Divertor detachment and re-attachment studies with mixed impurity seeding on ASDEX Upgrade

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This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Overview

Topic I: Ar and Ne radiation efficiency

Detachment qualifier [1]:

$$q_{det} \cong 1.3 \frac{P_{up}}{R_0}\left(\left(1+\sum_Z f_Z c_Z\right) p_{div}\right)^{-1}$$

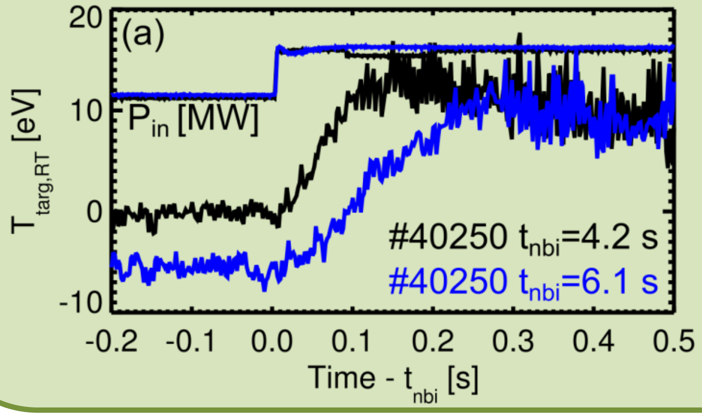
where f_Z is the SOL radiation efficiency.

$f_N = 18$ *tested experimentally*
$f_{Ne} = 45$ *atomic* $+ n_e\tau \sim 0.5\ 10^{20}\ \mathrm{ms}\cdot\mathrm{m}^{-3}$
$f_{Ar} = 90$ *atomic* $+ n_e\tau \sim 0.5\ 10^{20}\ \mathrm{ms}\cdot\mathrm{m}^{-3}$

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

Topic II: Transient divertor reattachment

Understanding divertor re-attachment time scales during power transients and gas cuts



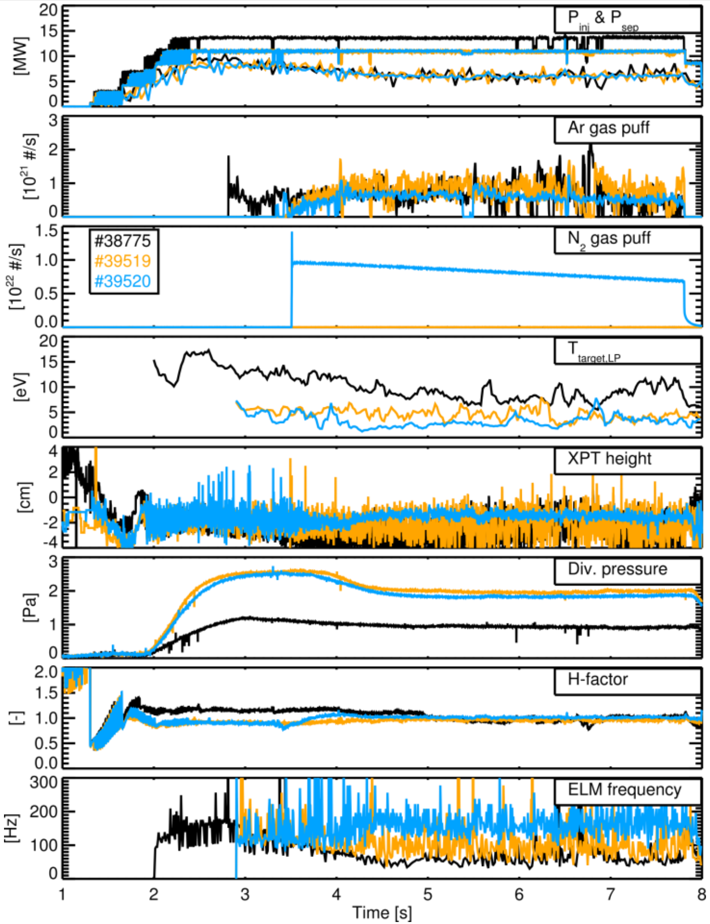
Detachment with N + Ar seeding

Scenario was developed at 1 MA with input power 14 MW

- Ar injected using feedback system controlling core radiation
- N_2 injected using feedforward waveforms
- Assessed Ar-only, N_2-only, and mixed Ar+N_2 seeding
- Low ELM frequency (~50 Hz) with Ar-only

Shots carried out within WP-TE to scan the following parameters

Parameter	Range	Units
Power injected	$11 < P_{inj} < 16.5$	MW
Power crossing separatrix	$5 < P_{sep} < 12$	MW
Divertor pressure	$0.7 < p_0 < 2.5$	Pa



Detachment with Ar-only

Achieving pronounced detachment/XPR with Ar-only seeding proved to be difficult

Similar to experience with Ne-seeding, high levels of Ar seeding (>1.5E21) typically unstable

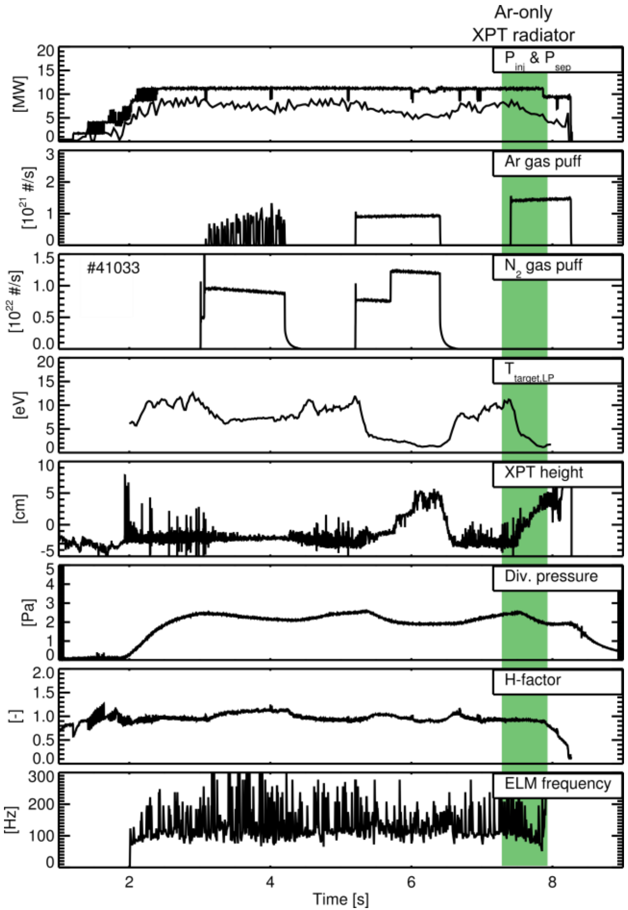
- Loss of ELM frequency
- Core impurity accumulation

Scan of divertor pressure

> 2 Pa
Short phase of XPR achieved

> 1 Pa
Partially detached divertor achieved

< 1 Pa
Divertor remained attached



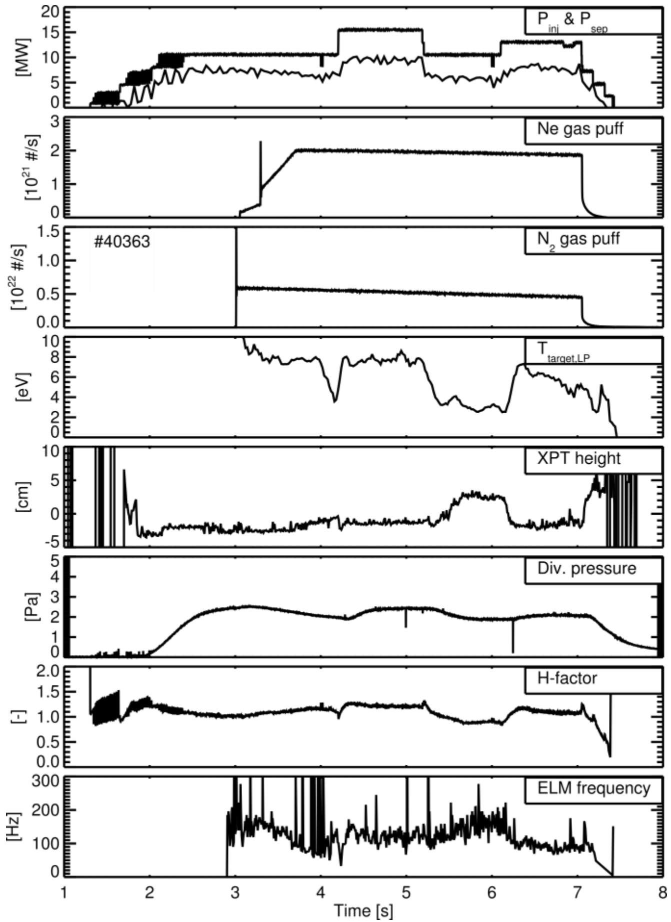
Detachment with N + Ne seeding

Scenario was developed at 1 MA with input power 14 MW

- Ne & N_2 injected using feedforward waveforms
- Contrary to previous AUG experience, detachment achieved (including XPR) with Ne and low level of N_2 puff
- Motivates future AUG scenarios at higher power with mixed N_2+Ne

