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Laser-induced fluorescence diagnosis of plasma processing sources

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Abstract

Laser-induced fluorescence (LIF) may be used to make non-perturbing diagnoses of ions in plasma processing sources. Among the measurements possible are ion density profiles, distribution functions, convection and diffusion. Plasma processing sources such those used for etching, sputtering and thin film deposition may be diagnosed. In this review of LIF, examples of argon ion distributions and flow velocities in filament, hollow cathode and radio frequency plasma processing system are presented.
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Keywords: Experimental methods; Laser-induced fluorescence; Plasma processing

1. Introduction

Plasma physics and its engineering applications have suffered long from difficulties in making diagnostic measurements of plasma phenomena without certainty of not perturbing the plasma. Langmuir probes often provide basic diagnosis of plasmas to give plasma density, electron temperature and floating potential. Yet the physical presence of the probe may perturb the plasma or introduce the chance of impurity introduction to the plasma volume. Optical diagnosis of plasmas offers the possibility of non-perturbing measurements of plasma properties, particularly of the ions. Researchers have taken advantage of natural emission spectroscopy from plasmas and realized that an optical diagnostic tool that could specify the spatial location and time for which the optical diagnosis could occur would be a great advantage over background plasma radiation. Presented here is a general overview of laser-induced fluorescence (LIF) as a diagnostic tool, its specific application to plasma processing sources and its potential for such further applications.

Early use of LIF in plasmas was reported by Stern and Johnson [1]. Basically, LIF involves the use of a single-mode laser to interrogate plasma ions with at least one bound electron, which can respond, with the right Doppler shift of the laser, to resonate by absorption of the laser photon with emission of a second photon. Often this process involves excitation of a metastable-state electron, with the emission of a photon when the electron drops back down to the metastable state or to another state in the ion. The natural resonance frequency at which the ion will absorb the photon is offset in frequency by the ion velocity component in the direction of the laser beam. That is, fluorescence occurs when:

$$\omega_{\text{laser}} - \vec{k}_{\text{laser}} \cdot \vec{v}_{\text{ion}} = \omega_{\text{resonance}}$$

where ω_{laser} is the laser frequency, $\vec{k}_{\text{laser}}$ is the laser wave vector, $\vec{v}_{\text{ion}}$ is the ion velocity and $\omega_{\text{resonance}}$ is the frequency at which a stationary ion would fluoresce. While the details are somewhat complicated, in essence the fluorescence signal is commonly proportional to the number of ions with the specific velocity component at the laser-interrogated place and time. By sweeping the laser frequency across the Doppler-shifted range of ion velocities, the ion distribution function (in the direction of the laser beam) may be obtained. Suppose, for example, the laser is pointed in the y-direction and the plasma optics are aligned with the laser to examine spatial position x, then we obtain $f_i(x,v_y,t)$. Often the laser system preferred to make these Doppler sweeps is a tunable dye laser. More recently, diode laser systems have been devised [2], which are advantageous in some circumstances. Some reasons for picking one type of laser system over another is discussed below.

By invention of the technique of optical tagging [3], numerous plasma transport properties can be measured. Optical tagging involves using LIF to alter deliberately the quantum state in which the electron resides on the ion, with the aim of locating that altered ion at a later

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time. This allows the ion to be followed, such as in its Larmor orbit, or the determination of spatial ion-diffusion coefficients in plasmas dominated by Coulomb collisions [4] or by turbulent diffusion [5]. In addition, velocity space convection and diffusion, the Fokker–Planck coefficients, may be measured [6].

By changing the angle at which the laser beam passes through the interrogated volume, and thus altering the velocity component for which the Doppler-shifted resonance occurs, it is possible to obtain two- and three-dimensional velocity distribution functions, $f_i(x,v,t)$, via a process called optical tomography [7]. The latter work shows, for example, the non-Maxwellian nature of an ion beam formed from contact ionization at a thermionically emitting surface and then subjected to a flaring magnetic field after acceleration away from the beam source.

