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Pre-excitation studies for rubidium-plasma generation

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ABSTRACT

The key element in the Proton-Driven-Plasma-Wake-Field-Accelerator (PWFA) project is the generation of highly uniform plasma from Rubidium vapor. A scientifically straightforward, yet highly challenging way to achieve full ionization is to use high power laser which can assure the barrier suppression ionization (BSI) along the 10 m long active region. The Wigner-team in Budapest is investigating an alternative way of uniform plasma generation. The proposed Resonance Enhanced Multi-Photon Ionization (REMPI) scheme can be probably realized by much less laser power. In the following we plan to investigate the resonant pre-excitations of the Rb atoms, both theoretically and experimentally. In the following our theoretical framework is presented together with the status report about the preparatory work of the planned experiment.

1. Introduction

After building LEP and LHC, and planning ILC the size and cost of classical high energy particle accelerators are reaching their limits around 50 MeV/m.

In their historical article [1] in 1979 Tajima and Dawson predicted: “glass lasers of power density 10^{18} W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectron volts of electron energy per centimeter of acceleration distance.” With the availability of high power short pulse lasers their ideas are becoming reality.

It turned out that it is possible to build not only Laser Wake Field Accelerator (LWFA) but also Particle Driven Wake Field Accelerator (PWFA). In the laboratories 100 GV/m accelerating gradient was demonstrated with laser driven systems [2] and 50 GV/m with electron driven case in SLAC [3–5].

At CERN the AWAKE collaboration [6] has been formed in order to demonstrate proton driven plasma wake field acceleration for the first time, where the Wigner team is interested in the creation of high uniform plasma which is required to reach the plasma frequency stability at the percent level.

The SPS proton beam in the CNGS facility will be injected into a 10 m plasma cell where the long proton bunches will be modulated into significantly shorter micro-bunches. These micro-bunches will then initiate a strong wakefield in the plasma with peak fields above 1 GV/m. Though this peak field is much less than the one achieved by laser or electron driven systems, the future accelerator based on this technology can have a much reduced length compared to proposed linear accelerators.

In the proposal [7] a uniform plasma was assumed to be generated by high enough laser power with barrier suppression ionization (BSI), achieving saturation along the whole length of the 10 m plasma. In this paper we propose a much softer method by applying the so-called Resonance Enhanced Multi-Photon Ionization (REMPI) scheme. It is a three photon process which requires significantly lower laser power than the non-resonant BSI process. We will investigate the two-photon resonant excitation process with theoretical method and the whole ionization with an experimental setup.

2. Experimental setup

To study the resonant photoionization process in the near future we present our experimental setup which is under

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construction. In order to produce a desirable homogeneous laser plasma for the wake field acceleration of particles the ionization process by high intensity laser pulses has to be studied. Therefore the aim of the first experiment is the investigation of high field ionization gain from rubidium atomic beam by using the commercial regenerative Ti:sapphire based chirped-pulse amplifier laser system (Coherent Legend Elite HE-USP). The amplifier delivers 35 fs pulses at 800 nm central wavelength with 1 kHz repetition rate and with 4 mJ pulse energy. In the recent experiment the length of the laser impulse is fixed, therefore effects coming from the pulse length cannot be studied. The characteristic noise ratio of the average power is smaller than 0.5%. The maximum achievable focused peak intensity is around $10^{16}-10^{17}$ W/cm^2 depending on the focusing optical element. Our theoretical calculations show that a 10^{12} W/cm^2 peak intensity is sufficient for a three-photon ionization if a resonant two-photon excitation took place. Hundred percent three-photon ionization without prior two-photon resonant excitation needs much higher intensity. The applied seed oscillator for the amplifier is a standard home-build Ti:sapphire oscillator delivering 20 fs long pulses with 80 MHz repetition rate and with 7 nJ pulse energy. The intensity dependence and the presumable saturation of the ionization probability of the free atoms will be measured by detecting the ions and/or electrons. The experimental setup can be seen in Fig. 1.

