STACKING SIMULATIONS FOR COMPTON POSITRON SOURCES OF FUTURE LINEAR COLLIDERS

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Abstract

The Compton positron source of a future linear collider must obtain the target bunch population by accumulating a large number of positron packets, arriving either in a number of bursts from a 'Compton ring', with intermediate damping of the scattering electron beam, or quasi-continually from a 'Compton energy recovery linac'. We present simulation results for the longitudinal stacking of Compton positrons in the ILC damping ring (DR) and the CLIC pre-damping ring (PDR), discussing parameter optimization, stacking efficiency, possible further improvements, and outstanding questions.

INTRODUCTION

A conceptual design of a polarised positron source based on laser Compton scattering in a dedicated "Compton ring" was first proposed at the Snowmass'05 workshop [1] for the International Linear Collider (ILC). Updates & improvements were obtained and documented in the course of several successive workshops [2], at which a Compton source for the Compact Linear Collider (CLIC) has also been studied, and various scenarios have emerged. As an alternative to the original Compton Ring (CR), a Compton Energy Recovery Linac (CERL) is now being considered [3]. Such ERL based source would operate in cw mode, without transient effects, and with larger bunch spacings, with reduced charge per e^- bunch, and at lower bunch frequency. A Compton ring, can or would, operate in a pulsed mode, where short periods of injecting e^+ bunchlets are followed by longer damping intervals.

The Compton sources considered produce positrons in the following way. An electron beam of 1.3–1.8 GeV is collided with a high-power laser pulse stored in an optical cavity, with a laser wavelength of order 1 μm. The total photon yield is about 1 gamma per electron for six 600 mJ cavities with a typical rms spot size of 5 μm at the electron-laser collision point. The Compton scattered photons are next converted into e^+e^- pairs, of which the e^+'s are selected and captured with a simulated yield per photon of order 1%. The total number of positrons produced per pulse in this type of scheme is about 50–1000 times smaller than the number of e^+'s per bunch required in a future linear collider. To reach the desired bunch charge, it is proposed to stack the positrons in an accumulation ring. For example, assuming 10^{10} electrons per bunch in the initial Compton ring or CERL, yields about 10^8 positrons, which means that, for CLIC, at least 40–60 positron bunchlets must be stacked in the same bucket of an accumulator ring to obtain the design bunch charge of about 4×10^9. A schematic of a possible CLIC-CERL positron source is shown in Fig. 1.

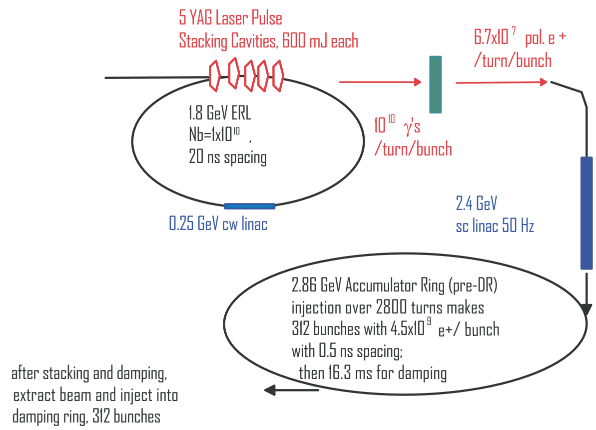

Figure 1: Schematic of CLIC CERL Compton source including typical yields at various steps of the e^+ generation.

