IL NUOVO CIMENTO **48 C** (2025) 108
DOI 10.1393/ncc/i2025-25108-0

Colloquia: IFAE 2024

Study of a high intensity positron source based on oriented crystals(*)

D. Boccanfuso([1])(**), F. Alharthi([3]), L. Bandiera([2]), N. Canale([2]), I. Chaikovska([3]), R. Chehab([3]), V. Haurylavets, A. O. M. Iorio([1]), L. Malagutti([2]), A. Mazzolari([2]), V. Mytrochenko([3]), R. Negrello([2]), G. Paternò([2]), M. Romagnoni([2]), M. Soldani([2]), A. Sytov([2]) and V. Tikhomirov

([1]) *Dipartimento di Fisica "Ettore Pancini", Università degli studi di Napoli "Federico II" Napoli, Italy*
([2]) *INFN, Sezione di Ferrara - Ferrara, Italy*
([3]) *Laboratoire de Physique des 2 Infinis Irène Joliot-Curie - Orsay, France*

received 2 December 2024

Summary. — Positron sources are a key element for present and future lepton colliders, such as FCC-ee and ILC, which impose stringent requirements on electron and positron beams: they must have high intensity and low emittance in order to achieve high luminosity. The conventional method for making a positron source is to use a tungsten target hit by a high energy primary electron beam, generating photons by Bremsstrahlung that subsequently convert to e^+e^- pairs. However, the high thermal load and high energy density deposited in the target limits the intensity achievable with this technology. A possible way to overcome these limitations is to exploit the radiation processes that occur when charged particles pass through oriented crystals. A concrete proposal for an intense positron source with parameters of interest to FCC-ee based on this method has been advanced in the e+BOOST project. In this work, the proposal will be described in detail together with simulation results based on Geant4.

1. – Introduction

The European strategy for particle physics envisages a leptonic collider as the next step after the Large Hadron Collider. The Future Circular Collider (FCC) is one of the options under consideration: it proposes a 100-km circumference ring at CERN, which will house first a high-energy, high-luminosity leptonic collider (FCC-ee), and then a hadronic collider (FCC-hh), following in the footsteps of the LEP and LHC programmes. Eventually, an electron-proton collider (FCC-eh). FCC-ee would operate at different

(*) IFAE 2024 - "New Technologies" session
(**) Corresponding author and presenter.

energies in the centre of mass to study the heaviest known particles: at the Z pole (91 GeV), at the WW threshold (161 GeV), at the HH threshold (240 GeV) and close to the $t\bar{t}$ threshold (340-365 GeV) [1]. The main advantage of FCC-ee would be the very high achievable luminosity of $2 \times 10^{36}\, cm^{-2}s^{-1}$ at the Z pole and $1.5 \times 10^{34}\, cm^{-2}s^{-1}$ at the $t\bar{t}$ threshold. For comparison, LEP achieved the maximum luminosity of $10^{32}\, cm^{-2}s^{-1}$ [3]. Such luminosities require high beam currents, which are achieved with the technicque known as top-up injection, which keeps the beam current constant by injecting particles on top of the already circulating beam. The current required is 1.28 A per beam at the Z pole [2]. A high-intensity positron source is therefore essential to meet the intensity of already available electron sources.

2. – Conventional source

The conventional method of obtaining a positron beam, used by all e^+e^- colliders, is to send a beam of energetic electrons against a high atomic number target, typically tungsten. The electrons produce photons by bremsstrahlung and then the photons interacting with the nuclei produce e^+e^- pairs, the cross section for both these processes depends on the square of the atomic number Z, hence the use of high-Z materials. The main downside of this technique is the high amount of energy deposited in the target, which can lead to overheating and damage to the target. The distribution of energy deposited by the primary beam in the target is not homogeneous, this implies a strong temperature gradient and so a high thermo-mechanical stress, that is related to the target failure threshold. For this reason, the peak energy deposition density (PEDD) is used as the reference quantity for assessing the reliability of the source operation. A study conducted on SLC target set the limit for the PEDD of 35 J/g, for an amorphous tungsten target [4].

