Laser-aided diagnostics on a cool atmospheric pressure plasma jet

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Atmospheric pressure plasma jets

- small
- non-equilibrium
  - low gas temperature (300–2000 K)
  - high electron temperature (~20000 K)
- open to air
- used in Star Trek!
Plasma chemistry

- **Air chemistry important:**
  - O, NO, OH, O_3
  - driven by electrons

Source: Eliasson et al, 1991
Used plasma jet

Pin-ring electrode geometry

Pin-plate electrode geometry

- **Gas**: Ar with 0–4% air
- **RF Power**: 13.6 MHz modulated
Outline

• Laser induced fluorescence (LIF) of NO
  • rotational temperature and density

• Two-photon absorption LIF (TALIF) → O density
  • Xe calibration at atmospheric pressure

• Raman scattering → N₂ and O₂ density
• Thomson scattering → electron density
  • disentangling Thomson/Raman signals

• Chemistry in plasma jet
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- Chemistry in plasma jet
LIF on NO: excitation scheme

NO excited state (A)

\[ v'' = 0 \text{ vibrational states} \]

collisional quenching

247 nm fluorescence

rotational states

NO ground state (X)

\[ v' = 2 \]

\[ v' = 0 \]

226 nm laser

pump laser 355 nm
dye laser 452 nm
SHG 226 nm

4 kHz

UV monochrometer

PMT

PC with time digitizer

laser power meter
NO density

![NO density graphs]

- **NO X density (m\(^{-3}\)) \times 10^{21}**
- **Axial position (mm)**
- **Radial position (mm)**
Rotational temperature from LIF

Ground state: $T_{\text{rot}} = 1007$ K

Excited state: $T_{\text{rot}} = 1479$ K

(measured on microwave jet)
Gas temperature from Rayleigh scattering

Rayleigh scattering image of 532 nm laser beam

Heavy particle temperature

(does not work for He plasmas)
Laser induced fluorescence (LIF) of NO
- rotational temperature and density

Two-photon absorption LIF (TALIF) \(\rightarrow\) O density
- Xe calibration at atmospheric pressure

Raman scattering \(\rightarrow\) N\(_2\) and O\(_2\) density
- Thomson scattering \(\rightarrow\) electron density
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Chemistry in plasma jet
TALIF on O: excitation scheme

**Atomic oxygen**

\[ \text{O } 2p^4 3p_{2,1,0} \]  
2 × 225.57 nm  
\[ \text{O } 3s \, ^3S \]  
845 nm  
\[ \text{O } 3p \, ^3P_{1,2,0} \]  

**Xenon**

\[ \text{Xe } 5p^6 \, ^1S_0 \]  
\[ \text{Xe } 6s'[1/2]_1 \]  
2 × 224.24 nm  
835 nm  
\[ \text{Xe } 6p'[3/2]_2 \]

**TALIF on O challenges:**

1. **calibration:** with Xe, *in situ*, at atmospheric pressure  
2. **collisional quenching:** using Raman scattering to measure gas composition
TALIF on O: calibration

- O in plasma jet:

- Xe in vessel, 2 mbar:

\[ n_0 = C \cdot \alpha \cdot E^2 \cdot I \]

\[ n_{Xe} = C' \cdot \alpha \cdot E^2 \cdot I \]
TALIF on O: calibration

- O in plasma jet:
  \[ n_0 = C \cdot \alpha \cdot E^2 \cdot I \]

- Xe in jet, 1000 mbar:
  \[ n_{Xe} = C \cdot \alpha \cdot E^2 \cdot I \]
  \[ \alpha \text{ values available} \]

- Xe in vessel, 1000 mbar:
  \[ n_{Xe} = C' \cdot \alpha \cdot E^2 \cdot I \]

- Xe in vessel, 2 mbar:
  \[ n_{Xe} = C' \cdot \alpha \cdot E^2 \cdot I \]

- total accuracy \(~50\%\)
TALIF on O: results

Collisional quenching from $N_2$ and $O_2$ determined with Raman scattering
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Laser scattering: experimental setup

Scattering signals:
- Rayleigh (heavy particles)
- Raman ($N_2$ and $O_2$)
- Thomson (electrons)

$T_e \sim 1 \text{ eV}$
Laser scattering: example spectrum
Laser scattering: results Raman scattering

![Graph showing plasma density comparison with and without plasma.](image)

- **Axial position (mm)**
  - Values range from 0 to 30 mm.

- **Radial position (mm)**
  - Values range from -1 to 1 mm.

- **Air density (m$^{-3}$)**
  - Values range from $10^{24}$ to $10^{25}$.

**Plasma off**
- The graph on the left shows a typical distribution of air density without plasma.

**Plasma on**
- The graph on the right shows the distribution of air density with plasma.

**Legend**
- Colors indicate different density levels.
Laser scattering: results Thomson scattering
Time dependent electron density and temperature

20 kHz plasma modulation

decay of Thomson signal

13.6 MHz RF cycle
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Overview measured profiles

- $O_3$ (UV absorption measurement)
- Atomic oxygen
- NO ground state
- Gas temperature
- Air
- Electrons

Image of a plasma torch with measured profiles.

(TU/e Technische Universität Eindhoven, University of Technology)
Production and destruction processes

- **atomic oxygen**
  - **production:** \( O_2 + e \rightarrow 2O + e \)
  \( O_2 + N_2^* \rightarrow 2O + N_2 \)
  - **O\(_2\)** dissociation degree \( \sim 20\% \)
  - **destruction:** \( O + O_2 \rightarrow O_3 \)

- **NO**
  - **production:** \( O_2 + N \rightarrow NO + O \)
  - maximum \( 1.0 \cdot 10^{21} \text{ m}^{-3} \)
  - **destruction:** \( NO + O \rightarrow NO_2 \)
    oxidation into \( N_x O_y, HNO_x \)

- **electrons**
  - maximum \( 1.6 \cdot 10^{19} \text{ m}^{-3} \) (ring)
  \( 2.0 \cdot 10^{20} \text{ m}^{-3} \) (plate)
Conclusion

- Laser diagnostics performed on time-modulated RF plasma jet
  - LIF on NO → NO density
  - Rayleigh scattering → gas temperature
  - TALIF on O → O density
  - Raman scattering → N₂ and O₂ density
  - Thomson scattering → electron density and temperature

- Densities measured in situ, spatially resolved
  - O TALIF calibration with Xe at atmospheric pressure
  - Disentanglement of Raman and Thomson signals

- Validation of plasma chemistry models
Thank you for your attention

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- Feel free to ask for a copy of my thesis: