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Optimisation of JET-DT and ITER operation by developing an understanding of the role of low-Z impurity on the H-mode pedestal

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JET

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Acknowledgments

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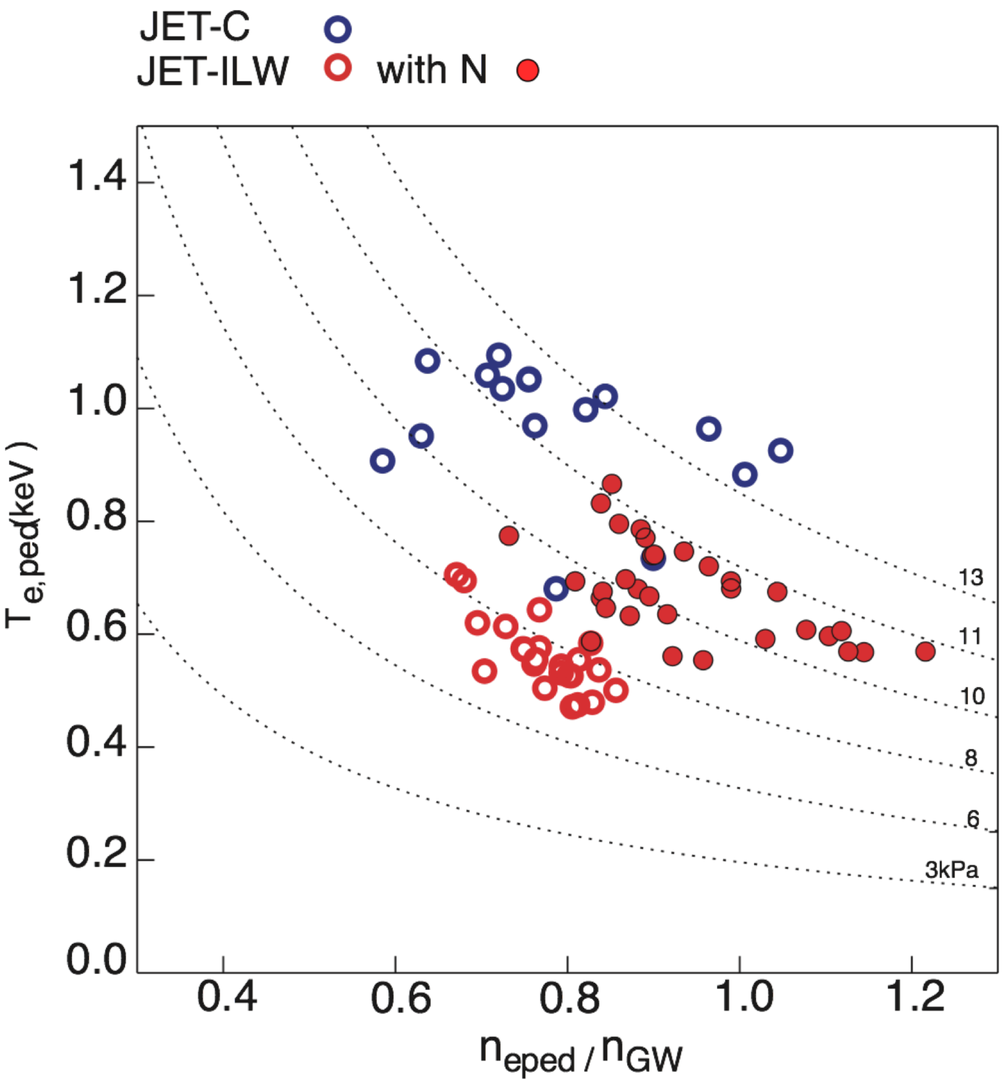
Introduction

2.5MA/2.7T , P_{nbi}=16MW, β_N=1.2, δ=0.4



Changing the first wall material from C to Be walls with W divertor (ILW) led to reduction in pedestal pressure height and temperature in JET.

D-gas injection and W radiation play a role but the absence of carbon had crucial impact.

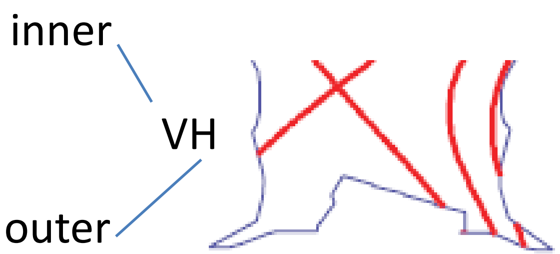
Understanding the impact of extrinsic impurity on the pedestal and disentangling its effect from that of other key mechanisms is necessary for robust JET-DT and ITER predictions.

Neon is preferred extrinsic impurity for ITER, being not active chemically. Nitrogen leads to tritiated ammonia.

Neon is seed impurity of choice for power load control in JET-DT. N is forbidden.

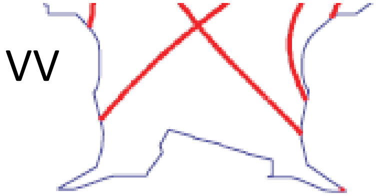
Previous experiments in JET-ILW have compared N and Ne and divertor configuration in low-β_N plasmas

2.5MA/2.7T , P_{nbi}=16MW, β_N=1.2, δ=0.4, ν^*_e = 1-2



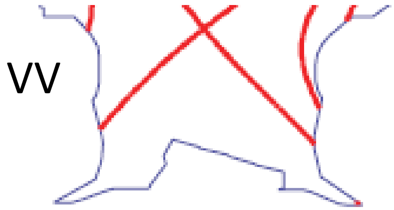
Nitrogen at 2% concentration

- Increased the pedestal density $n_{e,ped}$
- raised pedestal temperature $T_{e,ped}$ in pre-elm interval
- increased of the pedestal pressure



Nitrogen at 2% concentration

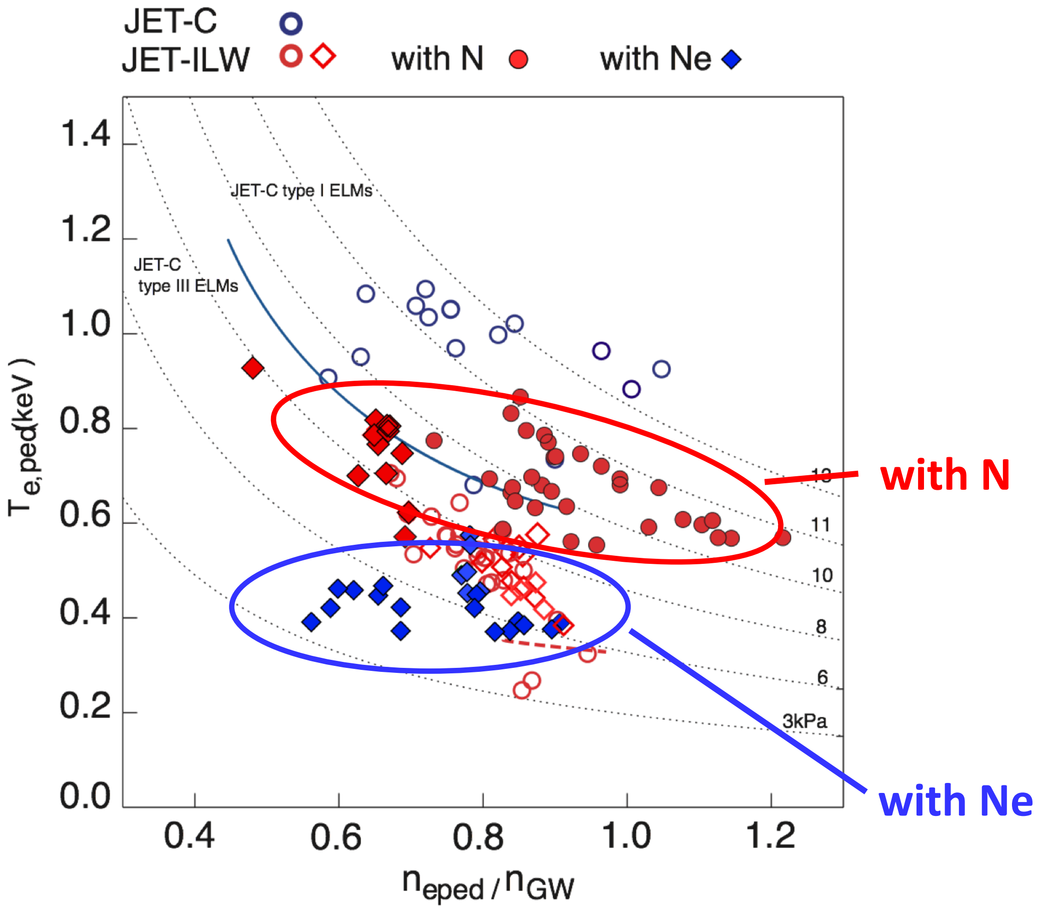
- decreased the pedestal density $n_{e,ped}$
- raised in $T_{e,ped}$ in pre-elm
- increased of pedestal pressure