The electrons are produced by the 35 fs laser pulses in the high field ionization of the Rb atomic beam of slab like shape from the electrically heated disperser and accelerated by an electrical field of 1000 V on the electrodes A and B in the direction of the cathode (D) of a double chevron microchannel plate (MCP) through the drift tube (C). The resulting impulse is observed on the anode (E) of the MCP by an oscilloscope. A simple rubidium disperser manufactured by Saes getters serves as the first version of the source of the atomic beam (see Fig. 2). It contains a suitable compound (chromate) of rubidium which, under appropriate heating by current, emits neutral Rb atoms, while the rest of the components are absorbed by the reducing agent of the dispenser, thus producing a clean source of Rb atoms. Alkali metal dispensers are commonly used as controlled sources of rubidium atoms e.g. for loading magneto-optical traps in quantum optics experiments, e.g. Ref. [8], and several constructions have been developed to produce directed beams from metal dispensers in this field [9,10].

The shape of the dispenser (A) is slab of 30 mm length and 1 mm widths. The metallic slab containing the rubidium compound is heated by electric current. The rubidium atoms released after the dissociation of the compound disperse from the source of temperature of some hundred degrees and distributed in almost 2π solid angle. For the aim of the experiments the atoms restricted to a narrow solid angle by two slit apertures positioned to 10 mm distance.

The construction of the rubidium source box can be seen in Fig. 2 (except for the side openings which are not indicated here).

The dispenser and one of the two slit apertures are placed in a closed metallic box (B) the top of which contains the second aperture (C). The two slits collimate the emission of the atoms in a narrow region of the vacuum space. The side walls of the two regions of the box have openings in order to avoid the buildup of dense gas phases. Atoms emitted by the dispenser wire can only propagate directly towards the slits. Closely spaced cover plates gather the atoms escaping the box through the side openings. The advantage of using disperser as the source of atomic beam is its flexibility in switching on or off securing its economic long time use. We have produced well collimated atomic emission profiles with this source with low background densities of rubidium. The atomic density was monitored by measuring the fluorescence excited by resonant laser radiation. The beam of an external cavity diode laser, frequency stabilized close to the strongest resonance line of the ^{85}Rb atoms, was sent through the atomic beam parallel to the slits, and the fluorescence intensity was measured at different positions of the beam. The accumulated profile of the fluorescence can be seen in Fig. 3, and a full width at half maximum of about 1.8 mm has been obtained a few mm above the source surface.

This experimental arrangement placed into a stainless steel vacuum chamber with the ports for entry and exit of the laser pulses, for the optical observations and for the electrical feedtroughs. The vessel is pumped by turbo molecular pump to better than 10^{-6} mbar vacuum. From our former experiments [13–16] with Rb atoms in a similar geometry we expect a plasma density of 10^{12} atom/cm^3.

The Rb dispenser and the vacuum system was successfully tested at the end of October 2013. Recently, the resonant three

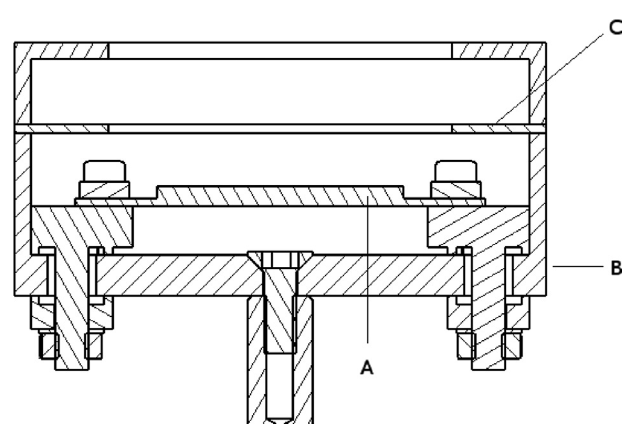

Fig. 2. Side view of the rubidium source box geometry.

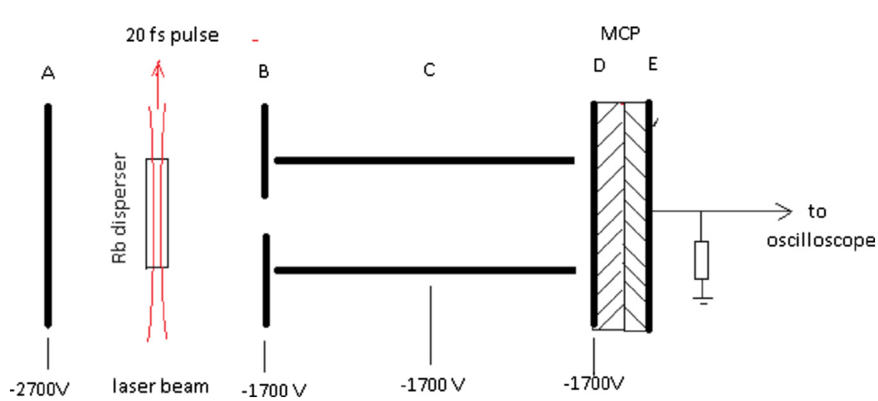

Fig. 1. The scheme of the experimental setup.

photon ionization experiment is under way. Later the role of the liner chirp will be investigated. As a long-range perspective we plan to investigate a much longer plasma geometry of a meter distance. The same method (resonant pre-excitation) would be feasible to massively reduce the applied laser intensity in any kind of three-photon ionization of atoms, which is one of the crucial messages of our next study.

