J. Synchrotron Rad. (1996). 3, 201–206

Production of Intense Low-Energy Positron Beams with Synchrotron Radiation

A. Ando,[a] V. N. Belyaev,[b] S. Daté,[c] H. Kamitsubo,[a] A. V. Kiselev,[d] G. N. Kulipanov,[d] N. Kumagai,[a] N. A. Mezentsev,[d] Y. Miyahara,[a] T. Nakamura,[a] A. N. Skrinsky,[d] K. Soutome,[c] M. Takao,[c] H. Tanaka[a] and I. S. Voronchev[b]

[a]JAERI-RIKEN SPring-8 Project Team, SPring-8, Kamigori, Hyogo 678-12, Japan, [b]Moscow Engineering Physics Institute, Kashirskoe Shosse 31, 115409 Moscow, Russia, [c]Japan Synchrotron Radiation Research Institute, SPring-8, Kamigori, Hyogo 678-12, Japan, and [d]Budker Institute of Nuclear Physics, Academician Lavrentyev 11, Novosibirsk 630090, Russia

(Received 23 December 1995; accepted 8 May 1996)

A low-energy positron beam is a unique probe of Fermi surfaces, defects, surfaces and interfaces. In high-energy electron and positron storage rings ($E > 6$ GeV) it is possible to generate intense synchrotron radiation with 1–3 MeV photons by installing a high-field superconducting wiggler. The strength of the wiggler should be ~8–12 T. High-energy photons are emitted from the wiggler and converted to low-energy positrons by using a suitable target–moderator system. For an 8 GeV electron storage ring at a beam current of 100 mA, final yields are estimated to be $\sim 10^{10}$–10^{12} (slow-e^+ s^{-1}) with the size of positron source $\sim 10^2$–10^3 cm^2. The possibility of increasing the brightness of the low-energy positron beam is discussed. Advantages of using synchrotron radiation for producing positrons are pointed out. The effect of a superconducting wiggler on the stored electron beam is also discussed.

Keywords: positrons; superconducting wigglers; pair production; low-energy positron beams.

1. Introduction

A low-energy positron beam can be a useful probe in the fields of atomic physics, solid-state physics, surface and thin-film physics and chemistry, materials science, physics of defects in solid semiconductor electronics *etc.* The low-energy positron beam can be used as (see *e.g.* Schultz & Lynn, 1988; Tanigawa, 1991; Puska & Nieminen, 1994):

(i) A probe of the Fermi surface. When a positron is incident on a substance, pair annihilation and subsequent two-photon emission occurs. By analyzing the angular correlation of these photons, information on the Fermi surface can be deduced.

(ii) A probe of defects. Since positrons have positive charge, they feel repulsive forces from ionized atoms and are captured selectively at defects like vacancies. This means that the positron beam can be used to study defects in metals, semiconductors *etc.* It can also be used to detect impurities.

(iii) A probe of surface and interface. By utilizing the process of losing energy, diffraction and re-emission, information on surfaces and interfaces can be obtained. It should be noted that if the energy of the positron beam is tunable, studies of defects at a given depth from the surface will be possible.

(iv) A micro-probe. Several kinds of microscopes using positrons will become available if high-intensity positron beams are provided: the transmission positron microscope, the scanning positron microscope, the positron re-emission microscope and the positron tunneling microscope have been proposed. For example, the positron re-emission microscope can be used to analyze surface structures or surface defects with high resolution.

In general, there are two main ways of obtaining low-energy positrons. One is to moderate positrons produced by β^+-decay of isotopes and the other is to moderate positrons produced *via* the pair-production process.

In the first method isotopes with different lifetimes are used: (i) relatively long-lived isotopes, *i.e.* ^{22}Na (2.6 y) or ^{58}Co (71 d), are used in many laboratories; (ii) relatively short-lived isotopes can also be used in some special research centres. These isotopes are ^{64}Cu (12.7 h), produced in nuclear reactors by irradiating thermal neutrons on copper, and ^{18}F (110 min) or ^{11}C (20 min), produced with cyclotrons.

