Plasma temperature via internally consistent H-α/H-β line width comparison

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1. Motivation

Why is the plasma temperature important?

The temperature achieved by the plasma in a capillary discharge plasma source has an impact in a variety of different ways:

- Controls the process of parabolic channel formation, essential for LWFA.
- Influences the temperature of the plasma cell and therefore the max. rep. rate.
- Complicates density derivation methods such as Optical Emission Spectroscopy (**OES**).

Determining the plasma temperature is therefore of significant interest in plasma diagnostics.

2. Plasma temperature methods [3]

What methods have been used before and why don't they work?

There are a multitude of methods to determine the plasma density, unfortunately none of the common approaches work with pure hydrogen plasma.

- **Boltzmann plotting method:** Requires multiple emission lines to be accurate. *Hydrogen has only 3, one of which is very weak.*
- **Boltmann-Saha method:** Requires multiple ionization states. *Impossible in hydrogen which has only 1 electron.*
- **Multi-element Boltzmann-Saha method:** Requires multiple elements. *Impossible in pure hydrogen.*

We need something else!

3. OES derived density evolution

Density derivation is temperature dependent

By taking spectra of the plasma light and then analyzing the width of the hydrogen spectral lines it is possible to **derive the density** of the plasma as the lines are broadened mainly via **Stark** (**pressure) broadening.**

$$\Delta\lambda_i = A_i(T_e) \times N_e^{B_i(T_e)}$$

'i' subscripts refer to either the α or β line, T_e is the plasma temperature and A/B are constants derived from simulations in [2] .

Unfortunately, spectral lines are also broadened by **Doppler (thermal) broadening** which reduces the accuracy of this measurement. Furthermore the Stark broadening process is a temperature effect which means a **temperature assumption** is needed. The value chosen has a significant impact on the density as shown in Figure 1.

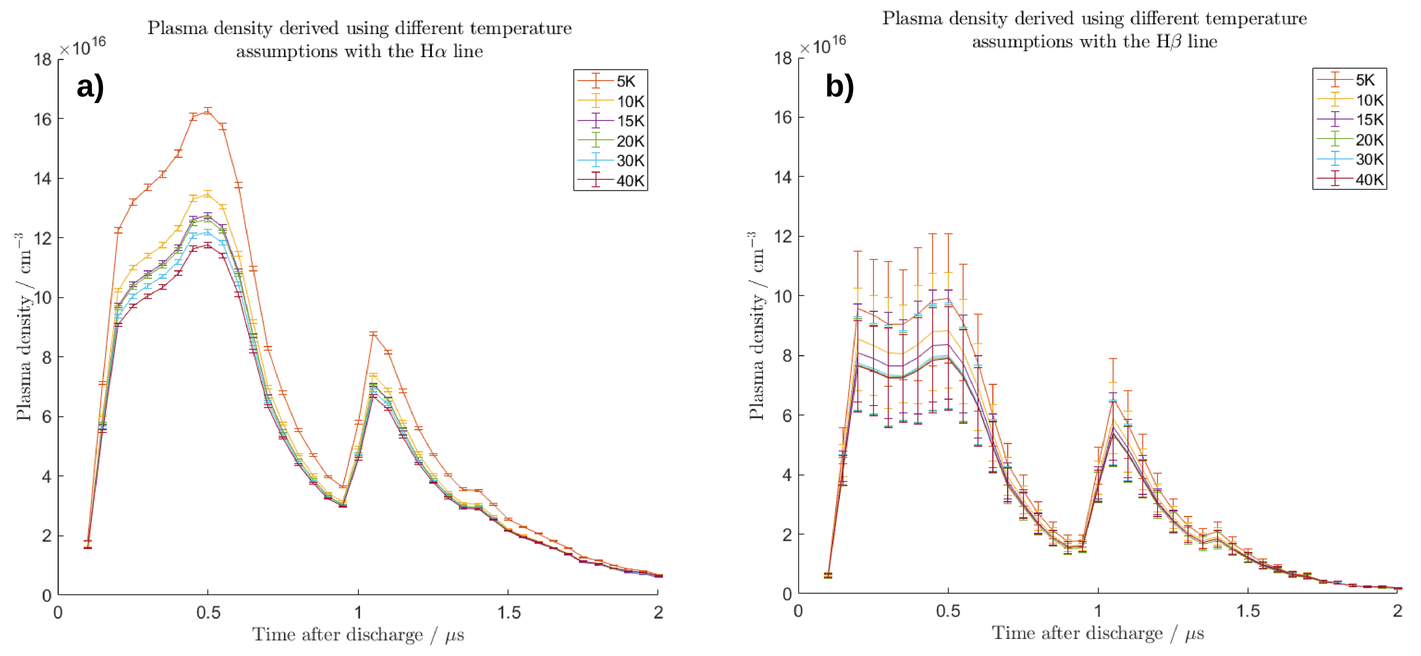

Figure 1: Density evolution for a capillary discharge plasma source derived using OES. Figure a) uses the H-α line (656 nm) while Figure b) shows the results from the H-β line (486 nm)

