Chapter 5

Beam extraction, diagnostics and testing

This chapter discusses the activation of the positron beam by placing $^{22}$Na source and W (100) moderator into the assembly. The velocity selection of slow positrons is implemented using a combination of aperture and magnetic bend. The slow positrons have been successfully extracted and transported to the target chamber without the pulsing electrodes. The transported positrons are used to carry out demonstrative S-parameter measurements on Cu and Silicon (100) and thus the depth selectivity is demonstrated. The internal wiring of the pulsing electrodes is completed and they have been inserted into the beam line for vacuum testing, beam steering and finally for pulsing.
5.1 Introduction

The primary components for the assembly of the pulsed positron beam have been designed, procured or fabricated. The integration of these parts and their testing in two steps will be discussed in this chapter. The first step involves the extraction of the slow positrons through the magnetic bend up to the target without the pulsing electrodes inside and the demonstration of its use as a conventional slow positron beam. The second step involves the insertion of the pulsing electrodes and steering the slow positrons through the pulsing electrodes. After these objectives have been achieved the pulsing electrodes would be fired up according to the design described in the previous chapter and the final testing of the pulsed positron beam will be done. At the time of this thesis, the first stage has been completed and the required cable connections to the pulsing electrodes inside the UHV are done. The vacuum testing and beam steering through the electrodes is going through presently. Hence these will be presented here and the future work involved will be highlighted.

5.2 Moderator Annealing

Tungsten (W) single crystal in (100) orientation is used as the moderator in the transmission geometry. The thickness of the crystal is ~1µm. For handling and mounting the moderator easily, the foil is sandwiched between two Tantalum (Ta) sheets (99.999% polycrystalline sheets) of 100 µm thickness. These Ta sheets have a central hole of 8 mm, which helps in exposing the W to the source side and towards the extraction optics. After placing the W (100) crystals between Ta sheets, they are spot welded at four corners.

The moderation efficiency of the W(100) depends on the defect content and the surface condition. The W (100) mount in Ta sheets may have some positron-trapping
open volume defects created during handling and processing. The surface may also have a thin layer of native oxide as well as adsorbed contaminants like carbon which increases the surface trapping of positrons and thus decreases the moderation efficiency. These can be removed by controlled high temperature annealing of the moderator set-up in a vacuum of the order of $10^{-6}$ mbar. A high vacuum, diffusion pump operated physical vapour deposition (PVD) unit has been earmarked for the moderator annealing. A 99.999% pure W polycrystalline sheet cut in the required dimension acts as the boat of the PVD set up. The W (100) crystal inside Ta sheets is annealed after placing them on the customized boat. Before the start of the annealing process the chamber as well as the copper electrodes is cleaned to remove all possible contaminants using organic solvents. First the W-boat is fixed between the copper electrodes, and a vacuum of $2 \times 10^{-6}$ mbar is obtained. Then the secondary current through the boat is gradually increased at the rate 0.5A/s. Temperature is measured using the disappearing filament optical pyrometer. Temperatures were measured at 1373 K, 1873 K and 2273 K, to calibrate the secondary current and the temperature. Proper cooling to the glass chamber and to the nearby neoprene o-rings are provided using fans. The annealing is not carried out in a single step, but given in pulses to avoid excessive bending of the W boat, increase in chamber and o-ring temperatures and to avoid large increase in pressure inside the chamber. A two minute pulse at 2273 K is followed by 2-5 minute pulse at 1373 K. The vacuum degrades to $5\times10^{-6}$ mbar during the higher temperature pulse. The time kept for low temperature pulse is adjusted to get back the starting vacuum of $2-3 \times10^{-6}$ mbar and to avoid excessive heating near the o-ring. Ten such high pulses are applied after which the secondary-current is brought down at 0.5A/s. After proper cooling of the W-boat the vacuum is released and the W (100) crystal inside the Ta sheets is placed on the boat. The procedure is repeated as shown in Fig. 1(a) and (b) where we could see the low
pulse and the high pulse regime. After annealing and proper cooling, the vacuum is released at the time of mounting the moderator on to the beam line. The process need not be hurried through, as good moderation efficiency was obtained even after a one hour exposure in air. The efficacy of the above process was tested by mounting a similarly annealed moderator on the slow positron beam facility in the lab where a tenfold increase in counts was observed after annealing.