3. – Oriented crystals

A way to overcome the limits of the conventional source is to exploit the poperties of oriented crytstals. The features of the interaction of a charged particle passing close to an axis or plane of the crystal can be described by effective axial or planar potentials, in a simpler manner than considering the potential of all the atoms separately. The electric field generated by this potential is of the order of 10^{12} V/cm, which is extremely intense, for instance compared to common radiofrequency cavities reach 50 MV/m. The interaction of the charged particle with the periodic lattice of the crystal, and the presence of the intense electric field, leads to many interesting phenomena, depending on the energy of the impinging particle and on the misalignment angle, which is the angle between the axis direction and the direction of the momentum of the particle.

Axial channeling is the confinement of the motion of a charged particle into a trajectory that follows the direction of an axis. For this type of motion to occur, the particle should impact with a misalignment angle no greater than the critical angle $\theta_L = \sqrt{\frac{2U_0}{pv}}$, where U_0 is the total potential barrier height. The oscillation of a channeled particle (electron or positron) in the axial potential results in the emission of electromagnetic radiation, called channeling radiation, which is different from Bethe-Heitler bremsstrahlung, although standard bremsstrahlung is always present. This motion leads to an increase in the radiation emitted, especially of soft photons, which then produce low-energy positrons that are suitable for capture systems. For crystalline tungsten, the potential barrier height U_0 is 1 KeV, and considering electrons of 6 GeV, the critical angle is 600 μrad. Due to multiple scattering in the high-Z crystal and because of crystal imperfections, it is difficult for particles to stay in a channeling. In fact, the increase in emitted radiation is observed also for overbarrier particles, in the case of particles striking at a misalignment angle around 10 times the critical angle due to lattice coherent effects, *e.g.*, coherent bremsstrahlung, therefore contributing to the photon emission enhancement. All these intricate dynamics and radiation processes are incorporated into the Monte Carlo simulations to create a scenario that is as realistic as possible.

4. – Simulation of the positron source

In Monte Carlo simulations that can be created with Geant4 [5], matter is described as homogeneous and isotropic, so typical crystal effects cannot be reproduced. To overcome this limitation, specific libraries have been developed [6] for the purpose of including the effects of crystals in Geant4, called G4ChannelingFastSimModel. The calculation of the energy lost by channeling radiation is based in particular on the semi-classical Baier-Katkov method. In fact, at high energies, the motion of the particle can be treated classically, since the particle De Broglie wavelength is small enough to prevent the formation of interference patterns and bound states are characterized by a large number of energy levels, the classical description works for particle above 100 MeV. The higher the energy, the more adequate the classical treatment is. At the same time, at high energies the effect of quantum recoil imposed on the electron by the emitted radiation cannot be neglected. Thus, a semiclassical approach is best suited to compute the radiation emission.

Including this library, a Geant4 application was written, which allows us to simulate a positron source with the freedom to vary a wide range of parameters, and thus study different configurations for our purposes. Three main configurations were studied: a conventional source (fig. 1), composed of single amorphous target, in order to benchmark the performance of crystal based source against it; a crystalline source (fig. 1), composed of a single crystal target; and a hybrid source (fig. 2), composed of a thin crystal used to produce photons (radiator), followed by a thicker amorphous target used for the pair production (converter), with the aim to reduce the PEDD.

The application allows to change the size of the elements of a hybrid source, the separation distance between them, and the materials from which the targets are made; the most suited element is tungsten, as already stated, but other materials like diamond could prove convenient at energies above 20 GeV, because having low Z means less incoherent scattering, although the thickness of the target needs to be increased.

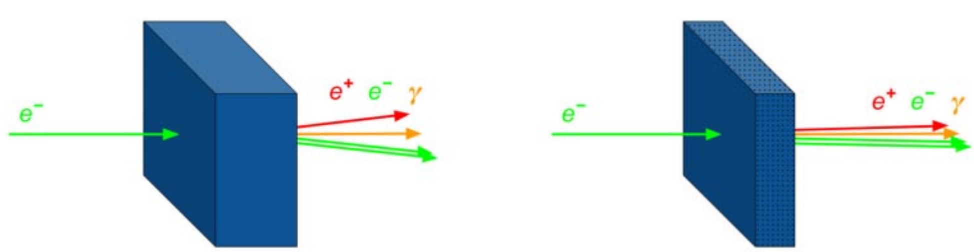

Fig. 1. – (Left) Sketch of a single amorphous target, (right) sketch of a single oriented crystalline target (right).

