Use of a hydrogen ion beam to measure weak electric fields in a plasma

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Introduction

Knowledge of the local electric field with a high sensitivity and a good space-time resolution is necessary for many problems in Plasma Physics. Spectroscopic diagnostics such as *Stark broadening*, deflection of particle beam, Laser Induced Fluorescence, etc. can be used if the electric field is strong enough (few V/cm). Hence, the measurement of electric fields in plasmas with a high sensitivity (few mV/cm) and a good space-time resolution would provide a useful diagnostic. Such a non-intrusive diagnostic is currently being developed at PIIM laboratory. We present here first results for a constant electric field produced between two vertically movable biased plates either in vacuum or in a plasma. It is actually measured from a hydrogen ion beam with a sensitivity of V/cm as a consequence of *Stark mixing*. We plan to use a metastable H(2s) beam to improve the diagnostic and to reach a sensitivity of mV/cm.

Measurements principle

The principle is to produce a probing hydrogenic atom or ion beam prepared in the metastable 2s state ($\tau_{2\text{s}} = 0.12$ s). The unperturbed system ($n = 2$) is described by the fourfold degenerate eigenfunctions Ψ_{200}, Ψ_{210}, Ψ_{211} and Ψ_{21-1}. As a consequence of *Stark effect*, when the beam crosses an applied electric field, the 2s state becomes a mixed state between the $2\text{s}_{1/2}$ state (Ψ_{200}) and the radiative $2\text{p}_{1/2}$ state (Ψ_{210}) ($\tau_{2\text{p}} = 1.6$ ns) which radiates at the Lyman α line (121.6 nm). For a given hydrogen atom in the 2s state at $t = 0$, we can write [1] the time-dependant wave function of the atom for $t > 0$:

$$\Psi(\mathbf{r},t) = \left[\Psi_{200}(\mathbf{r})\cos\left(\frac{\Delta E}{\hbar}t\right) + \mathrm{i}\Psi_{210}(\mathbf{r})\sin\left(\frac{\Delta E}{\hbar}t\right)\right]\exp\left(-\mathrm{i}\frac{E_{n=2}t}{\hbar}\right) \tag{1}$$

where $E_{n=2}$ is the energy of the unperturbed system for $n = 2$ and ΔE is given by the first-order correction $E^{(1)} = \pm 3eE_0a_0 = \pm\Delta E$; e is the electron charge, a_0 is the Bohr radius and E_0 is the applied electric field. When the probing beam interacts with the applied electric field, oscillations occur in the state probabilities (Fig. 1) for Ψ_{200} and Ψ_{210}, corresponding respectively to the square modulus of the probability amplitudes (1). In the presence of a continuous electric field E_0, the radiative transition $2\text{p}_{1/2} - 1\text{s}_{1/2}$ has a transition rate given by

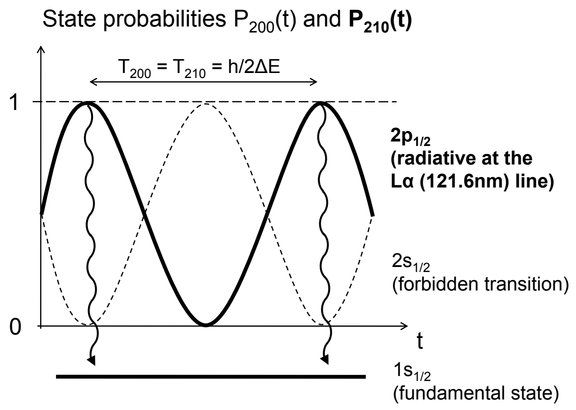

Figure 1: $2s_{1/2}(200)-2p_{1/2}(210)$ mixed state probabilities versus the time.

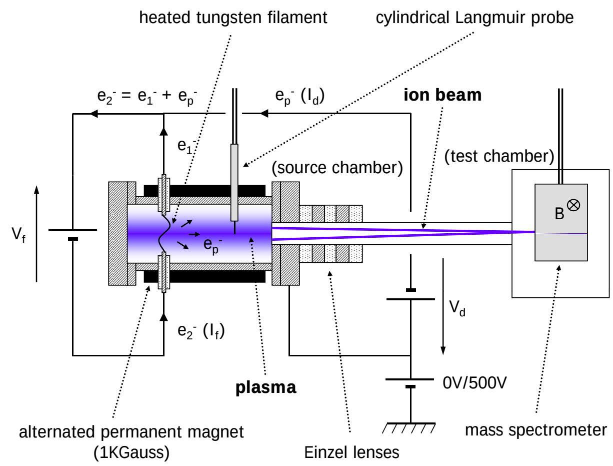

Figure 2: Scheme of the DC multicusp ion source with the extraction Einzel lenses.

