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Study of Laser Wakefield Accelerators as injectors for Synchrotron light sources

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ABSTRACT

Laser WakeField Accelerators (LWFA) feature short bunch lengths and high peak currents, combined with a small facility footprint. This makes them very interesting as injectors for Synchrotron light sources. Using the ANKA Synchrotron as an example, we investigate the possibility to inject a LWFA bunch into an electron storage ring. Particular emphasis is put on the longitudinal evolution of the bunch.

1. Introduction

Laser WakeField Accelerators (LWFA) feature short bunch lengths and high peak currents, combined with a small facility footprint [1,2]. This makes them very interesting as injectors for Synchrotron light sources, as the length of the emitted photon pulse is directly proportional to the length of the emitting electron bunch. LWFA with their intrinsically short bunches would, therefore, allow to study processes on a much faster time scale than currently possible with the bunch lengths customary for Synchrotron storage rings. Furthermore, for wavelengths longer than the length of the emitting electron bunch, the photon emission becomes coherent [3]. As a result, the intensity increases dramatically. Therefore, LWFA bunches would 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 [4] as an example, we investigate the possibility to use a LWFA as an injector and to store ultra-short bunches in a Synchrotron.

2. LWFA simulations

To generate an input distribution for the following studies, 3D particle in cell simulations have been carried out using VLPL [5]. 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.

Depending on the purpose, operation with a larger momentum acceptance or a stronger momentum collimation can be considered. For momentum acceptance changes of a few percent, the other beam parameters remain almost identical, with only a change in charge. Bunch charges for exemplary cuts are given in Table 3.

For comparison, Table 4 gives the parameters of the ANKA lattice used.

3. The ANKA Synchrotron

Depending on the priorities, ANKA offers different modes of operation, ranging from small beam size at the insertion devices (down to $\sigma_x \approx 1$ mm) to small bunch length for increased THz and infrared emission (down to $\sigma_z \approx 0.3$ mm achieved to date, depending on the beam energy and bunch charge [6]). Due to its higher momentum acceptance, we have used the ANKA injection optics for our studies, re-scaled to match the momentum of the LWFA

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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

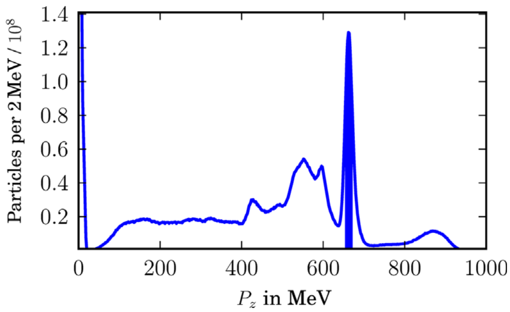

Fig. 1. Longitudinal momentum distribution of LWFA generated electrons. The ANKA lattice used has an acceptance of 662 MeV ± 1%, indicated by the solid area.

Table 2
LWFA e⁻-beam parameters after plasma.

Central momentum p_0 in MeV	662
Allowed momentum range in MeV	655–669
RMS momentum spread δ	5×10^{-3}
Bunch charge q in pC	160
Number of particles N	1.0×10^9
Geometric emittance ε_{geo} in m × rad	1.8×10^{-8}
Normalized emittance ε_{norm} in m × rad	2.3×10^{-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}

Table 3
Resulting bunch charge for different momentum windows, cf. Fig. 1.

Max. $\lvert\Delta p/p_0\rvert$	100%	5%	0.25%
Charge q in pC	24,000	270	61
No. of particles N	1.5×10^{11}	1.7×10^9	3.8×10^8

Table 4
Equilibrium top level parameters of the ANKA lattice used.