3. Theory: pre-excitation of rubidium atoms

When considering generation of laser plasma with high homogeneity using multi-photon or BSI, it is advantageous to find ways for decreasing the threshold conditions for the ionization, especially when generation of a spatially extended plasma is the main goal. One of the ways to decrease the threshold of the laser multi-

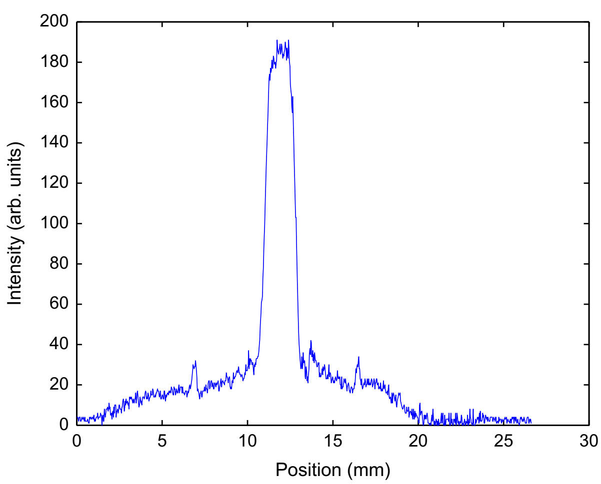

Fig. 3. The shape of the Rb atomic beam above the opening slit.

photon ionization (MPI) or BSI is to transfer atomic population from its ground state to one of the excited states before the ionization process, thus significantly decreasing the ionization potential. Of course, such pre-excitation of the atoms must be performed by methods that are robust and are not too sensitive to the laser pulse parameters including duration, fluctuations in pulse intensity, phase, etc.

One of the most efficient ways to transfer the atomic population to a target state with probability close to unity is to utilize the method of rapid adiabatic passage (RAP). The word rapid relates to the interaction time that must be shorter than all relaxation times in the system. On the other hand, the variation of the laser parameters must be adiabatically slow to maintain the atom in a given dressed state [11,12]. An approximate condition for adiabaticity is $\Omega\tau_L > 1$, where Ω is the peak Rabi frequency, and τ_L is the duration of the laser pulse. While the relaxation times in gases are in the nano- and pico-second time range, the relaxation processes may be avoided already for laser pulses in the femto- (tens of femto-) second durations range.

RAP may be efficiently realized using phase-modulated (frequency-chirped (FC)) laser pulses, which frequency varies monotonically in time during the laser pulse. An instructive example of the population transfer produced by FC pulse is the action of such a pulse on a model two-level atom. While action of a laser pulse with constant frequency results in the well-known Rabi oscillations with an average of 50% population transfer, all the atomic population is transferred from one state to another one when a FC laser pulse is applied, the frequency of which is swept through the resonance with the atomic transition. An important feature of the interaction is its robustness concerning variations of the laser parameters [11,12].

The FC pulses were successfully utilized also in more complicated multilevel atomic or molecular structures [13–20]. In Ref. [14], for example, FC pulses from a diode laser having a central frequency resonant with the D2 line of ^{85}Rb produced a complete population transfer from a ground state to manifold of excited

