THE SHERPA EXPERIMENT

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1 Introduction

LINAC's high-current electron radio-frequency (RF) are commonly used to produce ultra-relativistic (>> MeV) positrons with a very wide range of pulse duration, from below ps (by photo-injectors) up to few μs (by thermo-ionic guns and uncompressed RF power). The reachable repetition rate is up to hundred Hz and charge generally ranges from pC to few nC per pulse. Usually positron beams have a very high emittance because are produced by Bremsstrahlung onto high-Z targets and need to be focused by strong magnetic fields. Positron extraction lines from circular accelerators are, on the contrary, quite rare, also due to the relatively small number of positron machines, and they come directly from the LINAC or from the storage ring. A valid alternative is the secondary positron beams production by photon pair production, as it happens in the CERN H4 line able to deliver up to 200 GeV positrons using Bremsstrahlung from 400 GeV protons extracted from the SPS on one of the North Area targets.

Currently, the only available positron beam at INFN-LNF is the Beam Test Facility (BTF) [1], delivered directly from the DAΦNE LINAC [2]. This facility provides 0.5 GeV positrons at the 49 Hz maximum repetition rate, in pulses of 10^9 e^+ of maximum length 320 ns [3, 4, 5], with an energy spread of 0.5 % and an emittance of 10^{-5} m·rad. The beam pulse length is mainly limited by the compression of the RF power, needed to reach higher accelerating gradients with fewer klystrons. In order to produce a high-intensity positron beam using short pulses, high number of positrons per bunch are used thus producing pile-up, which can spoil single event precise measurements in fixed-target experiments. One of the clearest examples is the Positron Annihilation into Dark Matter Experiment (PADME) [6] that started taking data using the DAΦNE LINAC beam in September 2018. An almost continuous extracted beam, extending the pulse duration to the ms scale, with a very good emittance and energy spread, could increase significantly the PADME sensitivity and its discovery potential.

A primary positron beam with such characteristics has never been extracted so far from a circulating machine. The main challenge of the SHERPA project is to develop a smart core solution to achieve this unprecedented performance.

2 The SHERPA experiment

The SHERPA ("Slow High-efficiency Extraction from Ring Positron Accelerator") project aim is to develop an efficient technique to extract a positron beam from one of the accelerator rings composing the DAFNE accelerator complex at Frascati, setting up a new beam line able to deliver positron spills of O(ms) length, excellent beam energy spread and emittance.

The most common approach to slowly extract from a ring is to increase betatron oscillations, approaching a tune resonance. It consists in generate an circumscribed unstable region of the phase space in one of the transverse planes, for example the (x,x'), applyng a proper sextupole configuration. Then, particles slowly approach an unstable resonant frequency characterised by the extraction separatirx, in order to gradually eject particles from the circulating beam.

SHERPA proposes a paradigm change using coherent processes in bent crystals to kick out positrons from the ring, a cheaper and less complex alternative. This non-resonant technique, already successfully used and still developed mainly in hadron accelerators, will provide a continuous multi-turn extraction of a high quality beam [7, 8, 9, 10]. Alternatively, it can complement the resonant technique, providing an angular kick to unstable particle in place of the extraction septum.

Realising this for sub-GeV leptons is challenging, however would provide the world's first primary positron beam obtained with crystal extraction. At the DAΦNE Beam Test Facility (BTF), sub-GeV positrons have already been deflected using crystals, proving the technique feasibility [11, 12]. Other tests at the MAMI [13] and SAGA [14] accelerators with sub-GeV electrons have been performed with very promising results. An immediate application of this new extracted beam line would be the PADME experiment, currently strongly limited by the duty cycle. Using the proposed extraction, PADME could increase the statistics by a factor 10^4 and its sensitivity by a factor 10^2.

The BTF beam is ideal to test and characterise the crystal prototypes, in particular to measure their deflection angle and efficiency using pixel detectors to reconstruct the particle distribution beyond the crystal.

SHERPA is a feasibility study experiment and, over a period of two years (2020-2022), aims to achieve the following mile stones:

1. Study promising optical configurations of the existing DAΦNE complex that allow crystal slow extraction.
2. Design and built a crystal prototype with the characteristics necessary for slow extraction.
3. Built an experimental apparatus for crystal characterisation at the BTF.
4. Characterise the crystal prototype.

3 Activity of the SHERPA LNF group

3.1 Crystal extraction optics studies

To slow extract a particle beam, in this case positrons, it is necessary an accumulator ring, a device and a technique able to extract a small portion of the beam "turn by turn". At the Frascati accelerator complex there are two possible options: use one of the DAΦNE main rings or use the damping ring. The main ring solution could be more efficient as it allows the use of numerous devices (quadrupoles, kickers, beam monitors, sextupoles, etc.) to manage and control the beam parameters and optimise the quality and the intensity of the extracted beam. On the other side, this option requires greater efforts in terms of know-how, manpower and costs of maintenance. Instead, the damping ring solution is more simple and cheeper, but harder to be optimised due to the lower adaptability and tuneability of the machine structure. Nevertheless, it could provide and adequate extracted beam quality.

In 2020, both solutions have been preliminarily investigated for crystal extraction by the SHERPA team, obtaining extremely promising results applying minimal modifications at the actual main and damping ring hardware configuration, apart from the presence of the crystal. The optical parameters of the machine have been slightly modified and tuned to allow the circulating beam to interact with the crystal and deflect positrons functionally to the slow extraction process. In particular, particle tracking simulation has been used to establish and optimise the crystal extraction parameters: the angular deflection range needed, the crystal longitudinal and transversal positions, the transversal displacement range at the extraction point, the longitudinal position and geometry of the extraction septum.

These simulations have been performed at LNF by O.R. Blanco-Garcia, using the MAD (Methodical Accelerator Design) software [15], the standard already used for DAΦNE.

3.1.1 DAΦNE main ring studies

Based on previous experimental results of channeling with leptons at ~ 1 GeV, obtained and reported in [13], the best performance of a Silicon bent crystal (~ 30 μm thick along the beam direction) are ~ 1 mrad of deflection with a channeling efficiency of the order of $\sim 20\%$ with e^- (it is important to specify that with e^+ the deflection efficiency will be higher inasmuch positive charged [16]). These two parameters have been chosen as the starting point for the following extraction study.

The first conclusion is that "local extraction", in which the crystal is positioned at the extraction point, seems difficult due to the space requirements. Ignoring any optics considerations, a deflection below 1 mrad would separate the extracted beam from the circulating one by few mm over a line several meters long.

The solution was found in the "non local" crystal extraction: a kick is imparted in one point of the ring by a crystal allowing particles to reach a septum with the adequate transversal displacement for a further deflection after a given phase advance or even some turns, depending on the ring optics parameters. Positrons can encounter the crystal multiple times and get further kicks or got lost (Fig.1).

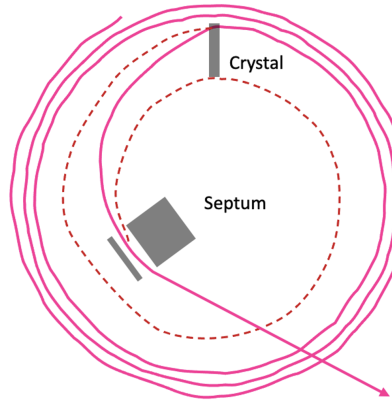

Figure 1: *Non local extraction scheme.*

In the linear approximation for the optics, the displacement x_2 at location 2 (septum) due to a kick x'_1 given at location 1 (crystal) can be calculated from the formula:

$$x_2 = \sqrt{\beta_1 \beta_2} sin(2\pi \Delta\mu) x'_1 \tag{1}$$

where $\Delta\mu$ is the phase advance, β_1 and β_2 the β functions at the point 1 and 2 respectively. In order to have maximum displacement, the β functions should be as large as possible and $\Delta\mu$=1/4.

Considering the main ring optics model used for the INFN SIDDHARTHA experiment in 2019, several locations were evaluated, finding different promising options for the crystal "non local" extraction. The best one obtained is with the crystal positioned just upstream (high β) and the septum just downstream the ring crossing point, so the extraction will happen few meters downstream the crystal (Fig. 2).

A positron with an energy offset of ∼1% will encounter the crystal, positioned at 8 mm from the circulating beam axis, at the 6^{th} turn in the machine and will be extracted in the same turn (Fig. 3).

In this configuration the transversal displacement obtained at the extraction point is ∼ 20 mm (Fig. 4), more than enough to overcome a extraction septum of thickness Δx ∼ 15 mm.

A specular configuration around the Interaction Point 1 (IP1) was also studied, obtaining similar results.

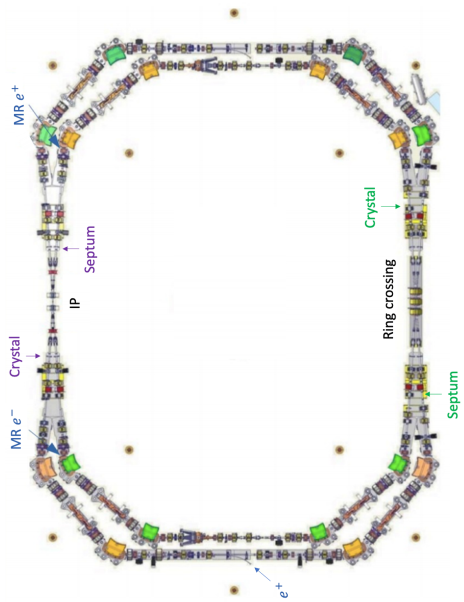

Figure 2: *Crystal and extraction septum positions along the DAΦNE main ring.*

Positrons that gradually lose energy, for example by "Touschek effect" or simply by synchrotron radiation, will be slowly extracted. This is possible with the "Radio Frequency" (RF) devices off, or not at the nominal value applied to recover the energy loss and keep the beam stable along the ring. The rate of the extraction, determining the extracted beam pulse length, is still under investigation.

This preliminary study shows that it is possible to slow extract a positron beam from the actual DAΦNE ring using a bent crystal with already verified deflection performance.

Obviously, this solution has to be optimised in terms of optics parameters, crystal position and septum features to obtain the best result in terms of extracted beam quality. In particular the extracted beam main parameters to be optimised are: spill length, intensity, emittance and energy spread.

For the main ring configuration, a resonant solution has been also investigated [17, 18] and it could be implemented together with the crystal solution for a hybrid "resonant-non resonant" extraction approach. This option is still under study.

3.1.2 Damping ring studies

Another very interesting alternative is to use the damping ring (also called "accumulator"), applying the same "non local" extraction approach.

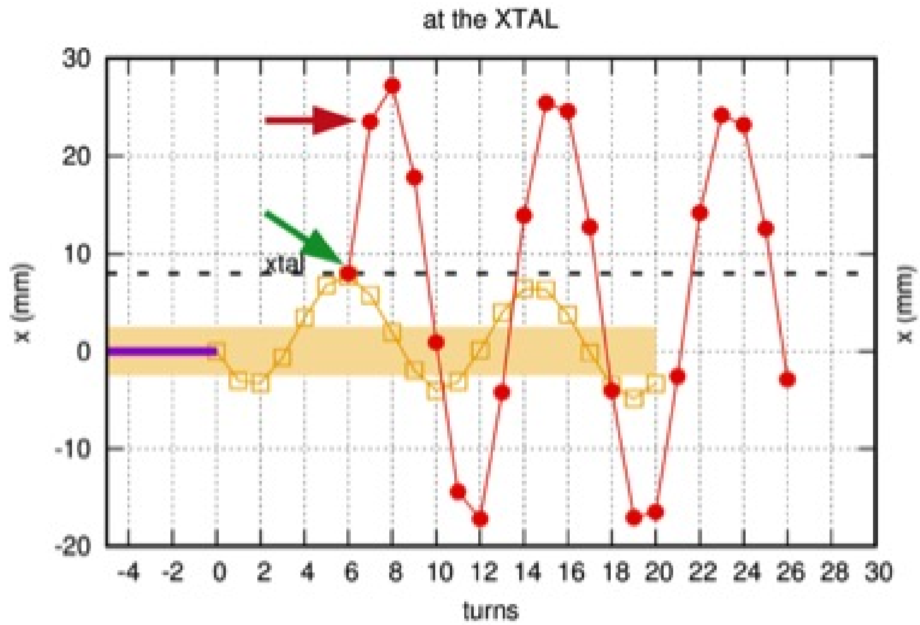

Figure 3: *Transversal position of a positron with energy spread 1%, reported turn by turn, before and after interaction with the crystal.*

The standard accumulator optics has chromaticity $\xi \sim 0$ and small β, at advantage of a large momentum acceptance. To permit a slow extraction using a crystal it is necessary to modify the accumulator optics to have largest possible β in the straight sections and have a chromaticity $\epsilon \neq 0$, in spite of a reduction on the ring momentum acceptance. The chosen crystal position is at one of the kickers position and the extraction point is the same used to extract the beam towards the DAΦNE main ring, where a septum is already present (Fig. 5).

Our studies show that positrons with an energy loss of 0.6%, with respect to the nominal one, will have a transversal displacement $x =$ - 5 mm (inwards) at the crystal position, and $x =$ - 3 mm at the septum. It means that positrons can interact with the crystal getting a kick of 1 mrad, producing a greater transversal displacement $x =$ - 11 mm at the septum in the same turn. This dynamic allows positrons to be slowly extracted with a rate and beam features which have to be optimised, together with the septum parameters. As a reference, positrons loose 0.6% of energy by synchrotron radiation in 600 turns, thus the extraction time could be around $60\mu s$. As in the case of the DAFNE main ring, it is necessary to switch off the RF to allow positrons to spontaneosly loose energy and "diffuse" towards the crystal.

The extraction rate can be tuned, for example, acting on RF, extending in time the positron energy loss process and, consequently, the extracted spill length.

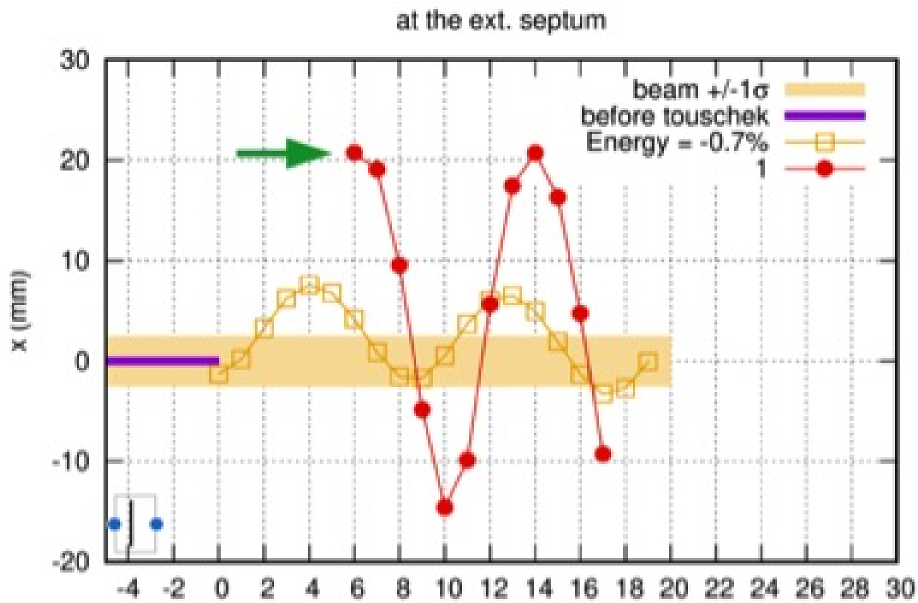

Figure 4: *Transversal position of a positron with energy spread 1%, reported turn by turn, at the septum position after the crystal kick.*

