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Brilliant positron sources for CLIC and other collider projects

L. Rinolfi [a,*], R. Chehab [b], O. Dadoun [c], T. Kamitani [d], V. Strakhovenko [e], A. Variola [c]

[a] CERN, Geneva, Switzerland
[b] IPNL, Lyon, France
[c] LAL, Orsay, France
[d] KEK, Japan
[e] BINP, Novosibirsk, Russia

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A B S T R A C T

The CLIC (Compact Linear Collider), as future linear collider, requires an intense positron source. A brief history is given up to the present baseline configuration which assumes unpolarized beams. A conventional scheme, with a single tungsten target as source of e^-e^+ pairs, has been studied several years ago. But, in order to reduce the beam energy deposition on the e^+ target converter, a double-target system has been studied and proposed as baseline for CLIC. With this "hybrid target", the positron production scheme is based on the channeling process. A 5 GeV electron beam impinges on a thin crystal tungsten target aligned along its ⟨1 1 1⟩ axis, enhancing the photon production by channeling radiation. A large number of photons are sent to a thick amorphous tungsten target, generating large number of e^-e^+ pairs, while the charged particles are bent away, reducing the deposited energy and the PEDD (Peak Energy Deposition Density). The targets parameters are optimized for the positron production. Polarized positron beams are an option for CLIC, which needs R&D. Some brilliant positron sources are briefly reviewed.

1. Introduction

A very brief history of the CLIC (Compact Linear Collider) study is given in the next paragraph. A possible design of a multi-TeV linear collider is described in [1]. The CLIC study has been presented in major conferences, CLIC workshops and Linear Colliders workshops (LCWS). At the LCWS'08 workshop in Chicago, a new ILC/CLIC common working group was created as "e^+ sources" [2]. The present beam parameters and the corresponding layout for the main beam injector complex are given. The CLIC web page [3] provides the up-to-date data. The studies based on conventional positron sources are described first, followed by the studies optimizing hybrid targets configuration where channeling process occurs. The various approaches to generate polarized e^+ beam for CLIC are presented.

2. A very brief CLIC history

In 1985, when the study started, the acronym CLIC stood for "CERN Linear Collider" and the first CLIC Note was published in August.

Ten years later, in 1995, it becomes obvious that such linear collider would be built only within an international collaboration and the acronym of CLIC became "Compact Linear Collider". At this time, six linear collider projects were studied around the world: TESLA, SBLC, JLC, NLC, VLEPP and CLIC.

In 2004, an International Technology Recommendation Panel selected the Superconducting RF technology (TESLA based) versus room temperature copper structures (JLC/NLC based). The ILC (International Linear Collider) was born, based on RF frequency at 1.3 GHz for the TeV scale while CLIC study continued with a RF frequency at 30 GHz for the multi-TeV scale.

In 2007, major changes occurred in the CLIC study: The RF frequency of 30 GHz was reduced down to 12 GHz and the accelerating gradient was reduced from 150 MV/m down to 100 MV/m.

In 2008, a new ILC/CLIC common working group was created as "e^+ sources".

In July 2012, there was an observation at LHC of particle consistent with the long-sought Higgs boson. Today, the CDR (Conceptual Design Report) is published [4].

3. CLIC main beam parameters

The nominal CLIC parameters are given in Table 1.

The e^+ and e^- are generated in the Main Beam Injector Complex. The constraints for the design study of the brilliant positron source are derived from the parameters requested at the Interaction Point.

* Corresponding author. Tel.: +41 76 487 3059.
E-mail address: louis.rinolfi@cern.ch (L. Rinolfi).

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Table 1
CLIC main beam parameters [5].

