Phase resolved measurements of ion dynamics with laser induced fluorescence

A. Stark[1], Jan Egedal[2], Will Fox[2], O. Grulke[1], T. Klinger[1]
1) Max–Planck Institute for Plasma Physics, EURATOM Association, Greifswald, Germany and
2) Massachusetts Institute of Technology, Plasma Science and Fusion Center, Cambridge, USA

Laser induced fluorescence (LIF) has become a standard diagnostic for ion temperature and ion drift measurements in plasmas. LIF is non-invasive and provides a high spatial and a high energy resolution. With the recent development of advanced laser systems LIF is more and more used to detect also perturbations of the ion velocity distribution function (IVDF) and to get detailed information about the ion dynamics. This paper reports on a method to perform phase resolved measurements of the IVDF in periodically perturbed plasmas. As an example LIF measurements during magnetic reconnection are discussed. The parallel component of the IVDF is measured with and without reconnection. If reconnection is driven, the ion temperature is found to be twice as high as without reconnection. The evolution of the IVDF during a reconnection cycle reveals strong variations of the ion temperature correlated with the reconnection drive.

PACS numbers: 52.35.Vd, 52.72.+v

Many dynamical plasma phenomena require for their detailed understanding the kinetic description of both electrons and ions. The respective energy distribution functions can be separated in an equilibrium and a perturbative part, the latter mostly a function of time. From the experimental point of view, it is necessary to conduct well defined laboratory experiments, where electron and ion kinetics can be investigated under highly reproducible conditions. Powerful diagnostic techniques are needed to measure energy distribution functions and their moments. Two different experimental techniques to measure the ion kinetic are (invasive) probes and (non-invasive) spectroscopic methods. Mach probes provide an easy access to spatially resolved measurements of the ion flow; gridded energy analyzer yield the ion velocity distribution function [1]. Both disturb the plasma and tend to fail in presence of magnetic fields or have to cope with limited energy resolution [2]. The energy resolution of passive spectroscopic methods [3] is limited by the optical setup alone, and the energy distribution function is averaged along the line of sight. Active spectroscopic methods avoid these drawbacks: Induced plasma light emission is observed with a suitable optical detector. The energy resolution is given by the finesse of the excitation source. Spatial resolution is achieved by crossing the sight lines of active excitation and passive observation.

This paper reports on phase resolved laser induced fluorescence measurements of perturbed ion energy distribution functions in a periodically forced magnetic reconnection experiment [4]. Here macroscopic changes in the magnetic topology are generated by driven reconnection, *i.e.* breaking and reconnection of magnetic field lines [5].

In laser induced fluorescence (LIF) ions (or atoms) are excited from a metastable atomic level by resonant laser light absorption [6]. Only those ions are excited, whose velocity meets the resonance condition for the Doppler shifted absorption frequency. The excited ions emit characteristic fluorescent light, whose intensity is proportional to the number density of the metastable ions with the respective velocity. Tuning the laser wavelength yields the ion velocity distribution function (IVDF). Since the finesse of moderns lasers is extremely high, the velocity resolution is limited only by the natural line width of the excited transition. Both requirements - tunability and narrow bandwidth - are met by dye and diode lasers [7, 8]. Due to a their advantages, diode lasers become increasingly popular to measure the IVDF in plasmas [9]. To investigate dynamical plasma phenomena with LIF a suit of methods has been developed to measure also perturbed ion velocity distribution functions [10, 11]. The perturbation appears as a deviation of the distribution function from a Maxwellian and can be of static or transient nature. A standard way to measure the perturbative part of the IVDF alone is to discriminate the PMT signal with a reference signal taken from the plasma perturbation [10]. This method works only if the plasma equilibrium does not vary coherently with the perturbation signal. In the present experiment, this condition cannot be taken for granted, such that different schemes must be applied.