4. Temperature from H-α / H-β comparison

Using the temperature sensitivity to our advantage

The H-α line is more significantly affected by the temperature, we can use the apparent disagreement in density to derive the contribution temperature must be making.

$$T = C_3\left[\ln\left(1 - \frac{C_1 N_{e,\beta} + C_2}{N_{e,\alpha}}\right)\right]^{-1}$$

Where C_k are constants derived experimentally [3].

We take an **internally consistent** approach:

1. Assume an initial temperature
2. Derive the density evolution from both the H-α and H-β lines
3. Use these to derive the temperature
4. Recalculate the density using this new temperature
5. Repeat steps 2-4 until the results have converged

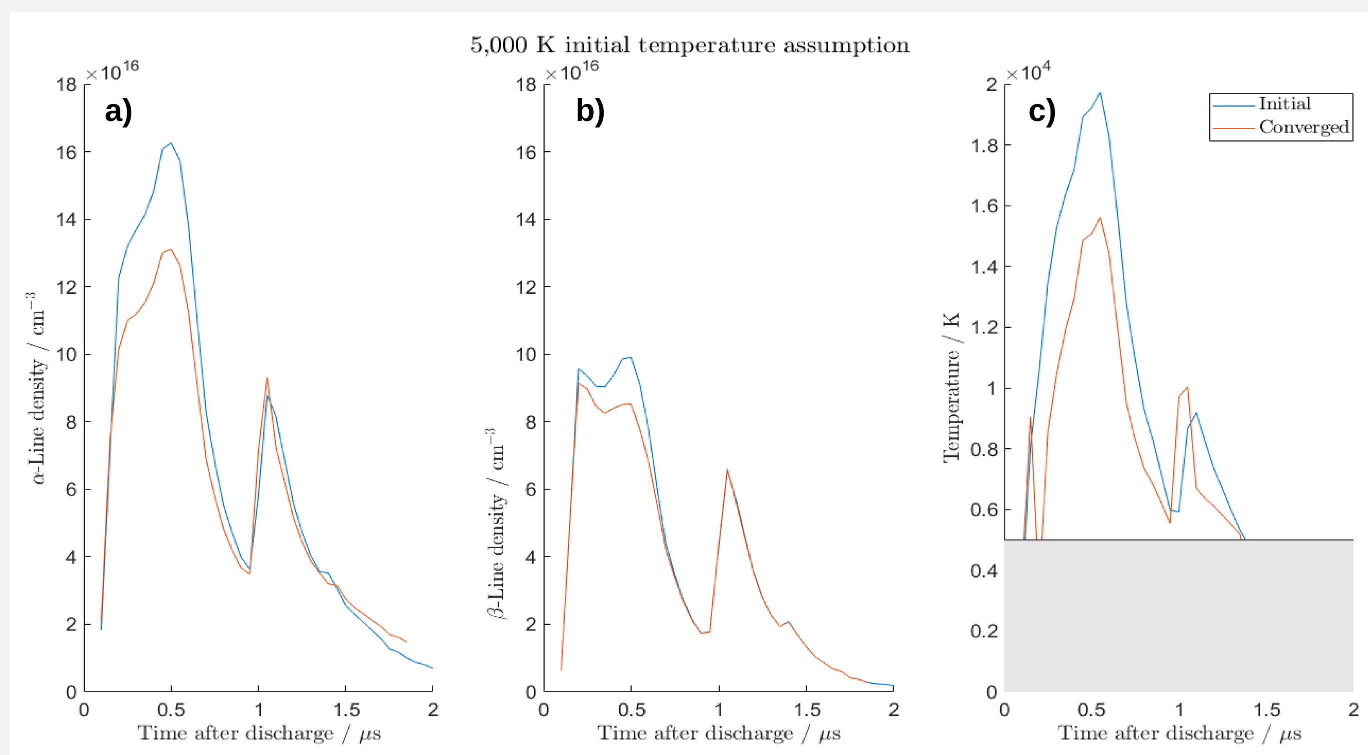

Figure 2: Comparison between initial 'naïve' result and the fully converged result.