LIF provides the possibility of high-resolution, non-perturbing measurements of the plasma ions: velocity resolutions of a few percent of the ion thermal speed and spatial resolutions of 1 mm in extent are routine [2–7]. Plasmas in magnetic fields have Zeeman effects that can be deconvoluted straightforwardly [7] when needed. While many LIF systems run in a steady state, pulsed systems are commonly utilized as well (see, for example [8]).

LIF has been used on occasion to measure ions in plasma processing sources, such as for plasma magnetron [9], ECR [10], helicon [11] and ion-beam processing [12] sources, but its use has not been widespread. The present paper gives examples of LIF use in plasma processing sources utilizing filament discharge, hollow cathode and radio frequency sources. In each of these cases, the species diagnosed is singly ionized argon, although LIF may be used on many species, neutral or ionized.

2. Diagnostic arrangements

LIF may be fielded in a variety of configurations; sometimes multiple set-ups will be equally suited for a particular application. A common and flexible arrangement is the use of tunable dye lasers in the configuration shown in Fig. 1a. In this set-up, an ion pump laser of typically 5–10 W powers the dye laser, which may be of linear or ring configuration with single-mode capability. The older Coherent 599 linear-geometry lasers are more difficult to hold in single mode compared to the Coherent 699 or 899 ring lasers. However, the 599 model runs easily in a 'broadband' mode, in which the laser rapidly hops among many modes over a frequency range much broader than the thermal ion Doppler-shift range. The ring lasers do not run in this 'broadband' mode easily. This is an instance where older technology retains an advantage for some experiments. A ring laser set-up may be easily supplemented by a relatively

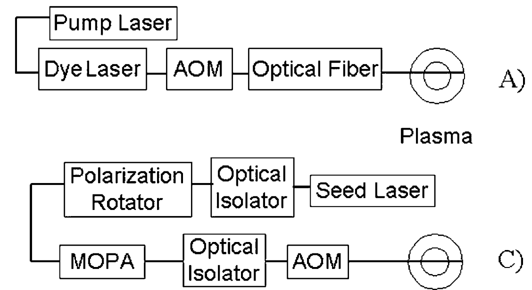

Fig. 1. (a) Dye laser configuration with a pump laser driving a tunable dye laser for which the output reaches the plasma via fiber optics. (b) A diode laser set-up in which a low-power, tunable, stable single-mode diode seed laser is amplified by a tapered-amplifier laser diode chip run in the MOPA configuration.

inexpensive 599 obtained in the used laser market if 'broadband' tagging experiments for spatial diffusion measurements are desired. The output of the dye laser may be run through an acousto-optical modulator (AOM) if noise reduction is an issues, and then sent to the plasma via fiber and associated optics.

A second and more recent development has been the possibility of using diode lasers for LIF plasma experiments. One diode configuration is shown in Fig. 1b. In this case a low-power (<10 mW) single-mode seed laser (such as sold by New Focus) is amplified via a single pass through a high-power tapered-amplifier diode chip. High-power diodes, up to 500 mW, often cannot easily run in single mode as stand-alone lasers, but the chip can be used as a single-pass amplifier instead to obtain sufficient power in a single mode. In this configuration, the high-power chip is running in what is termed a master oscillator power amplifier (MOPA) arrangement. High-power diode chips have proved to be sporadically available due to high failure rates on the wafer production runs of these chips. For some frequencies, seed lasers of up to 20 mW are available, and for some plasma experiments LIF may be performed acceptably with laser power under 20 mW. In many cases, laser power of approximately 100 mW is needed. In any diode laser arrangement selected, optical isolators are a necessity, as the seed and amplifier lasers are adversely affected by reflected laser light. The availability, laser output power requirements and frequency needed guide the choice of LIF set-up.

