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Mini-conference on laser-induced fluorescence in plasmas[a]

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A mini-conference on laser-induced fluorescence in plasmas was held on 29 October 2003 as part of the 45th meeting of the Division of Plasma Physics of the American Physical Society. This paper summarizes material discussed in the talks presented as part of the mini-conference. The mini-conference was also an occasion to honor Raul Stern on his 75th birthday and to recognize his many contributions to plasma physics and to the applications of laser-induced fluorescence.
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I. INTRODUCTION

Laser-induced fluorescence (LIF) encompasses a large array of laser-aided diagnostic techniques that have found application in the study of a wide range of fundamental and applied problems. Because LIF is specific to the quantum state of ions, it is often possible to determine something about electric and magnetic mean fields and microfields through their effects on the ionic energy levels. However, through the Doppler effect or the time of flight of test particles, LIF can also simultaneously resolve both position and velocity variables and provide an important window into the dynamics in the phase space (x,v) of ion motion. The mini-conference primarily focused on this exploration of the ion phase space through LIF. In addition, some of the approach and analysis applied to LIF data has found application in analogous diagnostics. These extensions beyond LIF were also discussed at the mini-conference.

This paper summarizes the oral contributed papers presented at the mini-conference on laser-induced fluorescence held concurrently with the 2003 Annual Meeting of the Division of Plasma Physics of the American Physical Society. The organization is by topic and not by the temporal order of the presentations during the mini-conference. References are given to provide further information on the topics discussed during the mini-conference, but no attempt has been made to provide a comprehensive list of references. Furthermore, we do not completely cover the full spectrum of LIF techniques that is in current use. In addition to regular contributed papers, the mini-conference had a tutorial lecture (Fred Skiff) and a review lecture (Roger McWilliams). Brief excerpts from these presentations are also included here. A poster session, which included part of the morning and afternoon, was an important component of the mini-conference that was not possible to include in this short summary.[1]

II. FAMILIES OF TECHNIQUES

Laser-induced fluorescence in plasmas refers to observed changes in the light coming from the spontaneous allowed transitions of plasma ions due to changes in their quantum state densities produced by laser-optical pumping. Typically, one starts with an ion in the ground state or in a metastable state (1), and laser excitation transfers the ion to an excited state (2) that ideally decays to a third level (3) with a large branching ratio through an allowed transition. A diagram of the situation is shown in Fig. 1. Because ionic transitions tend to be narrow, the use of a single-frequency laser easily allows for Doppler selection of the ion motion along the direction of the laser beam to the level of 100 m/s nominally. Measurement of much lower velocities is possible depending on the signal to noise or by using, for example, time of flight. Typically, LIF observations are resolved in all three spatial variables since the signal comes from the intersection of the cylindrical volume illuminated by the laser beam and the viewing volume of the light collection system. Because the decay of the excited state is rapid $(\sim 10\ \text{ns})$, the LIF signal depends principally on the number of ions in this diagnostic volume that are optically pumped to the excited state.

The phase-space nature of laser-optical pumping is evident in $W(\overline{x},\overline{v})$, the rate of induced transitions

$$W(\overline{x},\overline{v}) = \frac{I_0(\overline{x})}{\|\overline{k}\|^2 4\hbar\omega_0} A \int \phi(\omega) L(\omega - \overline{k}\cdot\overline{v})\, d\omega,$$

where I_0 is the spatial intensity profile of the laser beam, A is the rate of spontaneous transitions, k is the laser wavevector, $\hbar\omega$ is the energy difference between the pumped levels, $\phi(\omega)$ is the frequency dependence of the laser light $[\phi \sim \delta(\omega-\omega_l)$ for a single frequency laser], and

$$L(\omega) = \frac{A/2\pi}{(\omega-\omega_0)^2 + \left(\dfrac{A}{2}\right)^2}$$

is the natural (Lorentzian) line shape of the pumped transition.

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[a] Mini-conference, Bull. Am. Phys. Soc. **48**, 6 (2003).
[b] Organizers.

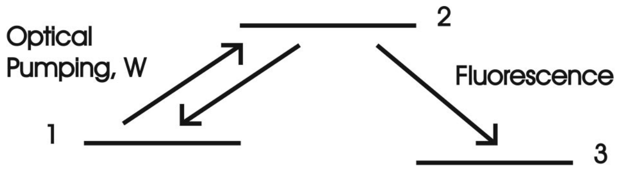

FIG. 1. Energy level diagram for LIF in a three-level system.