Central momentum p_0 in MeV	662
Linear energy acceptance in %	1.1
Cavity voltage in kV	200
Cavity frequency in MHz	499
Circumference L in m	110.4
Revolution time in ns	368
Momentum compaction factor α_c	0.008
Radiation energy damping time in ms	79
Natural RMS energy spread δ	2.4×10^{-4}
Geometric emittance $\varepsilon_{geo,x}$ in m × rad	6.8×10^{-9}
Normalized emittance $\varepsilon_{norm,x}$ in m × rad	8.8×10^{-6}
Synchrotron tune in kHz	22.7
Synchrotron tune in turns	119.5
RMS bunch length σ_z in mm	4.0
RMS bunch length σ_z in ps	13.4

Table 5
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

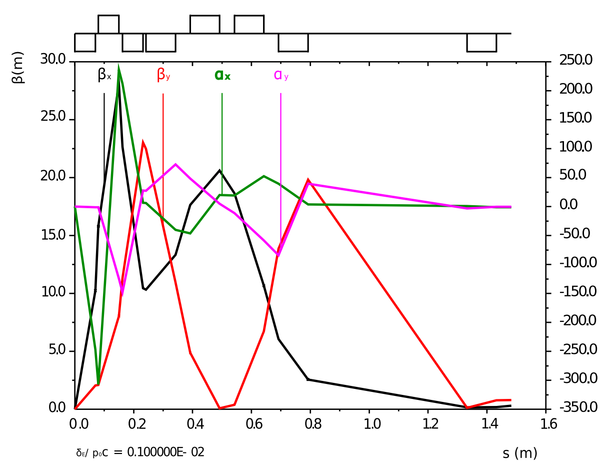

Fig. 2. Exemplary transfer line, matching the LWFA generated bunches to the ANKA storage ring. Rectangles above/below the horizontal line give the position of the focusing/defocusing quadrupoles.

electrons. The key parameters of the lattice used are given in Table 4.

4. Transfer to Synchrotron

To inject the LWFA electron bunch into ANKA, the initially round beam described in Table 2 has to be matched to the flat beam parameters accepted by the ANKA storage ring, listed in Table 5. We have used MAD-X [7] to perform the matching.

Due to the combination of large divergence and high beam energy, we were not able to find a solution using the field strengths and inner diameters customary for normal conducting quadrupoles. Owing to the possibility of quenches induced by radiation and mis-focused particles, we did not consider super conducting magnets. However, a solution has been found using pulsed quadrupoles, offering a field strength of approximately 1400 T/m [8]. For this solution, the beam pipe diameter always corresponded to at least $10\sigma_{x/y}$.

The preliminary transfer line is shown in Fig. 2. It has not been optimized to the fullest extend yet, as the main focus of this work is the behaviour of these short bunches in a storage ring.

In particular, the chromaticity has not been corrected. Owing to the different path lengths travelled by particles of different momentum, this leads to a significant lengthening of the bunch along the transfer line. For our example with $\lvert\Delta p_{max}/p_0\rvert = 0.01$, the bunch length increased by three orders of magnitude to $\sigma_z \approx 5$ mm.

The challenges associated with the coupling of LWFA beams with conventional accelerators have been studied in more detail e.g. in Refs. [9,10]. For now, we will assume that a suitable transfer solution can be found.

