EUROfusion

Experimental impurity concentrations required to reach detachment on AUG and JET

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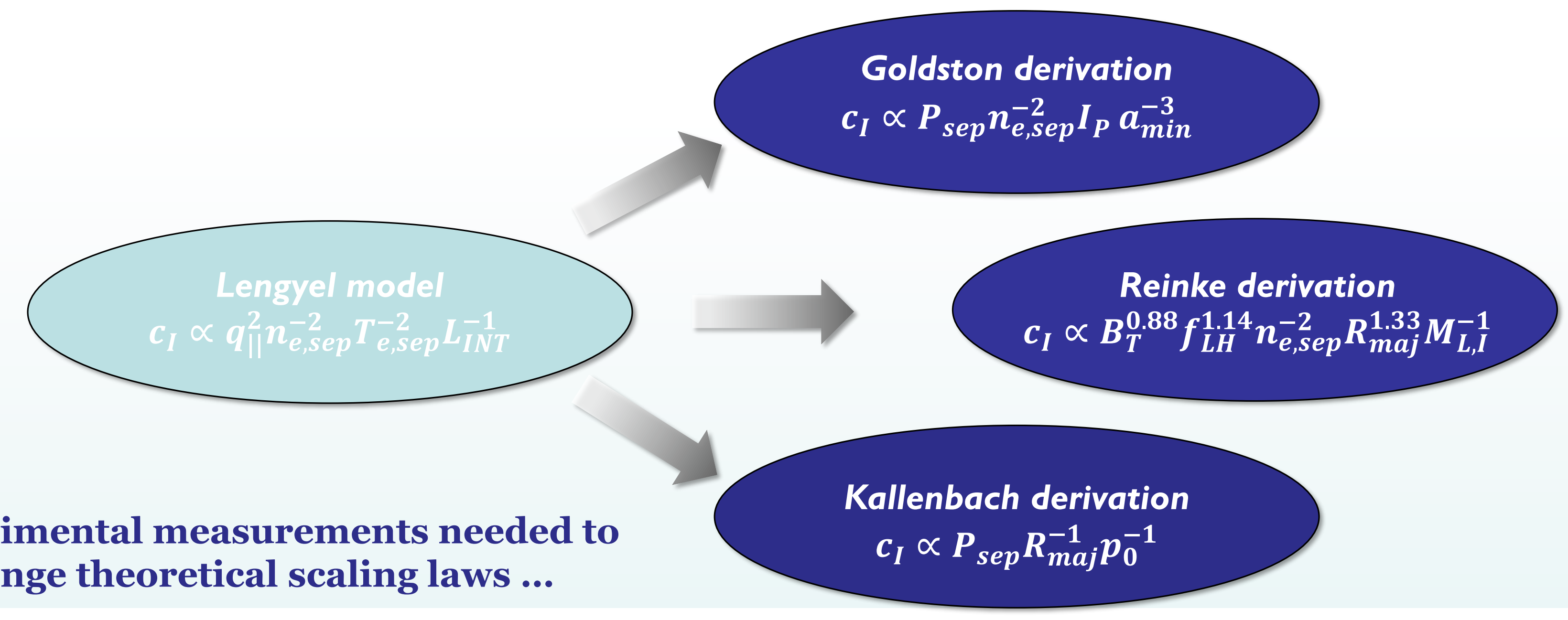
** See the Appendix of H. Meyer et al., Nucl. Fusion 59 (2019) 112014, B. Labit et al., Nucl. Fusion 59 (2019) 086020, and J. Mailloux et al., to be published in Nuclear Fusion Special issue: Overview and summary papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)*

