CERN – EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CLIC – Note – 925

SUPERCONDUCTIONG POSITRON STACKING RING FOR CLIC

Rinolfi, L (CERN) ; Zimmermann, F (CERN) ; Bulyak, E (Kharkov, KIPT) ; Gladkikh, P (Kharkov, KIPT) ; Omori, T (KEK, Tsukuba) ; Urakawa, J (KEK, Tsukuba) ; Yokoya, K (KEK, Tsukuba)

Abstract

This paper describes a superconducting storage ring dedicated to positron accumulation as part of a polarized positron source based on Compton scattering in a Compton storage ring (CR). The superconducting stacking ring (SR) can provide a synchrotron damping time of order 100 μs. Together with a novel combined injection scheme in the longitudinal and transverse plane, such a ring may solve the problem of accumulating a positron beam with the beam intensity required for CLIC.

Presented at: 2nd International Particle Accelerator Conference, San Sebastian, Spain, 4 - 9 Sep 2011

Geneva, Switzerland
Date 14/09/2011

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN – ACCELERATOR AND TECHNOLOGY SECTOR

CERN-ATS-2011-129

SUPERCONDUCTING POSITRON STACKING RING FOR CLIC

L. Rinolfi, F. Zimmermann, CERN, Switzerland
E. Bulyak, P. Gladkikh, NSC KIPT, Ukraine
T. Omori, J. Urakawa, K. Yokoya, KEK, Japan

Abstract

This paper describes a superconducting storage ring dedicated to positron accumulation as part of a polarized positron source based on Compton scattering in a Compton storage ring (CR). The superconducting stacking ring (SR) can provide a synchrotron damping time of order 100 μs. Together with a novel combined injection scheme in the longitudinal and transverse plane, such a ring may solve the problem of accumulating a positron beam with the beam intensity required for CLIC.

SUPERCONDUCTING POSITRON STACKING RING FOR CLIC

L. Rinolfi, F. Zimmermann, CERN, Switzerland
E. Bulyak, P. Gladkikh, NSC KIPT, Ukraine
T. Omori, J. Urakawa, K. Yokoya, KEK, Japan

Abstract

This paper describes a superconducting storage ring dedicated to positron accumulation as part of a polarized positron source based on Compton scattering in a Compton storage ring (CR). The superconducting stacking ring (SR) can provide a synchrotron damping time of order $100\ \mu$s. Together with a novel combined injection scheme in the longitudinal and transverse plane, such a ring may solve the problem of accumulating a positron beam with the beam intensity required for CLIC.

INTRODUCTION

Compton scattering of an electron beam off a high-power laser pulse in a so-called Compton Ring (CR) [1] is a promising option to realize a polarized positron source for a future linear collider such as CLIC. Due to practical limits on the laser pulse energy and the electron bunch charge the number of positrons produced per beam-laser collision is limited to at most a few 10^7 positrons. The CLIC design bunch charge is 50–100 times higher. Therefore, a Compton-based source must obtain the target bunch population by accumulating a large number of positron packets arriving in a number of bursts from the CR, with intermediate damping of the scattering electron beam and of the accumulating positrons.

Simulations of a Compton positron source indicate that a yield of a few 10^7 positrons per pulse is possible, with a longitudinal rms emittance around 0.2–0.3 meV-s, and a transverse normalized rms emittance of 8×10^{-3} rad-m [2]. To obtain a high degree of polarization high-energy positrons have to be selected. An energy selection providing a beam polarization larger than 60% also decreases the transverse rms emittance, by an estimated factor 2–4, and discards more than 70% of the produced positrons. The total gamma yield from the CR has to be adjusted accordingly. This effect can be taken into account in the Compton ring design.

LONGITUDINAL INJECTION

Longitudinal accumulation and injection of several bunches into the same RF bucket have been routinely used at LEP [3]. In the case of stacking for a future Compton positron source many more injections are needed into the same RF bucket. Efficient stacking requires the size of the RF bucket to be much larger than the longitudinal edge emittance of the injected positrons.

