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

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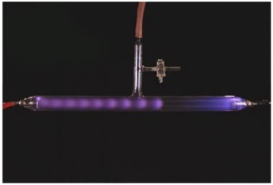
DAMOP-2014

4 June 2014

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

Plasma discharges, the sheath and the Bohm Criterion



ECDL based LIF

Experimental results in low temperature 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.*

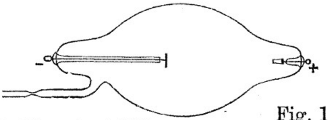
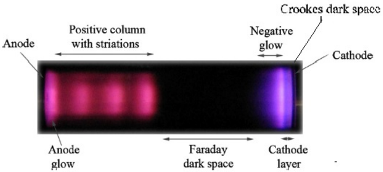


Fig. 1.

Read December 5, 1878.



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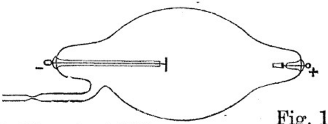

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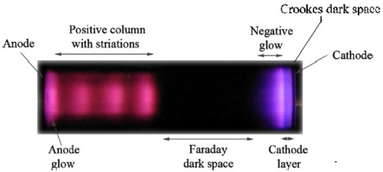
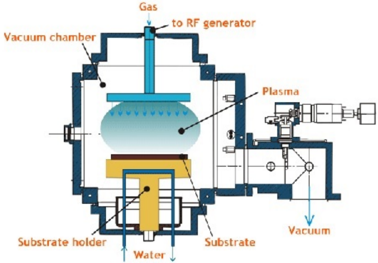
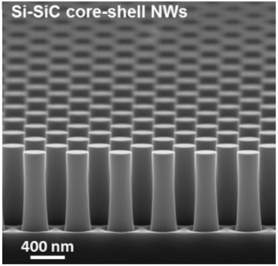
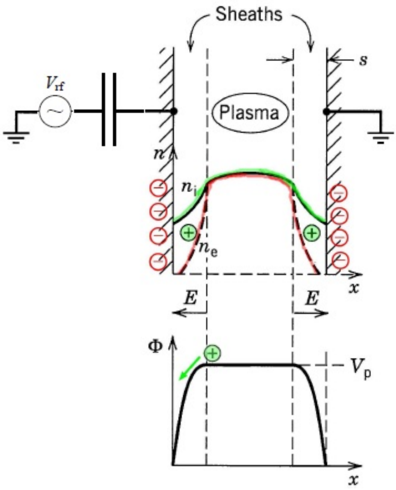
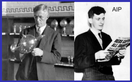


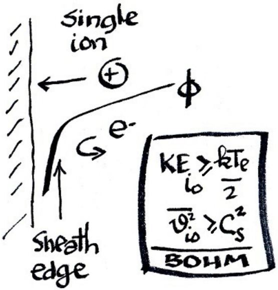


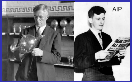


The sheath is a non-neutral region that normally forms at plasma boundary so as to balance electron and ion losses




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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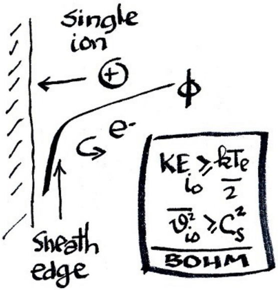
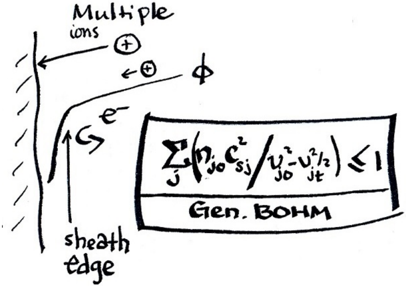
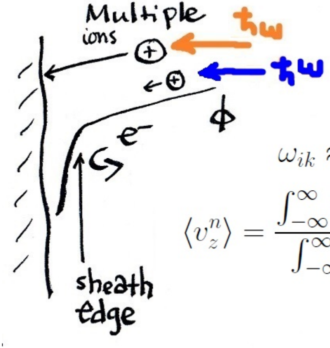


GBc: v_{io} now indeterminate



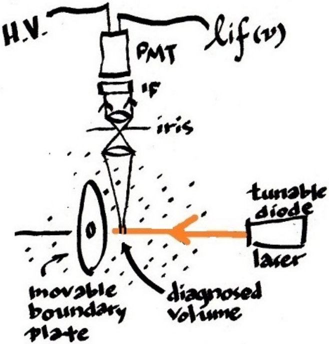
first results, Sheridan, Goree, & Goeckner, verified $v_{io} > C_s$ in the sheath. Phys. Fluids B 4 (1992) 1663; GBc: K.-U. Riemann, IEEE Trans. Plasma Sci. 23, 709 (1995).