![Image](image-url)

Fig. 1: (a) Moderator annealing during the low temperature pulse (~1373K). Cu electrodes, W boat, Ta back foil and W (100) are marked. (b) Flash during the high temperature pulse (~2273K).

### 5.3 Source Mounting and Radiation Shielding

A 50 mCi source of $^{22}\text{Na}$ is envisaged to be used in the positron beam line. The source comes inside a Titanium capsule sealed on the front with a Titanium window [1]. A $^{22}\text{Na}$ source of activity greater than 10 mCi is considered to be posing an A-level hazard as given by the radio nuclide safety data sheet. Hence, a lead shielding is required to reduce the exposure rate to less than 2mR/hr at a distance of 1 foot from the source [2]. Hence, a lead shielding is built around the source chamber with enough thickness such that the standards are met. The half value layer for the 1280 keV $\gamma$ field of the source is 0.67 cm of lead and a reduction in intensity by a factor of 1000 is obtained for 13 cm of
lead. Thus an interpenetrated lead stacking of 15 cm is built around the source. The lead shielding starts at ~ 17 cm from the source position (5 cm – CF 35 flange radius & 12 cm for tightening the bolts). The calculated dose rate using the RadPro [3] calculator at 30 cm for a 50 mCi source with 15 cm lead shielding is 0.08 mR/hr or 0.7 µSv/hr. For a 3.5 mCi source this is 0.05 µSv/hr. Shielding is also provided at the bend where there will be 511 keV γ field due to fast positron collision with the tube. Apart from this, additional shielding is provided near the straight section to reduce the background for the gamma detector. Thickness of the shielding was higher very near to the source position and at the aperture which is in between the CF 63 I tube and magnetic bend and was 20 cm. A table to hold approximately 3 ton of lead was made for the Pb stacking.

Majority of the shielding was completed before source mounting and only a window was left open for the source mounting such that after the source was inserted, rest of the lead stacking could be completed from the shielded side with minimum exposure time. Enough space is put between the lead shield and the UHV system just to tighten the nuts using custom wrench. The bolts are welded on to the CF 35 flange so that minimum handling is involved while tightening the nuts. Teflon gasket is used at this flange so that better sealing is obtained with minimum effort. Since the intensity of the gamma field reduces according to the square law, remote handling is preferred. Hence, while mounting the source, a 1m long custom tweezers were used for screwing the source on to the source-moderator mounting arrangement. The Teflon cylinder holding the moderator is pressed on to the source after this. Manual handling is only required at the step where the CF 35 zero length adaptor with source-moderator assembly and all biasing wires are inserted into the UHV tube and nuts are hand tightened. Further tightening is done with custom wrench. For testing the slow positron beam and transport of positrons through the magnetic field a 3.5 mCi source is inserted in the beam line. The
measured dose rate on the lead shield which is approximately 30 cm away from the source was < 0.1 µSv/hr which matches with the calculations above. Fig. 2 shows the lead shielding provided at the source side, near bend and at the start of the straight section.

![Lead shielding provided at the source side, near bend and at the start of the straight section.](image)

**Fig. 2**: Lead shielding provided near the source side, at the bend and near the straight section.

### 5.4 Slow positron extraction and measurements

The system after full assembly is as shown in Fig. 3. The extraction of the slow positron beam was done in two stages. First extraction was at the end of the magnetic bend and the second one at the target. The beam was deviated from its path, and was forced to hit the wall of the UHV tube by keeping a 300 Gauss horse shoe magnet at one
side of the CF 63 magnetic bend perpendicular to the beam path. Annihilation 511 keV $\gamma$ was detected by NaI (Tl) based detector which was kept at the opposite side. Once the beam was obtained at the straight section, the slow positron beam was transported to the target chamber by activating the Helmholtz coils. The Doppler broadening S-parameter measurements were carried out at three representative points on two standard samples to confirm the depth selectivity. The low activity of the source was responsible for the measurements being done only at three points.

