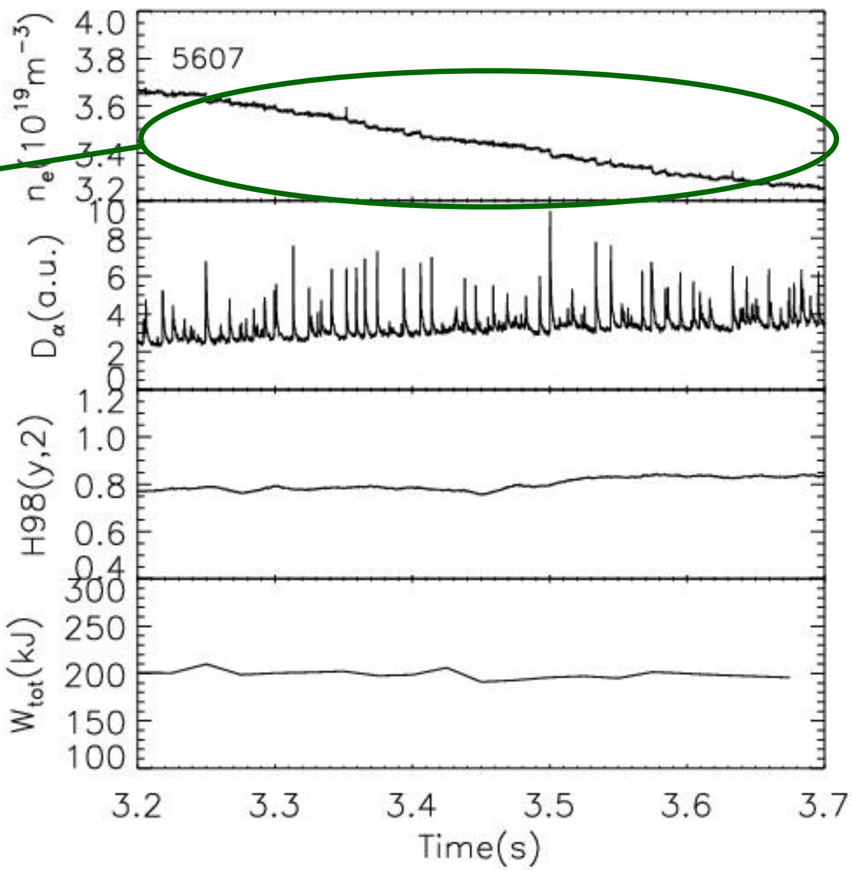
  - High ELM frequency (f_{ELM}=50-250Hz), small ELM size ($\Delta n_e/n_e$ below 1%, normally ≤ 0.5%), poorer confinement quality ($H_{98(y,2)}$ = 0.7-0.8)

