

Determination of the timing properties of the pulsed positron lifetime beam by the application of an electron gun and a fast microchannel plate

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Abstract

We show that the timing properties of a pulsed low-energy positron lifetime beam can be conveniently tested by an electron beam. We apply this method to study time resolution of the beam and electron scattering in a flat and a 'sawtooth' shaped choppers. The results show that (i) time resolution of 160 ps is obtained, (ii) the scattering of the electrons and the secondary electron yield of the flat chopper make the time resolution worse and background poor, and (iii) both these problems can be solved by using a 'sawtooth' shaped chopper. We also compare these results to beam simulations.

Key words: Positron spectroscopy, Pulsed positron beam, electron scattering
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1 Introduction

Positron lifetime spectroscopy is a powerful technique to study vacancies and other open volume type defects in solid materials, for example in semiconductors. Conventional positron lifetime spectroscopy is based on using β^+ -active isotopes (e.g. ^{22}Na) is limited to thick samples and is not applicable to thin samples or thin layers. To expand the applicability of the lifetime spectroscopy, the positron lifetime beam has been developed. [1–3]

The timing properties of the beam can be determined with positrons and a suitable target e.g. stainless steel using a scintillator and a photomultiplier tube (PMT) as a detector. When the system is tested it is advantageous if the measurement times are short and the resolution good. This can be

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accomplished if the positron source is replaced with an electron gun and a fast microchannel plate (MCP) is used as a detector.

2 Setup and Methods

2.1 The pulsed positron lifetime beam

The general structure of the magnetically guided pulsed positron beam in HUT Laboratory of Physics is described elsewhere [1,4] and only the main details are revised here. The source, velocity selector and the beam bunching and chopping stages float at high voltage whereas the sample is at ground potential. The source area comprises a ^{22}Na source followed by a W-moderator. Slow positrons are separated from fast ones with a 90° bend in the beam. The first pulsing stage, the prebuncher, is an unmatched, nonresonant, two frequency (33.3 MHz and 66.6 MHz) double gap buncher, followed by a drift tube and a pre-accelerator where positrons reach an energy of 1 keV. After this acceleration the beam is chopped in a deflection type chopper shown Fig.1, where a deflecting field drives the positrons into the walls of the chopper in-between the pulses. The chopper is described in more detail in section 2.3. The chopped beam is then bunched in the main buncher at a frequency of 166.7 MHz. The final acceleration will be done with an accelerator-decelerator stage.

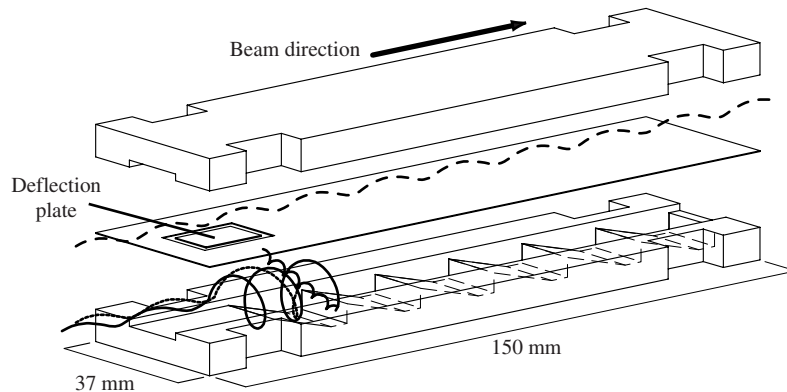


Fig. 1. The sawtooth grooves in chopper reduce the number of scattered electrons passing through to detector. The flat portions between the slopes and ridges are necessitated by the machining. According to simulations, they don't change the performance of the chopper. The lines illustrate simulated trajectories of positrons.

2.2 Electron test setup

The testing of the system requires that the timing spectra can be obtained fast and accurately. With conventional isotope sources and moderators and a BaF_2 scintillator detectors the count rate is limited to hundreds of counts per second resulting in relatively long measurement times. In our case it is also difficult to provide the necessary magnetic shielding for the photomultiplier tube of the detector in the test configuration of the beam.

To overcome these limitations we developed a new method for the testing of timing properties of a pulsed positron beam. We used a small, low-temperature electron source to obtain a narrow electron beam with high brightness. This enables to obtain easily high, controllable count rates. As a detector we used a microchannel plate, which is insensitive to magnetic fields. Other additional advantages of this setup are that (i) the energy distribution of beam is narrower, (ii) the beam diameter is much smaller compared to that generated from a positron source and (iii) the time resolution of the MCP detector is better than the resolution of a scintillator detector.

