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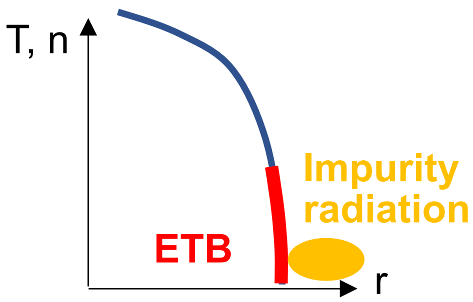
RMP induced H-mode transition during divertor detachment with enhanced edge radiation in deuterium plasmas in LHD

M. Kobayashi, R. Seki, Y. Takemura, Y. Hayashi, T. Oishi, K. Tanaka, K. Mukai, S. Morita, K. Ida, S. Masuzaki, and the LHD Experiment Group

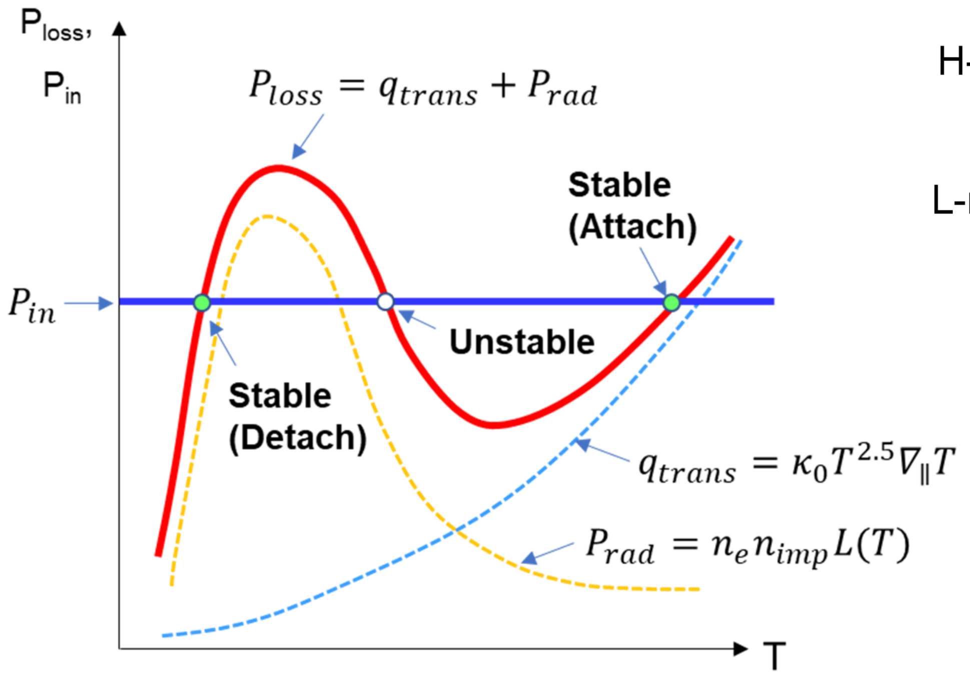
National Institute for Fusion Science

Compatibility of good core plasma performance with divertor heat load mitigation



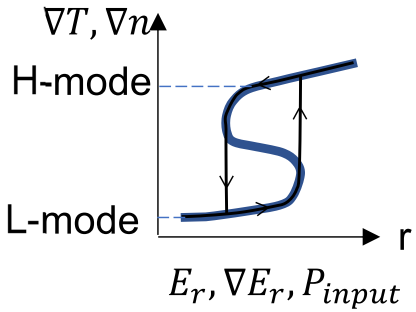
ETB & impurity radiation (detachment) are compatible each other?
If so, how they interact each other?

Bifurcation of detachment



Kobayashi, Tokar Fusion Energy 2019

Bifurcation of ETB



Adiabaticity parameter :
Ratio of //-electron diffusion speed and turbulence propagation speed

$$\alpha_{adi} = \frac{k_{\|}^2 v_{the}^2}{|\omega| \nu_{ei}} \propto T_e^2/n$$

T↓, n↑ → α_{adi} ↓
→ collapse of shear layer (Zonal flow)

Hajjar PoP 2018

Resistive pressure gradient driven MHD instability:

$$\gamma_{interchange} \propto \eta^{1/3} L_p^{-2/3} \propto L_p^{-2/3} T_e^{-0.5}$$

T↓, n↑ → α_{dia} ↓ → Drift resistive MHD transport enhanced

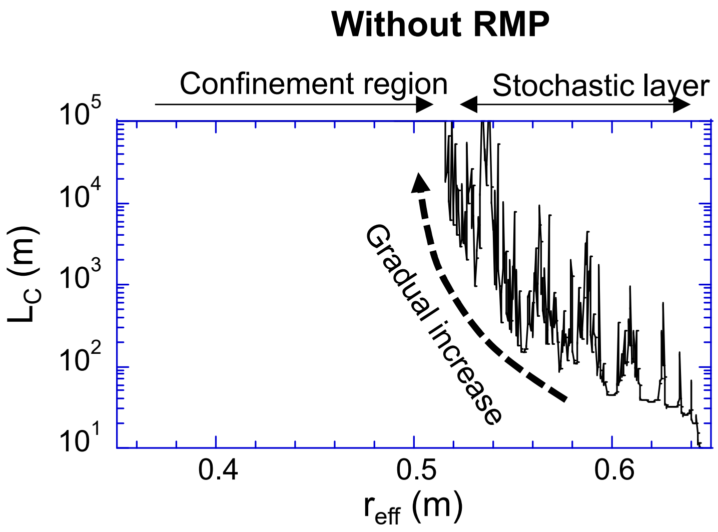
$$\alpha_{dia} \propto \sqrt{D_{gB}/D_{DRB}}$$