MOTIVATION

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

EXPERIMENTAL DIVERTOR CONCENTRATIONS

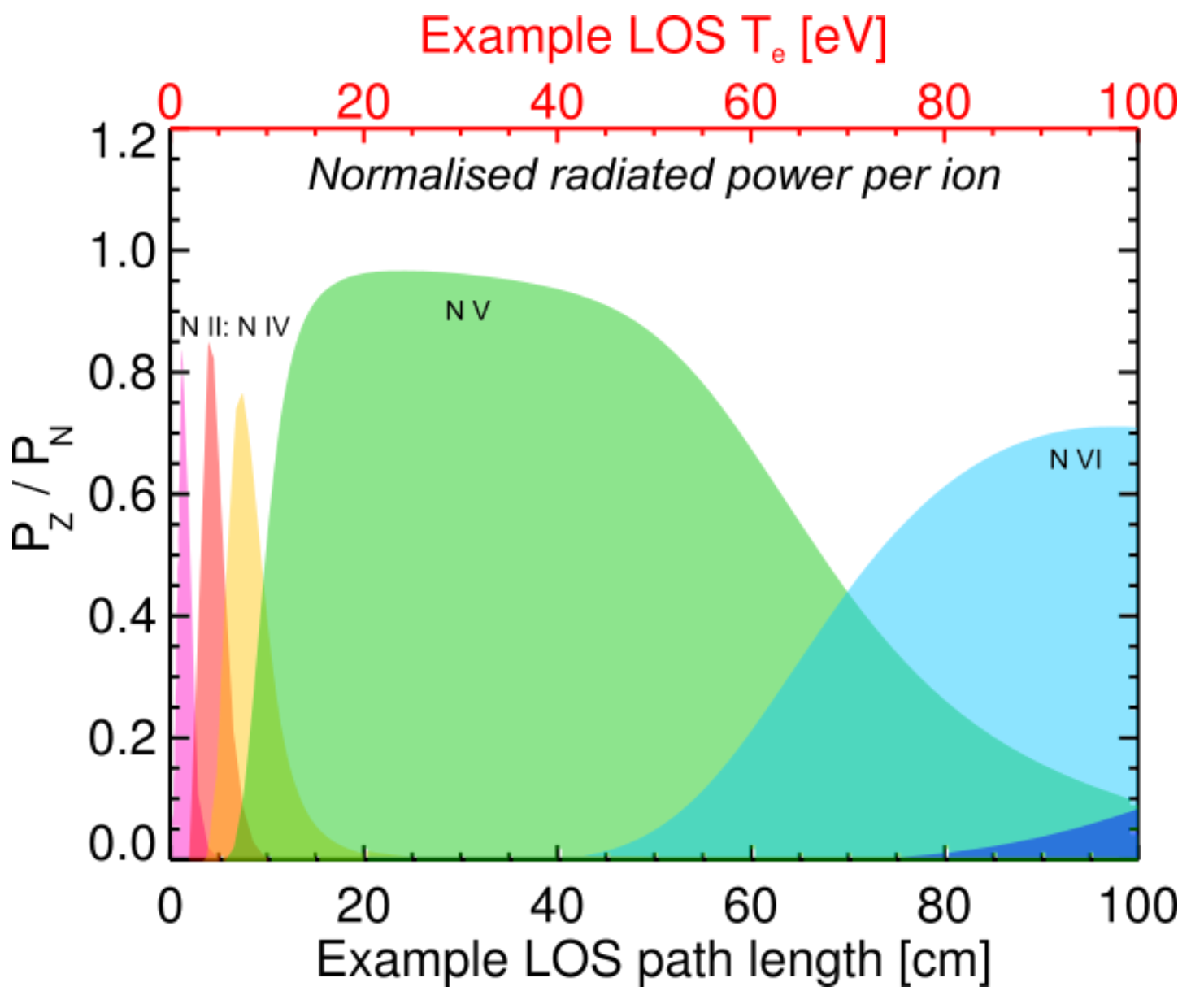


FIG. 1. Example distribution of N radiated power

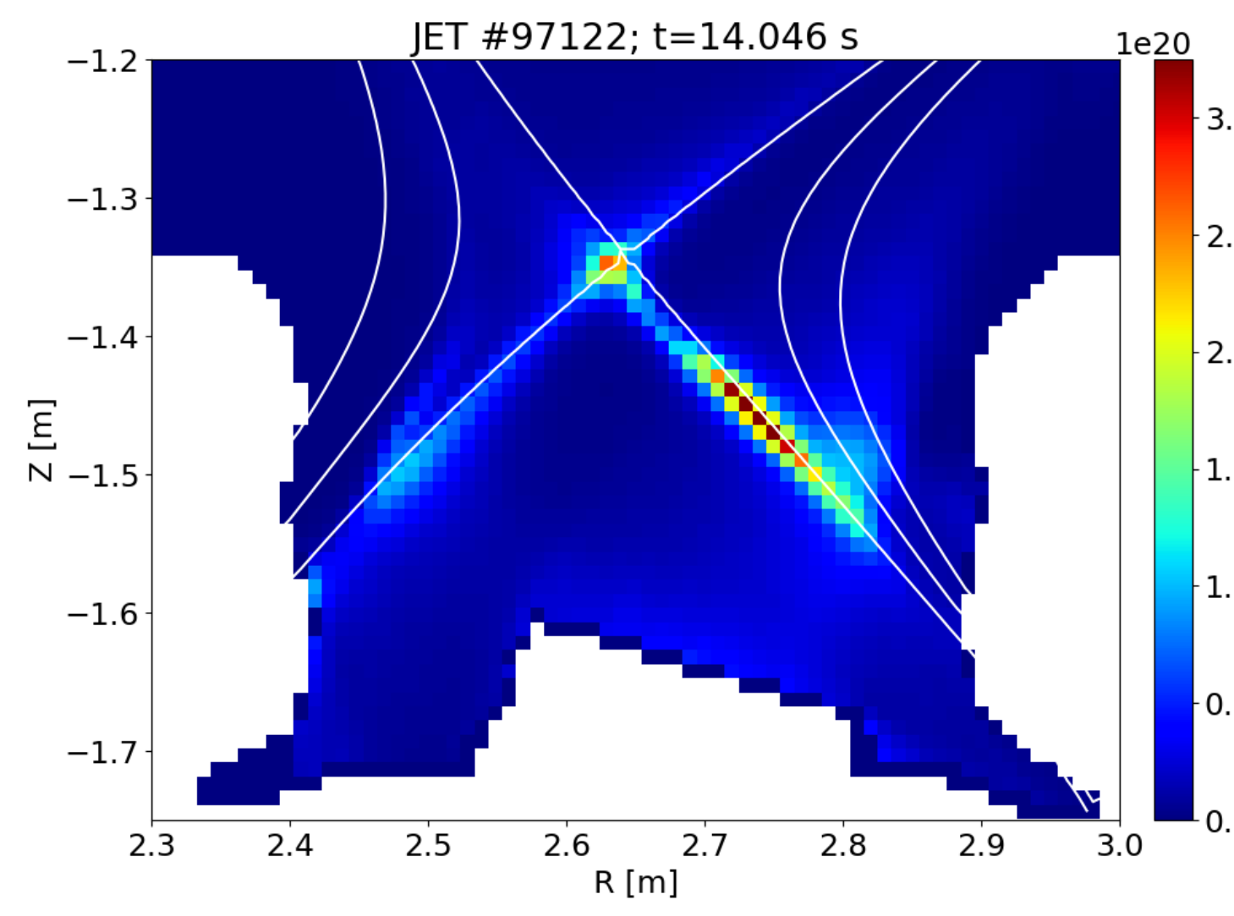


FIG. 2. Inverted camera image of N II emission

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

$$c_I = \frac{\overset{\text{Ion emission}}{4\pi \int \varepsilon_{I,Z} dl}}{\underset{\text{Atomic coefficient}}{TEC_{I,Z}}} \frac{1}{\underset{\text{Length of emission}}{\Delta L n_e^2}}$$

