Designing a Dielectric Laser Accelerator on a Chip

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Abstract. Dielectric Laser Acceleration (DLA) achieves gradients of more than 1 GeV/m, which are among the highest in non-plasma accelerators. The long-term goal of the ACHIP collaboration is to provide relativistic (>1 MeV) electrons by means of a laser driven microchip accelerator. Examples of "slightly resonant" dielectric structures showing gradients in the range of 70% of the incident laser field (1 GV/m) for electrons with beta=0.32 and 200% for beta=0.91 are presented. We demonstrate the bunching and acceleration of low energy electrons in dedicated ballistic buncher and velocity matched grating structures. However, the design gradient of 500 MeV/m leads to rapid defocusing. Therefore we present a scheme to bunch the beam in stages, which does not only reduce the energy spread, but also the transverse defocusing. The designs are made with a dedicated homemade 6D particle tracking code.

1. Introduction
The Accelerator on a Chip (ACHIP) collaboration [1] aims to construct a source of relativistic electrons out of a shoe-box size Dielectric Laser Accelerator (DLA). Furthermore, the collaboration also aims at radiation generation by means of laser driven undulators. Beyond the acceleration of relativistic electrons [2], recent experiments also addressed DLA for subrelativistic electrons [3, 4]. Since only the evanescent near field which decays as exp(-ωy/(βγc)) contributes to acceleration, both the gradients and the apertures are smaller in subrelativistic structures. In Figure 1 we present a novel DLA structure that contains both features of a side-coupled grating accelerator and a Bragg-waveguide accelerator. This structure is "slightly resonant" and thus presents a compromise between filling time and acceleration gradient. The structure constant is the ratio between the gradient and the incident laser field and can be conveniently expressed by the normalized resonant spatial Fourier coefficient \( \xi_m \) as

\[
SC = \frac{\max \{\Delta W\}}{eE_{z0}\lambda_y} = |\xi_m|,
\]

where \( E_{z0} \) is the incident (z-polarized) laser field and \( \varphi = 2\pi s/\lambda_y \) is the phase of a particle at a distance \( s \) behind a design particle. The resonant integer \( m \) fulfills the Wideroe condition \( \lambda_y = m\beta\lambda_0 \), where \( \lambda_y \) is the structure period. Usually the fundamental \( |\xi_1| \) is the largest coefficient so we will restrict ourselves to \( m = 1 \) in the following. The thickness of the Bragg reflection layers is \( d = (1/4 + n/2)\lambda_0/\sqrt{\varepsilon_r} \), where the integer \( n \) can be chosen according to practical requirements of the fabrication aspect ratio and the required height. The structure constant can be determined using time domain simulations (here: CST MWS [5]), evaluated at the center frequency of the broadband spectrum. Alternatively, we developed a dedicated finite element (FEM) code in the frequency domain [6], which was also used to optimize the \( \beta = 0.91 \) version of the Bragg structure.
2. Accelerator Design
We propose a structure that comprises ballistic bunching followed by velocity matched acceleration, see Figure 2. For simplicity we assume that the structure is driven from both lateral sides with a cw laser. In the choice of initial electron beam parameters we follow [3], i.e. $\beta = 0.3165$, $\sigma_E = 10$ eV and the transverse emittance is disregarded at first. The parameters of the structure are summarized in Table 1 and shall be discussed in detail in the following.

2.1. Velocity bunching
Velocity bunching is well known for both ion and electron beams. The idea is to modulate a coasting beam such that it has a sinusoidal correlated energy spread pattern. A following drift section for subrelativistic beams (or a dispersive chicane for relativistic beams) will transform the energy modulation into a phase modulation of $\Delta \phi = \pi/2$, at which the longitudinal focus is
Table 1. Accelerator parameters

| Parameter                        | Value                      |
|----------------------------------|----------------------------|
| Laser strength                   | 1 GV/m                     |
| Aperture                         | 200 nm                     |
| Buncher periods                  | 3                          |
| Buncher period length $\lambda_{g0}$ | 620 nm        |
| $\Delta W_{\text{corr}}$ (incl. fringe) | $\approx 1.6$ keV |
| $L_{\text{Drift}}$ (total)      | 5.06 $\mu$m                |
| $L_{\text{Drift, int}}$         | 8 $\lambda_{g0}$           |
| $L_{\text{Drift, frac}}$ (incl. ph. corr.) | 0.16 $\lambda_{g0}$ |
| Accelerator $|\xi_1|$ | 0.73 (initial) |
| Linear chirp $\Delta z$         | 3.2 nm/cell                |
| Chirp decrement $\Delta \Delta z$ | 16 pm/cell |
| Synchronous phase $\varphi_s$   | 47$^\circ$                 |
| Acceptance $\Delta E_{\text{max}}$ | 2 keV                     |
| Synchrotron frequency $f_s$     | 4.53 THz (initial)         |
| Gradient                         | 500 MeV/m (initial)        |

reached. This happens in $T = \lambda_g/(4\Delta \beta c)$ and thus the length needs to be

$$L_{\text{int}} = \beta c T = \frac{\lambda_{g0}}{4} \frac{\beta}{\Delta \beta} = \frac{\beta^2 \gamma^3}{4} \frac{m_e c^2}{\Delta W_{\text{kin}}} \lambda_g,$$

(2)

where the energy-velocity differential is $d\beta = d\gamma/(\beta \gamma^3)$. The energy modulation can be realized with more than one grating cell, since the drift between the cells is negligible, see Figure 3. The particles pile up at the zero crossing of the modulator phase and can be injected exactly at the designed synchronous phase $\varphi_s$ by a fractional period drift

$$L_{\text{frac}} = \lambda_{g0} \frac{\pi}{2} - \varphi_s + \Delta \varphi_B,$$

(3)

where $\Delta \varphi_B$ is a phase correction due to the buncher fringe fields, see Figure 2 bottom. The total length of the drift is $L_{\text{Drift}} = \lambda_{g0}[L_{\text{int}}/\lambda_{g0}] + L_{\text{frac}}$, where the square brackets denote integer rounding.