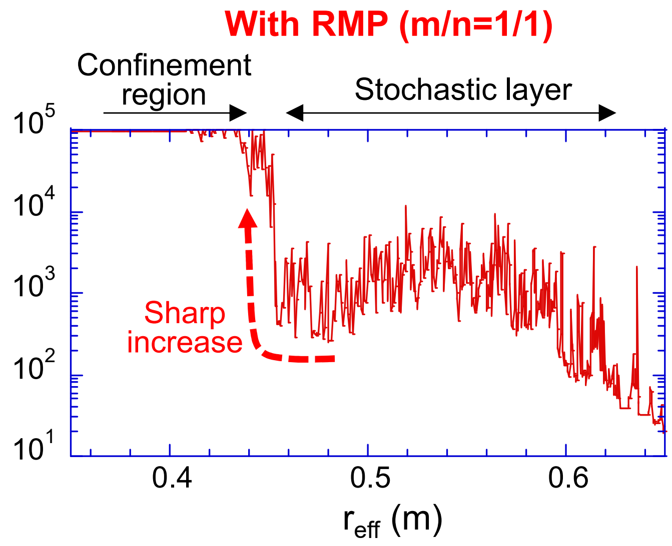
Rogers PRL 1998

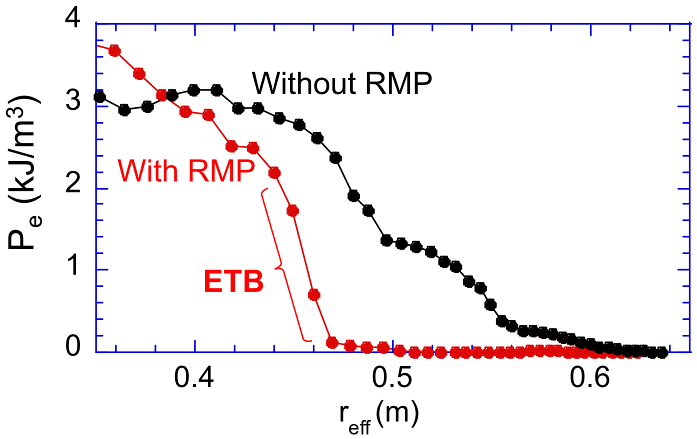
Detachment needs low T at the edge ⟷ Low edge T degrades ETB

Compatible ?
How interact each other ?

Change of edge magnetic field structure for study on compatibility of confinement with detachment RMP application → Sharp boundary btw confinement region and stochastic layer







Without RMP:
Intrinsic edge stochastic layer
Gradual increase in L_C toward confinement region → no ETB formation

With RMP:
Stochastic layer widened → **Increased impurity radiation volume**
Sharp boundary between confinement and edge region → **ETB formation**

Edge magnetic structure/topology impacts on radiation enhancement & core confinement (Compatibility of ETB with cold edge plasma with impurity radiation)

Contents of the talk

1. Introduction: Compatibility of divertor heat load mitigation & confinement
   Change of edge magnetic field structure in LHD by RMP application

2. Impact of edge magnetic field structure on density limit, radiated power, and core confinement
   ETB formation and cold front penetration, core transport

3. Confinement mode transitions during detached phase with RMP application
   Interaction between cold edge plasma, ETB, and core transport
   Pedestal formation and τ_E scaling

