THE SHERPA EXPERIMENT

M. Garattini (Resp., AdR), P. Gianotti, S. Guiducci (Ass.),
A. Liedl (Tec.)

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 [3–5], 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'), applying 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 [7]. 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 [8–11]. 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 [12,13]. Other tests at the MAMI [14,15] and SAGA [16] 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 three 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.

The first two mile stones have been successfully completed and all the results are reported in the 2020 and 2021 activity reports and in [17]. The last two milestones results are described below and will be completed in 2023.

3 Activity of the SHERPA LNF group

3.1 Crystal system construction

In 2021 the first prototypes of silicon crystals have been produced by 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. Also two special crystal bending holders, based on a previous design, executed by the INFN-Fe, INFN-Pa and INFN-LNL, were produced by CINEL scientific instruments company in Padova (Italy), on the basis of what was realised in 2020 by the LNF SPCM (Servizio Progettazione e Costruzioni Meccaniche). At LNL-INFN laboratories (thanks to the collaboration with D. De Salvador) one crystal have been mounted on one of the bending dynamic holder and their have been successfully bent as shown in Fig.1.

In 2022 the SHERPA LNF team continued the work performed in 2020 and 2021. With the support of the SPCM of LNF, we have optimized a third bending holder, almost identical to the INFN-Fe/LNL one. The idea is to simplify the mechanical requirements of the holder and to improve the Silicon crystal gluing and mounting procedure. In Fig.2 shows the components of the system realised for this purpose. Using this new set of tools, it will be possible to glue the silicon crystal on their cylindrical pins in a very precise way. Then the crystal and the pins will be

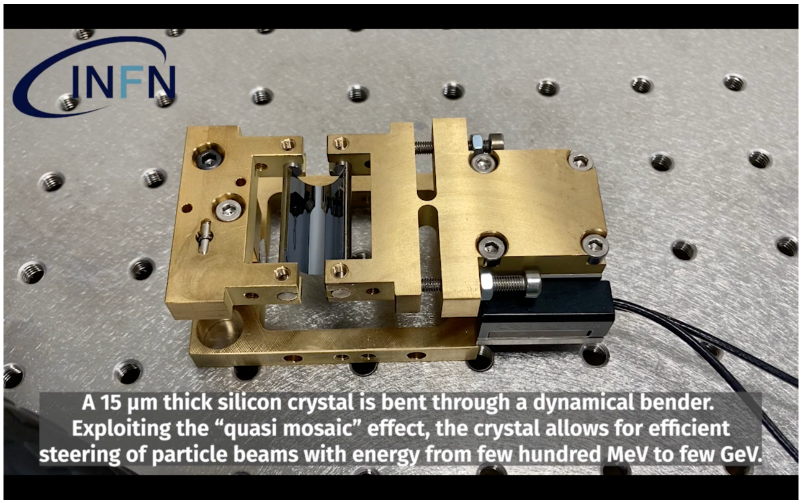

Figure 1: *Crystal active bending holder. The bent silicon crystal plate, in between the two brass forks, is bent by the horizontal movement of one of them by the piezo motor.*

clamped in a dedicated plastic "sandwich support" used to easily and safely insert the crystal in the holder forks. At this point the crystal can be bent using the piezo motor, as usual. During the whole procedure the crystal is protected by the risk of breakage.

