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# PROPOSAL FOR USING DAΦNE AS PULSE STRETCHER FOR THE LINAC POSITRON BEAM

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*Abstract*

The PADME experiment [1] aims at searching for the dark photon ($A'$) in the $e^+e^- \to A\gamma'$ process in a positron-on-target experiment, exploiting the positron beam of the DAΦNE Linac at the INFN Frascati National Laboratory (Italy). The Linac can provide a number of positrons in excess of $10^{10}$ in a 200 ns long pulse but, in order to keep the pile-up probability in the calorimeter at an acceptable level, the number of positrons for PADME has to be below $10^5$/pulse, in particular by using the attenuating target in the BTF beam-line. The experiment is then essentially limited by the low duty factor ($10^{-5}$=200 ns/20 ms). In this paper, an alternative proposal to use the DAΦNE positron ring as a Linac pulse stretcher, by injecting each pulse into the ring and extracting it by a slow resonant extraction using the $m/3$ resonance, is presented. This would allow for distributing the positrons of a single Linac pulse over a much longer time interval (0.2–0.5 ms), increasing the duty factor up to ~1%. The required modifications of the DAΦNE positron transfer line and ring are described. A dedicated lattice for the positron ring has been designed and tracking of the positrons injected in the ring has been performed in order to optimize the extraction parameters and to give a preliminary estimate of the extracted beam characteristics.

## INTRODUCTION

The PADME experiment aims at collecting $10^{13}$ positrons-on-target running in the last six months of 2018, using a positron beam produced impinging electrons accelerated by the Linac on the Beam Test Facility (BTF) target [2]. In order to get the longest possible pulse, of the order of 200 ns, the Linac gun configuration has been recently optimized [3, 4, 5]. The expected parameters for the positron beam at the end of the BTF line are listed in Table 1.

Table 1: BTF Beam Parameters for PADME

| | |
|---|---|
| Energy (MeV) | 550 |
| Number of $e^+$/pulse | 2 $10^4$ - $10^5$ |
| Pulse length (ns) | 40 - 200 |
| Repetition frequency (Hz) | 49 |

The PADME requirements from the point of view of the beam are:

- a longest possible beam pulse, in order to keep the pile-up probability in the calorimeter as low as possible, given its granularity and the beam intensity;
- a beam spot below 1 mm, divergence below 1 mrad;
- a beam momentum spread below 1%.

After the end of the DAΦNE operation as a collider [6], foreseen for the end of 2019, it can be envisaged to use the DAΦNE positron ring as a Linac pulse stretcher to distribute the positrons of a single Linac pulse in a much longer pulse, increasing the duty factor by 3 orders of magnitude.

## GENERAL DESCRIPTION

In the present injection configuration, the Linac positron beam is injected into a damping ring and extracted after about 2 damping times. In the proposed pulse stretcher configuration, the transfer line will be modified to transport the beam directly into the DAΦNE ring. The positron beam will be then slowly extracted with the resonant extraction method, by using a proper sextupole configuration and an extraction septum. The septum can be installed in the long straight section where the IR1 Interaction Region is presently located.

### *Resonant Extraction Scheme*

The theory of resonant extraction can be found in [7, 8], the scheme adopted here is based on the work done at LNF for the ALFA proposal [9, 10].

Adopting a value of the betatron tune near to the 1/3rd resonance and a proper setup of sextupoles, the stability region in the horizontal phase space $(x, x')$ is delimited by a triangle. In Fig. 1 a schematic layout of the beam horizontal phase space at the extraction septum is shown. The injected beam has a hollow shape inside the triangle.

The particles outside the borders of the triangle are unstable and move outward along three lines, which are the continuation of the triangle's sides, the jump $\Delta x$ between two successive passages increases going outward. After injecting the beam inside the triangle, it is possible to extract all the particles in a given time reducing the size of the triangle by moving the betatron tune toward the resonance. We will adopt a monochromatic extraction: the chromaticity will be adjusted in such a way that as the particles lose energy by synchrotron radiation their distance from the resonance $\Delta\nu_x$ decreases. When the energy loss is equal to the initial relative energy spread of the

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injected beam $\Delta E/E_L$ all the particles on the external invariant are extracted in a time $T_{ext}$:

$$T_{ext} = T_0 \, \Delta E/E_L/U_0$$

with $U_0$ the energy loss per turn and $T_0$ the period of the ring.

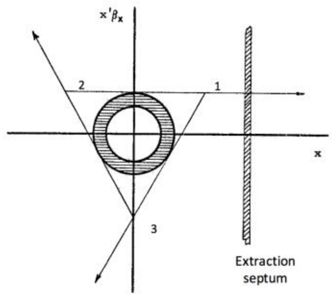


Figure 1: Schematic layout of the beam horizontal phase space at the extraction septum

To extract the particles with a smaller invariant a larger energy loss is needed, this gives the energy spread of the extracted beam.

