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Plasma shape effects on L-H power threshold and H-mode in JET-ILW

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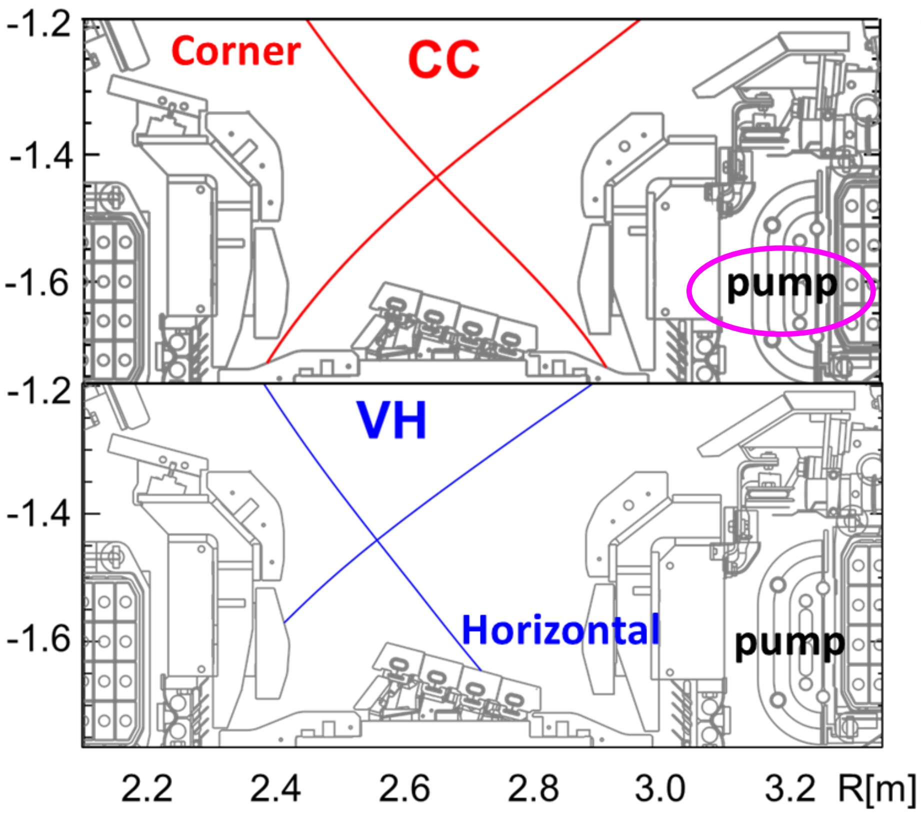
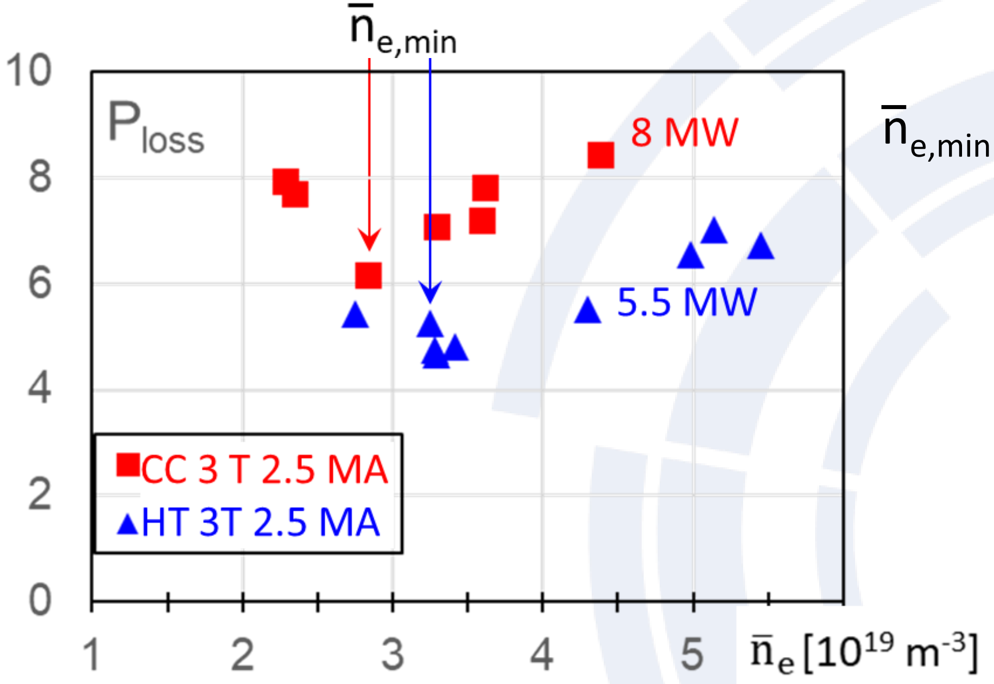
In JET-ILW L-H studies the divertor configuration affects $n_{e,min}$ and $P_{LH,min}$





$\bar{n}_{e,min} \propto f_{GW} \propto I_p$

Abundant reports of JET-ILW configuration effect on P_{LH}

E. Delabie et al (2014) IAEA 25th FEC, St. Petersburg, Russia
C. F. Maggi et al (2014) Nucl. Fusion 54 023007
E.R. Solano et al (2021) Nucl. Fusion 61 124001
C. Silva et al (2022) Nucl. Fusion 62 126057

JET's configuration effect on P_{LH} is not explained by critical pre-transition E_r (Silva 2021, **EPS 2026**), nor pumping differences, as far as we can tell.
Dithers and partial detachment may play a role (Delabie IAEA 2014, Silva 2021).

Multimachine L-H power threshold scaling: JET configuration effect, B_{pol}

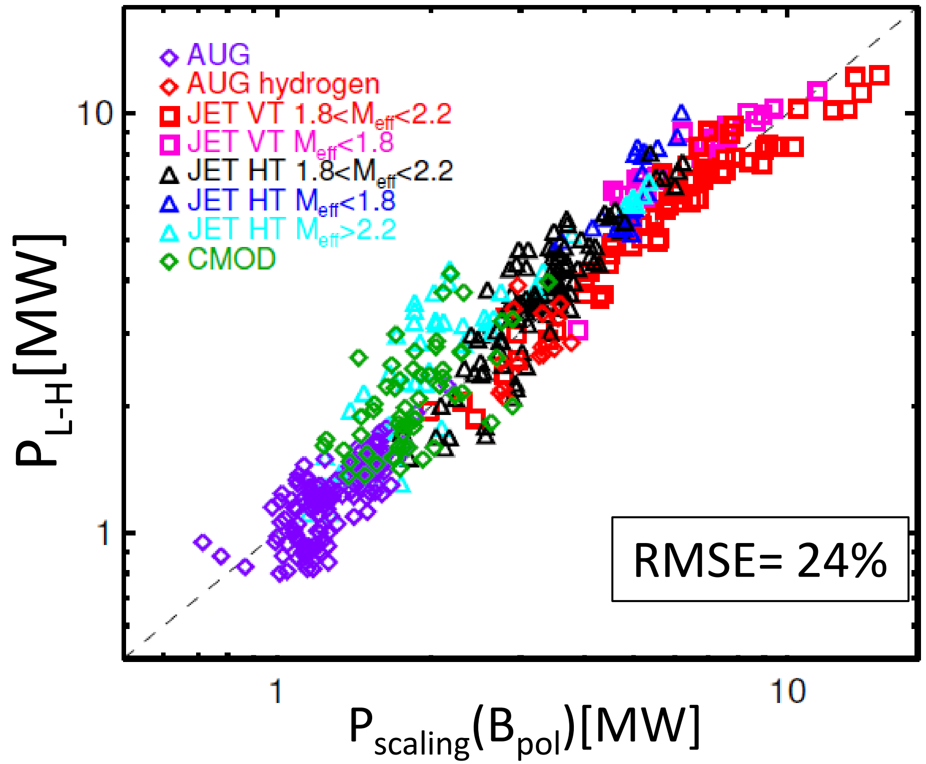
$P_{L\text{-}H} = 0.044\,\boxed{D}\,B_{tor}^{0.58}\,\langle n_e\rangle^{1.08}\,S^1\,2/M_{eff}^{0.97}$

D = 1 for JET HT, others, **D** = 1.93 for JET VT/CC

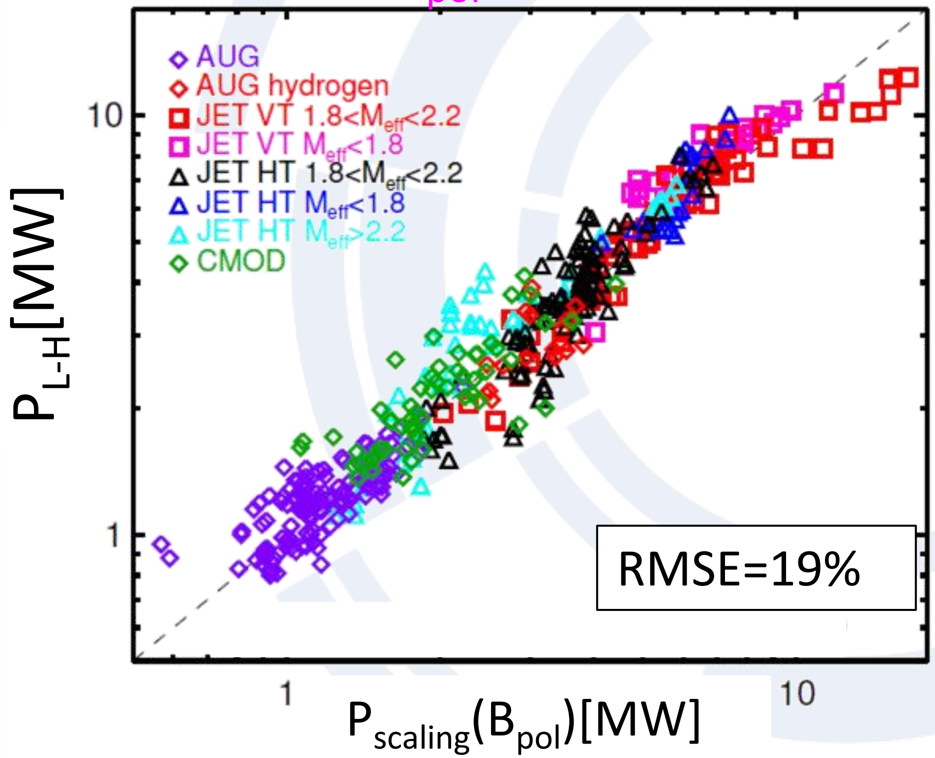
$P_{L\text{-}H} = 0.167\,\boxed{D}\,B_{pol}^{0.631}\langle n_e\rangle^{1.08}\,S^1\,2/M_{eff}^{1.00}$

D = 1 for JET HT, others, **D** = 1.66 for JET VT/CC

B_{tor} scaling



B_{pol} scaling



For comparison: $P_{L\text{-}H\ ITPA\ 2008} = 0.0488\ B_{tor}^{0.803}\ \langle n_e\rangle^{0.717}\ S^{0.94}$, RMSE= 30%

$$B_{pol} = \frac{\mu_0 I_p}{S/(2\pi R)}$$

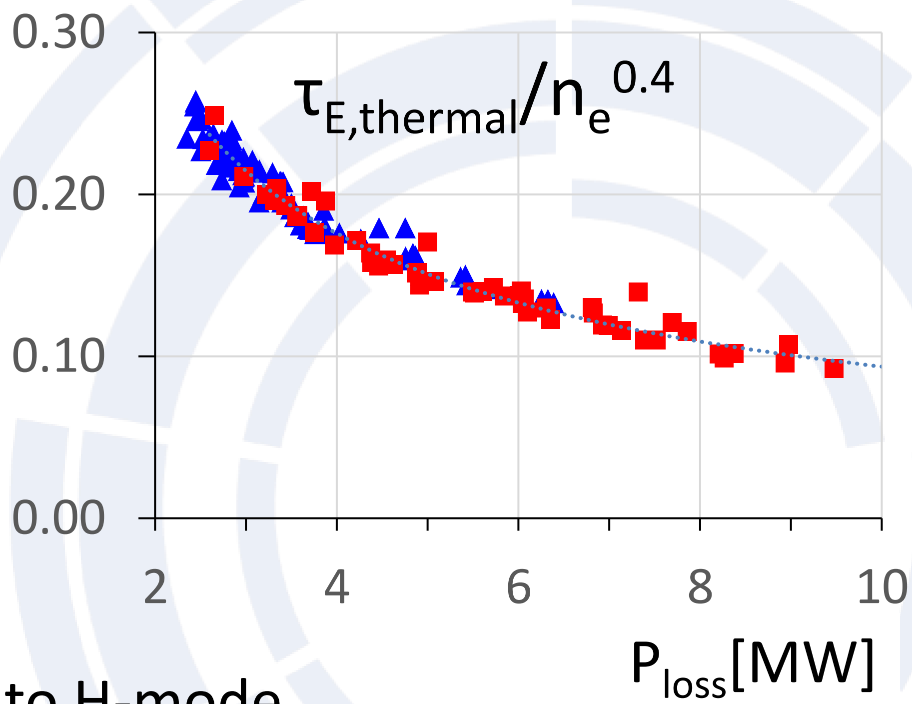
E. Delabie et al Nucl. Fusion 66 036016 (2026)

Why is P_{LH} higher for Corner? Is its confinement worse in L-mode?

