



Application of TALIF for the Characterization of Negative Hydrogen Ion Production in Ion Sources for NBI

IPP

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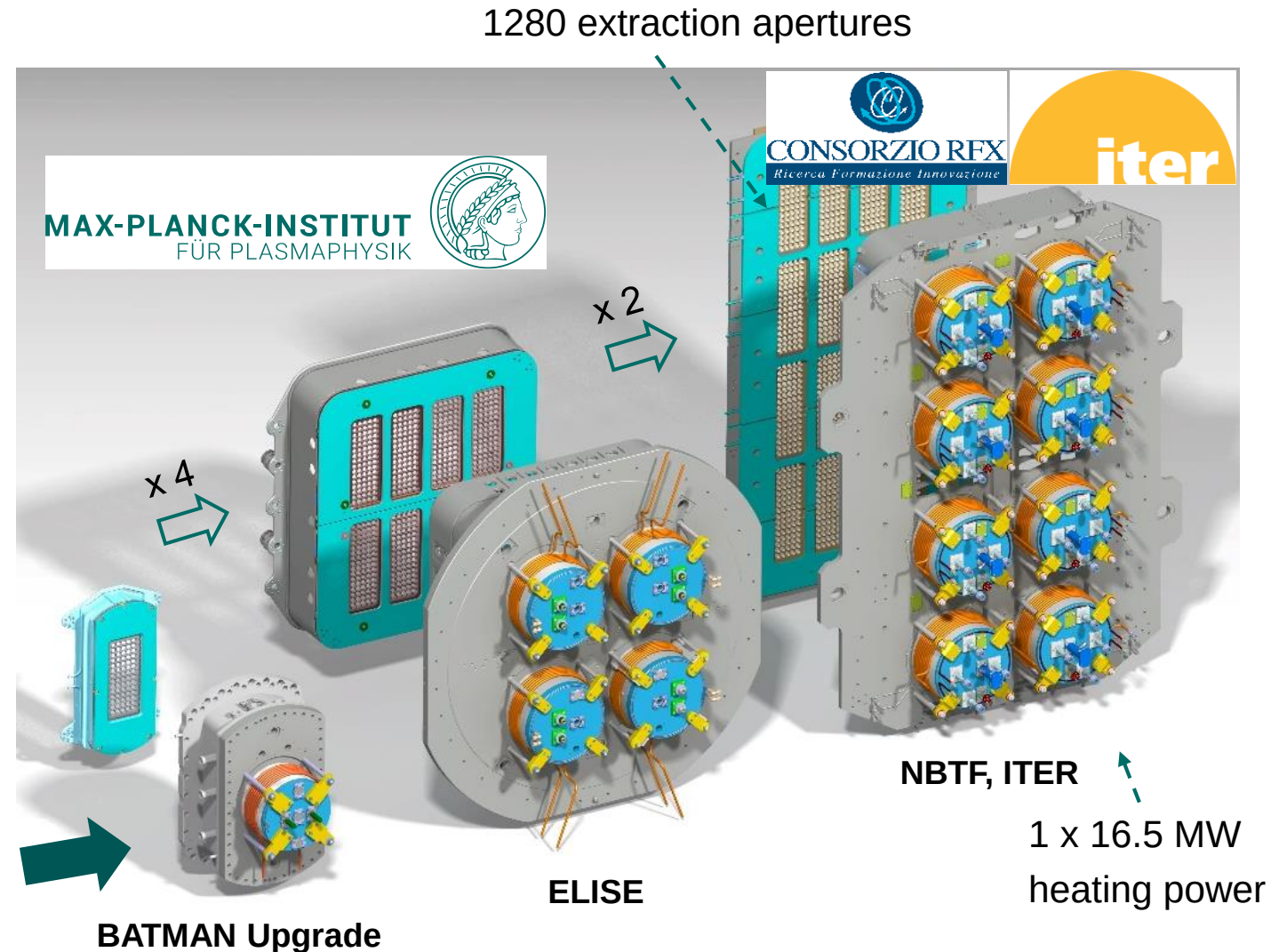


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Introduction to Negative Hydrogen Ion Sources for Fusion

Experimental Facilities for ITER's Neutral Beam Injection

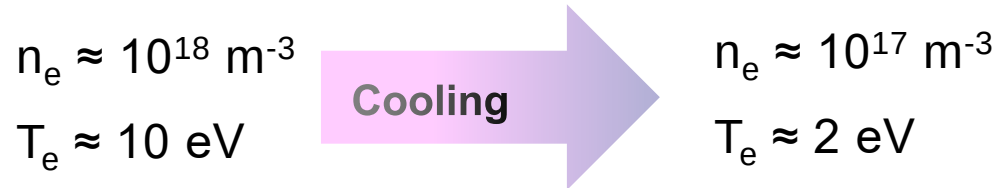
- **Requirements for the ITER NBI**
 - 2 beamlines @ 16.5 MW heating power
 - Up to 1 MeV particle energy
 - Neutralization of H^+ very inefficient
 - Neutralization of H^- only alternative
 - Up to 1h pulse duration
 - H & D operation
- **Requires large negative ion sources**
- **Focus here:** smallest facility BATMAN Upgrade (BUG) as flexible testbed



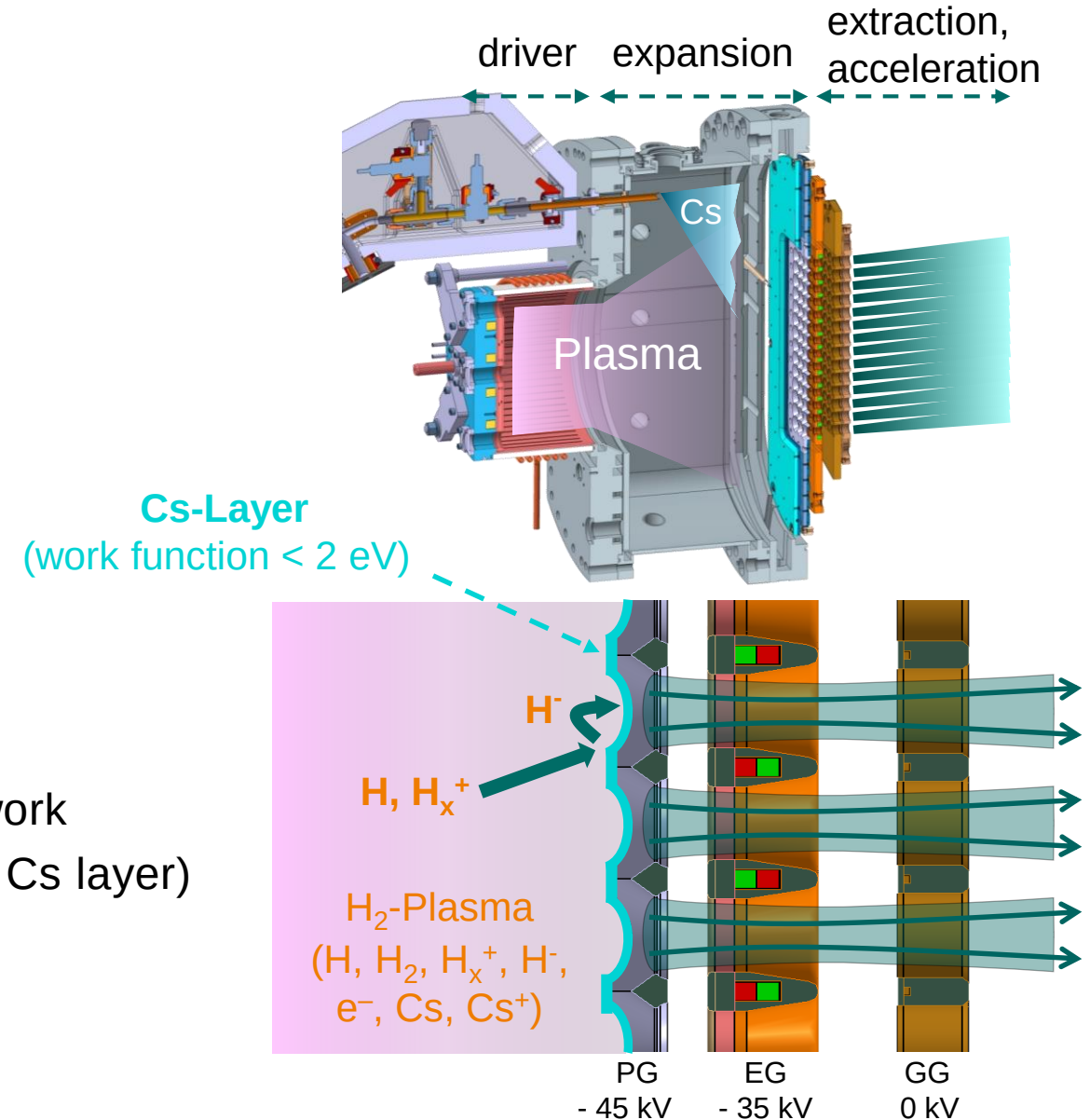
Negative Hydrogen Ion Sources for ITER NBI

