Measurement of alkali metal vapor density using interferometric methods for the proton driven wakefield accelerator at CERN

F. Batsch, P. Muggli, E.Öz, Max Planck Institute for Physics, Munich, Germany (September 2014)

Application Note

1 Introduction

The latest idea for accelerating electrons or positrons to energies higher than 1 GeV over short distances is the use of proton-driven, plasma-based particle accelerators. Proton beams are interesting as drivers because they carry large amounts of energy and could therefore be used to produce very high energy e^- and e^+ bunches. Therefore, the Advanced Wakefield Experiment (AWAKE) Collaboration will start the world's first proton-driven plasma wakefield accelerator experiment at CERN in 2016. Proton bunches will enter a plasma where they will become modulated transversely by the self-modulation instability and split into micro-bunches at approximately the plasma wavelength. These micro-bunches can drive wakefields in the GV/m range and over long distances (10's - 100's of meters) [1] thereby allowing in principle for the large energy gain. By comparison, conventional accelerators operating today use accelerating fields smaller than 100 MeV/m.

2 The experiment

The essential part of the experimental setup is the plasma source consisting of a heated, 10 m long pipe. In this pipe, the plasma is created by ionizing a rubidium (Rb) vapor with a short and intense laser pulse [2]. Fast valves enclose the vapor and open within 15 ms allowing the ionizing laser pulse to enter the pipe. Rubidium is heated to 150 – 200 °C to create a vapor, and after ionization a plasma forms with a density in the 10^{14} to 10^{15} cm^3 range. An optimal acceleration process requires a very uniform Rb temperature and vapor density. Because all atoms are singly ionized by the laser pulse, the Rb plasma density and uniformity are equal to those of vapor density and temperature. Thus, the plasma density can be determined by just measuring the vapor density.

The density is measured optically by using the so-called hook method [3]. This method takes advantage of the fact that as all alkali metals, Rb has optical atomic transitions in the visible range from its ground state, at λ_1 = 780.24 nm and λ_2 = 794.98 nm. The strong absorption of light by atoms in the ground state (almost all atoms at these lower temperatures) leads to significant anomalous dispersion in the vicinity of these two lines. That is, the index of refraction n changes as a function of wavelength. This property can be used in an interferometer system. Figure 2 (a) shows the real part of the relative permittivity ε, which is linked to the index of refraction by $\varepsilon = n^2$.

In the experiment, broadband coherent light is sent through a Mach-Zehnder interferometer where one arm contains the Rb vapor and the other one air (see Fig. 1 for the setup). As light source, we use a normal, commercially available halogen lamp which exhibits coherence in the wavelength range of interest (770 to 790 nm). The interferometer is adjusted to form interference fringes at an angle with respect to the entrance slit of the imaging spectrograph (Shamrock SR-750-D2-SIL). Figure 2 (b) shows the interference pattern in the image plane of the imaging spectrograph, i.e., dispersed by wavelength. This pattern is recorded with an attached ICCD camera (Andor iStar DH334T-18F-73, 1024 x 1024 pixels). The CCD sensor can be cooled down to -40 °C, which allows for detecting low light with a low noise level by integrating over a long time. This property is needed, because the coherent light intensity is low since it originates from a low power broadband source (100 W) emitting in a 4ϖ solid angle. The initial measurement presented here consists in measuring the static Rb vapor density when the valves are closed.

However, the opening of the valves leads to the loss of the Rb vapor. Then, the vapor density after the valves opening needs to be measured at the millisecond time scale. This measurement requires the time-resolving properties of the Andor iStar camera (i.e. the intensifying and gating features) and will be performed later once the fast valves will become available.

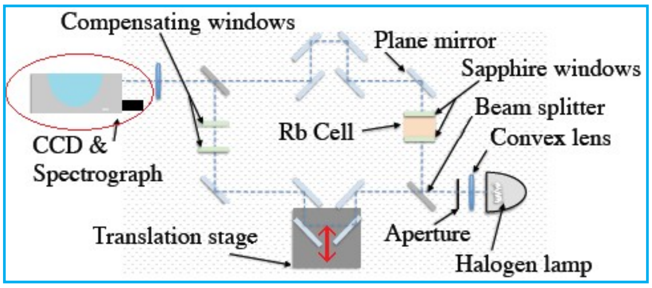

Figure 1: A drawing of the setup with a halogen lamp as a white light source, the components of the Mach-Zehnder interferometer, the spectrograph and the ICCD camera.

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The anomalous dispersion of Rb causes the formation of hooks around the absorption wavelength as shown in figure 2 (c). The Rb vapor density N can be calculated using the fact that it is proportional to the square of the hook distance Δ ($N \propto \Delta^2$), which can be determined from the spectrograph image with a computer program. The equation is

$$N = \frac{\pi K}{l r_0 f_i \lambda_i^3} \cdot \Delta^2 \quad (1)$$

l = 3.5 cm being the vapor column length through which the light passes, r0 the classical electron radius, $\lambda_i = \lambda_{1,2}$, $f_i \approx 0.7$ the oscillator strength of the transition and $K \approx 800$ a constant depending on the interferometer's path length difference.

