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F. Zimmermann, O.S. Brüning, Y. Papaphilippou, D. Schulte, P. Sievers, CERN, Geneva, Switzerland; V. Yakimenko, BNL, Upton, NY, USA; L. Rinolfi, JUAS, Archamps, France; A. Variola, F. Zomer, LAL, Orsay, France; E.V. Bulyak, NSC/KIPT, Kharkov, Ukraine; H.-H. Braun, PSI, Villigen, Switzerland; M. Klein, U. Liverpool, UK

Abstract

The full physics program of a future Large Hadron electron Collider (LHeC) [1] requires both pe^+ and pe^- collisions. For a pulsed 140-GeV or an ERL-based 60-GeV Linac-Ring LHeC this implies a challenging rate of, respectively, about 1.8×10^{15} or 4.4×10^{16} e^+/s at the collision point, which is about 300 or 7000 times the rate previously obtained, at the SLAC Linear Collider (SLC). We consider providing this e^+ rate through a combination of measures: (1) Reducing the required production rate from the e^+ target through colliding e^+ (and the LHC protons) several times before deceleration, by reusing the e^+ over several acceleration/deceleration cycles, and by cooling them, e.g., with a compact tri-ring scheme or a conventional damping ring in the SPS tunnel. (2) Using an advanced target, e.g., W-granules, rotating wheel, sliced-rod converter, or liquid metal jet, for converting gamma rays to e^+. (3) Selecting the most powerful of several proposed gamma sources, namely Compton ERL, Compton storage ring, coherent pair production in a strong laser, or high-field undulator radiation from the high-energy lepton beam. We sketch some of these concepts, present example parameters, estimate the electrical power required, and mention open questions.

MOTIVATION

It is the physics beyond the standard model and the searches for it which pose the highest demands on the e^+p luminosity. Important example processes which require high-statistics positron (and electron) data include the determination of the fermion number of leptoquarks, disentangling the nature of new contact interactions, resolving differences in the strange (and top) quark and anti-quark distributions, accessing valence quarks at low x and generalized parton distributions at low Q^2, and a precision measurement of the longitudinal structure function F_L.

POSITRON REQUIREMENTS

Table 1 compares the e^+ beam flux foreseen for the LHeC with those obtained at the SLC, and targeted for CLIC and the ILC. The requested LHeC flux for pulsed operation at 140 GeV (a factor 300 compared to SLC) could be obtained, in a first approximation, with 10 e^+ target stations working in parallel. Several more advanced solutions are proposed to meet the requested LHeC flux for the CW option (a factor 7300 compared to SLC).

Table 1: Comparison of e^+ rates in various colliders. For SLC, CLIC and ILC the energy quoted refers to the exit of the damping ring. The CLIC parameters are for 3 TeV c.m. energy.

	SLC	CLIC	ILC	LHeC pulsed	LHeC ERL
E [GeV]	1.19	2.86	4	140	60
$\gamma\epsilon_x$ [μm]	30	0.66	10	100	50
$\gamma\epsilon_y$ [μm]	2	0.02	0.04	100	50
$e^+[10^{14}\mathrm{s}^{-1}]$	0.06	1.1	3.9	18	440

MITIGATION SCHEMES

Two main approaches can lessen the demands on the rate of positrons to be produced at the source, namely

- **Recycling the positrons after the collision**, with considerations on e^+ emittance after collision, emittance growth in the 60-GeV return arc due to synchrotron radiation, and possible cooling schemes, e.g. introducing a tri-ring system with fast laser cooling in the central ring (see below), or using a large damping ring. If 90% of the positrons are recycled the requirement for the source drops by an order of magnitude.
- **Repeated collisions on multiple turns**, e.g. using a (pulsed) phase-shift chicane in order to recover 60 GeV when reaching the collision point again on the following turn.

COOLING OF POSITRONS

One of the most challenging problems associated with the continuous production of positrons is cooling (damping) of the positron beam emerging from a source or being recycled after the collision. Possible cooling scenarios include pushing the performance of a large conventional damping ring with the size of the SPS, and a novel compact tri-ring scheme.

Damping Ring

The 6.9-km SPS tunnel can accommodate a train of 9221 bunches with 2.5 ns bunch spacing. A tentative parameter list for low (10 Hz) and high repetition rate (100 Hz) is shown in Table 2, considering 234 bending magnets of 0.5-m long dipoles with 1.8-T bending field. The wiggler field for the high-repetition option of 1.9 T along with a wiggler period of 5 cm is within the reach of modern hybrid wiggler technology. A big challenge is the high energy loss per turn for this case, which requires around 300 MV of total RF voltage and implies an average synchrotron-radiation (SR) power of 25 MW. In the low repetition case, the RF voltage and SR power are an order of magnitude more relaxed.

