EUROfusion

Experimental studies of the nitrogen concentration required for divertor detachment in ASDEX Upgrade

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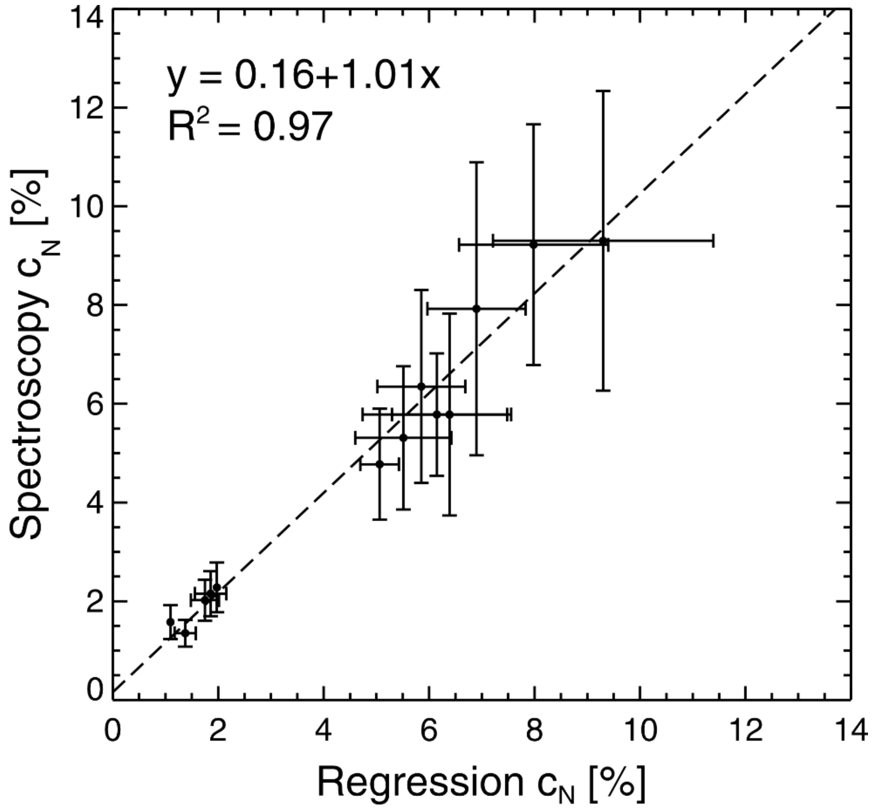
Talk preview

This talk will describe how we obtain the following scaling law for detachment from experimental measurements, how it compares to a simple model of impurity cooling, and what we should consider for future tokamaks

$$\boldsymbol{c_N = 5.92\, P_{sep}^{0.999\pm0.35}\; I_p^{1.04\pm0.66}\; n_{e,sep}^{-2.63\pm0.63} \times \left(1+\kappa^2\right)^{-1} a^{-3}}$$



Introduction and motivation

Recent derivations, based on Lengyel's work[1], have attempted to predict the concentration of impurity required to reach detached conditions in future tokamaks

[2] Goldston $c_Z \propto {}^{P_{sep}}\!\big/_{B_p(1+\kappa^2)^{1.5} f^2_{GW,sep}}$ ⇨ focus on upstream density

[3] Reinke $c_Z \propto B_T^{0.88} R^{1.33}$ ⇨ focus on machine size scaling

[4] Kallenbach $c_Z \propto {}^{P_{sep}/R}\!\big/_{p_{div}\lambda_{int}R^{rz}}$ ⇨ focus on momentum and energy loss

However, direct measurements of the impurity concentration in the divertor are difficult to make and therefore currently there are no experimental studies to validate these scaling laws to guide expectations for ITER and DEMO

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[1] Lengyel L L 1981 Analysis of radiating plasma boundary layers IPP Report1/191

[2] R J Goldston et al 2017 Plasma Phys. Control. Fusion **59** 055015

[3] M.L. Reinke 2017 Nucl. Fusion **57** 034004

[4] A Kallenbach et al 2016 Plasma Phys. Control. Fusion **58** 045013

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Experimental measurements

Residual gas analyser

- c_N inferred from ammonia
- ***Not discussed in this talk***

A. Drenik et al 2019 Nucl. Fusion **59** 046010

Fractional impurity influx

- c_N inferred from valve fluxes
- Neglects wall sticking/release
- Average SOL measurement
- **Measurement widely available**

Kallenbach *et al.* 2019 NME **18** 166

Spectroscopy

- c_N inferred from line emission
- Transient/steady state
- Spatially resolved
- ✓ ***Focus of this talk…***

Henderson et al 2018 Nucl. Fusion **58** 016047

This talk focuses on a new spectroscopic technique for measuring the divertor nitrogen concentration

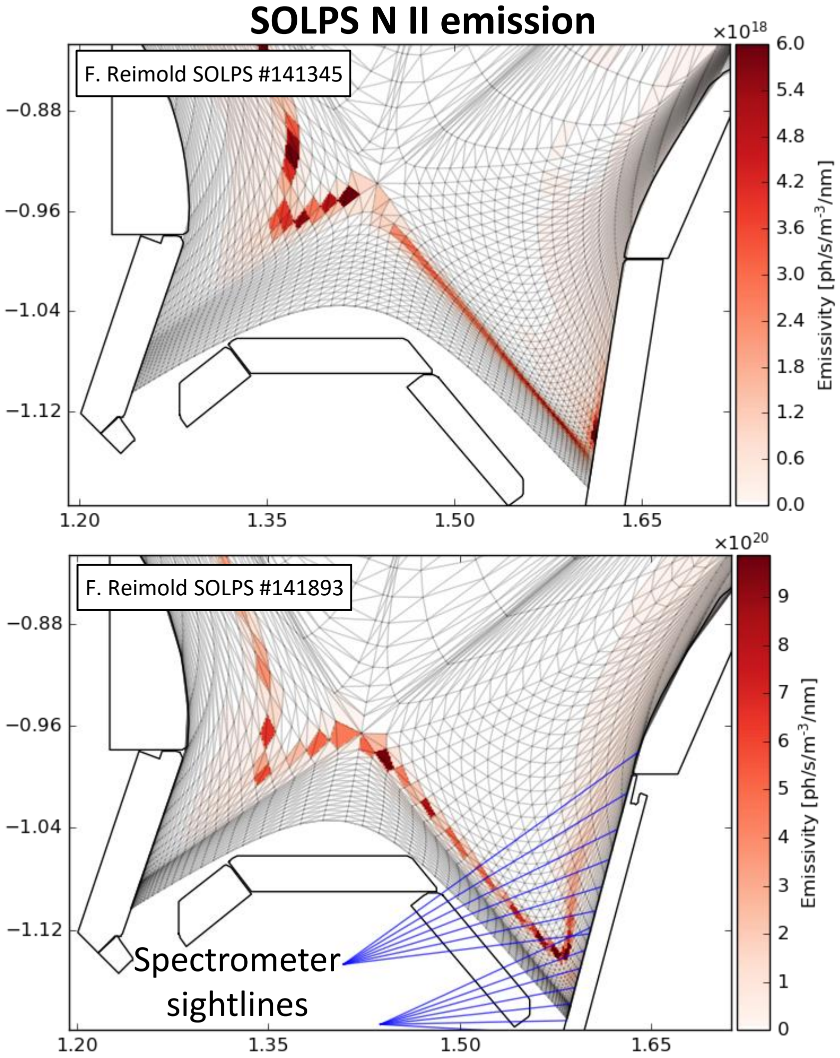
Nitrogen spectroscopy in the divertor

The nitrogen concentration in the divertor is calculated using N II line emission

