CLIC POLARIZED POSITRON SOURCE BASED ON LASER COMPTON SCATTERING

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Abstract

We describe a possible layout and parameters of a polarized positron source for CLIC, where the positrons are produced from polarized gamma rays created by Compton scattering of a 1.3-GeV electron beam off a YAG laser. This scheme is very energy effective using high finesse laser cavities in conjunction with an electron storage ring. We point out the differences with respect to a similar system proposed for the ILC.

INTRODUCTION

At Snowmass 2005, a polarized-positron source based on laser-Compton scattering was proposed for the ILC [1]. Polarized photons generated by laser-electron scattering are here converted into polarized positrons via pair production in a target. Two novel features distinguish the "new" ILC Compton source from its single-pass predecessor developed for the JLC in the 1990's [2], namely photon stacking using high-finesse optical cavities in a Compton storage ring and positron stacking in a damping ring, both of which relax the laser requirements. The case of a Compton source is bolstered by recent experimental results from the KEK/ATF, where the production of 10^4 polarized positrons per bunch with $73\% \pm 15(\mathrm{stat})\% \pm 19(\mathrm{syst})\%$ polarization has been demonstrated [3], as well as by an improved understanding of compact Compton storage rings [4, 5]. In this paper we discuss how the ILC Compton scheme can be adapted, and scaled down, to CLIC.

ILC COMPTON SCHEME

The ILC Compton source [1] comprises a Compton ring with 30 optical cavities, which are either coupled in a daisy chain or powered by separate lasers. Various types of lasers can be used. In Ref. [1], YAG or CO2 lasers were considered, which require a different beam energy of 1.3 GeV or 4.1 GeV, respectively, and a different ring circumference of 277 m or 649 m. During 100 or 50 Compton-ring turns 10×2800 "bunch-lets" of about 2×10^8 polarized positrons are produced from polarized photons generated in 30 laser-electron collisions. Next, a 100-Hz 5-GV s.c. linac accelerates these positrons to 5 GeV. On 10 successive damping-ring turns, positron bunch-lets are injected 10 times into each of 2800 ILC damping-ring rf buckets. Then the injected positron emittance is damped by synchrotron radiation for 10 ms. The entire process is repeated 9 times, always leaving a 10-ms damping time between sets of 10 consecutive injections. After 90 ms the accumulation is completed. The ILC damping ring now stores the full-intensity positron bunches for 100 further ms before extraction to the main linac. A major challenge in the ILC Compton-ring design are the 30 laser-beam interaction points (IPs), which result in a large energy spread, reducing the photon yield, and which likely compromise the dynamic aperture. In case the 30 cavities are coupled, a novel multi-chamber feedback is needed.

Table 1: CLIC and 3-km ILC damping ring parameters.

variable	CLIC	ILC
energy	2.424 GeV	5 GeV
circumference	360 m	3230 m
bunch population	2.56×10^9	2×10^{10}
# bunches per train	110	280
gap (missing bunches)	≥ 47	80
# trains per pulse	2	10
bunch spacing	0.533 ns	2.8 ns
hor. normalized emittance	600 nm	5 μm
vert. normalized emittance	5–10 nm	20 nm
rf frequency	1.875 GHz	650 MHz
repetition rate	150 Hz	5 Hz

ILC-CLIC DIFFERENCES

The positron sources for ILC and CLIC must provide the bunches required in the respective damping rings. From Table 1, we infer the main differences between ILC and CLIC: (1) The CLIC bunch charge is almost 10 times lower and the number of bunches per pulse about 20 times smaller than for the ILC. (2) The bunch spacing for CLIC is about 6 times shorter. (3) The CLIC repetition rate is higher by a factor 30.

As a consequence of the first point, the number of laser cavities in the CLIC Compton ring can be reduced, ideally to a single one, a case which will soon be tested experimentally in the ATF damping ring.

CLIC SCHEME

Figure 1 displays a schematic of the polarized positron source proposed for CLIC. Its main components are a compact Compton ring with a single optical cavity, a photon target and positron collection system, a 2.4-GeV 150-Hz n.c. linac, and the 2.424-GeV pre-damping ring used for accumulation. Table 2 compares preliminary parameters of the CLIC source with those of the ILC.

For simplicity, we here consider only the case of a YAG laser. Due to its 10 times shorter wavelength λ_L, for the YAG laser the injection linac is 3 times shorter and the Compton-ring energy 3 times lower than for a $CO2$ laser.

