The role of the density profile in the ASDEX-Upgrade pedestal structure

M. G. Dunne[1], S. Potzel[1], F. Reimold[2], M. Wischmeier[1], E. Wolfrum[1], L. Frassinetti[3], M. Beurskens[4], P. Bilkova[5] M. Cavedon[1,6], R. Fischer[1], B. Kurzan[1], F. M. Laggner[7], R. M. McDermott[1], G. Tardini[1], E. Trier[1], E. Viezzer[8], M. Willensdorfer[1], the EUROfusion MST1 Team[9], and the ASDEX-Upgrade Team[1]

[1] *Max-Planck-Institut für Plasmaphysik, D-85748 Garching,Germany*
[2] *Forschungszentrum Jülich,D-52425 Jülich, Germany*
[3] *Division of Fusion Plasma Physics, Association EURATOM-VR, KTH, SE-10044 Stockholm, Sweden*
[4] *Max-Planck-Institut für Plasmaphysik, D-85748 Greifswald,Germany*
[5] *Institute of Plasma Physics, Prague, Hlavni Mesto, Praha, Czech Republic*
[6] *Physik-Department E28, Technische Universität München, Garching Germany*
[7] *Institute of Applied Physics, TU Wien, Fusion@ÖAW, 1040 Vienna, Austria*
[8] *University of Seville, San Fernando 4, 41004 Seville, Spain*

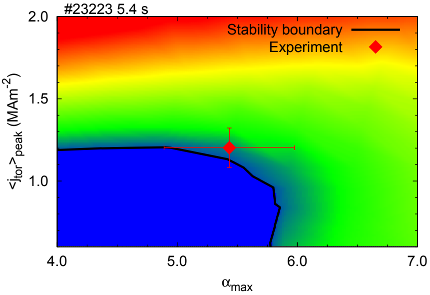
[9] *See appendix of H. Meyer et.al. (OV/P-12) Proc. 26th IAEA Fusion Energy Conf. 2016, Kyoto, Japan*

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.

What determines the pedestal structure?

Peeling-ballooning

- Simple interpretation - critical pressure gradient (α) and current density (j_{tor})
- Critical gradient depends on pedestal width - wider pedestal means lower gradient allowed



$$\alpha = -2 \times \frac{Rq^2}{B^2}\frac{\mathrm{dp}}{\mathrm{dr}}$$

$$j_{tor} \propto \nabla T_e, \nabla n_e, \nu^*, Z_{eff}, \ldots$$

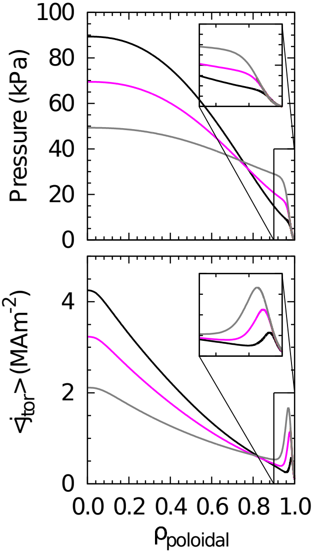
Can we do this in a more controlled fashion?

Predictive analysis

Allows separation of variables

- First incarnation: EPED code[a]
- Can change just one thing (unlike many experiments)
- Inputs: I_p, B_T, shape, density, global β, (Z_{eff}, density location)
- Vary $T_{e,ped}$ to change pedestal top pressure
- Pedestal width $\propto \sqrt{\beta_{pol,ped}}$
- Calculate consistent edge current density and stability boundary

[a]Snyder, NF 2011

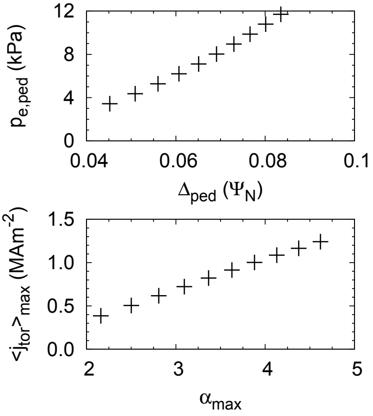


Predictive analysis

Allows separation of variables

- First incarnation: EPED code[a]
- Can change just one thing (unlike many experiments)
- Inputs: I_p, B_T, shape, density, global β, (Z_{eff}, density location)
- Vary $T_{e,ped}$ to change pedestal top pressure
- Pedestal width $\propto \sqrt{\beta_{pol,ped}}$
- Calculate consistent edge current density and stability boundary

