Positron Facilities in Europe

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Positron Facilities in Europe

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Abstract: Positron annihilation is a well established method in solid state physics and material science. The positron being a very sensitive probe, can give very precise information on the momentum distribution of electrons in metals and alloys as well as on lattice defects in crystals. Starting with the energy distribution of positrons from a radioactive decay, the current development is directed more to monoenergetic positrons of variable energy and of high intensity. Pulsed and continuous beams of moderated positrons have been designed and developed to study very efficiently surface and near surface regions in metals and semiconductors. Especially a pulsed positron beam with narrow beam pulses (~ 150 ps) enables positron lifetime experiments as a function of the positron energy. The impact of intense positron beams is straightforward: a decrease of the counting time. There are various possibilities and approaches to realize intense positron beams. Developments at several institutes in Europe are under way. The aim is to obtain a beam intensity in the order of $\sim 10^{10}$ positrons/sec. Parallel to the installment of intense positron beams, the development of positron microscopes is pursued. Two types of positron microscopes are being set up: a scanning positron microscope with a pulsed beam of 100 ps and a beam diameter of 1 μm and a positron reemission microscope with about the same beam diameter.

1. Introduction

Experiments in physics involving the interaction of matter with antimatter are fascinating. Positron annihilation has advanced to a standard method for studies of microscopic properties in condensed matter [1]. The field of low energy positron physics has expanded significantly in recent years. This includes not only particle and atomic physics but most extensively the areas associated with condensed matter and material science. The interaction of a positron with solids shows a wide variety [2]. The use of positrons as very sensitive probes in solid state physics can be roughly divided into various categories: as electronic structure probes, as lattice defect probes, as surface and interface probes and as microbeam probes. The advances in positron annihilation methodology from the use of a broad inhomogeneous beam of high–energy positrons from radioactive nuclei to a narrow homogeneous beam of monoenergetic positrons of variable energy, expanded the object of studies from only bulk properties to surfaces and depth specified near surface layers and interfaces, and even further to three–dimensionally specified microscopic regions. In the following sections I will primarily discuss these very recent and current developments involving positron beams as well as intense positron sources. Thereby I will concentrate on the activities in Europe.

2. Positron Beams

2.1 Continuous Positron Beams

The application of low–energy positron beams to study metals and semiconductors has increased significantly. This can primarily be attributed to the development of more efficient moderators, i.e. the conversion of fast positrons to slow positrons. Such a "conventional" positron beam system has basically the following structure: a radioactive isotope as primary positron source, a "moderator" acting as secondary source of low–energy positrons, a suitable device to separate the high–energy positrons of the primary source from the low–energy positrons of the moderator, an electric or magnetic guiding field and a detector for the positrons or for the annihilation photons from the target. The desired energy of the positrons reaching the target can be varied by applying the appropriate voltage between moderator and target. In most systems the target is at ground potential so that the temperature of the specimen can be varied without great problems. The most suitable detector in such a system is a Ge–diode in order to determine the Doppler broadening of the annihilation photon as a function of positron energy [3]. In atomic physics applications particle detectors are being used.

2.2 High Intensity Positron Beams

2.2.1 LINAC Based Beams

The first intense positron sources were based on the pair production from Bremsstrahlung resulting from an electron linear accelerator (LINAC) [4]. It has been established that one electron in the energy range of 50–120 MeV can produce 10^{-7} – 10^{-6} positrons. The operation mode of most LINACs is a pulsed one with a repetition rate dependent on the particular accelerator used (~ 50 – 1000 Hz).
Therefore the produced positrons possess also a pulsed structure, but for many experiments a continuous beam would be preferable. At the university of Gent, Belgium, a Penning trap is used to create a quasi–continuous beam from the 300 Hz pulses with a pulse length of 3 μs (Fig. 1).