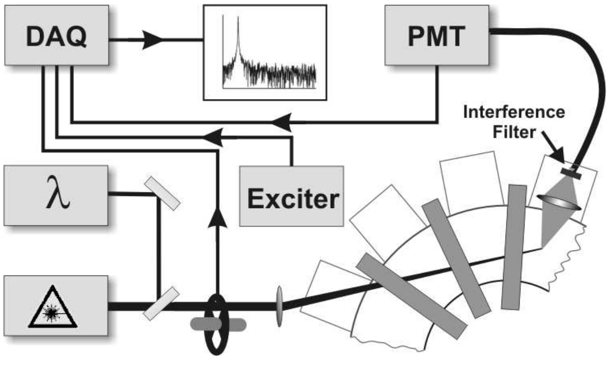

FIG. 1: Schematic plot of the LIF setup used at the VTF. Chopped laser light is injected tangentially into the device to measure the parallel component of the ion velocity distribution function. Via interference filter and photomultiplier tube (PMT) the fluorescent light is observed. Signals of the chopper, PMT and exciter are digitized for offline processing.

The LIF setup consists of an amplified diode laser with 60 mW output power, a center wavelength of 668 nm and a bandwidth of 1 MHz. The laser is tunable over a range of 25 pm ($\sim$ 15 GHz), which allows to cover a velocity range of 10 km/s. The laser pumps argon ions at the 668.614 nm line ($3d\,^4F_{7/2} - 4p\,^4D_{5/2}$) and the fluorescent light is observed at 442.72 nm ($4p\,^4D_{5/2} - 4s\,^4P_{3/2}$). The system was used at the versatile toroidal facility (VTF) magnetic reconnection experiment at the MIT plasma science and fusion center [4]. The toroidal vacuum chamber is immersed in a set of poloidal and toroidal field coils, forming a magnetic cusp field. A pulsed plasma is generated via electron cyclotron resonance heating at a frequency of 2.45 GHz and output power of 20 kW providing highly reproducible collisionless argon plasmas (electron temperature $T_e \sim 15\,\mathrm{eV}$, plasma density $n \sim 10^{17}\,\mathrm{m}^{-3}$). The schematic experimental arrangement is depicted in Fig. 1. The laser beam is injected tangentially into the plasma. Hence, the parallel component of the IVDF is observed. During a discharge shot the laser is kept at a fixed wavelength and monitored by a wavelength meter (0.1 pm accuracy). The fluorescent light is guided through an interference filter (1 nm bandwidth) and its intensity is measures by a photomultiplier tube (PMT). To discriminate spontaneous fluorescence from laser induced fluorescence the laser light is chopped. The PMT output signal, the reconnection drive and the chopper drive are recorded by a 16 bit digitizer board with a sampling rate of 2 MHz. Off-line spectral analysis yields the LIF signal, where the intensity is proportional to the power spectral density of the PMT signal taken at the chopper drive frequency. To gain sufficient statistical significance it is made an average over 30 shots at a fixed laser wavelength. The information derived from time averaged measurements is summarized in Fig 2(a). Shown is a schematic IVDF with a traveling Maxwellian and a perturbation (bump) on the tail of the distribution function.

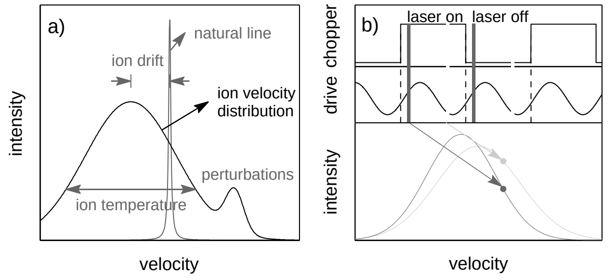

FIG. 2: (a) LIF resolves the full IVDF including perturbations and information as the ion temperature and the mean ion drift. (b) For phase resolved measurements the perturbation drive is synchronized to the chopper signal. The drive frequency is twice the copper frequency. Data binning yields the IVDF at different phase lag.

