New experiment stations at KEK Slow Positron Facility

2013 J. Phys.: Conf. Ser. 443 012082

(http://iopscience.iop.org/1742-6596/443/1/012082)

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Abstract. Recent development of the Slow Positron Facility at the Institute of Materials Structure Science, High Energy Accelerator Research Organization (KEK) is reported. The facility, equipped with a dedicated 55 MeV linac, provides a high-intensity, pulsed slow-positron beam. The beam is produced in a production unit at a high tension of up to 35 kV and guided magnetically through a grounded beam line, and then branched using compact branching units in the experiment hall. An overview, some details of three experiments currently conducted and the outlook of the facility are described.

1. Introduction

This article reports recent development of the Slow Positron Facility (SPF) at the Institute of Materials Structure Science (IMSS), High Energy Accelerator Research Organization (KEK). This facility provides a slow-positron beam produced by using a dedicated linac. First, an overview and the present status of the facility is given. Next, three experiment stations in the facility, namely, those for a Ps negative ion (Ps^-), a reflection high-energy positron diffraction (RHEPD), and positronium time-of-flight (Ps-TOF) are reported. Then the outlook of the facility is described.

2. Overview

The KEK-IMSS-SPF provides a high-intensity, pulsed slow-positron beam produced by using a dedicated linac. The electron-beam energy of the linac is 55 MeV with the operation power of 600 W at the maximum. The maximum repetition rate is 50 Hz. It operates in two pulse modes: the long pulse mode of 1 μs pulse width, and the short pulse mode of variable 1–10 ns pulse width. In October 2010, a new positron converter and moderator assembly was introduced, yielding an increase of an order of magnitude in the intensity of the beam [1]. The long pulse mode provides 5×10^7 slow-e$^+$/s, and the short pulse mode provides 5×10^6 slow-e$^+$/s. The initial beam diameter is about 20 mm.

The experiment hall of the facility consists of two floors. The dedicated linac and the positron converter and moderator assembly is on the basement floor. Currently, there are four beam-line branches (figure 1): two of them (SPF-A1, SPF-A3) lies on the basement floor, and one branch (SPF-A2) goes up to the deck floor and comes down vertically, and the last one (SPF-B1) goes up on the ground floor.

