High radiation scenarios in pronounced detached divertor conditions at ASDEX Upgrade

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Motivation

DEMO requirements:

- **Detached divertor** necessary to reduce power and particle flux
  
  With deuterium: No full / pronounced detachment in H-mode
  
  \[\Rightarrow\] Seeding impurities necessary for power dissipation

- **95%** of exhaust power needs to be **dissipated**
  
  Only achievable with radiation inside and outside confined region
  
  \[\Rightarrow\] Core and edge radiators necessary

Possible with a conventional divertor using strong impurity seeding
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**Goal:** Test scenarios in present day experiments

**Match SOL plasma**

\[ P_{sep}/R \approx 15\text{MW/m}, \quad f_{GW} \approx 1, \quad H_{98} \approx 1 \]

- What is the maximum \( f_{\text{rad}} \)?
- How stable are these regimes?
The ASDEX Upgrade Divertor

- \( P_{\text{heat}} = 27 \text{ MW} \) (available 20 MW NBI, 6 MW ECRH, 6 MW ICRH)
- \( R = 1.65 \text{ m} \)

\[
P_{\text{heat}}/R \approx 16 \text{ MW/m}
\]

- Fueling
  - Main fueling and seeding from divertor
  - High-Z seeding from outer midplane

- Divertor
  - Closed divertor
  - Vertical targets
  - Tungsten coated CFC
  - Solid tungsten tiles (outer target) \( (q_{\text{max}} > 10 \text{ MW/m}^2) \) [Hermann, NF 2015]
Detachment (in H-mode)

- Inner divertor typically detached

- Progress of outer divertor detachment:
  - Partially
  - Pronounced
  - Fully

- Outer divertor detachment correlated with increase of plasma density
  - Changed fueling?

- Detachment in H-mode only achieved with intense seeding, e.g. N
  - Full detachment only inter-ELM
  - ELMs: Complex sequence of detachment states
The different radiators

Various seeding impurities possible
- Nitrogen: Divertor
- Neon: SOL
- Argon: SOL & pedestal
- Krypton: Pedestal & core

What is the optimal impurity mix?
High radiation scenarios

Nitrogen:

\[ P_{\text{heat}} = 21 \text{ MW} \]
\[ P_{\text{heat}}/R = 12.7 \text{ MW/m} \]

- Pronounced detachment

\[ f_{GW} \approx 0.95 \]

\[ H_{98} \approx 0.9 \]

- Small reduction of confinement

\[ c_{N,\text{core}} \approx 2-3\% \]

\[ f_{\text{rad}} \approx 90\% \]

- Dominant radiation from inside confined region
High radiation scenarios: Nitrogen

- Strong radiator at X-point
  \[ \Rightarrow \text{MARFE-like radiation condensation} \]

- With ongoing detachment:
  Radiator moves at X-point from outside to inside of confined region

- Time evolution of several seconds
  \[ \Rightarrow \text{RT control possible} \]
High radiation scenarios: **Nitrogen**

- Radiator can be reproduced by SOLPS
- Temperature reduction within confined region
  - $T_e < 5\text{eV}$
  - D line radiation observed

$\Rightarrow$ Parallel temperature gradients inside confined region!
High radiation scenarios: **Nitrogen**

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  $\Rightarrow$ Parallel temperature gradients inside confined region!

- Pedestal top pressure reduced at similar core performance
High radiation scenarios

**Krypton:**

\[ P_{\text{heat}} = 19 \text{ MW} \]
\[ P_{\text{heat}}/R = 11.5 \text{ MW/m} \]

- Pronounced detachment

\[ f_{GW} \approx 0.8 \]

- Small reduction of confinement

\[ H_{98} \approx 0.9 \]

- Low impact on dilution

\[ c_{Kr} < 0.1\% \]

- Radiating ring around pedestal top

![Graph showing Langmuir Probes](image)
High radiation scenarios: **Krypton**

- Krypton radiates in ring at pedestal top
- Nonlinear response to Kr seeding level
  ⇒ poloidally symmetric radiation condensation?
- Discharges only quasi-stable (stable for less than $10 \tau_E$)
- Kr modulated by ELMs
  - ELM frequency reduces
High radiation scenarios:

Stable (AUG #30503)

- $P_{\text{heat}} = 19 \text{ MW}$
- Radiation within pedestal
- Temperature reduction compensated by density increase

Reducing (AUG #31648)

- $P_{\text{heat}} = 10.5 \text{ MW}$
- Radiation moves inside
- Density increase too small

⇒ Radiation outside pedestal top
High radiation scenarios: Comparison

**Nitrogen:**
- Pronounced detachment of outer divertor at highest heat fluxes
- Most radiation inside confined region
- Poloidally localized radiation (above X-point) $\rho_{pol} \geq 0.985$
- Small reduction of confinement (<10%)
- $f_{ELM}$ increases
- Quasi-stable for more than 2s

$Z_{eff}(3\%N) \approx 1.91, d_{fuel}(3\%N) \approx 6\%$

**Krypton:**
- Radiating ring $0.8 \leq \rho_{pol} \leq 1$
- Impact on confinement varying
- $f_{ELM}$ decreases
- Stable vs ELMs, full stability not shown yet
- Lower impact on fuel dilution

$Z_{eff}(1\%Kr) \approx 1.91, d_{fuel}(1\%Kr) \ll 1\%$
Radiation concentrated at X-point independent of seeding species

- Peaking of radiation density \((\text{W/m}^3)\) varies with seeding species as well as poloidal extent
- For Ne + N\(_2\) extent appears similar to distribution in Ne
- No radiating belt formed
Summary

Detached divertor possible at high heating powers using N and/or Kr
- Conventional divertor
- \( P_{\text{heat}}/R \approx 12 \text{ MW/m} \) (Demo: \( P_{\text{sep}}/R=15\text{MW/m} \))
- \( f_{\text{rad}} \leq 90\% \)
- Dominant radiation inside the confined region
- Scenarios quasi-stable (N)
- Real time control most likely possible
- Impact on confinement differs with radiation location (Kr)
- A possible solution for DEMO and ITER?

Outlook
- Stability (Kr) and controllability (N) to be tested
- Where do Ne and Ar radiate in AUG?
Open questions, points of discussion

• What is the stabilizing mechanism for the X-point radiator?
• Why didn’t it work for carbon walls?

• How does the radiation influence the H-mode threshold?
• Does maybe $P_{ped}$ matter instead of $P_{sep}$?
• How to estimate $P_{sep}$?

• What is the best impurity mix?
• Do future machines need other impurities (e.g. xenon)?

• Impurity behaviour with pellet fueling?
• Increased impurity divertor compression?