PULSE STRETCHER FOR THE PADME-X17 EXPERIMENT

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Abstract

The PADME-X17 experiment is searching for a light dark matter candidate. The experiment would greatly benefit from the availability of a dedicated beam with long pulse duration and minimal instantaneous current. In this contribution, a third-order resonant slow-extraction scheme is considered, starting from the present lattice of the DAFNE damping ring. This solution, already integrated with the DAFNE complex, could provide the necessary positron-beam improvements within the existing facility. This study, currently aimed at improving the sensitivity of fixed-target experiments with positrons, could open new possibilities for beamlines based on the beam extracted from the damping ring.

INTRODUCTION

The PADME-X17 experiment [1] aims at searching for a light dark-sector candidate using positron interactions on a fixed target. The experimental sensitivity would benefit from a dedicated positron beam with a pulse duration significantly longer than that presently available at the BTF facility, namely 1–2 ms instead of about 250 ns, and with a reduced instantaneous current, about 0.1 instead of 13 e^+/ns [2]. This would mitigate event pile-up in the detector and improve the control of beam-induced background. Depending on the effective spill duration and on the total integrated statistics, such an improved beam is expected to reduce the total uncertainty by a factor between two and ten.

The DAΦNE complex offers a possible route to provide such a beam by using the damping ring as a pulse stretcher. In this scheme, the beam is injected in the ring and is then slowly extracted by means of a third-order resonant process. The concept is motivated by the possibility of exploiting an accelerator infrastructure already available at LNF, while extending the use of the complex to extracted-beam applications. This activity is therefore part of a broader effort to assess the flexibility of the DAΦNE complex beyond collider operation, including the use of the damping ring for dedicated experimental programs and accelerator studies [3].

Similar studies were previously performed using the DAΦNE positron ring [4] and the same damping ring [5], with the aim of providing a longer pulse for the original PADME experiment at higher energy [6].

Beam Requirements for PADME-X17

The main beam requirements are driven by the need to reduce the instantaneous particle rate on the target while preserving a sufficient integrated positron flux. The relevant quantities, summarized in the Table 1 are the beam energy, the average particle flux, the spill duration, the instantaneous rate, the transverse beam size and divergence at the target, and the energy spread.

Table 1: Indicative Beam Requirements for PADME-X17

Parameter	Target value
Beam species	e^+
Beam energy	280 ± 30 MeV
Energy tunability	1 MeV step
Average particle flux	$\gtrsim 4 \times 10^6$ e^+/s
Instantaneous rate	$\lesssim 0.1$ POT/ns
Spill duration	> 1 ms
Repetition rate	50 Hz
Beam spot at target	1×1 mm^2
Divergence at target	< 1 mrad
Energy spread	< 0.3 %

SLOW-EXTRACTION CONCEPT FROM THE DAΦNE DAMPING RING

The proposed scheme is based on third-order resonant slow extraction from the DAΦNE damping ring. The horizontal tune is moved close to a third-integer resonance,

$$Q_x = n + \frac{1}{3} + \Delta Q_x,$$

where ΔQ_x is the distance from the exact resonance. Sextupole magnets excite the resonance and generate a triangular separatrix in the horizontal phase space. Particles outside the stable triangular region move along the separatrix and can be extracted by means of a septum.

The resonant dynamics can be described, in normalized phase-space coordinates, by a Hamiltonian of the form

$$H = 3\pi\Delta Q_x \left(X^2 + X'^2\right) + S\left(3XX'^2 - X^3\right),$$

where S is the third-order resonance driving term generated by the sextupole configuration. The extraction efficiency depends on the separatrix size, the step size at the septum, the septum thickness, the available aperture, and the stability of the mechanism used to drive the particles toward the resonance. A detailed discussion of slow-extraction theory can be found in Ref. [7].

Two possible extraction approaches are under study. In the first one, the RF is switched off and the resonance condition is reached naturally through the combination of synchrotron-radiation energy loss and chromaticity. This “free extraction” scenario has the advantage of requiring limited additional hardware, but the spill duration is essentially determined

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by the ratio between the injected beam energy spread and the energy loss per turn. For the damping-ring parameters considered here, spill durations of the order of 1–2 ms are expected.

In the second approach, the RF remains on and the extraction is externally driven, for example by a transverse excitation. This "forced extraction" scenario would require additional equipment and a dedicated spill-control system, but it could in principle provide much longer spills, limited mainly by the stored charge and by the allowed duty cycle. The present study is focused on the "free extraction" scenario only.

From the operational point of view, the proposed solution is designed to be compatible with the existing DAΦNE infrastructure. The damping ring would be filled by the LINAC, and the beam would then be slowly extracted toward the fixed-target beamline. The use of the existing damping-ring hardware is one of the main advantages of the scheme, but it also imposes important constraints on the achievable repetition rate, duty cycle and beam transport.