BATMAN Upgrade (BUG)

- RF driver generates plasma



- To avoid H^- destruction, cooling through expansion and horizontal magnetic filter field
- Production of negative ions
 - Surface conversion of H (D) and H_x^+ (D_x^+) on low work function (WF) surfaces (Molybdenum covered with Cs layer)



Surface Production of Negative Ions

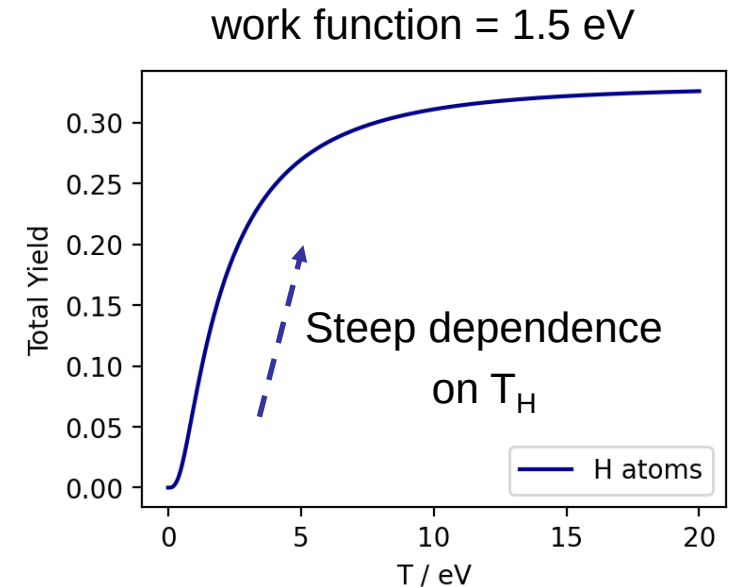
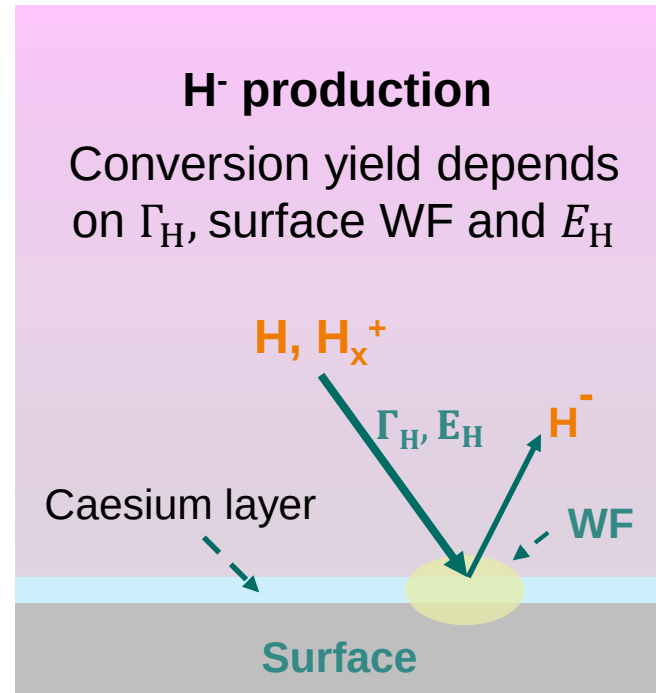
Improve the understanding of H^- / D^- ion sources

H^- surface production depends on:

- Flux of particles (Γ_H , $\Gamma_{H_x^+}$)
- Surface work function (WF)
- Precursor particle energy (E_H , H_x^+ energy distribution function (EDF))

➤ Goal:

- Understanding the process of H^- (D^-) production
- Which channel dominates H (D), H_x^+ (D_x^+)?



H^- conversion yield as function of H atom temperature¹.

¹ Adapted from M. Seidl, H. L. Cui, J. D. Isenberg, et al. Negative surface ionization of hydrogen atoms and molecules. Journal of Applied Physics, 79 (1996), 2896–2901.

➤ Diagnostic for neutral hydrogen (EDF and n_H): Two photon **A**bsorption **L**aser **I**nduced **F**luorescence (TALIF)

