A PROTON-DRIVEN PLASMA WAKEFIELD ACCELERATOR EXPERIMENT WITH CERN SPS BUNCHES

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Abstract

A proton-driven plasma wakefield experiment using long CERN SPS bunches is proposed. Externally injected electrons are accelerated by the $0.1 - 1\ GV/m$ amplitude plasma wakefields resonantly driven by the self-modulated proton bunch. This experiment is the start of a broad program aimed at exploring the possibility of generating energy frontier electron bunches in a single plasma section driven by a high-energy proton bunch. We briefly describe the general goals and parameters of the proposed experiment.

INTRODUCTION

Plasma-based accelerators driven by a charged particle bunch also known as plasma wakefield accelerators (PWFAs) have demonstrated that very large accelerating gradients ($\sim 52\ GeV/m$) can be sustained over meter-scale plasmas leading to $42\ GeV$ energy gain by trailing electrons [1]. Experiments are currently performed at the SLAC National Accelerator Laboratory FACET facility to show that high quality particle bunches in the $40\ GeV$ energy range can be produced in a PWFA [2]. However, current electron bunch drivers carry less than $100\ J$ of energy ($N = 2\times 10^{10} e^-$/bunch, $E_0 = 23\ GeV$ at SLAC), thereby limiting the final energy of the accelerated bunch.

The bunch of a future linear collider at the energy frontier will carry on the order of $1.6\ kJ$ ($N = 2 \times 10^{10}\ e^-$/bunch, $E_0 = 500\ GeV$). Electron bunch drivers would therefore be appropriate for acceleration in multiple stages, on the order of 50, to reach the TeV energy scale with gain $\sim 20\ GeV$/stage. Staging introduces new challenges such as tight synchronization and alignment requirements of the drive and witness bunches. Staging also leads to gradient dilution because of the long distances between high-gradient plasma cells required to in-couple new drive bunches and to capture and re-focus the very short beta-function witness bunch.

Proton bunches carry very large amounts of energy, $112\ kJ$ for a single LHC bunch with 10^{11} protons at $7\ TeV$. One can can therefore dream of using such proton bunches to produce TeV-class electron bunches in a single (or a few) PWFA stage(s). This idea was explored by Caldwell et al. [3]. While the expected peak gradient ($\sim 1\ GV/m$) is modest for a plasma-based accelerator, it is equal to the average gradient and is reached at relatively low plasma density ($\sim 10^{14} - 10^{15}\ cm^{-3}$). This relatively low n_e leads to a relatively large accelerating structure ($\sim 100\ \mu m$), which relaxes temporal and spatial alignment tolerances, as well as the witness bunch parameters. The proton-driven PWFA is a very interesting alternative to the already considered electron-driven PWFA scheme.

However, because of their large mass and inertia ($\sim \gamma m_p c^2$), relativistic protons are difficult to compress to very short lengths (sub-picosecond as in [3]). This led to the idea of using self-modulated proton bunches to resonantly drive wakefields to large amplitudes. Long bunches ($\sigma_z >> \lambda_{pe}$) are subject to a transverse two-stream instability [4], the self-modulation instability or SMI. This instability results from the low level wakefields driven by the long bunch in the high-density plasma. Their transverse component radially modulates the proton bunch at the plasma wave period. The bunch density modulation resonantly drives wakefields that grow both along the the bunch and along the plasma.

PROPOSED EXPERIMENTS

We are proposing a self-modulated proton-driven PWFA experiment using the CERN SPS bunch with the goal of accelerating a trailing electron bunch. Possible experimental parameters are investigated through numerical simulations with various 2D and 3D codes including VLPL [5], OSIRIS [6] and LCODE [7]. The experimental parameters are listed in Table 1. The proton bunch is extracted from the SPS along the TT61 beam line and the West Experimental area. The bunch is focused to a transverse size of $\sim 200\ \mu m$. This size determines the maximum plasma density since the plasma skin depth $c/\omega_{pe} \sim n_e^{-1/2}$ must be kept larger than the transverse bunch size to avoid the possible occurrence of another instability, the transverse current filamentation instability or CFI [8]. This instability has recently been observed and breaks up the particle beam into smaller, higher current density filaments. The plasma density is therefore in the $\sim 10^{14} - 10^{15}\ cm^{-3}$ range. With the incoming bunch emittance the beam beta function $\beta_0 = \gamma_0 \sigma_r^2/\epsilon_N \cong 5\ m$ is on the order of the plasma length. This makes external focusing along the plasma unnecessary.

The purpose of the initial experiments is to let the SMI develop, saturate, and resonantly drive accelerating field amplitudes in the $0.1 - 1\ GV/m$ range over $\sim 8 - 10\ m$ of plasma. At the point along the plasma where the SMI saturates and the phase velocity of the wakefields becomes equal to that of the drive bunch ($\sim 3\ m$) test electrons from an rf photoinjector gun at $\sim 10 - 20\ MeV$ will be externally injected and will sample the wakefields over $5 - 7\ m$ of plasma. These electrons will be *side-injected*

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Parameter	Value
n_e $[cm^{-3}]$	6×10^{14}
c/ω_{pe} $[\mu m]$	217
L^{plasma} [m]	3+7
L^{plasma} $[c/\omega_{pe}]$	$\sim 1.4 + 3.2 \times 10^4$
E_0 $[GeV]$	450
γ_0	480
σ_r [μm]	200
σ_r $[c/\omega_{pe}]$	~ 0.9
σ_z [cm]	12
σ_z $[c/\omega_{pe}]$	~ 553
N_{part}	11×10^{10}
n_b/n_e	2.4×10^{-3}
ϵ_N [mm · mrad]	3.83

Table 1: Typical parameters for the long proton bunch experiments. The particle bunch length and transverse width are given by σ_z and σ_r, respectively. In addition, the plasma length is denoted by L^{plasma} and ϵ_N is the normalized emittance.

