Comparison of Peeling-Ballooning limited JET-C and JET-ILW plasmas

E. Stefanikova, L. Frassinetti, S. Saarelma, C. Perez von Thun, J. Hillesheim

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

OUTLINE

- **GOAL of the work and basic strategy**

- **DATASET used for analysis**
  - → experimental characterization:
  - → pedestal height (p_e, T_e and n_e), width, relative shift and pedestal position, n_e^{sep}
- **EUROPED modelling**
  - → detailed analysis of specific JET-C/JET-ILW couple
  - → investigation of parameters that affect the P-B stability (n_e^{pos}- T_e^{pos}, n_e^{ped}, Z_{eff}, w_{pe}, β_N)
  - → goal is to understand and quantify their effect on pedestal stability
  - → application to a wider dataset
  - → discussion

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JET

GOAL of the work and basic strategy

- The goal of this work is
  - to contribute to the understanding of the different pedestal performance between JET-C and JET-ILW in PB limited plasmas.

- This will be done by:
  - selecting specific JET-C and JET-ILW pulses (both located on the PB boundary)
  - identifying their difference in the parameters that can affect the PB stability
  - test the effect of these parameters on the PB stability for a specific couple of pulses
  - extend the work from these two pulses to a wider dataset of JET-C/JET-ILW discharges.

- Pulses for which the ELMs are triggered well before the PB boundary is reached (typically, pulses with high gas fuelling and high power [Maggi NF2015]) are not considered in this work.

DATASET used for analysis

- JET EUROfusion DB [Frassinetti EPS2018] was used to identify shots that are on the P-B boundary
  - → important for this analysis
  - → (when not on the boundary, P-B model cannot be used to reliably explain the pedestal behavior)
- Criteria used: $0.85<\alpha_{crit}/\alpha_{exp}<1.15$
- Limitations: not many JET-ILW shots with Ip>2.5MA, contains less JET-C shots

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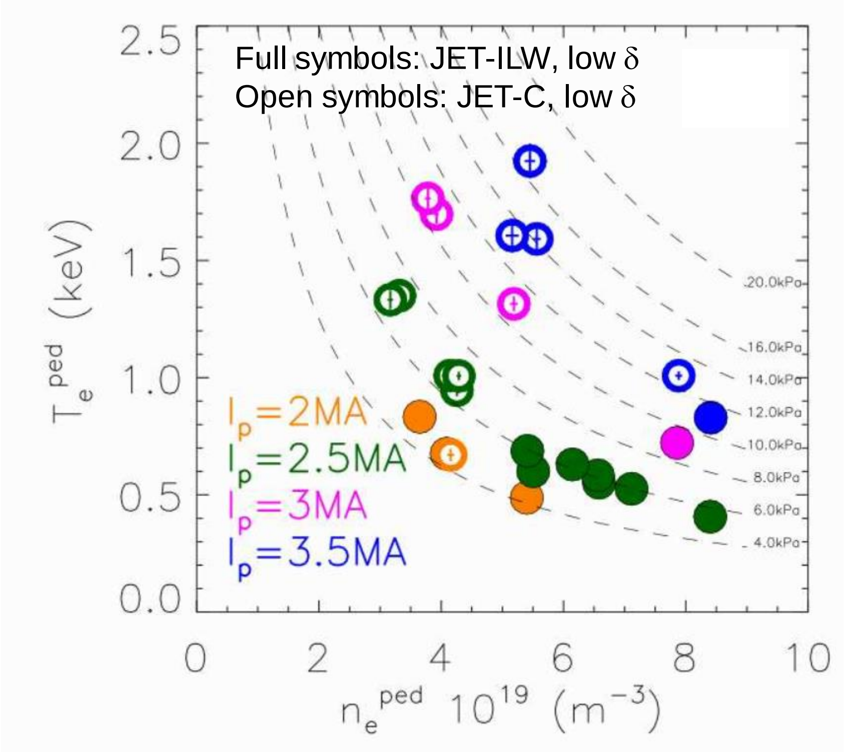

- Dataset: JET-ILW and JET-C with:
  - low δ,
  - No seeding, no RMPs, no kicks, no pellets
- Four I_p levels have been considered
- For each Ip level, JET-C/JET-ILW subsets were identified with similar:
  - P_{NBI}
  - Triangularity (only low-delta)
  - q_{95}
  - Divertor configuration (but not always possible to obtain a perfect match)
  - $0.85<\alpha_{crit}/\alpha_{exp}<1.15$ (this condition limits significantly the number of available pulses)
- **<u>Key difference in the selected JET-C/JET-ILW subsets:</u>**
  - Gas fueling is higher in the JET-ILW subsets

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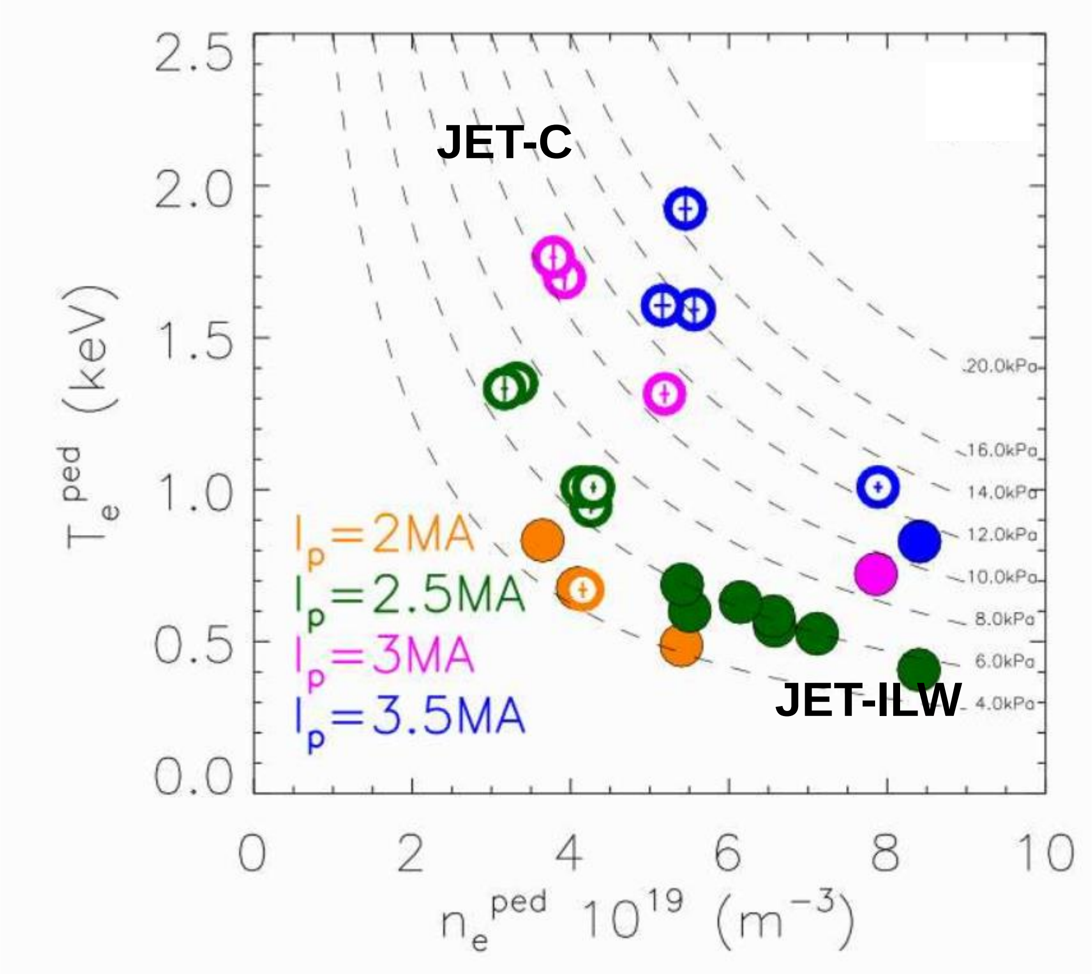
JET

Pedestal temperature and density



- JET-ILW dataset has lower T_e^{ped} than JET-C
- (shown in many earlier studies, e.g. [Beurskens PPCF2013])

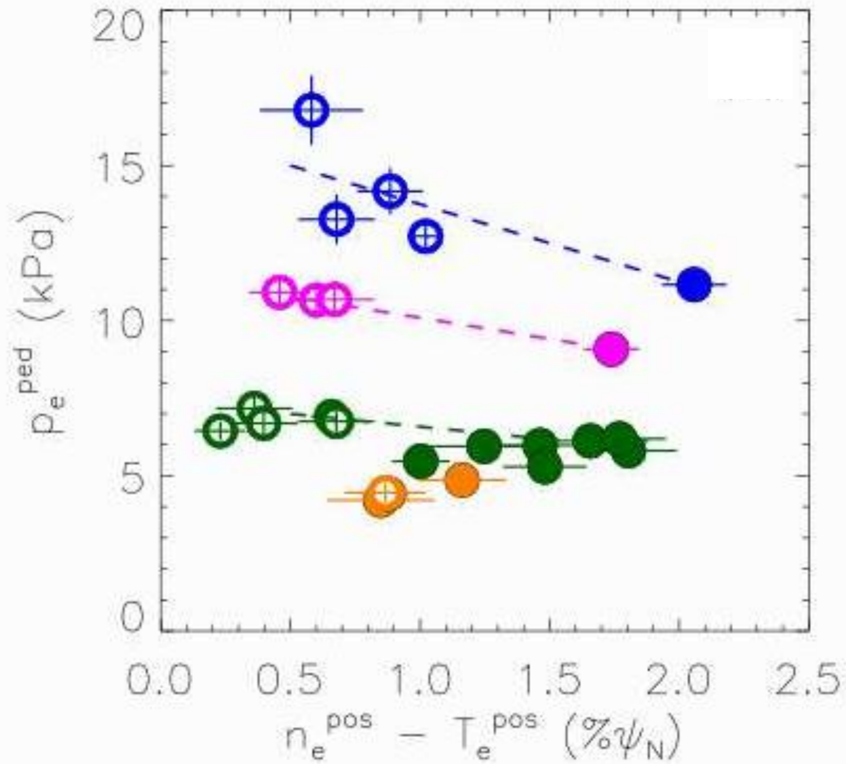
- JET-ILW tends to have higher n_e^{ped} than JET-C
- This is likely due to higher gas fuelling rate compared to JET-C

→ higher n_e^{ped} can affect j_{bs} and have further effect on P-B stability

JET

Experimental characterization

Pedestal pressure height vs relative shift



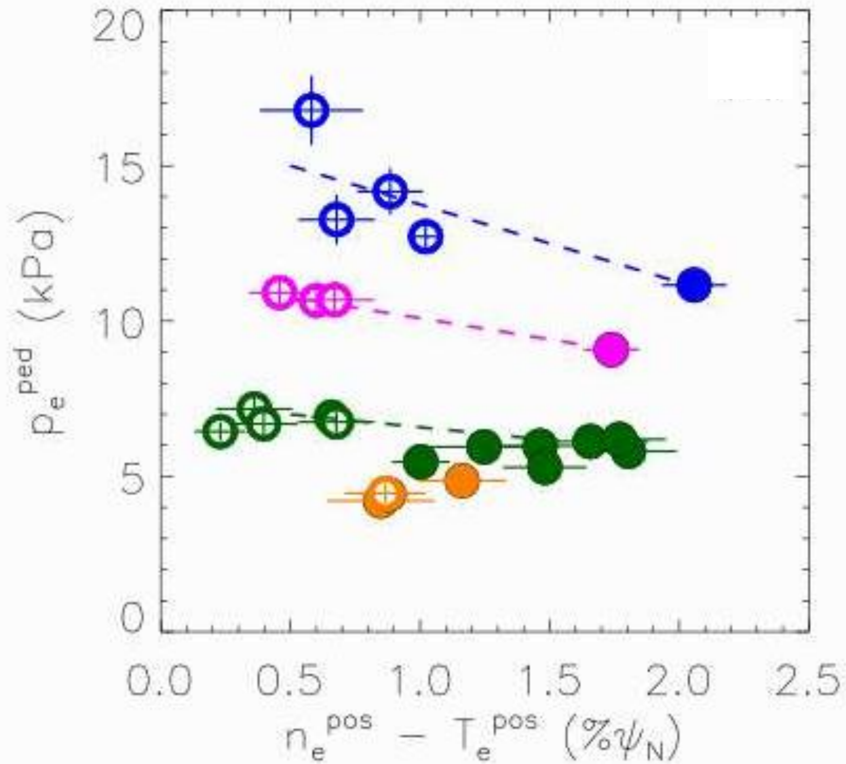
Full symbols: JET-ILW, low δ
Open symbols: JET-C, low δ

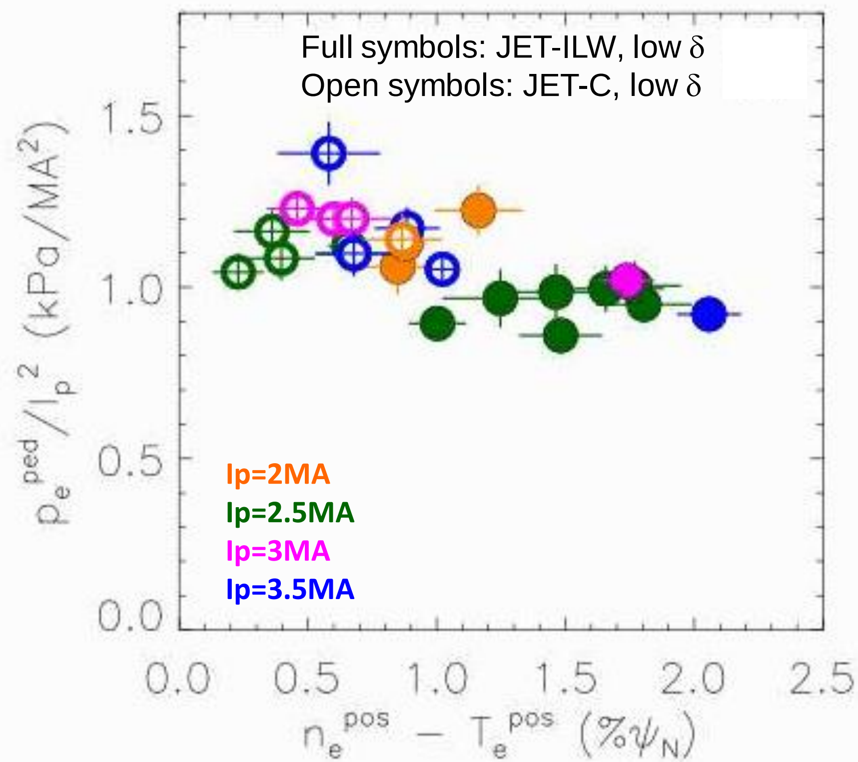
Ip=2MA
Ip=2.5MA
Ip=3MA
Ip=3.5MA

- For each *Ip* level (except 2MA), JET-ILW has lower pedestal pressure than JET-C
- JET-ILW tends to have > rel. shift (0.8-2%ψ_N) compared to JET-C (0.2-1%ψ_N)
- The difference in p_e^{ped} seems larger with higher *Ip*

Experimental characterization

Pedestal pressure height vs relative shift



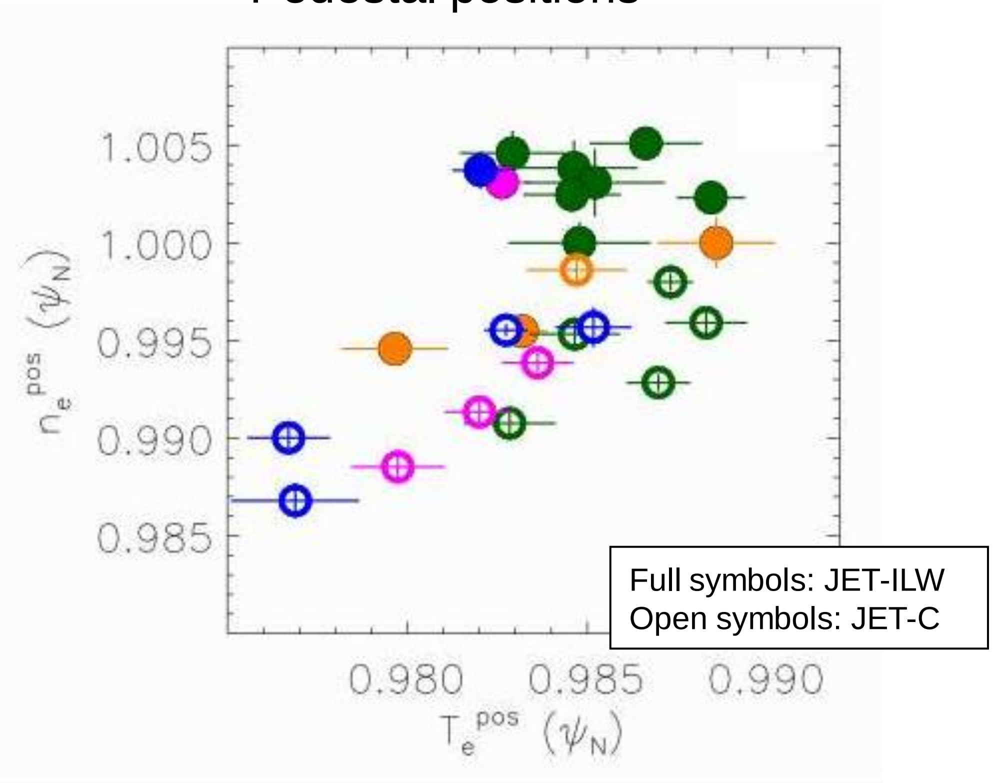


- For each I_p level (except 2MA), JET-ILW has lower pedestal pressure than JET-C
- JET-ILW tends to have > rel. shift (0.8-2%ψ_N) compared to JET-C (0.2-1%ψ_N)
- The difference in p_e^{ped} seems larger with higher I_p
- However, this is due to the I_p^2 dependence
- JET-C dataset has β_{pol}^{ped} approx. 20-30% higher than JET-ILW