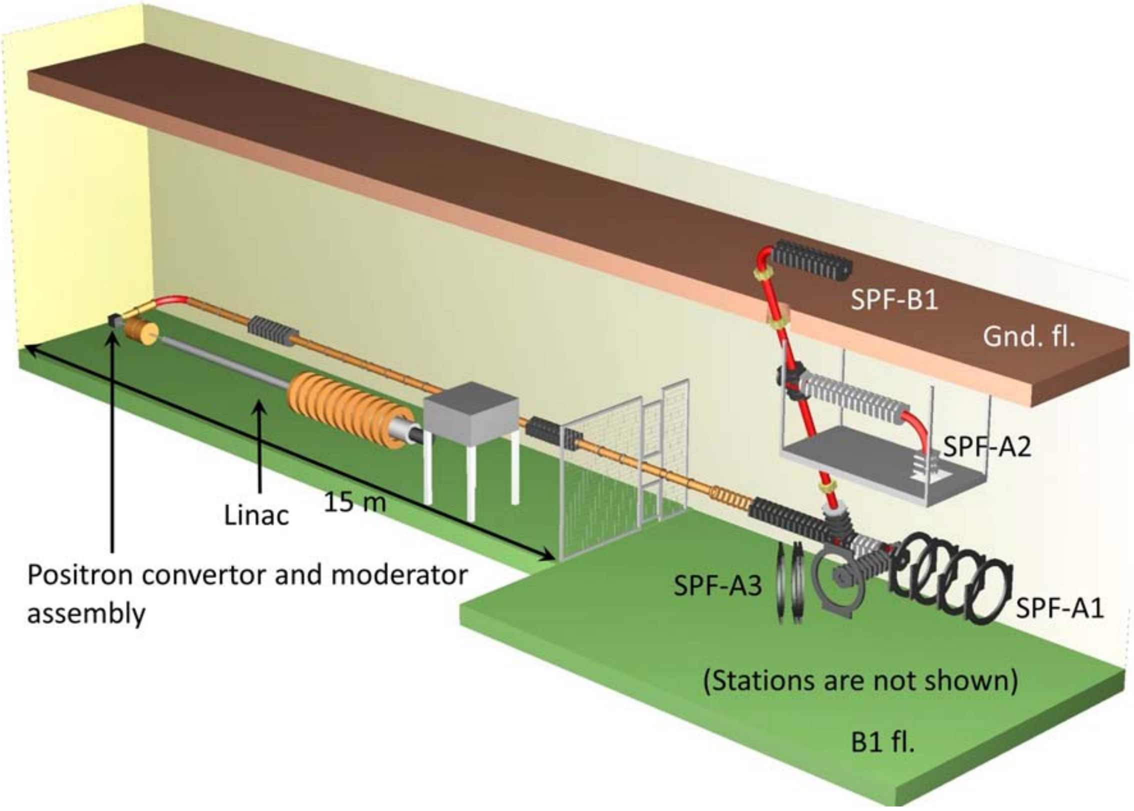

Figure 1. A schematic view of the KEK-IMSS-SPF beam-line.

The positron converter and moderator assembly is at high tension of up to 35 kV with reference to the grounded potential slow-positron beam line, and the tension is adjusted in accordance with the requirements of individual experiments. Standardized beam-line-branching units for the transportation energy of up to 35 keV allow flexible rearrangements of the branches.

3. Present experiment stations

3.1. Ps negative ion experiment station

A method to efficiently produce positronium negative ion (Ps$^-$), an exotic system composed of one positron and two electrons bound through Coulomb interaction, has been developed by Nagashima et al. [2, 3]. The photodetachment of the Ps$^-$ ions produced by using the pulsed positron beam in this facility was performed [4] at the branch SPF-A1. The incident positrons hit the target of 25 μm W film coated with one ML of Na, and Ps$^-$ ions were formed on the surface. The emitted Ps$^-$ ions are then accelerated by an electrostatic field. Immediately after that, the photodetachment was accomplished by irradiation of 25 Hz pulsed (width 12 ns) Q-switched Nd:YAG laser. Since the slow positron beam is provided in 50 Hz, the data with and without the laser irradiation were obtained simultaneously. The Doppler shifted annihilation γ-rays from the accelerated Ps$^-$ detected by two Germanium detectors verified the formation of the Ps$^-$ ions and the reduction of them the photodetachment into Ps atoms.

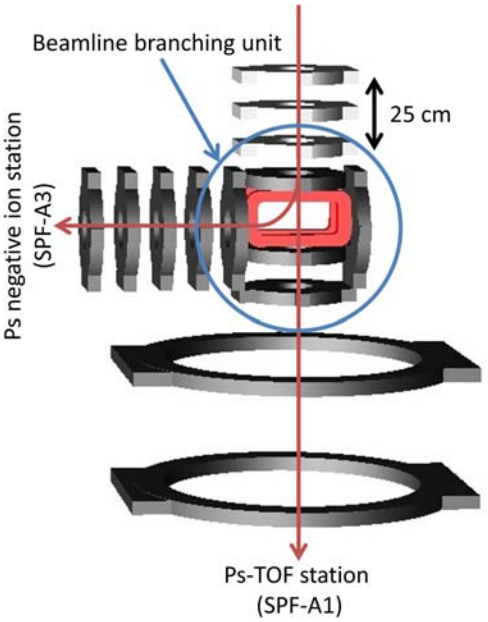

Figure 2. The beam-line-branching unit (within the blue circle) standardized for the transportation of the positrons with energy of up to 35-keV. Only the configuration of the magnetic coils are shown.