Shots carried out within WP-TE to scan the following parameters

Parameter	Range	Units
Power injected	$11 < P_{inj} < 16.5$	MW
Power crossing separatrix	$5 < P_{sep} < 12$	MW
Divertor pressure	$1.8 < p_0 < 2.5$	Pa



Detachment with Ne-only

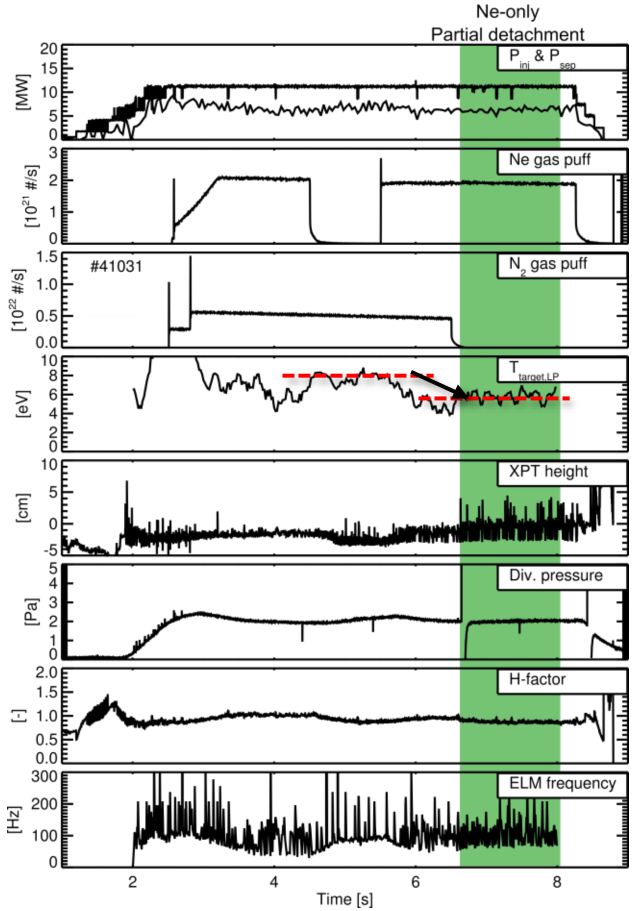
Previous experience on AUG concluded (e.g. #32272, P_{in}=16 MW)

- *Ne puff < 2E21 -> attached*
- *Ne puff > 2E21 -> unstable*

And therefore no detachment possible with Ne seeding

Adding small N_2 puff (c_N<2%) helps to achieve pronounced detachment, likely by keeping up ELM frequency.

Scenario shown has a phase of Ne-only seeding (~2E21) and divertor temperature is lower (partial detachment) than no-seeding



Ne and Ar as SOL radiators

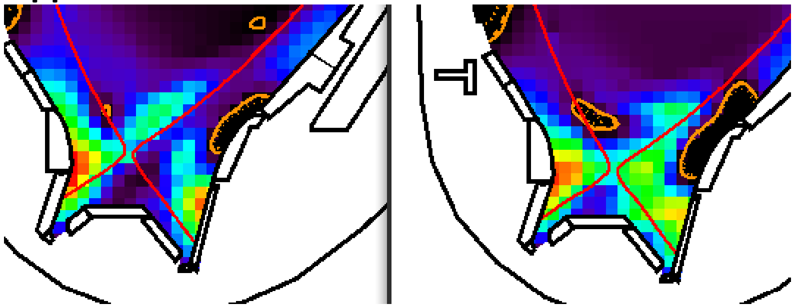
Ne and Ar are more efficient at radiating in the SOL than N, but much higher N concentrations can be puffed before degrading core

Therefore it is difficult to measure changes in divertor radiation using bolometry that are induced by Ar or Ne seeding