JET

Experimental characterization

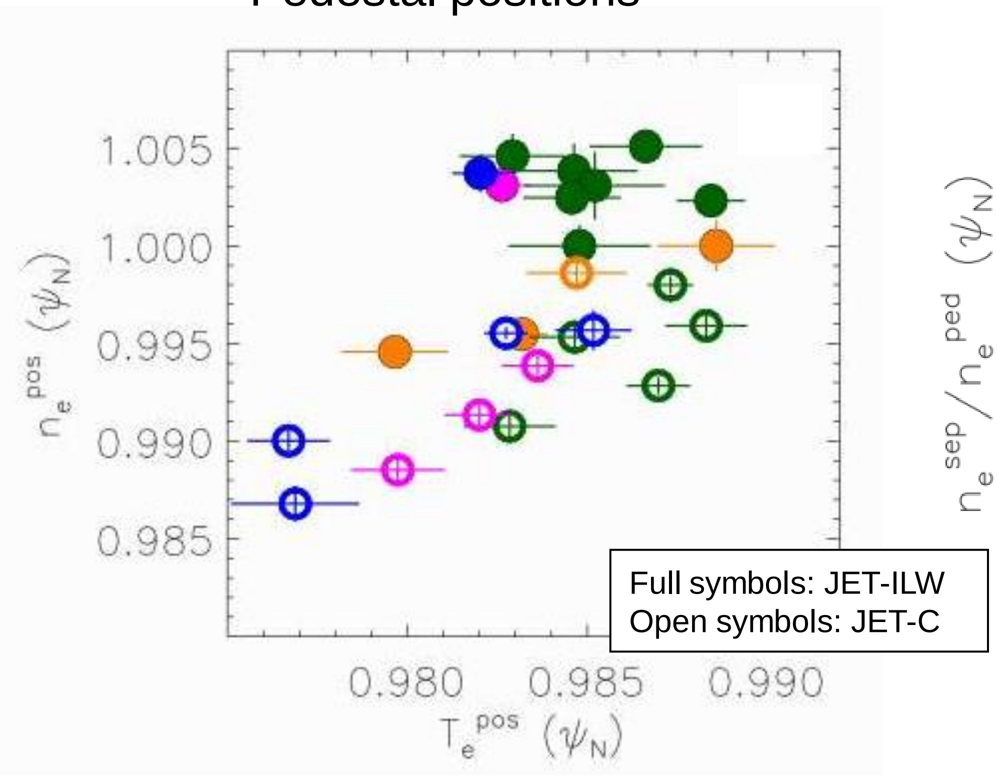
Pedestal positions



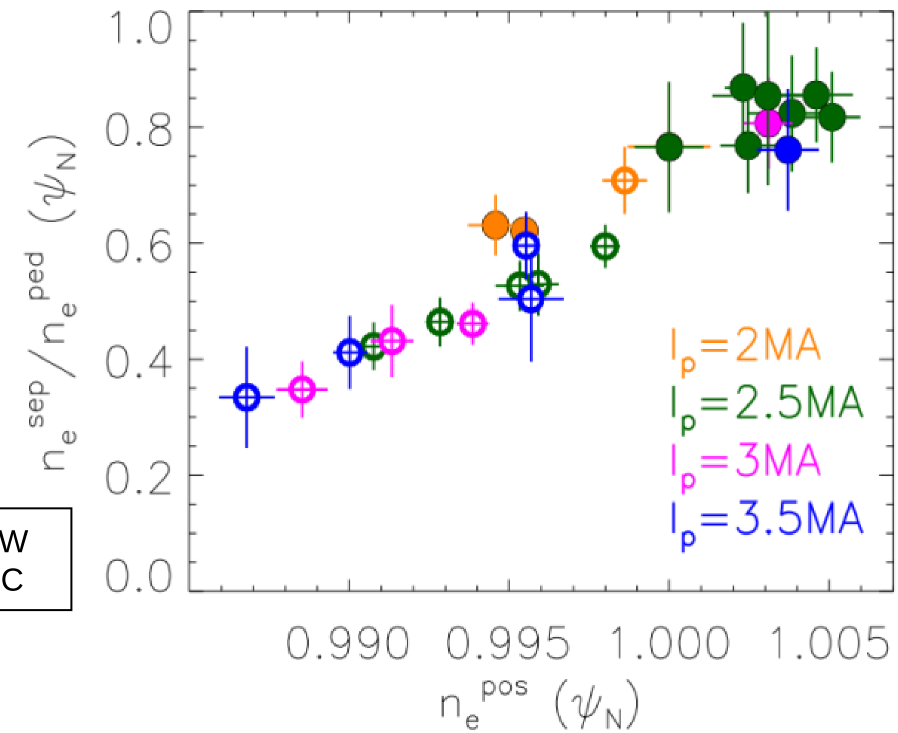
- n_e^{pos} of JET-C dataset is located more inwards - consistent with [Stefanikova NF2018, Frassinetti NF2019]

Experimental characterization

Pedestal positions



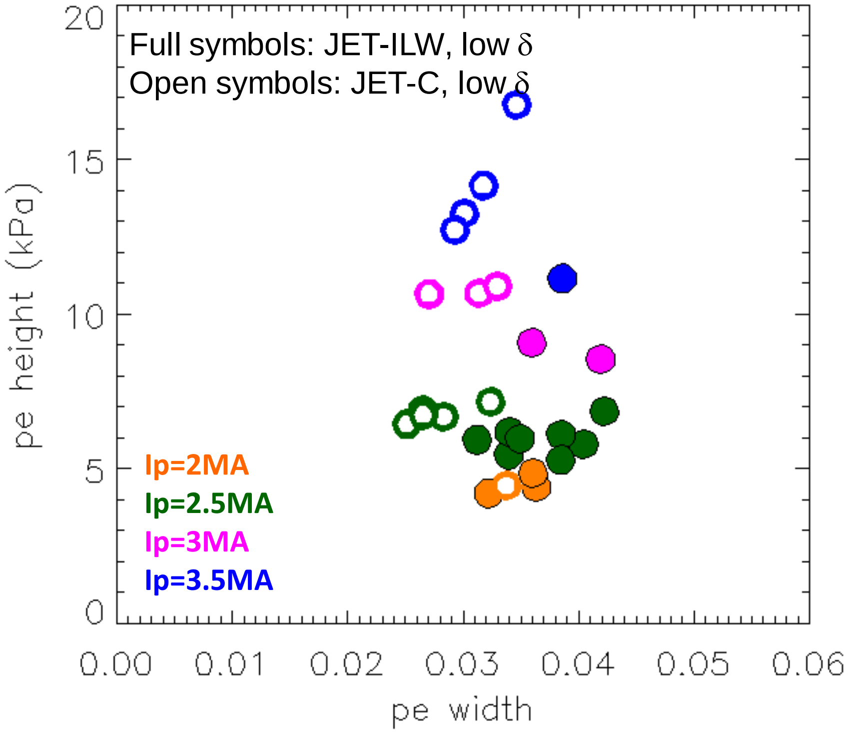
Separatrix density



- n_e^{pos} of JET-C dataset is located more inwards - consistent with [Stefanikova NF2018, Frassinetti NF2019]
- n_e^{sep} of JET-C dataset is lower than n_e^{sep} of JET-ILW dataset.
- Strong correlation between the separatrix density and pedestal density position

JET

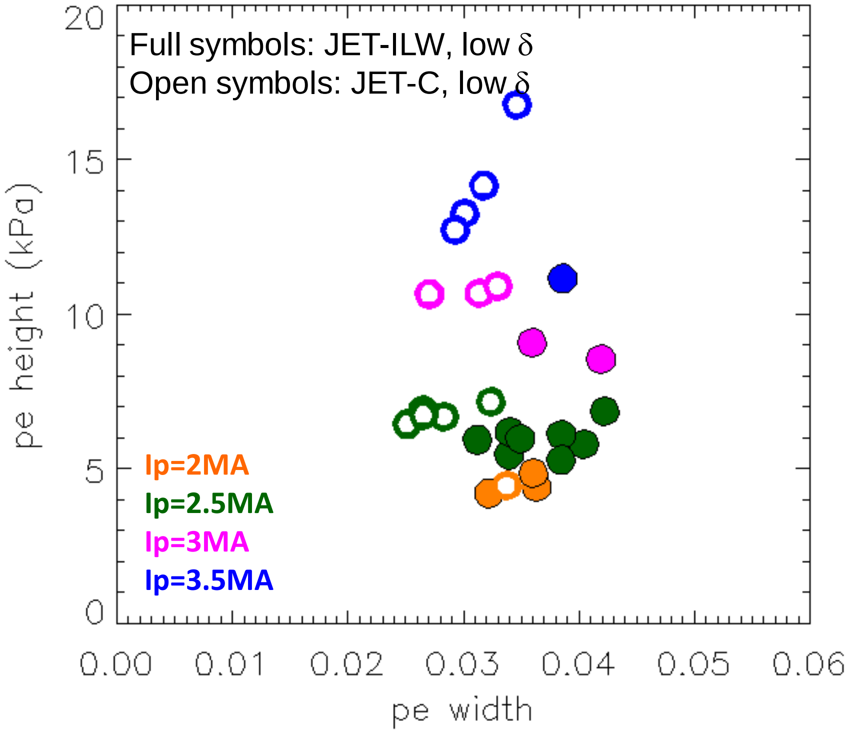
Experimental characterization – pedestal width

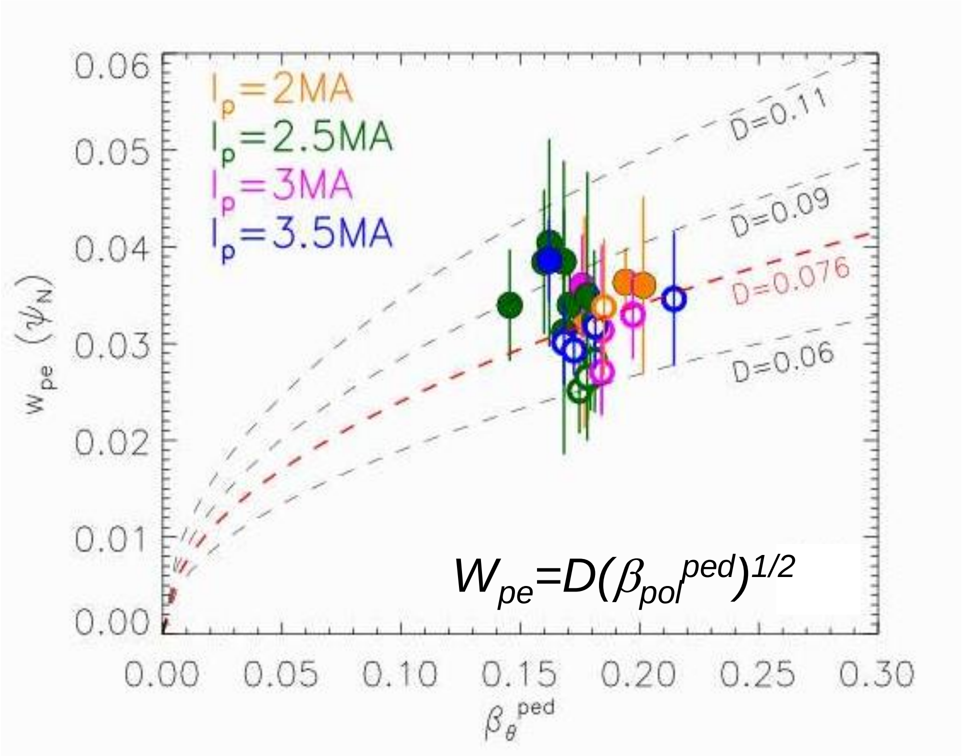


- JET-ILW dataset tends to have larger pedestal width than JET-C, consistent with earlier works, e.g.[Maggi NF2017]. However, there is a weak overlap
- Pressure width is estimated using 'standard' definition:
  - $w_{pe}=(w_{Te}+w_{ne}/2)$, w_{Te} and w_{ne} estimated from mtanh fits.
  - alterntive definitions are discussed in the next slides.

JET

Experimental characterization – pedestal width





- JET-ILW dataset tends to have larger pedestal width than JET-C, consistent with earlier works, e.g.[Maggi NF2017]. However, there is a weak overlap
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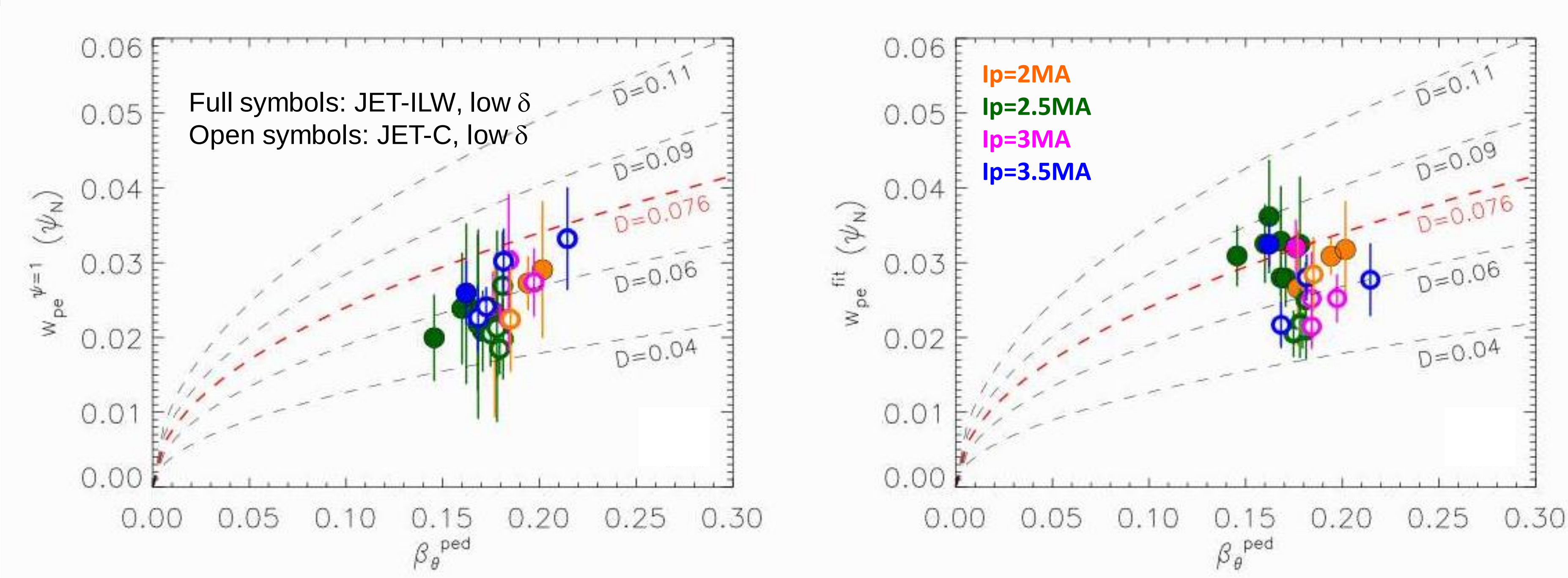
  - alterntive definitions are discussed in the next slides.
- Figure on the right: width versus pedestal beta poloidal.
  - EPED1 model assumes $w_{pe}=0.076(\beta_{pol}^{ped})^{1/2}$

JET

Experimental characterization – pedestal width



- pressure width has been investigated using three different definitions:
  - 'standard definition': $w_{pe}=(w_{Te}+w_{ne}/2)$ (previous slide)
  - Pedestals considered only inside the separatrix (left)
  - Fit to the pressure profiles (right).
- There are some quantitative differences, but qualitative the three definitions lead to similar conclusions:
  - The pressure width is slightly wider for the JET-ILW dataset,
  - but a small overlap can be present

JET

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  → experimental characterization:
  → pedestal height (p_e, T_e and n_e), width,
  relative shift and pedestal position, n_e^{sep}

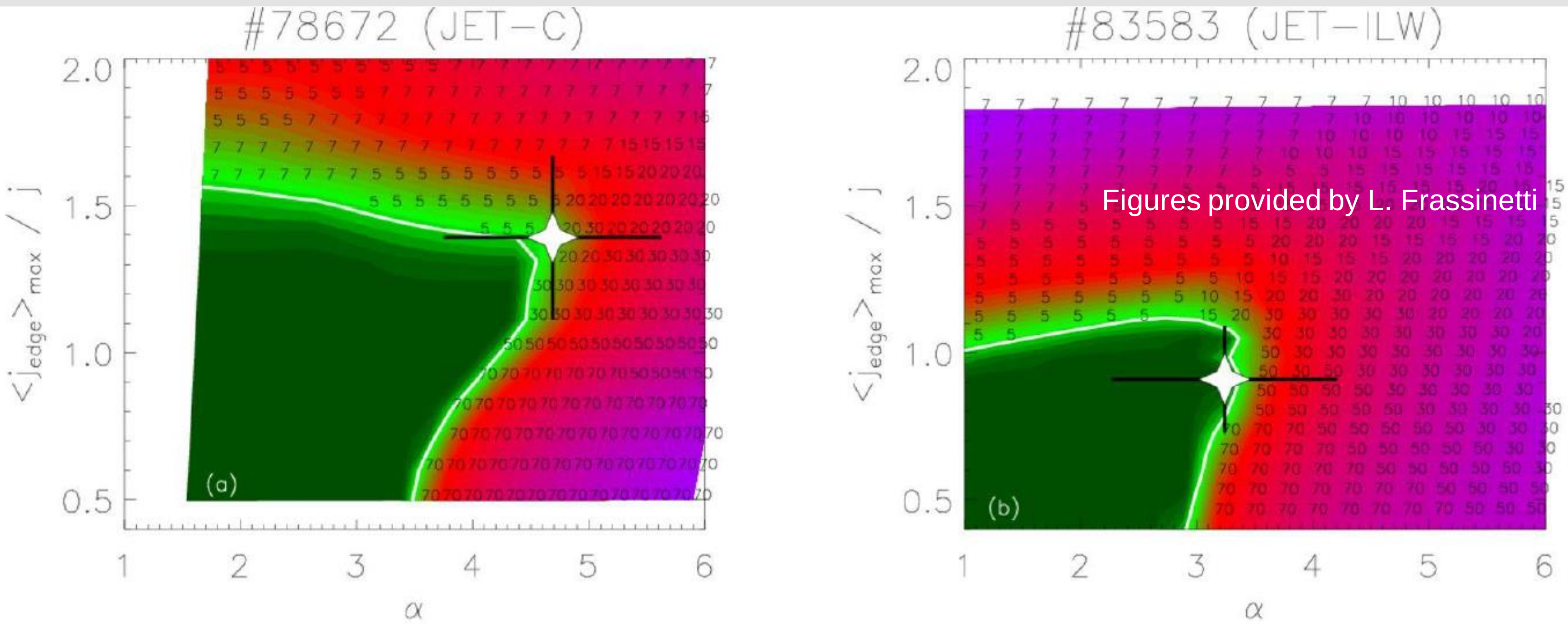
- **EUROPED modelling**
  - goal: to understand the difference in the pedestal pressure
  - Step 1: analysis of one JET-C pulse and one JET-ILW pulse with
    - Ip=2.5MA, P_{NBI}=11-12MW, low δ, $q_{95}\approx$2.7-3.0
    - Higher gas fueling rate in the JET-ILW pulse