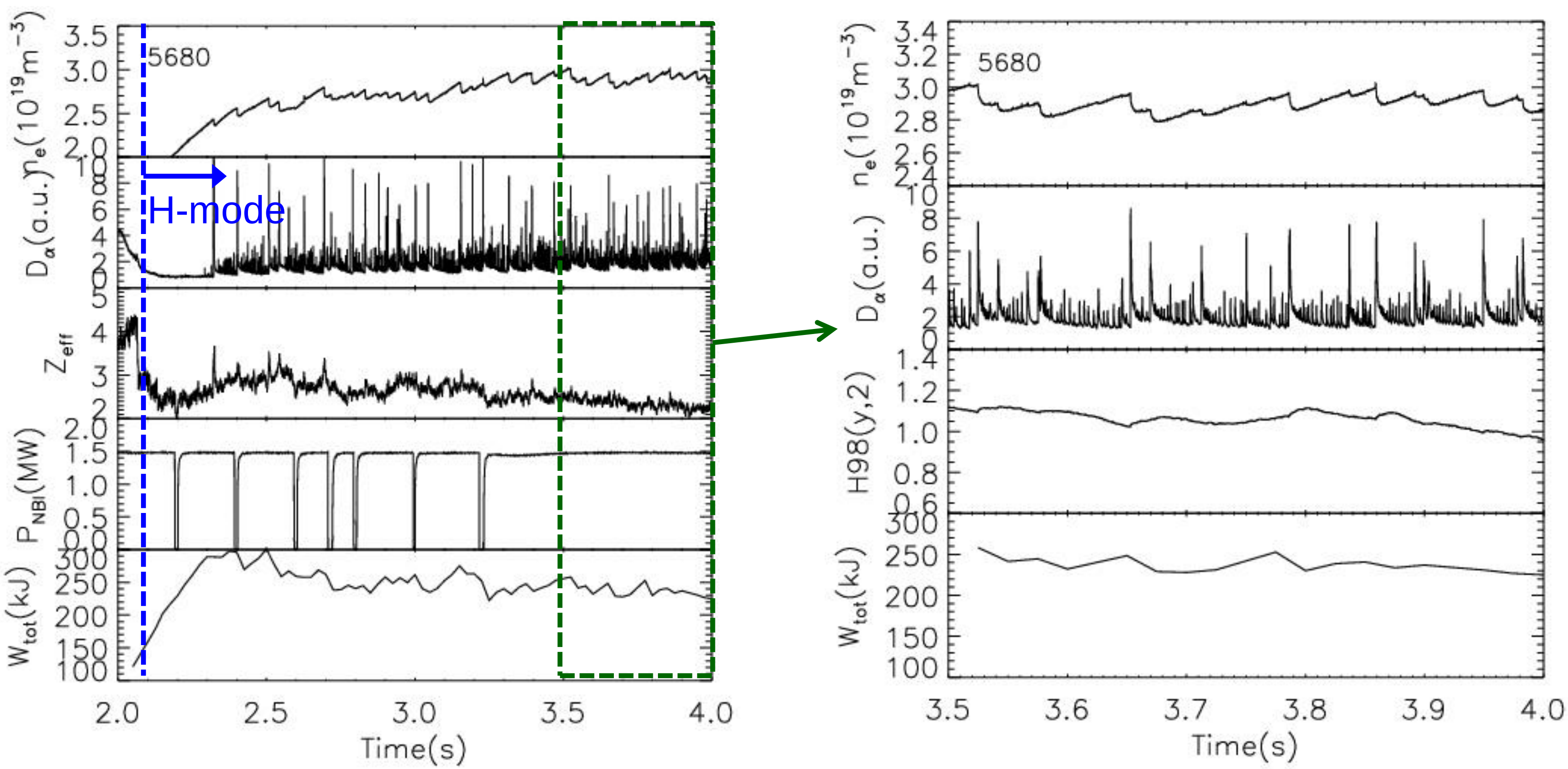




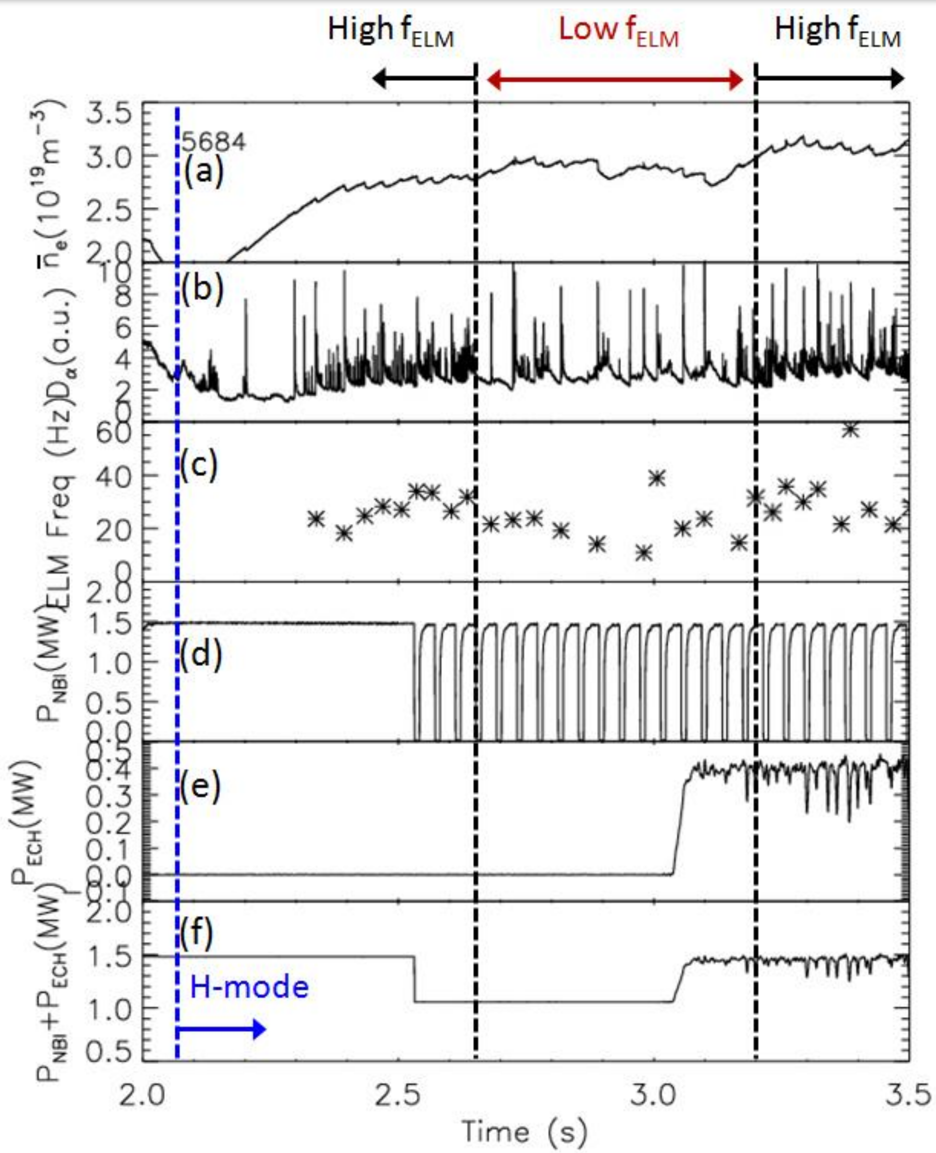
- No clear correlation between ELM size and frequency

ELMs appear to be in three distinct regimes 3: Mixed ELMs

- Mixed (large and small) ELMs
  - Low (f_{ELM}=10-50Hz) and high (20-250Hz) ELM frequency, large (1-4% of $\Delta n_e/n_e$) and small (below 0.5% of $\Delta n_e/n_e$) ELM size, good confinement quality ($H_{98(y,2)}$ ~1)



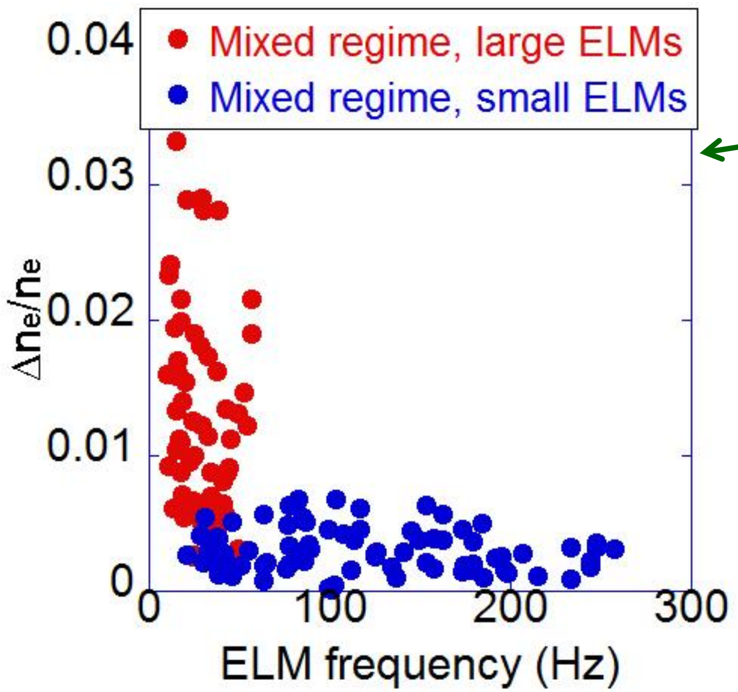
Mixed ELMs: Large ELM peaks are type-I ELMs