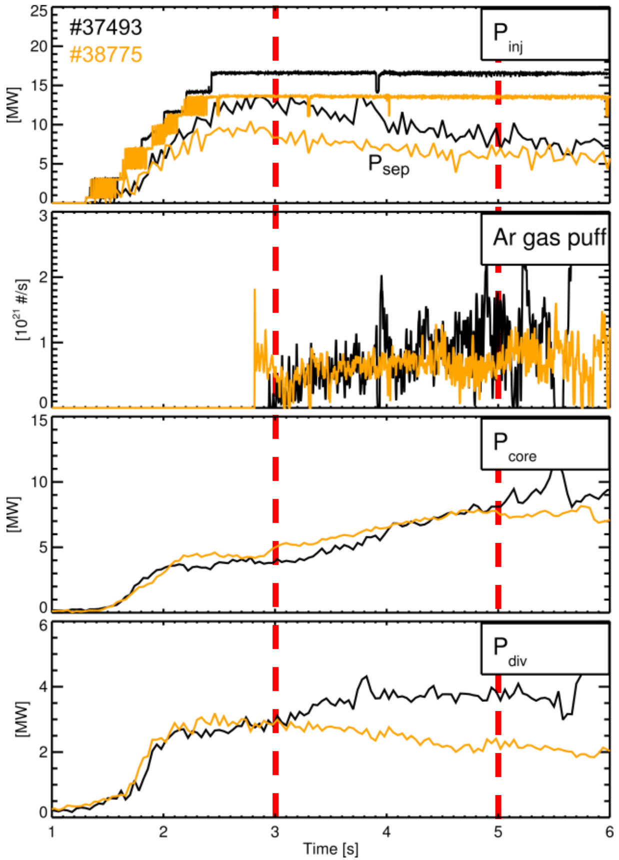
- *Reduction* in divertor radiation is often observed
- Radiation from HFSHD likely dominating

Scenario with higher power and Ar seeding (c_{Ar}~0.4 %) shows some evidence of increased divertor radiation following Ar injection

Apparent shift of divertor radiation from HFS to LFS

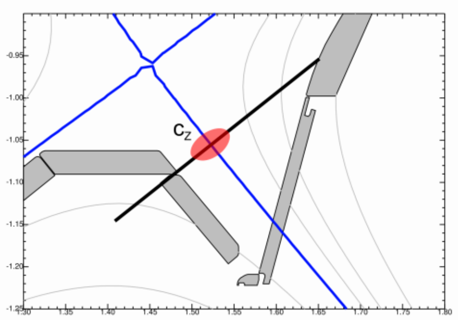


37493 t=3.0 s **37493 t=5.0 s**

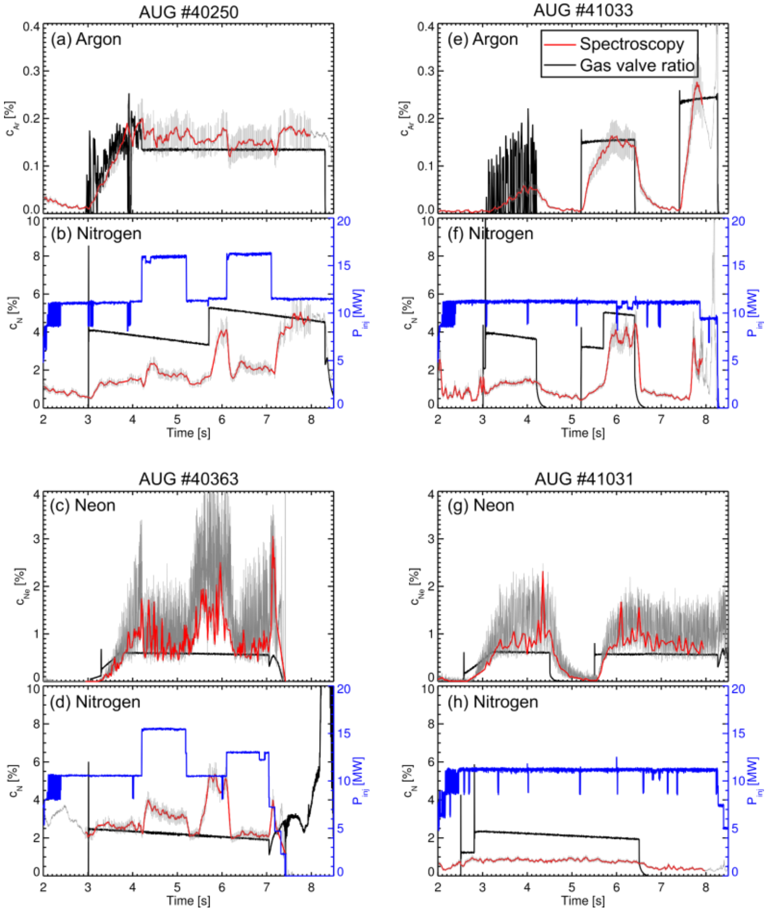


Divertor impurity concentrations

Divertor spectroscopy allows for a local measurement of the impurity concentration in the divertor [Henderson et al. JNME 28 101000 (2021)]



Ne & Ar model discussed at IAEA FEC 2021 and developed since



Generally good agreement between spectroscopy and gas valve ratio models of c_Z for Ne and Ar

Interesting observations

1. **Ne shows bigger variance during ELMs**

2. **Strong deviations from gas valve ratio found during XPT radiation highlights spectroscopy model limitations**

Detachment qualifier – partial detachment

Detachment qualifier [1] including ***multiple impurities***:

$$q_{det} \cong 1.3 \frac{P_{up}}{R_0} \left(\left(1 + \sum_Z f_Z c_Z \right) p_{div} \right)^{-1}$$

Where f_Z is the SOL radiation efficiency.