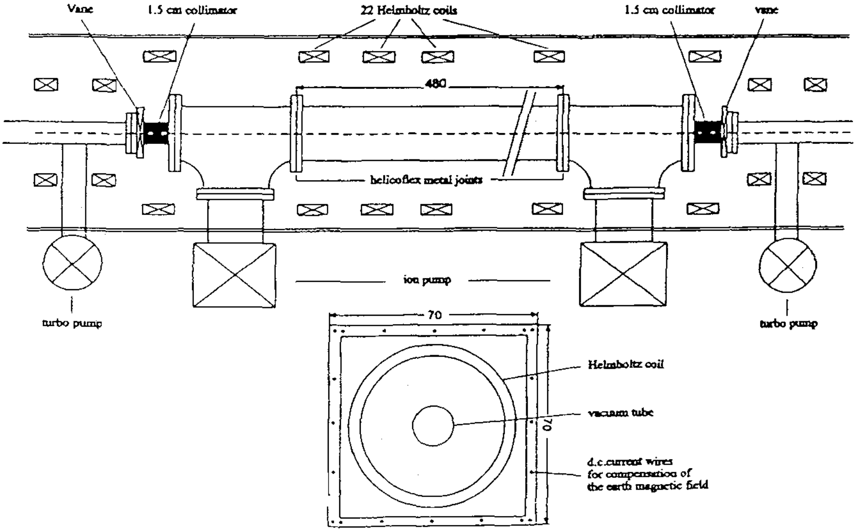


Fig. 1: Lay–out of the installation of the Penning trap. Ref. [5]

The typical intensity obtained is 4 x 10^7 slow positrons per second with 1.3 x 10^5 positrons per pulse [5]. A real continuous beam could be obtained only with a continuously operating LINAC. Such a device of a superconducting LINAC is being considered at the Research Centre at Rossendorf, Germany. A very serious problem, however, remains with all LINAC based beams: the heating and the cooling of the target.

2.2.2 Reactor Based Beams

In contrast to the LINAC based beams, a reactor based beam will deliver a constant intensity of positrons. Two different approaches are being pursued: activation of a short lived positron emitting isotope, i.e. ^{64}Cu, by thermal neutrons near the reactor core or pair production from high energy gamma rays after capture of thermal neutrons in ^{113}Cd. The first method is being used by Van Veen and his group at the reactor at Delft. The set–up is shown in Fig. 2. ^{64}Cu is

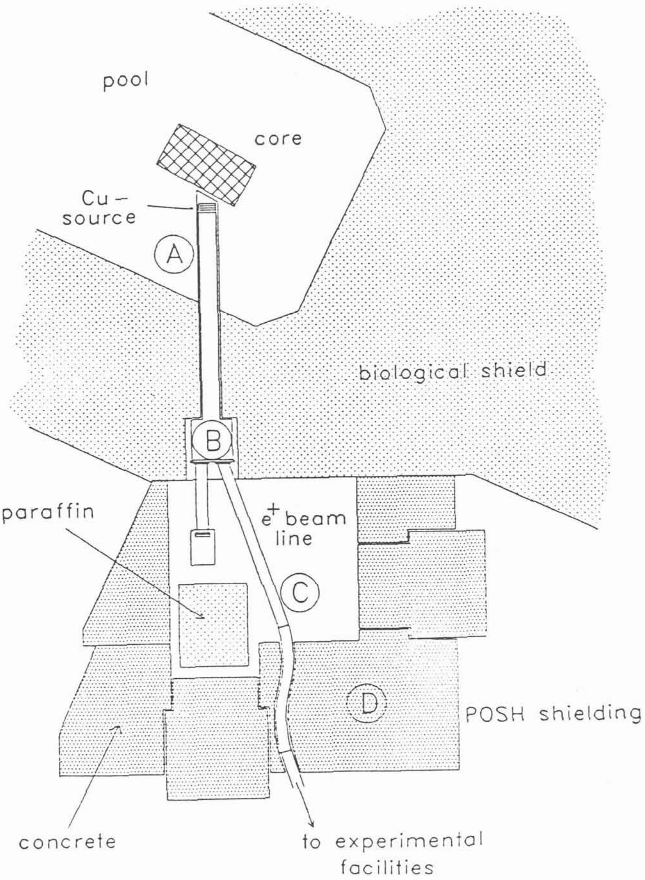


Fig. 2: Schematic setup of the Delft positron beam facility. A: vacuum tube with copper source and magnetic guiding system. B: deflection part of positron beam and neutron beam stop. C: positron beam guiding, bending and monitoring. D: shielding of neutron and gamma radiation.

