Optimized operation of dielectric laser accelerators: Single bunch

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(Received 11 September 2017; published 9 May 2018)

We introduce a general approach to determine the optimal charge, efficiency and gradient for laser driven accelerators in a self-consistent way. We propose a way to enhance the operational gradient of dielectric laser accelerators by leverage of beam-loading effect. While the latter may be detrimental from the perspective of the effective gradient experienced by the particles, it can be beneficial as the effective field experienced by the accelerating structure, is weaker. As a result, the constraint imposed by the damage threshold fluence is accordingly weakened and our self-consistent approach predicts permissible gradients of \( \sim 10 \text{ GV/m} \), one order of magnitude higher than previously reported experimental results—with unbunched pulse of electrons. Our approach leads to maximum efficiency to occur for higher gradients as compared with a scenario in which the beam-loading effect on the material is ignored. In any case, maximum gradient does not occur for the same conditions that maximum efficiency does—a trade-off set of parameters is suggested.

DOI: 10.1103/PhysRevAccelBeams.21.054001

I. INTRODUCTION

Today’s electron accelerators are predominantly driven by rf sources. Being structure-based systems, operating with the lowest electromagnetic mode, the accelerating gradient is limited by the breakdown in the metal’s surface [1]. However, in the optical regime it has been experimentally shown [2,3] that dielectric materials held higher fields before breakdown. Therefore, it indicates what should be the general trend, namely operating at sub-mm or optical wavelengths, as this allows higher accelerating gradients. For example, the Stanford Linear Collider’s gradient is of the order of 20 \( \text{MeV/m} \) [4], while in an optical accelerator 50 times this value is anticipated [5].

Another profound difference between a laser driven accelerator as compared with its microwave counterpart is their material. At optical frequencies Ohm loss makes metals prohibitively lossy. Thus, low loss dielectric materials are virtually the only alternative for an accelerating structure, regardless of whether the latter is used as an optical electron collider [6], a possible light source [7], or as a module for medical devices [8]. Throughout the years several dielectric structures have been proposed [9–12] and more recently experimental results were reported [13–15]. In all these configurations fluence damage [16] is a limiting factor, whereas in rf machines, breakdown at the metal-vacuum interface is a critical impediment [17].

Both rf and laser accelerators have an important phenomenon in common, this is the beam loading. It results from the wakefield generated by each particle [18], thus reducing the effective gradient experienced by the same or trailing particles. As shown subsequently, the field reduction may be beneficial, since the structure is exposed to a weaker electromagnetic field.

In the framework of this paper we present a general approach relevant to any guided-mode or resonant Floquet harmonic in a dielectric laser-driven acceleration structure, which aims to achieve a self-consistent analysis of the optimal charge, gradient, and efficiency. Contrary to the approach in Ref. [19], we take into account the short range wakefield only once. But in addition, we account for its effect on the dielectric material too. Proper design of the operation parameters, indicates that beam-loading although reduces the effective gradient experienced by the particles, it also enlarges the gap between the maximum field experienced by the material and the damage threshold fluence. As a result, the laser power may be increased and so is the amount of accelerated charge. The optimization process developed predicts an unloaded gradient of \( \sim 10 \text{ GV/m} \). This is one order of magnitude higher than previous experiments demonstrated [14,15].

II. SYSTEM DESCRIPTION

Let us now introduce the general approach. Common to all various structures is the vacuum channel, where the electrons propagate, and the single TM\(_{01}\) mode that accelerates them. Although preliminary results were...