Development towards an ELM-free DEMO pedestal radiative cooling scenario in ASDEX Upgrade

Arne Kallenbach, R. Dux, M. Bernert, M. Cavedon, P. David, M. Dunne, M. Griener, R.M. McDermott, V. Rohde, ASDEX Upgrade team¹, EUROfusion MST1 team²

Max-Planck-Institut f. Plasmaphysik, Garching, Germany

L. Gil

Instituto de Plasmas e Fusao Nuclear, IST, Lisboa, Portugal

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 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

¹see author list of H. Meyer et al. 2019 Nucl. Fusion 59 112014
²see author list of B. Labit et al. 2019 Nucl. Fusion 59 086020
DEMO must operate in a no-ELM scenario

Toolbox for an integrated no-ELM scenario

Outer core radiative cooling to reduce $P_{sep}$

- **core radiation**

Mechanism for reduction of pedestal pressure (gradient, current, ..)

- **ped. radiation**
- **RMP**
- **MHD**
- **turbulence**

Divertor radiation to achieve detachment

- `X-point radiator` → Fri, M. Bernert, EX-7
Radiation is a key element of the integrated no-ELM scenario.

Core radiation, pedestal radiation, and MHD elements have to match together. Different requirements will call for impurity mix.

This talk will address a few topics regarding integration of impurity seeding using as example the EDA H-mode.
Outline

• Development of a typical AUG discharge with increasing Ar puff level
• Pedestal tailoring by argon seeding in the EDA H-mode
  – behaviour of the quasi-coherent mode (QCM) with seeding
• Integration with divertor radiation / detachment
• Conclusions and next steps
Standard H-mode response to rising Ar puff level

X-point radiator
Standard H-mode response to rising Ar puff level

### Power Density (MW m⁻²) vs ΔS (cm)

- **t=2.40-2.60s**
- **t=3.80-4.00s**
- **t=4.80-5.00s**
- **t=5.80-6.00s**

### Additional Graphs:
- **f_sheath = 8.0**
- **Δt = 10.0 ms median**

**H98**

**W / MJ**

**ELMs:**
- **L-mode**
- **Type-1**
- **type-1** smaller
- **180Hz**
- **350 Hz**
- **above X**
- **below X**

**T_e, T_e sep / eV**

**Z X-pt radiator / cm**

**# 37419**

12.05.2021

Arne Kallenbach
EDA H-mode in ASDEX Upgrade (high shaping)

EDA H-mode obtained at AUG at relatively low ECRH power
- upper power threshold to type-I ELMs

→ to be combined with impurity radiation at or inside pedestal

L. Gil et al., NF 2020
very similar to C-Mod EDA H-mode
Variation of $P_{\text{sep}}$ by Ar seeding (EDA conditions)

**Diagram:**
- **Pheat**
  - $P_{\text{sep}}$ vs. time
  - Ar radiation
  - Complete ELM suppression at very low $P_{\text{sep}}$
- **H98**
  - Target power monitor
  - Type I ELMs
  - Marginal ELMs
  - No ELMs

12.05.2021
Arne Kallenbach
EDA H-mode extended to high power by controlled Ar seeding

power to divertor controlled via Ar seeding

quite narrow power window in Psep for L-EDA - ELMy

very good performance: $H_{98}>1$, $\frac{n}{n_{GW}}=0.9$, $\beta_N = 2$

low tungsten concentration $< 10^{-5}$

completely ELM-free

quasi-coherent mode

QCM @ 20-30 kHz provides full ELM suppression
Quasi-coherent mode directly seen by He-beam diagnostic

Helium-beam diagnostic visualises QCM

radial and poloidal l.o.s tangent to flux surfaces
QCM rotates in electron-diagmagnetic direction (upward in omp)

He line 587 nm intensity

structures not equally spaced → quasi-coherent

typical: \( v = 3 \text{ km/s}, f = 30 \text{ kHz} \)

\[ \rho_p \approx 0.99 \]
EDA H-modes only at low $P_{\text{sep}}$

QCM frequency decreases with $P_{\text{heat}} - P_{\text{rad}}$

$v$ decreases with $f$
take 3 km/s at 30 kHz assume $v_{\text{hfs}} < v_{\text{lfs}}$

$\rightarrow m \sim 100, \ n \sim 20$

Ar radiation reduces pedestal top pressure, retains stored energy
Scenario integration for partial divertor detachment
Double radiative feedback for high power, no-ELM, detachment

- Argon to maintain quasi-coherent mode and no-ELM state
- Nitrogen for divertor partial detachment

$H_{98} = 1.05$
$\beta_N = 2.4$
$q_{95} = 5.8$
Combined Ar and N radiation in the pedestal

- effect of charge exchange ~ triples pedestal radiation
- \( c_{\text{Ar}} \approx 0.3 \% \), \( c_{\text{N}} \approx 1 \% \) → more pedestal radiation per dilution from Ar
EDA H-mode is stable close to ballooning limit

![Graph showing MHD stability analysis](image_url)
Partial detachment with combined Ar+N achieved

- Langmuir probes along outer divertor target
Core fuel dilution must be restricted to minimum

$\Delta Z_{\text{eff}} = 1.5$ by $\text{Ar} \rightarrow c_{\text{Ar}} \approx 0.5\%$

$\rightarrow 9\%$ dilution
Divertor enrichment is a key parameter for detachment efficiency

Enrichment: $\eta = \Gamma_{z0}/\Gamma_{D0} \text{ (div)} / n_z/n_e \text{ (core)}$

$\eta$ is a measure for relative divertor radiation / core dilution

Argon performance much better compared to Neon

only for standard $I_p/B_t$ direction

- modelling with full drifts required
- element for divertor optimization
Summary and next steps

Integration of a no-ELM scenario and divertor detachment achieved on ASDEX Upgrade in EDA H-mode with Ar and N double feedback

Next:

- reduce safety factor $q_{95}$ (X3 heating instead of X2 for tungsten control)
- extend to higher divertor neutral pressure to make Ar an efficient divertor radiator (→ QCE scenario ?)
- alternative divertor configuration ?
- direct control of the quasi-coherent mode ?
- modelling for extrapolation (divertor, transport, MHD and stability)