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

	# 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

CONCLUSIONS

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

MACHINE SIZE SCALING

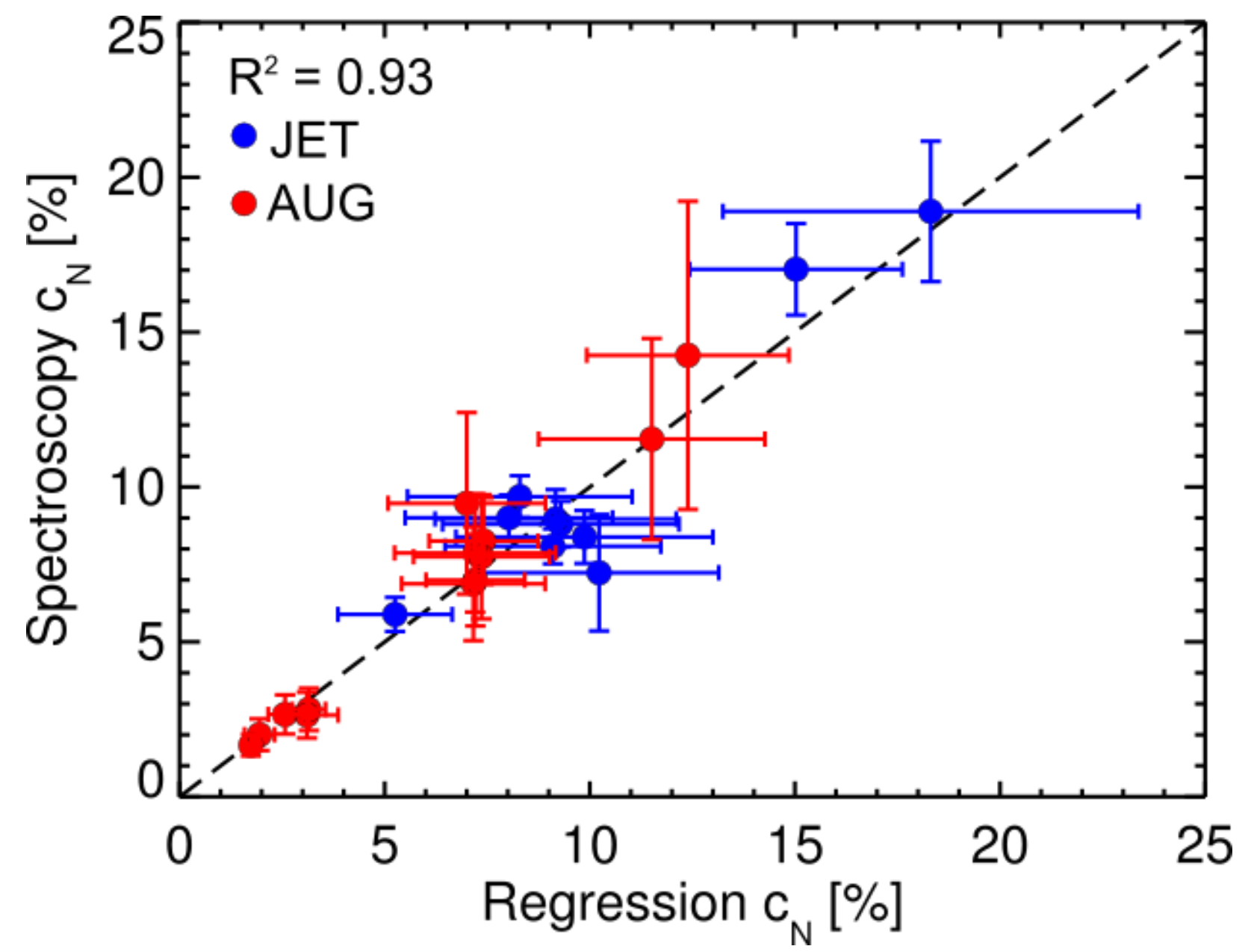


FIG. 3. The result of the least squares regression analysis of the database of c_N measurements.

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 $c_N \propto I_P a_{min}^{-3}$