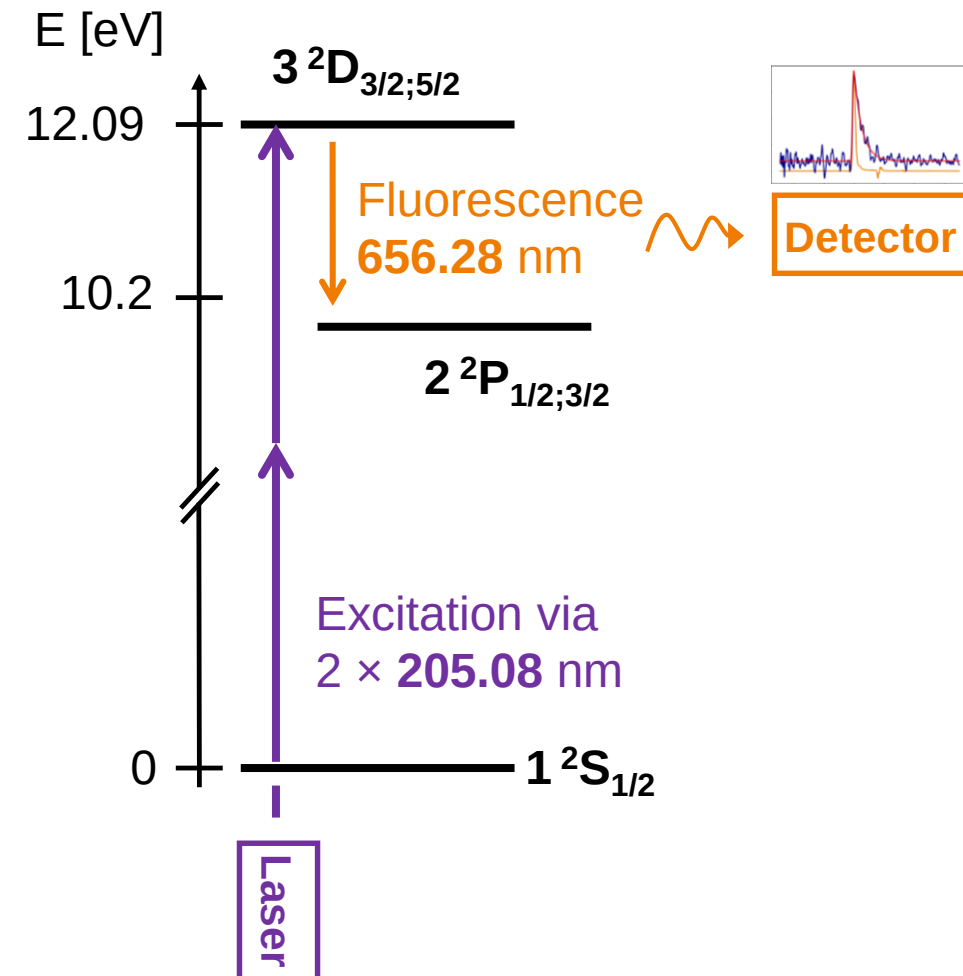
Two photon Absorption Laser Induced Fluorescence

Two photon Absorption Laser Induced Fluorescence (TALIF)

TALIF principle of operation

- H atom excitation by laser ($n=1 \rightarrow n=3$)
 - 2 photons of 205.08 nm
- Avoids problem of single 102 nm photons which are strongly absorbed in air and hydrogen plasma
- Two-photon excitation cross section much smaller
 - High laser intensity needed
 - Advanced laser setup necessary
- Observation of fluorescence light ($n=3 \rightarrow n=2$)
 - Fluorescence at 656.28 nm (Balmer alpha)

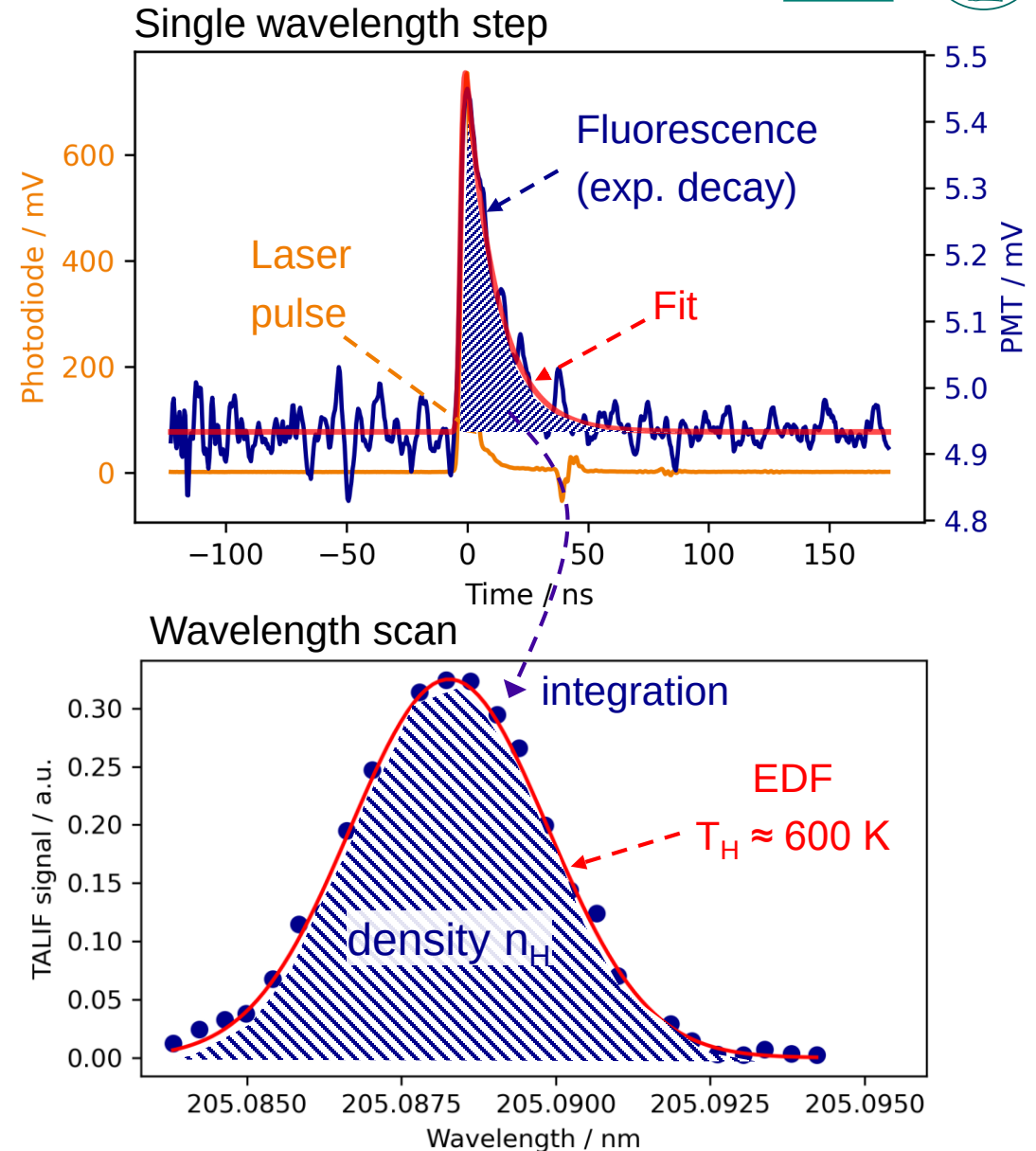
Neutral hydrogen atom



How a TALIF Measurement Works

Wavelength scan needed to resolve EDF and n_H

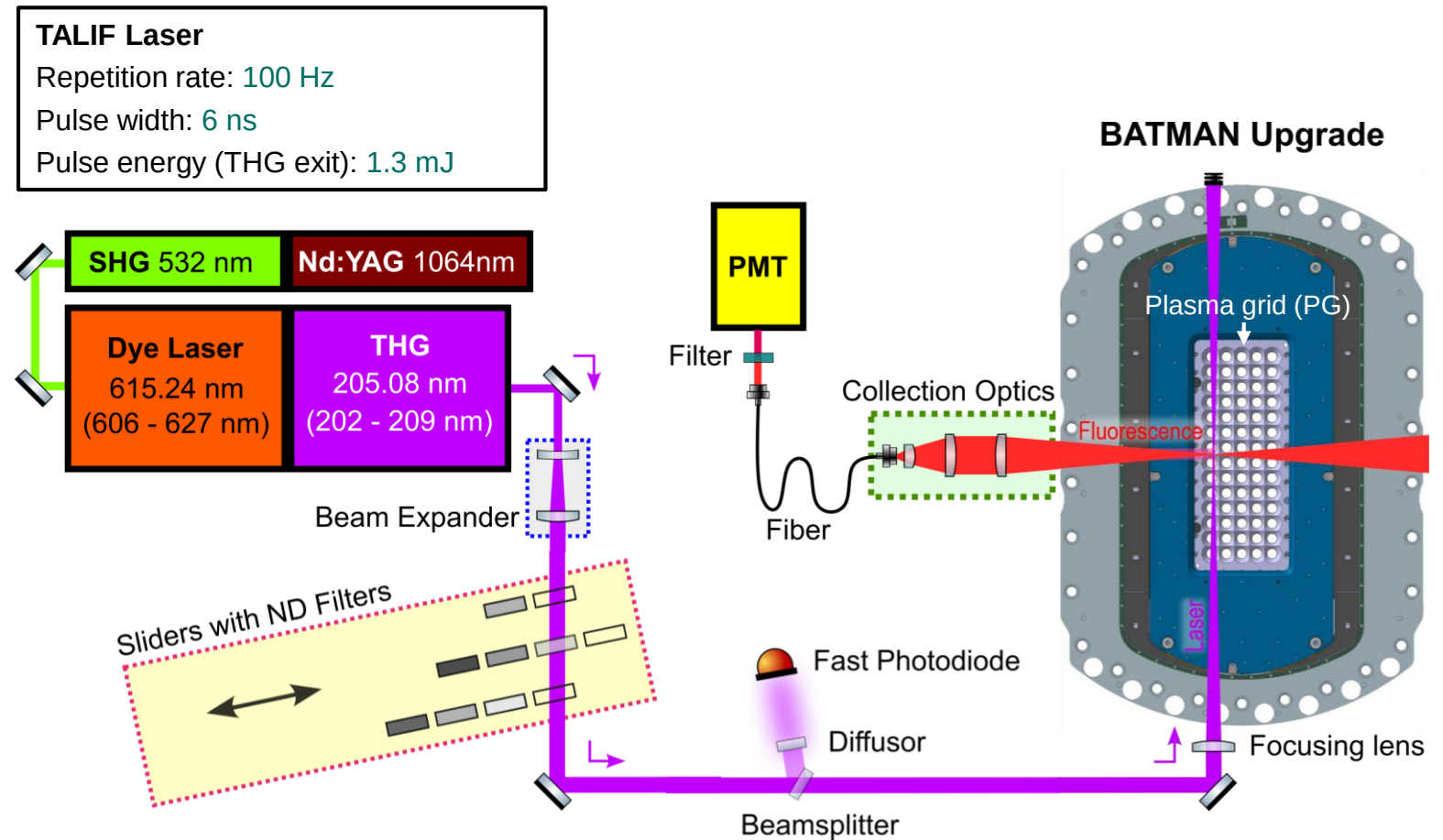
- **Single wavelength measurement:**
 - Fluorescence is measured after each laser pulse with photomultiplier tube (PMT)
 - **Wavelength scan:**
 - Laser wavelength is tuned over two photon absorption resonance
 - Doppler broadened line profile can be resolved
 - Doppler broadening is dominant broadening
 - Temperature / EDF from Gaussian fit
- Density values from EDF integral and calibration with TALIF measurement on reference gas



Experimental Setup

BATMAN Upgrade

- Dye laser with third harmonic generation: 205.08 nm
- Beam expansion: minimize divergence over 12 m
- Variable laser attenuation for calibration (0% - 98%)
- Pulse energy measurement
- Laser focusing into BUG, 2.5 cm in front of PG
- Fluorescence collection optics and photomultiplier tube (PMT)



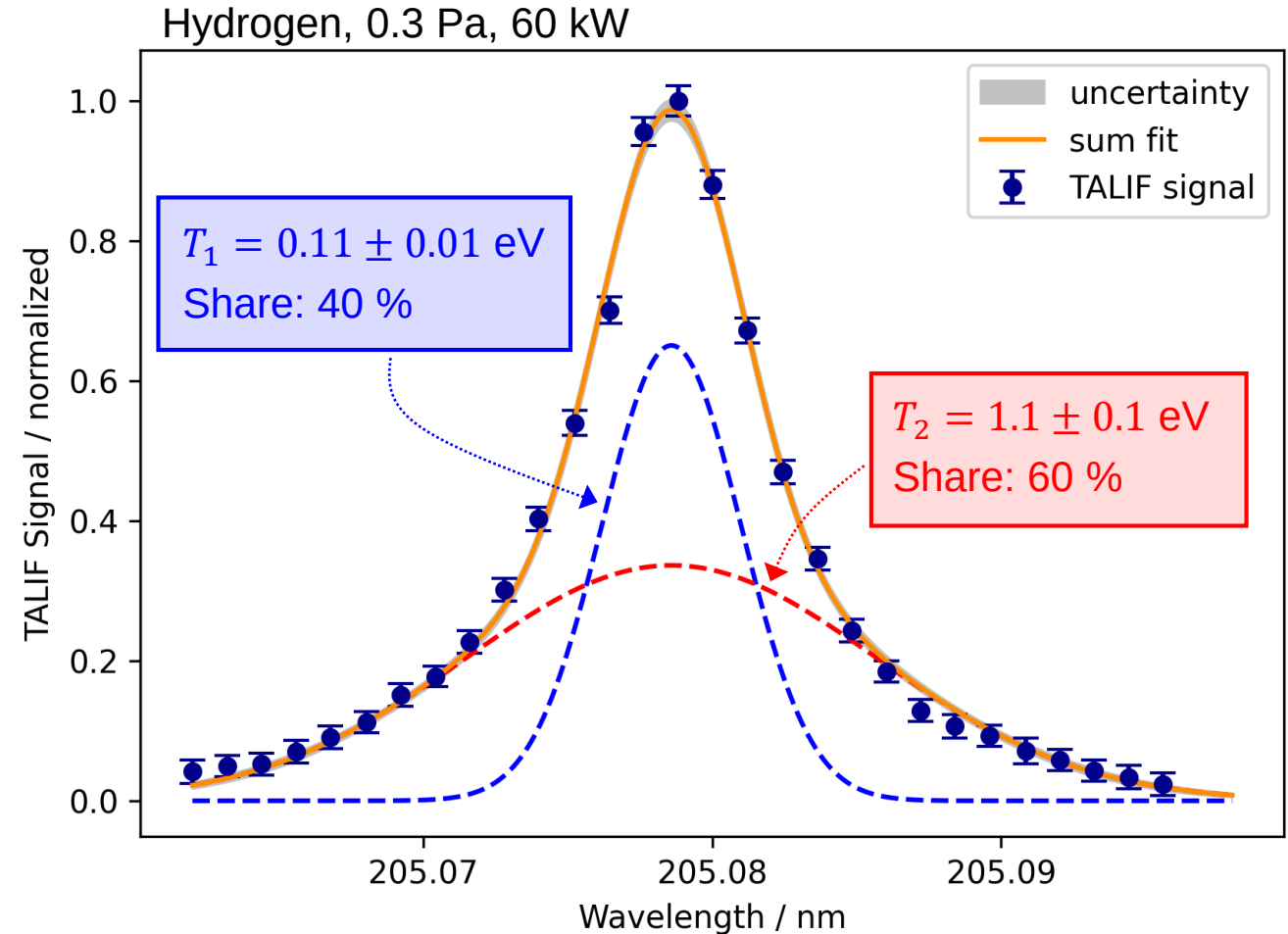
- No standard diagnostics, requires advanced laser setup
- Laser power, attenuation unit, focusing, collection optics and data acquisition was improved

