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Operation regimes of a dielectric laser accelerator

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A R T I C L E   I N F O

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A B S T R A C T

We investigate three operation regimes in dielectric laser driven accelerators: maximum efficiency, maximum charge, and maximum loaded gradient. We demonstrate, using a self-consistent approach, that loaded gradients of the order of 1 to 6 [GV/m], efficiencies of 20% to 80%, and electrons flux of 10^{14} [el/s] are feasible, without significant concerns regarding damage threshold fluence. The latter imposes that the total charge per squared wavelength is constant (a total of 10^6 per μm^2). We conceive this configuration as a zero-order design that should be considered for the road map of future accelerators.

The road map for a future linear collider was drawn recently [1] and it includes several schemes: plasma wake field acceleration (PWFA) [2], laser wake-field acceleration (LWFA) [3,4] and two-beam accelerator (TBA) [5,6]. In the first case a short electron bunch generates a *plasma* wake and the latter accelerates a trailing bunch. A similar wake is generated by a laser pulse in the second paradigm. In the framework of the third one, a driving bunch generates an *electromagnetic* wake which in turn accelerates a trailing bunch. Concerns of space-charge effects, low efficiency and modest luminosity, excluded the dielectric laser accelerator (DLA) from the list of viable alternatives. While the gradients experimentally demonstrated by the plasma based paradigms, are incredibly high comparing to what was conceived feasible before the pioneering work of Tajima and Dawson [7], there is still a long and rough road to overcome plasma instabilities at the necessary repetition rate and positron acceleration in the framework of these schemes.

Recent developments in fabrication [8,9] and experimental demonstrations [10,11] showed a realization towards high gradients of DLA (∼1 GV/m), dictated by the damage fluence threshold that materials can withstand. However, in order for the DLA to be further considered as a viable alternative, even higher gradients are required, as well as a considerable amount of accelerated charge with decent efficiency. Therefore, understanding its optimal operation regimes opens up a pathway to further DLA applications. This optimal operation is facilitated by the fact that the dielectric structure is not exposed to the entire laser energy flux since a significant part of the latter is absorbed by the electrons – thus the required high efficiency.

In this study we present the results of a self-consistent optimization of the operating parameters of an idealized acceleration module [12]. Subject to some simplifying assumptions that will be specified subsequently, our analysis indicates that loaded gradients approaching the 6 GV/m level are definitely feasible, efficiencies exceeding 50% are achievable and with current laser technology the required luminosity of a linear collider is already in reach. It is important to emphasize already at this stage that high efficiency implies significantly lower electromagnetic energy density in the dielectric near the vacuum tunnel thus reducing the concerns of fluence damage or other non-linear effects.

Our analysis assumes a 1 μm laser though indications (shown subsequently) are that a CO$_2$ laser (10.6 μm) may perform reasonably well. For the numerical examples presented, the acceleration structure is adopted to be a dielectric $\left(\varepsilon_r = 2.1\right)$ loaded waveguide, whereby for a given dielectric (fused Silica) and vacuum tunnel radius $\left(R_{\rm int}\right)$, the external radius $\left(R_{\rm ext}\right)$ is set by imposing single mode (TM$_{01}$) operation and phase velocity equal to the speed of light in vacuum. Note that in our specific configuration, imposing the group velocity sets $R_{\rm int}$ and vice versa. This choice of structure was made because of the analytic relations between the various parameters. Further, the laser pulse is conceived to be ideal in the sense that its rise and fall times are negligible comparing to its duration (τ_p).

With regards to the electron bunch, it is conceived to consist of a *single* point-charge (q) ignoring in the process space-charge effect. We discuss the latter in the last section and we present some of the main results of our analysis in the case of a train of micro-bunches; in any event, the single macro-particle case represents the best case scenario. We consider only the case of full overlap between the laser pulse that propagates at group velocity $c\beta_{\rm gr} < c$ and the relativistic bunch that moves practically at the speed of light (c). Furthermore, both the laser

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pulse and the wake leave the accelerating module before the next laser pulse fills in.