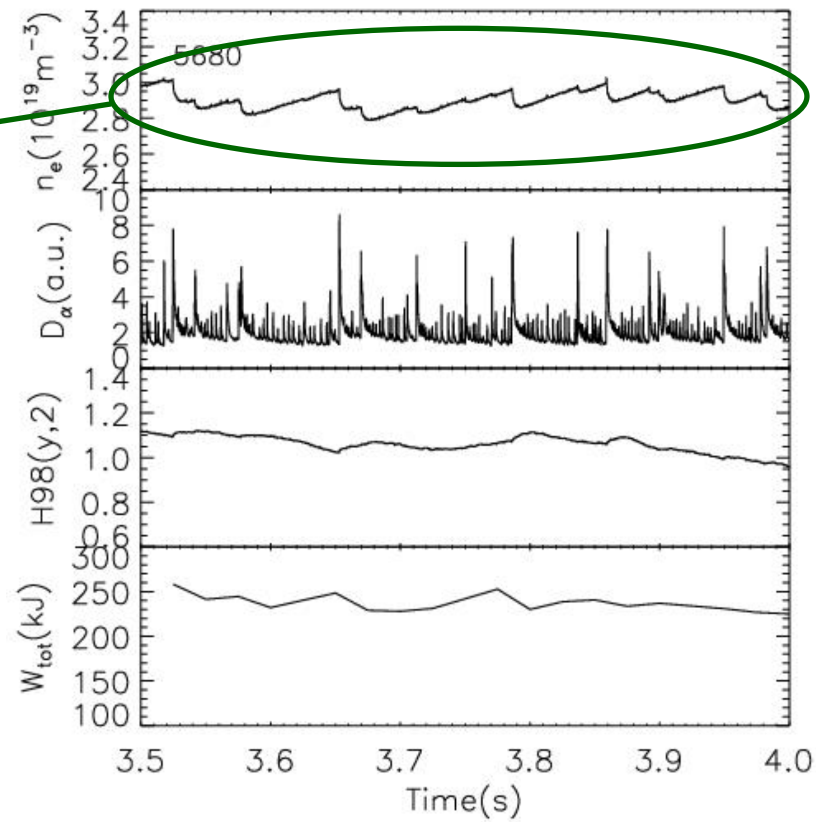


- Change of input power was achieved by NBI modulation plus ECH injection
- Frequency of large ELM peaks increases with increasing input power → type-I ELM
- Also, tiny ELM peaks between large ELMs disappear during the lower heating power stage
- Time delay of 150-200ms is consistent with NBI slowing down time and energy confinement time

Mixed ELMs: Large and small peaks show distinctive features from each other

- Mixed (large and small) ELMs
  - Low (f_{ELM}=10-50Hz) and high (20-250Hz) ELM frequency, large (1-4% of $\Delta n_e/n_e$) and small (below 0.5% of $\Delta n_e/n_e$) ELM size, good confinement quality ($H_{98(y,2)}$ ~1)

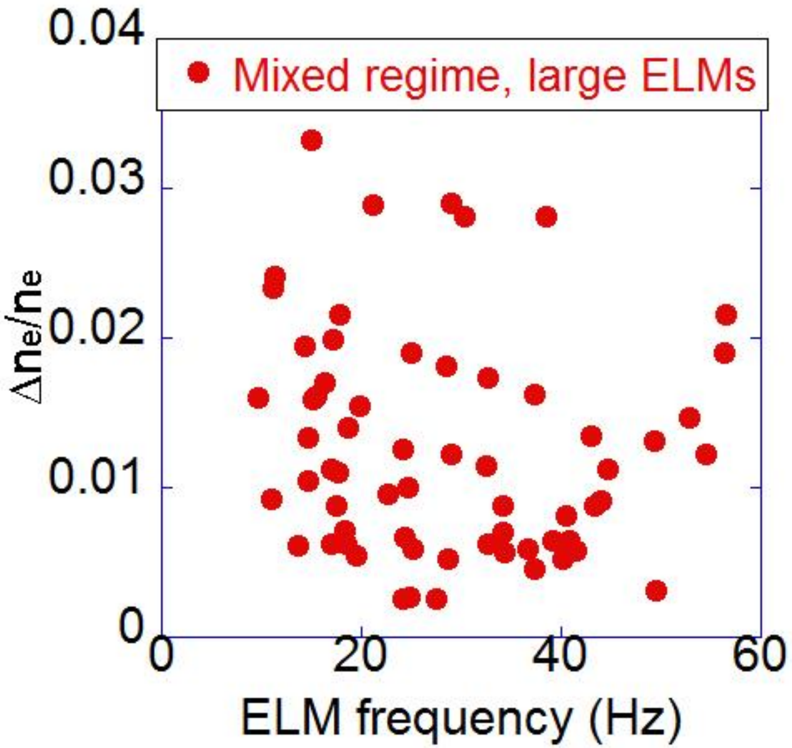


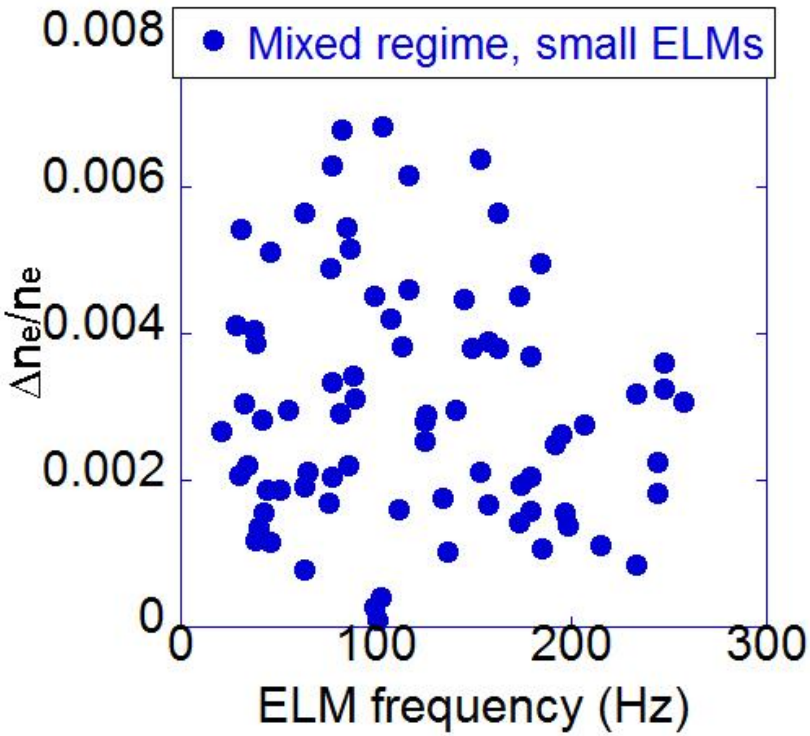


- Two distinctive ELM behaviors are exhibited

Mixed ELMs: Large ELMs barely obey inverse size-freq relation but small ELMs do not follow it

- Size of large ELMs appears to be inversely related with the ELM frequency although scatter is larger than that for type-I ELMs
- Small ELMs do not have size-frequency correlation





When does each type of ELMs occur?

