The University of Texas at Austin

Time Dynamics of an Inductively Coupled Plasma Torch

Dan Fries, Noel Clemens, Philip Varghese

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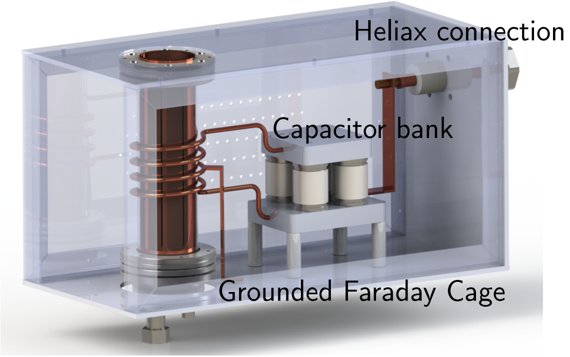
PSAAP III

ICP Torch

Inductively coupled plasma torch:
$\sim 30 - 60$ kW input power
$\sim 7 - 20$ MJ/kg enthalpy
$\sim 7 - 20$ m/s exit velocities

- Power coupled by RF circuit at 6 MHz.
- Swirl stabilized plasma core.
- Measurements in core and 10 mm above nozzle.
- How steady is plasma plume?[a] $\rightarrow$ Material testing.
- Experimental conditions: argon 35-50 slpm at 10 kV, air 25-35 slpm at 10 kV and 11 kV.



[a] Playez and Fletcher (2008), *J. Thermophys. Heat Tr.*

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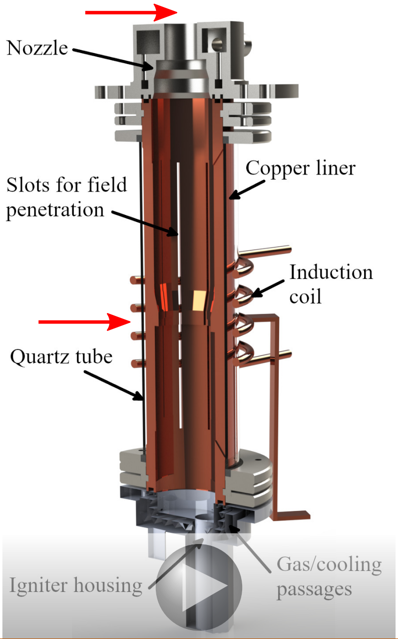


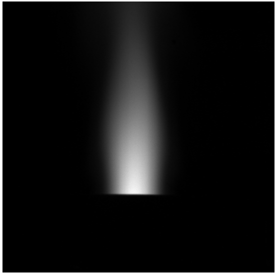
[a]Playez and Fletcher (2008), *J. Thermophys. Heat Tr.*

High-Speed Imaging

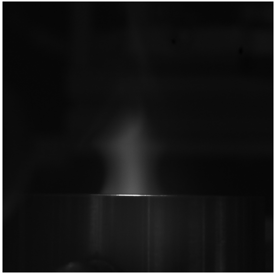
Fluctuations in Radiant Flux

Photron Nova at 1 kHz. 30 slpm air, 40 slpm argon at 10 kV DC anode voltage.

