Nonlinear wake amplification by an active medium in a cylindrical waveguide using a modulated trigger bunch

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Abstract

Cerenkov wake amplification can be used as an accelerating scheme, in which a trigger bunch of electrons propagating inside a cylindrical waveguide filled with an active medium generates an initial wake field. Due to the multiple reflections inside the waveguide, the wake may be amplified significantly more strongly than when propagating in a boundless medium. Sufficiently far away from the trigger bunch the wake, which travels with the same phase velocity as the bunch, reaches saturation and it can accelerate a second bunch of electrons trailing behind.

For a CO₂ gas mixture our numerical and analytical calculations indicate that a short saturation length and a high gradient can be achieved with a large waveguide radius filled with a high density of excited atoms and a trigger bunch that travels at a velocity slightly above the Cerenkov velocity. To obtain a stable level of saturated wake that will be suitable for particle acceleration, it is crucial to satisfy the single-mode resonance condition, which requires high accuracy in the waveguide radius and the ratio between the electron phase velocity and the Cerenkov velocity. For single-mode propagation our model indicates that it is feasible to obtain gradients as high as GV m⁻¹ in a waveguide length of cm.

Keywords: laser–plasma interaction; novel optical material and device

1. Introduction

Currently, high electron energies of tens of GeV are achieved with radio-frequency (RF) linear accelerators that operate in the GHz frequency range with a typical length of a few kilometers[l]. In idealized conditions, breakdown[2] limits the accelerating electric field to the order of a few hundreds of MV m⁻¹. In practice, gradients reach values of 25 MV m⁻¹ when operating at room temperature[l] and 35 MV m⁻¹ in their superconductive counterpart[3].

In the past two decades, with the immense progress in laser technology, laser plasma accelerators have become able generate hundreds of GV m⁻¹[4–6]. In this scheme, high intensity focused laser pulses with lengths of the order of the plasma wavelength generate an intense wake. The plasma wake, which trails behind the laser pulse with the same group velocity, can accelerate electrons from the plasma itself. Work is in progress to accelerate electrons that do not originate in the plasma.

Based on the chirped pulse amplification (CPA) technique[7], pulsed laser technology facilitates focus on plasma target pulses with intensities as high as 10¹⁸ W cm⁻² and duration of the order of femtoseconds (10⁻¹⁵ s) for a laser wavelength of 1 μm that is optimized to a plasma density of 10¹⁸ cm⁻³. In a series of experiments reported in 2004[8–10], quasi-monoenergetic e-beams with energies of the order of 100 MeV have been demonstrated. More recently, several groups have demonstrated quasi-monoenergetic e-beams with energies of up to 2 GeV[11].

An intense wake may also develop by replacing the laser pulse with an energetic e-beam in plasma, and it is shown experimentally[12] that an initial bunch of 40 GeV can generate an intense wake of the order of 50 GV m⁻¹, which results in acceleration of a trailing bunch to an energy of about 80 GeV with about 16% energy spread. The total number of injected electrons in the bunch is 10¹⁰ and the spot size is 10 μm, whereas the number of electrons accelerated to 80 GeV is about 2.4 × 10⁶. For comparison, in a dielectric loaded waveguide, a 60 MeV bunch of electrons can generate Cerenkov gradients of 250 MV m⁻¹[13]. The total number of injected electrons in the bunch is 3 × 10⁶ and the spot size is 10 μm, whereas the number of accelerated electrons is about 70 × 10³.

In the paradigm analyzed here, the gradients are more modest (order of 1 GV m⁻¹) and it is conceptually closer to a conventional two-beam acceleration scheme. It relies on transferring energy stored from the active medium to a train of electron bunches – see Refs. [14, 15]. In contrast