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Ion velocity distribution functions around the x-line of a collisionless reconnection region experiment

A. Stark[1], J. Egedal[2], W. Fox[2], O. Grulke[1], T. Klinger[1]

[1] *Max–Planck Institute for Plasma Physics, EURATOM Association, Greifswald, Germany*

[2] *Massachusetts Institute of Technology, Plasma Science and Fusion Center, Cambridge, USA*

In a variety of magnetized plasmas - in space[1, 2, 3], in laboratory [4, 5] and fusion devices[6] - phenomena are observed, which lead to a global change of the magnetic field topology by breaking and rearranging of magnetic field lines. This process, referred to as magnetic reconnection [7], permits the release of magnetic energy to particle kinetic energy. Although theory and laboratory experiments contributed much to a deeper understanding, the mechanisms of energy conversion and the role of the ions dynamics still remain unclear. The present paper reports on laser induced fluorescence measurements in a collisionless reconnection experiment.

The studies are performed in the Versatile Toroidal Facility (VTF) at the MIT plasma science and fusion center [8]. In a toroidal vacuum chamber a magnetic cusp field with a superimposed toroidal guide field is produced by sets of magnetic field coils. Plasma is generated by electron cyclotron resonance heating. Electron temperatures around $T_e \sim 20\,\text{eV}$ and plasma densities up to $n = 1 \times 10^{17}\,\text{m}^{-3}$ are achieved. The mean free path of the electrons is $\lambda_e \sim 50\,\text{m}$, hence VTF plasmas are collisionless. Reconnection can be periodically driven by the transformer action of an additional coil mounted on the inside of the vacuum chamber.

Ion velocity distribution functions (IVDFs) are measured by means of LIF. The schematic experimental arrangement is shown in Fig. 1. An amplified diode laser (60 mW cw, 668 nm) is used to pump argon ions at the 668.614 nm line ($3d\ ^4F_{7/2} - 4p\ ^4D_{5/2}$). By tuning the laser wavelength over a range of $\Delta\lambda \pm 20\,\text{pm}$ a velocity range of $10\,\text{km/s}$ is covered. The fluorescent light is observed at 442.72 nm ($4p\ ^4D_{5/2} - 4s\ ^4P_{3/2}$) in orthogonal direction via interference filter by a photomultiplier tube (PMT).

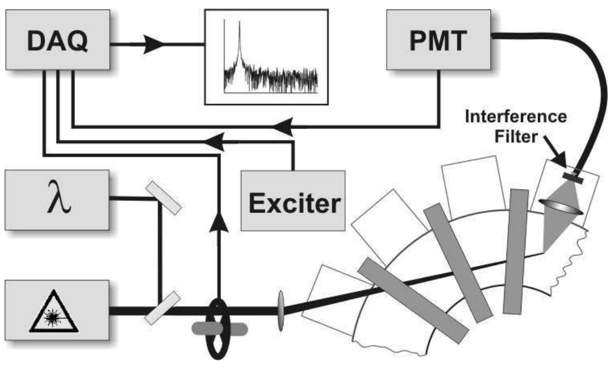

Figure 1: Schematic plot of the LIF setup at VTF.

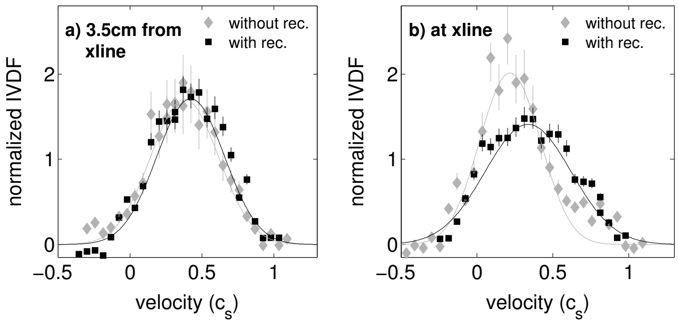

Figure 2: LIF measurements of the IVDF and Gaussian fits 3.5 cm from the X-line (a) and at the X-line (b) with and without reconnection (gray diamonds and black squares respectively). Error bars are obtained from the 95% confidence interval of the periodogram estimation.

