Laser based plasma diagnostic techniques: Velocity distribution by Laser Induced Fluorescence (LIF) technique

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Principle of Laser Spectroscopy

Laser frequency is tuned to a specific transition of interest

Either in Laser Absorption or in Laser Induced Fluorescence techniques, spectral information comes from the first step: absorption of photons
Principle of Laser Spectroscopy

\[ I_0(\nu) = I(\nu) \]

- From absorption signal

\[ \ln\left(\frac{I_0(\nu)}{I(\nu)}\right) = l \cdot \alpha(\nu) \]

- From LIF signal

\[ I_{LIF}(\nu) \approx \Phi(P_{Laser}) \cdot \alpha(\nu) \]

Absorption Coefficient

\[ \alpha(\nu) = \frac{4\hbar B_{12}}{\lambda \gamma} \left( n_1(\nu) - \frac{g_1}{g_2} n_2(\nu) \right) \]
What can we learn by measuring $\alpha(\nu)$?

$$\alpha(\nu) = N k \Phi(\nu)$$

- Density traces Detection
- transition probability
- Line profile Analysis

$\Phi(\nu)$
Units used in spectroscopy

1 eV = 1.6 \times 10^{-19} \text{ J} = 8065 \text{ cm}^{-1} \quad \text{Wavenumber}

300 kT = 207 \text{ cm}^{-1}

1 \text{ cm}^{-1} = 30 \text{ GHz}

\nu = \frac{c}{\lambda} \quad \Delta \nu = \frac{c \Delta \lambda}{\lambda^2}

\text{Photon energy:}
\lambda = 500 \text{ nm} \quad \frac{1}{\lambda} = 20000 \text{ cm}^{-1}

\text{Linewidth:}
\text{At 563 nm,} \quad \Delta \lambda = 1 \text{ nm} \rightarrow \Delta \nu = 1000 \text{ GHz}
Different type of Lasers

**Frequency fixed**: (often used as pump laser)
- Ar⁺, Kr⁺, Nd-Yag, Excimer (XeCl), Cu, HeNe ..... $\Delta \nu_L \approx 10 \text{ GHz}$

**Tunable lasers**:
- **Pumped by a laser**: Dye, Ti:Sa, OPO (tuning range 10 to 100 nm)
  - Lasers available from 400 nm to $\mu$m (+ frequency doubling)
  - **Pulsed lasers**: P up to 10 mJ, $\Delta t \approx 3$ to 30 ns, $\Delta \nu_L \geq 1 \text{ GHz}$
  - Convenient for frequency doubling and $n$ photon transitions
  - **CW lasers**: P= up to a few W, $\Delta \nu_L \approx 0.001 \text{ GHz}$
  - Convenient for high resolution spectroscopy

- **Diode laser**: lasers available from 400 nm to 10 $\mu$m with
  - * tuning range up to 10 nm
  - * P= up to a few 10 mW, $\Delta \nu_L \approx 0.001 \text{ GHz}$ (if single mode)
  - They are more compact, easier to run and cheaper
How the line profile is related to the velocity distribution function?

Doppler shift: \( \nu = \nu_0 (1 + \frac{\vec{k}_L \cdot \vec{V}}{c}) \)

\[
\frac{\nu - \nu_0}{\nu_0} = \frac{\Delta \nu}{\nu_0} = \frac{V_{//\vec{k}}}{c}
\]

The frequency shift is related to only velocity along the laser propagation direction.

