Nuclear Inst. and Methods in Physics Research, A 884 (2018) 25–30

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

# Real-time interferometric diagnostics of rubidium plasma

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A R T I C L E I N F O

*Keywords:*
CERN AWAKE project
Laser plasma
Interferometry
Plasma diagnostics

A B S T R A C T

A method of interferometric real-time diagnostics is developed and applied to rubidium plasma created by strong laser pulses in the femtosecond duration range at different initial rubidium vapor densities using a Michelson-type interferometer. A cosine fit with an exponentially decaying relative phase is applied to the obtained time-dependent interferometry signals to measure the density–length product of the created plasma and its recombination time constant. The presented technique may be applicable for real-time measurements of rubidium plasma dynamics in the AWAKE experiment at CERN, as well as for real-time diagnostics of plasmas created in different gaseous media and on surfaces of solid targets.



## 1. Introduction

Plasma generation in gases and on surfaces of solid targets by intense ultrashort laser pulses has found an extremely broad spectrum of applications in different fields of science and technology. These include high order harmonics generation widely used for ultrashort laser pulse generation, (see review paper [1] and references therein), plasma wake-field based particle acceleration in novel compact accelerators for charged particles, [2–6] and many others.

In this communication, we report results of our study of plasma generation in rubidium (Rb) vapors by intense laser pulses of femtosecond duration using the interferometry method. This study is directly related to the Advanced Wake-Field Experiment (AWAKE) project at CERN, [7,8], which will be the first ever in the world proton-driven plasma wake-field experiment. The aim of this project is the construction of a relatively compact (and cheaper) accelerator of electrons (positrons) to TeV energies in a single acceleration stage utilizing the proton bunch available at the Super Proton Synchrotron (SPS) at CERN. The length of the SPS proton bunch is in the range of 10–30 cm. The estimations and simulations have shown that the maximum wake-field acceleration in plasma is achieved when the length of the proton bunch is equal to the length of the plasma wave, which is in the range of 100 μm [7,9]. Since short ($\sim 100\,\mu$m) proton bunches are not available at SPS up to now, transverse modulation of the current proton bunch was proposed by means of the self-modulation-instability in plasmas. Thus, it would be possible to obtain micro-bunches with length equal to the plasma wavelength, [10].

As earlier estimations have shown, strict conditions on the plasma density uniformity must be satisfied for an efficient self-modulation instability effect [11], but according to recent numerical simulations, some longitudinal plasma density gradient could be useful [12]. In any case, the plasma density and its spatial distribution is a critical issue for the successful transverse modulation of the proton bunch and the efficient electron acceleration in the plasma wake field driven by the produced proton micro-bunches. To assure the desired plasma density it is necessary to ionize the single outer electron in all of the atoms in the Rb vapor along the pass of the proton bunch. In this case, the plasma density will be the same as the neutral Rb vapor initial density, which can be controlled by the temperature of the Rb vapor. The strict requirement on the plasma density uniformity can be fulfilled by confining Rb vapor in a steel tube with extremely homogeneous distribution of the vapor temperature provided by external oil heating [11]. The relatively low ionization potential of Rb, (4.18 eV) [13,14], makes it relatively easy to ionize the single outer electron of Rb atoms. Thus, one could fully ionize Rb vapor in the extended volume of the tube by sufficiently intense (energetic) ultra-short laser pulses. It is worth noting that the laser plasma source is an essential part of the setup of the AWAKE experiment.