$\gamma_{210}(\mathrm{s}^{-1}) = 2,8\ 10^3 E_0^2(\mathrm{V/cm})$ [2]. We can measure it through the Lyman α radiation which follows a quadratic law with the applied electric field E_0:

$$I_\alpha \propto n_{2\mathrm{s}}\gamma_{210}(t) \propto \Omega n_{2\mathrm{s}} E_0^2 \quad (2)$$

where $n_{2\mathrm{s}}$ is the metastable species density and Ω is a global factor for the transmission of the signal (solid angle, efficiency ...).

Experimental set-up

A hydrogen plasma is produced in a small multicusp ion source (Fig. 2) of 16 cm length and 10 cm diameter, surrounded by eight alternated permanent magnets of 1 kGauss. The gas pressure is in the range of 10^{-5} to 10^{-4} mbar. A hot cathode made of a Tungsten filament is biased negatively ($V_\mathrm{d} = -80$ V) with respect to the wall of the chamber to extract primary electrons ($I_\mathrm{d} = 3$ A). An ion extraction system is made of two stainless steel electrodes separated by ceramics (*Einzel lenses*). The maximum kinetic energy of the beam is fixed at 500 eV. In a previous study, the beam was first focused inside a test vaccum chamber containing a mass spectrometer. Measured spectra of the hydrogen ion species are presented in Fig. 3. It shows that the main parameter which governs the ion production is the gas pressure. The beam is now focused in the test vacuum chamber between two vertically movable biased plates (Fig. 4) replacing the mass spectrometer. One can apply vertical electric fields in a range from 0 to 100 V/cm and scan them. The Lyman α radiation ($\lambda = 121.6$ nm) is collected at a 90° angle by a VUV photomultiplier and the signal is measured by a lock-in detection synchronized on the frequency modulating either the beam intensity or the electric field.

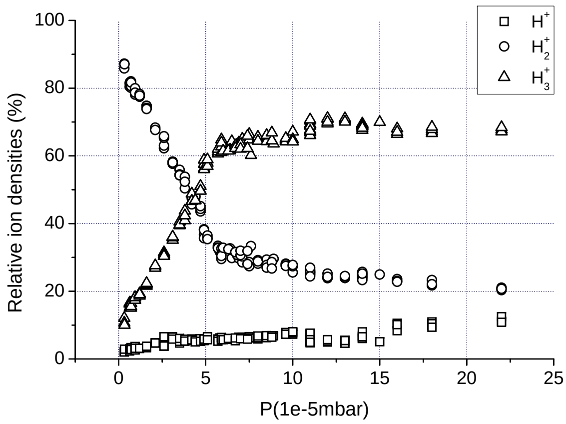

Figure 3: Relative ion densities measured in the ion beam.

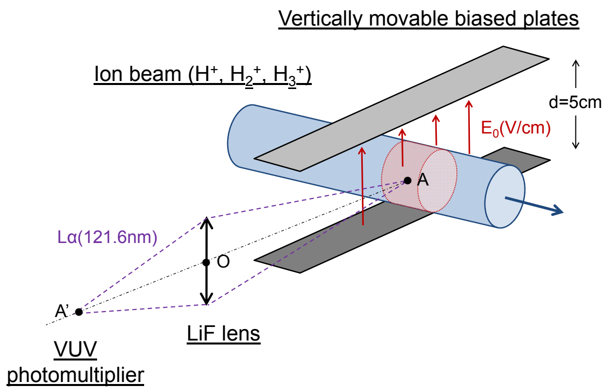

Figure 4: Scheme of the electric field measurement area.

Results in vacuum

A first measurement is made in vacuum varying the applied electric field E_0 between the plates (centered position). The ion source parameters for the ion beam are adjusted to have a high enough signal. We see in Fig. 5 that the quadratic law (4) applies for low voltages ($E < 25$ V/cm). Saturation occurs for higher voltages due to the transit time of the reacting species which becomes too long with respect to the oscillating period $h/(2\Delta E)$ (Fig. 1) ; the metastable species density n_{2s} decreases and the signal falls.