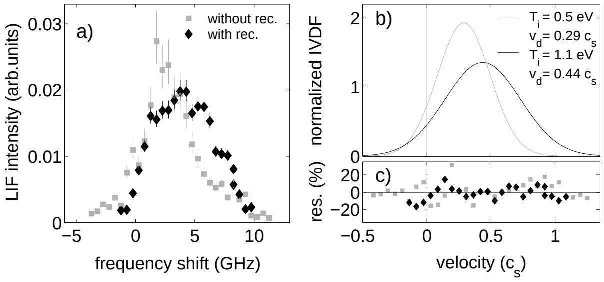

FIG. 3: (a) Scanning the laser frequency over a certain range yields the raw LIF signal (gray data = without reconnection, black = with reconnection). (b) Gaussian functions (including Zeeman splitting) fitted to the data. (c) Residua show the quality of the fits.

Periodic perturbations of the IVDF are generated in the VTF experiment by driving magnetic reconnection. A toroidal coil mounted at the inside of the vacuum chamber acts as a transformer and periodically forces the poloidal component of the magnetic field at a frequency of $f_d = 15\,\mathrm{kHz}$. The reconnection process is located at the X-line of the cusp field and has a maximum reconnection rate when the induced electric field has its maximum [5]. The plasma response to the periodic perturbation was previously investigated by detailed probe measurements [4]. To study the response of the ions to magnetic reconnection the above described LIF technique is used and the laser beam was aligned to the X-line. Of particular interest is if ions are heated during a reconnection cycle [12]. To achieve phase resolution of the IVDF measurement the chopper and the reconnection drive are phase locked and off-line analysis of consecutive phase segments is performed. This means that the reconnection drive is operated phase locked at frequency twice the chopper drive frequency, ensuring that each chopper on (and off) interval covers one period of the reconnection drive. From the recorded data, small segments at a particular phase are taken, both with and without laser radiation, as indicated in Fig 2(b). These data "snippets" from several hundred reconnection cycles are combined to form a set of new time series. Spectral analysis yields again the LIF signal, where the intensity is given by the power spectral density taken at the new (resampled) chopper frequency.

The above described method was used to investigate the heating and non-equilibrium kinetics of ions during magnetic reconnection. The results are published in Ref. [13]. An example of an IVDF, measured in the VTF device, is shown in Fig. 3. The LIF intensity with and without reconnection (gray diamonds and black squares respectively) is plotted versus the shift of the laser light frequency with respect to the center frequency (Fig. 3(a)). Gaussians (including Zeeman splitting) fitted to the raw data are depicted in Fig. 3(b). Note that the abscissa scale is velocity normalized to the ion sound speed c_s. There is a remarkable increase of the ion temperature from $T_i = 0.5\,\mathrm{eV}$ to $T_i = 1.1\,\mathrm{eV}$ and the mean ion drift from $v_d = 0.3\,\mathrm{c_s}$ to $v_d = 0.45\,\mathrm{c_s}$ if reconnection is driven. The observed ion heating is consistent with recent results from spectroscopic measurements in the MRX reconnection experiment [12].

To get more detailed information about the observed ion heating, phase resolved IVDFs were obtained as described above. The results are shown in Fig. 4 in a velocity versus time diagram. The time interval of $t \approx 65\,\mu$s corresponds to one complete reconnection cycle. The maximum reconnection rate is achieved at $t \sim 15\,\mu$s and $t \sim 50\,\mu$s, respectively. The raw data are plotted in gray scale and the fitted Gaussian functions are included as solid lines. Additionally, the temporal evolution of the ion temperature is indicated in the diagram. It is found that the IVDF underlies strong temporal variations. The data gap around $t = 45 - 55\,\mu$s is of technical origin and results from finite time on-to-off transitions of the chopped laser light. From the fitted Gaussians the intensity variation of the IVDF becomes quite obvious and it is seen that the ion temperature strongly varies. At $t = 55\,\mu$s the ion temperature has a minimum of $T_i = 0.5\,$eV and at $t = 40\,\mu$s a maximum of $T_i \sim 3\,$eV. In between the ion temperature increases monotonously. It is found that the highest ion temperature is located close to the maximum of the reconnection rate in the positive half cycle of the drive. Surprisingly, there is a lack of symmetry, i.e. no increase of T_i is found in the negative half cycle.