Since the laser beam is aligned tangentially into the guide field the parallel component of the IVDF is observed. The laser light is chopped to discriminate naturally occurring from induced fluorescent light. The PMT signal, the chopper drive, the toroidal plasma current and the loop voltage (as a reference for the reconnection drive) are sampled with a 16 bit digitizer board. The laser wavelength is monitored with a wavelength meter ($\Delta\lambda \pm 0.1\,\mathrm{pm}$). Offline spectral analysis yields the LIF signal; the LIF intensity is proportional to the power spectral density of the PMT signal taken at the chopper drive frequency. To overcome the intrinsically low signal-to-noise ratio, an average is made over 30 shots at a fixed laser wavelength. The observation volume ($\approx 1\,\mathrm{mm}^3$) can be positioned to measure the IVDF at different locations in the poloidal plane.

The IVDFs are measured at two different poloidal positions: First 3.5 cm from the X-line, outside the reconnection layer, and second at the X-line. The LIF intensities and fitted Gaussians (including Zeeman splitting) are plotted in Fig. 2, both with and without reconnection. Outside the reconnection region, it is observed that the IVDF remains the same with and without reconnection. The ion temperature is found to be $T_i = 0.6\,\mathrm{eV} \pm 0.1\,\mathrm{eV}$ and the mean ion drift is $0.35\,c_s$, with c_S being the ion sound speed (cf. Fig. 2(a)). A different observation is made at the X-line. Here, if reconnection is driven the ion temperature doubles from $T_i = 0.5\,\mathrm{eV}$ to $1\,\mathrm{eV}$ and the ion drift increases from $v_d = 0.2\,c_s$ to $0.3\,c_s$. This result indicates that ion heating takes place in the reconnection region only. Ion heating of the same order of magnitude was previously observed with spectroscopic measurements in the MRX device [9].

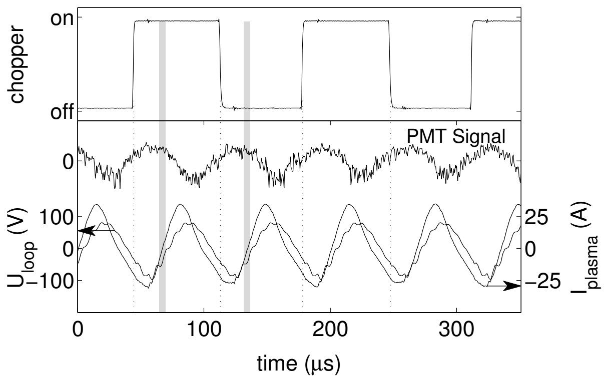

Figure 3: Chopper signal (top trace), PMT signal fluctuations (middle trace), loop voltage U_{loop} and total plasma current I_{plasma} (bottom trace).

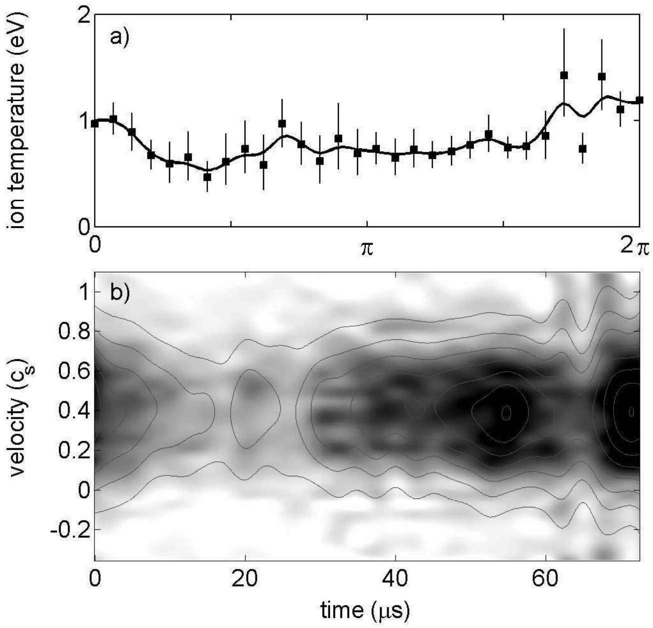

Figure 4: a) Temporal evolution during a reconnection cycle of the ion temperature 3.5 cm from the X-line and (b) of the IVDF (gray shaded plot) with contours of fitted Gaussians (black lines).

