Design and simulation of a pulsed positron beam at ELI-NP

N Djourelov and D Dinescu

Extreme Light Infrastructure - Nuclear Physics, Horia Hulubei National Institute for Physics and Nuclear Engineering, 30 Reactorului Street, P.O. Box MG-6, 077125 Magurele, Ilfov county, Romania

E-mail: doru.dinescu@eli-np.ro

Abstract. The design of the pulsing system for the slow $e^+$ beam at ELI-NP is presented. It will deliver narrow time width $e^+$ pulses, achieved by a combination of prebuncher, chopper and buncher. The effect of the different components on the pulse compression is simulated by a Matlab program. The results show that the best compression of the $e^+$ pulses, which can be achieved by the proposed pulsing system, is limited to about 100 ps (FWHM). The most effective solution, applied up to now, for minimizing the influence of the backscattered $e^+$ on the PALS spectra by using a bent tube filter is simulated by Comsol Multiphysics.

1. Introduction

For the development of new functional materials, the investigation of lattice defects and various atomic imperfections in solids constitutes an important step. Conventional positron annihilation methods use energetic $e^+$ directly emitted from radioisotopes such as $^{22}$Na and are suited to measurements of bulk materials. For analyzing subsurface layers and thin films, slow $e^+$ beams are necessary [1]. If a radioisotope is used as the source of fast $e^+$ the intensity of the moderated slow $e^+$ is limited to $\sim 10^6$ e$^+$ s$^{-1}$. For creating a slow $e^+$ beam with a higher intensity another kind of source has to be utilized. At the European Light Infrastructure (ELI-NP), a brilliant $\gamma$-beam will produce fast $e^+$ in a suitable converter using the pair production mechanism. The creation of a slow $e^+$ beam will be achieved using a converter of tungsten foils, which also acts as the moderator [2].

One of the most powerful positron based techniques for the quantification of defects is Positron Annihilation Lifetime Spectroscopy (PALS). To perform PALS with a $e^+$ beam a start signal is needed. For generation of a start signal several methods have been applied: detection of secondary $e^-$ produced by incident $e^+$ [3], $e^+$ trapping in a field and using a trigger to release the trapped $e^+$ [4], and the method with the best possible time resolution, injection of ultra short pulses using the timing signal of the pulsing device [5].

In the present paper we report on the designed pulsing system which will deliver short $e^+$ pulses. The pulsing technique by chopping and bunching consists in modulating the longitudinal velocity of $e^+$ by applying a time dependent electric field to accelerate/decelerate the $e^+$ that would arrive too late/early at the time focus. The technique is well-known and has been applied previously by a number of groups in order to develop pulsed $e^+$ beam from a DC $e^+$ source.

2. Design and simulations

The designed pulsing system is presented in Figure 1. It is composed of a prebuncher, chopper, pre-accelerator, buncher, decelerator, accelerator, and bent drift tube. We have developed a Matlab
program to calculate the movement of $e^+$ in time varying electric fields with the goal of recording the time of arrival of the $e^+$ at various points of the pulsing part. The possible spherical aberrations are neglected as the time resolution ($e^+$ pulse width) is basically dominated by the chromatic aberrations. The system was designed for incoming $e^+$ with energy of 29 eV with a realistic energy distribution of 1 eV (FWHM). The $e^+$ will be confined close to the beam line axis by a longitudinal magnetic field of 60 G provided by solenoid coils. In the following sections we will discuss the various components of the pulsing system and their effect on the quality of the pulsing.

![Figure 1. The 3D design of the in vacuum electrodes of the pulsing system. It consists of a prebuncher, chopper, pre-accelerator, buncher, decelerator, accelerator, and drift bent tube. The longitudinal magnetic field will be provided by a solenoid coil wound directly on the vacuum tubes and Helmholtz coils where a solenoid is not possible. The mechanical supports for the electrodes are omitted for simplicity.](image)

2.1. Prebuncher

The purpose of the prebuncher is to bunch the $e^+$ beam in such a way that in the most $e^+$ will arrive at the main buncher gap during the linear parts of the sine wave potential which is applied to the main buncher [5].

![Figure 2. The periodic modulation potential to be generated by AWG and applied to the first gap of the multi-electrode prebuncher.](image)

![Figure 3. The simulated time compression of $e^+$ after the prebuncher. The shaded area represents the chopper transmission window chosen as 2.1 ns.](image)

The ideal shape for the potential of the prebuncher electrode is a periodic saw-tooth function ($\sim t^2$). However, in a double gap prebuncher unwanted wrong energy modulation is given to $e^+$ when passing the second gap. One way to avoid the unwanted energy modulation is to use a multi-electrode prebuncher without drift [6]. The potential difference at the first gap determines the initial $e^+$ energy modulation. Then the $e^+$ travel in varying electric field generated by a number of electrodes. The varying potential is spread by a voltage divider over several gaps formed. If the time $e^+$ need to pass the prebuncher electrodes length (chosen 500 mm) is equal to one period of the saw-tooth function, the extra energy modulation averages to zero [6]. For our simulation we used a wave of 40 MHz $\sim t^2$ with
an amplitude of 8 V (see Figure 2), which can be generated by a commercially available arbitrary wave generator (AWG) with slew rate of 20 V/µs. The resulting time compression after the DC e+ beam passed the prebuncher is shown in Figure 3.