Fig. 3: Positron beam line assembly without the pulsing electrodes inside. The set up was tested for its ability to extract and transport slow positrons from the source to the target.

5.4.1 Magnetic Shielding

One of the major problems of using a photo multiplier based scintillation detector in a magnetic field is its effect on the accelerating electrons inside the photo multiplier tube resulting in a reduction in the amplitude of the output pulse. This is seen as a shift in the peak towards lower channels as well as a reduction in intensity as shown in Fig. 4.
where the detector is placed anti-parallel to the field and the field intensity at the detector is \( \sim 20 \) Gauss. Hence appropriate magnetic-shielding from the field is required to have faithful reproduction of the gamma signal. High permeability Mu-metal sheets with high saturation field were wound around the detector. A reduction in magnetic field intensity is seen inside the handmade shield. However the field was still high enough to affect the output. It was observed that when the detector was kept perpendicular to the guiding field near the solenoid winding at the magnetic bend, the attenuation in the amplitude was less and the provided shield was enough to have negligible amplitude reduction. This is because, the magnetic shield works best when the shield is perpendicular to the field and the transverse field has less effect on the photo multiplier tube. When the beam was transported to the target chamber where it was necessary to put the detector along the axial field, high purity germanium (HpGe) detector was used instead of scintillation detectors as the initial tests were to reproduce S-parameter curves. The HpGe detector showed negligible effect with axial magnetic field. However similar shield was put around the detector as well. For future use the strategy used in the NCSU pulsed beam [4] will be followed with solenoid winding on the shielded detector to nullify the magnetic field at the PMT.

5.4.2 Magnetic Field for slow positron extraction

The schematic of the geometry used till the magnetic bend is as shown in Fig. 5. As described in Chapter 4, an aperture of 16 mm diameter is put at 26 cm from the source between the CF 63 I tube and the magnetic bend. This helps in avoiding the fast positrons from entering the magnetic velocity selector as well as ensuring that the beam is centred. Two coils attached to the flanges correct for the dip in the field due to the absence of solenoid winding right on top of the flange. Hence the parameters to be
adjusted to extract positrons were the magnetic field up to the bend and drift correction coils on the bend. A positive bias is given to the moderator with respect to the extracting electrode. Hence the positron which is emitted with work function energy of 3 eV gets repelled by the moderator and hence acquires an additional energy equal to the repulsive potential. Thus a positive bias of 75V leads to an overall energy of 78 eV for the positron.

Majority of the fast positrons do not undergo moderation and just pass through it. The separation between these fast positrons and slow moderated one’s are achieved using the magnetic bend. Fast positrons escaping the moderator along the magnetic axis pass straight through the aperture and hit the upper wall of the bend due to the large Larmor radius of its helical path. Whereas the fast positrons which are emitted at an angle with field follows the magnetic field in a helical path and depending on the value