High Resolution of H EDF

Enabled by improved setup

- Setup improvements enable 10 times higher SNR
- High resolution EDF obtained
 - Two temperature EDF in front of PG
- EDF as sum of two gaussians: 3 parameters; two temperatures and their share
- Example: 0.3 Pa, 60 kW
 - 60% hot population $T_{\text{hot}} \approx 1$ eV
 - 40% cold population $T_{\text{cold}} \approx 0.1$ eV

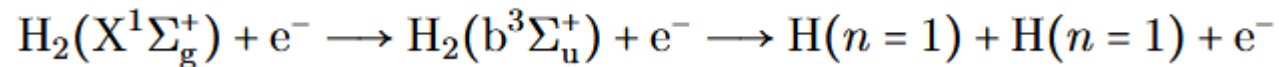
➤ Hot atoms are there! Where do they come from?



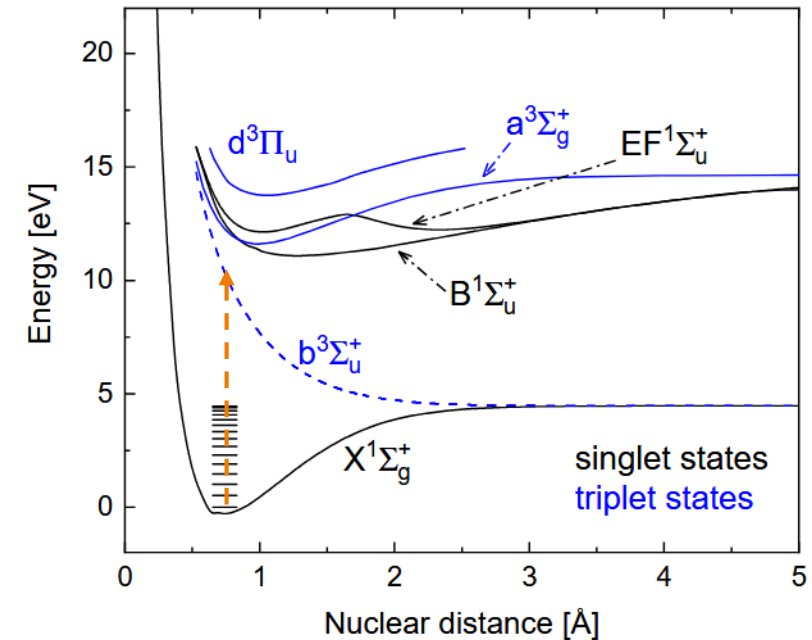
Possible Origin of Hot Temperature

High energetic EDF tail

- **Dissociation of H_2**
 - Dissociation by electron impact dissociation



- Atoms have half the Franck-Condon energy: $E_H \approx 2$ eV
- **Recombination of ions at wall**
 - Acceleration of ions in plasma sheath prior to recombination
 - Hot atoms (up to a few eV) can be reflected back
- **DSMC simulations² suggest similar contributions from both processes**

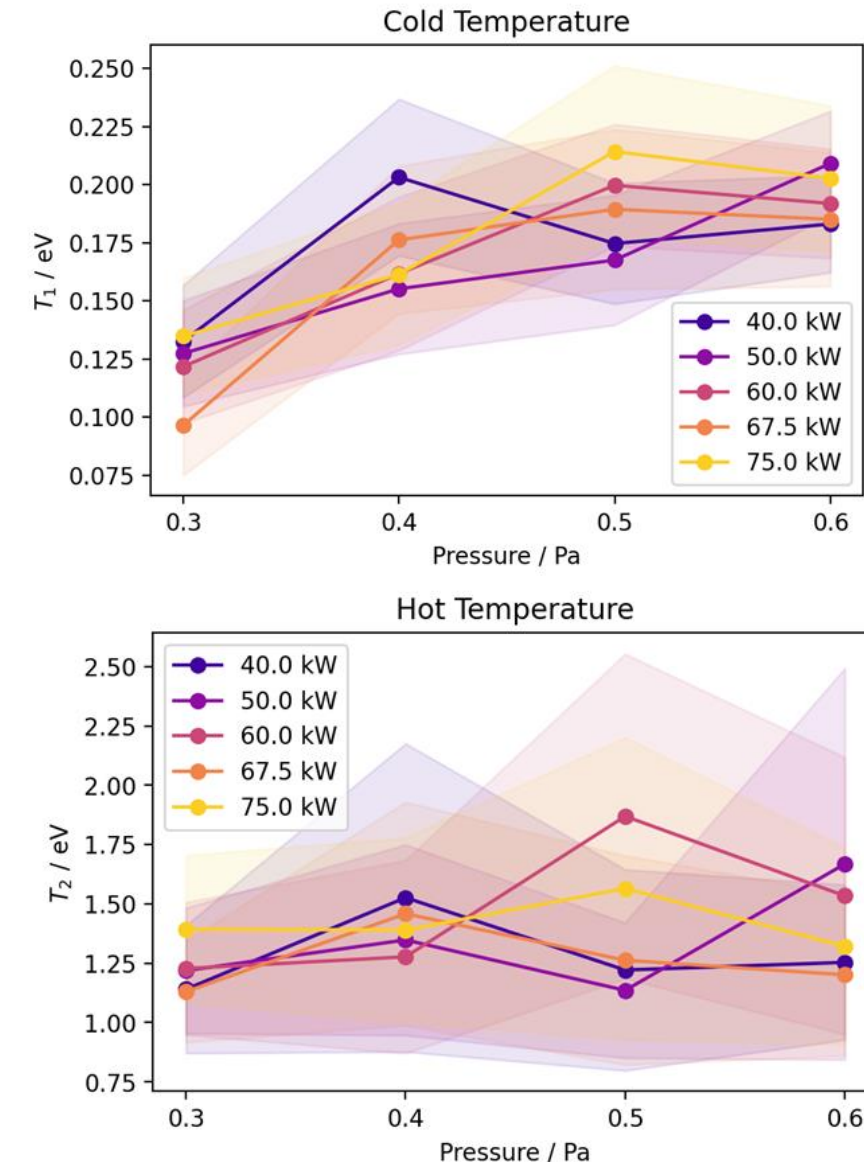


² N. Kohen. Physique et modelisation d'une source d'ions negatifs pour l'injection du faisceau de neutres sur ITER. PhD thesis, Universite de Toulouse III Paul Sabatier, 2015

