ENERGY SPECTROMETER STUDIES FOR PROTON-DRIVEN PLASMA ACCELERATION*

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Abstract

Plasma-based acceleration methods have seen important progress over the last years. Recently, it has been proposed to experimentally study plasma acceleration driven by proton beams, in addition to the established research directions of electron and laser driven plasmas. Here, we present the planned experiment with a focus on the energy spectrometer studies carried out.

INTRODUCTION

Current day e^+-e^- linear collider (LC) design studies predict a length of several 10 km [1, 2]. Plasma based acceleration techniques have seen remarkable progress over the last years, and acceleration gradients of several 10 GeV/m have been demonstrated for both electron beam and laser drivers. It is hoped that these gradients could be used to reduce the length (and cost) of a future LC by at least one order of magnitude. However, these high gradients have only been achieved over relatively short distances, limiting the total energy gain. This means that in both driver cases staging of several acceleration modules is necessary to reach the TeV energy scale currently envisaged [3, 4]. This necessity is due to the fact that the energy stored in a laser or electron driver is too low to accelerate a witness bunch to TeV energies in one single stage. In particular, for electron-beam drivers the energy gain of the accelerated particles cannot exceed twice the initial energy of the driving electrons [5]. It has therefore been proposed to study proton beams as drivers, in addition to established research directions [6]. To test this idea experimentally, a demonstration experiment using CERN's SPS (Super Proton Synchrotron) 450 GeV proton beam was proposed [7].

Here, we give an introduction to the proposed experiment and provide an overview of the spectrometer studies carried out so far.

THE PROPOSED EXPERIMENT

In [6], it has been assumed that the driving proton bunch is compressed to a length comparable to the plasma wave length to efficiently accelerate electrons in the blowout regime. For the SPS beam, this would mean a compression by 4 orders of magnitude, translating into GV of RF voltage and kilometers for the bunch compressor chicane [8], which is beyond the scope of a demonstration experiment. However, recent studies [9] have shown that comparable acceleration gradients can also be achieved via a modulated proton bunch, which allows for an experiment using the uncompressed SPS bunch. In the scheme foreseen now, a high intensity proton bunch will be tightly focused into a plasma cell of about 10 m length, where it will self modulate. The plasma density is roughly given by the condition that the plasma skin depth is at least the transverse size of the proton bunch σ_r for the bunch modulation to be effectively produced, i.e. $k_p\sigma_r \leq 1$. An overview over the planned proton beam parameters is given in Table 1. An idea of the plasma cell parameters is given in Table 2. The exact numbers are still subject to optimization studies. Simulations indicate that for the proton bunch modulation to grow faster than competing instabilities like hosing, the modulation has to be seeded [9]. In the simulations, this was achieved via a so called half-cut beam where the first half of the beam was assumed to be cut of. In the experiment this could for example be realized via a lithium vapor plasma source and an ionizing laser pulse propagating at a fixed phase wrt. the proton bunch. This way, the first half of the bunch would propagate in neutral gas and the plasma would only see the second half of the proton bunch, with a sharp current flank.

Table 1: Planned Proton Beam Parameters

Reference Energy E_P in GeV	450
Number of Protons N_P (10^{11})	1.1 - 3.0
RMS energy spread σ_P in MeV	135
RMS bunch length σ_z in cm	12.0
RMS beam radius σ_r^* at focus in μm	200
Geometric emittance in $\mathrm{nm}\cdot\mathrm{rad}$	7.3

Table 2: Planned Plasma Parameters

Electron density n_e in cm^{-3}	1-7$\cdot 10^{14}$
Density fluctuations in %	≤ 1
Cell length in m	5-10

The work done at CERN towards a conceptual design of the beam transfer, focusing section and experimental area is presented in [10]. An in-detail description of the experiment can be found in the letter of intent [7].

SIMULATION RESULTS

The work presented here is based on beam plasma simulations carried out by K. Lotov, LCODE [11], A. Pukhov, T. Tückmantel, VLPL [12] and J. Vieira, L. Silva, Osiris

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[13, 14]. Some exemplary proton beam parameters shall be reviewed first (simulation: K. Lotov, LCODE).