  → detailed analysis of specific JET-C/JET-ILW couple
  → investigation of parameters that affect the P-B stability *(n_e^{pos}- T_e^{pos}, n_e^{ped}, Z_{eff}, w_{pe}, β_N)*

  - Step 2: extension to a wider dataset
  - Discussion

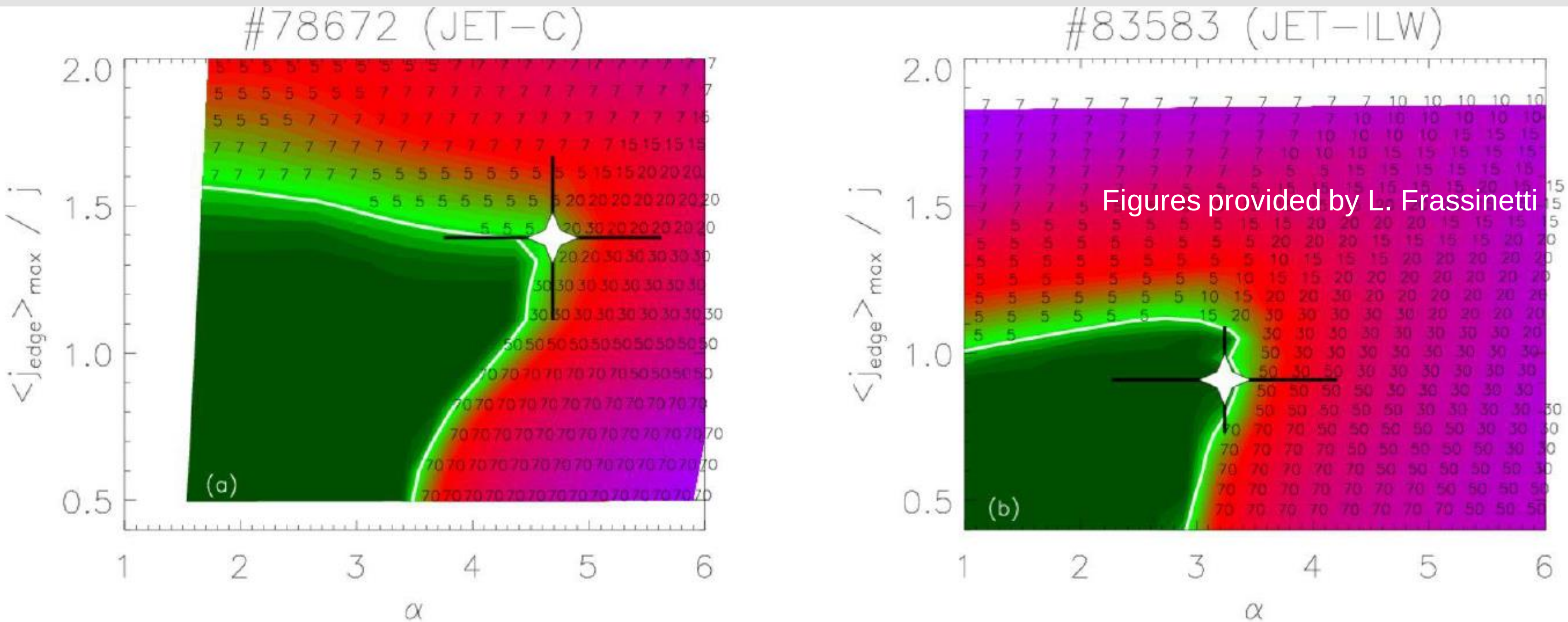
JET

Comparison of selected JET-ILW/JET-C couple



- Both pulses are on the PB boundary (obviously, since the dataset was selected to be on the boundary)
- the two stability boundaries are rather different:
  - In the JET-C pulse, the boundary reaches higher α and higher j_{bs} than in the JET-ILW pulse
  - the most unstable mode (as predicted by MISHKA) is in the range $n=5$-30 for the JET-C case and in the range $n=30$-70 for the JET-ILW case.
    - consistent with experimental MHD analysis (thanks to C. Perez von Thun)

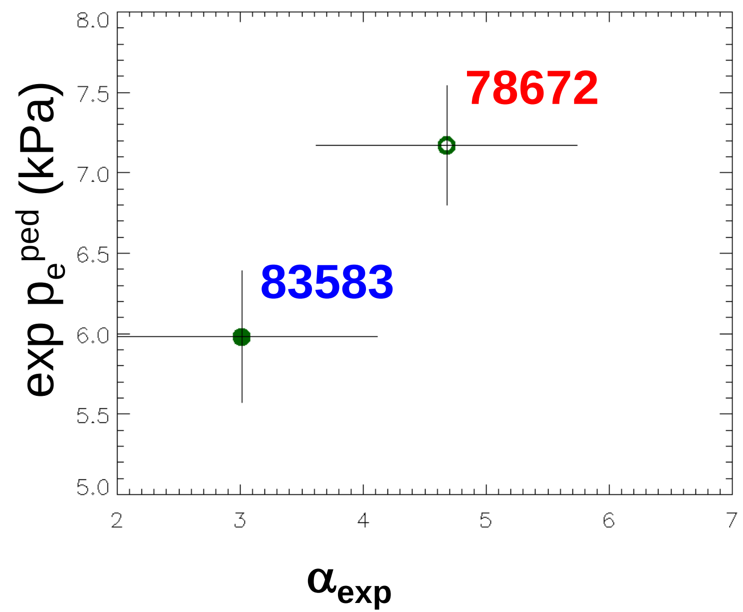
Comparison of selected JET-ILW/JET-C couple



The JET-ILW pulse has

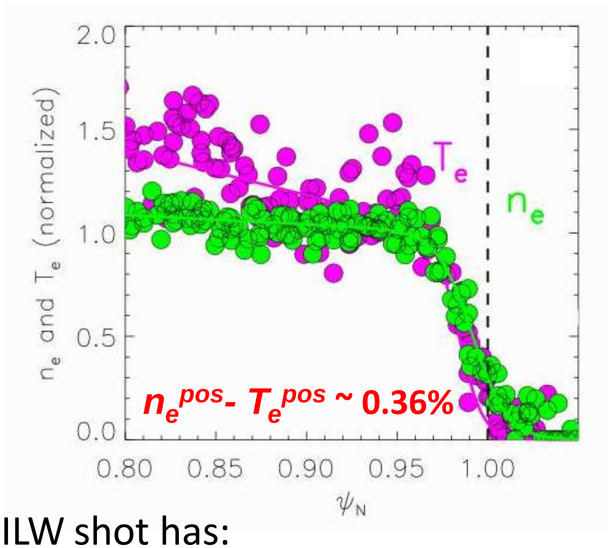
- lower p_e^{ped}
- lower α_{exp}

$$\alpha = -\frac{2\partial_\psi V}{(2\pi)^2}\left(\frac{V}{2\pi^2 R_0}\right)^{1/2}\mu_0 p'$$

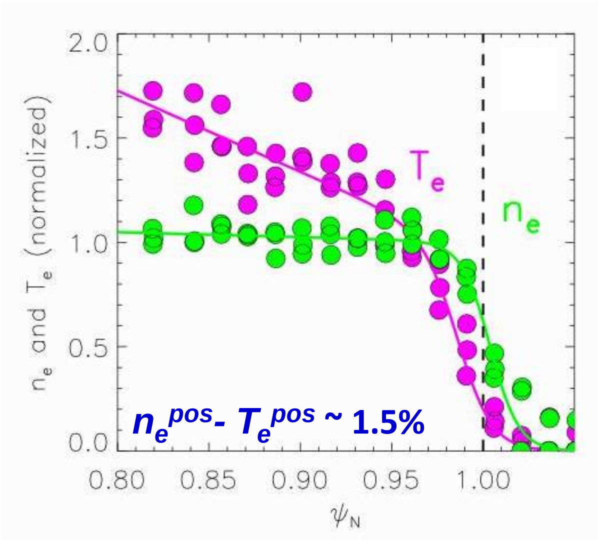


Comparison of selected JET-ILW/JET-C couple

HRTS profiles 78672



HRTS profiles 83583



- The JET-ILW shot has:
  - larger relative shift
  - higher n_e^{ped}
  - higher n_e^{sep}/n_e^{ped} (we assume T_e^{sep}=100eV)
  - slightly wider pedestal width $w_{pe}=(w_{Te}+w_{ne}/2)$ (actually almost comparable)
  - lower Z_{eff}
  - Lower β_N
- <u>All these parameters affect the pedestal stability</u>

JET-C #78672	JET-ILW #83583
n_e^{pos}- T_e^{pos} ≈ 0.36 %ψ_N	n_e^{pos}- T_e^{pos} ≈ 1.46 %ψ_N
w_{pe} ≈ 0.032	w_{pe} ≈ 0.035
n_e^{ped} =3.3	n_e^{ped} =7.1
Z_{eff} ≈ 2.5	Z_{eff} ≈ 1.1
β_N=1.8	β_N=1.4

JET

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  → pedestal height, width, relative shift, pedestal T_e and n_e

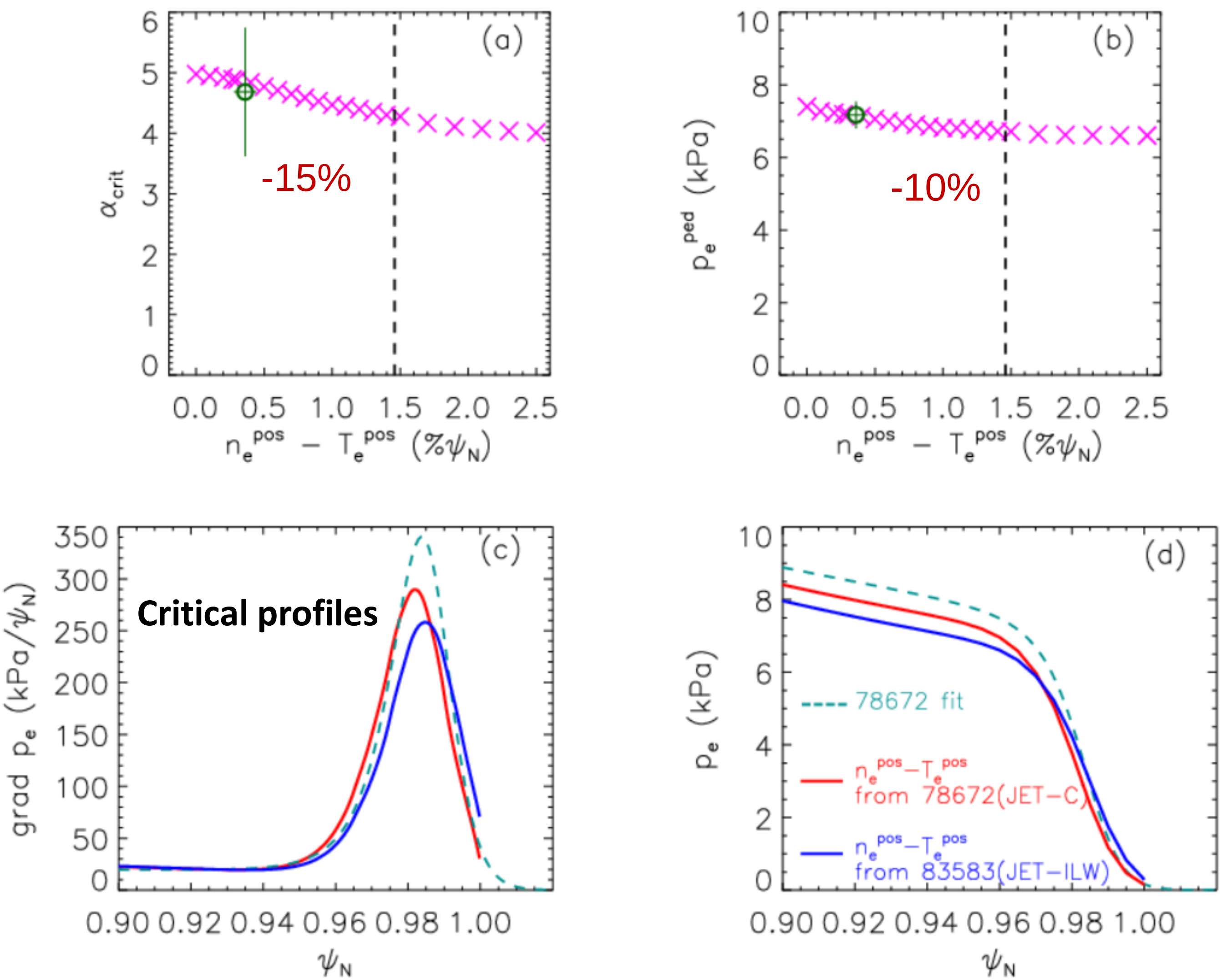
- **EUROPED modelling**
  → detailed analysis of specific JET-C/JET-ILW couple
  → **investigation of 5 parameters that affect the P-B stability**
    - Pedestal relative shift
    - Pedestal density
    - Zeff
    - β_N
    - Pedestal pressure width

    → first separately
    → together
  → goal is to understand their effect on pedestal stability
  → application to a wider dataset

JET

EUROPED modelling – relative shift scan for 78672

Normalized pressure gradient | **Pedestal height**



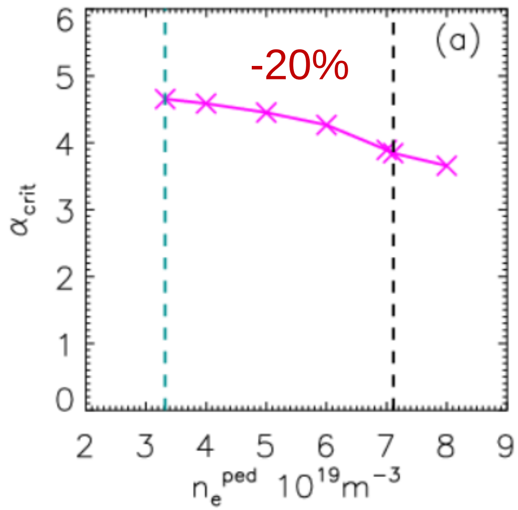
EUROPED modelling for shot 78672

Scan over wider range of rel. shift

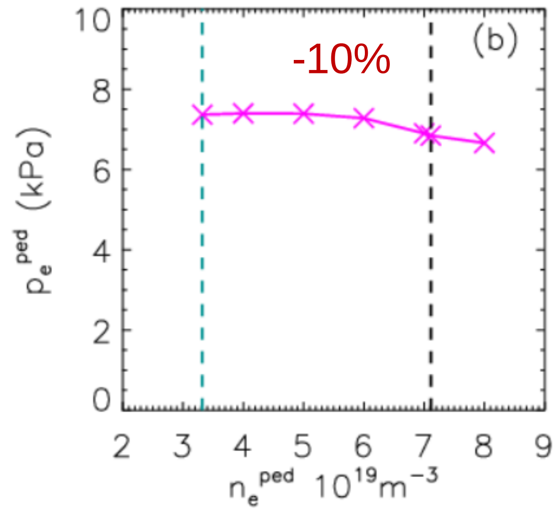
New setting:
Fixed width parameter (we can now use exp. width as input)

EUROPED modelling – pedestal density scan

Normalized pressure gradient



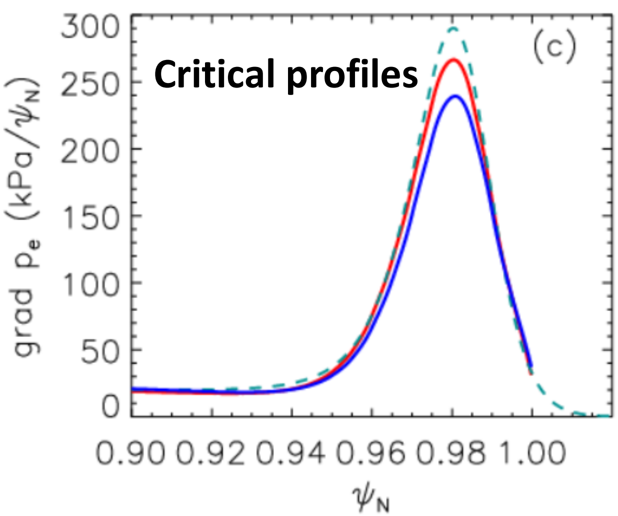
Pedestal height

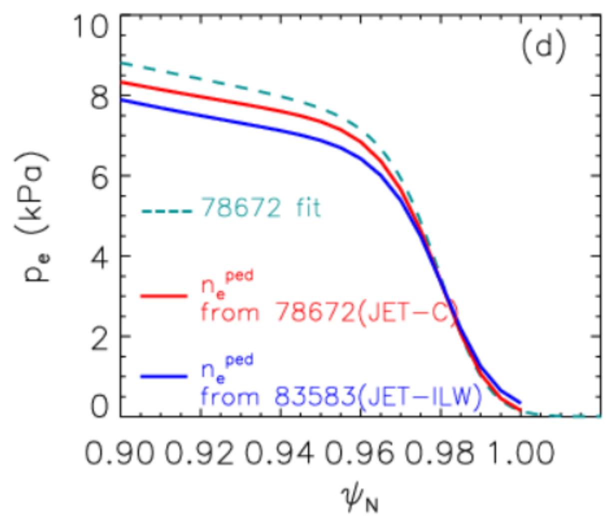


EUROPED modelling for shot 78672

Scan over wider range of pedestal density

New setting:
Fixed width parameter (we can now use exp. width as input)

