OPTICAL DIAGNOSTIC BASED ON THE LAMB SHIFT EFFECT FOR THE MEASUREMENT OF THE MICROFLUCTUATIONS OF THE LOCAL ELECTRIC FIELD IN A LOW DENSITY PLASMA

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One critical problem in experimental plasma physics is measuring electric fields. We propose a new plasma diagnostic technique which measures the absolute value of local electric fields with high space time resolution and exceptional sensitivity. The feasibility of this technique has been previously experimentally demonstrated [1]. We describe a newly built experimental set-up that allowed electric field test measurements.

Hydrogen-like atoms possess a lowest excited state which contains two nearly-degenerate pair of levels ($2s_{1/2}$, $2p_{1/2}$) separated in energy by the Lamb shift [2]. The $2p_{1/2}$ level has a short spontaneous lifetime $\tau_{2p} = 1.6 \ 10^{-9}$ s and decays rapidly, emitting intense radiation in a discrete Lyman α line (L_α, 1216 Å). In contrast, $\tau_{2s} = 0.12$ s and the 2s level is thus strongly metastable and decays very slowly, emitting radiation over a broad continuum. A weak electric field (less than 1V/cm) is able to mix levels, shorten the $2s_{1/2}$ lifetime and largely enhance the intensity of the radiation emitted by the $2p_{1/2}$ particles. This effect is several orders of magnitude more sensitive than other Stark processes.

Figure 1. Principle of the experiment.
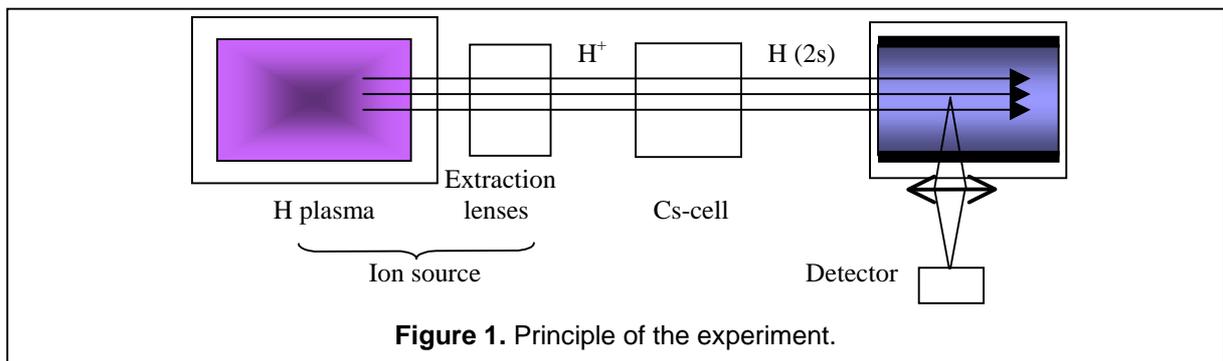
The technique that is described in this paper is based on the injection into a plasma of a small diameter, low divergence « test - beam » of atomic hydrogen in the 2s state, and on the detection of the L_α emission enhanced by the fields supported by the plasma along a direction normal to the beam axis, as sketched in Fig. 1. The relationship between the electric field E and the L_α emission intensity I_α is precisely known and, for Hydrogen, is given by [1] :

$$I_\alpha \ (s^{-1}) \ = 2.8 \ 10^3 \ n_b \ V \ E^2 \tag{1}$$

where n_b is the density of metastable H(2s), V is the viewing volume, and E is expressed in V/cm. This formula applies both for steady and fluctuating electric field with a frequency lower than ν_0, where $h\nu_0$ is the $2s_{1/2} - 2p_{1/2}$ energy difference (1GHz in H). Therefore the line intensity measurement I_α provides an absolute value of E-field strength and spectrum. Because the Lamb shift is a high order quantum electrodynamics effect [2], the lifetime of metastable hydrogen-like particles in a plasma is particularly sensitive to local electric fields and fluctuations and this property provides a diagnostic scheme with very high sensitivity, several orders of magnitude higher than other methods, as shown by the quadratic field dependence and the high value of the numerical coefficient in Eq. (1).

