# Spectroscopic Investigations of the Ion Source at BATMAN Upgrade

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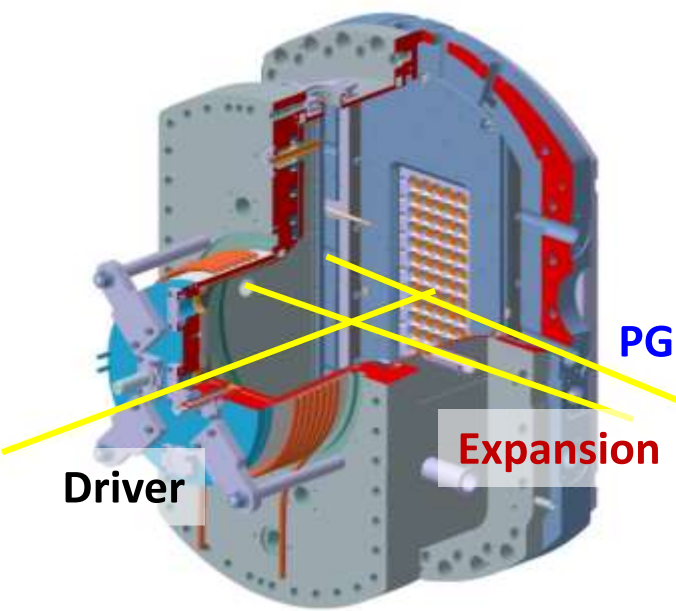



- Improved OES setup and analysis
- Gas temperature and $T_H$
- Plasma parameters $n_e$ and $T_e$
- Density ratio $H/H_2$

# Prototype RF ion source – Why again results from OES?

OES investigations were already performed FANTZ ET AL., NUCL. FUSION **46** (2006) S297

**New insights due to**

**Additional diagnostic ports**

**High resolution spectrometer**

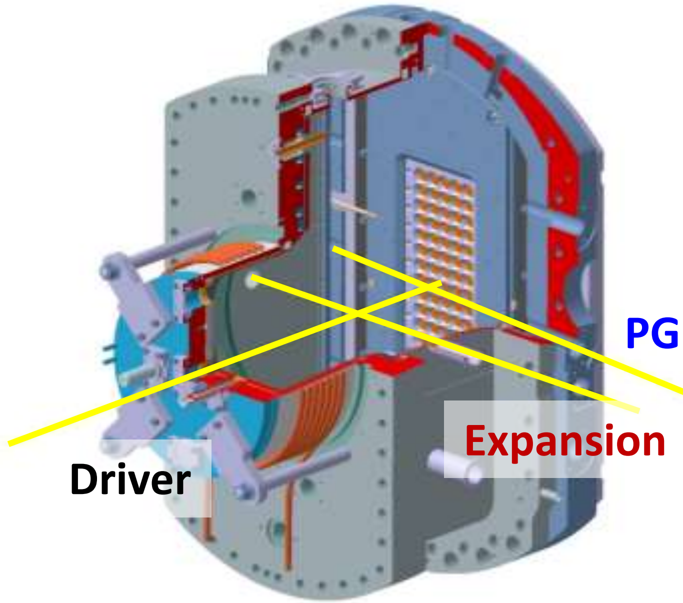
$\Delta\lambda_{FWHM} \approx 15$ pm @ 600 nm

**Improved evaluation**

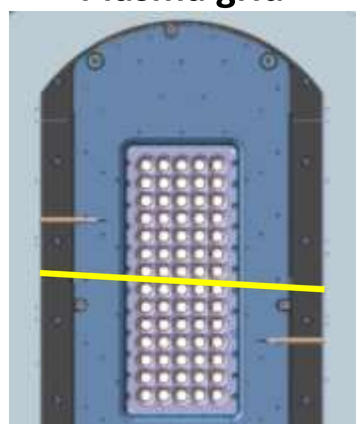
Collisional radiative models

Molecular Fulcher-$\alpha$ band analysis

**Ion source**

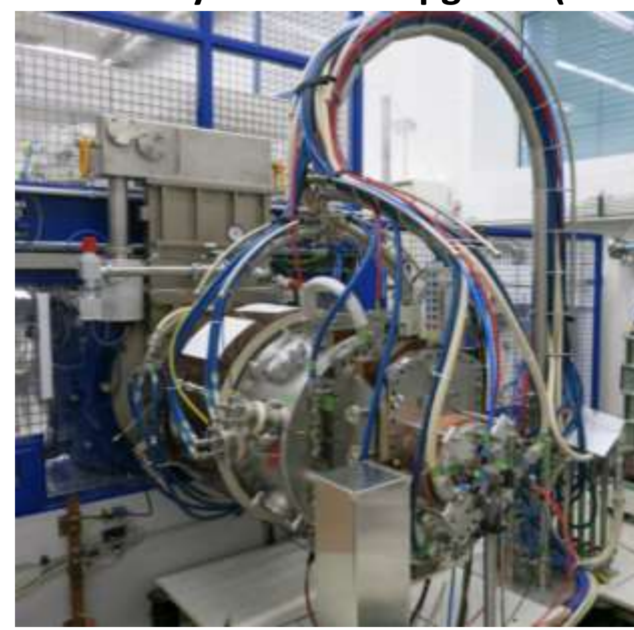



**Plasma grid**



Results of probe measurements: L. Schiesko P1-12

**Test facility BATMAN Upgrade (BUG)**



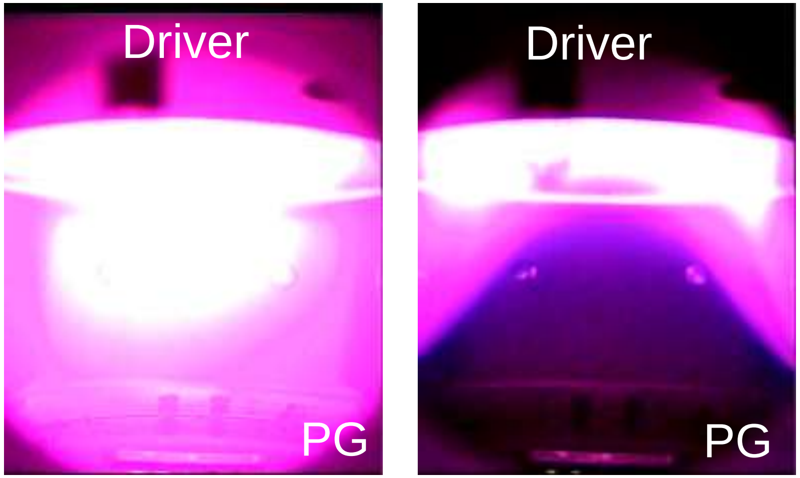
**Results in hydrogen and without caesium in source**