The measured velocity distribution function is an integral over the other two directions:

\[
f(V_x) = \int_{V_y} \int_{V_z} f(\vec{V}).dV_y.dV_z
dataframe f(\nu) = \frac{\nu_0}{c}.f(V_x)
\]
## LAS vs LIF

<table>
<thead>
<tr>
<th>Laser Absorption Spectroscopy</th>
<th>Laser Induced fluorescence</th>
</tr>
</thead>
<tbody>
<tr>
<td>- provides sight of line averaged quantities</td>
<td>- has very high space resolution</td>
</tr>
<tr>
<td>- has limited sensitivity</td>
<td>- is very high sensitivity (a single atom can be excited many many times); photon counting</td>
</tr>
<tr>
<td>- Provides absolute density of absorbing species</td>
<td>- But cannot provide absolute densities without a calibration method</td>
</tr>
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</table>
Origin of optical saturation

\[ \alpha(\nu) = \frac{4hB_{12}}{\lambda \gamma} \left( n_1(\nu) - \frac{g_1}{g_2} n_2(\nu) \right) \]

\(\alpha\) becomes no more proportional to \(n_1\)

• 1- Laser beam transfers a significant number of atoms from the lower to the upper state and \(n_2\) becomes no more negligible compared to \(n_1\). (short pulse lasers)

• 2- Atoms in the upper state are lost by radiation, or collisional transfers, to a 3\textsuperscript{rd} state and atoms in the lower state are not renewed fast enough: the lower state becomes depleted. (cw lasers)
Rate equations governing the population densities $N_1$ and $N_2$ of states $|1\rangle$ and $|2\rangle$ are:

$$
\frac{dN_1}{dt} = (B_{21}\rho + A_{21})N_2 - (B_{12}\rho + 1/\tau_1 + \sum_q k_{1,q}M_q)N_1 + C_1
$$

$$
\frac{dN_2}{dt} = B_{12}\rho N_1 - \left( B_{21}\rho + A_{21} + A_{23} + \sum_q k_{2,q}M_q \right)N_2 + C_2
$$

$$
B_{21} = \frac{g_1}{g_2}, \quad B_{12} = \frac{A_{21}}{8\hbar \pi}
$$

is the Einstein coefficient for stimulated emission.

We assume $g_1 = g_2$, $\rho$ is the energy density of the beam, $C_i$ accounts for the repopulation of state $|i\rangle$ from different paths, including diffusion transport into the laser volume and radiative cascades.

$$
\mathcal{R}_1 = 1/\tau_1 + \sum_q k_{1,q}N_q
$$

$$
\mathcal{R}_2 = \sum_{i=lower} A_{2i} + \sum_q k_{2,q}N_q
$$

are the total relaxation rates of the states.
in steady state, \((\text{d}N_1/\text{d}t=0)\) the density difference of states \(|1\rangle\) and \(|2\rangle\) is:

\[
\Delta N=N_1-gN_2=\frac{\Delta N^0}{1+S\frac{R_2-A_{21}+gR_1}{R_1+R_2}}
\]

Where \(\Delta N^0=N_1^0-gN_2^0=\frac{C_1}{R_1}C_2(\frac{g-A_{21}}{R_1})\) is in the absence of laser beam \((\rho=0)\), and

\[
S=B_{12}\rho/\mathcal{R}^*
\]

is \textit{The saturation parameter}

related to the \textbf{mean relaxation rate}.\[\mathcal{R}^*=\frac{R_1R_2}{R_1+R_2}\]

The resulting population density in the lower state is:

\[
N_1=\frac{C_1(\frac{gS+R_2}{\mathcal{R}^*})+C_2(\frac{gS+A_{21}}{\mathcal{R}^*})}{S[R_2-A_{21}+gR_1]+(R_1+R_2)}
\]

\text{When} \quad C_2 \to 0 \quad \text{When} \quad C_2 < 0

\[
N_1=\frac{C_1(\frac{gS+R_2}{\mathcal{R}^*})}{S[R_2-A_{21}+gR_1]+(R_1+R_2)}
\]

\textbf{Larger S is, lower the measured population will be}

\[
\text{When } \rho \to 0, \quad N_1 = \frac{C_1}{R_1} \quad \text{For } \rho \to \infty \quad N_1=\frac{g(C_1+C_2)}{R_2-A_{21}+gR_2}
\]
Intensity of Laser Induced Fluorescence signal

