EX/7-2: Impurity Seeding on JET to Achieve Power Plant like Divertor Conditions

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Acknowledgements

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*See the Appendix of F. Romanelli et al., Proc. 25th IAEA FEC 2014, St Petersburg, Russian Federation

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Limit on acceptable erosion:
- With impurity seeding and higher charged states enhancing erosion: $T_e < 2 - 5 \text{ eV}$

Expected power handling limit of actively cooled DEMO divertor component $< 10\text{MW/m}^2$:
- Limit on particle flux to limit power deposition by surface recombination ($15.8 \text{ eV per ion – electron pair}$)

Power handling limit combined with erosion limit
- completely detached divertor
ITER to DEMO:
Similar volume and size of divertor \(\Rightarrow\) similar absolute amount of radiation in SOL and divertor (ITER \(\sim\) 60\% – 70\% of \(P_{\text{SOL}}=120\text{MW}\) \(\Rightarrow\) 70MW)
Radiation: minimize in core
Radiation: minimize in core & optimize edge

Core

separatrix

Edge radiation

Divertor power dissipation in DEMO similar to ITER

Edge + core > 70% radiation
DEMO requires > 90 – 95% radiation

Total radiation required sums to > 90% - 95% of $P_{\text{heat}}$

Maximize radiation in EDGE and SOL $\Rightarrow$ main guidance
Vertical target geometry

\[ B_T = 2.7T \]
\[ I_P = 2.5MA \]
\[ \delta = 0.22 \text{ (low triangularity)} \]
\[ q_{95} = 3.3 \]
\[ P_{\text{heat}} = P_{IN} \cdot \frac{dW}{dt} (14-28\text{MW}) \]
\[ \frac{P_{\text{heat}}}{R} \sim 5 - 9 \]
\[ \frac{P_{\text{sep}}}{R} \sim 3 - 6 \]

\[ R = 3m \]
Maximum $f_{\text{rad}}$ independent of $P_{\text{heat}}$

- $\sim 70\% f_{\text{rad}}$ at maximum $P/R \sim 9$
- Highest $f_{\text{rad}}$ with only $N_2$ seeding
- Performance of $N_2$ + Ne seeding evolves qualitatively very similar to pure Ne seeding
- ASDEX Upgrade reaches $f_{\text{rad}} > 85\%$ but higher $c_W$ ($W$ from MCW)
Maximum $f_{\text{rad}}$ increases with seeding

$P_{\text{heat}}: 18 - 20$ MW

Close to maximum: $f_{\text{rad}}$ low efficiency of seeding on $f_{\text{rad}}$

Nitrogen seeding rate [el s$^{-1}$]
Higher $P_{\text{heat}}$ $\rightarrow$ higher seeding for $f_{\text{rad}}$

Total heating power [MW], $R=3m$

- $1.0 \times 10^{23}$ el s$^{-1}$
- $0.5 \times 10^{23}$ el s$^{-1}$
- $1.8 \times 10^{23}$ el s$^{-1}$

Total radiated power fraction $f_{\text{rad}}$
N$_2$ seeding into H-Mode plasma: stable radiation of 75%

- N$_2$ → leads to ELM mitigated H-mode with $f_{\text{rad}}$ of $\sim$75%
- ELM mitigated phase with magnetic activity similar to M-Mode (E. Solano et al., EPS 2013)
- $c_W$ in core at detection limit ($<10^{-5}$)

A. Huber et al. EPS 2014, M. Wischmeier PSI 2014
Poloidal radiation at highest $f_{\text{rad}}$

Ne seeding

Radiative instabilities with transient $f_{\text{rad}}$ of up to 90%
Radiative instabilities with transient $f_{rad}$ of 90%
Poloidal radiation at highest $f_{\text{rad}}$

Ne seeding

Radiative instabilities with transient $f_{\text{rad}}$ of 90%

Ar seeding

Maximum $f_{\text{rad}}$ ~60%

N$_2$ seeding

Maximum $f_{\text{rad}}$ ~75%
Concentrated around X-point
Radiation concentrated at X-point independent of seeding species

- Ne seeding
- Ar seeding
- N$_2$ seeding

- Peaking of radiation density (W/m$^3$) varies with seeding species as well as poloidal extent
- No radiating belt formed
According to reconstruction at highest $f_{\text{rad}}$ this accounts for largest part of edge & SOL radiation.