# Filter field configurations at BUG

**Generation of filter field via**

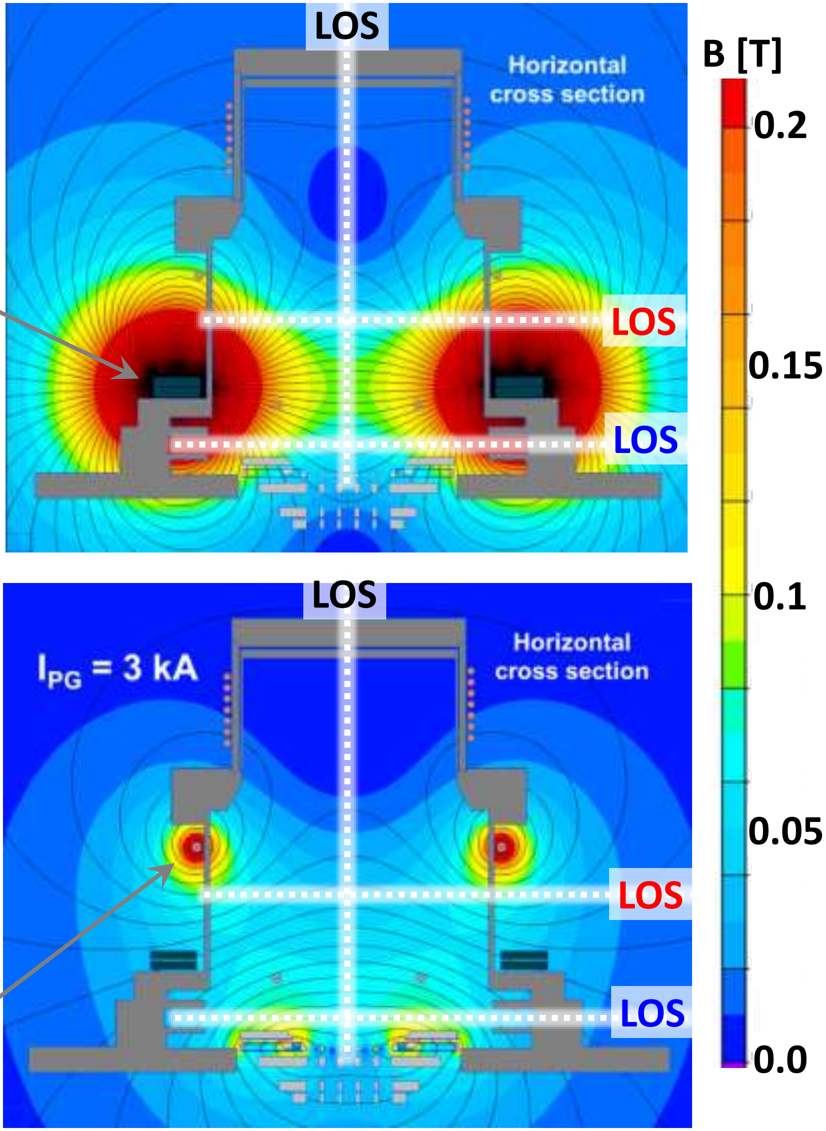
- **Permanent magnets** (old BATMAN)
- **Plasma grid (PG) current**

**No filter field** | **With filter field ($I_{PG}$)**




**View from top to bottom of source**

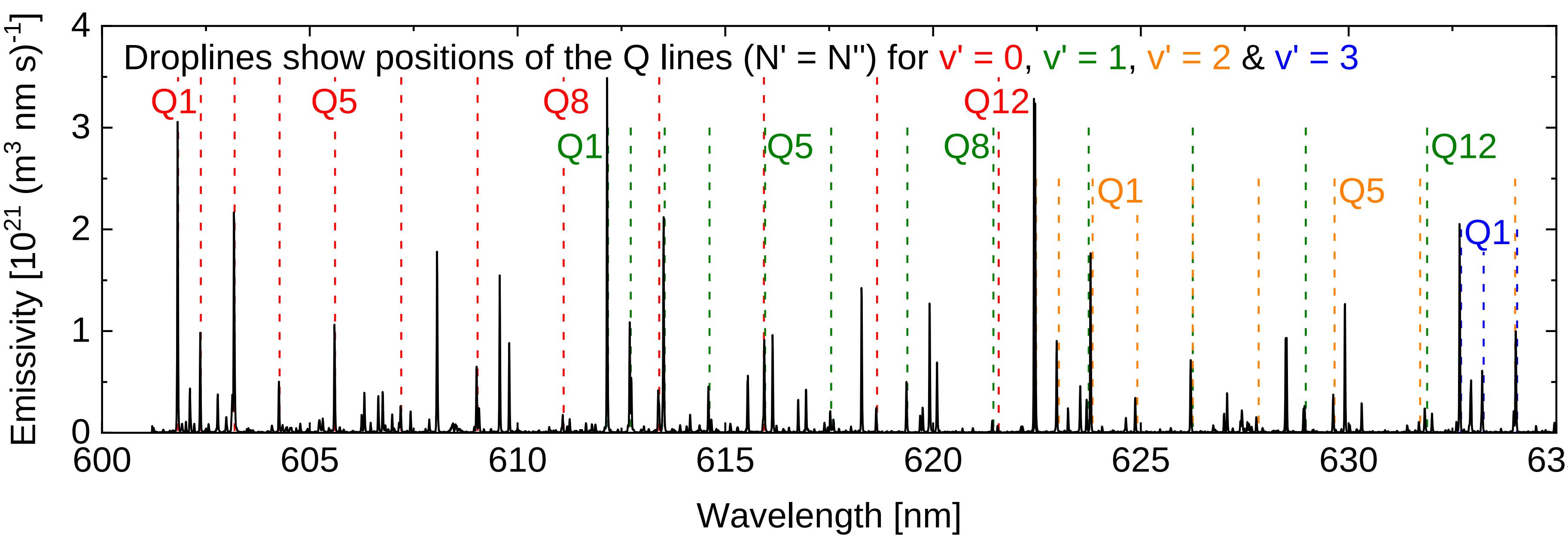
**Filter field pushes plasma towards driver**



# Improved Fulcher-$\alpha$ analysis for $T_{gas}$ determination

## Evaluation of $H_2$ Fulcher-$\alpha$ transition (d $^3\Pi_u$ → 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
  - $T_{rot}$ (v’ = 2) in d $^3\Pi_u$ state projected to ground state → $T_{gas}$
- **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’)



