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Use of Laser Spectroscopy for High-Accuracy Investigations of Relatively-Dilute Pulsed Plasmas with Nanosecond Time Resolution

K. Tsigutkin[1], E. Stambulchik[1], R. Doron[1], V. Bernshtam[1],
A. Fisher[2], D. Osin[1], and Y. Maron[1]
[1]*Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel*
[2]*Technion-Israel Institute of Technology, Haifa, Israel*

In this report we describe the development of new approaches to measure the electric field and properties of relatively dilute plasmas under high-power pulses at the nanosecond time scale. These approaches are based on high-resolution laser spectroscopy. The study is carried out in a coaxial-pulsed-plasma configuration. The plasma was doped with a laser-produced lithium beam, followed by pumping of a selected transition in LiI using a tunable dye laser. This setup enables to perform spatially resolved sub-mm measurements of the electric field properties and the plasma parameters. For the first time, line-shape diagnostics with a sub-microsecond resolution was successfully applied to low-density plasma, down to 10^{13} cm^{-3}.

Introduction

Atomic physics and spectroscopy have traditionally been used for the development of the most important methods for plasma diagnostics. One of the biggest challenges of researchers in this field is achieving high spatial and temporal resolution measurements. Such measurements are important to test and validate theories and detailed calculations, now available due to rapid development of computational capabilities. In this report, we describe a method capable of measuring the electric field and plasma parameters, such as temperature and density, on a sub-milimeter-scale. The approach described here is based on the doping of the plasma with an atomic or ionic beam, whose properties responds to the local plasma parameters, followed by laser-induced fluorescence (LIF). This technique allows for very high spatial resolution of the measurements [1]. Having a short pulsed excitation laser, a temporal resolution can be made fine enough for nanosecond-scale observations. In the present work this new approach is employed for determination of local plasma parameters using laser-produced lithium beam and LIF.

Experimental setup

This study is performed in a coaxial-pulsed-plasma configuration called Plasma Opening Switch (POS) [2]. In a POS, a large current is driven through prefilled plasma, followed by an abrupt rise in the plasma resistance and subsequent switching of the current to a parallel load. POS’s are widely used to upgrade pulsed power generators.

As it is shown on **Figure 1**, the plasma is produced by the flashboard-plasma-source [3] and injected inwards ($n_e=2\times10^{14}$ cm^{-3}). Upon bridging of the electrodes by the streaming plasma, a current pulse (rise time of *100 ns*) is initiated between the electrodes. Typical conduction time and opening were registered of *70 ns* and *10 ns*, respectively.

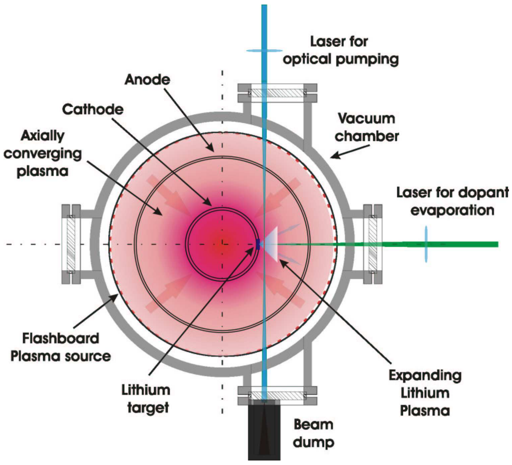

Figure 1 Experimental and diagnostic setup.

In the LIF technique discussed here, the plasma is doped with a laser-produced lithium beam using Nd:YAG laser with the intensity of 5×10^7 W/cm^2, followed by pumping of a selected transition of LiI using a tunable dye laser (see **Figure 1**). The dye laser delivers a power density of *1* MW/cm^2 at the observation region, having a pulse length of *15 ns*. The spot size of the dye laser, which can be easily reduced to sub-mm scale, determines the spatial resolution of the measurement.

The diagnostic system is equipped with two 1-m UV-visible spectrometers. The output of one spectrometer is collected by an array of 10 photomultiplier tubes allowing for recording of the temporal evolution of the spectrum. The output of the second spectrometer is recorded by a gated (down to *5 ns*) intensified CCD camera, for obtaining high-resolution (down to *0.2 Å*) broadband spectra.

The LiI atomic system

Our diagnostic method is based on the LIF technique combined with lineshape analysis of dipole-forbidden transitions [4,5]. The diagnostics make use of *LiI 2p-4d* (dipole-allowed) and the *2p-4f* (dipole-forbidden) transitions. The dye laser is tuned to excite the *LiI 4p* level from the ground state (see **Figure 2**). Collisional excitations by the plasma electrons then lead to population of the *4d* and *4f* levels (and of a number of neighboring levels). Since the forbidden line amplitude strongly depends on the electric field strength [5], the intensity measurement of forbidden lines is an efficient tool for detecting the presence and propagation of electric fields in plasma.

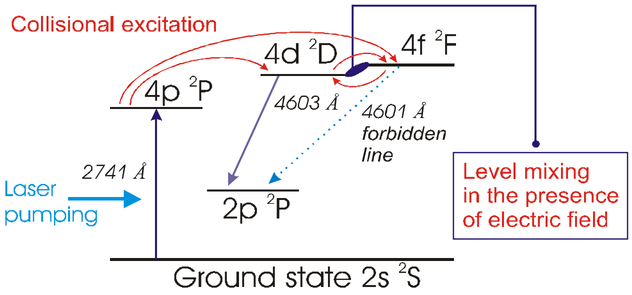

Figure 2. The scheme of the laser-driven excitation of the **LiI** levels.

