EUROfusion

Experimental impurity concentrations required to reach detachment in ASDEX Upgrade and JET

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** See the Appendix of H. Meyer et al., Nucl. Fusion 59 (2019) 112014, B. Labit et al., Nucl. Fusion 59 (2019) 086020, and J. Mailloux et al., to be published in Nuclear Fusion Special issue: Overview and summary papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)*

JET IPP CCFE CULHAM CENTRE FOR FUSION ENERGY UK Atomic Energy Authority

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Impurity seeding for tokamak exhaust

Impurity seeding is generally regarded as a viable technique for dissipating the target power load, with divertor detachment of central importance for reactor designs

The goal is to measure the difficulty of achieving divertor detachment in terms of:
input power, **machine size**, **density**, **plasma current**, **impurity species**

The simple analytical Lengyel model provides the basis for relating the divertor conditions to the power dissipated. Other derivations have since followed

Lengyel model
$c_I \propto q_{||}^2 n_{e,sep}^{-2} T_{e,sep}^{-2} L_{INT}^{-1}$

Goldston derivation
$c_I \propto P_{sep} n_{e,sep}^{-2} I_P\, a_{min}^{-3}$

Reinke derivation
$c_I \propto B_T^{0.88} f_{LH}^{1.14} n_{e,sep}^{-2} R_{maj}^{1.33} M_{L,I}^{-1}$

Kallenbach derivation
$c_I \propto P_{sep} R_{maj}^{-1} p_0^{-1}$

Experimental measurements needed to challenge theoretical scaling laws

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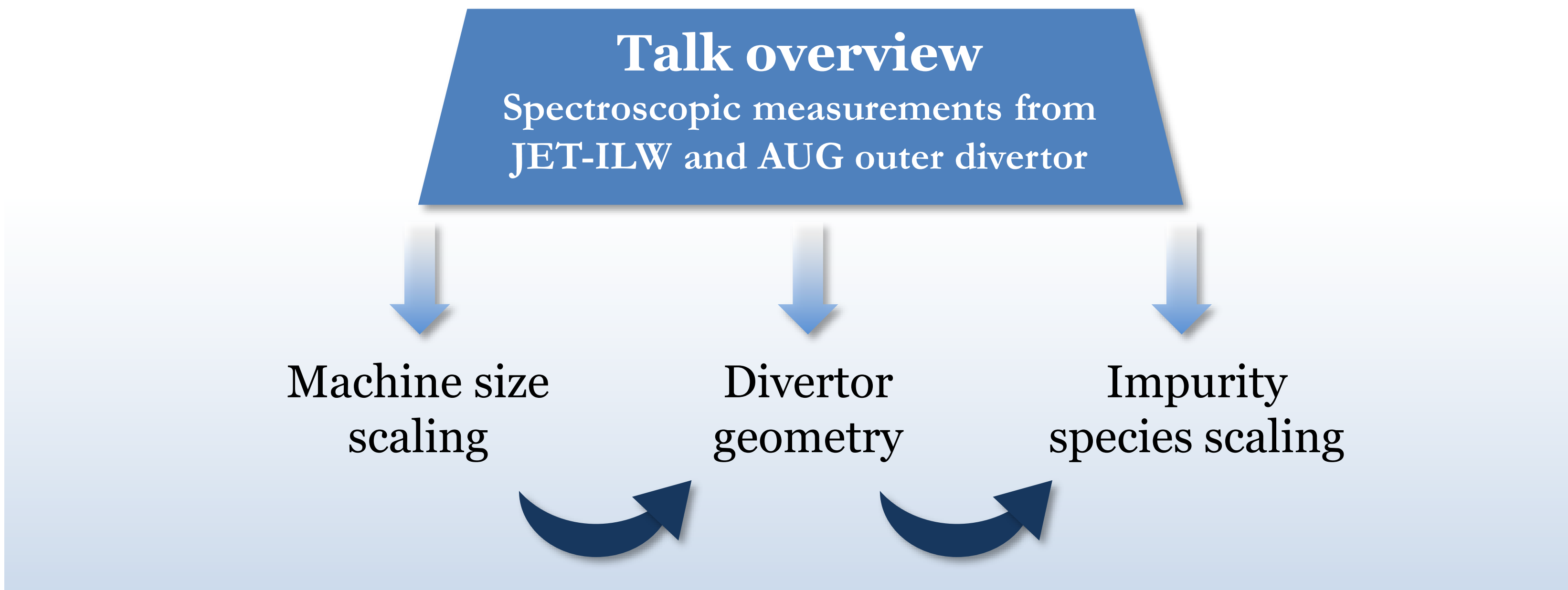
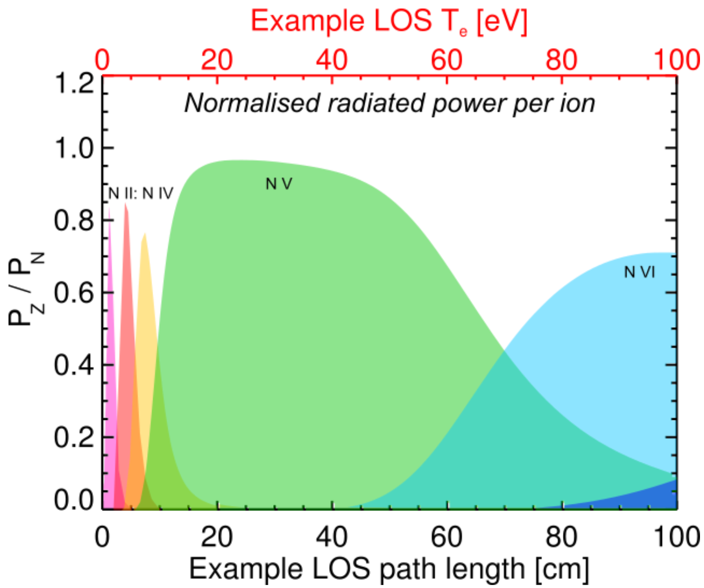
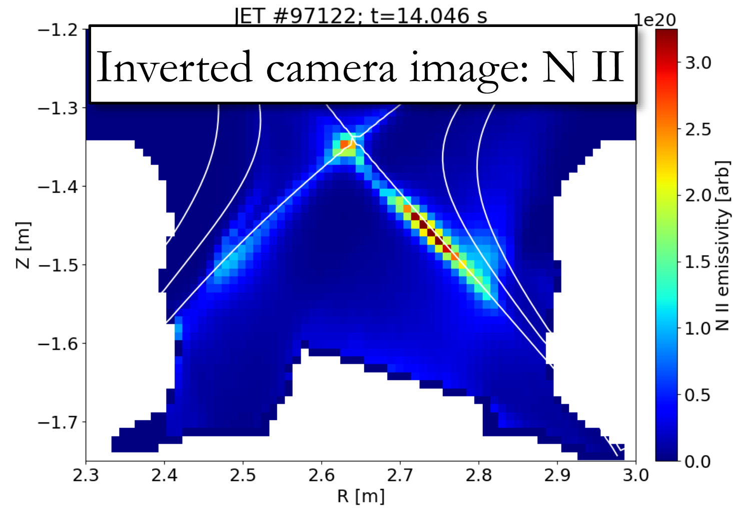