# Improved Fulcher-α analysis for $T_{gas}$ determination

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

$T_{gas}$(driver) ≈ 1000 K **<** **?** $T_{gas}$(PG) ≈ 1200 – 1500 K

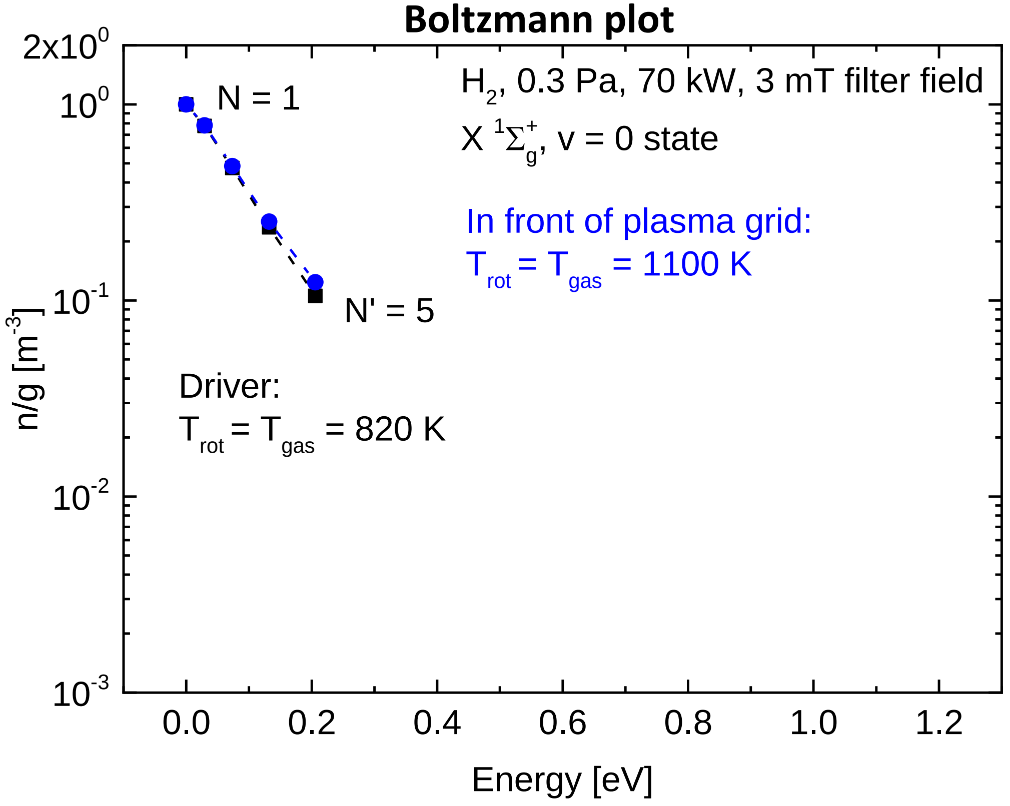
**Current campaign, standard Fulcher-α evaluation**

$T_{gas}$(driver) = 820 K **<** $T_{gas}$(PG) = 1100 K

⇨ slightly lower values

⇨ increase also present

**Boltzmann plot**



# Improved Fulcher-α analysis for $T_{gas}$ determination

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

$T_{gas}$(driver) ≈ 1000 K **<?** $T_{gas}$(PG) ≈ 1200 – 1500 K

### Current campaign, improved Fulcher-α evaluation

**Two-temperature** rotational distribution

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

↑ **heavy particles, reflects $T_{gas}$**

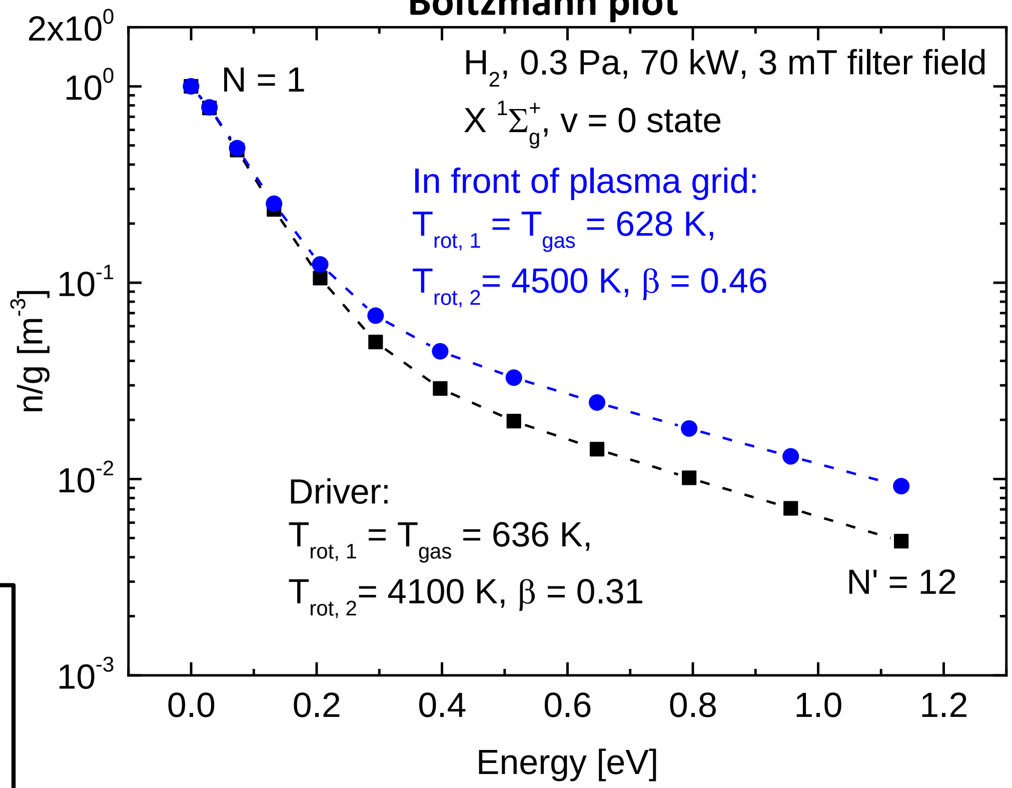
↑ wall recombination dissociation of $H_3^+$

