Design of an Acceleration Gap for Brightness Enhancement in a Reactor-Based Slow Positron Beamline

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Design of an acceleration gap using mesh electrodes of the brightness enhancement system for the slow positron beamline of Kyoto University research reactor was studied to improve the performance of brightness enhancement. The transmittance and the increase in the angular divergence of the beam resulting from acceleration with the mesh electrode were estimated by trajectory simulations. The effect of the increase in the beam emittance on the beam radius at the focus point was estimated based on the analytical solution of the beam envelope equation. Using the obtained beam transmittance and beam radius, the beam brightness after remoderation was evaluated. Then, the influence of the mesh electrode configuration on the brightness was investigated.

DOI: 10.12693/APhysPolA.132.1620
PACS/topics: 78.70.Bj, 41.75.Fr, 29.27.Eg, 41.85.Ja

1. Introduction

A slow positron beamline is currently under development for the Kyoto University research Reactor (KUR) [1–4]. The KUR slow positron beamline is composed of a positron source, a brightness enhancement system, a pulsing system, and a measurement chamber. Positrons are generated by pair production from high-energy gamma rays. A W convertor/W moderator assembly is used to generate a slow positron beam. At the KUR, the initial beam diameter is expected to be around 30 mm, which is significantly larger than the size of a typical sample (around 10 mm). Therefore, it is desirable to reduce the initial beam size to below 10 mm while maintaining the beam intensity as high as possible. Therefore, the brightness enhancement system [3] was installed in the beamline.

The brightness enhancement system consists of an acceleration gap, a magnetic lens, a transmission-type remoderator, and several coils (Fig. 1). A positron beam is magnetically guided from the positron source and is subsequently accelerated to 5 keV by the acceleration gap; it then reaches a low magnetic field region ($B_{\text{low}}$ in Fig. 1), in which the beam diameter is expanded. The beam is focused onto the remoderator by the magnetic lens, and a fraction of positrons is re-emitted from the opposite surface of the remoderator. In this process, although the total positron flux decreases, the flux density increases, resulting in enhanced brightness. We use a 150-nm-thick Ni (100) thin film [5] as a remoderator purchased from the University of Aarhus. The principle of the brightness enhancement method is described in detail elsewhere [3, 6–9].

For brightness enhancement, the acceleration of the positron beam is essential to obtain sufficient focusing through the magnetic lens and is also essential to maximize the re-emission efficiency at the remoderator. In this study, an acceleration gap consisting of a pair of electrodes with two wire meshes was used (Fig. 1). This was referred to as a mesh electrode. The beam is accelerated by the electric field formed between two electrodes. An ideal mesh electrode is virtual mesh with 100% transmittance in which the ratio between the wire diameter $d$ and the aperture width $w$ and the ratio between $w$ to the distance between two electrodes $L$ are negligibly small. Using an ideal mesh electrode, a positron beam can be accelerated through a uniform electric field without any loss in the beam intensity (i.e. the beam transmittance $\eta_a \approx 1$). That is, there is no degradation of the beam brightness through acceleration. However, this is not the case with actual mesh electrodes. First, there is a loss of intensity at the wire mesh due to the collision ($d/w > 0$). Secondly, the beam is disturbed by the lens effect due to the distortion of the electric field around the apertures of the wire mesh ($w/L > 0$). The distribution of the angle $\theta_k$ along the beam axis of each particle $k$ spreads and the Larmor radius increases, resulting in an increase in...
the angular divergence of the beam $\theta$ (or the beam emittance). Therefore, the beam radius at the focus point $r_F$ becomes larger. These two factors cause the degradation of the beam brightness. Thus, the properties of the mesh electrode which affects $\eta_o$ and $\theta$ should be optimized.

In this paper, the influence of the parameters of the mesh electrode on $\eta_o$ and $\theta$ were estimated by beam trajectory simulations. The effect of the increase in the beam emittance on $r_F$ was estimated by an analytical solution of the beam envelop equation. Using the obtained values of $\eta_o$ and $r_F$, the beam brightness $\beta_r$ after the remoderation were estimated. Then, three different mesh electrodes were evaluated to investigate the optimal mesh electrode.

2. Methods and results

To understand the dependence of $\eta_o$ and $\theta$ on the characteristics of the mesh electrode, three types of wire meshes were investigated. These wire meshes are characterized by following parameters: the number of apertures per unit inch $N$, the aperture width $w$, the wire diameter $d$, and the normalized open screening area $A_o (= w^2/(w + d)^2)$ (Table I). We chose commercially available wire meshes of $N = 30, 100$ and 150 apertures/inch. Three commercially available wire meshes of $N = 30, 100$ or 150 apertures/inch with $d = 0.03$ mm were tested in this study, and the distance between two electrodes was fixed to 10 mm; thus, $d/w$ and $w/L$ values were listed in Table I.

