PROCEEDINGS OF SCIENCE

# The SHERPA experiment

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The SHERPA project aim is to develop an efficient technique for extracting a positron beam from one of the accelerator rings composing the DAΦNE accelerator complex at the Frascati National Laboratory of INFN, setting up a new beam line delivering positron spills of O(ms) length, excellent beam energy spread and emittance. The main idea is to use coherent processes in bent crystals to slowly 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. In this manuscript an overview of the whole experiment will be given, describing in particular the crystal extraction principle, the accelerator optics studies, the crystal prototype and its characterization. A first estimation of the crystal extraction performance at DAΦNE is also reported.

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## 1. Intoduction

Primary positron extraction lines from circular accelerators are quite rare, also due to the relatively small number of positron machines, and they come directly from the LINAC or from the storage ring.

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. 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 the PADME statistics by a factor $10^4$ and its sensitivity by a factor $10^2$, improving significantly the discovery potential.

A primary positron beam with such characteristics has never been slowly extracted so far from a circulating machine. The main challenge of the SHERPA ("Slow High-efficiency Extraction from Ring Positron Accelerator") project is to develop a smart core solution to achieve this unprecedented performance.

## 2. The SHERPA experiment

The SHERPA project aim is to develop an efficient technique to extract a positron beam from one of the accelerator rings composing the DAΦNE 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 and generating a circumscribed unstable region of the phase space in one of the transverse planes applying a proper sextupole configuration. Then, particles slowly approach an unstable resonant frequency, characterised by the extraction separatrix, in order to gradually eject particles from the circulating beam [7, 8].

SHERPA proposes a paradigm change based on the possibility to kick out charged particles using the channeling effect in bent single crystals, a cheeper and less complex alternative. Charged particles impinging on the crystal with small angles relative to the lattice planes move oscillating between two neighboring planes, and consequently can be deflected by the crystal bend angle [9].

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 [10–13].

Realising this for sub-GeV leptons is challenging but feasible, as proved by several previous experiment [14, 15].

The BTF beam is ideal to test and characterise the crystal prototypes performance.



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## 3. 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 smaller 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 cheaper, 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.

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 layout, 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. These simulations have been performed at LNF using the MAD (Methodical Accelerator Design) software [16, 17], the standard already used for DAΦNE.

### 3.1 Damping ring studies

The damping ring could be considered as a good option because its structure is already used for beam extraction therefore requiring simpler modifications. In particular, the present extraction septum and the connected beam line can be used.

The proposed crystal location is shown in Fig. 1, together with the extraction septum, which is the same used to extract the beam towards the DAΦNE main rings. Particles interact with the crystal and are extracted few meters downstream in the ring.

Particle tracking and theoretical estimations show that positrons with an energy of -1.0%, with respect to the nominal one, will arrive at the crystal location with an horizontal displacement of -7.5 mm. Those particles could interact with the crystal and thus be kicked by about 1 mrad, producing a larger horizontal displacement of about -11 mm at the septum position. In order to effectively achieve the slow extraction of those positrons it is necessary to adjust the initial position of the beam, the crystal position and the ring parameters.

Since positrons in the accumulator ring loose 1.0% of energy by synchrotron radiation in 1000 turns, the extraction time is estimated to be $\sim$100 $\mu$s after injection at nominal energy, given that the RF ("Radio Frequency") is kept off, thus allowing positrons to loose naturally energy and "diffuse" until they reach the crystal. Alternatively, one could modify and tune the extracted beam spill duration using the RF cavity for extending the time required to loose the same fraction of energy.

We start the simulations considering that the energy spread of the beam is uniformly distributed between $\pm$1%, which is the energy acceptance of the ring. Considering the septum located at -20 mm away from the beam pipe center, we bring the beam close to the septum by adjusting the kicker for off-axis injection, 10 mm away from the beam pipe center. The injection oscillation brings the beam close to the septum, which is 2.5 mm thick, and the crystal provides the additional jump to pass the septum thickness.

