SIMULATIONS AND PLANS FOR A DIELECTRIC LASER ACCELERATION EXPERIMENT AT SINBAD

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Abstract

In this work we present the outline of an experimental setup for dielectric laser acceleration of relativistic electron bunches produced by the ARES linac under construction at the SINBAD facility (DESY Hamburg). The experiment will be performed as part of the Accelerator on a Chip International Program (ACHIP), funded by the Gordon and Betty Moore Foundation. At SINBAD we plan to test the acceleration of already pre-accelerated relativistic electron bunches in a laser-illuminated dielectric grating structure.

In addition to the conceptual layout of the experiment we present first start-to-end simulation results for different ARES working points. The simulations are performed using a combination of the well known particle tracking code ASTRA and the self-consistent particle in cell code VSim.

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 will conduct related test experiments at its SINBAD facility. The goal is to inject ultra-short relativistic electron bunches produced by the ARES linac [1], which is currently under construction at SINBAD [2], into a Dielectric Laser Accelerator (DLA) [3] for further acceleration or deflection.

Here we present plans for the first DLA experiments at SINBAD using electrons produced by ARES. In addition to the conceptual layout of the experiment we present possible linac working points and a first estimation of the expected results using a β-matched dual grating type DLA structure [4] illuminated by a 2 micron laser. To this end we combine the particle tracking code ASTRA [5] and the self-consistent Particle-In-Cell (PIC) code VSim 7.2 [6].

The SINBAD Facility

The dedicated accelerator R&D facility SINBAD (Short INnovative Bunches and Accelerators at Desy) is a new facility at DESY, which is foreseen to host multiple independent experiments. Two experiments are currently under construction: ARES (Accelerator Research Experiment at Sinbad) and AXSIS. The ACHIP experiments are planned to be conducted at the ARES linac (see Fig. 1). The ARES linac is a conventional 100 MeV S-band linac, which is designed to produce sub-fs electron bunches with charges in the range of 0.5-20 pC. To this end the electrons are first accelerated in a 1.5 cell S-band gun to 5 MeV and then further accelerated in two S-band travelling wave (TW) structures. The first of the two TW structures can be used for velocity bunching.

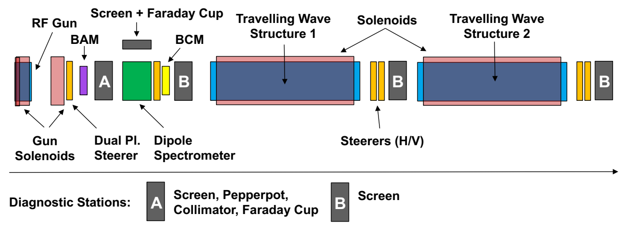

Figure 1: The ARES linac.

Transverse focusing is achieved using multiple solenoids (cf. Fig. 1). The accelerator is planned to be available for experiments in mid 2019. In a future upgrade a second compression technique using a magnetic chicane with a slit is planned to be implemented [7]. In order to be able to match into the chicane four quadrupoles form a matching region 4 m downstream the second TW structure (see Fig. 2).

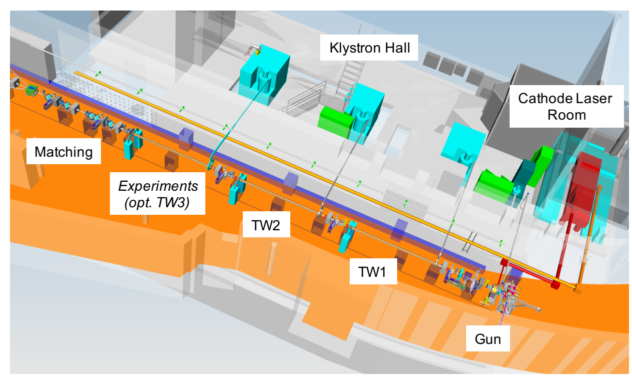

Figure 2: The ARES linac, experimental area and matching region.

PLANS FOR A DLA EXPERIMENT

In the first stage the ACHIP experiments are planned to be conducted within the 4 m gap between the two TW structures and the matching region (see Fig. 3). After the interaction

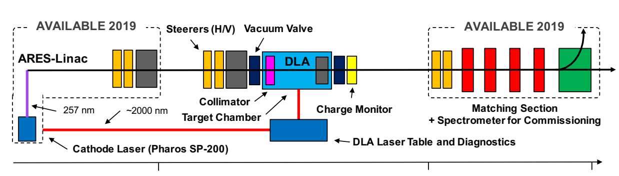

Figure 3: Sketch of the ARES beam line and the preliminary layout of the first ACHIP experiment.

point the beam will be transported through the matching region to a dipole spectrometer in order to measure the energy gain/modulation. For the first ACHIP experiments we plan to use part of the ARES cathode laser beam as the driver for the DLA. To this end the initial 1030 nm beam is split and converted on the one hand to 257 nm and on the other to 2000 nm, which is needed to drive the DLA. Since in the currently planned setup this split is permanent and cannot be bypassed, the splitting ratio is chosen to maximize the pulse energy at the DLA while taking the constraint into account that other high charge experiments are still possible. Since both the photo emission and the DLA are driven by the same laser system, in this configuration the relative electron to laser phase jitter is simply given by the RF-induced beam arrival time jitter contribution. An important property of this system is the intrinsic coupling of cathode and DLA laser beam parameters. This is important to note, because the laser pulse length should be as short as possible at the cathode (ultra-short, low-emittance electron bunches), but long enough to maximize the interaction length at the DLA. This issue is discussed in more detail in the following.