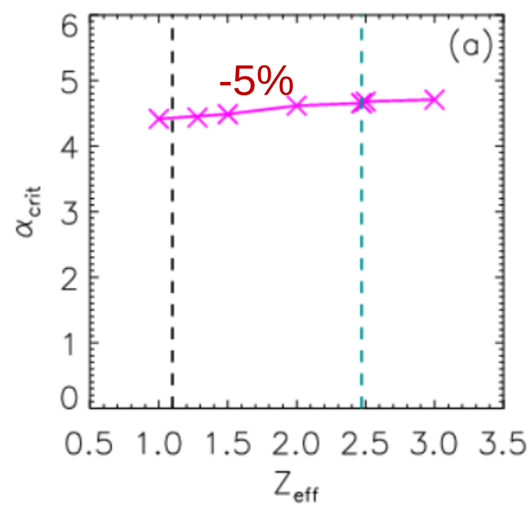




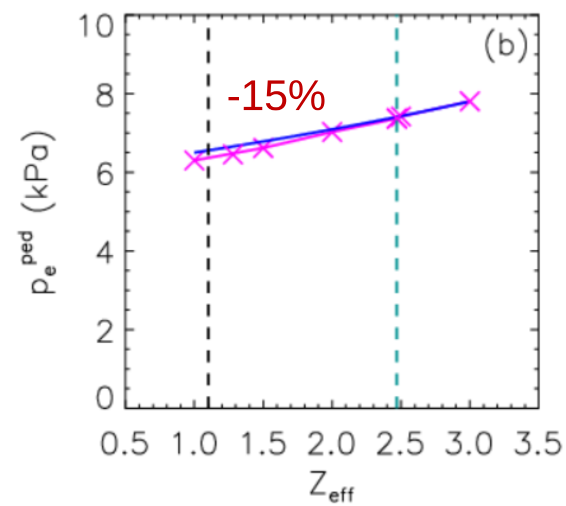
JET

EUROPED modelling – Zeff scan

Normalized pressure gradient



Pedestal height

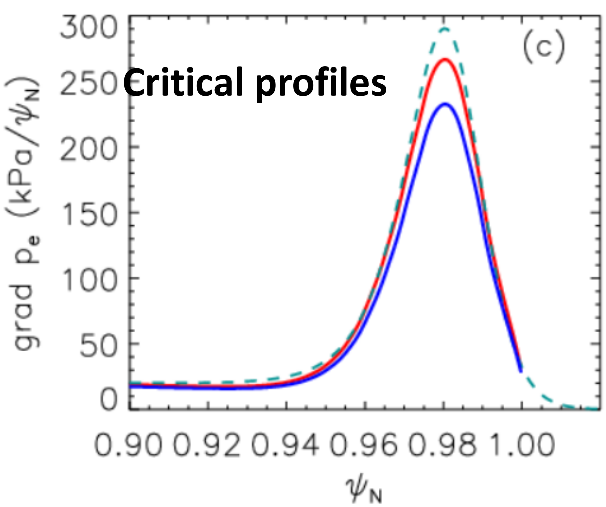


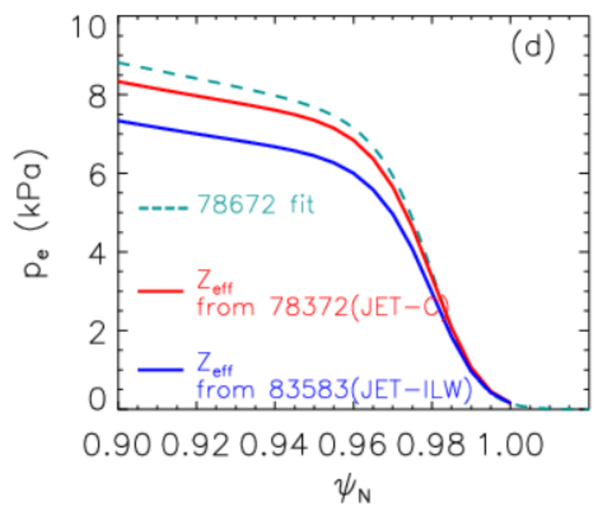
EUROPED modelling for shot 78672

Scan over wider range of Zeff

New setting:
Fixed width parameter (we can now use exp. width as input)

Critical profiles

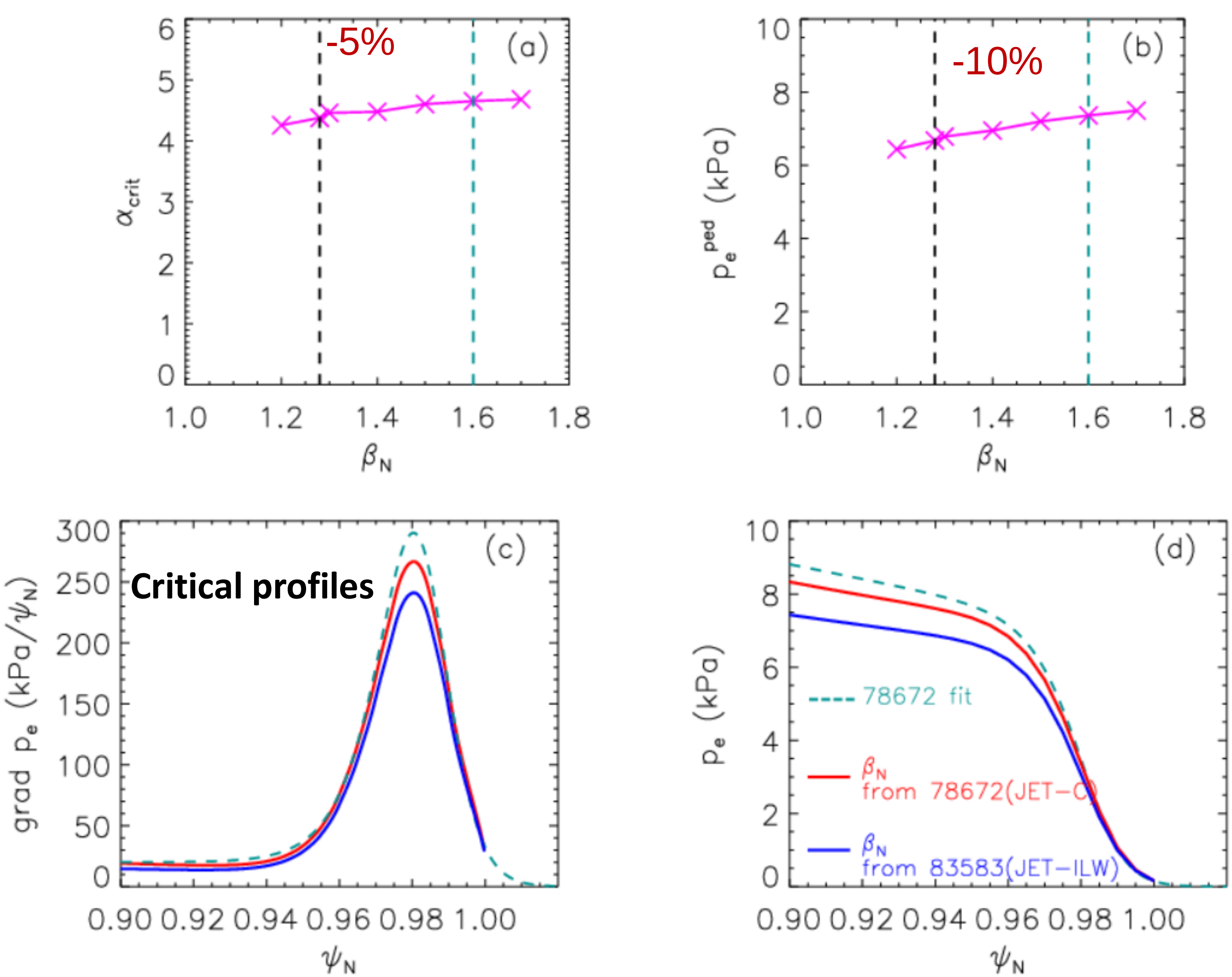




JET

EUROPED modelling – β_N scan

Normalized pressure gradient **Pedestal height**



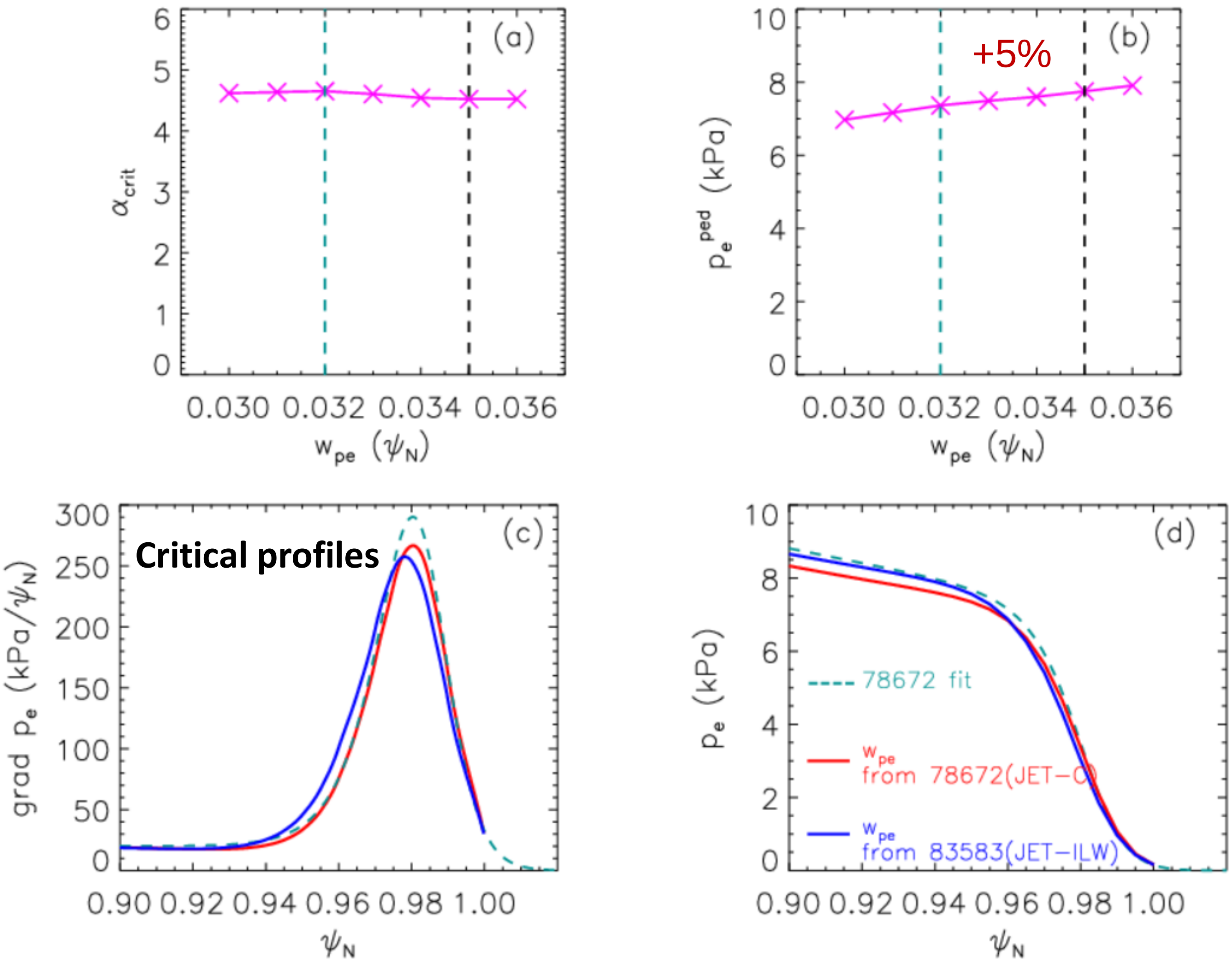
EUROPED modelling for shot 78672

Scan over wider range of β_N

New setting:
Fixed width parameter (we can now use exp. width as input)

EUROPED modelling – pedestal width scan

Normalized pressure gradient **Pedestal height**

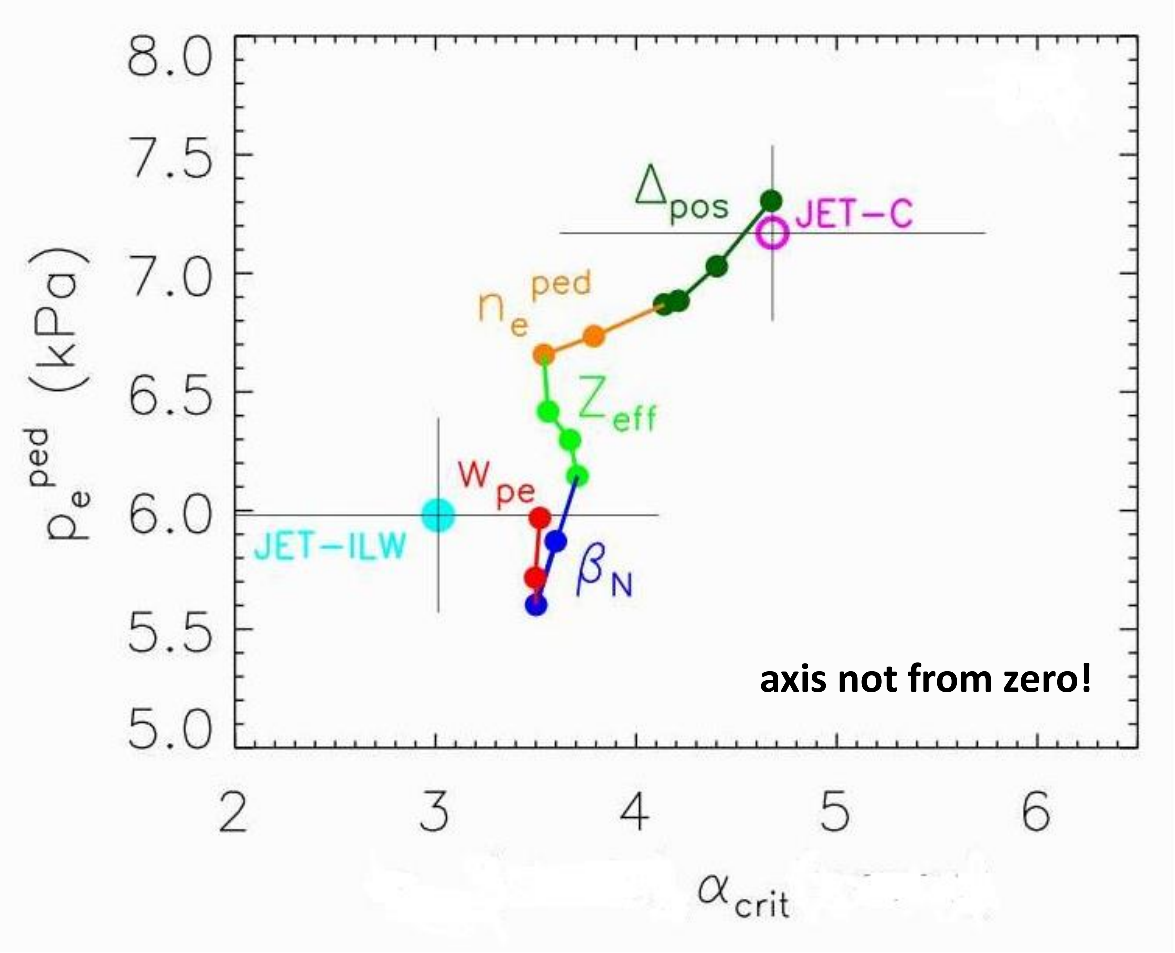


EUROPED modelling for shot 78672

Scan over wider range of pressure width

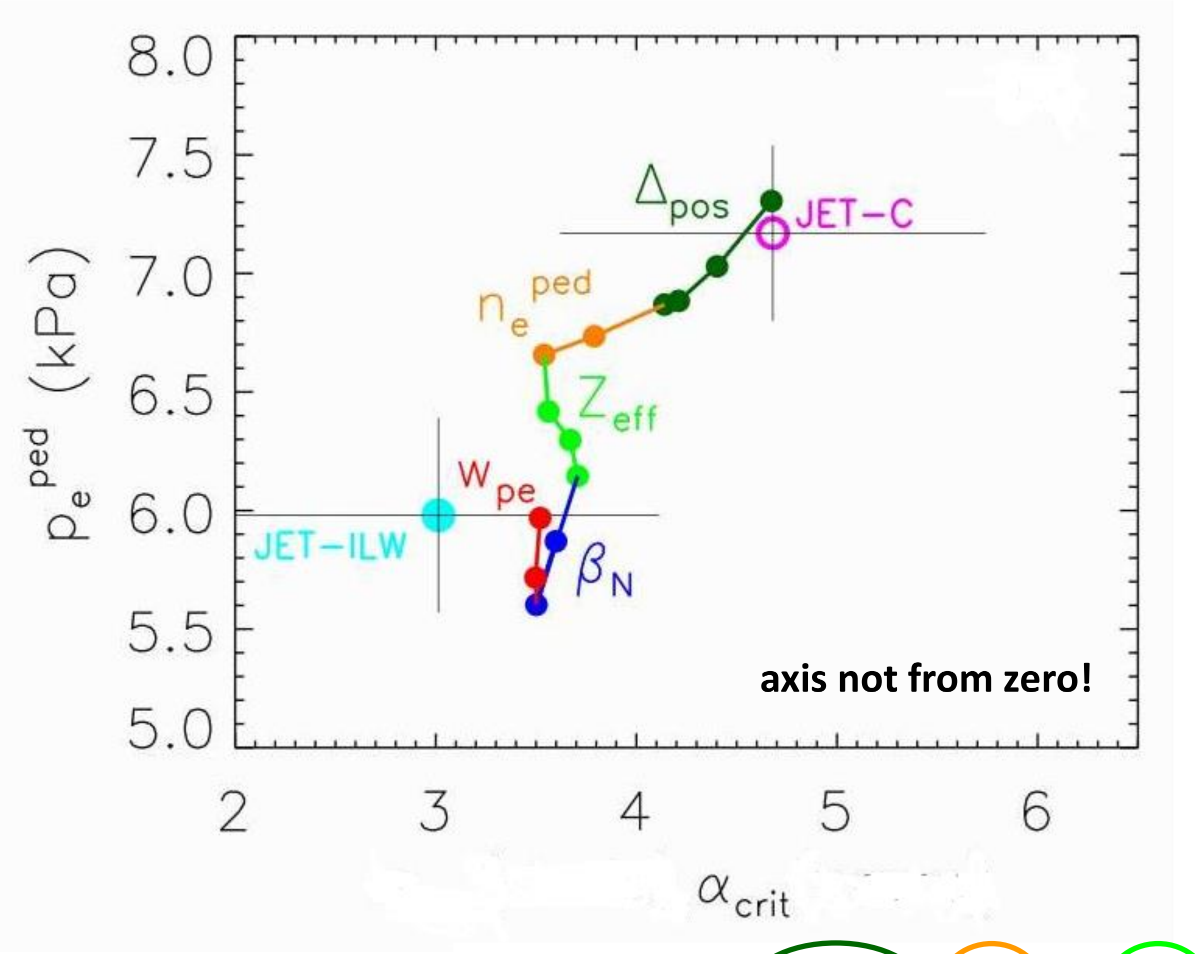
New setting:
Fixed width parameter (we can now use exp. width as input)