There are significant differences between ILC and CLIC with regard to a Compton source: (1) CLIC has a 5 times smaller bunch charge and about 10 times less bunches per pulse than ILC. (2) The CLIC bunch spacing is 0.5 ns instead of about 3 or 6 ns for the ILC DR, which means that at CLIC one cannot stack on every turn in every bucket, but e.g. on every 40th turn with a 20-ns CR/CERL e^- spacing. (3) The CLIC DR needs to produce a beam with an extremely small emittance and is limited in dynamic aperture. Therefore, a PDR is required. This PDR can be used and optimized for stacking the polarized positrons from the CR or CERL source. Alternatively, for CLIC, an efficient stacking could also be performed in two dedicated small stacking rings operated in alternation [4, 5]. The ILC DR has a large circumference to store the much higher number of bunches. Adding a PDR is neither required, nor practical. Therefore, we assume that for ILC the stacking is done in the DR proper. It will be necessary to optimize the parameters of the CLIC PDR and the ILC DR for maximum stacking efficiency. With or without such optimization, the ILC DR has a larger bucket area and a higher synchrotron tune, both facilitating the stacking. (4) The higher CLIC repetition rate of 50 Hz compared to the 5 Hz for ILC can be outweighed by a more than 10-times shorter PDR damping time.

In the following we report on studies of positron stacking for the ILC and CLIC, considering both CR and CERL configurations. The input parameters describing the positrons to be stacked were taken from simulations, which considered 5 optical cavities of 600 mJ each and an electron bunch population of 10^{10}, and showed a yield of 6.65×10^7 positrons per pulse, a longitudinal edge emittance (roughly 10 times the rms emittance) of 0.72 meV-s at 200 MeV, and a transverse normalized edge emittance of 0.63 m-rad [6].

STACKING SIMULATIONS

We consider positron stacking in the longitudinal phase space. Efficient stacking requires the size of the RF bucket to be much larger than the longitudinal edge emittance of the injected positrons. Stacking simulations have the following ingredients: sinusoidal RF, linear and second-order momentum compaction factors, radiation damping, quantum excitation, a nonzero synchronous phase, realistic parameters for the injected positron bunchlets, and the equilibrium beam distribution. It is assumed that the injection septum is placed at a location with large dispersion, and that the thickness of the septum blade is much smaller than the transverse beam size, so that losses on the septum blade can be ignored.

CLIC Pre-Damping Ring

CLIC stacking simulations have been performed considering injection and accumulation in the PDR, whose acceptance we have increased with respect to the present baseline design [7], by doubling the RF voltage and increasing the field of the wigglers (or doubling their number), and through a ten-fold reduction in the momentum compaction factor $\alpha_{c,1}$ (the latter could be increased to its original value after the stacking process, e.g. to stabilize the damped beam). Figure 2 illustrates the bucket size for the design parameters and for the stacking-optimized version. The optimized parameters are listed in Table 1.

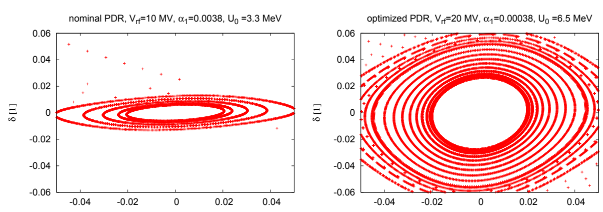

Figure 2: Longitudinal phase space of the CLIC PDR design (left) and stacking-optimized version (right).

Similar to the case of CLIC, the ILC-CR stacking efficiency was optimized by additional DR wigglers for two times faster damping, and a 1.5 times larger RF voltage (see Table 1). Alternatively, one could consider stacking e^+ for only 50 ms simultaneously in both the electron and positron DRs.

The ILC-DR final vertical rms emittance should be $\gamma\epsilon_{y,\mathrm{f}} = 17$ nm. For an initial positron emittance of $\gamma\epsilon_{y,0}$ of 6 mm, the minimum store time T_{store} required, after stacking, follows from $\epsilon_{y,\mathrm{f}} \exp(2T_{\mathrm{store}}/\tau_y) \leq \epsilon_{y,0}$, which yields $T_{\mathrm{store}} \geq 6.4\tau_y = 79.4$ ms, leaving 120 ms for stacking (this number would be 60 ms for the original wiggler strength and/or number of ILC-DR wigglers).

