A NOVEL LASER IONIZED RB PLASMA SOURCE FOR PLASMA WAKEFIELD ACCELERATORS

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Abstract

We describe the plans for a plasma source [1] that can produce a 10 m long 2 mm diameter plasma with 0.2% density uniformity during a relativistic beam-plasma interaction. The plasma source consist of rubidium vapor with a density adjustable from 10^{14} to 10^{15} cm^{-3} confined in a 10 m long 4 cm diameter, stainless-steel tube. The long tube is uniformly heated by an oil heat exchanger. Access to the vapor during the interaction is provided by custom built fast valves. The vapor is fully tunnel ionized (first e^-) by a laser pulse therefore the plasma density and uniformity are equal to those of the vapor. The source will be used for the world's first proton driven plasma wakefield accelerator experiment (advanced wake (AWAKE)) at CERN.

INTRODUCTION

Over the recent years plasma acceleration techniques have shown great promise as alternative to conventional radio frequency based accelerators; however, all of the existing schemes (electron and laser beam driven wakefield acceleration) would have to rely on staging in order to produce a TeV e^-/e^+ bunch of the kind that is envisioned for the next linear collider. This is because the required energy of the TeV bunch is on the order of several kJs whereas only few tens of joules are available in an electron or laser drive beam. In order to avoid staging, the AWAKE collaboration recently proposed to use proton beams that are already available at CERN as the drive bunch for the plasma wakefield acceleration [2]. In the proposed experiment a long (σ_z=12 cm) 400 GeV SPS proton bunch carrying 19.2 kJ of energy is sent into plasma where the bunch becomes transversely modulated by the self-modulation-instability (SMI) and turns effectively into a train of micro-bunches of plasma wavelength size (~1 mm) which resonantly drive a GeV/m scale wakefield. Externally injected electrons are accelerated to high energies (> 1 GeV) in this wake. The experiment has to rely on SMI since mm scale proton bunches do not exist. The mm-scale p$^+$ bunches are required to reach GeV/m gradient. SMI brings a strict requirement on the plasma density uniformity namely 0.2% everywhere along the plasma for the injected bunch to remain in the focusing and accelerating phase of the wakefield [3]. Hence a unique plasma source is needed for the AWAKE experiment. For an ideal gas the density uniformity is equal to the temperature uniformity, $\frac{\Delta n}{n} = \frac{\Delta T}{T}$. By providing uniform temperature the required density uniformity is achieved. Here we describe the Rb vapor plasma source shown in Fig. 1 which has four main components: a long stainless steel tube uniformly heated by an oil heat exchanger, fast valves confining the Rb, an ionizing laser, and the valved reservoirs that replenish Rb.

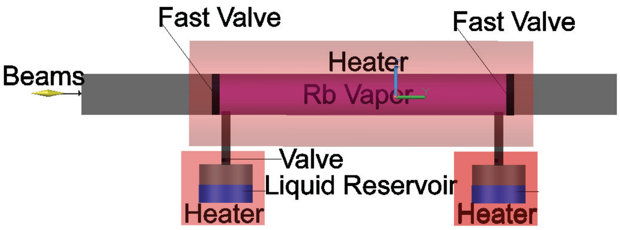

Figure 1: Sketch of the plasma source: long oil heated vapor section with fast valves for proton, electron and laser beam access and valved Rb liquid reservoirs.

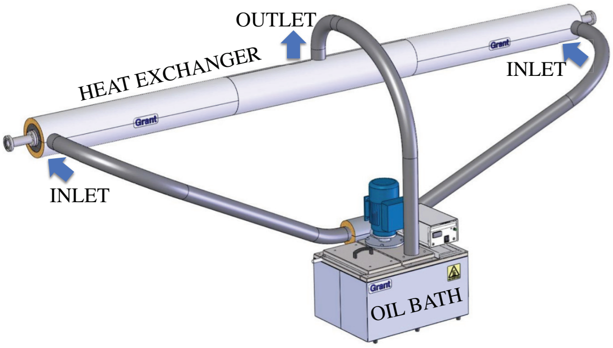

Figure 2: A CAD drawing of the oil heating system which consist of an oil bath and a heat exchanger (Courtesy of Grant Instruments, UK).