- Type-I ELMs:
  - Most common
  - Observed in a range of P_{NBI} from 0.8MW to 1.5MW
  - Tend to occur in lower density level with $0.35 < n_e/n_G < 0.45$

- Intermediate ELMs (type-III?):
  - High density appears to lead to this ELM regime more easily
  - Tend to occur toward later stage of a shot, between large ELM peaks (or later shots during a run day, wall condition matters?)
  - Wider density range of $0.35 < n_e/n_G < 0.55$

- Mixed ELMs (type-I + small ELMs):
  - Often occur in late H-mode as well as in main H-mode
  - Wider density range of $0.38 < n_e/n_G < 0.57$

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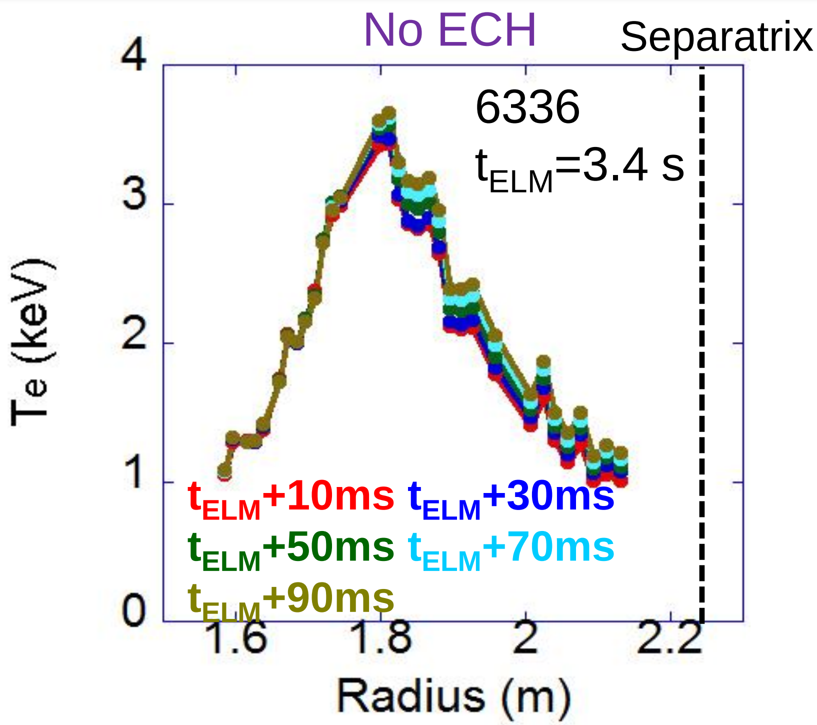
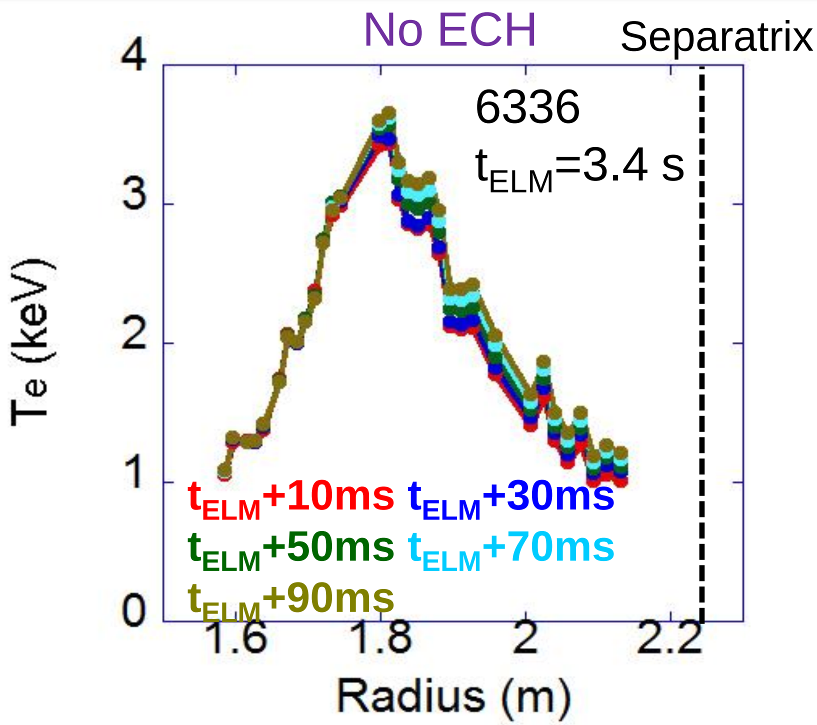
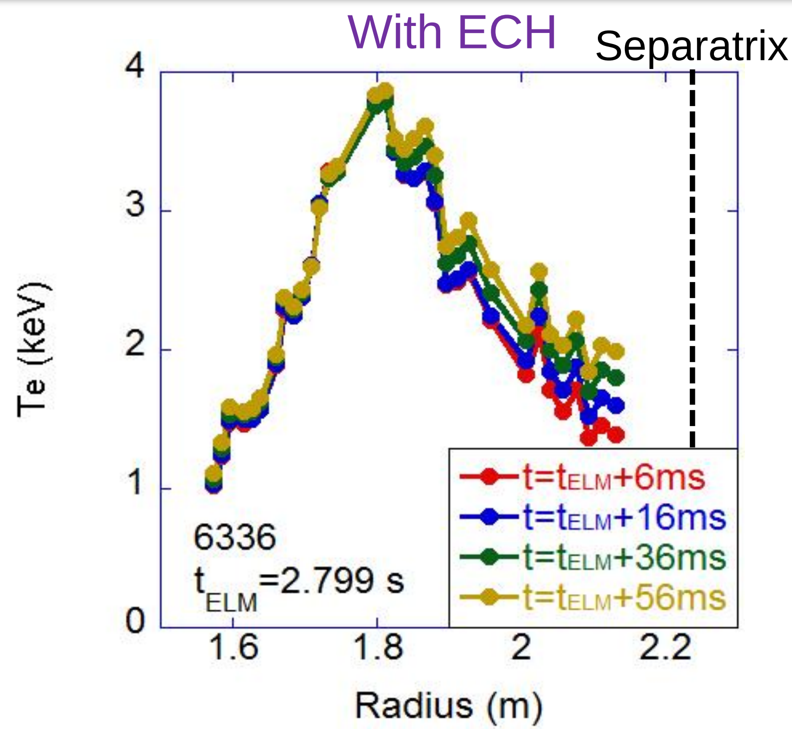
T_e drop by type-I ELM is only on LFS and the profile builds up continuously for whole ELM cycle