Hot

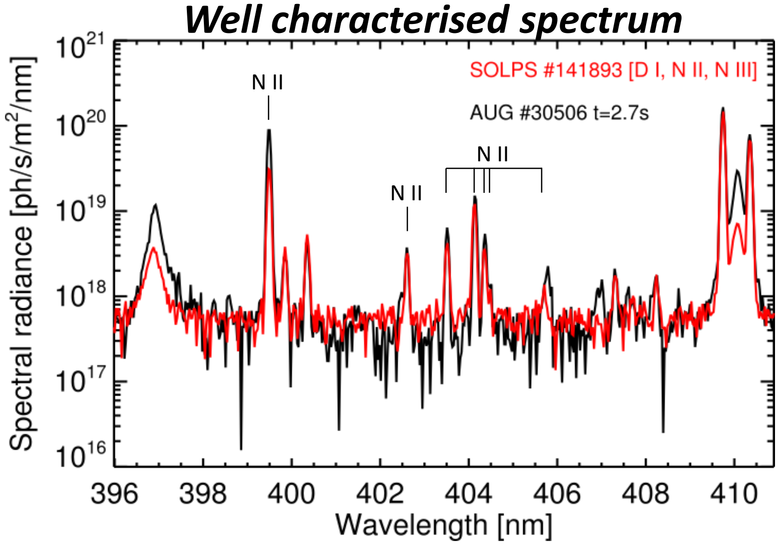
Divertor temperature

Cold



SOLPS N II emission

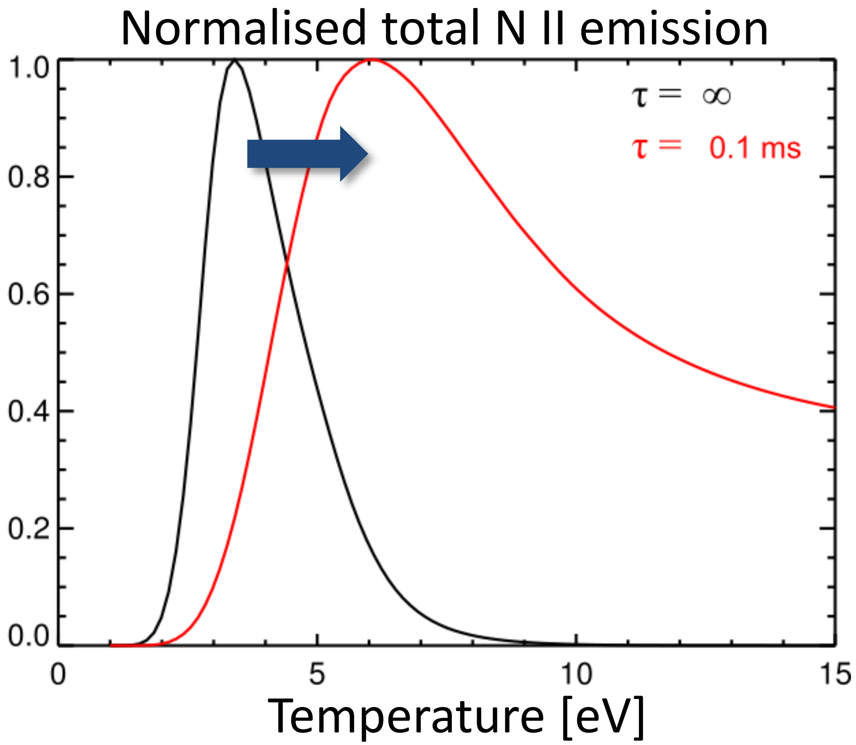
N II emits in a narrow, localised band in the PFR which spreads into the SOL as the divertor temperature cools



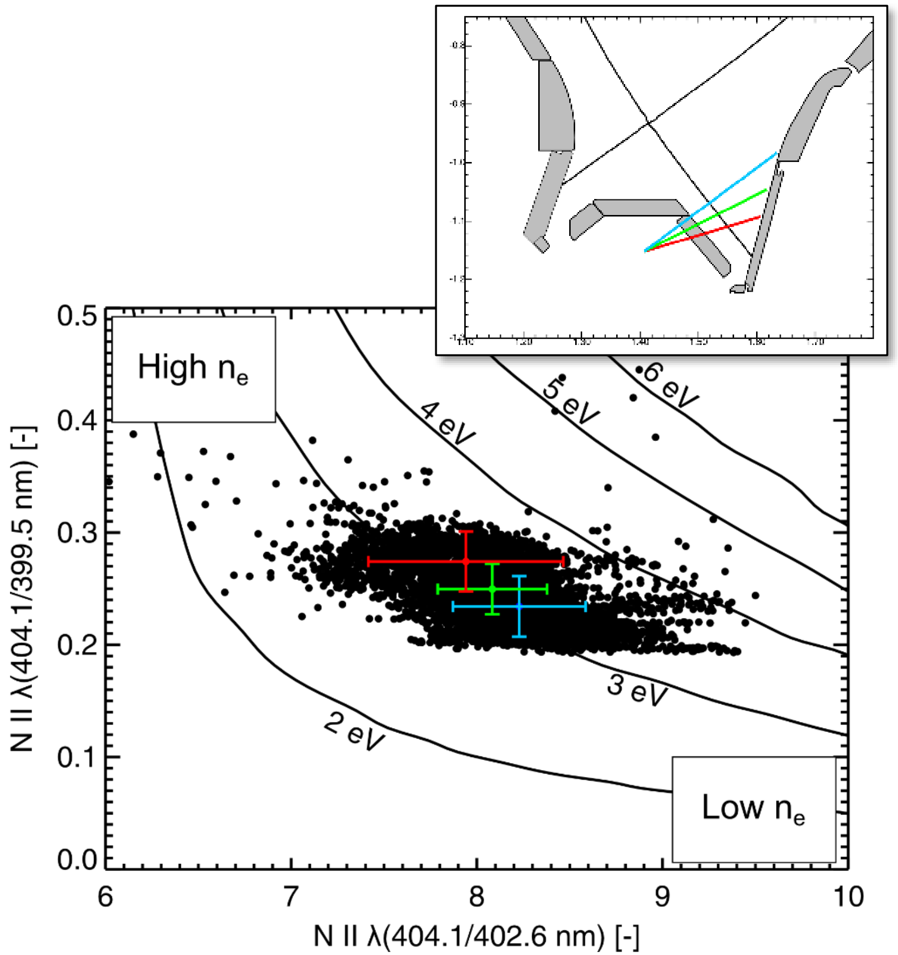
Well characterised spectrum

Line ratios provide measurements of n_e and T_e in the emitting region

Impact of plasma transport



If transport is significant, then the N II emission could be shifted to hotter temperatures [1] *and compromise the concentration measurement*



