Spectroscopic Investigations of the Ion Source at BATMAN Upgrade

Ursel Fantz, Stefan Briefi for the NNBI Team

- Improved OES setup and analysis
- Gas temperature and $T_H$
- Plasma parameters $n_e$ and $T_e$
- Density ratio $H/H_2$
Prototype RF ion source – Why again results from OES?

OES investigations were already performed

\[ \text{New insights due to} \]

- Additional diagnostic ports
- High resolution spectrometer
  \[ \Delta \lambda_{\text{FWHM}} \approx 15 \text{ pm} @ 600 \text{ nm} \]

- Improved evaluation
  - Collisional radiative models
  - Molecular Fulcher-\(\alpha\) band analysis

Results in hydrogen and without caesium in source

FANTZ ET AL., NUCL. FUSION 46 (2006) S297

Results of probe measurements:
L. Schiesko P1-12

Test facility BATMAN Upgrade (BUG)
Filter field configurations at BUG

**Generation of filter field via**
- Permanent magnets (old BATMAN)
- Plasma grid (PG) current

No filter field

With filter field ($I_{PG}$)

View from top to bottom of source

Filter field pushes plasma towards driver
Improved Fulcher-α analysis for $T_{\text{gas}}$ determination

Evaluation of H$_2$ Fulcher-α transition ($d\,^3\Pi_u \rightarrow a\,^3\Sigma^+_g$, 590 – 650 nm)

- **Analysis 2006**, standard evaluation
  - First 5 emission lines of Q branch ($N' = N''$) for $v' = v'' = 0, 1, 2, 3$
  - $T_{\text{rot}}$ ($v' = 2$) in $d\,^3\Pi_u$ state projected to ground state $\rightarrow T_{\text{gas}}$

- **Improved analysis**:
  - **First 12 emission lines** of Q branch, **populations calculated in ground state**
  - Transfer to excited state via $e^-$ impact rate coefficients & fit to measurement (all $v'$)

Droplines show positions of the Q lines ($N' = N''$) for $v' = 0$, $v' = 1$, $v' = 2$ & $v' = 3$
Improved Fulcher-\(\alpha\) analysis for \(T_{\text{gas}}\) determination

Analysis 2006: Mystery of gas temperature increase from driver to PG

\[ T_{\text{gas}}(\text{driver}) \approx 1000 \text{ K} < T_{\text{gas}}(\text{PG}) \approx 1200 - 1500 \text{ K} \]

Current campaign, standard Fulcher-\(\alpha\) evaluation

\(T_{\text{gas}}(\text{driver}) = 820 \text{ K} < T_{\text{gas}}(\text{PG}) = 1100 \text{ K}\)

\(\Rightarrow\) slightly lower values
\(\Rightarrow\) increase also present

Boltzmann plot

In front of plasma grid:
\(T_{\text{rot}} = T_{\text{gas}} = 1100 \text{ K}\)

Driver:
\(T_{\text{rot}} = T_{\text{gas}} = 820 \text{ K}\)
Improved Fulcher-$\alpha$ analysis for $T_{\text{gas}}$ determination

**Analysis 2006: Mystery of gas temperature increase from driver to PG**

$$T_{\text{gas}}(\text{driver}) \approx 1000 \text{ K} < T_{\text{gas}}(\text{PG}) \approx 1200 - 1500 \text{ K}$$

**Current campaign, improved Fulcher-$\alpha$ evaluation**

**Two-temperature rotational distribution**

$$n(N) = \tilde{n}(N, T_{\text{rot}, 1}) + \beta n'(N, T_{\text{rot}, 2})$$

- heavy particles, reflects $T_{\text{gas}}$
- wall recombination dissociation of $H_3^+$

$T_{\text{gas}} \approx 630 \text{ K in whole source}$

but

relevance of hot distribution increases towards PG

$T_{\text{gas}}$ determines gas density in front of and in between grids

Consequences for stripping losses!

**Boltzmann plot**

- **Driver:** $T_{\text{rot}, 1} = T_{\text{gas}} = 636 \text{ K}$, $T_{\text{rot}, 2} = 4100 \text{ K}$, $\beta = 0.31$
- **In front of plasma grid:** $T_{\text{rot}, 1} = T_{\text{gas}} = 628 \text{ K}$, $T_{\text{rot}, 2} = 4500 \text{ K}$, $\beta = 0.46$

$N' = 12$
Variation of operational parameters

- Gas temperature **not influenced by filter field and RF power**
- $T_{\text{gas}}$ increases with pressure
- $T_{\text{vib}} \approx 3000 \pm 500 \, \text{K}$, constant for all investigations (previously 4000 – 6000 K)
Balmer lines – Line profile analysis

Determination of atomic hydrogen temperature $T_H$
from Doppler broadening of Balmer emission lines

Analysis 2006 ($\Delta \lambda_{\text{FWHM}}^{\text{Apparatus}} \approx 33 \text{ pm}$): $T_H \approx 0.8 \text{ eV}$

Current campaign ($\Delta \lambda_{\text{FWHM}}^{\text{Apparatus}} \approx 15 \text{ pm}$)
at all LOS similar results

