Time resolved LIF with a fast-scanning diode laser

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Abstract. Ion phase-space resolved fluctuations carry detailed information pertaining to transport as well as to the plasma degrees of freedom. Using a 500 mW diode laser that can scan over Doppler broadened Argon ion lines in less than 50 microseconds we observe fluctuations and correlations with an adjustable bandwidth by means of a comb-filter. The high laser intensity coupled with fast scanning makes optical pumping between the Zeeman sublevels observable. This opens a new strategy for optical tagging as well as observing correlations between fluctuations at different ion velocities. The experiments are performed in a 2 meter length 0.1 meter diameter CW Argon gas discharge created by a 10 MHz inductive plasma source in a uniform 1 kG magnetic field. The plasma density is typically $10^9$ cm$^{-3}$, the electron temperature is 2 eV and the ions have a temperature of 0.1 eV. Under these conditions the ions are weakly collisional.

1. Introduction
Coherent detection is useful for the study of reproducible [1] and especially harmonic fluctuations [2] using laser-induced fluorescence (LIF). Recently particle-velocity-resolved plasma cross-power spectra and higher-order spectra have been measured using the cross-correlation approach [3]. In the earliest measurements, fluctuations in the fluorescence light are cross-correlated between two points along a single laser beam. Extending this technique, correlations between fluctuations at different ion velocities requires two separate tunable laser systems. An alternative strategy for measuring fluctuating distribution functions which we explore here is to rapidly scan the wavelength of a single laser so as to obtain a measurement of a distribution function in a time short compared to the periods of the fluctuations of interest. The advantage of the technique is that it can be performed using a single laser and a single detection system. Furthermore, it is not necessary to chop the laser so long as the rapid scan extends past the Doppler broadened line so that the level of collisionally induced fluorescence light can be determined. Of course, as the laser intensity is increased in an effort to increase the photon count rate one invariably has to deal with optical pumping and its effects on the measurement. Here we present first results of using a fast-scanning diode laser system to measure fluctuating distribution functions with a bandwidth that is equal to the scan frequency (each period of the scan frequency measures the distribution function twice), but adjustable through the use of a comb filter. Difficulties encountered in implementing the technique are discussed. The role of optical pumping on the results is observed and compared to a collisional-radiative simulation of the experiment. We note that fast scanning LIF has been done previously with the intent of measuring a distribution function in a single pulsed plasma discharge, but was not used to study fluctuations [4].
2. Experimental set up
The experiments are performed in a weakly-collisional inductively coupled RF gas discharge at 10 MHz. The plasma is a cylinder of 3 meter length and 0.1 meter diameter immersed in a straight magnetic field along the axis that is 1kG. The neutral pressure is regulated to 0.2 mTorr of Argon. The plasma density is typically $10^9$ cm$^{-3}$ of singly ionized Argon with an electron temperature of 2 eV and an ion temperature of 0.1 eV. The experimental set-up for cross correlated LIF is shown in figure 1. For these experiments we used a Toptica DL-100 0.5 W tuneable diode laser operating at 668nm which is a metastable line with fluorescence observed at 442nm. This transition is widely used for diode laser LIF [5]. The Toptica diode laser can be modulated rapidly, using the internal ramp, (which drives a piezo-stack on the grating used in the external cavity and can also scan the diode current for enhanced stability during the grating scan). Because the nominally triangular ramp signal does not necessarily correspond to the actual grating position or laser frequency, and there may be other electronic phase shifts, we monitor the instantaneous relative laser wavelength using a home-made Michelson interferometer with an output that is digitized at the same time as the LIF signal. Signals are digitized at 1 MHz sample rate for files of duration 1 second.

3. Initial Results and analysis
The fluctuations in the PMT signal at low frequency are dominantly caused by the background light (collisionally induced fluorescence). By constructing a comb filter in the frequency domain that is a sum of bandpass filters centered on each of the harmonics of the scan frequency it is possible to have a measurement of the distribution function with a specified bandwidth. Fourier reconstruction of the filtered data is shown in Figures 2 and 3 for a 10 Hz and 1 Hz fluctuation bandwidth respectively and a scan period of 176 $\mu$s. With such strong filtering it is clear that the distribution functions, that are nominally recorded every 80 microseconds, only manifest variations over longer timescales. By subtracting this average distribution from a less filtered time series it is possible to look at the fluctuations $f - <f>$. In the plasma cylinder the fluctuations are mostly due to $m=1$ convectively stabilized dissipative drift instability driven by the radial electron pressure gradient. These fluctuations occur near the electron drift frequency ($\sim 1.5$ kHz).