Earlier simulations of the stacking process considered only the longitudinal dynamics including first and second order momentum compaction, the sinusoidal RF voltage, radiation damping and quantum excitation. Simulation results for the longitudinal stacking of Compton positrons in the CLIC pre-damping ring (PDR) [4], reconfigured as a stacking ring were presented in [5]. The acceptance of the PDR was increased by raising 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 $\alpha_{c,1}$ (which could perhaps be increased again to its original value after the stacking process, e.g. to stabilize the damped beam). The optimized PDR parameters are listed in Table 1 (center column).

For CLIC the number of stacking turns is less than 100. A possible longitudinal stacking scenario is, for example, to inject on every 40th turn positron bunchlets into the same PDR bucket. Accordingly a 20-ns bunch spacing is the needed for the CR electron beams, and a suitable CR cicumference difference with respect to a multiple of 20 ns, 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 per bunch. Following the stacking period would be 12225 turns (16.3 ms) of damping at a CLIC repetition rate of 50 Hz. As the longitudinal damping time of the stacking-optimized PDR is only 0.56 ms, a significant reserve exists, which could be used for relaxing the laser requirements in the Compton Ring.

A maximum longitudinal stacking efficiency of about 89% was obtained from simulations, when the beam is injected with a constant phase offset $z_{\rm off} = 0.01$ m , and with an optimized constant momentum offset δ of 4% from the center of the bucket [5]. Two snapshots taken during the simulated stacking process are presented in Fig. 1.

An important point to highlight is that with the purely longitudinal injection, a fast orbit bump at the septum created by fast kickers is required to ensure that newly injected positrons do not hit the septum on the turn following the injection. The bump amplitude chosen for the PDR, $A_{\rm bump} = D_{\rm septum}\delta_{\rm bump}$, of about 4 mm, for $D_{\rm septum} = 1$ m corresponds to 4 times the initial energy spread after energy pre-compression [6].

An alternative stacking scheme based on combined longitudinal-transverse injection and a dedicated higher-energy superconducting stacking ring, presented next, avoids the fast septum bump, allows for a much larger initial longitudinal emittance, and achieves a higher stacking efficiency, in full 6D simulations.

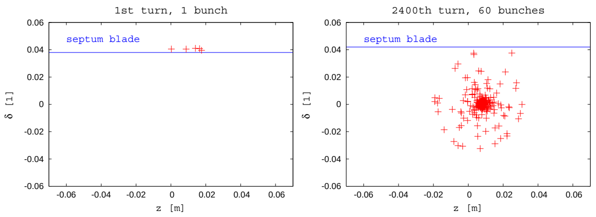

Figure 1: Phase-space snapshots for CLIC-PDR stacking process: first bunchlet on first turn (left), and 60 bunches on turn 2400 (right) [5]. The blue line indicates the location of the septum blade, which changes after the injection turn due to a fast orbit bump.

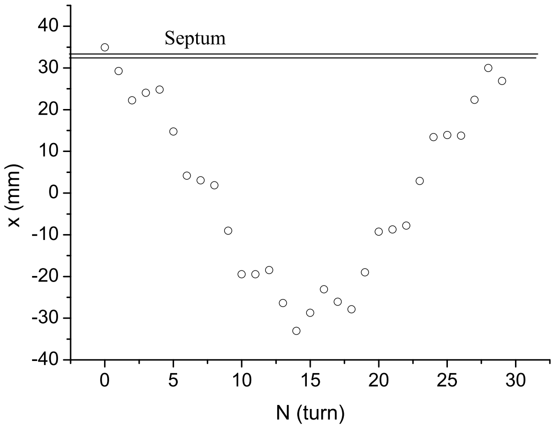

Figure 2: Transverse position of an injected particle at the injection point over 30 successive turns, for an initial momentum deviation $\Delta p/p_0 = +3\,\%$ at a dispersion function $\eta_{\rm i} = 1\,{\rm m}$, an initial betatron-oscillation amplitude $X_{\rm b} = 5\,{\rm mm}$, a fractional betatron tune $Q_{\rm x} = 0.75$, and synchrotron damping time $\tau_{\rm s} = 100\mu{\rm s}$ (333 turns).

COMBINED X-δ INJECTION

We can ease some of the requirements of the previously described purely longitudinal injection scheme by longitudinal injection away from the transverse equilibrium orbit. In this case the motion of injected bunchlets consists of both synchrotron oscillations of the equilibrium orbit around the reference one, and of betatron oscillations around the instantaneous equilibrium orbit. Choosing betatron oscillations with an appropriate tune value the injected particle may miss the injection septum for several turns after injection into the ring. This allows us either to decrease the momentum deviation of the injected particle (and to decrease the required energy acceptance) or to increase the required damping time for the synchrotron oscillations (or both to increase the damping time and to decrease the initial momentum deviation).