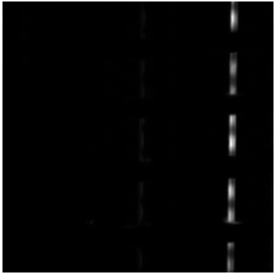
Air Plume



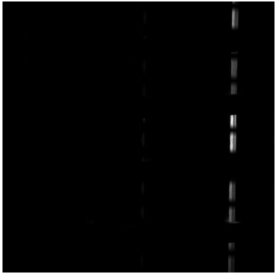
Argon Plume



Air Core



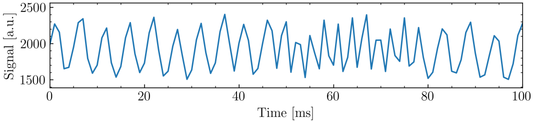
Argon Core



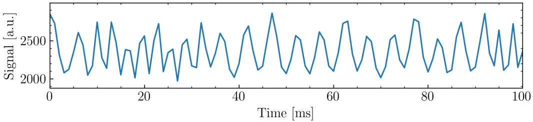
High-Speed Imaging

Fluctuations in Radiant Flux

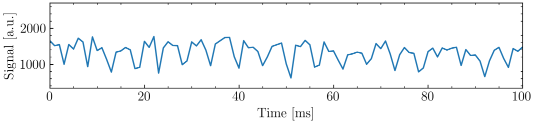
Air plume: 30 slpm, 10 kV anode voltage



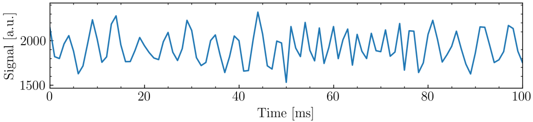
Air core: 30 slpm, 10 kV anode voltage



Argon plume: 40 slpm, 10 kV anode voltage

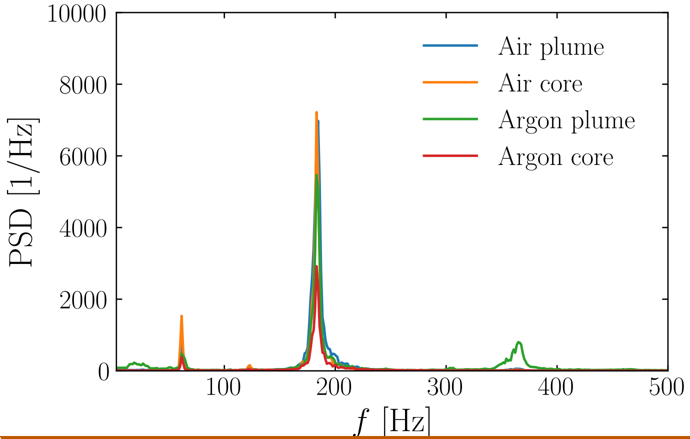


Argon core: 40 slpm, 10 kV anode voltage



High-Speed Imaging

Fluctuation Frequencies

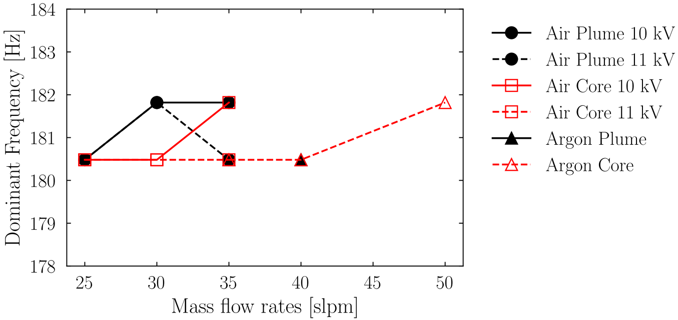


- Fluctuations at 180 Hz not sensitive to: mass flow rate, applied power, working gas.
- Origin: **circuit properties**, vortex shedding[a], acoustics.
- Other frequency components currently not considered further.

[a] Playez and Fletcher (2008), *J. Thermophys. Heat Tr.*; Cipullo et al. (2014), *J. Thermophys. Heat Tr.*

High-Speed Imaging

Fluctuation Frequencies



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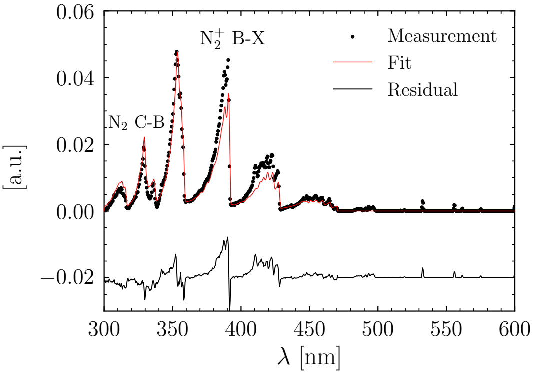
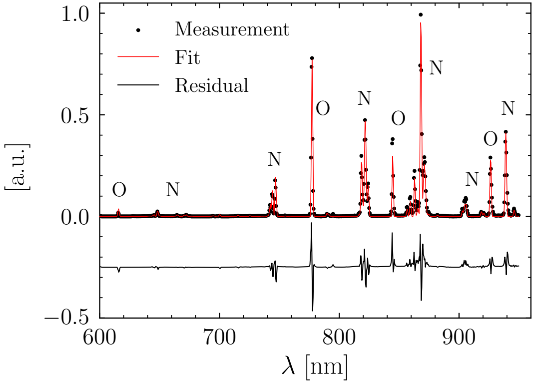
Emission Spectroscopy

