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The SHERPA project: Bent crystal-assisted beam extraction simulations

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Summary. — In this article, we report on the SHERPA project, aiming at developing an efficient technique to extract a positron beam from one of the rings of the LNF DAΦNE collider, creating $\mathcal{O}$(ms) long pulses. The most common slow extraction method is the resonant technique: after having created an unstable region in phase space, particles are gradually extracted from the circulating beam using a combination of electrostatic and magnetic septa. Instead, SHERPA proposes to use coherent processes in bent crystals, a cheaper and less complex alternative. This non-resonant technique, already used in hadron accelerators, will provide continuous multi-turn extraction with high efficiency. Various Geant4 simulations were carried out to study the channeling properties of positrons below GeV, in preparation for the first beam tests of the crystals produced for SHERPA. For positrons in this energy region, no experimental data exist on crystal channeling. Validation of the Geant4 simulations was obtained using a combination of analytical theoretical equations and other Monte Carlo simulations.

1. – Introduction to bent crystal channeling and the SHERPA project

A charged particle impinging on a crystal lattice, like silicon or germanium, can behave differently depending on its alignment with the crystal. If aligned with the crystal planes, the particle can be trapped by the inter-planar potential, following a path constrained by the minima of this potential. This effect is known as channeling. If the crystal is bent, the particle will follow the crystal plane bending, and will be thus deflected. If the particle is not aligned with the crystal planes, the passage in the crystal will be instead dominated by Coulomb multiple scattering. A complete overview of channeling and other coherent processes in bent crystals can be found in [1].

The INFN LNF DAΦNE accelerator complex is based on a 60 m long, S-Band LINAC, providing up to 500 MeV positrons or 800 MeV electrons. It produces 1.5 to 350 ns long pulses at the maximum repetition rate of 50 Hz, corresponding to a maximum duty-cycle of 10^{-5}. Converting one of the DAΦNE rings into a pulse-stretcher for the LINAC would produce an almost continuous extracted positron beam of $\sim$500 MeV, useful both for fundamental experiments physics and test purposes [2]. Both resonant and non-resonant extraction schemes have been investigated, the latter offering some potential advantages like the high collimation of the channelled particles, thus providing an excellent quality of the extracted beam.

The SHERPA project [3] aims at studying crystal-assisted beam extraction in two different configurations: a single DAΦNE ring or the Damping Ring. The crystal bending angle is limited by the crystal size: in order to deflect 500 MeV particles, its thickness should not exceed few micrometers, otherwise particles could experience other undesired coherent effects, such as de-channeling [1]. This consideration has a direct consequence: the bending radius cannot be too small, otherwise the crystal can be broken by excessive mechanical stress while bending it. The design bending angle is $\sim$1 mrad.

2. – Geant4 simulation of coherent processes in bent crystal outline

The simulations presented in this work are aimed to study the crystal channeling. To understand the beam parameters necessary to observe the channeling process with a $\sim$ 500 MeV positron beam, the existing Geant4 routine dedicated to the channeling process has to be validated with leptons in this momentum range. Coherent bent crystal processes have been implemented by Bagli *et al.* [4] in the Geant4 Version 10.05.p01. This routine was specifically optimized in order to reproduce the UA9 experimental setup at the CERN high-energy proton beam-line H8 [5], and it has been modified in order to reproduce other experimental setups of interest, such as the Mainz Mikrotron and the SHERPA setup at the INFN LNF Beam Test Facility. In this routine, the main coherent processes have been implemented: channeling, de-channeling, volume capture and volume reflection. Re-channeling has not been implemented, but considered a posteriori, according to [6]. The only lattice plane available is the (110). The beam and crystal parameter and orientation can be modified by data cards, thus allowing high flexibility when studying several configurations. The Geant4 simulations provide, as output variables, the impinging and outgoing x and y angles, and the impinging and outgoing x position. These variables are computed numerically and do not suffer smearing induced by the detector resolution or other effects depending on the DAQ/readout systems.

To our knowledge, the routine has never been used before in practical applications, and no publication exists on its performance while simulating leptons. All Monte Carlo results presented in [6] are obtained via analytical simulations.

3. – Geant4 simulation benchmark

A simplified geometry description of the CERN H8 setup [5] includes the bent silicon crystal with three Silicon strip detectors placed at -9.998 m (T1), -0.320 m (T2) and 10.756 m (T3) with respect to the crystal position. The primary events are 400 GeV protons, produced at -10.500 m from the crystal with $\sigma'_x = 13.36\,\mu$rad and $\sigma'_y = 11.25\,\mu$rad divergence [7]. In order to test the Geant4 routine, the H8 experimental setup was simulated with 50000 protons events, with the crystal oriented in channeling configuration. In order to replicate the angular cut in [7], we set $\sigma'_x = 2.5\,\mu$rad, in order to have 95.4% of the beam in the angular region delimited by $|\theta_{x0}| < 5\,\mu$rad. The deflection angle distribution is shown in fig. 1. The peak on the left side in fig. 1(a) and (b) is due to particles which were not captured into the channeling states at the crystal entrance. Particles with deflection angles between the two maxima in fig. 1 are the de-channeled

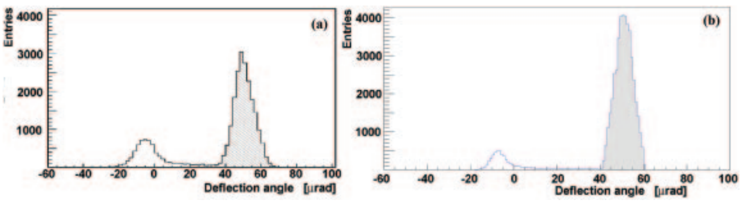

Fig. 1. – Deflection angle distribution for 400 GeV protons from UA9 data (left) [7], and Geant4 simulation (right).