**$T_{gas}$ ≈ 630 K in whole source**

but

relevance of hot distribution increases towards PG

**Boltzmann plot**



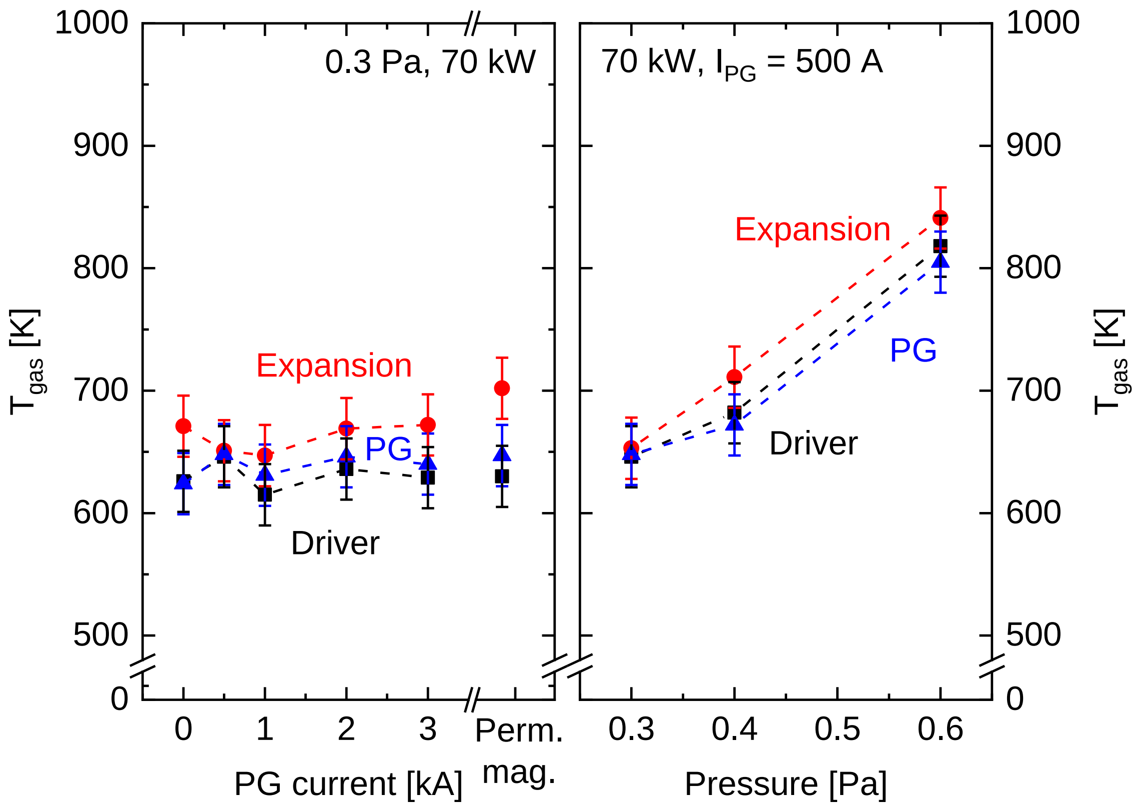

**$T_{gas}$ determines gas density in front of and in between grids**

**Consequences for stripping losses!**

# Results for $T_{gas}$ and $T_{vib}$

## Variation of operational parameters

- Gas temperature **not influenced by filter field and RF power**
- $T_{gas}$ increases with pressure
- **$T_{vib}$ ≈ 3000 ± 500 K**, constant for all investigations (previously 4000 – 6000 K)



## Determination of atomic hydrogen temperature $T_H$

from Doppler broadening of Balmer emission lines

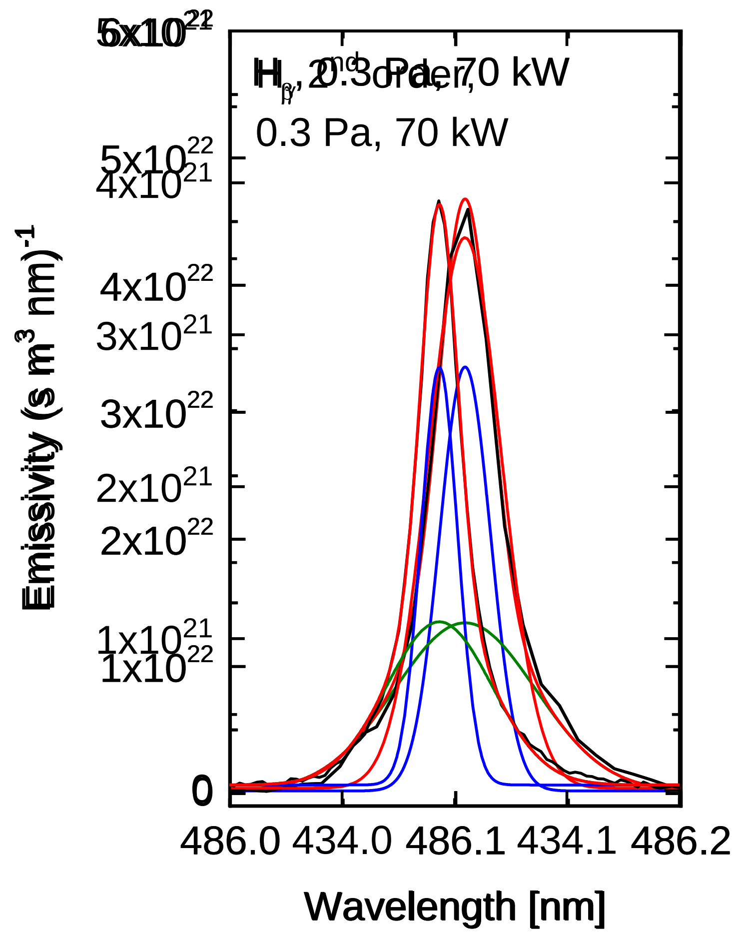
**Analysis 2006** ($\Delta\lambda_{FWHM}^{Apparatus}$ ≈ 33 pm): **$T_H$ ≈ 0.8 eV**

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

- **Single Gaussian** fit: $T_H$ ≈ 0.8 eV
- **Two-Gaussian** fit: $T_{H, cold}$ ≈ 0.3 eV
  $T_{H, hot}$ ≈ 3.7 eV
- **Two-Gaussian** fit, considering **fine structure**:
  $T_{H, cold}$ ≈ 0.23 eV
  $T_{H, hot}$ ≈ 3.6 eV
- **$H_\gamma$ 2nd order** ($\Delta\lambda_{FWHM}^{Apparatus}$ ≈ 9 pm)
  **Two-Gaussian** fit, considering **fine structure**