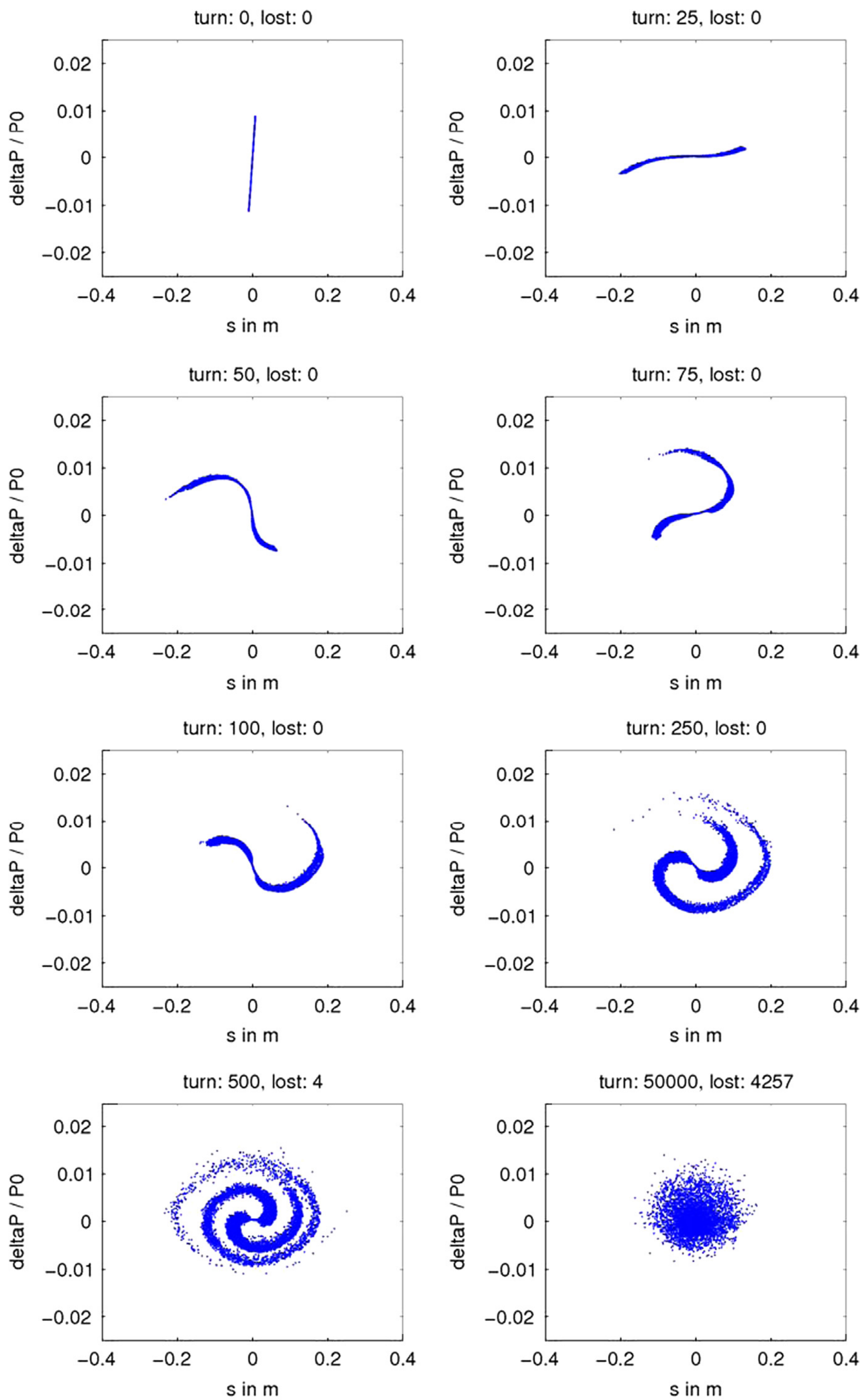

Fig. 3. Evolution of longitudinal phase space (top left to bottom right) for a maximal initial energy deviation $\Delta p_{max}/p_0 = 0.01$. Simulations were carried out with 10^4 particles. Cf. Table 4 for the parameters of the lattice used. Also, cf. Fig. 4.

5. Longitudinal behaviour

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, i.e. a few million turns. If a LWFA were to be used as full energy injector at this energy, this could have been sufficient for dedicated user operation.

