Lyman-α radiation of a probing metastable hydrogen beam to measure electric fields in diluted fluids and plasmas

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The interaction between a metastable H(2*s*) atomic hydrogen beam and an external electric field leads to the emission of the Lyman-α line. It originates in the Stark mixing of the near-degenerate $2s_{1/2}$ and $2p_{1/2}$ levels separated by the Lamb shift [1]. The radiation proportional to the square of the electric field amplitude is recovered in vacuum by using such an atomic probe beam. For larger electric field, saturation is observed and related to the beam finite transit time. We also observe the strong enhancement of the signal when the field is oscillating at the Lamb shift frequency. This technique is applied in a plasma, offering an alternative way to measure weak electric fields by direct and non-intrusive means [2].

Principle of the experiment

Hydrogen atoms prepared in the metastable $2s_{1/2}$-state undergo a radiative transition to the ground state at the Lyman-α wavelength via the $2p_{1/2}$-level when they are in the presence of an electric field of module E_0. Because of a Stark mixing process, the lifetime of $2s_{1/2}$ is greatly reduced, depending on the frequency of the electric field. A perturbation theory leads to the following expression of the $2s$ decay rate :

$$\gamma_{2s}(\omega)=\left(\frac{3ea_0 E_0}{\hbar}\right)^2 \frac{\gamma_{2p}}{(\omega-\omega_0)^2+\gamma_{2p}^2/4}$$

The intensity of the observed Lyman-α line is proportional to γ_{2s}, therefore to the square of the electric field amplitude, as long as the transit time of the emitter in the light detection volume is shorter than the perturbed lifetime of $2s$. This provides us with an electric field measurement technique with a very high sensitivity, of the order of 10^{-2} V/cm for static fields and up to 10^{-3} V/cm for oscillating fields.

Description of the experimental set-up

A view of the experimental setup is displayed in Fig. 1. A hydrogen plasma produced by a hot cathode discharge and confined by a magnetic multipole (number (1) in Fig. 1) forms the basic source of ions [3]. A W-shaped tungsten filament (cathode) is heated by a current up to 15A and is negatively biased (typical discharge voltage V_d = 80V) with respect to the wall (anode). A discharge current up to 3A is established, the primary electrons being responsible for the dissociation and ionization of H_2, introduced in the chamber at a pressure ranging from about 10^{-5} to 10^{-4} mbar. The plasma contains different charged species such as H^+, H_2^+ and H_3^+, which population ratio can be measured by a custom mass spectrometer in the measurement chamber. The ion extraction focusing Einzel lens is a conventional three stainless steel electrodes separated by ceramics. The first electrode is biased to a positive potential and the second is biased to a very negative potential, in order to decelerate the electrons and focus the beam. The potential difference between the third electrode which is simply grounded and the wall of the ion source can be varied between 0 and 500 V and sets the kinetic energy of the extracted ion beam.

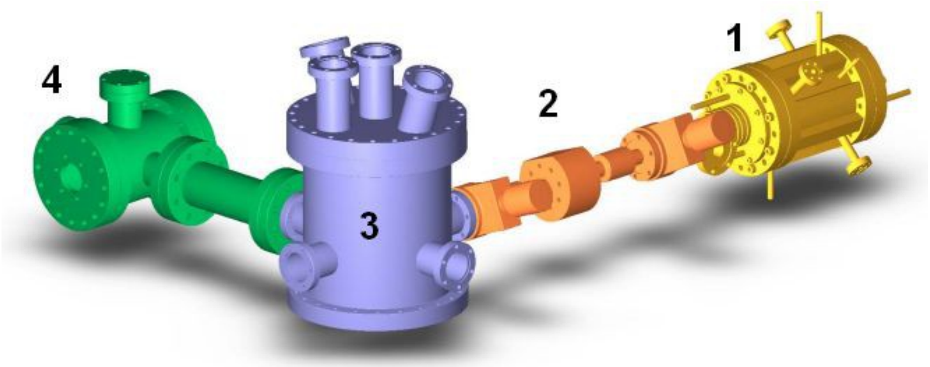

Fig. 1 : view of the experimental set-up (1 : ion beam source chamber, 2 : charge exchange cell, 3 : test chamber, 4 : detection chamber (V-UV photomultiplier inside))

A temperature-monitored charge exchange cell containing cesium (Cs) vapor (number (2) in Fig. 1), built from a previously existing device [4], is used to produce the metastable hydrogen atoms from the proton in the ion beam according to the equation

$$H^+ + Cs \rightarrow H(2s) + Cs^+$$

We work with a 500 eV ion beam, which corresponds to the maximum cross section of the charge exchange process [5]. The resulting atomic beam is then injected into a measurement chamber (number (3) in Fig. 1) where two horizontal parallel plates separated by 5 cm can be externally biased to create a static or oscillating electric field. One plate is grounded while the other can be biased. The Lyman-α light is collected in a direction perpendicular to the beam by a lithium fluoride lens and detected by a UV-photomultiplier operating in vacuum (number (4) in Fig. 1). Spatial resolution is only determined by the size of the photocathode and the lens magnification. In order to improve the signal to noise ratio, either the beam current can be pulsed at a low frequency (1Hz) or the non-grounded plate can be biased in a pulsed mode at a low frequency (typically 1 kHz), and the pulsed signal is detected with a lock-in amplifier (Fig. 2(a)). In this latter case, the continuous background of spontaneous emission from the beam is not recorded, only the part of the signal due to the field, synchronized with the biased plate modulation, is observed. The hydrogen pressure in the measurement chamber is usually about one tenth of the pressure in the source. This allows us to make measurements even with a pure ion beam through collisions between ions and the residual gas [6].