In the second method, different kinds of γ-ray sources are available for producing positrons: (iii) in the nuclear reactor Cd is used as an absorber of thermal neutrons, from which high-energy γ-rays are emitted; (iv) by using electron linacs one can inject high-energy electrons into a target and generate γ-rays by *Bremsstrahlung*; (v) superconducting wigglers installed in high-energy electron/positron storage rings produce an intense beam of synchrotron radiation with energies well above the threshold of pair production.

The linac method has been adopted (or is to be adopted) in many facilities for obtaining high-intensity low-energy positron beams. However, the use of linacs suffers from radiation hazards and induced radioactivity of target–moderator systems. It has been pointed out (Kulipanov & Skrinsky, 1988; Kulipanov, Mezentsev & Skrinsky, 1992; Kulipanov, 1992; Belyaev, Voronchev, Kulipanov, Miksheev & Skrinsky, 1992) that these problems can be solved if synchrotron radiation is employed for the production of positrons, and with this method high-intensity positron beams can be obtained.

In the present paper we show that in high-energy storage rings it is possible to provide an intense beam of low-energy positrons. To illustrate our argument, we take as an example an 8 GeV electron storage ring at the SPring-8 facility, which is currently under construction in Japan. We estimate the positron yield by using realistic parameters of the SPring-8 storage ring and check the effect of a superconducting wiggler on beam dynamics. We will then conclude that after some research and development processes it is indeed possible to install such a high-field wiggler and generate intense positron beams by using synchrotron radiation. We also point out some advantages of using synchrotron radiation.

2. Positron production with synchrotron radiation

2.1. *High-field superconducting wiggler*

As mentioned above, for the purpose of producing an intense beam of synchrotron radiation photons with an energy well above 1 MeV, high-field superconducting wigglers should be installed in high-energy electron storage rings. To obtain an intense beam of low-energy positrons, the flux of energetic positrons before moderation, and thus the flux of incident photons, must be sufficiently high. For example, in an 8 GeV electron storage ring it is necessary to install a superconducting wiggler with a field strength higher than 8 T if one aims at a positron beam intensity of the order of 10^{10} (slow-e^+ s^{-1}).

The first superconducting wiggler with a field strength of 7.5–8 T was constructed and installed in the Budker Institute of Nuclear Physics (INP) in 1984 (Anashin *et al.*, 1984). Recently, a 7.5 T superconducting wiggler with a warm vacuum chamber has also been constructed at the Budker INP and will be installed in the Pohang Light Source (PLS) 2 GeV electron storage ring to enhance the performance of the machine in the short-wavelength region (Grudiev *et al.*, 1995; Mezentsev, Shkaruba, Fedurin & Borovikov, 1995). This wiggler has a three-pole structure with a maximum field strength of 7.5 T for a central pole and 1.6 T for side poles. NbTi superconducting wires are used, and with the same material it is possible to make an 8 T wiggler. In order to achieve a field strength of ~10 T or higher it is necessary to use other materials, such as NbSn. NbSn wire is fragile, however, and some research and development is necessary to realize very high field superconducting wigglers (see *e.g.* Fukushima, Ohmi, Yamakawa & Fujiwara, 1993). In the following we estimate positron yields for 8, 10 and 12 T wigglers, since an 8 T wiggler will be available after some research and development and 10 or 12 T wigglers will also become available in the near future. It should be noted that even in the 8 T case we will be able to obtain a 'rather intense' slow-positron beamline, and we can have a unique facility where both synchrotron radiation and positron beamlines are available at the same time.

The photon flux for these wigglers installed in the 8 GeV electron storage ring is shown in Fig. 1. For the 10 T wiggler, for example, the critical photon energy is 0.43 MeV, the horizontal divergence angle of the synchrotron radiation is ~30 mrad and the total power emitted is ~90 kW.

2.2. *Positron production*

We assume that (i) the energy of the stored electron beam is 8 GeV, (ii) the stored current is 100 mA, (iii) the distance from the superconducting wiggler to the target–moderator system is 35 m, and (iv) the vacuum chamber and magnets are designed appropriately so that one can extract synchrotron radiation photons with a horizontal divergence angle of 10 mrad.