EUROPED modelling – all parameters step by step



JET-C	**JET-ILW**
78672	**83583**
Pe width: 0.032	Pe width: 0.035
Shift: 0.36	Shift: 1.46
Neped: 3.3	Neped: 7.1
Zeff: 2.5	Zeff: 1.1
betaN: 1.8	betaN: 1.4

EUROPED modelling – all parameters step by step



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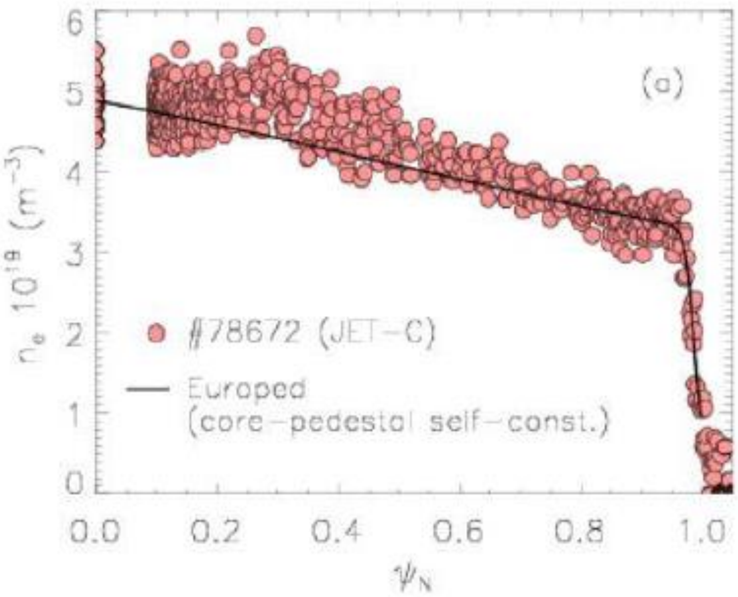
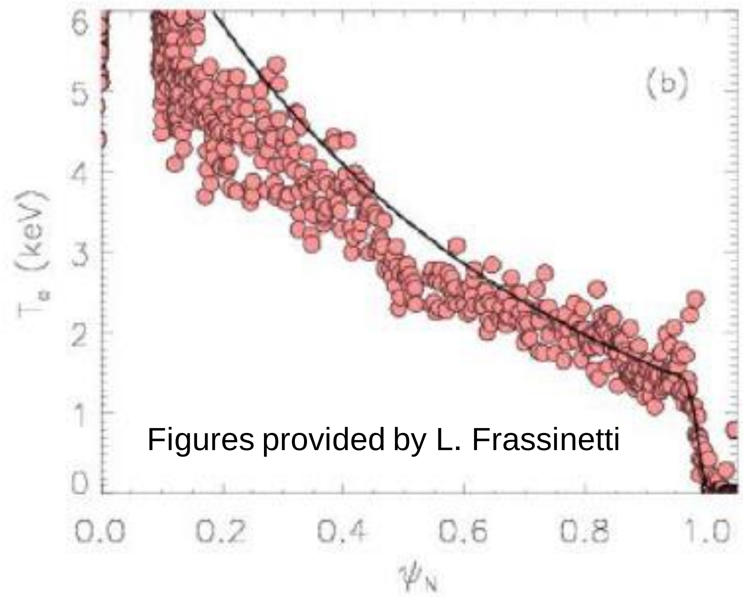
Pe width: 0.032	Pe width: 0.035
Shift: 0.36	Shift: 1.46
Neped: 3.3	Neped: 7.1
Zeff: 2.5	Zeff: 1.1
betaN: 1.8	betaN: 1.4

Contribution of:	n_e^{pos}-T_e^{pos}	n_e^{ped}	Z_{eff}	β_N	w_{pe}	total
to α_{crit}	-46%	-52%	+14%	-18%	+2%	-100%
to p_e^{ped}	-33%	-16%	-38%	-40%	+27%	-100%

JET

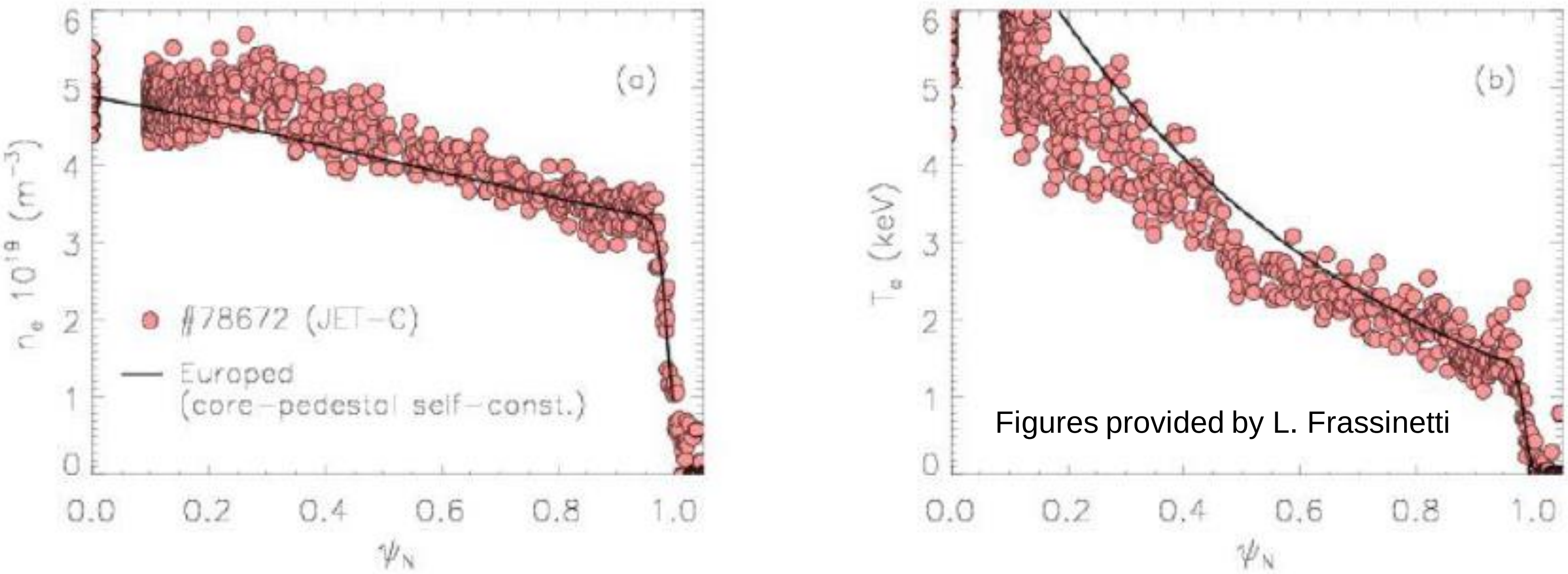
EUROPED modelling – self-consistent core-pedestal setting





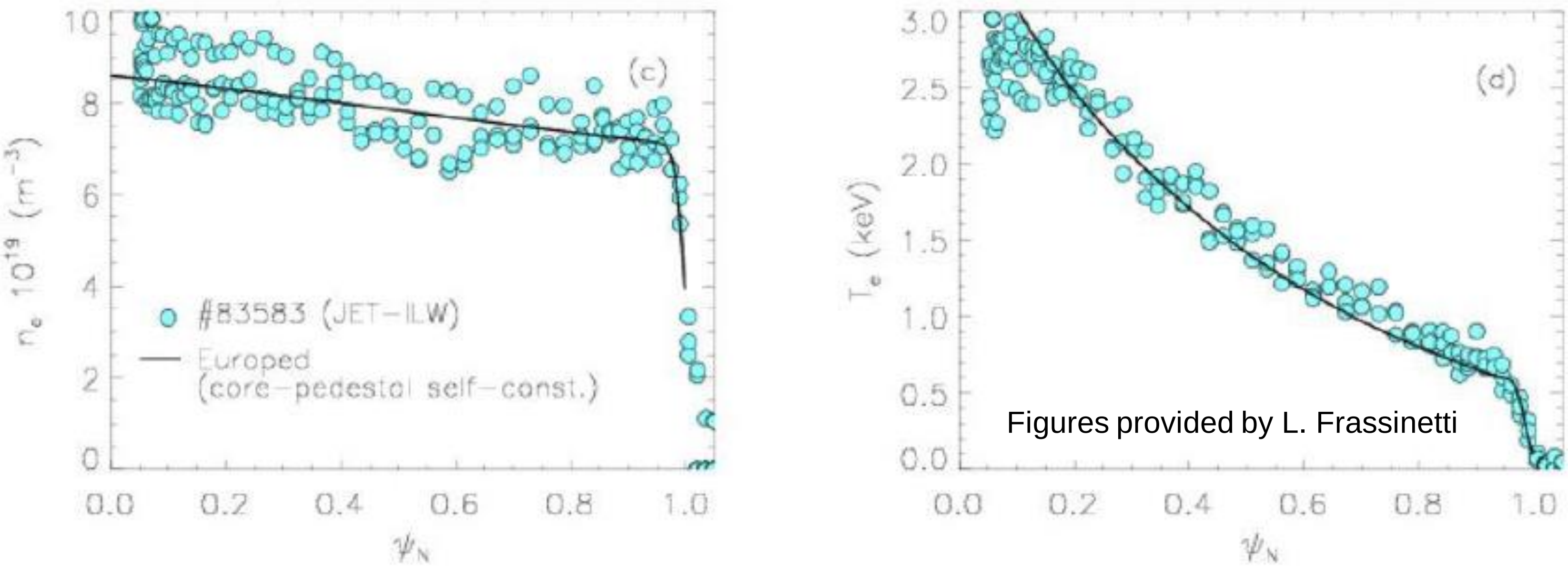
- Self-consistent core-pedestal simulations (SCCP) with Europed– implement simple core transport model → β_N is not an input parameter any more.
- Core transport model used in Europed described in more detail in [Saarelma PoP2019]
  → assumes stiff temperature profiles
  → implemented using heat diffusivity $\chi_{e,i}$=0.1 m^2/s below normalized critical temperature gradient length $(R/LT_e)_{crit}$ and $\chi_{e,i}$=0.1 m^2/s + 2 m^2/s $[(R/LT_e)-(R/LT_e)_{crit}]$ otherwise
  → $(R/LT_e)_{crit}$ =5 is used [Saarelma PoP2019], core density peaking is modelled using it to the empirical trends of peaking vs collisionality

EUROPED modelling – self-consistent core-pedestal setting



- SCCP simulations performed with JET-C shot #78672:
- red data show experimental profiles of electron density (left) and temperature (right) of JET-C shot 78672
- Black lines show SCCP of 78672 with experimental input parameters (n_e^{pos}- T_e^{pos}, n_e^{ped} Z_{eff}, w_{pe}, β_N)

EUROPED modelling – self-consistent core-pedestal setting



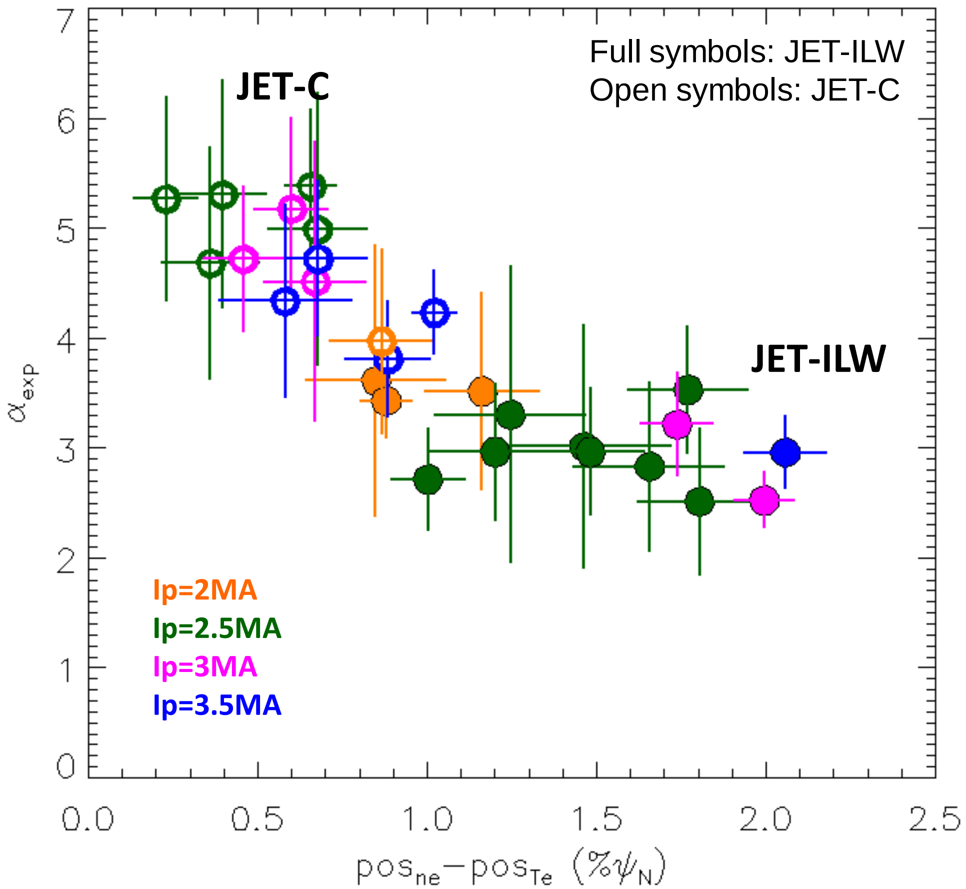
- SCCP simulations performed with JET-C shot #78672:
- blue data show experimental profiles of electron density (left) and temperature (right) of JET-ILW shot 83583 with similar engineering parameters to 78672 (as shown previously)
- Black lines show SCCP of 78672 with ILW input parameters from 83583 (n_e^{pos}- T_e^{pos}, n_e^{ped} Z_{eff}, w_{pe}, β_N)
  → SCCP is able to correctly predict reduction of β_N from JET-C case to JET-ILW
  → reduction of β_N can be explained by the effect of n_e^{pos}- T_e^{pos}, n_e^{ped} Z_{eff}, w_{pe} on the pedestal

OUTLINE

- **DATASET used for analysis**
  - → experimental characterization:
  - → pedestal height, width, relative shift, pedestal T_e and n_e , n_e^{sep}
- **EUROPED modelling**
  - goal: to understand the difference in the pedestal pressure
  - Step 1: analysis of one JET-C pulse and one JET-ILW pulse with
    - Ip=2.5MA, Pnbi=12MW, low-d, q_{95}≈2.7-3.0
    - Higher gas fueling rate in the JET-ILW pulse
  - → detailed analysis of specific JET-C/JET-ILW couple
  - → investigation of parameters that affect the P-B stability (n_e^{pos}- T_e^{pos}, n_e^{ped}, Z_{eff}, w_{pe}, β_N)
  - Step 2: extension to a wider dataset
  - Discussion

JET

- Europed modelling for extended JET-ILW/JET-C dataset
- Simulations in β-contrained version (no self-consistent core-pedestal prediction)
- First step – simulations with experimental parameters to obtain α_{crit} corresponding to each shot



Application to a wider JET-ILW/JET-C dataset

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→ all 5 at once (n_e^{pos}- T_e^{pos}, n_e^{ped}, Z_{eff}, w_{pe}, β_N)
→ one by one

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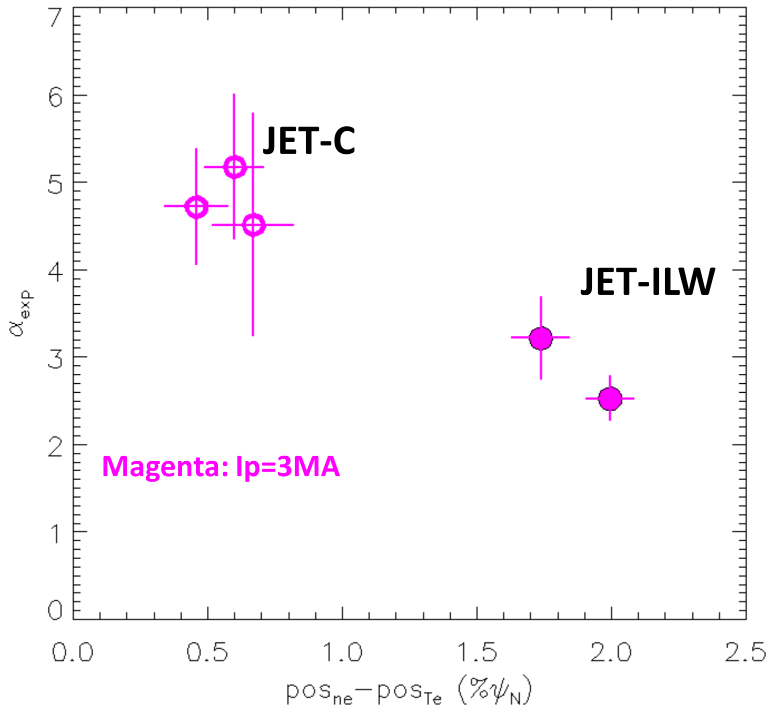

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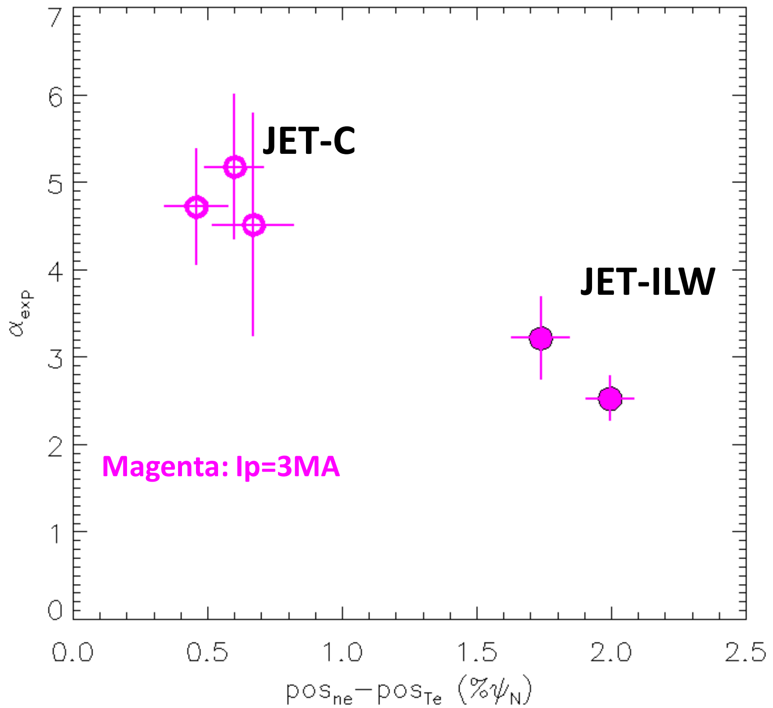