**$T_{H, cold}$ ≈ 0.19 eV ≈ 2200 ± 700 K > $T_{gas}$ ≈ 650 K**

**$T_{H, hot}$ ≈ 2.5 eV** (suggests Franck Condon energy)

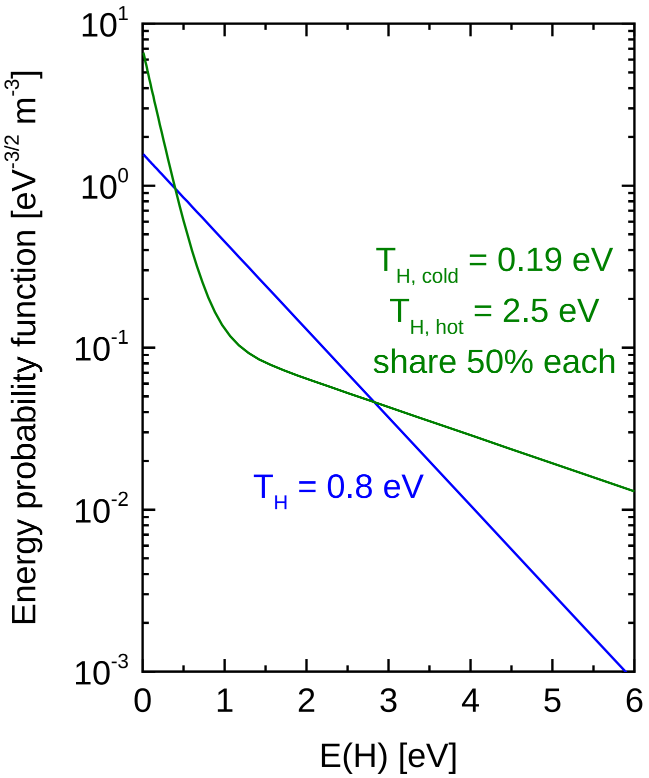


# Balmer lines – Line profile analysis

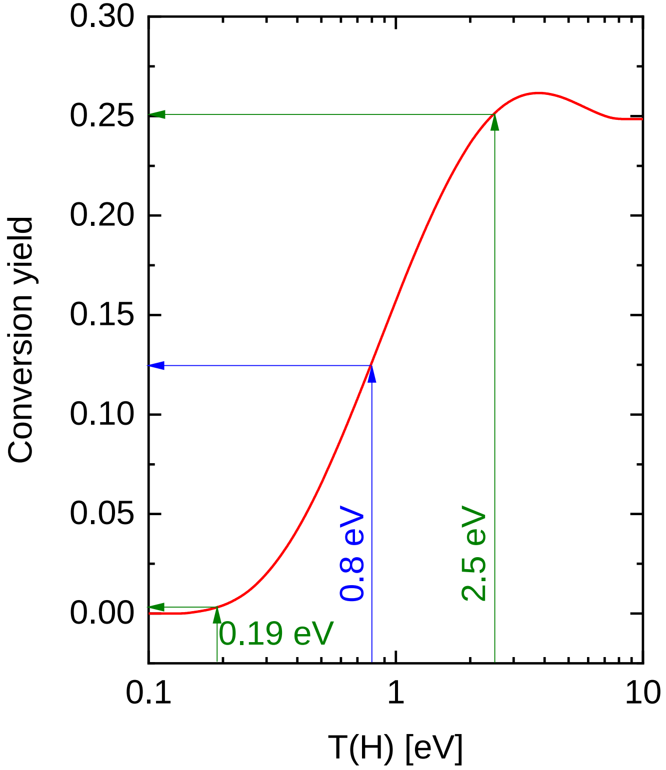
## Consequence on conversion yield of H to $H^-$ at cesiated surfaces

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

**Total conversion yield: 12.6%**




Lee et al, Appl. Phys. Lett. 61, 2857 (1992)



# Evaluating $T_e$, $n_e$ and $H/H_2$ density ratio

## Application of collisional radiative (CR) models

- CR models predict population densities in dependence on plasma parameters
- Application of **CR models Yacora H and Yacora $H_2$**

  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)

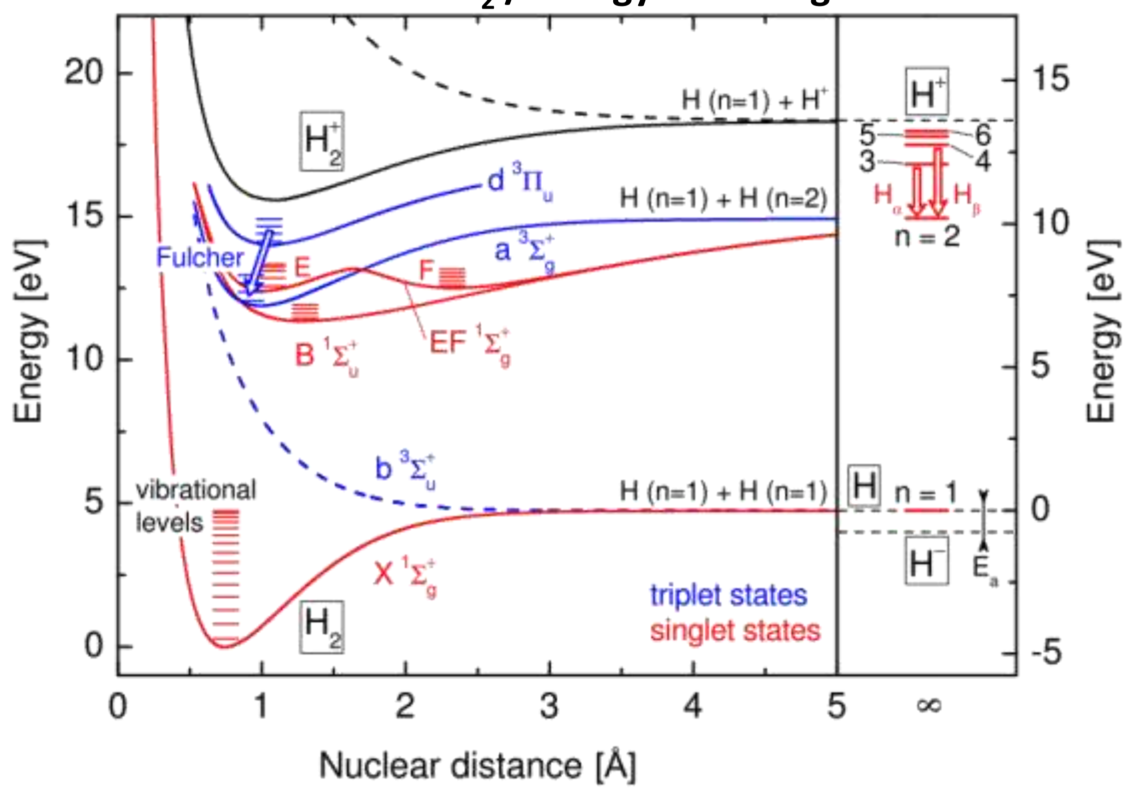
- **Yacora on the Web**

  Visit **www.yacora.de**

  **Providing CR models for plasma spectroscopists**

  - Available up to now: H, $H_2$ & He
  - Extensive documentation
  - Easy to register