In any choice of laser set-up, it is often advantageous to have an iodine cell used for absolute frequency (and therefore, ion velocity) calibration. The use of an iodine cell simultaneous with the LIF plasma interrogation can alert the user to laser mode hops as well. A competent glass shop can easily construct such cells with a little advice from someone who has made them. Beam dumps may be used in vacuum systems in which reflected laser light might contribute unwanted LIF signals. However, it is commonly the case that beam dumps are not

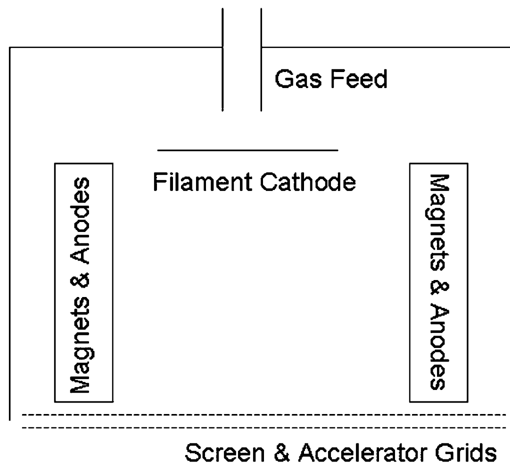

Fig. 2. Geometry of typical Kaufman ion gun with filament cathode.

necessary when optical path geometries are considered. Moreover, in some circumstances a reflected laser signal may be used to advantage in finding the absolute zero in a velocity distribution if no iodine cell is available (see for example [12]).

3. Plasma processing sources tested

In the present experiment reported, three types of plasma processing sources were interrogated with LIF: filament, hollow cathode and radio frequency ion sources of the Kaufman-type neutralized ion beam and its evolved sources. LIF may be applied to the plasmas internal to such sources and to the output ion beams.

Fig. 2 shows the general layout of a filament or hollow-cathode Kaufman ion gun. The plasma is formed within the ion beam source via electron-impact ionization of neutral gas bled into the source. The electrons are provided in these cases via thermionic emission from a biased filament or from the interior of a biased hollow-cathode source run either in the cold-cathode mode or as a thermionic emitter. The resulting plasma volume provides the flux to the beam accelerator grids. Ion beams of $<1–10$s of cm in diameter have been produced with these sources. LIF may be used to examine the ion distributions inside these sources and in the accelerated beams, helping to understand the physics of beam uniformity questions such as beam energy spread, divergence and fluctuations. While Fig. 2 explicitly shows a filament source, the hollow cathode configuration is quite similar, with the hollow cathode approximately replacing the filament near the top center of the figure, with much of the remaining chamber remaining similar.

Fig. 3 essentially shows an RF ion beam source such as available from Veeco/Ion Tech. This type of source has plasma-processing advantages of avoiding filament or hollow cathode replacement and a reduction in impurities in the beam due to the filament or hollow cathode.

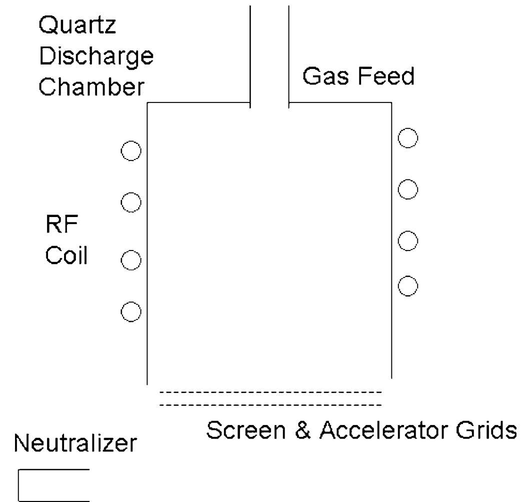

Fig. 3. RF ion beam source such as produced by Veeco/Ion Tech.

4. Measured ion distribution functions

In the case of a filament cathode source, an LIF measurement of the ion distribution function inside the source is shown in Fig. 4. In this case, a dye laser excited at 611.5 nm induced fluorescence observed at 460.9 nm. A diode laser exciting at 668.6 nm and inducing fluorescence observed at 442.6 nm yielded similar distributions. More details of these transitions are given elsewhere [2]. The distribution function observed appears nearly Maxwellian, with a slight drift velocity in the direction of the laser beam. The ion temperature is typically approximately 0.1 eV and den-