The electron source was a self-made electron gun where a BaO-disc (Kimball Physics ES-015 BaO cathode) was used as the electron emitter. An adjustable slit was placed 250 mm away from the electron gun to reduce the electron current to sub fA-level during timing tests. The e-gun was also used for beam alignment, where a phosphor screen and a picoammeter were used as beam monitors.

The timing detector, a microchannel plate (Hamamatsu F4655-12), was mounted next to the buncher and floating at 2.6 kV voltage. The accelerator-decelerator structure was not employed. It was observed that the MCP was very sensitive to the residual gas ions and electrons created in the ion pumps. Therefore, the system was pumped only with turbopumps during the tests. The stop signal from the MCP to the timing electronics was connected through a insulated BNC-feedthrough and 'double' DC-block (both signal and ground connection are isolated) made of high-voltage high-Q ceramic capacitors in a coaxial arrangement. The start-signal was obtained from the pulsing electronics via a fiber optic link.

2.3 *The chopper*

The chopper is made of two grounded sandwiched copper blocks with a thin double sided printed circuit board in between them, see Fig.1. The beam passes through the chopper via a slit machined to both copper blocks. An isolated area in the thin central copper plate acts as an electrode at the entrance end of the chopper. This electrode is part of a 16.67 Mhz resonator circuit which creates a sinusoidal electric field perpendicular to the beam. The phase of the field is adjusted so that the positron bunch from the prebuncher passes the electrode at the zero crossings (zero field) letting the bunch straight through the chopper. Between the bunches, the electric field increases the transversal momentum of the positron, which in turn increases the radius of larmor precession resulting the positrons to collide with the chopper walls. The chopper time acceptance window can be adjusted by varying the slew rate at the zero crossing. This is simply done by adjusting the amplitude of the chopping RF-signal.

When low energy electrons are used to test the system care must be taken to avoid disturbance caused by the electron scattering. This is especially important in the chopper that is based on colliding the beam to the chopper walls by deflection. In this collision there is a relatively large probability for scattering and secondary electron production when the energy is in the 1 keV range [5,6]. These electrons, which have a lower energy than those in the original beam,

are detrimental to the time resolution of the beam. To reduce the number of these electrons we designed a chopper, which is opaque for the scattered and secondary electrons.

Two geometrically different choppers were designed and studied experimentally and the results were compared to simulations [7]. The first chopper was entitled as the 'flat' chopper and the second as 'sawtooth' chopper. Both choppers consist of a deflection plate as described earlier, followed by a long slit machined to the copper body of the chopper. In the flat chopper the slit is smooth, while in the sawtooth chopper the longitudinal cross-section of the slit resembles a sawtooth (see Fig. 1). This structure consists of tilted slopes and six ridges perpendicular to the beam minimizing the probability for deflected electrons to pass through the chopper. The angle of the tilted surface and the height of the ridge were chosen so that the mirror-like reflection does not occur in the forward direction more than once. In addition to the reflected electrons there are always secondary electrons emitted with low velocities to nearly random directions so that they can pass over the ridge and scatter again. However, the probability is small for an electron to pass through all six ridges and exit the chopper. This kind of sawtooth surface has been used in large proton and positron accelerators to reduce photoelectron emission from accelerator chamber surfaces [8].

3 Results

3.1 Results from the measurements

3.1.1 The flat chopper and the chopping power

The electron scattering effects in the flat chopper are illustrated by the timing spectra shown in Fig. 2. In this figure the timing spectra for a beam that was only chopped, is shown. With a low amplitude of the field in the chopper (dashed curve) the peak is broad and the background is high. When the field amplitude is increased the peak gets narrower and the background becomes asymmetric (solid curve) showing a larger number of electrons arriving earlier (right hand side).