Figure 2. Schematic of the experiment - see text for the legend.
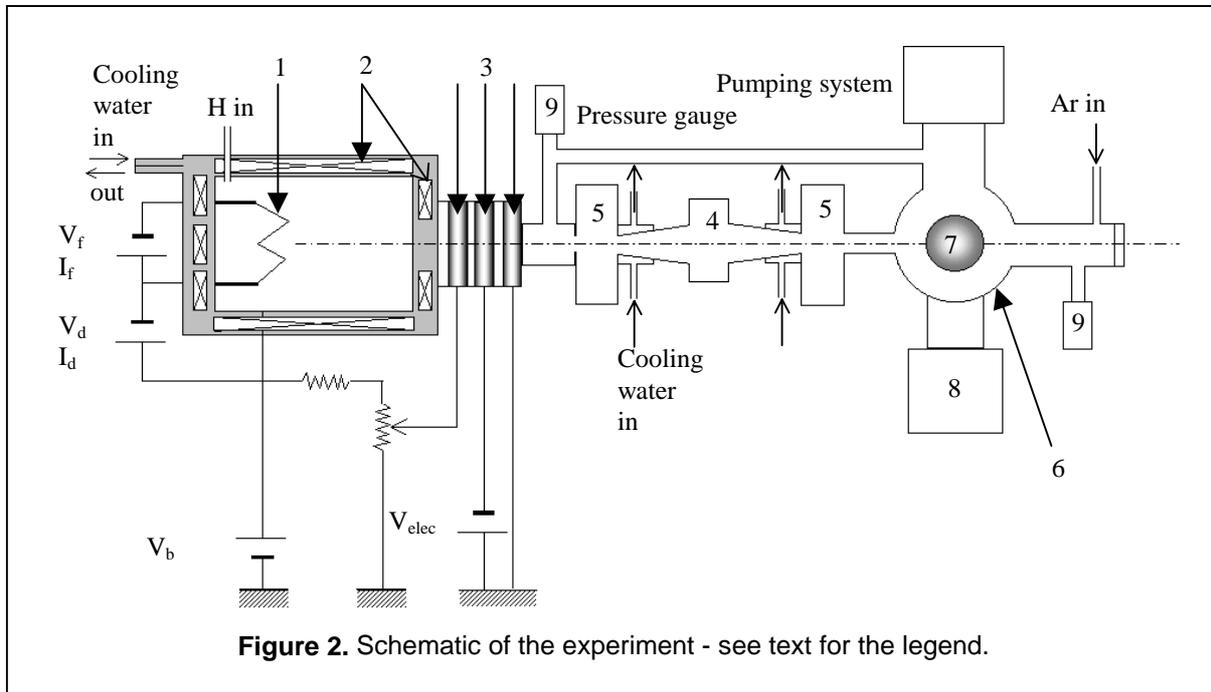
A plasma produced by a hot cathode discharge and confined by a magnetic multipole forms the basic source of ions (see Fig. 2). A Tungsten filament (Fig. 2 : #1) of 0.5 mm diameter with several W shaped bends forms the electron source [3]. The water cooled discharge chamber with 10 cm in length and 10 cm in diameter forms the anode. It is surrounded by 8 magnets of 3.4 kGauss (Fig. 2 : #2) along the circumference and three magnets at one end to form a magnetic cage with a strong cusp field as suggested by measurements made with a Hall probe sensor inside the chamber. A plasma of Hydrogen is produced with the following typical operating parameters : neutral pressure P = 1 mTorr, discharge voltage V_d = 75 V, discharge current I_d = 3 A. A cylindrical Langmuir probe gives the plasma density n = 3-5 10^{11} cm^{-3}, the electron temperature T_e = 2-3 eV, the floating potential V_f = -18 V and the plasma potential V_p = 3 V, in the above operating conditions.

