DESIGNING A DIELECTRIC LASER ACCELERATOR ON A CHIP

U. Niedermayer*, O. Boine-Frankenheim and T. Egenolf, TEMF, TU Darmstadt, Germany

Abstract

Dielectric Laser Acceleration (DLA) achieves gradients of more than 1GeV/m, which are among the highest in non-plasma accelerators. The long-term goal of the ACHIP collaboration [1] 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.

INTRODUCTION

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 $\exp(-\omega y/(\beta\gamma c))$ contributes to acceleration, both the gradients and the apertures are smaller in subrelativistic structures. In Fig. 1 we present a novel DLA structure that

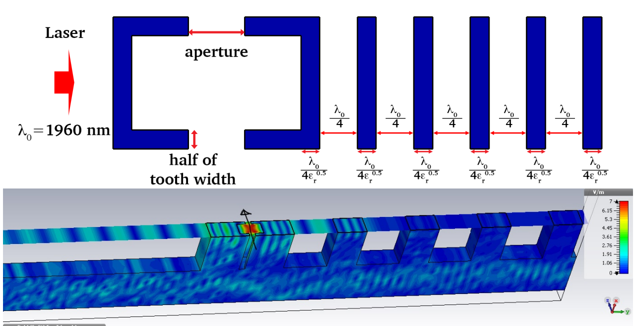

Figure 1: Bragg mirror cavity structure (Silicon $\varepsilon_r = 11.63$, length $\lambda_g = 620$nm) for n=0 (top) and 3D simulation for n=3 and height 3μm (bottom). The black arrow indicates the electron trajectory at which the structure is periodic.

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 $\underline{e}_m$ as

$$SC = \frac{\max_\varphi\{\Delta W\}}{eE_{z0}\lambda_g} = |\underline{e}_m|, \qquad (1)$$

* niedermayer@temf.tu-darmstadt.de

where E_{z0} is the incident (z-polarized) laser field and $\varphi = 2\pi s/\lambda_g$ is the phase of a particle at a distance s behind a design particle. The resonant integer m fulfills the Wideroe condition $\lambda_g = m\beta\lambda_0$, where λ_g is the structure period. Usually the fundamental $|\underline{e}_1|$ 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.

ACCELERATOR DESIGN

We propose a structure that comprises ballistic bunching followed by velocity matched acceleration, see Fig. 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 Tab. 1 and shall be discussed in detail in the following.

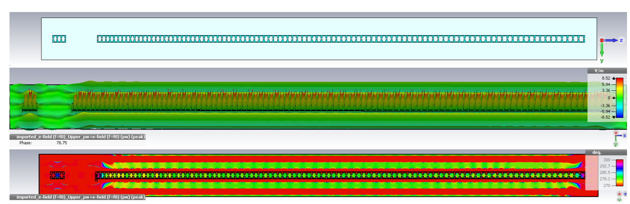

Figure 2: Chirped accelerator structure with 100 periods (top), longitudinal electric field amplitude (center), and phase (bottom) along the chirp.

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 $\Delta\varphi = \pi/2$, at which the longitudinal focus is reached. This happens in $T = \lambda_g/(4\Delta\beta c)$ and thus the length needs to be

$$L_{\text{drift,int}} = \beta c T = \frac{\lambda_g}{4}\frac{\beta}{\Delta\beta} = \frac{\beta^2\gamma^3}{4}\frac{m_e c^2}{\Delta W_{\text{kin}}}\lambda_g, \qquad (2)$$

where the energy-velocity differential is $\mathrm{d}\beta = \mathrm{d}\gamma/(\beta\gamma^3)$. The energy modulation can be realized with more than one

Copyright © 2017 CC-BY-3.0 and by the respective authors

ISBN 978-3-95450-182-3

Table 1: Accelerator Parameters

Laser strength	1 GV/m
Aperture	200 nm
Buncher periods	3
Buncher period length λ_{g0}	620 nm
ΔW_{corr} (incl. fringe)	$\approx$ 1.6 keV
L_{Drift} (total)	5.06 μm
$L_{\text{Drift,int}}$	8 λ_{g0}
$L_{\text{Drift,frac}}$ (incl. ph. corr.)	0.16 λ_{g0}
Accelerator $\lvert \underline{e}_1 \rvert$	0.73 (initial)
Linear chirp Δz	3.2 nm/cell
Chirp decrement $\Delta\Delta z$	16 pm/cell
Synchronous phase φ_s	47°
Acceptance ΔE_{max}	2 keV
Synchrotron frequency f_s	4.53 THz (initial)
Gradient	500MeV/m (initial)

grating cell, since the drift between the cells is negligible, see Fig. 3. The particles pile up at the zero crossing of the modulator phase and can be injected exactly at the designed synchronous phase φ_s by a fractional period drift

$$L_{\text{frac}} = \lambda_{g0} \frac{\pi/2 - \varphi_s + \Delta\varphi_B}{2\pi}, \tag{3}$$

