# Ejection of plasma electrons due to interaction of plasma column with long proton beam

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## Introduction

Proton-driven plasma wakefield acceleration (proton-driven PWFA) is an actively developing novel method of accelerating light charged particles [1, 2, 3]. The first experiment that showed the feasibility of this method is the Advanced WAKefield Experiment (AWAKE)[4, 5]. The experiment demonstrated the first seeded self-modulation of the long 400 GeV proton beam from SPS [7]. Electron bunches with the energy of 19 MeV were injected into the wakefield of the proton microbunches and accelerated up to 2 GeV [6]. The second run of AWAKE is

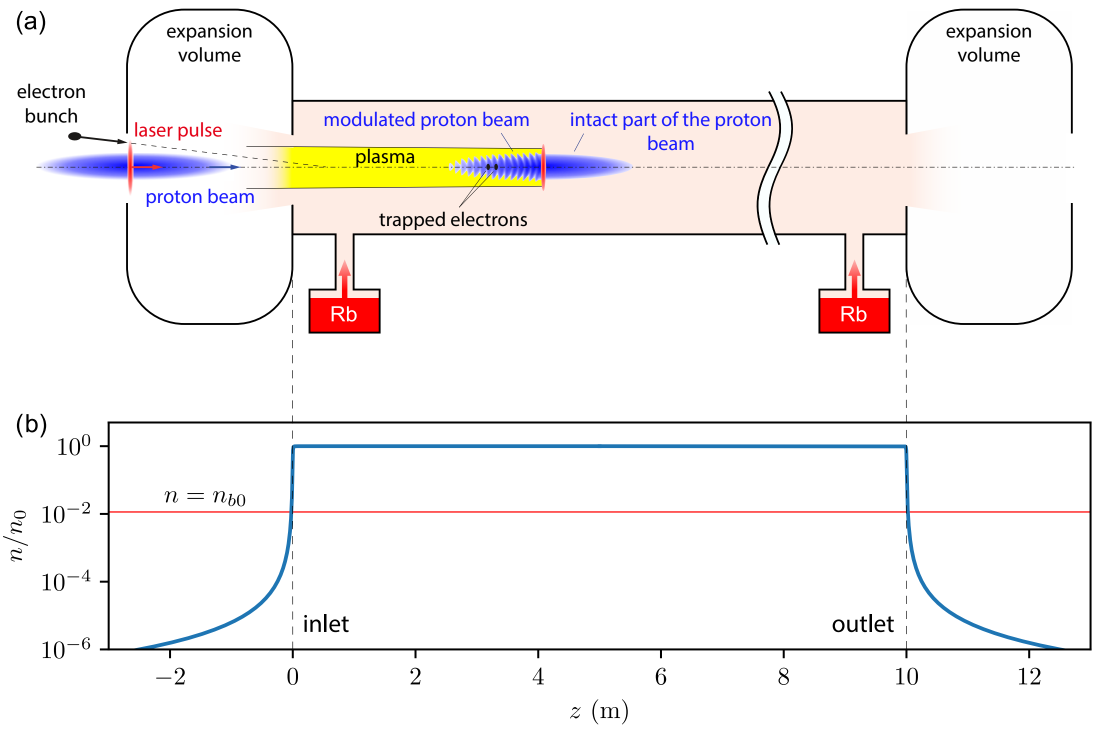


Figure 1: (a) The AWAKE schematic layout and (b) the plasma density profile $n(z)$ along the plasma cell. The red line corresponds to the maximum density of the proton beam $n_{b0} = 4 \times 10^{12}\,\mathrm{cm}^{-3}$.

under development now. It aims to produce a stable self-modulated proton beam in the first plasma cell, and then accelerate an electron beam in the second plasma cell to multi-GeV energy preserving its quality.