- Outboard pedestal T_e (and n_e from interferometer) continuously builds up through the whole ELM cycle → continuous pedestal p_e rise. No changes on the inboard side
- Estimated electron collisionality for LFS pedestal is ν_e*=0.5-0.6 with pedestal T_e drop by an ELM ~ 100-200eV

ECH injection makes the LFS T_e drop by an ELM much bigger than without ECH





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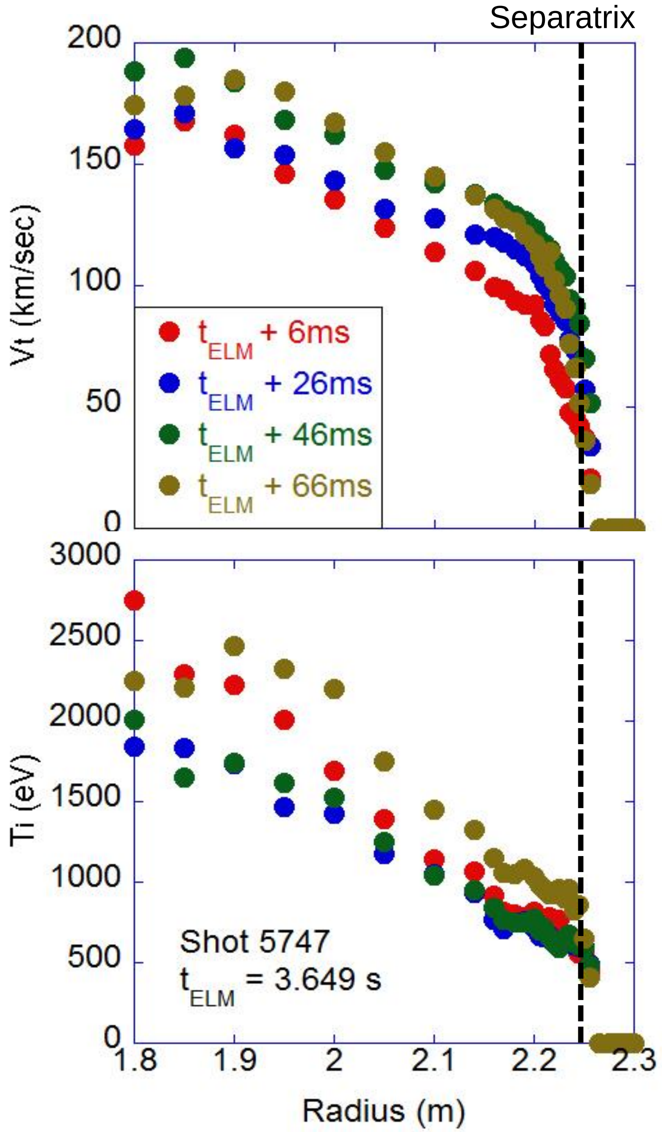
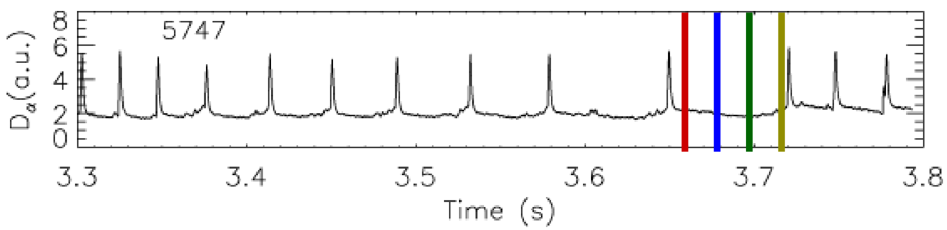
- Estimated electron collisionality for LFS pedestal is ν_e*=0.5-0.6 with pedestal T_e drop by an ELM ~ 100-200eV
- LFS T_e drop by an ELM can reach 600-700eV when ECH power is injected, while HFS T_e drop is still very moderate, LFS ν_e*~0.2
- ECH doesn't make LFS n_e drop much bigger

T_i profile data suggests that ion pressure might play an important role in pedestal ELM stability





- Very clear pedestal structure is measured for both V_t and T_i profiles
- V_t pedestal top is located further inside the separatrix
- V_t build up is also continuous, but T_i (therefore, p_i) pedestal only rises at the last stage → T_i might play an important role in ELM pedestal stability