Neon at 1% concentration

- decreased $n_{e,ped}$
- decreased $T_{e,ped}$
- decreased the pedestal pressure

Summary of previous experiments



		$n_{e,ped}$		$T_{e,ped}$	$T_{i,ped}$
N	low-β_N	VH	↗	$T_{e,ped}=T_{i,ped}$ ↗	
		VV	↘		
Ne	low-β_N	VH	↘	↘	
		VV	↘		

In JET-DT, it would be beneficial if the use of Ne for power load control is optimised to obtain the best performance

- Do condition exists where neon can increase the pedestal temperature, pressure as N does ?
- How does nitrogen impact on the different transport channels? or Carbon ? C being a better seed impurity for this investigation

New experiments investigated the impact of D-gas and C_2D_4 on the pedestal of high-β_N plasmas

1.4MA/1.9T

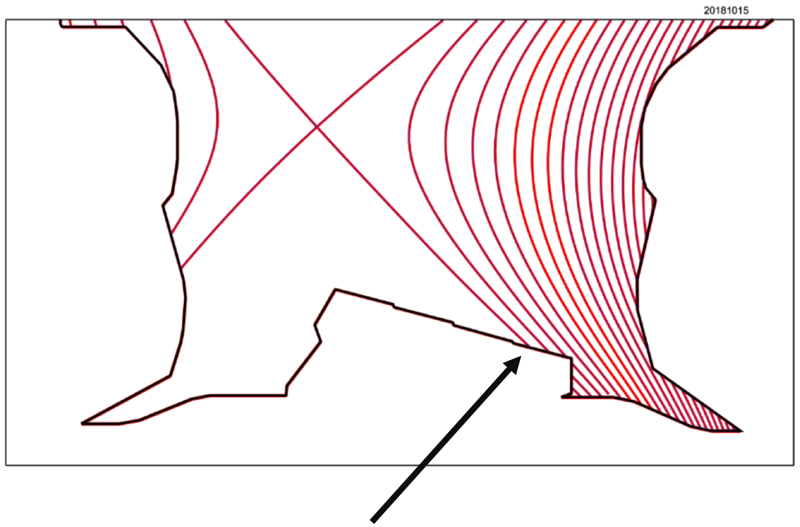
P_{nbi}~16.5-17.5MW kept constant

β_N=2.5 (at low el/s), δ=0.2

P_{sep}/P_{LH}>2, ν_e^* =0.1-0.6 , q_{95}=4.4

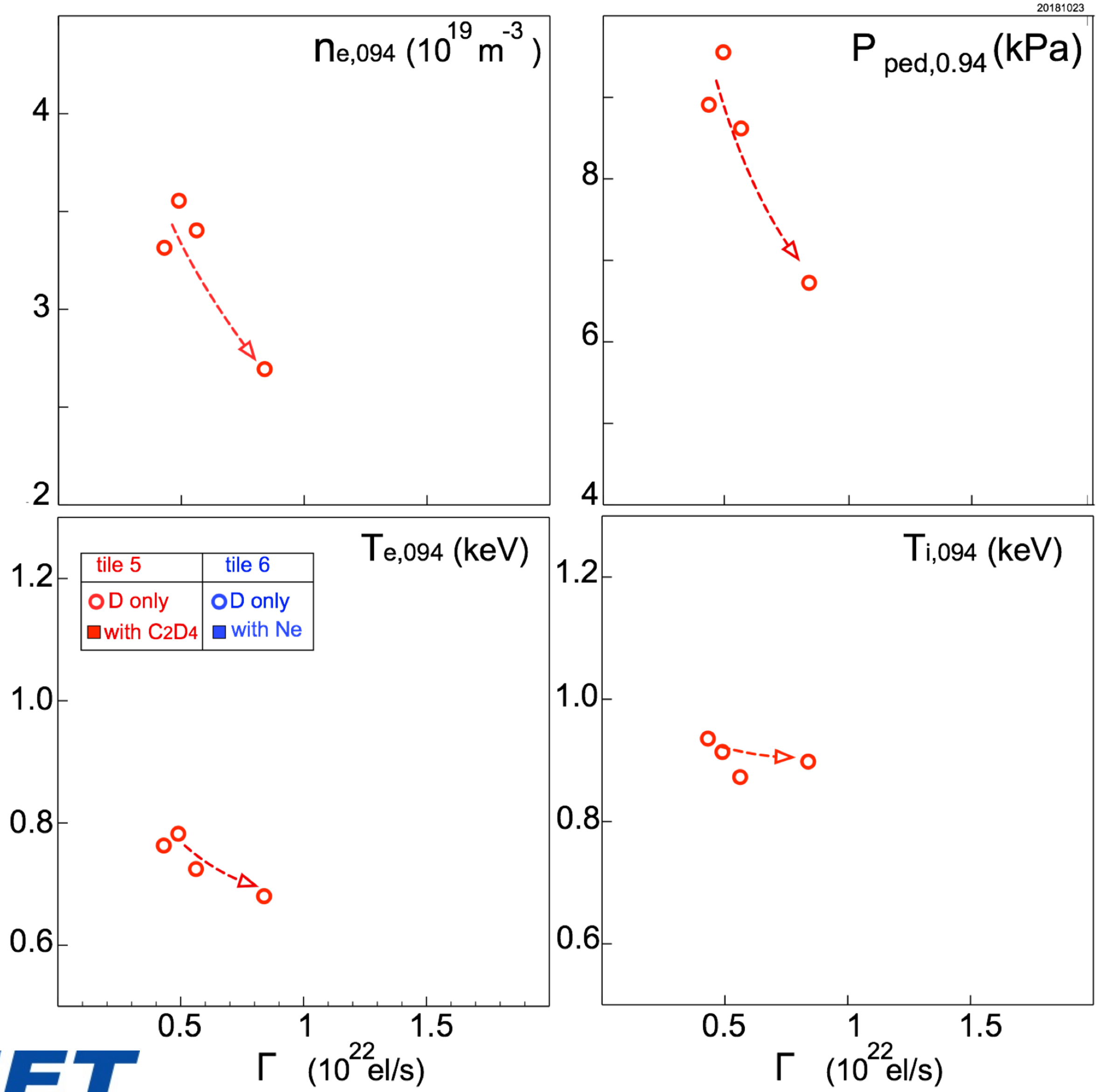
Z_{eff} = 1.5

Tile 5 configuration



Outer strike on tile 5

Impact of D-gas on the pedestal of high-β_N plasmas



- D-gas scan:

  H_{98} 1.05 → 0.9

  β_N 2.6 → 2.2

  ν_{elm} 25 → 80 Hz

- Pedestal values

  $n_{e,ped}$ ↘

  $T_{e,ped}$ ↘

  $T_{i,ped}$ →

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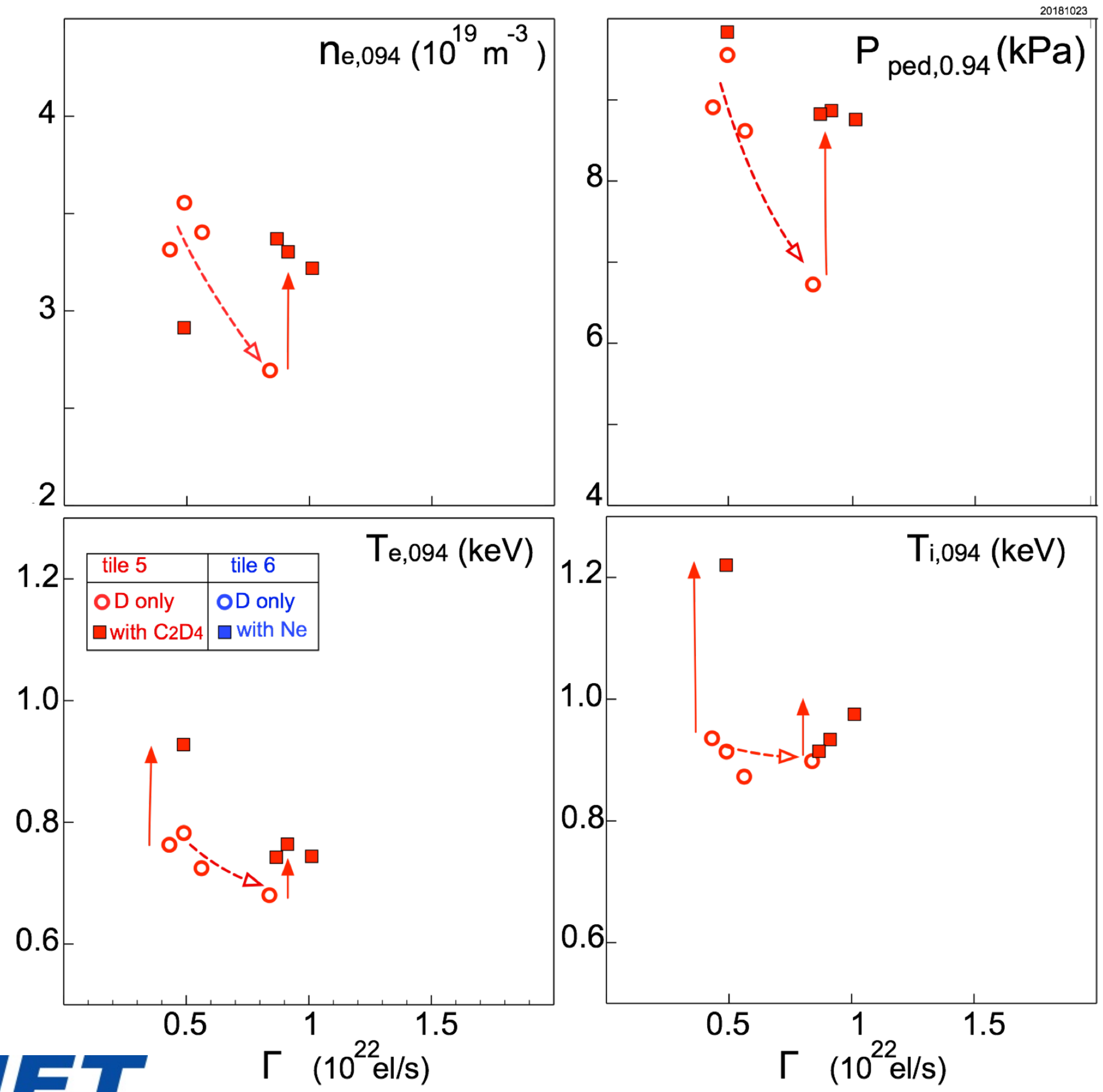
Impact of C_2D_4 on the pedestal of high-β_N plasmas



- C_2D_4-gas scan at high el/s

  - H_{98}, β_N, Z_{eff}, ν^*_e, ν_{elm} back to value of D-gas only at low el/s
  - nc/ne : 0.1 → 0.3%

- Pedestal values with C_2D_4 at high el/s w.r. to D-gas

  $n_{e,ped}$ ↗
  $T_{e,ped}$ ↗
  $T_{i,ped}$ ↗

  Counterbalance D-gas at high el/s

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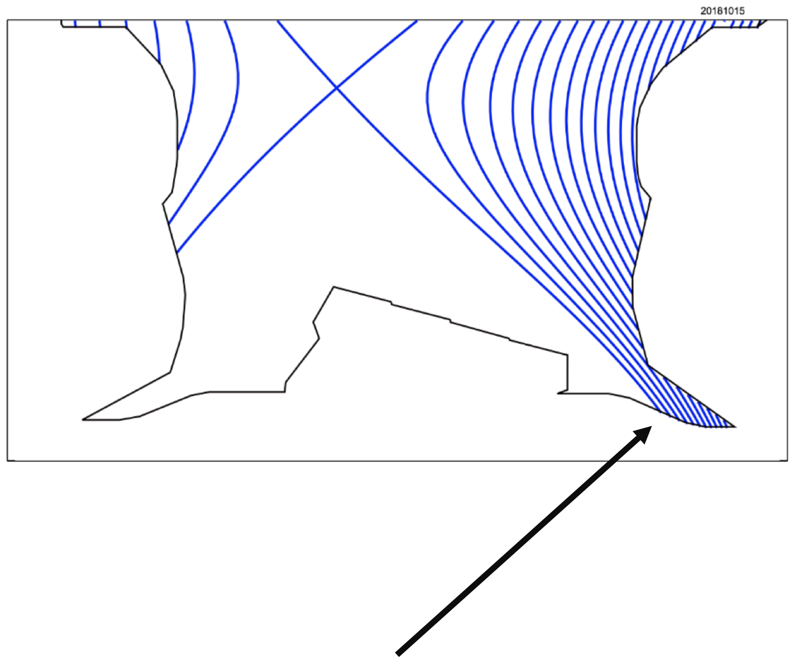
Impact of D-gas and Neon on the pedestal of high-β_N plasma