4. Behavior of impurity during detachment and improved mode

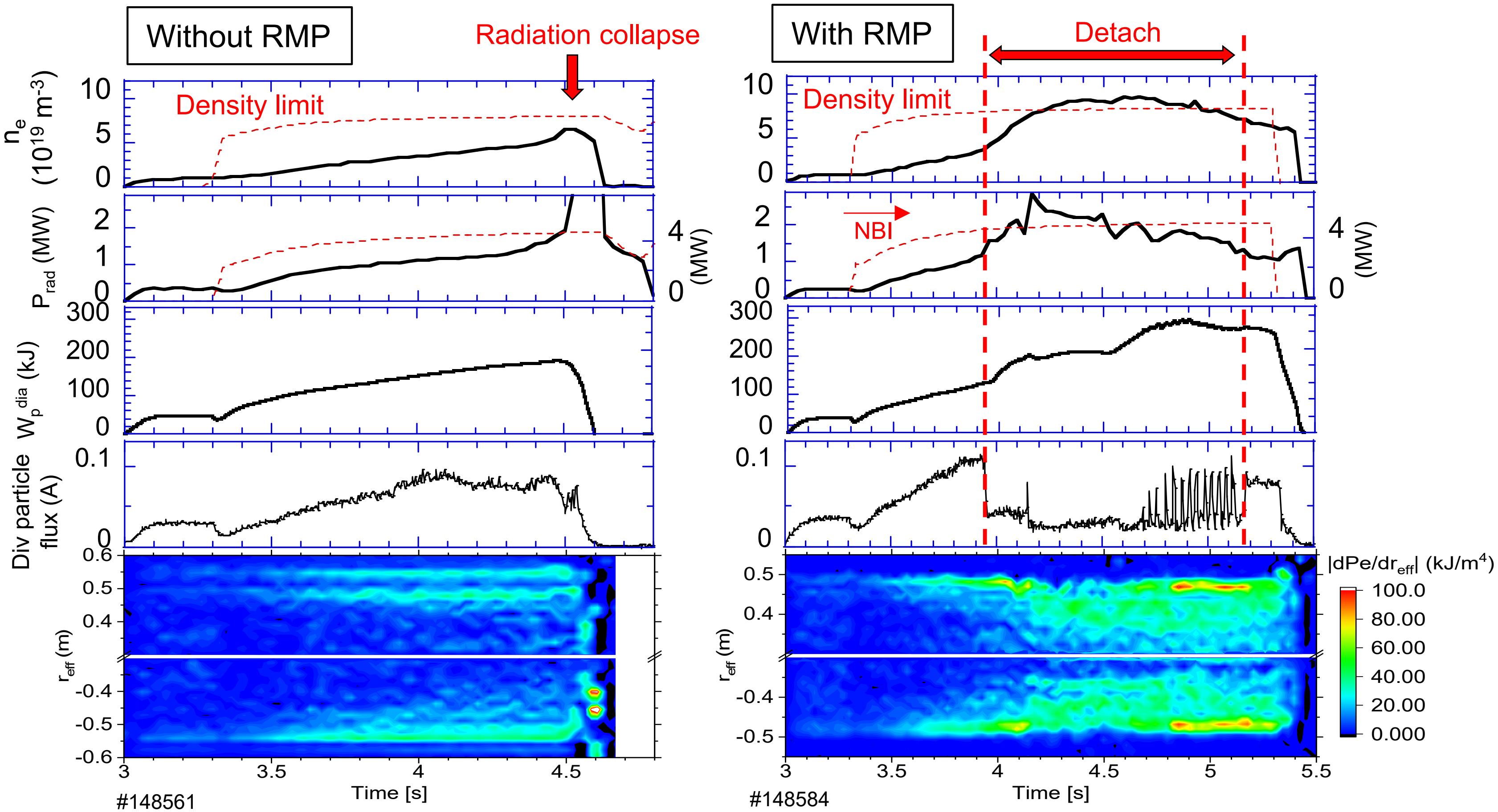
5. Divertor heat load distribution

6. Summary

Impact of RMP on density limit, radiated power, and global energy confinement

Density ramp-up discharges with & without RMP application

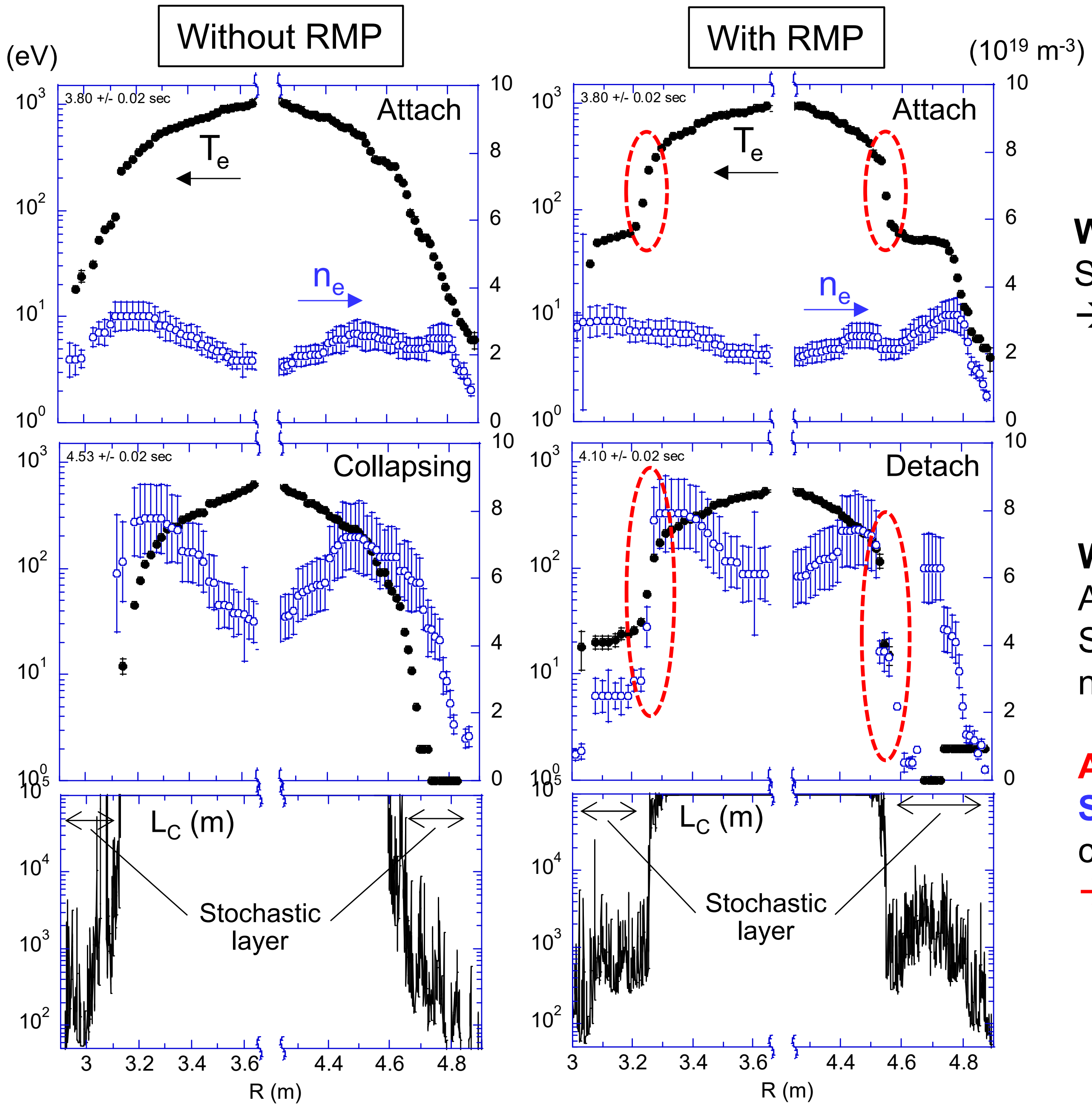
- ✓ Detachment is induced with density ramp-up, NBI is kept constant at ~ 5MW
- ✓ Main radiator is carbon from divertor plate. No impurity seeding.



Change of edge magnetic field structure/topology resulted in significant difference in core and divertor performance.
With RMP → Higher density, higher radiation (stable detachment), higher confinement (confinement mode transition, ETB formation).

Edge magnetic structure plays a key role on compatibility of confinement and radiation enhancement

Impact of RMP on edge plasma parameter profiles: Edge transport barrier at confinement boundary

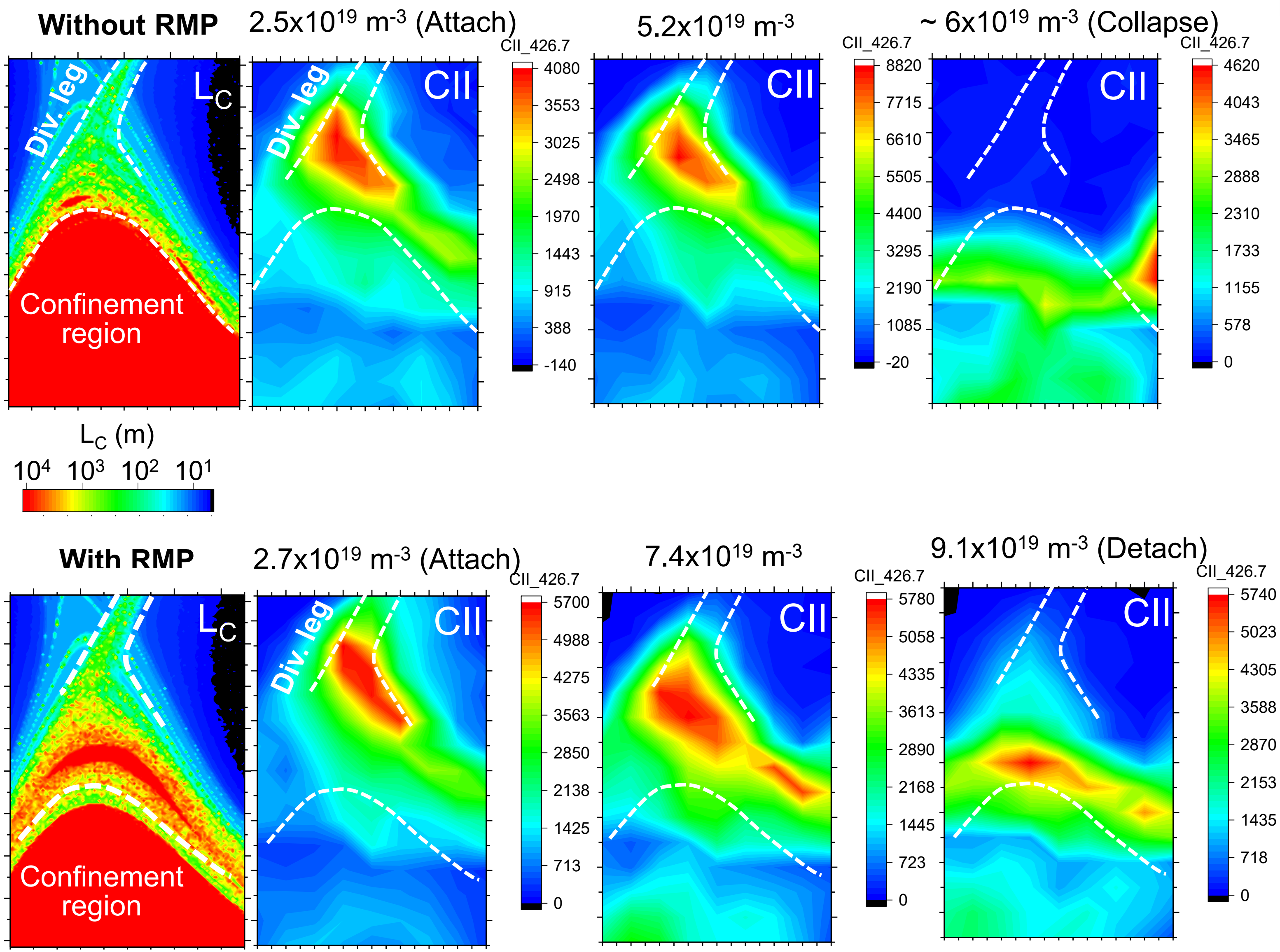


Without RMP:
Smooth radial decay of T_e and n_e
→ Shrinkage of profiles with high density
→ radiation collapse