J-W. Ahn, submitted to NF

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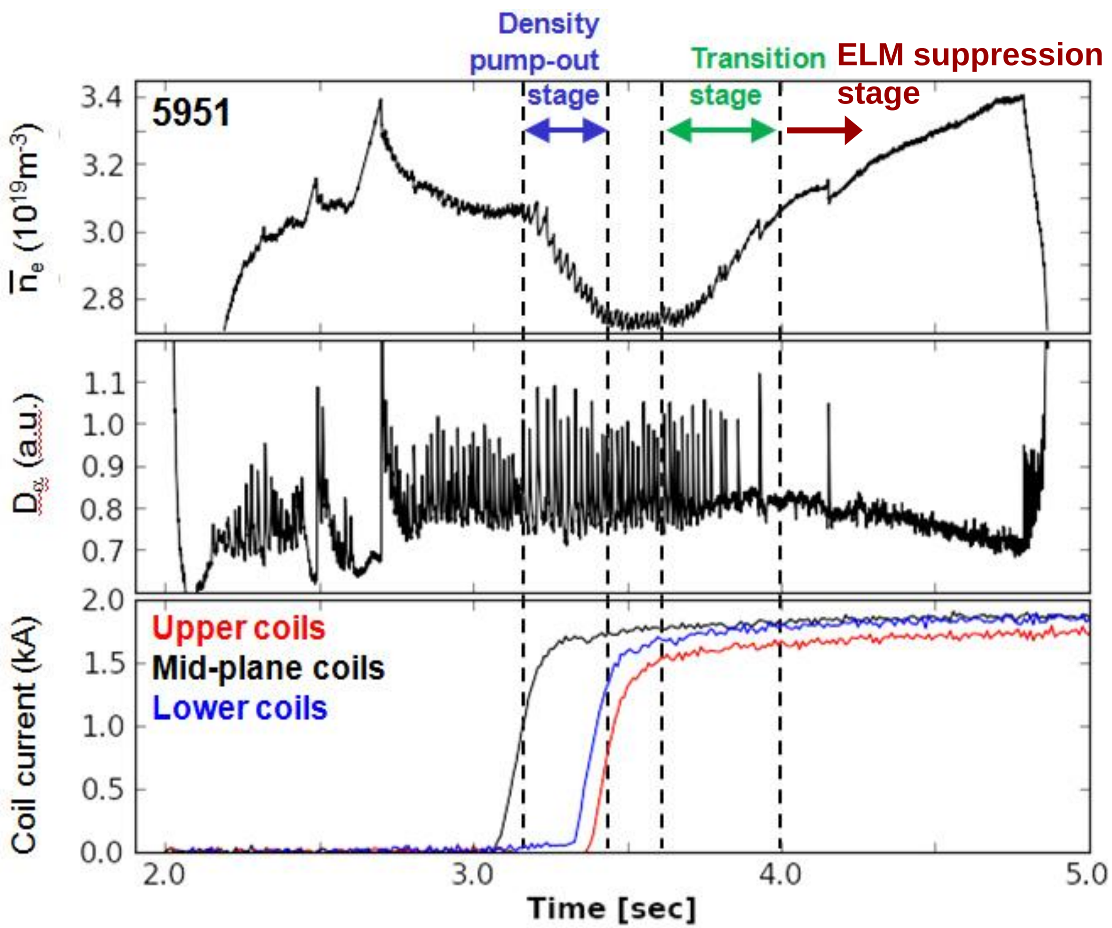
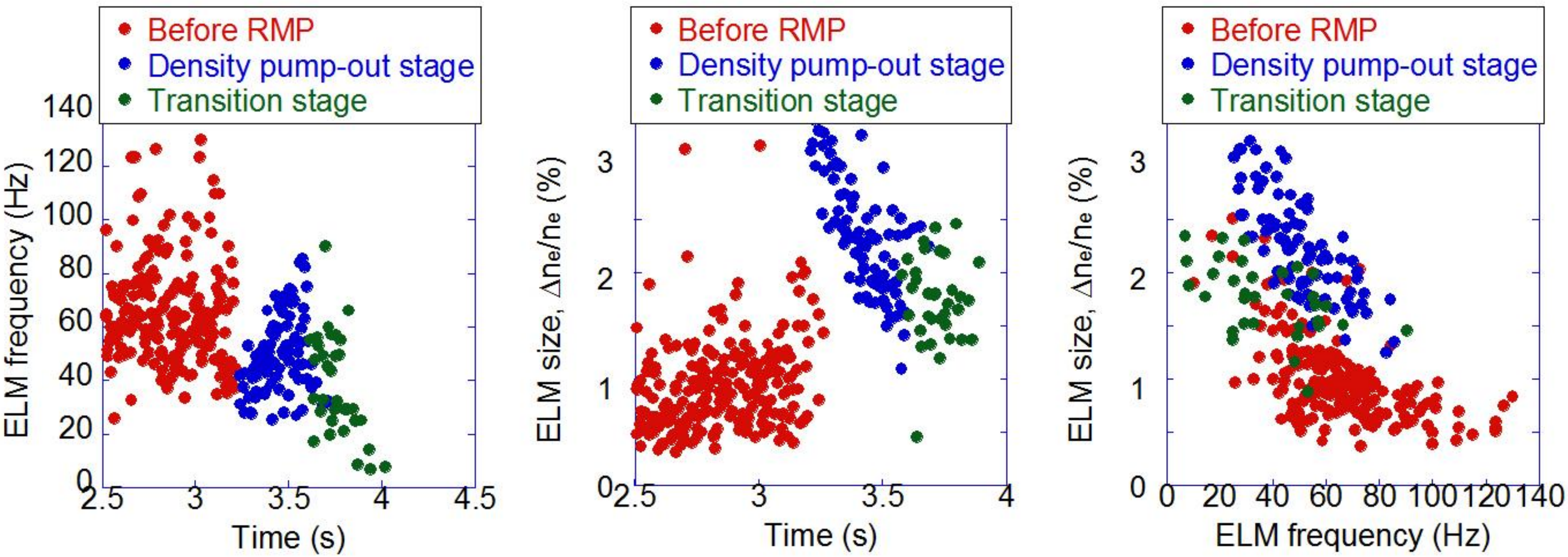
RMP initially deteriorates confinement but it rises back up as the ELMs are suppressed

RMP experiment led by Y.M. Jeon and J.-K. Park



- ELM suppression by RMP was successfully achieved in 2011
- There are several stages observed during the RMP ELM suppression
  - Density pump-out initially induced, both n_e and W_{tot} decrease
  - They begin to rise again after upper and lower coils are applied
  - ELM suppression stage

Each stage of RMP ELM suppression exhibits distinctive ELM characteristics



- With the beginning of density pump-out stage, ELM size (frequency) suddenly jumps (drops), i.e. ELMs become 'intensified', and then rapidly decreases (increases) until it reaches the transition stage

- In the transition stage, ELM frequency quickly drops but the size grows only weakly in time, leading to weak inverse correlation between size and freq.

