DAΦNE TECHNICAL NOTE
INFN - LNF, Accelerator Division

Frascati, 11/01/2017
Note: **G-73**

PRELIMINARY CONSIDERATIONS ON THE USE OF DAΦNE POSITRON RING AS A PULSE STRETCHER FOR THE DAΦNE LINAC

S. Guiducci

Introduction

The PADME experiment proposes a search for the dark photon (A') in the $e^+e^- \rightarrow \gamma A'$ process in a positron-on-target experiment, exploiting the positron beam of the DAΦNE linac [1, 2]. The positron beam for the PADME experiment will be produced impinging the electrons on the Beam Test Facility (BTF) target and using the long pulse configuration in the gun [3, 4, 5]. With this configuration the BTF will provide to the PADME experiment a positron beam with the parameters listed in Table 1.

Table 1 – PADME beam from Linac.

Energy (MeV)	550
Number of positrons per 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:

- 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;
- Beam spot below 1 mm, divergence below 1 mrad;
- Beam momentum spread below 1%.

Using the positron converter the linac could provide a number of positrons as high as 10^9/pulse in a 200 ns pulse but the number of positrons is limited below 10^5/pulse in order to keep the pile-up probability in the calorimeter low enough. If we are able to stretch the linac pulse length we can increase by the same factor the number of positrons, up to 10^9/pulse, keeping the same pile-up probability.

Since the operation of the PADME experiment is foreseen in dedicated mode during the DAΦNE shutdown, it can be envisaged to use the DAΦNE ring as a linac pulse stretcher to distribute the positrons of a single linac pulse in a much longer pulse.
In the following some preliminary estimates of the beam characteristics that could be achieved by injecting each pulse into DAΦNE and extracting it by a slow resonant extraction are presented.

System description

A schematic layout of the DAΦNE injection system is shown in Fig. 1. In the pulse stretcher configuration the linac beam will be injected directly into the DAΦNE ring without passing through the accumulator ring, presently used for injection in the DAΦNE rings. This will require a modification of the transfer line to bend the beam directly in the DAΦNE hall (as it was for ADONE). The transfer line lattice from the linac to the positron injection septum will need to be modified to accept the linac beam and to match the dispersion and beta functions at the septum.