If the laser is pulsed quickly, the ions have a short lifetime in the laser beam, or the laser intensity is sufficiently weak; then, the LIF signal will be simply proportional to the classical expectation value of W averaged over the viewing volume with respect to the velocity distribution function f of the target ionic state (1)

$$S=\int f(x,v)W(x,v)d^3x\,d^3v.$$

This contribution of each part of phase space to the LIF signal is local and the circumstance is called the linear regime of LIF because the signal is proportional to laser intensity. In the linear regime, the measurement is truly nonperturbing.

However, if optical pumping is strong enough, it will eventually deplete the density of ions in the target state and extinguish the LIF signal. As this nonlinear regime is entered, the signal becomes increasingly dependent on the nature of the orbits of particles as they pass through the laser beam—this is nonlocal in the particle phase space. Ion tagging uses the state density modifications caused by optical pumping as a way to label test particles. These test particles may be subsequently detected by the original beam, or by a secondary (search) laser beam. In two-beam tagging, the dependence on particle orbits extends to the region between the two lasers which the particles must cross in order to be detected by the search beam. The linear/nonlinear regimes described above can be used to roughly distinguish two classes of LIF techniques: ones which form Eulerian picture of the ion phase space through local measurements of $f(x,v)$, and those which require a Lagrangian picture of the phase space because one must follow particle orbits. We will use this classification scheme to organize our summary of the mini-conference papers.

Roger McWilliams reviewed the development of both Eulerian and Lagrangian LIF techniques at the University of California Irvine over the past 25 years. These include the measurement of ion distribution functions,[2] application of tomography to LIF,[3] measurement of spatial and velocity-space diffusion and convection,[4–6] and the use of diode lasers.[7] The many contributions of Raul Stern were also highlighted.[8,9]

III. EULERIAN TECHNIQUES

Eulerian techniques are based on a picture of phase space composed of local measurements in the space of position and velocity. The primary goal is usually to determine the density distribution and the velocity or energy distribution of plasma ions. The majority of applications of LIF is of this type. This kind of measurement can be obtained either by operating in the linear regime of LIF or by using a short ($\sim$10 ns) pulse that optically pumps all the ions as a kind of snapshot during which the ion motion is negligible.

Plasma sheaths have been an object of study and controversy for many years. Noah Hershkowitz showed how LIF is used to study ion acceleration in the presheath near the edge of a plasma.[10] The measurements show differences between the behavior of plasmas with one (Ar^+) or with two (Ar^+, He^+) ion species. In the case of one ion species the ions are accelerated in the presheath so that they exit the plasma at a velocity near the Bohm velocity. However, in two ion species plasmas, the ions are accelerated to significantly higher velocities. This presheath acceleration can, through the effects of collisions, result in hotter ions near the plasma edge. LIF was used to cross check and calibrate various techniques such as the Mach probe and the use of ion acoustic waves to determine ion flow. LIF was performed on argon ions using a diode laser.

Ultracold and dense plasmas produced by photoionization expand due to electron pressure. The electron pressure can be controlled by tuning the energy of the photoionization photons. A wide range of collective phenomena should occur in such plasmas that have begun to be studied experimentally.[11] Tom Killian showed results of experiments on neutral plasma clouds of singly ionized strontium where laser absorption was measured instead of detecting the fluorescence photons. An optical image of the plasma cloud, using an intensified CCD camera, is used to infer the ion dynamics. Strontium ions have an optical transition at 421.7 nm which is pumped in this experiment by doubling the output of a high-power 843.3 nm diode laser. Data showing the expansion of these plasma clouds were presented.

Paul Kleiber showed how LIF can be used to probe the dynamics of gas-phase atomic and molecular collisions that involve both inelastic and chemically reactive collisions.[12] By probing the continuum states of reaction products it is possible to infer, for example, the dependence of reaction rates on the orientation of molecules when they collide. The data also reveal information on the (Born–Oppenheimer) potential energy of interaction surface for the collision. The branching ratio of collisions into the various final states can also be determined. Data were presented from studies of metal atom–rare gas collisions and metal atom–H2 reactive quenching collisions.

A second group of Eulerian techniques looks at the perturbations on the ion velocity distribution due to collective modes. Frequently this is accomplished by locking-in on the mode frequency and averaging using synchronous detection.[13] Because the theory of linear modes is well developed, it is often possible to perform detailed comparisons between theory and experiment and to determine parameters related to the plasma equilibrium.