Experimental line ratios typically indicate T_e=3 – 4 eV suggesting ***transport effects are negligible*** *for this particular emission region (e.g. N II PFR)*

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[1] P G Carolan and V A Piotrowicz 1983 *Plasma Phys.* **25** 1065

Divertor detachment state

The extent of N II emission through a sightline, which is proportional to the nitrogen concentration, is also dependent on the divertor detachment state

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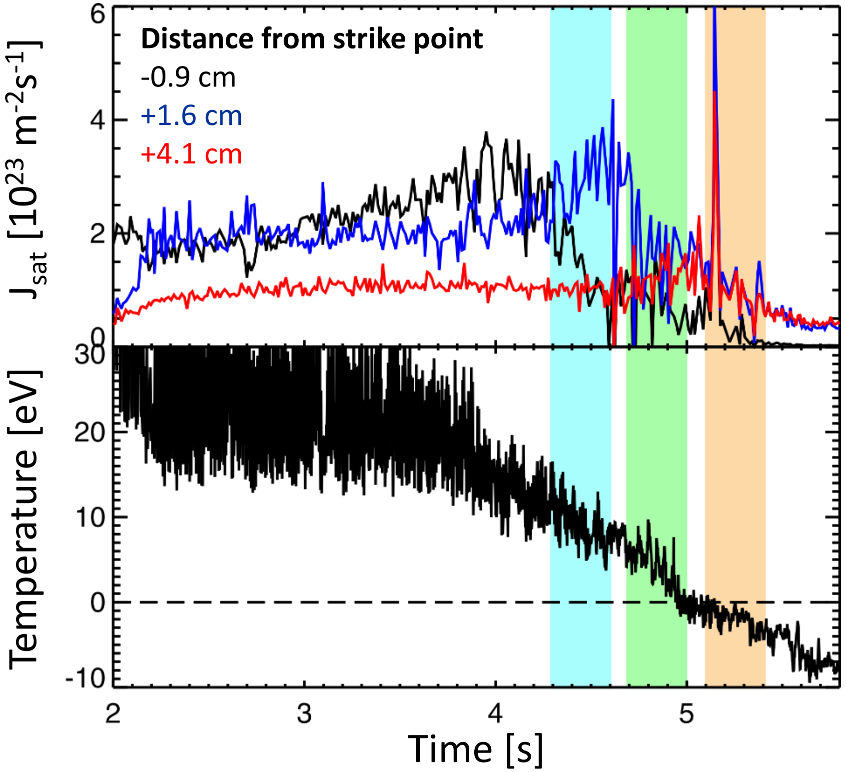
In this analysis, the real-time estimate of the outer divertor temperature, derived from shunt measurements, is used as a proxy for describing the detachment state [1]



Onset detachment Tdiv = 5-10 eV

Partial detachment Tdiv = 0-5 eV

Full detachment Tdiv < 0 eV

[1] A. Kallenbach *et al* 2015 *Nucl. Fusion* **55** 053026

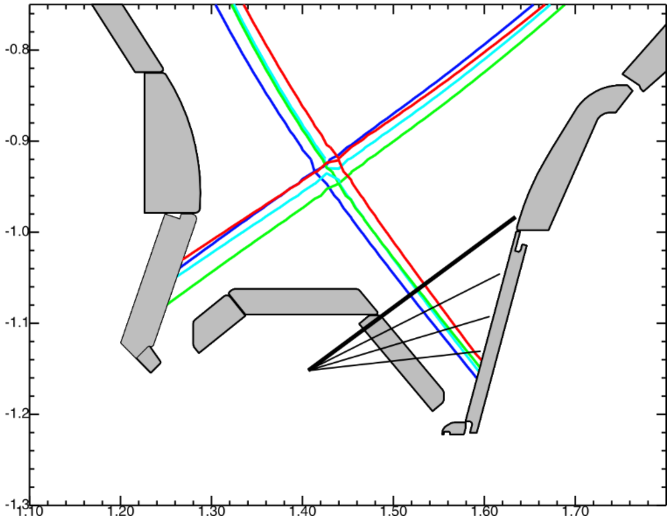
Deriving the nitrogen concentration

Measured intensity

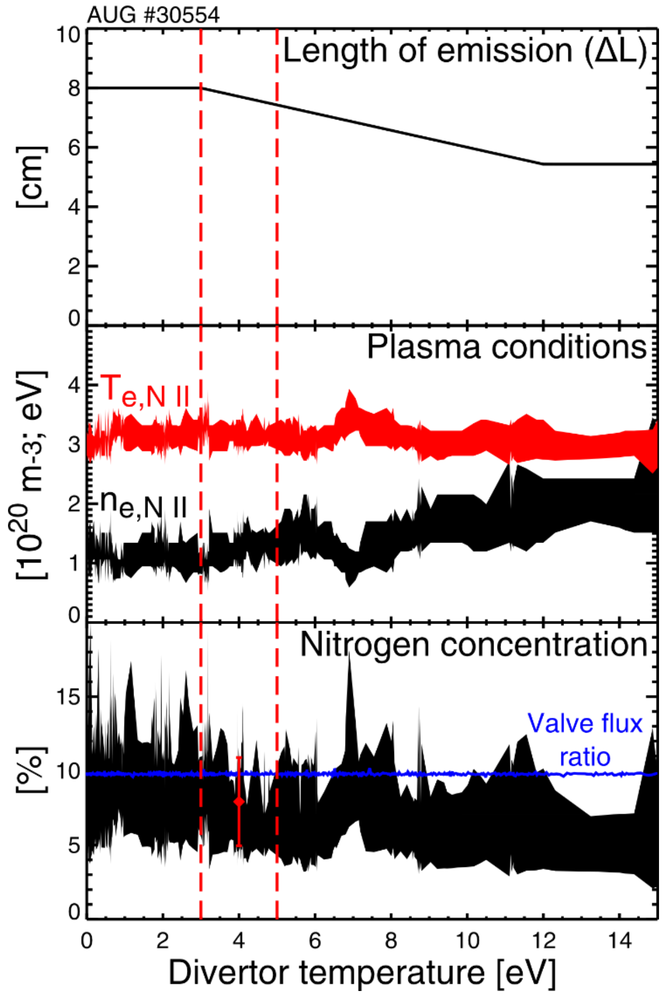
$$c_N = \frac{4\pi I_{NII}}{(f_{N^+} PEC^{exc} + f_{N^{2+}} PEC^{rec})} \frac{1}{\Delta L n_{e,NII}^2}$$

