2D theory of wakefield amplification by active medium

Miron Voin a,⁎, Wayne D. Kimura b, Levi Schächter a

a Department of Electrical Engineering Technion—Israel Institute of Technology, Haifa 32000, Israel
b STI Optronics, Inc. 2755 Northup Way, Bellevue, Washington 98004, USA

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A B S T R A C T

A train of microbunches generates in a passive dielectric-loaded waveguide an electromagnetic wake which propagates at the speed of the particles. This wake consists of propagating modes provided the electrons exceed the Cerenkov velocity. If the material is replaced with an active dielectric, identical to that of a laser, the wake is amplified. Another train of bunches, lagging many wavelengths behind, may be accelerated by this amplified wake. The gradient is limited by breakdown and saturation of the medium. Beam loading may be partially or even completely compensated by the gain along the trailing bunch. Preliminary results of a linear theory will be presented, assuming a 300 MeV beam and high-pressure CO2 mixture as an active medium. In spite of many hundreds of modes excited by the front beam, the spectrum of the amplified field corresponds to a monochromatic wave determined primarily by the bandwidth of the medium. The analytic approach facilitates simple assessment of the effect of the various parameters on the accelerating gradient.

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1. Introduction

In the category of structure-less acceleration schemes there are two main conceptual mechanisms which may be divided according to the initial origin of the energy: in one case, an intense laser pulse [1] is injected in a plasma and the particles are accelerated by the trailing space-charge wake. Obviously, the initial energy required for acceleration is stored in the laser pulse. In the second paradigm, the laser pulse is replaced by an intense electron beam [2,3] as the energy source – the acceleration itself is again facilitated by the emerging space-charge wake. A third possibility, which will be investigated in detail here, is to store the energy within the medium and the particles may gain energy at the expense of the latter. The proof of principle experiment of the concept for a structure-less configuration was performed at Brookhaven National Laboratory-Accelerator Test Facility (BNL-ATF) in 2006 [4]. Its essence was to velocity modulate a 45 MeV electron beam by a 0.5 GW CO2 laser in a wiggler [5]. After 2.5 m drift the velocity-modulated beam emerging from the first module becomes density-modulated and it is injected in a second module which consists of a 30 cm long vessel filled with a CO2 mixture identical to that of the CO2 laser. This mixture was kept at 0.25 atm and could be excited by a (30–40 keV) discharge circuit. Comparing the electrons’ spectrum with the discharge on and off, a significant fraction (more than 10%) of the electrons gained about 200 keV corresponding to an accelerating gradient of less than 1 MV/m. In the framework of this experiment there was no confining structure that facilitates acceleration, the electrons in the train extract energy from the active medium and the mixture is designed such that no Cerenkov radiation is generated.

In this publication our goal is to present the details of an analysis of a new paradigm whereby all three constraints mentioned above are removed: (i) Rather than energy being transferred from the medium to the same bunch that stimulates the medium, the energy is transferred to the Cerenkov radiation which in turn may be used to accelerate a different train of electron bunches trailing many wavelengths behind. (ii) The active medium is confined in a cylindrical waveguide such that the multiple reflections facilitate a significant enhancement of the wake. In fact, the trailing train of bunches is to be located in the region where the radiation-medium interaction reaches saturation. See schematic of the concept in Fig. 1.

In the present study, it is tacitly assumed that the active medium is gaseous (CO2 mixture); however, most arguments hold for a solid-state medium (e.g. Nd:YAG). With one extra condition: since the electrons move in a vacuum channel of radius R surrounded by a solid-state active medium, it is necessary that the exponential decay of the relevant evanescent wave is as small as possible (2πR/γλ0 ≪ 1). For example, in a vacuum tunnel of R = 5 mm and medium which resonates at 1 μm, the energy of the electrons must be larger than 15 GeV.

2. Model description

For a conceptual description of the paradigm we examine the wake generated by a thin charged loop (Qb of radius Rb, located at