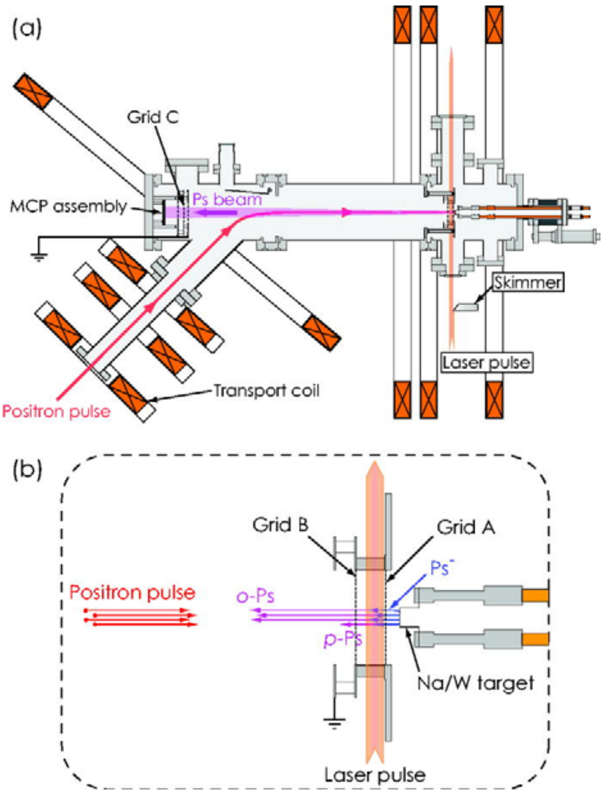

Figure 3. Schematic of the energy-tunable-Ps-beam production and detection system: (a) a whole view; and (b) details of the Ps$^-$ source and its photodetachment region (not to scale).

After developing the above technique, we built a new beam-line branch, SPF-A3, and an energy-tunable Ps beam was successfully produced in ultra-high-vacuum environment and detected [5]. The energy of the Ps, which is a neutral atom and hence cannot be accelerated by a static electric field directly, tuned accelerating the Ps$^-$ ions before the photodetachment.

Figure 2 shows the branching unit together with the coils around it (the beam-line duct is not shown). The branching unit is standardized and compatible with the positron energy up to 35 keV. The positrons are guided into selected direction by switching relevant Helmholtz coils. A pair of steering coils (shown in red in Figure 2) is used to suppress the perpendicular drift of the curving positron-beam trajectory.

Figure 3a shows the station at the end of the new branch. The slow-positron beam of 4.2 keV was guided by 45° along a curved magnetic field and led to the target. The Ps$^-$ ions emitted from the target were accelerated by an electrostatic potential of 0.3-2.3 kV, and then photodetached by the pulsed laser (Figure 3b). The resulting ortho-Ps atoms traveled in the direction of the acceleration of the Ps$^-$ ions, and were detected by a Microchannel Plate (MCP) with a pulse-counting mode, placed at 80cm away from the target. All the charged particles back-scattered from the target were transported back along the curved magnetic field and not detected by the MCP. Some of the γ-rays from positron annihilations in the target were detected by the MCP and gave information on the time of the Ps formation. The time interval of the detections of this γ-ray and the Ps clearly showed that the Ps flew with the energy expected from the electrostatic acceleration of the Ps^- ions [5]. Production of an energy-tunable Ps beam from 300 eV to 1.9 keV in an ultra-high-vacuum environment was achieved.

3.2. Reflection high-energy positron diffraction experiment station

Reflection high-energy positron diffraction (RHEPD) is the positron version of the reflection high-energy electron diffraction (RHEED). Since the crystal potential for the positron is positive, positrons incident at a small glancing angle are totally reflected, which is not the case for the electrons. Thus the positron diffraction is a very sensitive method for the topmost surfaces [6]. RHEPD was proposed by A. Ichimiya [7] and was brought into practical use by Kawasuso and Okada [8] with a ^{22}Na-based slow-positron beam at Japan Atomic Energy Agency (JAEA).

In 2010, a RHEPD station was installed at the end of the beam-line branch SPF-B1 in KEK-IMSS-SPF [1]. Magnetically transported positrons with an energy of 10 keV were introduced into the magnetic-field-free region, which were isolated from the magnetic field of the transportation coils by a 3 mm thick iron plate. About a half of the transported positrons went through a magnetic lens placed in the magnetic-field-free region, a $\phi 10\,\mathrm{mm}$ aperture, a set of Einzel lens, and a $\phi 3\,\mathrm{mm} \times 30\,\mathrm{mm}$ collimator, then reached the sample. The observed specular intensity was 14 times intensified [1] over the former measurements with the ^{22}Na-based beam at JAEA.