2.2. Chopper

The purpose of a chopper is to filter out those e+ which will not arrive at the proper time at the buncher gaps. As a result, the chopping eliminates possible satellite peaks in the spectrum and improves the peak to background ratio. A retarding potential chopper consists of three tungsten meshes. The first and last meshes are grounded, and a chopping signal (40 MHz square-wave, 2.1 ns width and a bias voltage of 40 V) is supplied to the second mesh. In Figure 3 the transmission window of an ideal chopper is shown. The challenge in application of this type of chopper is the amplification of the square-wave. To preserve the shape of the generated square-wave, a wide bandwidth amplifier is required. Even though, in a realistic retarding potential chopper, an appearing of pulse tails due to e+ which are almost stopped and then accelerated is a disadvantage and may deteriorate the final time resolution. These effects are not simulated in the present work. It would be worthy to try to design an E×B chopper [5, 7]. The time compression achieved by the prebuncher and the width of the chopper transmission window determines the beam intensity losses due to the pulsing system. For the signals described above the transmission efficiency of the pulsing system is 65%.

2.3. Main buncher

The main buncher is the second time focusing component of the pulsing system. In order to minimize the chromatic aberration in this component (due to the energy modulation introduced by the prebuncher as the first focusing component), after the chopper, the e+ are pre-accelerated to 1.5 keV [8]. It has to be mentioned that, where technically possible, either acceleration or deceleration of a charged particle confined in longitudinal magnetic field should be done by multi electrode system as it introduces smaller extra longitudinal velocity spread as compared to one gap acceleration/deceleration. This was simulated and confirmed by Comsol multiphysics.

The designed main buncher is a simple single frequency (120 MHz) sinewave double gap buncher with a 96 mm central electrode. As a result of the Matlab optimization, we found that for obtaining the best time compression (shortest bunches at the target) a sine wave with amplitude of 47.5 V biased at 1.5 kV is necessary. The effect of the buncher on the phase space of the e+ is shown in Figure 4. The resulted time distribution of the e+ in a pulse is very close to a Gaussian with FWHM = 109 ps (see Figure 5). Considering these conditions, the time focus after the buncher occurs at 43.5 ns which corresponds to a drift length of ~ 1 m. By combination of the potentials applied at the deaccelerator and accelerator, together with small changes of the sine wave amplitude, one can adjust the time focus to occur at the target position for the different desired e+ incident energies in the range 0.2-30 keV [9].
2.4. Simulation of the backscattered $e^+$

When incident $e^+$ hit the target some fraction of them are backscattered. If these positrons reach the accelerator they can be re-accelerated and implanted into the sample with delay from the initial $e^+$ bunch. This causes PALS spectrum distortions as side peaks. The best solution applied up to now uses a bent tube solenoid equipped with steering coils [7]. The longitudinal bent magnetic field guides the incident $e^+$ bunch through the bend and to the target, but does not allow backscattered $e^+$ to reach the accelerator.

In order to optimize the bend radius and the angle of the bend, we simulated this process in Comsol. As an example, Figure 6 shows the trajectories of $e^+$ accelerated to 4 keV in a 30˚ bent tube with a bend radius of $R=1$ m followed by a 290 mm straight tube with the target at the end. Due to Comsol limitations, the magnetic field of the bent solenoid was simulated by suitable Helmholtz coils. The bent and straight tubes form a Faraday cage for $e^+$ drift. The backscattered $e^+$ are simulated as secondary particles in Comsol, with realistic, but uncorrelated, angular and energy distributions [10]. Figure 6 shows that the backscattered $e^+$ are guided back into the beamline, but they do not reach the accelerator, and, instead, they annihilate (the annihilation places are represented by balls) on the tube wall far away from the target giving negligible chance for the annihilation $\gamma$-rays to be detected. The tube sizes optimization work is in progress.

3. Summary

The design of a pulsing system for a DC $e^+$ beam was presented. The simulation of the effect of the different pulsing components on the $e^+$ phase space was performed by a Matlab program. Optimization of the signal amplitudes showed that compression to about 100 ps (FWHM) $e^+$ pulses at the sample position is a limit of this setup. The most effective solution, applied up to now, of minimizing the effect of backscattered $e^+$ by using a bent tube filter was simulated by Comsol.

References

[1] Schultz P J and Lynn K G 1988 Rev. Mod. Phys. 60 701
[2] Djourelov N, Hugenschmidt C, Balascuta S, Lea C, Oprisa A, Piochacz C, Teodorescu C and Ur C A 2016 Rom. Rep. Phys. 68 S735
[3] Szpala S, Petkov M and Lynn K G 2002 Rev. Sci. Instrum. 73 147
[4] Gilbert S J, Kurz C, Greaves R G and Surko C M 1997 Appl. Phys. Lett. 70 1944
[5] Schödlbauer D, Sperr P, Kögel G and Triflshäuser W 1988 Nucl. Instrum. Meth. B 34 258
[6] Piochacz C and Hugenschmidt C 2013 J. Phys: Conf. Ser. 443 012093
[7] Jungmann M, Haebeler J, Krause-Rehberg R, Anwand W, Butlering M, Wagner A, Johnson J M and Cowan T E 2013 J. Phys: Conf. Ser. 443 012088
[8] A Laakso 2005 Construction of a pulsing system for low-energy positrons Phd Thesis (Helsinki, Finland)
[9] Butterling M, Jungmann M, Bondarenko V, Sachtel S, Brauer G, Anwand W and Krause-Rehberg R 2011 J. Phys: Conf. Ser. 265 012027
[10] Marinov H, Djourelov N, Nédélec P and Petrov L 2013 Nucl. Instrum. Meth. A 729 569