

EFFECT OF PROTON BUNCH-INDUCED IMPACT IONIZATION ON A WITNESS ELECTRON BUNCH IN AWAKE RUN 2c EXTERNAL INJECTION REGION

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Abstract

The injection of the witness electron bunch in the AWAKE Run 2c experiments will occur in a ~ 30 cm gap separating two plasmas. In this gap, the 400 GeV, self-modulated drive proton bunch and witness bunch will co-propagate in a Rubidium vapor. This vapor will be partially ionized by the protons through impact ionization, and will thus result in the presence of a low-density ($\sim 10^{12} \text{ cm}^{-3}$) plasma. Under the influence of the space-charge fields induced by the proton bunch, the plasma electrons form an on-axis filament that acts as a defocusing element for the witness electron bunch. This filament may prevent proper matching of the witness electron bunch in the second plasma, and/or lead to emittance growth before injection. In this work, we investigate, using numerical simulations, the process of impact ionization resulting from the propagation of the protons, the formation of the plasma electron filament, and discuss its potential effect on the witness electron bunch.

INTRODUCTION

The Advanced Wakefield Experiment (AWAKE) at CERN investigates proton-driven plasma wakefield acceleration as a path towards high-gradient accelerators for particle physics applications [1, 2]. The experiment aims to demonstrate the generation of high-amplitude ($> 1 \text{ GV/m}$) wakefields over tens to hundreds of meters of plasma using as driver a 400 GeV proton bunch from the Super Proton Synchrotron.

To excite high-amplitude wakefields, the long proton bunch must first undergo the self-modulation (SM) process [3]. High-gradient acceleration of a witness electron bunch can only occur after saturation of SM. In AWAKE Run 2c, the baseline scheme therefore uses two distinct plasmas: the first one to self-modulate the proton bunch, the second one to accelerate an externally injected witness electron bunch. The injection takes place across a ~ 30 cm gap separating the two plasmas (see Figure 1). In this region, a magnetic field bends the trajectory of the 150 MeV witness bunch so that it co-propagates on-axis with the proton bunch before both meet a counter-propagating ionizing laser pulse, thereby entering the accelerator plasma. The witness enters the plasma matched to the focusing fields of the plasma ions,

i.e., with a transverse size $\sigma_m = \sqrt{\frac{2}{\gamma_e} \frac{c}{\omega_{pe}} \epsilon_N}$.

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Within the gap, both bunches propagate in the Rubidium vapor with density $n_{Rb} = 7 \times 10^{14} \text{ cm}^{-3}$. This vapor is partially ionized by impact ionization induced by the protons. This low-density plasma is produced along the bunch, and the plasma electrons move towards the axis under the influence of the proton bunch space-charge fields, thus forming an on-axis plasma electron filament [4, 5]. This electron filament acts as a defocusing element on the witness electron bunch, and may affect its dynamics before it is captured in the wakefields, e.g., by leading to emittance growth or by changing its size at waist, or waist location. Finally, this filament could deflect the electron bunch coming from the side (see Fig. 1), thus potentially leading to a position and angle misalignment with respect to the driver [6].

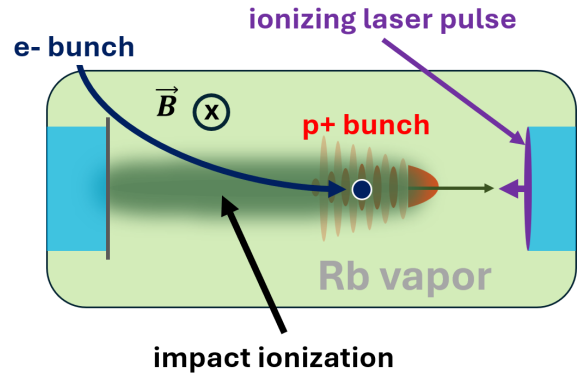


Figure 1: Schematic of the injection region in AWAKE Run 2c.

An understanding of the effect of the filament on the witness bunch is therefore key for the design of the injection region of AWAKE Run 2c.

