Feasibility study of neutron production at SLRI beam test facility

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Abstract. SLRI Beam Test Facility (SLRI-BTF) has been constructed in order to increase usage of the Siam Photoc Source injector. SLRI-BTF aims to provide electron test beams for calibration and testing of high-energy particle detectors and diagnostic instrumentations. The test-beam energy varies from 40 MeV to 1.2 GeV with adjustable intensity from a few to several millions of electrons per repetition rate. Since the test-beam energy is sufficiently large, the electron test beam can be used to produce photoneutrons resulted from collision of high-energy electrons to metal targets. Similar to the electron test beams, this neutron source will be utilized for calibration and testing of neutron detectors and instrumentations. In this work, the neutron production and its angular dependence has been investigated using the PHITS simulation code. The results show that photoneutrons generated by collision of the high-energy electron beam on a tungsten target are in range of intermediate and fast neutrons or 0.01 - 10 MeV with peak contribution at 0.6 ± 0.1 MeV and uniformly distributed in angular direction. For the primary beam of 10⁸ electrons per spill at SLRI-BTF, the photoneutron flux is predicted to be around 50 neutrons/cm². Based on this study, the possibility to service a neutron source for users in the future will be determined further.

1. SLRI Beam Test Facility

The SLRI Beam Test Facility (SLRI-BTF) is a newly extended experimental station at the Synchrotron Light Research Institute (SLRI) [1]. Built to increase a variety of researches conducted, SLRI-BTF directly utilizes high-energy electrons produced from the Siam Photon Source (SPS) injector. The electron test-beam energy is tunable from 40 MeV to 1.2 GeV depending on acceleration time of a booster synchrotron. The intensity of the electron test beam is adjustable from a few to millions of electron per spill using an electron-beam intensity reduction system. However, not only is the test beam used for calibration and testing of high-energy particle diagnostic devices and instrumentation [2], it can be used as a primary beam to produce photoneutrons. Successfully demonstrated at the DAFNE beam test facility, Frascati, photoneutrons are generated by using the electron beam of 510 MeV that impinges on a tungsten target [3]. In order to maximize benefits from photoneutron production at SLRI-BTF, it is necessary using simulation to determine properties and understand characteristic of these neutrons before installing all components.
Figure 1. Layout of the Siam Photon Source injector and the location of the SLRI beam test facility.

SLRI-BTF entirely situates in the injector hall and shares the entrance with the synchrotron booster and other accelerator components. Figure 1 illustrates the layout of the SPS injector on the basement, which includes all accelerator components up to half of the high-energy beam-transport line (HBT), and the location of SLRI-BTF. The SPS injector consists of an electron gun, a linac with two accelerating structures, a low-energy beam-transport line (LBT), a synchrotron booster, and HBT. The electron beam with energy of 40 MeV at the exit of the linac section is accelerated to 1.2 GeV by the synchrotron booster and extracted to HBT. At HBT, the high-energy electron beam is transported via a 4-degree bending magnet and controlled by two pairs of focusing-defocusing quadrupoles, one horizontal steerer, and three vertical steerers. Depicted in Figure 2, the area of 3.5 x 3.5 x 4 m³ next to the vertical bending magnet that deflects the electron beam to the SPS storage ring is allocated for the SLRI-BTF experimental setup. This area was once used for measuring electron-beam current at HBT during commissioning of the SPS injector.

Table 1 lists electron-beam parameters at HBT. The electron beam with maximum energy of 1.2 GeV can be transported while energy spread of 0.05% was determined at 1.0 GeV. The extracted electron beam has structure of 10 buckets with 8.5 ns pulse duration and 0.5 ns bunch length. The repetition rate of the 1-GeV electron beam is at 0.5 Hz and decreases to 0.33 Hz for the 1.2-GeV electron beam. Without an electron-beam intensity reduction system, the number of electrons has been measured to be around 10⁸ electrons per spill.

During the operation of SLRI-BTF, the electron-beam intensity at HBT can be adjusted using the metal target to attenuate primary electron beam at LBT. Installed in the LBT target chamber, the wedge tungsten target with maximum thickness of 6 mm and positional resolution of 0.1 μm provides fine tuning of secondary electron-beam intensity and fast response to intensity fluctuation [4]. In addition, this target can alternatively be used as an option for adjusting the photoneutron production rate that is proportional to the electron beam intensity impinging on the target. The neutron flux can be reduced by half when the half of the target is inserted.
Table 1. Electron-beam parameters at High-energy Beam Transport line (HBT).

| Parameters          | Value                      |
|---------------------|----------------------------|
| Particles           | electron                   |
| Energy              | 40 MeV – 1.2 GeV           |
| Energy spread       | 0.05% at 1.0 GeV           |
| Pulse duration      | 8.5 ns                     |
| Bunch length        | 0.5 ns                     |
| Repetition rate     | 0.5 Hz at 1.0 GeV          |
| # of electrons per spill | 10$^8$               |

Figure 2. SLRI-BTF experimental area next to the vertical bending magnet that transport high-energy electron beam to the SPS storage ring.

Figure 3. Location of the target chamber at the end of LBT. The wedge tungsten target is mounted on a manipulator with a flat side facing an electron beam.