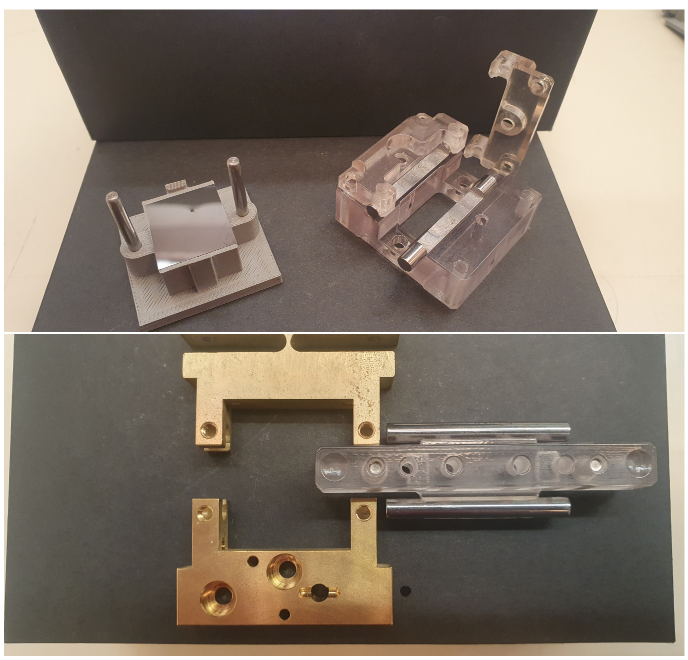

Figure 2: *Up on the right the seat for the silicon crystal during the gluing, on which the support for the crystal bending pins (up on the left) is clumped . The glue is deployed on the two pins before superimpose them on the crystal. Then, the crystal glued on its pin is clamped in a dedicated "sandwich support" used to insert it in the two brass forks of the bending holder.*

Completed the bending procedure, the crystal system is ready to be mounted on the 3-axis handling system to be characterised with 0.5 GeV positrons and electrons during a test beam scheduled in 2023 at the BTF.

3.2 Crystal characterisation

The feasibility study of crystal extraction foreseen the crystal characterisation with 0.5 GeV positrons (and electrons). The main goal is to measure the crystal deflection angle and efficiency. The two beam facility involved during 2022 have been the BTF and the CERN East Area, accelerator.

3.2.1 Crystal characterisation apparatus

The experimental apparatus is composed of three main parts: the 3-axis handling system (called "goniometer") to orient the crystal, bent by its holder, with respect to the incoming beam, the pixel detector (TimePix3) 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. 3.

The entire apparatus has been realised in 2020-2021.