Table 1: Key parameters for the stacking-optimized CLIC PDR and ILC DR. The momentum compaction factor α is expanded as $\alpha_c = \alpha_{c,1} + \alpha_{c,2}\delta + \ldots$, which defines α_2.

parameter	CLIC PDR	ILC DR
#bunches/train	312	2625
bunch spacing	0.5 ns	6.2 ns
final #e$^+$/bunch	4.2×10^9	2.0×10^{10}
circumference	397.74 m	6695 m
RF frequency	2 GHz	650 MHz
RF Voltage	20 MV	36 MV
$\alpha_{c,1}$	0.00038	0.00042
$\alpha_{c,2}$	0.00088	0.0
beam energy	2.86 GeV	5 GeV
longit. damping time	0.58 ms	6.4 ms
eq. momentum spread	0.1%	0.09%
synchrotron tune	0.033	0.084
eq. bunch length	0.9 mm	5.2 mm
bucket area / π	28 meV-s	41 meV-s

CLIC CERL/CR Scheme

For CLIC the number of stacking turns is small, less than 100, and we can, therefore, consider the same stacking process for both the CR and CERL scenarios, where on every 40th turn positron bunchlets are injected into the same PDR bucket. Accordingly a 20-ns bunch spacing is considered for the CERL or CR electron beams, and a suitable CR/CERL-cicumference difference with respect to a multiple of 20 ns is assumed, e.g. 0.15 m corresponding to an injection shift by 0.5 ns from turn to turn. Over 2800 turns or 3.7 ms, 70 injections would be realized, providing the target number of positrons. Following the stacking period would be 12225 turns (16.3 ms) of damping. As the longitudinal damping time is only 0.56 ms, a significant reserve exists, which could be used for lowering the laser power by a factor of 3–5, or the number of collision points, increasing the capture efficiency. The beam is injected with a constant phase offset $z_{\mathrm{off}} = 0.01$ m , and with an optimized constant momentum offset δ of 4% from the center of the bucket, as is illustrated in Fig. 3. The maximum stacking efficiency is about 89%. Snapshots taken during the simulated stacking process are presented in Fig. 4.

A fast orbit bump at the septum ensures that newly injected positrons do not hit the septum on the turn following the injection. The bump amplitude chosen, $A_{\mathrm{bump}} = D_{\mathrm{septum}}\delta_{\mathrm{bump}}$, corresponds to 4 times the initial energy spread ($\delta_{\mathrm{bump}} = 4\sigma_{\delta,0}$), which is taken to be 2.9 MeV and accompanied by an initial bunch length of 7.3 mm, as may be obtained after energy pre-compression [6].

If either the synchrotron tune or the energy loss from synchrotron radiation per turn were very high one could avoid the fast septum bump. In the latter case the condition for avoiding the bump is that the energy loss per turn be larger than the magnitude of the fast septum bump, or $\Delta E_{SR} > 4\sigma_{\delta,0}$. In our example the energy loss is about 6 MeV per turn, which is half of the 12 MeV bump ampli-

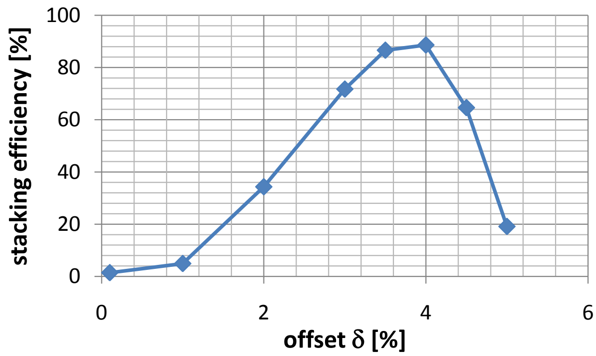

Figure 3: Simulated stacking efficiency for the CLIC-PDR vs. the momentum offset at injection, $\delta_{\rm off}$, for $z_{\rm off}$ = 10 mm. Each bunchlet is represented by 5 macroparticles.