Source Parameter Variation: Temperatures

0.3 Pa – 0.6 Pa, 40 kW – 75 kW

- **TALIF Characterization of BUG**
 - 2D parameter variation: 20 measurements in total
 - Pressure range: 0.3 Pa – 0.6 Pa
 - RF power range: 40 kW – 75 kW
 - **Cold Temperature**
 - $\bar{T}_{\text{cold}} = 0.165 \text{ eV}$
 - Significant change observed between 0.3 Pa and 0.4 Pa
 - **Hot Temperature**
 - $\bar{T}_{\text{hot}} = 1.35 \text{ eV}$
 - T_{hot} does not change much within uncertainty
- Possible to fix T_{hot} to its mean value of 1.35 eV to reduce free parameters to 2 - does not worsen fit

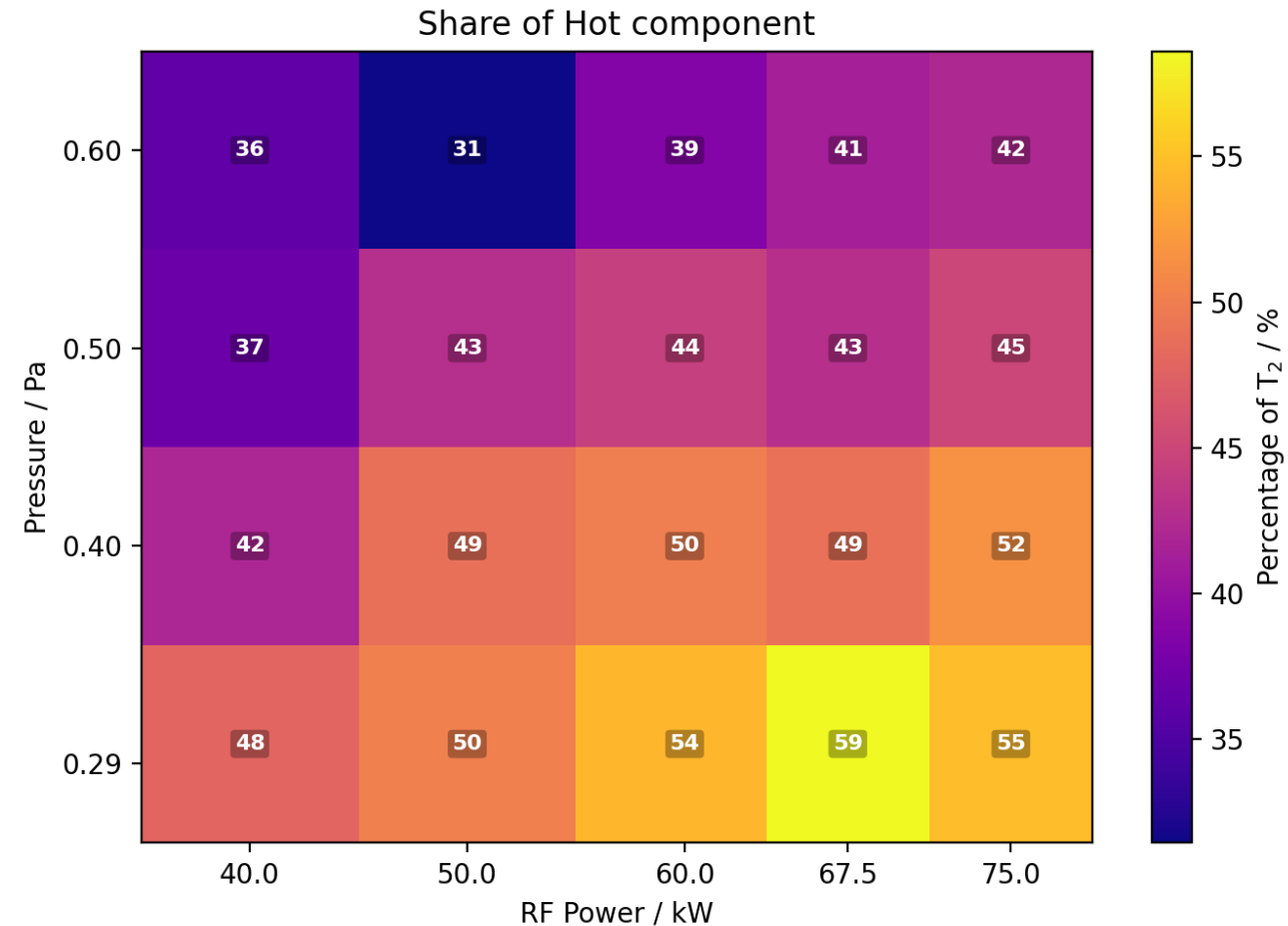


Source Parameter Variation: Temperatures

0.3 Pa – 0.6 Pa, 40 kW – 75 kW

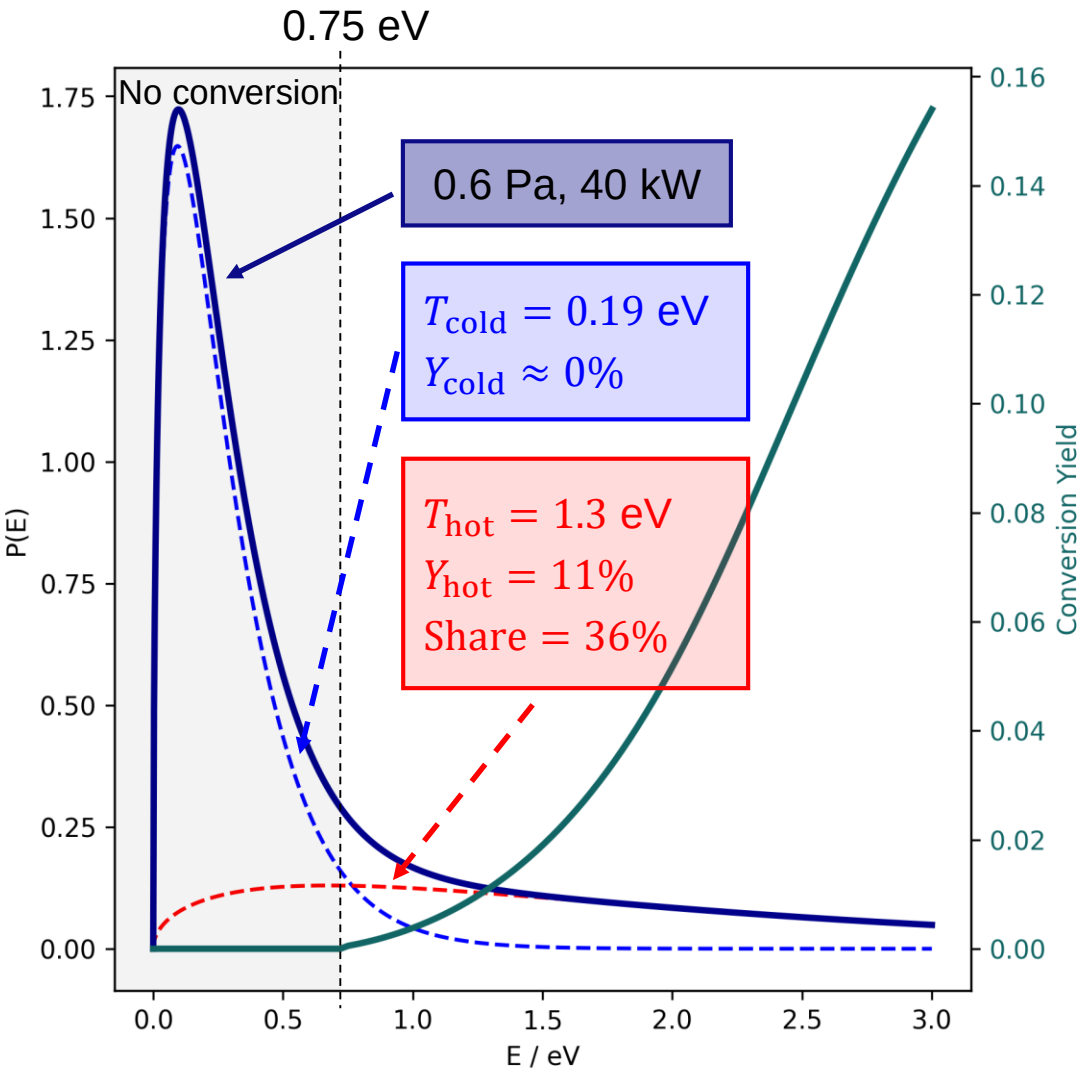
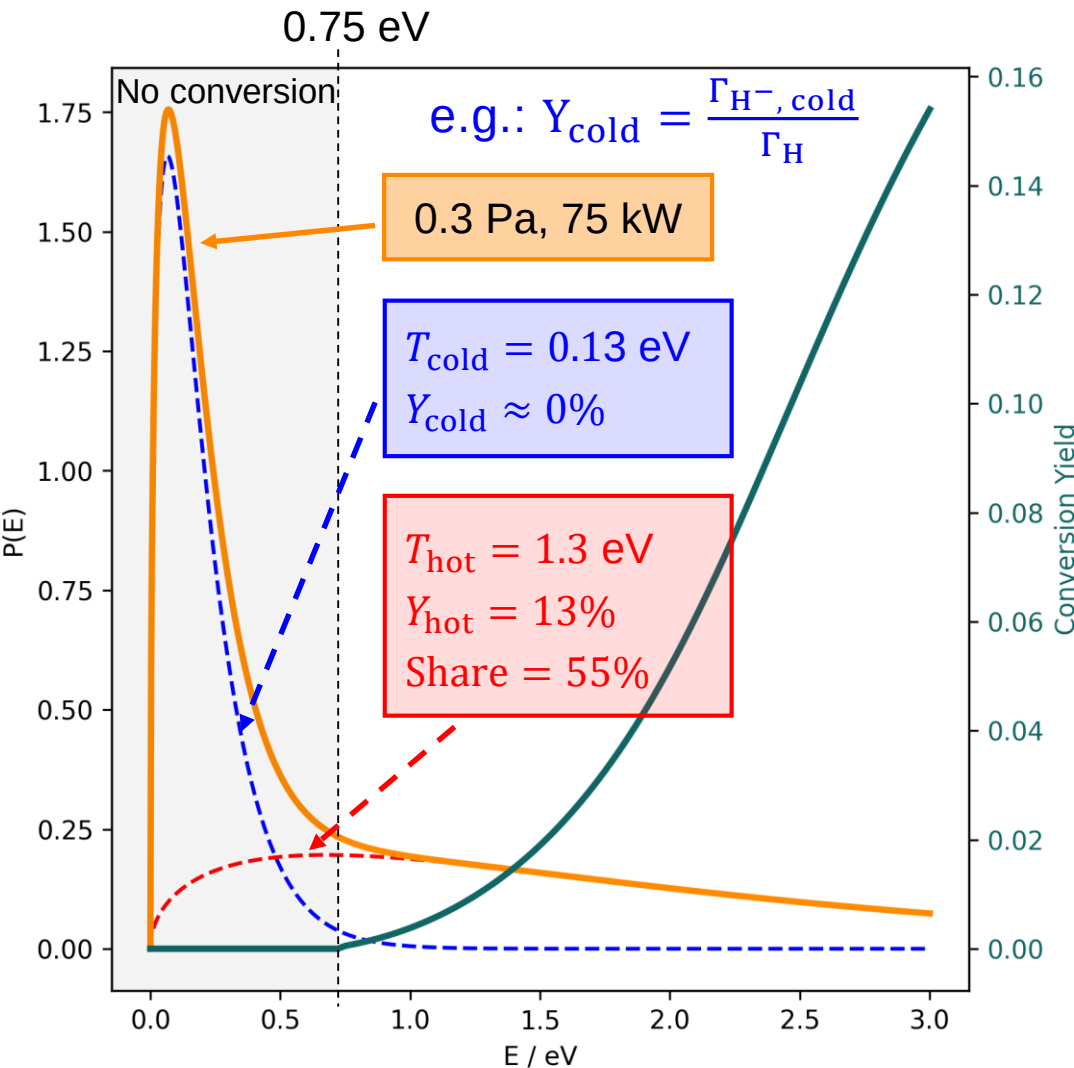
- Further plots with $T_{\text{hot}} = 1.35$ eV, fixed
- Free parameters T_{cold} and share
- Share
 - Share of hot component increases with lower pressure and higher RF power
 - $\approx 40\%$ @ 0.6 Pa, 40 kW
 - $\approx 60\%$ @ 0.3 Pa, 75 kW
 - As T_{cold} does not change much, the share describes the energy content of the EDF