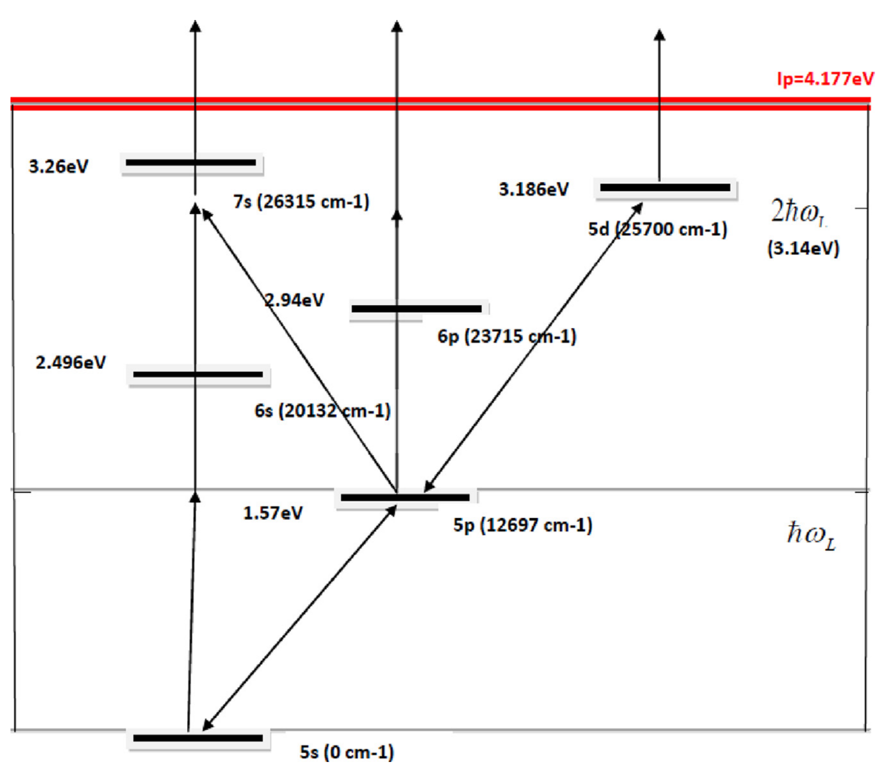

Fig. 4. The relevant energy levels of the Rb atom along with the two-photon excitation and three-photon ionization scheme.

states and back, each time transferring a twice of photon momentum to the atom by a pair of counter-propagating pulses [16–18]. The FC pulses were used in Ref. [21] to perform resonance enhanced multi-photon ionization in sodium atoms.

In this communication, we show by taking Rubidium as an example (see Fig. 4) that pre-excitation of the multilevel atom may be efficiently and robustly performed by application of FC laser pulses. As it is seen from Fig. 4, absorption of three photons of radiation of 800 nm wavelength (typical for the Ti:Sa laser) provides ionization of Rb atom from the ground state 5 s. The efficiency of the ionization process may be increased in some extent using intermediate resonances providing resonance enhanced multi-photon ionization, (see e.g. Ref. [21]). However, the threshold of the ionization processes may be drastically decreased if one could transfer the atomic population from the ground level 5 s to excited states 5d or 7 s, from which only one-photon transition to the vacuum-state provides ionization of the atom.

We have analyzed the possibilities of excitation of the Rb atom by laser pulses having a Gaussian shape with duration equal to 30 fs, peak intensity in the range of a few 10^{12} W/cm^2 with a linear frequency chirp of a few fs^{-2}. Since the duration of the laser pulse is much shorter than the atomic relaxation times, the Schrödinger equation for the probability amplitudes of the working atomic levels of Rubidium in Fig. 4 is solved numerically and the dynamics of the atomic populations in the field of the FC pulses is determined.

The Schrödinger equations for the atomic probability state-vector $\mathbf{a} = (a_0, a_1, a_2, a_3, a_4, a_5)^T$ has the form

$$i\hbar \frac{d}{dt}\mathbf{a} = \hat{H}\mathbf{a} \tag{1}$$

with the interaction Hamiltonian $\hat{H}$ having the following matrix elements:

$$H_{kj} = -\frac{\hbar}{2}\Omega_{kj}(t)\exp[i\varepsilon_{kj}(t)t], \quad H_{jk} = H_{kj}^{*}. \tag{2}$$

The Rabi frequency is $\Omega_{kj} = d_{kj}A(t)/\hbar$ with the d_{kj} dipole matrix element for transition between states $|k\rangle$ and $|j\rangle$, $(k, j = 0, 1\ldots5)$. The following notations are adopted for the applied states: $|0\rangle = |5s\rangle, |1\rangle = |5p\rangle, |2\rangle = |5d\rangle, |3\rangle = |6p\rangle, |4\rangle = |6s\rangle, |5\rangle = |7s\rangle$, see. Fig. 4.