In the following we proceed to evaluate the effect of the bent crystal on the beam position at the extraction septum, using a beam deflection of ±1 mrad, in agreement with the experimental results of a Silicon crystal ∼20 $\mu$m thick [14, 15]. As shown in Fig. 2 and 3 the effect of the crystal at the first turn is to displace the particles by about 4.0 mm at the extraction septum. The position of the crystal is chosen in order to interact with the particles which are very close to the extraction septum in order to extract them with the 1 mrad kick. The crystal is placed at -3 cm from the beam center in the horizontal plane.

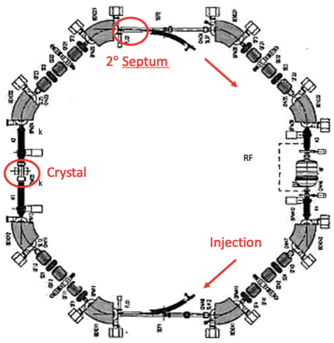


**Figure 1:** Accumulator Ring: location of the bent crystal and extraction septum.

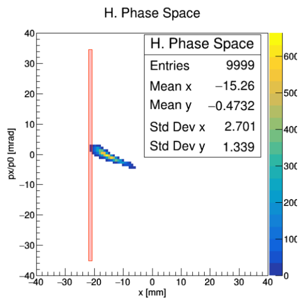


**Figure 2:** H Phase space at the extraction septum of particles after 1 turn without a kick by the crystal.

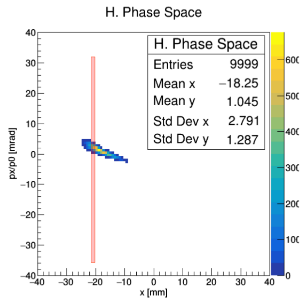


**Figure 3:** H Phase space at the extraction septum of particles after 1 turn with a 1 mrad kick by the crystal.

The rate of particles passing through the crystal at -30 mm and achieving a displacement of -20 mm or more at the extraction septum is plotted in Figure 4. There is a peak in the rate at the first turn, which can be reduced by further optimization of the initial conditions. After the first peak the rate of particles is rather stable up to about 1500 turns. It means an extraction time of ∼0.1 ms, ∼1000 times longer than the present BTF pulse.

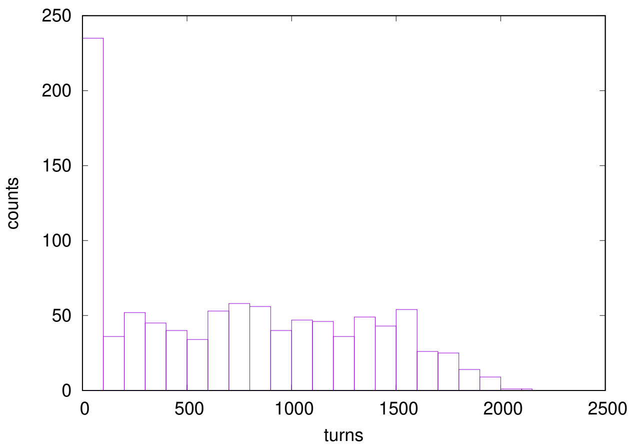


**Figure 4:** Rate of particles achieving -20 mm of displacement, or more, at the extraction point. The initial tracked population is $10^3$ particles and each turn corresponds to 0.1 $\mu$s. Each bin corresponds to 100 turns.

### 3.2 DAΦNE main ring studies

Starting from the DAΦNE collider configuration used for the SIDDHARTA2 (2019) [18] experiment, we have modified the optics model, finding different promising options for the crystal extraction.

The best configuration is the one with the crystal positioned just before the rings crossing point (IP2), shown in Fig. 5, and the extraction septum placed just downstream the IP2. The extraction would be thus performed only a few meters downstream the crystal, in the same straight section of the MRp ring. In this configuration, a positron with an energy offset of the order of -0.7% will encounter the crystal, positioned at 8 mm from the circulating beam axis, at the 6th turn in the machine, and will be extracted in the same turn, as shown in Fig. 6, 7. The transverse displacement obtained at the extraction point is about 20 mm due to the large horizontal beta $\beta_x$ of about 17 m at both locations, enough to reach the typical offset separating the beam and the extraction septum.