With RMP:
At low density (Attached phase)
Sharp gradient in T_e at confinement boundary
n_e is flat

At detachment
Sharp gradient in both T_e and n_e at confinement boundary
→ **ETB formation**

Edge impurity radiation distribution obtained by 2D imaging spectroscopy



Without RMP

- Attached phase: impurity emission along divertor leg
- **With increasing density, impurity emission penetrates confinement region → collapse.**

With RMP

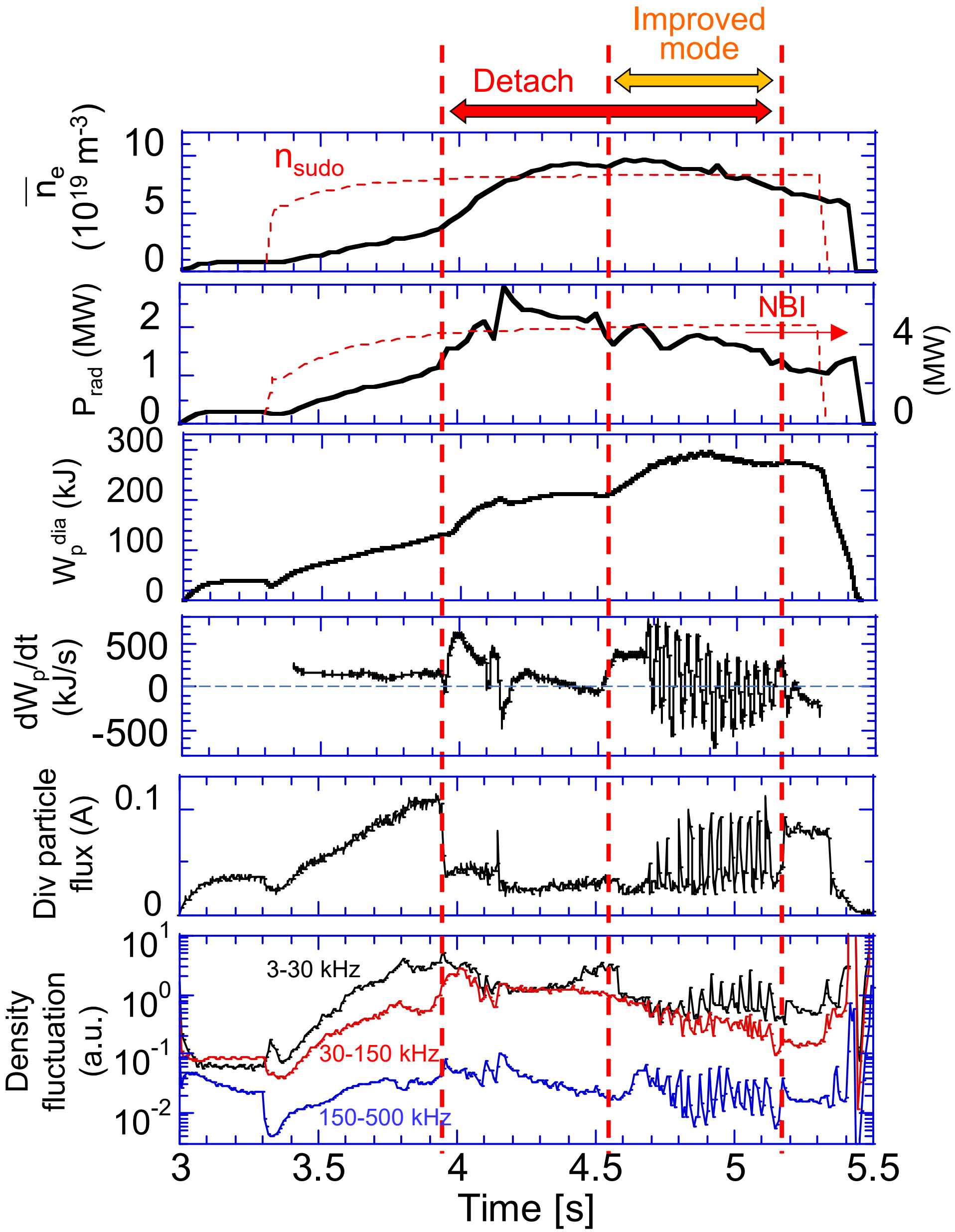
- **Attached phase: impurity emission along divertor leg**
- **Detached phase, impurity emission moves toward confinement region → Stops at boundary**

Blocking of radiation penetration by ETB (?!)