[9] and will form short bunches that will be accelerated to a final narrow energy spread. Since the proton bunch is many plasma wavelengths long the resonant excitation of the wakefields and the acceleration of the low energy electrons require a very good plasma density uniformity, especially in the accelerator plasma section.

The required plasma density uniformity is determined by the development of the instability along the first (modulation) plasma section [10] and by the acceleration of the witness electron bunch in the following plasma section. Since in the side injection scheme these electrons have a relatively low energy so that they do not simply cross the wake transverse potential before capture, they are sensitive to dephasing with respect to the wakefields and to their transverse defocusing component. The density uniformity required is at the 0.1% level [11].

SMI SEEDING

The long proton bunch is also subject to the electron hose instability [12]. This instability competes with the SMI [13, 14] and can destroy the bunch. However, simulations [14] and calculations seem to suggest that seeding of the SMI mitigates the development of the hose instability. There are a number of seeding options including a preceding short and intense laser pulse or a dense charged particle bunch to generate wakefields, and the shaping of the bunch current profile with a sharp rise time. These require a pre-ionized plasma. Only the field-ionization of a gas or vapor by a short laser pulse synchronously propagating within the proton bunch seems to be compatible with the plasma density requirements. This option combines full ionization of a very uniform density gas or vapor with the instability seeding while leaving a minimum amount of time for the plasma density to evolve. Seeding is only necessary along the first plasma section (~ 3 m), or along a part of it, where the SMI grows. Therefore, another pre-ionized plasma source with similar uniformity could be used for the longer accelerator section (~ 5 m here, but possibly hundreds of meters in the future). In particular, plasma discharge [15] and helicon [16] sources are investigated.

Options to compress the SPS bunch using rf bunch manipulations are explored to decrease the bunch length and increase the bunch current. Initial results show that compression by a factor 3 to 10 may be possible [17]. However, such compression may drive the wakefields into the nonlinear regime of the PWFA, a regime not necessarily favorable for positively charged bunches, leading to emittance growth [18] and strong defocusing and particle loss [14].

Higher accelerating gradients and thus shorter plasma sections (for the same final electrons' energy) would make the accelerator more compact and the plasma density uniformity requirements easier to achieve.

DIAGNOSTICS

The occurrence of SMI results in the longitudinal modulation of the bunch radius and therefore density. The radius modulation at the plasma period can be directly observed using optical transition radiation (OTR) because the plasma density is relatively low and the plasma period is 4.5 ps at $n_e = 6 \times 10^{14}$ cm^{-3}. The OTR light can therefore be directly imaged onto the slit of a streak camera with ~ 200 fs resolution and the growth of the instability along the bunch measured. Note also that time integrated OTR images should show the defocusing of approximately half the protons. The intensity and spectrum of coherent transition radiation (CTR) also contains information about the bunch local transverse size or self-modulation. The CTR energy scales as N^2/σ_z, and with the self-modulation leading to m bunches of length $\sim \sigma_z/2m$ and a remaining charge $\sim N/2$ the CTR energy increases by a factor $\sim m/2$ when self-modulation occurs. Note that m is on the order of $\sigma_z/(2\pi c/\omega_{pe}) \sim 88$ for the parameters of Table 1. The CTR spectrum can be directly measured using Smith-Purcell radiation. Since the number of self-modulated bunches is large, the spectrum should exhibit a discrete feature at the plasma frequency. Beam collimation can in principle be used to scrape large radius protons, leading to a bunch current modulation and enhancement of the CTR energy and spectrum.

In addition, electro-optic sampling (EOS) can also be used to measure the self-modulation of the proton bunch. Again, since the number of self-modulated bunches is large, the self-modulated bunch fields can generate side bands in the laser pulse spectrum shifted by the plasma frequency. This diagnostic is currently being developed [19]. The possibility of measuring the wake fields directly inside the plasma is also explored.

Measurements of the electrons' energy gain requires a large energy acceptance spectrometer with a few $\%$ energy resolution from $\sim 0.1 - 1$ GeV, the expected range after acceleration from $\sim 10 - 20$ MeV. Due to the low num-

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ber of electrons trapped in the side-injection scheme, single electron detectors may be required in the image plane of the spectrometer. However, on-axis injection of a higher energy and charge bunch is also considered.

Associated with the proton bunch self-modulation is a plasma density perturbation. Plasma diagnostics can in principle evidence this perturbation. For example laser shadowgraphy or Schlieren measurements, as well as Faraday rotation (combined with the self-modulated bunch magnetic field) could provide local density perturbation along the growth of the instability. At the same time, a photon acceleration diagnostic could provide a length integrated measurement, especially along the accelerator plasma section.

SUMMARY

Proton bunches carrying large amounts of energy can drive wakefields to GV/m amplitudes in low density plasmas [3]. Initially long SPS bunches resonantly driving wakefields after the SMI has developed will be used in proof-of-principle experiments. In these experiments externally injected low energy electrons will be accelerated to the GeV energy level. The experiments are in the planning phase. These experiments will serve as the first phase of a broader experimental, simulation and theoretical program aimed at exploring the possibility of producing high-energy electron bunches in a single plasma section driven by a high-energy proton bunch.

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