Deep saturation of a Cerenkov wakefield amplified by an active medium

Z. Toroker and L. Schächter

Department of Electrical Engineering, Technion Israel Institute of Technology, Haifa 32000, Israel

(Received 25 January 2015; published 7 July 2015)

A trigger bunch of electrons traveling inside or in the vicinity of a dielectric medium generates a Cerenkov wake. If the dielectric medium is active, a small fraction of the spectrum of the wake is amplified and far behind the trigger bunch where the active medium is fully depleted, the amplitude and the phase of the wake are virtually constant. In this range, a second bunch of electrons trailing behind the trigger bunch can be accelerated. For optimal operation, the trigger bunch should be density modulated at the resonant frequency of the medium. However, we demonstrate that even if the bunch is uniform along many wavelengths we may still take advantage of the saturation characteristics to obtain conditions adequate for acceleration. Further we demonstrate that for large enough number of electrons it is possible to have a coherent amplified wake after a saturation length which is determined analytically and tested numerically. In addition, we show that almost 100% of the stored energy in the active medium can be transferred to the acceleration of the trailing bunch electrons. The relatively large energy spread due to the beam loading is well suited to a medical accelerator. When the beam loading is weak, the gradient is virtually constant but the acceleration efficiency drops to about 2% for typical parameters.

DOI: 10.1103/PhysRevSTAB.18.071301 PACS numbers: 29.20.-c, 29.27.-a, 41.60.-m, 41.75.-i

I. INTRODUCTION

Electron acceleration by radio-frequency linear accelerator (rf linac) is the most developed technique that facilitates the generation of a small emittance and energy spread beams of electrons [1–3]. It relies on a single transverse-magnetic (TM) mode which is excited in a metallic circular waveguide and is designed to propagate at the speed of light in vacuum yet it possesses a longitudinal component of the electric field. Since the major limitation of rf linacs is breakdown, the maximum gradient is of the order of tens of MV/m and as a result, a few km’s long machine is required for accelerating e-beams to energy of ten’s of GeV. The goal of all the new advanced acceleration concepts is to reduce significantly this length by enhancing the gradient while keeping the emittance and the energy-spread as low as possible.

In the past few decades with the advent of high-intensity laser [4] and micro-electronics technologies there is an effort to accelerate electrons to GeV in a table-top structure. As of today, the record gradients were achieved in the plasma based schemes [5,6] and dielectric based accelerator [7]. In the former, an intense laser pulse is injected into a plasma to generate a wakefield of hundreds MV/m. The plasma wake, which trails behind the laser pulse can accelerate electrons. In fact, the record energy transferred so far to a bunch of electrons was achieved when the plasma wake was induced by an intense electron bunch [8]. In dielectric based accelerator, it has been demonstrated that a bunch of electrons can excite Cerenkov wake of hundreds MV/m [7].

Another technique of electron acceleration relies on transferring energy stored from active medium (AM) to a bunch of electrons [9,10]. In the first approach of this technique, spatially modulated electron bunch with periodicity equal to the resonance wavelength of the AM is injected into effectively boundless structure. That bunch generates a wakefield which is amplified by the AM. As a result, the amplified wake directly accelerates the electron bunch. This approach is effective below the Cerenkov condition and it has been demonstrated in an experiment performed at Brookhaven National Laboratory-Accelerator Test Facility [11], in which a density modulated bunch with energy of 45 MeV gained energy of 200 keV from active CO2 gas mixture.

In the second approach considered here electron bunch is accelerated by an amplified Cerenkov wake inside a bounded AM [12]. More specifically, a trigger bunch of electrons travels inside a cylindrical waveguide filled with AM generates TM modes of Cerenkov wake. When the single mode resonance condition is satisfied, only a single TM mode of Cerenkov wake is amplified until full depletion of the population inversion density (PID) occurs. At this point the effective gain is reduced to zero and the wake reaches saturation. Depending on the AM parameters the wake can reach at saturation values as high as GV/m a few cm’s after the trigger bunch. In the region where saturation is reached, a trailing train of bunches may be accelerated by the amplified Cerenkov wake for schematic, see Fig. 1. It is interesting to note that this paradigm resembles the two beam accelerator (TBA) with one major