STUDY OF LASER WAKEFIELD ACCELERATORS AS INJECTORS FOR SYNCHROTRON LIGHT SOURCES

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Abstract

Short bunch lengths, high beam energies, and small facility footprint make Laser WakeField Accelerators (LWFA) very interesting as injectors for Synchrotron Light Sources. In this paper, we describe exemplary investigations for the ANKA storage ring.

INTRODUCTION

In addition to their high achievable beam energy and small footprint, the short bunch lengths customary for Laser WakeField Accelerators (LWFA) make them very interesting as injectors for Synchrotron light facilities for two reasons: i) The length of the emitted photon pulse is directly proportional to the length of the emitting bunch. LWFA bunches would, therefore, allow to study processes on a much faster time scale. ii) For wavelengths longer than the length of the emitting bunch, the emission becomes coherent. As a result, the intensity increases dramatically. LWFA bunches would, therefore, allow to extend the radiation spectrum of storage rings far into the THz, a region currently difficult to access with high intensity.

Using the ANKA light source at KIT [1] as an example, we investigate the possibility to use an LWFA as injector and to store ultra-short bunches in a Synchrotron.

We show that whilst it is possible to store LWFA generated bunches, it is difficult to preserve their ultra short length over many turns.

LWFA SIMULATIONS

3D Particle In Cell (PIC) simulations have been carried out using VLPL [2]. The input parameters are given in Table 1. The resulting longitudinal electron energy distribution is shown in Fig. 1. The ANKA lattice used for our investigations has a momentum acceptance $\Delta p/p_0 \approx \pm 1\,\%$, indicated by the solid area. Discarding all particles outside this energy window, the resulting beam parameters are given in Table 2. Note that despite the small emittance, the very small beam size leads to very large divergence angles. Table 4 gives the parameters of the used ANKA lattice for comparison.

Table 1: VLPL Input Parameters

Plasma density n_0 in cm^{-3}	9×10^{18}
Laser wavelength λ_L in nm	800
RMS Laser pulse duration τ_L in fs	13
RMS Laser radius at focus r_L in nm	720
Laser pulse energy E_L in J	4.6

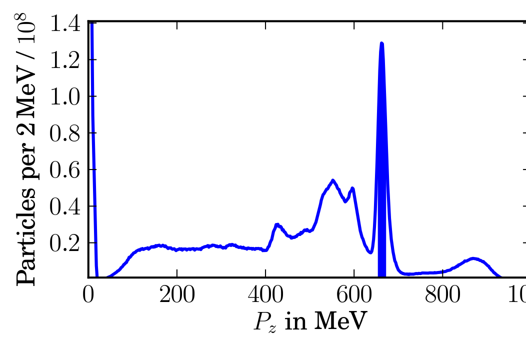

Figure 1: Longitudinal energy distribution of LWFA generated electrons. The energy acceptance of the used ANKA lattice of 662 MeV ± 1 % is indicated by the solid area.

Table 2: LWFA e^--Beam Parameters

Central energy p_0 in MeV	662
Allowed energy range in MeV	655 - 669
RMS energy spread δ in %	0.5
Bunch charge q in pC	160
Number of particles N	1.0×10^9
Geometric emittance ϵ_{geo} in m × rad	$1.8 \cdot 10^{-8}$
Normalized emittance ϵ_{norm} in m × rad	$2.3 \cdot 10^{-5}$
RMS Bunch length σ_z in μm	1.1
RMS Bunch length σ_z in fs	3.7
RMS Bunch radius σ_r in μm	1.6
RMS Divergence in rad	0.01
Twiss $\alpha_x = \alpha_y$	0.0
Twiss $\beta_x = \beta_y$ in m	1.4×10^{-4}

TRANSFER TO SYNCHROTRON

The initially round beam beam described in Table 2 has to be matched to the flat beam parameters accepted by the ANKA storage ring, listed in Table 3. Using MAD-X [3], a solution has been found using pulsed quadrupoles [4]. These quadrupoles offer a field strength of about 1400 T/m,

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ISBN 978-3-95450-122-9

significantly higher than conventional quadrupoles. However, due to their pulsed nature, the injection would be limited to 1 pulse every few seconds. The exemplary transfer line is shown in Fig. 2. It has not been studied in detail yet, as the main focus of this work is the behavior of these short bunches in a storage ring. In particular, the chromaticity has not been corrected, leading to a noticeable lengthening of the bunch. The challenges associated with the coupling of LWFA beams with conventional accelerators have been studied in more detail e.g. by [5, 6]. For now, we will assume that a suitable transfer solution can be found.

