Optimized operation of dielectric laser accelerators: Multibunch

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We present a self-consistent analysis to determine the optimal charge, gradient, and efficiency for laser driven accelerators operating with a train of microbunches. Specifically, we account for the beam loading reduction on the material occurring at the dielectric-vacuum interface. In the case of a train of microbunches, such beam loading effect could be detrimental due to energy spread, however this may be compensated by a tapered laser pulse. We ultimately propose an optimization procedure with an analytical solution for group velocity which equals to half the speed of light. This optimization results in a maximum efficiency 20% lower than the single bunch case, and a total accelerated charge of $10^6$ electrons in the train. The approach holds promise for improving operations of dielectric laser accelerators and may have an impact on emerging laser accelerators driven by high-power optical lasers.

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I. INTRODUCTION

In the past two decades direct electron acceleration driven by laser was experimentally demonstrated. Bounded by gradient limitations ($\sim 100$ MV/m), it has been shown [1–3] that net acceleration could be achieved by a train of microbunches spaced at the optical period. However, some applications require significantly higher accelerating gradients than provided by conventional rf linear accelerators, such as compact radiotherapy devices [4] and miniaturized light sources [5,6].

Dielectric laser accelerator (DLA) structures have the potential to facilitate higher gradients and high efficiency, as was recently demonstrated [7,8]. However, these experiments utilized an electron beam that was much longer than the laser period, resulting in energy modulation rather than net acceleration. The question is therefore could we benefit from both worlds—namely, have net acceleration and at the same time high gradient in the DLA?

In order to achieve net acceleration, several research groups are considering generation of optically-spaced electron microbunches [9–14]. Novel schemes have been presented [9,10] as well as experimental demonstrations [11–14]. While the issue of generating optically-spaced electron microbunches is beyond the scope of this study, below we discuss a phenomenon common to all such schemes—beam loading.

Beam loading effect is slightly different in rf as compared to an optical regime. In most cases in rf machines, only one or very few microbunches exist in the acceleration module simultaneously [15–19], whereas in an optical regime hundreds or even thousands of microbunches may coexist in the accelerating module at any given moment. Therefore, in an optical regime the wake exerted on each microbunch may have a more significant effect.

As a result of this wake, there is a need for a tapered laser pulse in order to compensate for its effect. The tapering should take into account the laser’s group velocity, which is much higher in DLA as compared to rf systems. The subject of compensating for beam loading by way of tailoring the driving rf pulse has been studied extensively over the years [20–22]. Among the common methods are either local [23] or global [24,25] correction schemes. However, to the best of our knowledge, systematic study of this subject in the context of dielectric laser accelerators (DLA) has not been pursued as of yet.

By leveraging beam loading effect, in part I of this study we proposed [26] a way to optimize a single bunch operation of DLA. We solved a self-consistent set of nonlinear constraints, taking into account the beam loading reduction on the material at the dielectric-vacuum interface; this case was referred to as the reduced case. For a given efficiency, the reduced case presented a higher loaded gradient than the un-reduced case (whereby the field reduction on the material is ignored). For example, maximum efficiency of 60.5% occurred for a loaded gradient of 6 GV/m in the reduced case, as compared with 2.5 GV/m in the unreduced case. In any case, the optimal charge to be accelerated was found to be a total of $\sim 10^6$ electrons in the bunch. Splitting the electron beam into a train of microbunches could be beneficial due to weakening the space...