Center-of-mass energy	0.5 TeV	3 TeV
Peak luminosity	2.3×10^{34} cm^{-2}s^{-1}	5.9×10^{34} cm^{-2}s^{-1}
Repetition rate	50 Hz	50 Hz
loaded accelerating gradient	80 MV/m	100 MV/m
Main Linac RF frequency	12 GHz	12 GHz
Bunch charge at IP	6.8×10^9	3.72×10^9
Number of bunches	354	312
Bunch spacing	0.5 ns	0.5 ns
Beam pulse duration	177 ns	156 ns
Beam power per beam	4.9 MW	14 MW
Horizontal/vertical emittances	2400/25 nm	660/20 nm
Horizontal/vertical beam size at IP before pinch	202/2.3 nm	40/1 nm
Total site length	13 km	48.3 km
Total power consumption	130 MW	415 MW

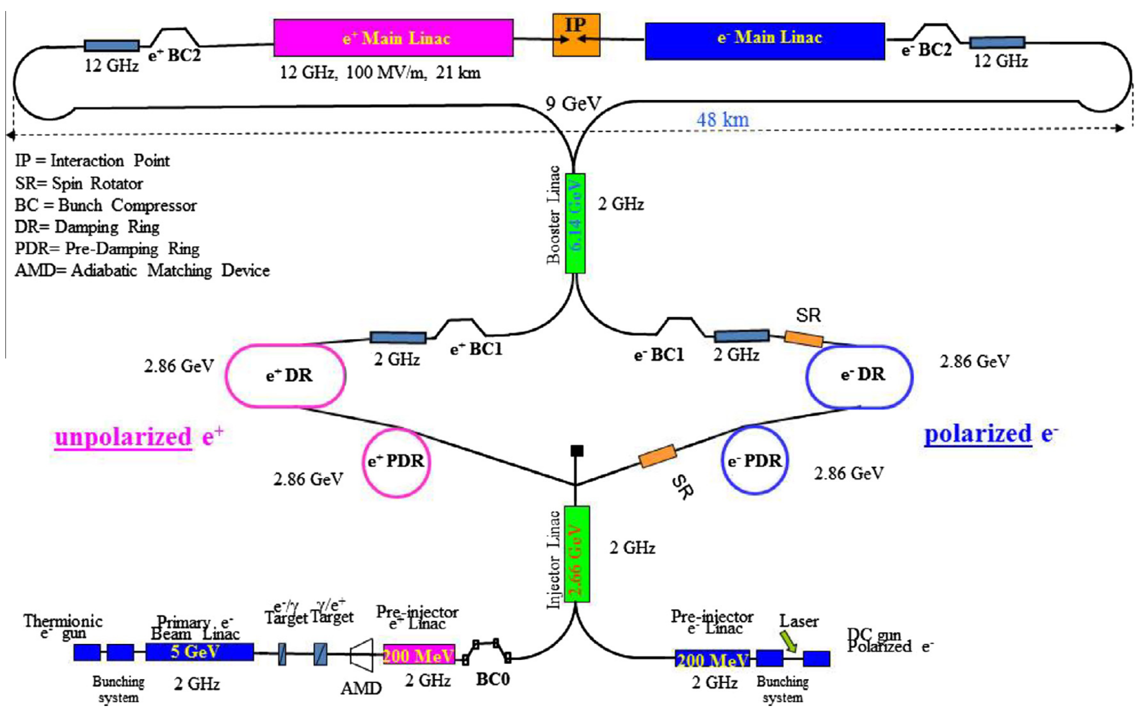

Fig. 1. CLIC main beam injector complex.

Fig. 1 shows the main beam injector complex for the baseline configuration.

For the positron generation, a thermionic gun with a bunching system followed by a Primary Beam Linac provides an e^- beam at 5 GeV onto a target. The positron source itself is composed of hybrid targets: one thin crystal target, followed by one amorphous target and an Adiabatic Matching Device (AMD). A Pre-injector Linac captures bunches and accelerates the emitted e^+ (and secondary e^-) up to 200 MeV.

4. Conventional e^+ production scheme with single target

A first study related to the main beam injector complex is reported in [6]. The e^+ production is based on standard technology developed at SLC and using a single target. The number of bunches is four but the repetition rate is 1700 Hz. In 1997, preliminary simulations [7] were performed for a $W_{75}Re_{25}$ conversion target, similar to the SLC target. Following the LCWS'97, several issues and proposals concerning the positron source and other components were reported in [8].