Table 3: ANKA Twiss Parameters at Injection Point

Horizontal beta β_x in m	16.6
Vertical beta β_y in m	6.5
Horizontal alpha α_x	-0.03
Vertical alpha α_y	-0.07

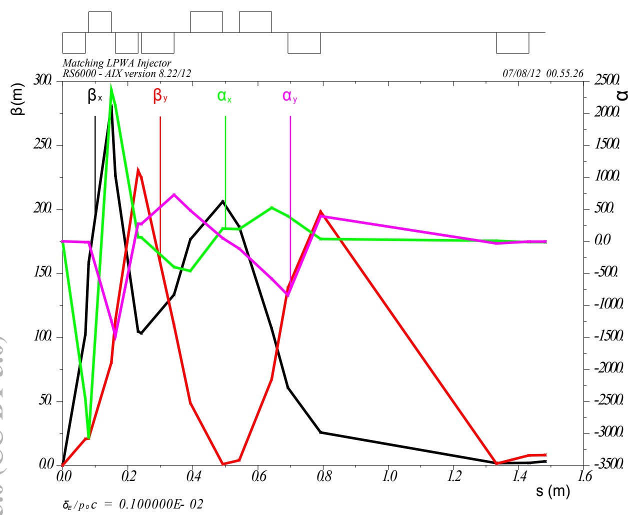

Figure 2: Exemplary transfer line, matching the LWFA generated bunches to the ANKA storage ring.

BEHAVIOR IN SYNCHROTRON

Naively, one might assume that the lengthening of the initially short LWFA bunch happens on a time scale given by the radiative damping time. For the ANKA lattice at 662 MeV studied here, this would correspond to a few hundred ms (a few million turns). If a LWFA would be used as full energy injector (for this energy), this could have been sufficient for dedicated user operation. Unfortunately, simulations using the Accelerator Toolbox for Matlab [7] show that the initially short bunch lengthens much faster, already by several orders of magnitude in the first revolution. This can be understood by looking at the momentum compaction factor $\alpha_c = 1/L \times \oint [D(s)/\rho(s)]ds$, the integral over the dispersion D along the ring. Via the relation

$$\alpha_c \frac{\Delta p}{p_0} = \frac{\Delta L}{L} \qquad (1)$$

it gives the path length difference ΔL per revolution for a particle of energy deviation Δp [1]. ANKA has a circumference $L = 110.4\,\mathrm{m}$. Depending on the optic used, the momentum compaction factor is in the order of $10^{-4} < \alpha_c < 10^{-2}$. Due to its larger momentum acceptance, we used the ANAK injection optics for our studies, resulting in a large α_c. For the particles with the maximal investigated energy deviation $\Delta p/p_0 = 0.01$, this results in a path length difference of $1\,\mathrm{cm} \lesssim \Delta L \lesssim 100\,\mu\mathrm{m}$ or $30\,\mathrm{ps} \lesssim \Delta L/c_0 \lesssim 300\,\mathrm{fs}$ respectively - much more than the initial $1.1\,\mu\mathrm{m}$! The bunch quickly expands to the maximal acceptance of the RF system, reaching it after about 100 turns. Then, it starts to converge back towards the equilibrium bunch length of the lattice. The process is illustrated in Fig. 3 and Fig. 4. The parameters of the used ANKA lattice are given in Table 4.

Table 4: Used ANKA Lattice Parameters at 662 MeV

Central energy p_0 in MeV	662
Cavity voltage in kV	200
Cavity frequency in MHz	499
Circumference in m	110.4
Revolution time in ns	368
Momentum compaction factor	0.008
Natural RMS energy spread	2.4×10^{-4}
Natural geometric emittance in m×rad	$6.8 \cdot 10^{-9}$
Radiation energy damping time in ms	79
Linear energy acceptance in %	1.1
Synchrotron tune in kHz	22.7
Synchrotron tune in turns	119.5
RMS Bunch length in mm	4.0
RMS Bunch length in ps	13.4

DISCUSSION

The work presented here investigated fundamental principles, it has not been optimized to the fullest extend possible. In particular:

i) LWFA simulations have been performed to the point of depletion of the driving Laser pulse. Effects at the plasma exit have not been considered. The decrease of plasma density at the boundary should result in an increase of beam size and a decrease in beam divergence. This would mitigate the constraints on the transfer line.

ii) For our exemplary study, ANKA has not been optimized for maximal energy acceptance. It seems reasonable to increase the maximal energy acceptance to a few percent. For $\Delta p_{max}/p_0 = 0.03$, this would allow to store about 50 % more charge from the initial LWFA bunch.

