The University of Texas at Austin

Characterization of periodic changes in an inductively coupled plasma using emission spectroscopy (among other things)

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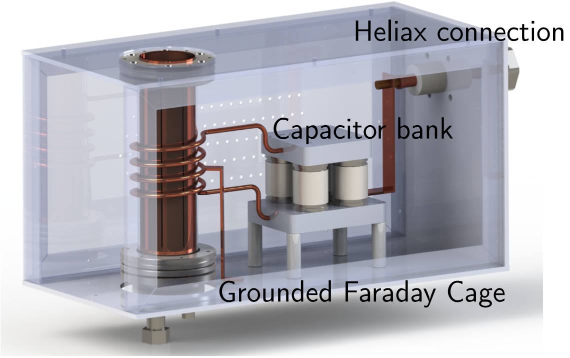
PSAAP III

ICP Torch

Inductively coupled plasma torch:
$\sim 30 - 60$ kW input power
$\sim 7 - 20$ m/s exit velocities
~ 5000 K expected in plasma plume.
Power coupled by RF circuit at 6 MHz.
Swirl stabilized core.

- Applications: material testing, gas conversion, propulsion.
- How steady are the plasma properties?
- Operating conditions: atmospheric pressure, argon 40 slpm & 10.2 kV, air 30 slpm & 10 kV.



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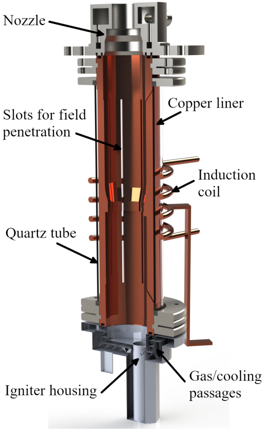


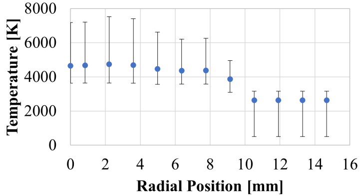
Measurements Utilized and Plume Properties

Measurement techniques used:

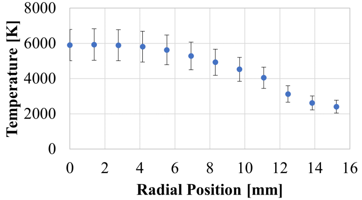
- Rogowski coils (current).
- Water cooled pitot probe[a] (dynamic pressure)
- High-speed imaging.
- N_2 Coherent Anti-Stokes Raman Scattering[b] (CARS, T_{vib}).
- Ar and O optical emission spectroscopy (OES, T^*_{el}).
  - Ar transitions from 4p manifold, 18 transitions $\Delta E_{max} \approx 1.8$ eV.
  - O two transitions at 10.74 (777.194 nm) and 10.99 eV (844.636 nm).

CARS/OES radial temperature profiles + equilibrium density calculation + pitot probe measurements:

Argon



Air



[a] Measurements performed by Dillon Ellender
[b] collab. Sean Kearney & Rajkumar Bhakta (Sandia National Labs), Spenser Stark

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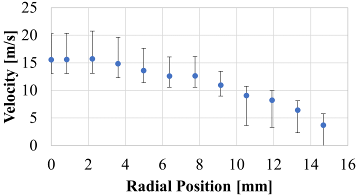

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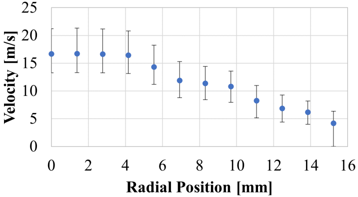

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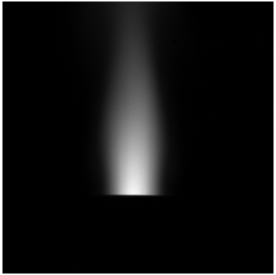
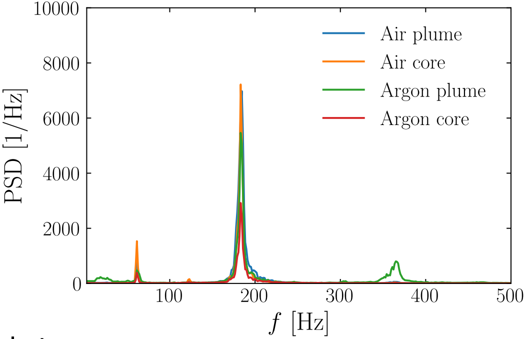
Periodic Changes in Plasma - Fast

Results from Photron Nova camera at 4 kHz:

Argon Plume

Air Plume





→ Also discussed in Fries et al.[1] and 180 Hz visible in current measurements.

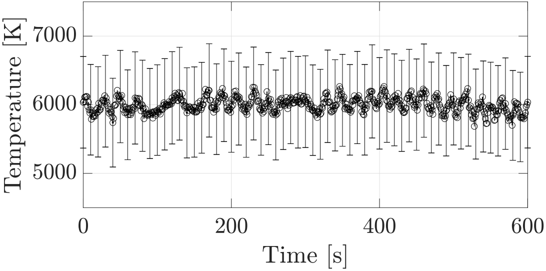
→ OES temporally under-resolved at $f = 200$ Hz.

→ Average excitation temperature changes are relatively small: Ar $\pm 9\%$ (mean 5128 K), O $\pm 3\%$ (mean 5150 K).