Below we will return to the curious feature that the distribution function appears to depend on direction of scan. Also, the laser light was linearly polarized so that both of the (p polarized) Zeeman components are visible. Nevertheless, one can look at a given point on the distribution function and look at the fluctuations as a function of the scan number. In order to overcome the photon statistics fluctuations (the LIF photon count rate is close to $10^7$ per sec) we calculate the cross correlation:

$$C(z_2 - z_1, v_2, v_1, t_2 - t_1) = \langle f(z_1, v_1, t_1) f(z_2, v_2, t_2) \rangle$$
As a point of departure, we can calculate a velocity-integrated cross correlation integrating $C$ over the single variable $v_1=v_2=v$. The result of computing this integrated correlation function from the data in a single 1 second record is shown in figure 4. A velocity-resolved power spectrum from fast-scanning is shown in Figure 5.

4. Complications

There are a number of complications that arise in implementing the fast-scanning technique which we need to briefly discuss. Firstly, because diode lasers, including the Toptica laser used here, have not been used extensively in this fast-scanning mode it is not known if one will significantly shorten the life of the piezo stack by scanning the laser at high frequency and with large amplitudes. Running the scan for more than a second appears to produce a thermal drift which could be related to heating of the piezo.

Secondly, it is necessary to monitor in detail the actual laser frequency and mode purity because scanning can cause the laser to mode hop. During fast scanning it is not possible to use a conventional spectrum analyzer because they scan too slowly. We built a simple Michelson interferometer to monitor the output wavelength in real-time and observed occasional irregularities. We also monitored the laser output power with good time resolution in an effort to catch mode hops. We used the internally generated triangular ramp for the scan, but it is evident from the data that the mechanical scan becomes sinusoidal as the scan frequency is increased (Figure 3). For increased stability, the
diode laser controller uses a “feed-forward” slight modulation of the diode current during a piezo scan to inhibit mode hopping. This feed-forward is also a dynamical system which can sometimes be used in fast scanning but can introduce complications in the wavelength-vs-time dynamics. At some points the Michelson output becomes difficult to interpret (the direction of phase progression is ambiguous). What we did was to work on the laser alignment (and oscillator diode temperature) to the point that the laser was stable and scanning well and all the signals made sense, but there were situations where the laser output was not easy to interpret. For this reason it may be best to avoid using the “feed-forward” signal when possible.

Finally, there is the complication of optical pumping which usually occurs at some level in LIF measurements. Even when the laser is circularly polarized, there are six components to each of the σ polarized groups for the 668nm metastable line in Ar II. Each of these lines corresponds to a coupling between particular magnetic sublevels of the upper and lower states of the ion. If fluorescence is observed then the ion has decayed to a third level (producing fluorescence at 442 nm in this case), but there is also the possibility of optical pumping between the magnetic sublevels which becomes noticeable as the laser intensity in increased – and produces an apparent shifting of the lines (depending on the direction of scan) evident in figures 3 and 4. This optical pumping effect (related to “spin-tagging” [6]) can be simulated using a simple collisional-radiative model for the three-level system which includes spontaneous decay, electron collisional excitation as well as laser pumping. It may be possible to exploit the sublevel redistribution due to optical pumping as an implementation of a particle labelling technique.

5. Summary
We have experimentally explored the technique of periodic fast-scanning using a tuneable diode laser to measure fluctuating ion velocity distribution functions in a linear magnetized plasma column. Despite the complications it has been possible to obtain cross-correlation functions and power spectra that are particle velocity resolved. Optical pumping between the magnetic sublevels of the metastable state is observed and can be qualitatively reproduced from a collisional-radiative model.

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References
[1] Biloiu I A, Sun X and Scime E 2006 Rev. Sci. Instrum. 77 10F301-1-3
[2] Skiff F 2002 IEEE Trans. Plas. Sci. 30 26-27
[3] Skiff F, Uzun I and Diallo A 2007 Plasma Phys. Control. Fusion 49 B259-B265
[4] Honda C, Nishimura K, Maeda M, Muraoka K and Akazaki M 1983 J. Phys. D: Appl Phys. 16 1943-1952
[5] Severn G D, Edrich D A and McWilliams R 1998 Rev. Sci. Instrum. 69 10-15
[6] Skiff F, Good T N, Anderegg F and Paris P J 1989 Phys. Lett. A 137 57-59