Same plasma parameters as before

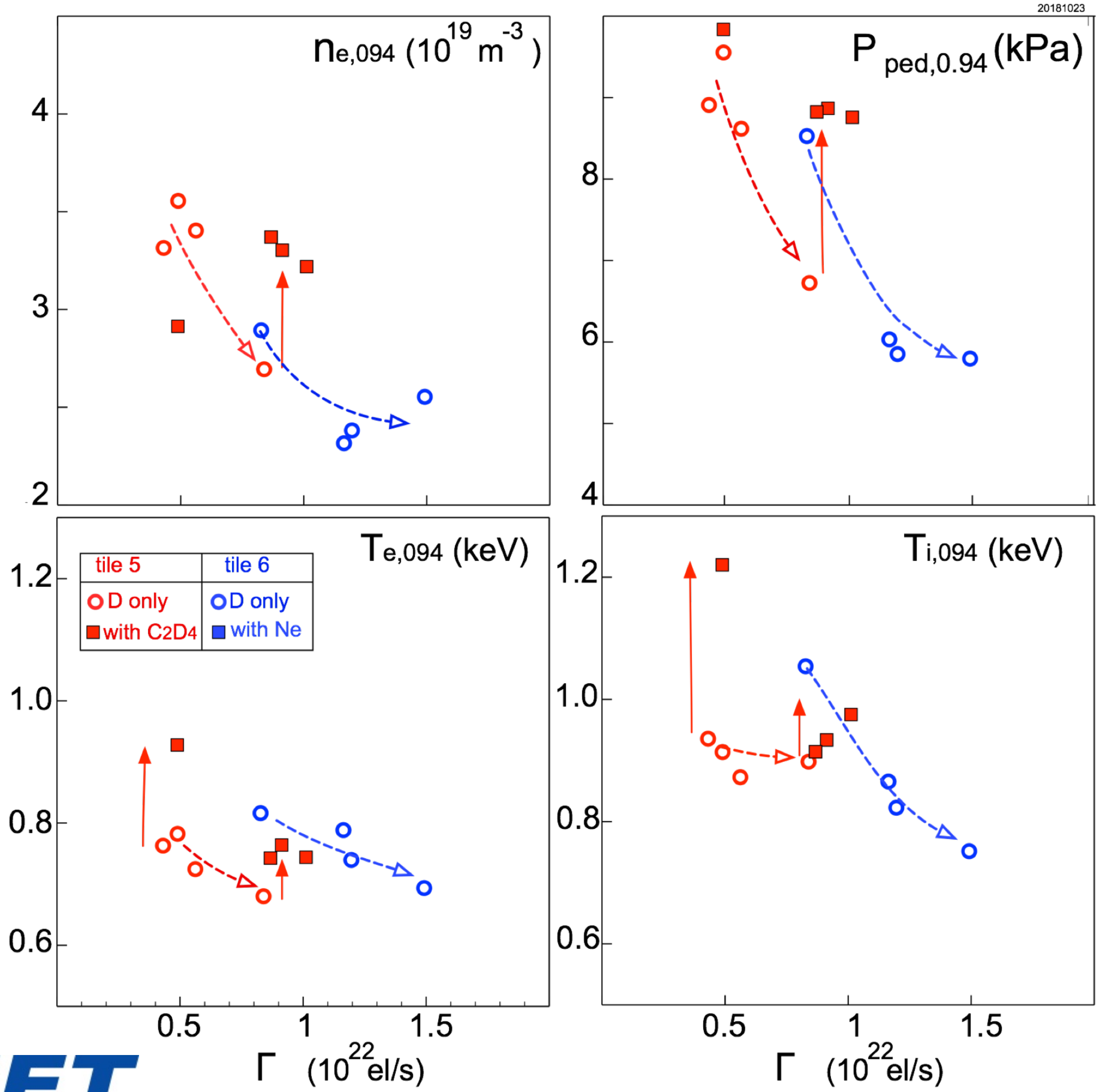
Tile 6 configuration



Outer strike point on tile 6

- Outer strike closer to the divertor pump duct entrance

Impact of D-gas on the pedestal of high-β_N plasmas with OS on tile 6



- D-gas scan tile 6 :

  H_{98} 1.2 → 0.9

  β_N 2.9→2.2

  Z_{eff} 1.8

  $\nu^*_{e,ped}$ 0.6

  ν_{elm} 40 → 120 Hz

- Pedestal values

  $n_{e,ped}$

  $T_{e,ped}$

  $T_{i,ped}$

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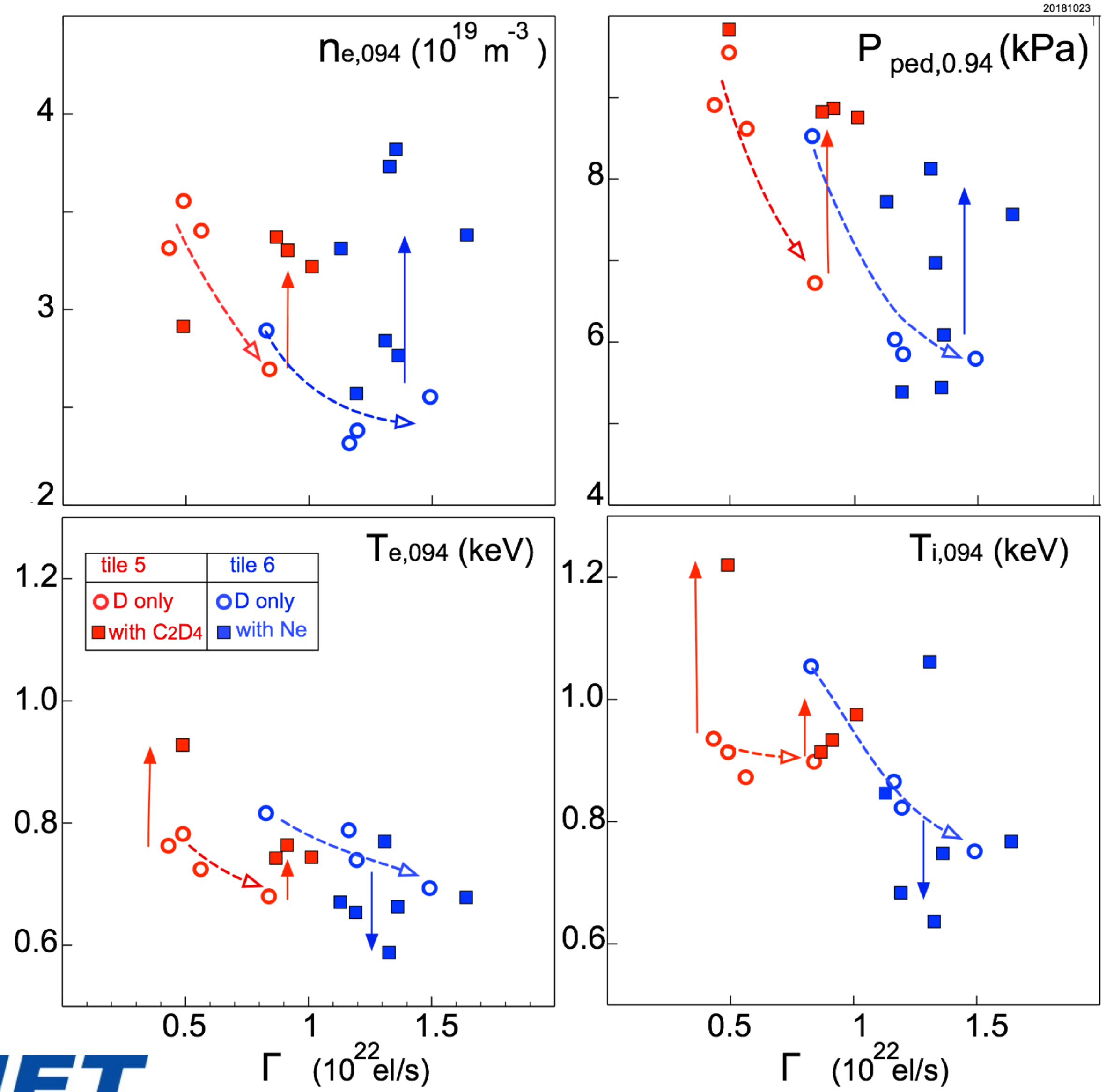
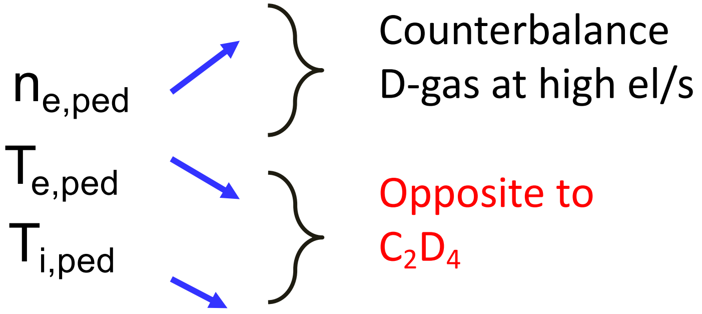
Impact of neon on the pedestal of high-β_N plasmas with OS on tile 6