**Potential curves of $H_2$ / energy level diagram of H**



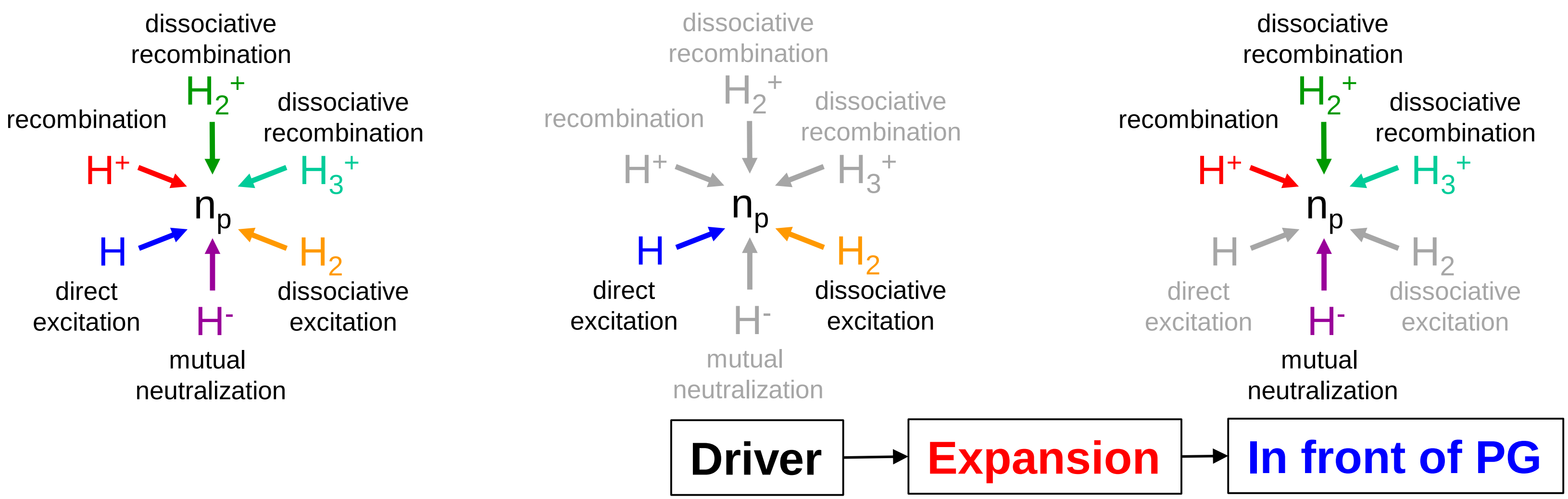
# Evaluating $T_e$, $n_e$ and $H/H_2$ density ratio

## 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-α** transition
Parameters: **$T_e$, $n_e$, densities of neutral & ionic species**

**Excitation of atomic hydrogen… …in ionizing… …and recombining plasmas**

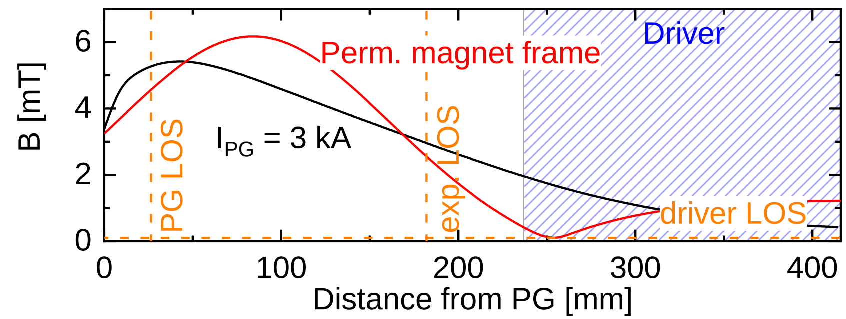


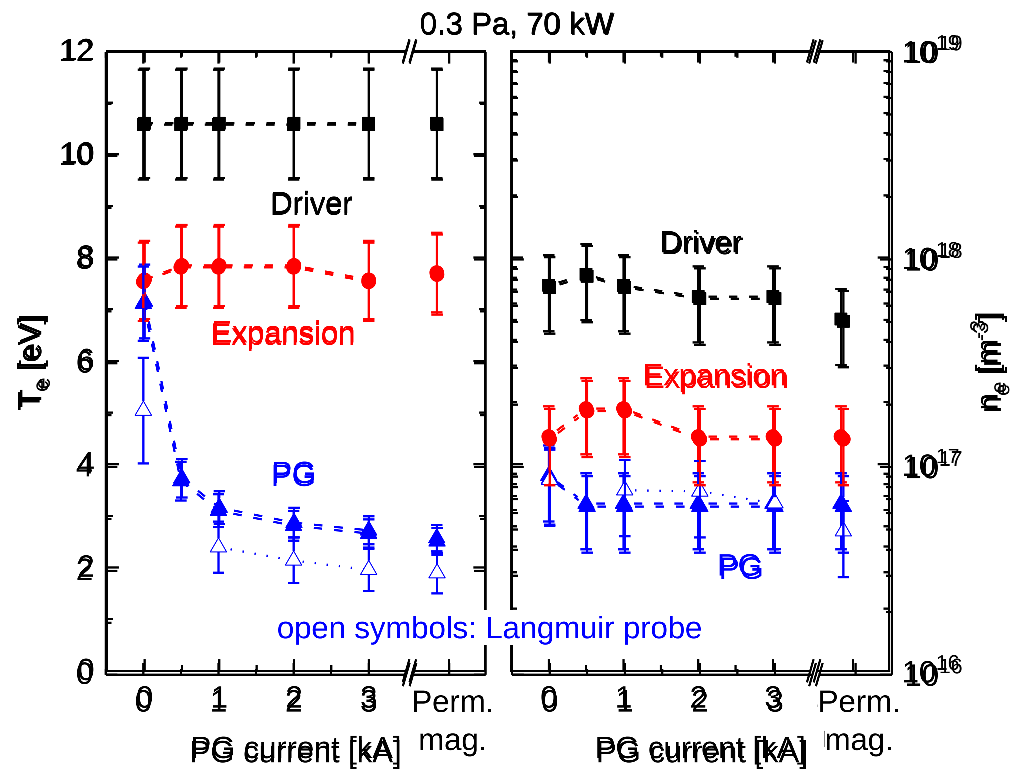

**Huge number of free parameters ⇒ Evaluation needs experience**

# 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 x $10^{17}$ $m^{-3}$
- **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