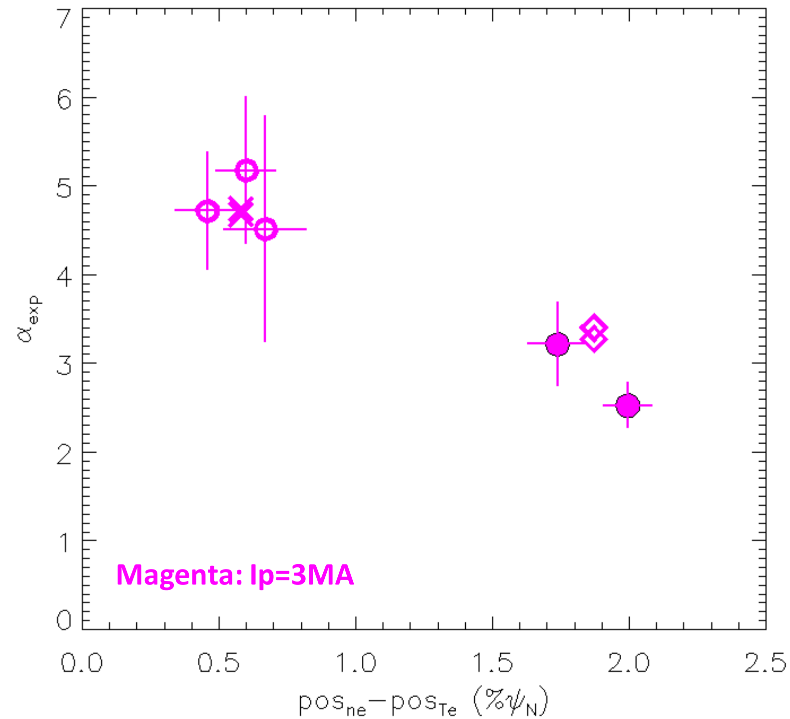

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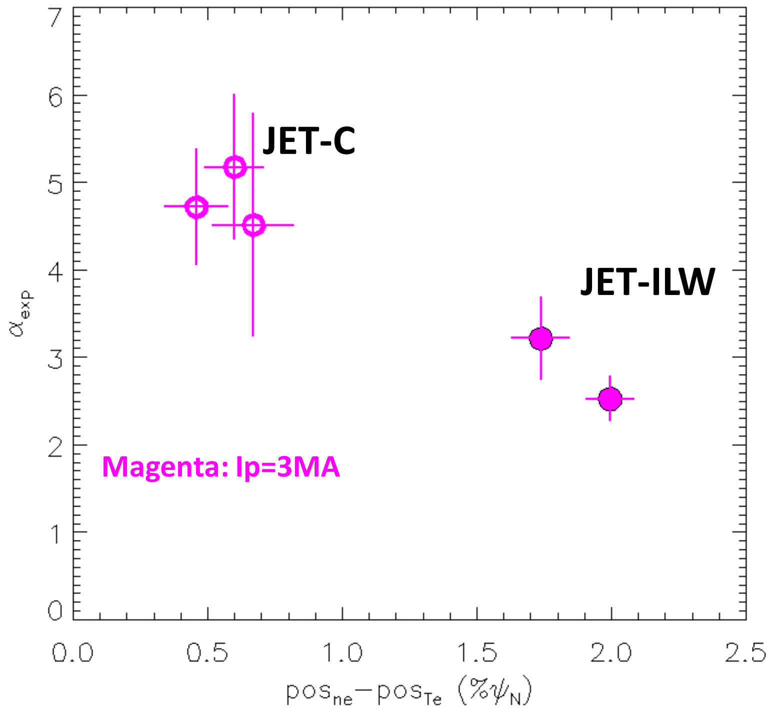

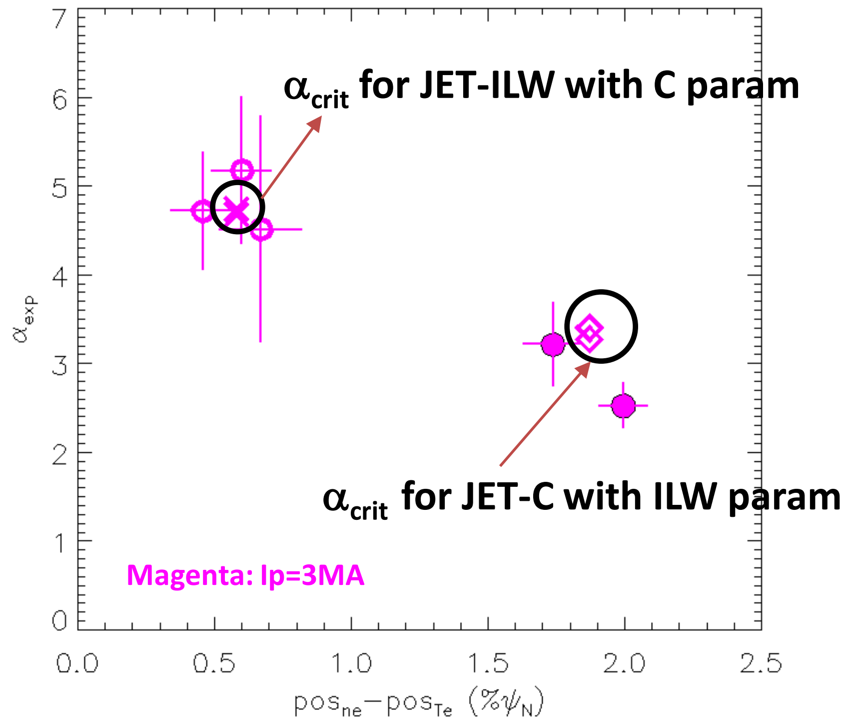

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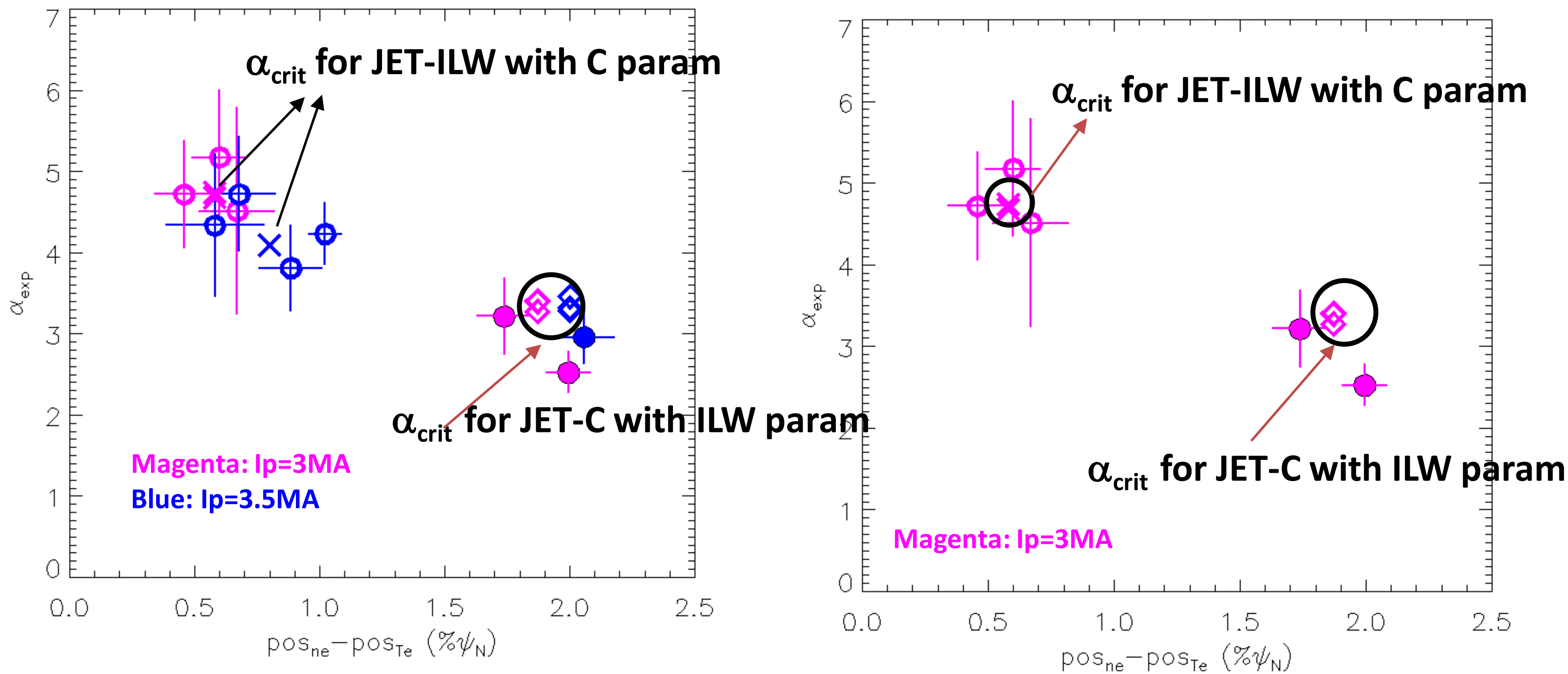

JET

Application to a wider JET-ILW/JET-C dataset

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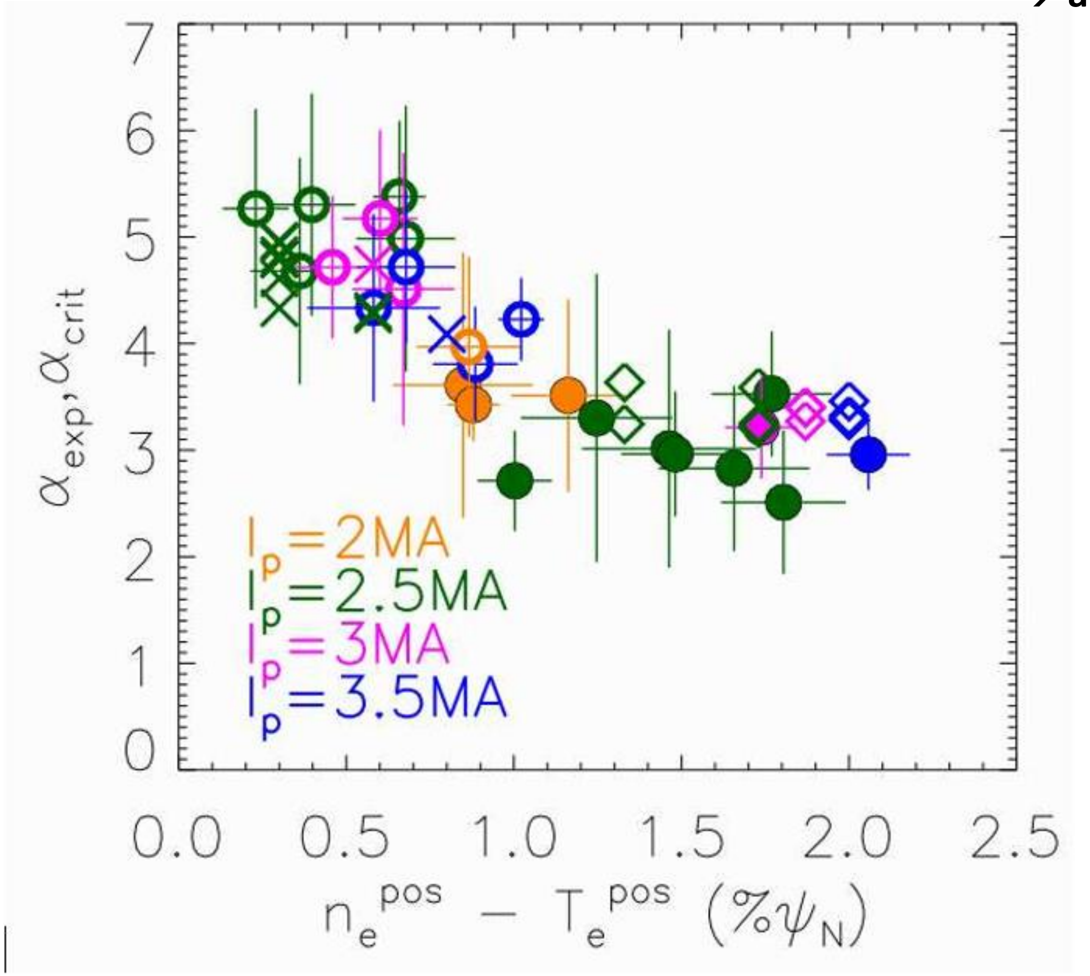
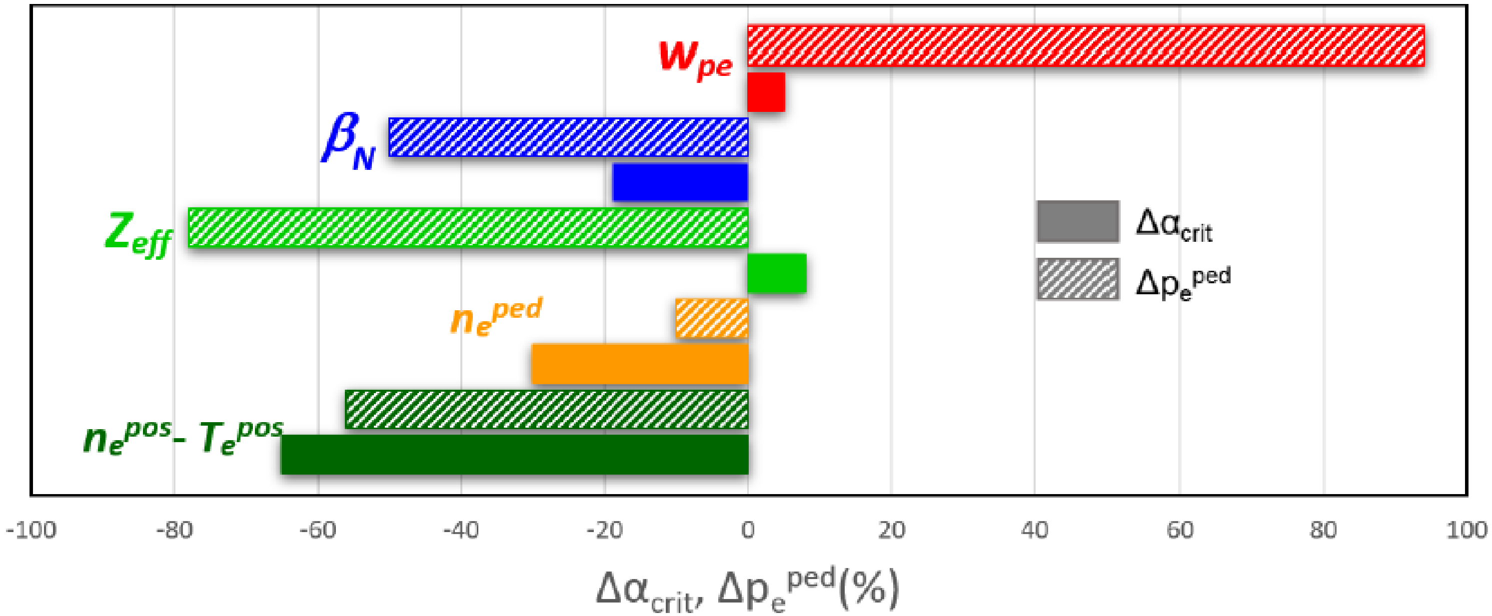


crosses: JET-ILW with C param

squares:JET-C with ILW param

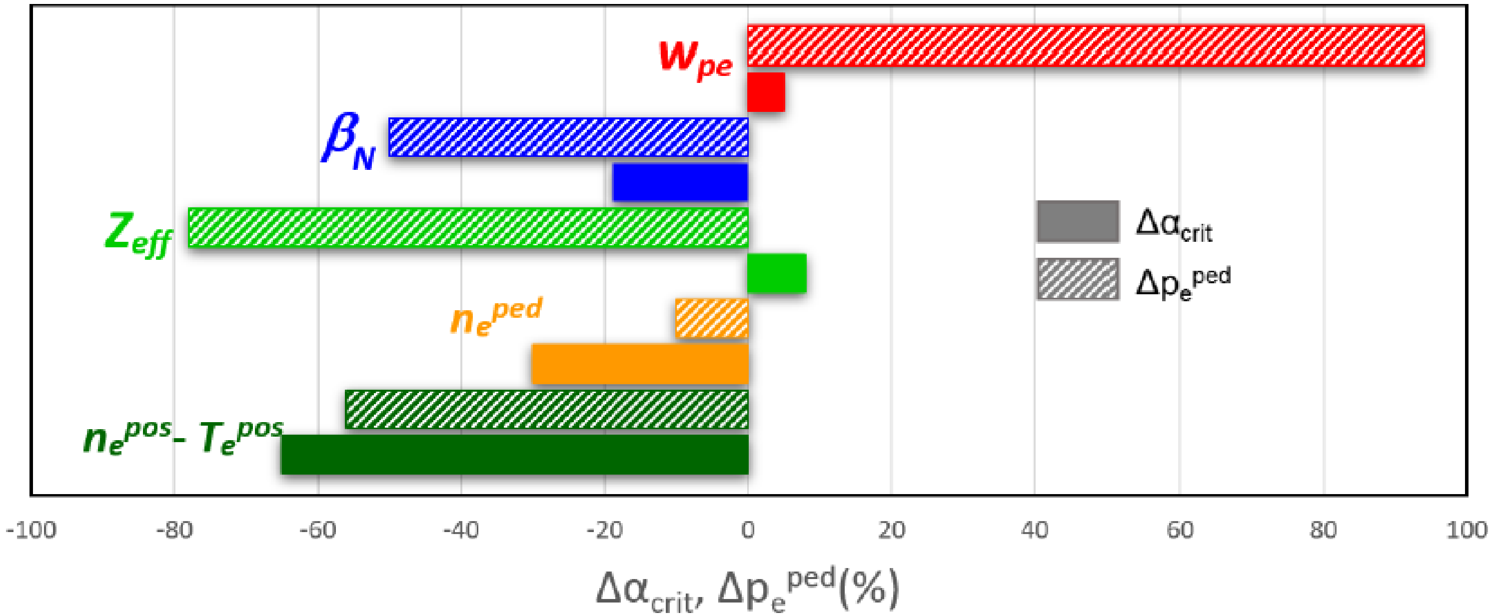
Application to a wider JET-ILW/JET-C dataset