Fig. 4: Effect of magnetic field on the output of the NaI (Tl) + PMT based scintillation detector. A reduction in intensity as well as shift to lower voltages is seen for field as low as 20 Gauss
of the field intensity, velocity and emission angle it could be filtered out at the aperture. Hence, the first parameter which needs optimization is the axial field. A uniform field of 90 Gauss was initially maintained in the region denoted in schematic in Fig. 5 and this is given in Fig. 6(a) where the source, aperture and magnetic bend positions are marked. The variation in the counts (under the region of interest -511 peak) as a function of the moderator bias voltage for this field arrangement is shown in Fig. 6(b). An increase in counts is seen with the bias voltage, however the background i.e. counts at zero moderator bias is high and a clear 511 keV peak could be seen even at an opposite bias i.e. the extraction electrode at a small positive bias with respect to the moderator, making it difficult to identify the origin of the 511 keV from slow positrons alone. This shows that some of the fast positrons are able to cross the aperture and get transported across the bend due to its shallowness as well as due to the high field intensity. Hence it was decided to reduce the field very near the source side such that the radius of the helical path of high velocity positrons is such that it would not cross the aperture. Thus the
aperture acts as a first level screening for slow positrons and the bend acts like a second
velocity selection. The variation in zero bias counts with different source side magnetic
field values are shown in Fig. 6(c). From this it was decided to have ~ 20 Gauss near the
source side with counts just above the background. The variation in counts with bias
voltage is shown for ~ 20 Gauss in source side and ~ 90 Gauss at the magnetic bend is by
red circles in Fig. 6 (b). From this it was seen that at a bias of +75 V i.e. at 78 eV
maximum number of positron are transported till the straight section of the bend to be
detected by the detector. Keeping a +75 V bias on the moderator, the output of the
detector is shown in solid green line, whereas with a +75 V bias on the extraction
electrode, the output of the detector is shown in dashed red lines in Fig. 7. This shows
clearly the extraction and separation of slow positrons across the bend. The extracted
slow positrons are transported till the target chamber by activating the Helmholtz coils
and detecting 511 keV counts using the NaI (Tl) based detector kept perpendicular to the
beam path and using horse shoe magnet as before on the walls of the UHV tube. The net
field from the magnetic bend to the target chamber is shown in Fig. 8.

As the bend was shallow and since the aperture made sure of the beam centring,
drift correction or steering was not required for the extracted beam. However both drift
and steering coils need to be activated when the beam is steered through the pulsing
tubes of 15 mm internal diameter and when the target position is centred with respect to
this pulsing arrangement with 15 mm exposure area. For Doppler broadening
measurements 25 mm diameter sample mounting was used. For S-parameter
measurements an HpGe detector having an energy resolution of 1.45 keV at $^{137}$Cs 662
kev γ line with a shaping time of 6 µs is placed inside the detector well.
Fig. 6: (a) Transport magnetic field from source up to the magnetic bend. Black solid line indicates 90 gauss from the source side to the magnetic bend whereas red dashed line indicates 20 Gauss near the source side and 90 Gauss at the magnetic bend. (b) Variation of counts with different moderator bias with two source side field values – one at 90 Gauss (solid lines) and another at 20 Gauss (dashed lines). (c) Keeping the bend at 90 Gauss, the zero bias counts are noted for different source side field.
Fig. 7: Beam count at the bend with different moderator bias. Beam on (green) when moderator is at +75 V and beam off (red) when the extraction electrode is at +75 V. This is achieved after fixing the axial field at 20 Gauss – 90 Gauss combination.

Fig. 8: Magnetic field intensity from the bend region to the target chamber. The target position and solenoid to Helmholtz field transition region are shown using arrow marks.
5.4.3 Doppler Broadening Measurements

The extraction of the slow positrons up to the target position was further confirmed by carrying out Doppler broadening S-parameter measurements on Copper plate used as a temporary sample mounting arrangement as well as on Silicon (100) single crystal. For Doppler broadening measurements, the moderator was biased to +250 V and hence the mean energy of the positrons reaching the target chamber will be 253 eV. Measurements were carried out at three representative target high voltages. The measurement was limited to three points due to low count rate with 3mCi source. The results are shown in Fig. 9 where an increasing trend is seen for Silicon and a decreasing trend is seen for the Copper plate. This is consistent with the reported S-parameter trends for Cu and Si.