LIF signal is proportional to \( N_2 \) density given by:

\[
I_{23} \propto N_2 A_{23} \propto N_1(E_l, V, R)A_{23} \frac{B_{12}\rho}{B_{21}\rho + \mathcal{R}_2}
\]

When LIF is used to determine the relative populations of two different species, m and n:

**At low laser power limit**, the LIF signal ratio is:

\[
\frac{I_{23}^m(m;2 \rightarrow 3)}{I_{23}^n(n;2 \rightarrow 3)} = \frac{N_1(m)}{N_1(n)} \frac{B_{12}^m}{B_{12}^n} \frac{A_{23}^m}{A_{23}^n} \frac{\tau_{m,2}}{\tau_{n,2}}
\]

\( \tau \) could be \( p \) and \( T \) dependent

**At high laser power limit**, the LIF signal ratio is:

\[
\frac{I_{23}^m(m;2 \rightarrow 3)}{I_{23}^n(n;2 \rightarrow 3)} = \frac{N_1(m)}{N_1(n)} \left( \frac{g_{2,m}}{g_{1,m}} \right) \left( \frac{g_{1,n}}{g_{2,n}} \right) \frac{A_{23}^m}{A_{23}^n}
\]
Calculation of the saturation parameter $S$

1- Pulsed laser:

$\lambda = 589 \text{ nm} ; \quad \tau_2 = 16 \text{ ns} ; \quad A_{21} = 6 \times 10^6 \text{ s}^{-1} ; \quad R_2 = 1/\tau_2 = 6.25 \times 10^7 \text{ s}^{-1} ;$

$R_1 = (1/\text{transit time inside a beam of } \phi = 2 \text{ mm}) = (0.5 \text{ km.s}^{-1})/(2 \text{ mm}) = 2.5 \times 10^5 \text{ s}^{-1}$  

$g_2 = g_1$

Laser pulse: $P = 1 \text{ mJ} ; \quad \Delta L = 4 \text{ ns pulse duration} ; \quad \Delta \nu_L = 0.2 \text{ cm}^{-1} = 6 \text{ GHz} ; \quad \phi = 2 \text{ mm}$

$\Delta L < \tau_2$

$$\rho = \frac{P}{\Delta L \cdot s \cdot c \cdot \Delta \nu_L} = \frac{10^{-3}}{4 \times 10^{-9} \cdot \pi \cdot (10^{-3})^2 \cdot 3 \times 10^8 \cdot 6 \times 10^9} = 4 \times 10^{-8} \text{ J.s/m}^3$$

$B_{12} = \frac{\lambda^3 A_{21}}{8 \pi h} = \frac{(589 \times 10^{-9})^3 \times 6 \times 10^6}{8 \pi \times 6.6 \times 10^{-34}} = 7.3 \times 10^{19} \text{ m}^3/\text{J.s}^2$

$$\bar{R} = \frac{R_1 R_2}{R_1 + R_2} = R_1 = 2.5 \times 10^5 \text{ s}^{-1}$$

$B_{12} \cdot \rho = 3 \times 10^{12} \text{ s}^{-1} \gg R_2$

Then immediately during the laser pulse

$\delta \nu_S = \delta \nu \cdot \sqrt{1 + S} = 3500 \cdot \delta \nu = 35 \text{ GHz}$

If: $\tau_2 = 5 \text{ ns} ; \quad A_{21} = 2 \times 10^7 \text{ s}^{-1} ; \quad R_2 = 1/\tau_2 = 2 \times 10^8 \text{ s}^{-1} ; \quad P = 1 \text{ mJ} ; \quad \Delta L = 40 \text{ ns} > \tau_2$

$B_{12} \cdot \rho = 1 \times 10^{12} \text{ s}^{-1} \gg R_2$

$$S = \frac{B_{12} \cdot \rho}{R_1} = 1.2 \times 10^7 \text{ Very Big}$$

Then in the end of the laser pulse

$N_2 = N_1 = N_1^0 \exp(-R_2 \Delta L/2) = N_1^0 \exp(-4) = 0.018 \times N_1^0$
Calculation of the saturation parameter $S$

cw laser:

$\lambda = 589$ nm ; $\tau_2 = 16$ ns ; $A_{21} = 6 \times 10^6$ s$^{-1}$ ; $R_2 = 1/\tau_2 = 6.25 \times 10^7$ s$^{-1}$;

$R_1 = (1/\text{transit time inside a beam of } \phi = 2 \text{ mm}) = (0.5 \text{ km.s}^{-1})/(2 \text{ mm}) = 2.5 \times 10^5$ s$^{-1}$ \hspace{1cm} $g_2 = g_1$

Laser power: $P = 10$ mW; \hspace{1cm} $\Delta v_L = 1$ MHz $<< 1/(2\pi \tau_2)$ ; $\phi = 2$ mm

$$\rho(v) = \rho_0 \frac{(\delta v/2)^2}{(v-v_0)^2 + (\delta v/2)^2}$$

$$\delta v = \frac{1}{2\pi \tau_2} = \frac{R_2}{2\pi}$$

$$\int \rho(v) dv = \rho_0 \frac{\pi \delta v}{2} = \frac{P}{s*c}$$

$$\rho_0 = \frac{4*P}{s*c*R_2} = \frac{4*1*10^{-2}}{\pi*(10^{-3})^2*3*10^8*6.25*10^7} = 6.7*10^{-13} \text{ J.s/m}^3$$

$$B_{12} = \frac{\lambda^3 A_{21}}{8\pi \hbar} = \frac{(589*10^{-9})^3*6*10^6}{8*\pi*6.6*10^{-34}} = 7.3*10^{19} \text{ m}^3/\text{J.s}$$

$$S = \frac{B_{12} \rho}{R_1} = 200$$

Large saturation: $\delta v_S = \delta v \sqrt{1+S} = 14 \delta v = 140$ MHz

But much smaller than the Doppler width at 300 K ($\cong 1000$ MHz)
Examples of LIF experiments

- Velocity distribution function of Ar* metastable atoms in a helicon reactor
- Velocity distribution function of Ar* atoms in an expanding arc jet
- Velocity of Ar\(^+\) ions in ECR reactor
- Velocity distribution function of Xe\(^+\) in a Hall thruster
- Velocity of sputtered Al atoms under Ar\(^+\) ion bombardment
Velocity distribution function of Ar* metastable atoms in a Helicon reactor
Recorded signals when the laser frequency is scanned

For frequency calibration

LIF Signal

Signal [arb. u.]

LASER ON

LASER OFF

discharges on

discharges off

Laser Intensity

channel number

Fabry-Perot

signal number
Determination of the Doppler width

Cl$_2$ + 10% Ar at 5 mTorr

$\delta \nu_D (GHz) = \frac{(2v_0 / c) \sqrt{2 \ln 2 (RT / M)}}{\lambda_0} = 7.16 \cdot 10^{-16} \frac{c}{\lambda_0} \sqrt{T / M}$
Line profile in presence of strong magnetic field

Zeeman components of the absorbing lines of Argon

772.38 nm; $2p_\uparrow \leftarrow ^3P_2$ line

772.42 nm; $2p_\downarrow \leftarrow ^3P_0$ line

$k \perp B$ if $E \perp B$ only $\sigma^+$ and $\sigma^-$ lines exist

$k \perp B$ if $E \parallel B$ only $\pi$ line (s) exist

$k \parallel B$ then only $\sigma^+$ and $\sigma^-$ lines exist
Experimental profiles of the 722.38 nm line with two different polarization fitted with Gaussians

- polarization perpendicular to B
- polarization parallel to B

- $\sigma, \Delta M = +1$
- $\sigma, \Delta M = -1$
- $\pi, \Delta M = 0$

helicon, 20W, 3.7 sccm
B strong
absorption between B2-B3
772.38 nm

B = 146 gauss
T = 248 K
Reflexion of Ar* atoms on Pyrex surface

LIF signal near the surface from laser beam \( \perp \) to the surface

\[ R = \frac{|j-|}{|j+|} = \frac{\int_0^{+\infty} |v| f(v) \, dv}{\int_{-\infty}^{0} |v| f(v) \, dv} \]

\[ R = 0.28 \pm 0.05 \]

Figure 3. Experimental set-up for the DSLIF experiments near the plasma tube wall.