This asymmetry can be understood if the spectrum is thought to be composed of two spectra: the chopped spectrum and the background spectrum due to scattered electrons. The electrons in the chopped spectrum have passed through the chopper with unmodified energy when the chopping field is negligible in the chopping window and no scattering occurs. The background spectrum is from those electrons that arrive outside chopping window and have been deflected and subsequently scattered. In the inelastic scattering the electrons lose energy and the flight time to the target increases. This causes the background spectrum to shift to later times i.e. left and the 'hole' in the background spectrum (due to chopped spectra) appears on the left hand side of the main peak. This explains the 'shoulder' on the right hand side of the main peak, which is due to electrons scattered during the previous cycle of the deflecting field. This effect is not visible in the low amplitude spectrum since the chopping window is large and the chopping amplitude too low so that some electrons can pass through the chopper all the time and the num-

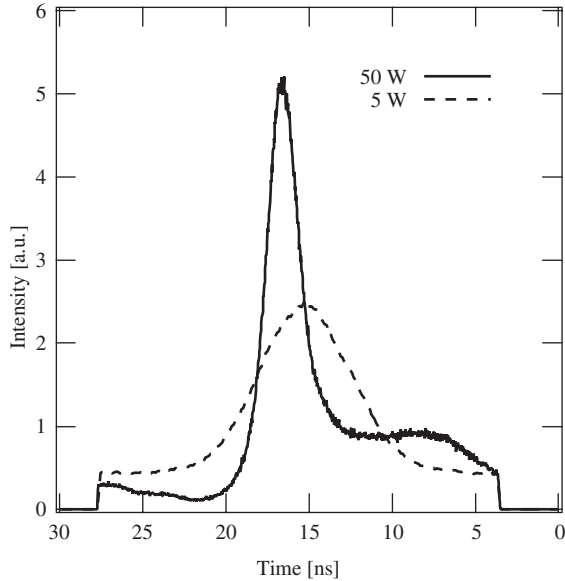


Fig. 2. *Increasing the chopping power from 5 W to 50 W improves pulse width but changes the pulse shape due to scattering and secondary electron effects.*

ber of inelastically scattered electrons is low. Thus, the background due to scattering is constant. From these results, it is evident that the flat chopper is not suitable for lifetime beam testing if electrons are used as test particles.

3.1.2 The sawtooth chopper

The results from the measurements with the sawtooth chopper and using all pulsing components are shown in Fig. 3. The amplitudes and phases of different pulsing components were adjusted to yield as narrow final bunches as possible. The topmost curve shows how the prebuncher compresses electrons into the chopping time window increasing the efficiency of the beam (curve a)). The full width at half maximum (FWHM) is 3.1 ns and the asymmetry of the peak can be explained by the phase difference between f and $2f$ components in the prebuncher waveform. The spectrum shown by the curve b) is collected when only the chopper is running. It shows that the chopper is working: the FWHM is 2.3 ns, the background is flat and low and the peak-to-background ratio is approximately 100:1. When the prebuncher and the chopper are operating simultaneously, the peak-to-background ratio improves to 300:1 and FWHM of the peak is 1.8 ns, as seen from the curve c).

The spectrum recorded with only the main buncher on is shown by curve d) in Fig. 3. The periodic structure of five similar peaks is due to the 6 ns main bunching period in a 30 ns base time window (166.67 MHz bunching rate vs. 33.33 MHz base frequency). The width of an individual peak is good, 160 ps, but the background is high (P/B ratio of 30:1).

When all pulsing stages are operating, the spectrum of Fig. 3 curve e) is obtained. The signal phases of different pulsing components have been adjusted so that the middlemost bunching peak matches the prebuncher and chopper time window. The FWHM of the final peak is 160 ps. The peak-to-background ratio is good, better than 1000:1. The background is not completely flat, due to the five main bunching periods during one base operating cycle. This uneven background should not be a problem for data analysis, since its shape