ones [7]. It is evident that the 400 GeV proton Geant4 simulation matches well the data, as expected. The efficiencies values obtained $\mathcal{E}_{G4} = (75.30 \pm 0.68)\%$ and $\mathcal{E}_{ST} = 76\%$ [7] respectively also show a very good agreement. After verifying the correct behaviour of the Geant4 routine, the MAMI experimental setup geometry was simulated with an 855 MeV electron beam ($\mathcal{E}_{G4} = (21.9 \pm 1.9)\%$) and then compared with the experimental results $\mathcal{E}^{Exp}_{MAMI} = (20.1 \pm 1.2)\%$, $\mathcal{E}^{MC}_{MAMI} = 21.2\%$ in [6]. The latter configuration has in addition been simulated with positrons, and the results obtained have been compared with analytical simulation ($\mathcal{E} = 86.2\%$ in both cases), described in [8, 9]. After this benchmark phase, it could be claimed that the routine is producing reasonably good results, compatible with the observed phenomenology. Finally, we started to study the SHERPA LNF BTF-II configuration, with both 511 MeV electrons and positrons. The main goal is to define requirements for the beam spot size and divergence, in order to successfully observe the channeling effect at LNF.

4. – LNF BTF simulation

In this section, we present the simulation of the beam images the SHERPA TimePiX3 detector should see during a test at the LNF BTF facility with $\sim$500 MeV positrons. Different beam spot size and divergence values along bending coordinate x are probed. The main constraints are given by the available BTF beam emittance $\mathcal{E} = 1$–$2\,\mathrm{mm \cdot mrad}$. The divergence along the y coordinate $\sigma'(y)$ will be fixed at 300 μrad. The size of the BTF experimental hall does not allow the distance in-between crystal and the imaging sensor to be greater than $\sim$2–3 m. Under these conditions, the size of the beam spot at crystal position plays a crucial role in the capability of the experiment to observe the channeling peak online. Figure 2 shows the results obtained for the beam spot for 2 m crystal to sensor distance. This simulation was performed with variable RMS beam spot size $\sigma(r) = 0$–1 mm and variable divergence $\sigma'(x) = 0$–$500\,\mu$rad. It is clear that the crucial parameter is the beam spot. At short distances, just 2 m from the crystal, the channeling peak is barely visible for a beam with 500 μrad divergence and 1 mm radius

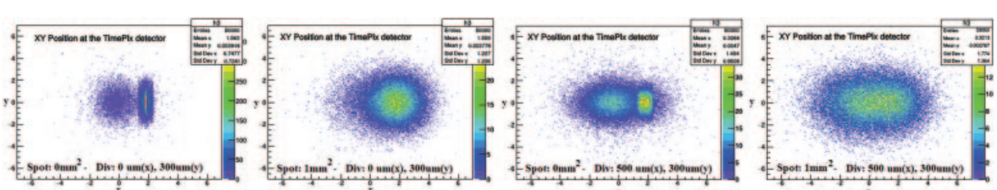

Fig. 2. – Beam spot at the TimePix3 plane for a detector to crystal distance of 2 m. Beam spot RMS size: $\sigma(r) = 0 \sim 1$ mm; divergence: $\sigma'(x) = 0$–$500\,\mu$rad.

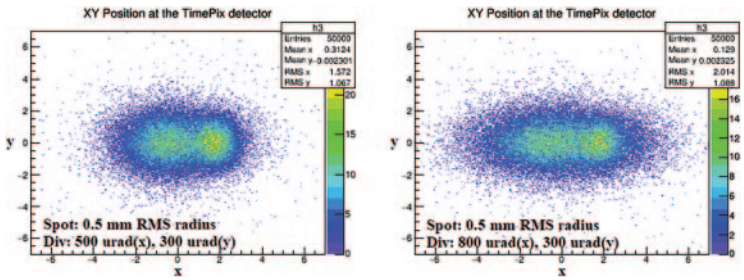

Fig. 3. – Beam spot at the TimePix3 plane for a detector to crystal distance of 2 m. Beam spot RMS size: $\sigma(r) = 0.5\,\mathrm{mm}$; divergence: $\sigma'(x) = 500$–$800\,\mu\mathrm{rad}$.

RMS beam spot. On the contrary, if the spot size is very small, the channeling can be clearly observed even at short distance from the crystal. To mitigate the effect of the spot size, we tried to move the detector 1 m downstream: at 3 m from the crystal the channeling peak can be identified even with a beam divergence of $500\,\mu\mathrm{rad}$. To simulate the effect of the beam optics, we also tried a configuration with higher values of angular divergence $\sigma'(x) = 500\,\mu\mathrm{rad}$, $\sigma'(x) = 800\,\mu\mathrm{rad}$ and smaller beam spot size of just 0.5 mm radius. This could be obtained by acting on the BTF transfer line quadrupoles. Figure 3 shows the results for the 2 m crystal to sensor distance beam spot simulation.

5. – Conclusions

Several simulations were performed to study the reliability of the Geant4 channeling routine and all the simulated configurations gave compatible results with the experimental data, when available. Therefore, it was possible to extend the study towards the SHERPA configuration at INFN LNF Beam Test Facility. In order to observe channeling in the LNF BTF configuration it is necessary to keep the beam spot size as small as possible, even slightly increasing the divergence. The best configuration, for a detector to crystal 2 m distance, should be $\sigma(r) = 0.5\,\mathrm{mm}$, $\sigma'(x) = 500\,\mu\mathrm{rad}$.

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