In contrast, preserving the ultra-short bunch length seems challenging. With a dedicated low-α optic, the momentum compaction factor α_c can be reduced by two orders of magnitude compared to the one of the lattice used in our studies. Applying a stricter energy cut of e.g. $\Delta p_{max}/p_0 = 10^{-3}$ could reduce the path length difference per revolution by another order of magnitude (at the

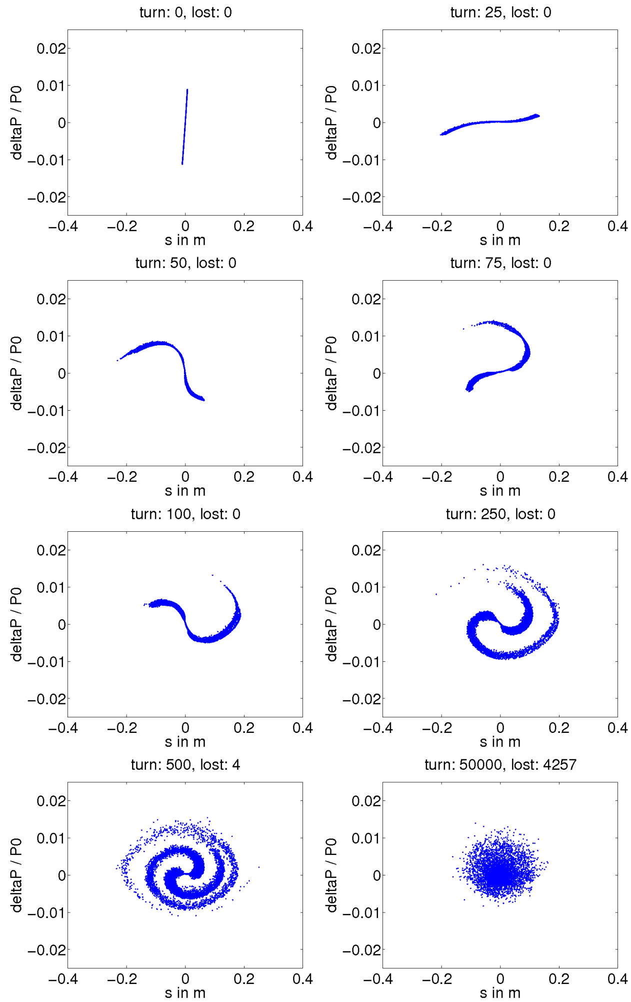

Figure 3: Evolution of longitudinal phase space (top left to bottom right) for a maximal initial energy deviation $\Delta p_{max}/p_0 = 0.01$. The change in longitudinal position is consistent with Synchrotron oscillations. Simulations were carried out with 10^4 particles. Cf. Table 4 for the parameters of the lattice used.

cost of a factor of ∼5 in charge). Neglecting all effects in the transfer line, a back of the envelope calculation using Eq. 1 yields that the bunch should lengthen to the ps bunch length, customary for state of the art light sources with dedicated low-α optic, within a few 100 turns.

For an operational facility, the transfer line would have to be studied in more detail, in particular the tolerance for fluctuations of energy and pointing.

SUMMARY

Laser Wakefield Accelerators (LWFA) have been studied as injectors for electron storage rings, using the ANKA Synchrotron light source as an example. Our simulations show that it seems reasonable to inject and store these beams. However, it is difficult to preserve the ultra short length characteristic for LWFA over many turns.

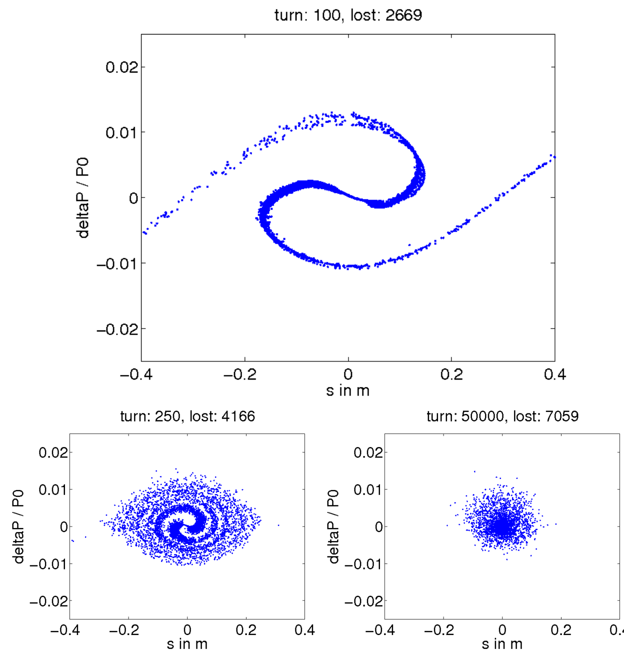

Figure 4: Evolution of longitudinal phase space for a maximal initial energy deviation $\Delta p_{max}/p_0 = 0.03$, exceeding the energy acceptance of the ANKA lattice used. Note how the face space evolves much faster compared to Fig. 3. Also, note that significant fraction of the initial 10^4 simulated particles gets lost very quickly.

ACKNOWLEDGMENT

This work was supported by the Wolfgang-Gentner-Programme of the German Bundesministerium für Bildung und Forschung (BMBF) and by BMBF-Projekts 05K10VKC at ANKA / KIT and F020214006 at HHUD.

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ISBN 978-3-95450-122-9