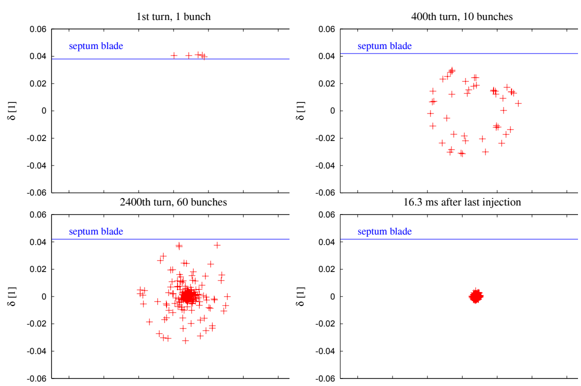

Figure 4: Phase-space snapshots for CLIC-PDR stacking process: first bunchlet on first turn (top left), 10 bunchlets on turn 400 (top right), 60 bunches on turn 2400 (bottom left), and 16.3 ms after last injection (bottom right). The blue line indicates the location of the septum blade.

tude. Therefore, with a two times stronger damping than assumed here the fast bump could be omitted.

ILC CR Scheme

Since 4–5 times more bunchlets need to be injected, the stacking scheme considered here consists of several periods of injections, with intermediate damping. Between successive injections in one injection period the orbit at the septum is monotonically varied with fast bumper magnets and, at the same time, the energy of the injected beam is ramped such that the transverse septum position is always separated by the equivalent of $2\sigma_{\delta,0}$ from the injected beam centroid.

We propose a scheme where bunchlets are injected every second turn (80 MHz) into the same RF bucket of the damping ring, 30 times in total. This is followed by a waiting time of 10 ms (equal to about 450 turns, or 1 damping time) and the entire process is repeated 9 times. The total number of injections per bucket is 300. Such bursting mode of operation still needs to be demonstrated for an optical Fabry-Perot cavity at high finesse.

Injecting with a constant longitudinal offset $z_{\rm off}$ = 0.45 m and with a momentum offset that is minimum at the start of an injection period, $\delta_{\rm min} = 5.7 \times 10^{-3}$, and then increases linearly by $\delta_{\rm step} = 0.175 \times 10^{-3}$ per turn, the simulated stacking efficiency is about 95%.

ILC Compton ERL

For the CERL scheme, instead of cycles, we consider continuous stacking. We choose a bunch frequency of about 32 MHz (implying 18 MW power in the optical cavities). A period of 1020 continuous injections over 5100 turns (injecting into the same bucket on every 5th turn) is followed by 3853 turns (about 86 ms) of damping with a damping time of 6.4 ms. The stacking efficiency is optimized by adjusting the injection momentum offset and injection phase, which are held constant throughout the process. equal to $z_{\rm off} = 0.10$ m, and $\delta_{\rm off} = 1.5\%$. For the ILC the synchrotron phase advance per turn is so high that no fast orbit bump is required at the septum, especially with properly optimized injection phase. The simulated stacking efficiency is 94.2%.

CONCLUSIONS AND OUTLOOK

We presented stacking schemes for CLIC and ILC Compton positron sources based either on an energy-recovery linac or a Compton ring. The parameters of the CLIC PDR and of the ILC DR were optimized for efficient stacking (Table 1). The stacking processes are summarized in Table 2. Stacking efficiencies of about 90% or higher are obtained with off-momentum off-phase injection for all schemes. There is quite some flexibility in the design assumptions. Nevertheless a few challenges remain, for example related to the off-momentum dynamic aperture of the stacking rings. Stacking is helped by a short damping time, a small energy spread of the injected positrons (possibly with energy pre-compression), a large ring momentum acceptance (small $\alpha_{c,1}$, low $\alpha_{c,2}$, large RF voltage, higher harmonic rf), and a sufficiently long store time.

Table 2: Stacking Processes and Simulated Efficiencies

parameter	CLIC	ILC	
	CR/CERL	CR	CERL
#injections/bucket	70	330	1020
e^-/bunch [10^9]	10	10	3.4
total injection time	3.7 ms	100 ms	114 ms
remaining time	16.3 ms	100 ms	86 ms
simulated efficiency	89%	95%	94%
e^+/bunch [10^9]	4.2	21	22

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