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

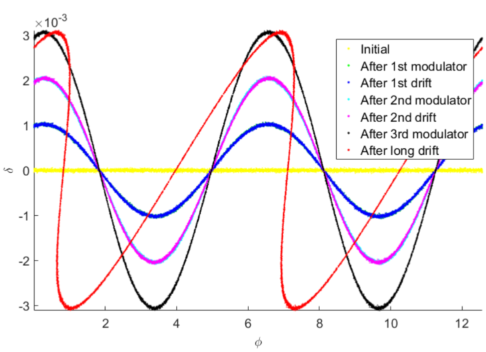

Figure 3: Buncher longitudinal phase space.

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

$$H(\varphi, \delta) = \frac{m_e c^2}{2\beta^2\gamma}\delta^2 - eE_{z0}|\underline{e}_1|\frac{\lambda_g}{2\pi}(\sin\varphi - \varphi\cos\varphi_s). \tag{4}$$

The separatrix is found by the value of H at the saddle point

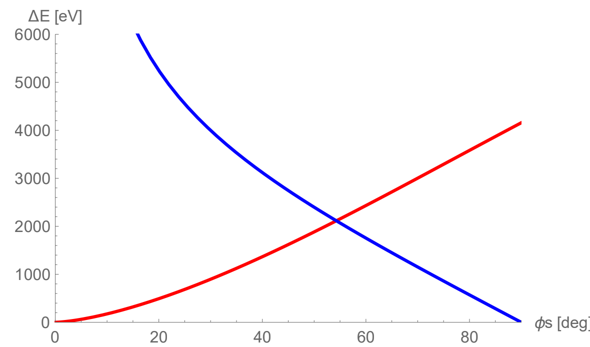

Figure 4: Energy spread acceptance (red) and energy gain per quarter synchrotron period (blue) as function of the synchronous phase φ_s

$\varphi_{\text{saddle}} = -\varphi_{\text{s}}$ as

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

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

$$\frac{\partial^2\varphi}{\partial t^2} = \frac{2\pi}{\gamma^3}\frac{eE_{z0}|\underline{e}_1|}{m_e\lambda_g}[\cos(\varphi) - \cos(\varphi_s)] \tag{6}$$

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

$$f_s = \frac{\omega_s}{2\pi} = \sqrt{\frac{eE_{z0}|\underline{e}_1|}{2\pi\gamma^3 m_e\lambda_g}\sin(\varphi_s)}. \tag{7}$$

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

$$t = t^{(0)}\left(\frac{\lambda_g/\lambda_g^{(0)} - 1}{\xi} + 1\right), \tag{8}$$

with $t^{(0)}$ =200 nm and optimal phase flatness for $\xi \approx 2.7$, see Fig. 5. Once phase stability is established, the design of

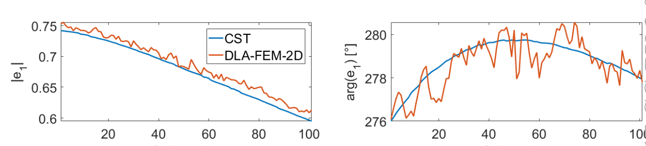

Figure 5: Establishing (almost) constant phase (4 deg jitter) by adjusting the tooth width.