Results

We first applied these techniques for the determination of the parameters of the laser-produced lithium beam, which is important for controlling the effect of the dopant on the plasma conditions. In **Figure 3** results of the lineshape analysis are presented. To analyze the *2p-4d* experimental data, we have calculated the Stark-broadened spectrum and then subsequently convolved it with the instrumental and the Doppler broadening functions. T_i was determined to be *~2 eV* based on the Doppler-dominated profile of the *2p-3d* line at *6104Å*. It was found that only a combination of $n_e = 5\times10^{13}\ cm^{-3}$ and low frequency oscillations with amplitude of *3 kV/cm* provide good fit to the measured spectra [4]. This fact possibly indicates a presence of ion-acoustic waves in the laser-produced plasma.

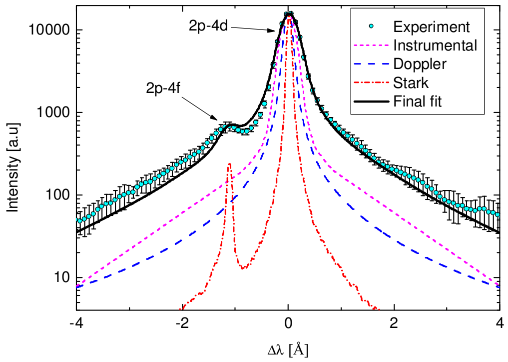

Figure 3. Measured and calculated **LiI** *2p-4d* line shapes including the *2p-4f* forbidden line. $n_e=4\times10^{13}\ cm^{-3}$

In a second stage, the method of the lineshape analysis was employed for experiments with the plasma prefill and the lithium beam (still, without activating the generator). Two alternative scenarios of the plasma doping were investigated. The first is co-streaming of the dopant beam and the flashboard plasma from the anode towards the cathode, and the second is counter-streaming against each other. In these measurements, in addition to the diagnostic method described above, polarization spectroscopy was implemented. Profiles of the lines were obtained with a selection of different polarizations. The intensity of the forbidden *2p-4f* line measured in horizontal polarization only, showed no difference in both cases of co-streaming and counter-streaming. However, a marked difference, far beyond error bars (see **Figure 4**), is shown in vertical polarization. These observations indicate a connection between the

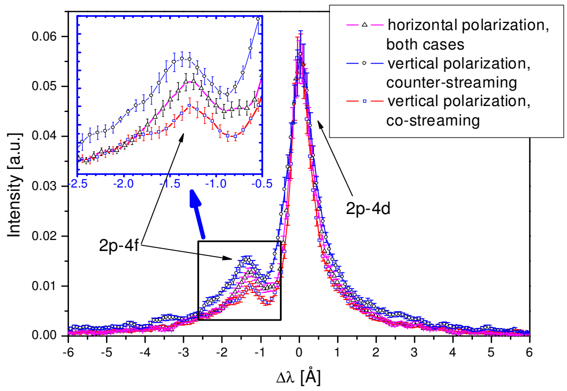

Figure 4. *2p-4d*, *2p-4f* lineshapes measured in different polarizations for two cases of the plasma doping.

motion of plasma particles and the mechanisms leading to population equilibration among different *4f* states. Full analysis of the observed phenomena is yet to be completed.

In the final stage, the method described above (forbidden-allowed line ratios) was employed for measurements of the E-field in the plasma in the vicinity of the cathode (*1 mm*) during the current-conduction phase. A current pulse of *180 kA* was applied to the plasma bridging the electrodes. **Figure 5** presents forbidden-to-allowed line ratios as a function of time during the conduction. The ratio obtained prior to the current application is subtracted, in order to provide the pure current contribution. The current trace at the load (I_{down}) is also shown in the **Figure 5**. Time "0" corresponds to a moment of the pulse application. At a moment of *70 ns* (where the derivative of the current is maximum) the current is switched to the load. The ratio has a maximum at a moment of *55 ns*. This maximum corresponds to an E-field of *~4 kV/cm*, that is in agreement with the predicted Hall-field [6]. We hope that the ongoing experiments will soon provide additional data for a description of the effects that have been observed.

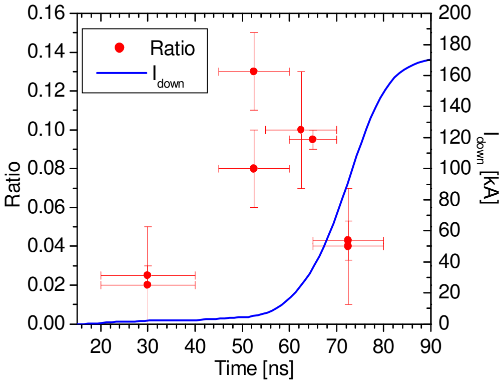

Figure 5. Ratio of forbidden to allowed lines of LiI during the current conduction. Ratio of *0.14* corresponds to E-field of *4 kV/cm*.

Summary

Using the advantages of the LIF technique a new method for diagnostics of local parameters of dilute plasmas was developed and successfully applied. For the first time, measurements of the low plasma density using spectroscopy exhibit sub-millimeter spatial and nanosecond temporal resolutions. A new experimental approach was introduced for diagnostics of electric fields in current-carrying plasmas and applied for pulsed-power application. We believe that the diagnostic methods described here are applicable for studying a wide variety of laboratory transient plasmas.

References

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