DESCRIPTION OF THE PLASMA SOURCE

Rubidium vapor confined in a 10 m long closed stainless steel tube at a constant temperature (T) everywhere along the tube satisfies the density uniformity condition. The length of the plasma source is chosen to be 10 meters in order to allow SMI to reach saturation (~4 m) and to demonstrate electron acceleration to a high energies (~2 GeV). Rubidium is used for the plasma because of its low ionization potential (4.18 eV). The plasma is formed using a laser pulse that has enough intensity (1.7×10^{12} Wcm^{-2} [4]) to field or over-the-barier ionize Rb. Since this is a threshold process, the vapor is fully ionized; therefore, the plasma density and uniformity are equal to the vapor density and uniformity. By adjusting of the temperature of the liquid Rb from 150 to 200 ^{o}C (see Fig. 4 plotted from vapor pressure curve of Rb [5]) the required vapor densities in the 10^{14} to 10^{15} cm^{-3}range for optimum plasma acceleration can be reached. In order to provide a constant temperature within the requirement (T ~ ± 0.4 K) an oil bath with a heat exchanger is used. A custom made 3-m long prototype by GRANT Instruments of UK has been tested (see Fig. 2) using silicon diode, DT670,

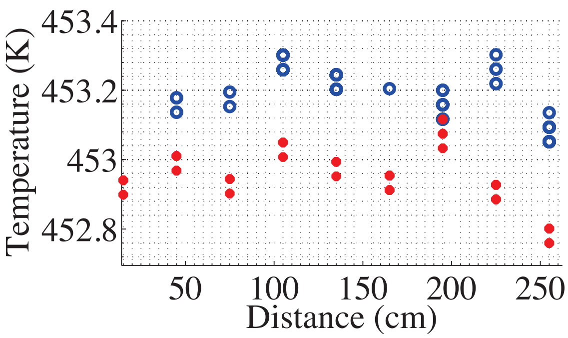

Figure 3: Temperature profiles measured along the heat exchanger. The blue circles correspond to the normal configuration where the oil is pumped in from the sides and goes out in the middle. The red stars correspond to the modified heater where the oils is pumped in from one end and goes out at the other end. In both cases the measurements remain within ± ~0.1 K.

temperature sensors inserted every 30 cm along the center axis of the tube. The sensors were calibrated in the oil bath to an accuracy of ±0.05 K relative to each other. Note that only the temperature uniformity is important since the SMI develops and forms the bunch train with appropriate spacing regardless of the plasma density (~absolute temperature). The oil is pumped in from the ends and returns to the bath from the center of the heat exchanger. In this configuration within the accuracy of the probes, no temperature gradient was detected (Fig. 3). Therefore the heat exchanger was reconfigured where the center outlet was plugged and one end inlet was used as an outlet in order to have a longer path for the oil. However, even in this configuration no gradient was measured either as shown in Fig. 3. Each point on this plot represent data points taken every 10 seconds over an hour long period. The ±0.05 K variation at each position is due to the intrinsic property of the sensors. The measured data shows that at 453 K (180 ^{o}C) the temperature variation over a 2 meter long region is within ± ~0.1 K within the required range. We observe greater temperature variations at the ends because the isolation of the ends was not optimized. In the future this will be reduced with better isolation and with heated valves placed at the ends. Besides non-uniformities over short distances at the ends do not have a detrimental effect on the acceleration process but simply reduce the effective plasma length.