Copyright © 2017 CC-BY-3.0 and by the respective authors

ISBN 978-3-95450-182-3

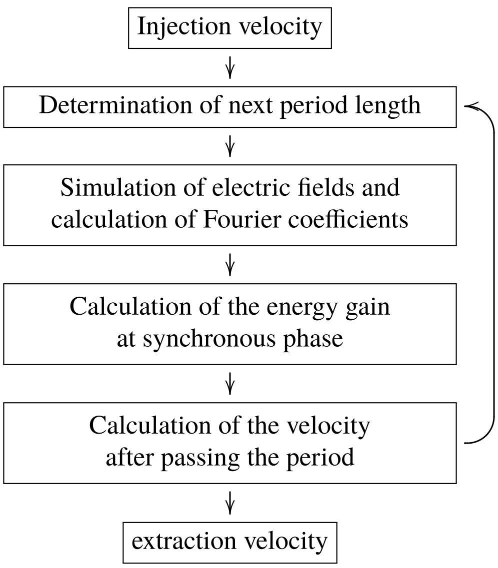

Figure 6: Iteration for the design of a chirped grating.

the entire structure can proceed according to the scheme in Fig. 6. The linear chirp $\Delta z^{(n)} = \lambda_g^{(n+1)} - \lambda_g^{(n)}$ is given by

$$\Delta z^{(n)} = \lambda_0 \Delta\beta = \frac{\lambda_0 \Delta\gamma}{\gamma^3 \beta} = \left[\frac{\lambda_0}{\beta\gamma^2} \frac{\Delta W(\varphi_s)}{\gamma m_e c^2} \right]^{(n)}, \tag{9}$$

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 $\underline{e}_1$ is taken into account by writing $\Delta z^{(n)} = \Delta z^{(1)} - (n-1)\Delta\Delta z$. Note that Δz 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 (Fig. 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 Fig. 7, where 72 particles represent a uniform distribution. The synchrotron motion is clearly visible, its initial period agrees roughly with $\lambda_s^{\mathrm{init}} = 21\ \mu$m calculated by Eq. 7.

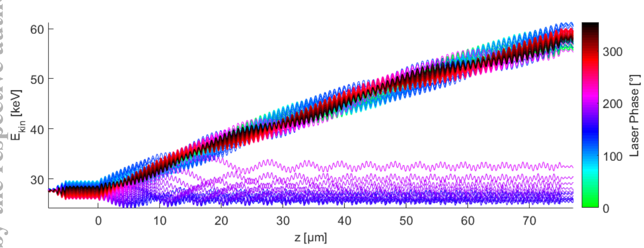

Figure 7: Energy gain along the structure for 72 particles launched at $t = 0$ sweeping over the laser phase in steps of 5 degrees. The fraction of trapped particles is 81%.

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 Fig. 8. The headline of the transverse plots gives the percentage of particles that survived the aperture.

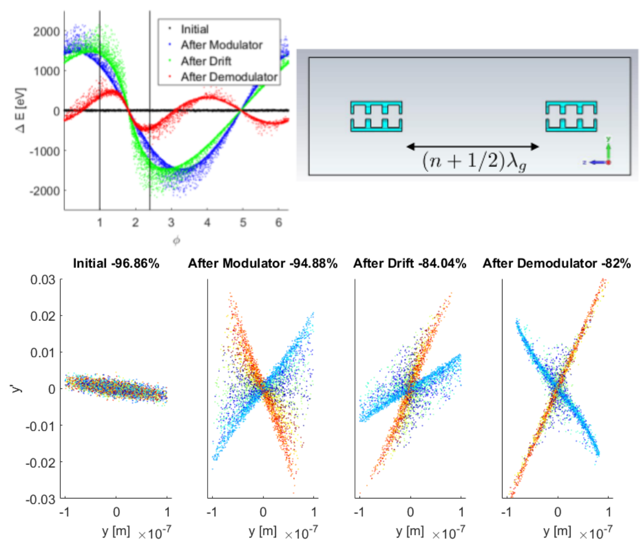

Figure 8: Longitudinal phase space and grating setup (top) and transverse phase space ($y' = \gamma\beta_y$), where the color indicates the particle phase φ (bottom).

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.

ACKNOWLEDGMENT

This work is funded by the Gordon and Betty Moore Foundation (Grant GBMF4744 to Stanford) and the German Federal Ministry of Education and Research (Grant FKZ:05K16RDB).

REFERENCES

[1] ACHIP website: `https://achip.stanford.edu`

[2] E. A. Peralta et al., Nature 503, 91 (2013)

[3] J. Breuer and P. Hommelhoff, PRL 111, 134803 (2013)

[4] K. J. Leedle *et al., Optics Letters* 40, 18 (2015)

[5] `www.cst.com`

[6] T. Egenolf et al., paper WEPVA002, presented at IPAC 2017.

Copyright © 2017 CC-BY-3.0 and by the respective authors