The injection of the electron witness bunch into the plasma was one of the most sophisticated stages of the first run of experiments. Because of the 3d geometry and short time scale of this process, it is worth enormous amount of CPU time to simulate in full PIC code. This is why it is still not fully understood. In the experiment, the witness bunch was injected into the plasma near the inlet of the plasma cell. The trajectory of injection (Figure 1 (a)) is tilted with respect to the axis of the system, so the bunch enters the vacuum chamber having an offset and crosses the plasma boundary further inside the plasma cell. This approach was chosen due to the fact that the plasma in the experiment has a non-uniform longitudinal profile (Figure 1 (b)). Near the ends of the vacuum chamber the plasma density gradually falls towards the expansion volumes, and the on-axis injection leads to the almost full destruction of the accelerating bunch in the low plasma density region [9]. Even though the witness injection trajectory avoids the dangerous on-axis defocusing region, only a small fraction of the electrons was captured, accelerated and registered in the energy spectrometer after the plasma cell [6]. Full PIC 3d simulations showed that this happens due to the complex mechanism of the capturing of the injecting electrons in Cartesian geometry, which does not agree with the predictions from axisymmetric codes [8].

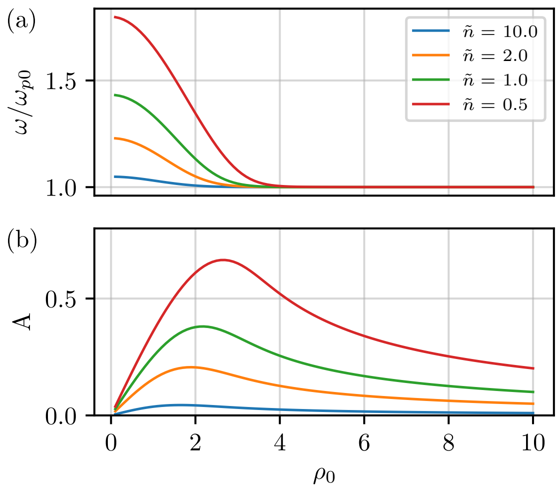


Figure 2: (a) Frequency $\omega$ and (b) amplitude $A$ of plasma electron oscillations as functions of the initial electron radius $\rho_0$ obtained by solving the equation (2) numerically for different $n_{b0}/n$.

## Plasma electron halo

In this paper we study another process that could significantly distort the quality of the injected electron bunch and change the angle and the point at which it crosses the plasma boundary due to the interaction of the long proton beam with a plasma column. To be specific, we consider the rear half of a Gaussian proton beam with the density

$$n_b(\xi, r) = n_{b0} e^{-r^2/(2\sigma_r^2) - \xi^2/(2\sigma_z^2)} \tag{1}$$

given in cylindrical coordinates ($\xi = z - ct, r$), where $c$ is the speed of light. The phenomenon called the plasma electron halo occurs in plasmas with densities of the order of the peak density of the beam. Jets of plasma electrons escape from the plasma after a number of plasma periods depending on the plasma density [9]. The plasma is charged positively, so the ejected electrons return to the column after some time. The space between the plasma boundary and the trajectory of the outer ejected electron is covered with a radial electric field $E_r$ and an azimuthal magnetic field $B_\phi$ that create the radial force $F_r = -e(E_r - B_\phi)$, where $e$ is the elementary charge, focusing for ultrarelativistic electrons. Given the approximate size of the area covered with the radial force and its magnitude, the estimate for the radial momentum gain for a single electron of the witness bunch crossing this area is $\Delta p_r \approx -e/c \times 0.1\,\text{MV/m} \times 10\,\text{cm} = 0.01\,\text{MeV}/c$ that deflects a 19 MeV electron by approximately 0.5 mrad.