In 2000, detailed studies and simulations [9] were performed according to new CLIC parameters. Simulations were performed with EGS4 for the energy deposition inside the target. A new tracking simulation program SOLEIL was used [10]. It was initially implemented for the design of the positron source of the KEK B-factory injector linac. The trajectories of the particles are traced by step-by-step numerical integration of the relativistic equations of motion with the 4th order Runge–Kutta method. The simulation results have been compared to analytical formula [11] and showed rather good agreement. Fig. 2 gives the layout of the CLIC e^+ source up to the exit of the capture section at 200 MeV. The results are reported in [12].

With the new CLIC parameters, it becomes challenging to use a single target as e^+ source. The issues are related to the beam energy deposition and the shock waves. Simulations have been performed with FLUKA code and confirm the risks of breakdowns.

Since several projects requiring a brilliant e^+ sources are under study, it is interesting to compare what is presently requested with the SLC e^+ source (which was the only one built for a linear collider). Table 2 shows the e^+ flux for the SLC (Stanford), CLIC

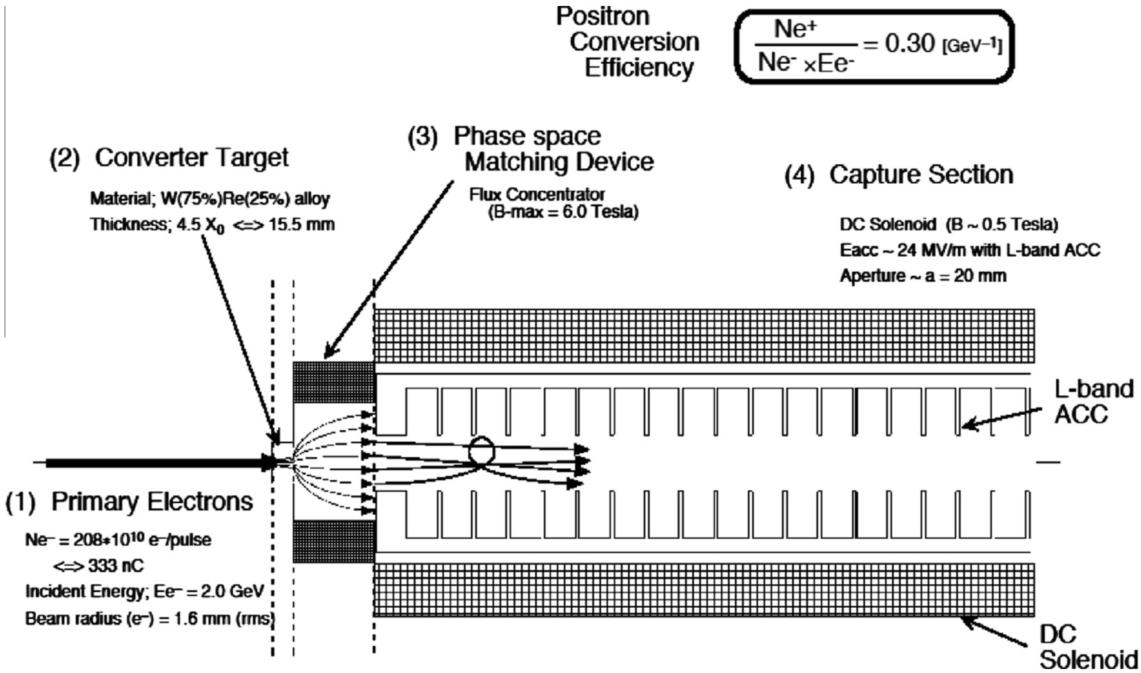

Fig. 2. Layout of the CLIC e+ source with a single target.

Table 2
Positron flux for different studies compared to the SLC.