Lastly, additional assumptions of the present study: (i) for the structure of interest, the wake parameter (κ) is known, and it determines the intensity of the decelerating wakefield in terms of the driving charge. The wake's projection on the first accelerating mode is $\kappa_1 = W_1 \kappa < \kappa$. (ii) The coupling of power into the accelerating module is 100% efficient. (iii) At the laser's wavelength ($\lambda = 1$ μm), the dependence of the Damage Threshold Fluence $F(\tau_p)$ on the pulse duration (τ_p) in Fused Silica, is known [13]:

$$F\left(\tau_p\right) = \left[\frac{\mathrm{J}}{\mathrm{cm}^2}\right] \begin{cases} 1.44\tau_p^{1/2} & \tau_p\,[\mathrm{ps}] > 10 \\ 2.51\tau_p^{1/4} & 0.4 < \tau_p\,[\mathrm{ps}] < 10 \\ 2 & \tau_p\,[\mathrm{ps}] < 0.4 \end{cases} \tag{1}$$

Two observations warrant attention here: at very short pulse duration ($\tau_p < 0.4$ [ps]) the Damage Threshold Fluence (DTF) is limited to 2 J/cm^2 whereas for long pulse duration ($\tau_p > 10$ [ps]) the DTF exceeds 5 J/cm^2.

Based on the assumptions above, we may formulate the constraints that limit the number of degrees of freedom in our model. While the full analysis is presented in our previous work [12], in what follows we briefly summarize the main steps. We start with the observation that virtually in all dielectric based acceleration structures the energy flux reaches its maximum at the vacuum-dielectric interface. If we ignore the effect of the wake on the accelerating mode, the maximum energy flux $\left(S_z^{\max}\right)$ in the dielectric is proportional to the square accelerating gradient on axis $\left(G_0\right)$. Note that for a given gradient, the larger the dielectric coefficient, the lower the energy flux.

In the framework of this study we consider a reduction in the maximum energy flux due to the *wakefield* on the fundamental mode (denoted as κ_1). Thus we replace $G_0 \to G_0 - \kappa_1 q$; this peak value of the energy flux is limited by the Damage Threshold Fluence (DTF) that the material can withstand, thus

$$\frac{F\left(\tau_p\right)}{\tau_p} \equiv S_z^{\max} = \frac{1}{2\eta_0 \varepsilon_r}\left(\frac{\pi R_{\mathrm{int}}}{\lambda}\right)^2 \left(G_0 - \kappa_1 q\right)^2. \tag{2}$$

Clearly, for establishing the DTF we need to know the pulse duration. The latter, in turn, is determined, based on the overlap condition specified above, in terms of the group velocity and the geometric interaction length (L_{geo})

$$\tau_p = \frac{L_{\mathrm{geo}}}{c}\left(\beta_{\mathrm{gr}}^{-1} - 1\right). \tag{3}$$

This last parameter determines also the energy gained, $mc^2 \Delta\gamma$, along the module in terms of the *loaded gradient* on the bunch $G_0 - \kappa q$,

$$mc^2 \Delta\gamma = e\left(G_0 - \kappa q\right) L_{\mathrm{geo}}. \tag{4}$$

In this set of non-linear equations, for any given set of parameters $\left(\Delta\gamma, R_{\mathrm{int}}\right)$, there are two unknowns: the unloaded gradient G_0 and the bunch charge q. Explicitly, for a pre-selected charge q the unloaded gradient is a solution of Eq. (2) with $\tau_p = mc^2 \Delta\gamma \left(\beta_{\mathrm{gr}}^{-1} - 1\right)/ec\left(G_0 - \kappa q\right)$ and vice-versa, for a prescribed unloaded gradient, the charge is a solution of Eq. (2).

With these two quantities established $\left(G_0, q\right)$, the efficiency may be readily calculated [14]

$$\eta_1 = \frac{q\left(G_0 - \kappa q\right) L_{\mathrm{geo}}}{U_{\mathrm{EM}}} = 4\eta_{\max} \frac{\kappa q}{G_0}\left(1 - \frac{\kappa q}{G_0}\right) \tag{5}$$

where U_{EM} is the electromagnetic energy, and the maximum efficiency is $\eta_{\max} \equiv \kappa_1/\kappa$. This maximum efficiency imposes an additional constraint on the choice of G_0 or q. For example, the requirement of operating at maximum efficiency, determines both the charge and the gradient. Other constrains may lead to different regimes of operation – as discussed subsequently.