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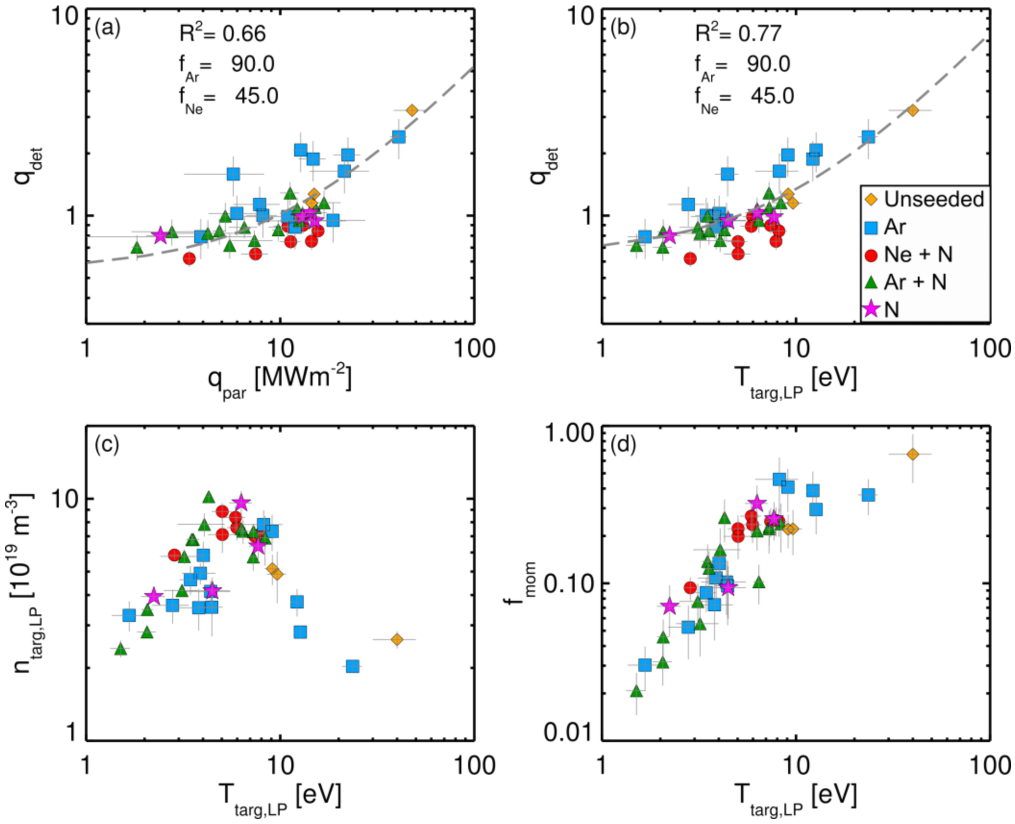

Partial detachment point

- q_{det} shows linear correlation with $T_{targ,LP}$ and q_{par}
- $q_{det} = 1$ corresponds to partial detachment
- $q_{det} \sim 0.5$ corresponds to pronounced detachment