➤ Most energetic EDF found at low pressure high power



Source Parameter Variation: EDF

Cold component does not contribute to H⁻ production

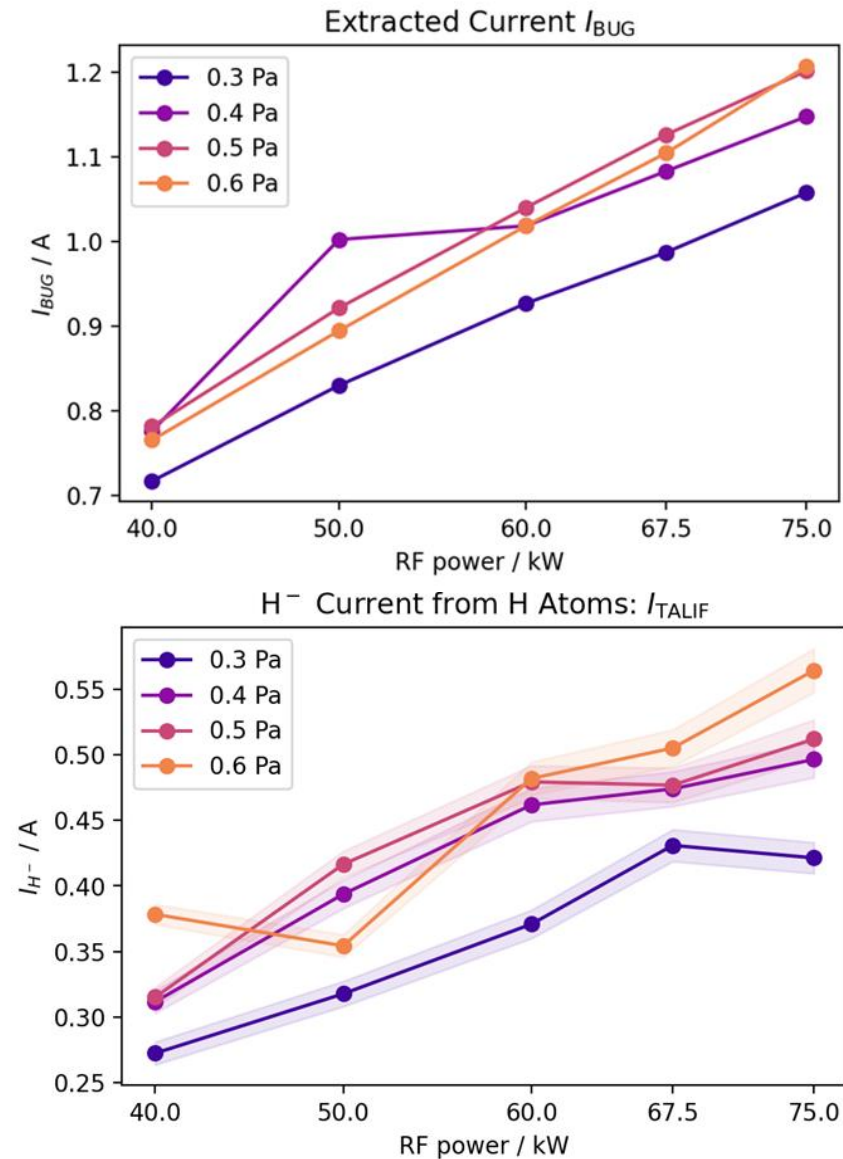


Extracted H⁻ Current

TALIF vs. Current measurement

- H⁻ current from BUG (current measurement)
 - Current increase between 0.3 Pa and 0.4 Pa, then stagnation
- H⁻ current from TALIF
 - H⁻ conversion yield at EDF: Y_{EDF}
 - EDF and n_{H} give the flux: Γ_{H} } $\Gamma_{\text{H}}^- = Y_{\text{EDF}} * \Gamma_{\text{H}}$ H⁻ flux
 - Extracted current I_{TALIF} from Γ_{H}^- and source geometry with 30 % extraction probability
- I_{BUG} and I_{TALIF} agree by roughly 50%
 - Similar trends in both currents

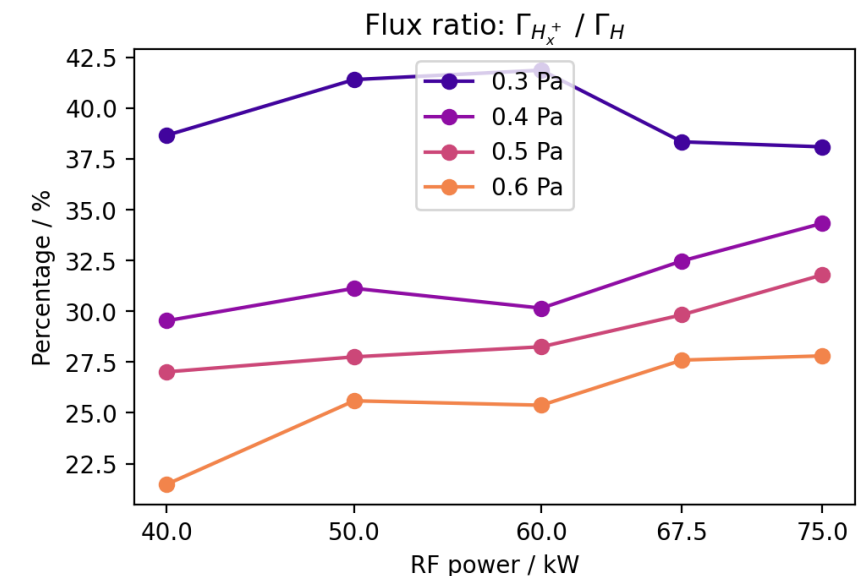
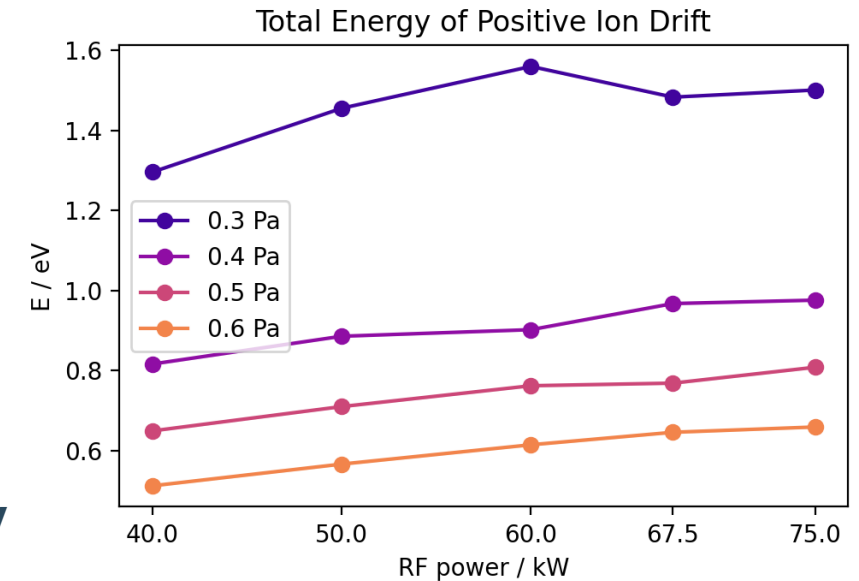
- I_{TALIF} produced from H atoms could explain current alone
- Absolute uncertainties on I_{TALIF} are high: $\pm 100\%$ possibly (calibration, saturation, yield calculation, H⁻ extraction)



Positive Ions

Do positive ions contribute to H^- current?

- **Positive ion flux determined by Mach probe**
 - Assumed composition: 40% H^+ , 40% H_2^+ , 20% H_3^+
 - $m_{H_x^+} \approx 1.8 * m_{H^+}$
 - Mach number from Mach probe, T_e , n_i from Langmuir probe
 - **Energies (0.6 eV – 1.5 eV) mostly below threshold of 0.75 eV**
 - **Potential sheath drop towards grid could add up to 4 eV**
 - Up to 18 % conversion yield at ≈ 5 eV for composition of H_x^+
 - Up to 6% conversion yield with H EDF (0.1 eV + 1.1 eV)
 - 3 times lower flux could be compensated by 3 times higher conversion yield → similar contribution to I_{H^-}
- Highest contribution at 0.3 Pa
 - Upper limit for positive ions: could contribute similarly to I_{H^-}



Conclusions

- Significant improvements of the setup made high resolution EDF possible
- The EDF is most energetic at low pressure, high power → most efficient production of H^-
- H^- currents deduced from TALIF are comparable to currents measured at BUG
- Similar trend, agree by 50%
- H atoms probably dominate H^- production, also positive ions could contribute – especially at 0.3 Pa
- First results, correlations with more diagnostics are in progress