Experiments to challenge scaling predictions





Passive spectroscopic measurements of singly charged ion emission provide a transient, non-perturbative, and local estimation of the divertor concentration

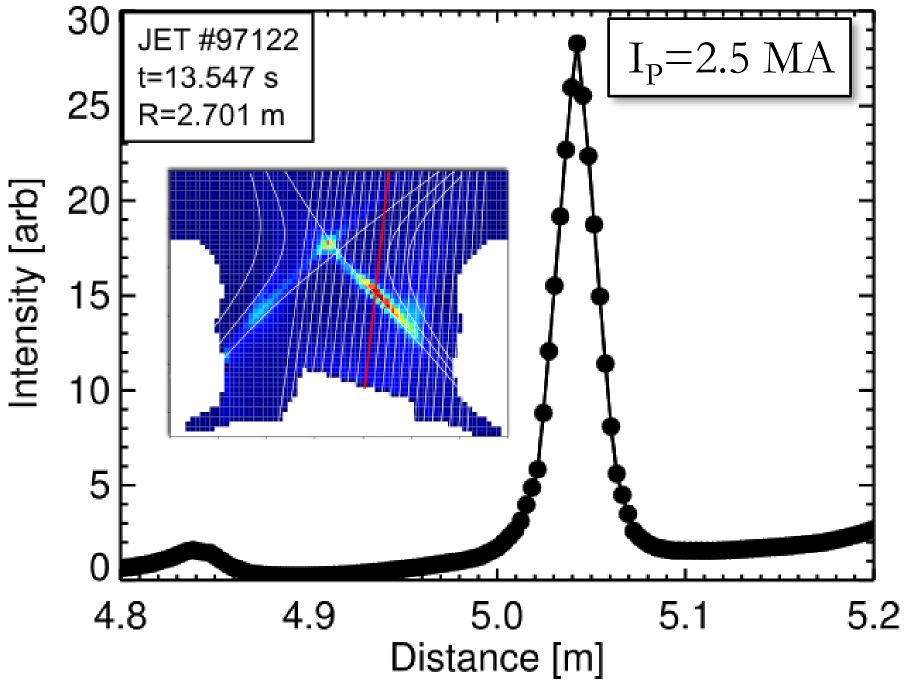
Ion emission

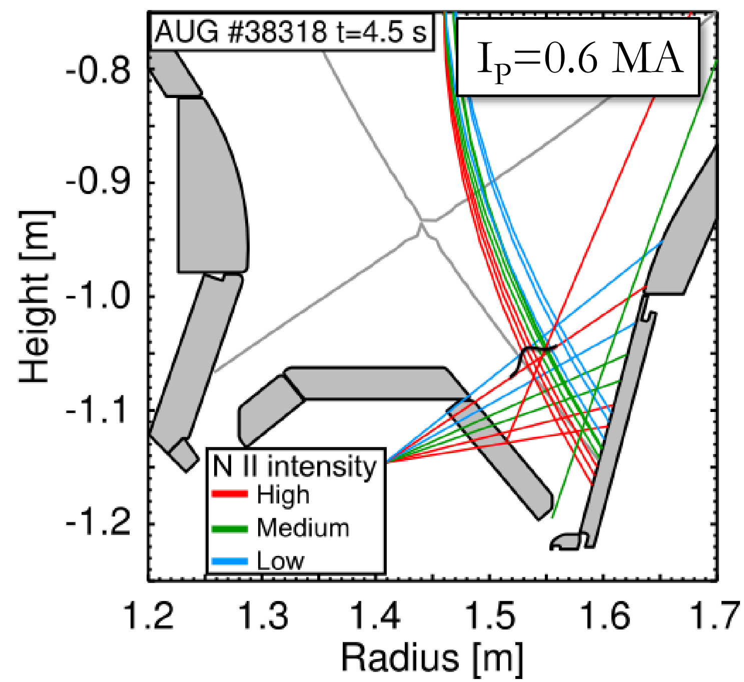
$$c_I = \frac{4\pi \int \varepsilon_{I,Z} dl}{TEC_{I,Z}} \frac{1}{\Delta L n_e^2}$$

Atomic coefficient

Length of emission

Poloidal emission distribution





To perform a least squares regression of JET and AUG data, first the poloidal distribution of N II emission must be established to quantify ΔL

