Measuring electric fields in plasmas through Lyman-α radiation of a test metastable hydrogen beam

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A non-intrusive method of measuring electric fields in plasmas is presented. It is based on the use of an atomic hydrogen beam prepared in the metastable fine structure quantum state $2s_{1/2}$. Interaction with the field that is to be measured causes Stark mixing with the closely lying $2p_{1/2}$ (Lamb-shift), whose spontaneous decay rate is much higher than that of $2s_{1/2}$. As a result, the total transition rate to the ground state (and consequently the intensity of the Lyman-α line at 121.6 nm) is increased according to the formula :

$$\gamma_{Stark} \approx 9 \left(\frac{a_0 q_e E_0}{\hbar} \right)^2 \frac{\Gamma}{\left(\frac{\Gamma}{2} \right)^2 + (\omega - \omega_{12})^2}. \tag{1}$$

where $\omega/2\pi$ is the frequency of the field, $\omega_{12}/2\pi$ is the Lamb-shift frequency and E_0 is the field amplitude.

To distinguish the part of the measured signal that is due to the field from background, the 500 V that accelerate the hydrogen ions in the beam preparation step are pulsed at a frequency of 1 Hz and a lock-in amplifier is used to detect, average and amplify the difference between the photomultiplier output with and without beam. Observations of emitted radiation from a region in which the interaction takes place are used to draw conclusions about the electric field, effectively providing a way to measure it [1].

Field profile between two plates in a plasma - sheath observation

In the measurement chamber, the beam passes between two plates, 5 cm apart. The upper plate is grounded and the lower plate can be biased either positively or negatively to create an electric field. It can also be subjected to an RF signal thus generating a field at a frequency close to the Lamb-shift frequency. A plasma is created by mean of a discharge in Argon at a pressure p : a heated filament is polarized with respect to the chamber wall to accelerate primary electrons at a potential referred to as discharge voltage U_D.

We have recorded the electric field profile between the plates by moving them vertically with respect to the beam and measuring the lock-in output at up to 28 points. The points around 5cm and 10 cm respectively correspond to the upper (grounded) and the lower (biased) plates being moved into and past the beam. Plasma parameters are p=(1.8$\pm$0.2) 10^{-5} mbar, U_D=80 V, and
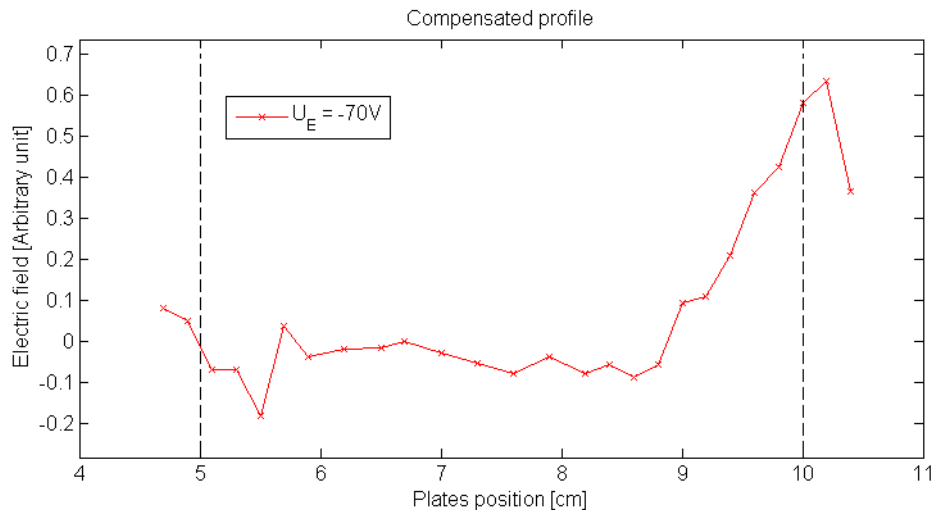
Compensated profile

Figure 1: *Profile measurement in plasma, resonant field case : one clearly sees the sheath of about 1 cm close to the plate at 10 cm.*

discharge current I_D=0.95 A. We measure the Lyman-α emission when the plates are biased at -70 V and 0 V. To obtain the corresponding field profile, we simply divide the -70 V recorded data with the zero field profile and then subtract offset. Fig. 1 clearly exhibits the sheath near the polarized electrode. Outside of the sheath, raw data at -70 V and 0 V are fairly equal, thus the field is about zero as expected.

In this run, the sheath is about 1 cm thick. The qualitative dependence of the sheath thickness on discharge current, pressure and plasma frequency has been studied. It appears to be in accordance with well established theory [3]. When it comes to RF fields, a possible standing wave pattern is detected in the plasma despite problems with low signal to noise ratio. Further investigations are necessary.

RF spectrum in vacuum

Measurement of lock-in output varying the applied electric field frequency while keeping a constant amplitude is displayed in Fig. 2. Several peaks are detected, looking like the hyperfine structure of the $2s_{1/2} - 2p_{1/2}$ system (Fig. 3). The theoretical curve, using eq. (1) with a natural line width of about 100 MHz for each transition, is scaled and overlaid in the same graph. Peak #3 perfectly coincide (up to our resolution) with the $\Delta f = 0$ transition.