	SLC	CLIC (3 Tev)	Clic (0.5 Tev)	ILC (RDR)	LHec (pulsed)	LHec ERL
Energy	1.19 Gev	2.86 Gev	2.86 Gev	5 Gev	140 Gev	60 Gev
e^+/bunch (at IP)	40×10^9	3.7×10^9	7.4×10^9	20×10^9	1.6×10^9	2×10^9
e^+/bunch (aft. capture)	50×10^9	7×10^9	14×10^9	30×10^9	1.8×10^9	2.2×10^9
Bunches/macropulse	1	312	354	2625	100 000	NA
Rep. rate (Hz)	120	50	50	5	10	CW
Bunches/s	120	15600	17700	13125	10^6	20×10^6
e^+/second $\times 10^{14}$	0.06	1.1	2.5	3.9	18	440

(2 energies: 3 TeV and 0.5 TeV), ILC (Reference Design Report) and LHeC (pulsed option, CW option with an ERL).

According to this Table 2, the CLIC e+ flux (at 3 TeV) requires a factor 20 compared to SLC, which is certainly an important challenge.

5. The hybrid target based on channeling process as e+ source

The idea to use channeling effects to enhance the e+ positron sources, for linear colliders, emerged in 1989 [13]. However this relies on the long term resistance of the crystal to radiation damages. Such damages have been tested on a 0.3 mm thick tungsten monocrystal exposed during 6 months to the 30 GeV incident electron beam of the SLAC Linear Collider (SLC). The crystal was placed in the converter region, orientated in a random direction and received an integrated flux of 2.10^{18} e^-/mm^2. The results [14] show that no damages occurred during these irradiations.

Later on, an experiment operated at CERN (WA 103) showed significant enhancements in positron production between W crystal and amorphous targets both of the same thickness: a factor 2, for an 8 mm target and a factor 4, for 4 mm target [15,16].

5.1. Simulations to optimize the e+ production for the present CLIC parameters

According to the most recent CLIC beam parameters, the e+ production is optimized using a hybrid targets configuration. This concept was proposed in [17] and represented in Fig. 3. With a tungsten crystal oriented on its ⟨1 1 1⟩ axis, one obtains an intense, relatively low energy photon beam due mainly to channeling radiation. Those photons are then impinging on an amorphous tungsten target producing positrons by e^+e^- pair creation. The optimization of the positron yield and the peak energy deposition density in the amorphous target are studied [18,19] according to the distance between the crystal and the amorphous targets, the primary electron energy and the amorphous target thickness.

Although the target is crucial for a brilliant e+ source, the optics downstream also plays a crucial role for the performance of the positrons. Therefore simulations have been performed from the exit of the amorphous target up to the entrance of the Pre-Damping Ring. Following detailed studies, it is deduced that the e+ yield obtained at the exit of the Pre-Injector Linac fulfills the CLIC requirements, using hybrid targets [20].

5.2. Targets

The conventional positron source is based on an electromagnetic shower created by electrons impinging on high-Z material target. For the CLIC baseline, channeling process occurs inside the thin crystal target which receives high-energy electrons, producing e^+/e^- pairs and photons. The latter are sent to the thick amorphous target producing e^+/e^- pairs while the electrons and positrons are swept around between the crystal target and the thick target. As already mentioned, an important issue is the beam deposition power inside

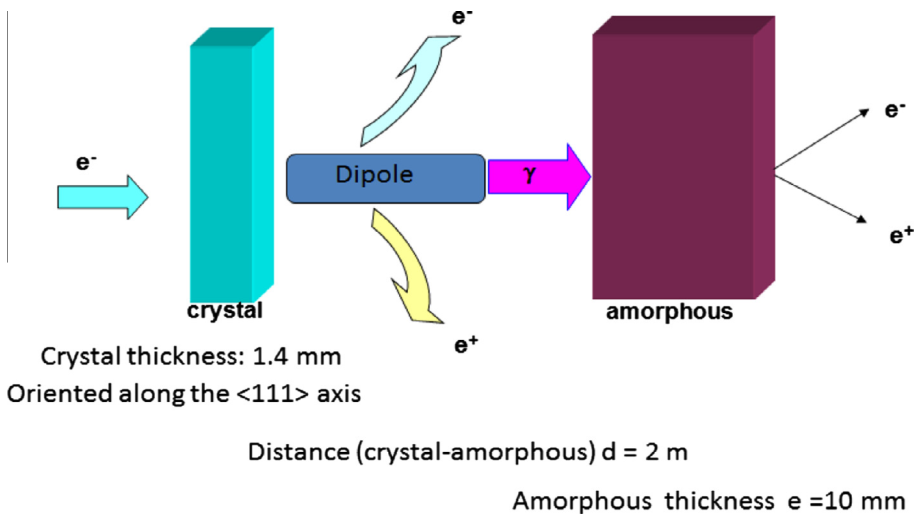

Fig. 3. CLIC hybrid targets configuration.