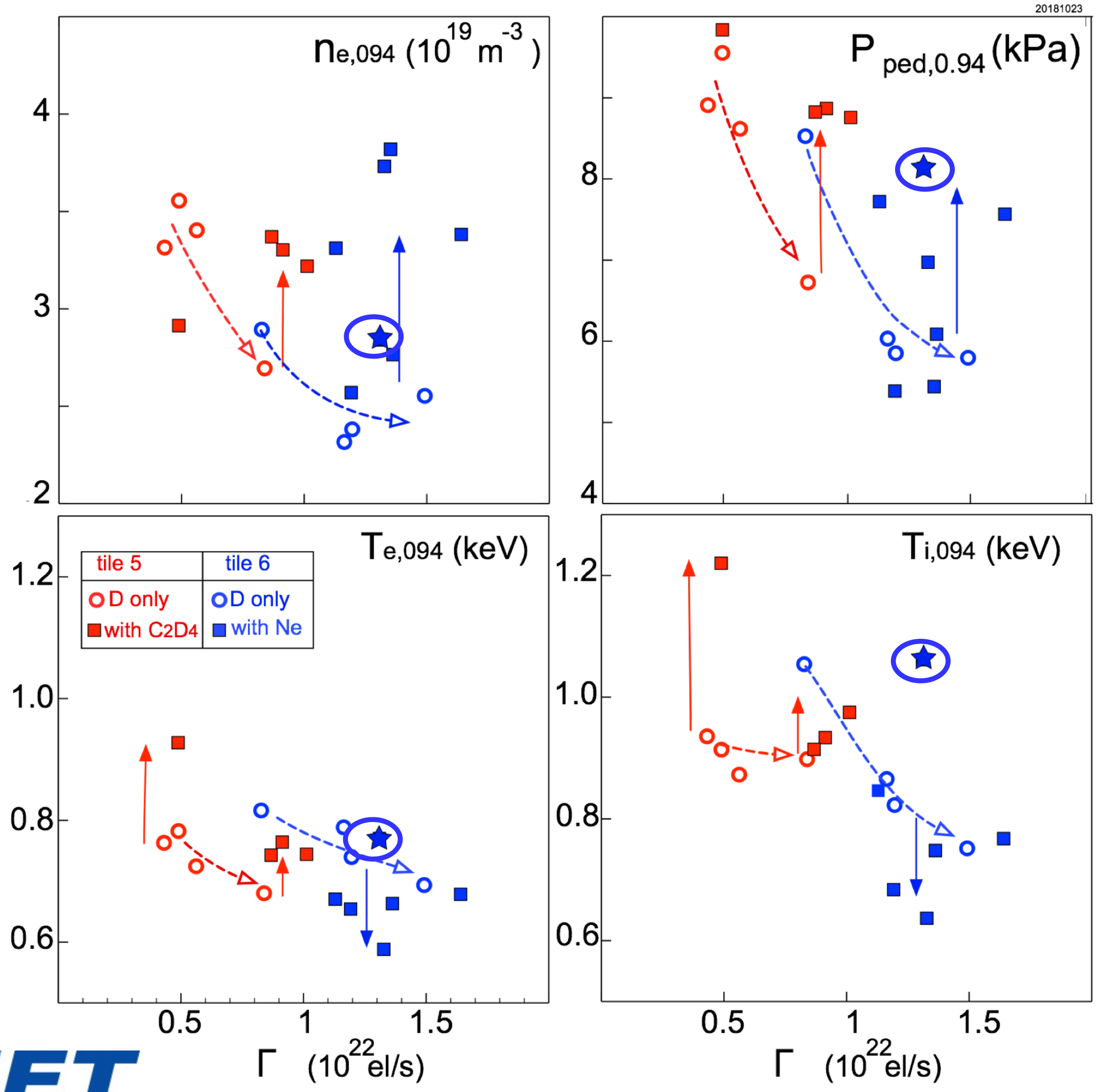


- Pedestal value with Ne at high el/s w.r.t. to D-gas only

  nNe/ne 0.6 → 1.2%



Impact of neon on the pedestal of high-β_N plasmas with OS on tile 6



- Pedestal value with C_2D_4 at high el/s wrt to D-gas only

  $n_{e,ped}$ ↗ } Counterbalance D-gas at high el/s

  $T_{e,ped}$ ↘

  $T_{i,ped}$ ↘ } Opposite to C_2D_4

- If with Ne:

  – $\nu^*_{e,ped}$ < 1

  - c_{Ne}=0.6% (low pedestal radiation)

➔ $T_{i,ped}$ and $T_{e,ped}$ can be maintained at similar values to those of D-gas injection at low el/s with Ne (★)

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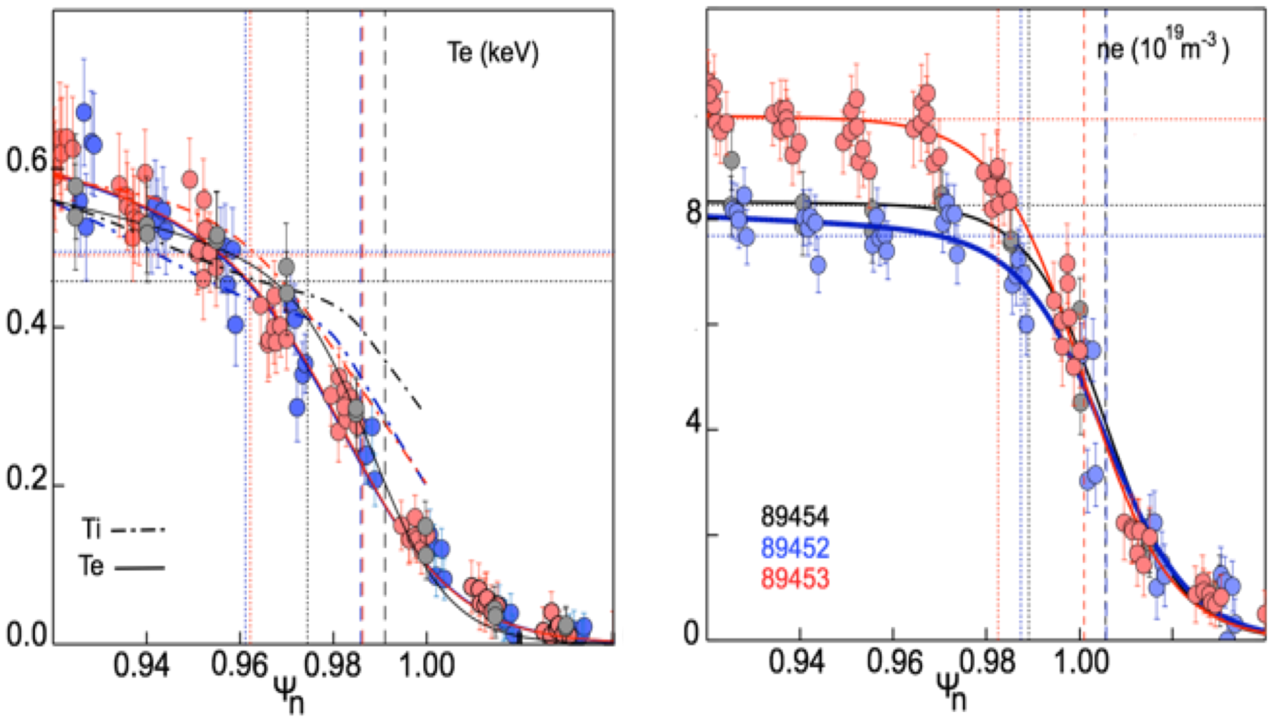
Low-β_N high-δ plasmas with CD_4