Contribution of:	n_e^{pos}-T_e^{pos}	n_e^{ped}	Z_{eff}	β_N	w_{pe}	total
to α_{crit}	(-65±5)%	(-30±6)%	(+8±6)%	(-19±3)%	(-5±5)%	-100%
to p_e^{ped}	(-56±8)%	(-10±11)%	(-78±26)%	(-50±9)%	(+94±16)%	-100%

JET

Application to a wider JET-ILW/JET-C dataset



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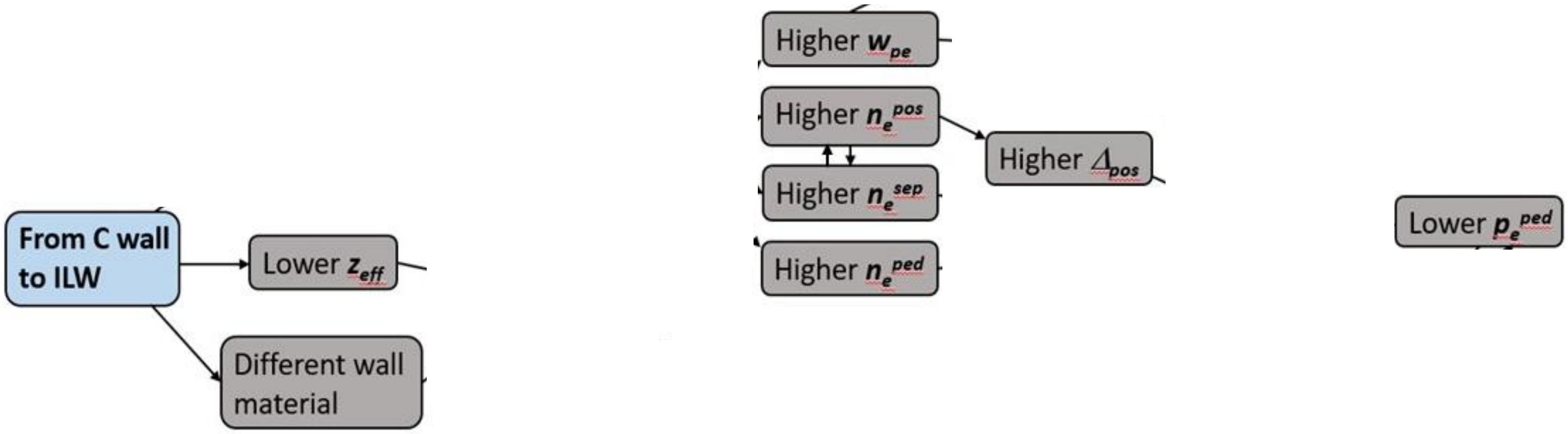
JET

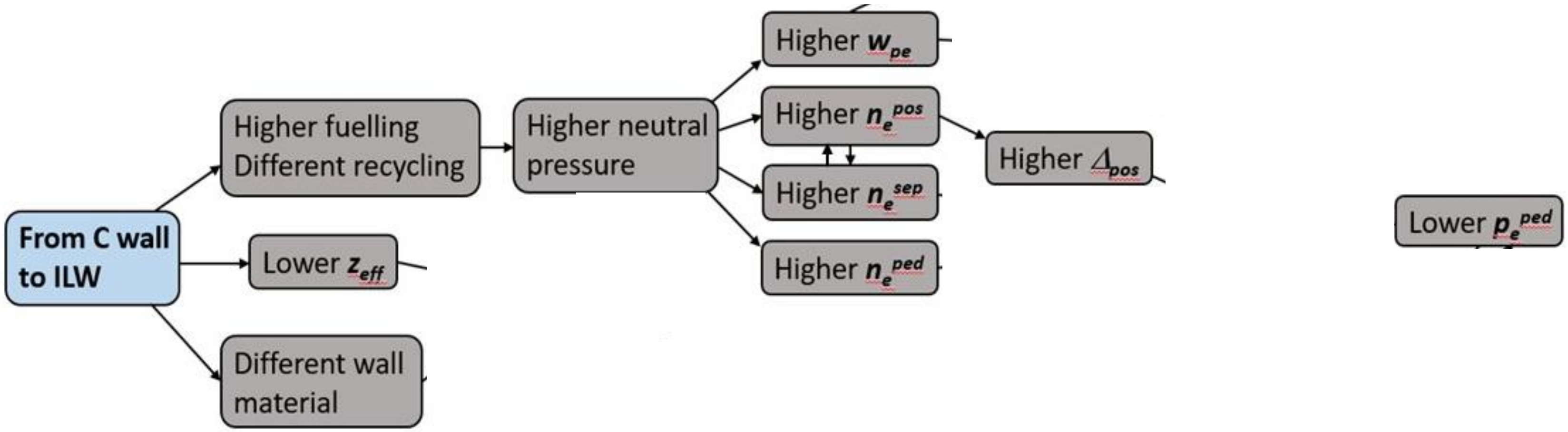
Discussion

- Experimental differences observed in this work



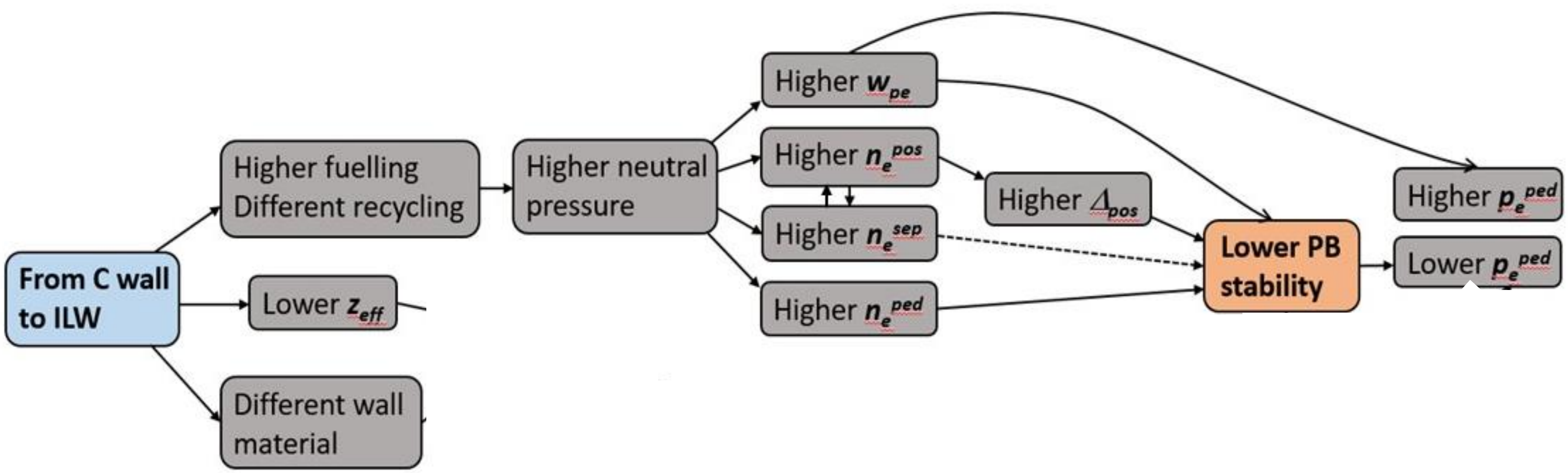
Discussion

- Experimental differences observed in this work
- Possible links to the differences in n_e^{pos}, n_e^{ped}, w_{pe}, n_e^{pos}- T_e^{pos} (hypothesis, not tested here)



Discussion

- Experimental differences observed in this work
- Possible links to the differences in n_e^{pos}, n_e^{ped}, w_{pe}, n_e^{pos}- T_e^{pos}
- Links between these differences and the pedestal height
  → tested with standard Europed



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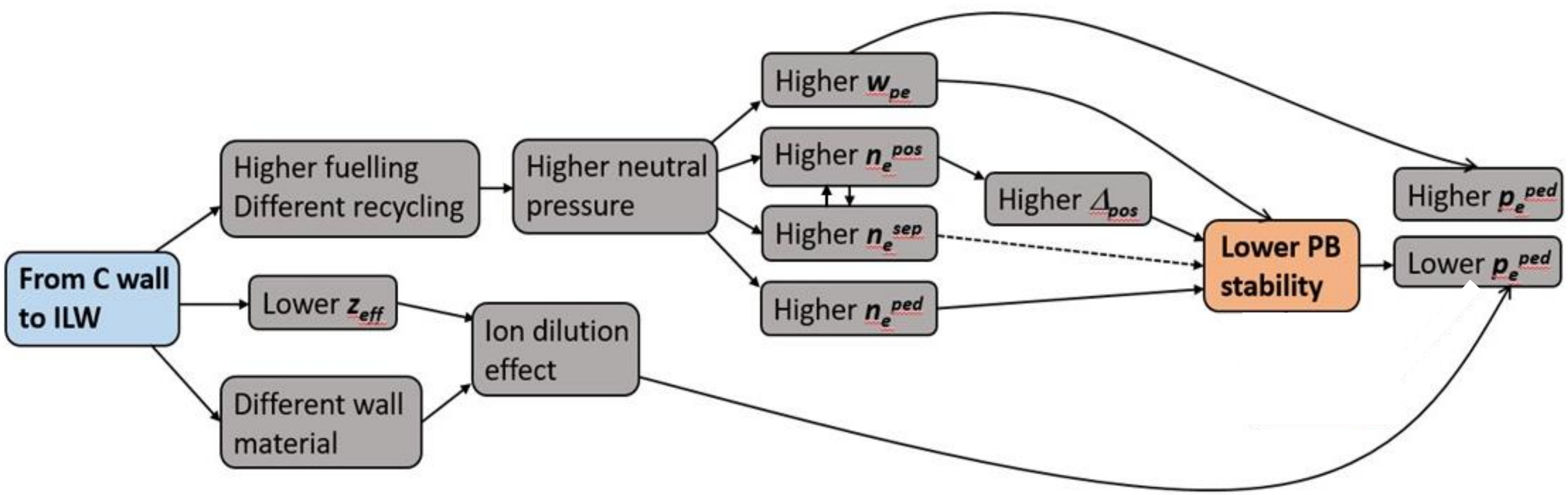
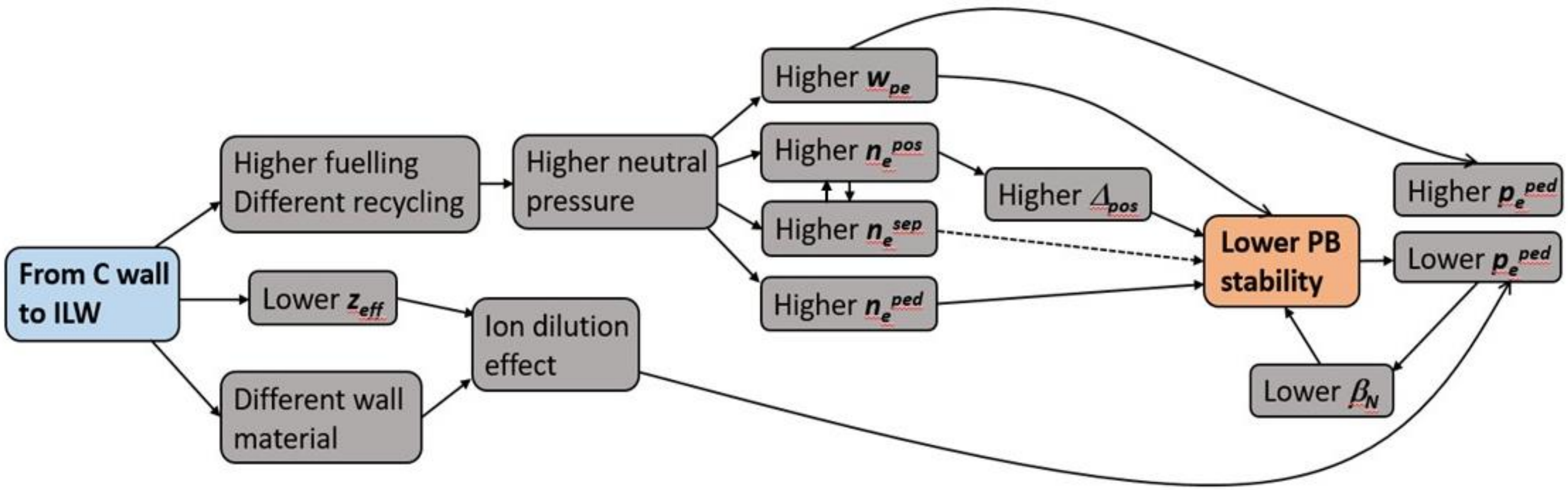


Discussion

- Experimental differences observed in this work
- Possible links to the differences in n_e^{pos}, n_e^{ped}, w_{pe}, n_e^{pos}- T_e^{pos}
- Links between these differences and the pedestal height
  → tested with standard Europed

- Links between β_N and the pedestal height
  → tested with self-consistent core-pedestal Europed



Conclusions

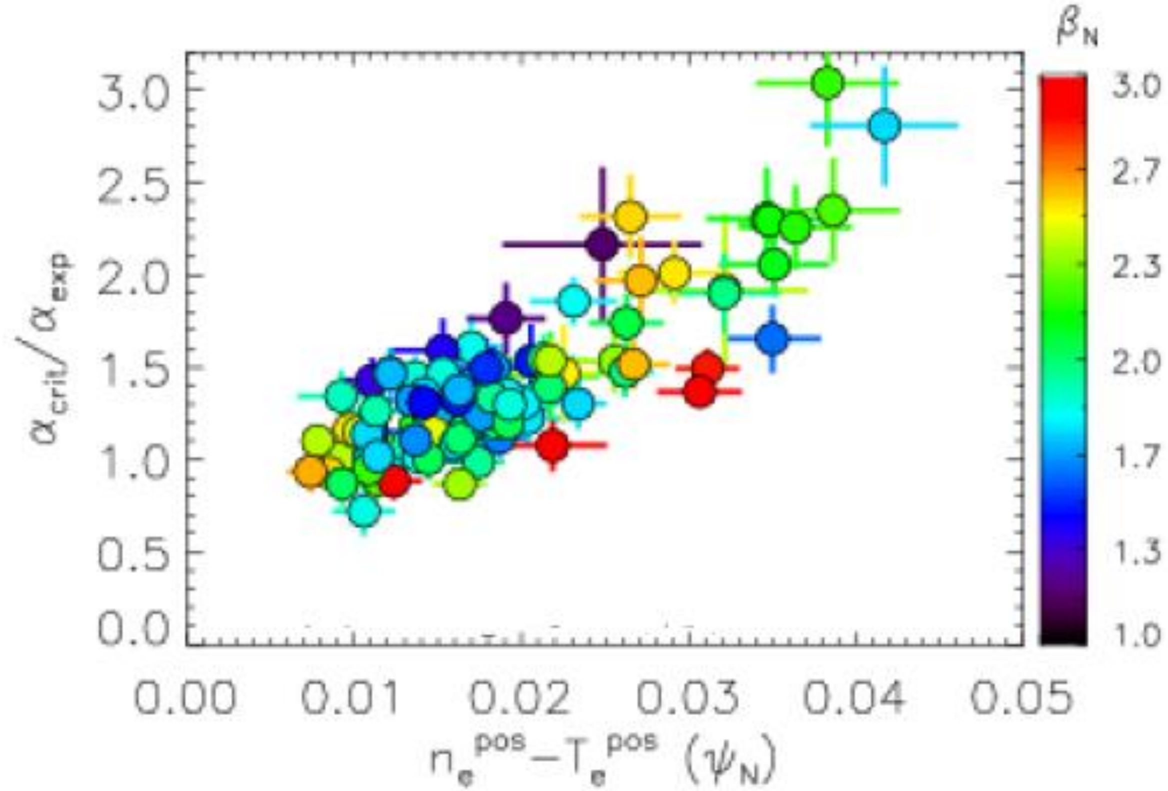
- This work investigates the differences in the pedestal stability of PB limited JET-C and JET-ILW discharges with similar engineering parameters
- Parameters that play a major role in pedestal stability (n_e^{pos}- T_e^{pos}, n_e^{ped} Z_{eff}, β_N, w_{pe}) have been studied by simulations with pedestal predictive code Europed
- Contribution of each parameter to the change in α_{crit} and p_e^{ped} has been quantified
- n_e^{pos}- T_e^{pos} and n_e^{ped} play a major role in affecting α_{crit}, while n_e^{pos}- T_e^{pos} ,w_{pe} and Z_{eff} have a major impact on p_e^{ped}
- Possible mechanism affecting the pedestal pressure height and the PB stability have been proposed

- This work contributes to the understanding of the different pedestal performance between JET-C and JET-ILW only in PB limited plasmas.
- This work does not address:
  - High-triangularity
  - Seeding (→ see works of C. Giroud)
  - Pulses not PB limited (→ see work of L. Frassinetti)

  } Further/complementary mechanisms must be invoked

Backup slides

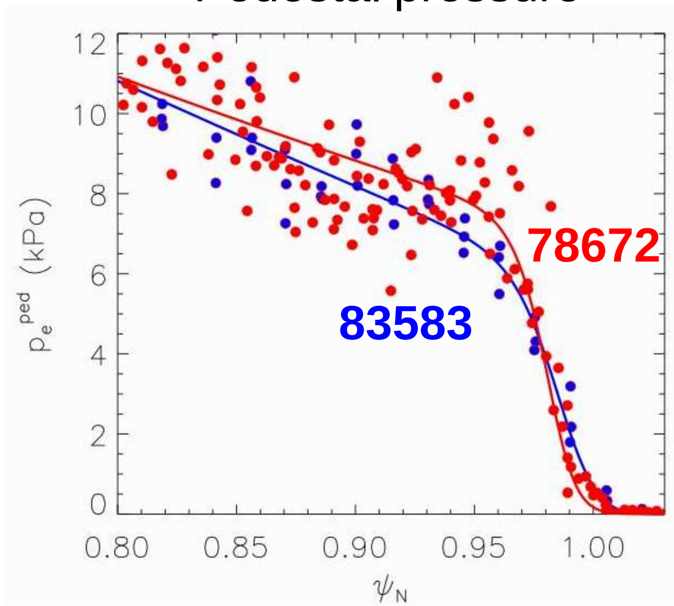
Non PB limited plasmas

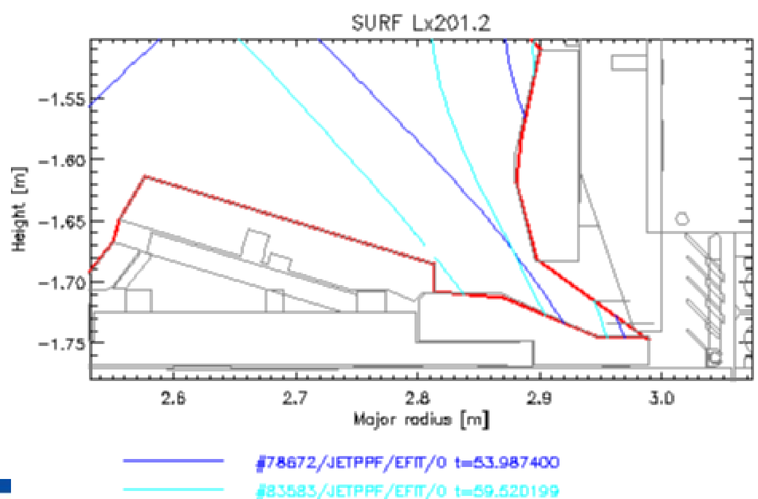


- Corelation between $\alpha_{crit}/\alpha_{exp}$ with the pedestal relative shift. Taken from [Frassinetti NF2020] (on the pinboard)
- Colors highlight different values of β_N.