Unfortunately, simulations using the Accelerator Toolbox for Matlab (AT) [11] show that the initially short bunch lengthens much faster, reaching a bunch length of several cm after only a few revolutions. This can be understood by looking at the momentum compaction factor

$$\alpha_c = \frac{1}{L} \times \oint \frac{D(s)}{\rho(s)}\, ds, \tag{1}$$

the integral over the dispersion D along the ring, normalized to the circumference L and the local curvature $\rho(s)$. Via the relation

$$\alpha_c \frac{\Delta p}{p_0} = \frac{\Delta L}{L} \tag{2}$$

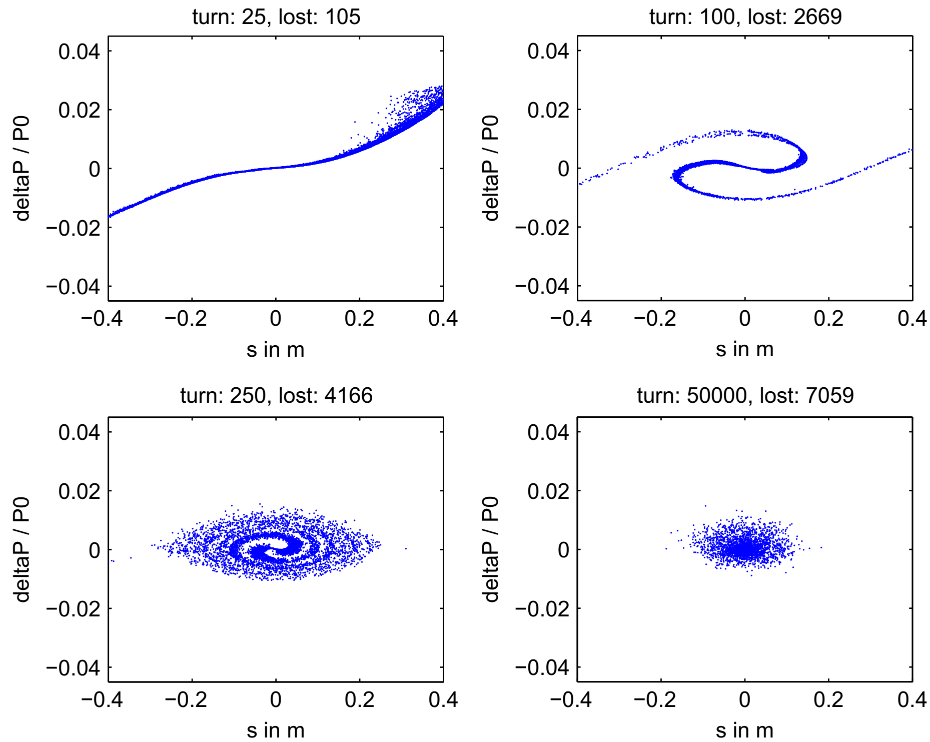

Fig. 4. Evolution of longitudinal phase space for a maximal initial energy deviation $\Delta p_{max}/p_0 = 0.03$, exceeding the energy acceptance of the ANKA lattice used. Note how the phase space evolves much faster compared to Fig. 3. Also, note that significant fraction of the initial 10^4 simulated particles gets lost very quickly by moving out of the acceptance of the RF system ($|s| \lesssim 0.2$ m). Transverse losses have not been considered in these simulations.

it gives the path length difference ΔL per revolution for a particle of momentum deviation Δp [4].

ANKA has a circumference $L = 110.4$ m and, for the optics used for our studies a momentum compaction factor $\alpha_c \approx 10^{-2}$, cf. Table 4. For the particles with the maximal investigated momentum deviation $|\Delta p/p_0| = 0.01$, this results in a path length difference of ± 1 cm or ± 30 ps.

The evolution of the longitudinal phase space is illustrated in Figs. 3 and 4.

Depending on the application, ultra-short radiation pulses are not required. In this case, the evolution of the longitudinal bunch density profile could still lead to interesting radiation properties. As illustrated in Fig. 5, the bunch density develops a sub-structure with a length scale of a few millimetre. This density modulation should lead to an increased production of Coherent Synchrotron Radiation (CSR) for the wavelengths corresponding to the characteristic length of the sub-structures – comparable to the radiation of several short bunches of corresponding charge. However, for a user facility, their reproducibility would have to be investigated further. In particular, the AT simulations did not include particle interaction and coherent effects. Space charge and CSR could therefore change the evolution of the bunch.