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



$$\omega_{ik} \approx \omega_o + \boldsymbol{k}_l \cdot \boldsymbol{v}_i$$

$$\langle v_z^n \rangle = \frac{\int_{-\infty}^{\infty} v_z^n f(v_z, z) dv_z}{\int_{-\infty}^{\infty} f(v_z, z) dv_z}$$



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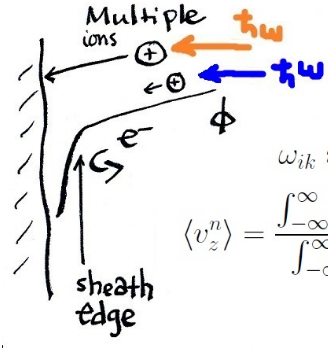

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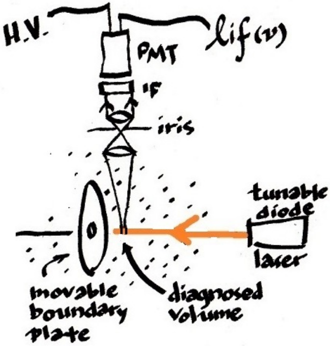
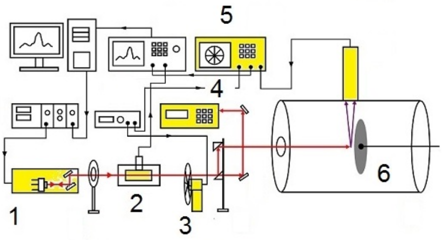
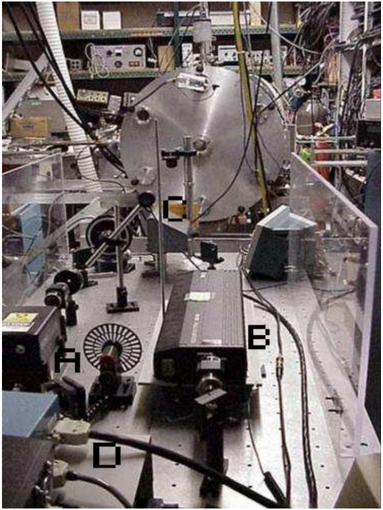


We had to find new LIF schemes for each ion

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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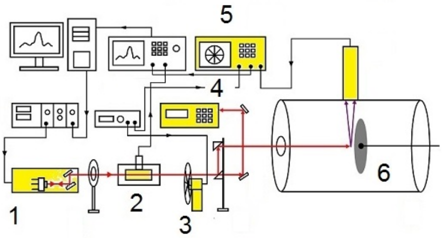

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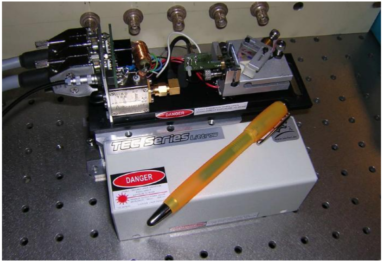

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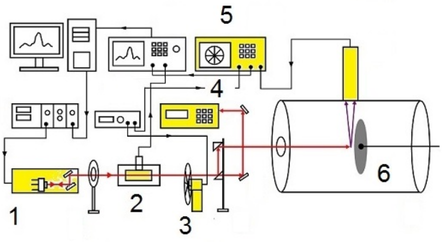

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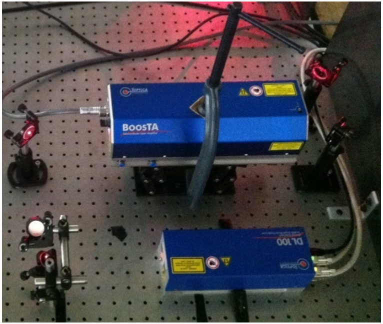
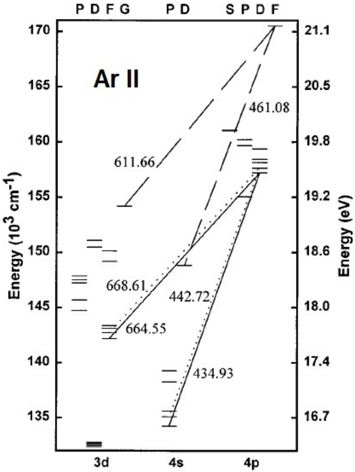


