A CONCEPT FOR PHASE-SYNCHRONOUS ACCELERATION OF MICROBUNCH TRAINS IN DLA STRUCTURES AT SINBAD

F. Mayet[1], R. Assmann, J. Boedewadt, R. Brinkmann, U. Dorda,
W. Kuropka[1], C. Lechner, B. Marchetti, J. Zhu[1], DESY, Hamburg, Germany
[1]also at University of Hamburg, Germany

Abstract

The concept of dielectric laser accelerators (DLA) has gained increasing attention in accelerator research, because of the high achievable acceleration gradients (GeV/m). This is due to the high damage threshold of dielectrics at optical frequencies. In the context of the Accelerator on a Chip International Program (ACHIP) we plan to inject electron bunches into a laser-illuminated dielectric grating structure. At a laser wavelength of 2 micro-meter the accelerating bucket is <1.5 fs. This requires both ultra-short bunches and highly stable laser to electron phase. We propose a scheme with intrinsic laser to electron synchronization and describe a possible implementation at the SINBAD facility (DESY). Prior to injection, the electron bunch is conditioned by interaction with an external laser field in an undulator. This generates a sinusoidal energy modulation that is transformed into periodic microbunches in a subsequent chicane. The phase synchronization is achieved by driving both the modulation process and the DLA with the same laser pulse. This allows scanning the electron bunch to laser phase and will show the dependence of the acceleration process on this delay.

INTRODUCTION

The Accelerator on a Chip International Program (ACHIP) funded by the Gordon and Betty Moore Foundation aims to demonstrate a working prototype of a particle accelerator on a chip until 2021. Being part of the ACHIP collaboration DESY aims to conduct related test experiments in its upcoming dedicated accelerator R&D facility SINBAD [1]. The goal is to inject ultra-short relativistic electron bunches produced by the ARES linac [2], which is currently under construction at SINBAD, into a Dielectric Laser Accelerator (DLA) structure [3] for further acceleration, or deflection.

In [4] first plans and simulations for a first DLA experiment at SINBAD using short low-charge single bunches are presented. Here we propose a scheme with intrinsic laser to electron synchronization and describe how it could be implemented at the SINBAD facility at a later stage using the ARES linac as the starting point.

The DLA grating structures to be used in the context of the ACHIP project are driven at a laser wavelength of 2 microns. Considering the theory behind the electromagnetic fields in the accelerating channel [5,6] it can be seen that for net-acceleration without significant induced energy spread a FWHM bunch length of <1.5 fs is needed. This implies the need for both ultra-short bunches and highly stable laser to electron phase and is pushing the limits of what is possible with the current classical accelerator technology.

In order to meet these requirements and also at same time inject as much charge as possible into the accelerating buckets, we propose to use a scheme that has already been proven to be successful in other contexts [7,8]. We want to apply this scheme in the context of grating DLAs.

The main idea of the scheme is to condition a relatively[1] long bunch in a way that it is transformed into a train of ultra-short microbunches. If done correctly, these microbunches then populate the periodic accelerating buckets in a phase stable manner. In the following the scheme is presented in detail.

BEAM CONDITIONING SCHEME

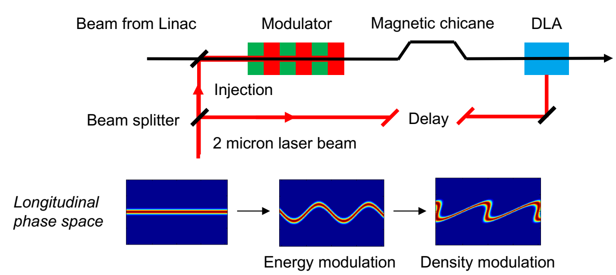

Figure 1: Basic representation of the microbunching scheme using a modulator and a chicane.

Figure 1 shows a sketch of how the scheme works. The incoming long electron bunch is modulated inside the *modulator*, into which a laser pulse is colinearly injected in a way that it overlaps with the electron bunch in time and space. The external laser field consequently imprints an energy modulation onto the electron distribution, which can in the plane wave approximation be expressed as [9]

$$\Delta\gamma = \sqrt{\frac{P_L}{P_0}}\frac{2KL_u\mathcal{J}}{\gamma w_0}\cos(k_L s), \qquad (1)$$

where s is the comoving longitudinal coordinate, P_L the laser beam power, $P_0 \approx 8.7\,\mathrm{GW}$, K the undulator parameter, L_u the undulator length, w_0 the laser waist, k_L the laser wave number and $\mathcal{J} = J_0(\xi/2) - J_1(\xi/2)$ with $\xi = K^2/(2+K^2)$. This energy modulation can then be transformed into a density modulation, which ultimately (and ideally) results in a train of microbunches. If the energy of the incoming electrons is low enough this transformation can be achieved by a simple drift, but in case of highly relativistic electrons a dispersive section such as a magnetic chicane has to be

[1] With reference to the 2 micron period length (→ 6.67 fs) of the DLA structure, relatively long would correspond to bunch lengths >100 fs.

used. Once the train of microbunches is formed it can be transported into the DLA structure. If both the modulator and the DLA are driven by the same laser and the relative phase jitter between the two arms is negligible, intrinsic phase synchronisation between the microbunches and the DLA field can be achieved. Any laser to electron bunch phase jitter in the DLA caused by the laser system or the electron time of arrival is compensated due to the fact that the intrabunch phase of the microbunch train is also shifted by the same amount. In other words: The modulator acts as a focusing device in the time/phase domain.

