USE OF LASER WAKEFIELD ACCELERATORS AS INJECTORS FOR COMPACT STORAGE RINGS*

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Abstract

Compact storage rings require a compact acceleration solution. We propose the use of a laser wakefield accelerator (LWFA) as an injector for compact electron storage rings to produce synchrotron radiation. In particular, we study the injection of 0.7 GeV and 3 GeV electrons into the DIAMOND storage ring and consider implications for future storage ring design. Whilst laser-based acceleration is well-known as a driver for future electron-positron colliders and future free-electron lasers, here we propose it is also advantageous to provide electrons for 3rd-generation storage rings. The electron beams produced by LWFAs have a naturally very small emittance around 1 nm and moderate energy spread of a few percent. Combining these beam parameters with the compact size of a LWFA makes them highly favourable compared to traditional linac or booster synchrotron injector chains.

INJECTION INTO 3RD-GENERATION STORAGE RINGS

Modern 3rd-generation electron storage rings are primarily used to deliver spontaneous synchrotron radiation (SR) at X-ray and longer wavelengths for a variety of scientific purposes, and over fifty such facilities are presently in operation around the world [1]. The most recent generation of rings make use of multi-bend achromat magnetic lattices [2–4] to deliver emittances that approach the diffraction limit of the emitted photons, with design natural emittances often below 1 nm. The very strong focusing required to minimise $< H_x >_s = < \beta_x \eta_x'^2 + 2\alpha_x \eta_x \eta_x' + \gamma_x \eta_x^2 >_s$ in the ring dipoles (once corrected by sextupoles) inherently reduces the dynamic aperture available for beam injection.

Whilst techniques exist to mitigate the vacuum aperture required for beam injection, it is still advantageous to use an injector system that achieves a small emittance. In most SR facilities today a booster synchrotron is used as the final part of the injector chain. A typical specification is illustrated by the present DIAMOND full-energy (3 GeV) booster synchrotron which achieves an emittance of around 150 nm for a circumference of about 150 m [5]. In common with storage rings, the emittance of booster synchrotrons can be readily reduced by increasing the number of dipoles (as demonstrated by the Swiss Light Source design [6]). Alternatively a linear accelerator may be used as is done at the Elettra light source [7]. Whilst the emittance may be much reduced, there is a significant cost and size penalty in using both these methods; even a small booster synchrotron can take up a significant percentage of a SR facility budget. If a reduced-circumference small-emittance (compact) storage ring design is used alongside a small-emittance booster, the building cost of the booster synchrotron will become a significant proportion of the whole facility.

LASER-BASED ACCELERATION

Particle acceleration based on the action of laser pulses has long been proposed as a compact source of high-energy particles, particularly electrons, with many potential applications [8]. One proposed application is to deliver high-energy electron bunches to drive future free-electron lasers (FELs) [9–11]. The motivations for this area of LWFA research are to minimise the cost and space required to achieve electron energies in the GeV range, and to obtain the very short bunch lengths important for FEL gain. However, it is recognised that present laser-based schemes struggle to achieve the circa 0.1 % energy spread needed for most FEL systems.

As a stepping stone toward LWFAs for FEL light sources, we propose their use as injectors into conventional 3rd-generation storage rings. Here, the very small emittances <1 nm are highly favourable for simple, low-loss injection and the energy spreads of a few percent are tolerable. Laser-based acceleration offers a significant saving in building footprint (and probable related cost) over conventional injector chains; for example the DIAMOND booster synchrotron requires roughly 1997 m^2 of land [5] compared to the Berkeley Lab Laser Accelerator (BELLA) facility which occupies a room approximately 650 m^2 [12]. A further advantage is that a small, single accelerator may be placed closer to the storage ring injection point thus eliminating parts of the beam transport system typically required between a booster synchrotron and a storage ring.

Currently LWFAs can produce electron bunches with energies up to 4.2 GeV in the laboratory [13], and with advances in high-intensity laser technology this is expected to increase in the near future to energies around 10 GeV [14]. Many projects are now making use of particle-in-cell (PIC) simulations to model the production of these higher-energy electrons.