Inspired by ITER L-96 L-mode confinement time scaling

$$\tau_E \approx 0.023\, I_p^{0.96} B_T^{0.03} R^{1.83} \kappa^{0.64} n_e^{0.40} M^{0.20} P^{-0.73} a^{-0.06}$$

L-mode data with 2.5 MA, NBI only. Plot $\tau_E/n_e^{0.4}$ vs P_{loss}



L-mode global energy confinement doesn't explain why $P_{L\text{-}H}$ is higher for Corner

- There are no L-modes in VH at high P_{loss}, they transition to H-mode
- There are L-modes in Corner at high P_{loss}, $P_{L\text{-}H}$ configuration effect

L-mode database courtesy of A. Kirjasuo

Operational history

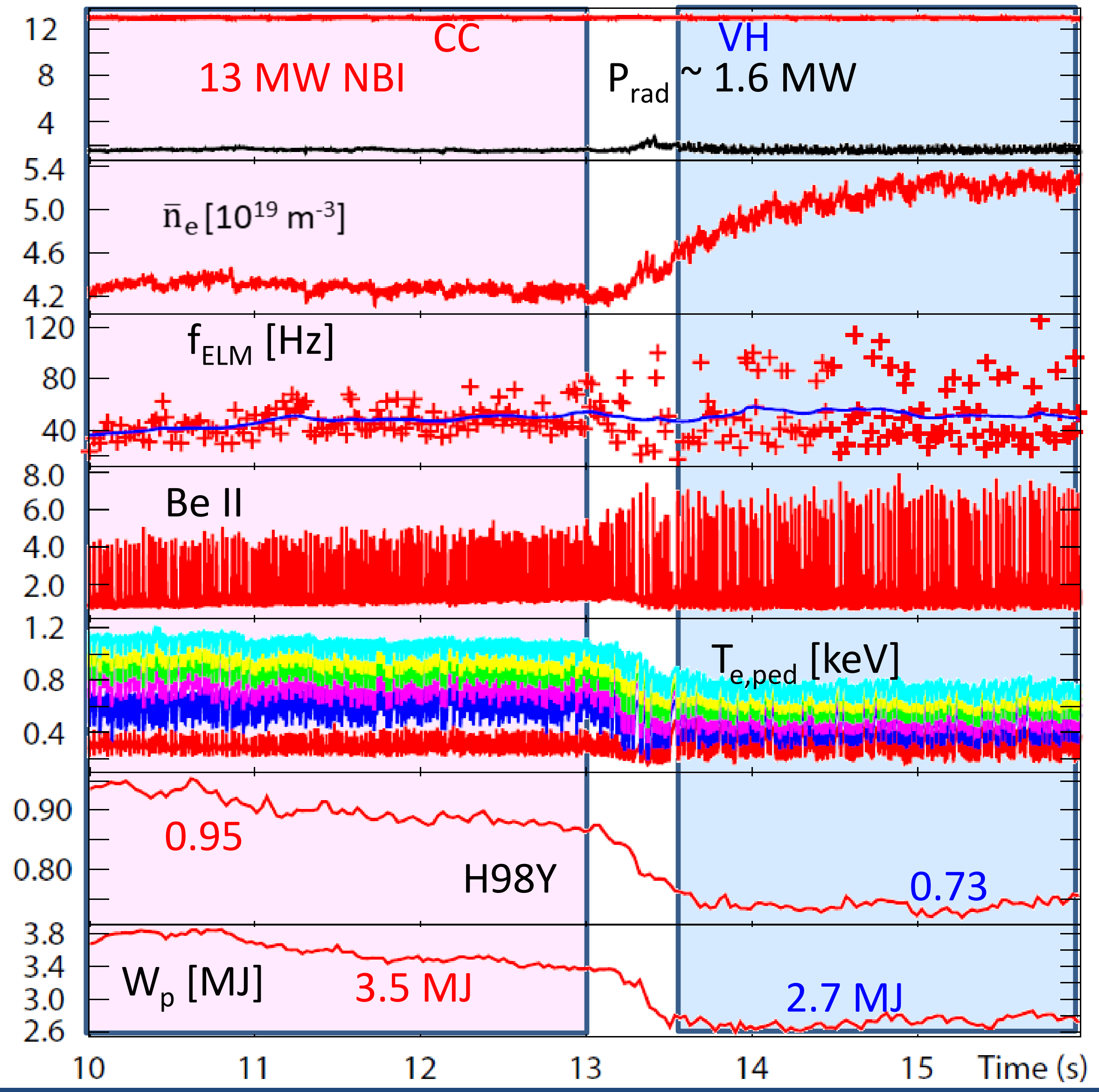
Up until 2013, JET-ILW research programme was **VH**-dominated to match ITER triangularity

At 2 MA it was actually possible to obtain H=1 in VH

At 2.5 MA there were only very few H=1 steady phases in VH

In H-mode, change shape, NBI and fueling constant: confinement changes

JET 84647 2.3T 2 MA



Constant power & top fuelling: change **CC** to **VH**

CC H_{98} ~0.9

- good confinement in H-mode
- despite higher P_{LH}
- $P_{NBI}+P_{Ohm}$=13.4 MW, P_{LH}=8.2, ratio= 1.6

GOOD H-MODE

VH H_{98} ~0.70

- poor confinement in H-mode
- despite lower P_{LH}
- $P_{NBI}+P_{Ohm}$=13.5 MW, P_{LH}=7.0, ratio= 1.9

POOR H-MODE

Higher ratio of heating power to P_{LH} doesn't correlate with good confinement *because divertor configuration changes density*

Operational history, impact on databases

Up until 2013, JET-ILW research programme was **VH**-dominated to match ITER triangularity

At 2 MA it was actually possible to obtain H=1 in VH

At 2.5 MA there were only very few H=1 steady phases in VH

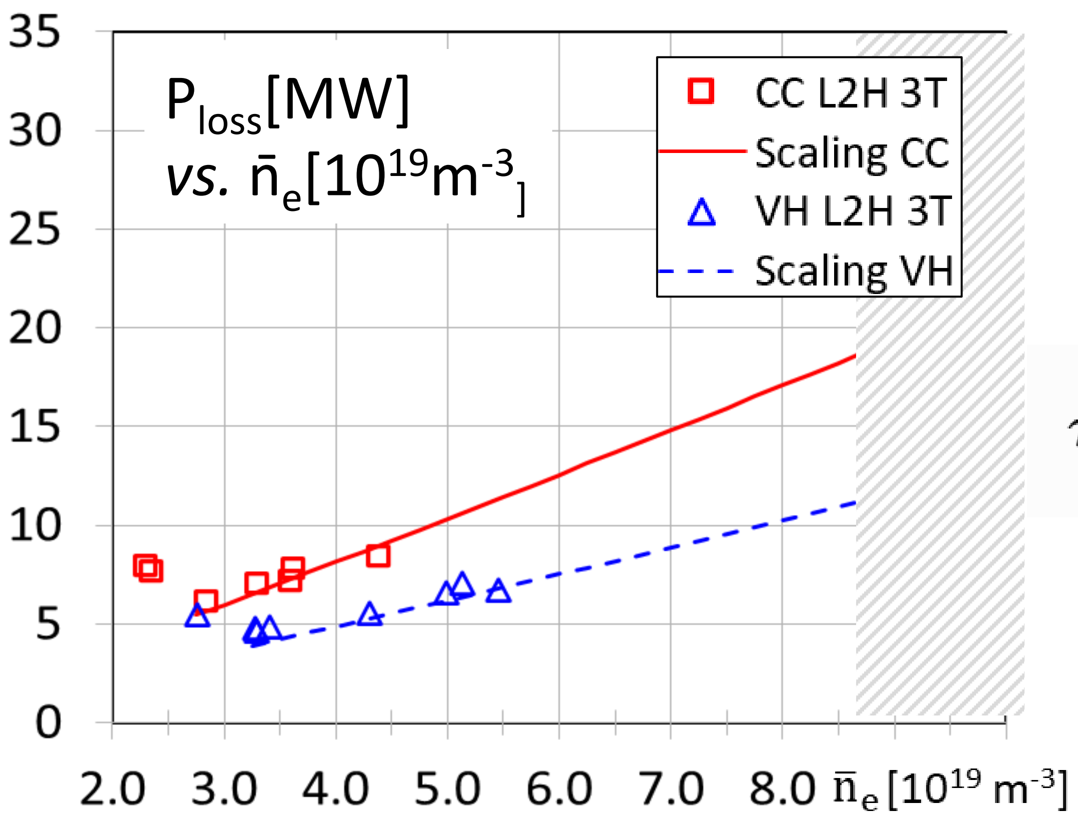
After 2013, research program discards **VH**, selecting **CC** for better confinement

3MA and above: CC (and VT), with top gas fuelling instead of divertor fuelling

Comparison only useful/possible at 2.5 MA

Note:
VT configuration not discussed here

Steady H-modes with good confinement, 2.5 MA, Deuterium only



- L-H and steady H-mode data with 2.5 MA
- $P_{L\text{-}H}(B_{pol})$ scalings

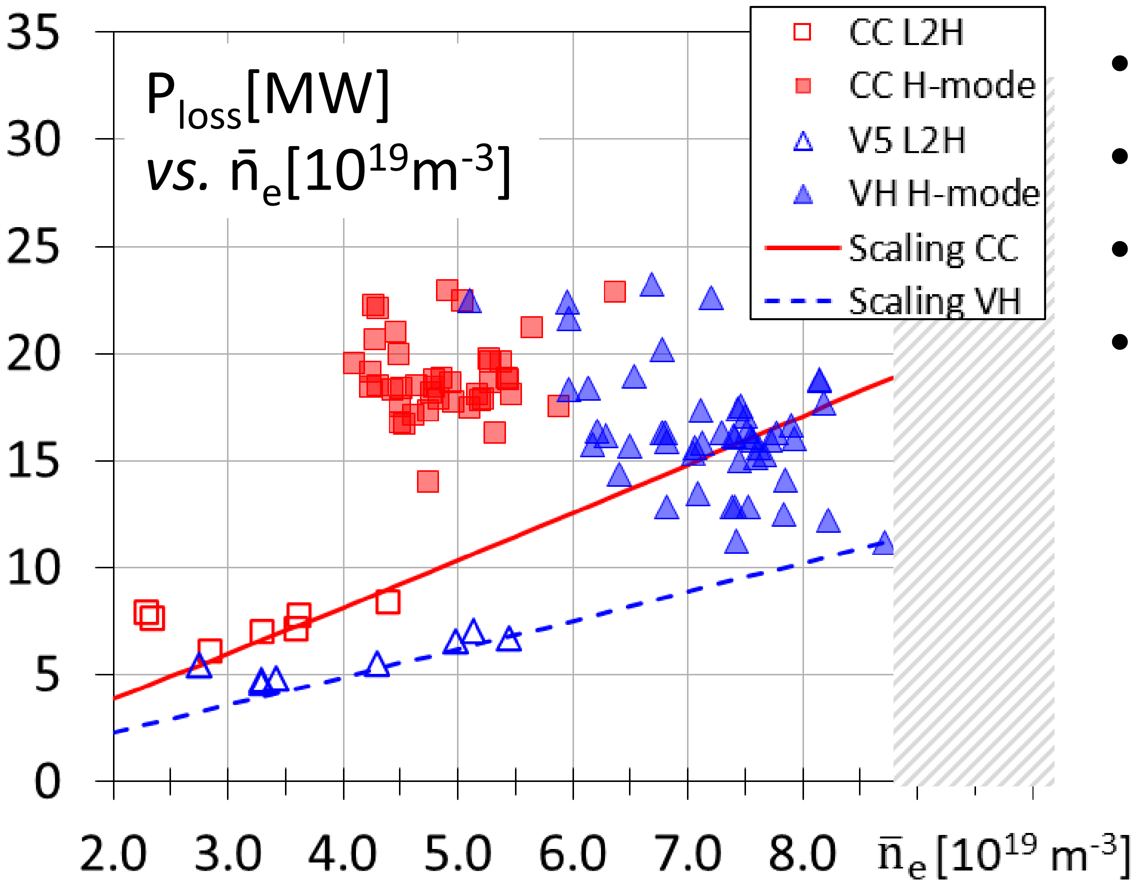
H-mode confinement scaling:

$$\tau_E^{98(y,2)} = 0.064\, I_p^{0.93} B_T^{0.15} n_e^{0.41} P^{-0.69} R^{1.97} \kappa^{0.78} \left(\frac{a}{R}\right)^{0.58}$$