Table 3
CLIC e+ targets.

Targets		Crystal	Amorph.
Material		W	W
Length	mm	1.4	10
Radiation lengths	χ_0	0.4	2.9
Beam power deposited	kW	0.2	7.5
Deposited P/Beam Power	%	0.2	8
Energy lost per volume	10^9 GeV/mm^3	0.8	1.9
Peak Energy Deposition Density (PEDD)	J/g	7	15

the amorphous target. The failure threshold for W target was measured, at SLAC, and found to be around 35 J/g. For the amorphous CLIC target, and based on results obtained in [18], the values of the present optimized configuration are given in Fig. 3.

Table 3 gives a summary for the CLIC hybrid targets. The beam power on the crystal target is 94 kW. With a repetition rate of 50 Hz, the deposited power in the crystal target is 0.2 kW while the deposited power in the amorphous target is 7.5 kW.

Preliminary and encouraging experimental results, using hybrid targets, are obtained at KEK [21]. Fig. 4 shows the e+ yield measured downstream the amorphous target versus the thickness of the amorphous target. The blue color is for a conventional amorphous target. The red is for hybrid targets using channeling. The green is for hybrid target but the crystal target is rotated and behaves as amorphous. Experimental points are compared to simulations for energy of 20 MeV.

The limited acceptance of the experimental set-up on the KEKB Linac and the expected larger divergence of the positrons generated in the hybrid target, could explain the better e+ yield (above ~8 mm) for the conventional case. Further verifications and checks are on-going at KEK.

6. The polarized e+ for CLIC

The source is based on a positron production scheme in which polarized photons are produced by a Compton process. One option is the Compton backscattering, where an electron beam of ~1 GeV interacts with circularly-polarized photons in an optical resonator. The resulting circularly-polarized gamma photons are sent onto an amorphous target, producing pairs of longitudinally polarized e− and e+ [22–24].

For CLIC, the photon flux coming out from a “Compton ring” is not sufficient to obtain the requested charge. Therefore a stacking process is required somewhere (Pre-Damping Ring, Stacking Ring) [25,26]. Another option is to use a Compton Energy Recovery Linac (ERL) where a quasicontinual stacking could be achieved [27,28]. A

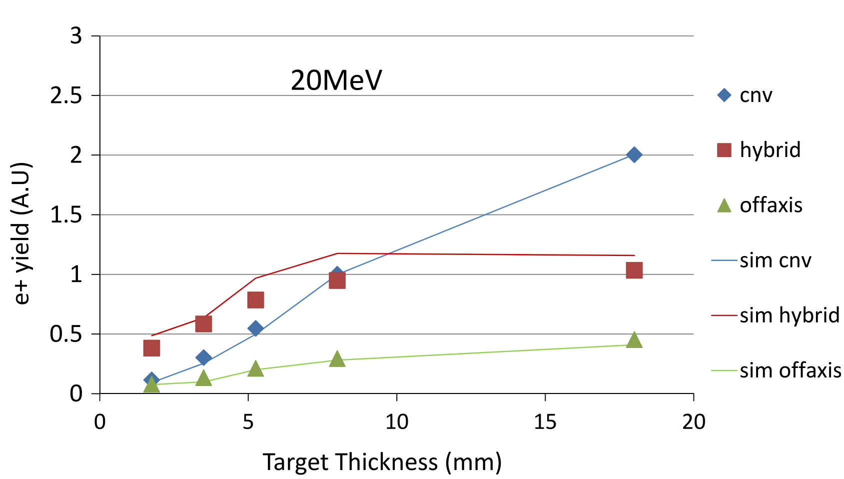

Fig. 4. Experimental results at KEKB linac.

third option is to use a "Compton Linac" which would not require stacking [29].