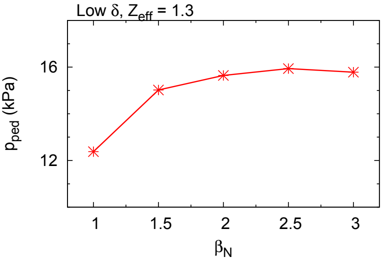
[a]Snyder, NF 2011



Modelling the influences on stability

Pedestal top increases with:

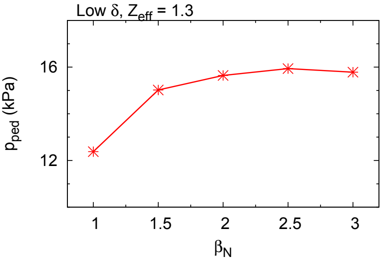
1. Beta β_N

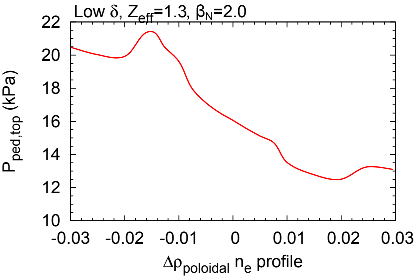


Modelling the influences on stability

Pedestal top increases with:

1. Beta β_N
2. n_e profile shift $(\Delta\rho_{pol} n_e)$
   - T_e fixed due to power balance





How can we influence the density profile?

Possible effects:

- Recycling (NSTX, Maingi PRL 2011)
- Pedestal modes (DIII-D, Osborne, NF 2015)
- LHCD (C-Mod Terry, NF 2015)
- the HFSHD (this talk)

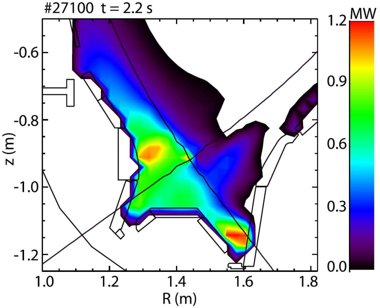
How can we influence the density profile?

Possible effects:

- Recycling (NSTX, Maingi PRL 2011)
- Pedestal modes (DIII-D, Osborne, NF 2015)
- LHCD (C-Mod Terry, NF 2015)
- the HFSHD (this talk)

What is the HFSHD?

- Region of high density localised in the HFS SOL
- Measured via Stark broadening in divertor



Potzel et al., JNM 2014

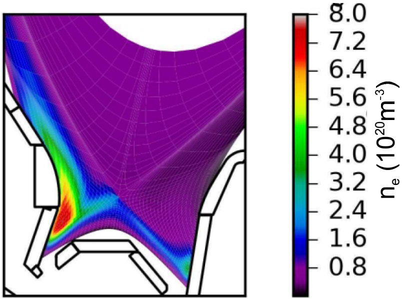
How can we influence the density profile?

Possible effects:

- Recycling (NSTX, Maingi PRL 2011)
- Pedestal modes (DIII-D, Osborne, NF 2015)
- LHCD (C-Mod Terry, NF 2015)
- the HFSHD (this talk)

What is the HFSHD?

- Region of high density localised in the HFS SOL
- Measured via Stark broadening in divertor
- Recently modelled with SOLPS



F. Reimold, EX/P6-22 (Thursday)

How do we vary the HFSHD?