2.5MA/2.7T , P_{nbi}=16MW, β_N=1.2, δ=0.4



- Pedestal value with CD_4 at low C_C =0.7-0.8 %

$n_{e,ped}$ ↗

$T_{e,ped}$ = $T_{i,ped}$ →

unseeded β_N= 1.17
seeded 1.3
seeded 1.45

- Existence of a threshold in D-gas rate at which C does not improve the pre-ELM pedestal pressure (with C_C<1%), also observed in N
- Significant increase of $n_{e,ped}$ in seeded plasma at lower D-gas injection rate, before increase in $T_{e,ped}$

Impact of impurity on pedestal values

		$n_{e,ped}$		$T_{e,ped}$	$T_{i,ped}$
N C	low-β_N	VH	↗	$T_{e,ped}=T_{i,ped}$ ↗	
		VV	↘		
	high-β_N	VH	↗	↗	↗
Ne	low-β_N	VH	↘	↘	
		VV	↘		
	high-β_N	VC	↗	↘	↘

In comparison with D-gas at high el/s

C & N-seeding increases $T_{e,ped}$ and $T_{i,ped}$

Neon-seeding decreases $T_{e,ped}$ and $T_{i,ped}$

Depends on
- **Divertor configuration**
- **and value of P_{sep}/P_{LH}**

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Impact of impurity on pedestal values

			$n_{e,ped}$	$T_{e,ped}$	$T_{i,ped}$
N	low-β_N	VH	↗	$T_{e,ped}=T_{i,ped}$ ↗	
		VV	↘		
C	high-β_N	VH	↗	↗	↗
Ne	low-β_N	VH	↘	↘	
		VV	↘		
	high-β_N	VC	↗	→ ↘	→ ↘

In comparison with D-gas at high el/s

C & N-seeding increases $T_{e,ped}$ and $T_{i,ped}$

Neon-seeding decreases $T_{e,ped}$ and $T_{i,ped}$

but at low enough pedestal ν^*_e (low pedestal radiation loss)
→ JET- DT plasma ☺

Depends on
- **Divertor configuration**
- **and value of P_{sep}/P_{LH}**

Effect of C and N on
- $T_{i,ped}$ increases as concentration increases
- $n_{e,ped}$ seems less dependent an increased concentration

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Impact of impurity on pedestal values

		$n_{e,ped}$		$T_{e,ped}$	$T_{i,ped}$
N	low-β_N	VH	↗	$T_{e,ped}=T_{i,ped}$ ↗	
		VV	↘		
C	high-β_N	VH	↗	↗	↗
Ne	low-β_N	VH	↘	↘	
		VV	↘		
	high-β_N	VC	↗	↘ →	↘ →

In comparison with D-gas at high el/s

C & N-seeding increases $T_{e,ped}$ and $T_{i,ped}$

Neon-seeding decreases $T_{e,ped}$ and $T_{i,ped}$

but at low enough pedestal ν^*_e (low

In high-β_N plasmas, recovered similar results to AUG with increase of $T_{e,ped}$ and $T_{i,ped}$ with N and increase $n_{e,ped}$ with neon

Depends on

- **Divertor configuration**
- **and value of P_{sep}/P_{LH}**

Effect of C and N on

- $T_{i,ped}$ increases as conc
- $n_{e,ped}$ seems less depen concentration

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Robust predictions for ITER would require that the ELM trigger is explained

- Are we able to understand when the ELM is triggered in fuelled and seeded plasmas ? Which MHD model is it necessary to use ?

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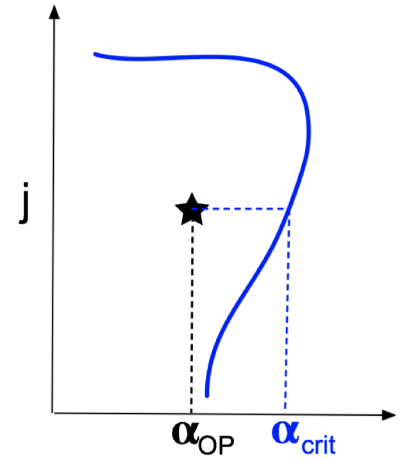
Which MHD model is consistent with the ELM trigger conditions ?

- **In JET-C:** Ideal MHD model was able to explain the ELM trigger with T_e=T_i, neglecting effect of rotation shear and diamagnetic effect

Criterion for ELM trigger being reproduced

$$\left|\frac{\alpha_{crit}-\alpha_{OP}}{\alpha_{OP}}\right| \leq 0.2$$



- **In JET-ILW:**
  - Standard method insufficient, in particular in high-β_N high D-gas injection [Maggi NF '15]
  - Linear non-ideal MHD model (MINERVA-DI*) : T_i measured, with ion diamagnetic effect (ω^*_i) and effect of rotation on PBM stability
    - IDEAL : Ti measured
    - DIAwoR: Ti measured + diamagnetic effect
    - DIAwR: Ti measured + diamagnetic effect + rotation shear

* *Aiba PPCF 2016*

  - Assessment done for plasmas with β_N~1.2-1.5 , ν_e^*>1, done in [Aiba PPCF '18]
  - Repeating this study for wider set of high-β_N plasmas

Aiba NF 2017
Aiba PPCF 2018

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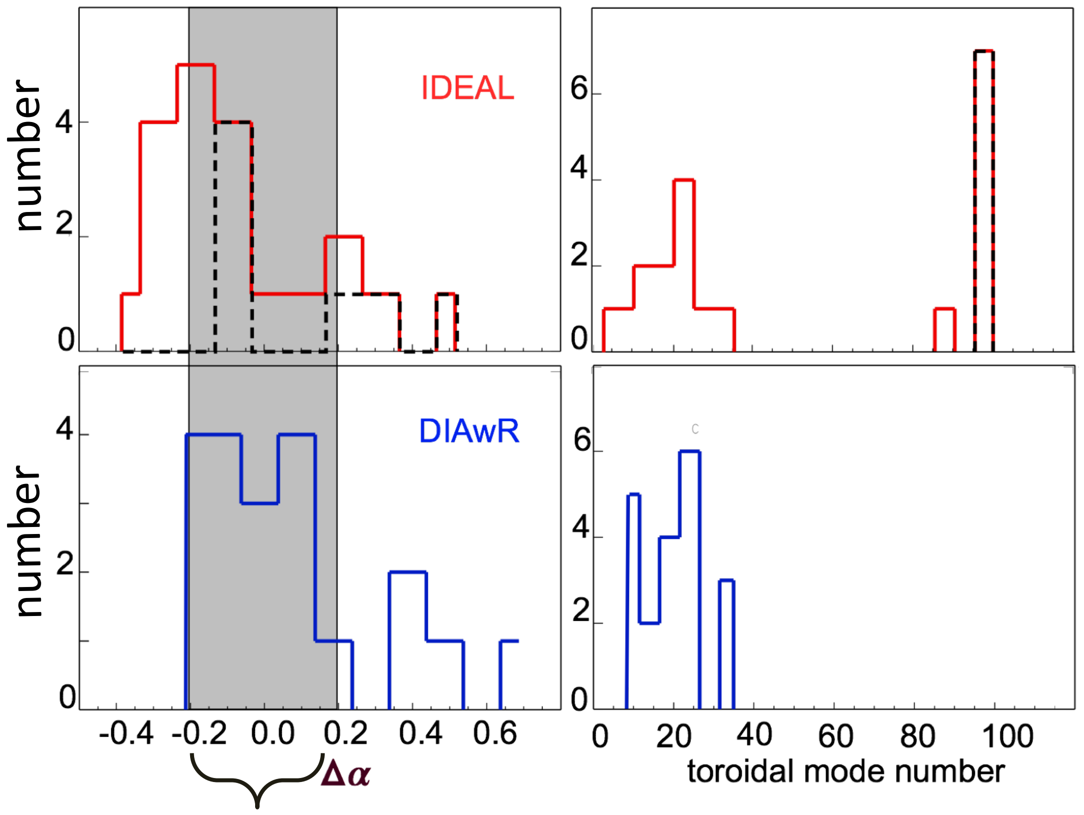
Linear MHD model DIAwR agrees with the ELM trigger conditions in high-β_N plasmas

