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MAPPING CHARGE CAPTURE AND ACCELERATION IN A PLASMA WAKEFIELD OF A PROTON BUNCH USING VARIABLE EMITTANCE ELECTRON BEAM INJECTION

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Abstract

In the Phase 2 of the AWAKE first experimental run (from May to November 2018), an electron beam was used to probe and test proton-driven wakefield acceleration in a rubidium plasma column. The witness electron bunches were produced using an RF-gun equipped with a Cs_2Te photocathode illuminated by a tailorable ultrafast ultraviolet (UV) laser pulse. The construction of the UV beam optical system enabled appropriate transverse beam shaping and control of its pulse duration, size, and position on the photocathode, as well as time delay with respect to the ionizing laser pulse that seeds the plasma wakefields in the proton bunches. Variable photocathode illumination provided the required flexibility to produce electron bunches with variable charge, emittance, and injection trajectory into the plasma column. In this work, we analyze the overall charge capture and shot-to-shot reproducibility of the proton-driven plasma wakefield accelerator with various UV illumination and electron bunch injection parameters.

INTRODUCTION

In the AWAKE experiment, an electron bunch is used to probe the proton-driven wakefield acceleration in plasma. During the initial experimental run in 2018, the first demonstration of electron beam acceleration was successfully achieved [1]. The experiments confirmed that the injected 19 MeV electron beam was in a 10 m long plasma cell, with a maximum energy gain of up to 2.0 GeV. The shot-to-shot performance of this accelerator was still not comparable to standard linac-based electron accelerators. With a view on improving parameters such as charge capture rate and overall acceleration efficiency, the AWAKE Run 2 experiment is currently being prepared. The goal is to achieve a charge capture efficiency and an energy gain of over 90%, while producing 10 GeV high charge electron beams [2].

To accomplish this goal the electron beam parameters at the plasma entrance must be accurately controlled, including: the pointing jitter, size, charge and emittance of the electron bunches. With the aim of understanding the sensitivity and limitations of AWAKE's experimental setup, we study here the influence of the several of those parameters on the overall charge capture and reliability measured during the first experimental run.

In the AWAKE experiment, a 400 GeV proton beam is extracted from the CERN Super Proton Synchrotron (SPS) and utilized as a drive beam for wakefields in a plasma column to accelerate electrons. The plasma is generated in a 10 m long rubidium vapour source via the over-the-barrier ionization employing a high intensity laser field. In this scheme, an ultrafast infrared laser pulse (~100 fs) co-propagates with the SPS proton beam and initiates a self-modulation process at the front of the plasma column. As a consequence, the long SPS proton bunch (σ_z=12 cm) is heavily modulated into a train of longitudinal micro-bunches which in turn drive a periodic wakefield [3, 4], as shown in Fig. 1.

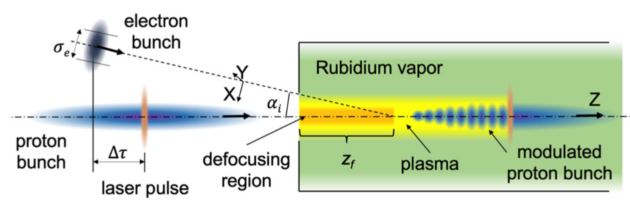

Figure 1: The oblique electron injection arrangement: an electron bunch of variable charge and size σe is injected into the plasma wakefields at an angle αi.

The injection of electrons into the wakefield is carried out at an angle and a distance z_f with respect to the plasma entrance. This is done to avoid the loss of electrons at the density transition region at the entrance of the plasma cell (defocusing region in Fig. 1). In this arrangement, the electrons approach the central axis in the region of constant plasma density and therefore get trapped into the established plasma wave.

The required injection angle α_i and radial offset of the electron beam at the orifice placed at the entrance of the plasma cell are small enough so the oblique injection does not require any hardware changes in the facility design, as compared to the on-axis injection. According to early theoretical models, the parameter space for good trapping is quite large when compared to the electron beam portrait [5, 6], so no fine-tuning of the injection angle or focus point is required for the best performance.

In this paper, we further present experimental results regarding the electron acceleration performance by varying some of the main electron beam parameters, including position, angle, size, emittance and charge. The goal is not to

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identify a single, optimal parameter set for the witness bunch, but rather to quantify approximately the impact of these various parameters on the reliability of the acceleration, providing thus feedback for future design decisions.

We also show experimentally that under favorable circumstances, the efficiency of the charge capture of the wakefields can surpass 10%. The results are accompanied by measurements of electron beam emittance and extracted bunch charge in relation to the photoinjector UV beam parameters in the experimental parameter space during the AWAKE first experimental run.

EXPERIMENTS

The electron bunch is supplied by the electron beam photoinjector consisting of an RF-gun and a booster structure [7]. The electron bunch in the RF-gun is produced using a photoemission driven by an UV beam generated from the AWAKE main laser system. The laser system comprises a mode-locked fibre laser oscillator locked to a RF reference, a pulse stretcher, a series or Ti:Sapphire multi-pass amplifiers, and two separate grating pulse compressors (one dedicated to the ionizing beam, and a second one for generating the UV pulses for electron beam), see [8] for more details regarding this system.