produced by neutron capture of ^{63}Cu and decays with a half–life of 12.8 hours. After a certain time, depending on the neutron flux, an equilibrium positron intensity is obtained. The details of the copper source arrangement are given in Fig. 3. For a thermal neutron flux of 8 x 10^{12}cm^{-2}s^{-1}

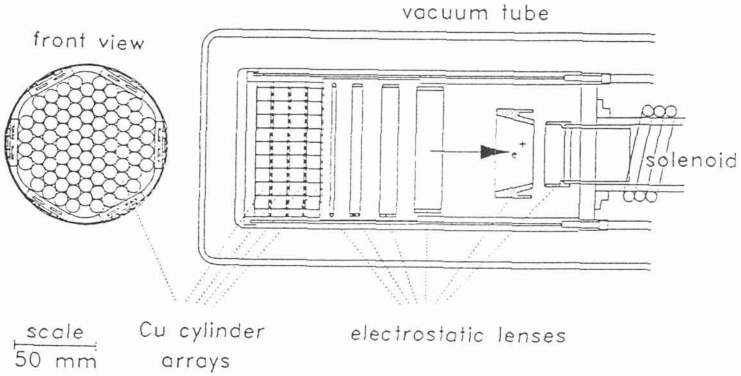


Fig. 3: Details of the Delft source configuration

the group at Delft estimate a positron yield of about 10^6 positrons per cm^2 and second. With an emitting area of 1000 cm^2 the total intensity would then be 10^9 positrons per second, and after remoderation a positron beam of 1 cm diameter and 2 x 10^8 e^+s^{-1} is being expected [6].
The alternative method is being applied by my group in Munich. The basic principle is shown in Fig. 4. Tungsten foils annealed at about 2800 K in ultra high vacuum (~ 10^{-9} mbar) are

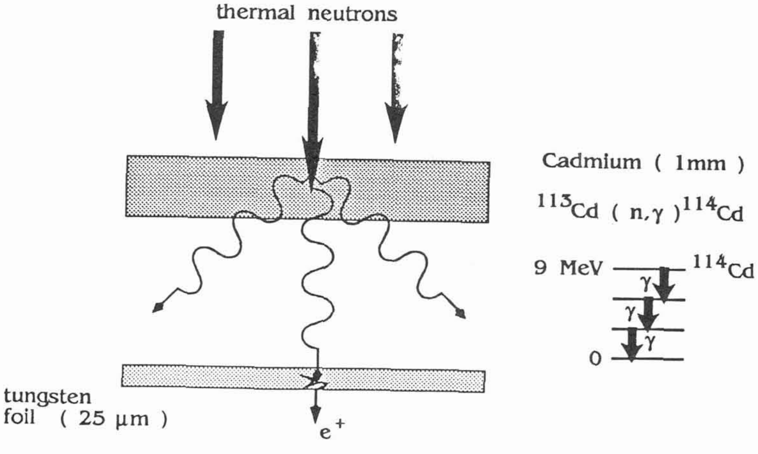


Fig. 4: Principle of the reactor based positron production

simultaneously used as converters for the pair production as well as moderators to obtain low energy positrons. The arrangement, as shown schematically in Fig. 5, consists of an array of concentric double rings surrounded by a cylinder of cadmium (~ 1 mm thick) closed at one end. The device will be placed in a beam tube parallel to the reactor core. For a thermal neutron flux of 10^{12} cm^{-2}s^{-1} and the given geometry of the foils, a positron intensity of 10^{10} e^+s^{-1} is expected, and after remoderation a positron beam of about 5 mm diameter and 10^9 e^+s^{-1} will result. This device will be the prototype for a similar but more intense beam system at the high flux reactor at the ILL at Grenoble, France [7].