Converged results were **independent** of starting temperature assumption. Temperatures below 5000 K are generated from significant extrapolation and therefore not reliable.

5. Error consideration and results

Putting everything together

By analytically propagating the errors from the two linewidth measurements and the four A/B variables we can produce an estimate for the error on this measurement. Interestingly, the **vast** majority of the uncertainty comes from the error in the simulated coefficients (A/B) [2].

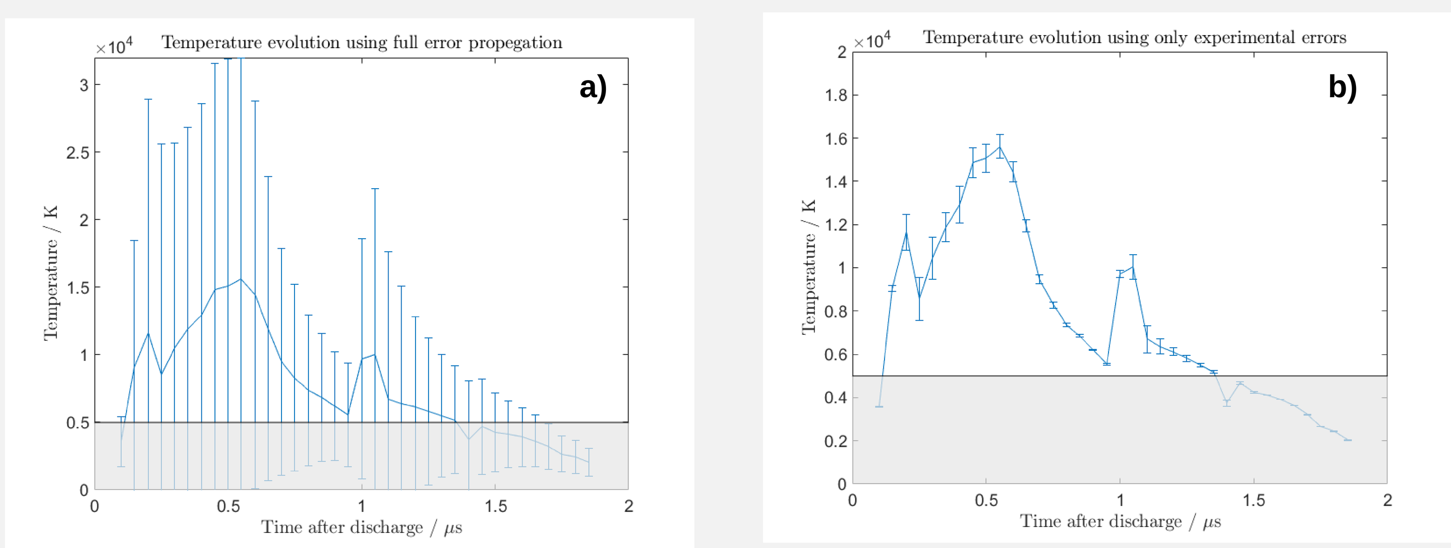

Figure 3: Temperature evolution with full error propagation (a) and experimental errors only (b).

6. Conclusions and further work

Main results

- Using this method we have potentially calculated the temperature evolution of pure hydrogen plasma to approximately ~100 % error.
- The results are independent of initial temperature assumption.
- Most significant contribution was from the simulated variables [2] emphasizing a need to improve here.

What's next?

- Further experimental testing to see how the predicted temperature changes with cell diameter and discharge voltage.
- Benchmarking against better simulation codes.

[1] **Völker**, Tobias, and Igor B. **Gornushkin**. "Extension of the Boltzmann plot method for multiplet emission lines." *Journal of Quantitative Spectroscopy and Radiative Transfer* 310 (2023): 108741.

[2] **Gigosos**, Marco A., and Valentin **Cardenoso**. "*New plasma diagnosis tables of hydrogen Stark broadening including ion dynamics.*" Journal of Physics B: Atomic, Molecular and Optical Physics 29.20 (1996): 4795.

[3] **Mijatović**, Z., et al. "*Plasma density determination by using hydrogen Balmer Hα spectral line with improved accuracy.*" Spectrochimica Acta Part B: Atomic Spectroscopy 166 (2020): 105821.

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