Figure 1 shows the longitudinal energy distribution after a 10 m plasma cell. One can clearly see how the energy

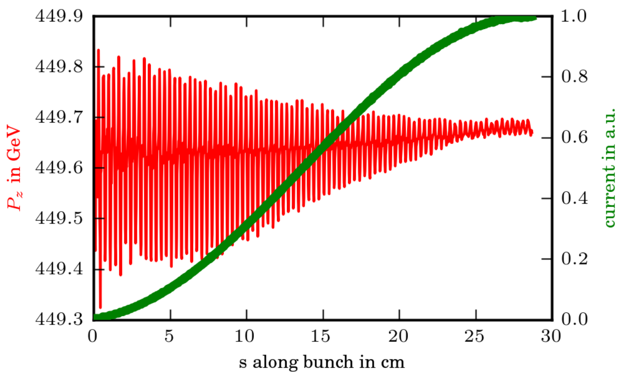

Figure 1: Current and energy distribution along a proton bunch after 10 m of propagation in a plasma cell ($N_P = 1.15 \cdot 10^{11}$, $n_e = 1 \cdot 10^{14}\,\mathrm{cm}^{-3}$). The x-axis gives the position along the bunch, with propagation direction towards higher s values. The green curve shows the hard cut current distribution along the bunch, the red curve the average energy per bin in GeV. The energy modulation is strongest at the very tail of the bunch. Note that the absolute energy change is relatively small compared to the initial energy of ~450 GeV.

modulation grows along the bunch. Figure 2 shows the corresponding transverse beam size before and after the cell. Both the longitudinal momentum as well as the transverse momentum and beam size are modulated with the plasma wavelength. The transverse density modulation is the cause of the longitudinal fields, i.e. it is desirable. For the shown example, the longitudinal energy spread σ_p increases from 135 to 150 MeV, while the normalized transverse emittance

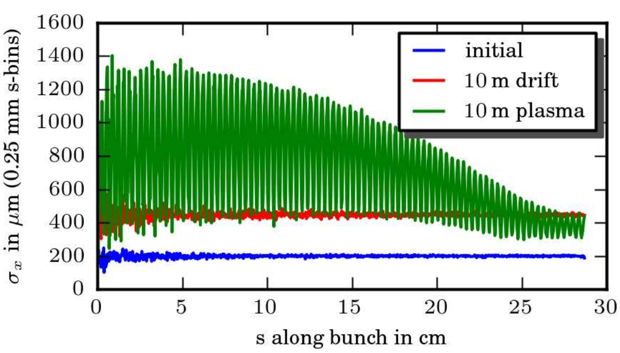

Figure 2: RMS transverse beam size along the beam before and after a 10 m plasma cell ($N_P = 1.15 \cdot 10^{11}$, $n_e = 1 \cdot 10^{14}\,\mathrm{cm}^{-3}$). A strong increase in σ_x is observed. The beam size which would result from a 10 m drift has been plotted for comparison. The modulation length is the plasma wavelength $\lambda_p \approx 3\,\mathrm{mm}$. The transverse momentum is modulated in a similar way (not shown).

grows from 3.5 to about 20 μm. This is problematic, since both effects lead to a broadening of a spectrometer image and have to be distinguished.

Figure 3 shows the energy distribution of an 10 MeV electron beam which has been injected along with the driving proton bunch in a 7 m plasma cell (simulation: A. Pukhov, VLPL). The spectrum is very broad and reaches

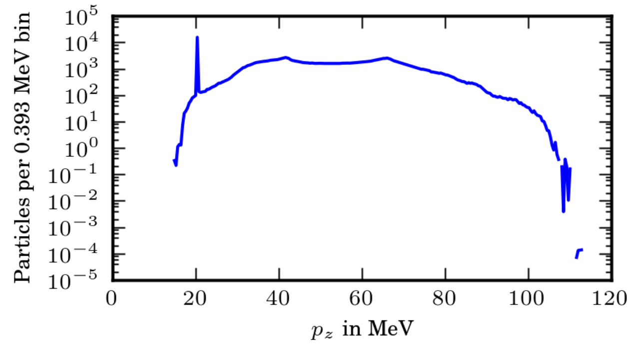

Figure 3: Energy spectrum of an electron bunch (particles per energy interval over particle energy) which copropagated with the driving proton bunch for 7 m. The initial electron energy was 10 MeV. ($N_P = 1.15 \cdot 10^{11}$, $n_e = 1 \cdot 10^{14}\,\mathrm{cm}^{-3}$)

energies of over 100 MeV. This is due to the fact that for this simulation, the injected electron bunch was much longer than one plasma wavelength. As a result, the bunch sampled all phases of the field distribution generated by the proton bunch. Furthermore, for a low energy electron bunch the changes in energy are strong enough to lead to velocity differences and therefore a phase slippage along the propagation distance. As for the protons, the transverse momentum and size increase as well (the electrons do not only sample the accelerating and decelerating longitudinal fields but also the focusing ans defocusing transverse fields). However, as the change in energy is much higher, the relative effect on the spectrometer image is much smaller.

For the later phases of the project, a laser-plasma based electron source could provide ultra short pulses, leading to quasi mono energetic bunches. Methods to improve beam quality and energy are investigated in [15].