The last two assumptions mean that the horizontal size of the target is set at 350 mm. If the target is allowed to be closer to the synchrotron radiation source point (wiggler), the horizontal size for accepting the same number of photons can be smaller than 350 mm. Note also that if *e.g.* only 1 mrad of the synchrotron radiation beam can be extracted instead of 10 mrad, all the results must be multiplied by a factor of 0.1. In this case the target width is 35 mm.

The vertical divergence angle of synchrotron radiation photons depends on their energies. Higher energy photons have smaller divergence angles. At the target position, 1 MeV photons spread about 2 mm in the vertical direction and 3 MeV photons about 1 mm. Thus, the target thickness in this direction should be less than 2 mm in view of the positron annihilation probability, which approaches unity as the target becomes thick.

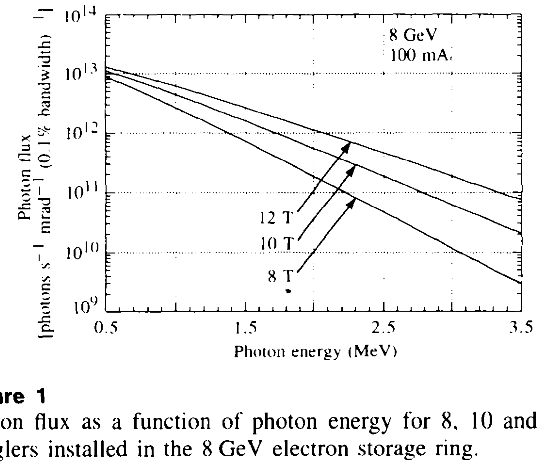

Figure 1
Photon flux as a function of photon energy for 8, 10 and 12 T wigglers installed in the 8 GeV electron storage ring.

Table 1
Positron production efficiency for 8, 10 and 12 T wigglers.

Pb target of size 350 × 20 mm × thickness. The third column is the total number of incident photons and the last column is the total number of positrons emitted from the target. The fourth column is the ratio of the number of positrons produced in the target to the number of incident photons, and the fifth column is the ratio for positrons emitted from the target.

Wiggler field (T)	Target thickness (mm)	Photon number (s^{-1})	Positrons/photon (produced)	Positrons/photon (emitted)	Positron number (emitted) (s^{-1})
8	2.0	6.22×10^{15}	1.8×10^{-2}	2.0×10^{-4}	1.2×10^{12}
	1.0	3.83×10^{15}	1.9×10^{-2}	9.7×10^{-4}	3.7×10^{12}
	0.5	2.03×10^{15}	2.1×10^{-2}	2.5×10^{-3}	5.0×10^{12}
	0.25	1.03×10^{15}	1.8×10^{-2}	3.2×10^{-3}	3.3×10^{12}
10	2.0	1.20×10^{16}	2.5×10^{-2}	6.3×10^{-4}	7.6×10^{12}
	1.0	7.15×10^{15}	2.4×10^{-2}	1.3×10^{-3}	9.5×10^{12}
	0.5	3.75×10^{15}	2.6×10^{-2}	3.3×10^{-3}	1.2×10^{13}
	0.25	1.89×10^{15}	2.5×10^{-2}	6.5×10^{-3}	1.2×10^{13}
12	2.0	1.86×10^{16}	3.0×10^{-2}	7.0×10^{-4}	1.3×10^{13}
	1.0	1.08×10^{16}	3.2×10^{-2}	3.0×10^{-3}	3.2×10^{13}
	0.5	5.64×10^{15}	3.0×10^{-2}	4.1×10^{-3}	2.3×10^{13}
	0.25	2.85×10^{15}	3.0×10^{-2}	7.9×10^{-3}	2.2×10^{13}