<table>
<thead>
<tr>
<th>$N$ [1/inch]</th>
<th>$w$ [mm]</th>
<th>$d$ [mm]</th>
<th>$A_o$</th>
<th>$d/w$</th>
<th>$w/L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.82</td>
<td>0.030</td>
<td>0.93</td>
<td>0.037</td>
<td>0.082</td>
</tr>
<tr>
<td>100</td>
<td>0.22</td>
<td>0.030</td>
<td>0.78</td>
<td>0.134</td>
<td>0.022</td>
</tr>
<tr>
<td>150</td>
<td>0.14</td>
<td>0.030</td>
<td>0.68</td>
<td>0.215</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Generally, the brightness $\beta$ of a positron beam is defined as [6, 8, 9]:

$$\beta = I \left( r^2 \theta^2 E_r \right)^{-1},$$ (1)

where $I$ is the beam intensity, $r$ is the beam radius, $\theta$ is the angular divergence of the beam, and $E$ is the beam energy. The brightness after remoderation $\beta_r$ can be calculated as $\eta_o Y_r I_m (r^2 \theta^2 E_r)^{-1}$, where $I_m$ is the beam intensity before acceleration, $Y_r$ is the re-emission efficiency of the remoderator, and $\theta_r$ and $E_r$ are the angular divergence of the beam and the beam energy after remoderation, respectively. These four parameters do not depend on the mesh electrode, so the value of $\beta_r$ normalized to the brightness obtained with an ideal mesh electrode is a function of $\eta_o Y_r^{-1}$. $\eta_o$ can be calculated as the square of the transmittance, $A_o^2$ (solid line in Fig. 2a), for the set of the first and second wire meshes.

As the analytical estimation for the increase in $\theta$ may be difficult, beam trajectory simulations were performed using the SIMION code (version 8.1). The results of the trajectory simulations are shown as $XY$ cross-sectional views in Fig. 3. The simulation volume was 50 mm × 11 mm × 11 mm on the right-handed Cartesian coordinates ($XYZ$ coordinates). The origin corresponds to the center of the beam duct at the left end (see Fig. 3). The beam propagation direction corresponds to the $X$-axis, and the start point of the beam is $X = 0$ mm. The first and second wire meshes are located at $X = 20$ mm and $X = 30$ mm, respectively. An acceleration voltage of −5 kV was applied to the second electrode, and the boundary condition between two electrodes along the wall of the beam duct was the natural boundary condition (i.e. the electric field in a normal direction was assumed to zero). The equipotential surfaces around the first wire mesh ($X = 18–20$ mm) in each case are shown in Fig. 4. It should be noted that these equipotential surfaces were calculated results around the center (i.e. far from the wall) of the beam ducts. In other words,
The results of the trajectory simulations shown in Fig. 3 clearly indicate that the divergence of the beam increases as the aperture width is widened. The distortion of the electric field around each aperture (Fig. 4) works as a lens for the positrons. As the aperture width increases, the distortion of the electric field increases, and hence, the beam diverged more significantly. Around the second wire mesh, similar distortions were also observed (not shown) in the electric field. However, the lens effect of these distortions was less significant because the beam had already been accelerated to ≈ 5 keV upon reaching the second wire mesh, and the influence of a distortion in an electric field becomes relatively small for higher-energy beams. These results suggest more suitable mesh electrodes could be selected: a first mesh with a smaller $w/L$ ratio and a second mesh with a smaller $d/w$ ratio.

3. Discussion
Design of an acceleration gap with mesh electrodes for the brightness enhancement system of the KUR slow positron beamline was studied to improve the performance of brightness enhancement. The beam transmittance and the increase in the angular divergence of the beam at the mesh electrode were estimated by trajectory simulations. The effect of an increase in the beam emittance on the beam radius at the focus point were estimated by applying an analytical solution to the beam envelope equation. From these estimations, the beam brightness after the remoderation was evaluated. The obtained results suggest that the optimal condition for relatively large-diameter (>30 mm) beams, such as that of the reactor-based positron source, can be attained using a coarse mesh (i.e., an electrode with a wire mesh of 30 apertures/inch).

**4. Summary**

Figure 2a shows the \( \eta_a \) values estimated based on the values of \( A_\text{eff}^2 \) (solid line) and the corresponding simulated values (closed circles). These results agree with each other, indicating that the beam transmittance can be estimated without characterizing the distortion of the electric field. The inverse squares of the \( r_F \) values with \( N = 30, 100, \) and 150 normalized to the \( r_F \) value obtained with the ideal mesh electrodes are shown in Fig. 2c. The values vary slightly with the 30-mm-diameter beam, but they differ significantly with the 4-mm-diameter beam. This is because the increase in \( \theta_{\text{out}} \) affects \( Q^2 \) (i.e., \( r_F \)) more significantly in the 4-mm-diameter beam. The evaluated normalized brightness values shown in Fig. 2d indicate that, with a 30-mm-diameter beam, the brightness can be maximized using a wire mesh with \( N = 30 \) because the effect of \( \eta_a \) on the brightness is more significant than the influence of \( r_F \) on the brightness. The brightness values when \( 2r = 40, 50, \) and 60 mm were also evaluated and the highest brightness values were obtained with a wire mesh of \( N = 30 \). On the contrary, in the case of a 4-mm-diameter beam, wire meshes with \( N = 100 \) or 150 resulted in higher brightness than a wire mesh of \( N = 30 \) because, in this case, the \( r_F \) value had a more significant effect on the brightness than \( \eta_a \).

Another potential candidate for the acceleration of a positron beam is an acceleration tube, which consists of several ring electrodes without any wire meshes. It may be informative to make a critical comparison between a mesh electrode and an acceleration tube to further improve the performance of the brightness enhancement system.

**Acknowledgments**

We would like to thank Drs. K. Sato (Kagoshima Univ.), Q. Xu (KURRI), and K. Ito (AIST) for valuable discussion and also thank our colleagues at AIST, Tohoku Univ., Kyoto Univ., KEK, and the Tokyo Univ. of Science for their invaluable assistance.

**References**


