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A Pulsed Positron Microbeam.

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Abstract. – The first pulsed microbeam for positrons in the keV energy range is described. The principle of operation and the construction details are given. The performance achieved is: 20 μm (FWHM) spot diameter; 350 ps (FWHM) time resolution; 5000 $e^+/(s\,mCi)$ at 5 keV final energy.

Introduction. – Positron beams are increasingly used as a tool for near-surface defect analysis [1-3]. The use of a monoenergetic beam allows depth profiling of defects through the use of Positron Annihilation Techniques. In most positron beams the Doppler broadening technique is being used [2, 4, 5], which has the advantage of being of simple implementation. The disadvantage lies in the inability of this technique to distinguish unambiguously between different defect types.

On the other hand, the lifetime technique is more defect-specific but requires a pulsed positron beam with a pulse duration of about 100 ps [6, 7]. Additional difficulties arise if a beam with a spot size in the micrometre range is required [8].

In the following a positron beam is described which simultaneously exhibits a spot size and a time resolution close to the best values, achieved until now only in separate systems.

The pulsed microbeam has been designed to be a part of a Scanning Positron Microscope [9, 10]. This goal has determined the design of the described system. Nevertheless, the present beam is a stand-alone apparatus of unique performance. The construction scheme and preliminary results will be described in this paper.

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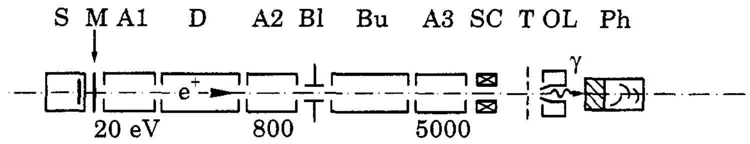

Fig. 1. – Schematic drawing of the pulsed positron microbream: S, ^{22}Na radioactive source; M, W (110) moderator; A1, first accelerator; D, drift tube; A2, second accelerator; Bl, blanker; Bu, buncher; A3, third accelerator; SC, scanning coils; T, target; OL, objective lens; Ph, scintillator and photomultiplier.

Apparatus: conceptual description. – Figure 1 shows the schematics of the pulsed microbeam. The source-moderator assembly coupled with a first accelerator produces a d.c. beam of 20 eV kinetic energy which is injected into the drift tube. A sawtooth signal with a repetition rate of 50 MHz is applied to the drift tube. This compresses the positrons in each 20 ns segment of the beam into bunches with a width of 2 ns (see fig. 2 for the timing diagram at various points). The drift tube compression is much more efficient than the conventional chopping of the beam [11] (about a 30% positron loss compared to a 90% loss, respectively). The transport through the drift tube has been achieved with an unusual axial-magnetic-field configuration (see [12]).

Positrons leaving the drift space are accelerated up to 800 eV and injected into a 100 MHz sine wave buncher. A beam blanker positioned before the entrance to the buncher suppresses the background of positrons outside the pre-bunched pulse. The main buncher compresses

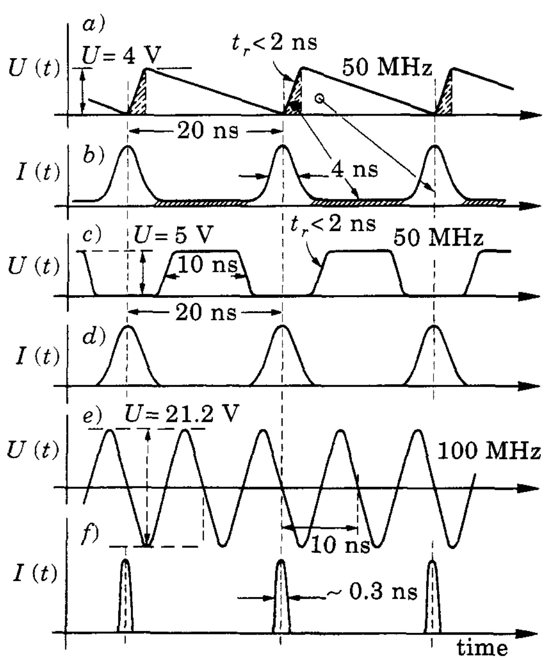

Fig. 2. – Timing scheme of the positron microbeam: *a*) the sawtooth voltage in the drift tube; *b*) the pre-bunched beam at the exit of the drift tube; *c*) a rectangular voltage to the blanker; *d*) the beam pulses at the entrance of the main buncher; *e*) 100 MHz sine wave to the buncher; *f*) the beam bunches at the target.

the 2 ns pulses down to the final 350 ps (FWHM) duration at the target position. A further electrostatic lens system accelerates positrons up to the final energy and defines the angular and radial dimensions of the beam. This lens system could be operated without further modifications at any energy between 2 keV and 10 keV. With minor modifications this range could be extended. The measurements shown in this paper were performed at 5 keV.

The positron beam is then directed onto a single-pole magnetic objective lens, which will later be used at the remoderator stage of the Scanning Positron Microscope [9, 13]. The purpose of this final lens is to demagnify the beam by a factor of 150, down to about 20 μm. One of the advantages of the single-pole configuration lies in the relatively large space in front of the lens where a sample can be positioned.

Apparatus: construction details.

The source-moderator assembly. The radioactive source used in the tests of timing was a 5 mCi, ^{22}Na source from Du Pont, with a nominal diameter of 1 mm (claimed by the company) placed at a distance of about 1 mm from the moderator foil, resulting in an effective source diameter of about 3 mm on the moderator. The activity was protected by a 5 μm titanium foil. The moderator was a 1 μm thick W (100) single crystal supplied by Dr. J. Chevallier (Åarhus University, Denmark). A facility for *in situ* heating of the moderator was constructed with a 50 W electron gun, additional pump and a valve separating the preparation chamber from the main vacuum system. The efficiency of the moderator was measured as the ratio of positrons reaching the drift tube, divided by the total number of positrons emitted in the radioactive decay. Typical values of $6 \cdot 10^{-4}$ can be achieved with great reproducibility.

The first lens system extracts the slow positrons from the moderator. In order to separate the slow-positron beam from fast unmoderated positrons and to achieve a better shielding of the source, the beam is bent by 45° using a toroidal coil [13]. Afterwards, the 3 mm diameter beam is injected with an energy of 20 eV into the drift tube.

The drift tube. A homogeneous axial magnetic guiding field is present along the entire drift space (length 37 cm). The operating magnetic field is about 0.5 mT. The guiding field acts like a thick lens and images the entrance of the drift tube onto the exit aperture [14]. The drift tube is constructed in two parts. The direction of the axial field is opposite in these two parts. This avoids image rotation and minimizes the transverse momentum introduced by the axial magnetic field (see [12]). Field terminators were placed at both ends of the drift tube to avoid magnetic-field leakage out of the drift space. A third terminator at the centre of the drift tube matches the two regions.

The *second electrostatic lens system* accelerates the beam to 800 eV maintaining a very low divergence of the trajectories. The time buncher has the same design already used in a previous machine [6]. The buncher is a resonant cavity with an active gap and has been designed as a thermally compensated unit. The measured quality factor of the cavity is about 450, the drift in the resonance frequency between 20 °C and 90 °C is less than $4 \cdot 10^{-4}$. The bunching gap is supplied with a 100 MHz sine wave of about 100 V amplitude.

After the buncher, *the third lens system* accelerates the beam to the final desired energy, focusing it in a 3 mm diameter spot at a distance of 520 mm from the exit of the last electrode. At this position the beam can either be used directly to perform positron lifetime measurements on a millimetre size samples or additionally focused into a 20 μm spot. This focus size was achieved with the single-pole magnetic lens of the remoderator stage of the Scanning Positron Microscope [13], with a focal length of 14 mm and spherical and chromatic aberration coefficients of 3 and 6 mm, respectively.

Results of tests.

Total intensity of the beam. The beam intensity has been evaluated in separate tests with a specially manufactured radioactive source of 1 mm diameter and a channeltron (Glasspol, Poland) as a detector. The 0.6 mCi ^{22}Na activity was deposited on a 1 mm diameter copper needle. A 5 μm titanium window was used to cover the source capsule. An effective distance of about 0.3 mm between the moderator and the radioactive spot was achieved. In this configuration a 3 mm diameter of moderated positrons corresponds to 30% of the total solid angle into which the β^+ radiation is emitted. The efficiency of the channeltron for positrons as a function of the energy was not determined. Rather the measurements by Seah [15] were used to assume a detection efficiency of 40% at 5000 eV positron energy. The detected counting rate was checked to scale with energy with the same law as the efficiency values measured in ref. [15].

With a freshly conditioned moderator up to 2000 counts/s at the channeltron were obtained. A very reproducible situation, lasting several weeks in a vacuum of 10^{-9} mbar, yielded 1400 counts/s. This corresponds to an overall yield of more than 5000 $e^+/(s\,mCi)$. Transforming this number into an efficiency, this quantity has to be defined as the product of the conventional moderator efficiency and the positron optics efficiency. This product turns out to be $6\cdot 10^{-4}$. It can be interpreted as produced by a high-efficiency tungsten film moderator ($\varepsilon \geqslant 6\cdot 10^{-4}$) and a nearly perfect collection and transmission of the slow positrons.

Spatial resolution. The spatial resolution achieved with the final single-pole lens has been measured using a gold grid (360 μm spacing, 30 μm bars). The grid was placed at the image plane of the single-pole lens. The beam was allowed to pass through the bore of the lens. Positrons not intercepted by the grid structure were annihilating close to the end of a 3″ × 3″ NaI(Tl) scintillator. The annihilation photons originating from the grid (50 mm from the scintillator) were mainly shielded by the metal structure of the lens. Furthermore, the solid angle for detection of these γ-rays was smaller. In this way, a decrease of the counting rate was obtained when the beam was intercepted by the grid bars.

Figure 3 shows the first image of the gold grid, obtained by scanning the beam with 300 × 300 pixels resolution under computer control. Also an example of a single-line scan is shown in the insert of fig. 3. As can be evaluated from this scan, the FWHM of the beam is

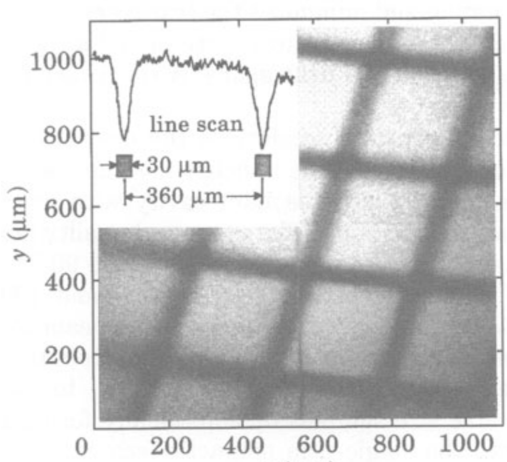

Fig. 3. – The 300 × 300 pixel positron-annihilation image of the gold mesh (30/360 μm).

less than 15 μm and the total spot diameter is less than 20 μm. The distortion of the image is to be attributed to an imperfect positioning of the beam scanning coils. No influence on the spatial resolution by the energy modulation applied for the bunching of the beam could be detected.

Time resolution. The time duration of the positron bunches has been evaluated for the beam stopped at the end cap of the vacuum vessel. A BaF_2 scintillator coupled with a fast Valvo XP 2020 Q photomultiplier was used for the γ-ray detection. The experimental set-up was similar to that described in [6]. The analysis of the measured positron lifetime spectra yielded a prompt curve which is a convolution of the pulse duration and the detector resolution function (about 200 ps FWHM). From this we evaluated a width of $\Delta t < 350$ ps for the duration of the positron pulses. It is very likely that the actual pulse duration is much smaller than this value because in the simple test configuration described above, annihilation events from scattered and re-emitted positrons will cause an additional time spread. Further work is in progress to reduce the pulse width well below 200 ps.

With minor modification of the third lens system, the present beam could be used at final energies varying from 0.5 to 10 keV. Without the final objective lens, the beam could be used for lifetime measurements on millimetre-size samples with a time resolution close to 250 ps. Adding a single-pole objective lens could allow the same measurements with a spot size less than 20 μm. In the final configuration, a ^{58}Co source of about 1 Ci will be used. This will give about $7.5 \cdot 10^5\ e^+/s$ in the beam.

If a positron remoderator is inserted, the phase-space density of the emitted positrons from this pulsed positron microsource will exceed the one from the first moderator by a factor of at least $2.5 \cdot 10^4$, assuming a remoderation efficiency of 20%. Up to now, the typical gain in phase-space density of a single remoderation stage [16] was about 20. Therefore in the scanning positron microscope our microbeam will replace three conventional remoderation stages by a single one, reducing the required strength of the primary source factor of 25. This progress is due to i) the perfect linear transport in the microbeam, ii) the outstanding optical properties of the single-pole lens and iii) the simultaneous application of time bunching, which contributes with a factor of more than 50 to the total gain in the phase-space density.

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