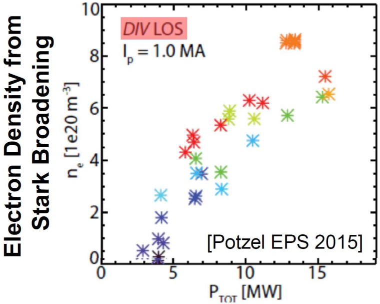
Experimental and modelling dependencies:

- Increases with increasing input heating power
- Increases with higher gas puff
- Decreases with nitrogen seeding

Experiments:

Varied:

1. Gas puff
2. Impurity seeding
3. Heating power (changes global $\beta \rightarrow$ also impacts stability)

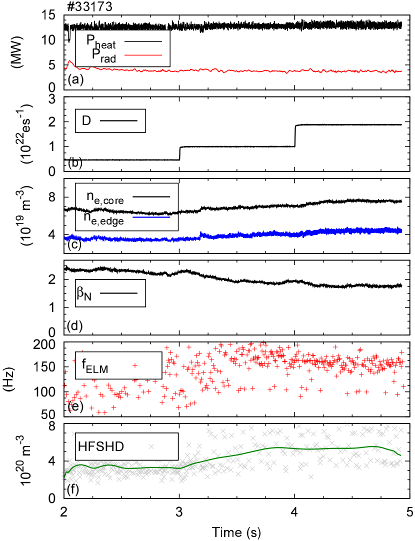


Tot. Heating Power

Fuelling scan

Ramp from low to high fuelling

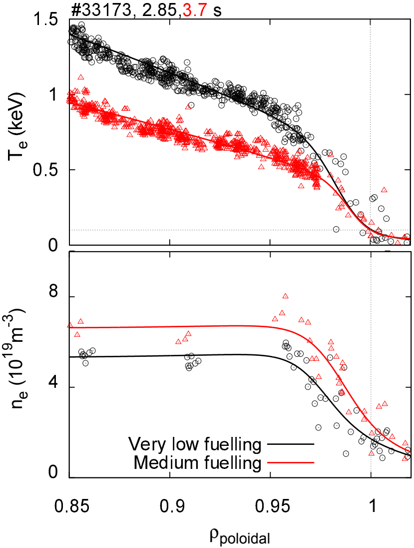
- Stored energy (and hence also confinement) drop at otherwise constant parameters



Fuelling scan

Ramp from low to high fuelling

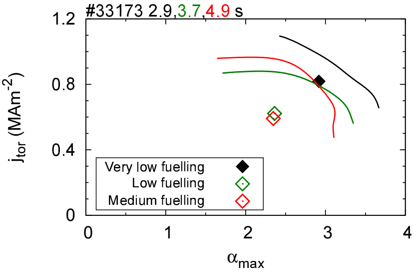
- Stored energy (and hence also confinement) drop at otherwise constant parameters
- Temperature at pedestal decreases significantly
- Density increases, but not enough to compensate → pedestal pressure loss



What does stability say about this?

Stability analysis shows good agreement with experiment

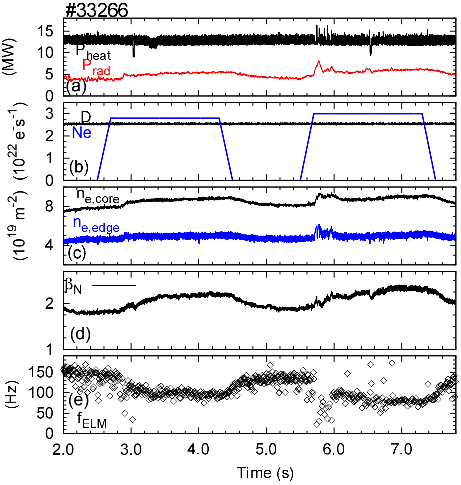
- Accessible area reduced in higher gas puff phases
- Results in lower pressure gradient/allowed pedestal width
- Also recently seen at JET in fuelling scan (Stefanikova, EPS 2016)



Reversing the effect with neon and nitrogen

Two ramps of neon seeding

- Two different levels, higher confinement improvement with more neon
- ELM frequency strongly changed (main chamber radiation)



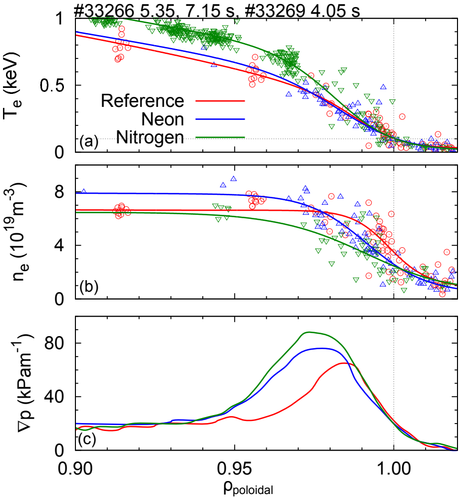
Reversing the effect with neon and nitrogen