The coordinates of the triangle's upper vertices are:

$$x_{1,2} = \pm\rho\sqrt{\frac{\beta_x^{ext}}{R}\frac{\Delta\nu_x}{2\sqrt{3}H_{33}}} \qquad x'_{1,2} = \rho\sqrt{\frac{1}{\beta_x^{ext}R}\frac{\Delta\nu_x}{6H_{33}}}$$

where $R$ and $\rho$ are the ring radius and the average bending radius respectively. The value of $H_{33}$ depends on the betatron phases $\mu_j$ and on the integrated strengths of the sextupoles along the ring, $K_j = (1/B\rho)\, d^2B/dx^2 \cdot L_j$:

$$H_{33} = \sum_j \left(\frac{\rho\,\beta_j^{3/2}}{48\pi\sqrt{R}}\right) K_j \cos\left(3\mu_j + \frac{\pi}{2}\right)$$

with the condition to have the extraction direction parallel to the $x$ axis:

$$\sum_j K_j \sin\left(3\mu_j + \frac{\pi}{2}\right) = 0$$

Analytic expressions, reported in [8], have been used to choose the injection and extraction parameters and to give a preliminary estimate of the extracted beam parameters. Tracking studies have then been performed to achieve a more precise estimate.

The total area of the extracted beam in the horizontal phase space $W_r$ is given by:

$$W_r = \Delta x \cdot \Delta x'$$

$$\Delta x = \frac{X_S^2 - X_0^2}{X_0 \coth(3\sqrt{3}\pi\Delta\nu_x) - X_s} \quad , \quad \Delta x' = \frac{\sqrt{W_M} - \sqrt{W_m}}{\sqrt{\beta_x^{ext}}}$$

where $X_0$ is the triangle vertex nearest to the septum, $X_s$ is the position of the extraction septum, $\Delta\nu_x$ is the betatron tune distance from the resonance, $W_M$ and $W_m$ are the maximum and minimum Courant-Snyder invariants of the injected beam, $\beta_x^{ext}$ is the betatron function at the extraction septum.

The value of $\Delta\nu_x/H_{33}$ is given by the condition to have the triangle tangent to the external contour of the injected beam $W_M$:

$$\Delta\nu_x/H_{33} = 6\sqrt{RW_M}/\rho$$

The value of $\Delta\nu_x$ gives the value of the jump $\Delta x$. The choice of $\Delta x$ is a compromise between the extraction efficiency and the extracted beam emittance. Extraction losses are due to particles hitting the septum and therefore the extraction efficiency is approximately given by the ratio between the extraction septum thickness and $\Delta x$. Using an electrostatic septum of thickness 100 μm and $\Delta x$=5 mm an extraction efficiency of about 98% can be achieved.

## LATTICE MODIFICATIONS

A dedicated lattice has been designed. The present low-$\beta$ in IR1 has been removed making both IRs equal to the present IR2, with non-colliding beams, to get the ring symmetric. The extraction septum is in the IR1 straight section, where there is space for the extraction line. At the extraction septum, the $\beta_x^{ext}$ value is the ring maximum, the function $\alpha_x$ and the dispersion function $D_x$ are zero to minimize the extracted beam emittance. The horizontal tune is near the 1/3 resonance. The parameters are listed in Table 2.

Table 2: Ring Parameters for the Pulse Stretcher

| | |
|---|---|
| $E$ (GeV) | 0.51 |
| $C$ (m) | 97.6 |
| $Q_x, Q_y$ | 4.30, 4.27 |
| $\xi_x, \xi_y$ | -3.3, -6.3 |
| $K_{sf}, K_{sd}$ (m$^{-2}$) | 2.06, -1.29 |
| $\beta_x^{max} = \beta_x^{ext}$ (m) | 20 |
| $\beta_x^{inj}$ (m) | 15 |
| $U_0$ (KeV/turn) | 8.94 |

## INJECTION PARAMETERS

At present, we can achieve in the Linac $N^+ \sim 10^{10}$ positrons/pulse with an emittance $W_x \sim 10^{-5}$ m·rad and a total energy spread $\Delta E/E_L$=0.02.

The beam will be injected into DAΦNE by using the present septum and kickers. The kicker's pulse length has to be increased in order to have a flat-top as large as the bunch length. In the following we assume to get ten times smaller emittance with half the energy spread by collimating the beam and reducing the number of positrons per pulse to $5 \cdot 10^7$. The kicker angle is used to choose the displacement $x_0$ of the injected beam with respect to the reference orbit at the injection septum.

At the exit of the transfer line, the vertical optical functions and the horizontal dispersion need to be matched to the ring optical functions in order to avoid an increase of the injected beam dimension. The value of the $\beta_x^{TL}$ function has been adjusted to 3.5 m (1/4 of the ring $\beta_x^{inj}$) in order to minimize the thickness of the injected beam in phase space. This is important since the emittance and momentum spread of the extracted beam depend on the

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injected beam size. The injected beam coordinates in the horizontal phase space, for $\Delta p/p$=0 and $x_0$=0.02 m, are shown at the injection septum in Fig. 2. The initial coordinates (blue ellipse), are tracked for 32 turns at fixed momentum.