One of the results with the installed RHEPD station is the determination of the temperature-dependent atomic configuration of well-ordered and defect-less Pt-induced nanowires on the Ge(001) surface [9]. This research was performed along with scanning tunneling microscopy (STM) and angle-resolved photoemission spectroscopy (ARPES).

The other results is the experimental evidence for the correlation of the spin splitting and the outward displacement of the Pb atoms in Ag_2Pb alloy on Ag(111)/Si(111) surface [10], which shows giant Rashba effect. The shift of the position of the Pb atom for each Ag thickness was determined by using RHEPD rocking curves (specular intensity as a function of the glancing angle of the incident positrons). Then the electronic states of Ag_2Pb alloy on the Ag(111)/Si(111) surface were investigated by using angle resolved photoemission spectroscopy (ARPES), while controlling the position of the Pb atom by changing the Ag(111) thickness. These results confirmed that the magnitude of the Rashba energy depends on the outward displacement of the Pb atoms as theoretically predicted [11]. They also suggest that the Rashba energy can be controlled by changing the substrate Ag thickness.

After the above experiments, a brightness-enhancement unit was installed at the magnetic-field-free region. Details of the unit will be reported elsewhere [12]. The unit consists of a magnetic lens, transmission-type remoderator of 100-nm-thick W(111) crystal, and several extraction electrodes. The W crystal was annealed *in situ* by the passage of an electric current. The incident positrons with a beam energy of 15 keV were focused by a magnetic lens on the W crystal at an applied voltage of 10 kV. The diameter of the beam spot focused on the crystal is 3 mm at FWHM. The remoderated beam was transported through a set of Einzel lens to the sample, where the beam diameter is less than 1 mm. The energy spread of the 10 keV beam was improved from 110 eV at FWHM without the remoderation to 8 eV with it. The observed diffraction patterns from the Si(111)-7×7 surface with the remoderated beam shows the fractional index spots due to the 7×7 super structure, which were not clearly identified with the former [12].

The obtained RHEPD rocking curve with remoderated beam yielded 45 times brighter than that with ^{22}Na-based slow-positron beam (Figure 4).

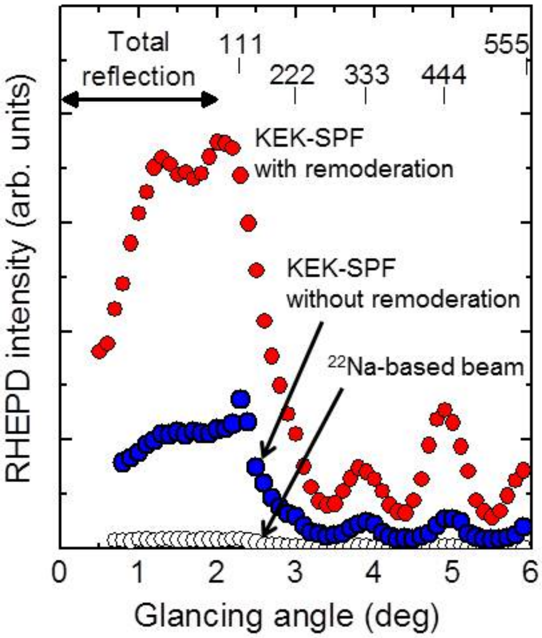

Figure 4. RHEPD rocking curves from a Si(111)-7×7 surface observed with 10 keV positron beams. The data obtained by the linac-based beams with and without remoderation at KEK-IMSS-SPF, and that by a ^{22}Na-based beam are presented.

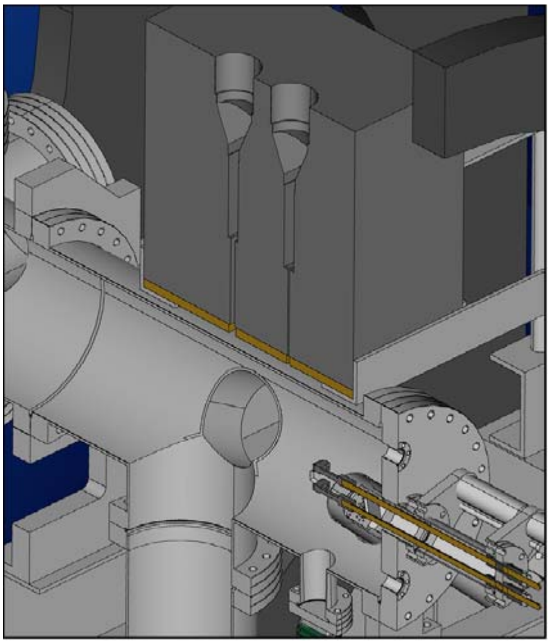

Figure 5. A cross section of the revised positronium time-of-flight detection system. The annhilation γ-rays are viewed by detectors through two sets of lead slits.