SIMULATIONS AND THEORETICAL CONSIDERATIONS

Laser Pulse Length Optimization

As already stated above for the first DLA experiments at SINBAD the cathode laser system will drive both the cathode and the DLA. Without additional optics on the DLA laser arm the laser pulse length at the cathode and the DLA are directly linked. In the following it is assumed that the individual pulse lengths are more or less equal[1]. At the cathode the laser pulse length directly determines the achievable electron bunch length at the interaction point. For a given charge and optimized maximum compression in TW1 a minimal bunch length can be found (due to the space charge limit, or the minimal achievable laser pulse length of 80 fs rms). For optimal acceleration in the DLA (low curvature and hence minimal induced energy spread) it is desirable to aim for as short bunches as possible. At the same time the interaction distance is limited by the laser pulse duration (and the laser spot size) at the DLA[2]. It is hence possible for a given pulse energy to find an optimal laser pulse length, which both maximizes the overall energy gain (via the interaction length) and minimizes the induced energy spread due to field curvature. For the following simple illustration we assume that the laser spot size is always adjusted in a way that the pulse length is limiting the interaction distance[3].

For the derivation of the optimal laser pulse length in the coupled case the following quantities need to be defined. We are interested in the accelerating gradient in the DLA channel. We define it as $G = E \cdot \eta$, where E is the incident electric field and η is the conversion efficiency to the synchronous spatial harmonic. It is desireable to give the accelerating gradient in terms of the laser pulse energy $W_L = \int_0^T P(t)dt$, where P_L is the laser power defined by $P(t) = I(t) \cdot A$ and T is the pulse length[4]. The intensity of a momochromatic linearly polarized lase beam in vacuum is given by $I(t) = \frac{\epsilon_0 c_0}{2} E(t)^2$, where ϵ_0 is the vacuum permittivity and c_0 is the speed of light in vacuum. For simplicity we assume a round laser spot and hence the area $A = \frac{\pi d^2}{4}$, where d is the beam diameter. Now it is possible to express the accelerating gradient in terms of the laser pulse energy and the laser pulse σ.

$$G(t) = \sqrt{\frac{8}{c_0^3 \epsilon_0 \pi} \frac{W_L}{\sigma^3} \frac{1}{2\sqrt{\pi}}} \cdot e^{-\frac{t^2}{2\sigma^2}} \cdot \eta \qquad (1)$$

Here $d = c_0 \cdot 2\sigma$ was used, which physically means that the interaction distance due to the spot size is set equal to the interaction distance due to the effective temporal pulse length. In order to stay below damage threshold the laser spot size can be increased. The gradient is hence given by the piecewise function

$$G = \begin{cases} G & \text{if } \frac{G}{\eta} < E_{\mathrm{thr}} \\ E_{\mathrm{thr}} \cdot \eta & \text{if } \frac{G}{\eta} \geq E_{\mathrm{thr}} \end{cases} \qquad (2)$$

where E_{thr} is the damage threshold field for the given material.

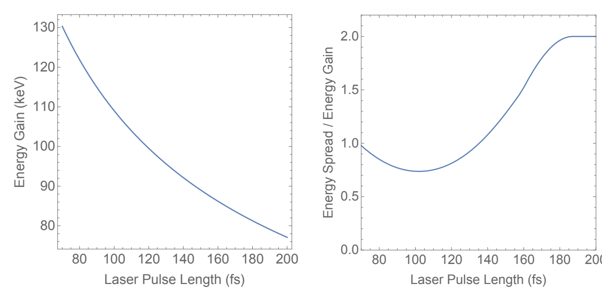

Figure 4: Laser pulse length optimization for a case of limited laser pulse energy of 6 µJ at the DLA. E_{thr} for our case is assumed to be ~8 GV/m (fused silica [8]).

Working Points

Figure 4 shows both the achievable energy gain and the ratio between induced energy spread and energy gain as a function of the laser pulse length. The calculation is based on Eq. (2) and ASTRA simulations of the achievable electron bunch length. In order to minimize the ratio between energy gain and induced energy spread shown in 4 a laser pulse length of 100 fs was chosen for the determination of possible ARES working points. This would correspond to an ideal achievable accelerating gradient of ~2 GeV/m. The possible properties of the electron bunch at the interaction point can

[1] In reality because of non-linear processes during the conversion processes the pulse lengths will differ.

[2] Due to the strong velocity bunching we assume that our bunch is always much shorter than the interaction distance.