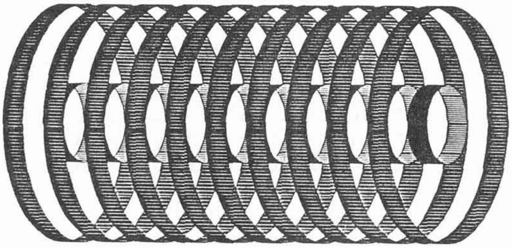


Fig. 5: Schematic array of the tungsten foils

2.2.3 Radioactive Isotope Based Beam

A new concept for obtaining an intense positron beam has been proposed by Taqqu and collaborators at the Paul Scherrer Institute at Villingen, Switzerland [8–10]. An intense primary positron source (i.e. ^{18}F with halflife 109 min) is deposited as a thin layer on a very thin foil. The schematics are shown in Fig. 6. Confining electric and magnetic fields force the high energy positrons to return towards the foil and are slowed down by passing through the foil. Just before they reach an energy to be completely stopped in the foil, they are directed away from the confinement onto a moderator, and the slow emitted positrons are extracted from the confining field and form a slow positron beam. In a first step it is reported that a confinement efficiency of 82% was obtained, and with a solid neon moderator, an overall conversion efficiency of 41% is quoted [11]. This work is still in progress and may result in an high intense low energy positron beam with various user facilities.

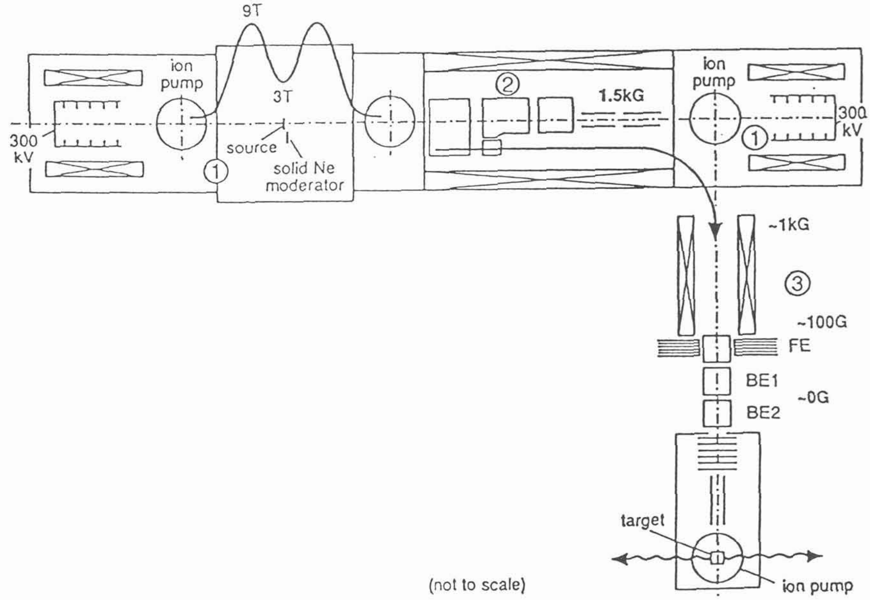
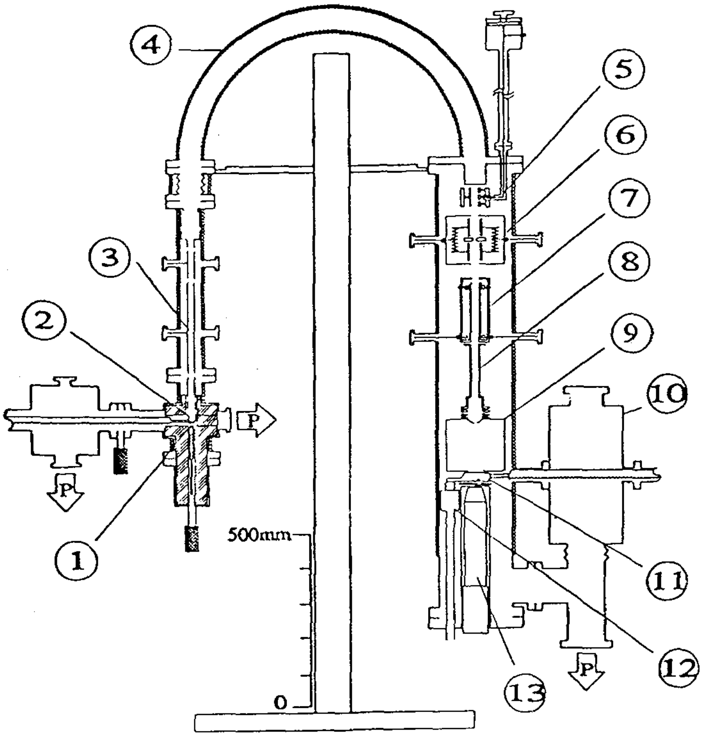