Figure 4. Velocity distribution functions of \( \text{Ar}^*(3P) \) metastable atoms measured in the immediate vicinity of the internal surface of the Pyrex wall at \( p = 0.09 \) Pa. The vdf’s are normalized by their surfaces and vertically shifted to better distinguish their shapes.

Figure 5. Same as in figure 4 but for 0.5 Pa argon pressure.
Velocity mapping of argon atoms (metastable) in an expanding cascaded arc jet

By Laser Induced Fluorescence technique & by absorption
Experimental determination of argon atoms \textit{vdf} in an expanding arc jet by LIF (Eindhoven)

- \(P = 5 \text{ kW}\)
- \(T_e = 1 \text{ eV}\)
- \(n_e = 10^{22} \text{ m}^{-3}\)
- \(p_{\text{source}} = 5.10^4 \text{ Pa}\)
- \(p_{\text{bg}} = 10 \ldots 100 \text{ Pa}\)

Expected density and velocity distribution along the jet axis

\[ M \gg 1 \quad M < 1 \]

\[ \text{Density} \]

\[ \text{Velocity} \]
Laser Doppler-Shift setup
Ar* velocity distribution functions

- **z=26 mm**: Axial velocity distribution at the axis center.
- **z=46 mm**: Axial velocity distribution.
- **z=59 mm**: Axial velocity distribution.
- **z=100 mm**: Axial velocity distribution.
- **z=174 mm**: Axial velocity distribution.

- **z=50 mm**: Radial velocity distribution at z = 50 mm.

- **r=25 mm**: Radial velocity distribution.
- **r=0 mm**: Radial velocity distribution.
Velocity distribution of Ar$^+$ metastable ions in an ECR reactor
In 1990\textsuperscript{th}, the goal for µ-electronics industry is to separate the generation of the plasma from the energy of ions impinging on the substrate

- Electron Cyclotron Resonance (ECR)
- Helicon
- Inductively coupled plasmas (ICP)
Pulsed versus CW laser for the LIF

FIG. 2. LIF excitation and detection scheme used in this work (solid lines). The dashed lines show scheme used previously with pulsed laser excitation (Ref. 18).

\[ \Delta \nu_L \approx 1 \text{ GHz} \]

Pulsed laser

\[ \Delta \nu_L < 0.1 \text{ GHz} \]

CW laser

FIG. 3. Comparison of LIF line profiles resulting from (a) pulsed and (b) cw laser excitation illustrating the enhancement in both signal-to-noise ratio and spectral (velocity) resolution. These \( f(v_x) \) profiles are obtained under the same conditions given in the caption to Fig. 3. Profiles at different values of \( x \) are shown as indicated.
Acceleration of Ar$^+$ ions leaving the ECR zone

FIG. 1. Schematic representation of ECR system.

FIG. 9. Parallel $f(v_z)$ distributions as a function of $z$. Each distribution is normalized to its maximum value to illustrate changes in shape. Note the acceleration along $z$ and the compression of the distribution function near the platen (at 56.2 cm). Plasma conditions: $I_1 = 180$ A, $I_2 = 100$ A, $I_3 = 0$ A, $F_{Ar} = 3.5$ sccm, $F_{H_2} = 6.3$ sccm. The arrows denote estimates of maximum ion energy.
Azimuthal velocity of Ar$^+$ ions due to the ExB Lorentz force

FIG. 23. Schematic illustration of geometry employed for $v_\theta$ measurement. The laser propagates antiparallel to $\hat{x}$ so that a negative Doppler shift corresponds to motion in the direction of $\hat{x}$. Observation is along $\hat{y}$ and the laser beam intersects $\hat{y}$ at $y = 4.7$ cm so that any shift must come from azimuthal rotation, indicated by the dashed circle. Magnetic field points (×) into plane of the figure.