Tri-Ring Scheme

Another possible solution to cool down a continuous positron beam, both the recycled beam and/or a new beam from a source, is the tri-ring scheme illustrated in Fig. 1.

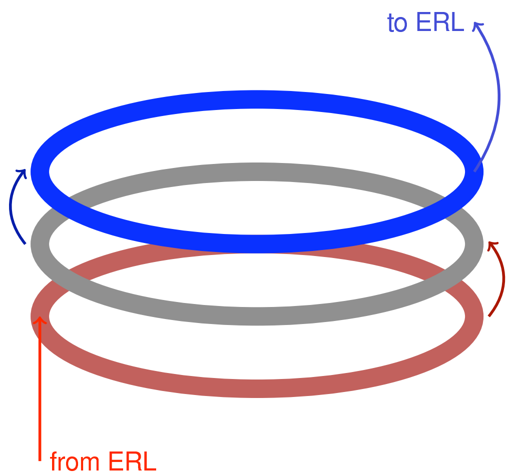

Figure 1: Tri-ring scheme.

In this scheme, the basic cycle lasts N turns, during which the following processes happen simultaneously: N-turn injection from the ERL into the accumulating ring (bottom); N-turn cooling in the cooling ring (middle) possibly with fast laser cooling [3]; and N-turn slow extraction from the extracting ring (top) back into the ERL. At the start of the cycle there is a one-turn transfer from the cooling ring into the extracting ring, and a one-turn transfer from the accumulating ring into the cooling ring. The average current in the cooling ring is N times the average ERL current.

Table 2: Parameter List for a Damping Ring in the SPS Tunnel with High and Low Repetition-Rate Options

repetition rate [Hz]	100	10
energy [GeV]	10	7
bunch population [10^9]	1.6	1.6
bunch spacing [ns]	2.5	2.5
number of bunches/train	9221	9221
repetition rate [Hz]	100	10
damping times trans./long. [ms]	2/1	20/10
energy loss/turn [MeV]	230	16
horizontal norm. emittance [μm]	20	100
total wiggler length [m]	800	-
longitudinal norm. emittance [keV-m]	10	10
RF voltage [MV]	300	35
average SR power [MW]	23.6	3.6

PRODUCTION SCHEMES

Positrons can be produced by pair creation when high-energy electrons or photons hit a target. Conventional sources, as used at the SLC, send a high-energy electron beam on a conversion target. Alternatively, a high-energy electron beam can be used with a hybrid-target configuration where the first thin target is used to create high-energy photons, through a channeling process, which are then sent onto a thick target. The prior conversion into photons reduces the heat load of the target for a given output intensity and it may also improve the emittance of the generated positrons. There exist a number of other schemes that can accomplish the conversion of electrons into photons. Several of them employ Compton scattering off a high-power laser pulse stacked in an optical cavity. According to the electron-beam accelerator employed, one distinguishes Compton rings, Compton linacs, and Compton ERLs. An alternative scheme uses the photons emitted by an electron beam of very high energy (of order 100 GeV) when passing through a short-period undulator. Finally, there even exists a simpler scheme where a high-power laser pulse itself serves as the target for (coherent) pair creation.

Targets

For the positron flux considered for the LHeC the heating and possible destruction of the target are important concerns. Different target schemes and types can address these challenges: (1) multiple, e.g. 10, target stations operating in parallel; (2) He-cooled granular W-sphere targets; (3) rotating-wheel targets; (4) sliced-rod W tungsten conversion targets; (5) liquid mercury targets; and (6) running tape with annealing process.

The LHeC ERL option requires a positron current of 6 mA or 4×10^{16} e^+/s, with normalized emittance of $\leq$50 μm and longitudinal emittance $\leq$5 MeV-mm. For a conventional conversion target with optimized length the power of the primary beam is converted as follows $P_{primary}(100\%) = P_{thermal}(30\%) + P_\gamma(50\%) + P_{e^-}(12\%) + P_{e^+}(8\%)$. The average kinetic energy of the newly generated positrons is $< T_{e^+} > \approx 5$ MeV, which allows estimating the total power incident on the target as P_{target} = 5 MV $\times$6 mA / 0.08 = 375 kW. Assuming an electron linac efficiency of $\eta_{acc} \approx 20\%$ we find $P_{wall} = P_{target}/0.2 = 1.9$ MW. This wall-plug power level looks feasible and affordable. However, also considering a capture efficiency (for the 'useful' e$^+$) of about 5%, P_{wall} becomes 38 MW.

Presently with conventional targets, the transverse normalized rms beam emittances, in both planes, are in the range of 6000 to 10 000 μm. A strong reduction of emittances is mandatory for the requested LHeC performance.