Before we proceed to analysis of the various feasible regimes of operation, it warrants to emphasize that maximum efficiency is smaller than 10% in the case of Bragg reflections waveguide, either planar (PBA) or cylinder (CBA) for typical existing materials (Silica and Zirconia) – see Fig. 1 (red and green curves). Similar maximum efficiency (6%) was estimated [15] for honey-comb structure (black star), whereas in the present case (dielectric loaded waveguide – blue and purple curves) the maximum efficiency reaches 62% for the same group velocity $\beta_{\mathrm{gr}} = 0.6$ as in [15] for $R_{\mathrm{int}}/\lambda = 0.44$, $\lambda = 1$ μm. Moreover, preliminary estimates [16] indicate that meta materials with characteristics similar to "ferro-magnetic" properties may exceed this value and reach efficiencies in excess of 90% for loaded waveguide, or 30% for Bragg structures. This is a major improvement over the present situation that beyond maximum efficiency improvement, leads to almost one order of magnitude in the gradient, as will be demonstrated next.

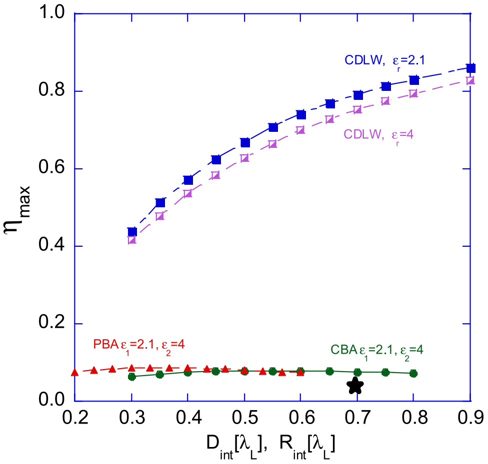

Fig. 1. (Color online) Maximum efficiency as a function of the vacuum clearance for three types of structures; (i) Cylinder Dielectric Loaded Waveguide (CDLW) with either Silica (blue) or Zirconia (purple) loading, (ii) Planar or (iii) Cylinder Bragg Accelerator (PBA or CBA) with alternating layers of Silica and Zirconia. The latter two structures present the lowest efficiency (~10%). The black star represents the honey-comb [17] fiber.

Table 1
Parameters of the Laser and the envisaged structure.

Parameter	Symbol	Value
Laser		
Laser wavelength [μm]	λ	1
Group velocity	β_{gr}	0.74
Phase velocity	β_{ph}	1.0
Interaction impedance [Ω]	Z_{int}	173
Laser power [kW]	P_L	$7.2\left\{G_0\left[\frac{\mathrm{GV}}{\mathrm{m}}\right]\right\}^2$
Structure		
Internal radius [λ]	R_{int}	0.7
External radius [λ]	R_{ext}	0.82
Dielectric constant	ε_r	2.1
Wake coefficient $\left[\frac{\mathrm{GV}}{\mathrm{m \cdot pC}}\right]$	κ	36
Energy gain required	$\Delta\gamma$	1.7
Maximum efficiency [%]	$\eta_{\max}$	80

In order to determine an *optimal* operation regime, we consider the effect of the accelerating module's length on the gradient and efficiency given the intrinsic set of parameters in Table 1. The results of such self-consistent analysis are presented in Fig. 2: unloaded gradient G_0 (top) and loaded gradient G_{Loaded} (bottom) versus the efficiency η normalized to its maximum value (80%) for various values of geometrical length (colorbar). Notably, both the efficiency and unloaded gradient reach maximum. However, maximum efficiency, maximum unloaded (corresponds to maximum charge) and loaded gradients occur for different geometrical lengths, and therefore cannot be satisfied together. In what follows, we examine the *three* different regimes – maximal efficiency, maximal charge, and maximal loaded gradient.