- **Single Gaussian** fit: $T_H \approx 0.8 \text{ eV}$
- **Two-Gaussian** fit: $T_{H, \text{cold}} \approx 0.3 \text{ eV}$
  $T_{H, \text{hot}} \approx 3.7 \text{ eV}$
- **Two-Gaussian** fit, considering **fine structure**:
  $T_{H, \text{cold}} \approx 0.23 \text{ eV}$
  $T_{H, \text{hot}} \approx 3.6 \text{ eV}$
- **$H_\gamma$ 2nd order** ($\Delta \lambda_{\text{FWHM}}^{\text{Apparatus}} \approx 9 \text{ pm}$)
  Two-Gaussian fit, considering **fine structure**
  $T_{H, \text{cold}} \approx 0.19 \text{ eV} \approx 2200 \pm 700 \text{ K}$
  $T_{H, \text{hot}} \approx 2.5 \text{ eV}$ (suggests Franck Condon energy)
Consequence on conversion yield of H to H\(^-\) at cesiated surfaces

- **Analysis 2006:** \(T_H \approx 0.8\) eV results in **conversion yield of 12.5%**
- **Current campaign:** \(T_{H,\text{cold}} \approx 0.19\) eV, \(T_{H,\text{hot}} \approx 2.5\) eV, share 50% each (emissivity ratio)
  \[ \rightarrow 0.3\% \rightarrow 25\% \text{ conversion yield} \]

**Total conversion yield: 12.6%**
Application of collisional radiative (CR) models

- CR models predict population densities in dependence on plasma parameters
- Application of **CR models Yacora H and Yacora H\textsubscript{2}**
  
Large effort over the last years for obtaining **reliable and consistent set of cross sections and transition probabilities**  
  
WÜNDERLICH AND FANTZ, ATOMS 4 26 (2016)

- **Yacora on the Web**
  
Visit [www.yacora.de](http://www.yacora.de)

**Providing CR models for plasma spectroscopists**

- Available up to now: H, H\textsubscript{2} & He
- Extensive documentation
- Easy to register

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**Potential curves of H\textsubscript{2} / energy level diagram of H**
Evaluating $T_e$, $n_e$ and $H/H_2$ density ratio

Evaluating OES data with Yacora H & Yacora $H_2$

- Analysis of line ratios gives rough estimates
- Full evaluation gives detailed picture!

⇒ Fit of all emissivities of atomic $H_\alpha - H_\delta$ lines & molecular Fulcher-$\alpha$ transition

Parameters: $T_e$, $n_e$, densities of neutral & ionic species

Excitation of atomic hydrogen...

...in ionizing...

...and recombining plasmas

Huge number of free parameters ⇒ Evaluation needs experience
Results for electron density and temperature

Influence of filter field on plasma parameters

- **Driver**
  - $T_e$ constant at 10.6 eV
  - $n_e$ constant around $8 \times 10^{17}$ m$^{-3}$

- **Expansion region**
  - Reduced $n_e$ & $T_e$ compared to driver
  - Expansion cools plasma

- $n_e$ & $T_e$ not influenced by filter field

- **In front of PG**
  - $n_e$ further reduced
  - $T_e$ decreases strongly with higher filter field
  - No difference using $I_{PG}$ or permanent magnets
  - Reasonable agreement with Langmuir probe data
Results for electron density and temperature

Influence of pressure on plasma parameters

- Driver and PG results compared to those of 2006 campaign
  
  $T_e$ similar to analysis 2006, $n_e$ now slightly lower but with higher reliability due to improved evaluation and absence of strong B field gradients (better uniformity along LOS)

- New insight in expansion region
Results for $H/H_2$ density ratio

Variation of filter field strength and pressure

- **Analysis 2006**: $H/H_2$ (driver) = 0.35 and $H/H_2$ (PG) = 0.2, slight increase with pressure
- **Current campaign**: $0.3 \pm 0.1$ in whole source
  within the error bars: no dependence on filter field strength and pressure range

High uncertainty $\Rightarrow$ independent method would be desirable, e.g. TALIF
Comparison of OES results for BUG and ELISE

Comparison for driver plasma

Moderate spectral resolution at ELISE

Different positioning of LOS

0.3 Pa, 70 kW/driver, filter field 3.5 mT

ELISE upper right driver
Summary and Outlook

New insights from OES investigations due to improved setup and analysis

- Plasma parameters of expansion region now accessible
- Two-temperature rotational distribution in H$_2$, $T_{\text{cold}}$ represents $T_{\text{gas}}$
- Two ensembles of $T_H$
- All three LOS: no difference between $I_{\text{PG}}$ or permanent magnets

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<thead>
<tr>
<th></th>
<th>Analysis 2006</th>
<th>Current campaign</th>
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<tbody>
<tr>
<td>$T_{\text{gas}}$</td>
<td>1000 – 1200 K</td>
<td>630 K</td>
</tr>
<tr>
<td>$T_{\text{vib}}$</td>
<td>4000 – 6000 K</td>
<td>3000 K</td>
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<tr>
<td>$T_H$</td>
<td>0.8 eV ≈ 9300 K</td>
<td>2200 K &amp; 2.5 eV</td>
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<tr>
<td>$n_H / n_{H_2}$</td>
<td>driver 0.35, PG 0.2</td>
<td>0.3 ± 0.1</td>
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<tr>
<td>0.6 Pa, driver $T_e$, $n_e$</td>
<td>6 eV, 2×10$^{18}$m$^{-3}$</td>
<td>9 eV, 2×10$^{18}$m$^{-3}$</td>
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Outlook

- Characterize vertical uniformity in front of PG
- Investigate influence of caesium on plasma parameters
- Repeat analysis for D$_2$ campaign to clarify isotope effects