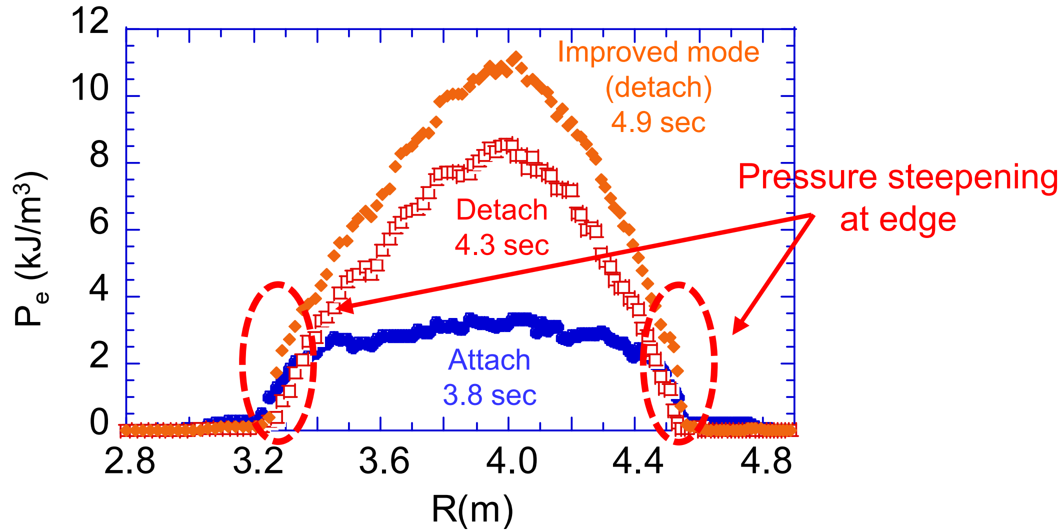
CIII shows similar behavior

M. Kobayashi+ RSI **88** (2017) 033501.

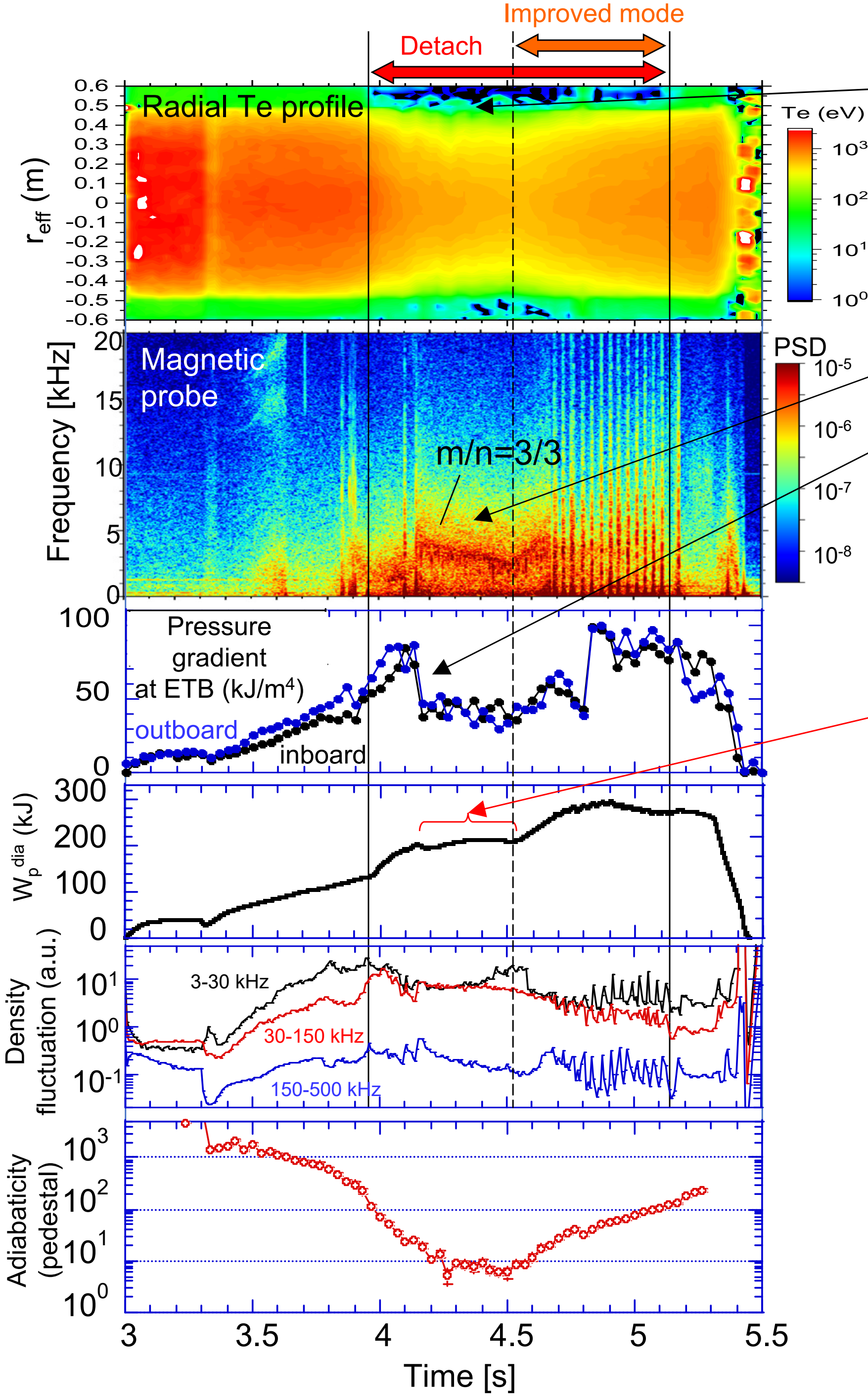
Confinement mode transitions in detachment with RMP (m/n=1/1) application



- ✓ Detachment is induced with density ramp-up, NBI is kept constant at ~ 5MW
- ✓ Main radiator is carbon from divertor plate. No impurity seeding.
- ✓ Detached at ~ 3.95 sec (reduction of div particle flux)
- ✓ Discharges are sustained up to density limit (n_{sudo})
- ✓ **Spontaneous increase of Wp occurs at t~3.95 and 4.55 sec during detached phase**
  - **→ Reduction of density fluctuation**
  - **→ ELM-like spikes in B_θ and div particle flux**
- ✓ **ETB developed at inner edge of island induced by RMP**



Interaction between edge cooling, ETB, and core transport: MHD activity degrades ETB → fluctuation increase → confinement mode transition



As the detachment deepens, the edge Te decreases due to impurity radiation → resistivity increases

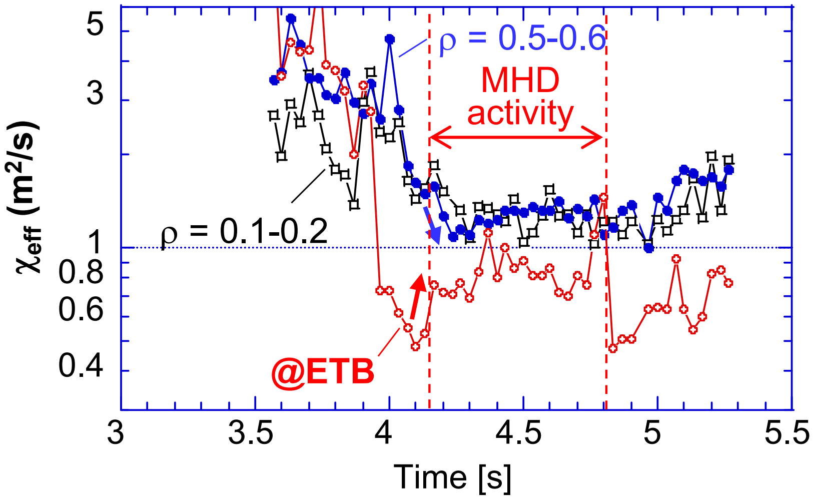
$$\gamma_{interchange} \propto \eta^{1/3} L_p^{-2/3} \propto L_p^{-2/3} T_e^{-0.5}$$

MHD activity is excited by pressure gradient at ETB (m/n=3/3)