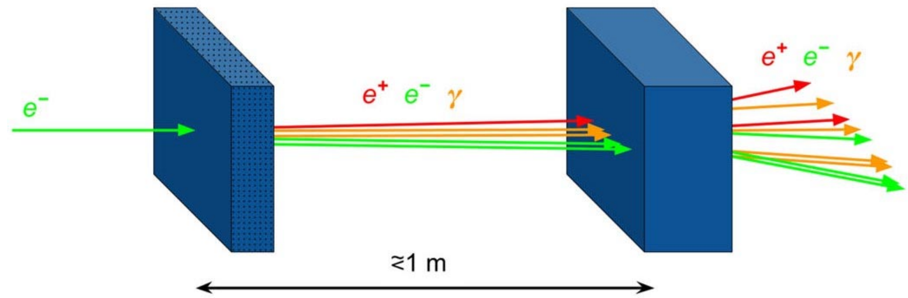

Fig. 2. – Sketch of a hybrid source composed of oriented crystalline radiator and an amorphous converter.

Another interesting option to study is the introduction of a collimator or magnetic field between the radiator and converter in a hybrid source, in order to block or swipe the secondary particles produced in the radiator that hit the converter and increase the total deposited energy. This option is particularly useful for linear colliders, where the intensity of the primary beam needs to be higher than a circular collider, so the PEDD in the converter is automatically higher, the proposed configuration would allow to significantly reduce it by removing secondary particles [7].

Finally, the Geant4 application allows the possibility to simulate a granular target, composed of packed spheres instead of a single block, which has the benefit of dissipating heat faster, but it also makes the source more difficult to manufacture.

The positrons coming from the source must be focused immediately by a magnetic field so as to avoid the dispersion of the beam, the magnet responsible for it is called matching device. Then, positrons are usually bunched by radiofrequency cavities and accelerated towards the damping ring, which is a relatively small ring where positrons lose energy by synchrotron radiation in order to reduce the longitudinal momentum. Each component of the injector system has a certain acceptance, which affects the fraction of positrons that are successfully transported to the storage ring. This implies that the efficiency of a positron source, intended as the number of positrons produced per primary electron, is a global concept. We simulate these stages following the positron source using the RF-Track framework, developed at CERN [8]. The injector system suggested for FCC-ee is composed of an Adiabatic Matching Device (AMD), which is a high-temperature superconducting solenoid, RF cavities and Linac with FODO sequence before the damping ring.

Some results obtained from the simulation are presented in this paper. The primary electron beam used consists of 10000 electrons at an energy of 6 GeV and beam width of 0.3 mm. The real beam that will be used for FCC-ee will likely have width between 0.5 mm and 1.0 mm. Reducing the beam width has the benefit of increasing the fraction of positrons accepted by the AMD, but also the downside of increasing the PEDD drastically. Secondary particles are tracked using scoring screens placed after the target, in the case of a hybrid source, scoring screens are placed after the radiator, and before and after the converter. The energy density is evaluated by recording the energy deposited in a small cubic volume, called a voxel. A voxel should have side length equal to half the beam width. The PEDD is taken to be the energy of the greatest energy deposit divided by the volume of the voxel, we expect the PEDD to be along the beam axis.

Since the goal of the e+BOOST project is to obtain a higher positron yield while

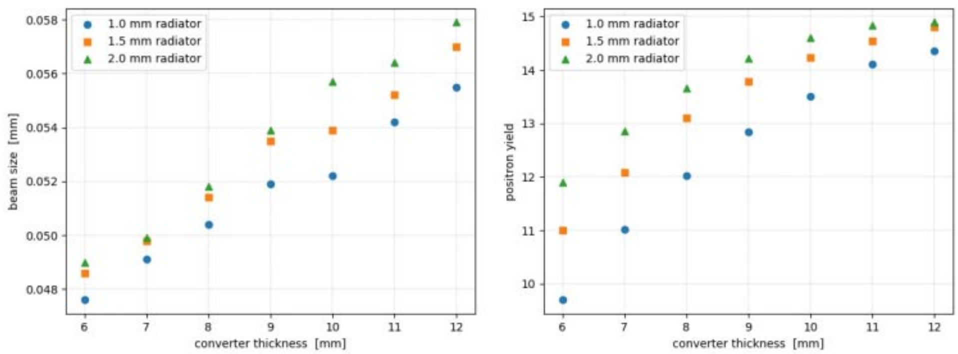

Fig. 3. – Positron beam size after the converter (left), number of positrons after the converter per primary electron (right).

