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Advanced positron sources

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ABSTRACT

Positron sources are a critical system for the future lepton colliders projects. Due to the large beam emittance at the production and the limitation given by the target heating and mechanical stress, the main collider parameters fixing the luminosity are constrained by the e^+ sources. In this context also the damping ring design boundary conditions and the final performance are given by the injected positron beam. At present different schemes are being taken into account in order to increase the production and the capture yield of the positron sources, to reduce the impact of the deposited energy in the converter target and to increase the injection efficiency in the damping ring. The final results have a strong impact not only on the collider performance but also on its cost optimization. After a short introduction illustrating their fundamental role, the basic positron source scheme and the performance of the existing sources will be illustrated. The main innovative designs for the future colliders advanced sources will be reviewed and the different developed technologies presented. Finally the positrons-plasma R&D experiments and the futuristic proposals for positron sources will reviewed.

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1. Introduction: why positron sources are so important for linear colliders?

After the expected Higgs boson discovery, the fundamental high-energy physics community is now pointing out the future accelerators projects to explore both the high energy and the high luminosity frontier. These are lepton colliders enabling the exploitation of the Higgs boson physics potential and also showing the path for search of new physics. In this framework, different international collaborations are assessing the feasibility and the cost of linear colliders based on cold technology like the ILC [1] or on X Band accelerating structures like the CLIC [2]. A concept based on a circular lepton collider in an 80–100 km tunnel is also under study in the framework of the TLEP project [3]. In the framework of the LHeC project, the proposal of a very high energy lepton accelerator integration in the LHC complex should provide the access to the terascale lepton-hadron physics [4]. Recently, the introduction of new collision schemes in the interaction point [5] has also boosted the design of high luminosity b-factories [6,7]. The SuperKEKB project [7] is now under construction for a machine that is expected to deliver luminosity nearly two orders of magnitude larger than the present achievements.

The requirements for very high luminosity in the lepton colliders projects lead to the fundamental role played by the positron source. In fact, considering the basic luminosity formula [8]:

$$\mathcal{L} = \frac{N_e N_{ph} f \cos(\phi/2)}{2\pi\sqrt{\sigma_{ye}^2+\sigma_{yph}^2}} \cdot \frac{1}{\sqrt{(\sigma_{xph}^2+\sigma_{xe}^2)\cos^2(\phi/2)+(\sigma_{ze}^2+\sigma_{zph}^2)\sin^2(\phi/2)}} \quad (1)$$

where N_e, N_{ph} are the number of the electrons in the bunch and the number of the photons in the laser pulse respectively, f is the repetition frequency, ϕ is the angle of the collisions and $\sigma_{\vec{r}_e}$ and $\sigma_{\vec{r}_{ph}}$ indicates respectively the RMS sizes of the electron bunch and the laser pulse. It is straightforward to appreciate that the luminosity is proportional to the bunch population and to the average flux of particles and inversely proportional to the interaction point beam sizes given, at fixed β^*, by the emittance. The main limitation on the optimization of all these parameters is the positron source. In fact, positrons are produced in targets by gamma ray conversion $\gamma \to e^- + e^+$, where the minimum pair production energy of 1 MeV is required. In this process the particle–matter interactions dominate as far as the produced current and 6D emittance are concerned, fixing the source parameters. Peak energy deposition (PEDD) introduces a high thermo-mechanical stress and a related target failure threshold, limiting the positron production per bunch. The thermal property of the material, in particular its melting point, constrains the average

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current. On the other hand, the shower production processes, associated with the multiple scattering in the material, increase the angular divergence and the energy spread so that the 6D emittance at the target exit results in values orders of magnitude higher than in electron sources. Therefore, the first design phase of a positron source is the optimization of the target material and thickness, in order to produce enough positrons while keeping the target operation safe. These limitations also have an impact on the capture and cooling chain of the collider. In fact, due to the high production divergence, appropriate capture, focusing and post acceleration sections need to be integrated immediately after the target. Their geometry, the magnetic B field and the RF characteristics fix respectively the system transverse and longitudinal acceptance with a further positron current reduction. Furthermore, the adiabatic damping given by the subsequent post acceleration usually is not sufficient to reduce the geometrical emittance for a clean injection in the damping ring (DR) where the entire bucket might be filled. The high 6D emittance values require many DR damping times to achieve the required emittance value.

All these considerations clearly show that the main collider parameters like the peak and average current, the emittances, the damping time, the repetition frequency and consequently the luminosity are determined by the positron source characteristics.