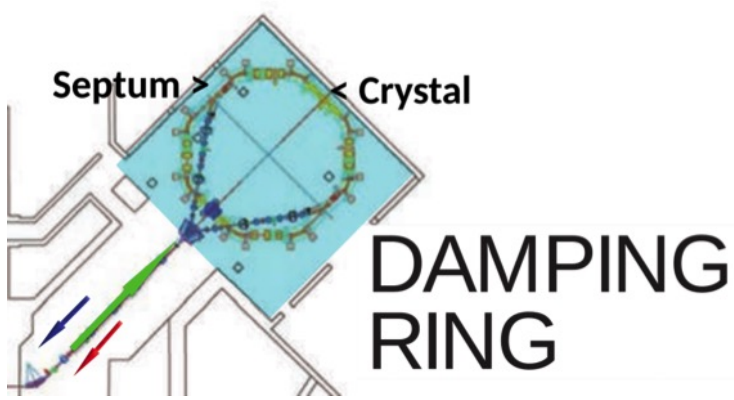

Figure 5: *Crystal and septum position along the Damping ring.*

Also for the accumulator, a resonant solution and a hybrid "resonant-non resonant" crystal extraction is under study.

4 Crystal system design and construction

The crystal system consist of two main parts: the Silicon crystal and the bending holder that imparts the curvature necessary to deflect charged particles.

The most common material used for crystals is single crystal Silicon, due to the high purity (99.99995 %) and low dislocations number (< 1 cm^2) obtained in the semiconductor technology. Germanium could be anyway investigated: its higher atomic potential with respect to Silicon will provide a more efficient deflection of particle with the same energy. Anyway, it is necessary to take into account the higher cost and the supply difficulties of Germanium crystals.

To steer by channeling sub-GeV leptons is quite challenging with respect to the case of high energy hadrons. In fact, it is necessary to reduce a lot the thickness of the bent crystal along the beam direction to limit electronic dechanneling, the effect whereby the particles exit the atomic channel due to the interaction with the Silicon electrons. In fact, for low energy positrons this effect is much more important than for high energy hadrons [16]. To obtain a reasonable channeling efficiency is thus necessary to reduce the crystal thickness from some mm to few tens of μm, pushing at the technological limit the bending device to avoid breaking the crystal during the bending procedure and guarantee a homogenous curvature.

Concerning the crystal, the production is under the responsibility of the INFN-Fe and consist of two steps: the industrial production of the bulk Silicon and the treatments necessary to obtain the shape and especially the extremely small thickness needed. The industrial production will guarantee the high purity of the Silicon (in terms of contaminations and defects) and the right orientation of the crystal planes with respect to the external macroscopic surfaces, following our technical requests. The delicate step to reduce the thickness up to ~ 30 μm will be carried out in the INFN-Fe laboratories (V. Guidi, A. Mazzolari, L. bandiera, M. Romagnoni, M. Soldani and A. Sytov) in a close scientific collaboration with the INFN-LNF SHERPA team. The industrial production of 25 samples its almost completed and they will be delivered to INFN-Fe to be processed. When the $\sim 30\mu$m plates will be ready, they will be glued on a special support and mounted on a dedicate active holder able to impart the chosen curvature to the crystal. Then, their curvature will be measured and checked using optical diffractometry techniques, before to be tested on the BTF beam.

The SHERPA crystal holder, based on a previous design, executed by the INFN-Fe, INFN-Pa and INFN-LNL, is under construction at LNF under the responsibility of the SPCM (Servizio Progettazione e Costruzioni Meccaniche) and, in particular, of the service leader T. Napolitano. The holder is active and, thanks to two dedicate piezo motors, is able to bend the crystal with a very high precision. This feature is extremely useful during the characterisation at the BTF, where it will be possible to change or correct in real time the curvature and torsion following the beam measurement response.

In Fig. 6 the 3D design of the active bending holder with the Silicon crystal plate in the middle is shown. A picture of the first components realised by the

LNF workshop is instead reported in Fig. 7.

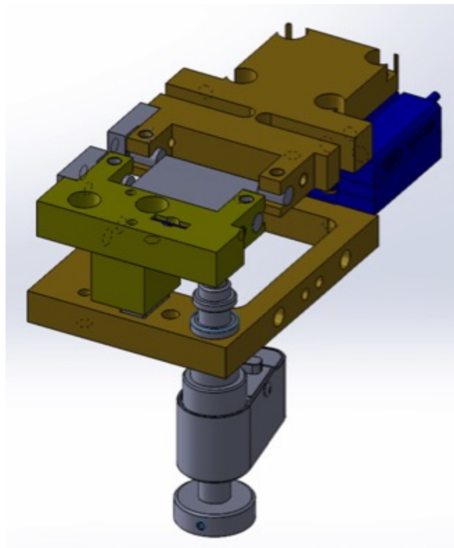

Figure 6: *Crystal active bending holder 3D design. The crystal plate (Silicon) and its support (stainless steel) are visible in grey in the center. The yellow and brown (brass) forks are the supports to bent the crystal. The blu part is the translational piezo motor that will bent the crystal (moving the brown fork) and the grey one below is the piezo actuator to correct the crystal torsion (pushing on the yellow fork).*

The most critical aspect in the holder processing is the high level of machining tolerances, in particular of the surfaces of the two hollowed out cylinders on which the crystal plate is glued. In fact, they have to rotate inside their seats with an extremely low friction allowing the crystal to be bent, by piezo actuators, without breaking and with a very homogeneous curvature. For this purpose, also the parallelism of the components is crucial.