PHASE SPACE AND STABILITY CONSIDERATIONS

Even though the scheme ideally completely mitigates incoming timing jitter, in reality both the phase space of the to-be-modulated beam, as well as the machine stability can impair its performance. In the following some aspects are exemplarily discussed.

Longitudinal Phase Space

The process of microbunching is ultimately based on energy dependent path lengths in a dispersive section. Assuming ideal microbunching due to the modulation process, the longitudinal phase space of the incoming beam defines the best achievable microbunch train quality in terms of length and dephasing of the individual microbunches. Consider an electron with an energy deviation $\Delta\gamma = \gamma - \gamma_0$ from the reference energy γ_0. The longitudinal displacement due to this energy deviation after traversal of a beamline section with longitudinal dispersion R_{56} is given by

$$\Delta s = R_{56}\delta, \qquad (2)$$

where $\delta = \Delta\gamma/\gamma_0$. Hence any uncorrelated energy spread will lead to a broadening of the microbunch. Therefore the minimum microbunch length due to uncorrelated energy spread σ_δ can be estimated as

$$\sigma_{s,\mathrm{min}} \approx |R_{56}|\sigma_\delta . \qquad (3)$$

For the same reasons any correlated energy spread will result in a dephasing of the individual microbunches. Thus the incoming correlated and uncorrelated energy spread need to be kept as small as possible. Expanding on the above mentioned the permissible energy deviation δ_{max} can be estimated. In order to allow for efficient net acceleration without large energy spread growth we set the maximum allowed phase difference due to longitudinal dispersion to $\pi/4$ (corresponding to 0.83 fs). Hence

$$|\Delta\phi| = k_{\mathrm{DLA}}|\Delta s| = k_{\mathrm{DLA}}R_{56}\delta \leq \frac{\pi}{4}, \qquad (4)$$

where $k_{\mathrm{DLA}} = k_0/\beta$ is the synchronous wave number of the DLA structure [5] with the wave number of the drive laser k_0 and the normalized particle velocity $\beta = v/c$. From this we obtain

$$\delta \leq \frac{\pi}{4} \cdot \frac{1}{k_{\mathrm{DLA}}R_{56}}. \qquad (5)$$

In our case $\lambda_0 = 2\,\mu$m, $R_{56,\mathrm{tot}} \approx 500\,\mu$m and hence $\delta \leq 5 \cdot 10^{-4}$.

Stability

As already mentioned the timing jitter of the incoming electron beam is minimized due to the fact that the both the modulator and the DLA are driven by the same laser. Nevertheless however timing jitter does have an effect on the performance of the microbunching process. This is mainly due to the finite laser pulse length and its assumed Gaussian time profile. If the laser pulse is not uniform in time, any relative laser to electron timing jitter in the modulator will influence the quality of the overlap. The consequence of this is that the time of flight jitter is mapped to a microbunch length jitter as the modulation strength changes.

One of the most crucial parameters of the incoming electron beam is its mean energy stability. Due to the non-zero R_{56} of the modulator beam line section all incoming energy jitter is directly mapped to a longitudinal phase jitter at the DLA (see above). This is a substantial contribution to any residual laser to RF jitter at the DLA interaction point. Hence the energy stability of the linac is of upmost importance for this scheme to work. Imposing the same phase difference limit of $\pi/4$ and using the same arguments as above, the energy stability of the linac needs to be better than $5 \cdot 10^{-4}$. According to the expected rms amplitude and phase stability of the S-band system at ARES [10, 11] the simulated energy stability of the working point used for this study is $4.3 \cdot 10^{-4}$, which would correspond to an rms phase jitter contribution slightly smaller than our limit of $\pi/4$.

EXPERIMENTAL SETUP AND SIMULATIONS

In this section a possible extension of the ARES beamline as well as simulations based on a 10 pC ARES working point are presented.

Experimental Setup

Figure 2 shows a sketch of the beamline. It comprises the ARES linac with its S-band gun and two S-band travelling wave structures, the modulator beamline, a DLA target and a spectrometer.The modulator beamline can be devided into a matching section the modulator itself and the dispersive section including final focusing to the DLA.

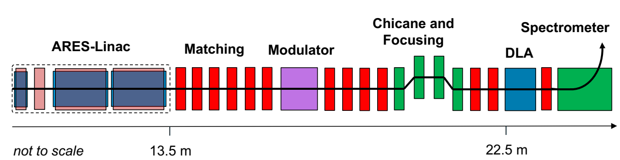

Figure 2: Schematic overview of the proposed beamline. The beam direction is from left to right. The schematic is not to scale. Red elements correspond to quadrupoles, green elements to dipoles.