For the current experiments, the UV compressor grating was set to a position corresponding to a pulse duration of 5.2 ps FWHM. The main path connecting the UV generation area with the electron gun was arranged inside a straight vacuum pipe of 14.2 m length. This UV beam transfer system was designed to ensure a maximal stability of the beam and conformity to laser safety requirements.

A motorized iris was then imaged onto the photocathode plane using a combination of reducing telescope (M=1:2) and a single lens with the focal length of 1000 mm, producing a final beam size on cathode. Steering of the UV beam was performed using a motorized mirror mount with high precision. A motorized filter wheel equipped with a set of neutral density filters was used for varying the energy of UV laser pulses, while the laser energy meter provided online reading of the pulse energy. The length of the UV optical path was adjusted to match arriving of electron bunches to the plasma source with ionizing laser pulses.

The RF-gun was equipped with a highly efficient Cs_2Te photocathode that was produced in the CERN photoemission laboratory and showed a quantum efficiency of QE ~ 20%. The QE dropped to ~ 2% after two years of operation. The produced electron bunch length was measured using a streak camera, yielding a FWHM duration of $\Delta\tau_e \sim 4$ ps, roughly matching the UV pulse duration.

This setup enabled to vary the UV spot size, fluence and energy independently, which in turn allows for adjustment of the electron bunch charge and emittance. The performance in terms of emittance and charge of the resulting electron beam is summarized in Fig. 2. Here the iris position corresponds to the size of the aperture used, which modulates the exact size of the UV beam on cathode. With this setup it was possible to vary the charge of the electron beam from 100 pC up to approximately 1 nC. In terms of emittance, the different illumination conditions allowed the production of bunches with normalized emittances from less than 2 mm·mrad to up to 37 mm·mrad.

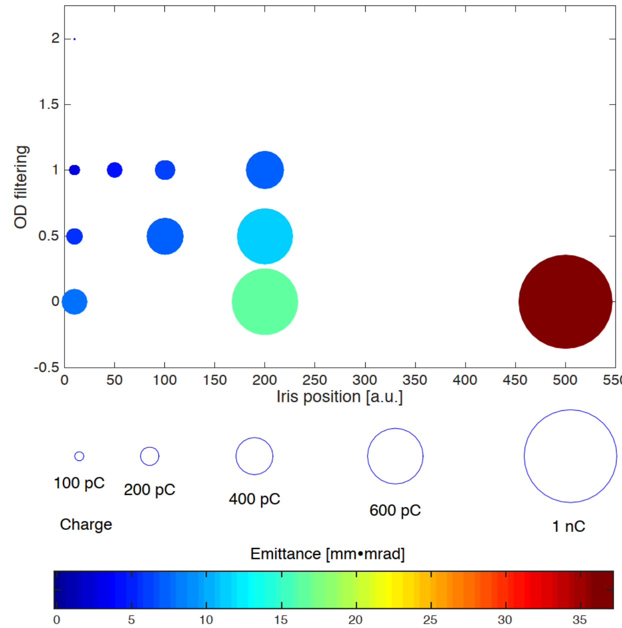

Figure 2: Electron beam charge and emittance for various UV photocathode illumination configurations by adjusting OD filtering and Iris positions (corresponding to UV pulse energy and spot size on cathode).

The RF-gun accelerates then the electron bunches to an energy of 5.5 MeV, and the booster can add a maximum energy of 16 MeV. More details of the electron beamline performance can be found in [7].

The core of the experiment is a 10-m-long rubidium vapor source: a long, fluid-heated heat exchanger evaporates rubidium at 180 °C – 230 °C to reach the required vapor density of $0.5 - 10 \times 10^{14}$ atoms/cm^3. We used beam-position monitors (BPMs) to measure the position of the proton and electron beams along the beam line and scintillating screens (BTVs) to measure their transverse bunch profiles [9].

To inject and accelerate the electrons, we spatially and temporally overlapped them with the plasma wakefields [10]. This means that the electron and proton beam trajectories have to cross within the plasma cylinder. To investigate the acceleration process and to characterize the wakefields, we injected the electron bunches at various locations of the plasma entrance and at various angles with respect to the proton beam trajectory. We observed that the highest capture and acceleration efficiency occurred when the electron beam was injected ~1 m downstream from the entrance [11]. This was therefore the baseline setup for the subsequent acceleration experiments.

Figure 3 shows the average charge capture for various parameters of the electron bunch. The capture is maximum (6%) for small emittance and charge and decreases for larger emittances. The maximum recorded charge (orange stars) show that it is possible to achieve a capture >16%. For low emittance electron beams, acceleration events

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were observed in less than 10% of the runs, whereas for large emittance this number raised to more than 80%.