Fractional ion abundance and emission coefficients

Path length of emission



The intensity measured in the **highlighted sightline** is mostly immune to strike-point position and provides signal in detached conditions



The concentration for detachment is defined as the average between **3-5 eV**

Database studies

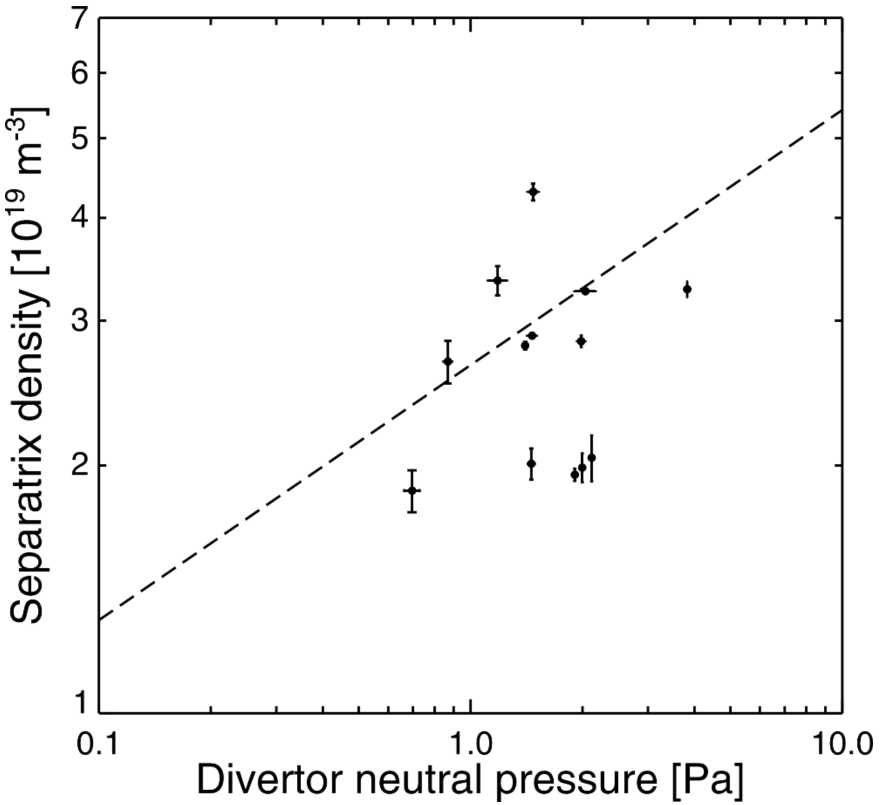
The database requires N-seeded H-mode discharges with a ramp of divertor temperature in steady conditions (e.g. power, fuelling, stored energy)

Database spans the following parameters:

$$\begin{aligned} n_{e,core} &= 7.00 - 10 \times 10^{19} m^{-3} \\ n_{e,sep} &= 1.80 - 4 \times 10^{19} m^{-3} \\ P_{sep} &= 1.50 - 5\ MW \\ I_p &= 0.83 - 1.2\ MA \\ \kappa &= 1.68 - 1.75 \\ a &= 0.49 - 0.51 \end{aligned}$$

Reasonable agreement with scaling law [1]

$$n_{e,sep} = 2.65 p_{div}^{0.31}$$



[1] A Kallenbach *et al* 2018 *Plasma Phys. Control. Fusion* **60** 045006

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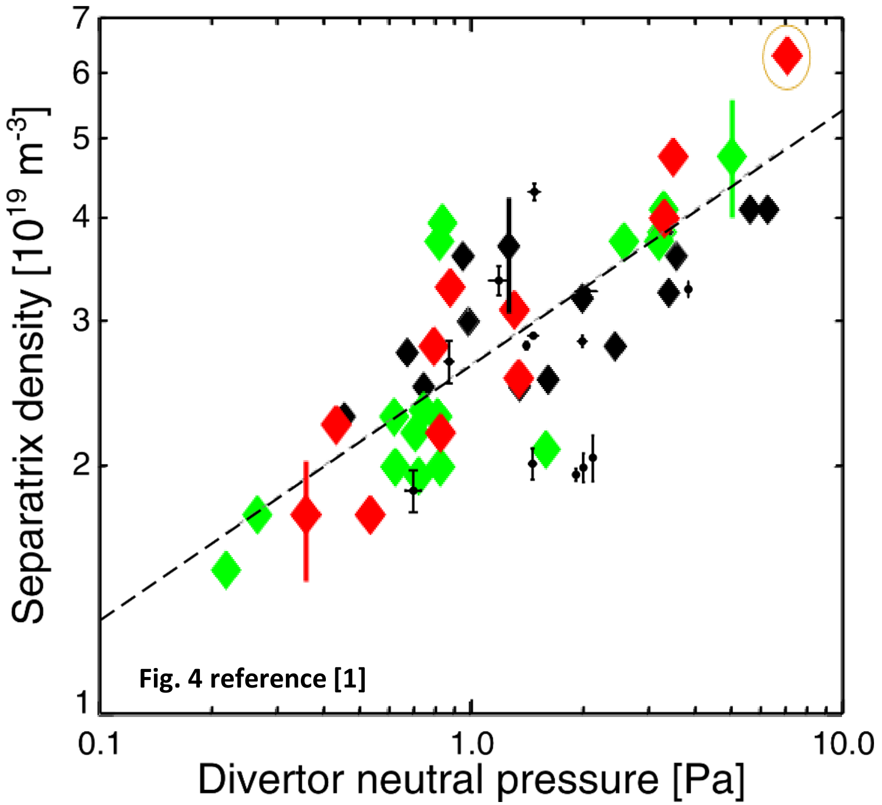


Fig. 4 reference [1]