2. Positron sources. The "classical" scheme

In the past, only one basic scheme was adopted to produce positrons. A first linear accelerator produces an electron beam accelerated up to an energy value given by the flux requirements (see Fig. 1). The beam impinges on the target producing gamma rays by bremsstrahlung (the beam producing the hard photons is called "primary beam") subsequently converted into e^-e^+ pairs in the nuclear potential of the atoms. The produced pairs consequently start participating in gamma rays and pair production, thereby originating the development of an e.m. shower. In this way all the primary beam characteristics "memory" is lost in positron production. Energy losses by ionization are also present for the lower energy population imposing the limit for the PEDD and the thermal stress. Typical melting temperatures are 3695° for tungsten, 1940° for titanium and 3460° for rhenium. The PEDD limits are an experimental parameter; one of the best known results [9] shows a threshold of 35 J/g for a 6 X_0 thickness W-25Re target.

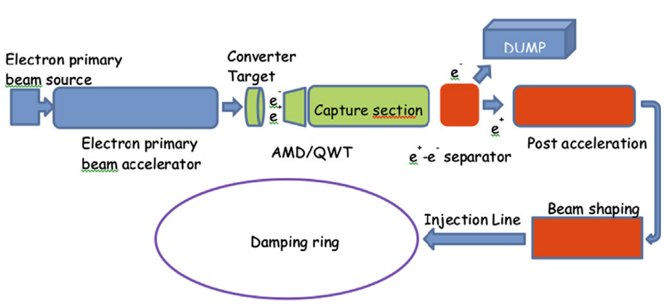

Fig. 1. Different systems of the positron source basic scheme.

After the production, the positron beam has a strong angular divergence resulting from the shower processes and from the multiple scattering. It is so mandatory to immediately introduce a focusing system reducing the angular spread to the detriment of the beam sizes. This device provides a strong axial magnetic field of the order of few Tesla in which the positron spiralizes. The field has a peak close to the target location and then it decreases to a constant lower value. If the field is adiabatically decreasing, the system is called AMD (Adiabatic Matching Device) if the transition is abrupt QWT (Quarter Wave Transformer) [10]. Angular and radial acceptances are functions of the B peak and lower value, of the system aperture and logically of the particles' momenta. For the transverse capture Lithium lenses are also used [11] providing the focusing by an azimuthal B field with a focal strength limited by the maximum achievable current in the lens.

After the transverse shaping, it is necessary to longitudinally bunch and post-accelerate up to few hundreds MeV the beam by means of a capture section, i.e. a series of RF sections enclosed by solenoids at the lower B Field constant value (between 0.25 and 0.5 T). Downstream the capture section it is possible to separate the positrons from the electron beam with a dipole, discarding the electrons in a dump, and to post-accelerate the positrons in a regular FODO channel up to the DR energy. Before the injection in the damping ring, bunch or energy compressors and diaphragms provide a 6D emittance beam shaping to reduce the injection losses. The main parameters for some existing colliders positron sources are summarized in Table 1. It is possible to point out the performances achieved in bunch population of the order of few 10^{10} e^+/bunch and in average current lower than 1 μA (except the PEPII case ~1 μA).

3. Future positron sources. Linear colliders: the intensity frontier

Almost all the above-mentioned positron sources were integrated in the injector complex of circular lepton colliders. As previously said, the next frontier of the HEP experimental physics should be the set-up of a linear collider, overcoming the rigid constraints imposed on circular machines by the synchrotron radiation emission at high energy. As far as the positron sources are concerned, the design philosophy change is impressive. From a scheme in which a single bunch is injected to restore the ring average current, the positron source upgrade must now directly produce all the current necessary for the high luminosity. So the different designs foresee multibunch trains resulting in an average current at least more than one order of magnitude higher than the

Table 1
Positron sources parameters.

Facility	**PEP-II**	**KEKB**	**DAFNE**	**BEPC**	**LIL**	**CESR**	**VEPP-5**
Research center	**SLAC**	**KEK**	**LNF**	**IHEP**	**CERN**	**Cornell**	**BINP**
Repetition frequency, Hz	120	50	50	12.5	100	60	50
Primary beam energy, GeV	33	3.7	0.19	0.14	0.2	0.15	0.27
Number of electrons per bunch	5×10^{10}	6×10^{10}	1.2×10^{10}	5.4×10^{9}	3×10^{9}	3×10^{10}	2×10^{10}
Target	W-25Re	W	W-25Re	W	W	W	Ta
Matching device	AMD	QWT	AMD	AMD	QWT	QWT	AMD
Matching device field, T	6	2	5	2.6	0.83	0.9	10
Field in solenoid, T	0.5	0.4	0.5	0.35	0.36	0.24	0.5
Capture section RF frequency	S-band	S-band	S-band	S-band	S-band	S-band	S-band
Positron yield, 1/GeV	0.054	0.023	0.053	0.014	0.0295	0.013	0.1
Positron output, 1/s	8×10^{12}	2×10^{11}	2×10^{10}	2.5×10^{8}	2.2×10^{10}	6.6×10^{10}	10^{11}

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