Two ramps of neon seeding

- Two different levels, higher confinement improvement with more neon
- ELM frequency strongly changed (main chamber radiation)

Profiles show shift of density for both nitrogen and neon

- Total pressure gradient shifts further inside and becomes higher



Reversing the effect with neon and nitrogen

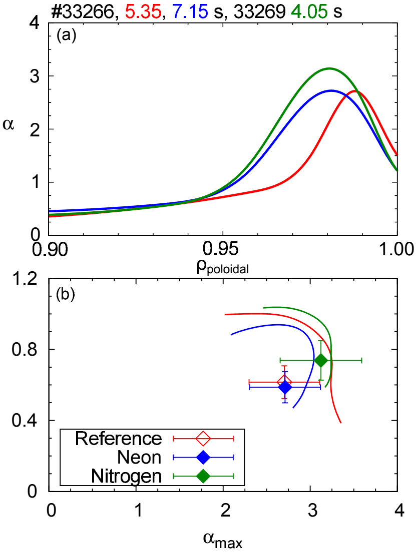
ASDEX Upgrade

Two ramps of neon seeding

- Two different levels, higher confinement improvement with more neon
- ELM frequency strongly changed (main chamber radiation)

Profiles show shift of density for both nitrogen and neon

- Total pressure gradient shifts further inside and becomes higher
- See almost constant $\alpha_{\max}$ in both experiment and theory



Reversing the effect with neon and nitrogen

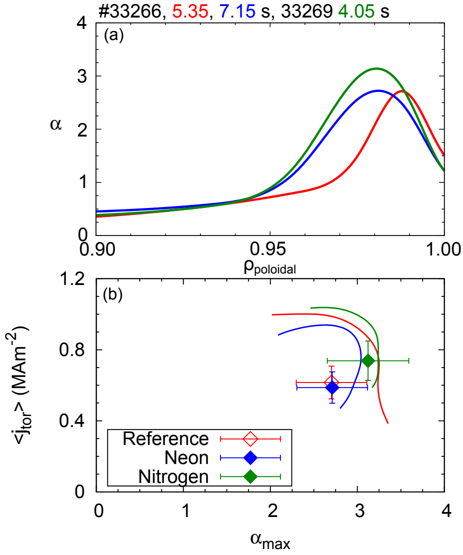
Two ramps of neon seeding

- Two different levels, higher confinement improvement with more neon
- ELM frequency strongly changed (main chamber radiation)

Profiles show shift of density for both nitrogen and neon

- Total pressure gradient shifts further inside and becomes higher
- See almost constant $\alpha_{\max}$ in both experiment and theory

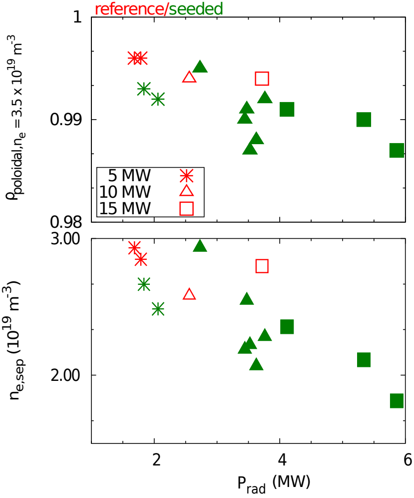
Caveat: Neon seeding tricky/unstable



Observe strong correlation between P_{rad} and profile location

P_{rad} and profile location interlinked

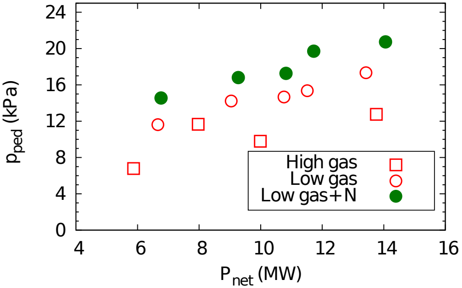
- As impurities seeded, radiated power in SOL increases, $n_{e,sep}$ decreases and profile shifts inwards
- Highest seen $= \Delta\rho_{poloidal} = 0.015$
- Z_{eff} also increases $\rightarrow$ more benefit for stability