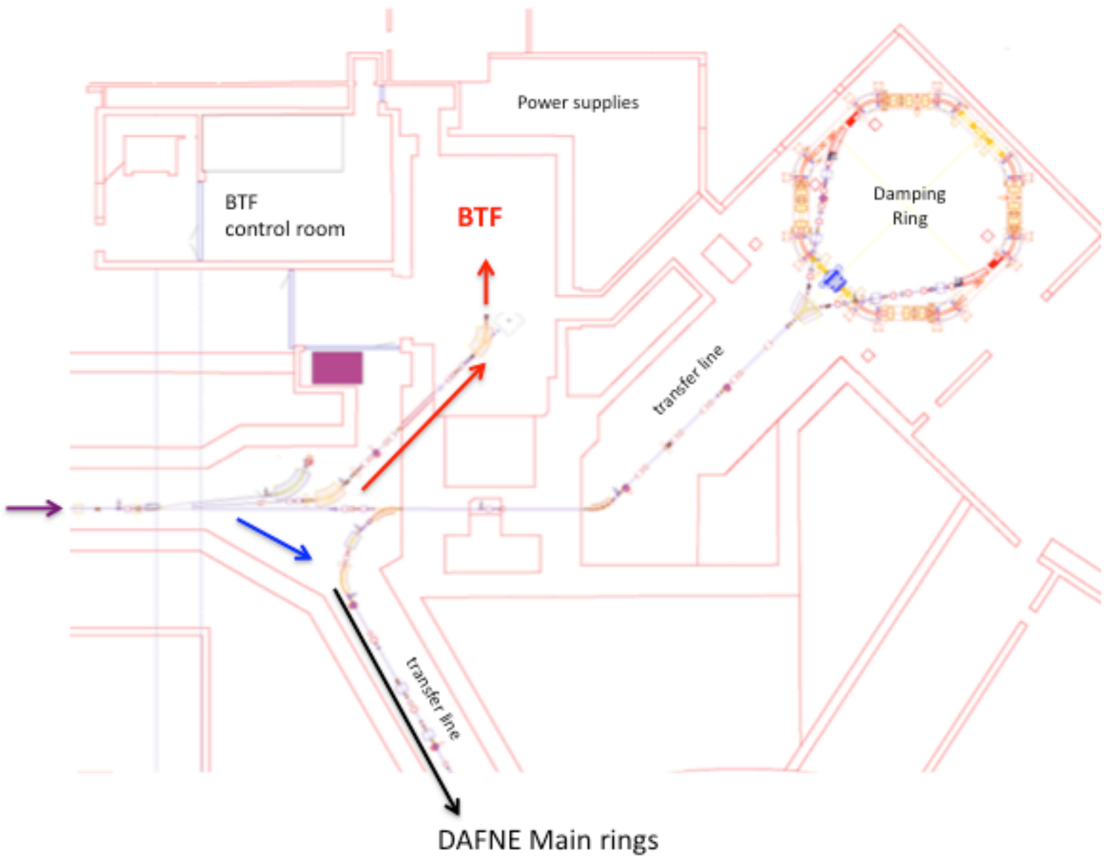

Figure 1 - Layout of the DAΦNE injection system.

The positron beam will be slowly extracted from the DAΦNE ring by resonant extraction by using a proper sextupole configuration and an extraction septum. The septum could be installed in the IR2 interaction region.
All the following considerations are based on the work done at LNF for the ALFA proposal [6 ,7].

Initial conditions

The initial parameters of the beam at injection into DAΦNE are listed in Table 2.

Table 2 - Linac beam parameters

N^+/pulse	5.00E+07
Repetition frequency (Hz)	50
Pulse duration (ns)	150
E (GeV)	0.5
$(DE/E)_L$	0.01
Emittance W_x (m)	1.00E-06

At present we can achieve in the Linac $N^+ \sim 10^9$ positrons/pulse with an emittance $W_x \sim 10^{-5}$ mrad and a total energy spread $(\Delta E/E)_L = 0.02$. 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 $5\text{x}10^7$.

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. If the kicker's pulse duration is longer than one turn, the second kicker will be used to close the bump on the second turn.

The angle of the kicker is chosen in order to have a given value of the maximum betatron oscillation at the injection septum x_M^{inj}. The optical functions, and in particular the dispersion, at the exit of the transfer line need to be matched to the ring optical functions in order to avoid an increase of the injected beam dimension. This is important since the emittance of the extracted beam depends on the injected beam size.
In the phase space $(x, x'\beta_x)$ the injected beam has a hollow shape delimited by two circles. The emittances corresponding to the two circles, W_M and W_m are given by:

$$W_M = \frac{\left(x_M^{inj}\right)^2}{\beta_x^{inj}}; \quad W_m = \frac{\left(x_M^{inj} - 2\sqrt{W_x \beta_x^{inj}}\right)^2}{\beta_x^{inj}} \tag{1}$$

The injection parameters used in the following are listed in Table 3, where x_s^{inj} is the horizontal position of the injection septum, Δs its thickness, β_x^{inj} and β_x^{kick} are the beta functions at the injection septum and kicker respectively and x_{bump} is given by the expression:

$$x_{bump} = x_s^{inj} + \Delta s + 2\sqrt{W_x \beta_x^{inj}} - x_M^{inj} \quad (2)$$

Table 3 - Injection parameters	
X_s^{inj} (m)	3.20E-02
Δs (m)	4.00E-03
x_{bump} (m)	2.30E-02
β_x^{inj} (m)	9.0
β_x^{kick} (m)	3.0
θ^{kick} (rad)	4.43E-03
x_M^{inj} (m)	0.019
x_m^{inj} (m)	0.013
W_M (m)	4.00E-05
W_m (m)	1.87E-05

Extraction conditions

With a proper setup of sextupoles and a value of the betatron oscillation near to the $1/3^{rd}$ resonance the stability region in the horizontal phase space (x, x') is delimited by a triangle. The particles out of the borders of the triangle become unstable and move outward along three lines, which are the continuation of the triangle's sides.

It is then possible to extract all the particles in a given time by reducing the size of the triangle by moving the betatron tune toward the resonance.

In our case we will adopt a "monochromatic" extraction by using the chromaticity of the ring. The chromaticity will be adjusted in such a way that as far as the particles lose energy by synchrotron radiation their tune gets closer to the resonance and they are extracted.