[1] A Kallenbach *et al* 2018 *Plasma Phys. Control. Fusion* **60** 045006

Comparison with valve flux estimation

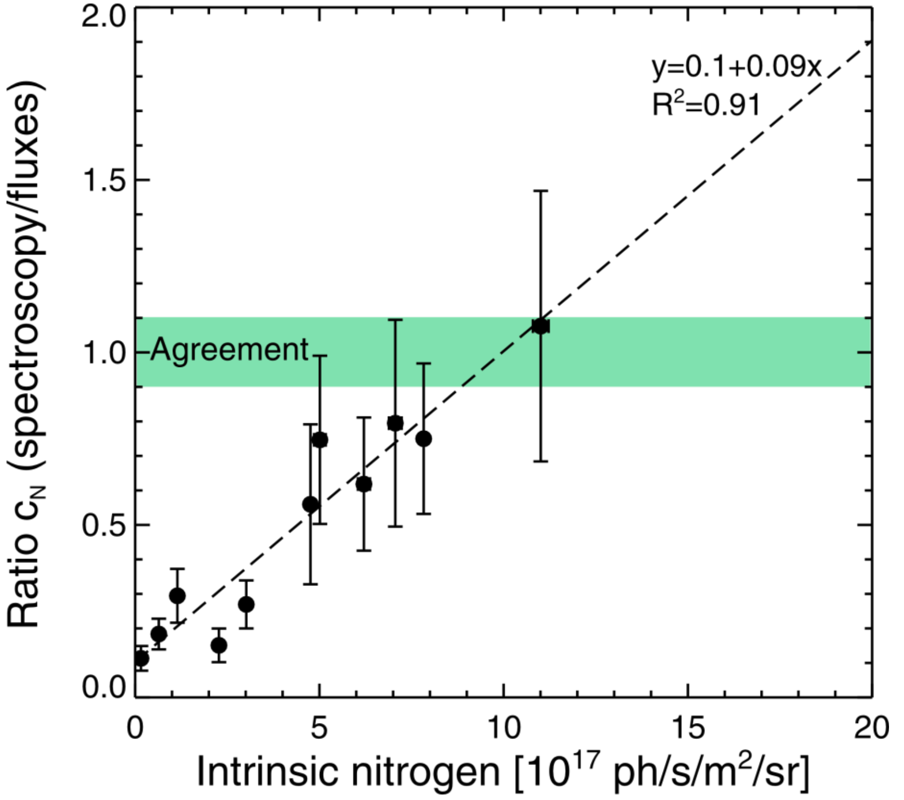
In steady state conditions, the gas valve fluxes can provide an estimate of c_N if the wall sticking/release is negligible and the D and N pumping speeds are equal

The ratio of valve fluxes is defined as:

$$\boldsymbol{c_N} = {}^{\boldsymbol{\Gamma_N}}\!/_{\boldsymbol{\Gamma_D+\Gamma_N}} \; [1]$$

If D & N are pumped equally then it is useful to compare c_N from flux ratios and spectroscopy in the database of shots

Agreement with spectroscopy is mostly dependent on the intrinsic nitrogen content before seeding which is linked to the wall loading of vessel surfaces



[1] A Kallenbach *et al* 2016 *Plasma Phys. Control. Fusion* **58** 045013

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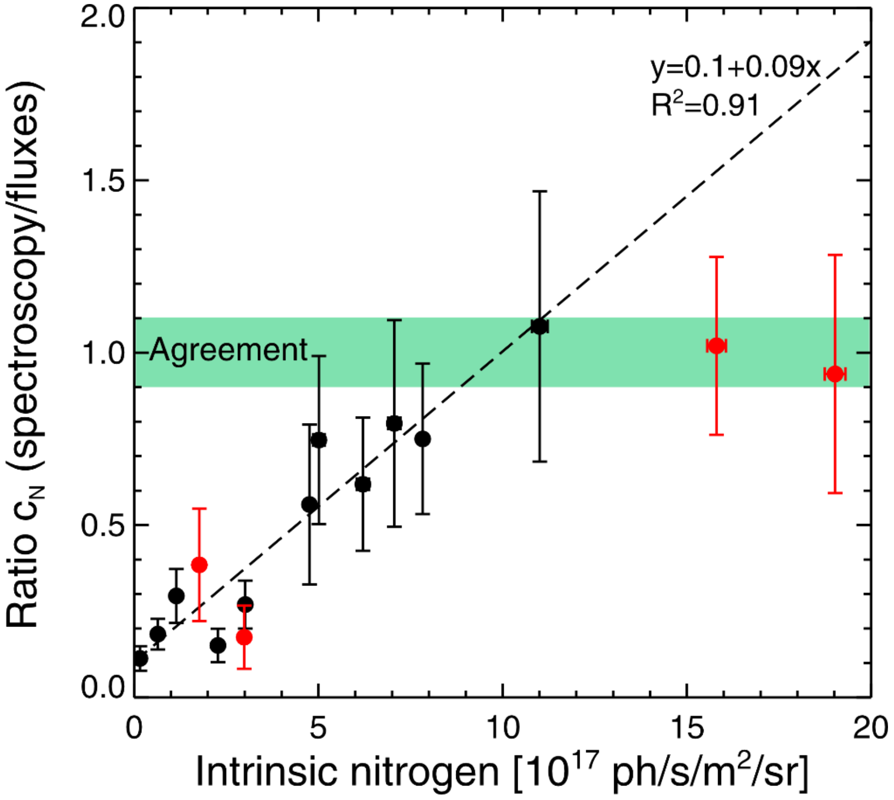
Including shots with changing input power shows agreement of the two measurements at higher levels of intrinsic nitrogen



[1] A Kallenbach *et al* 2016 *Plasma Phys. Control. Fusion* **58** 045013

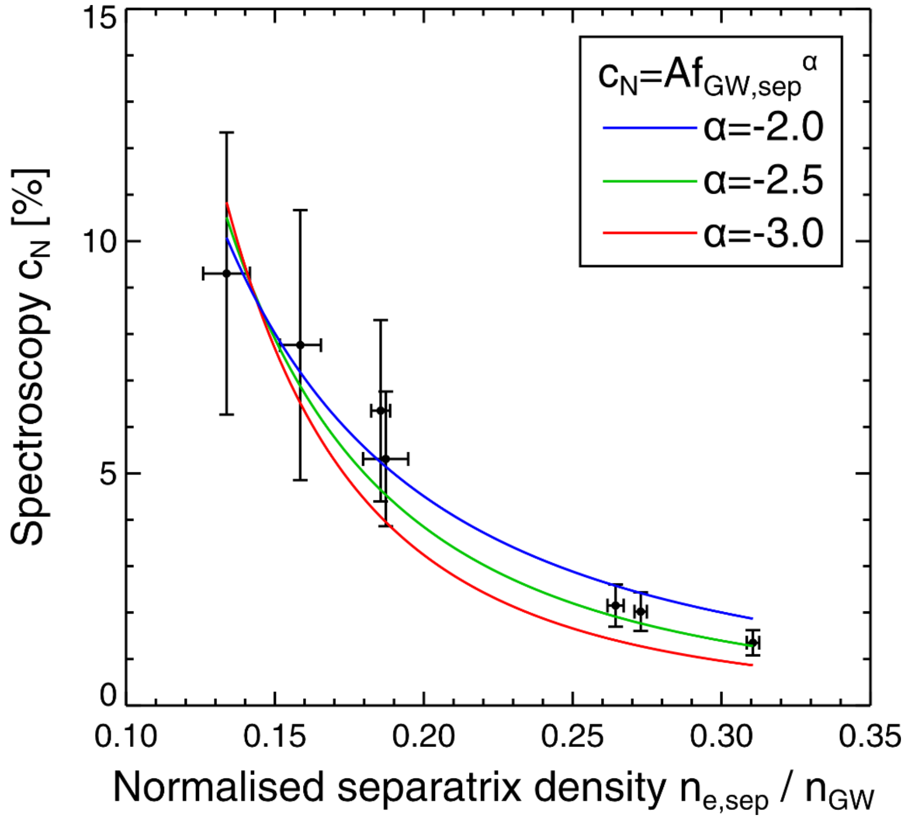
Scaling with separatrix density

Goldston's scaling law predicts that the impurity concentration should scale inversely with the square of the normalised separatrix density