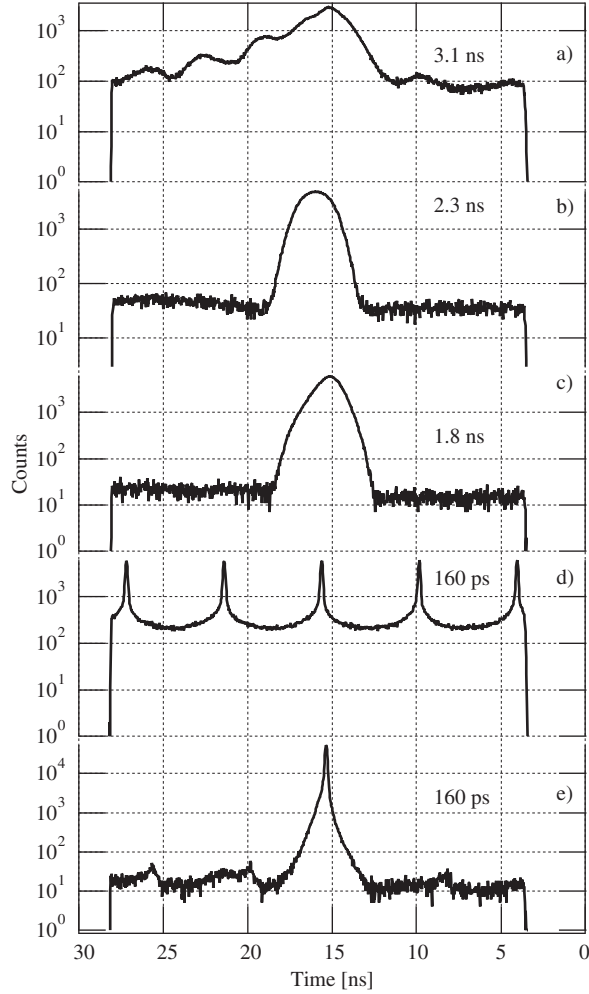


Fig. 3. The spectra measured from bunchers and the chopper and their combinations show that a time resolution of 160 ps, is obtainable with the sawtooth chopper. a) prebuncher, b) chopper, c) prebuncher and chopper, d) buncher and e) all together. The FWHM for each component and combinations of them is given in the figure.

is not dependent on the acceleration energy and thus it can be subtracted from the data. If the peak positions in the spectra in Fig. 3 are compared, a small peak shift is observed when the prebuncher is on. This is due to a small additional energy introduced by RF-acceleration in the prebuncher because of non-optimal initial energy of the beam [9].

3.1.3 Comparison between the sawtooth and the flat chopper

The measured timing spectra using a flat chopper and sawtooth chopper are compared in Fig. 4 (right hand side is same as curve e) Fig. 3, but now with linear scale). The superiority of the sawtooth chopper over the flat one is evident: the flat chopper spectrum shows side peaks, the peak-to-background ratio 1:10 is low and there is a significant nonlinear background. None of these problems are present in the spectra obtained with the sawtooth chopper.

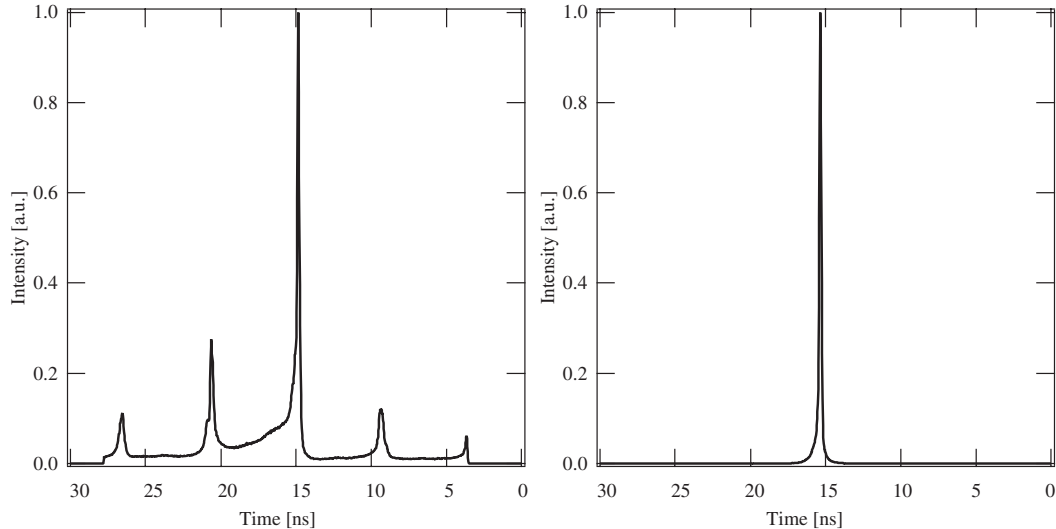


Fig. 4. *The time spectrum measured with the flat (left) and sawtooth (right) chopper when all pulsing components are on. The FWHM 160 ps is good in both cases, but the background and peak-to-background ratio is relatively poor for flat chopper.*

3.2 Results from simulations

Computer simulations were done to compare the properties of the two chopper designs [7]. The main challenge with simulation is the treatment of the scattering in a proper way. Theoretical and experimental data of scattering probabilities and secondary electron yields were found from the literature [5,6]. Also, detailed studies using a model from [7] were done. As a result it was found that a simple model where 33 % of electrons colliding with the wall scatter elastically and 67 % inelastically is sufficient to describe the scattering. The elastically scattered electrons were assumed to reflect from the surface, while the inelastic ones lose on average 40 % of their energy in the scattering [7]. The direction of the inelastic scattering is randomized but weighted in the calculation so that it points to the direction of forward scattering.