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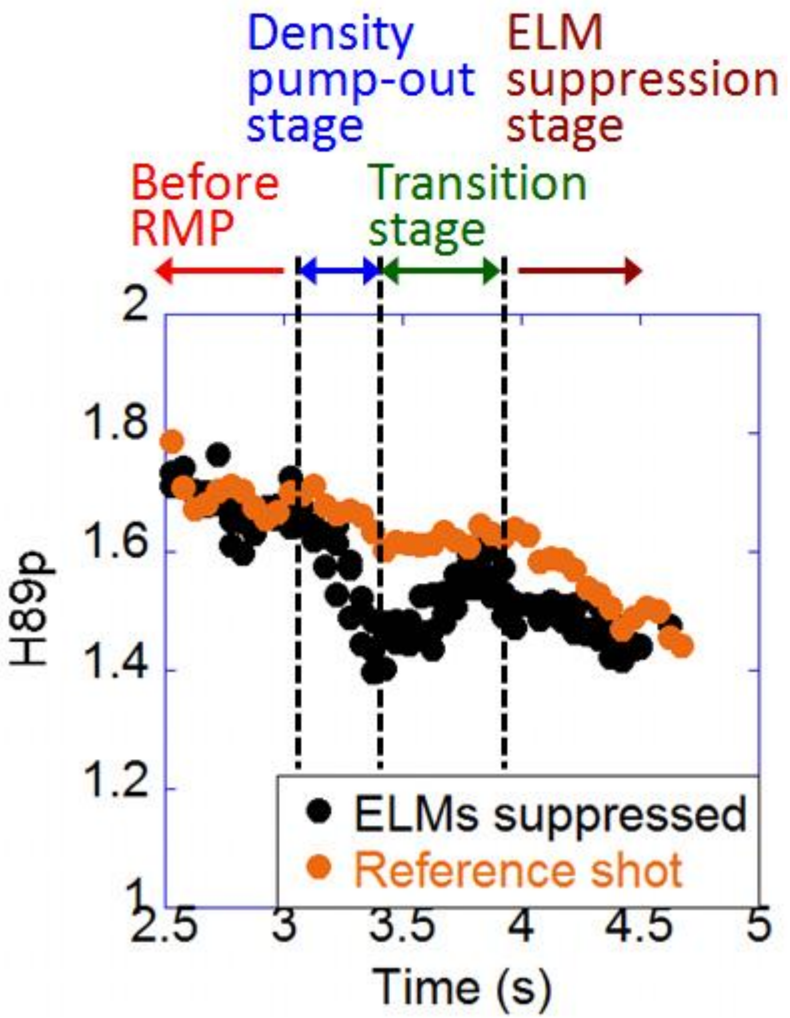
Confinement quality initialy drops but recovers with the achievement of ELM suppression



- H-factor rapidly drops during the density pump-out stage, similar to the density drop
- It slowly increases during the transition stage and finally reaches similar level to the reference case
- During the ELM suppression stage, H-factor behaves similar to the reference.

J-W. Ahn, submitted to NF

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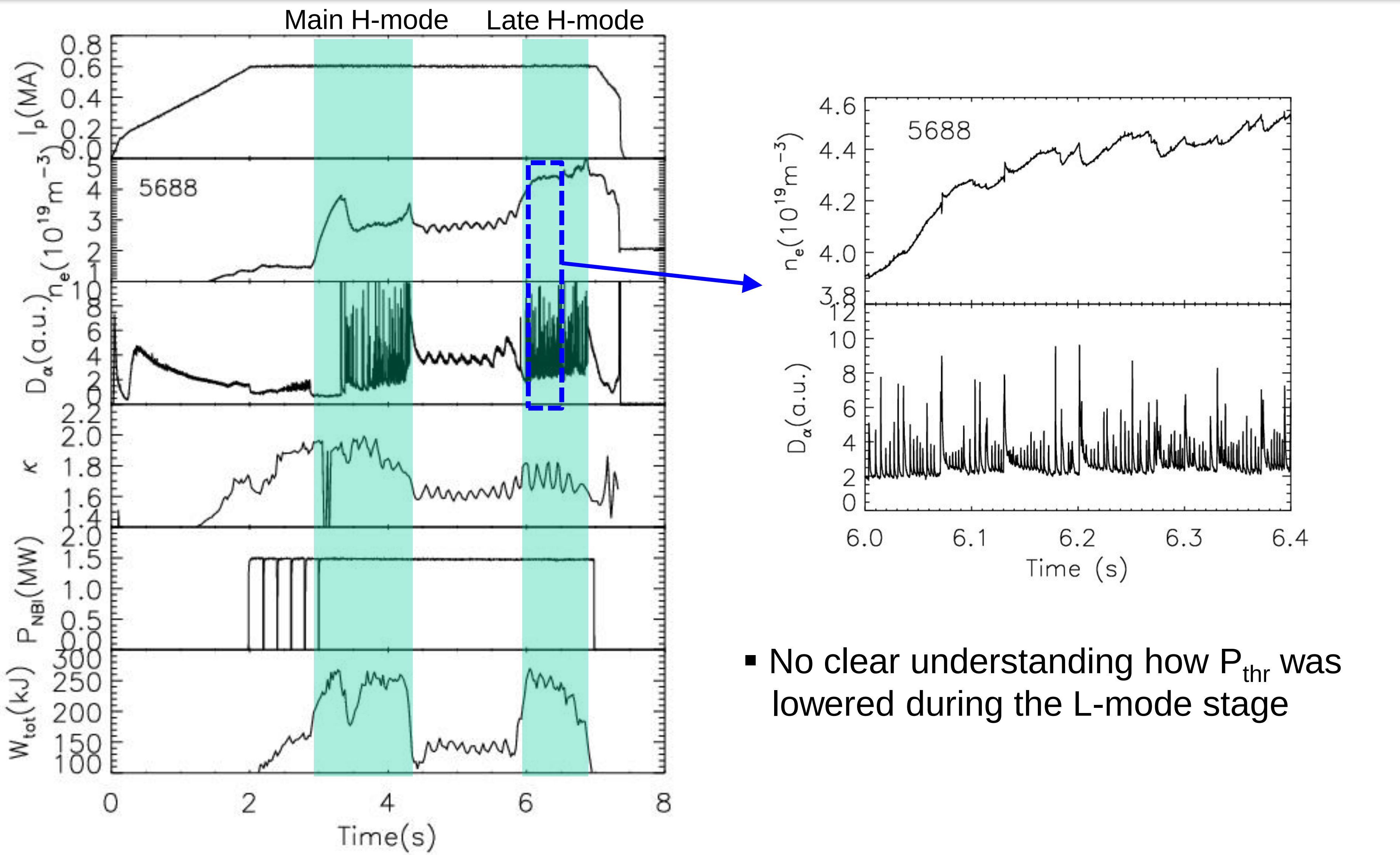
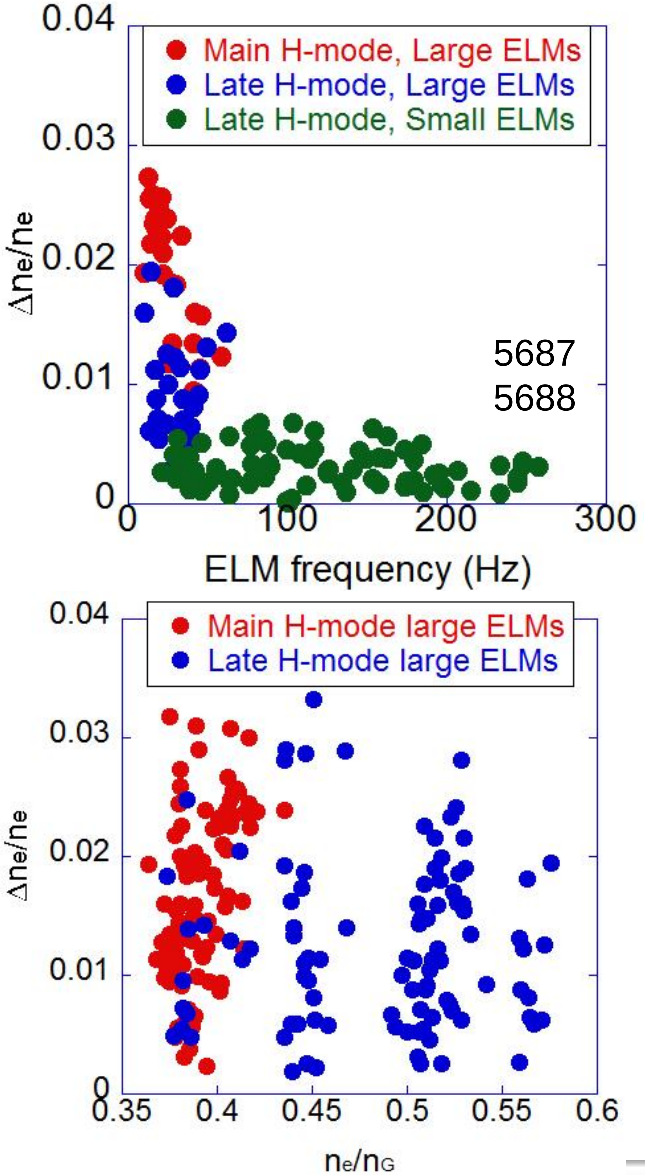
Transition to 2nd H-mode in later stage was observed for some discharges