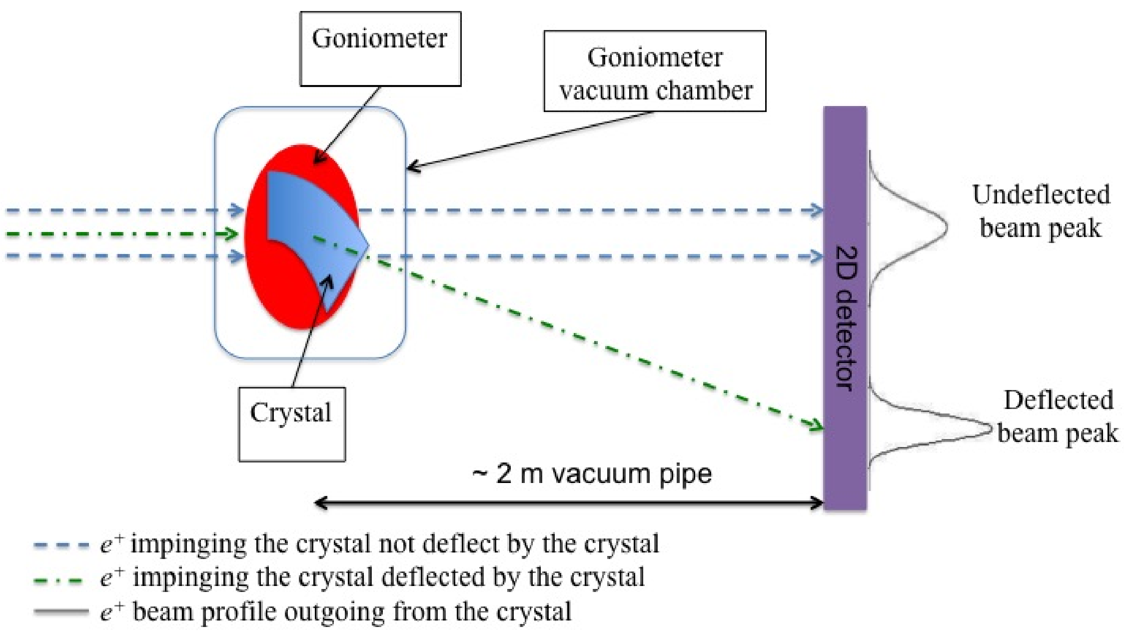

Figure 3: *SHERPA BTF apparatus scheme.*

3.2.2 The first BTF test beam

In June 2022, a very first test beam was performed at the BTF in Frascati with 0.5 GeV positron beam. The two main goals were: test and calibrate the TimePix3 detector with a real particle beam, then evaluate the possibility to use a collimator, upstream the crystal, to reduce the beam spot size, the beam divergence and the background at the same time.

The TimePix3 was calibrated and has shown a very good response to this kind of beam. In fact, it was able to visualize the effect of two different kind of collimators made with two blocks of lead-glass and iron respectively. In the Fig.4 is reported a picture of the two collimators used and the respective TimePix3 beam spot produced.

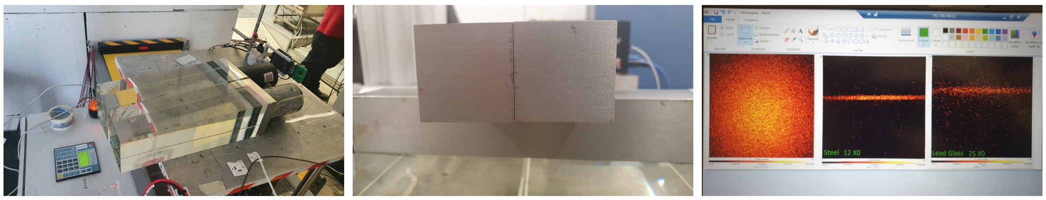

Figure 4: *On the left the lead-glass collimator. In the center the iron collimator. On the right the TimePix3 pictures of the beam without collimators, with iron collimator and lead-glass collimator respectively (∼0.15 mm gap).*

The conclusion is that the use of a collimator during the crystal characterisation with 0.5 GeV positron beam will be very useful to distinguish the particles deflected by the silicon crystal ("the Channeling spot"). The iron collimator blocks seem the best solution, especially considering their reduced dimensions and weight.

3.2.3 The CERN East Area Test beam

After the preliminary apparatus test at the BTF, waiting for additional beam time at LNF, in July 2022 we moved to CERN East Area to try to characterise our first Silicon bent crystal sample with a 0.5 GeV positron and electron beam.

The whole SHERPA apparatus was transported on the T9 PS extraction line, where we connected our crystal vacuum chamber and beam pipe directly on the main vacuum of the line. This time the crystal, mounted and bent on its bending holder, was put and aligned on the beam using the 3-axis handling system (see Fig.5 left). Also the two blocks of iron were used to collimate the beam upstream the crystal position.

Downstream, in between the crystal and the TimpePix3 detector, a 3 m vacuum pipe was mounted to permit to distinguish the crystal deflected beam from the non-deflected one. In fact, having the crystal a bending of ∼1 mrad, the "channeling spot" was expected to be crosswise displaced at more or less 3 mm from the beam axis. Fig.5 (right) shows the TimePix3 positioned at the end of the beam pipe, in air.

Unfortunately, the beam parameters (spot size, divergence and intensity) where more than one order of magnitude worst than expected and no useful measurements were possible in these conditions. Anyway, the test beam was very useful to familiarise with the apparatus, especially concerning the crystal and collimation system.

4 Conclusions and future prospects

In the third year of life, SHERPA has made significant progresses especially in the crystal system and characterisation apparatus hardware.

The Frascati SHERPA team now is ready to glue, mount and bend several samples at least on three different bending holder, demonstrating a very good crystal system engineering.