Comparison of selected JET-ILW/JET-C couple

Pedestal pressure





similar

JET-C 78672	JET-ILW 83583
Ip ≈ 2.5MA	Ip ≈ 2.5MA
P_{NBI} ≈ 11MW	P_{NBI} ≈ 12MW
q_{95} ≈ 2.64	q_{95} ≈ 3
low δ	low δ
$\alpha_{crit}/\alpha_{exp}$ ≈ 1	$\alpha_{crit}/\alpha_{exp}$ ≈ 1

different

Δpos ≈ 0.36 %ψ_N	Δpos ≈ 1.46 %ψ_N
Pe width ≈ 0.032	Pe width ≈ 0.035
ne(ped)=3.3	ne(ped)=7.1
Z_{eff} ≈ 2.5	Z_{eff} ≈ 1.1
β_N=1.8	β_N=1.4

Application to a wider JET-ILW/JET-C dataset

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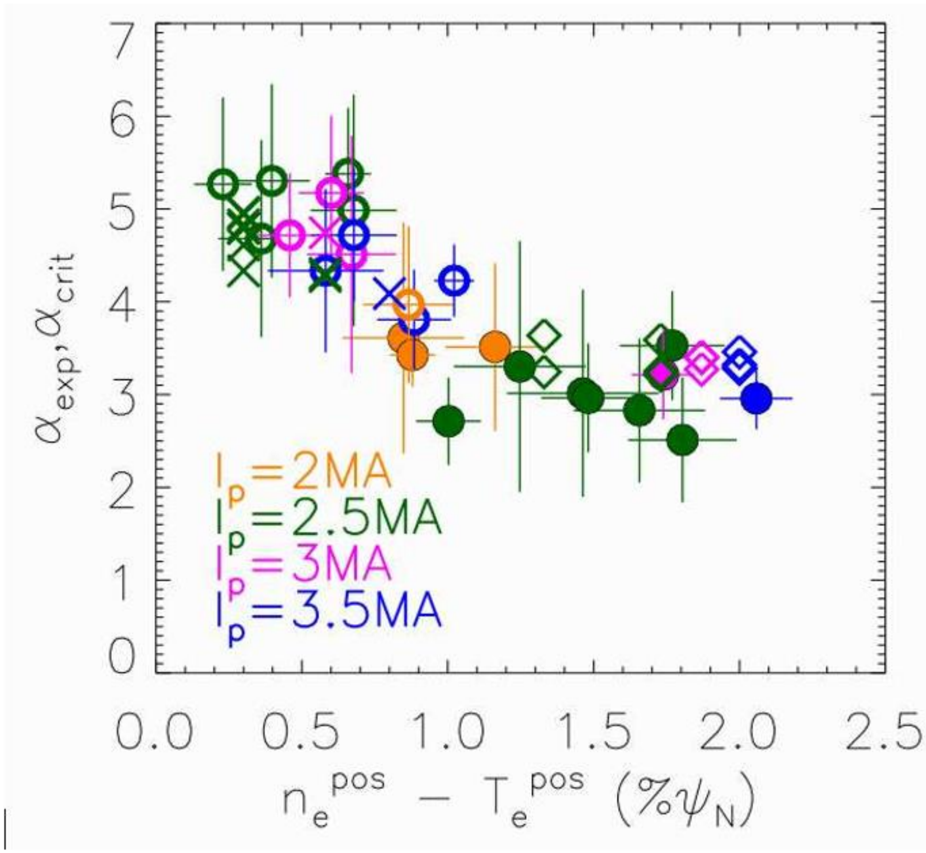
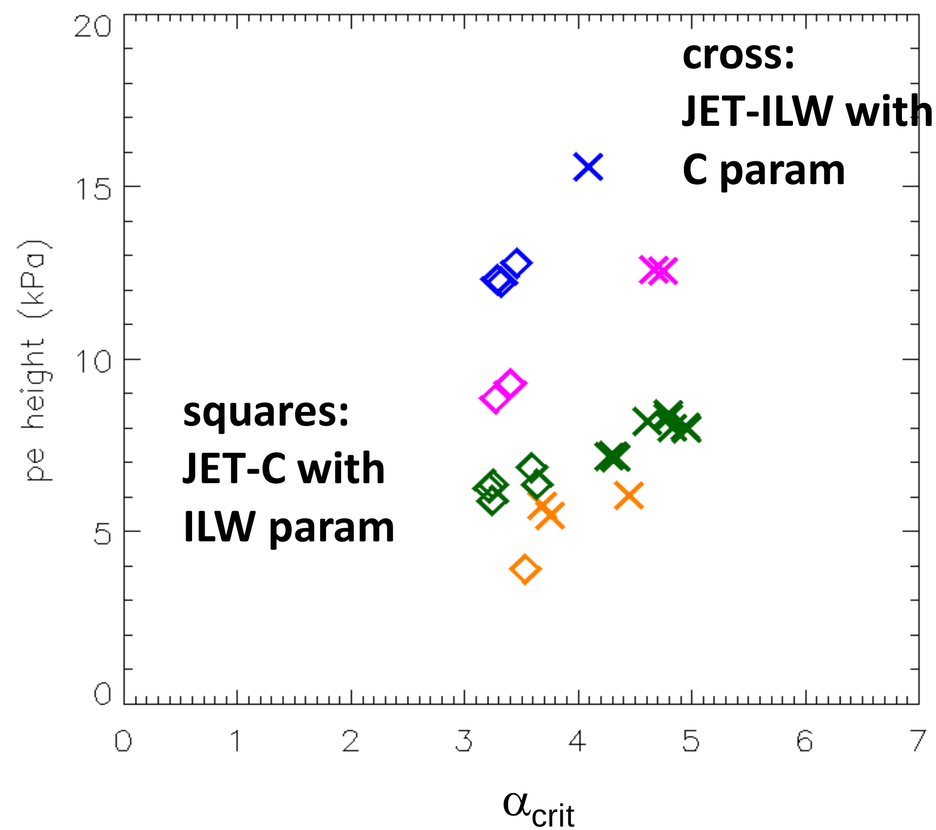
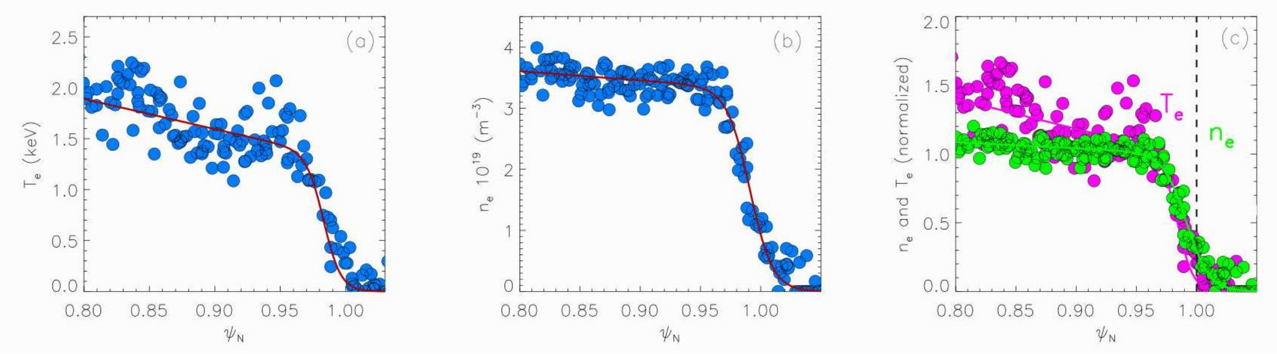




Pedestal profiles



JET-C 78672

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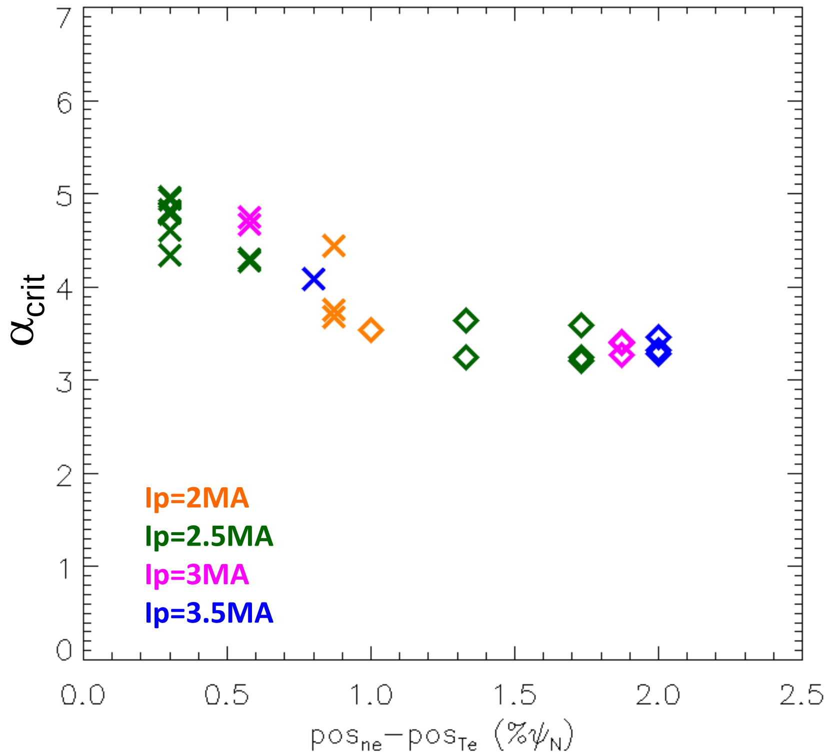

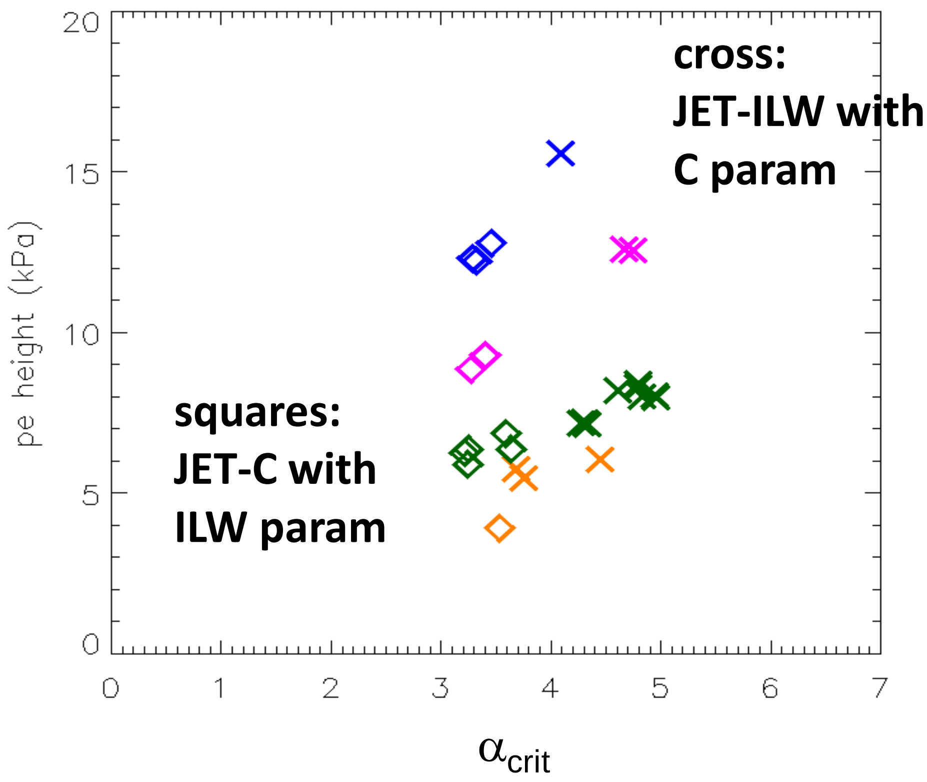

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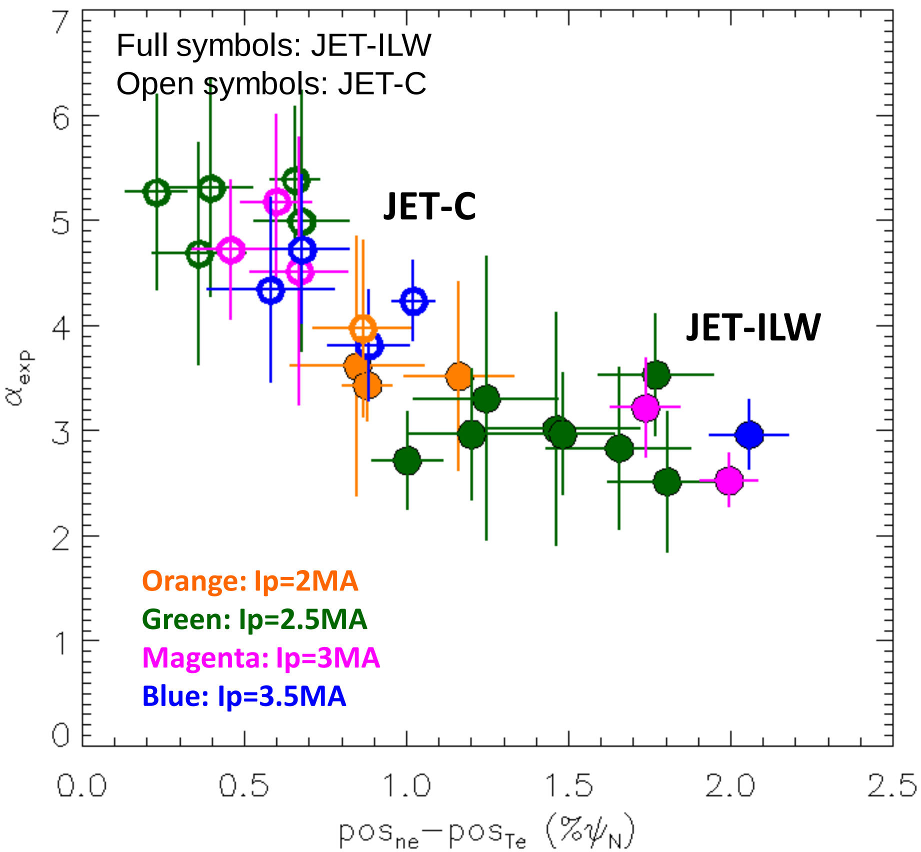

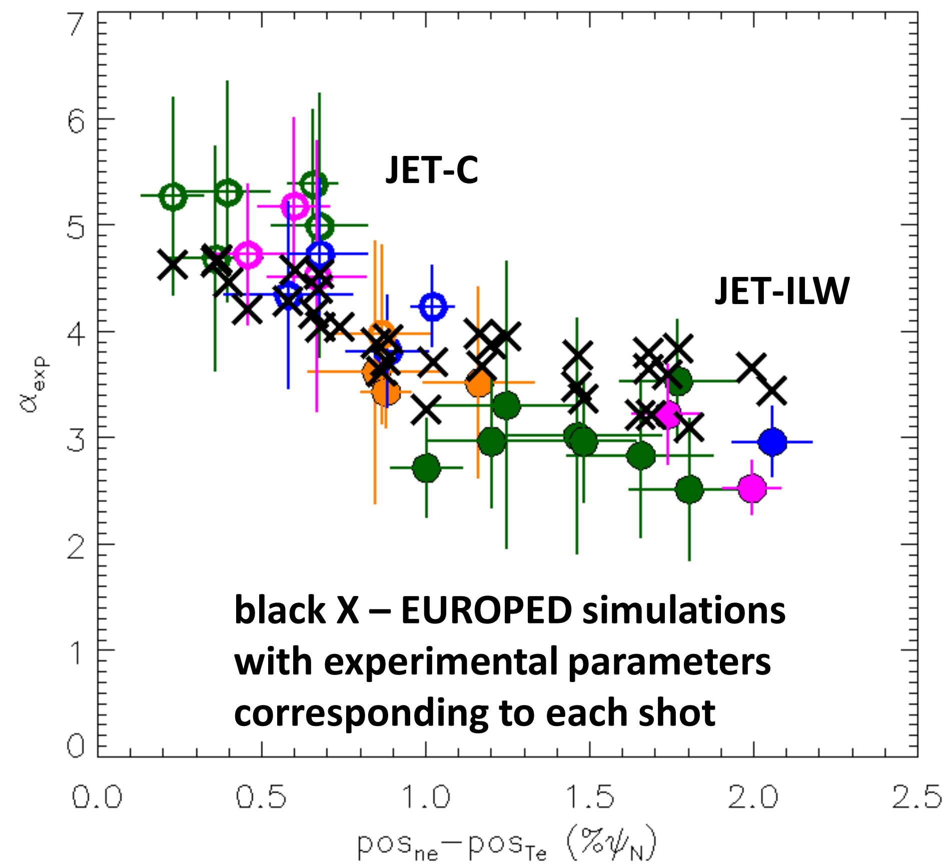

JET