The integration study must address the extraction-line layout, the matching to the fixed-target beamline, and the diagnostics needed to monitor the extracted spill.

A major limitation is related to the transport of the extracted beam to an experimental area suitable for a PADME-like setup. The DAΦNE transfer lines include a common section for injection into and extraction from the damping ring, and contain pulsed elements. Therefore a flexible solution would require dedicated upgrades of the extraction line.

OPTICS AND RESONANCE-EXTRACTION STUDIES

The starting point of the study is the present DAΦNE damping-ring lattice. The ring is composed of four arcs, each including two 45° dipoles, three quadrupoles and two sextupoles. The machine also includes the main systems required for injection, orbit control and diagnostics, such as kickers, RF cavity, beam-position monitors and correctors. The present study therefore aims at exploiting as much as possible the existing magnetic layout and infrastructure.

The optics is modified in order to move the horizontal tune close to the third-integer resonance while preserving acceptable values of the optical functions, chromaticity, dynamic aperture and beam size at the extraction septum. The resulting betatron functions and horizontal dispersion are shown in Fig. 1. The present working configuration is based on a beam energy within the range required by PADME-X17 and is optimized around the central value of 280 MeV. The fractional horizontal tune is 0.328, close to the resonance. The sextupole configuration is optimized by combining the existing sextupole families in order to maximize the extraction efficiency while keeping the losses under control. The quadrupoles and sextupoles are powered in three and two families, respectively. As a consequence, the available tunability is limited unless the magnet power-supply configuration is modified. In Table 2, the list of relevant lattice parameters is given. he values for the nominal ring are taken from Ref. [8].

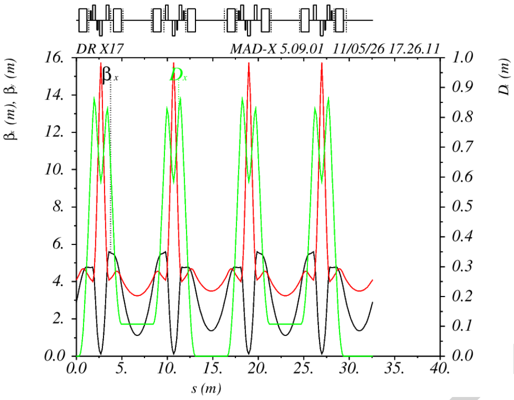

Figure 1: Optical functions of the extraction lattice. The plot shows β_x, β_y, and the horizontal dispersion D_x along the damping ring. The machine starts at the injection septum. The extraction septum is located after the second arc structure.

Table 2: Main lattice parameters for the nominal and stretcher optics. The second column refers to the energy of 280 MeV.

Parameter	Nominal	Stretcher
E_{beam} [MeV]	510	250–310
L_{DR} [m]	32.56	32.56
Horizontal tune, Q_x	3.12	3.328
Vertical tune, Q_y	1.14	1.156
Nat. chrom., ξ_x	-4.4	-5.2
Nat. chrom., ξ_y	-4.2	-5.8
$\beta_x(septum)$ [m]	2.25	2.91
$\beta_y(septum)$ [m]	3.98	4.22
D_x at septum [m]	0.0	0.0
Nat. emit. [mm mrad]	0.253	0.092
Mom. comp.	0.034	0.031

TRACKING RESULTS AND EXPECTED BEAM PERFORMANCE

Particle tracking is used to evaluate the extraction process and the quality of the extracted beam. The simulations include the resonant optics, the sextupole configuration, the extraction septum and the selected mechanism for driving the beam toward the resonance. The initial distribution includes the transverse emittance, the injected energy spread and the longitudinal time spread expected for the beam delivered to the damping ring.

Tracking studies were performed using the PTC-MADX module [9] and the results have been analyzed turn-by-turn within the ROOT framework to properly take into account the different physical apertures along the ring.

In the free-extraction scenario, the beam is injected with the RF off. The synchrotron-radiation energy loss changes the particle momentum turn by turn; through the machine chromaticity, this produces a corresponding tune shift. Particles are therefore progressively brought onto the third-order resonance, where they move along the separatrix and reach the septum. In the present configuration, the energy loss is about 0.65 keV/turn and the horizontal chromaticity is used to control the rate at which particles approach the resonance.

The available mechanical information indicates an iron plate thickness of about 1.5 mm, while the effective geometrical separation, including beam-pipe thicknesses and mechanical tolerances, is 3.7 mm. Figure 2 shows the horizontal phase space at the extraction septum.