LOW-ENERGY INJECTION INTO DIAMOND, WITH RAMPING

We illustrate the use of laser-based injection by showing preliminary tracking results of a laser-derived bunch from PIC simulation, the parameters of which are shown in Table 1. The electrons accumulate in the DIAMOND storage

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Table 1: Properties of the Laser-Derived 0.7 GeV Bunch at Injection

Energy	0.7 GeV
Emittance	2.1 nm
RMS Energy Spread	7 %
Bunch Length	0.9 fs
Bunch Charge	40 pC
Injection Repetition Rate	1 Hz

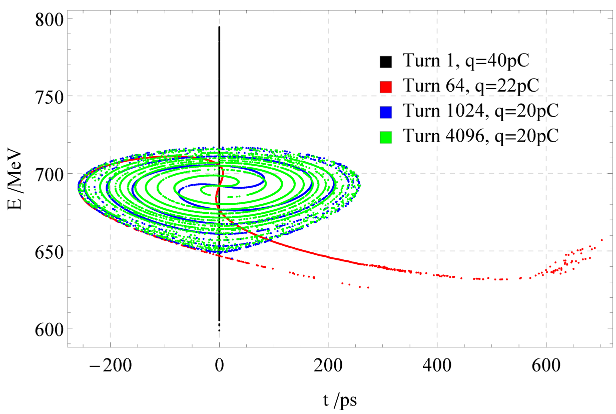

Figure 1: Evolution of the longitudinal phase space for a 0.7 GeV laser-derived electron bunch in DIAMOND.

ring using off-axis injection at 0.7 GeV and the ring energy is then ramped to 3 GeV after sufficient current (e.g. 200 mA) is obtained. Ramping requires a reasonably-long beam lifetime of a few hours (as opposed to using top-up), but this has been used at numerous facilities. Tracking through the DIAMOND lattice was carried out using the Elegant code [15]; the radio frequency (RF) voltage was scaled for 3% momentum acceptance at 0.7 GeV.

Figure 1 shows the evolution of the longitudinal phase space following injection of the 0.7 GeV electron bunch into DIAMOND. As expected, the injected bunch filaments and fills the longitudinal phase in a few synchrotron oscillation periods. The effects of damping from synchrotron radiation emission are weak because of the low beam energy. The predominant source of particle loss, shown in Fig. 2, is due to the injected energy spread being somewhat larger (7%) than the momentum acceptance of DIAMOND (3%) [5]. Most particle loss occurs in the first few turns and by approximately turn 100 the bunch profile has become stable. The injected bunch length is extremely small at 0.9 fs (see black plot on Fig. 1), compared to the natural bunch length of around 17 ps. Hence we may ignore any small lengthening (due to time-of-flight differences) of the injected bunch between the exit of the injector and the entrance of the storage ring, which is only a few femtoseconds in this regime.

FULL-ENERGY INJECTION INTO DIAMOND

Full-energy injection into DIAMOND requires 3 GeV electrons, which are now obtainable by leading-edge LWFAs.

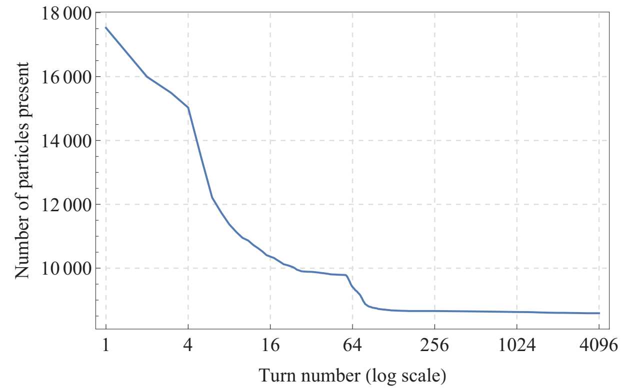

Figure 2: Macro particle loss per turn up to 4096 turns, showing a plateau at around 8600 particles.

