Evaluation of the optical performance of a brightness enhancement system developed for the KUR slow positron beamline

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Abstract. A slow positron beamline using a nuclear reactor is under development at the Kyoto University Research Reactor (KUR). A brightness enhancement system was designed to reduce the initial positron beam size (~30 mm) below typical specimen sizes (<10 mm) and keep the intensity of the beam as high as possible. After installation of the brightness enhancement system at the beamline, we tested its optical performance using an electron beam. The experimental result indicated that the system would have enough capability to obtain a small-sized beam suitable for positron measurements.

1. Introduction
Positron annihilation spectroscopy (PAS) with energy-variable positron beams is a powerful tool to investigate open-volume-type defects of atomic dimensions such as vacancies, vacancy agglomerates and micro voids near surfaces or in thin films [1]. An intense positron source is one of the key components in the slow positron beam system to achieve efficient and precise PAS measurements. We have recently developed a reactor-based, high-intensity slow positron beamline at KUR [2]. The beamline consists of a positron source, a brightness enhancement system, a pulsing system and an experiment chamber. A slow positron beam with an intensity of $1.4 \times 10^6$ s$^{-1}$ was successfully obtained under 1 MW reactor operation (the reactor has a maximum power of 5 MW) [2].

At KUR, the initial diameter of the positron beam is around 30 mm, and this is much larger than the size of typical samples (~10 mm) used in other slow positron beam facilities. Therefore it is desirable to reduce the initial beam size to below 10 mm and to keep the beam intensity as high as possible. We are developing a brightness enhancement system to achieve this purpose.

2. Design of a brightness enhancement system
The KUR brightness enhancement system was designed based on the system developed by Oshima et al. at AIST [3]. An initial slow positron beam generated in a solenoidal magnetic field is extracted to the outside of the magnetic field and focused on a transmission-type remoderator. Positrons re-emitted from the remoderator have a greatly reduced angular dispersion, leading to an increase in the beam brightness. At AIST, the brightness enhanced beam (remoderated beam) is then transported by electrostatic fields while in the KUR design it is transported by continuous solenoidal magnetic fields.
At KUR, we have to guide the brightness enhanced beam over a distance of ~1.5 m to the pulsing system by keeping a relatively low beam energy in the range of several eV to a few tens of eV. Electrostatic guiding through the pulsing system may be possible but would be quite complex; so solenoidal magnetic fields are used to efficiently guide the brightness enhanced beam.

In addition, when we measure large samples bigger than 30 mm, it is better to use the initial positron beam without brightness enhancement for higher count rates. The brightness enhancement system was designed taking into consideration the above points.

2.1 The characteristics of our brightness enhancement system
A schematic view of our brightness enhancement system is shown in figure 1. The system is composed of guiding coils (LA–LG), an acceleration gap, extraction coils (LC, LD, MA and MB), a magnetic lens, a transmission-type remoderator (movable) and a solenoid coil (SC). To observe the beam spot, a movable micro-channel plate (MCP) with a phosphor screen can be installed at the remoderator position. Experiments can be performed with two guiding modes in the following ways:

(1) Brightness enhancement mode: The initial positron beam magnetically transported from the positron source is accelerated by an acceleration gap (~5 keV) and extracted to a low magnetic field region by the extraction coil (MA). The large coils LE and LF are not used. The beam is focused on the transmission-type remoderator (150 nm-thick crystalline Ni) using the magnetic lens, and positrons are re-emitted from the remoderator. The brightness enhanced beam is magnetically guided to the pulsing system.

(2) Non-brightness-enhancement mode: In this case, the initial beam coming from the source is magnetically transported with the large coils (LA–LG) and without the medium and solenoid coils (MA, MB and SC). To keep a quasi-uniform magnetic field around the magnetic lens, the lens is weakly excited. The remoderator can be retracted from the center of the beamline to transport the beam without brightness enhancement.

2.2 Guiding of the brightness enhanced beam with solenoidal magnetic fields
If the positron beam is adiabatically transported by a solenoidal magnetic field, the relationship between the magnetic field and the transverse energy is given by the following equation [4]:

$$\frac{E_{\tau}}{B_{\tau}} \approx \frac{E_{\tau}}{B_{\tau}},$$  \hspace{1cm} (1)

where $B_{\tau}$ and $B_{\tau}$ are the magnetic fields at the remoderator and the pulsing system, respectively. $E_{\tau}$ and $E_{\tau}$ are the transverse energies at the remoderator and the pulsing system, respectively. Considering the law of conservation of energy ($E_{\tau} + E_{\tau} = E_{\tau} + E_{\tau}$) where $E_{\tau}$ and $E_{\tau}$ are the longitudinal energies at the remoderator and the pulsing system, respectively, the following equation is derived using equation (1):
\[ E_{lp} \approx E_{lr} + \left(1 - \frac{B_p}{B_r}\right)E_{sr}. \]  