Fig. 6: Layout of the beam production stages (300kV – 300kV distance ~ 10 m, 300kV – target distance ~ 6m). 1 = premoderation stage (~ 5 ./. 10keV) and 2 = extraction/final moderation stage (~ eV). These stages produce the high intensity slow positrons. 3 = field extraction/μbeam formation stage (~ μ/eV). It is forming the slow positrons into a usable μbeam in field free space. FE = field extraction, BE= brightness enhancement.

2.3 Pulsed Positron Beam

During recent years radio frequency pulsed slow positron beams have proved to be a very valuable tool for positron lifetime spectroscopy in the near surface region [12]. The underlying principle is to compress a continuous beam of monoenergetic positrons to pulses of about 150 ps or less at the target by means of special radio frequency components. The timing signals for the lifetime measurements are derived from the corresponding clock signal of the radio-frequency system and the annihilation photons, respectively. The Munich Pulsed Low Energy Positron System was the first such operating system [13]. Later a similar device was installed in Japan [14]. During the last year the Munich beam has been upgraded in order to improve the quality of the lifetime spectra, to achieve a higher efficiency and to enable temperature dependent measurements [15]. This improved version is shown in Fig. 7. An additional preparation chamber has been added for



1: ^{22}Na source with tungsten shielding
2: tungsten single crystal (1 µm) transmission moderator
3: pre-buncher (saw tooth)
4: magnetic guiding field (7 mT)
5: pre-chopper
6: main chopper (sine wave)
7: main buncher (sine wave)
8: drift tube
9: Faraday cage
10: preparation chamber
11: specimen holder (cooling and heating)
12: cryostat for liquid N_2
13: scintillator (BaF_2) and photomultiplier

Fig. 7: Schematic layout of the upgraded pulsed positron beam system

in situ annealing of the single crystalline tungsten moderator. A pre–buncher was installed right after the moderator. This pre–buncher compresses the DC beam to pulses of about 1.7 ns width by applying a saw–tooth voltage of frequency of 50 MHz to a drift tube. About 45% of all moderated positrons are thus shifted into a time interval of 2 ns. With a 16mCi ^{22}Na source the count rate is 130 counts per second and the measured beam diameter at the target is 4 mm for beam energies up to 15 keV and increases to about 5 mm for the maximum energy of 28 keV. Apart from the possibility to perform lifetime measurements as a function of the positron energy and hence of the penetration depth of the positron into the specimen, there is another important advantage compared to conventional lifetime measurements: no restriction of the positron intensity because of accidental coincidences. Since one of the timing signals is taken from the radio–frequency system, the final coincidence rate is equivalent to the counting rate of the detector for the annihilation photons (singles rate). This count rate can then be increased almost unlimited if an appropriate intense primary positron source can be used (Sec. 2.2)

2.4 Positron Microscope

An almost natural consequence, after the existence of a positron beam of several mm in diameter, is the upgrading step to reduce this diameter to micrometer dimensions. For the realisation of such microscopic beams two different developments are under way in Europe.