Diagnostics of the plasma generated by the ionizing laser pulses in such a system is crucial for having an insight into the ionization processes of the Rb atoms, and for detecting the density of the created plasma as well as its time–space evolution. In Ref. [15], a method for accurate measurement of the density of neutral Rb atoms was developed

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https://doi.org/10.1016/j.nima.2017.12.004
Received 27 July 2017; Received in revised form 30 November 2017; Accepted 4 December 2017
Available online 7 December 2017
0168-9002/

using Mach–Zehnder type interferometry, similar to the method described in Ref. [16]. Using this technique, the density of neutral Rb vapor can be accurately measured using the anomalous dispersion around the atomic transitions from the ground state of atomic Rb to the first excited states (D1 and D2 lines) by applying a broadband light source. While this interferometric scheme is well applicable for measurements of the density–length product for a stationary ensemble of neutral Rb atoms, the ionization dynamics of the atoms, including density variation in time and space of the created plasma, are beyond the scope of this method.

In this communication, we propose and apply another plasma diagnostics method that allows for the *real-time* determination of the plasma density–length product, as well as for estimation of recombination constants for the generated laser plasma at different temperatures (initial densities) of the Rb vapor.

The diagnostics of the generated plasma in our scheme is performed using Michelson-type interferometry. Accordingly, a probe CW diode laser beam propagates twice (back and forth) through a glass cell filled with Rb vapor and located in one (probe) arm of the Michelson interferometer. This probe beam creates an interferometric picture (fringe pattern) with a reference beam from the same laser propagating in the air in the other (reference) arm of the interferometer. Time variations of the interferometric signals are measured by fast detectors in a real-time regime. The measured signals are fitted by functions including time-decay terms describing the phase difference between the probe laser beams in the two arms of the interferometer induced by the ionizing laser pulses. The fitting technique allows us to measure the plasma density–length product and its variation in time along with the recombination time constants at different temperatures of the Rb vapor.

## 2. Experimental setup

The setup for the generation of laser plasma is shown in Fig. 1. It contains vacuum chambers incorporating a temperature-controlled oven with a glass cell filled with Rb vapor. The rubidium cell is a 75 cm long cylindrical glass tube of 2.5 cm outer diameter with end windows of optical quality. It is set in a temperature-controlled oven consisting of a stainless steel tube as heat reflector with longitudinal heating wires set around the glass cell inside the tube. The temperature of the Rb cell and respectively, the density of the Rb vapor are varied during the studies. In order to produce a homogeneous temperature distribution and avoid the condensation of rubidium at the end windows of the cell, the openings of the tube at both ends are equipped with additional heating elements. To avoid the turbulence in the air and to increase the heat insulation, the whole oven with the cell is placed in a vacuum chamber where the pressure is about $10^{-6}$ Torr. The temperature is measured alongside the surface of the cell at five locations with Pt-100 platinum thermo-resistors.

The plasma channel in the rubidium vapor is generated by the ionizing Ti-sapphire laser (Legend, Coherent Inc.), which operates at 800 nm wavelength and 1 kHz repetition rate, and has a pulse duration of about 40 fs with maximum pulse energy of 4 mJ. The beamline in our experiments delivers about 2 mJ pulse energies, and with a diameter of 10 mm it provides a peak intensity of about $10^{11}$ W/cm$^2$ at the center of the beam. This ionizing laser beam is aligned longitudinally along the glass cell inside the vacuum system and the transmitted fraction is blocked by an appropriate beam dump.

The Michelson-type interferometer (see Fig. 1) is adjusted in a quasi-collinear arrangement with the laser plasma channel to avoid the direct exposure of the detectors to the ionizing laser. The probe arm of the interferometer is aligned at a 1.5° angle to the direction of the plasma channel through the vacuum chamber, while the reference arm is set up at the optical table in the air. A continuous beam of a tunable Newport TLB–6712 "Velocity" external cavity diode laser (ECDL) is used for the interferometric measurements. The frequency of the diode laser can be tuned in a single mode and mode-hop-free operation across the 780 nm atomic resonance of Rb through tilting the cavity grating by a piezo-transducer. The frequency of this probe laser is measured by generating the beat signal between its beam and the beam of another ECDL (Toptica DL100), whose frequency is stabilized to the $F = 1 \rightarrow F' = 2$ hyperfine atomic transition of the D2 line of $^{87}$Rb using the saturated absorption method. The beat signal is fed to a fast photodetector of 4.5 GHz bandwidth (New Focus 1591) and the frequency is monitored and calculated in real time by fast Fourier transformation on an oscilloscope (Tektronix DPO 7354).