The minimum required laser energy to ionize a 10 m long 2 mm diameter plasma is calculated by solving the wave equation with ionization depletion term using the split-step Fourier method [6]. Based on this calculation and taking a safety factor into account a 450 mJ 120 fs 780 nm Ti:Sapphire laser system will be used. Note also that Rb has a strong absorption line at 780.2 nm near the central laser wavelength. Energy depletion due to this absorption line has been estimated to be small. Moreover since the laser is tunable this can be further avoided.

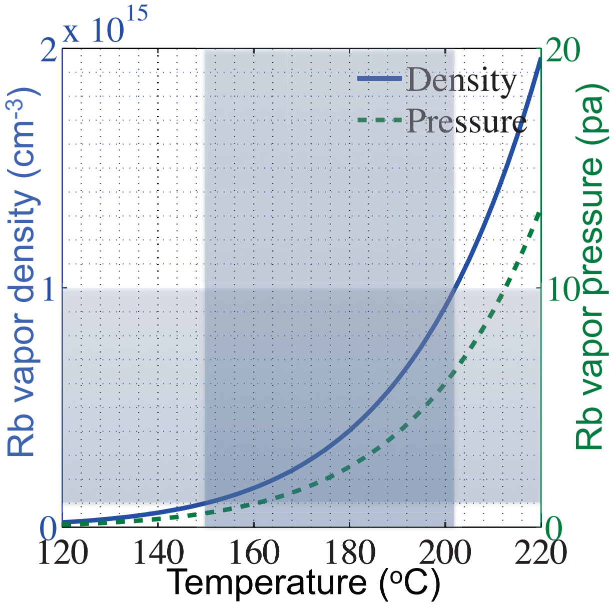

Figure 4: Rubidium vapor density (blue line) and vapor pressure (green dashed line) as a function of temperature. Region between 10^{14} and 10^{15} cm^{-3}, and the corresponding temperature shows the parameter range of interest for AWAKE.

In order for the p^+, laser and e^- beams to access the Rb vapor fast valves are used at the ends. The effect of the valves on the density uniformity is studied using the gas dynamics code MOFLOW [7]. Note that for this geometry and density the gas flow is in the transitional flow regime which is determined by the ratio of the mean free path of molecular collisions to the system size, i.e. Knudsen number (K_n). In our case, K_n lies between 0.1 and 1. In order to apply the simulation results to our case, they are scaled. The results show that the gas is depleted from the ends without affecting the density inside of the cell. Therefore for a valve opening time of 10 ms the density non-uniformity is confined to several centimeters at both ends. This depletion can also be used to our advantage by adjusting the delay between the valve opening and the beams in order to control the plasma length. Custom built fast valves that can open in ~ 10 ms , work in the required temperature range and Rb environment, and perform at least 43 000 times during a two week experimental run with beams going through every other 30 seconds are developed by VAT incorporated [8].

Two independently heated and valved liquid Rb reservoirs that are located near the ends supply the Rb vapor. The heat exchanger section and the valves are kept at a higher temperature than the reservoirs in order to prevent condensation of Rb anywhere else other than in the reservoirs. Between the reservoirs and the heat exchanger sapphire windows are installed in order to optically determine the vapor density. A test setup is shown in Fig. 5 (a) and (b) was used to measure Rb density. A 1 g break-glass Rb capsule is placed in a DN16 stainless steel bellows in order to be able to break the