5 BTF experimental apparatus

The feasibility study of crystal extraction foreseen the crystal characterisation at the BTF with 0.5 GeV positrons. The main goal is to measure the crystal deflection angle and efficiency. The experimental apparatus is composed of three main parts: the movimentation system to orient the crystal, bent by its holder, with respect to the incoming beam, the pixel detector to measure the deflected particles flux with respect to the undeflected ones and the vacuum chambers containing all the devices to reduce the effect of the multiple scattering due to the air. A scheme of the basic experimental SHERPA BTF apparatus is shown in Fig. 8.

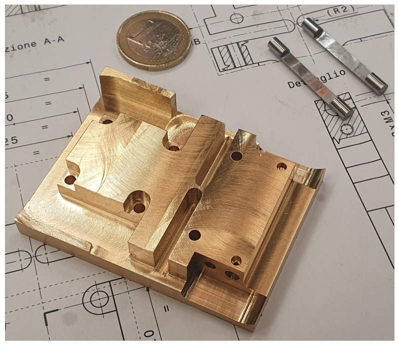

Figure 7: *Picture of one of the brass fork of the crystal holder together with the two cylinders where the crystal plate will be glued.*

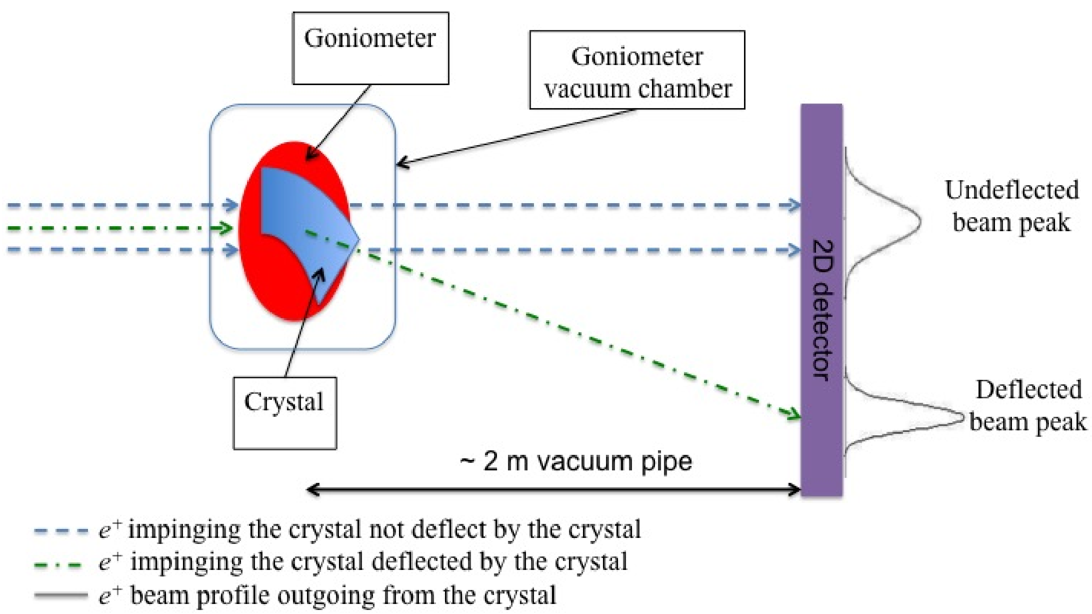

Figure 8: *SHERPA BTF apparatus scheme.*

5.1 The crystal movimentation system

The remote controlled three axis movimentation system (traditionally called "goniometer") is composed of: a transversal linear stage to move the crystal in and out of the beam and two angular actuator stages, horizontal and vertical, to precisely orient the crystal with respect to the beam direction.

This system has been selected and bought in 2020 from the company "Physik Instrumente (PI) S.r.l." and is the almost identical to the one used for crystal studies at CERN. The three stages are mounted all together (Fig. 9 and Fig. 10) and the crystal holder will be mounted on the top. The angular accuracy of both the angular actuator is ~ 1 μrad and the linear stage has an accuracy of ~ 1 μm.