A fast amplified photodetector (New Focus 1591) measures the interferometric signal and its variation in time caused by variation of the relative phase between the probe laser beams propagating in the two arms of the interferometer. The time variation of the relative phase is a result of the strong laser pulse ionizing a fraction of the Rb atoms, as well as of the recombination processes in the created plasma in the probe arm of the interferometer. Measurements are done for different values of detuning of the probe diode laser from the $5S_{1/2}\ F = 1 \rightarrow 5P_{3/2}\ F' = 2$ hyperfine transition of $^{87}$Rb atoms.

## 3. Laser plasma generation and interferometric real-time diagnostics of the plasma

A picture of the generated laser Rb plasma is shown in Fig. 2.

The measured interferometric signals are shown in Fig. 3(a)–(d) together with least squares fits at Rb cell temperatures of 95 °C and 120 °C and the probe laser detunings equal to 4.0 GHz and 3.2 GHz respectively. The rubidium vapor density as a function of temperature was calculated using data of Ref. [13]. The calculated density values corresponding to the two Rb vapor temperatures were $4.3\times10^{12}$ cm$^{-3}$ and $2.0\times10^{13}$ cm$^{-3}$, respectively. The intensity of the transmitted signal ($I_{tr}$) measured with closed reference arm of the Michelson interferometer ($I_{ref} = 0$) is also shown in the figure. The spike of the signals near the zero time point is a parasitic scattered signal coming from the ionizing laser pulse traversing the Rb cell at this time point. The signal value of $I_{ref}$ (recorded with the transmitted beam blocked, $I_{tr} = 0$) was about 183 mV and 172 mV for the measurements with vapor temperatures of $T = 95$ °C and $T = 120$ °C, respectively.

For fitting of the measured interferometry signals (with intensity $I_{interf}(t)$), the following expression is applied:

$$I_{interf}(t) = I_{tr}(t) + I_{ref} + 2\epsilon\sqrt{I_{tr}(t)I_{ref}} \cdot \cos(\varphi_0 + \varphi_1(t)), \quad (1)$$

where $I_{tr}(t)$ is the time-dependent intensity of the probe signal transmitted through the Rb cell, $I_{ref}$ is the (constant) intensity of the reference signal propagating in the air, $\epsilon$ is the interference efficiency. $\varphi_0$ is the initial phase difference between the transmitted and reference signals that may vary from measurement to measurement due to the mechanical noises (with typical frequency in the kHz range) but can be considered as a constant during the lifetime of the plasma of a few microseconds. $\varphi_1(t)$ is the time-dependent variation of the relative phase between the transmitted and reference signals induced as a result of the change of the refractive index in Rb vapor due to the action of the ionizing laser pulses:

$$\varphi_1(t) = (2\pi/\lambda)L\Delta n(t), \quad (2)$$

with $L$ being the propagation length of the transmitted probe in the Rb cell, and $\Delta n(t)$ being the time-dependent variation of the refractive index in the Rb cell.

Some part of the neutral Rb atoms being initially in their ground states is ionized and other part of the atoms is excited to higher energy states by the strong laser pulse. Both the excited and the ionized atoms induce some change of the refractive index for the probe laser signal leading to the time-dependent variation $\varphi_1(t)$ of the relative phase. The two processes however have distinctly different relaxation times. While the spontaneous decay time from excited states to the ground state of the Rb atoms is in the range of a few tens of nanoseconds, (see for example [13]), the recombination of the plasma takes place in the microsecond time range [17]. It means that after a relatively fast relaxation of the excited atoms, a relatively slower plasma recombination