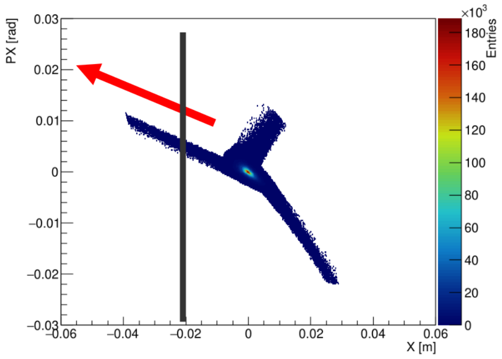

Figure 2: Horizontal phase space at the extraction septum. The separatrix induced by the third-order resonance is clearly visible, the red arrow indicates the one crossing the septum. The density map represents the evolution of a bunch of positrons with energy of 280 MeV, $\delta_E = +1.5\,\%$ and emittance of 1 mm mrad at the injection circulating into the "ideal" damping-ring until lost. The vertical line represents the extraction septum.

Preliminary tracking results show that slow extraction from the damping ring is feasible, although the efficiency strongly depends on the lattice configuration, especially the sextupole setup. A representative optimized configuration based on the present sextupole families gives an extracted fraction of about 38 % in the ideal lattice for particles injected with nominal energy. Figure 3 shows the results of a set of simulations used to optimize the sextupole settings.

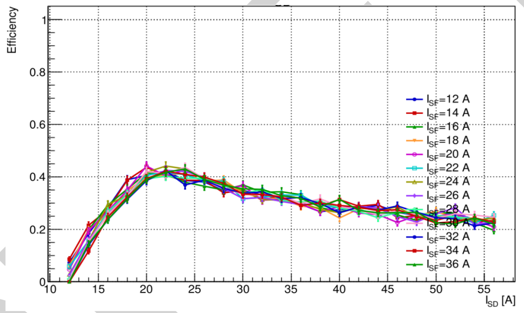

Figure 3: Extraction efficiency as a function of the sextupole families excitation currents. The best values, around 40 %, are obtained with moderate currents (~ ±20 A) that corresponds to $K_2L \simeq \pm 1.6\,\text{m}^{-2}$ in MADX units. The simulation shown is limited to particles with nominal energy (280 MeV).

When magnet imperfections, alignment errors and the corresponding orbit correction are included, the efficiency decreases significantly (25–30 %), as shown by the results of the error simulation based on 50 different seeds limited to the nominal energy beam. Further tracking on the optimized ring lattice with imperfections included and a realistic initial beam distribution must be performed in order evaluate the expected extraction efficiency and the extracted beam parameters. The results on the ideal damping-ring lattice are shown in Fig. 4, where the instantaneous beam current and energy distribution corresponding to a realistic nominal injected beam are reported. The extracted energy spread is fully compatible with the experimental requirement, while the beam current time profile appears quite flat and with the expected duration for the chosen extraction method.

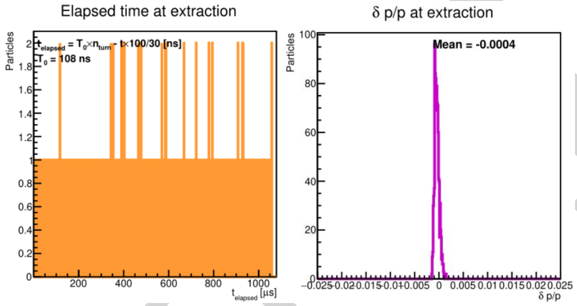

Figure 4: Simulated extracted beam intensity as a function of elapsed time (left) and energy distribution (right). The spill structure is one of the key performance indicators for the PADME-X17 application. The injected beam energy spread is 1.5 %. The energy resolution of the extracted beam exceeds the needs of the experiment, while the spill duration confirms the expectations.

CONCLUSIONS AND OUTLOOK

A third-order resonant slow-extraction scheme from the DAΦNE damping ring has been considered as a possible way to provide an improved positron beam for the PADME-X17 experiment. Starting from the existing damping-ring lattice, optics conditions suitable for resonant extraction can be obtained with limited modifications to the present facility.

Presently, only the "free extraction" scenario, with the RF off and relying on synchrotron-radiation energy loss and chromaticity to bring the particles onto the resonance, has been evaluated. This solution is attractive because it requires limited additional hardware, but the spill duration is intrinsically linked to the injected energy spread and to the energy loss per turn.

Preliminary tracking studies indicate that slow extraction from the damping ring is possible, with an extraction efficiency around 30 % for nominal beam, despite the thickness of the extraction septum. The next steps will include a refined optimization of the resonance sextupoles, realistic magnetic and alignment error studies, orbit correction, a detailed assessment of the septum geometry, and the design of the extraction beam line toward the PADME-X17 target.

The same scheme could also provide a flexible positron source for future fixed-target beamlines based on slow extraction from the DAΦNE damping ring.

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