maintaining an acceptable heat load, a hybrid source was investigated first, as it is the most promising configuration concerning the reduction of the PEDD. However, the accepted yield at the AMD drops significantly with increasing separation distance between the radiator and converter, the highest yield is obtained when there is no separation.

Increasing the thickness of the radiator or converter increases the positron yield, but beyond a certain thickness positrons begin to be absorbed by the target itself and the yield decreases.

Figure 4 summarizes the results for some configurations of the positron source, including the accepted yield before the damping ring obtained by the RF-Track simulation. The first row represents the results of the simulation of the conventional source currently proposed for FCC-ee, it is a 17.5 mm target of amorphous tungsten. The table shows that a hybrid source composed of a 2.0 mm radiator, and a 12.0 mm converter with no separation between them, achieves an accepted yield $\sim 10\%$ higher and, at the same time, a $\sim 15\%$ reduction of the PEDD and deposited power compared to the conventional source.

Source type	**Accepted Yield**	**PEDD [J/g/pulse]**	**Deposited Power [kW]**
Conventional	7.0	7.67	1.13
Converter 7.0 mm	6.33	7.43	0.47
Converter 9.0 mm	7.22	6.88	0.65
Converter 12.0 mm	7.72	6.50	0.99

Fig. 4. – Comparison between a conventional positron source, composed of 17.5 mm of amorphous tungsten, and a hybrid source composed of a 2.0 mm crystalline radiator and amorphous converter, with no separation between them.

5. – Conclusions

The proposed leptonic collider, FCC-ee, would allow the study of the electroweak sector with unprecedented precision, thanks to its extremely high luminosity, which, however, requires the use of intense beam currents, up to 1.4 A. The properties of oriented crystals can be exploited to realize a high-intensity positron source, as charged particles passing through a crystal produce photons through a mechanism called channeling radiation, leading to an increase in photon production and thus positron yield, compared to an amorphous target. The e+BOOST collaboration is able to simulate the entire injection system envisaged for FCC-ee and study the characteristics of the positron beam at each stage. The simulation performed so far shows that a hybrid source with a crystalline radiator effectively leads to an improvement of the overall performance compared to a conventional source, by increasing the positron yield by $\sim 10\%$ and reducing the deposited power and the PEDD by $\sim 15\%$.

* * *

We acknowledge financial support under the National Recovery and Resilience Plan (NRRP), Call for tender No. 104 published on 02.02.2022 by the Italian Ministry of University and Research (MUR), funded by the European Union–NextGenerationEU–Project Title: "Intense positron source Based On Oriented crySTals - e+BOOST" 2022Y87K7X–CUP I53D23001510006.

REFERENCES

[1] FCC Collaboration (Abada A. *et al.*), *Eur. Phys. J. C*, **79** (2019) 474.
[2] FCC Collaboration (Abada A. *et al.*), *Eur. Phys. J. ST*, **228** (2019) 261.
[3] Assmann R. W., *APAC '01, Beijing, China* (September 2001).
[4] Bharadwaj V. K. *et al.*, *PACS2001, Proceedings of the 2001 Particle Accelerator Conference, Chicago, IL, USA*, Vol. **3** (IEEE) 2001, pp. 2123–2125, https://doi.org/10.1109/PAC.2001.987297.
[5] Agostinelli S. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **506** (2003) 250.
[6] Sytov A. *et al.*, *J. Korean Phys. Soc.*, **83** (2023) 132.
[7] Soldani M. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **1058** (2024) 168828.
[8] Latina A., *RF-Track Reference Manual* (CERN, Geneva, Switzerland) 2024, https://doi.org/10.5281/zenodo.3887085.