Table 2: Properties of the Gaussian 3 GeV Bunch at Injection

Energy	3.0 GeV
Normalised Emittance	2.8 µm
RMS Energy Spread	6 %
Bunch Length	10 fs
Bunch Charge	6 pC
Injection Repetition Rate	1 Hz

Beam parameters for 3 GeV are not readily available, but those for higher-energy beams with (likely) larger energy spread have been published [13]. We make use of these higher-energy beam properties to estimate parameters for a 3 GeV bunch; these values are given in Table 2, where moderate transverse beam sizes of 25 µm, and bunch length of 10 fs have been assumed. A bunch with these parameters (Table 2), Gaussian transverse profiles, linear longitudinal profile and correlated momentum chirp was created and tracked through the DIAMOND light source lattice with the appropriate RF voltage (5.1 MV) for 3% momentum acceptance.

Figures 3 and 4 show the results of the 3 GeV tracking. Again we find that the primary limitation of using this laser-based scheme is due to a larger than desired energy spread. In a similar way to the 0.7 GeV case, the 3 GeV bunch filaments and loses most particles in the first few turns. At this higher energy the effect of radiation damping is apparent, as demonstrated by the emittance reduction between turns 1024 and 4096 on Fig. 3.

FULL-ENERGY INJECTION INTO VERY LOW EMITTANCE STORAGE RINGS

Future electron storage rings for SR production may make use of novel designs that minimise circumference whilst achieving a small emittance; one example is the stacked storage ring [16], another is the torus-knot storage ring [17]. In principle these rings will have similar dynamic aperture and momentum acceptance to earlier 3rd-generation designs and laser-based injection will yield similar efficiencies.

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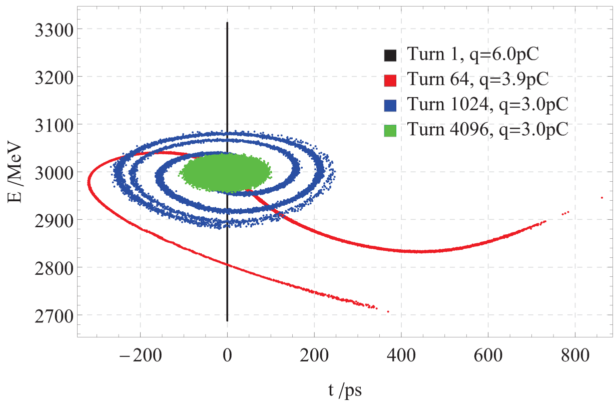

Figure 3: Evolution of the longitudinal phase space of a 3 GeV LWFA-like electron bunch in DIAMOND.

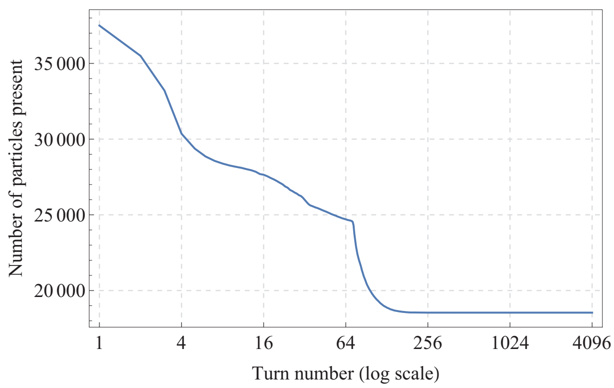

Figure 4: Macro particle loss per turn up to 4096 turns, showing a plateau at around 18500 particles.

CONCLUSIONS

We have shown it is possible to use LWFA electron bunches for injection into 3rd-generation SR storage rings, using the DIAMOND light source as an example. The overall size of a LWFA room and injector is likely to be much smaller than the alternative booster synchrotron or linac, with associated lower cost. For large facilities like DIAMOND the use of LWFA injectors may not provide a significant saving compared to the total build cost, however for future small-circumference storage rings a LWFA injector would be advantageous. The main deficiency in the use of laser-derived electrons is their larger than desired energy spread. Our future work will address whether this drawback can be mitigated in different acceleration schemes without sacrificing the space and cost advantages.

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