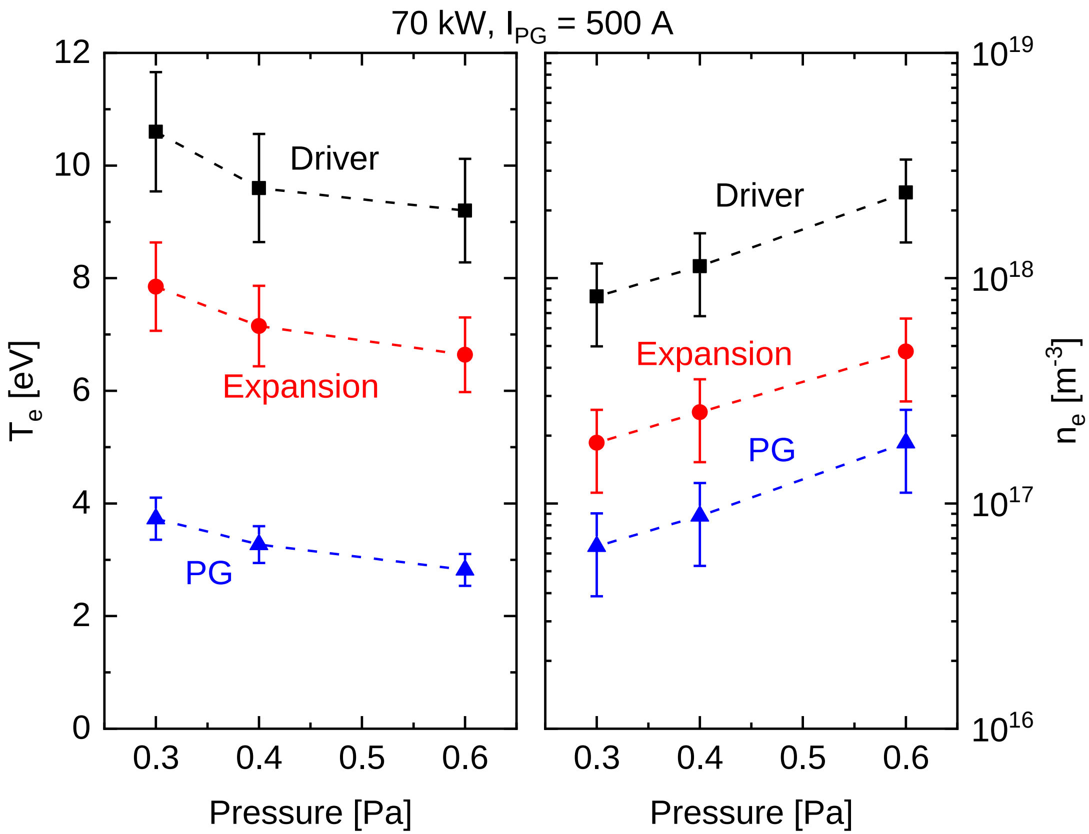
# Results for electron density and temperature

## 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**

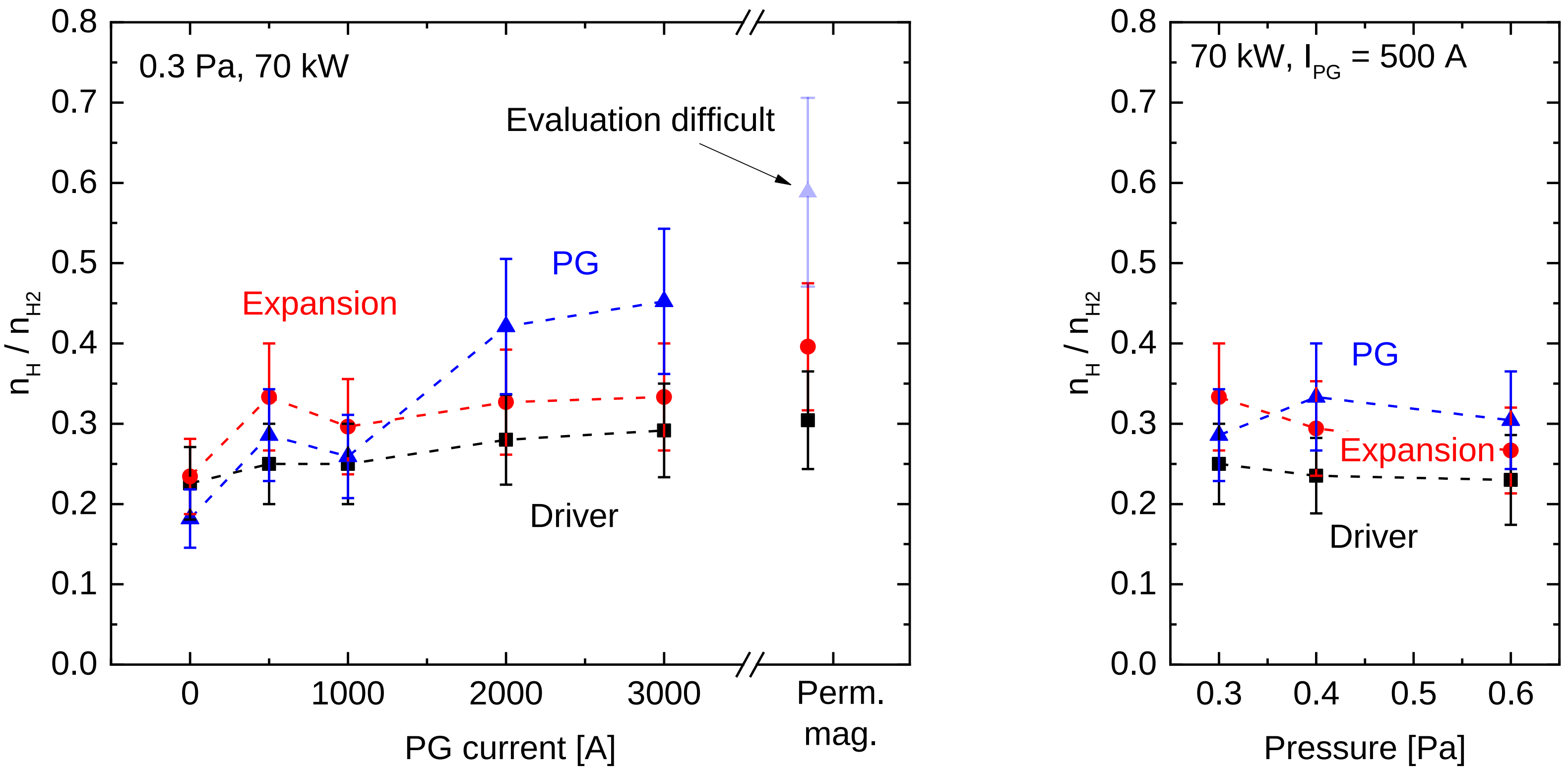


# Results for $H/H_2$ density ratio

## 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 ± 0.1 in whole source**

  within the error bars: no dependence on filter field strength and pressure range




**High uncertainty ⇨ independent method would be desirable, e.g. TALIF**

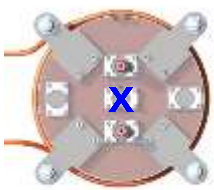
# Comparison of OES results for BUG and ELISE