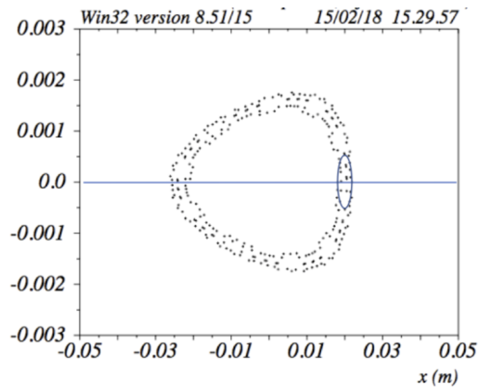


Figure 2: Horizontal phase space for $\Delta p/p$=0 (fixed momentum) and $x_0$=0.02 m at the injection septum.

## TRACKING STUDIES

Tracking studies have been performed with MAD8 code in order to evaluate the extracted beam parameters. First we looked for the extraction momentum for the particle at the center of the injected beam. Eleven particles have been tracked at fixed momentum with the same initial coordinates ($x$=0.02 m, $x'$=0, $y$=0, $y'$=0) and different momentum deviation $\Delta p/p$ from $-0.0045$ to +0.0045, in steps of $10^{-3}$. The particle coordinates in the $(x, x')$ plane at the extraction septum are plotted in Fig. 3; only the particle with $\Delta p/p$=−0.0045 is extracted.

Tracking coordinates for particles distributed uniformly on the injected ellipse (blue in Fig. 2), with $W_x$ = $10^{-6}$ m·rad, $\beta_x^{TL}$= 3.5m, the ellipse center at $x_0$=0.02 m, $x'_0$=0.0 and the initial momentum $\Delta p/p$=−0.0045, are shown in Fig. 4. Tracking is done with the average radiation energy loss (no fluctuations), RF cavity off, and collimators inserted in all the high $\beta_x$ locations.

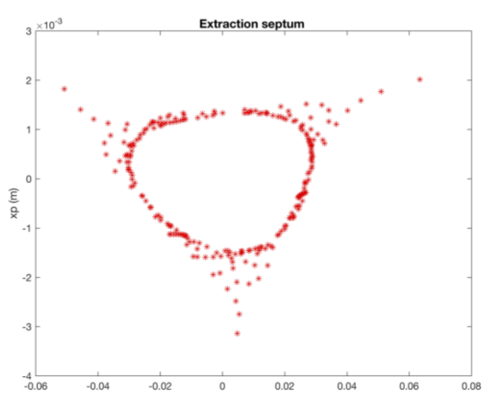


Figure 3: Particle tracking in the x, x' plane, at the extraction septum, for energies from Δp/p=-0.0045 to +0.0045 in steps of 0.001.

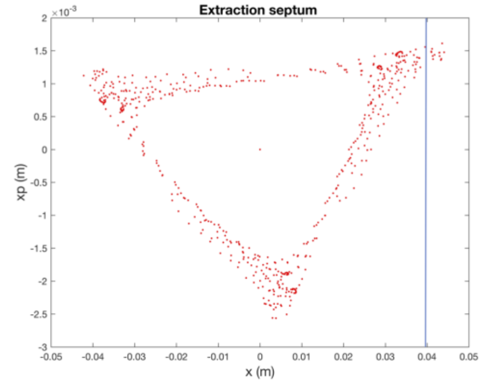


Figure 4: Particle tracking in the x, x' plane, at the extraction septum, with initial Δp/p=-0.0045 and energy loss.

The ring aperture has a radius $A_x$=0.045 m and the extraction septum has been placed at $x_s$=0.040 m in order to avoid particle losses elsewhere in the ring.

All the particles with initial $\Delta p/p = -0.0045$ are extracted at the septum within 90 turns and the coordinates of the extracted particles are in the range given in Table 3. The total area of the extracted beam in the phase space is $W_r$= 7.8·$10^{-7}$ m·rad and the total extracted relative momentum spread is 1.4x$10^{-3}$. If the injected beam has a momentum spread +.0055> $\Delta p/p > -0.0045$ the extraction time is the time needed for particles with $\Delta p/p$=0.0055 to get to $-0.0045$ (570 turns) plus 90 turns, i.e. $T_{ext}$ = 660 turns = 0.21ms. Since the time between injections is 20 ms the duty factor is 1%.

In order to have a more precise estimate it will be necessary to perform a study of all types of jitters and errors, in particular for the initial conditions of the injected beam coming from the Linac. It is also important to study a diagnostics system capable of monitoring the very low beam currents during the extraction process.

Table 3: Extracted Beam Coordinates

| | x (cm) | x' (mrad) | Δp/p |
|---|---|---|---|
| min | 4.10 | 1.36 | -0.0047 |
| max | 4.41 | 1.61 | -0.0061 |

## CONCLUSION

A proposal to explore the possibility to use the DAΦNE positron ring as a Linac pulse stretcher for the PADME experiment was presented. A preliminary estimate gives a duty factor of a factor 1000 greater than in the option of using the BTF beam, with an emittance below 1mm·mrad and a momentum spread of a few per mil.

Detailed studies of all the error sources and of the required beam diagnostics are needed to give a more precise estimate of the extracted beam parameters.

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