Investigating the role of neutral particles in the linear device Magnum-PSI

Ivo Classen, Hennie van der Meiden, Gijs Akkermans, Renato Perillo, Jonathan van den Berg, Richard Engeln
Outlook

• Introduction to Magnum-PSI

• A: Detachment studies in Magnum-PSI
• B: Investigating Nitrogen chemistry: N-MAR
• C: Plasma-neutral interaction in the pre-sheath

• D: Plans for VUV-LIF on Magnum-PSI: $\text{H}_2(r,\nu)$
Magnum-PSI

- Cascaded arc plasma source: H, D, He, Ar, ...
- Superconducting magnet
- Target manipulator + TEAC
- Many diagnostics
  - TS, CTS
  - OES, fast camera, bolometer
  - IR, pyrometer, Probes, calorimetry
  - ....
Magnum-PSI as a divertor simulator

$T_e$ up to 5 eV

$n_e = 10^{19} – 10^{21} \text{ m}^{-3}$

$\Gamma_i$ up to $10^{25} \text{ m}^{-2}\text{s}^{-1}$

$q$ up to 50 MWm$^{-2}$

Pulses: up to 20eV and 1GWm$^{-2}$

Differential pumping:

neutrals: 0.3 Pa during plasma
Section A
Detachment studies in Magnum-PSI

Gijs Akkermans et al.
PoP, 27 (2020) 102509
Seeding gas in target chamber simulates detached states

Higher neutral background pressure →
Pressure and Fluxes strongly reduced
Balmer: 3 regimes

- 0.3 Pa
  \[ T_e = 4.5 \text{ eV} \]
  Peaked
  Overpopulated

- 3.5 Pa
  \[ T_e = 1.2 \text{ eV} \]
  Hollow

- 12.7 Pa
  \[ T_e = 0.06 \text{ eV} \]
  Peaked
  Underpopulated
Fulcher Band measurements

\( Q_{(0,0)}, Q_{(1,1)} \) and \( Q_{(2,2)} \) branches

No hollow profiles observed
Fitting rotational and vibrational temperatures

Higher branches have lower $T_{\text{rot}}$

Fitting for $T_{\text{vib}}$ fails at low neutral densities
(Franck-Condon excitation from ground state in Boltzmann distribution)
Detachment scan: Temperatures and reaction rates

- Better measurement of $T_{\text{vib}}$ needed

Ionization, MAR, recombination
Section B
Investigating Nitrogen chemistry: N-MAR

Renato Perillo et al.
PoP, 26 (2019) 102502
PPCF, 60 (2018) 105004
## Global model of $H_2 + N_2$ plasma chemistry

### $H_2$ species

$H, H_2, H^+, H_2^+, H_2(v_{n=4}), H_3^+$

### $N_2$ species

$N_2, N, N_2^+ (A^3 \Sigma), N_2^+, N^+$

### $H_2$-$N_2$ species

$NH, NH_2, NH_3, NH_3^+, NH_2^+, NH^+, N_2H^+, NH_4^+$

### Equations

<table>
<thead>
<tr>
<th>$k_{\text{Rate}}$</th>
<th>Reactions</th>
<th>Rate coefficients $(cm^3 molecule^{-1} s^{-1})$</th>
<th>References</th>
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</table>

Ivo Classen  | TM on Tungsten and Hydrogen
29 maart 2021

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## Reduced set of reactions

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<th>Reaction</th>
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<td>$H + e^- \rightarrow H^+ + 2e^-$</td>
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<td>$H_2 + e^- \rightarrow H_2^+ + 2e^-$</td>
<td>Ionization</td>
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<td>$N_2 + e^- \rightarrow N + N + e^-$</td>
<td>Dissociation</td>
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<td>$H_2 + e^- \rightarrow H_2v + e^-$</td>
<td>Vibrational excitation</td>
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<td>$H_2v + H^+ \rightarrow H_2^+ + H$</td>
<td>Ion conversion</td>
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<td>$H_2^+ + e^- \rightarrow H + H$</td>
<td>Dissociative recombination</td>
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<tr>
<td>$H_2 + N \rightarrow NH + H$</td>
<td>Atom transfer</td>
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<td>$N_2 + H_2^+ \rightarrow N_2H^+ + H$</td>
<td>Proton transfer</td>
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<td>$N_2H^+ + e^- \rightarrow N_2 + H$</td>
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<tr>
<td>$NH + H^+ \rightarrow NH^+ + H$</td>
<td>Ion conversion</td>
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<td>$NH^+ + e^- \rightarrow N + H$</td>
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<td>$H + e^- \rightarrow H + e^-$</td>
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</table>
New recombination pathway: N-MAR

1) $H^+ + NH_x \rightarrow NH_x^+ + H$
2) $NH_x^+ + e^- \rightarrow NH_{x-1} + H$