Table 2: YAG-laser Compton-source parameters.

parameter	CLIC	ILC
Compton ring energy	1.3 GeV	1.3 GeV
C.-ring circumference	42 m	277 m
rf frequency	1.875 GHz	650 MHz
bunch spacing	0.16 m	0.923 m
number of bunches	220	280
bunch population	6.2×10^{10}	6.2×10^{10}
no. of optical cavities	1	30
total γ's/bunch/turn	2.8×10^{9}	5.8×10^{10}
selected γ's/bunch/turn	6.9×10^{8}	1.36×10^{10}
pol. e+/bunch/turn	9.8×10^{6}	1.9×10^{8}
injections/bunch	300	100
total # injections	6.6×10^{4}	2.8×10^{5}
# e+/pulse	6.5×10^{11}	5.3×10^{13}
# e+/second	9.7×10^{13}	2.7×10^{14}
# Compton-ring turns	300	100
Compton-pulse duration	42 μs	90 μs
pause between cycles	6.1 ms	9.9 ms

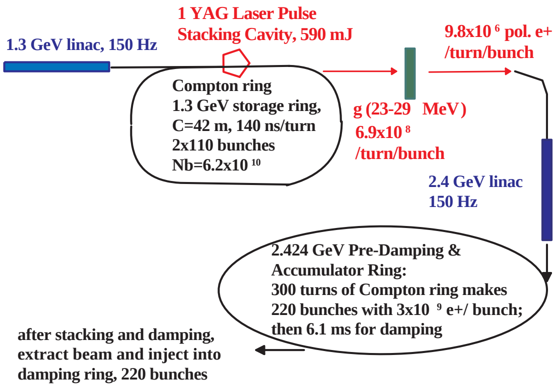

Figure 1: Schematic view of CLIC Compton source.

COMPTON RING

The Compton ring can be designed as a racetreack with four straight sections [1, 4, 5]. Two of these accommodate wigglers, counteracting the effect of the Compton collisions by enhanced longitudinal damping, one houses an rf system which restores the energy lost in Compton collisions and in the wigglers, and the last one contains the Compton collision point with optical cavity.

Parameters for the Compton collision point are summarized in Table 3. The maximum back-scattered photon energy is 29 MeV. Photons between 23.2 and 29 MeV are selected for polarized positron generation. Laser pulse depletion from Compton scattering is negligible compared with losses on the optical mirrors. Also nonlinear Compton effects can be ignored. Transverse emittance growth due to either the ponderomotive force or quantum diffusion in the laser field is small too.

Table 3: Parameters of Compton collision.

parameter	value
e- bunch length at Compton IP	5 mm
e- rms hor./vert. beam size	25, 5 μm
e- beam energy	1.3 GeV
e- bunch charge	10 nC
laser type	YAG
laser photon energy	1.164 eV
rms laser radius	5 μm
laser pulse energy	592 mJ
# laser cavities	1
crossing angle	$\sim 10^{\circ}$
photons in cavity pulse	3.2×10^{18}
polarized γ's/bunch/turn	6.9×10^{8}
positron yield e+/γ	0.014
effective e+ yield/γ	3.5×10^{-3}

A simulation of the turn-by-turn photon yield per electron which considered an optimized 1st order momentum compaction $\alpha_{c,1} = 2 \times 10^{-6}$, a zero second order $\alpha_{c,2}$, and strong wiggler damping, predicts an average total photon yield per electron of about 0.0447, which is close to the ideal value expected for a longitudinally point-like bunch [5]. The yield stays almost constant as a function of time, unlike for the ILC [1, 5]. The positron yield per collision and per Compton-ring electron is estimated by multiplying the simulated total photon yield with a factor 0.248 (about 25% of the photons are selected) [1] and with a factor 0.014 for the approximate positron yield per photon [1].

The electron-beam energy spread induced in a Compton collision is [6] $\Delta\sigma_E \approx \sqrt{(7/10)E_\gamma(\Delta E)}$, with E_γ the photon energy, $\Delta E = (32\pi/3)r_e^2\gamma^2 E_L/(Z_R\lambda_L)$ the average energy loss, E_L the laser pulse energy, r_e the classical electron radius, and Z_R the laser Rayleigh length. The YAG laser requires a large momentum acceptance of 7–8% in the Compton-ring, which may be difficult to achieve. Possible remedies include decreasing the turn number and increasing the number of electron bunches (and ring circumference), introducing additional wigglers, or using a $CO2$ laser with higher λ_L. Many other improvements considered for the more demanding ILC conditions, such as rf phase manipulation, low & nonlinear momentum compaction factor, pulsed momentum compaction lattice, and strong rf focusing with minimum bunch length at the Compton IPs [5, 7], could also be applied at CLIC.