2.4.1 Positron Reemission Microscope

In all positron reemission experiments it is the spatially averaged emission from a surface that is measured. The retention of spatial information by faithful magnification of the reemitted positron intensity distribution allows direct imaging of features of a surface which affect positron emission. In this way the positrons provide a view of a surface which is inherently different from that yielded by electron and other microscopies developed to date. Prominent among such features will be surface defects. Imaging of large adsorbate structures may be also feasible with positron reemission microscopy. However, there is only a very limited number of materials which can in principle reemit positrons, i.e. materials which have a negative work function (e.g. W, Cu, Ni). Prototype positron reemission microscopes have been constructed [16,17] and the one at the University of East Anglia is shown schematically in Fig. 8 [18]. The two times remoderated

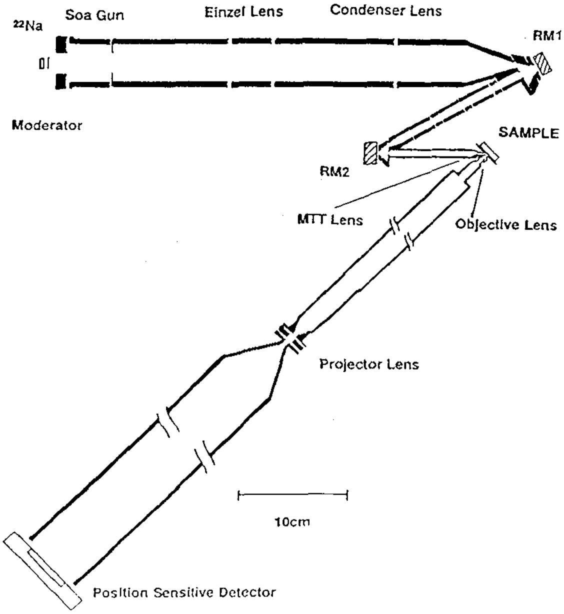


Fig. 8: Schematic layout of the positron reemission microscope

positron beam has been completed and is being tested. This system is expected to achieve a magnification of the reemitted positron distribution of approximately 1700 and a resolution of about 1 μm [19]. Because the fate of a positron diffusing from the bulk towards the surface is decided right at the surface itself (i.e annihilation, trapping in surface state, positronium formation, reemission, trapping at defect) positron reemission microscope will supply information about the surface properties rather than about near–surface conditions. These informations will be obtained in much more detail with a pulsed and scanned microbeam of variable energy.

2.4.2 Scanning Positron Microscope

A logical advancement of a pulsed positron beam of several mm diameter and of variable energy [13] leads to a scanning beam but of microscopic dimensions. About two years ago we started in Munich and Trento, financially supported by the European Community, the project of a scanning positron microscope (SPM). Based on our pulsed beam system [15], a second and cooled moderator is added, so that the final beam diameter at the target will be 1 μm. The schematic set up is shown in Fig. 9. Integrated in the system is an electron beam which is focussed and scanned