The motion resulting from such combined longitudinal-transverse injection is presented in Fig. 2. One can see that thanks to the effect of the betatron oscillation we can choose quite slow a synchrotron oscillation in order to avoid beam losses after one synchrotron period. The betatron oscillation makes the injected beam miss the septum during the first couple of turns. Simulations demonstrate the high efficiency of such injection scheme. This method still requires a few percent energy acceptance of the SR.

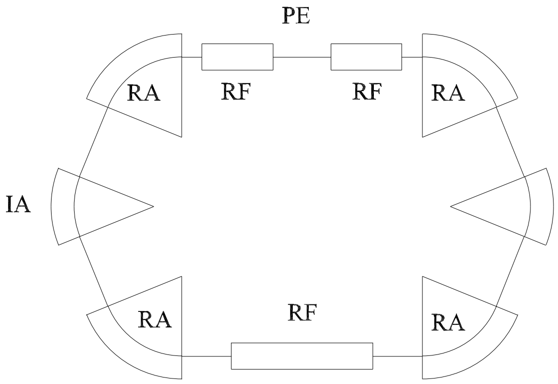

Figure 3: Stacking Ring layout. IA: injection arc; RA: regular arc; RF: rf cavities; PE: positron extraction.

The CLIC PDR, which needs to meet several other requirements, had already been pushed to (or beyond) its limits as a potential stacking ring [5] and a new dedicated SR is required to achieve the desired short longitudinal damping time. Taking into account the aforementioned considerations we have designed the lattice of a superconducting SR with a positron energy of 5 GeV and a bending field of 6 T. Its layout is presented in Fig. 3.

The ring is of race-track type with a circumference $C \approx 125\,{\rm m}$. The bending is distributed over four regular arcs and two shorter arcs, one of which serves for injection. A single arc consists of 10 bending magnets and comprises 4 sextupoles for chromatic correction. Positrons are injected between ‘large’ dipoles at a location with 1-m dispersion. At the chosen values of positron beam energy and bending field the energy loss is approximately 20 MeV per turn, corresponding to a synchrotron damping time close to $100\ \mu$s. The SR parameters are listed in Table 1 (right column).

The dynamic aperture (DA) for the injected off-momentum beam is limited by high-order chromatic effects. The dynamic aperture increases for lower momentum offset. The DA was computed with MAD-X. The simulated dynamic aperture at the injection point is presented in Fig. 4.

Such dynamic aperture enables the injection of positron bunches with a normalized emittance of up to 2×10^{-3} rad-m without significant beam loss.

Simulations considered an initial normalized transverse beam emittance of 2×10^{-3} rad-m and a longitudinal rms emittance of about 1 meV-s (0.2% rms energy spread at 5 GeV, and about 0.1 ns rms bunch length). To simulate the Compton scattering process, a corresponding lattice element was introduced in the DeCA code, which models the full 6D motion $(x, x', y, y', z, \Delta p/p)$, including transverse

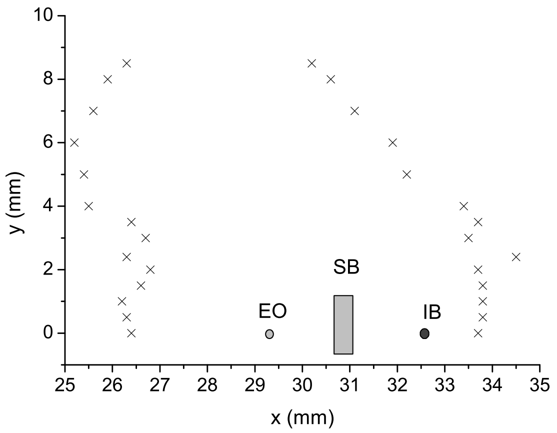

Figure 4: Dynamic aperture at the injection point. IB: injected beam; EO: equilibrium orbit for $\Delta p/p_0 = +3\,\%$; SB: septum blade.