dataset: C_2D_4 and Ne series

$\nu^*_{e,95} \leq 1$



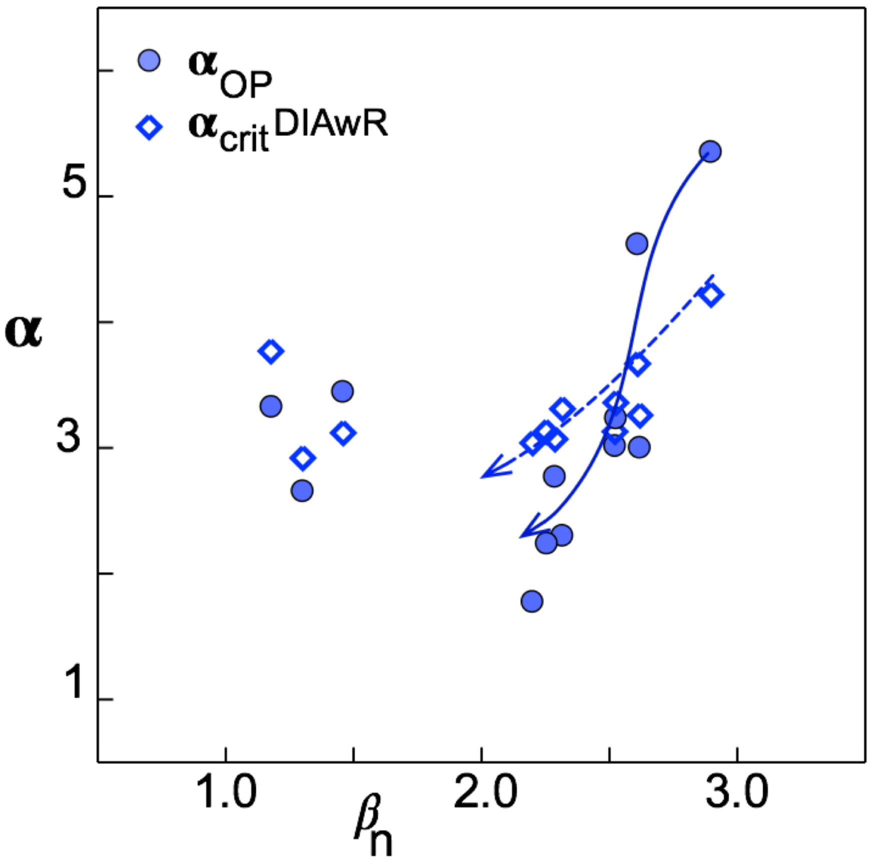
$|\Delta\alpha| \leq 0.2$

$$\Delta\alpha = \left(\frac{\alpha_{crit} - \alpha_{OP}}{\alpha_{OP}}\right)$$

- IDEAL model can underestimate α, and most unstable mode can be max. mode number considered
- DIAwR model best able to understand the ELM trigger
  - $|\Delta\alpha|$ >0.2 due to low time resolution of T_i measurement, necessary that ν_{elm}<100Hz
  - **DIAwoR (not shown here) sufficient for plasmas with ν^*_e <1 but not for high ν^*_e plasmas**

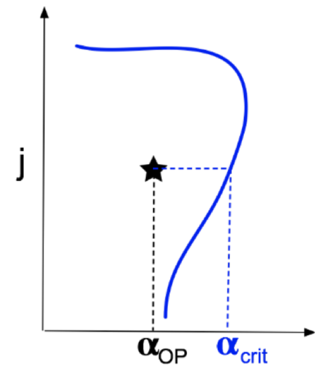
Aiba NF 2017
Aiba PPCF 2018

DIAwR agrees with the ELM trigger conditions in high-β_N plasmas at high D-gas rate



dataset: Ne series and low-β_N with CD_4 series

Only plasmas with ν_{elm}<100Hz



➔ Linear MHD model with diamagnetic effect and rotation shear effect is in agreement with the ELM trigger conditions for plasma with D-gas injection and seeding (criterion $|\Delta\alpha|<0.2$ applied !)

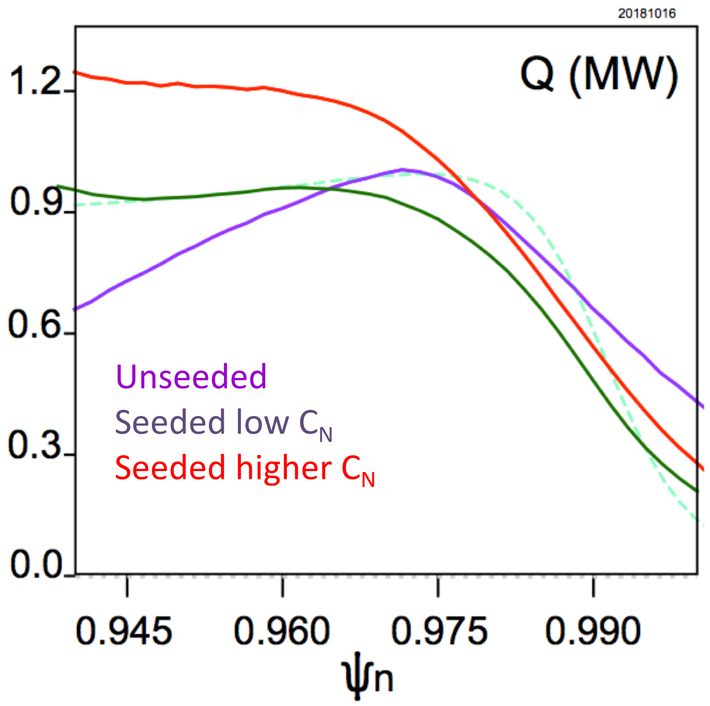
Robust predictions for ITER requires understanding the reason for higher T_{ped} in presence of C (JET-C). Confirmation that neon can provide the same effect in ITER would be ideal

- Is neoclassical transport governing the ion channel in the pedestal in the inter-ELM period ?
- Which instability is causing heat and particle transport ?

Evidence for ion heat transport not being neoclassical in JET pedestal

2.5MA/2.7T , P_{nbi}=16MW, β_N=1.2, δ=0.4

Total collisional ion heat flux



I. Pusztai, S. Buller (Chalmers)

- Radially global neoclassical modelling of JET plasmas done with PERFECT*
- Ion heat flux is ~ one order of magnitude lower than input power
- Ion heat transport carried by a significant remnant ion scale turbulence