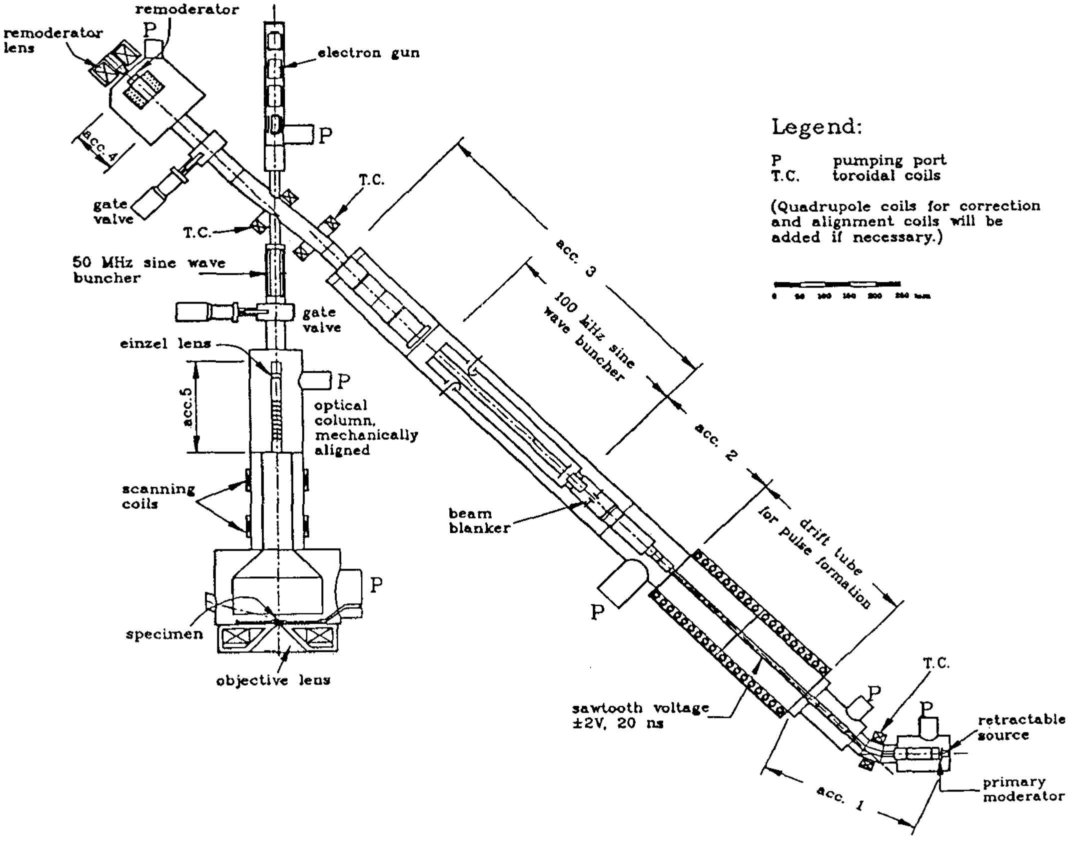


Fig. 9: Schematic layout of the scanning positron microscope

with the same electron optics as the positron beam. The electron beam will give a topological picture of the specimen surface whereas the positron beam will give depth profiles of near surface microscopic regions. From the characteristic positron lifetimes, defects as well as defect structures can be distinguished from defect-free regions. We see applications of the scanning positron microscope in various areas of material science and for microelectronic devices.

3. Positron Annihilation Angular Correlation

In metals and alloys, the measurement of the angular correlation of positron annihilation radiation gives detailed information on the electron-positron momentum density especially if position sensitive detectors are used [20]. Facilities with such devices are in Europe at the Universities in Geneva, Bristol and Munich. Because of the almost negligible contribution of the positron to the total momentum, the electron momentum density can be determined and the Fermi surface can be deduced [21]. Single crystals are required to investigate the electron momentum distributions. Size and quality of the crystals are very important parameters. For some compounds, i.e. high T_c superconductors, it is difficult to grow high quality single crystals of appropriate dimensions in order to be measured with conventional positron sources from radioactive isotopes. Positrons from such sources penetrate on the average 100–200 μm into the specimen before they annihilate. This means that the thickness of the single crystals has to be of the same order of magnitude. Intense and narrow positron beams would be an obvious advantage for the investigation of solids. In some materials it is difficult or even impossible to prepare large enough single crystals of good quality and with stable homogeneous composition. Monoenergetic positrons of variable energy (up to 50 keV) would allow selection of penetration depth and hence angular correlation measurements in samples made of films grown by epitaxy on substrates.

4. Conclusions and Outlook

It is quite obvious that the future direction of positron research is towards intense positron beams of variable energy and micrometer dimensions. The current efforts in Europe are following the trend of this development. In not too far away time such systems will come into operation and will open up new kinds of experiments and exciting applications to solid state physics and materials science. Many fascinating experiments with positrons remain to be done.

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