Power, fuelling, and seeding scans -measurements and predictions

p_e generally increases

- Have large variation at each heating power
- Increase is linear with heating power in each fuelling step



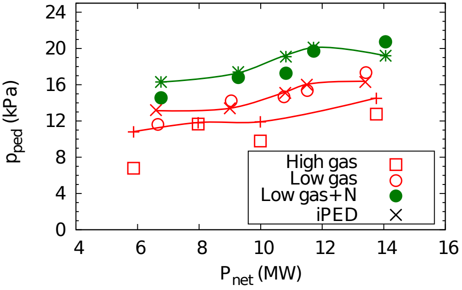
Power, fuelling, and seeding scans -measurements and predictions

p_e generally increases

- Have large variation at each heating power
- Increase is linear with heating power in each fuelling step

Inclusion of shift allows correct pedestal top to be modelled

- For higher fuelling: $\Delta\rho_{\text{pol}} = +0.01$
- Nitrogen seeding: $\Delta\rho_{\text{pol}} = -0.005$ and $Z_{\text{eff}} = 2.0$
- Also include experimental β, $n_{\text{e,ped}}$, Z_{eff}

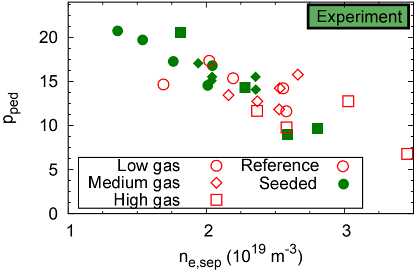


Correlation of pedestal top with SOL influence

ASDEX Upgrade

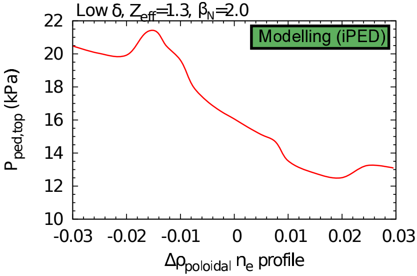
Measured pedestal top lines up nicely with separatrix density

- $n_{e,sep}$ good marker for density profile location
- Even with variation in $\beta, Z_{eff}, n_{e,ped}$, dominant trend of pedestal top with separatrix density



Shift of density profile has strong impact on pedestal top pressure

- Scan density profile location beyond what is observed
- See $\pm$25% change in pedestal top within experimentally observed shift range



Conclusions

SOL properties influence plasma profiles

- HFSHD; change of how plasma close to separatrix is fuelled from SOL
    - Acts to increase separatrix density and shift profile outwards
- Degrades pedestal top and global β

Outward shift of density profile degrades pedestal top

- HFSHD shifts pedestal outwards and lowers attainable gradient
- Lower pedestal top leads to lower beta and even lower pedestal top...

Impurity seeding can reverse this!

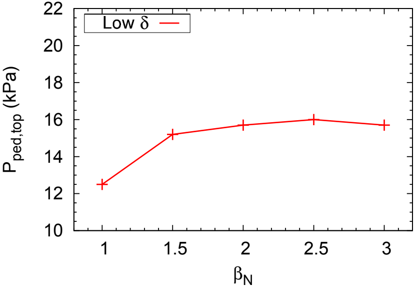
- Reduces HFSHD $\rightarrow$ density pedestal shifts inwards
- Pedestal top improves $\rightarrow$ confinement improves

Need to know how the plasma is fuelled to make accurate pedestal predictions

Modelling the influences on stability

Pedestal top increases with:

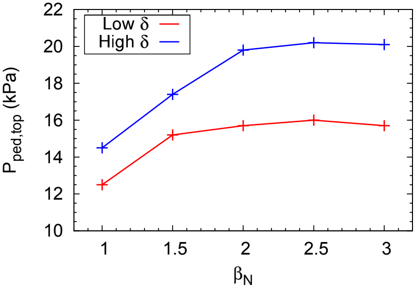
1. Beta β_N



Modelling the influences on stability

Pedestal top increases with:

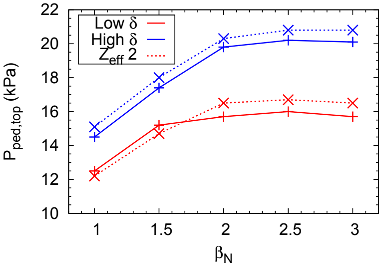
1. Beta β_N
2. Triangularity δ



Modelling the influences on stability

Pedestal top increases with:

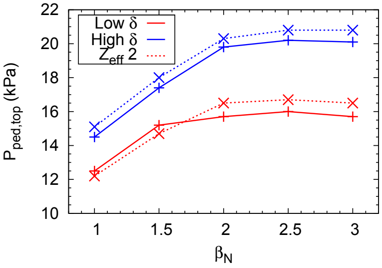
1. Beta β_N
2. Triangularity δ
3. Effective charge Z_{eff}

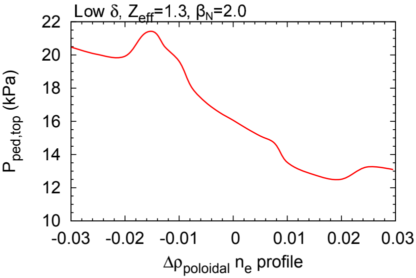


Modelling the influences on stability

Pedestal top increases with:

1. Beta β_N
2. Triangularity δ
3. Effective charge Z_{eff}
4. n_e profile shift ($\Delta\rho_{pol} n_e$)





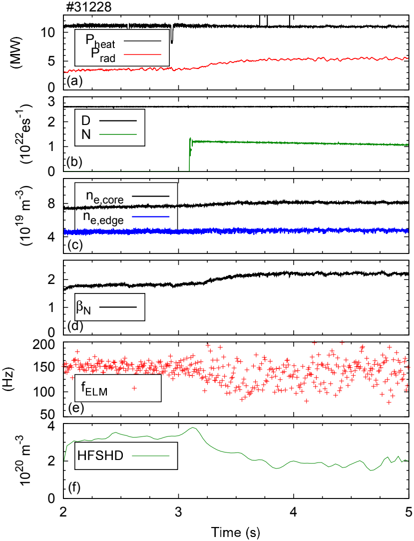
Effect of nitrogen seeding

Well known that nitrogen increases the pedestal top pressure

- Observed at AUG, JET, C-Mod
- Typically T_e increases, sometimes also density

What causes this?

- Nitrogen also reduces HFSHD



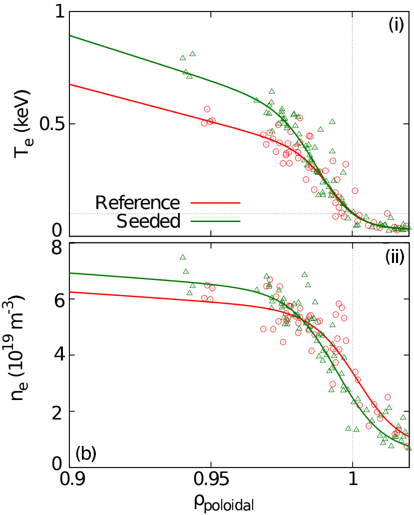
Effect of nitrogen seeding

Well known that nitrogen increases the pedestal top pressure

- Observed at AUG, JET, C-Mod
- Typically T_e increases, sometimes also density

What causes this?

- Nitrogen also reduces HFSHD
- Data show a reduction of separatrix density and inward profile shift



Stability analysis

Scan in j-α space

- Consistent with peeling-ballooning

Why are the points in the same place?

- Boundary influenced also by wider pedestal - brings ballooning boundary to smaller $\alpha_{\max}$
- Since $\alpha \propto q^2 \times \frac{\mathrm{dp}}{\mathrm{dr}}$, same critical α and inward profile shift means higher real space pressure gradient extending further into the plasma
- Coupled with wider width, means higher pedestal top