FIG. 24. Shift in $f(v_x)$ at $x = 0$ cm and $z = 50.2$ cm showing effects of azimuthal plasma rotation. The lowest trace is measured for $y = 0$ cm and shows no shift as expected. The upper traces correspond to $y = 4.7$ cm and small shifts dependent on the sign of the magnetic field are apparent.
Velocity distribution function of Xe$^+$ metastable ions in a Hall effect thruster
The 5 kW-class PPS®X000 thruster in the Pivoine facility

High power Hall Effect Thruster
150 mm outer channel diameter
40 mm channel length
\( P = 2 \text{ – } 6 \text{ kW} \)
\( U_d = 200-1000 \text{ V} \)
\( \Phi_a = 3 \text{ – } 20 \text{ mg/s} \)
Experimental arrangement

Energy diagram and LIF scheme for metastable Xe$^+$ ions

LIF bench: high-power tunable single-mode laser diode

Energy levels:
- $6p^2 D_{5/2}^o$ at $113512.36 \text{ cm}^{-1}$
- $5d^2 F_{7/2}$ at $101535.67 \text{ cm}^{-1}$
- $6s^2 P_{3/2}$ at $95064.38 \text{ cm}^{-1}$

- $\lambda_{\text{air}} = 834.7233 \text{ nm}$
- $\lambda_{\text{air}} = 541.915 \text{ nm}$

Xe$^+$ metastable level

Hypothesis: fluorescence profile = VDF
Detection branch

1:1 imaging system
f = 40 mm lens
200 μm core optical fiber

x-y high-precision long range translation stages

Trouble: optics pollution and wear

The fluorescence collection lens housing and holder are at floating potential
Example of the Steady-state on-axis development of the IVDF

Macroscopic quantities
- mean velocity
- max velocity (10%)
- dispersion

\[ p = 2 \sqrt{2 \ln(2)} \times \sigma \]
Comparison between hybrid model outcome and experimental result

PPS®X000 thruster, 500V and 6 mg/s

The electron mobility through the magnetic barrier is inferred from outcome of PIC simulations.
**IVD Characteristics of the HET in the oscillating regime**

*The best performance*

**PPS100-LM** Hall thruster
- BN-SiO$_2$ walls
- $U_d = 250$ V
- $\Phi_a = 4.5$ mg/s xenon gas
- $I_c = 5$ A
- $P_{\text{back}} = 2 \times 10^{-5}$ mbar-Xe

**Discharge properties**
- $I_d = 4.1$ A
- $f = 21$ kHz

**Performances**
- $T = 69$ mN (wo line cut)
- $T = 67$ mN (w line cut)

**Anode discharge current power shutdown**
- $\tau_c = 10$ µs
- $f = 2500$ Hz

---

**Graph**
- Anode discharge current
- Quasi-normal oscillations
- Restarting
- Forced oscillations
Detection of LIF by Photon-counting technique

Requirements
to monitor the time evolution of the Xe⁺ VDF during a breathing oscillation time period (~20 kHz)

- LIF tool with a time resolution < 1 µs
- nb of fluorescence photons during 1 µs ≈ $10^{-2}$ (with $P_{\text{laser}} = 1$ mW)
- nb of background photons during 1 µs ≈ 1

a) Photon-counting technique → high time resolution
b) Real time add and subtract operation with chopped laser beam → high S/N

Remote discharge current break
discharge stability (quasi-periodic regime vs non-stationary regime)
trigger for all devices
forced as well as natural oscillations
Temporal traces at different Ion velocities

11 measurement locations along the channel axis

Extracted Time series for various velocity groups

Time-averaged electric field on-axis distribution. The electric field is inferred from the mean ion velocity.