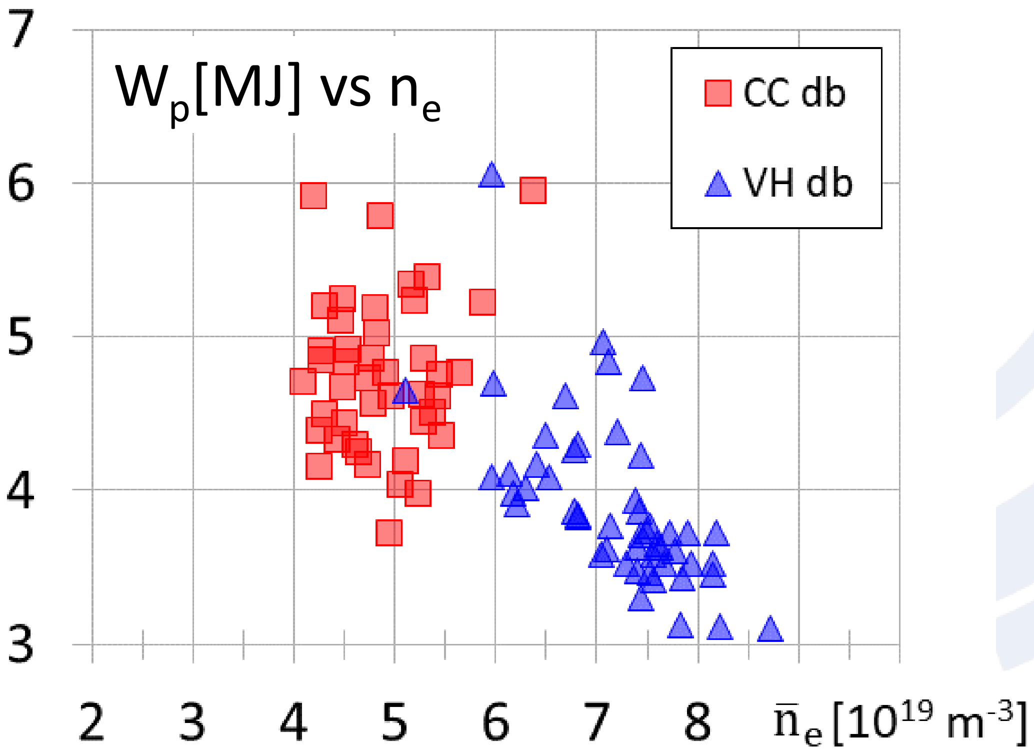
H98 energy confinement scaling itself justifies selecting H-mode datapoints by current

M. Maslov et al 2020 Nucl. Fusion 60 036007
G. Verdoolaege *et al* 2021 *Nucl. Fusion* **61** 076006

Steady H-modes with good confinement, 2.5 MA, Deuterium only



- L-H and steady H-mode data with 2.5 MA
- $P_{L\text{-}H}(B_{pol})$ scalings
- Low density H-mode rarely accessible in VH
- Clear change in confinement quality



M. Maslov et al 2020 Nucl. Fusion 60 036007

G. Verdoolaege *et al* 2021 *Nucl. Fusion* **61** 076006

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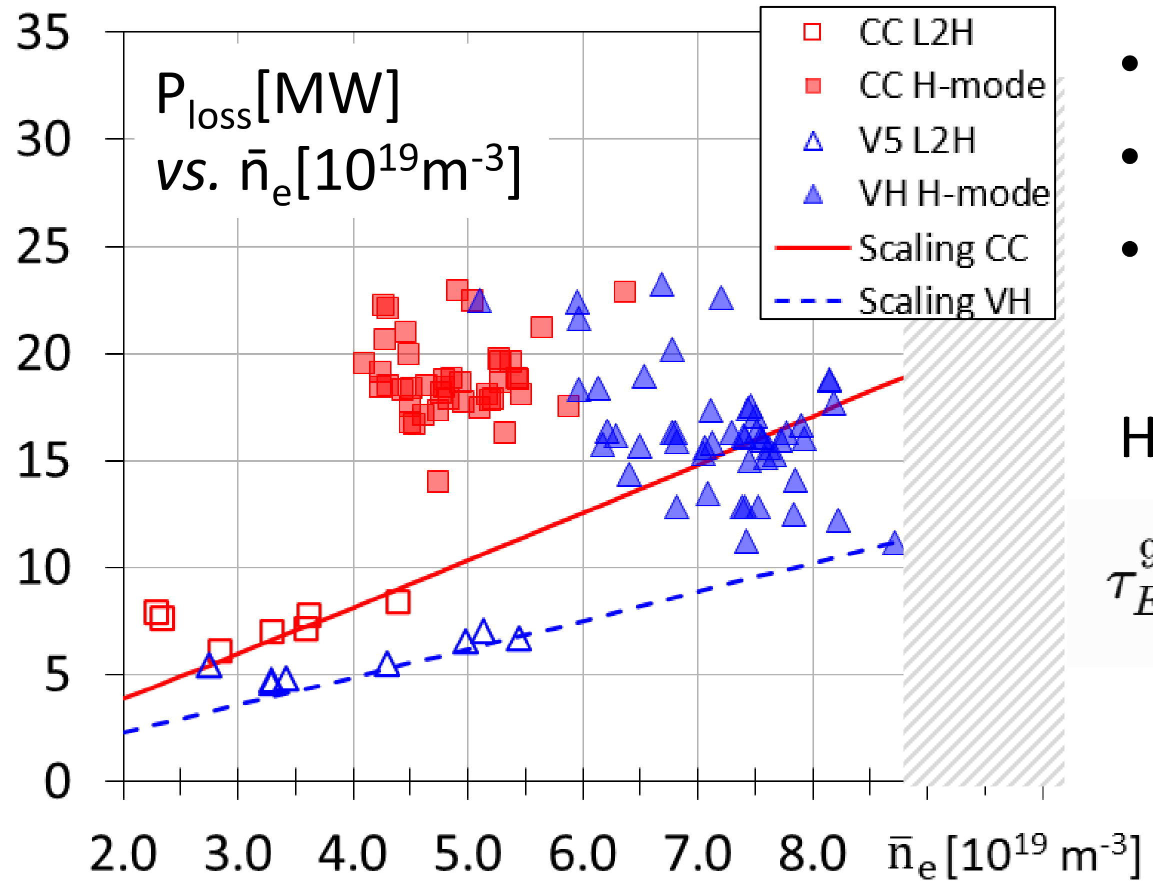

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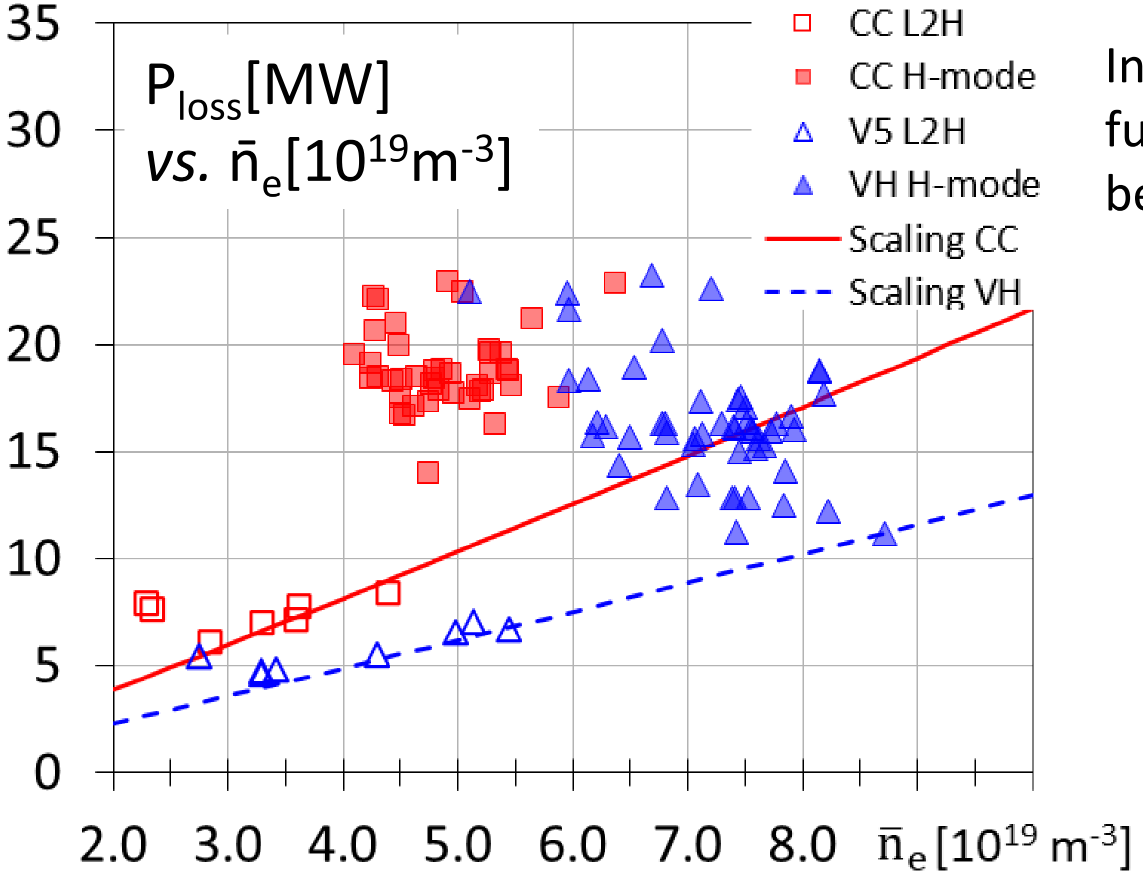
$H98 = \tau_E / \tau_E^{98(y,2)}$

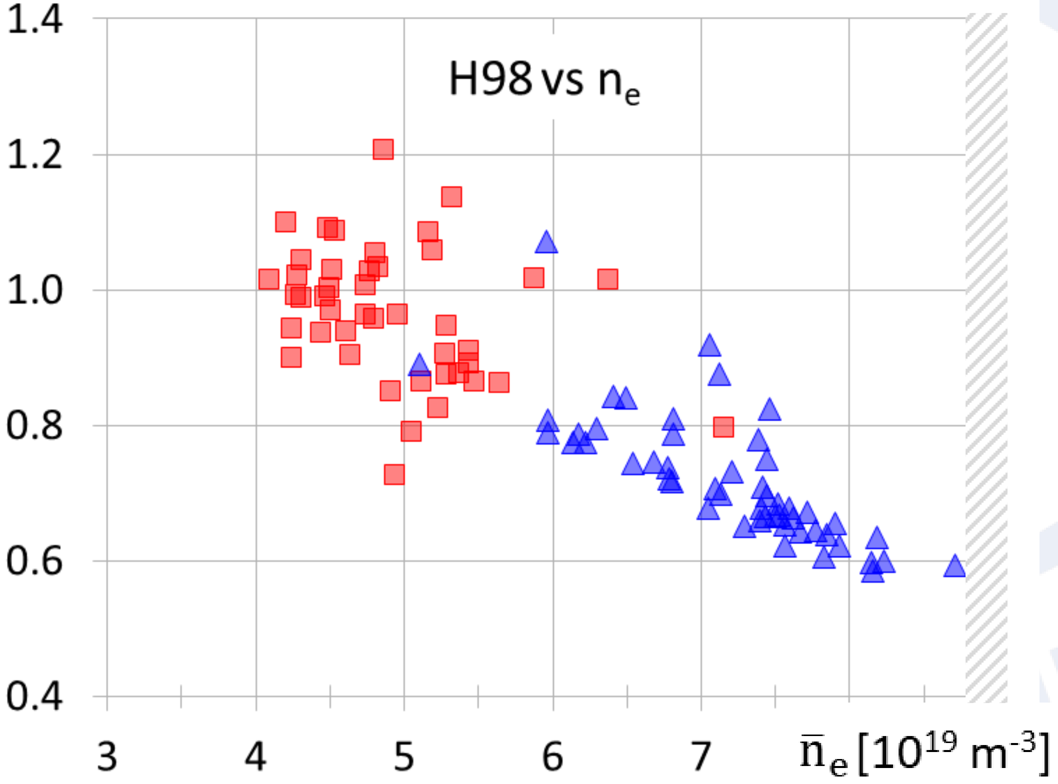
M. Maslov et al 2020 Nucl. Fusion 60 036007