By using a simulation code developed by Kiselev (1995), we estimated positron yields when the synchrotron radiation beam is incident on the target. The code is a kind of electromagnetic cascade simulator and is similar to the *EGS*4 code system (Nelson, Hirayama & Rogers, 1985). We checked the reliability of our code by calculating the yield for positron production in the target using *EGS*4. The target width in the horizontal direction was set at 350 mm as mentioned above, and the target 'depth' in the synchrotron radiation beam direction was set at 20 mm. The target thickness in the vertical direction was varied from 0.25 to 2 mm. Fig. 2(*a*) displays the target configuration. The results of the calculations are shown in Table 1 for a Pb target. We can see that maximum positron-production efficiency of is attained when the target thickness is ~0.5–1 mm. It is worth mentioning the target-depth dependence of the positron yield. For a 10 mm-depth target the yield reduces by ~40% compared with the 20 mm-depth case, and for 30, 40, 50 and 60 mm-depth targets the yield increases by ~25, 40, 50 and 55%, respectively. Use of a target with a depth larger than 60 mm is not effective in increasing positron yields. In the present paper we take the 20 mm-depth case as an example. It should be noted that in actual experiments it will be necessary to optimize the target size by taking account of the efficiency of moderation and brightness enhancement of the positron beam.

We next changed the target configuration as shown in Fig. 2(*b*) so that positrons can be emitted easily: we used a 0.1 mm-thick target of size 350 × 200 mm and set it so that the synchrotron radiation photons were incident with a 5 mrad injection angle. Since the longitudinal depth along the synchrotron radiation beam direction is unchanged (20 mm), the number of positrons created is the same as in the case of the 1 mm-thick target (Fig. 2*a*). The only difference is that the probability of emitting positrons is larger than in the case of Fig. 2(*a*). Positron yields in the case of Fig. 2(*b*) are listed in Table 2. We see that although the longitudinal source size becomes larger, the total number of emitted positrons is 5–7 times higher.

We also calculated positron yields for U and W targets. In general, the yield from the U target is ~20% larger than that from the Pb target, and the yield from the W target is ~10% smaller. Optimal target 'depth' for W and U targets is ~40–45% smaller than that for the Pb target. The most suitable target material should be determined by considering cooling, durability *etc.* as well as positron yields.

2.3. *Efficiency of moderation*

Positrons created in the target are collected and used as a positron beam. Since a positron beam with very low energies is required in many applications, positrons must be decelerated to a few eV with a suitable moderator. In

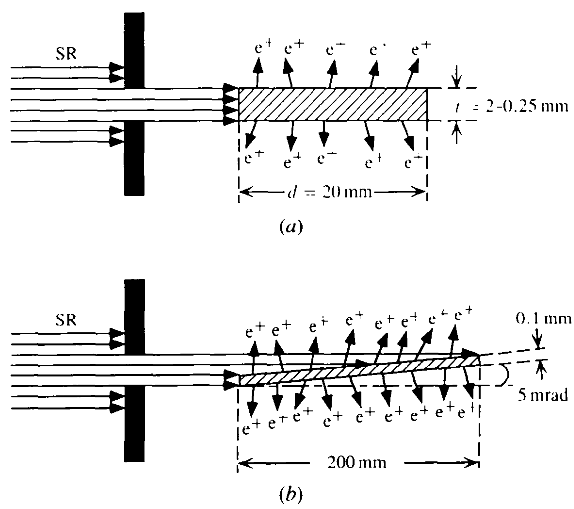

Figure 2
Arrangement of a target: (*a*) synchrotron radiation beam parallel to the target 'surface' (350 × 20 mm area); (*b*) synchrotron radiation beam incident on a thinner target with 5 mrad injection angle.

Table 2
Positron production efficiency for 8, 10 and 12 T wigglers.

Same as Table 1, but synchrotron radiation photons are incident on a thinner target (350 × 200 × 0.1 mm) with a 5 mrad injection angle as shown in Fig. 2(*b*).

Wiggler field (T)	Target thickness (mm)	Photon number (s^{-1})	Positrons/photon (produced)	Positrons/photon (emitted)	Positron number (emitted) (s^{-1})
8	0.1	3.83×10^{15}	1.8×10^{-2}	7.2×10^{-3}	2.7×10^{13}
10	0.1	7.15×10^{15}	2.2×10^{-2}	1.0×10^{-2}	7.4×10^{13}
12	0.1	1.08×10^{16}	3.0×10^{-2}	1.6×10^{-2}	1.7×10^{14}

our case, most positrons are emitted from the target with energies below 1 MeV. This can be seen from Fig. 3, where a typical kinetic energy distribution of the emitted positrons is presented. Energy distributions are almost the same in all cases of Pb, W and U targets.