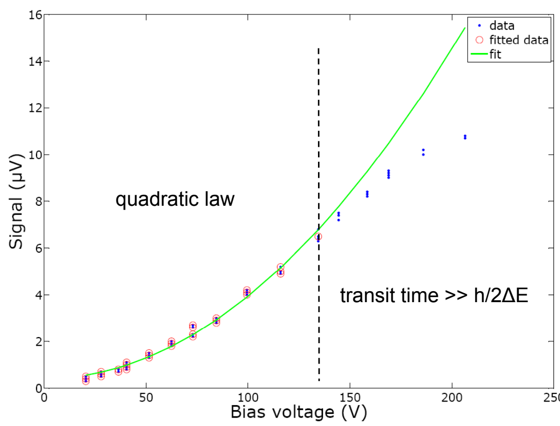

Figure 5: Lyman α radiation with an applied electric field in vacuum.

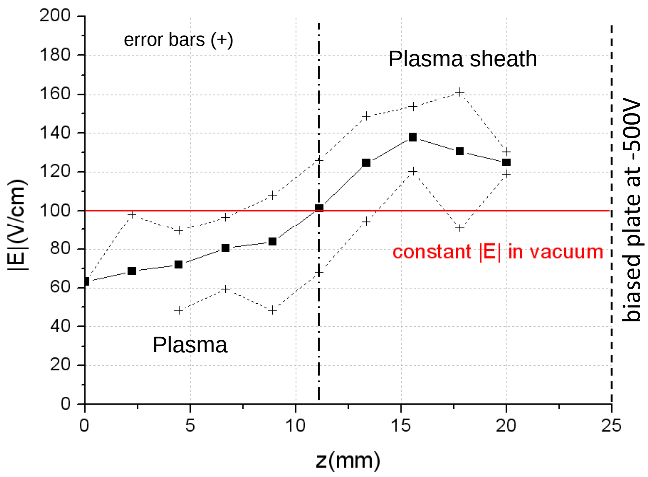

Figure 6: Radial E-field profile in a plasma.

Results in a hydrogen plasma

In the test chamber, we have a residual pressure from the ion source and we can create a DC hydrogen plasma ($V\text{d} = -60$ V, $I\text{d} = 4.4$ mA) as described previously. We can now measure the electric field in a plasma moving both plates vertically to explore the plasma sheath. In the following, we realized radial measurements for a grounded voltage and for a - 500 V applied bias voltage. We identified six noise sources for the radiation at the Lyman α line: 1. natural beam radiation ; 2. collisions with the neutral gas ; 3. inhomogeneous charge densities in the ion beam under a grounded plate ; 4. inhomogeneous charge densities in the ion beam under a - 500 V bias voltage ; 5. natural plasma radiation ; 6. collisions with the plasma. In both cases (*0 V* and - *500 V*), subtraction of the signal with *plasma OFF* to the signal with *plasma ON* deletes the five first terms. These two signals still carrying the information about the plasma noise (5. and 6.), we then subtract the *0 V case* (*plasma ON* $-$ *plasma OFF*) to the - *500 V case* (*plasma ON* $-$ *plasma OFF*) to only keep the contribution of the electric field. Finally, under these considerations, taking the square root of the signal (mV) and with a calibration made in vacuum for a given applied electric field (V/cm), we obtain the measurement on Fig. 6. From $z = 0$ mm at the centered position to $z = 11$ mm, the electric field is below the constant vacuum value (100 V/cm) which means that the plasma shields the electric field. Beyond, the electric field increases above the vacuum value, we are thus able to explore the plasma sheath.

Conclusions

A hydrogen ion beam allows to measure DC electric fields. The quadratic law is verified in vacuum for continuous applied electric fields. Plasma sheath is identified from the electric field profile. The sensitivity is actually about 10 V/cm but it can be improved by focusing the ion beam and by increasing $n_{2\text{s}}$ from the ion source. The time resolution is in the range of the mixed state period $h/(2\Delta E)$ (Fig. 1).

References

[1] B. H. Bransden and C. J. Joachain, *Physics of atoms and molecules*, Longman Scientific and Technical, Harlow, England, (1983)

[2] J. F. Benage, PhD Thesis, *Plasma effects on the metastable* $\text{H}^0(2\text{s})$ *atom*, University of Colorado, Boulder, CO, (1986)