Example Spectra Air

In the core, 30 slpm & 10 kV, phase averaged maximum



$T_{N_2} = 7781$ K, $T_N = 7707$ K, $T_O = 10678$ K

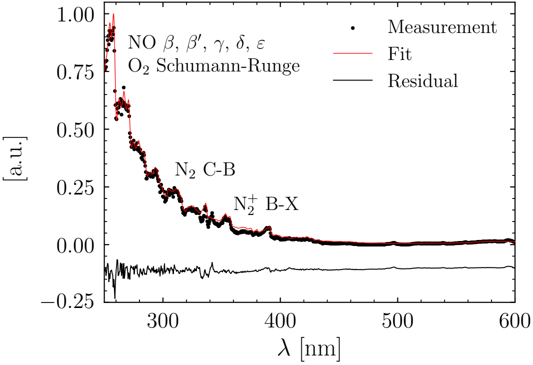


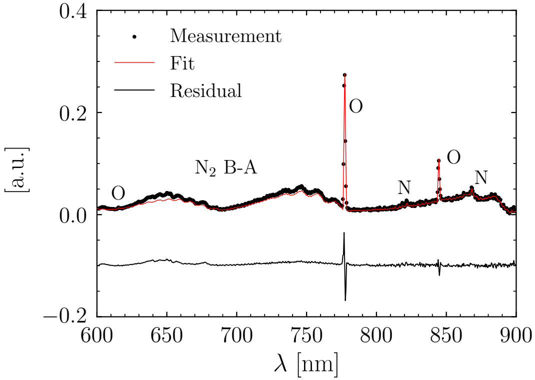
Emission Spectroscopy

Example Spectra Air

In the plume, 30 slpm & 10 kV,
phase averaged maximum

$T_{\text{equil}} = 5696$ K

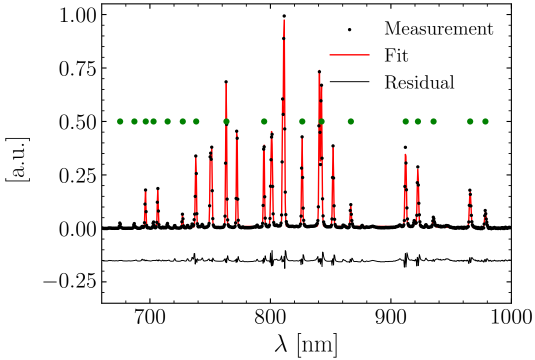


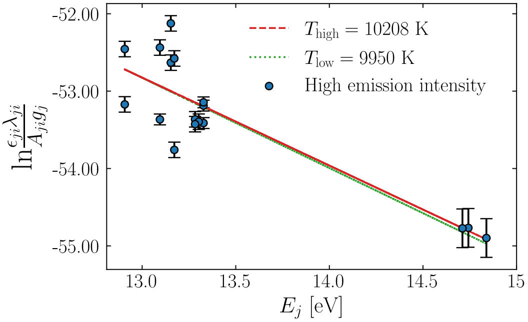


Emission Spectroscopy

Example Spectra Argon

In the core, 40 slpm & 10 kV,
phase averaged maximum





Emission Spectroscopy

Example Spectra Argon

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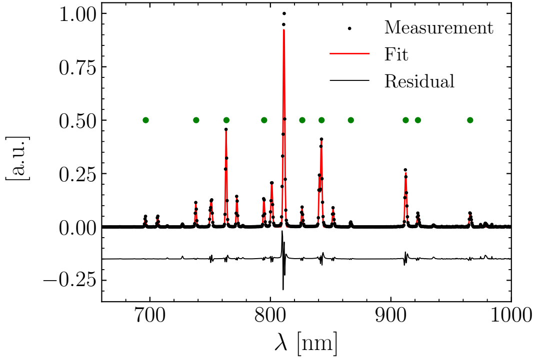
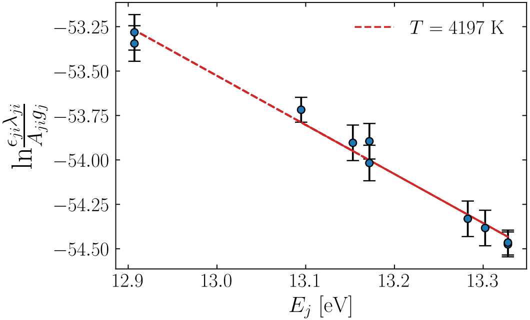


