Trapping of sub-relativistic particles in laser driven accelerators

Adi Hanuka$^a$ and Levi Schächter

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

(Received 16 September 2017; accepted 27 November 2017; published online 26 December 2017)

We investigate the longitudinal and transverse dynamics of sub-relativistic electrons during the trapping process, as facilitated by an adiabatically tapered dielectric structure. The characteristics of the trapped electrons are studied for different initial conditions and structure’s parameters. A set of optimal parameters that exemplify our approach are presented. Specifically, we determine the condition where the transverse emittance is preserved during the trapping process. Published by AIP Publishing. https://doi.org/10.1063/1.5005031

I. INTRODUCTION

Laser driven accelerators bear inherent advantages over conventional microwave accelerators due to the reduction of 4–5 orders of magnitude in wavelength. Accordingly, the former have become an appealing alternative to the latter for both high energy physics$^{1,2}$ as well as for medical applications.$^3$ This trend is also strengthened by the fact that over the last decade there has been significant progress in wall-plug to light efficiency of lasers.$^4–6$

Optical accelerators present a number of advantages over their microwave counterparts. Most notably, the reduction in wavelength facilitates a reduction in the length of the machine. An optical machine could be two orders of magnitude shorter than its RF counterpart.$^7$ For example, the 50 km long ILC machine could be readily accommodated in the 3 km SLAC tunnel.$^8$ Medical accelerators could be shrunk from 50 cm long to no more than a few centimeters.

Another appealing advantage of operating in the optical range is that higher accelerating gradients can be achieved.$^9$ Additionally, while in both microwave and optical machines, the accelerating gradient is limited by the material’s ability to sustain an intense electric field, in microwave machines breakdown limits the gradient to 20–50 MV/m, whereas in laser driven structures—most commonly made from dielectric materials$^{12}$—gradients of 1–10 GV/m have been theoretically shown to be feasible$^{13}$ prior to breakdown.

Beyond size and gradient, accelerators are also tested by the number of accelerated particles. In microwave machines,$^{14,15}$ the typical bunch contains roughly 10$^{10}$ electrons, and its dimensions are of the order of $\sigma_z \approx 300 \mu m$, $\sigma_x \approx 10 \mu m$, and $\sigma_y$ is tens of nanometers; thus, the density is of the order of $n_d \approx 5 \times 10^{19}$ cm$^{-3}$ at the interaction point (IP).

In contrast, in an optical machine, the volume needs to be a small fraction of the wavelength. Thus, assuming that the latter is $\lambda \approx 1 \mu m$, the bunch’s dimensions should be $\sigma_z \approx 0.1 \lambda$, $\sigma_x \approx 0.2 \lambda$. Regarding density, in this study, our analysis considers a point which is away from the IP, and thus we assume a density 100 times lower than microwave machines, namely $n_d \approx 10^{18}$ cm$^{-3}$. As a result, a single bunch in an optical machine could contain 5000 electrons.

This number of accelerated charge should satisfy the luminosity constraint as well as the medical dose requirements.$^3$ In microwave machines, these are facilitated by a repetition rate of 5 Hz, number of bunches in train of $\sim 2000$, and $2 \times 10^{10}$ electrons in one bunch$^{16}$, resulting in $\sim 1 \times 10^{14}$ electrons per second. For optical machines, we assume a train of $10^3$ bunches (3 ps) and a repetition rate of 25 MHz, and thus we anticipate a similar number of electrons per second as microwave machines.

From the operational perspective, the trapping process of sub-relativistic particles, governed by the trapping condition, also differs between microwave and optical machines. The condition for electron trapping$^{17}$ for a given initial velocity $(c \beta_m)$ is a minimum accelerating field of $E_{\text{min}} = 2\pi (mc^2/e\lambda) \sqrt{(1 - \beta_m^2)/(1 + \beta_m^2)}$, considering a uniform acceleration structure, wherein the accelerating field $(E)$ propagates at the speed of light.

In the case of initially slow electrons, the trapping constraint is several orders of magnitude higher if $\lambda$ is in the optical range rather than microwave. Specifically, in microwave machines, wherein $\lambda$ is of the order of centimeters and thus the typical value of the normalized longitudinal field $a = E \lambda/mc^2$ is unity, the electrons become relativistic within a few wavelengths. In contrast, since in the optical regime $\lambda = 1 \mu m$, the typical value of $a$ is smaller than unity. As a result, electrons may only reach relativistic velocities after many wavelengths. For actual acceleration, the charge must be kept in synchronization with the accelerating field throughout the interaction length. In other words, the amplitude and the phase of the accelerating mode must be tapered.

Ample designs and studies have been conducted with regard to trapping electrons in microwave machines. However, to the best of our knowledge—a design of a tapered structure for trapping sub-relativistic electrons in an optical regime, as well as a thorough investigation of the trapping process properties—has not been conducted as yet.

In this study, we present a quasi-analytic formulation, as well as numerical studies, of the trapping dynamics of sub-relativistic particles in a tapered laser-driven acceleration structure, which serves as a booster. This formalism enables us to examine the interaction in phase-space and optimize it.

As a primary step, in order to maximize the trapping efficiency, the structure’s longitudinal tapering is

$^a$Adiha@tx.technion.ac.il