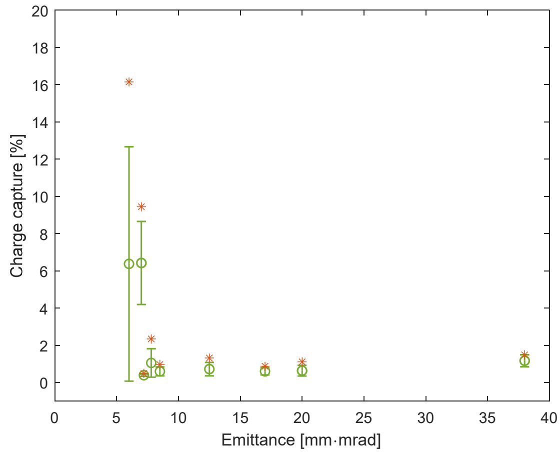

Figure 3: Measured charge capture rate for various input electron beam emittances. Green circles show the average charge capture rate (error bars are the standard deviation) and the orange stars show the maximum recorded capture rates.

A rather obvious conclusion from this test was that electron beams with low emittance can spatially overlap better with the wakefield accelerator capture window. This optimized spatial matching directly provides a higher charge capture rate. However, it is worth noting that the overall accelerated charge in this situation was essentially equivalent to that measured for high electron beam emittance and charge, which was in the range of 10 – 15 pC. The deviation in charge capture rate decreased as the emittance was increased, owing to the larger electron beam size at the injection point (and consequent immunity to spatial jitter). Overall, the average capture rate obtained was in the range of 2 - 3% for successful shots. The results, however, portray the possibility of higher charge capture rates employing this acceleration scheme, with a maximum experimentally measured capture rate of more than 16% (corresponding to 40 pC of accelerated charge) for the best shot. Note that here the driving phenomena for the capture efficiency is not electron beam initial emittance but rather the resulting beam size and spatial overlap with the wakefields at the injection point.

The spatial jitter of the electron beam at the injection point was estimated to be of several 100s of microns in rms, which allowed to effectively 'map' the wakefield accelerator spatial acceptance window experimentally. For this we relayed on precise BPM readouts averaged over 1 second prior to each proton shot to estimate the crossing point of the electron beam into the plasma employing the techniques described in [11]. The rms transverse size σ_e at the crossing point is one of the factors that contributes to the charge capture efficiency. Measuring the size near the crossing point is therefore important. In our experiments, the range of electron beam sizes at the crossing point varied from $\sigma_e = 0.19 – 0.55$ mm, and they were estimated from averaged measurements at the entrance of the plasma cell for different UV setups.

To effectively inject the witness bunch into the wakefields, its transverse size must be comparable to the transverse extent of the plasma wakefields. This is given by the plasma skin depth $c/\sqrt{n_e e^2/\epsilon_0 m_e}$ (where n_e is the plasma electron density, e the elementary charge, $\epsilon_0$the vacuum permittivity and m_e the electron mass). For the range of plasma electron densities used in our experiments, the skin depth corresponded to values of just below 0.5 mm.

With the extracted values of the electron beam transverse size σ_e, the relative position at the injection point, and the measured accelerated charge, we can now 'map' the overall spatial charge capture rate by including enough spatially distributed shots. The resulting plot is a convolution of the different electron beam transverse distributions with the spatial acceptance window of the wakefields, with an amplitude proportional to the electron capture rate per unit area. The results of this normalized 'map' are shown in Fig. 4. As it can be observed, the convolved width was approximately 0.5 mm in both X and Y axes, matching the expected skin depth of the plasma wakefields.

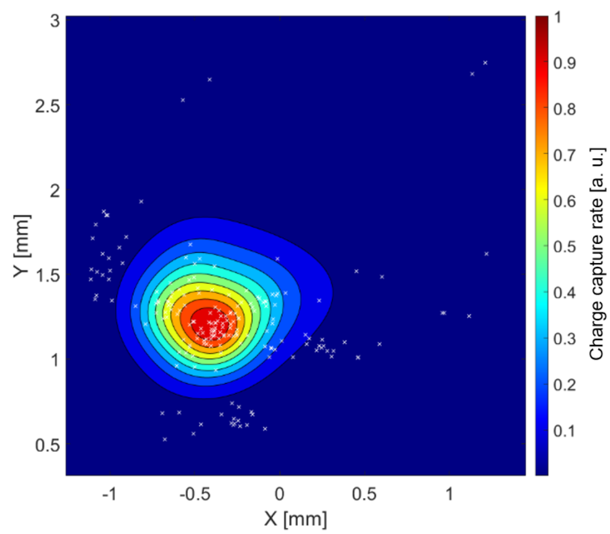

Figure 4: Results of the spatial convolution of the input electron beam (amplitude was scaled with the average charge capture rate and normalized) with the spatial acceptance window of the wakefields. The white crosses show all electron beam estimated locations.

CONCLUSIONS

In this work, we have experimentally measured the spatial wakefield acceptance map that enables high charge capture rate by varying the electron beam characteristics in terms of size, position, trajectory, and emittance. We found that, under optimized conditions, the charge capture rate is larger than 15% (~40 pC of accelerated charge for a 385 pC injected electron bunch), therefore approaching the theoretical limit of ~40%. In addition, we have studied the acceptable electron beam position jitter that enables consistent electron acceleration and compared it with the theoretically calculated wakefield acceptance map.

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