Number of on/off cycles ~ 1M

Width of a velocity group: $\delta v = 10$ m/s

Between 10-15 points to reconstruct the local ion VDF
Validity of the measurement technique: Checkout

At each location, comparison between

- **Time-averaged IVDF** measured by means of a lock-in detector \((\tau = 1\text{s}; \text{power cut})\)
- Combining **time-resolved IVDFs** recorded with the photon counting technique
Contour map of the IVDF(t)

Combining all velocity group time-series at a given measurement location

anode discharge current break

restarting
Velocity distribution of sputtered Aluminum atoms under Ar⁺ Bombardment

By Laser Induced Fluorescence technique
Sticking coefficient of sputtered Al atoms on trench side walls and on different surfaces strongly depends on their velocity (energy) distribution.

Laser absorption and (LIF) with a Diode Laser

Energy diagram of Al

\[ \Delta \nu = \nu - \nu_{0} \text{ (GHz)} \]
Hyperfine structure of the 396.15 nm transition of Al atoms

$^2S_{1/2} \rightarrow ^2P_{3/2}$

396.15 nm

394.40 nm

Hyperfine components:
- 4 to 3
- 3 to 3
- 3 to 2
- 2 to 3
- 2 to 2
- 1 to 2

0.014 eV

$\nu - \nu_0$ (GHz)
Absorption line profile
From zero collision to thermalization

<table>
<thead>
<tr>
<th>Gas pressure (mTorr)</th>
<th>0.5</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision mean free path (cm)</td>
<td>25</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>20</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>0.6</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Velocity distribution function of sputtered Atoms

Comparison with Thompson theory of velocity distributions recorded at very low argon pressure (0.4 mTorr)

\[ f(E, \theta) d\Omega dE \propto \cos \theta \times \frac{E}{(E + E_b)^3} \left(1 - \frac{E + E_b}{AE_1}\right) d\Omega dE \]

\( E_b \) surface binding energy

\textbf{angular distribution}

- LIF: \( V_z \) distribution
- Absorption: \( V_x \) distribution

\[ \theta (\degree) \]

\[ -90 \quad -60 \quad -30 \quad 30 \quad 60 \quad 90 \]

\[ -90 \quad -60 \quad -30 \quad 30 \quad 60 \quad 90 \]

\[ \ln \left( \frac{I_0}{I} \right) \]

\[ V_x \text{ distribution (a)} \]

\[ V_z \text{ distribution (b)} \]

Cosine (dashed)

Harte (solid)

\( V_x \) distribution (a)

\[ \text{velocity (km/s)} \]

\[ -8 \quad -6 \quad -4 \quad -2 \quad 0 \quad 2 \quad 4 \quad 6 \]

\[ 0.00 \quad 0.01 \quad 0.02 \quad 0.03 \]

\[ V_z \text{ distribution (b)} \]

\[ \text{LIF intensity (a.u)} \]

\[ 0.00 \quad 0.25 \quad 0.50 \quad 0.75 \quad 1.00 \]

\[ \text{velocity (km/s)} \]

\[ 0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \]

\[ 0.00 \quad 0.25 \quad 0.50 \quad 0.75 \quad 1.00 \]

\( \cos \theta \) (dashed)

Harte (solid)

\[ \text{Under low energy bombardment (ICP), the angular distribution of sputtered Al atoms is much closer to a “Hart shape” than to a cosine distribution} \]


- S. Mazouffre, D. Gawron and N. Sadeghi, A time-resolved laser induced fluorescence study on the ion velocity distribution function in a Hall thruster after a fast current disruption, Physics of Plasmas 16 (2009) 043504

- G. Bourgeois, S. Mazouffre and N. Sadeghi, Unexpected transverse velocity component of Xe+ ions near the exit plane of a Hall thruster, Physics of Plasmas 17 (2010) 113502