We had to find new LIF schemes for each of the lasers needed in these experiments, Ar was first



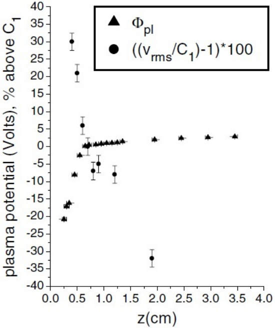
Review of Scientific Instruments

Argon ion laser-induced fluorescence with diode lasers,

G.D. Severn, D.A. Edrich, and R. McWilliams, Rev.

Sci. Instrum. 69 10 (1998)

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 $\sqrt{\langle v^2 \rangle} \gg v_{Bohm}$



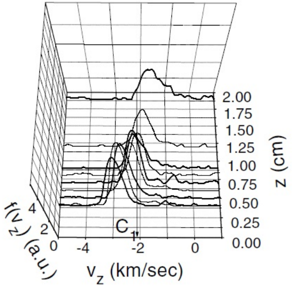


FIG. 1. A family of ivdfs for the pure Ar plasma case show. The rms velocity crosses c_1 at the sheath edge.

Experimental Studies of the Bohm Criterion in a Two-Ion-Species Plasma Using Laser-Induced Fluorescence, Severn et al., Phys. Rev. Lett. 90 1450001 (2003);LIF measurements of Ar^+ velocities near the sheath boundary of an $Ar + Xe$ plasma, Lee et al., J. Phys. D: Appl. Phys. 39 5230 (2006)

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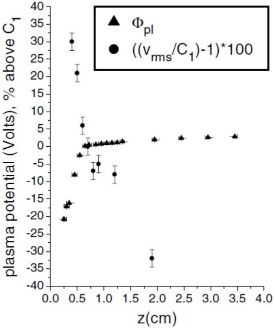

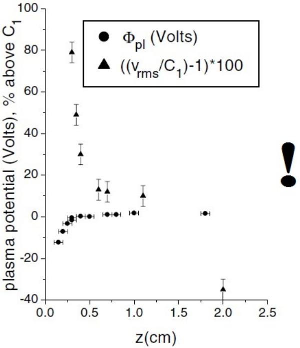

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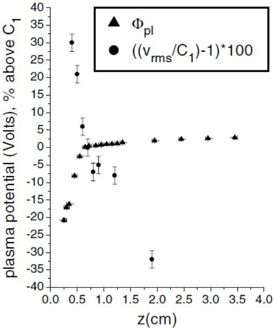
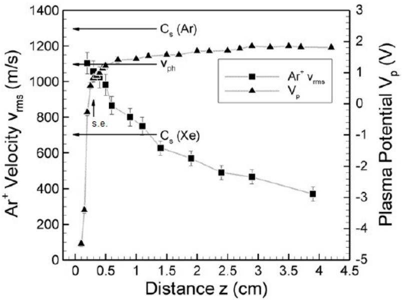


in $Xe + Ar$ plasmas, would Ar^+ be sub-Bohm? Yes!



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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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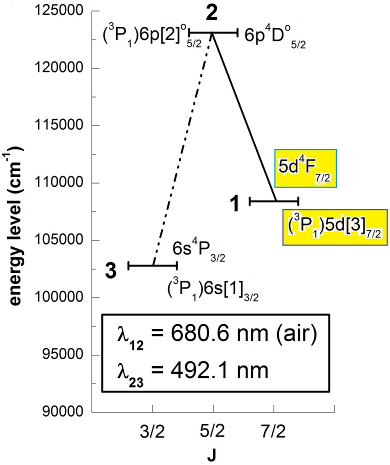