By selecting points from the database at reasonably constant P_{sep}, the trend with normalised separatrix density is assessed

The results suggest that there may be a moderately stronger dependence on the normalised separatrix density than suggested by Goldston's scaling law

A stronger dependence on $n_{e,sep}$ is also found from a database of ITER baseline SOLPS simulations with Ne seeding [1]



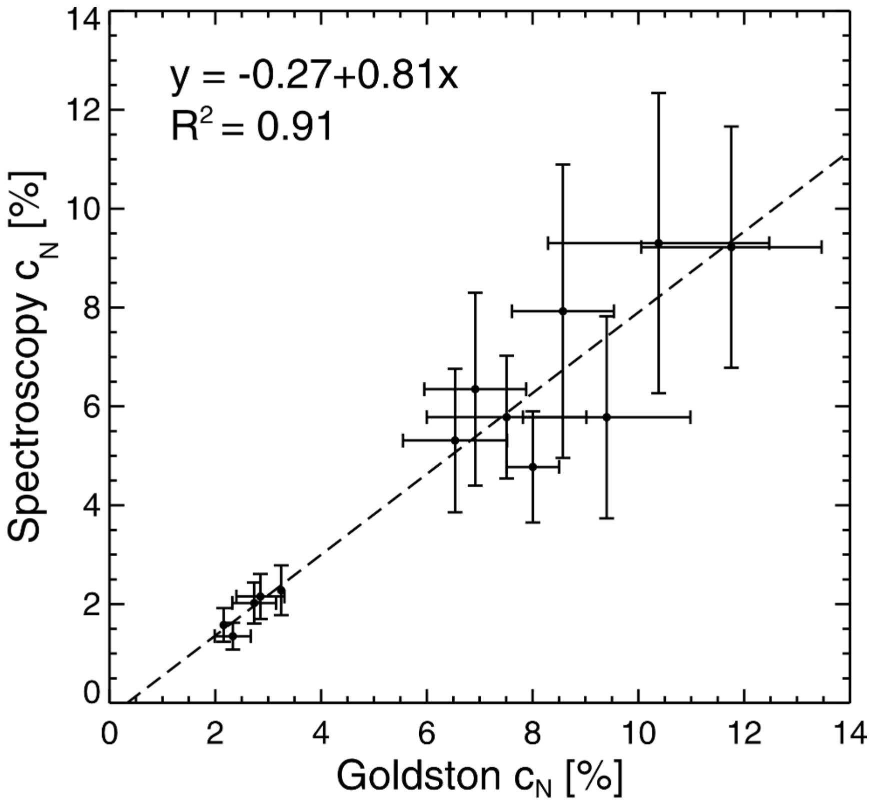
[1] Pitts et al 2019 Nucl. Mater. Energy **20** 100696

Comparison with scaling laws

Goldston's scaling law is proportional to $c_Z \propto {}^{P_{sep}}/_{B_p(1+\kappa^2)^{1.5} f_{GW,sep}^2}$

The absolute magnitude of the scaling law is found by normalising the result to the conditions of a simulation described by Kallenbach et al (2016)

Despite the offset in the absolute experimental concentration, the trends with P_{sep} and $f_{GW,sep}$ are reasonably well reproduced by Goldston's scaling law



Regression analysis

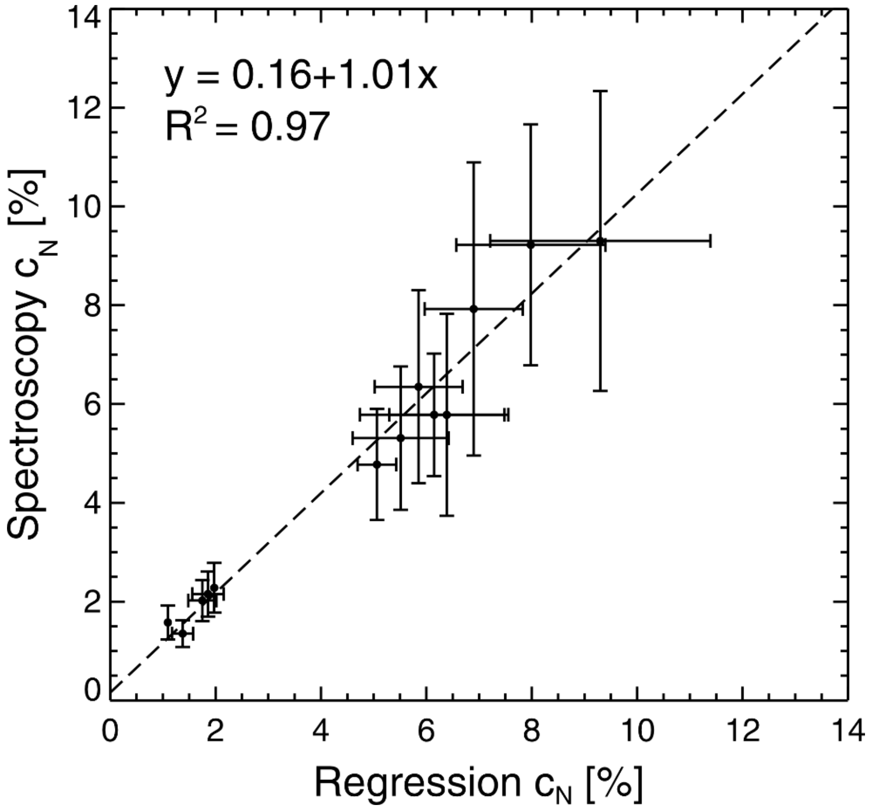
A regression analysis has been performed on P_{sep}, $n_{e,sep}$ and I_p to compare against Goldston's scaling law

Re-writing Goldston's scaling in terms of I_p i.e.
$\langle B_p \rangle \propto {}^{I_p}/_{a(1+\kappa^2)^{0.5}}$ and $n_{GW} \propto {}^{I_p}/_{a^2}$

gives $\boldsymbol{c_Z \propto {}^{P_{sep}I_p}/_{n_{e,sep}^2(1+\kappa^2)a^3}}$

regression of $P_{sep}\ [MW], n_{e,sep}\ [10^{19} m^{-3}]$ and $I_p\ [MA]$ gives

$$\boldsymbol{C_N = 5.92\, P_{sep}^{0.999\pm0.35}\ I_p^{1.04\pm0.66}\ n_{e,sep}^{-2.63\pm0.63} \times \left(1+\kappa^2\right)^{-1} a^{-3}}$$