The step on the background level that can be noted at 900 MHz is an instability of the discharge. The frequency for peak #5 matches exactly a transition between higher lying states $4s_{1/2}$ and $4p_{3/2}$, inducing a cascade decay to the ground state emitting, among other things, Lyman-α radiation [2]. Peaks #1 and #6 are not yet identified. The other peaks seem to deviate slightly
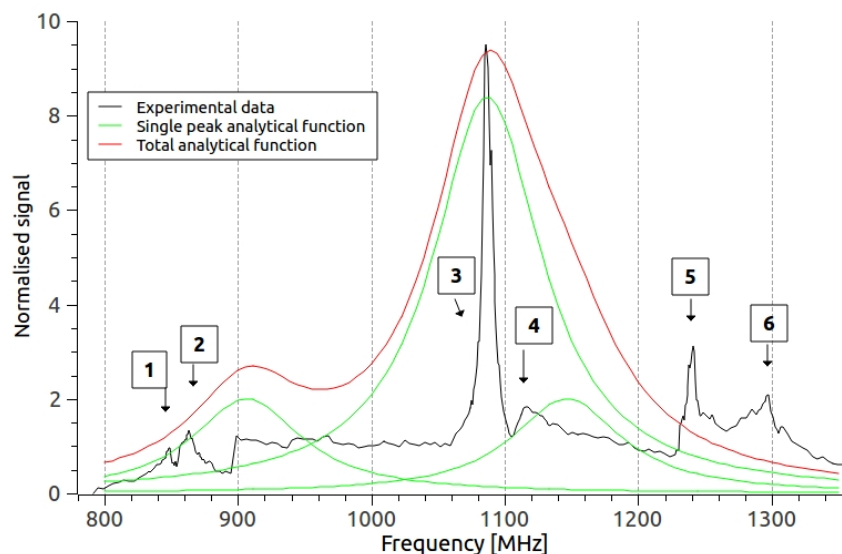
Figure 2: *Lyman-α signal as a function of RF-field frequency.*

from the theoretical curve. Peaks #2 and #4 do not exactly coincide in position. In addition to this, the widths of all peaks are much smaller than the natural linewidth of the theoretical curves. Further studies are underway to see if a shift and/or a change in the width of these lines happens when varying the field amplitude.
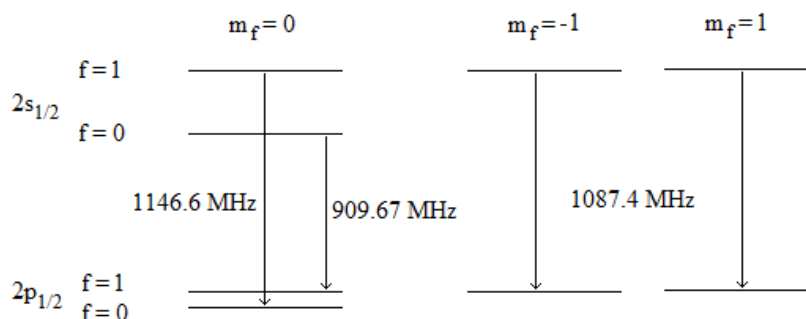

Figure 3: *Sketch of hyperfine states and transitions between them.*

Plasma resonance

Varying either the filament current or the discharge voltage results in a modification of the discharge current I_d in the plasma. Both have been made in the presence of a radio-frequency field of fixed amplitude at a frequency of 1059 MHz, resonant with the Lamb-shift frequency. The subsequent Lyman-α signal is displayed in Fig. 4 as a function of I_d.

The curve in Fig. 4 exhibits a resonance for $I_d = 2$ A. However it is not simply a direct coupling between the RF field and the plasma frequency. Indeed, the estimated electron density
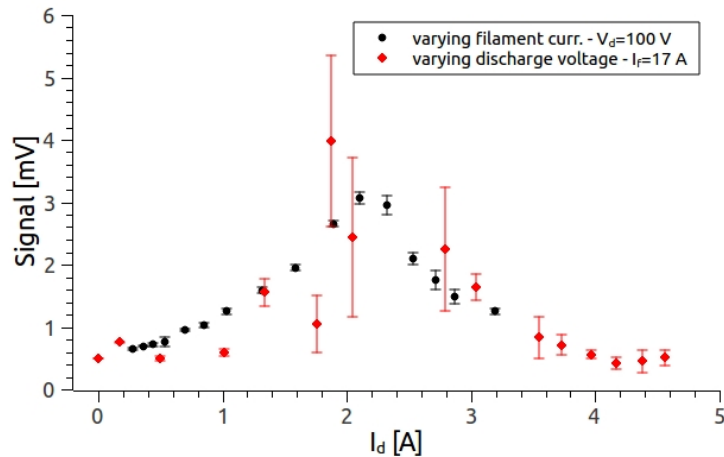
Figure 4: *Plasma resonance.*

(measured with a Langmuir probe) is $5 \ 10^{14}$ m^{-3}. This value would give a plasma frequency of about 200 MHz, which is far below the Lamb-shift frequency at which the RF field oscillates.

Conclusion

Measurements have been focused towards the intensity of Stark-mixing induced Lyman-α radiation in a well defined interaction volume between an atomic hydrogen metastable beam and a controlled electric field. Studies of the field profile between a pair of electrically polarized plates have been carried out. Static profile measurements in a plasma clearly show the formation of a sheath, which thickness depends, as expected, on plasma density. These results demonstrate that our method can be used to perform electric field measurements in a plasma. But the observation of the Lyman-α emission as a function of different parameters (not only the field amplitude) in such a controlled environment gives other interesting results. For example, a measurement of the dependence of the Lyman-α intensity on electric field frequency is presented. Despite the extreme sharpness of the lines, the spectrum seem to match the hyperfine structure of hydrogen theory. Furthermore, in the presence of an RF field resonant with the lamb-shift frequency, a plasma resonance is observed when varying the discharge current.

References

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