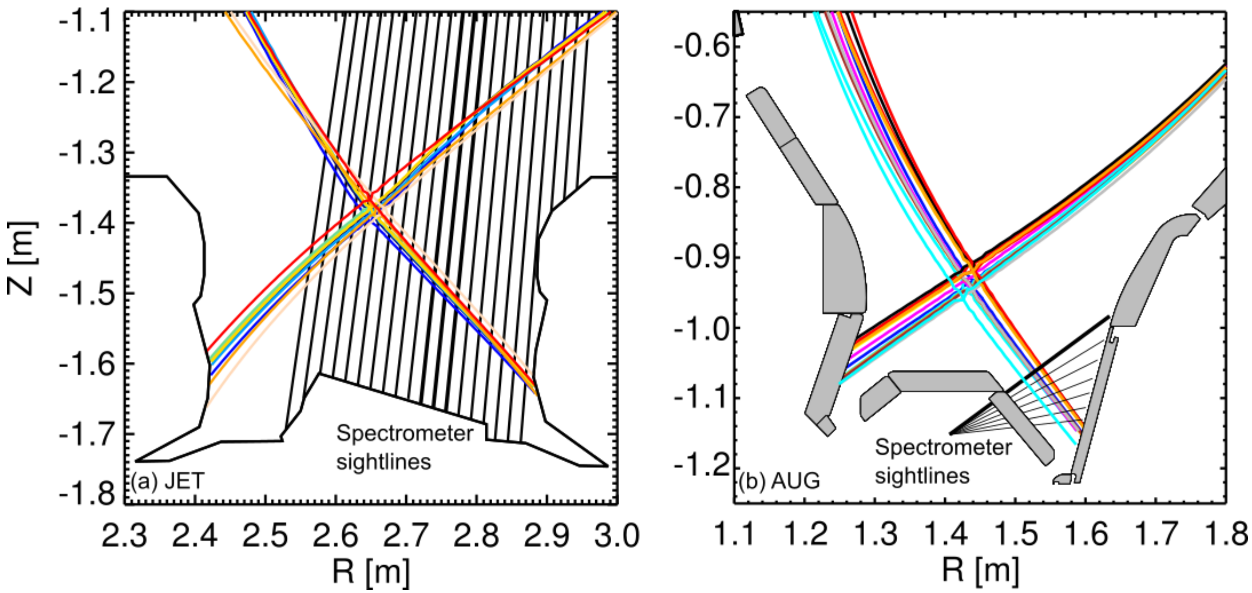
Absolute values are set (to account for reflections on JET) as:

AUG: $\Delta L = 0.052 I_P^{-0.62}$ (*e.g.* I_P*=0.6 MA* ΔL*~7 cm*)

JET: $\Delta L = 0.124 I_P^{-0.62}$ (*e.g.* I_P*=2.5 MA* ΔL*~7 cm*)

These are likely upper limits, especially on AUG

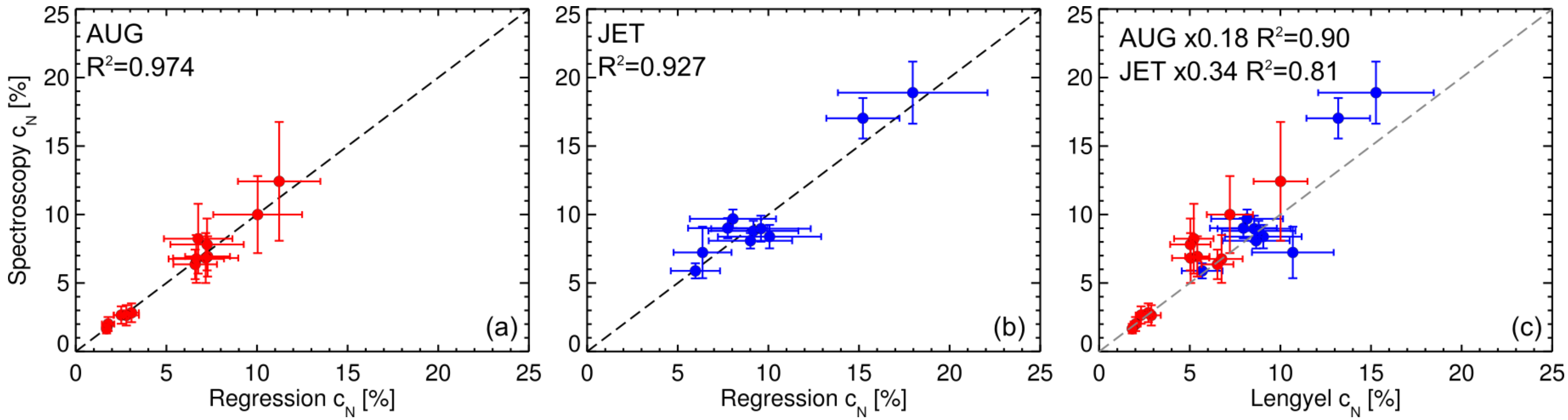
Experiments to challenge scaling predictions



A database now exists of divertor c_N measurements from JET-ILW and ASDEX Upgrade H-mode plasmas with partially detached outer divertors in vertical geometry

	# points	P_{sep} [MW]	$n_{e,sep}$ [10^{19} m^{-3}]	I_P [MA]	a_{min}	B_T [T]
AUG	13	3.5 – 12	2 – 4	0.8-1.2	0.5	2.5
JET	10	14 – 15.5	2.2 – 3.5	2.5	0.9	2.7

Experiments to challenge scaling predictions



[Henderson et al., PSI 2020]

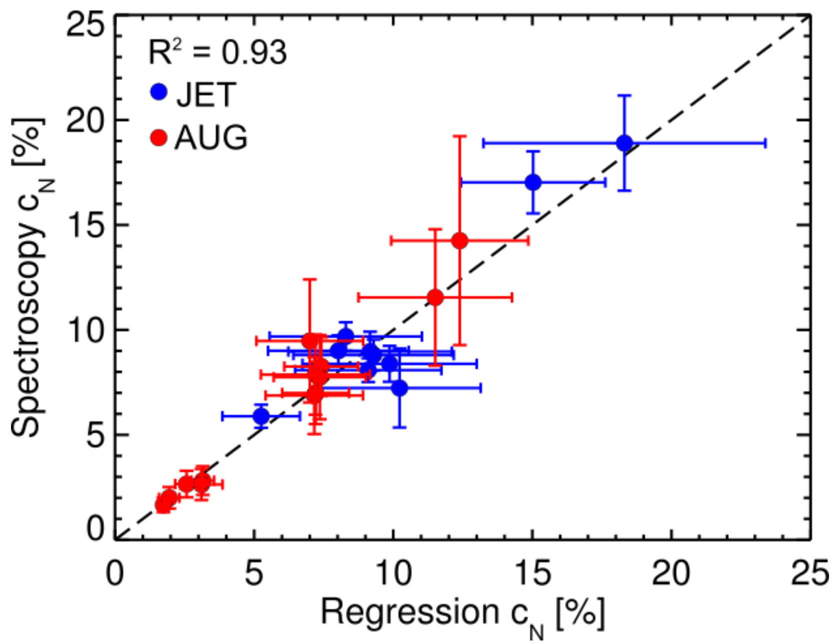
A previous study performed a least squares analysis of the data from JET and AUG separately to study the scaling of P_{sep} and $n_{e,sep}$:

AUG: $c_N \propto P_{sep}^{1.19\pm0.32} n_{e,sep}^{-2.77\pm0.36}$

JET: $c_N \propto n_{e,sep}^{-2.43\pm0.27}$

Consistent with theoretical scaling of P_{sep}, but suggests stronger dependency on $n_{e,sep}$ and lower absolute values

Machine size scaling



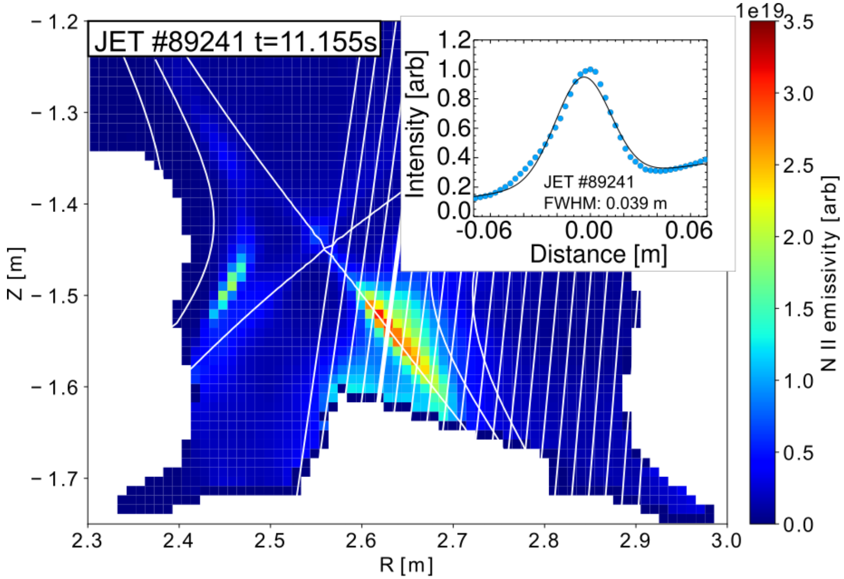
Performing least-squares regression of data from both JET and AUG gives

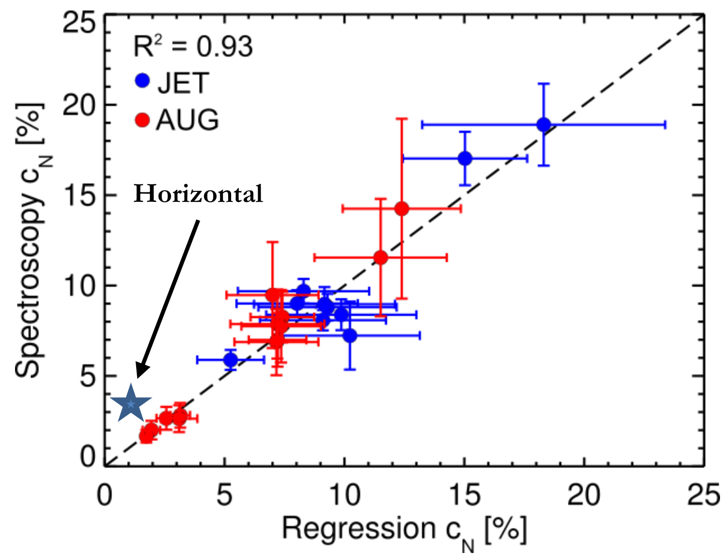
$$c_N = 5.89 \pm 2.73\; P_{div,outer}^{1.16\pm0.23} n_{e,sep}^{-2.72\pm0.22} I_P^{1.05\pm0.6} a_{min}^{-2.36\pm0.88}$$

Systematic uncertainty: reducing AUG ΔL by 1 cm gives $c_N \propto a_{min}^{-2.64\pm0.89}$

Consistent with Goldston scaling $c_N \propto I_P a_{min}^{-3}$

Divertor geometry assessment





Comparing with horizontal geometry provides assessment of neutral compression

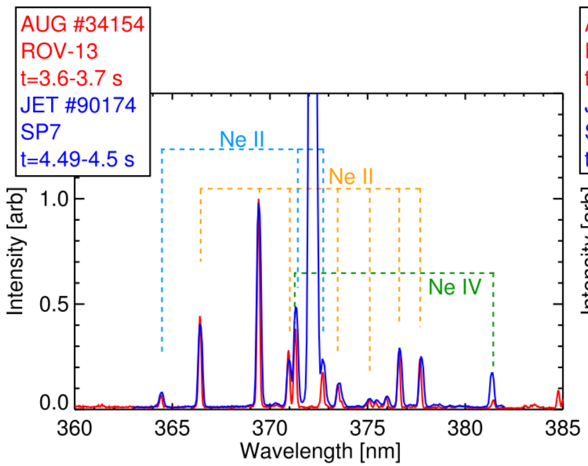
Parameters for JET #89421

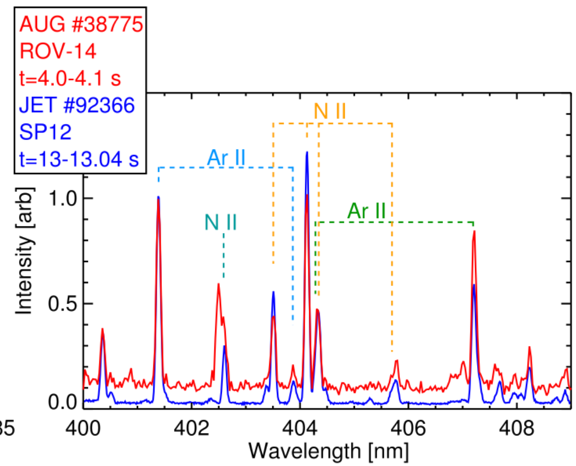
$P_{div,outer}$ = 1.24 MW, $n_{e,sep}$ = 2.9x10^{19} m^{-3}, I_P = 2 MA, and a_{min} = 0.94