Positrons emitted from the target then irradiate the moderator, in which positrons lose their energy due to processes of ionization, plasmon production, electron–hole pair excitation and phonon scattering. Although positrons can reach thermal equilibrium when phonon emission and absorption are maintaining the equilibrium, only a small fraction (10^{-2}–10^{-4}) of the incident positrons thermalize within a positron diffusion length and are re-emitted from the surface of the moderator. This re-emission is due to the negative work function that many metals have for positrons.

There are several possible configurations of the target–moderator system. One of these is presented in Fig. 4. Annealed polycrystalline W foils with thickness 10–25 μm can be used as the moderator. The efficiency of moderation is then a very important question.

Our simulation code, however, has a cut-off energy at 1 keV, below which we cannot follow the behaviour of positrons. In general, an accurate calculation of the efficiency of moderation is difficult, and in order to do this we need to make some assumptions concerning the behaviour of positrons in the moderator. Such calculations have been performed by Okada & Sunaga (1991). According to their results, moderation efficiencies for positrons whose energies are below 1 MeV can be as high as 10^{-2} if we use an assembly of thin foils as the moderator. We can also estimate the efficiency of moderation by using typical values of 0.1×10^{-3}–7×10^{-3} in the isotope method (Schultz & Lynn, 1988, Table 4), since the positron spectrum before moderation (Fig. 3) is very similar to the spectrum of positrons produced by β-decay of isotopes. It is then quite realistic that we can have a moderator with which high efficiencies of the order of 10^{-2} are achieved. With such a good moderation system we can expect from Tables 1 and 2 that final yields are $\sim 10^{10}$–10^{12} (slow-$e^+ s^{-1}$) for 10 mrad of the orbit arc.

It should be pointed out here that there can be other configurations of the target–moderator system. For example, a number of thin foils of *e.g.* W can be set perpendicular to the longitudinal (synchrotron radiation beam) direction and used as a combined target–moderator system. However, the problem in this case is the size in the longitudinal direction. If we use a 20 μm-thick W foil and require the same order of positron yields as in Table 1, the number of foils must be $\sim 1 \times 10^6$ and the resulting system becomes unrealistically long.

2.4. *Brightness of the positron source*

For many experiments with slow positrons, not only intensity but also minimum possible size and angular and energy spread of the positron beam are important. Then, the positron-beam brightness is a basic characteristic for users as in the case of synchrotron radiation:

$$B = N_{e^+} / \Delta E \Delta t \Delta S \Delta \Omega. \tag{1}$$

It is equal to the number of positrons (N_{e^+}) emitted into unit solid angle ($\Delta\Omega$) within a given energy range (ΔE) per unit time (Δt) and per unit source area (ΔS). In our case the

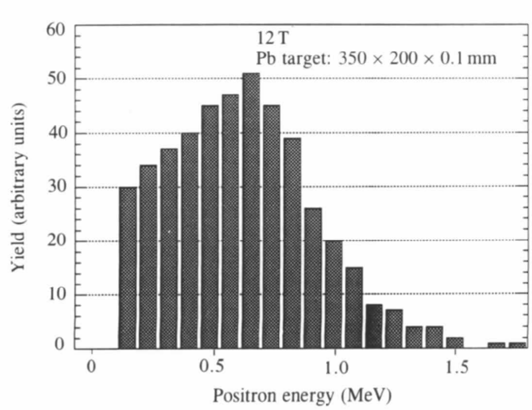

Figure 3
Kinetic energy distribution of positrons emitted from a Pb target for the 12 T wiggler.