The beam shape at the extraction septum in the phase space ($x, x'\beta_x$) is represented in Fig. 2 together with the stability triangle given by the vicinity of the betatron tune to the m/3 (m integer) resonance. The extraction directions and the shadow of the extraction septum in the phase plane are also indicated. Particles outside the stability triangle start moving on the extraction directions and the jump Δx between two successive passages increases going outward. The coordinates of the vertices of the triangle in the (x, x') plane are:

$$x_{o1,2} = \pm\rho\sqrt{\frac{\beta_x^{ext}}{R}\frac{\Delta\nu}{2\sqrt{3}H_{33}}} \qquad x_{o3} = 0$$
$$x'_{o1,2} = \pm\rho\sqrt{\frac{1}{\beta_x^{ext}R}\frac{\Delta\nu}{6H_{33}}} \qquad x'_{o3} = \pm\rho\sqrt{\frac{1}{\beta_x^{ext}R}\frac{\Delta\nu}{3H_{33}}} \tag{3}$$

Here R is the ring radius, ρ is the radius of curvature, Δν is the distance of the betatron tune from the m/3 resonance and H_{33} depends on the sextupole strengths and phases.

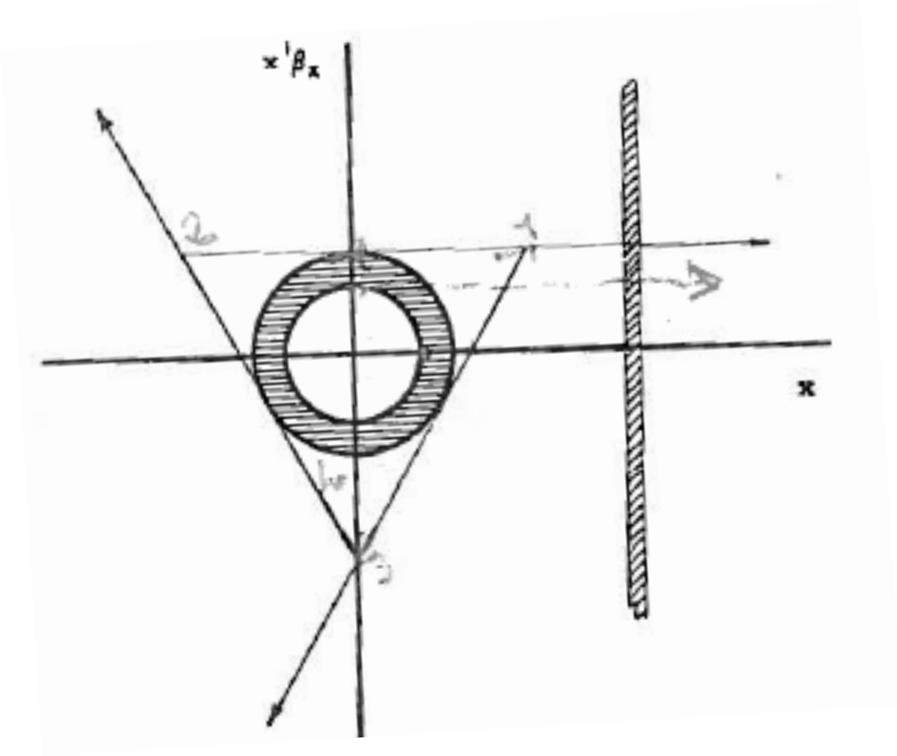

Figure 2 – Beam shape and stability triangle in phase plane at the extraction septum.

Beam parameters evaluation

The value of $\Delta\nu/H_{33}$ is calculated from the maximum beam emittance W_M in order to have the stability triangle tangent to the external beam contour.

$$\Delta\nu/H_{33} = 6\sqrt{R}/\rho\sqrt{W_M} \tag{4}$$

The coordinate X_o of the vertex nearest to the septum is calculated by (3) and reported in Table 4 together with $\Delta\nu/H_{33}$.

The extracted beam area W_r in the horizontal phase space can be estimated by the following relations:

$$W_r = \frac{\Delta x \cdot \Delta x'}{4} \tag{5}$$

$$\Delta x = \frac{X_s^2 - X_o^2}{X_o / \tanh(3\sqrt{3}\pi\Delta\nu) - X_s} \qquad \Delta x' = \frac{\sqrt{W_M} - \sqrt{W_m}}{\sqrt{\beta_x^{ext}}}$$

The first extracted positron has the maximum emittance W_M and the minimum relative energy deviation $-(\Delta E/E)_L/2$. The corresponding value of $\Delta\nu$, the distance from the resonance, is obtained from the expression (5) for Δx. This fixes the value of H_{33} that has to be achieved by choosing the phases and strengths of the sextupoles placed in a zero dispersion region. Another set of sextupoles placed in dispersive regions are used to control the chromaticity. Having fixed H_{33} the value of $\Delta\nu$ and Δx for the particles with the minimum emittance W_m can be evaluated. The extracted beam area W_r is calculated using the average value of Δx. A more accurate estimate of W_r can be achieved by a detailed tracking simulation.