Above X-point ~ inside LCFS excluding X-point ➔ due to poloidal distribution ~ core radiation

Divertor and X-point
- Lowest fraction of above X-point radiation for seeding that includes N₂
- Fraction of experimental radiation above X-point not directly comparable to requirements for DEMO
Above $f_{\text{rad}}$ of 70% close to L-H threshold

- Ar seeding even for low seeding rates close to L-H threshold
- $N_2$ seeding approaches threshold for highest $f_{\text{rad}}$
- At low ratios radiative instabilities in case of Ne

Graph showing $\frac{P_{\text{heat}} - P_{\text{MC}}}{P_{L-H}}$ (Martin scaling J. Phys. 08) vs. Total radiated power fraction.
In highly seeded discharges $H_{98}(y,2)$ is function of $\beta_N$. 
Impact of $\text{N}_2$ seeding on confinement scaling

![Graph showing impact of N$_2$ seeding on confinement scaling](graphic.png)

- **$H_{98(y,2)}$** represents the total radiated power fraction.
- The graph compares different plasma conditions, with a clear distinction between $\text{D only}$ and $\text{N}_2$ cases.

**Legend:**
- Blue diamonds: $\text{D only}$
- Red squares: $\text{N}_2$
Impact of $N_2$ seeding on confinement scaling

High fueling and seeding levels
$N_2$ rate: $5 - 18 \times 10^{22}$ el s$^{-1}$
$D_2$ rate: $2 - 6.5 \times 10^{22}$ el s$^{-1}$
With N2 seeding mainly pedestal $n_e$ depletes
Profiles recover and surpasses unseeded values in core
No reliable information on changes in SOL profiles yet
Highest $N_2$ seeding evolves to complete detachment on outer and inner target

Complete detachment coincides with strong radiation at X-point

Similar to ASDEX Upgrade (A. Kallenbach et al. EX/7-1, F. Reimold et al., subm. to Nucl. Fusion)
Operational stability of radiation

Loss of NBI power and no backup

Ch. 3
Ch. 5
Numerical modeling

- COREDIV: 1D core modeling and 2D slab geometry for SOL (G. Telesca et al. PSI2014)
  - For highest N2 seeding, radiation in divertor does not increase further due to low divertor $T_e$
  - Highest $f_{\text{rad}}$ with X-point not accounted for due to 1D core (strong poloidal gradients in $T_e$ and radiation)
- EDGE2D-EIRENE simulations demonstrate detachment achievable with $N_2$ seeding (TH/P5-34 A.E. Jarvinen et al.)
- Dedicated numerical modeling with full geometry pending
- SOLPS5.0 (w. EIRENE) simulations including activated drift terms for similar ASDEX Upgrade cases: complete detachment induced by loss of upstream pressure due to strong X-point radiation (EX/P3-16 P M. Wischmeier et al., F. Reimold et al. PSI 2014)
Stable discharges with radiation peaked around X-point for $N_2$, Ne, Ar and $N_2$+Ne

Maximum radiation independent of heating power
- Maximum radiation achieved 75% - DEMO requires > 90%
- Physics reason not yet understood – link to maximum stable radiation in edge region?
- ELM mitigation for marginal H-mode

Stable completely detached outer and inner divertor achieved

Pedestal profile degradation recovered by steeper core profiles

Future: Combine seeding of higher Z at higher $P_{\text{heat}}$ with $N_2$