Pressure gradient at ETB collapses → Wp increase stops

χ_{eff} by core transport analysis: Core-edge coupling

Core transport responds to compensate degradation of ETB → Wp kept constant during MHD activity



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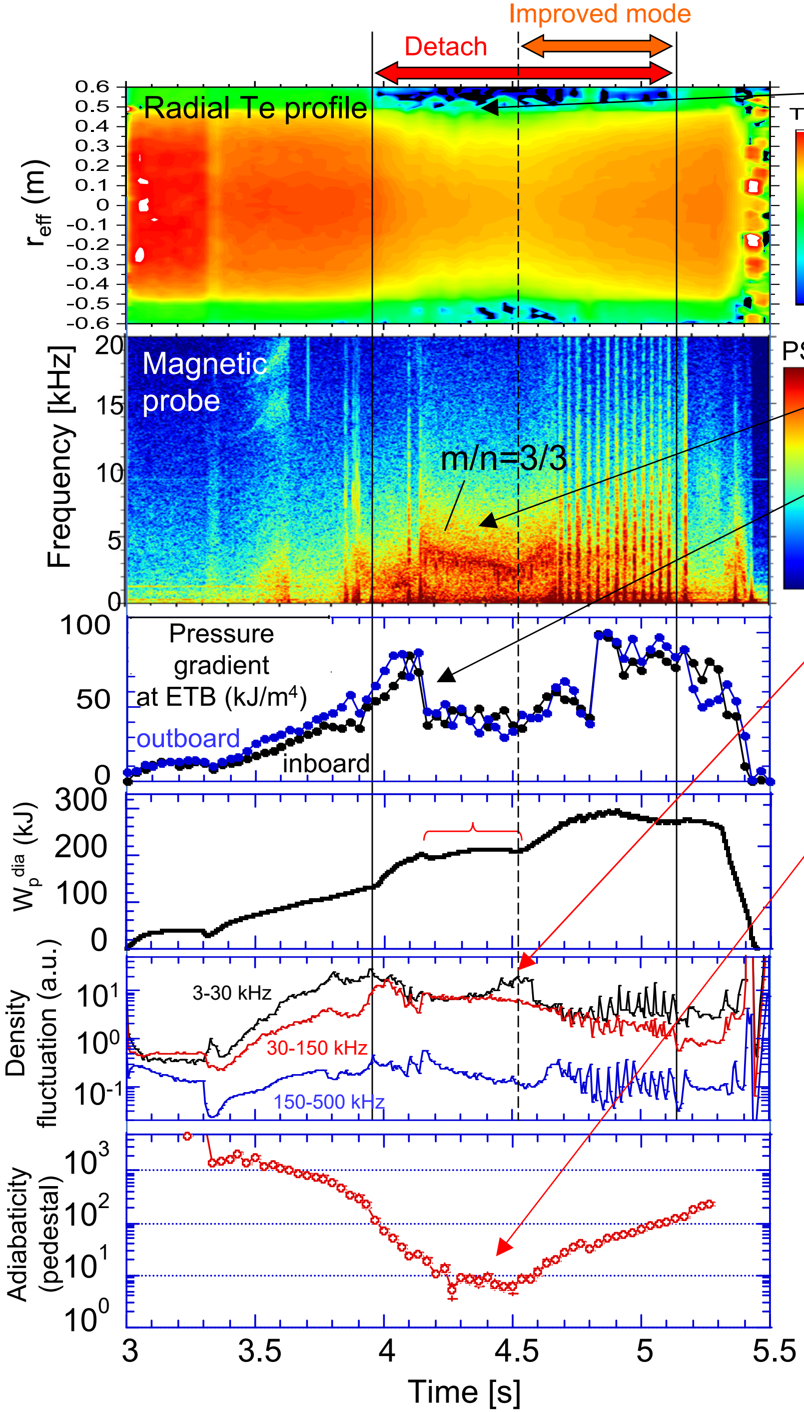

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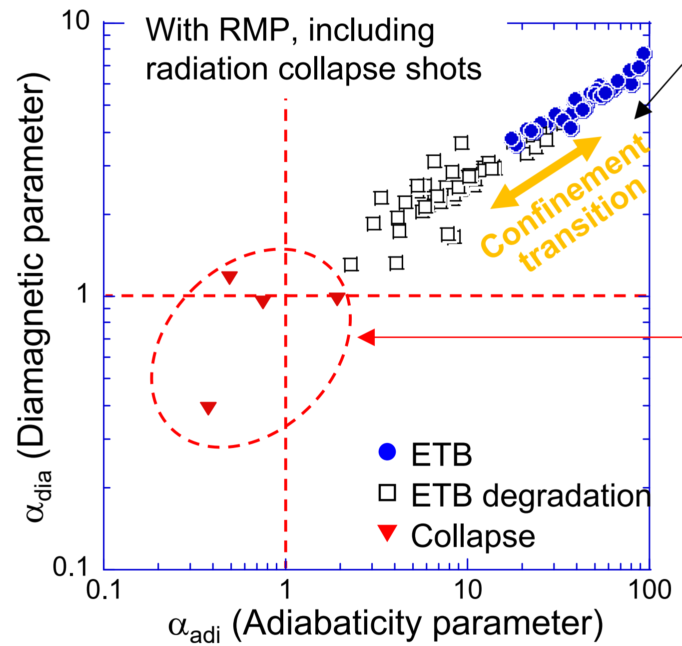
MHD activity is excited by pressure gradient at ETB (m/n=3/3)

Pressure gradient at ETB collapses → Wp increase stops

Gradual increase of density fluctuation (<30kHz) → Spontaneous recovery of ETB and increase of Wp resumes at t ~ 4.5 sec → Fluctuation decreases, ELM starts

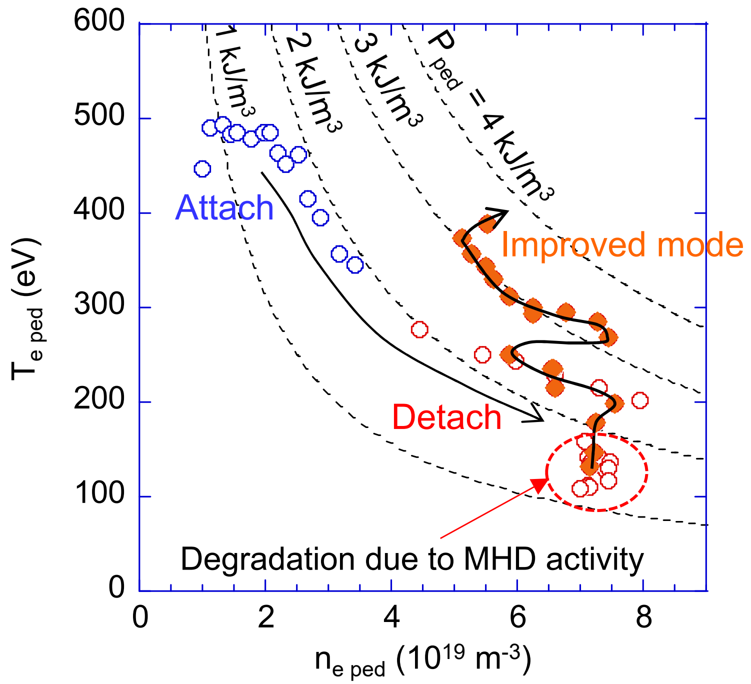
Adiabaticity still high > 1 ← ETB branch maintained



Transition possible

At operation limit: $\alpha_{adi} \leq 1$, $\alpha_{\delta\iota\alpha} \leq 1$ → both DW & DRB turbulence responsible

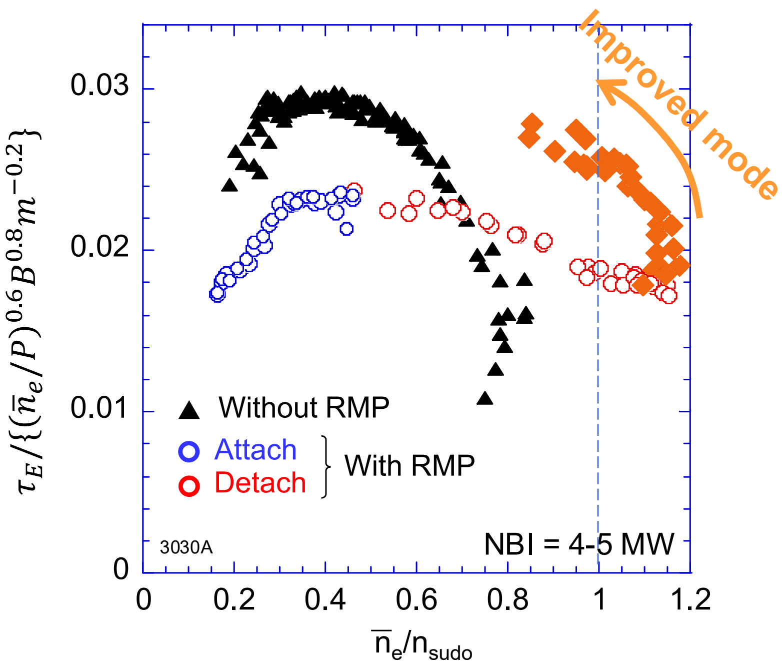
Development of pedestal during confinement mode transition and τ_E scaling



1. After detachment transition, development of pedestal with density increase
   ← Similar to standard H-mode transition

2. Degradation due to MHD activity occurs with T decrease

3. Confinement improvement proceeds with increase of T_{ped}.

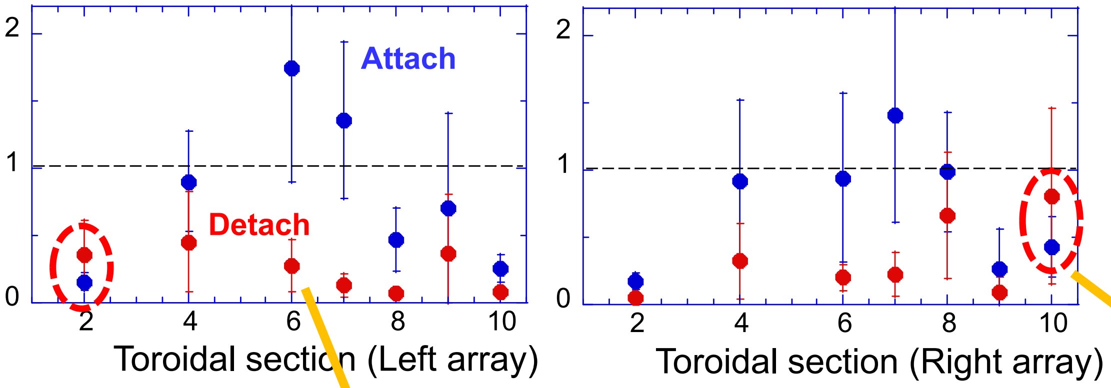


Confinement sustained at higher density with RMP application ← Due to ETB formation

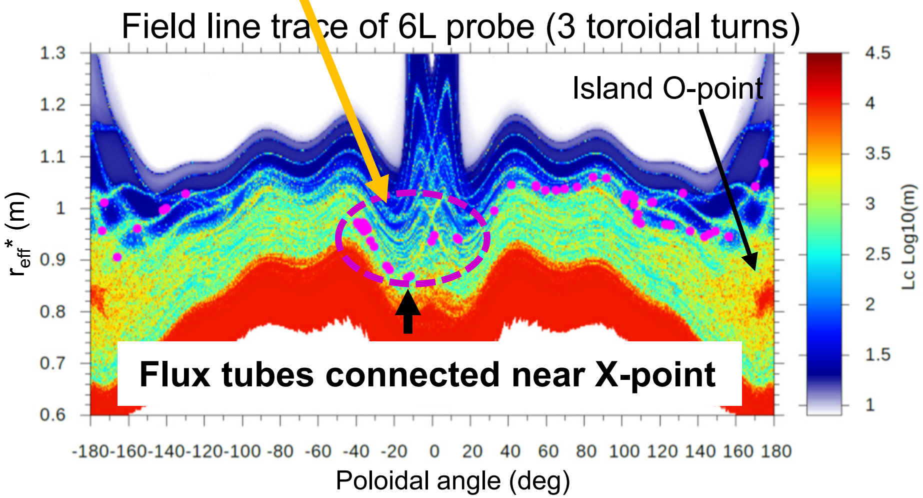
Confinement improvement significantly deviates from gyro-Bohm scaling

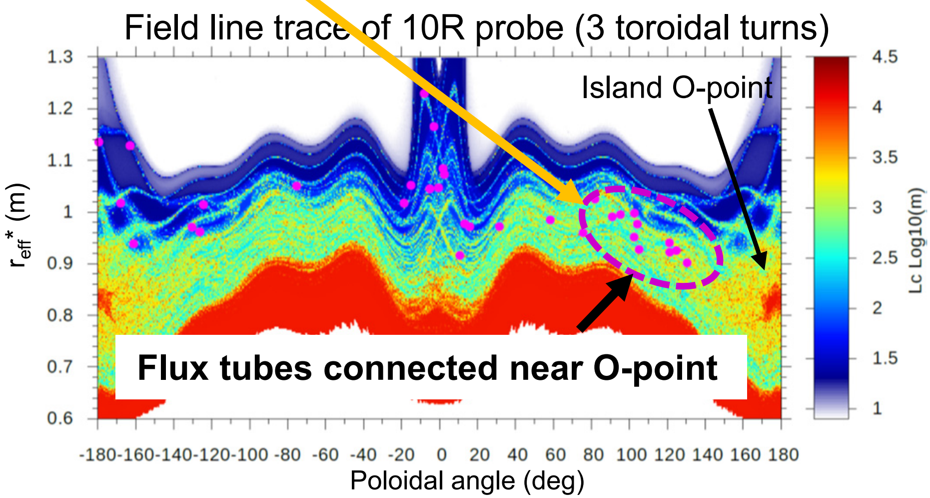
Divertor heat load pattern in toroidal direction with RMP application: Attached & detached phases