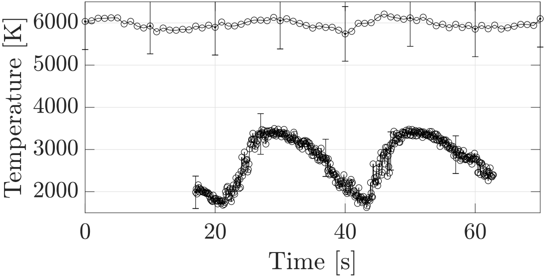
[1] Fries, Clemens, and Varghese (2022), "Time Dynamics of an Inductively Coupled Plasma Torch".

Periodic Changes in Plasma - Slow

CARS N_2 measurements at 10 Hz over 15 min reveal low frequency variations:



Oscillations become more pronounced in the shear layer at 0.05 Hz:



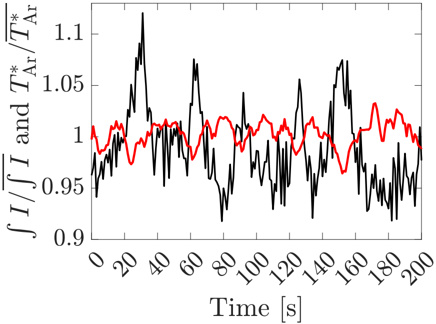
⇒ On centerline, temperature variations around $\pm 4\%$.

⇒ Does not show up as peak in current measurements.

⇒ Slow variations in supply gas flow, but not pronounced at 0.05 Hz and changes $\mathcal{O}(1\%)$.

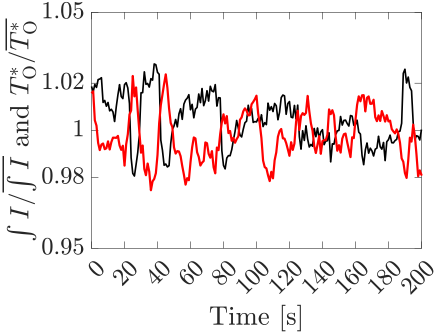
Periodic Changes in Plasma - Slow

Argon OES signal shows ~ 30 s time scale:



$\Rightarrow$ Ar mean temp 6512 K, changes $< 5\%$.

Atomic oxygen OES fluctuations less clear:



$\Rightarrow$ O mean temp 5150 K, changes $< 3\%$.

$\rightarrow$ Interestingly, higher temperature correlates with lower signal.

$\rightarrow$ Atomic oxygen results more noisy: only two transitions, small energy gap.

Plasma Plume Fluctuations Considered

Sources considered:

- Rectifier imperfections, i.e. fluctuations in current/voltage and B-field[a].
- Acoustic oscillations in axial direction.
- Vortex shedding at nozzle exit.
- Linear stability of plasma plume.
- Buoyancy[b].
- Non-buoyant oscillating mode for low density jets[c].

[a] Playez and Fletcher (2008), "Spectroscopic analysis of titan atmospheric plasmas".

[b] Cetegen and Kasper (1996), "Exp. on the oscillatory behavior of buoyant plumes of He and He-air mixtures".

[c] Kyle and Sreenivasan (1993), "The instability and breakdown of a round variable-density jet".

Device properties:

- Rectifier: three-phase half-wave with 60 Hz input AC.
- Reynolds numbers $\mathrm{Ar} \approx 200 - 330$, $\mathrm{Air} \approx 90 - 190 \Rightarrow$ can trigger growth of disturbances $Re > 40$[a].
- Density ratio $S_{\mathrm{Ar}} \approx= 0.05 - 0.10$ and $S_{\mathrm{Air}} \approx= 0.02 - 0.05$. Comparable to helium jets, or lower.
- Richardson number $Ri_{\infty} << 0.1 \Rightarrow$ shear dominated.

[a] Lessen and Singh (1973), "The stability of axisymmetric free shear layers".

Estimated Plasma Plume Fluctuations

Gas	Rectifier	Acoustics	Vortex	Linear	Buoyancy	Oscillating
Argon	180 Hz	802-1127 Hz	435-676 Hz	48-78 Hz	21-47 Hz	136-211 Hz
			neutral	11-17 Hz		
Air	180 Hz	1049-1333 Hz	442-707 Hz	49-79 Hz	21-49 Hz	120-192 Hz
			neutral	11-18 Hz		

Linear stability $\rightarrow$ max. amplification frequency and neutral disturbance.

Buoyancy and linear stability are close $\rightarrow$ Ri-number suggests shear dominated .

Observed:

- Rectifier oscillations $\rightarrow$ change in excitation temperature is small.
- Very low frequency oscillation < 0.1 Hz $\rightarrow$ no clear origin.

Conclusion

Results

- Many possible sources of periodic fluctuations in plume. Apparently dominant: rectifier and something else.
- Fast fluctuations should have no influence on bulk properties, kinetics.
- Slow OES temperature measurements of O in similar to N_2 CARS.
- OES temperature fluctuations have opposing trend to integrated signal strength.
- Slow N_2 ground state fluctuations strong enough to influence at least kinetics.

Future Plans

- Check for long period fluctuations in power input, with upgraded torch monitoring systems.
- Check for long period fluctuations from core: precessing vortex core.
- Quantify impact of fluctuations on bulk properties and kinetics at interfaces.
- Quantify fast fluctuations for ground state oxygen.

Thank you!

Acknowledgments

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References I

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