3 Results

We used a 1200 gr/mm grating, 800 ms integration time and chose 780 nm as center wavelength. The CCD sensor is cooled to -30 °C. We observe the expected interference pattern. Figure 2 (c) shows a spectrum obtained at a temperature of 200 °C. The hook pattern is clearly visible in the vicinity of the absorption wavelength. The hook distance Δ is defined as the wavelength difference between the "flat" regions of the fringe pattern at either side of λ_i. For this particular case, the distance Δ = 2.76 nm, which corresponds to a density of $N = 4.9 \times 10^{14}$ cm^{-3} (from eq. 1). We estimate the accuracy of the measurement to be better than 7%. This result shows that we can produce Rb densities sufficiently high for the AWAKE experiment with reasonable temperatures (<200 °C). These measurements are also in good agreement with densities expected from the vapor pressure curves of Rb.

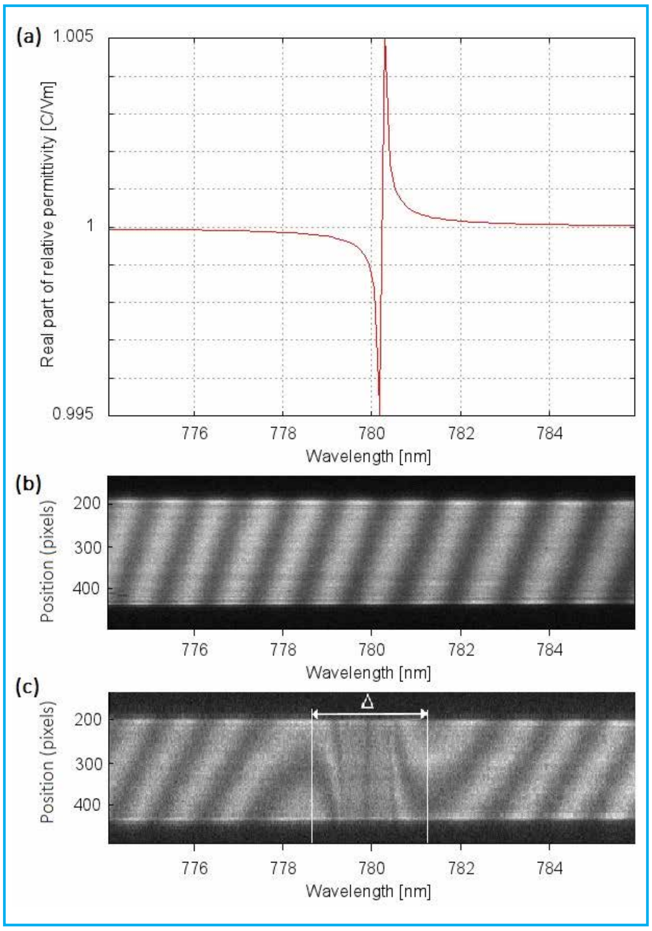

Figure 2: (a) The relative permittivity of Rb plotted versus wavelength near the Rb optical transition at 780.2 nm. The total height of the peaks is saturated due to a low sampling rate and is much larger than shown here. (b) An interference fringe pattern with light from halogen lamp without Rb absorption. (c) The fringe pattern with Rb vapor and hooks, the hook distance Δ is marked.

The implementation of this diagnostic in the AWAKE experiment will require full automation and remote operation of the measurement. We will therefore use a variant of the diagnostic in which the fringes are kept parallel to the spectrograph slit. The images, similar to those of Fig. 2 (b) and (c), can then be summed along the vertical direction to obtain one-dimensional traces such as that shown in figure 3. The trace 3 (b) can then be fitted with the expected phase shift caused by the anomalous absorption n(λ). This procedure gives results similar to those obtained with the hook method and is easier to automate. The signal to noise ratio is also better due to the image summation.

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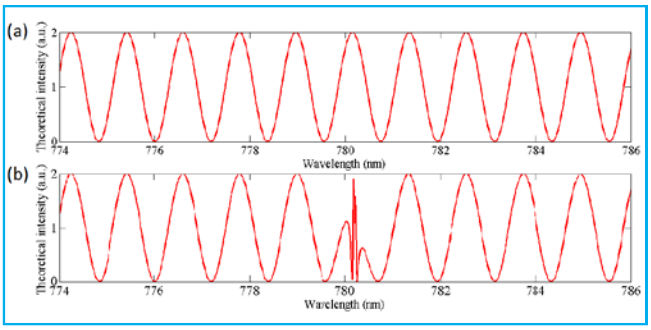

Figure 3: Intensity profile obtained by summing the spectrograph's images with vertical fringes in the vertical direction without Rb absorption (a) and with absorption (b).

Using the intensifying and gating functions of the ICCD camera, we will obtain figures similar to those of Fig. 3 but with ms time resolution to determine the dynamic loss of the Rb vapor.

References

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