Design optimization of a pulsed positron beam system at IGCAR, Kalpakkam

C Varghese Anto, R Rajaraman, S Abhaya, J Parimala and G Amarendra
Materials Physics Division, Indira Gandhi Centre for Atomic Research, Kalpakkam-603102
E-mail: amar@igcar.gov.in

Abstract. A pulsed positron lifetime system has been designed using RF pulsing scheme. The mechanical design of the ultra high vacuum (UHV) beam line has been made to incorporate the basic requirements of a magnetically guided slow positron beam as well as that of an RF pulsing system consisting of a reflection type grid based chopper, a double gap pre-buncher and a main buncher. The trajectory and the timing characteristics of positrons have been simulated using SIMION code. The amplitude of the chopper and buncher RF voltages has been optimized based on these simulations.

1. Introduction
Positron annihilation spectroscopy is an unique tool for the investigation of various atomistic imperfections especially open volume defects in materials [1]. Among the different positron based techniques, positron lifetime spectroscopy is more powerful in the identification and quantification of vacancy-defects. The inability of combining positron lifetime spectroscopy with the slow positron beam technology has been overcome in the past two decades using various ideas. One method involves the detection of secondary electrons produced upon the implantation of positrons on the surface for the generation of the start signal [2]. Another way is to use an RF pulsing system to generate the start pulse ([3]-[8]) or apply a longitudinal harmonic potential on the beam [9]. Another innovative method is to trap positrons in a field and use a trigger to release the trapped positrons. In this case, the trigger itself can serve the required start signal [10]. When compared to the conventional slow positron beam, pulsed positron beam has the advantage that it enables the study of surfaces, interfaces and thin solid films in a more quantitative way.

Beam based lifetime spectroscopy has been achieved at various labs across the world using the basic techniques listed above ([2]-[10]). Among these, the RF pulsing based system has the best possible time resolution. Any RF pulsing based system consists of two basic elements namely the chopper and the buncher. The principles of these two are borrowed from their use in various ion beam accelerators. The difference between various RF pulsed positron beams already constructed or under construction is in the arrangement, the number and the parameters of these two basic elements. Successful systems consist of one chopper and two bunchers. The way they are arranged are different for example, in one case a chopper is put first followed by two bunchers [4] whereas, in other a pre-buncher is put first followed by a chopper and a second buncher [6].
Two parameters are important here: (a) the frequencies at which these pulsing systems work and (b) the RF voltages.

We report here the design of a UHV based pulsed positron beam and the optimization of the RF pulsing parameters of the model system. A system consisting of a grid based chopper and two double gap bunchers, which work at harmonically related frequencies, are utilized here. SIMION code [11] has been utilized to get the trajectory and timing properties of the positrons passing through the model system. The initial results of these simulations are presented in this paper.

2. Design of the UHV system
A pulsed positron beam is basically a combination of a slow positron beam and the RF pulsing system. Therefore the design of a UHV system should cater to the requirements of a slow positron beam as well as that of pulsing system. In the present design we have a source mounting arrangement which is followed by a moderator assembly. A 50 mCi Na$^{22}$ source will be utilized here. The moderator is put on a motion manipulator for moving it to a separate vacuum annealing chamber. We envisage to use a W(100) foil as moderator in transmission geometry. The slow and fast positrons exiting the moderator are separated using a 90° magnetic bend based velocity selector. Beyond this point, we have a housing tube for the RF pulsing system and finally the sample chamber. The above arrangement will be connected to pumping stations, which provides vacuum in the range of $10^{-10}$ mbar. Two ion pumps with Ti sublimation filaments and a turbo pump are planned towards this. Keeping these basic requirements in picture, a mechanical design was arrived at based on standard vacuum fittings. A schematic view of the system under construction is shown in Fig. 1.

The transport of the positrons from the source through the moderator, velocity selector, RF pulsing system and finally to the sample is achieved with the help of a field of 0.01 T. To achieve this field a combination of solenoid and Helmholtz coils are used. Solenoid coil is used in the vertical portion where source and moderator are mounted. Helmholtz coils are used in the horizontal region of the beam to achieve uniform field through the mechanical centre of the beam line without much geometrical hindrance.

The chopper, pre-buncher and the main buncher are housed inside the long horizontal tube in the middle of the beam line. We also have a drift tube and graded accelerator arrangement beyond the main buncher. The sample chamber houses the faraday cage along with the sample. BaF$_2$ scintillator based photomultiplier tube will be put in one of the ports of the sample chamber for the detection of annihilation 511 keV $\gamma$ rays.

3. Optimization of RF pulsing parameters
Based on the mechanical design of the UHV beam line, a model of the RF pulsing system has been made using the software package SIMION [11]. SIMION is a finite difference based approach which calculates the 2D/3D electrostatic and scalar magnetic fields solving Laplace equations and then the trajectories of charged particles through it by constant step integration using a highly modified 4th order Runge-Kutta method. SIMION also follows a work-bench protocol where the physical entities making up the system could be placed on a gridded work bench. The electric potential as well as the magnetic field to the various electrodes could then be given and trajectory of the particle can be simulated. We have utilized the user programming capabilities of SIMION using LUA [12] to set static (dc) as well as quasi static (RF) potentials for the electrodes. The magnetic field was set as 0.01T throughout the beam line. The W(100) moderator is biased at 10 V and hence the monoenergetic positrons which pass through the bend have an energy of $\approx 13$ eV.