Measured and simulated spectra for the two chopper designs are compared in Fig.5 (the measured and calculated time distributions here are for a beam that is only chopped with a low power RF-amplifier.). It is clearly seen from the measured data (left in Fig.5) that the sawtooth chopper gives significantly better results compared to the flat chopper: the background is negligible and the peak is narrow. This result is verified by simulations seen in the right hand side of Fig.5, which replicates the measured spectra relatively well. These results suggest that the electron scattering and secondary electron generation plays an important role in the shape and the width of the final timing spectra.

4 Conclusions and discussion

We have shown that it is possible to test pulsing properties of a pulsed positron lifetime beam with electrons. For successful electron tests the beam chopper should be designed properly, in this case a sawtooth design was used to prevent electron scattering through the chopper. This design improves the system performance also with positrons by reducing positron scattering. We

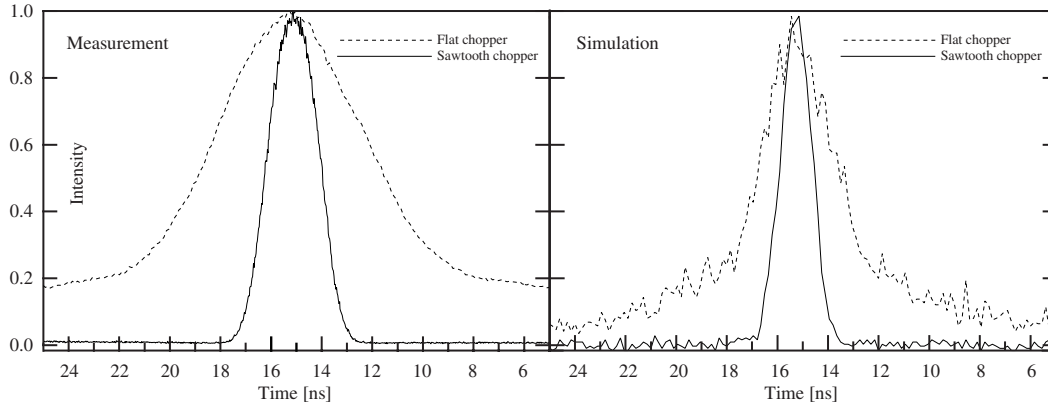


Fig. 5. Both the measured and the simulated spectra for the flat and the sawtooth chopper show that the introduction of the grooves improves time distribution significantly.

also show that it is possible to simulate electron scattering in the beam realistically and estimate its effects to the final time distribution.

The electron gun and a MCP proved to be an efficient way to study timing properties of a pulsed beam and to obtain accurate results rapidly. Tests showed that our system is working in the expected way with electrons and we can obtain a FWHM of 160 ps for the peak and a peak-to-background ratio better than 1000:1 in its test configuration.

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References

- [1] A. Laakso, K. Saarinen, P. Hautojärvi, *Physica B* 308-310 (2001) 1157–1160.
- [2] D. Schödlbauer, P. Sperr, G. Kögel, W. Triftshauser, *Nucl. Instr. Meth. B* 34 (2) (1988) 258 – 268.
- [3] R. Suzuki, Y. Kobayashi, T. Mikado, H. Ohgaki, M. Chiwaki, T. Yamazaki, T. Tomimasu, *Jpn. J. Appl. Phys.* 30 (3B) (1991) L532.
- [4] K. Fallström, T. Laine, *Appl. Surf. Sci.* 149 (1999) 44 – 48.
- [5] S. A. Schwarz, *J. Appl. Phys.* 68 (5) (1990) 2382–2391.
- [6] W. S. M. Werner, I. S. Tilinin, M. Hayek, *Phys. Rev. B* 50 (7) (1994) 4819–4833.
- [7] A. Laakso, M. O. Hakala, A. Pelli, K. Ryttsölä, K. Saarinen, P. Hautojärvi, *Mat. Sci. Forum* 445-446 (2004) 489–491.
- [8] Y. Suetsugu, M. Tsuchiya, T. Nishidono, N. Kato, N. Satoh, S. Endo, T. Yokoyama, *J. Vac. Sci. Technol. A* 21 (1) (2003) 186 – 195.
- [9] P. Sperr, G. Kögel, *Mat. Sci. Forum* 255-257 (1997) 109–113.