* *M. Landreman PPCF 2014*

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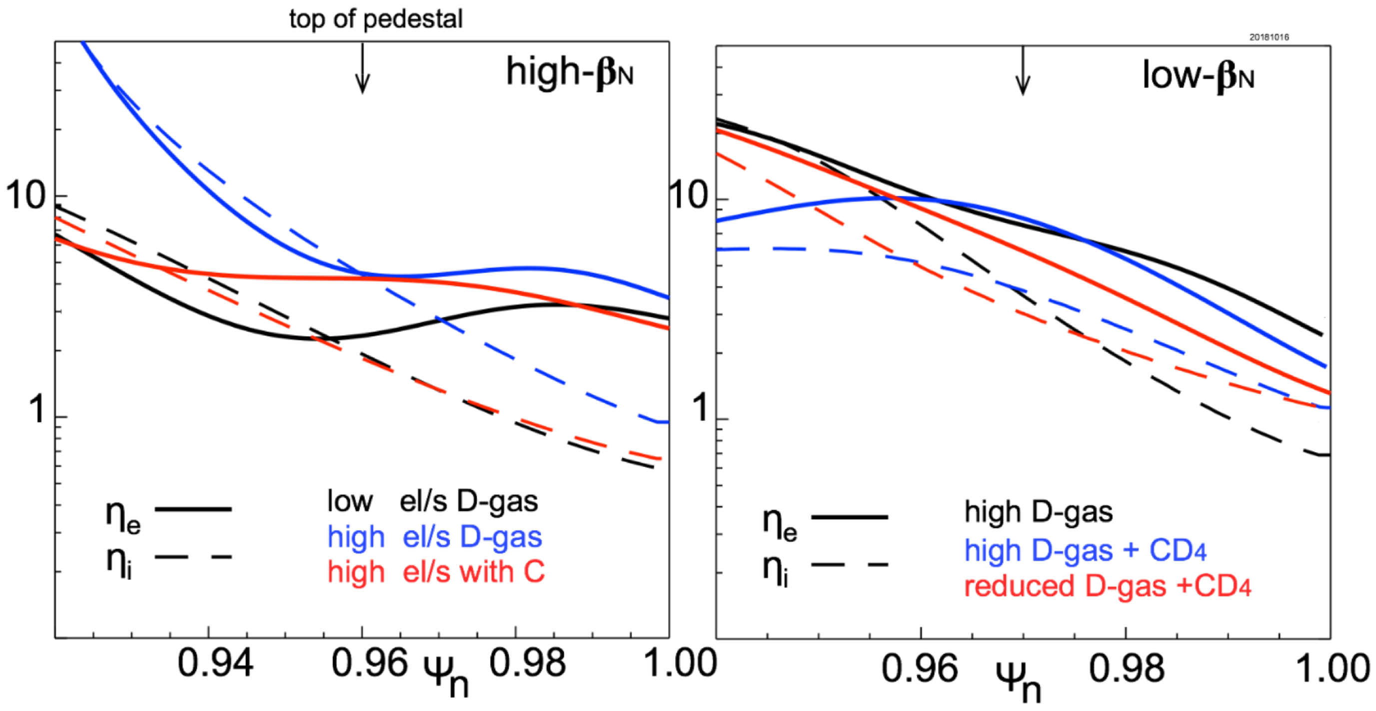
η_e is higher than η_i within the pedestal



$\eta = L_n / L_T = \frac{dln(T)}{dln(n)}$

- η_e is greater than η_i from experimental profiles
- High value of η_e points towards ETG dominated transport
- Improved pedestals in low-β_N and high-β_N plasmas have reduced η_e

Conclusions

- Nitrogen (or Carbon) and Neon impact on the pedestal density and temperature
  - Impurities can lead to either a decrease or increase of the pedestal density
  - N or C increased the pedestal temperature
  - no increase of the pedestal temperature observed with Ne injection

  → if pedestal radiation low enough, signs that high temperature can be maintained

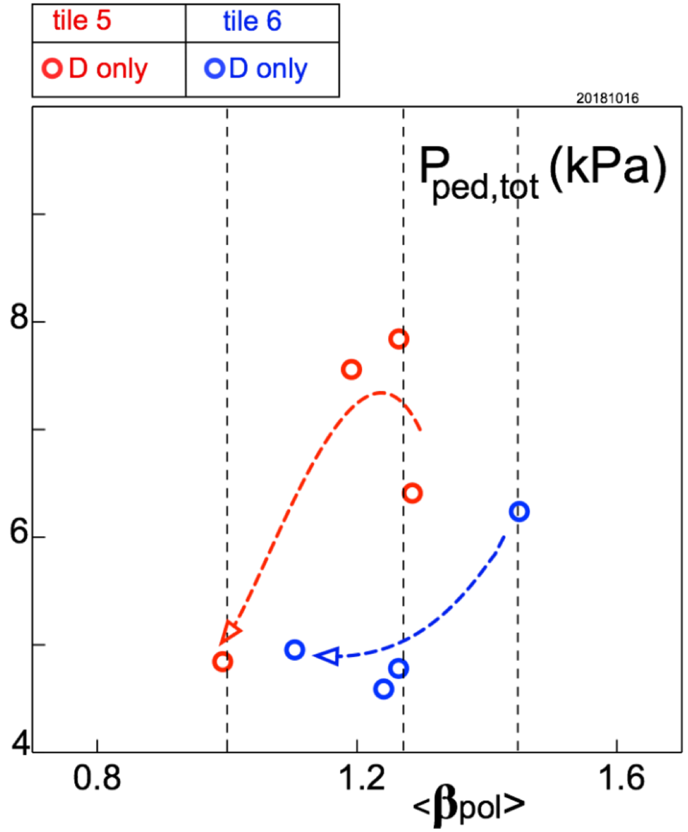
Important to obtain confirmation for ITER that neon can provide the same effect as N in JET-ILW

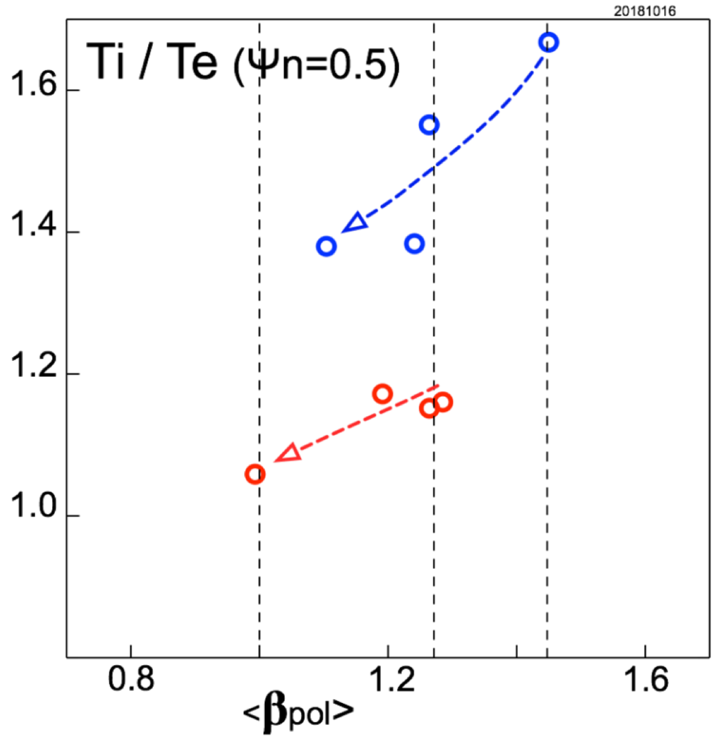
→ increased neon compression is needed

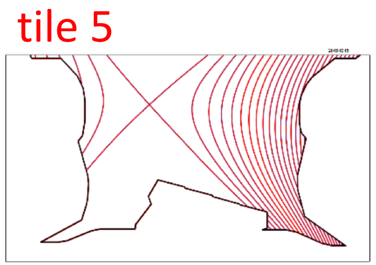
Robust predictions for ITER require understanding the reason for higher T_{ped} in presence of N, and also predictions of the pedestal density.

- Complex problem linking core, pedestal and SOL physics
- Linear MHD model with rotation and ion diamagnetic effect agrees with ELM trigger conditions ($|\Delta\alpha| < 0.2$)
- Key role of the ion temperature. Ion heat transport not neoclassical in JET pedestal

Increase in T_i is reason for the dependence of the pedestal height on divertor configuration







Hyun-Tae Kim EX/P1.5
Hyun-Tae Kim NF 2018

- Both configuration can reach $P_{ped,tot}$ =6 kPa, but $<\beta_{pol}>$ is higher for plasma with tile6 configuration
- Increased core pressure contribution mostly due to T_i for plasma with tile 6 configuration

➔ Decoupling of T_i and T_e key to improved confinement in JET-DT scenarios

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