G. Verdoolaege *et al* 2021 *Nucl. Fusion* **61** 076006

Steady H-modes with good confinement, 2.5 MA, Deuterium only



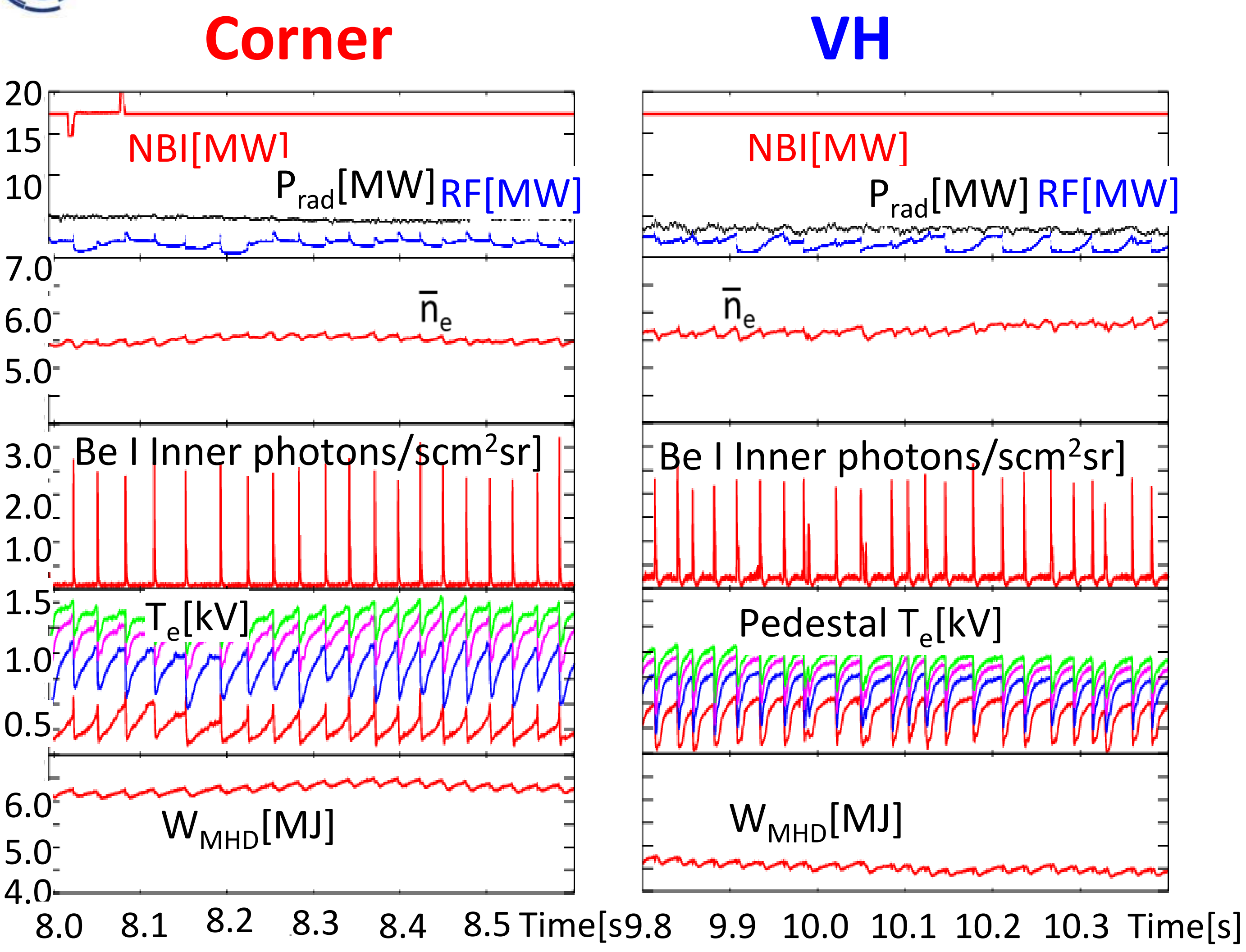
In terms of H98, CC displays better H-mode confinement fundamentally because higher power stationary H-modes become accessible at low densities



M. Maslov et al 2020 Nucl. Fusion 60 036007
G. Verdoolaege *et al* 2021 *Nucl. Fusion* **61** 076006

High H98 in low density operation space

Change shape and adjust gas, constant line averaged density



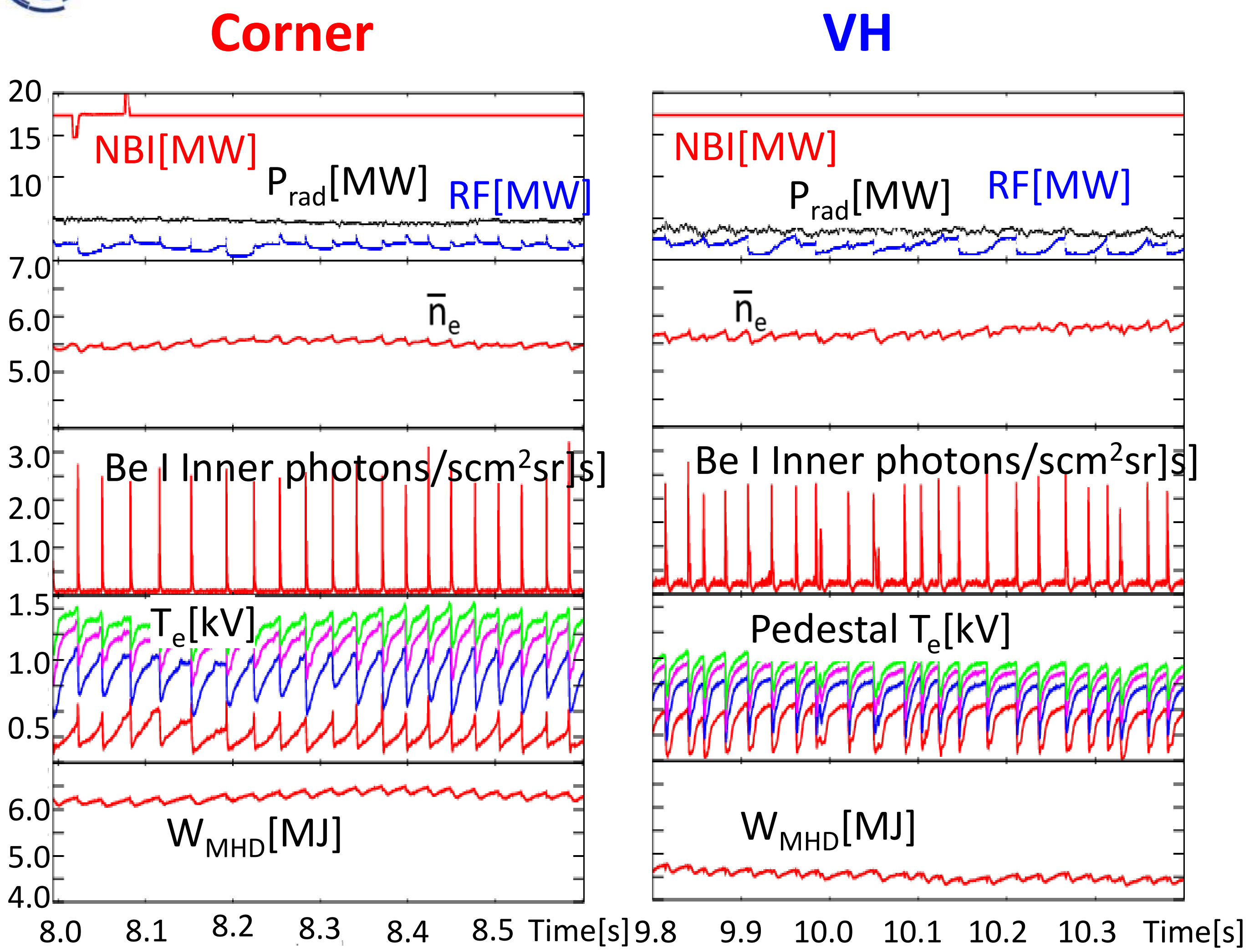
Same pulse, constant power, adjust gas to match f_{ELM}, $\bar{n}_e$
Shift strike position.

Corner: better confinement
τ_E = 0.32 s, H98=1.2, W= 6.3 MJ
P_{loss}=19.2 MW, P_{LH}=8.5 MW,
$P_{loss}/P_{LH,scal}$=1.3

VH: worse confinement
τ_E= 0.24 s, H98=0.87, W= 4.5 MJ
P_{loss}=18.6 MW, P_{LH}=4.5 MW,
$P_{loss}/P_{LH,scal}$=2.5

Maybe Corner has better confinement because it has less W?

Change shape and adjust gas, aim for constant line averaged density



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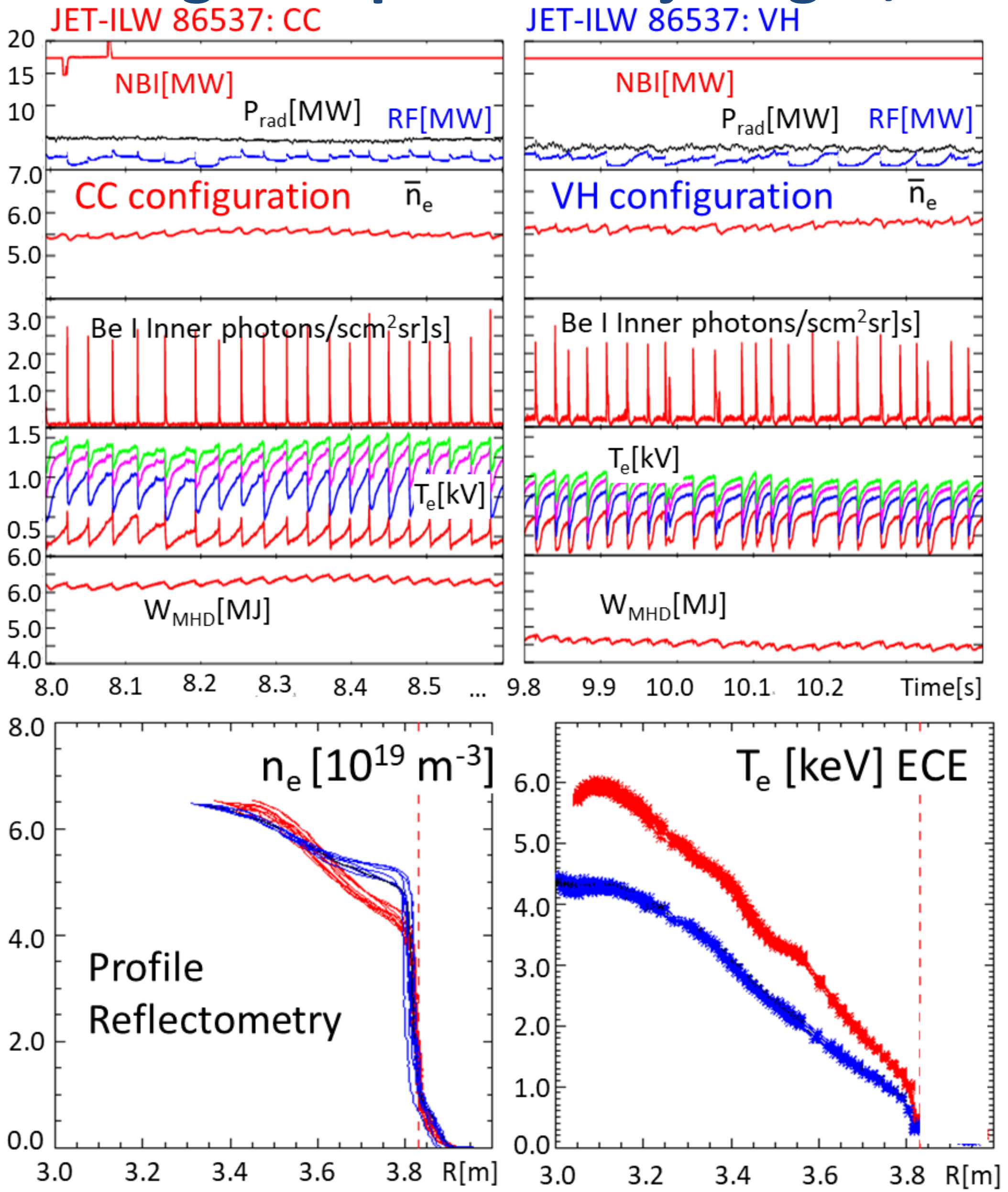
Maybe Corner has better confinement because it has less W?