A study where an undulator is implemented into the CLIC tunnel, has also been made. Based on the simulation results, the polarization of 60% can be achieved by using a 127 m long undulator with $K = 0.9$, $\lambda_u = 1.15$ cm and a photon collimator with an iris of 0.7 mm. The Ti target (0.4 χ_0 length) is located 400 m away from the end of the undulator [30,31].

7. Other brilliant e+ sources

7.1. ILC e+ sources

The baseline for the ILC positron source is using the circularly polarized photons generated by a high energy electron beam ($E > 150$ GeV) in a helical undulator to produce longitudinally polarized positrons in a thin amorphous target [32]. Collimation of the photons coming from the undulator is essential, so the conversion target is put at a large distance from the undulator, at least a distance equal to the length of the undulator. Due to the collimation, the photon spot is rather small and hence the lateral dimensions of the shower in the converter. That leads to important energy deposition densities. Henceforth, a rotating target with high velocity (100 m/s, tangential) is considered [33]. An important experiment, as a proof of principle, using a very short undulator, at a reduced power and without rotating target, has been successfully operated at SLAC (E-166) [34].

7.2. LHeC e+ sources

A presentation of the LHeC project is given in [35]. The requested LHeC flux (a factor 300 compared to SLC – see Table 2) for the pulsed option at 140 GeV could be obtained, in a first approximation, with 10 e+ target stations working in parallel. The idea is described in the CDR [36]. The requested LHeC flux (a factor 7300 compared to SLC) for the CW option, needs important studies and investigations.

7.3. SuperKEKB e+ source

In the SuperKEKB [37] injector linac undergoing upgrade construction, positrons are produced by 3.2 GeV primary electrons of 10 nC bunch intensity impinged on a tungsten target. Two bunches of positrons in 96 ns interval are generated in a beam pulse. An amorphous tungsten target of 14 mm thickness (4.0 χ_0) is used in a commissioning stage and it may be upgraded to a crystal tungsten target later to improve positron yield. The positrons from the target are captured by an adiabatic matching device consisting of 5-T SLAC-type flux concentrator and 0.4-T DC solenoids. They are accelerated by six 2 m-long large aperture S-band accelerating structure of 30 mm aperture diameter up to 120 MeV in the solenoidal focusing region. The structure may be upgraded to L-band counterparts of 35 mm aperture. They are accelerated up to 4.0 GeV in downstream accelerator modules. The positron intensity for injection is 4 nC per bunch.

7.4. SuperB e+ source

In SuperB [38] the injection is at 30 Hz with an injected charge per bunch of ~300 pC. Positrons are produced by electrons accelerated in a linac of 1.5 GeV, impinging on a positron converter target. A capture section in S band but with larger iris provides the longitudinal post acceleration and bunching. Then another S-band linac is used to accelerate positrons up to 1 GeV before DR injection where the longitudinal acceptance is $\sim + -$ 1%. Studies on the positron capture and acceleration system assure that the required positron yield is achieved with S-band linacs and good conversion efficiency. This solution has been preferred since it is well tested. An alternative solution, based on L-band capture and accelerating sections, showed better performances and could be adopted later if it is proven that this can reduce the costs.

8. Summary

The CLIC history spans over 27 years with many changes, upgrades, failures and success.

The requested CLIC e+ flux is very challenging (a factor 20 compared to what has been achieved on SLC). However the requested CLIC unpolarized e+ source parameters seem reachable based on channeling process for a hybrid targets configuration. But experimental demonstrations are mandatory. For the CLIC polarized e+ source, many studies have been performed and many paths explored, based on Compton rings, Compton ERL and Undulators. The Conceptual Design Report is just published. Studies related to the CLIC e+ sources are on-going, in close collaboration with many institutes around the world.

Other projects, like ILC, LHeC, SuperB's, involving brilliant positron sources are studied with a lot of exciting challenges.

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