SPECTROMETER ESTIMATES

To estimate possible spectrometer images, the spectrometer dipole magnet was treated as a so called point-kick. This means letting its length go to zero while keeping the product $B \cdot l$ of magnetic field strength B and dipole length l constant. For each particle i the position x_{fin} on a spectrometer screen is then given by

$$x_{fin,i} = x_{in,i} + \frac{p_{x,i}}{p_{z,i}} \cdot s + \theta_i \cdot s, \quad \theta_i \approx \frac{lBe}{\gamma_i m_0 c_0}. \quad (1)$$

Here, x_{in} is the initial transverse position, p_x/p_z is the angle the particle has with the initial reference trajectory due to its transverse momentum, θ is the energy dependent kick of the magnet, and s is the length of the drift space between the magnet and the spectrometer screen. In this treatment, $x = 0$ is the initial reference trajectory. The spectrometer screen is assumed to be orthogonal to the initial beam trajectory.

For protons, it was easily shown that a simple dipole is not sufficient as spectrometer, as for all reasonable magnet strengths the effect of the transverse momentum is much stronger than the energy dependent kick, $|p_x/p_z| \gg \Delta\theta$, with $\Delta\theta = |\theta(\gamma) - \theta(\gamma_0)|$ and γ_0 corresponding to the reference energy of 450 GeV. Figure 4 shows an estimated proton spectrometer image for the three cases of a 10 m drift, a 10 m plasma cell and the ideal case where the width of the image is only due to the different longitudinal particle energies (i.e. where $p_{x,i},\ x_{in,i} = 0\ \ \forall i$). All plots assume point-to-point focusing to remove the dependence on the transverse momentum ($p_x = 0$). Even with point-

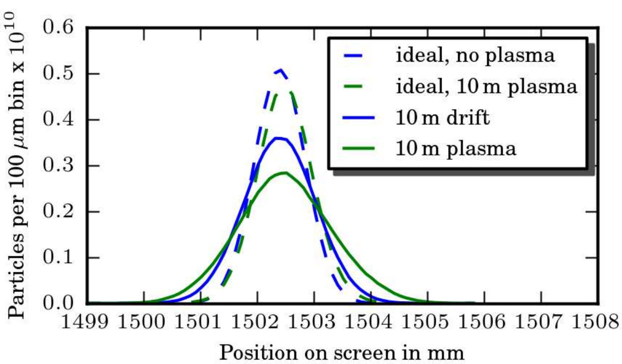

Figure 4: A possible proton spectrometer image as generated via eq. (1), assuming an integrated field strength of 22.5 Tm and 100 m drift (same data set as for Figure 1 and 2). Point-to-point focusing is assumed to remove the dependence on the transverse momentum (solid lines). For the ideal case, the dependence on the transverse position is also removed, the width being only due to the momentum spread (dashed lines). The x-axis gives the position on a spectrometer screen orthogonal to the initial beam trajectory. The y-axis gives the intensity at a given position. Higher energies are to the left. Note that the maximum of the distributions shifts to the right for the plasma-on case, due to an average energy loss to the plasma of ∼25 MeV.

to-point focusing, the signature of the energy modulation is not very clear. Additionally, given the final beam parameters, the minimal length of a focusing system is approximately 100 m (Deduced by MADX for realistic quadrupole fields at the beam energy considered. Simulations assumed a system of two quadrupole triplets). In the initial planning of the experiment, it was foreseen to only observe the energy modulation of a proton bunch by the plasma as a first phase. But for the two reasons mentioned above, it has been decided to not build a proton energy spectrometer.

For electrons, the effect of the energy modulation can be seen much easier, as is shown in Figure 5. It has therefore been decided to already have an electron injector and electron spectrometer in the early phases of the experiment.

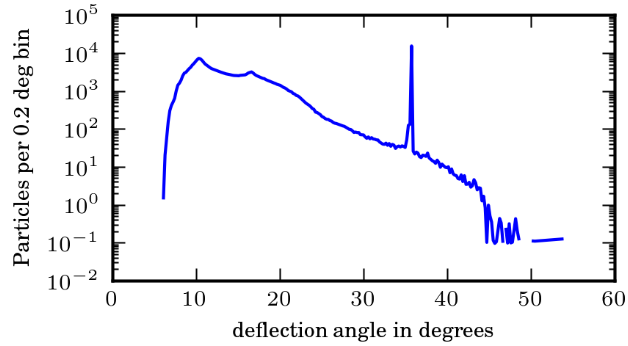

Figure 5: A possible electron spectrometer image as generated via eq. (1), assuming an integrated field strength of 0.04 Tm (Data set Figure 3). The peak at $\approx 37°$ corresponds to the initial energy.

SUMMARY / CONCLUSION

An introduction to the demonstration experiment in proton-driven plasma wakefield acceleration has been sketched. Based on beam plasma simulations by [11, 12, 13], spectrometer studies both for the driving proton bunch and an accelerated electron bunch have been carried out. In these studies, it was shown that is far more promising to already inject and diagnose electrons in the early phases of the experiment than to build an energy spectrometer for the modulated proton bunch.

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