W erosion due to ELMs higher for **CC** (higher $T_{e,ped}$).

W atoms/s	CC	VH
Inboard	6.5e19	4.0e19
Outboard	9.0e19	7.2e19

Change shape and adjust gas, aim for constant line averaged density



Corner: peaked density, better NBI penetration

τ_E = 0.32 s, H98=1.2, W= 6.3 MJ

P_{loss}=19.2 MW, P_{LH}=8.5 MW, $P_{loss}/P_{LH,scal}$=1.3

VH: higher pedestal density, worse confinement

τ_E= 0.24 s, H98=0.87, W= 4.5 MJ

P_{loss}=18.6 MW, P_{LH}=4.5 MW, $P_{loss}/P_{LH,scal}$=2.5

Select pre-ELM profiles in each phase:

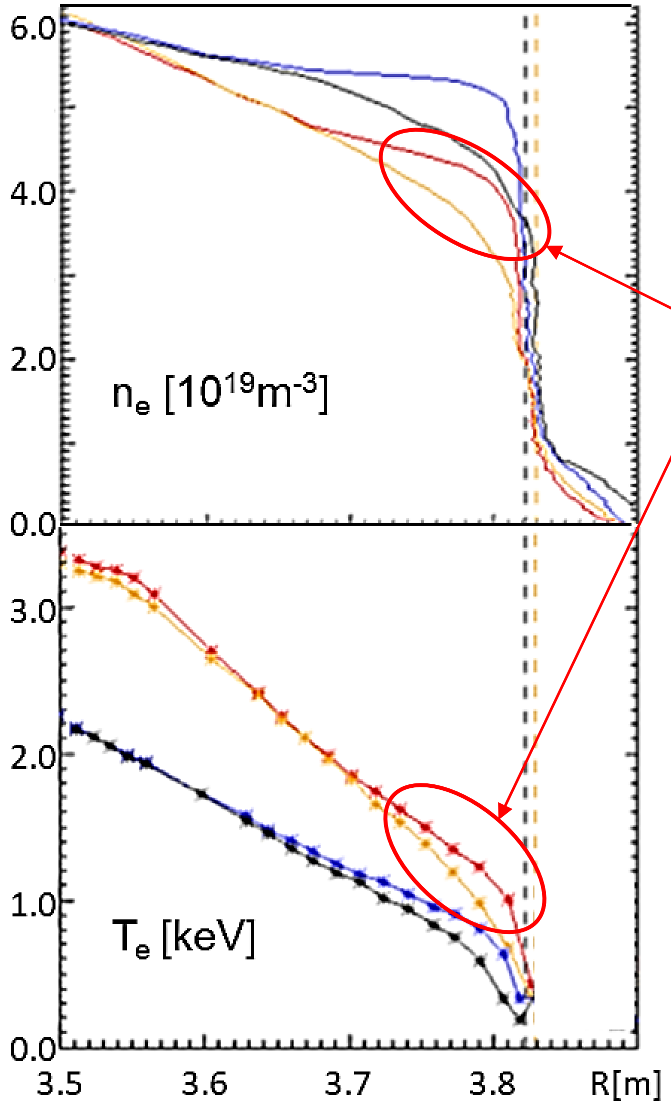
Corner: peaked n_e, lower $n_{e,ped}$, hotter T_e

VH: higher $n_{e,ped}$, colder core

R. B. Morales, Rev. Sci. Instrum. 95, 043501 (2024)

Zoom in, fast profiles at single time slices before and after ELMs

CC: good confinement associated to lower edge density, higher core temperatures



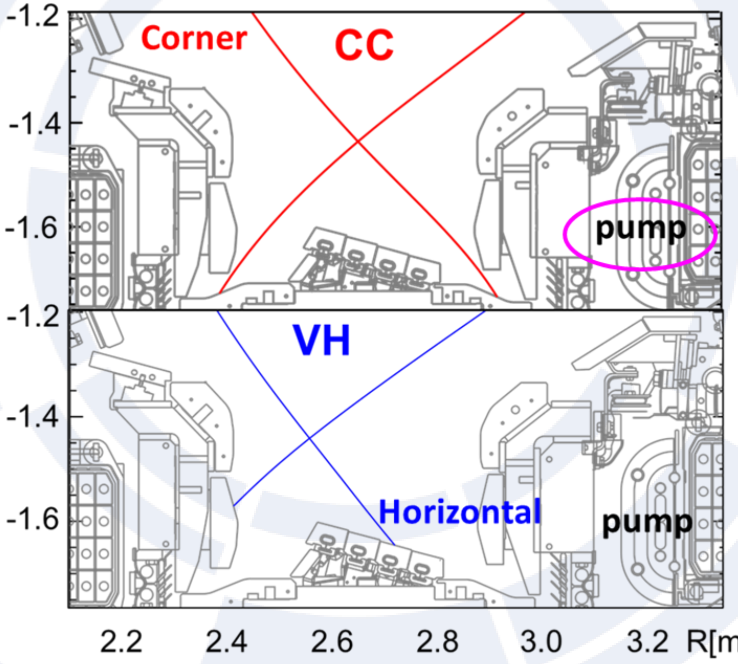
Select profiles

Pre-ELM CC | Pre-ELM VH

Post-ELM CC | Post-ELM VH

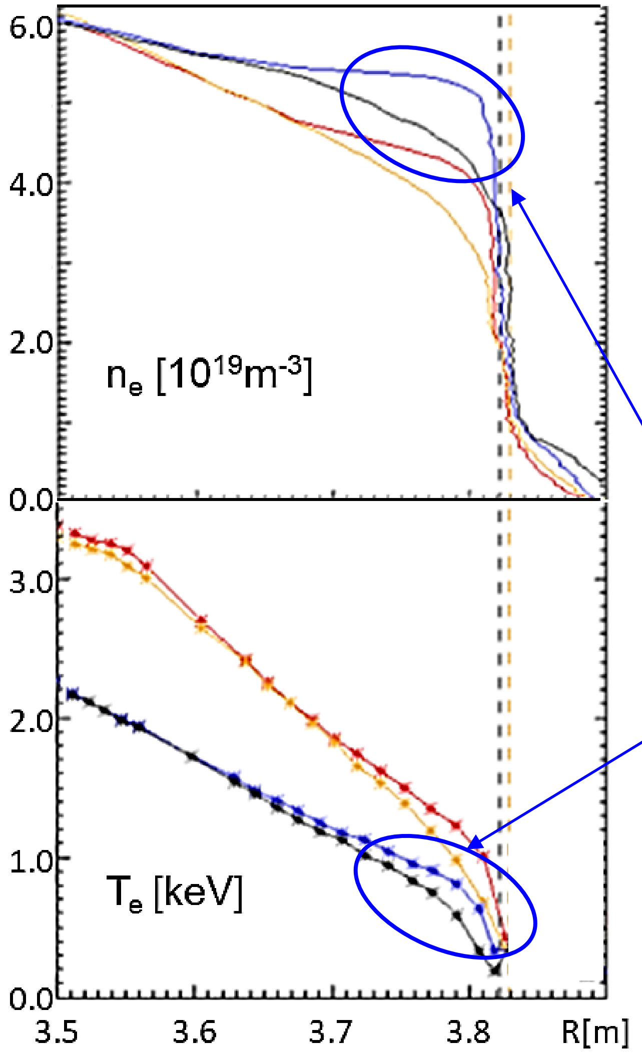
In CC:

- Lower $n_{e,ped}$, higher $T_{e,ped}$
- similar ELM particle loss
- better pumping
- Return to low $n_{e,ped}$ before next ELM



Zoom in, fast profiles at single time slices before and after ELMs

CC: good confinement associated to lower edge density, higher core temperatures



Select profiles

Pre-ELM CC

Post-ELM CC

Pre-ELM VH

Post-ELM VH

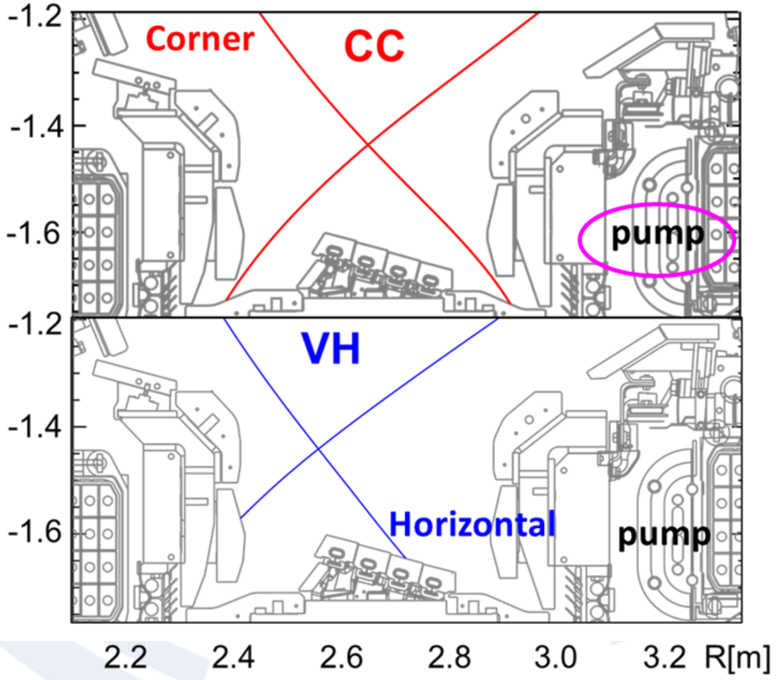
In CC:

- Lower $n_{e,ped}$, higher $T_{e,ped}$
- lower ELM particle loss
- better pumping
- Return to medium $n_{e,ped}$ before next ELM

In VH:

- Higher $n_{e,ped}$, lower $T_{e,ped}$
- higher ELM particle loss
- Less gas fuelling
- Worse pumping, higher recycling
- Return to high $n_{e,ped}$ before next ELM

In H-mode pumping matters:
Particles expelled by ELMs are
pumped away in CC
recycled back in VH



Modelling is required!

Conclusions

- In JET plasma shape at active X-point (and divertor hardware) affects $\bar{n}_{e,min}$ and $P_{LH,min}$

  reasons for configuration effect on P_{LH} at JET remains unknown

- Which P_{LH} scaling (**VH**, **CC**, B_{tor}, B_{pol}) to be applied to future devices?

  Configuration effect brings largest uncertainty

- Despite **lower P_{LH}** in **VH** configuration, **better H-mode confinement** is observed in **CC** configuration because a lower density operational window opens up.

  Because ELM-expelled particles are pumped away more efficiently? ***Modelling required!***

  Effect observed at 2.5 MA, not below

- $P_{loss}/P_{LH,scal}$ is not a good predictor of ELMy regime or good confinement

For any planned fusion operating regime

consider access and stationarity conditions for good overall confinement, different from conditions for low L-H power threshold.

