Laser-induced Fluorescence (LIF) studies of Discharge Plasma Sheaths

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In 3 steps we describe diode laser based LIF measurements used to test theories of sheath formation in Plasma discharges and the first to test the Bohm Criterion for multiple ion species plasmas.
Thanks to UW-USD collaborators: Noah and his students, and to the NSF-DOE Partnership for Basic Plasma for supporting this work since 2001.

Team Sheath UW-USD

- Noah’s current student on the project: Mr. Chi-Shung Yip
- His recent PhD’s: Dr. Xu-Wang, Dr. Dongsoo-Lee, Dr. Young-Chul Ghim (finishing at Oxford)
- at USD, Mr. Camron Proctor (‘10), Mr. Tim Welsh (‘14), Mr. Chris Yip (‘14)
Who cares? Those who are fascinated by the Glow!

The Bakerian Lecture.—On the Illumination of Lines of Molecular Pressure, and the Trajectory of Molecules.

By William Crookes, F.R.S., V.P.C.S.

Read December 5, 1878.
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Fig. 1.
The sheath is a non-neutral region that normally forms at plasma boundary so as to balance electron and ion losses.
Bohm’s criterion (c. 1949): ions must break the ion sound speed in order for quasi-neutrality to give way to space-charge and sheath formation.
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First results, Sheridan, Goree, & Goeckner, verified $v_{io} > C_s$ in the sheath. Phys. Fluids B 4 (1992) 1663; GBc:

LIF is used to infer the ion velocity distribution function parallel to $k_l$ of the laser, through the first order Doppler-shift.

$$\langle v_z^m \rangle = \frac{\int_{-\infty}^{\infty} v_z^m f(v_z, z) dv_z}{\int_{-\infty}^{\infty} f(v_z, z) dv_z}$$
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We had to find new LIF schemes for each ion.
Typical setup involves diode lasers, an evolving technology.

1-Diode Laser, 2-Iodine Cell, 3-Chopper, 4-Wavemeter, 5-Lock-in, 6-Boundary plate
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We had to find new LIF schemes for each of the lasers needed in these experiments, Ar was first.
What can you do with one laser for a two-ion species experiment? With one we showed that in Ar+He plasma, ArII ions reached the sheath edge with $\sqrt{\langle v^2 \rangle} \gg v_{Bohm}$.

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How to find a new LIF 'scheme'? To “prove” a new LIF scheme one must first 1) find one, 2) see if anyone else is using it (that’s good but not sufficient), and 3) try it out.

Checklist for new LIF scheme

- find a well populated (metastable) state with
- an accessible (via dl) short lived excited state that
- has one dominant decay channel which
- has a wavelength that hits the sweet spot of detector (pmt-blue is best)
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\[ \lambda_{12} = 680.6 \text{ nm (air)} \]
\[ \lambda_{23} = 492.1 \text{ nm} \]
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Finally, with 2 lasers: the generalized Bohm Criterion *is* satisfied for weakly collisional plasmas with comparable ion densities.

![Graph showing ion velocities and sheath boundary measurements](image)

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\[ \sum_i n_{io} C_i^2 = 0.97 \pm 0.5 \]

Measurements of Ar⁺ and Xe⁺ velocities near the sheath boundary of Ar⁺Xe plasma using two diode lasers, D. Lee, N. Hershkowitz, and G. Severn, Appl. Phys. Lett. 91, 041505 (2007)
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Mysteries...

1. what process was driving the two ions toward the system ion sound speed?
2. why the flow 'locking'?

Measurements of Ar\(^{+}\) and Xe\(^{+}\) velocities near the sheath boundary of Ar\(^{+}\)-Xe plasma using two diode lasers, D. Lee, N. Hershkowitz, and G. Severn, Appl. Phys. Lett. 91, 041505 (2007)
Breakthrough: Baalrud et al. predict Ion-Ion two stream instability, turns on for thermal ions $\Delta V \geq V_{crit}$

S. D. Baalrud and C. C. Hegna, *Determining the Bohm criterion in plasmas with two ion species* Physics of Plasmas 18, 023505 (2011)

$$\Delta V_c = -\frac{3}{2} |v_{T2} - v_{T1}| + \sqrt{\frac{1}{2} \left( v_{T1}^2 + v_{T2}^2 + \frac{n_2 T_1}{n_1 T_2} v_{T1}^2 + \frac{n_1 T_2}{n_2 T_1} v_{T2}^2 \right)}.$$ 

This was verified in our paper, "Experimental Test of Instability-Enhanced Collisional Friction for Determining Ion Loss in Two Ion Species Plasmas", Yip, CS; Hershkowitz, N; Severn, G. Phys Rev Lett. Vol.104 Iss:22 #225003 (2010)
We began new work with KrII in order to try the 3 ion species sheath formation problem, but also relevant to new work in Hall Thruster plasmas.

**Energy Levels (cm⁻¹)**

- \( \lambda_{12} = 729.0 \text{ nm (air)} \)
- \( \lambda_{23} = 473.9 \text{ nm} \)

**LIF Signal—obvious isotope shift effect**

- Krl LIF
- 300MHz FSR
- Etalon
- \( n_e = 3 \times 10^9 \text{ cm}^{-3} \)
- \( T_e = 1.5 \text{ eV} \)
- FWHM = 1.1 GHz
- \( T_i = 1,100 \text{ K} \)
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Because the main isotope shifts are of order of the room temperature Doppler Broadening 0.7 GHz, we need to perform noise tolerant deconvolution

**Basic Digital Algorithm**

\[ Ax = b, \text{ (}A \text{ is } n \times n \text{ matrix)} \]
\[ x \text{ (ivdf)} \]
\[ b \text{ (LIF)} \]
\[ \therefore x = A^{-1}b. \]
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**Tikhonov Regularization**

perform *singular value decomposition* of \( A, A = U\Sigma V^* \),
filter out contributions of the tiniest singular values \( \sigma_i \) using a *filter factor*, \( f_i \) with a ‘regularization parameter’, \( \alpha \);

\[ f_i = \frac{\sigma_i^2}{\sigma_i^2 + \alpha^2}, \]
yielding a modified matrix, \( \Psi \), giving \( A^{-1} = V\Psi^{-1}U^* \)
that minimizes \( Ax - b \) element by element.
Progress: the deconvolution gives a recovered ion velocity distribution function (IVDF) closer to room temperature 650K +/- 200K
First test of Bohm Criterion w. multiple ion species

New dLIF schemes to perform the measurements

New way of thinking of sheath formation
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AND THANKS FOR YOUR ATTENTION!