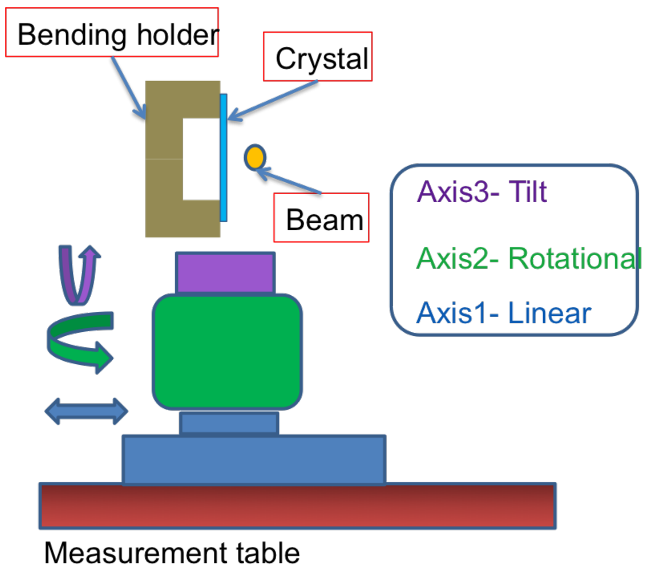

Figure 9: *Three axis goniometer scheme.*

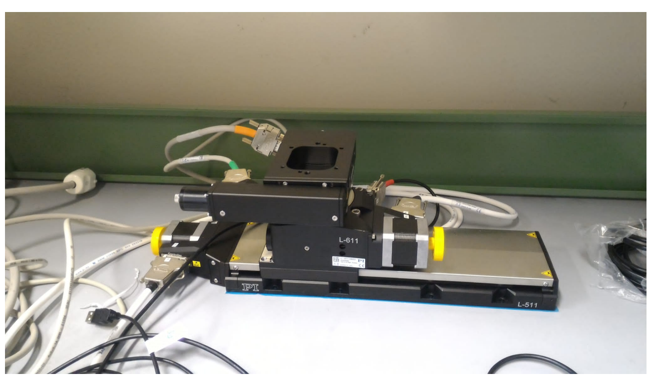

Figure 10: *Three axis goniometer picture.*

The goniometer is able to perform linear and angular scans with very small steps, allowing to center the crystal on the beam and find the best channeling orientation.

5.2 The pixel detector

The crystal characterisation imply the measurements of two main parameters: the channeling deflection angle and the channeling efficiency. The best device for this purpose is a telescope able to reconstruct the particle tracks upstream and downstream the crystal. The optimal configuration involves the use of four 2-dimensional detectors planes (Silicon pixel or strip detectors), 2 upstream and 2 downstream with respect to the crystal position. Each pair of planes have to be spaced the distance necessary to have the appropriate angular resolution, taking in to account the detectors spatial resolution. In this way, it is possible to select and study only the incoming particles that cross the crystal within the channeling acceptance angle θ_c, thus those with all the theoretical properties to be channeled by the Silicon planes. θ_c is defined by the formula:

$$\theta_c = \sqrt{2U_0/pv} \tag{2}$$

where U_0 is the Silicon electrostatic potential well, p and v are the positron momentum and velocity respectively [16].

Realising this apparatus for high energy hadrons is relatively simple, but in the case of sub GeV positrons is not trivial due to the high contribution of the multiple scattering generated by the detector planes. For this reason, a simpler first measurement apparatus will be composed by only one plane downstream the crystal with the goal to measure the deflected and undeflected beam peaks. The idea is to use a beam with a dimension of $\sigma_x = \sigma_y \approx$1 mm and divergence $\sigma_{div(x)} \leq 300$ μrad, the channeling acceptance angle θ_c at 0.5 GeV. In this way, all the particles hitting the crystal will be able to be channeled.

A detector with a pitch of ~ 50 μm, positioned 2 m downstream the crystal, provides an angular resolution of the order of $\sim$25 μrad, good enough for our purposes.

Three detector tipologies have been considered: the MIMOSA [19], already used and developed in the PADME experiment, the ALPIDE [22], developed for the ALICE experiment, and the TimePix3 [20, 21], already used at CERN for crystal application studies and in PADME. The last one, for the moment, is the best candidate to be used for the first BTF measurements in 2021 and two of them (100 and 300 μm thick) are at LNF as a loan for preliminary tests. In Fig. 11 is shown the 300 μm version, produced by the ADVACAM company.

The TimePix3 is the ideal as 2-dimensional monitor at the end of SHERPA BTF apparatus to "take a picture" of the crystal effect on the positron beam. Instead, to built a real 4 planes telescope, the TimePix3 technology could be not adeguate due to the sensor thickness and the consequent multiple scattering produced. The ALPIDE sensor seems more appropriate having a smaller thickness. For this reason, a collaboration with the INFN PAPRICA [23] experiment, that is developing an ALPIDE telescope, is ongoing.

Figure 11: *300 μm TimePix3 detector.*

The detectors issues are followed by the INFN-Roma1 team composed by P. Valente and M. Raggi, taking advantage of the know how already acquired for PADME purposes.

5.3 The vacuum chambers and thin windows

With the purpose to reduce the multiple scattering effect of positrons along their path, upstream and downstream the crystal, it is necessary to eliminate or reduce as much as possible the amount of material in between. In this way, the only object “seen” by positrons will be the crystal, allowing a precise measurement of their interaction with it. To remove the air along the path, the crystal and the goniometer will be placed inside a dedicated vacuum chamber (Fig. 12) and a 2 m vacuum pipe will be mounted between the crystal and the detector at the end (Fig. 13). For crystal characterisation a $10^{-3} - 10^{-4}$ mbar vacuum level is sufficient.