Remember also strong isotope dependence of $\bar{n}_{e,min}$ and $P_{LH,min}$

Acknowledgements

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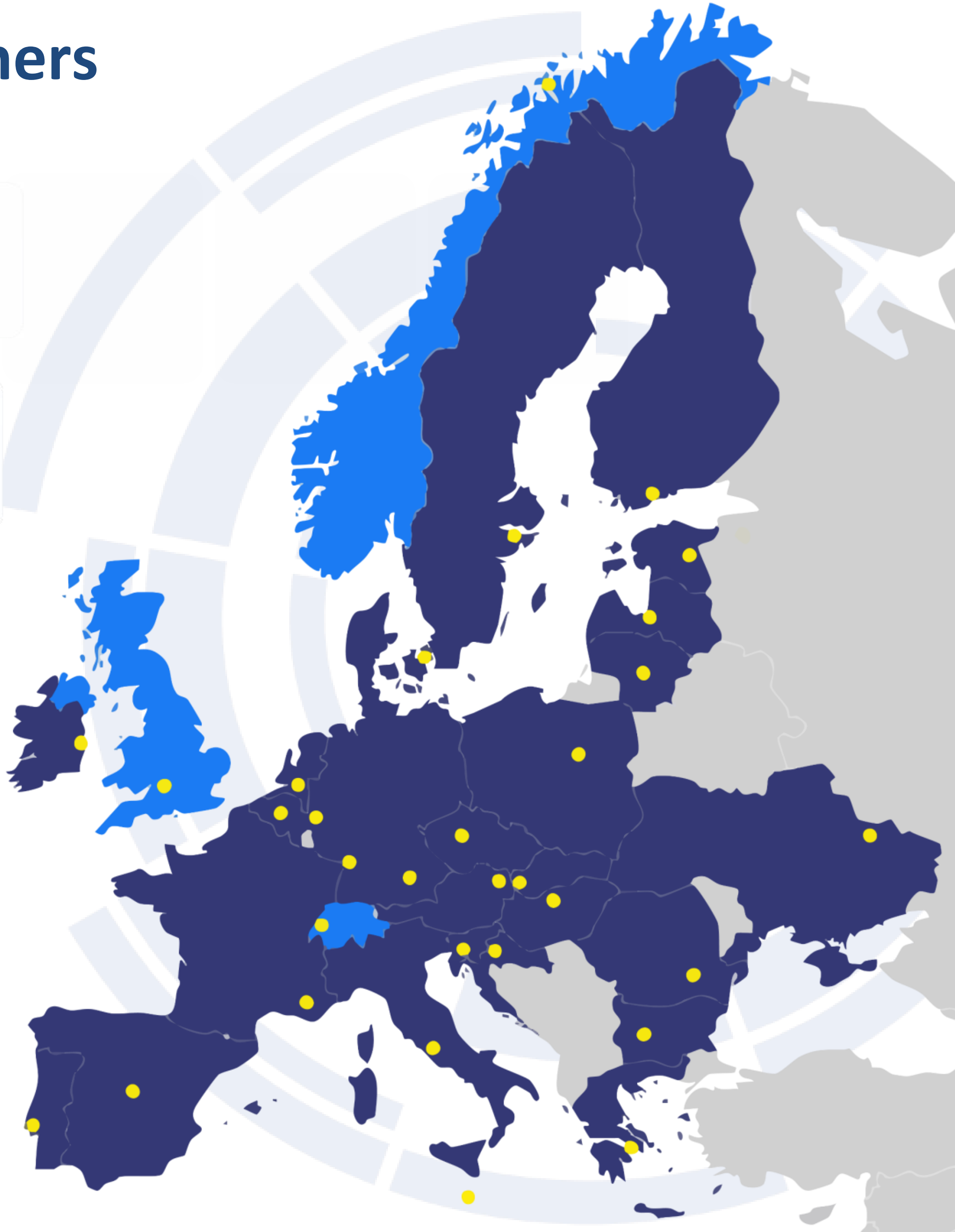
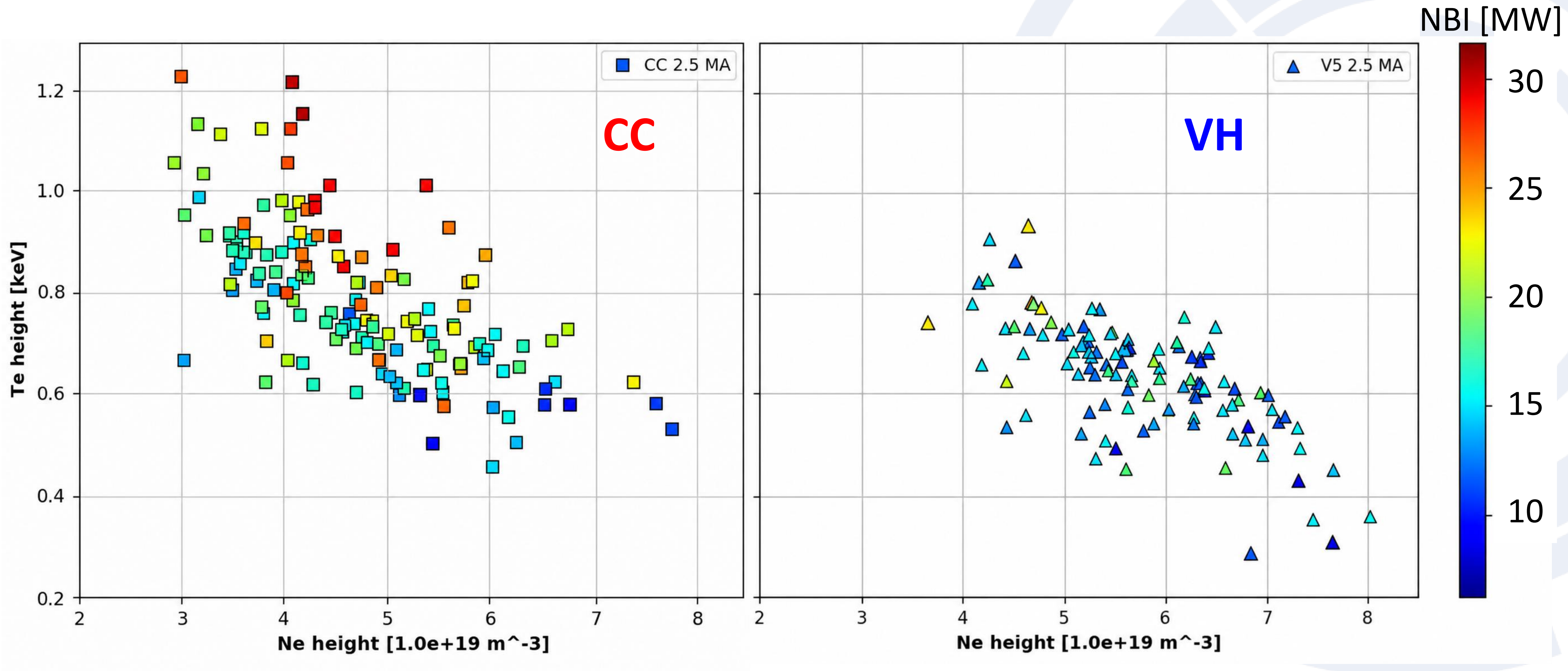


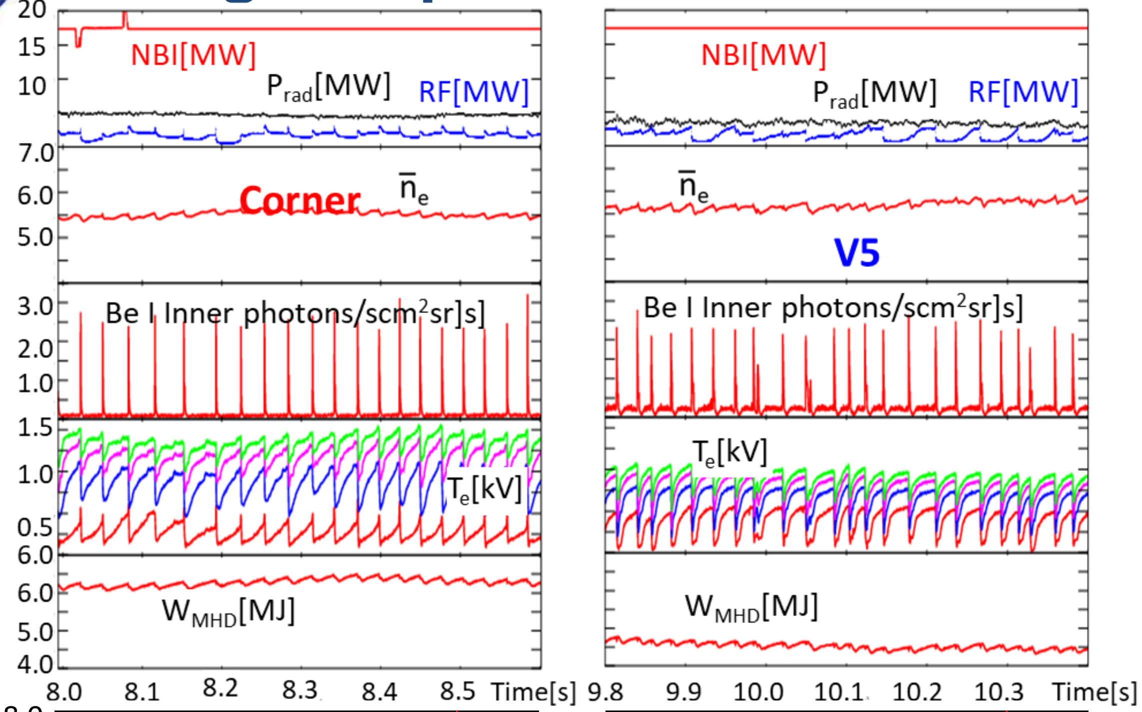
Pedestal parameters: hotter in Corner

Pedestal profile database of steady H-modes

CC: less dense, hotter, pedestal, higher powers ⟶ higher H98



Change shape and adjust gas, aim for constant line averaged density

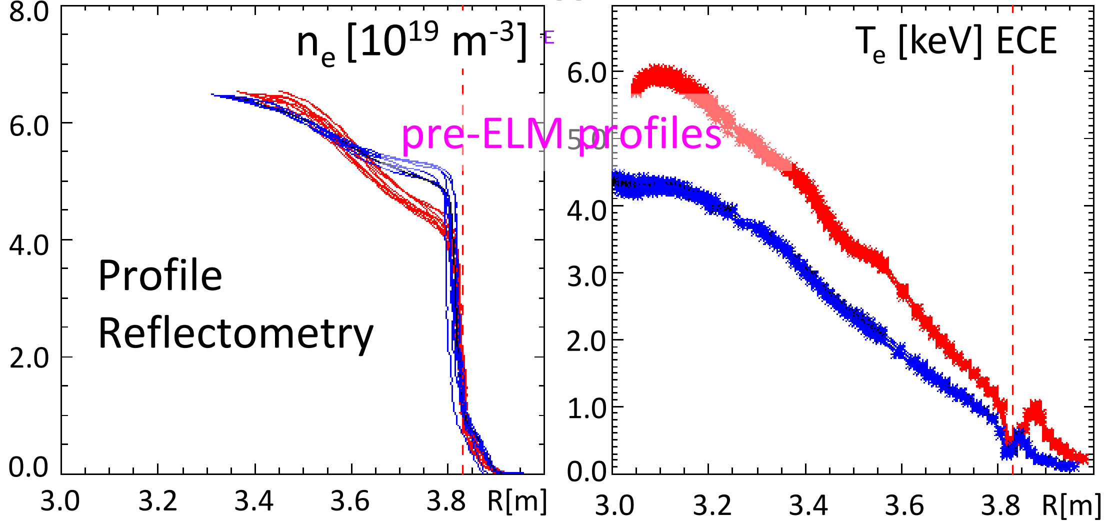


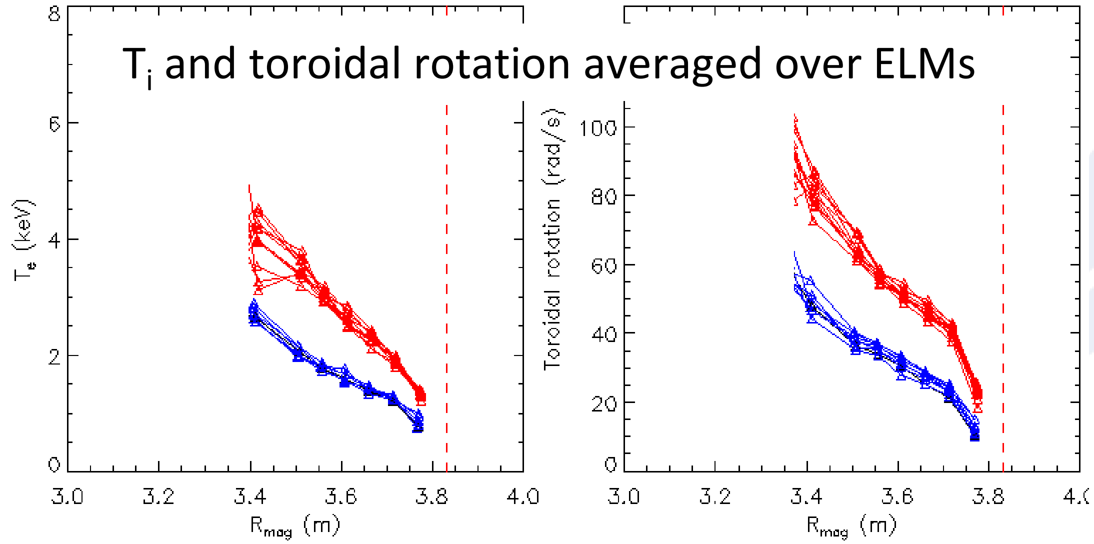
Corner: peaked density, better NBI penetration