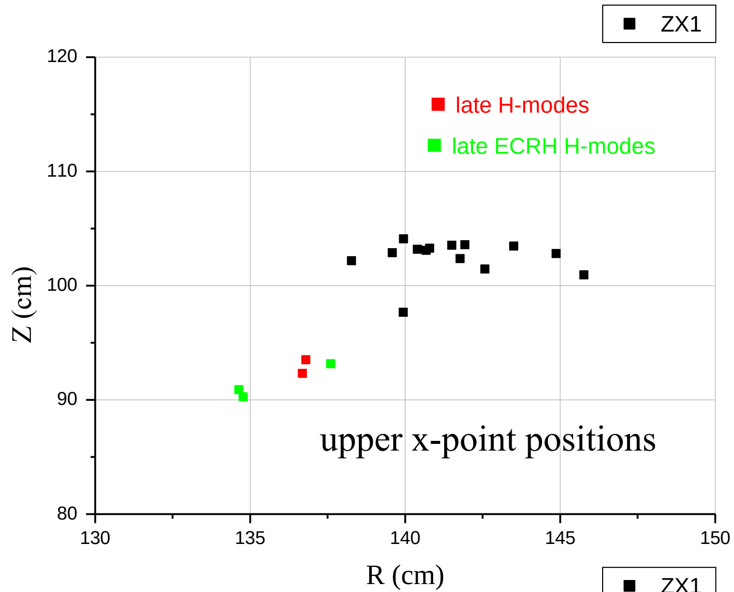
- No clear understanding how P_{thr} was lowered during the L-mode stage

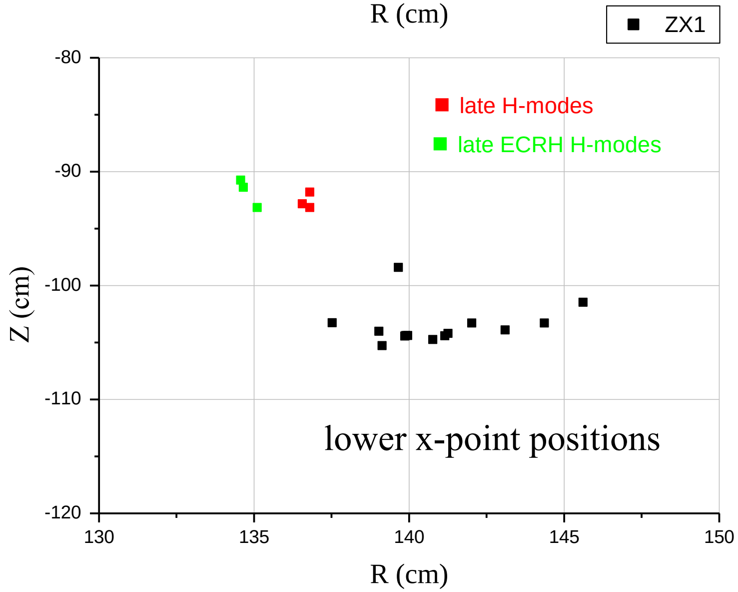
Mixed ELM regime occurs in late H-mode



- Mixed ELM regime (type-I + small)
  - Inversely proportional between ELM size and f_{ELM} for large ELMs
  - Wider range of Greenwald fraction ($0.38 < n_e/n_G < 0.57$) than for the preceding main H-mode ($0.36 < n_e/n_G < 0.42$)

X-point movement is opposite to NSTX report for lower power threshold





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  - Wider range of Greenwald fraction ($0.38 < n_e/n_G < 0.57$) than for the preceding main H-mode ($0.36 < n_e/n_G < 0.42$)

- Elongation was noticeably lower (κ=1.6-1.7) than for the main L-H transition (κ=1.8-1.9)
  → Smaller radius and larger height of X-points
  → Opposite to NSTX result regarding dependence of P_{thr} on R_X

A. England, to be submitted to PoP

Summary

- H-mode power threshold study yielded roll-over of P_{thr} at n_e~$2x10^{19}m^{-3}$.
- Fast ion component of total stored energy becomes more important in low density regime, therefore in estimation of thermal energy confinement time
- Three distinctive ELM types are observed
  - Type-I ELMs: Good confinement quality (H98~1), large ELM size, clear inverse correlation of ELM size with frequency
  - Small ELMs: Poorer confinement (H98=0.7-0.8), very small ELM size, no size-frequency correlation
  - Mixed ELMs: Good confinement quality (H98~1), large and small ELMs, large ELMs have inverse size-freq. correlation with scatter
- RMP initially deteriorates confinement but it rises back up as the ELMs are suppressed. ELMs exhibit distinctive characteristics in each stage
- Unusual late L-H transition occurs but the cause of lowered P_{thr} is yet unknown. Only mixed ELM regime is observed in wide density range.