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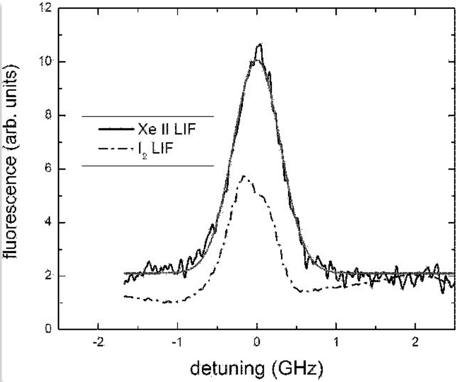

Xenon ion laser-induced fluorescence using a visible tunable diode laser near 680nm, G. Severn, D. Lee, and Noah Hershkowitz, Rev. Sci. Instrum., 78 116105 (2007)

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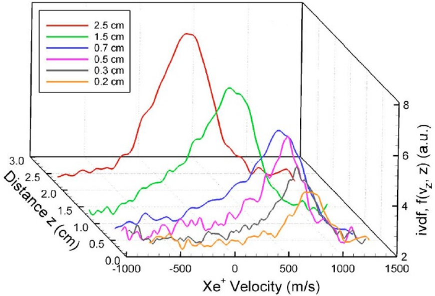

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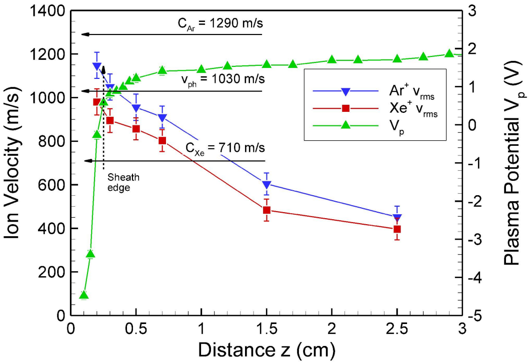
Finally, with 2 lasers: the generalized Bohm Criterion *is* satisfied for weakly collisional plasmas with comparable ion densities



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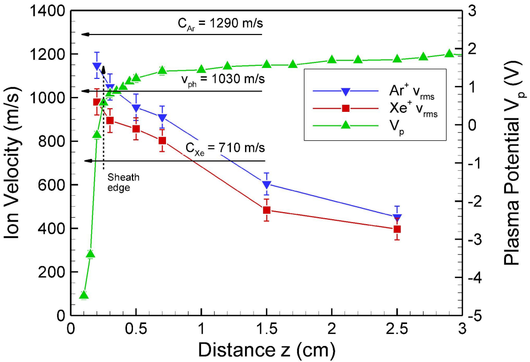

was Bohm's Criterion satisfied?

$$\sum_i \frac{n_{io} C_i^2}{n_{eo} v_{io}^2} = 0.97 \pm 0.5$$

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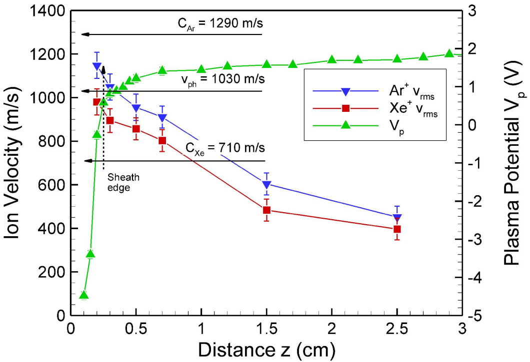


Mysteries...

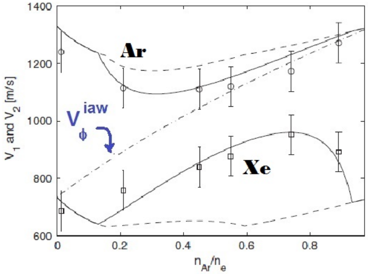
1. what process was driving the two ions toward the system ion sound speed?
2. why the flow 'locking'?

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 $\Delta V \geq V_{crit}$

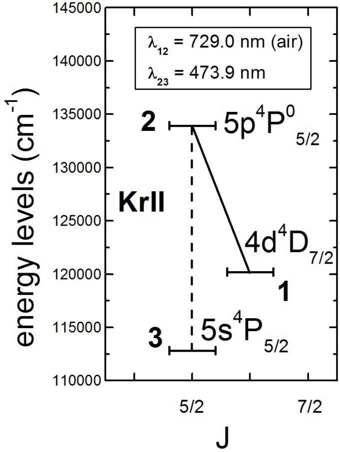
S. D. Baalrud and C. C. Hegna, *Determining the Bohm criterion in plasmas with two ion species* Physics of Plasmas 18, 023505 (2011)