VH: higher pedestal density, worse confinement

Corner: peaked density, lower $n_{e,ped}$, better NBI penetration, higher rotation

VH: higher pedestal density, colder core





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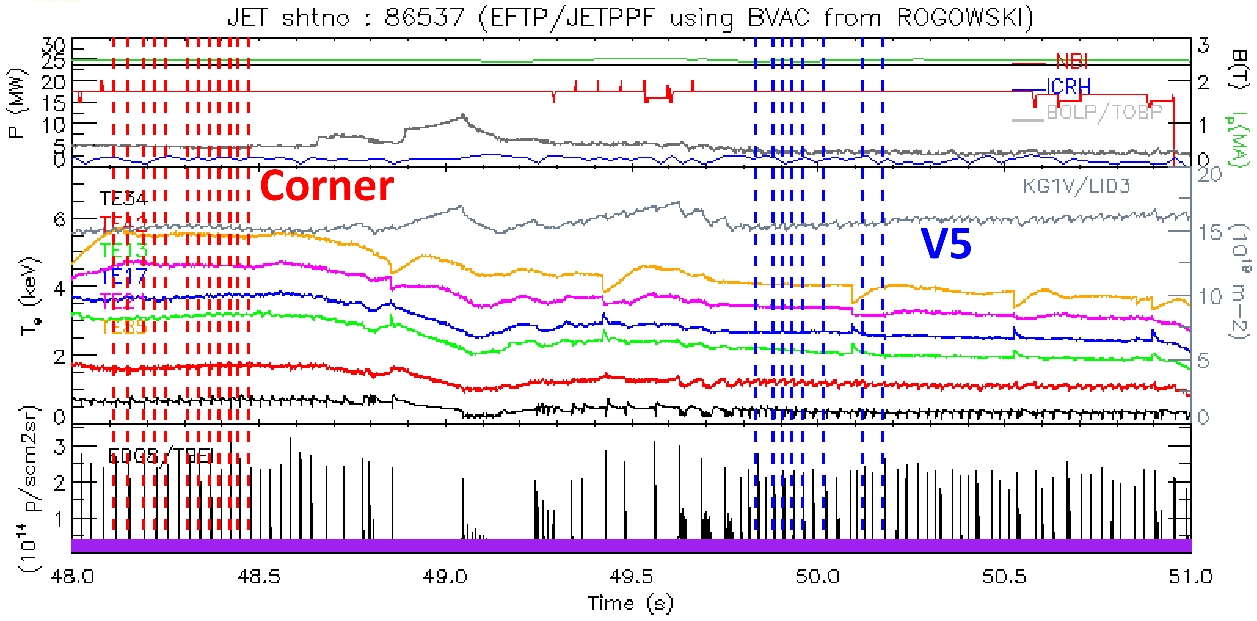
New comparison: adjust gas, aim for constant line averaged density



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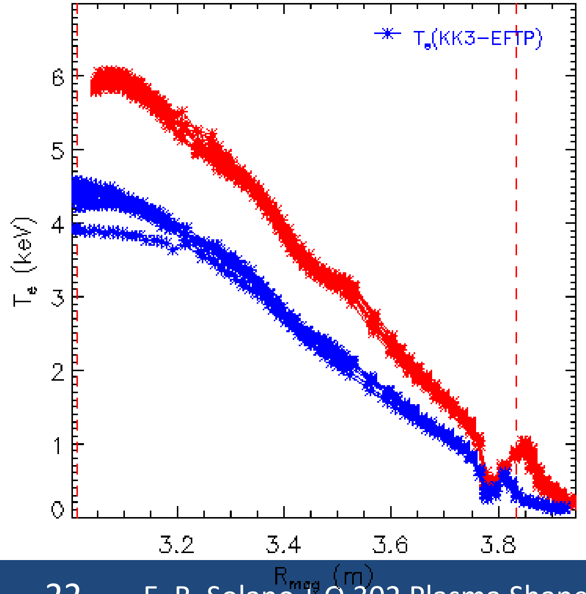
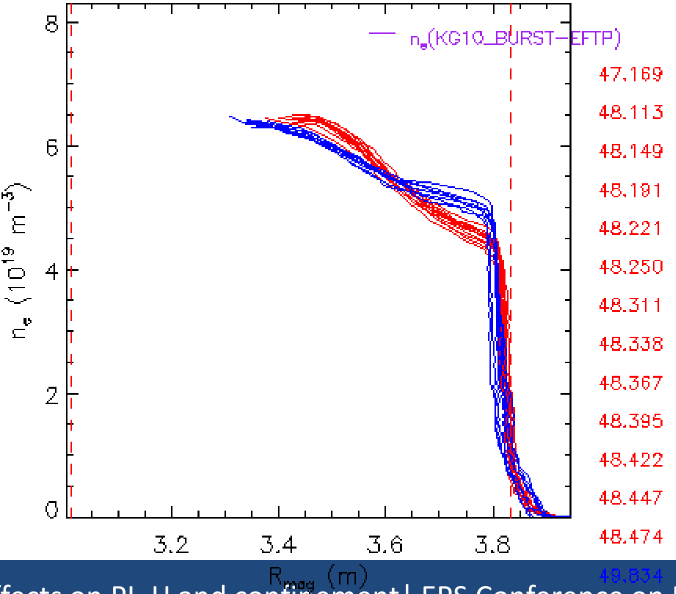
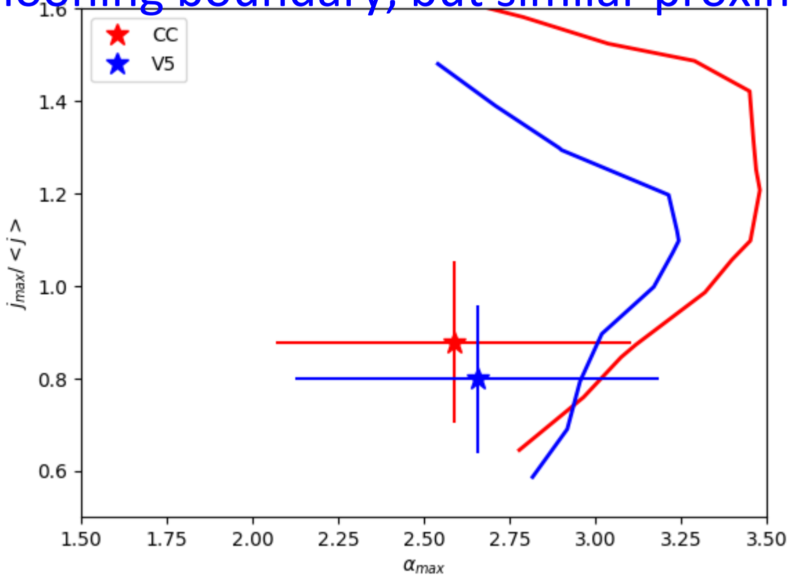
VH: higher pedestal density, worse confinement
tauE=0.24, H98=0.87
P_{loss}=18.6 MW, P_{LH}=4.5 MW, $P_{loss}/P_{LH,scal}$=2.5

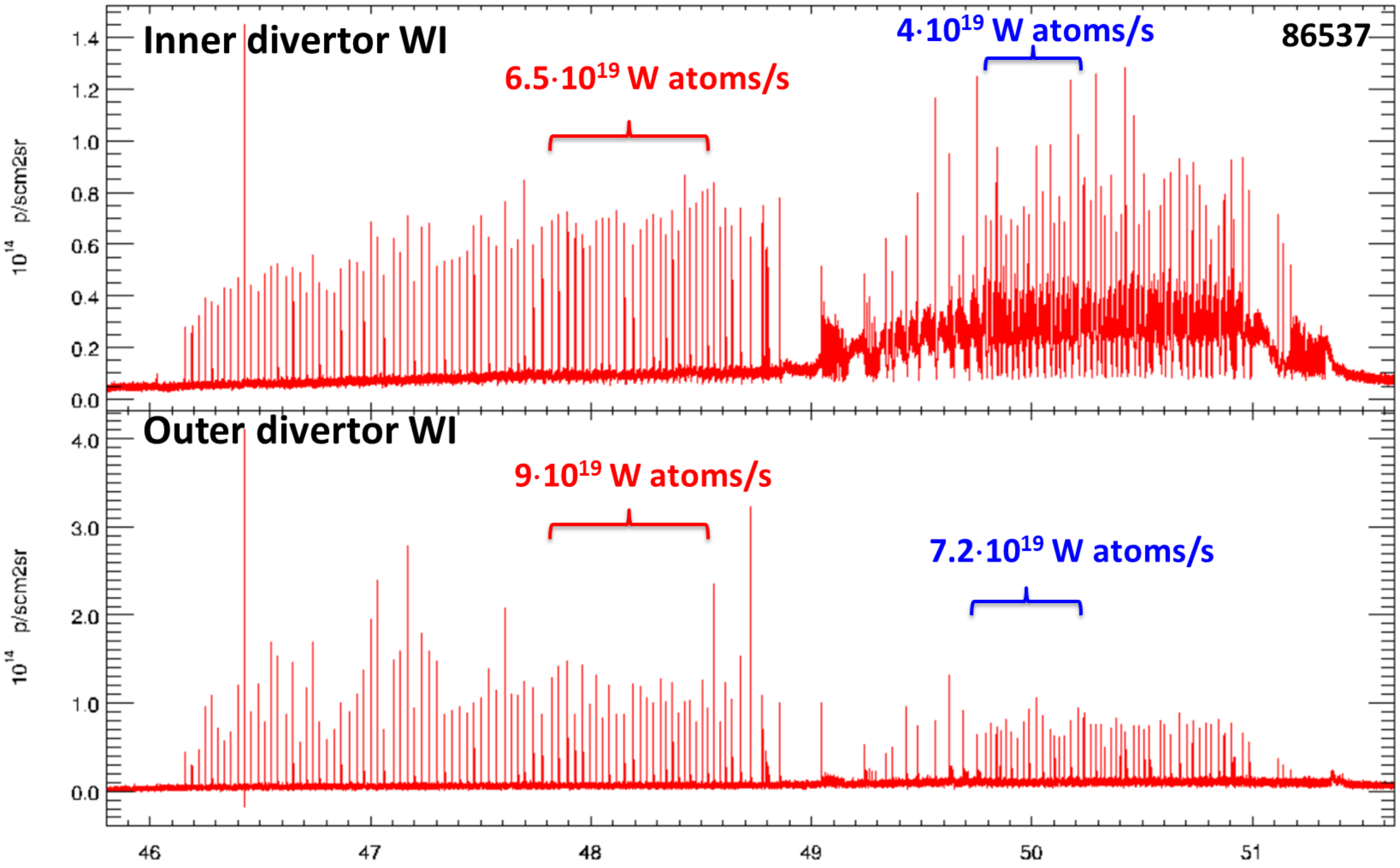
Pre-ELM ideal MHD stability shows different peeling ballooning boundary, but similar proximity to it