Another fundamental aspect to consider is the quality of the beam in terms of dimension, divergence and contamination (mainly due to photons produced by positrons interaction with accelerator components). For this reason SHERPA contributed to an innovative R&D study of thin windows to separate the main vacuum of the BTF-2 line from the SHERPA apparatus. This separation is crucial for safety and functionality of the BTF-2 and LINAC lines and will be useful for all the beam activities foreseen in the future, not only for SHERPA. The idea is to realise an extremely thin mylar window (50 or 23 μm) with high vacuum sealing performance and a good resistance to positron irradiation. In fact, the thermal stress produced by the intense BTF beam could deform or damage the window that could loose its functionality. A set of windows of both thickness has been realised and tested from vacuum sealing point of view with promising results. The next step will be the sealing test during positron irradiation at the BTF-2, with the purpose to study their resistance. Figure 14

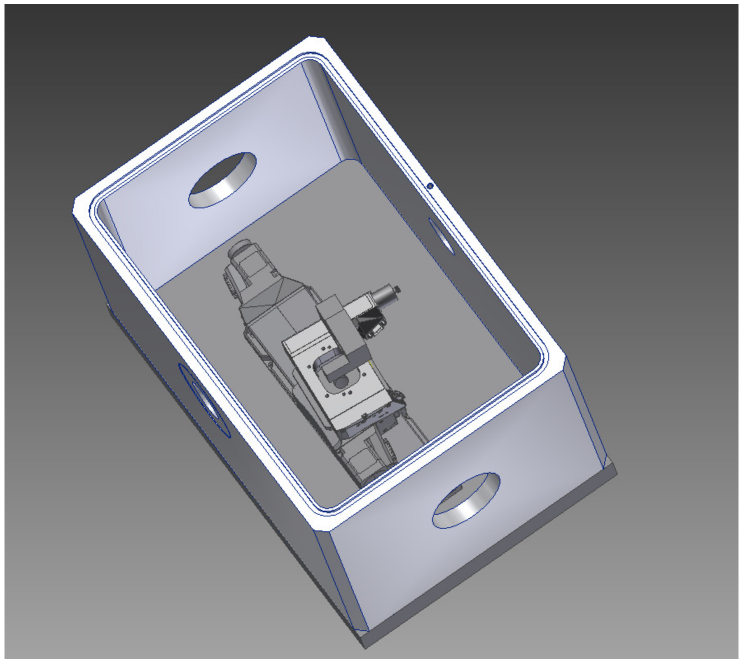

Figure 12: *Goniometer vacuum chamber.*

shows a picture of one of these windows mounted on a dedicated vacuum flange.

The design of the chamber, of the pipe and of the thin window, included all the necessary vacuum tests, have been mainly followed by A. Liedl and V. Lollo, with the support of the vacuum service team at LNF.

5.4 The measurement and analysis procedure

To measure the deflection angle and efficiency of the crystal it is necessary to measure, using the pixel detector, the flux peak of the deflected positrons with respect to the undeflected one. The distance between the crystal and the detector will be precisely measured, thus, from the distance between the the two peaks centroids on the detector plane, obtaining the deflection angle is simple. The efficiency will be measured performing the ratio between the number of deflected and undeflected particles. The standard procedure to find the channeling orientation and measure the crystal performance is:

1. Center the crystal on the beam axis.
2. Perform an horizontal angular scan (and vertical when necessary) to find the best alignment of the crystal planes with respect to the beam direction.
3. Check in real time the pixel detector to visualise the maximum peak of the deflected particles.

Figure 13: *2 m vacuum pipe.*

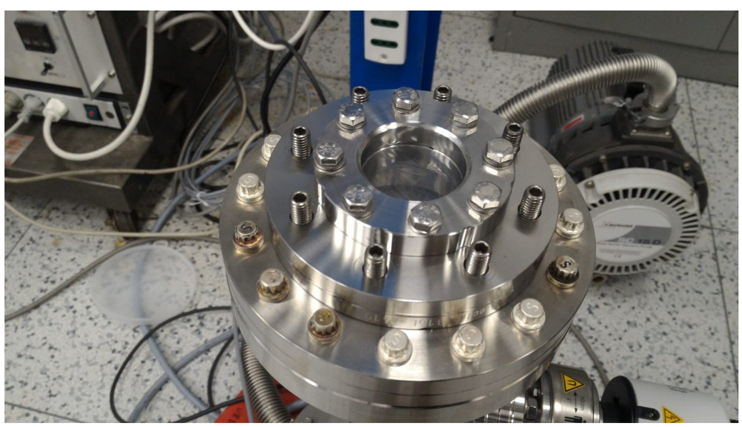

Figure 14: *Ultra thin window during preliminary vacuum tests.*

4. Perform and high statistics acquisition to obtain a precise measurements of the deflection angle and efficiency.

6 Monte Carlo simulations

For SHERPA purposes Monte Carlo simulations are crucial to study the BTF experimental apparatus and crystal behaviour. The software tool used until now is FLUKA. Concerning the BTF apparatus, simulations have been performed to understand the effect of matter along the beam line and find the best and practicable solutions to limit the multiple scattering, reducing beam divergence and background. Moreover, simulations of the pixel detector response are on going.

About the crystal, a FLUKA routine is already available for hadrons and its arrangement for positrons is on going in collaboration with the CERN FLUKA team. There is also a GEANT4 crystal routine, mainly developed by the INFN-Fe team, that will be used also for SHERPA purposes in the next future. The same for other existing analytical routines.

Concerning GEANT-4 simulations, also the INFN-Roma1 team is strictly involved.