$A(t)$ is the amplitude of the laser pulse with Gaussian shape: $E_L = \frac{1}{2}[A(t)\exp(i\omega_L(t)t) + CC.]$ where $A(t) = A_0\exp(-t^2/2\tau_L^2)$ with $2\tau_L$ being the full duration (at the e^{-1} level) of the laser pulse intensity $I_L(t) \propto |A_L(t)|^2$. The time dependent carrier frequency of the linearly chirped laser pulse is $\omega_L(t) = \omega_{L0} + \beta t$ with ω_{L0} and β being the central frequency and speed of the chirp. The detuning from resonance is $\varepsilon_{kj} = \omega_L(t) - \omega_{kj}^{(0)}$ with $\omega_{kj}^{(0)}$ being the resonant frequency for the $|k\rangle \leftrightarrow |j\rangle$ transition.

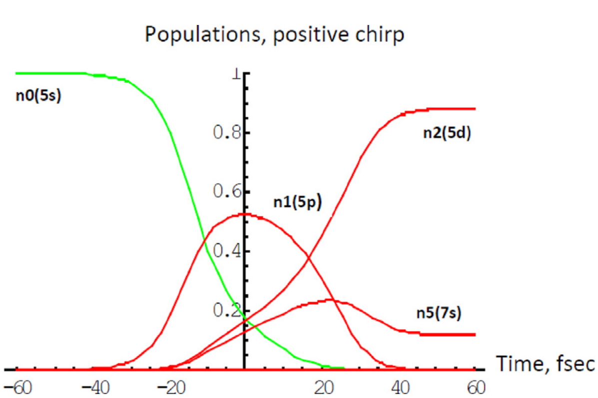

Fig. 5. Dynamics of the populations of the energy levels of Rb atom in the field of a Gaussian FC laser pulse of 30 fs duration and positive frequency chirp: the carrier frequency is increasing from the leading to the rear front of the pulse. The pulse peak intensity is equal to 3×10^{12} W/cm^2, the speed of the linear chirp is 0.3 fs^{-2}.

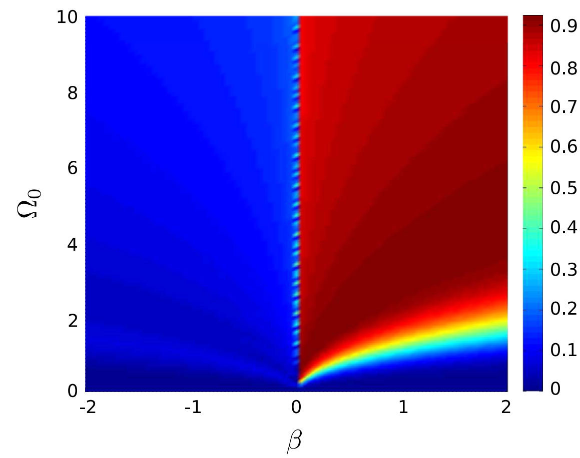

Fig. 6. Dependence of the final 5d population of the atom on peak Rabi frequency Ω_0 of the laser pulse (in units of fs^{-1}) and chirp speed β (in the units of fs^{-2}).

As it is clearly seen in Fig. 5, a complete population transfer from the ground state 5s to the excited states 5d and 7s is performed by a FC laser pulse. The robustness of the excitation process is well seen from the color map in Fig. 6: the population of the state 5d after the interaction with the laser pulse remains nearly the same value (close to unity) in a broad range of variation of the peak Rabi frequency and the speed of the positive chirp.

Note that the analysis above has been performed for isolated Rubidium atoms without taking into account propagation effects in an extended medium of Rb gas. These important effects include absorption of the laser pulse due to energy losses during the excitation of the atoms that depends on the density of Rb atoms and also on the fraction of the excited atoms. Other important effects to be addressed in our future publication will be self-action effects, such as self-focusing , de-focusing and filamentation of the laser radiation in the optically thick medium of Rb atomic gas.

We believe that the proposed technique of frequency chirped pulses may be useful not only in the case of alkali metals but for broad variety of samples with discrete energy spectrum of quantum states.

4. Summary

We presented our experimental setup which is under construction to study resonant three-photon ionization of Rb atoms producing a homogenous plasma for the planned CERN AWAKE experiment. Our parallel theoretical investigation clearly showed that a 10^{12} W/cm^2 peak intensity laser pulse with duration of 30 fs is capable of populating the desired 5d or 7s Rb energy levels with 100% when resonance took place. The resonant excitation of the Pb atom can be efficiently done with a linear chirp of the applied laser pulse. The process is robust against external noise and the variation of the pulse parameters.

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