Ion conversion
Dissociative recombination
Experimental evidence of N-MAR effect

Strong presence of NH observed

Pressure drops with $N_2$ content

@ constant $P_{\text{back}} = 2 \text{Pa}$
Nitrogen chemistry implemented in B2.5 Eunomia

Reduction of plasma pressure reproduced
Importance of N-MAR

H density rises with $N_2$: recombination

N-MAR most dominant $N_2$ process

N-MAR dominates over MAR
Section C
Plasma-neutral interaction in the pre-sheath

Jonathan van den Berg et al.
(submitted to Nuclear Fusion)
Plasma flux measurements

Plasma volume
Incoherent Thomson Scattering (TS): $n_e$, $T_e$
Coherent Thomson Scattering (CTS): $v_i$, $T_i$
TS + CTS: $\Gamma$, $p^{tot}$, $q_\parallel$

Target surface
Pyrometer + IR camera: $T_{surf}$
In-target thermocouple: $q$
In-target Langmuir probe for $I_{sat} = e\Gamma_t$
Parallel plasma velocities

At $d_{\text{target-laser}} = 25$ mm

- Velocity decreases with density
- Same for the Mach number $M = \frac{v}{c_s}$
- Almost complete stagnation during pulses
- Momentum conservation under isothermal conditions:
  \[ M_u = \frac{n_{se}}{n_u} = \frac{1}{M_{se}^2 + 1} = \frac{1}{2} \]
- Lower $M$ implies higher momentum losses in near wall region
At low $n_e$:
- Constant $T$
- Pre-sheath acceleration toward $M=1$ (Bohm)

At high $n_e$:
- Cooling towards wall
- No acceleration / stagnation, $M$ well below 0.5

At high $n_e \rightarrow$ losses to neutrals

(Energy and momentum losses in near wall region confirmed by comparison with target fluxes)
Losses to neutrals: 0D model

Simplified 0D model was derived to predict losses in p-n interaction region
- Recombining neutrals diffuse radially out
- Recombination, ionization and CX

→ Loss factors depend on density:
Substantial losses in dense conditions
Implications of near wall p-n coupling

- Pre-sheath acceleration not experimentally observed in high densities:
  ➔ Must occur in < 3mm
- Mach number still far below 0.5 at 3mm
  ➔ momentum loss region is very narrow
  ➔ strong gradients

Modelling:

- Near wall resolution of SOL models should be high enough:
  \[ d_{\text{grid}} < \lambda_{\text{neutral mfp}} \]
- If grid size too course the sheath boundary condition (Bohm) might fail: \( M < 1 \)
Section D
Plans for VUV-LIF on Magnum-PSI: $H_2(r,\nu)$
Motivation

• The ro-vibrational distribution plays a major role: MAR rate can vary multiple orders of magnitude

• Direct measurement difficult, but $H_2(r,\nu)$ distribution previously successfully measured in both linear plasmas and tokamaks (no current set-ups)

• ➔ Build new diagnostic on Magnum-PSI (divertor relevant plasmas) based on proven methods: VUV-LIF and CARS

• Grant application running at Dutch Scientific Organization (NWO)

From Vankan et al.
Active spectroscopy: 3 methods

- Deploy active spectroscopy for complete exploration of ro-vibrational distribution of H₂ ground state:

- **VUV-LIF** based on Stimulated anti-Stokes Raman scattering (population ν > 2, J)

- Coherent anti-Stokes Raman spectroscopy (**CARS**): (population ν ≤ 2, J)

- Two photon Absorption Laser Induced Fluorescence (**TALIF**) (density H atoms in ground state)
VUV-LIF principle

• Excite ground state ro-vib level to electronically excited state
• Measure fluorescence signal
• Scanning the laser wavelength excites different ro-vib states
• 110 to 165 nm for $\nu=0$ to $\nu=14$

VUV LIF spectroscopy of $\text{H}_2$ ground state
Planned VUV-LIF setup

- Laser in VUV range (down to ~ Ly $\alpha$)
  - Raman cell (SARS)
- In vacuum
- VUV monochromators
- Vacuum window transmission (>120 nm) prevents measuring lower vibrational states ($\nu$>2)
Complementary techniques: CARS

Lower vibrational states ($\nu \leq 2$) can be measured with CARS

- Same lasers as VUV-LIF
- No vacuum needed
- CARS:
  - 4-wave mixing process
  - 660-700 nm probe beam
  - 532 nm pump beam
Complementary techniques: TALIF

TALIF:
- Density of atomic H density
  Also applicable to N
- Excitation: 205.14 nm
  (for Ly β absorption with 2 photons)
- Fluorescence: Hα

Together with existing diagnostics, these active spectroscopy methods would provide a uniquely complete picture of the (molecular) processes in divertor plasmas
Magnum-PSI welcomes your experiments!

- Well diagnosed
- Accessible
- Simple geometry
- Steady state plasma

Contact: i.g.j.classen@differ.nl