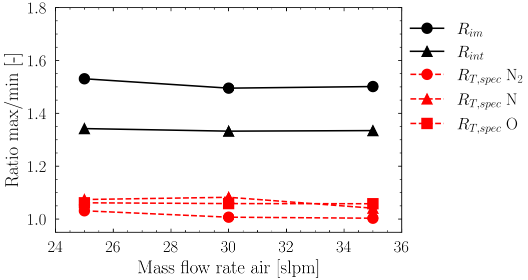
No phase average



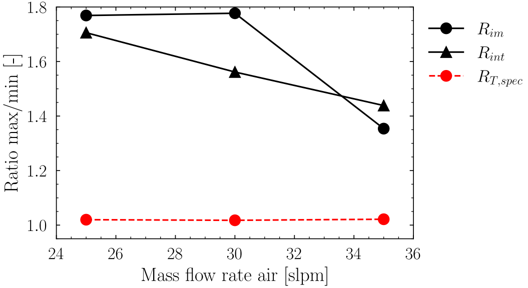
Quantification of Fluctuations

Air Plasma, 30 slpm & 10 kV

Core



Plume



→ non-equilibrium in core, near equilibrium in plume.

→ absolute temperature changes in plume around 2% (100-150 K). Temperature accuracy within 4-5%.

Quantification of Fluctuations

Air Plasma Signal

Spectrometer:

$$\mathrm{d}E_e(\nu) = \sum_{ji} \frac{n_0 g_j \exp(-E_j/k_B T_e)}{\sum_k g_k \exp(-E_k/k_B T_e)} A_{ji} \int_\Omega h\nu\varphi(\nu, \nu_{ji})\mathrm{d}\Omega\mathrm{d}s$$

Camera:

$$I = C(\nu) \cdot \int E_e(\nu)\mathrm{d}\nu$$

- Signal dependence: linear on density, exponential and more complex on temperature.
- 2% temperature change can explain large R_{im}/R_{int} observed, $\Rightarrow$ signal fluctuations mostly due to temperature changes.
- Inert surface[1]: $q_w \propto \sqrt{\rho} \cdot T_g \Rightarrow$ variations of $\leq 2\%$ at ~ 180 Hz.
- Not shown BUT other cases and argon yields similar results.

[1] White and Majdalani (2006).

Conclusions

Results

- Dominant fluctuations at 180 Hz: insensitive to mass flow, power, and working gas.
- Both argon and air temperature variations around 2%, absolute temperature changes on same order as uncertainty.
- Confirms assumptions in literature[a].
- Playez and Fletcher (2008)[b] observe larger temperature fluctuations using atomic oxygen TALIF.

[a] Playez and Fletcher (2008), *J. Thermophys. Heat Tr.*; Cipullo et al. (2014), *J. Thermophys. Heat Tr.*

[b] Playez and Fletcher (2008).

Future Plans

- More thorough characterization of uncertainties.
- Time-resolved voltage and spectroscopic measurements, to characterize temperature variations better.
- Compare line-of-sight averaged results with spatially resolved measurements.

Thank you! Questions?

References I

- Cipullo, A. et al. "Investigation of freestream plasma flow produced by inductively coupled plasma wind tunnel". *J. Thermophys. Heat Tr.* 28.3 (2014), pp. 381–393.
- Playez, M. and D. G. Fletcher. "Free stream test conditions determination in ICP windtunnel using the TALIF measurement technique". *40th Thermophysics Conference, Seattle, Washington*. 2008.
- — ."Spectroscopic analysis of titan atmospheric plasmas". *J. Thermophys. Heat Tr.* 22.2 (2008), pp. 150–156.
- White, F. M. and J. Majdalani. *Viscous fluid flow*. Vol. 3. McGraw-Hill New York, 2006.