Detachment qualifier – radiation efficiency

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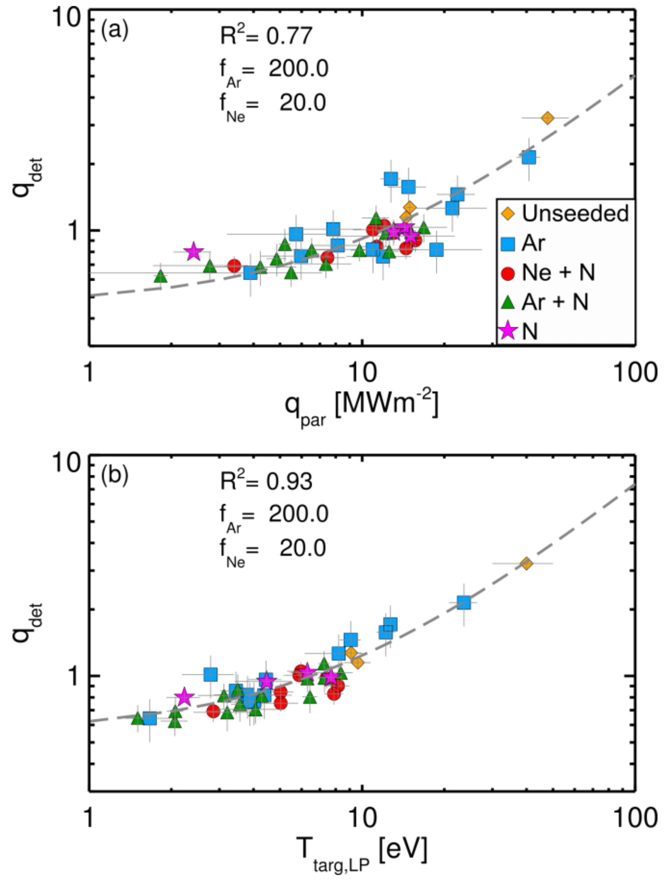
Impurity radiation efficiency

	Predicted	**Measured**
f_N	18	18
$\boldsymbol{f_{Ne}}$	**45**	**~20**
$\boldsymbol{f_{Ar}}$	**90**	**~200**

$\boldsymbol{f_{Ar}}$**~200 and** $\boldsymbol{f_{Ne}}$**~20** improve agreement on partial detachment point and on R^2 between q_{det} and $T_{targ,LP}$



Divertor response to transients

Scenario with mixed Ar + N and Ne + N have tested transient divertor response to

- **NBI power modulation**
- **Gas cut modulation**

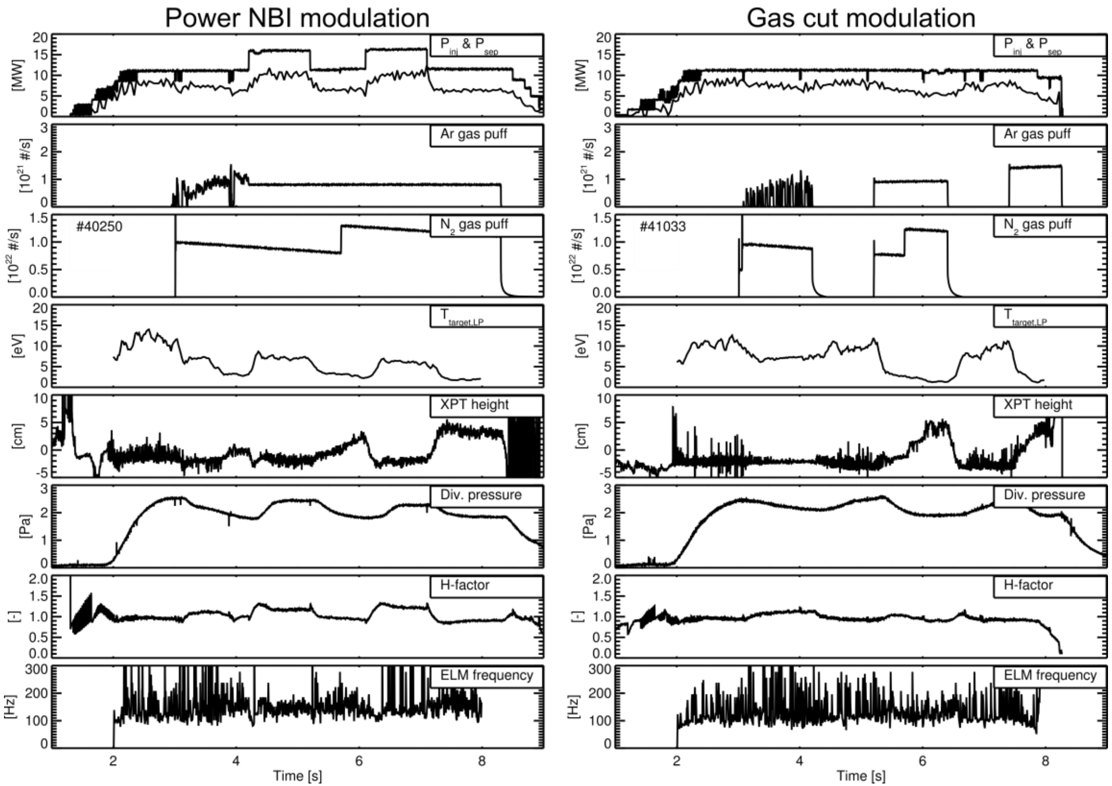
Different degrees of detachment achieved prior to modulations of power and gas