Experimental results

This method was first applied in vacuum to prove its great capacity to measure very weak electric fields. Fig. 2(b) displays the quadratic law for an oscillating field at the Lamb shift frequency, ν = 1057 MHz. The biased plate was used as an emitting antenna. For the lock-in detection, the amplitude of the RF-field was modulated at a low frequency of about 1 Hz. By comparing these results to measurements in a static field we could show the enhancement factor of more than 300 predicted by the calculation.

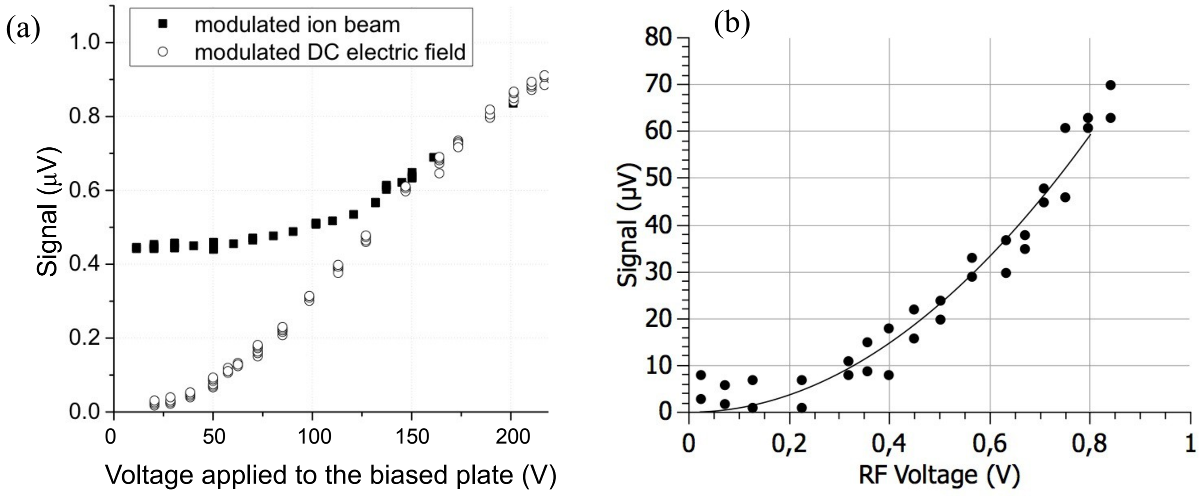

Fig. 2 : (a) Lyman-α emission as a function of the voltage applied to the biased plate with a pulsed ion beam (solid) or a pulsed voltage (open), (b) Lyman-α emission as a function of the radio-frequency (1GHz) voltage with a H(2*s*) beam

Then we applied the same method within a low density DC argon discharge plasma with density $n_e \approx 10^8$ cm^{-3} created at low pressure $P \approx 10^{-5}$ mbar from a heated tungsten filament biased at -60V. The measurements were done with a static electric field of 40 V/cm applied through the plasma between the plates and a modulated H(2s) beam for the lock-in detection. Fig. 3 shows the profile of the electric field strength obtained by moving the plates assembly vertically, up and down across the plasma-beam interacting volume, both in vacuum (open triangles) and in the presence of the plasma (black triangles). We observe here the Debye shielding of the plasma : the electric field is much stronger close to the electrode than in the center, due to the formation of a plasma sheath. The value at the center does not decrease to zero most likely because of the incompletely neutralized beam space charge. Measurements reveal boundary effects related to the beam width.

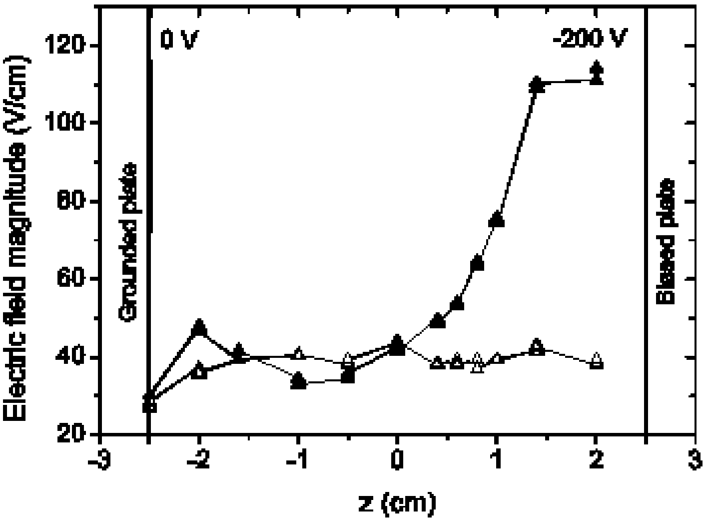

Fig. 3 : Electric field measured between two plates in vacuum (open triangles) and in a plasma (solid triangles) with a H(2s) atom beam.

In conclusion, this new diagnostic provides us with a local measurement of low electric fields with applications to industrial and fusion plasmas.

This work is part of A. Lejeune's PhD thesis who benefited from a grant by Ministère de la Recherche. It was inspired by late Prof. R. A. Stern to whom it is dedicated.

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