(2)

Therefore the longitudinal energy spread at the pulsing system \( \Delta E_{lp} \) can be approximately given by the error propagation rule with the longitudinal energy spread \( \Delta E_{lr} \) and the transverse energy spread \( \Delta E_{sr} \) at the remoderator position as follows:

\[ \Delta E_{lp} \approx \sqrt{\Delta E_{lr}^2 + \left(1 - \frac{B_p}{B_r}\right)^2 \Delta E_{sr}^2}. \]  

(3)

The pulse width obtained by the pulsing system is approximately proportional to \( \Delta E_{lp} \). Therefore, it is desirable to achieve \( B_p/B_r \approx 1 \) to obtain a pulsed beam with optimum time resolution. Since the designed \( B_p \) at the pulsing system is about 5 mT, the brightness enhancement system needs to have \( B_r \) of ~5 mT at the remoderator position.

2.3 Design of the magnetic lens

The following two points were considered when designing the magnetic lens.

(1) In the “brightness enhancement mode”, the magnetic lens needs to focus the beam to a spot as small as possible at the remoderator. In addition, the magnetic field \( B_r \) should be ~5 mT. In order to maximize the remoderation efficiency the positron beam energy is set to ~5 keV.

(2) In the “non-brightness-enhancement mode”, the positron beam with a diameter of ~30 mm must pass through the inner yoke of the lens.

The lens was designed to meet these requirements based on the magnetic lens used in AIST [3] (see figure 1). By varying the inner diameter of the lens from 10 mm to 90 mm, we calculated the magnetic field distributions for the focusing of a 5 keV positron beam at the remoderator position. In the calculation, the distance from the lens-edge to the remoderator was fixed to 10 mm and the thickness of the yoke was fixed to 5 mm. Calculation results are shown in figure 2. It is clear that the lens with an inner diameter of 50 mm meets all the requirements. Based on this calculation, the focusing lens was fabricated with an inner diameter of 50 mm and installed in the KUR system. The measured magnetic field distribution was in agreement with the calculated one.

![Figure 2](image)

(a) Magnetic field distributions formed by the magnetic lens when a 5 keV positron beam is focused on the remoderator (Inner diameter of the lens: 10, 50, 90 mm). (b) Magnetic field at the remoderator position \( B_r \) as a function of the inner diameter of the lens.

3. Evaluation of the optical performance using an electron beam

We performed experiments to evaluate the optical performance of the brightness enhancement system installed at the beamline and estimated the beam diameter at the focus point. Since KUR has not been in operation for about 2 years to comply with new safety regulations, an electron beam was used (see figure 1). Electrons generated by the photoelectric effect are extracted to form a beam with a bias voltage of 10 V. The beam spot was observed using an MCP with a phosphor screen and imaged by a camera. In this experiment, the initial beam diameter of the electron source was 15 mm.

A minimum beam spot size was obtained when the current of the focusing lens was around 2.3 A.
[see figure 3 (a)]. We estimated the focused beam diameters (full-width at half maximum, FWHM) and confirmed that an electron beam with an initial diameter of 15 mm was focused to 2.9 mm.

We calculated the beam trajectory using the GPT [5] and Poisson Superfish [6] codes with the same parameters as those of the experiment. The cross sectional view at the focus point is shown in figure 3 (b). From this calculation, it is confirmed that a 15 mm electron beam can be focused to 3.1 mm (FWHM) with a magnetic lens current at 2.3 A. This calculation value was in good agreement with the experimental value (2.9 mm). A similar calculation indicated that a 30 mm electron beam could be focused to 5.5 mm. This implies that the demagnification factor of our focusing system is ~1/5. Considering the reemission efficiency (around 10-20%) of the 150 nm Ni remoderator [7], the initial positron beam can be at least 2.5–5.0 times brightness enhanced.

The magnetic field at the remoderator ($B_r$) was 4.1 mT when the current of the lens was 2.3 A. This means that the ratio $B_p/B_r \approx 1$ was almost achieved.

We also tested the “non-brightness-enhancement mode” of the system using an electron beam. The electron beam passed successfully through the system keeping the same beam diameter ~15 mm.

![Image](a) ![Image](b)

**Figure 3.** The intensity profiles of the beam spot obtained when the lens current was 2.3 A by (a) the experiment and (b) the calculation.

4. Summary

We designed and installed a brightness enhancement system for the KUR slow positron beamline. Then, we performed experiments to evaluate the optical properties of the system using an electron beam. A demagnification factor of 1/5 was achieved, implying that typical samples (size: ~10 mm) can be measured with our system. To obtain smaller beam sizes, further optimization of the magnetic field distribution is in progress. In the near future, we will apply this brightness enhancement system to slow positron beams.

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