Tested two different levels of power modulation

- *2.5 MW and 5 MW*

Well diagnosed plasma scenarios useful for testing time-dependent modelling predictions

- ***invite further interest this***



Divertor response to power modulation

Main observation

Detached divertor with XPR takes longer to re-attach than divertor with front at target

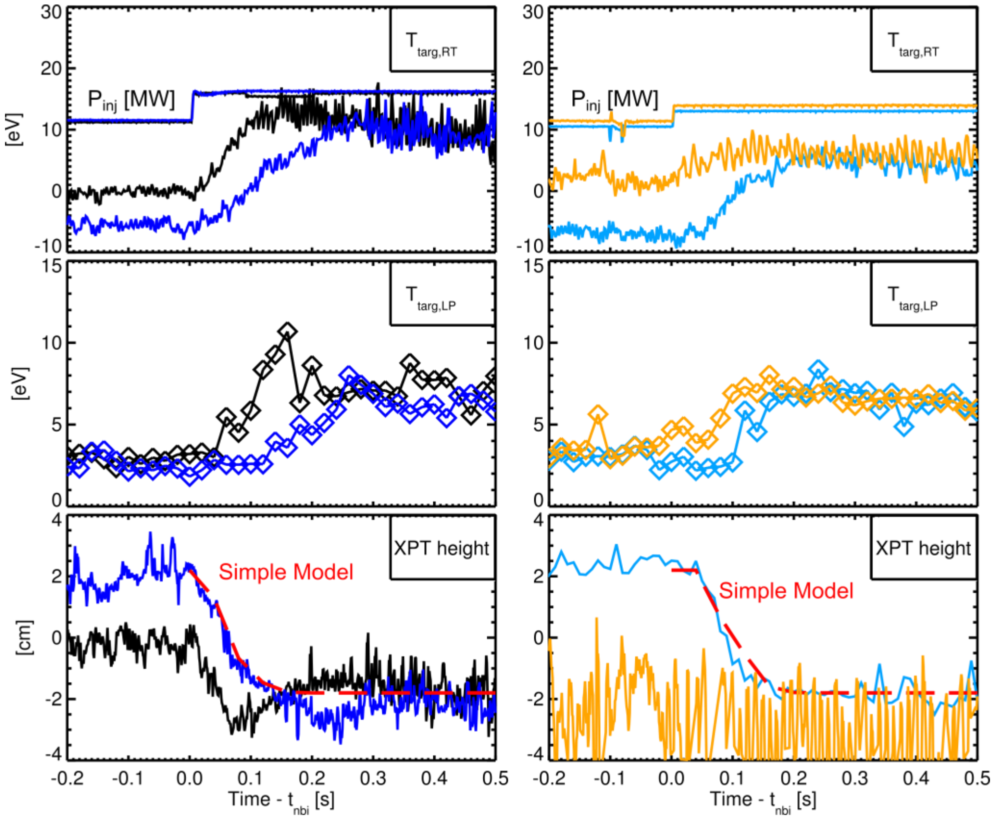
	Time [ms] 5 MW	Time [ms] 2.5 MW
Core confinement time	~60	~60
Partially detached	**~80**	**~80**
Fully detached	**~250**	**~200**

Simple model of front re-ionisation time

$$XPT_{height}(t) = XPT_{peak} e^{\frac{-tP(t)}{Vn_0 E_{ion} \frac{\tau_{resid}}{\tau_{ionis}}}}$$

Using $n_0 \sim 10^{21}\ \mathrm{m}^{-3}$, $E_{ion} \sim 30$ eV, ${}^{\tau_{resid}}/_{\tau_{ionis}} \sim 30$, $V \sim 2\pi R \times 0.2 \times 0.2 \sim 0.4\ \mathrm{m}^3$