IMPACT IONIZATION

The energy loss per unit length of a single proton in a gas of density ρ can be estimated using the Bethe-Bloch formula [7]:

$$\frac{dE}{dx} \rho = 0.307 \rho \frac{Z}{A} \frac{1}{\beta^2} \ln\left(\frac{2m_e c^2 \beta^2 \gamma^2}{I} - \beta^2\right) \quad (1)$$

where β and γ are the Lorentz factors, Z the charge of the nucleus, A the mass of the atom, m_e the mass of the electron and I the mean excitation energy.

In the case of a 400 GeV proton ($\beta \approx 1$, $\gamma = 427$) propagating through a Rubidium ($Z = 37$, $A = 85.47$, $I = 370 \text{ eV}$) vapor with density $n_{Rb} = 7 \times 10^{14} \text{ cm}^{-3}$, the energy loss

per unit length is $\frac{dE}{dx}\rho \approx 25.13$ eV/m. The resulting number of electron-ion pairs generated per proton and per meter of propagation can be estimated $\langle N_{e,i} \rangle = \frac{dE}{dx}\rho \frac{1}{W} \approx 3.06 \text{ m}^{-1}$, where $W \sim 8.2$ eV is the average energy spent for the creation of an electron-ion pair. Since impact ionization is a single-proton process, the corresponding plasma density induced by impact ionization for a transversely and longitudinally Gaussian bunch can be calculated as:

$$n_{pe}(r, \xi) = \frac{N_p \langle N_{e,i} \rangle}{(2\pi)^{3/2} \sigma_r^2 c \sigma_t} e^{\left(-\frac{r^2}{2\sigma_r^2}\right)} \int_{-\infty}^{\xi} e^{\left(-\frac{\xi'^2}{2(c\sigma_t)^2}\right)} d\xi'. \quad (2)$$

The plasma density has both transverse and longitudinal dependencies: it is the largest on axis, and increases along the bunch proportionally to the integral of the bunch population along ξ .

In the case of a bunch with rms size $\sigma_r = 200 \mu\text{m}$, the peak plasma density after the bunch passage ($\xi \gg \sigma_t$) has a value of $n_{pe,0} \approx 3.65 \times 10^{12} \text{ cm}^{-3}$.

NUMERICAL SIMULATIONS RESULTS

In order to understand the dynamics of the produced plasma electrons, we perform numerical simulations using the electromagnetic particle-in-cell code WarpX [8].

Although in AWAKE Run 2c, the proton bunch would be self-modulated when propagating in this gap region, we first perform the simulations using a transversely and longitudinally Gaussian bunch. We propagate the proton bunch with the AWAKE baseline parameters, i.e., duration $\sigma_t = 170$ ps, transverse rms size $\sigma_r = 200 \mu\text{m}$ at the entrance and emittance 2.2 mm-mrad, in the Rubidium vapor.

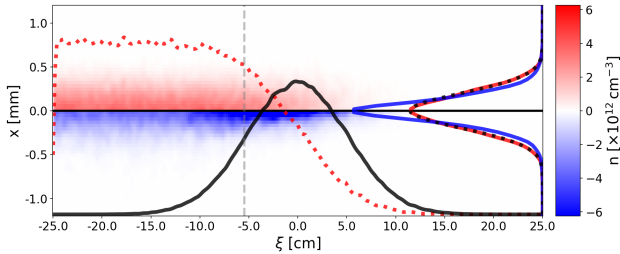


Figure 2: Plasma ion (top) and electron (bottom) density distributions. Longitudinal bunch distribution (black curve). Transverse bunch distribution (dashed black curve). Longitudinal ion distribution (red dashed curve). Transverse ion (red curve) and electron (blue curve) distributions at the vertical grey dashed line.

Figure 2 (top) shows the ion density distribution resulting from impact ionization (bunch propagating from left to right). As expected, the number of ions increases along the bunch (red dashed curve) proportionally to the integral of the bunch population, and the projection of their transverse distribution (red curve) matches that of the protons (black dashed curve). This shows that over this time-scale (bunch duration), the ions remain essentially immobile. Figure 2 (bottom) further shows that, under the influence of the space-charge fields induced by the proton bunch, the electrons moved towards

the axis and formed a filament with density larger than that of the background ions (narrower, and higher peak value of the transverse projection of the electrons distribution (blue curve) with respect to that of the ions (red curve)). The excess of plasma negative charges in this region is on the order of 10^{12} particles per cm^{-3} .