Here we present a semi-analytical theory examined with PIC simulations in LCODE [10] that allows to predict the region covered with the electron halo for a given plasma density profile. The theory is based on the Dawson's 1d hydrodynamic model [11]. It implies the axial symmetry, immobile ion background and neglects the longitudinal motion of the plasma electrons. Introducing the dimentionless quantities $\rho = r/\sigma_r$, $\rho_0 = r_0/\sigma_r$ and $\tilde{n} = n/n_{b0}$, the equation of motion of the plasma electrons for the beam density (1) takes a simple form

$$\frac{1}{k_p^2}\frac{d^2\rho}{d\xi^2} = \frac{1}{\rho}\left[\frac{\rho_0^2 - \rho^2}{2} - \frac{1}{\tilde{n}}\left(1 - e^{-\frac{\rho^2}{2}}\right)e^{-\frac{\xi^2}{2\sigma_z^2}}\right], \tag{2}$$

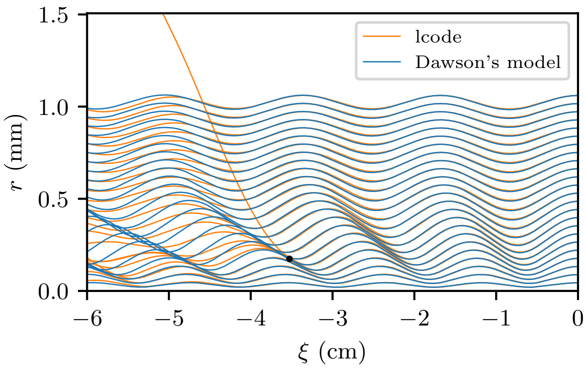


Figure 3: Plasma electron trajectories from LCODE simulations and from the numerical solutions of the equation (2) for $\tilde{n} = 1$. The black dot marks the point of the first intersection of the electron trajectories according to the Dawson's model.

where $r_0$ is the initial plasma electron radius, $n$ is the plasma density, $k_p = \sqrt{4\pi ne^2/(mc^2)}$ is the plasma wave number, and $m$ is the electron mass.

Solutions of this equation are periodic functions with amplitude $A$ and frequency $\omega$ that depend on the initial plasma electron radius as shown in figure 2. After a number of oscillations these differences cause the crossing of the electron trajectories at the point $(\xi_{wb}, r_{wb})$, which we call the wavebreaking point. In our theory we find it from the condition $\partial\rho/\partial\rho_0 = 0$. Comparing the trajectories of plasma electrons from LCODE simulations with the solutions of the equation (2) (figure 3) we state that the origin of the first jet of the ejected electrons corresponds to the wavebreaking point. The Dawson's model is applicable at $\xi > \xi_{wb}$, thus, using our theory we can predict this point and, therefore, find the region outside the plasma free from the electron halo. Increase of the plasma density shifts the wavebreaking point backwards in $\xi$, but this process is intermittent. At any plasma density the trajectories can cross each other only at the points where the electrons have positive radial momentum. Other words, the plasma wave has sharp plasma density crests, and the wavebreaking point leaps between them in varying plasma density (figure 4). Note that the equation (2) does not depend on the beam transverse size and beam or plasma density separately, so the results shown in figure 4 are universal.

## Conclusion

Summarizing all the above, in this work we developed a theory that allows to locate the region outside the plasma free from the electron halo that distorts the quality of the accelerating electron bunch during the injection in AWAKE-like setups. The window for the "safe" injection starts from the head of the proton beam and reaches the point at which the plasma electron trajectories are crossed at the first time. Since the location of this point depends on the ratio between the plasma and the beam density, the injection conditions allowing to avoid the destructive impact of the electron halo correspond to the regions where the plasma density is higher than the peak density of the proton beam.

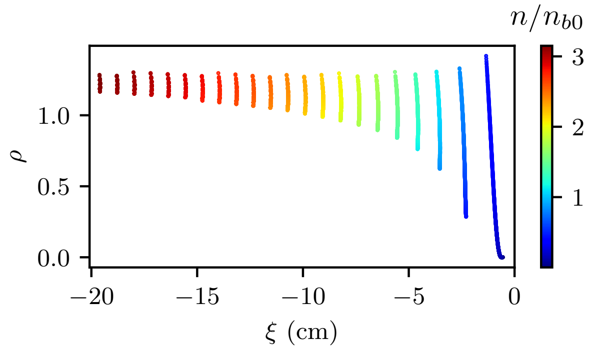


Figure 4: Wavebreaking points corresponding to different plasma densities.

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