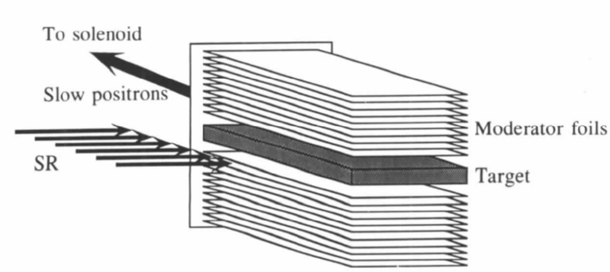

Figure 4
Scheme of positron production and moderation.

brightness of the initial slow positron beam is relatively low because of its large size ($20 \times 35\,\mathrm{cm}^2$).

However, contrary to the synchrotron radiation beam case, it is possible to increase the brightness of the positron source by remoderation of positrons (Mills, 1980). The process of positron-energy moderation is non-conservative, and phase-space limitations of Liouville's theorem do not restrict the possibility of brightness enhancement. A beam of slow positrons can be accelerated, focused to a small spot and remoderated to achieve the original angular and energy characteristics at a cost of ~80–50% of the beam intensity (Frieze, Gidley & Lynn, 1985). By using this process two or more times, one can increase the brightness by a factor of 100–500 (Schultz & Lynn, 1988), although the intensity will decrease one order of magnitude or more. It is an important task to increase the intensity of the initial positron source.

3. Effect of a superconducting wiggler on beam dynamics

Since emittance growth due to perturbations caused by the wiggler should be smaller than the natural emittance, the magnetic field integrals, $I^{(1)} \equiv \int B\,\mathrm{d}s$ and $I^{(2)} \equiv -\int sB\,\mathrm{d}s$, must be smaller than some threshold values. If the wiggler is to be inserted in the low-beta straight section of the SPring-8 storage ring, the conditions $|I^{(1)}| < 2.5 \times 10^{-3}\,\mathrm{T\,m}$ and $|I^{(2)}| < 2.5 \times 10^{-3}\,\mathrm{T\,m}^2$ must be satisfied. These are expected to be satisfied at least for an 8 T wiggler, since for the PLS 7.5 T wiggler it was concluded from field measurements that $|I^{(1)}| < 1.0 \times 10^{-4}\,\mathrm{T\,m}$ and $|I^{(2)}| < 3.5 \times 10^{-4}\,\mathrm{T\,m}^2$ (Mezentsev, Shkaruba, Fedurin & Borovikov, 1995). The vertical tune shift, stop band width and distortions of the amplitude function are estimated to be $\Delta\nu_y = 0.007$, $\Delta\nu_y^{(\mathrm{SB})} = 0.014$ and $(\Delta\beta_y/\beta_y)_{\max} = 5.5\%$, respectively, for an 8 T wiggler. The deviations $\Delta\nu_y$ and $\Delta\beta_y$ can be compensated locally by changing the strength of nearby quadrupole magnets (Miyahara & Lin, 1990; Soutome *et al.*, 1994). The effect on the damping times, energy spread and emittance is shown in Table 3. As can be seen from this table, the emittance is not increased by a superconducting wiggler when it is installed in the low-beta straight section. The emittance, however, can be increased by residual dispersions that exist due to errors, and careful control of these are required. For example, for an 8 T wiggler it is necessary to suppress residual dispersions so that $\eta_x \leq 0.010\,\mathrm{m}$ and $\eta'_x \leq 9.2 \times 10^{-3}$. We have also checked the effect on the dynamic aperture by tracking calculations. The resulting aperture was almost the same as that for the initial ring without a superconducting wiggler.

4. Summary and outlook

We have shown that synchrotron radiation photons are available for producing intense low-energy positron beams.

Table 3
Effect of a superconducting wiggler on the damping times τ_i ($i = x, y, s$), energy spread σ_E/E and emittance ε.

The wiggler is in the low-beta straight section where there is no residual dispersion.