## Comparison for driver plasma

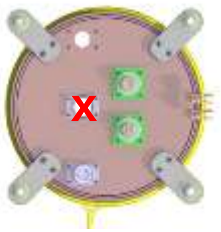
Moderate spectral resolution at ELISE

Different positioning of LOS

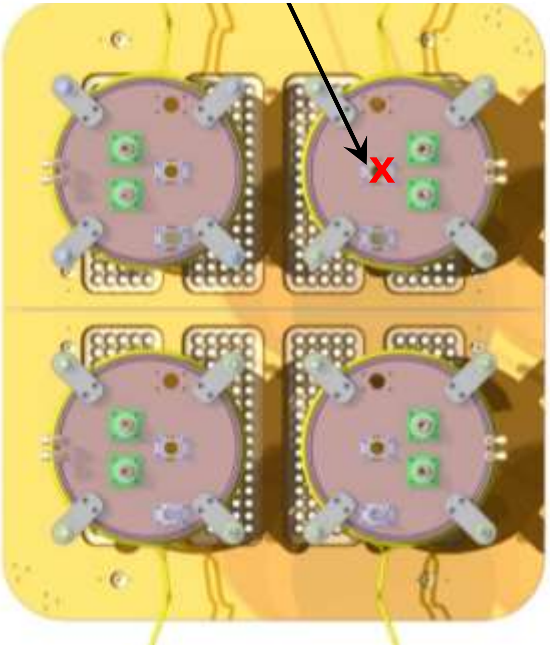
**BUG**
**ID 23.7 cm**



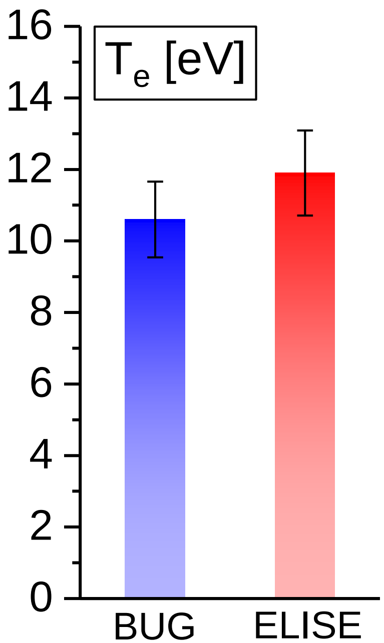

**ELISE**
**ID 27.6 cm**

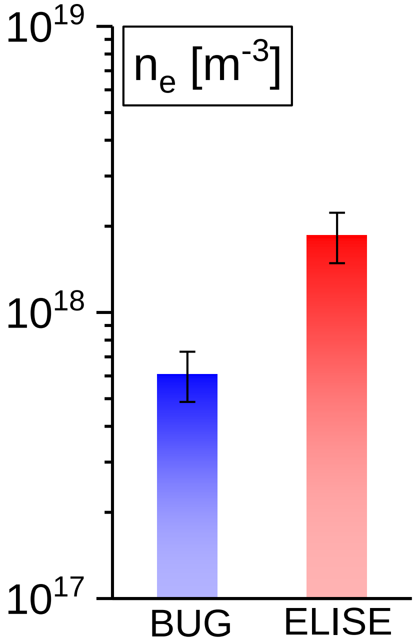


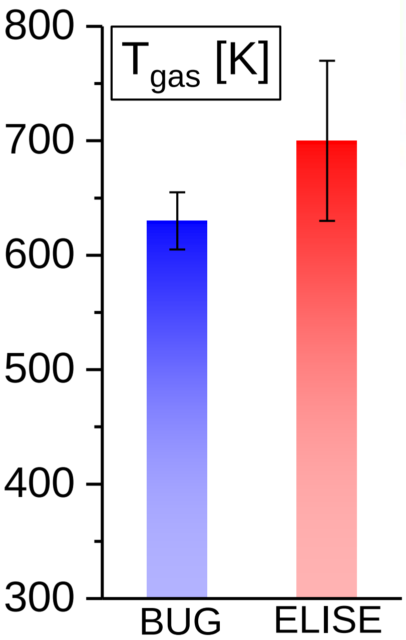

**ELISE upper right driver**




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



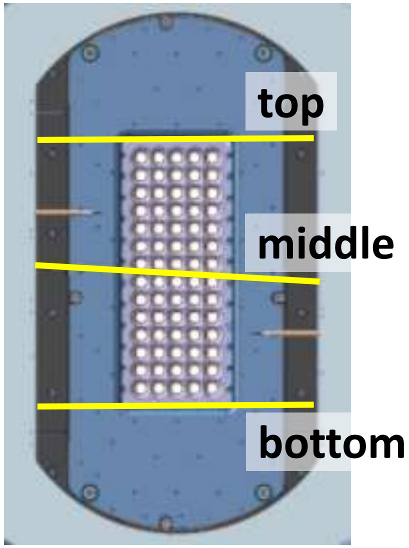



# Summary and Outlook

## New insights from OES investigations due to improved setup and analysis

- Plasma parameters of **expansion region now accessible**
- **Two-temperature rotational distribution in $H_2$**, $T_{cold}$ represents $T_{gas}$
- **Two ensembles of $T_H$**
- All three LOS: **no difference between $I_{PG}$ or permanent magnets**

| | Analysis 2006 | Current campaign |
|---|---|---|
| $T_{gas}$ | 1000 – 1200 K | 630 K |
| $T_{vib}$ | 4000 – 6000 K | 3000 K |
| $T_H$ | 0.8 eV ≈ 9300 K | 2200 K & 2.5 eV |
| $n_H / n_{H_2}$ | driver 0.35, PG 0.2 | 0.3 ± 0.1 |
| 0.6 Pa, driver $T_e$, $n_e$ | 6 eV, $2 \times 10^{18} m^{-3}$ | 9 eV, $2 \times 10^{18} m^{-3}$ |




## 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