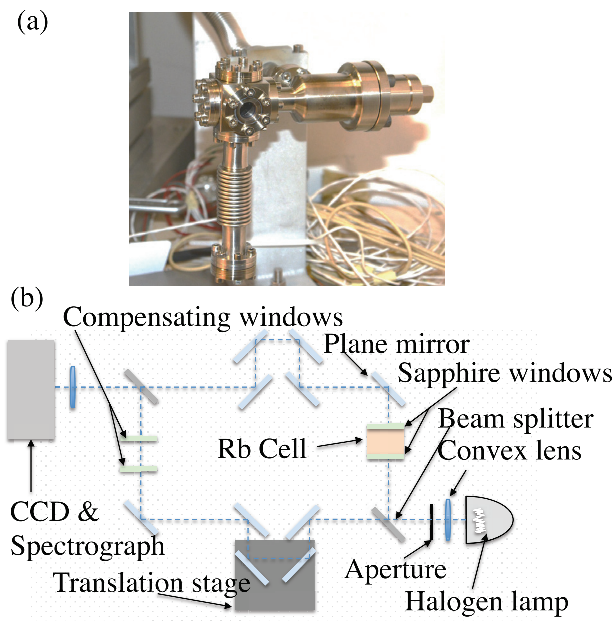

Figure 5: (a) Rb reservoir test set-up A stainless steel bellows is connected to a cube with sapphire windows and an all metal valve insulates the vapor from the rest of the vacuum system. (b) A schematic of the Mach-Zehnder interferometer with two delay lines.

capsule in vacuum without exposing Rb to air. The bellows is connected to a cube with sapphire viewports. A manual all-metal valve separates these parts from the vacuum pump. A liquid nitrogen cold trap is also placed between the cell and the pump for the startup to protect the pump before heating up the cell. Separate heating tapes are used to heat the bellows and the rest (the windows and the valve). Temperature is kept lower by 10-20 ^{o}C in the bellows where liquid Rb is located. A white light beam (produced from a commercial ~2 euro halogen lamp) is sent through a Mach-Zehnder interferometer where it goes though the Rb vapor column in one of the arms of the interferometer (see Fig. 5 (a)). The light is then sent to an imaging spectrograph and recorded by a CCD. The spectrograph dispersion is 0.0118 nm/pixel and central wavelength is set to 780 nm. The time integrated (0.8 s) interference fringes in the form of hooks are observed (see Fig. 6). One calculates the Rb density from the hook distance (Δ) [9]. In cgs units, the Rb number density (n) is given by $n = \frac{\Delta^2 \pi K}{l r_0 f \lambda_0^3}$ where $r_0 = 2.81 \times 10^{-13}$ cm is the classical electron radius, $K = 807$ is the hook constant which depends on the path length difference between the different arms of the interferometer and can be determined by counting the number of fringes (p) in a line free region ($\Delta\lambda$) near some λ and using $K = p\frac{\lambda}{\Delta\lambda}$, $l = 3.5$ cm is the vapor column length, $\lambda_0 = 780.2 \times 10^{-7}$ cm is the wavelength of the resonant Rb absorption line, and $f = 0.668$ is the corresponding oscillator strenth. An example image is shown in Fig. 6 where a hook distance of ~320 pixels corresponds to a Rb density of ~1.1 $\times 10^{15}$ cm^{-3}

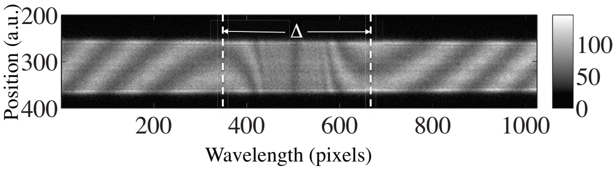

Figure 6: A measured spectrum of Rb from the Mach-Zehnder interferometer set-up. Spectrograph dispersion is 0.0118 nm/pixel. The separation between the hooks is Δ from which the vapor density can be determined.

SUMMARY

In summary, a novel plasma source for plasma wakefield accelerators is described. The source is designed to satisfy the 0.2% percent density uniformity over several meters during the beam-plasma interaction. This corresponds to a required temperature uniformity of $\Delta T < 0.8$ K over 10 meters. We measured the temperature profile along a 3-m long prototype. The measurement showed a uniformity ΔT < 0.2 K over 2 meters. Based on the measurement a 10 m prototype will be designed and built. we also used interferometry to measure the Rb vapor density in a test set-up. Such a diagnostic will be implemented in the real source for an online measurement of the vapor density. The plasma source will be used for the world's first proton driven wakefield accelerator experiment, AWAKE, at CERN, starting in 2016.

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