3.3. Positronium time-of-flight experiment station

The Ps time-of-flight experiment station was revised. More compact detection system gives a better time resolution: the revised detection system gives a time resolution of 14 ns, while that of the old one was 23 ns. The detailed configuration of the apparatus is reported elsewhere [14].

The incident positrons hit the target sample and the ortho-Ps atoms emitted from the surface annihilate in flight. The annihilation γ-rays were viewed through two sets of lead slits by detectors and the time of the detection is recorded. One pair of the lead slits, of 2 mm width, is located at 40 mm away from the target and the other, of 6 mm width, at 120 mm. The detector consists of set of plastic scintillators of $100 \times 100 \times 10\,\mathrm{mm}^3$, light guide, and mesh-type photomultiplier tubes. The prompt peak in the TOF spectrum caused by the γ-rays from the annihilations in the sample gives information of the time zero. With this revised system, an enhancement of the emission efficiency of the Ps was observed for Na-coated W-film [14].

4. Outlook

The RHEPD experiments with remoderated beam are starting from Oct. 2012. The low-energy positron diffraction (LEPD), which is the positron version of low-energy electron diffraction (LEED), will be installed at the end of the beam-line branch SPF-A2 in the year 2013.

A DC-beam section, which convert the pulsed slow-positron beam into the DC-beam using a penning trap with a pulsed voltage supply, will be installed next year. Then a coincidence-Doppler-experiment station will be arranged.

The user beam time in this facility is about 180-days in the years 2010 and 2011. Currently, the facility provide user beam time for two experiments, Ps^- and RHEPD. From October 2012, it is going to provide user beam times for five experiments, two Ps-TOF experiments and one positron-impact-induced ion-desorption experiment, as well as the continuing two experiments.

About 100 current sources for about 200 sets of magnetic coils for the slow-positron transportation must be optimized for each transportation energy and for each beam-line branches. For accommodating increasing needs for the readjustments of the currents, a client-server control system is being installed. With this system, current sources are controlled remotely from a client PC through the server and the programmable logic controller (PLC). About 30 current sources are already under control of the system. The system will be completed in October 2012. Then sets of optimized values of all the magnetic-coil current for one experiment will be switched smoothly to the next.

Any researcher can use the KEK-IMSS-SPF beam line through approval by the proposal approval committee in Photon Factory, KEK. The deadline of the application for experiments for a period from October to March is the first Friday in May of the same year, and for those for a period from May to July is the first Friday in November of the year before. Further information on the application for using the beam line will be provided by the corresponding author in response to inquiries.

5. Summary

The KEK-IMSS-SPF provides the slow-positron beam produced by using a dedicated linac. It is operated in a long-pulse mode providing 5×10^7 slow-e^+/s and a short-pulse mode providing 5×10^6 slow-e^+/s in 50 Hz at maximum. The positron converter and moderator assembly is at high tension of up to 35 kV and the entire slow-positron beam line is at ground potential, which allows one to perform an experiment just as is done in common laboratories. Beam-line branches are flexibly rearranged with a standardized branching unit compatible with a transportation energy up to 35 keV.

Production of an energy-tunable Ps beam with an energy variable from 300 eV to 1.9 keV in an ultra-high-vacuum environment was achieved. Recent results with the RHEPD station include temperature transition of Pt-induced nanowires on the Ge(001) surface and the correlation of the spin splitting and the outward displacement of the Pb atoms in Ag_2Pb alloy on Ag(111)/Si(111) surface.

With a brightness enhancement unit, the RHEPD specular intensity was significantly intensified and the resolution of the rocking curve was improved. The Ps-TOF station was revised, yielding a better time-resolution.

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