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

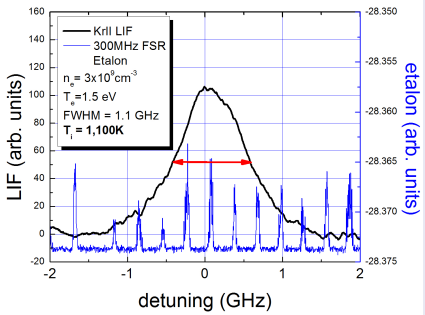


This was verified in our paper, "Experimental Test of Instability-Enhanced Collisional Friction for Determining Ion Loss in Two Ion Species Plasmas", Yip, CS; Hershkowitz, N; Severn, G. Phys Rev Lett. Vol.104 Iss:22 #225003 (2010)

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



first LIF signal–obvious isotope shift effect



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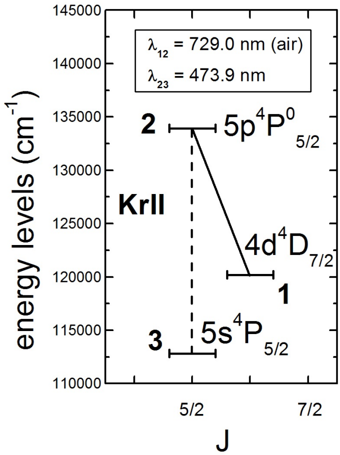

first LIF signal–obvious isotope shift effect

Naturally occurring krypton isotope properties.[1,14]

Mass (amu)	Abundance	Nuclear spin
78	0.35%	0
80	2.27%	0
82	11.56%	0
83	11.55%	$\frac{9}{2}$
84	56.90%	0
86	17.37%	0

Because the main isotope shifts are of order of the room temperature Doppler Broadening $0.7GHz$, we need to perform noise tolerant deconvolution

Basic Digital Algorithm

$A\mathbf{x} = \mathbf{b}$, (A is $n \times n$ matrix)
$\mathbf{x}$ (ivdf)
$\mathbf{b}$ (LIF)
$\therefore \mathbf{x} = A^{-1}\mathbf{b}$.

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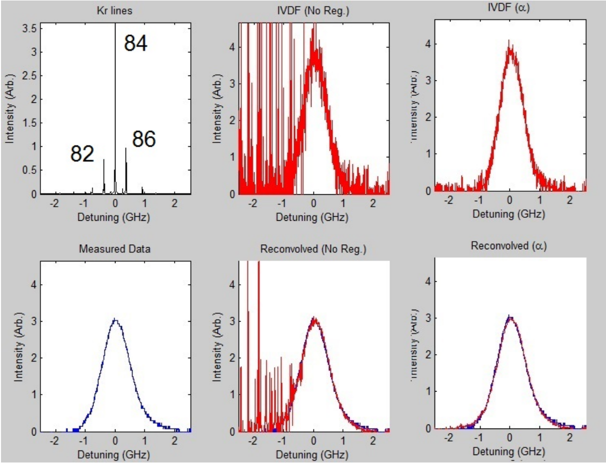
Tikhonev Regularization

perform *singular value decomposition* of A, $\mathbf{A} = U\Sigma V^*$,
filter out contributions of the tiniest singular values σ_i using a *filter factor*, f_i with a 'regularization parameter' , α;
$f_i = \frac{\sigma_i^2}{\sigma_i^2 + \alpha^2}$,
yielding a modified matrix, Ψ, giving
$A^{-1} = V\Psi^{-1}U^*$
that minimizes $A\mathbf{x} - \mathbf{b}$
element by element.

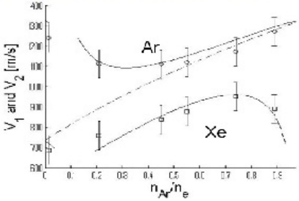
Progress: the deconvolution gives a recovered ion velocity distribution function (IVDF) closer to room temperature 650K +/- 200K



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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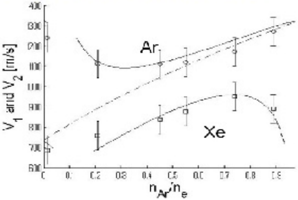

AND THANKS FOR YOUR ATTENTION!