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The design of an electrostatic variable energy positron beam for studies of defects in ceramic coatings and polymer films

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Abstract

An electrostatic variable energy positron beam for studying defects in ceramic coatings, polymer films and MOS-devices is developed for operation in Doppler-broadening (DB) and positron annihilation lifetime (PAL) modes. In DB mode the implantation energy can be varied between 3 and 30 keV with a beam diameter on the target ranging from 0.4 to 0.5 mm FWHM. In PAL mode the start-signal is given by secondary electron emission from a 25 nm thin carbon foil placed in front of the target. After passing the foil the positron beam is focused on the target with a spot size of 2 mm FWHM at 1 keV down to 0.6 mm FWHM at 30 keV. The target chamber is equipped with an in situ four-point bending device for studying defects introduced by tensile and compressive stresses. © 2002 Published by Elsevier Science B.V.

Keywords: Electrostatic positron beam; Doppler-broadening; Positron lifetime

1. Introduction

The positron annihilation Doppler-broadening (DB) and positron annihilation lifetime (PAL) techniques are known as sensitive methods for the characterization of defects in a wide variety of solids. Combined with a beam of variable energy positrons they offer the possibility to characterize not only the bulk, but also to study the properties of surfaces, interface regions and thin films. An overview of the facilities and techniques employed is given by, e.g. Coleman [1] and Schultz and Lynn [2]. In order to study ceramic and polymer coatings, and MOS-devices we designed a variable energy positron beam facility, which operates in both DB and PAL modes. Both techniques can be performed subsequently using the same beam-line. The position of the target remains fixed and the optical system, based on a set of electrostatic lenses, can be tuned according to the respective experiment.

2. Description of the facility

2.1. Doppler-broadening mode

The optical design of the facility is shown in Fig. 1. Positrons from a ^{22}Na source are moderated in a 3.5 μm thick annealed polycrystalline tungsten foil. A modified Soa gun and Einzel-lens, and additional deflection plates for fine alignment, focus the beam at the entrance of a cylindrical mirror, which bends the beam over 90° [3]. In DB mode the beam is

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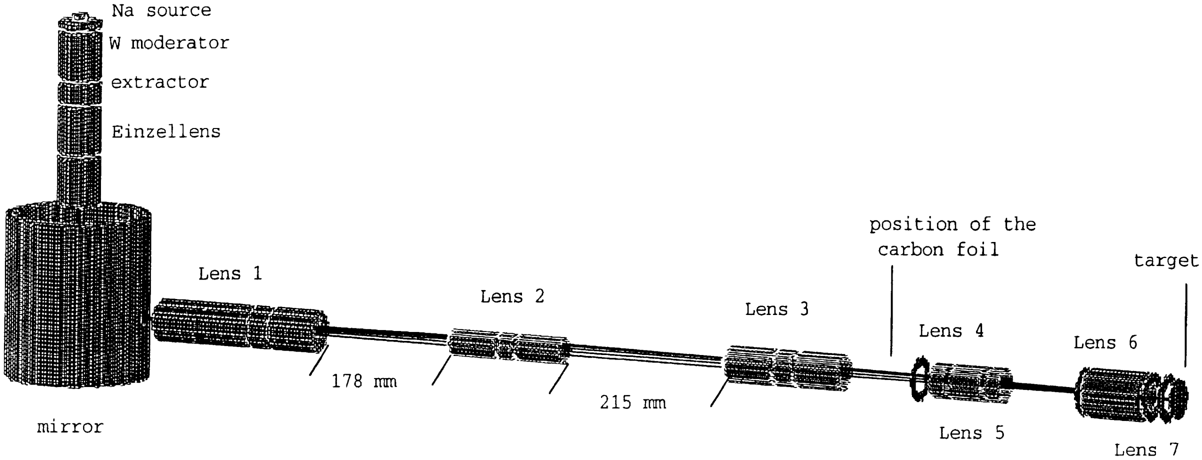

Fig. 1. Optical design of an electrostatic variable energy positron beam.

transported and focused on a target, which is kept at ground potential. The transportation and focusing are achieved by four symmetric Einzel-lenses (lenses 1, 2, 3 and 6). Lenses 4, 5 and 7 are at ground potential. The implantation energy is set by changing the potential difference between the source and the target and can be varied between 3 and 30 keV. Lenses 1 and 2 operate at a fixed voltage ratio. Their diameter (D) is 26 mm, the ratio $g/D = 0.15$, where g is the gap between the electrodes, and the ratio $A/D = 1$, where A is the sum of the middle electrode length plus the gap distance g. Lenses 3 and 6 have variable potential ratios. Their diameters are 38 and 44 mm, respectively. They have ratios of: $g/D = 0.1$, respectively 0.06 and $A/D = 0.73$, respectively 1.8. Behind the target, which is 35 mm away from the last lens, a Ge-detector is placed outside the vacuum chamber.

2.2. Positron lifetime mode

In order to perform positron lifetime measurements a 25 nm thin carbon foil can be introduced which intercepts the beam 60 mm behind the lens 3 (Fig. 1). The foil is mounted on a movable holder and is tilted over 45° with respect to the beam axis. The backwards emitted secondary electrons generated by the incident positrons are collected by a micro-channelplate (MCP) with anode assembly positioned normal to the foil surface, on the side where the positrons enter the foil. The output pulses of the MCP are fed into a time-to-amplitude converter (TAC) giving the start-signal of the lifetime measurement. The electrostatic lens system (lenses 4–7) focuses the transmitted beam on the target. There the annihilation γ are detected by a BaF scintillation detector providing the stop-signal of the TAC.

Monte Carlo simulations were performed for a set of selected energies of the incoming beam to calculate the fraction, energy and angular distributions of the transmitted positrons resulting from the inelastic and elastic positron scattering processes in the foil. The used methodology is described in [4]. Fig. 2 shows the calculated angular and energy distributions for positrons with an initial energy of 7 keV, at which the beam transmission profile is in optimum. At this energy 90% of the beam is transmitted within a solid angle of 15°. The average energy loss is calculated to be 3% of the initial value. These data determine the optical design, shown in Section 3.2.

In addition, the beam properties can be monitored by a channeltron at the position of the carbon foil or the target. The facility is equipped with a PC and software for automated settings and control of the lens potentials and data accumulation in both DB and PAL mode. A four-point bending device can be installed in the sample chamber for studying the defect generation and adhesion properties of polymer and ceramic coatings under compressive and tensile stress conditions.

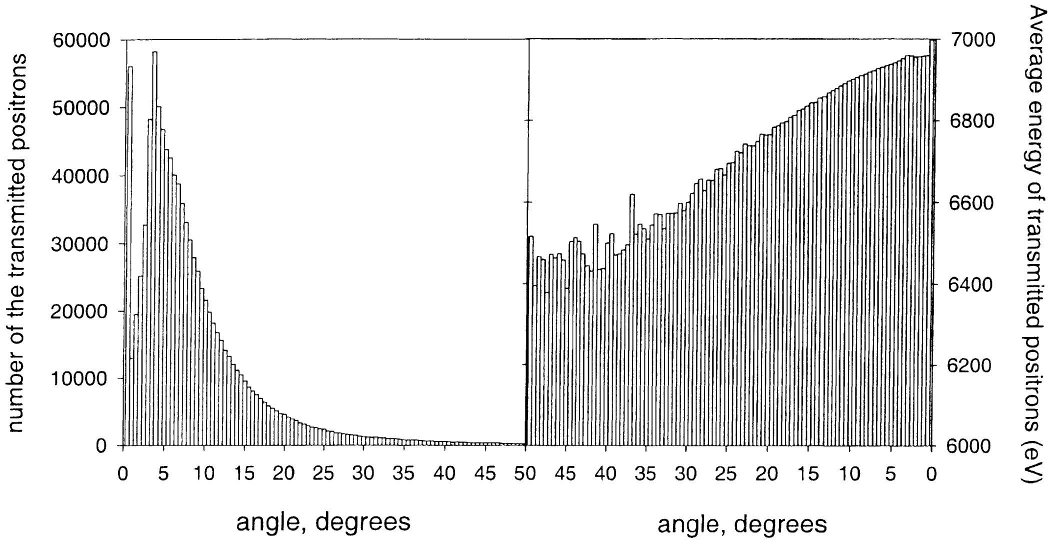

Fig. 2. Calculated angular and energy distributions for positrons with an initial energy of 7 keV transmitted through a 25 nm thin carbon foil.

3. Trajectory calculations

3.1. Doppler-broadening mode

The electric field distributions along the beam-line and ray-tracing are performed using the simulation program Simion 7 [5]. The emission angles of the moderated positrons from the tungsten foil surface are assumed to have a Gaussian distribution with an angular HWHM of 5° [2]. The work-function is −2.9 eV. The emitting area of the moderator foil has a radius of 3 mm. We have simulated the trajectories of positrons with 3 eV initial energy and assuming a uniform angular distribution within ±10°

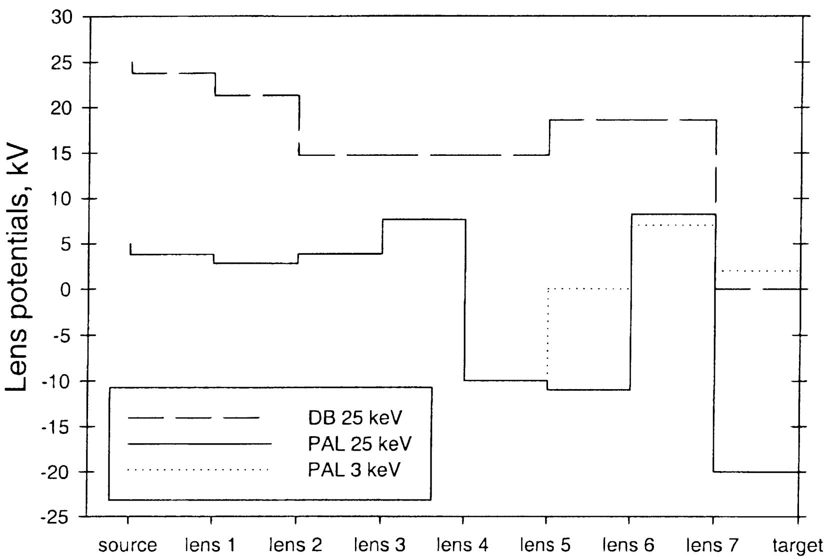

Fig. 3. Lens potential diagram in DB mode for 25 keV positrons and in PAL mode for 3 and 25 keV positrons, respectively.

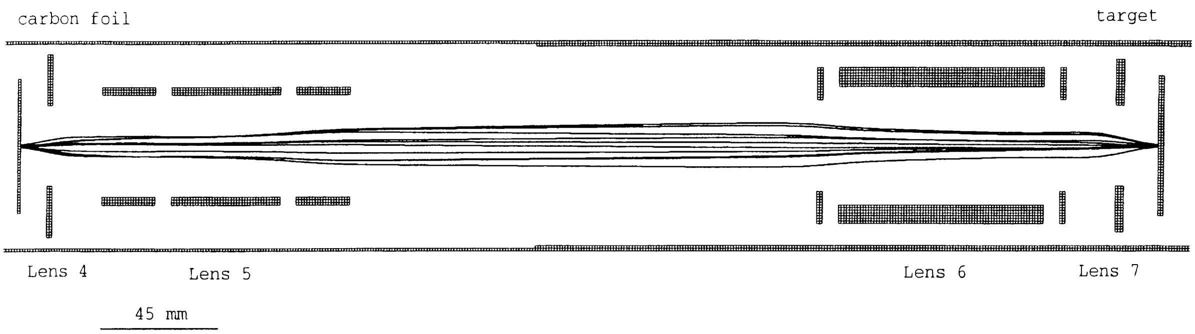

Fig. 4. Two-dimensional cut of the optical system between the carbon foil and the target.

emission angles, thereby taking into account the possible roughness of the moderator surface. Positrons are generated randomly from a uniform spatial distribution from surface with radius 3 mm. The lens potential diagram for achieving a beam of 25 keV positrons is presented in Fig. 3. The resulting beam diameter at the target is 0.4 mm FWHM. From 3 to 30 keV the beam diameter changes between 0.4 and 0.5 mm FWHM. In this energy range the longitudinal energy spread is calculated to be less than 0.1 keV.

3.2. Positron lifetime mode

In PAL mode the source is kept fixed at 5 keV. Lenses 1, 2 and 3 are set at 3.3, 2.8, and 3.8 kV, respectively. The positron beam is thus focused to a beam diameter less than 1 mm on the carbon foil, which is kept at −2 kV. A 2D cut of the optical system between the carbon foil and the target is shown in Fig. 4. Lenses 4 and 5 serve to minimize the beam divergence. Lenses 6 and 7 are used in combination to focus the beam onto the target. The final implantation energy can be varied between 1 and 30 keV by changing the potential on the target.

In the simulations the initial coordinates of the 8000 positrons are generated random from a spot of 1 mm diameter, angles and energies corresponding to the distributions shown in Fig. 2. The beam diameter at the target varies from 2 mm FWHM at 1 keV to 0.6 mm FWHM at 30 keV. For the energy range between 1 and 5 keV the optical system works in decelerating mode and from 5 to 30 keV in accelerating mode. Examples of derived optimum lens potentials for both cases are given in Fig. 3. The implantation energy spread coming from reduction of the longitudinal velocity is calculated to be 50 eV at 1 keV and 0.5 keV at 15 keV. This only causes small shifts in the lifetime depth-profiling data.

Examples of the time-of-flight distributions of the electrons (giving the start-signal) and the positrons for three implantation energies 1, 5, and 15 keV are shown in Fig. 5. From this data we estimate that the optical design contribution to the time resolution is, approximately 300 ps. The electronics contribution is in order of 250 ps.

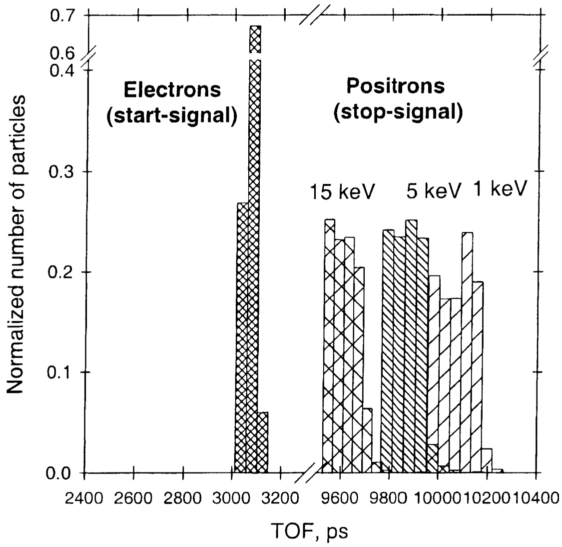

Fig. 5. Calculated time-of-flight distributions for electrons and positrons travelling from the carbon foil surface to the MCP and to the target, respectively.

4. Conclusion

An electrostatic variable energy positron beam is designed to operate in two modes. In DB mode the beam energy can be varied from 3 to 30 keV with an energy spread of less than 0.1 keV and beam diameter of 0.4–0.5 mm FWHM. In PAL mode the beam energy can be varied between 1 and 30 keV. The beam diameter varies from 2 to 0.6 mm FWHM. The positron implantation energy spread is less than 5%. The total time resolution of the facility is determined by the time-spread due to the optical design (300 ps) and the contribution of the electronics (250 ps).

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