Two different test beams have been performed, providing all the know how necessary to finalise the first complete crystal characterisation in 2023 at the BTF in Frascati.

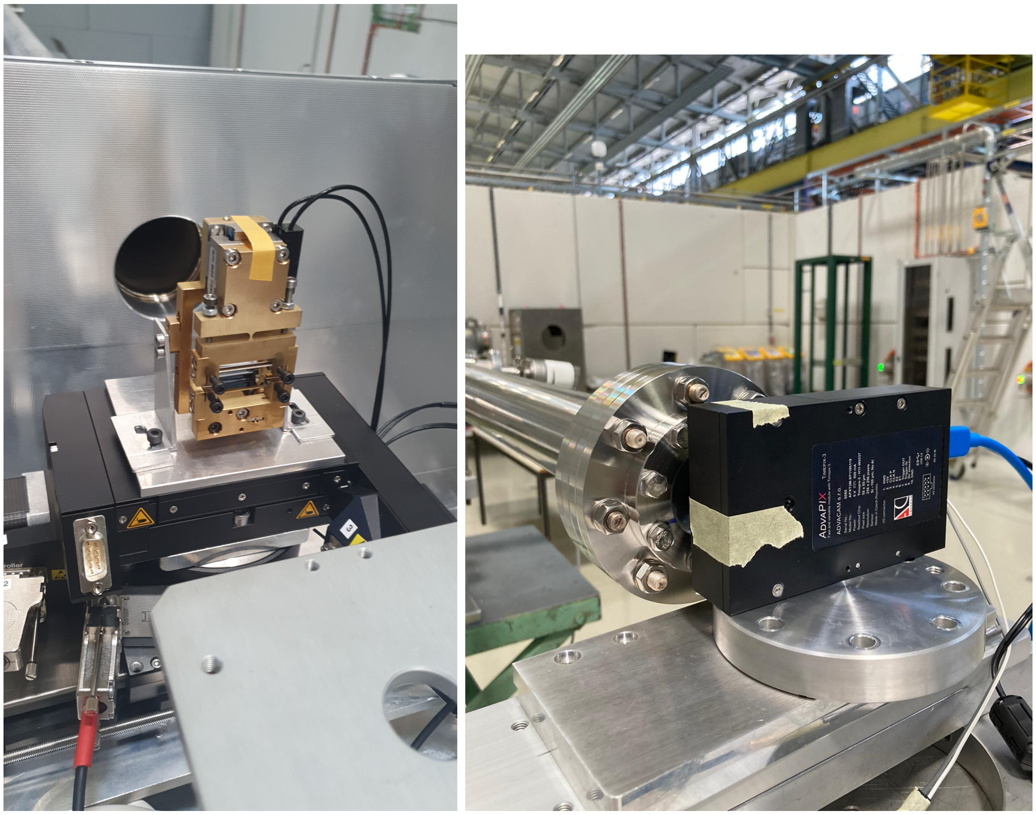

Figure 5: *On the left the Silicon crystal ∼15 μm thick bent by its holder, mounted on the 3-axis handling system and centered on the 0.5 GeV positron beam axis. On the right the TimePix3 detector positioned at the end of the T9 beam line, 3 m downstream the bent Silicon crystal. The TimePix3 is positioned in air, just downstream a Mylar window 50 μm thick that closes the beam pipe.*

All the results were also obtained with the precious help of our colleagues of the INFN-Roma1 (P.Valente) and of Sapienza Università di Roma (M. Raggi, D. Annucci, E. Long), strongly involved in the SHERPA experiment, and the support of the LNF management and infrastructures.

In the next future it is foreseen also a preliminary design of the new crystal system to be installed in DAΦNE, an evolution of the existing one.

If SHERPA will succeed, the very first ∼ 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.

The physics program of the DAΦNE machine does not foresee experiments in the next decade [18]. 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.

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