Summary and where to next

Main conclusion

Future fusion reactors depend on divertor detachment to limit the heat flux to the plasma facing components. This work provides experimental evidence from one device that the impurity concentration needed to reach detachment scales dominantly with $P_{sep} I_p n_{e,sep}^{-2.6}$; a result in reasonable agreement with a simple model for impurity cooling

Future experiments to address key points for DEMO

- comparison of measurements from another device would assess machine size scaling

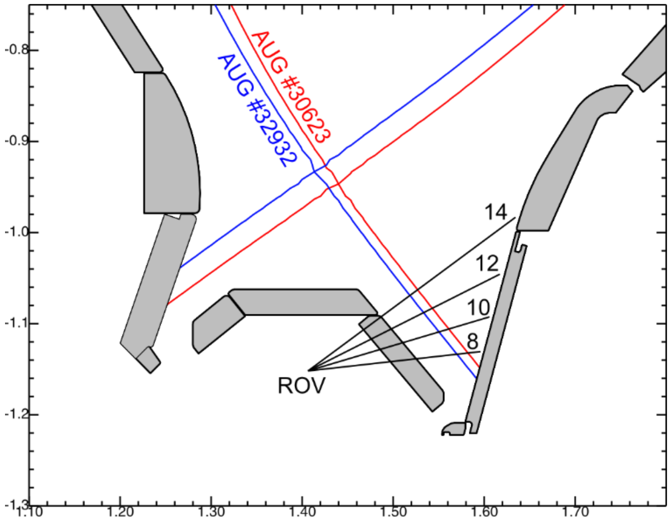
- what role does divertor geometry play, e.g. enrichment/compression?

- in different geometries, do these trends still hold?

- the atomic data and lines exist to perform this analysis on Ne

Appendix

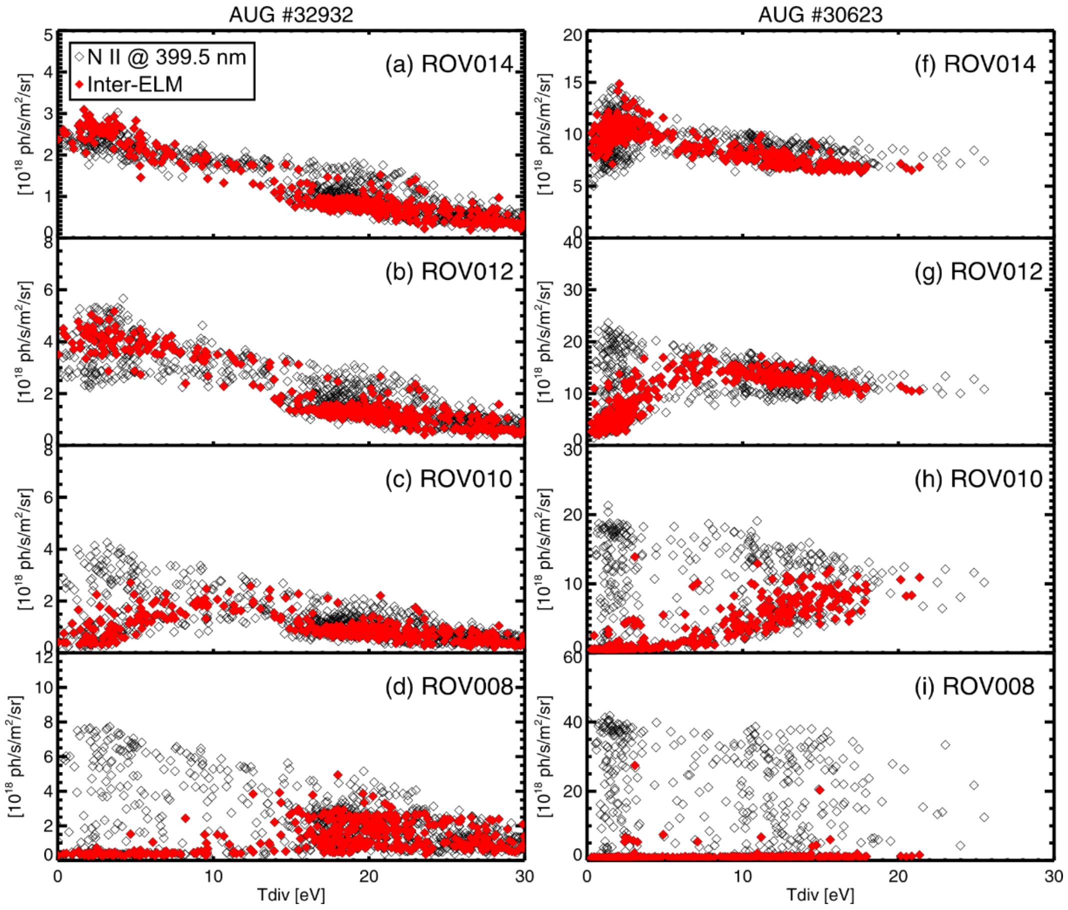
The extent of N II emission through a sightline is dependent on both the divertor detachment state and the strike-point position



Geometry of separatrix with respect to sightline and front location can alter the path length of the emission