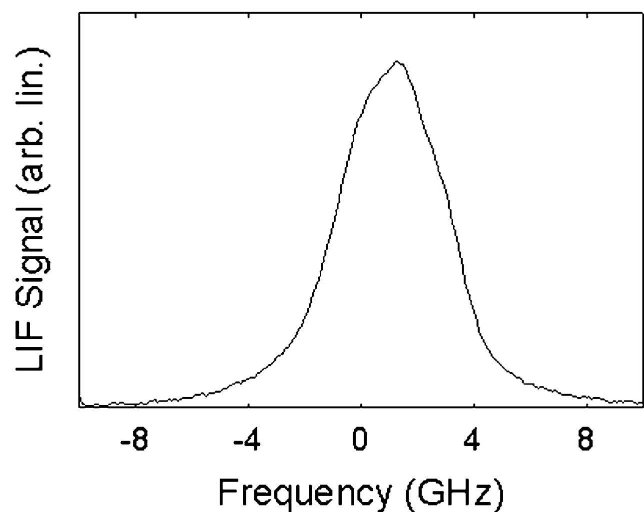

Fig. 4. LIF signal showing argon-ion distribution function in a filament cathode-produced plasma.

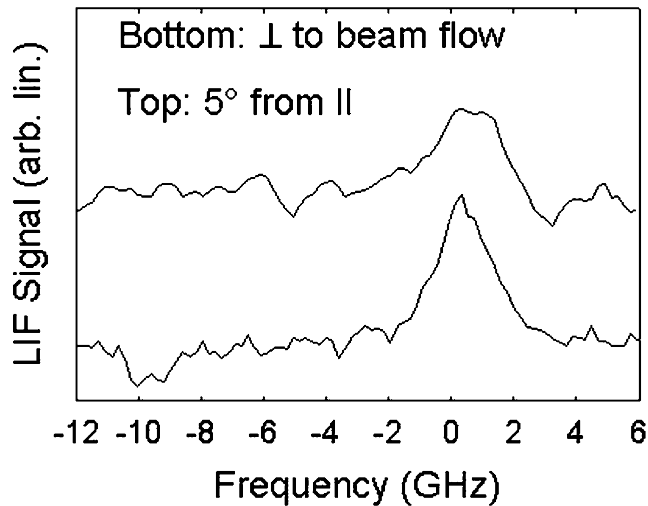

Fig. 5. LIF signals in the accelerated ion beam region external to the RF ion beam source. Bottom line shows ion distribution perpendicular to beam flow direction. Top line shows ion distribution at 5° laser inclination with respect to the ion beam flow direction.

sity $\sim 10^{10}$ cm^{-3}, with variations from this as plasma parameters such as background gas pressure (10^{-4} Torr in the figure) are changed. Similar distributions are observed near hollow cathodes inside Kaufman sources.

Next shown in Fig. 5 are distributions taken from the neutralized ion beam produced with an RF source (also at 10^{-4} Torr in the main chamber). With LIF excitation and detection external to the source, this particular beam was accelerated to 500 eV of directed energy. The laser beam was aligned perpendicular to the ion beam flow direction. The distribution observed is shown and is similar to those observed inside hollow cathode and filament sources. There is greater noise in the signal as the ion densities are lower in the beam region by one–two orders of magnitude, in the mid 10^{8} cm^{-3} range. By tilting the laser to approximately 5° off the perpendicular, observation of a parallel drift component of $\times$cos85° might be expected for the ion beam; that is, the distribution would be shifted to a drifting distribution separated from the perpendicular distribution by approximately 7 GHz (to the left, or negative direction in the figure). However, this is not observed. Here the tilted distribution is comparable to the perpendicular ion distribution and no drift component is observed. In this case, the ion beam produces substantial cold background plasma external to the beam source in the neutral pressure available there (gas flows out of the RF source through the grids, along with the ions). This cold plasma, in combination with the low argon-ion metastable population produced in the RF source (as compared to the filament source) means the ion beam is not observed in the LIF signal, since the cold, background plasma signal is much greater than that produced from the beam ions. Interpretation of LIF signals can require care in cases such as this.

5. Conclusions

LIF is a powerful, non-perturbing optical diagnostic tool, which may be quite useful in characterizing plasmas used in processing. With care in laser set-up selection and a successfully search for metastable ion populations sufficiently populated to observe LIF, high-resolution ion distribution functions may be obtained. From these distributions, many ion properties, including fluid convective velocities, spatial density profiles, thermal and non-thermal distribution properties, diffusion and density fluctuations may be determined.

Acknowledgments

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