[3] Investigations towards the possibility of stretching and/or further amplifying the DLA laser pulse are currently under way. Since stretching the pulse introduces a chirp, the DLA interaction might be substanially altered.

[4] Here a temporal Gaussian with a usable width of 2σ is assumed.

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be found in Table 1. The beam parameters were simulated using ASTRA including space charge and optimized using LinacOpt [9] for two different initial bunch charges. It has to be noted that the low charge working point (0.05 pC) is shown in order to illustrate the theoretical capabilities of the linac, reaching FWHM bunch lengths close to 1/4 of the DLA period. Due to the small channel width of ~1 µm the beam needs to be collimated. This can imply a substantial charge loss. Even though beams with charges <15 fC can be detected using specialized intensified camera arrangements [10], measuring the energy spectrum of such a beam is challenging.

Table 1: Simulated Working Points for Minimal Bunch Length Using Velocity Bunching

Parameter @ IP	**WP 1**	**WP 2**
Charge [pC]	0.05	0.5
Bunch Length [fs, FWHM]	1.8	2.1
E [MeV]	87.6	99.1
ΔE/E [%]	0.05	0.12
σ_{xy} [μm]	6.2	7.8
$\epsilon_{n,xy}$ [nm]	104	105

Simulation

We have conducted simulations for each working point using a combination of ASTRA and VSim 7.2. The procedure combines the simulation of the ARES working point up to the DLA (ASTRA-based) and the DLA interaction[5] (VSim-based). In this work we focus on the achievable energy gain/modulation. The beam is assumed to be collimated just upstream of the DLA. Figure 5 shows the energy spectrum of the transmitted part before and after the DLA interaction respectively. The results show that the bunch is already short enough to accelerate a sizable fraction of its collimated core ~80 % in both cases. In practice the realization of acceleration with low energy spread growth will of course rely strongly on the incoming time of flight jitter, which has to be kept to a minimum. A concept to drastically minimize this incoming arival time jitter is discussed in [11].

CONCLUSION AND OUTLOOK

We have presented plans and simulations for first DLA experiments to be conducted once the ARES linac is available for experiments mid 2019. The first experiments at ARES aim to show not only modulation of long electron bunches ($\sigma_z \gg 0.25 \cdot \lambda_s$), but also (net-)acceleration with as small as possible energy spread growth. Since the minimum achievable bunch length for the first experiments is limited by the velocity bunching scheme to values above 1 fs FWHM and incoming time of flight jitter can blur the spectrum significantly, in second tier experiments we also pursue the acceleration of phase-synchronous sub-fs microbunch trains [11]. Furthermore development of the laser system is still on-going in order to increase the possible interaction distance and with that the achievable energy gain.

[5] Any possible interaction of the electrons with the dielectric material is not taken into account.

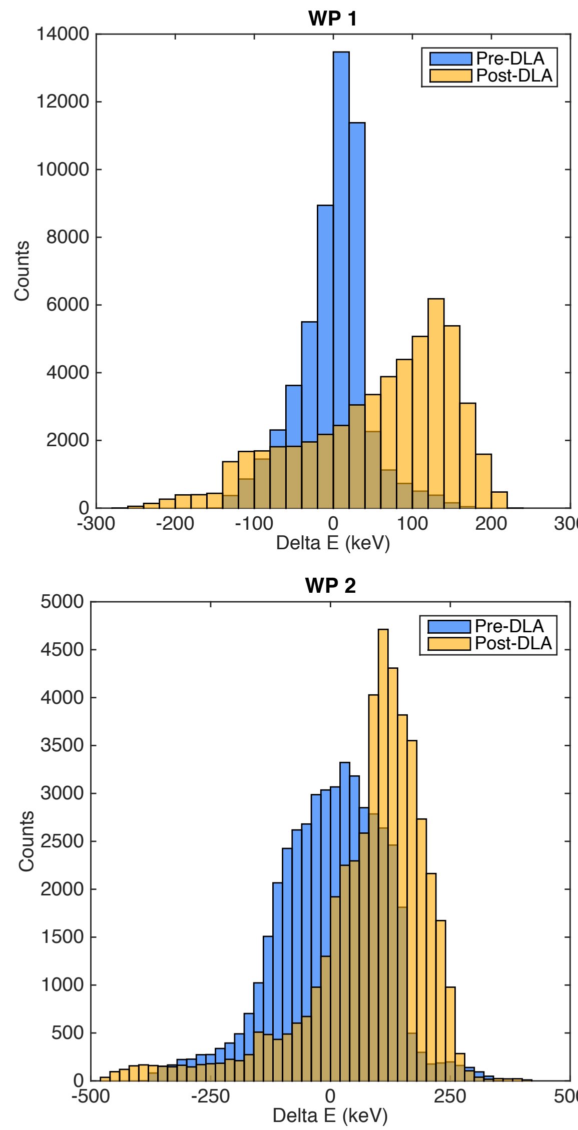

Figure 5: Simulated energy spectrum of the transmitted part of the bunch before and after the DLA interaction. The bins are chosen according to the expected minimum energy resolution of the spectrometer ($\sim 10^{-4}$).

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