From the other side, SHERPA data will be used as a benchmark for simulations, helping the tuning of all the different routines. In fact, until now, a little amount of experimental data is present in letterature about positron coherent affects in bent crystals. One of SHERPA main contributions will be to provide this data in the sub-GeV energy range.

7 Conclusions

If SHERPA will succeed, the very first $\sim$ 0.5-1 GeV primary positron slow extracted spill will be delivered, opening the possibility to manage positrons accumulated, and eventually accelerated, in a storage ring. Moreover, the study of positron beam steering using bent crystals will provide a know how that can be applied, in the next future, for several accelerating machine aspects, as collimation, extraction and beam splitting, contributing to a general improvement in the particle accelerator field.

Achieving top performance for this crystal extraction technique is feasible but challenging. Anyway, it is important to underline that also in the worst scenario of extraction with shorter beam spill lengths of 100 μs and very low positron extraction efficiency of 5 %, this solution would improve, for example, the PADME sensitivity by a factor between 50 and 100 with respect to the plain LINAC beam [18].

The availability of long positron pulses with excellent quality would also open a more futuristic option for dark sector searches in e^+e^- annihilations, that is a very asymmetric collider [24]. Colliding high-energy (E^+) positrons with a very low energy (E^-) electron beam, the accessible mass range would be greatly increased, since the center of mass energy becomes M^2=$2E^-E^+$. This requires an almost continuous beam to get a significant luminosity.

Another field of research that could profit of a high-intensity source of high-energy positrons is the study of radiation generation by means of crystal undulators [25], i.e. the enhancement of the photon emission due to the channeling effects of light positively charged particles in crystalline structures [26].

Moreover, positron beams manipulation has a further relevant role in the new concept of μ production for the next generations of μ^+/μ^- colliders. Indeed, using the annihilation process e^+ of O(GeV) energies with fixed target e^-, it is possible to obtain μ beams with very low emittance, avoiding complicated and expensive beam cooling systems. Also the beam quality would be better with a low background, small energy spread and very reduced losses due to μ decays. In this specific field of research the INFN is already involved with the LEMMA proposal, for which bent crystals could be a possible solution [27].

The physics program of the DAΦNE machine does not foresee experiments in the next decade [28]. SHERPA could provide a unique new beam test facility, very competitive for performance, construction time and costs, well integrated in the accelerator complex, opening different research veins, not only in accelerator technology, but also in fundamental physics.

References

[1] A. Ghigo *et al*, Nucl. Instrum. Meth. A515 (2003) 524

[2] R. Boni *et al*, Conf. Proc. C980622 (1998) 764

[3] B. Buonomo *et al*, Conf. Proc. C150503 (2015) TUPWA056

[4] P. Valente *et al*, Conf. Proc. IPAC17 (2017) TUPAB048

[5] P. Valente *et al*, EPJ Web Conf. 142 (2017) 01028

[6] M. Raggi *et al*, EPJ Web Conf. 142 (2017) 01026

[7] X. Altuna *et al*, Phis. Lett. B 357 (1995) 671-677

[8] A.G. Afonin *et al*, Phys. Rev. Lett. 87, 094802 (2001)

[9] W. Scandale *et al*, Phys. Lett. B 758 (2016) 129-133

[10] M.A. Fraser *et al*, 8th IPAC, Copenhagen (2017)

[11] S. Bellucci *et al*, JETP Lett. 2013, Vol. 98, No. 11, pp. 649?651

[12] S. Bellucci *et al*, Nucl. Instrum. Meth. Phys. Res. B 252 (2006) 3?6

[13] V. Guidi *et al*, Phys. Rev. Lett. 108.1 (2012): 014801

[14] Y. Takabayashi *et al*, Phys. Lett. B 751 (2015) 453

[15] http://mad.web.cern.ch/mad/

[16] M. Biryukov *et al*, Crystal channeling and its application at high-energy accelerators. Springer Science Business Media, 2013

[17] S. Guiducci *et al*, 9th IPAC18, IOP Conf. Series: Journal of Physics: Conf. Seres 1067 (2018) 062006

[18] P. Valente *et al*, INFN-LNF internal report, INFN/17-15-LNF (2017)

[19] J. Baudot *et al*, J. Baudot et al., IEEE Nuclear Science Symposium Conference Record (2009), N22-6

[20] M. Campbell *et al*, Nucl. Instrum. Meth. A 633 (2011) S1-S10

[21] A. Natochii *et al*, JINST 14 P03018 (2019)

[22] G. Aglieri Rinella *et al*, Nucl. Instrum. Meth. A 845 (2017) 583-587

[23] M. Toppi *et al*, PAPRICA:the PAir PRoduction Immaging ChAmber - Proof Of Principle", DOI: 10.3389/fphy.2021.568139

[24] B. Wojtsekhowski *et al*, arXiv:1705.00051 [physics.acc-ph]

[25] U.I. Uggerhj *et al*, Nucl. Instrum. Meth. B355 (2015) 35

[26] G.S. Sushko *et al*, J. Phys.: Conf. Ser. 438 (2013) 012018

[27] M. Antonelli *et al*, Nucl. Instrum. Meth. in Phys. Res. A 807 (2016) 101?107

[28] F. Bossi *et al*, INFN-15-05/LNF