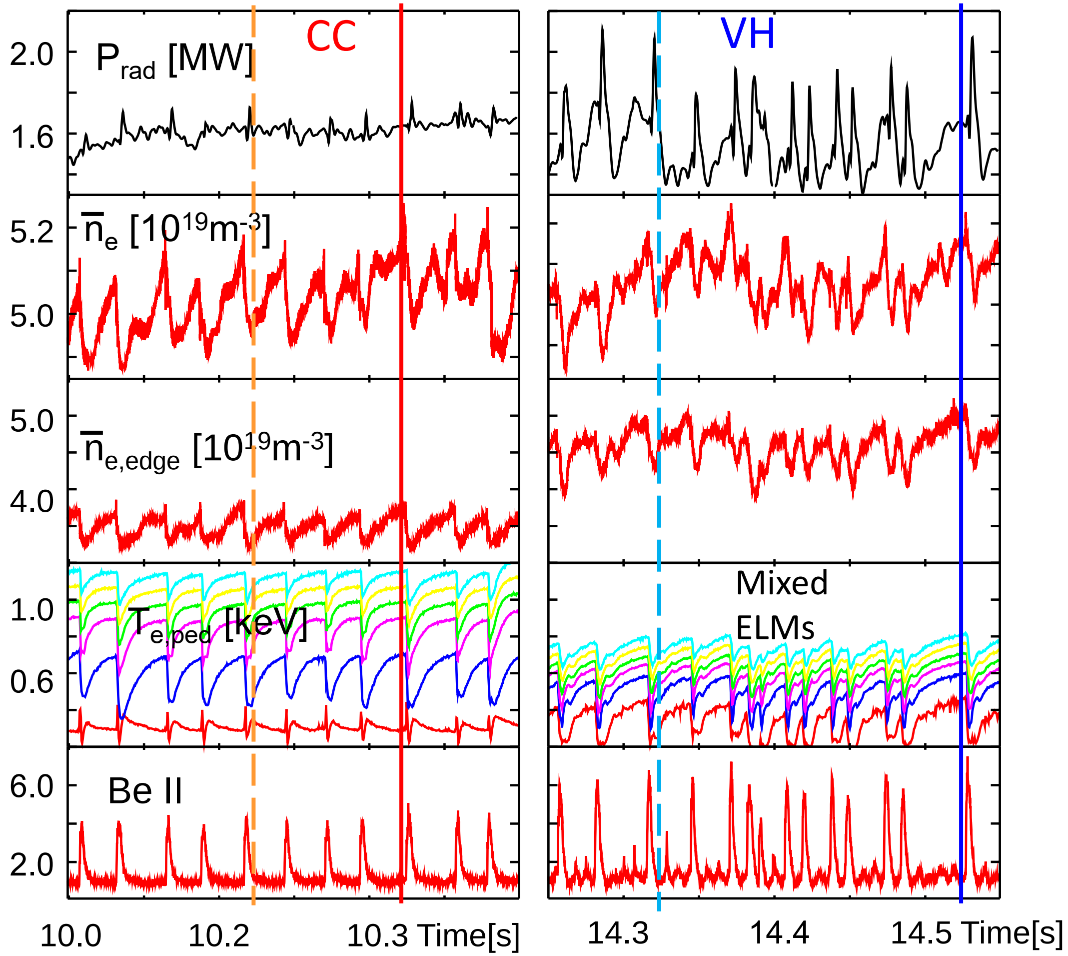
W erosion higher during Corner phase

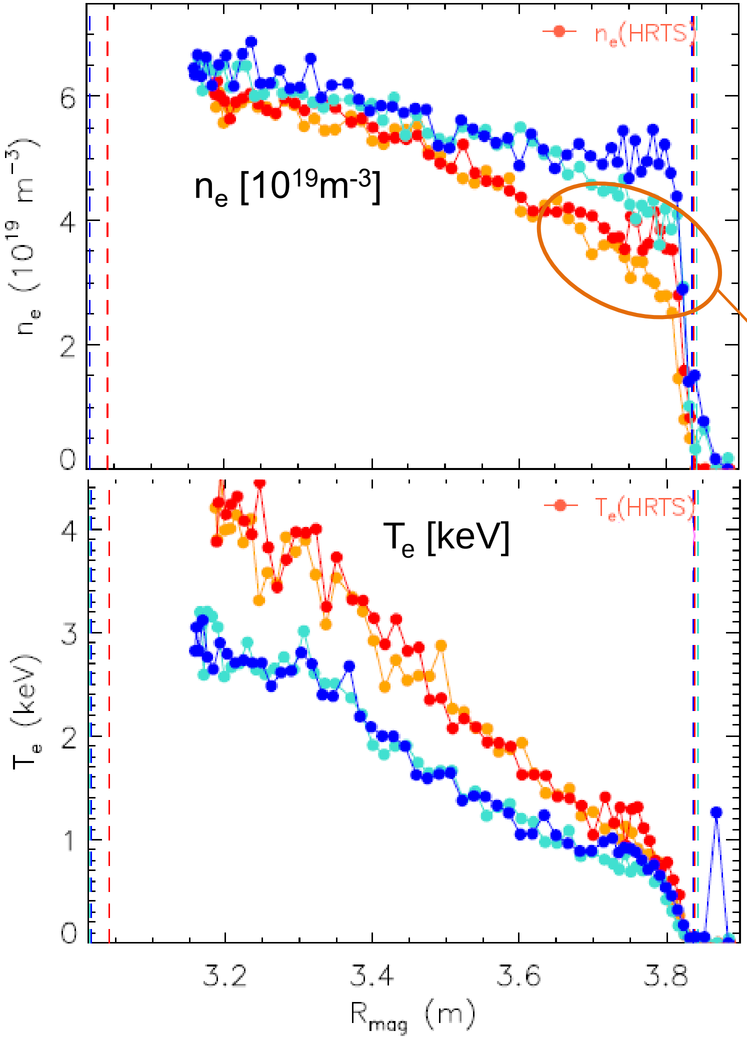


Consistent with higher pedestal T_e

Constant gas, Thomson Scattering profiles before selected ELMs

CC: good confinement associated to lower edge density, higher core temperatures





Select large ELM

Pre-ELM VH

Post-ELM VH

Pre-ELM CC

Post-ELM CC

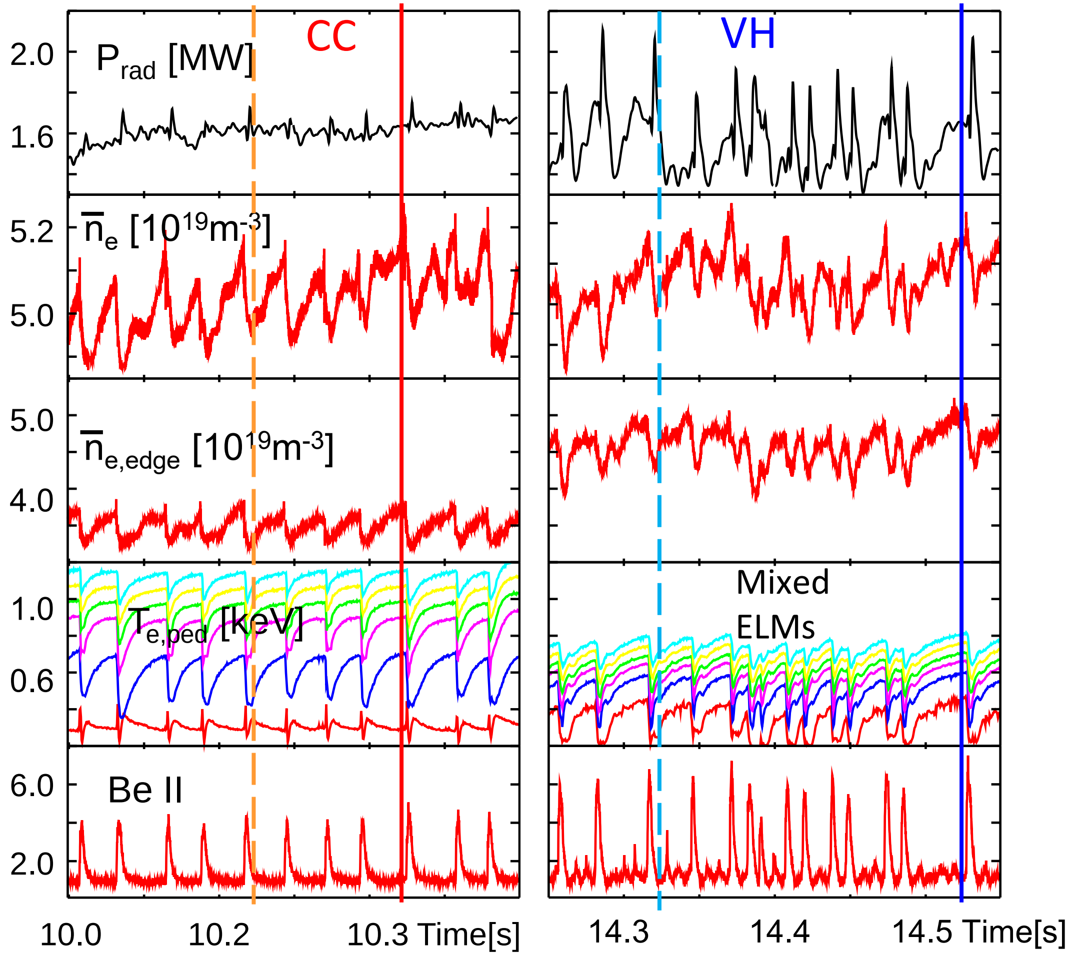
In CC:

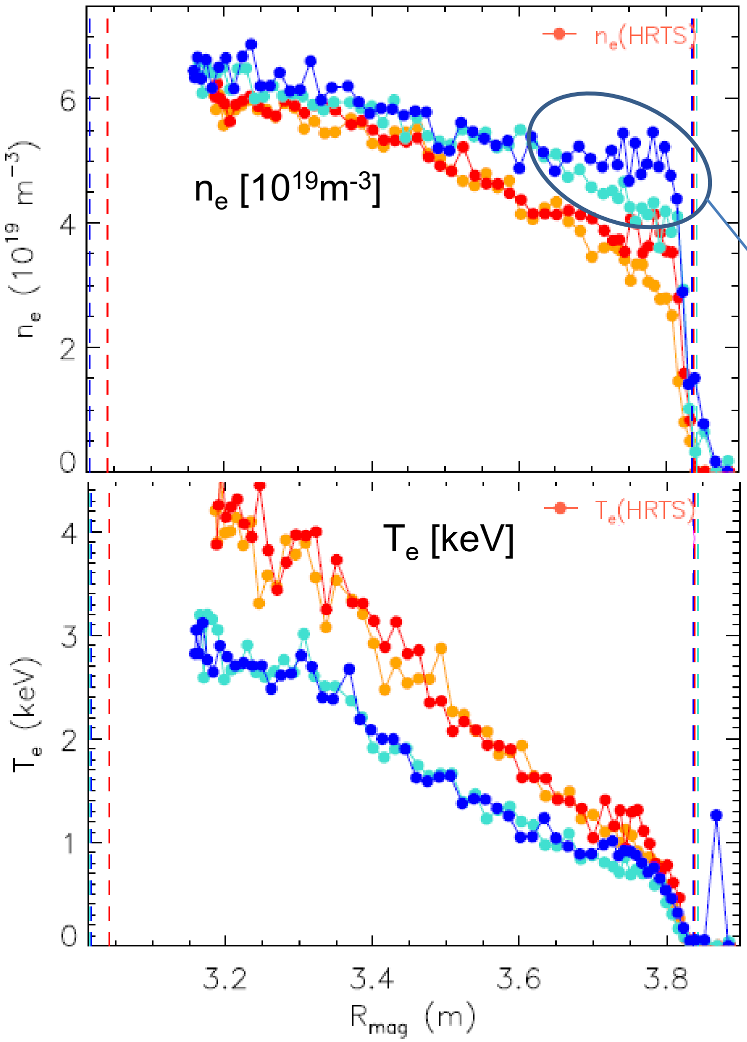
- Lower $n_{e,ped}$, higher $T_{e,ped}$,
- lower ELM particle loss
- less frequent steady ELMs

higher confinement

Constant gas, Thomson Scattering profiles before selected ELMs

CC: good confinement associated to lower edge density, higher core temperatures





Select large ELM

Pre-ELM VH

Post-ELM VH

Pre-ELM CC

Post-ELM CC

In VH:

- higher $n_{e,ped}$, lower $T_{e,ped}$,
- larger ELM particle loss
- more frequent ELMs

lower confinement