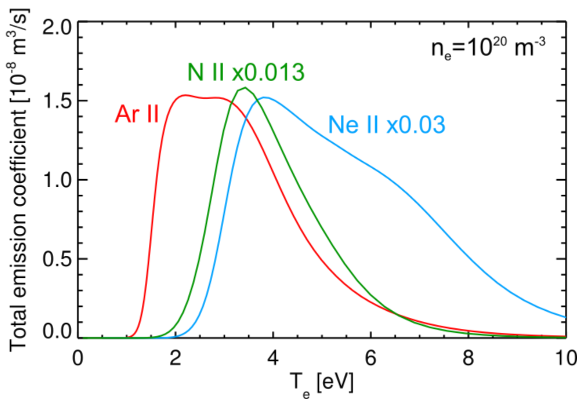
$c_N \sim 1\%$

Measured c_N higher than scaling law predictions, suggests achieving detachment harder in horizontal configuration

Impurity species scaling





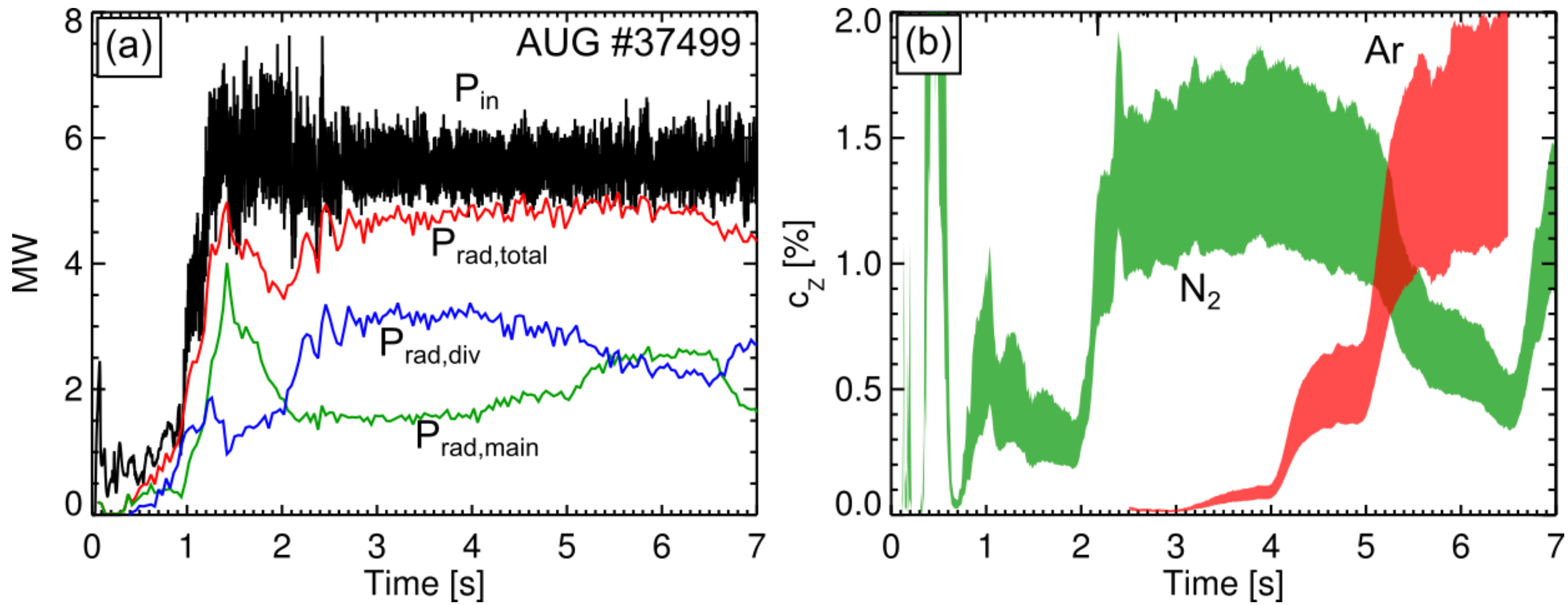


Reactor scale tokamaks will likely require Ne or Ar to radiate tokamak exhaust

A new set of spectroscopic lines and atomic data are used to analyse c_{Ne} and c_{Ar}

Total emission coefficients of N II, Ne II and Ar II all exist over a narrow T_e range

Comparing N and Ar concentrations



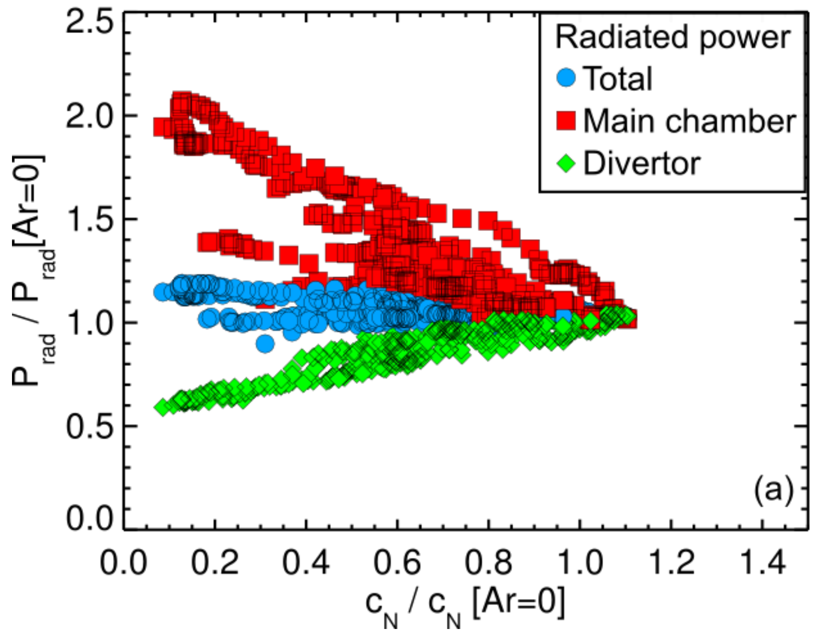
AUG experiment with partially detached scenario using N_2 and Ar seeding