Low strike point

High strike point



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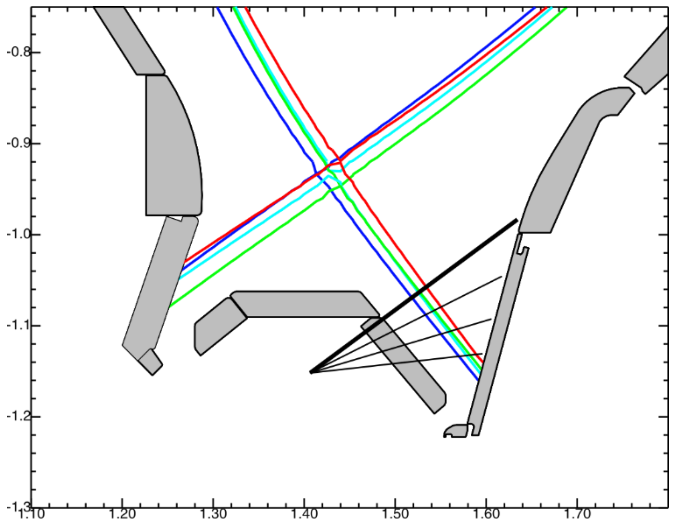
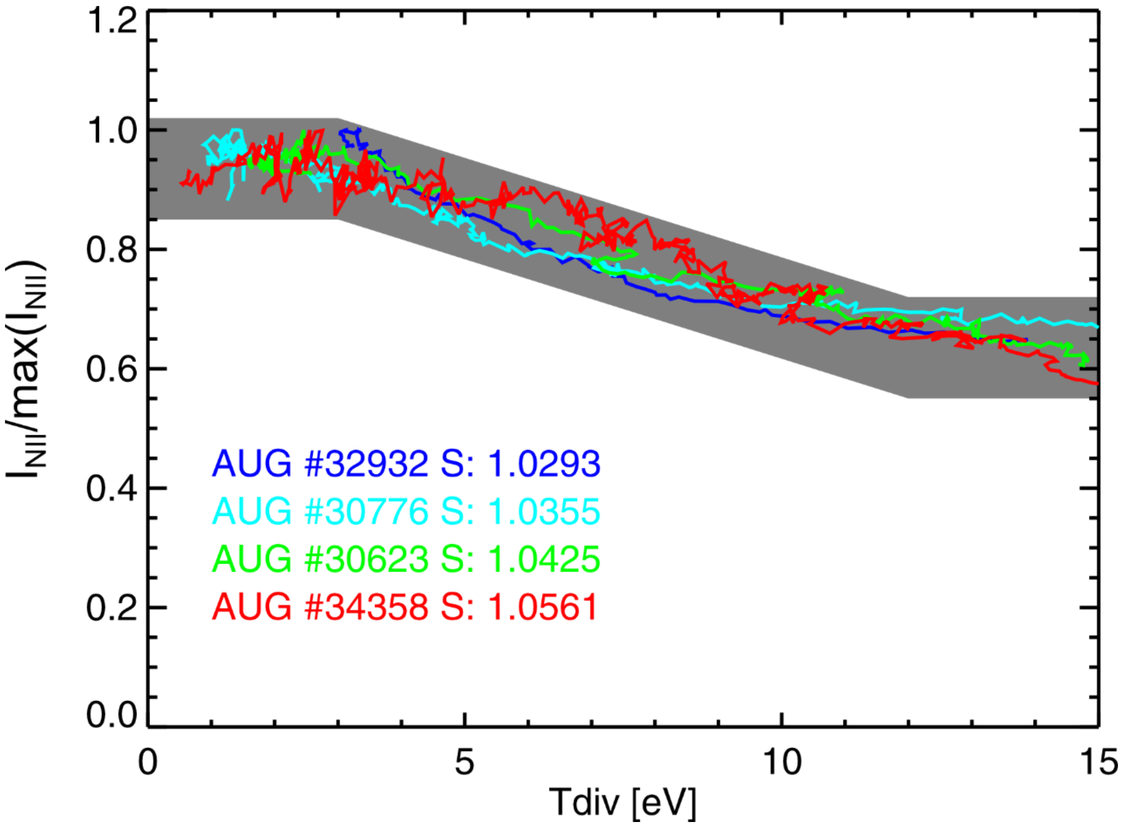


Sightline **ROV014** is relatively immune to strike-point position and provides reasonable signal down to partially detached conditions



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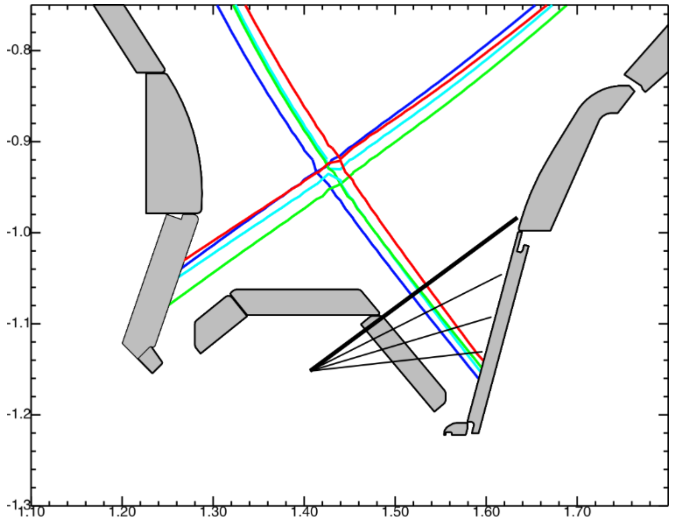

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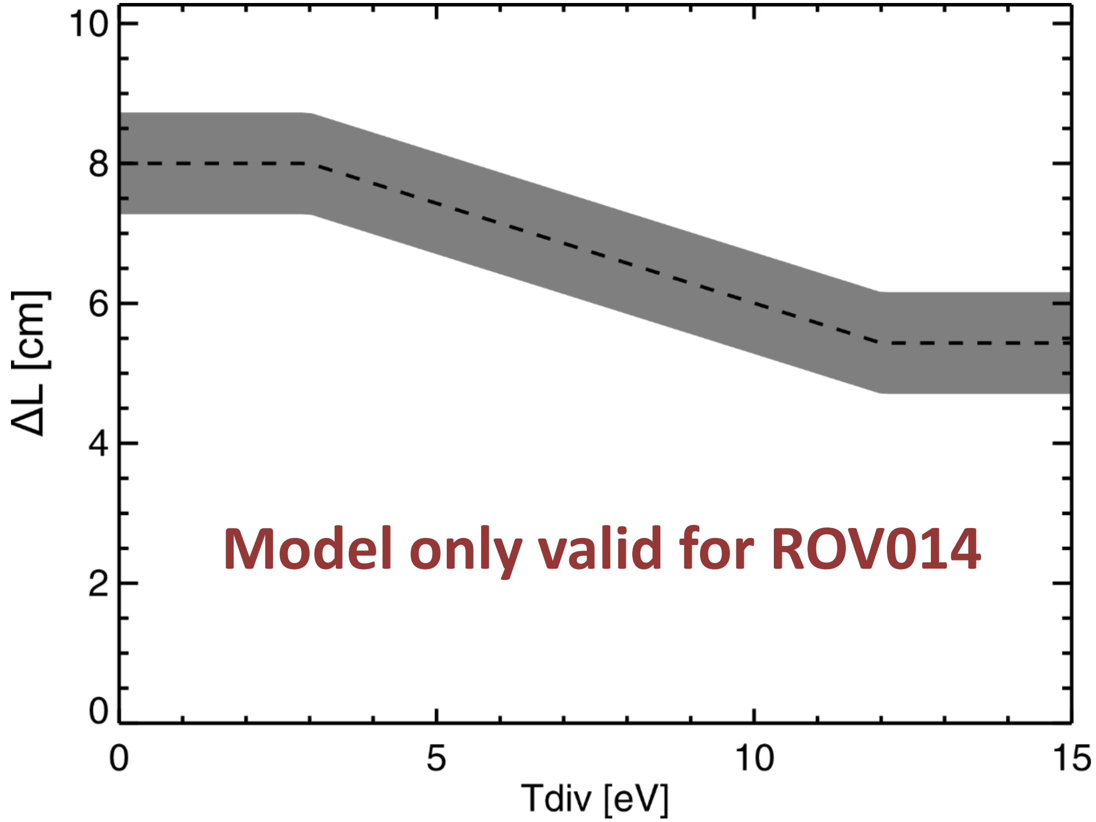

Model only valid for ROV014

Appendix

Nitrogen line ratio