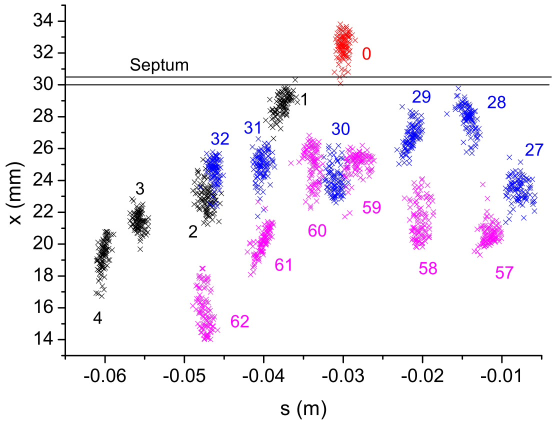

Figure 5: Beam positions at the beginning of the first synchrotron cycle (black “x”), at the end of the first (blue “x”) and the second synchrotron cycles (magenta “x”). Numbers near bunches indicate turn number (“0” indicates the injected beam).

Table 1: Parameters of modified CLIC PDR & SR

Parameter	PDR	SR
Positron energy	2.86 GeV	5 GeV
Circumference	397.7 m	125.0 m
Horizontal tune Q_x	18.44	10.77
Vertical tune Q_y	12.41	7.72
Momentum compaction	0.00038	0.0025
RF frequency	2 GHz	2 GHz
Number of bunches	312	104
Bunch population	4×10^9	1.5×10^9
Bunch-to-bunch spacing	0.5 ns	4 ns
RF voltage	20 MV	50 MV
Energy acceptance	$\pm 6\,\%$	$\pm 3.5\,\%$
Energy loss per turn	6 MeV	19.8 MeV
Longit. damping time	560 μs	104 μs
Dispersion at injection	1 m	1 m
Initial longit. rms emittance	0.1 meV-s	1 meV-s
Peak SR power / length	2 kW/m	3 kW/m

losses. Simulation results illustrating the injection into the proposed ring are presented in Fig. 5.

For a thickness of the final injection septum equal to 0.5 mm and the aforementioned beam parameters an injection efficiency of 95% is obtained in the simulation.

The number of injected turns for the stacking is limited by the synchrotron radiation power. Consider a CLIC beam consisting of 312 bunches with a population of 4×10^9 and a bunch-to-bunch spacing of 0.5 ns. For such pulse sequence circulating in the stacking ring the stored beam current is approximately 1.24 A and the average synchrotron radiation power is about 12.5 MW. To decrease the average synchrotron-radiation power load on the vacuum chamber we propose that the CR generates bursts of gamma-quanta at a higher cycle repetition rate, e.g. of 400 Hz. A single cycle consists of a generation period during which positrons are injected and stacked, and a period needed for the damping of both the electron beam in the CR and the positron beam in the SR. The two periods are about equally long, e.g. 0.5 ms each. Positrons are being injected and accumulated in the SR during a single generation cycle and are being extracted after the damping period. The average power load on the SR vacuum chamber in such operation mode is estimated to be of order 400 kW. The final CLIC positron beam can be produced from the damped SR bunches by 3-turn injection into a so-called time-diagram transformer ring with a circumference equal to the length of the CLIC bunch train, and/or by a second stage of stacking in either the PDR or the DR.

CONCLUSION

The proposed combined longitudinal-transverse injection into a superconducting stacking ring (SR) could be a solution to the problem of positron stacking under the condition of quasi-continuous positron generation. The CR operation mode with high repetition rate allows for the design of a superconducting stacking ring with realistic parameters. Preliminary estimates indicate that the SR beam energy can be 3.5-5 GeV, and that a high stacking efficiency of 95% can be achieved, with acceptable SR energy losses.

REFERENCES

[1] S. Araki *et al*, 2005 Snowmass, *physics/0509016*.

[2] A. Vivoli, private communication (2011).

[3] P. Collier, Proc. PAC1995 Dallas pp. 551 (1995); P. Baudrenghien, P. Collier, Proc. EPAC’96 Sitges pp. 415 (1996).

[4] F. Antoniou et al, Proc. PAC09 Vancouver (2009) p. 2760.

[5] F. Zimmermann et al, Proc. PAC’09 Vancouver (2009) p. 512.

[6] A. Vivoli, Pulse Stacking Meeting, LAL, 1 February 2008.