6. Transversal behaviour

In the previous section, the focus was on the lengthening of LWFA bunches in a Synchrotron. The transverse behaviour of the bunches has therefore been ignored. The emittance of the LWFA bunch is larger but comparable to the horizontal natural emittance of the ANKA lattice (cf. Tables 2 and 4). However, the vertical emittance of an electron storage ring is normally significantly smaller, typically $\varepsilon_y \lesssim 0.01 \varepsilon_x$.

In practice, the larger beam size due to the larger emittance would result in significant losses to the beam pipe, in particular for the vertical plane. This is especially true for larger accelerators and accelerators with full energy injectors, as their lower natural emittance allows for even smaller beam pipes.

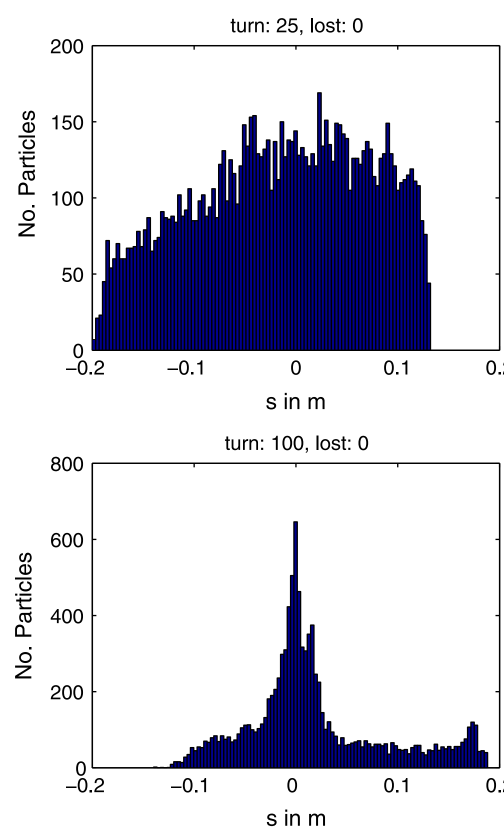

Fig. 5. Longitudinal charge density profiles after 25/100 turns. The bunch develops sub-structures with a characteristic length of a few millimetres. This could lead to an increased CSR production for the corresponding wavelengths.

Effects like β-beating due to the large momentum spread have not yet been studied, and could even accelerate this process.

7. 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 model study, ANKA has not been optimized for maximal energy acceptance. It seems reasonable to increase the maximal energy acceptance to a few percent, e.g. by increasing the RF voltage. In our case, 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_c 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 cost of a factor $\sim$5 in charge). Neglecting all effects in the transfer line, a back of the envelope calculation using Eq. (2) yields that within a few 100 turns, the bunch should lengthen to the ps bunch length, customary for state of the art light sources with dedicated low-α optic [6]. For rings with such capabilities, quasi-isochronous operation could allow for a slower lengthening of the bunch. In Ref. [12], very promising results about the conservation of a short bunch from a linac have been reported.

The evolution of the transverse phase space was not the main focus of this work, and losses to the beam pipe have therefore not yet been considered. In this regard, it is worth pointing out that:

(a) The LWFA simulations this work is based upon were carried out for the simplest case, a laser pulse generating a plasma bubble, accelerating self injected electrons. Methods to control the injection process and to reduce the beam emittance are a major interest, and are very actively researched by many groups, cf. e.g. [13–18].

(b) If a Synchrotron with the aim of producing CSR from ultra short LWFA bunches were to be build, the wavelength of the generated radiation might make the use of larger beam pipes necessary to avoid cut-offs. This in turn would again help to avoid transverse losses.

8. Summary

The evolution of LWFA generated electron bunches in a Synchrotron has been studied.

It was shown that preserving their ultra-short length is very challenging. However, the evolution of their longitudinal density profile could still lead to very interesting radiation properties.

Since LWFA produce round beams, especially their vertical emittance is large compared to the emittances customary for electron storage rings. This can lead to significant losses to the beam pipe.

Acknowledgments

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