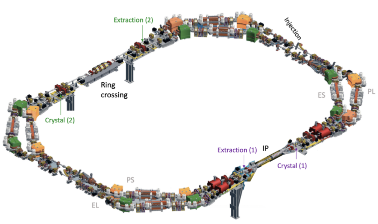


**Figure 5:** Extraction scheme using the DAFNE positron main ring.

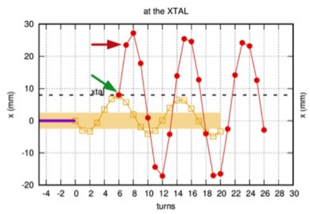


**Figure 6:** Turn by turn single particle tracking results seen at the Crystal location.

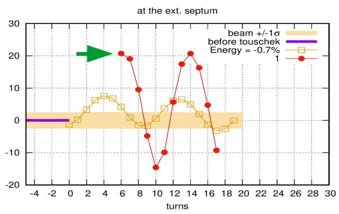


**Figure 7:** Turn by turn single particle tracking results seen at the Extraction Septum.

It has to be underlined that the energy loss considered in the simulation is realistic as several phenomena could change a particle energy, e.g. synchrotron radiation, inelastic beam-gas scattering or the intra-beam particle interaction (the so-called Touschek effect). In any of the previous cases particles losing the right amount of energy will be deflected by the bent crystal and slowly extracted with the help of a standard septum. The expected extraction time is $\sim$0.4 ms.

One could consider the possibility of forcing the migration of the bunch population to a negative energy offset by turning off the DAΦNE RF device, or even slow down this migration process by using the cavity to recover only part of the energy radiated by the bunch and at the same time to keep the beam stable along the ring.

In any case, this preliminary study already shows that it is possible to slow-extract positrons from the actual DAΦNE ring using a bending crystal with a realistic deflection. Similar performance are expected also with electrons. All the details of this study are reported here [19].

## 4. Crystal system design and construction

The crystal system consists 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.

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 (∼20 $\mu$m instead of few mm) to limit electronic dechanneling, the effect whereby the particles exit the atomic channel due to the interaction with the Silicon electrons. This aspect pushes at the technological limit the bending device to avoid breaking the crystal during the bending procedure and to guarantee a homogenous curvature.

The SHERPA crystal holder, based on a previous design executed by the INFN-Fe/Pd/LNL, is active and, thanks to two dedicate piezo actuators, is able to bend the crystal with a very high precision. When the ∼20 $\mu$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. In Fig. 8 a picture of the active bending holder with the a plastic mock-up crystal plate in the middle is shown. Some crystal samples, under production at INFN-Fe, are shown in Fig. 9.

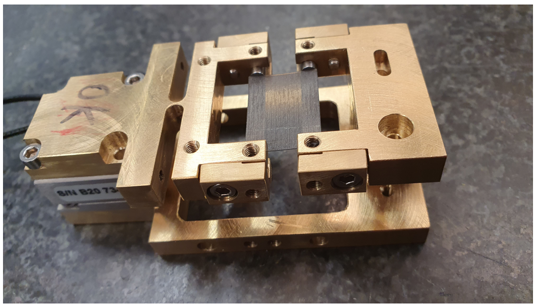

**Figure 8:** The crystal active bending holder.

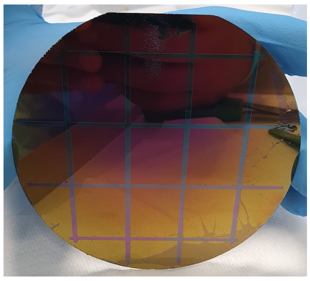

**Figure 9:** Set of nine crystals in process.

## 5. BTF experimental apparatus

The feasibility study of crystal extraction foresees 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 3-axis movimentation system, to orient the crystal 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.

## 6. Conclusions

If SHERPA will succeed, the very first sub-GeV primary positron slow extracted O(ms) 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 leptons accelerating machine aspects, as collimation, extraction and beam splitting.

The physics program of the DAΦNE machine does not foresee experiments in the next decade [24]. 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 [20–23].

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