![Graph showing S-parameter versus accelerating voltage for Copper and Si (100) crystal.](image)

Fig. 9: S-parameter versus accelerating voltage for Copper and Si (100) crystal.
5.5 Electrical connections in the vacuum side

The electrical connection to the pulsing electrodes which has to be inserted into the beam line is completed at the time of thesis. The RF power is coupled to the chopper ring by connecting the 50 Ω matched RG-58U high voltage, UHV compatible Kapton insulated cable (M/S Kurt J Lesker) to the ring using a through hole provided for electrical connection. The outer braid of the cable is connected to the front ring with respect to which the 50 MHz square wave and +15V DC bias is given. The other end of the cable is connected to the instrumentation feed through with grounded SMA type connectors. The central copper conductor of a similar cable is used to power the buncher electrodes; the outer braid providing insulation from cross talk or signal pick up as it goes to the beam ground. The electrodes which serve as ground for the RF power, is also DC offset to -250 V. These three tubes which are at -250 V are short using the RG58 U cable through the central conductor. Here again the outer braids are given to the ground preventing them from picking up any RF signals. A common output is taken from one of the three electrodes and taken to a CF 16 feed through. The connection to the feedthrough is through push fit connectors. The bias to the last drift tube is taken from a similar CF 16 electrical feedthrough. The cabling wires are again with protective ground outer braids. The graded accelerators are planned to be connected with 100 MΩ epoxy coated high voltage resistors with voltage tolerance of > 3.5 kV. However in the phase one testing of pulsing electrode the graded accelerators is biased to the final drift tube voltage. Fig. 10 (a-c) shows the connections given to each of the units described. After connection the part till the drift tube is inserted into the 120 cm long tube and is connected to the beam line. The graded accelerators are later connected through the CF 150 port of the target chamber. At the time of submission of thesis, vacuum testing and steering of positrons through the electrodes has been taken up.
Fig. 10: (a) Chopper and pre-buncher connected to the grounded feedthorugh using RG58 U cable’s central conductor. (b) Drift tube and 250 V bias is through braided wires which minimizes RF signal pickup. (c) Graded accelerator and drift short for the first phase of testing. The HV connection is given to the Faraday cage.

5.6 Summary

The UHV beam line to hold the pulsing system has been fabricated and assembled. The Na-22 source of activity 3.5 mCi has been mounted and lead shielding has been arranged for safe working environment around the beam line.

Annealed W (100) moderator was placed in front of the source for the production of slow positrons with proper extraction bias.
The slow positrons were extracted across the magnetic bend by optimizing the axial field at the source and the bend region.

The extracted positrons were transported up to the target chamber by activating the Helmholtz coils.

The depth selectivity was confirmed by carrying out Doppler broadening $S$-parameter measurements on Cu and Si (100) samples.

Electrical connections inside the UHV chamber are made taking care of signal pick up by stray Cu wires.

5.7 Future Steps

The capacitance values of the chopper and bunching electrodes at 50 MHz and 200 MHz has to be measured at the atmosphere side of the feedthrougths in the operating vacuum condition. This helps in determining the values of other components in the coupling network.

The slow positron beam has to be steered through the pulsing electrodes up to the target chamber by adjusting the drift correction as well as the steering coils near the target chamber.

The RF power and DC bias will be given to all the electrodes after the completion of above steps. The impedances are to be matched for maximum power transfer. The entire system is integrated along with the timing circuit consisting of two CFDD, Fast coincidence system and an MCA for lifetime measurements. The faithful generation of stop signal using square wave input to the CFDD has to be tested before the integration. The timing circuit integration also involves putting proper delay cables for getting TAC output.
A beam automation system has to be designed to have a complete control of the beam system. Hardware control to switch off the high voltage acceleration system as well as the RF power circuitry in case of vacuum failure has to be incorporated. Initial design of Labview control has been done where setting the HV is achieved using a programmable system on chip (PSoC) and MCA control is achieved.

A data analysis routine in line of VEPFIT [5] has to be designed for getting depth resolved lifetime components.

References