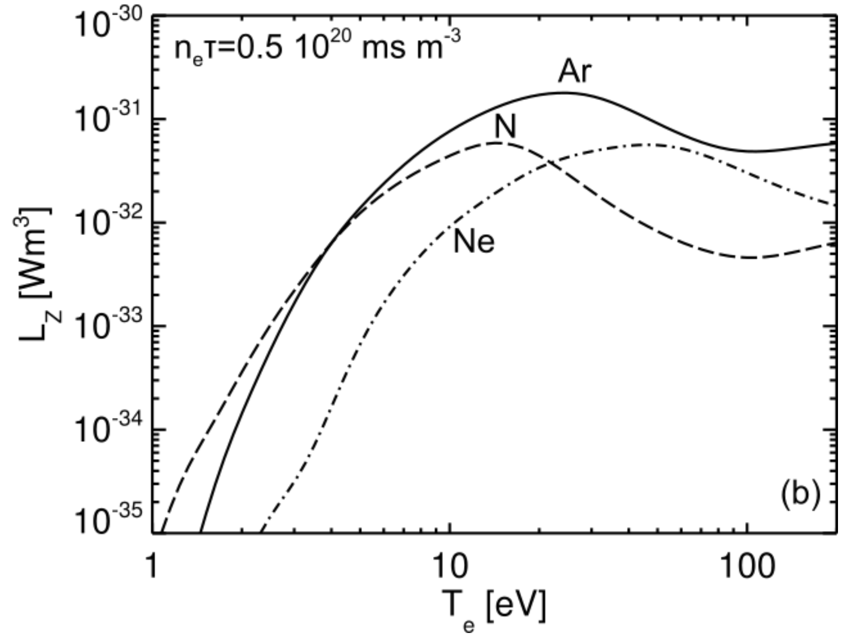
Measurements show $c_{Ar} \sim c_N$ in the window of N-only and Ar-only

The Reinke scaling $c_I \propto P_{sep}^{1.14} M_{L,I}^{-1}$ where $M_{L,Ar} \sim 7 - 8 M_{L,N}$ gives $c_{Ar} \sim 0.3 c_N$

Scaling law is average SOL prediction: **need to consider enrichment**

Comparing N and Ar radiated power





Database of AUG plasmas are combined to assess changes to radiated power

Comparing Ar-only to N-only

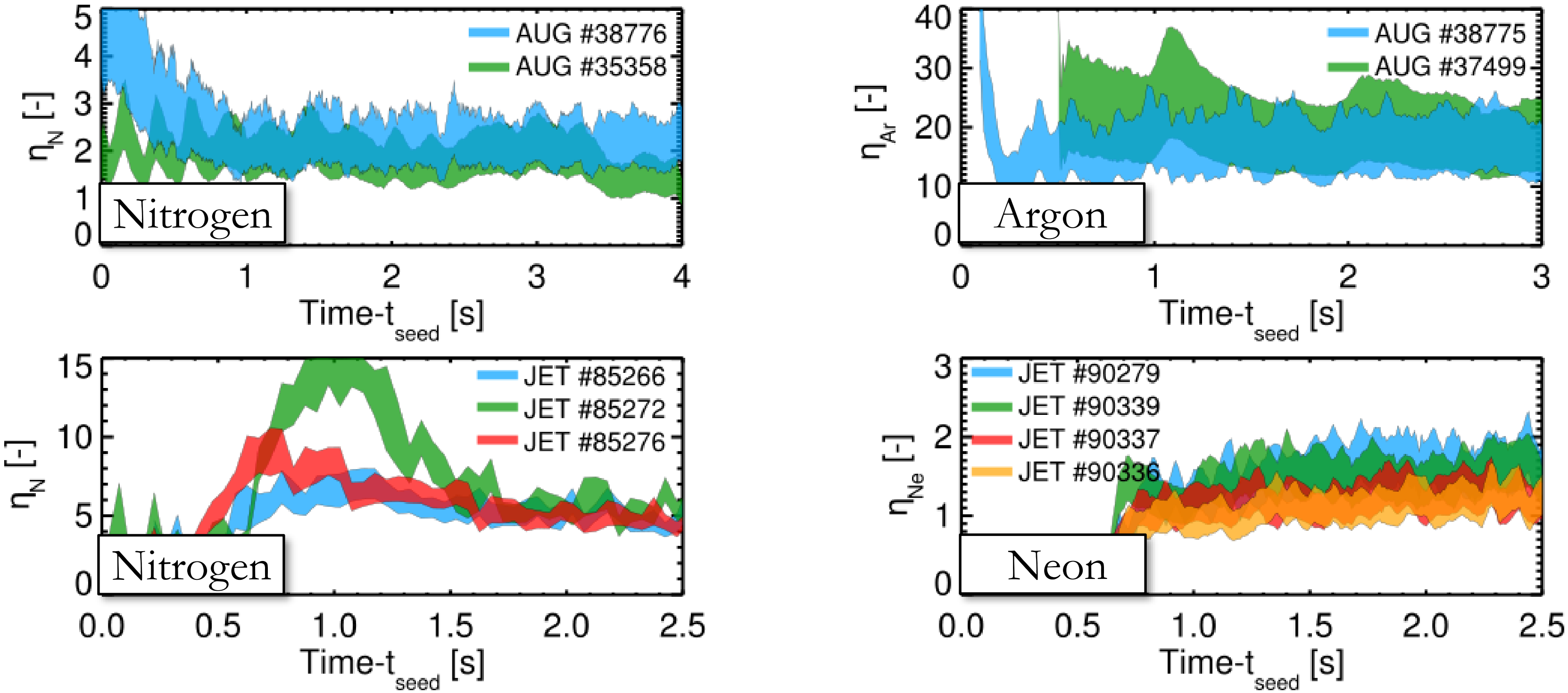
» **Divertor radiation** decreases by factor *2x*