A more detailed picture of ion heating arises from phase resolved measurements of the IVDF. This is achieved by phase locking the chopper to the reconnection drive, as shown in Fig. 3. It is seen from the time traces that each chopper on and off state covers one complete reconnection cycle. The recorded signals of the chopper drive and the PMT are cut into consecutive segments and are rearranged to form a set of new resampled time traces. Spectral analysis of each new time trace yields again the LIF signal, where the intensity is given by the power spectral density taken at the resampled chopper frequency.

The result for the position outside the reconnection region is shown in Fig. 4. The intensity of the LIF signal is plotted in gray scale in a velocity vs. time diagram (cf. Fig. 4(b)). Contours of Gaussians fitted, to each IVDF, are included in the diagram (solid lines). The resulting ion temperature is plotted in Fig. 4(a). Note that the time axis is scaled to the phase ϕ of the reconnection drive.

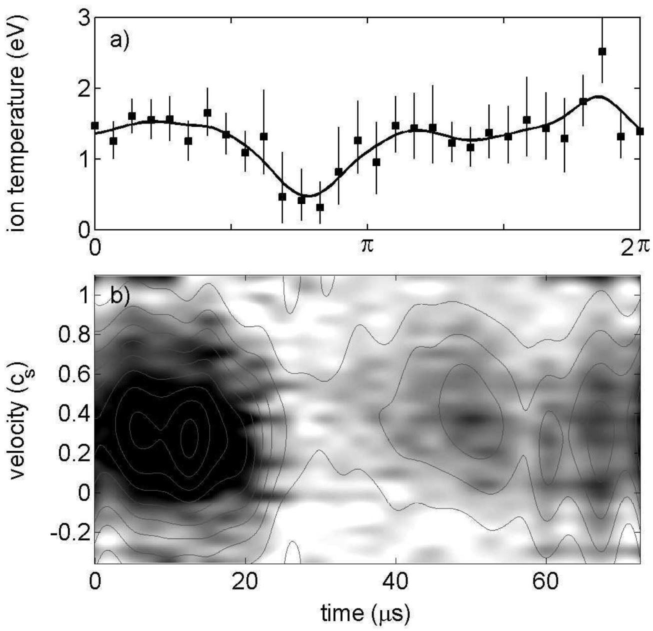

Figure 5: Phase resolved measurement of the IVDF and the ion temperature at the the X-line.

The ion temperature increases from $T_i = 0.5\,\text{eV}$ at $\phi = \pi/2$ to $T_i \sim 1\,\text{eV}$ at $\phi = 2\pi$. The ion density, the integral of the entire IVDF, is fluctuating within the reconnection cycle, and exhibits a dip from $t = 10$ to $30\,\mu\text{s}$ and a maximum at $t = 65\,\mu\text{s}$.

Fig. 5 shows the time evolution of the LIF intensity and ion temperature measured at the X-line. The ion temperature varies between $T_i = 0.5\,\mathrm{eV}$ and $2\,\mathrm{eV}$. The fluctuations of the ion density are by a factor of two stronger and the peak value is found at $t = 0$ to $25\,\mu\mathrm{s}$ followed by a strong decrease to $t = 35\,\mu\mathrm{s}$. A comparison of Fig. 4 and Fig. 5 yields similar patterns in the evolution of the LIF intensity with a time shift of $10\,\mu\mathrm{s}$. However, the magnitude of the ion temperature and density is much higher at the X-line. This effect is likely to be linked to the motion of plasma in the poloidal plane. Such flows are observed by Mach probe measurements and are explained as a response to an oscillating electric potential [10, 11].

To summarize, measurements of the ion velocity distribution functions were done with LIF outside and inside the reconnection region. While off the X-line no ion heating was observed, strong ion heating occurs in the reconnection region. It was shown by phase resolved analysis that the IVDF and the ion temperature reveal similar modifications at both positions, but with much stronger magnitude at the X-line.

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