To summarize, laser induced fluorescence has been used to measure the kinetic response of the ions to an externally applied perturbation in a reconnection experiment. Phase resolved measurements were done by synchronizing laser light chopper and reconnection drive, such that a twofold discrimination is possible. As an example it was shown, that magnetic reconnection leads to a prominent time evolution of the ion velocity distribution function and significant ion heating occurs. These findings underline the need of a kinetic description of magnetic reconnection to explain phenomena like ion heating and thermalization.

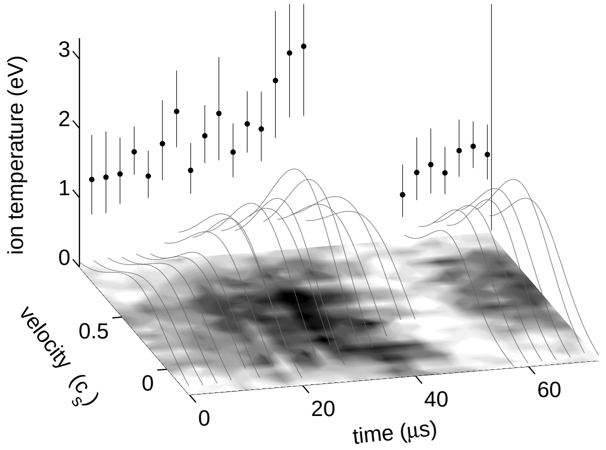

FIG. 4: Time evolution of the ion velocity distribution function (grayscale coded) within one cycle of the reconnection drive. Gaussians fitted to the data (solid lines) reveal significant variations of the ion temperature (black dots). Error bars are obtained from the Gaussian least square fit to the data.

---

[1] I. H. Hutchinson, *Principles of Plasma Diagnostics*, Cambridge University Press, Cambridge (UK), 2002.

[2] G. Donoso and P. Martin, Rev. of Sci. Instrum. **57**, 1502 (1986).

[3] H. R. Griem, *Principles of Plasma Spectroscopy*, Cambridge University Press, Cambridge (UK), 1997.

[4] J. Egedal *et al.*, Rev. of Sci. Instrum. **71**, 3351 (2000); J. Egedal and A. Fasoli, Phys. Rev. Lett. **86**, 5047 (2001); J. Egedal *et al.*, Phys. Plasmas **8**, 1935 (2001); J. Egedal *et al.*, Phys. Rev. Lett. **90**, 135003-1, (2003); J. Egedal *et al.*, Phys. Plasmas **11**, 2844 (2004); J. Egedal *et al.*, Phys. Rev. Lett. **94**, 025006 (2005).

[5] D. Biskamp, *Magnetic Reconnection in Plasmas*, Cambridge University Press, Cambridge (UK), 2000.

[6] R. Stern and J. Johnson, Phys. Rev. Lett. **34**, 1548 (1975).

[7] D.N. Hill *et al.*, Rev. of Sci. Instrum. **54**, 309 (1983).

[8] G.D. Severn *et al.*, Rev. of Sci. Instrum. **69**, 10 (1998).

[9] R.F. Boivin and E.E. Scime, Rev. of Sci. Instrum. **74**, 4352 (2003).

[10] F. Skiff and F. Anderegg, Phys. Rev. Lett. **59**, 896 (1987).

[11] M.Sarfaty *et al.*, Phys. Plasmas **3**, 4316 (1996).

[12] S. C. Hsu *et al.*, Phys. Rev. Lett **84**, 3859 (2000); S. C. Hsu *et al.*, Phys. Plasmas **8**, 1916 (2001).

[13] A. Stark *et al.*, Phys. Rev. Lett, (2005), submitted for publication.