- Using $n_e^2 c_{Ar} L_{Ar} = 0.5 n_e^2 c_N L_N$ then $c_{Ar} \sim c_N$

» **Main chamber radiation** increases by factor *2x*

- Using $n_e^2 c_{Ar} L_{Ar} = 2 n_e^2 c_N L_N$ then $c_{Ar} \sim 0.2 c_N$

Enrichment factors



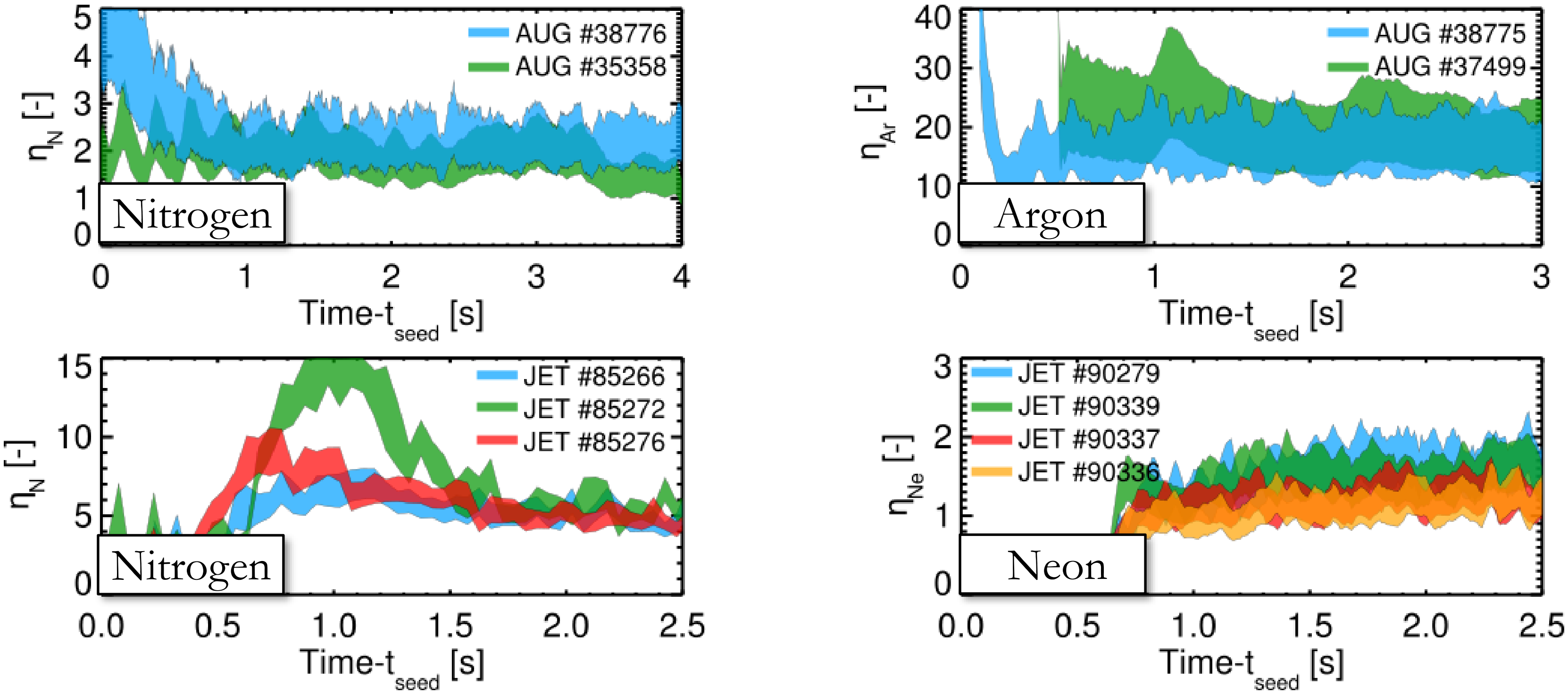
Direct comparison of the impurity enrichment factors, $\eta_I = \frac{c_{I,div}}{c_{I,core}}$, are possible by comparing core concentrations from CXRS

Neon enrichment is $\eta_{Ne} \sim 0.8 - 2$

Nitrogen enrichment is $\eta_N \sim 2 - 5$

Argon enrichment is $\eta_{Ar} \sim 10 - 20$

Enrichment factors



Argon enrichment is $\eta_{Ar} \sim 10 - 20$

- Measurements show divertor : $c_{Ar} \sim c_N$
- Measurements show core : $c_{Ar} \sim 0.1 c_N$
- Scaling law prediction : $c_{Ar} \sim 0.3 c_N$

This is approximately within the bounds of the scaling law prediction

Conclusions and next steps

Spectroscopic divertor measurements of N II, Ne II, and Ar II are used to challenge theoretical scaling laws of impurity concentration thresholds for divertor detachment

Machine size

- Least squares regression of spectroscopic c_N measurements from JET and AUG

$$c_N = 5.89 \pm 2.73\, P_{div,outer}^{1.16\pm0.23} n_{e,sep}^{-2.72\pm0.22} I_P^{1.05\pm0.6} a_{min}^{-2.36\pm0.88}$$

Impurity species

- New divertor measurements of c_{Ar} show similar values to c_N in partially detached plasmas, but Ar shows a stronger enrichment factor in comparison to N