The position of the extraction septum X_S is fixed based on aperture considerations. The choice of the "jump" Δx is a compromise between the extraction efficiency and the extracted beam emittance. The extraction loss is nearly the ratio between the extraction septum thickness and the jump. Using an electrostatic septum with a thickness of 100 microns and a jump of 5 mm an efficiency of about 98% can be achieved.

Due to chromaticity the betatron tune varies with the energy and as long as the particles lose energy by synchrotron radiation their distance from the resonance $\Delta\nu$ decreases, the triangle shrinks and they are extracted. When the energy loss is equal to $(\Delta E/E)_L$ all the particles on the external ellipse are extracted. To extract the particles with smaller emittances it is needed to loose more energy, which gives the energy spread of the extracted beam $(\Delta E/E)_{ex}$.

$$(DE/E)_{ex} = 12\frac{\sqrt{R}}{\rho} H_{33} \frac{\sqrt{W_x}}{C_x} \tag{6}$$

The extraction time is given by:

$$T_e = \frac{2\pi R\rho}{KE^3}\left((DE/E)_L + (DE/E)_{ex}\right) \tag{7}$$

with K = 2.65·10^4 GeV^{-3} m^2 s^{-1}. The parameters of the extracted beam listed in Table 4 are evaluated with the wiggler magnet OFF for a value of horizontal chromaticity C_x = -3. If the wiggler is kept ON the extraction time is shorter by a factor ~2. The vertical emittance of the extracted beam is the same of the injected one.

Table 4 - Extraction parameters	
W_M (m)	4.00E-05
R (m)	15.5
ρ (m) wiggler OFF	1.4
$\Delta\nu/H_{33}(W_M)$	0.11
Xo (m)	4.90E-02
Xs (m)	6.00E-02
Δx (m)	5.00E-03
$\Delta\nu(W_M)$	0.010
C_x	-3
H_{33}	0.094
W_r (m)	**3.44E-06**
(DE/E)ex	**1.06E-03**
T_e (s)	**4.56E-04**

Further studies and hardware modifications

The next step will be to calculate the distribution and strengths of the sextupoles in order to achieve the required values of H_{33} and chromaticity.

Before a study of some modifications of the DAΦNE lattice is needed:

- Remove the low beta in the KLOE IR
- Turn off the wigglers if this is the preferred configuration
- Adjust the beta function for the extraction septum at the IP2 position

Moreover the positron transfer line needs to be modified in order to match beta functions and dispersion at the ring entrance.

If with these modifications DAΦNE will result in being an efficient linac pulse stretcher, the following hardware modifications would be needed:

- Substitute the KLOE IR permanent magnet doublet with two electromagnetic quadrupoles
- Readjust the positions of the IR2 quadrupoles
- Install an electrostatic septum at IP2
- Install a couple of magnets in the linac transfer line in order to transport the beam directly to DAΦNE without passing trough the accumulator.

Conclusions

A preliminary proposal to explore the interest of using DAΦNE positron ring as a Linac pulse stretcher was presented. All parameters presented here require further optimization and a detailed simulation study to give a more precise estimate of the extracted beam parameters.

References

[1] F. Bedeschi et al., Frascati Physics Series vol. LX (2015).

[2] M. Raggi, V. Kozhuharov and P. Valente, EPJ Web Conf. 96, 01025 (2015).

[3] P. Valente et al., INFN-16-04/LNF, 11th March 2016.

[4] B. Buonomo, L. G. Foggetta, "Daφne Linac: Beam Diagnostics and Outline of the Last Improvements", TUPWA057, Proceedings of IPAC2015, Richmond, VA, USA.

[5] B. Buonomo, L. G. Foggetta, G. Piermarini, "New Gun Implementation and Performance of the Daφne Linac", TUPWA056, Proceedings of IPAC2015, Richmond, VA, USA.

[6] S. Guiducci, G. Martinelli, M. Preger, LNF-78/22(R), 22 maggio 1978.

[7] S. Guiducci, G. Martinelli, M. Preger, IEEE Trans. On Nucl. Sci., Vol. NS-26, No.3, June 1979.