Figure 3 shows that this excess of electron density is comparable to the peak density of the witness electron bunch foreseen for acceleration experiments in Run 2c, ~ 30 cm before the plasma entrance. It is therefore unclear whether the electron filament would be defocused by the witness electron bunch in this region. As a result, the transverse fields induced by the filament could act on the bunch before it reaches the plasma entrance.

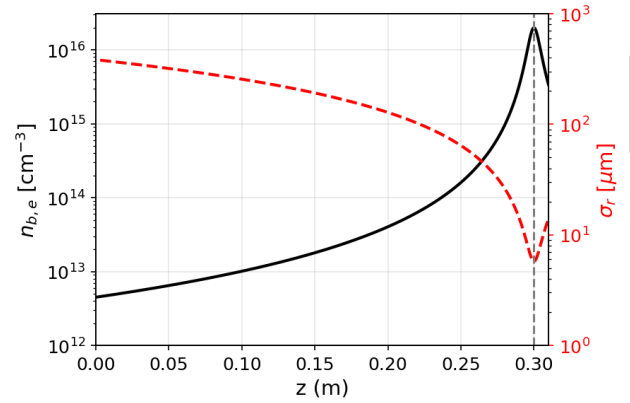


Figure 3: Electron witness bunch peak density (black curve) and transverse size (red curve) as a function of propagation distance. Grey dashed line: waist location ($z=30$ cm). $Q = 100$ pC, $\sigma_{r,waist} = 5.76 \mu\text{m}$, $\sigma_z = 60 \mu\text{m}$, $\beta^* = 4.5$ mm.

The amplitude of these fields is shown in Fig. 4, as a function of position and radius. We observe that, for possible injection positions along the bunch, e.g., $\xi \sim -c\sigma_t$ (grey dashed line), these fields reach peak amplitudes of ~ 3 MV/m (see inset). Since the witness electron bunch would come from the side (Fig. 1), these fields could deflect it and thus prevent on-axis alignment. The tolerances of relative position offset between the proton and electron bunch are studied in Ref. [6]. These fields could also increase of the electron bunch size at the plasma entrance, and thus prevent proper matching. Finally, because of the injection geometry (witness bunch entering from the side), the bunch may cross regions where the transverse fields are nonlinear, resulting in emittance growth before capture in the wakefields.

CONCLUSION

As a first investigation for the effect of impact ionization on the AWAKE Run 2c injection region, we performed numerical simulations of a transversely and longitudinally Gaussian 400 GeV proton bunch propagating through Rubidium vapor. We find that the partially ionized vapor and space-charge fields of the bunch result in the formation of a plasma electron filament that may affect the dynamics of the witness electron bunch before its capture in the wakefields.

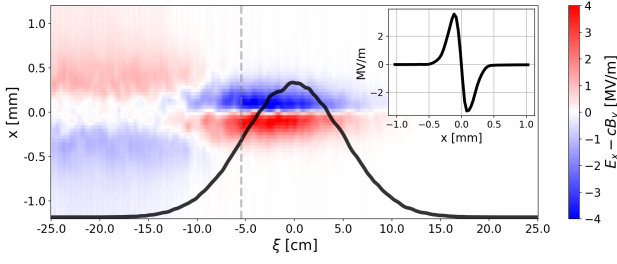


Figure 4: Electric field resulting from the plasma electron and ion density distributions. Black curve: Longitudinal bunch distribution. Inset: Lineout of the transverse fields amplitude taken at the vertical grey dashed line.

This observation motivates further studies, i.e., to include the witness electron bunch and modulation of the proton bunch in the simulations. We also note that the effect of the filament has been observed experimentally on the proton bunch when propagating over 10 m of Rb vapor, has been studied for different gas species (He, Ar, Xe) and densities, and will be the subject of another publication.

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