Improved Impurity Retention And Pedestal Performance In DIII-D Closed Divertor

by
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First Impurity Seeding Studies in the Small Angle Slot (SAS) Divertor at DIII-D

Impurities ($N_2$, $Ne$) injected simultaneously from gas valves at the corners of the slot

Suite of diagnostics in SAS:
- Langmuir probes (LPs)
- ASDEX neutral gauges (PGs)
- Surface eroding Thermocouples (SETCs)
- Vertical viewing chord:
  - Spectroscopy (EUV/VUV SPRED, NIRS)
  - Divertor Thomson Scattering (DTS) local $T_e$, $n_e$

General info on recent SAS studies (no seeding):
- H. Guo et al. NF 59 (2019)
- L. Casali et al. NME 19 (2019)
Outline

- Effect of divertor geometry: varying the OSP location, gas species fixed
- Effect of impurity species: varying the gas species (N, Ne), OSP location fixed
N₂ seeding in SAS induces detachment while the core is not significantly affected

- Significant neutral pressure rise ($p_0 > 10$ mTorr) occurs when N₂ is injected
- Reduction of heat flux in the SETCs
- Clear reduction in $T_e$ with N₂ detected by different DTS channel

Divertor Spectroscopy Confirms $T_e < 2$ eV with N$_2$ seeding

Absolutely calibrated (EUV/VUV):
- Bright resonance N$_2$ lines
- Rapid increase in Lyman-β, 1026Å indicating $T_e < 2$ eV
- N is the dominant divertor radiator

Absolutely calibrated spectrum from NIRS:
- Paschen series of D lines, which appear only when $T_e < 2$ eV (bottom).
Higher Levels of Relative $N_2$ Contamination in the Core Found in the SAS with OSP at the Outer Corner

Effect of divertor geometry: vary the strike point location with a fixed gas species

- Higher core N concentration consistently found with OSP at the outer corner
- This result holds for all the collected database at different power, different density
Dependence of Detachment on Strike Point Location

Matched nitrogen seeded discharges with different strike point location

- LPs shows that detachment onset requires less N\textsubscript{2} puff with OSP at the inboard side
- Results are confirmed by DTS and divertor spectroscopy measurements
With grad-B into divertor, more ionization occurs in PFR and HFS far SOL due to drifts

SOLPS-ITER modeling with full drifts, n-n collisions, D+C+N/Ne performed for the first time at DIII-D

- Drifts shift the source radially towards the inner target
- Drifts are necessary to interpret our experiments here
Different strike point locations correspond to different wetted area with a different distribution of the D source.

Source tightly trapped in the slot, within near SOL

Source out in the common flux region
Divertor Geometry Influences Plasma Flows Via Modification of the Ionization Source Affecting Impurity Transport

- Flow reversal: flow away from the divertor occurs in a flux tube where the ionization source exceeds the ion loss

- Impurity transport: main ions flow+ drifts

  \[ v_{pol} = \frac{B_{pol}}{B} v_{||} + v_{pol}^{ExB} \]

  Drifts

  \[ v_{||,I} \approx v_{||,i} + \frac{\beta}{\alpha} \tau m_i^{-1} \nabla || T_i \]

  Impurity Poloidal velocity

  Impurity parallel velocity

  Main ion parallel velocity

  I. Senichenkov et al. PPCF (2019)
  E. Sytova et al. NME (2019)

Effect of closure:
- Neutral trapping
- Shift in pressure balance

L. Casali et al. NF (2020)
L. Casali et al. CPP (2018)
B. Covele APS (2018)
Reduced Ion and Impurity Leakage with OSP at the Inboard Side

- $N_2$ is better retained in the divertor with inboard OSP:
  - Reduced core $N_2$
  - Less $N_2$ amount needed for detachment

Flow reversal for both main ions and impurities

-> all forces are directed away from target

-> leakage
For N/Ne Matched Input Parameters, Ne Increases Radiation In The core While Neutral Pressure In The Slot Decreases

Effect of impurity species: OSP location fixed, varying the gas species (N, Ne)

Radiation profile

Dissipation: - N through $P_{\text{rad,divertor}}$
- Ne through power loss upstream
Both N and Ne Reduce Target $q_{\parallel}$ at OSP But with Ne Particle Flux Down Into the Divertor is Dramatically Reduced

- How can a large reduction of the target heat flux be achieved with $T_e$ being high?
- With Ne: most of the power loss with Ne takes place upstream
SOLPS-ITER: N Accumulates In The Low $T_e$ Regions At Target, Ne Penetrates In The Core, Ne Dissipates Upstream

**SOLPS-ITER modeling**

- N accumulates where $T_e$ is low, Ne instead penetrates upstream
- This agrees with the experimental results that the core is more affected by Ne

Impurity density

$N$ $Ne$

$N$ is where $T_e$ is low (target)

Ne goes upstream

Impurity density

$N$ $Ne$

$N$ is where $T_e$ is low (target)

Ne goes upstream

$\Phi_{II,divertor entrance}$

$N$ $Ne$
Pedestal Reacts Differently to N and Ne Seeding

Two-point model (P. Stangeby 2000):

- Divertor and pedestal connected through heat flux and $f_{rad}$
- Neon reduces both $q_{II}$ and $(1-f_{rad})$ due to mantle radiation

Implication: for a given $T_e$ at the target, less SOL density is required with Ne
Different N/Ne Leakage Due To Different Ionization Potential

- Not much N goes in the core
- No change in pedestal

Ionization potential for N (14.5 eV): N ionizes close to the target: poloidal flow directed downstream, it is retained

Ne ionizes further upstream (21.6 eV) -> leakage
Ne concentration in the pedestal increases non-linearly via feedback mechanism with ELM frequency.

- Increased pedestal stability through diamagnetic stabilization
- Radiative mantle
  - \( \rightarrow \) reduced \( f_{\text{ELM}} \)

With lower \( f_{\text{ELM}} \), less Ne is flushed out into the divertor.

**Graphical Representation:**
- Time (s) vs. \( f_{\text{ELM}} \) (Hz)
- Start \( N_2/Ne \) puff
- Ne pushed out of the divertor into the pedestal
- Ne builds up in the pedestal
- Increased diamagnetic frequency
- \( 10n_{Ne}^{\text{PED}}/(10^{20} \text{m}^{-3}) \)
- \( dT_i^{\text{PED}}/d\psi_N(\text{kPa}) \)
- \( \omega_{ni}^{\text{PED}}(\text{kRad/s}) \)
- \( dp_e^{\text{PED}}/d\psi_N(\text{kPa}) \)
• Target shaping and drifts affect dissipation and impurity retention by redistributing the recycling source.

• Reversal flow for both main ions and impurities has been found in SAS. The impact on the impurity transport explains the experimental finding that $N_2$ is better retained when the OSP is at the inner slanted surface.

• N vs Ne seeding: different pedestal response consistent with the difference in ionization potential, divertor vs upstream dissipation.

• Self-enhancing mechanism of Ne involves both divertor and pedestal physics.
Conclusions

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