The first component of the RF pulsing system is a reflection type three grid chopper [4, 8]. The first grid is grounded whereas the third grid is for pre-acceleration. The second grid is given
Figure 1. A schematic view of the mechanical design of the UHV pulsed positron beam line. The source chamber is in the vertical portion of the beam line. The long horizontal tube with multiple ports houses the pulsing systems.

A square wave, whose primary purpose is to chop the continuous beam into bunches of positrons. In the present model system, this is achieved by biasing the chopper to a dc voltage of +15 V (to stop the 13 eV positrons) and a square wave of 50 MHz with an amplitude of -15 V. Hence, during 'on-cycle' we have transmittance, whereas during the 'off-cycle' we have reflection.

Following the chopper, we have two double gap bunchers i.e., a pre-buncher followed by a main buncher. The pre-buncher works at the same frequency as that of the chopper. The pre-buncher consists mainly of three tubes separated by a small bunching gap. The middle tube is given a sine wave with required amplitude with respect to the first two tubes. The positrons arrive at the first bunching gap in various time-positions of the negative going slope of the sine wave and hence, get differently velocity-modulated. The length of the middle tube is equal to \(\lambda/2\) so that bunching occurs at both gaps. The bunching amplitude is also adjusted so that there is a better time bunching. The purpose of the pre-buncher is also to improve the bunching efficiency as feeding from a lower frequency of 50 MHz of chopper to a buncher at higher frequency results in large loss with fewer positrons in the bunch. The positrons emanating from the pre-buncher are further bunched using the main-buncher, which has similar structure and working principle. The main buncher works at a higher frequency of 200 MHz. 

Following the main buncher, there is a drift tube which extends into the sample chamber and a Faraday cage to avoid back scattered positrons interfering with the timing signals generated [5]. The HV is applied to the sample through a graded accelerator consisting of six stages including the faraday cup. The potential is divided among the graded electrodes and the positrons are gradually accelerated from the pre-acceleration value of 250 V to the required HV, resulting in varying implantation depth. All the parameters were adjusted for a sample high voltage of 10 kV. This was done so as to have reasonable drift tube voltages when we moved from small accelerating voltages to the final HV. This also helps to have good time resolutions at the common operating voltages near 5-10 kV rather than at the surface.

The simulation using SIMION was carried out using \(1.5 \times 10^5\) positrons emanating from a source of diameter 6 mm. All the positrons are born at the same time and a time spread at the chopper is introduced by the energy spread in the beginning. For more realistic simulation a
time spread has to be introduced at the source position also which is currently under progress. The initial energy of positrons has a Gaussian distribution around the central value of 3 eV and has an fwhm of 0.6 eV. Energy was chosen as approximately equal to the work function of W (100) moderator [13]. The FWHM of the positron pulse (in time) at the target is the objective parameter to be minimized. The time of arrival is recorded at multiple planes of interest and at the target position.

For 10 kV acceleration, the drift tube voltage is set at the pre-acceleration voltage of 250 V. The peak voltage combination for the pre-buncher and the main buncher is arrived at by trial and error method. The primary method employed is to under-bunch the positrons at the target using the pre-buncher alone and to adjust the main buncher voltage to achieve the final bunching at the target. In this way, a peak voltage of 7 V is chosen for the pre-buncher where as a peak voltage of 3 V was found suitable for the main buncher.

The result of such a bunching process is shown in Fig.2 and Fig.3. At the chopper, the positrons having an energy between 12 and 14 eV alone are counted whereas at the main buncher all positrons are counted. As can be seen in Fig.2 (a), by the action of 50 MHz square wave at the chopper, we get a 10 ns positron pulse. This square pulse at chopper has been compressed to a pulse of less than 5 ns FWTM at the main buncher after one round of bunching by the pre-buncher, as seen in Fig.2 (b).

By the action of the main buncher, the 5 ns pulse is further compressed at the target as shown in Fig.3. The FWHM of this pulse is 32.4 ps and FWTM is ≤ 100 ps. The beam diameter at the target is 6.2 mm. So as to achieve this "pulsing", the energy of the positrons has been modulated at two bunchers. But this should not be very drastic so that the intended use of depth profiling is lost. In the present model, variation in energy at the target for 10 keV is from 9996 eV to 10030 eV. These numbers show that the above model system with the given RF voltages will able to achieve bunching of positrons at the target with minimum energy spread. These simulations were also repeated for different sample HV and appropriate drift tube voltages. The computed FWHM of the positron pulse at the target for all high voltages is below 70 ps.

Figure 2. Counts vs Time of arrival for positrons at (a) the chopper and at (b) the main buncher. Positrons having energy between 12 and 14 eV alone are counted at the chopper whereas all positrons are counted at the main buncher.
Figure 3. Counts vs Time of arrival for bunched positrons at the target for a target HV of 10 kV. Inset shows the peak region of the pulse.

4. Conclusion
The design of a pulsed positron beam system is described in terms of 90° velocity selector and RF based chopper, pre-buncher and main buncher. Beam parameters are optimized using SIMION simulations. The results show that the present model system is capable of generating positron pulses with FWHM less than 70 ps for all sample high voltages. Based on these results, the parameters for the RF modules were fixed. Currently, the UHV beam line is under construction.

Acknowledgments
One of the authors (C Varghese Anto) wishes to thank Department of Atomic Energy, India for the fellowship. Authors would like to thank Dr. C. S. Sundar and Mr. M. C. Valsakumar for their special interest and encouragement for the project.

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