Wiggler field (T)	$\Delta\tau_i/\tau_i$	σ_E/E	ε (nmrad)
0	0	1.09×10^{-3}	7.0
8	−0.07	1.38×10^{-3}	6.7
10	−0.11	1.60×10^{-3}	6.7
12	−0.16	1.87×10^{-3}	7.1

High-energy synchrotron radiation photons are obtained by installing a high-field (8–12 T) superconducting wiggler in high-energy storage rings. The effect of a superconducting wiggler on the stored beam can be neglected if it is installed in the low-beta straight section and residual dispersion is carefully controlled. For an 8 GeV storage ring with 100 mA beam current, final yields of positrons are estimated to be $\sim 10^{10}$–10^{12} (slow-e^+ s^{-1}) for a 10 mrad divergence angle of the synchrotron radiation beam, although further studies are required on target–moderator systems, beam size, intensity, monochromaticity *etc.* In Table 4 we list the efficiency of conversion and moderation and the (measured or expected) final yields in the isotope, linac and synchrotron radiation methods. Some features, such as energy spread and energy tunability, of a slow-positron beam generated by synchrotron radiation will be the same as those generated by a linac. The difference is in the source size, as discussed, and the pulse structure of the positron beam. In the typical operation mode of the SPring-8 storage ring there are ~1000 bunches of electrons circulating along the 1500 m orbit and the typical bunch length is of the order of cm. Thus, 5×10^2–5×10^4 positrons will be created in a pulse every 50 ns (on average). The pulse width is ~30 ps and this value is still larger than the characteristic time for thermalization (~10 ps). This suggests that after moderation we can expect a similar pulse structure in the slow-positron beam. The short-pulsed beam will be useful in some experiments where time resolution is required.

It should be pointed out that the synchrotron radiation method has advantages that cannot be found in other methods: (i) Radiation hazards are drastically reduced and induced radioactivity of target–moderator systems is eliminated. (ii) Cooling of a target is easy. (iii) The lifetime of a target is long. (iv) It is possible to provide 5–10 slow-positron beamlines with a single superconducting wiggler if the vacuum chamber and magnets are suitably designed for extracting a widely spread synchrotron radiation beam. (v) High-energy synchrotron radiation photons can be used not only for positron production but also for other purposes such as γ-ray spectroscopy. (vi) Since synchrotron radiation photons with finite vertical angles are elliptically polarized, it is possible to obtain polarized positron beams by using such photons. For example, photons emitted with a vertical angle of 0.02 mrad have a degree of polarization of ~50%. In order to realize a highly polarized positron

Table 4
Comparison of different methods of producing low-energy positrons.

Method	Facility	Source	Efficiency of conversion and moderation	Intensity (slow-e^+ s^{-1})
β^+-decay of isotopes	Nuclear reactor	^{22}Na (2.6 y) $\rightarrow e^+$ ^{58}Co (71 d) $\rightarrow e^+$ ^{64}Cu (12.7 h) $\rightarrow e^+$	$\sim 10^{-3}$	$\sim 10^6$
	Cyclotron (PSI)	^{18}F (110 min) $\rightarrow e^+$ ^{11}C (20 min) $\rightarrow e^+$	0.25	10^{10}
Pair production	Nuclear reactor (Grenoble)	$Cd(n,\gamma) \rightarrow \gamma \rightarrow e^+e^-$	10^{-3}	2.5×10^{10}
	Electron linac* 400 MeV, 400 kW (CEBAF)	$e^- \rightarrow \gamma \rightarrow e^+e^-$	4×10^{-6}	2.5×10^{10}
	8–12 T S/C wiggler (SPring-8)	$\gamma \rightarrow e^+e^-$	$\sim 10^{-5}$	$\sim 10^{10}$–10^{12}
	0.3 T 10 m wiggler (LEP70)	$\gamma \rightarrow e^+e^-$	$\sim 10^{-5}$	$\sim 10^{12}$

* Kossler, Greer & Hulett (1993).

beam, however, it is necessary to select positrons whose energies are near the kinematically allowed maximum value (Balakin & Mikhailichenko, 1983), and further studies are required for this. (vii) The low-energy positron beam and the synchrotron radiation beam can be used at the same time. This offers us a new and very unique method of analyzing substances (Shiotani, 1995).

Synchrotron radiation can be used not only as a probe but also as a source of new probes. The use of synchrotron radiation for producing positrons will open a new stage of materials research in the future.

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