Non-neutral ion clouds in traps exhibit a large number of collective modes that have been studied both experimentally and theoretically. John Bollinger presented pictures and analysis of laser-cooled beryllium ion plasmas in a Penning trap acquired through Doppler LIF. Sinusoidal applied voltages on the trap endcaps are used to excite single modes, and radiation pressure from a laser beam is used to produce a variety of wakes (because the ion cloud is in constant rotation). Detailed comparisons with the theory of collective modes and wakes were presented.[14,15]

Laboratory study of Alfvén waves in plasmas generally requires high density and a physically large experimental device. Walter Gekelman showed how the ion perturbations due to shear Alfvén waves are studied in the LAPD device.[16] Large-amplitude waves ($\delta B/B \sim 10^{-3}$) launched by an antenna are observed by Langmuir probes, magnetic probes, and a fiberoptically fed and movable LIF probe. The LIF probe contains a viewing dump that shields background light produced in the large plasma volume from the LIF signal. With this probe the correlated motion of plasma ions in response to the Alfvén wave is studied using LIF, and the role of the $E \times B$ and polarization drifts readily identified. Furthermore, it is possible to infer the relationship between $E_\parallel$ and $E_\perp$ through the observed ion response. In this experiment LIF was performed on the Ar^+ 611 nm metastable line in a plasma with $n \sim 10^{12}\ \mathrm{cm}^{-3}$ and $B = 1.5$ kG.

Ion acoustic solitons are a form of nonlinear wave that has been extensively studied using Langmuir probes, but not using LIF. The paper of Nicolas Claire (presented by F. Skiff) described a laboratory study of solitons produced in a double-plasma device.[17] Biasing one plasma relative to the other produces an ion flow at the central separating grid. The magnitude of this flow was demonstrated to have a large effect on the formation and separation of solitons launched by the conventional means (application of a positive pulse to the bias voltage). To improve photon statistics, a laser intensity was used that was sufficient to enter the nonlinear regime of LIF. Because of this, it is necessary to correct for the optical pumping effect in order to have a correct measurement of $f(x,v,t)$ or of moments such as the plasma density. This work builds on earlier work of the Marseille group on using the optical pumping produced by a single laser beam for Lagrangian (test-particle) diagnostics—the measurement of velocity space diffusion and of electric fields.[18]

IV. LAGRANGIAN TECHNIQUES AND EXTENSIONS

Test-particle techniques depend on labeling small regions of phase space and following the subsequent motion. The connection between the Eulerian and Lagrangian approaches is often subtle.[19,20] In practice, the two types of techniques are complementary in the kinds of information they provide. The primary application of Lagrangian techniques is test-particle transport.

Non-neutral plasma experiments have mostly been performed on electrons. However, there are several ion plasma experiments and they generally employ LIF. One example, of course, is the Penning trap experiments using beryllium mentioned above. Heat and particle transport in larger, weakly coupled pure-ion plasmas of singly ionized magnesium were discussed by Francois Anderegg.[21,22] Spin polarization by optical pumping is used to label test particles in a Penning–Malmberg trap, and LIF is used to track the diffusion of particles and heat. Use of the ''rotating wall'' technique permits long-time confinement of the plasma. Because of the cylindrical symmetry and plasma rotation, the transport of a cylindrical shell of plasma that has been optically spin-aligned by a pump beam is subsequently measured by a probe beam. Heat transport is studied by perturbing the plasma temperature by laser heating/cooling applied to the same (280 nm) Mg^+ transition.

In analogy to the use of optically labeled test particles, the nearly ballistic response of laser photodetached electrons can be used to probe plasmas containing negatively charged hydrogen ions. The plasma consists of hydrogen ions, electrons, and negative hydrogen ions. Electrons can be photodetached from the negative ions very effectively using the 1064 nm light from a pulsed YAG laser. After the creation of a pulse of free electrons with the pump laser, a Langmuir probe is used to observe the small pulse of test electrons. Further experiments involved using two closely spaced pump laser pulses. In analogy to optical tagging, Raul Stern named this technique ''nonresonant optical tagging.'' Marta Bacal described experiments on negative ion plasmas in hydrogen gas discharge plasmas where local transport velocity of the negative hydrogen ions was a primary concern.[23] In addition, the study of the collective effects associated with the pulse of electrons released during the photoionization process leads to further diagnostic possibilities. Lazar Friedland, using a kinetic model for the negative ions and fluid theory description for the other components, extended previous work on the response theory of the plasma and showed how photodetachment can be used to determine the velocity distribution function of the negative ions.[24]

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We wish to thank all the participants in the mini-conference. The success of the mini-conference can be attributed to the quality of the presentations of the participants both in the oral and in the poster presentations. A wide range of topics was covered in the mini-conference showing the wide range of techniques and physical experiments available using LIF. The large impact of Professor Raul Stern, through seminal work and through many collaborations with many of the participants, is gratefully acknowledged, as well as the opportunity to celebrate his 75th birthday with him.

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