LASER AND OPTICAL CAVITY

The laser system, sketched in Fig. 2, consists of three stages. The mode-locked laser oscillator produces seed pulses with about 170 nJ energy. The solid-state amplifier provides a gain by about a factor 3500 via chirped pulse amplification (CPA). For comparison, the existing amplifier of the ATF rf-gun laser achieves a factor 10000. The final enhancement by a factor 1000 to about 600 mJ pulse energy is accomplished by stacking in a high-finesse optical cavity. The optical cavities at the ATF have demonstrated enhancement factors of 300 (pulsed laser wire) and 1000 (cw laser wire).

Several alternatives exist: (1) increasing the laser pulse energy and decreasing the optical-cavity quality factor; 2) replacing the YAG laser by a 0.21 mJ/pulse CO2 laser; (3) continuous mode operation (with fiber laser?) at 50 MHz and 10 μJ/pulse combined with a higher cw optical-cavity quality factor of $10^4 - 10^5$ [8]; (4) feedback on the laser (LAL scheme) and/or on the optical cavity (KEK scheme).

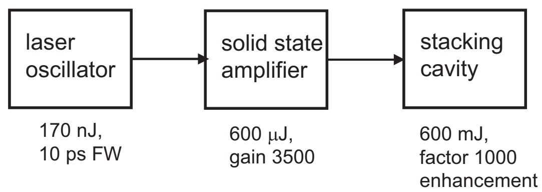

Figure 2: Schematic layout of laser system, including pulse energy and gain factors [9].

At the intersection of optical cavity and beam pipe, the latter features two elongated holes for the laser beam. The minimum cavity length is estimated as $l \approx 2d/\phi \approx 0.28$ m, where $d \approx 25$ mm is the size of the optical mirror, and $\phi \approx 10^\circ$ the laser-beam collision angle. This implies that, for CLIC, at least 3 or 4 pulses are stored in the same cavity.

Mode-locked lasers operating at frequencies as high as the CLIC bunch frequency of 1.875 GHz are not yet available. However, a lower-frequency laser can feed a single optical cavity whose length is tailored such that successively fed pulses are properly interleaved and the laser frequency is multiplied, as is illustrated in Fig. 3.

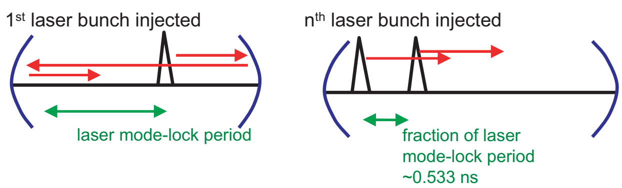

Figure 3: Schematic of laser frequency multiplication.

POSITRON STACKING

The accumulation ring used for positron stacking must have a large longitudinal and transverse acceptance, as well as provide fast damping. The only economical solution for the ILC is to use one or several of the 3 or 6-km long main damping rings for stacking, as the ILC accumulator ring should have at least the same circumference as the main damping ring. By constrast, at CLIC the pre-damping ring can be used for accumulation. The minimum required circumference for accommodating 220 positron bunches is only 42 m. In addition, this ring can be optimized for accumulation efficiency fully independently of any damping-ring constraints. The former 2-GeV 200-m NLC pre-damping ring optics [10] is a good candidate. It features a 10-fold symmetric double-bend achromat structure, wiggler damping equal to twice the arc damping, 0.4-m bunch spacing, 2-ms longitudinal damping time, 100–150 Hz repetition rate, and a dynamic aperture of 0.2 m-rad for $\Delta p/p = \pm 1.5\%$.

OUTLOOK

The Compton ring design is challenging due to the high current. Further optimization of ring circumference, bunch spacing, and bunch charge will likely be required.

An ongoing R&D programme at the KEK/ATF addresses the design and fabrication of laser-pulse stacking cavities with high enhancement factor and small spot size, the design of an IP with minimum collision angle, and the installation of laser-pulse stacking cavities in the ATF damping ring, culminating in X-ray generation. A parallel proposal to the European Union's 7th framework programme includes technological R&D on high-power high-repetition rate lasers and optical cavities, a design study of the Compton ring, collection system, and stacking schemes, as well as experiments at ATF and DAFNE.

Over the last decade, the output power of cw double-clad fiber lasers with diffraction limited beam quality has increased by a factor 400 [7, 11]. The demonstrated value of 2 kW is close to the power needed for the CLIC source (if a single laser is used). Extrapolating past evolution, an 8-kW cw fiber laser should become available around 2008/2009.

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