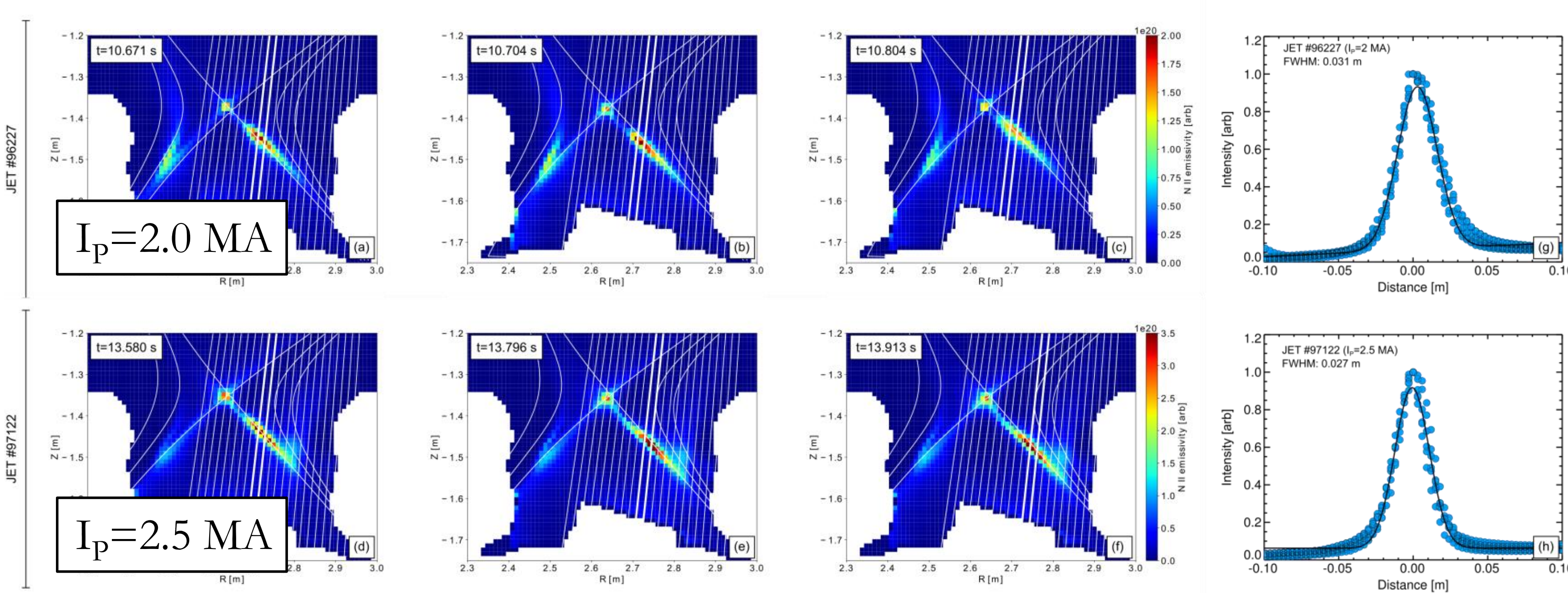
Theoretical scaling laws

- Generally consistent with experimental parameter dependencies with a moderate discrepancy on $n_{e,sep}$ but differ significantly on absolute concentrations

Where next

- Expand database to include scan of B_T

Appendix: ΔL analysis

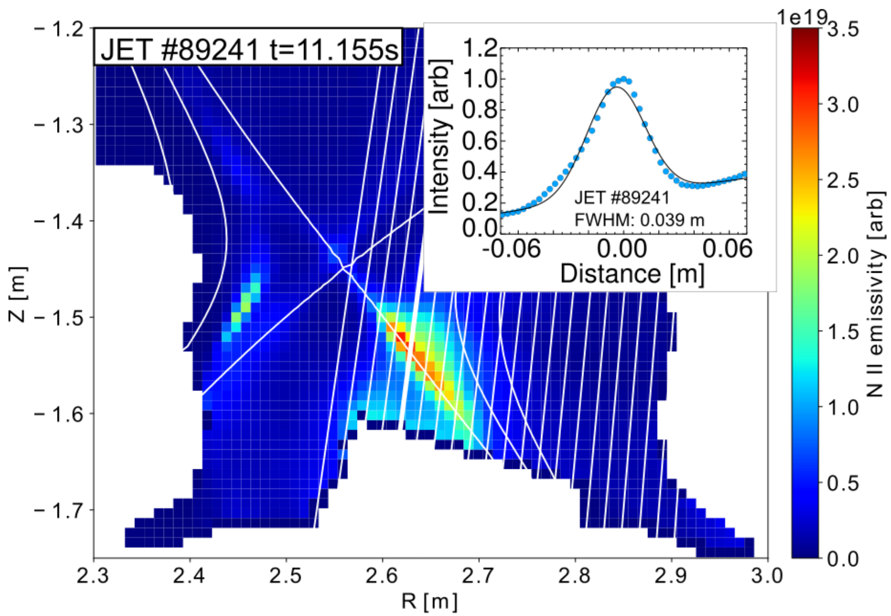


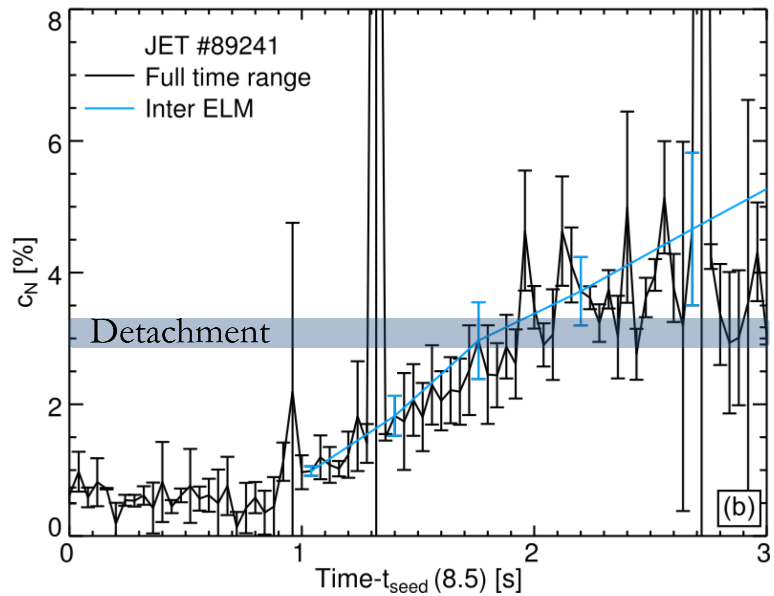
To perform a least squares regression of JET and AUG data combined, first need to quantify uncertainty of ΔL – absolute magnitude and how it varies with I_P

New analysis of inverted camera data on JET suggest a scaling of $\Delta L \sim I_P^{-0.62}$

Due to the dependence of ΔL on T_e and n_e, and therefore on spreading factor S

Appendix: divertor geometry assessment





Comparing with horizontal geometry provides assessment of neutral compression

Same model applied to scenario with horizontal outer divertor geometry but with a larger ΔL

Vertical: $\Delta L = 0.124 I_P^{-0.62}$ (*e.g.* $I_P = 2.5$ *MA* $\Delta L \sim 7$ *cm*)

Horizontal: $\Delta L = 0.154 I_P^{-0.62}$ (*e.g.* $I_P = 2.0$ *MA* $\Delta L \sim 10$ *cm*)