IMPURITY SPECIES SCALING

DETACHMENT EXPERIMENTS

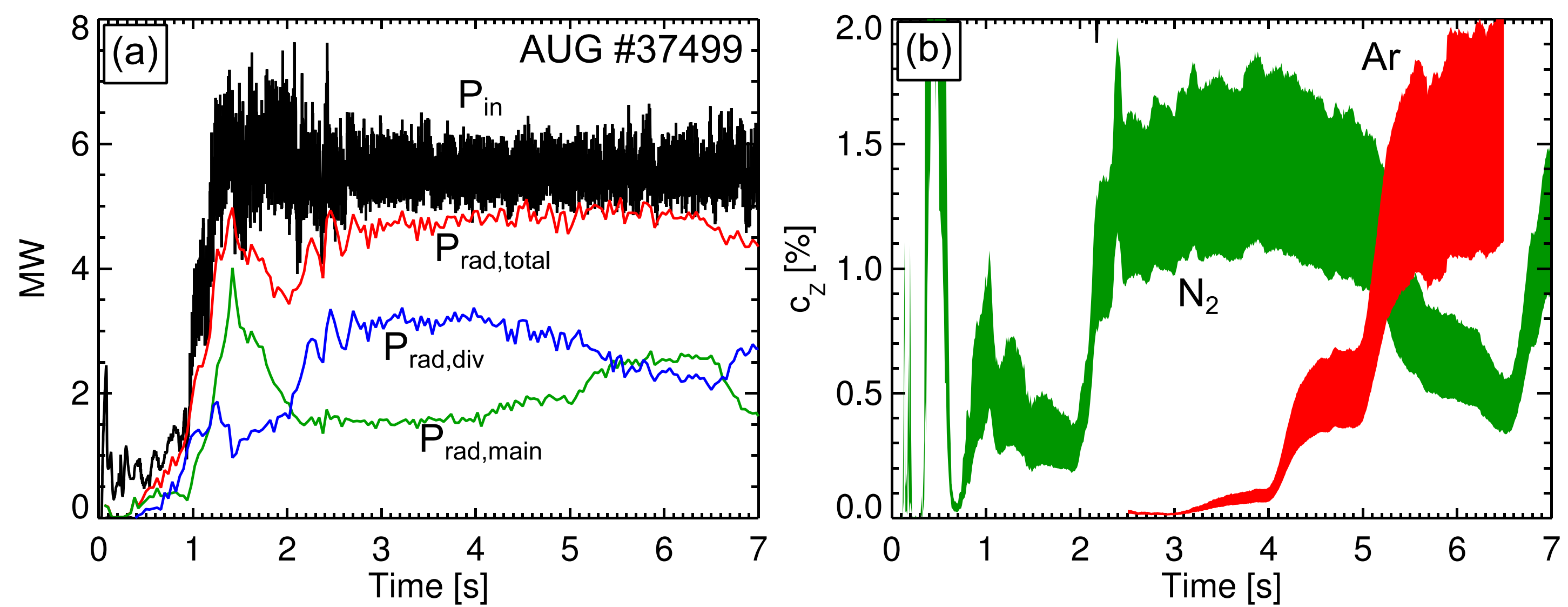


FIG. 4. The total heating power and radiated power from AUG #37499 is shown in (a). The c_N and c_{Ar} measurements for the shot are given in (b).

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**

ENRICHMENT MEASUREMENTS

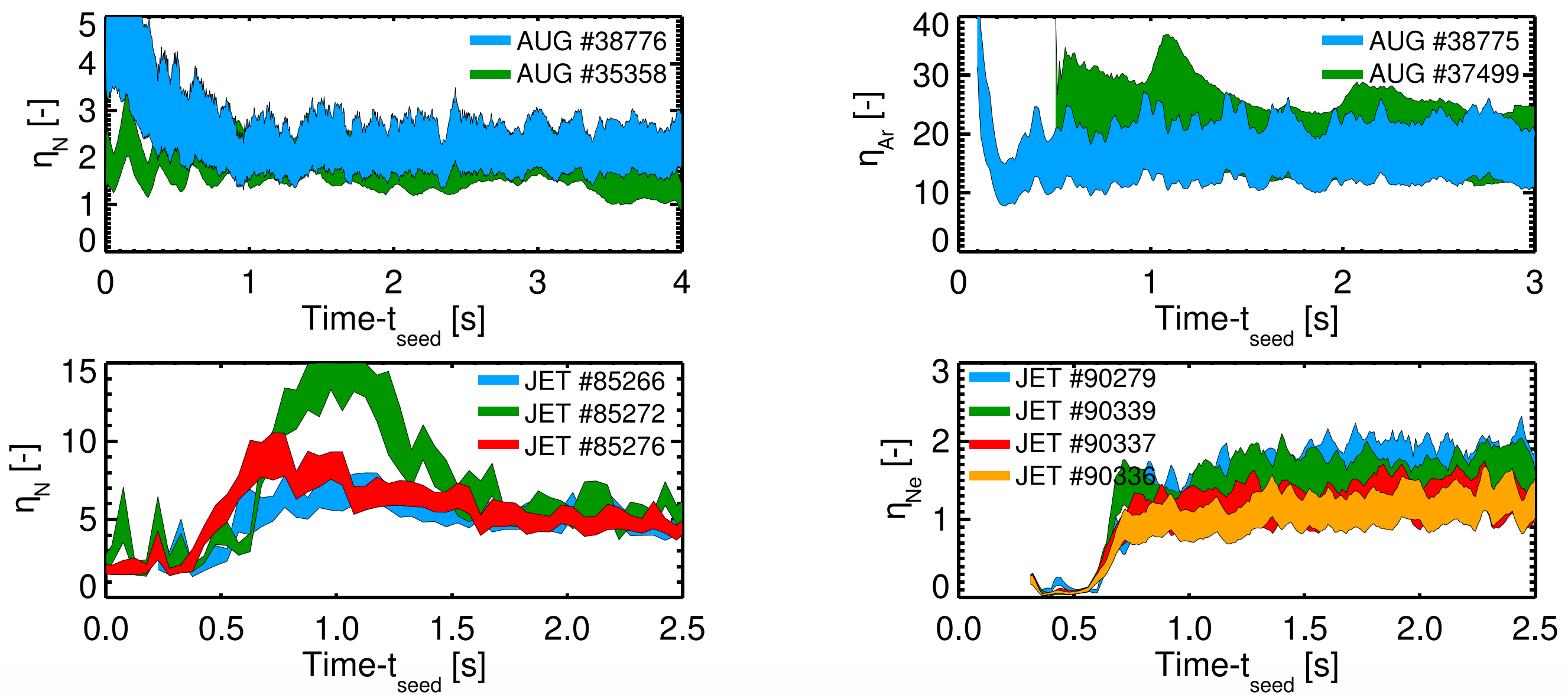


FIG. 5. The impurity concentrations in the divertor are shown in the top panels, the core concentrations from CXRS are shown in the middle panels, and the corresponding enrichment factors are shown in the bottom panels.

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 $\eta_{Ar} \sim 10 - 20$

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

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