For Compton sources the conversion of gammas to positrons is a bottleneck, which requires a study and optimization of effective convertor targets such as the sliced-rod converter. A typical tungsten convertor optimized for Compton gammas with a maximal energy of 20 MeV can deliver 0.02 positrons per incident scat-

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Table 3: IP e^+ current and the implied minimum e^- beam current in a Compton Ring. Electron-beam currents below 5 A are considered achievable.

	LHeC pulsed	LHeC ERL
I_{e^+} at IP [μA]	290	*7050*
typical I_{e-} [A]	4.3	*105.7*
I_{e-} with 5 J [A]	0.46	*11.2*
I_{e-} with 5 J+1 m rod [A]	0.065	1.6

tered gamma. A sliced-rod convertor target may produce 0.07/0.13 positrons per gamma for a 1 m or 3 m long rod, respectively [2].

Compton Sources

In Compton sources (polarized) positrons are generated by scattering of an electron beam off a higher-power laser pulse, and by converting the resulting gammas in a target.

Compton Ring Table 3 illustrates that a Compton-ring source equipped with an array of optical resonators yielding a total (single-IP 'equivalent') laser-pulse energy of 5 Joule, together with a sliced-rod conversion target, may produce the desired flux of polarized positrons even for the LHeC ERL option. The emission of 30-MeV gammas at the required rate can induce significant beam energy spread in the Compton ring, which requires further studies and optimization.

Compton Linac An optimistic power analysis for a single-pass Compton linac using a CO_2 laser shows that the wall plug power for generating the Compton-linac electron beam alone exceeds the limit of 100 MW set for the entire LHeC project.

Compton ERL A high current ERL appears to be a possible approach, e.g. a 3-GeV 1.3-A ERL with 2-micron wavelength optical enhancement cavities would provide the desired e^+ rate, with "only" 50 MW of wall plug power, and with upper-bound estimates on the transverse and longitudinal emittances for the captured positron beam of $\gamma\epsilon_\perp \leq 1.5$ m, and $\epsilon_{||,N} \approx 450$ μm.

The desired emittances are not reached from any Compton scheme source, even if the target is immersed in a strong magnetic field. Therefore, cooling or scraping would be required.

Undulator Source

An undulator process for e^+ production could be based on the main high-energy e^- (or e^+) beam. The LHeC undulator scheme can benefit from the pertinent development work done for the ILC. The beam energy at LHeC would be lower, e.g. 60 GeV, which might possibly be compensated by more ambitious undulator magnets, e.g. ones made from Nb_3Sn or HTS. However, the requested photon flux calls for a careful investigation. The undulator scheme could most easily be applied for the 140-GeV pulsed LHeC.

Coherent Pair Creation

The normalized transverse emittance of all positrons from a target is of order $\epsilon_N \approx 1 - 10$ mm, to be compared with a requested emittance of $\epsilon_N = 0.05$ mm. Therefore, a factor 100 emittance reduction is required. Possible solutions are cutting the phase space or damping. A third solution would be to produce positrons in a smaller phase space volume. Indeed the inherent transverse emittance from pair production is small. The large phase space volume only comes from multiple scattering in the production target.

Pair production from relativistic electrons in a strong laser field would not need any solid target, since the laser itself serves as the target, and it would not suffer from multiple scattering. This process has been studied in the 1960's and 1990's [4, 5, 6]. It should be reconsidered with state-of-the-art TiSa lasers and X-ray FELs.

CONCLUSIONS

The challenging requirements for the LHeC Linac-Ring positron source may be relaxed, to a certain extent, by e^+ recycling, e^+ re-colliding, and e^+ cooling. The compact tri-ring scheme is an attractive proposal for recooling the spent and recycled positrons, with a pushed conventional damping ring in the SPS tunnel as an alternative solution.

Assuming some of the aforementioned measures are taken to lessen the required positron intensity to be produced at the source, by at least an order of magnitude, and also assuming that an advanced target is available, several of the proposed concepts could provide the intensity and the beam quality required by the LHeC ERL.

For example, the Compton ring and the Compton ERL are viable candidates for the Linac-Ring LHeC positron source. Coherent pair production and an advanced undulator represent other possible schemes, still to be explored for LHeC in greater detail. The coherent pair production would have the appealing feature of generating positrons with an inherently small emittance.

In conclusion, it may be possible to meet the very demanding requirements for the LHeC positron source. A serious and concerted R&D effort will be required to develop and evaluate a baseline design for the linac-ring positron configuration. Among the priorities are a detailed optics & beam-dynamics study of multiple collisions and of the tri-ring scheme, a theoretical exploration of coherent pair production, and participation in experiments on Compton sources, e.g. at the KEK ATF.

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