Toroidal profiles of ratio of divertor peak heat load
With RMP / Without RMP



- ✓ Attached phase: Divertor heat load is modulated in toroidal direction (n=1 mode) with RMP
- ✓ **Detached phase: Divertor heat load is decreased at all section with RMP by ~ 70% on avrg.**
- ✓ Slight increase observed at 2L & 10R during detached phase
  ← Still lower than the case without RMP

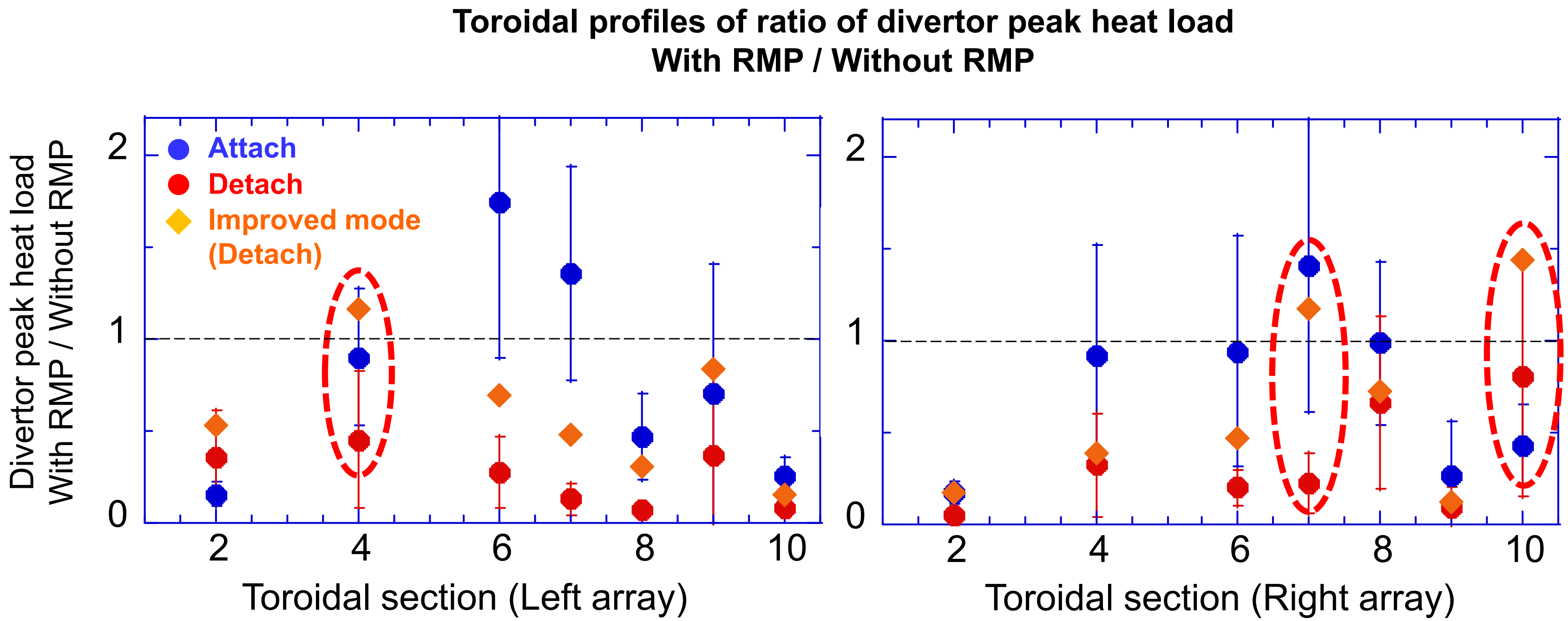




Field line tracing of divertor foot print:
10R (2L) are connected near island O-point
Others are connected near X-point (away from O-point)
O-point is less cooled down compared to X-point (?)

→ In the next experiments, impurity seeding is tried to cool down 10R & 2L sections further.

Divertor peak heat load slightly returns during improved mode



- ✓ Divertor heat load increases during the improved mode. Due to decrease in P_{rad} (decontamination during improved mode) and to ELM pulses.

  (heat load is time-averaged during & inter-ELM phase)

  → **Reduction of heat load is tried with impurity seeding in next experiments**

- ✓ Other sections remains low

Summary

Role of edge magnetic field structure/topology on detachment and compatibility with core plasma confinement is being investigated in LHD.

1. **Sharp boundary between confinement region and stochastic layer can be introduced with RMP (m/n=1/1) application**
   ETB formation at detachment onset → Higher density, higher radiated power, better confinement are achieved
   Cold front propagation stopped at the confinement boundary (at ETB)
   Core transport is similar level with and without RMP, except for the ETB formation in RMP case
   ETB is stronger in deuterium plasmas than hydrogen plasmas

2. **Confinement mode transition occurs with RMP application during detached phase (in deuterium):**
   2.1 ETB formation at detachment onset
   2.2 Interplay between edge cooling, MHD activity, and ETB during detachment
   Detachment deepens / Edge T decreases → Resistive pressure gradient driven MHD mode excited
   → ETB collapsed, but core transport responds to compensate degradation of ETB
   → Fluctuation increase → sudden recovery of ETB and confinement improvement
   Compatibility of confinement mode transition with cold edge plasma possible ($\alpha_{adi} > 1$)
   Operation limit at $\alpha_{adi} \leq 1$, $\alpha_{\delta\iota\alpha} \leq 1$ → both DW & DRB turbulence responsible

3. **Divertor heat load decreases during detached phase with RMP by 70% on average**
   n = 1 mode structure in attached phase → Spatial phase shift of heat load at detached phase
   At certain sections, slight increase is observed. (Heat load is already low at attached phase by RMP application)
   These sections are connected near O-point.
   Slight increase during improved mode due to decrease of P_{rad} (impurity decontamination) and ELMs

Key role of edge magnetic field structure: Enhancement of radiation with increased low Te volume, ETB formation at sharp boundary

Summary (continued)

Progress after Oct. 2020:

- ✓ Different characteristics of the mode transition found between D & H
  D plasmas have stronger ETB, and seem to be able to sustain higher radiation with better confinement

Next step:

- ✓ Combination with impurity seeding in order to further mitigate divertor heat load
- ✓ Increase of RMP amplitude with high power operation
- ✓ Change resonance position of RMP (R_{ax} = 3.90 → 3.85 m)