Figure 3. Buncher longitudinal phase space
2.2. Energy spread acceptance

The energy spread acceptance and the initial synchrotron frequency are determined similarly to ordinary RF accelerators. The tracking equations can be approximated by differential equations cast in the form of Hamilton’s equations, which can be integrated in the conjugate variables $\tau = \varphi / \omega_0$ and $\Delta W = \gamma m_e c^2 \delta$ to find the Hamiltonian as

$$H(\varphi, \delta) = \frac{m_e c^2}{2 \beta^2 \gamma} \delta^2 - e E_{z0} |e_1| \frac{\lambda_g}{2\pi} (\sin \varphi - \varphi \cos \varphi_s). \quad (4)$$

The separatrix is found by the value of $H$ at the saddle point $\varphi_{saddle} = -\varphi_s$ as

$$\delta_{sep}(\varphi) = \pm \sqrt{\frac{2 \beta^2 \gamma}{m_e c^2} \left[ H(-\varphi_s, 0) - H(\varphi, 0) \right]}.$$  \quad (5)

The bucket height gives the energy spread acceptance $\Delta E_{\text{max}} = \gamma m_e c^2 \delta_{sep}(\varphi_s)$ as depicted in Figure 4. Moreover, from the Hamiltonian in Equation (4) the second order differential equation

$$\frac{\partial^2 \varphi}{\partial t^2} = \frac{2\pi e E_{z0} |e_1|}{\gamma^3 m_e \lambda_g} \left[ \cos(\varphi) - \cos(\varphi_s) \right]$$

can be derived. Assuming $\varphi = \varphi_s + \Delta \varphi$ the small amplitude synchrotron frequency is found as

$$f_s = \frac{\omega_s}{2\pi} = \sqrt{\frac{e E_{z0} |e_1|}{2\pi \gamma^3 m_e \lambda_g}} \sin(\varphi_s). \quad (6)$$

2.3. Chirped grating

In order to trap the particles with energy spread and phase spread in the bucket and accelerate, the phase of the accelerating Fourier coefficient needs to be as constant as possible along the chirped grating. This is achieved in the same manner as tuning RF cavities, namely by adjusting a geometry parameter that is still free. Here, the tooth width $t$ is taken as

$$t = t^{(0)} \left( \frac{\lambda_g / \lambda_g^{(0)}}{\xi} - 1 \right) + 1,$$  \quad (8)}
Figure 5. Establishing (almost) constant phase (4 deg jitter) by adjusting the tooth width with $t^{(0)} = 200$ nm and optimal phase flatness for $\xi \approx 2.7$, see Figure 5. Once phase stability is established, the design of the entire structure can proceed according to the scheme in Figure 6.

The linear chirp $\Delta z^{(n)} = \lambda^{(n+1)}_g - \lambda^{(n)}_g$ is given by

$$\Delta z^{(n)} = \lambda_0 \Delta \gamma = \frac{\lambda_0 \Delta \gamma}{\gamma^2 \beta} = \left[ \frac{\lambda_0}{\beta \gamma^2} \Delta W(\varphi_s)^{(n)} \right]^{(n)}, \quad (9)$$

where $\Delta W^{(n)} = m_e c^2 \Delta \gamma^{(n)}$ is the energy gain in the $n$-th grating period. The decreasing amplitude of $\xi_1$ is taken into account by writing $\Delta z^{(n)} = \Delta z^{(1)} - (n-1) \Delta \Delta z$. Note that $\Delta z$ and $\Delta \Delta z$ are averages and are thus not requirements for the fabrication precision. The slight change in the phase of the Fourier coefficients (Figure 5) leads to an identical change of the synchronous phase, causing a small additional energy spread increase. The acceleration ramp obtained by a CST tracking simulation is shown in Figure 7, where 72 particles represent a uniform distribution. The synchrotron motion is clearly visible, its initial period agrees roughly with $\lambda^{\text{init}} = 21 \mu m$ calculated by Equation (7).

Figure 6. Iteration process for the design of a chirped grating
Figure 7. Energy gain along the structure for 72 particles launched at $t = 0$ sweeping over the laser phase in steps of 5 degrees. The fraction of trapped particles is 81%.

3. Optimized bunching
When taking into account finite transverse emittance, the acceleration defocusing plays a decisive role. Already in the modulator the electrons are strongly focused or defocused, depending on their arrival wrt. the laser phase. Adding a demodulator (same structure as the modulator but half a period displaced) at the end of the drift section will decrease the energy spread and the initially defocused particles will be focused and vice versa, see Figure 8. The headline of the transverse plots gives the percentage of particles that survived the aperture.

Figure 8. Longitudinal phase space and grating setup (top) and transverse phase space ($y' = \gamma \beta_y$), where the color indicates the particle phase $\varphi$ (bottom).
4. Conclusion and Outlook
We introduced a novel ”slightly resonant” DLA structure that combines Bragg waveguides and symmetric grating structures. We showed that the longitudinal dynamics in DLAs for low energy can be well controlled, in a similar manner as for conventional accelerators. The acceleration defocusing due to the high gradient can however not be compensated by solenoid or quadrupole magnets. Thus in future dedicated laser driven focusing schemes as outlined in the last section and approaches to the transverse dynamics have to be developed.

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