Simulations

We present preliminary simulations of the scheme using multiple codes. The ARES working point shown in Table 1 is simulated using ASTRA [12] including space charge and

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Table 1: Simulated Beam Parameters for the Exemplary ARES Working Point. The slice energy spread is given for the 6 period (12 µm) core of the bunch.

Parameter @ 13.5 m	Value
Charge [pC]	10
Bunch Length [fs, rms]	269
E [MeV]	68.6
δ	$1.1 \cdot 10^{-4}$
δ_{slice}	$0.4 \cdot 10^{-5}$
$\epsilon_{n,xy}$ [nm]	283

optimized towards minimal energy spread and chirp. The bunch is then inserted into the matching section, which is calculated using ELEGANT [13]. Following this step the distribution is converted to GENESIS [14] in order to simulate the laser-electron interaction in the modulator. The modulator parameters are summarized in Table 2. After that ELEGANT is again used to transport the energy modulated beam up to the DLA target. The DLA experiment is then simulated by employing an analytical tracking based on VSim 7.2 [15] results [6]. Figure 3 shows a slice of the $z-x$ phase space of the simulated beam at the DLA entrance, as well as the obtained microbunch properties. Prior to the DLA simulation the beam is collimated in order to accomodate the <2 µm channel width. Figure 4 shows the achieved energy gain of

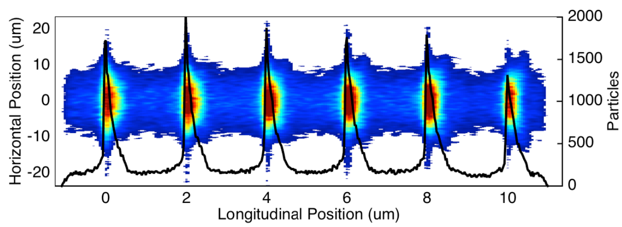

Figure 3: $z-x$ phase space of a longitudinal 6 period slice of the simulated beam at the DLA entrance showing 6 consecutive microbunches. The black line corresponds to the projection across the horizontal axis (y axis on the right). Microbunch length: (699 ± 88) as FWHM, spacing: (2.00 ± 0.01) µm.

Table 2: Modulator Parameters Used for the GENESIS Simulation

Parameter	Value
Laser Pulse	
Peak Power [MW]	2.0
Pulse Duration [fs,rms]	300
Pulse Energy [µJ]	1.5
Wavelength [µm]	2.0
Modulator	
Periods	30
Period length [m]	0.0314
Undulator Parameter	1.63

the slice due to the DLA interaction for the microbunched and unmodulated beam for comparison. It can be seen that the acceleration efficiency is cleary enhanced. In Fig. 5 the absolute energy spectrum is shown. We simulate a 100 period dual grating DLA with is operated close to damage threshold. This corresponds to a single particle energy gain of ~ 300 keV. The pre-DLA spectrum in Fig. 5 shows the energy spread caused by the modulation process. Post-DLA the spectrum shows substantial energy gain of the distribution, but also reveals a broadening due to un-bunched background electrons. The accelerated fraction is 0.75.

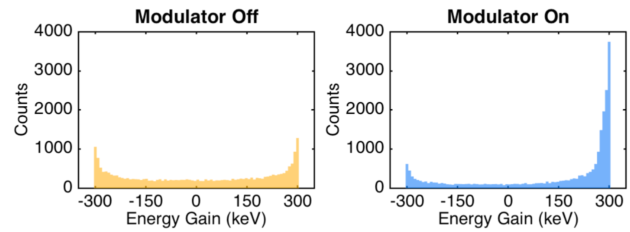

Figure 4: Simulated energy gain spectrum of the transmitted/collimated part of a 6 period slice after the DLA interaction. Acceleration is enhanced in the modulated case.

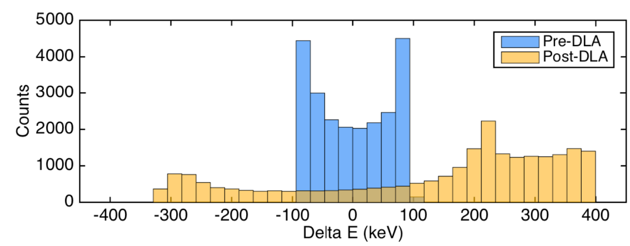

Figure 5: Simulated energy spectrum of the transmitted/collimated part of a 6 period slice of the modulated beam before and after the DLA interaction (ΔE w.r.t the initial mean energy).

CONCLUSION AND OUTLOOK

We have presented a scheme that can potentially increase the laser to electron phase stability in external injection based DLA experiments substantially. This concept has already been successfully tested with other laser-based acceleration methods. The challenging requirements of the 2 micron grating DLAs call for both ultra-short bunches and ultra-stable laser to electron phase. Therefore we think that the presented scheme is exceptionally well suited to be implemented in this context. We have furthermore shown preliminary simulations showing what beam parameters could be achieved with an extension of the ARES beamline at SINBAD. These simulations need to be expanded in the future to include collective effects such as space charge and CSR in the modulation beamline.

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