The ion extraction focusing Einzel lens is a conventional three electrodes accelerator-decelerator system (Fig. 2 : #3) made of stainless steel electrodes of 1 cm thickness separated by ceramics. The first electrode biased to a positive potential is the extraction electrode and the second, biased to a negative potential decelerates the electrons. The third electrode is simply grounded. The potential difference between the third electrode and the anode of the ion source (which can be varied between 0 and 500V) sets the energy of the extracted ions. A high voltage switching amplifier circuit was developed to bias the anode in pulsed mode, both for safety reasons and to improve the signal to noise ratio in L_α detection. A 3 dimensional ray tracing ion-optics code SIMION-3D [4] was used to study the ion trajectory for our given geometry. The voltages applied to the different electrodes are adjusted in the simulation to optimize the production of a low divergence (or parallel) ion beam. A high resolution retarding potential analyzer [5] was fabricated and has been used to measure the beam parameters such as divergence, energy, beam current and their variations with discharge parameters. It is important to note that the beam generated from hydrogen plasma contains many charged species such as H^+, H_2^+, and H_3^+. We have designed a compact mass spectrometer [6] which can be placed inside the vessel to measure the relative proportion of each species.
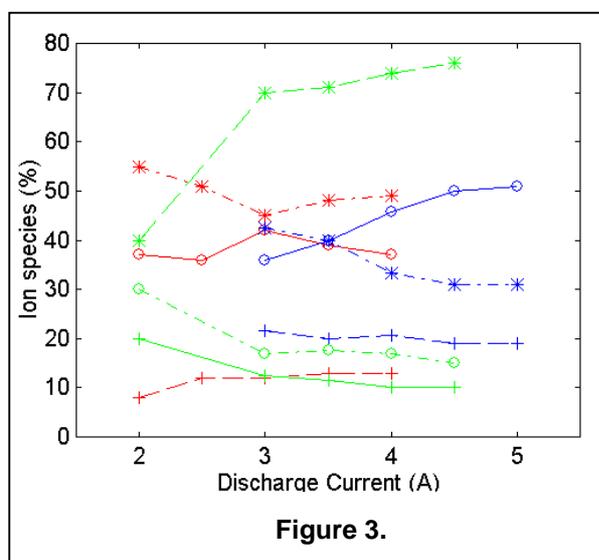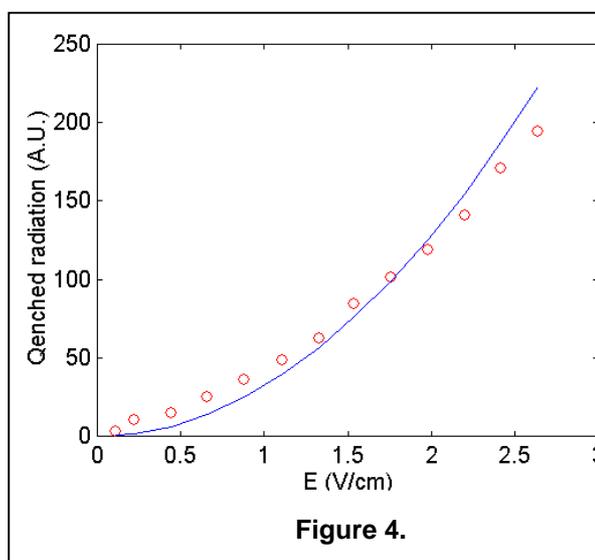

Figure 3.

Figure 4.

Fig. 3 shows the H^+ (∗ points), H_2^+ (∘ points) and H_3^+ (+ points) yields as a function of the discharge voltage for a given H pressure. It also summarizes various attempts to optimize the proton yield : blue curves are obtained by adding an extra emissive filament inside the discharge chamber in order to break the molecular ions ; green curves are obtained by introducing water vapor in the discharge chamber by flowing H gas through a small container with liquid water before entering the chamber.

A charge exchange cell (Fig. 2 : #4) containing Cesium (Cs) vapor is used to produce the metastable hydrogen atoms from the proton beam. It was obtained by modifying an existing device [7]. The heart of the cell is a Cs reservoir made of a thick stainless steel block and heated electrically up to a typical operating temperature between 80°C and 120°C. The temperature regulation is done using a thermocouple assembly with feed back. The reservoir has two radial ducts of 1.8 cm diameter and 15 cm length terminated with mating flanges for valves (Fig. 2 : #5). The ends of the ducts are held at 32°C (just above the melting point of Cs) by circulating water from a constant temperature bath to prevent Cs from escaping out of the cell. A small conical taper is included in the duct to enhance the flow of Cs back to the reservoir. A trap made of a few layers of stainless steel mesh is used to recycle the condensed Cs. The measured value of Cs vapor density in the center region of the reservoir is around n_{Cs} = 1.5 10^{14} cm^{-3} for a cell temperature of 110°C [7]. The Cs life time in the cell is larger than 450 hours. With a 500 eV beam, which corresponds to a maximum efficiency of the charge exchange process, we typically observe a 25% decrease of the H+ current when the Cs cell temperature is gradually raised. The resulting atomic beam is then injected into a chamber (Fig. 2 : #6) where two horizontal parallel plates (Fig. 2 : #7) can be externally biased (Fig. 1) to create a static electric field. The L_α light is collected by a lithium fluoride f/2 lens working in the Weierstrass conditions and detected by a blind photomultiplier (Fig. 2 : #8) operating in vacuum. Fig. 4 shows that the intensity of the recorded L_α line varies like the square of the magnitude of the applied electric field, indicating that the quenching of the levels is really observed and that fairly low electric fields can be detected.

This method can be applied to non-intrusive measurements of static and fluctuating electric fields in low pressure argon discharge plasma. Since the polarization of the emission depends on the vector electric field, a diagnostic of the electric field direction can also be obtained. Using H (2s) beam with known velocity **v**, the strength and direction of a magnetic field become also measurable through the $\vec{V} \times \vec{B}$ motional field acting on the metastable particles.

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