Very simple model but difficult to pin down exact values for each term

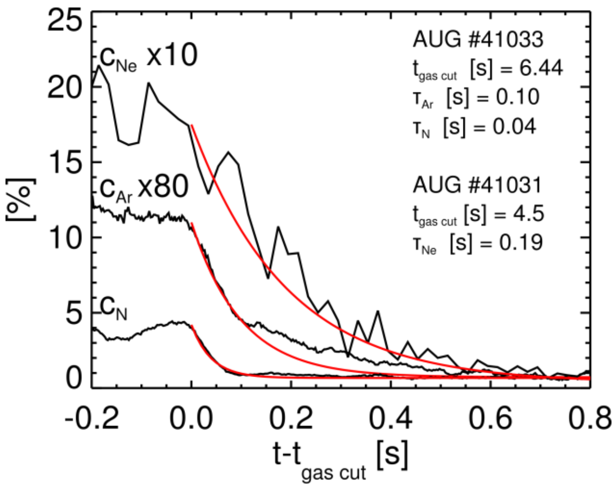


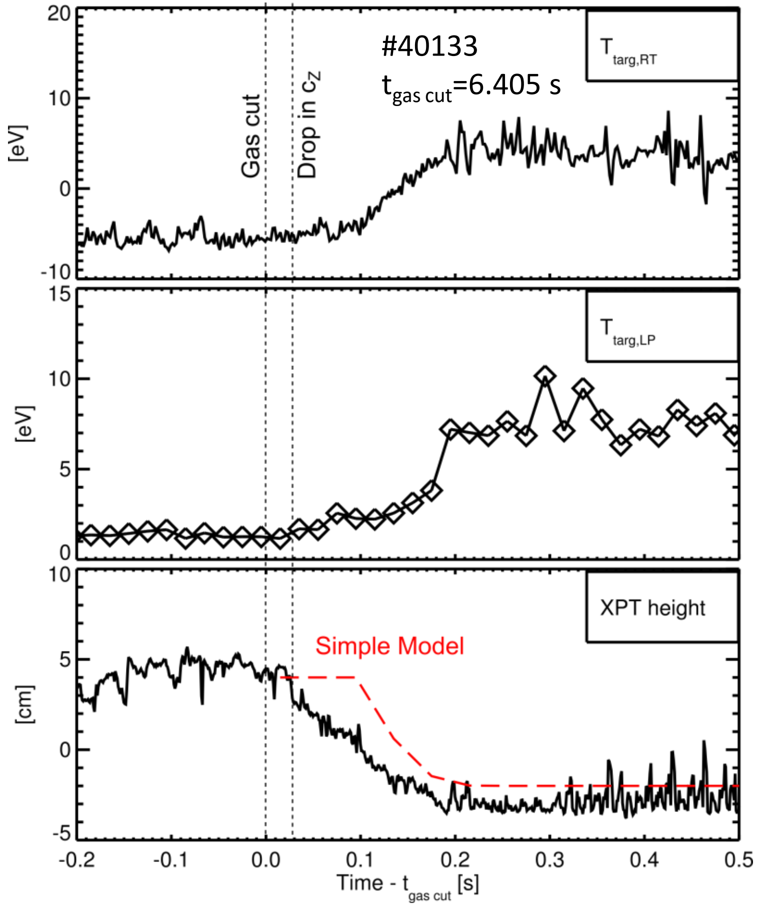
Divertor response to gas cuts

Main observation

- Cut in Ar+N seeding causes ~3 MW power transient
- Front decays earlier than simple model predicts

- *Could be due to faster loss of N compared to Ar*





Summary

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$f_N = 18$ *tested experimentally*

$f_{Ne} \sim 20$ *tested experimentally*

$f_{Ar} \sim 200$ *tested experimentally*

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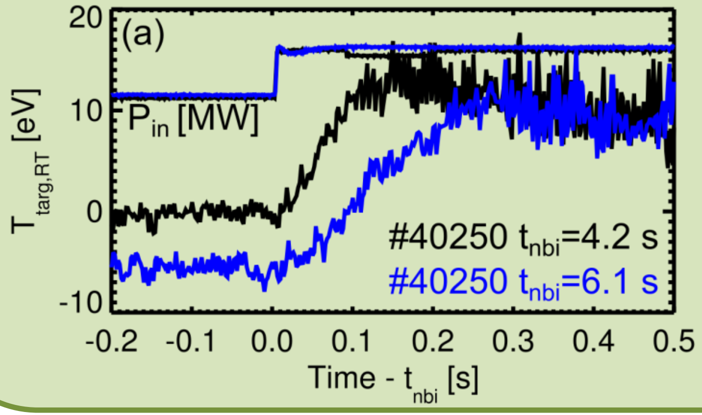
Topic II: Transient divertor reattachment

Fully detached divertors with front at XPT take more than twice the confinement time to attach following a power perturbation



Discussion points

- More experience with Ne required, preferably at higher input power and mixed with low level of N_2 puff, to verify conclusion on radiation efficiency

- Multi-machine database of q_{det} should include both W and C walled machines, assuming summation of $f_Z c_Z$ term over dominant impurities

- Further assessment of attachment timescales for detached divertor through power modulation on different sized machines, with combinations of gas cuts at different divertor pressures