2. Simulation of photoneutron production

2.1. PHITS simulation code

In preparation to provide neutrons for testing instrumentation at SLRI-BTF, it is essential to understand characteristics of photoneutrons produced. The Particle and Heavy Ion Transport code System (PHITS), which is a general purpose Monte Carlo particle transport simulation code developed under collaboration among JAEA, RIST, KEK and other institutes [5], has been used. Including several nuclear reaction models and data libraries, PHITS is able to calculate transport and collision of almost all particles with wide range of energy from 1 keV/nucleon - 1 TeV/nucleon. Moreover, PHITS is user-friendly designed as the entire content is contained in one package and can be easily executed in all platforms. Parallel calculation is conveniently implemented with Message Passing Interface (MPI) protocols and open-multiprocessing (openMP) directives. Physical quantities, such as production yields, track length, etc., can be obtained with various tally estimate functions. The simulated geometry can be constructed with general geometry format similar to one used in MCNP [6] or by auxiliary GUI softwares, for example, SimpleGEO [7] and SuperMC [8].
2.2. Simulation parameters
The simple geometry that imitates a setup for neutron production at SLRI-BTF consists of an electron-beam exit with a 0.5-mm (equivalent to 0.14% in radiation length unit) thick beryllium window, a tungsten target, and lead shielding. Since the energy spread of the 1.2-GeV electron beam has not been identified, the electron beam with Gaussian distribution of 0.5-cm FWHM in transverse plane and of 60-MeV FWHM in energy is thus used as a primary electron beam. The tungsten target of 5 cm thick is placed 50 cm away from the exit window outside a vacuum beam duct and on a test stand surrounded by 10-cm thick lead shielding. The target is also aligned on the beam axis. The open hole with a diameter of 10 cm reserved for installation of a neutron detector is perpendicular to the target plane. A removable cylindrical lead shield is placed inside the hole in order to filter undesired particles. In calculation of photoneutron production at SLRI-BTF, the EGS5 package [9], which is a general purpose package for Monte Carlo simulation of the coupled transport of electrons and photons with energy ranging from a few keV to several hundred GeV, is activated since the primary electron-beam energy is larger than 1.0 GeV. Simulation has been performed with the total of $10^6$ electrons.

2.3. Results and discussion
Simulation results showing flux of neutrons, protons, electrons, and photons produced after the collision by the electron beam of 1.2 GeV are illustrated in Figure 4. The neutron flux uniformly distributed in the target area and outside of the shielding block while protons are slightly produced and well confined inside the shield. Since the collision of electrons first occurs at the beryllium window, the flux and tracks of secondary electron beam are found from the beryllium window to the target. Due to high energy of the electron beam and the thin beryllium window, a large number of electrons can traverse to the back shielding wall while the scattering of the electron beam is small and negligible. Secondary electron flux largely decreases and is well shielded by 10-cm thick lead blocks. Photon flux is also confined inside the lead shield and significantly reduced at the detector area.

Figure 5 depicts the angular flux distribution of neutrons, protons, and electrons at the detector hole. Flux of neutrons recorded at the detector holes, at $r = 24.0 - 25.0$ cm and $\theta = 160 - 200$ degrees, is approximately 20% larger than average flux. Since the target area is cylindrical asymmetric, the photon flux is observed with large fluctuation. The shield inside the detector hole is intentionally placed to reduce the photon flux to be detected in the detector hole that could potentially influence to the detection efficiency of the photoneutrons. Due to interaction in the shield, the electron flux around the detector hole is less attributed by geometry than that of photons. The electron flux found at the detector hole is 1.4% larger than the average flux. The proton flux is tiny because of low production rate.

For the flux distribution as a function of longitudinal position at radius of 24.0 - 25.0 cm and angle between 160 - 200 degrees, shown in Figure 6, it is apparent that the highest neutron and electrons fluxes are recorded at the detector hole. This results from the position of the target where it is transversely aligned with the detector hole and from the geometry of the shield. However, significant electron flux outside the target area could be contributed by backscattered and secondary electrons. In addition, significant amount of photon flux found outside the shield leaks through the open gap for incoming electron beam. Flux of protons is slightly detected in the detector hole and the other area.
Energy distributions of neutron, proton, and electron at the detector hole are illustrated in Figure 7. Energy of detected photoneutrons ranges from 0.01 - 10 MeV with a peak at 0.6 ± 0.1 MeV or in intermediate and fast neutron energy ranges. However, the flux of low energy neutron (<10 keV) could be slightly observed from the simulation if the statistic is sufficiently large. The energy of detected electrons ranges from 0.1 - 10 MeV while low energy electrons is absorbed by the shield. Although the proton flux increases along with proton energy, the amount of flux is negligible. Even in the situation of the real electron-beam intensity, the proton flux only gains by two orders of magnitude. For the photon flux seeming slightly large, it is still lower than the desired limit of the neutron detector. With the primary beam of $10^8$ electrons per spill, the maximum photon flux could be up to 10 photons/cm$^2$.
3. Summary and outlook
SLRI-BTF has been developed to provide not only electron test beams but also neutrons from photoneutron production for testing and calibration of neutron diagnostic devices. Flux of photoneutrons generated after collision of high-energy electrons has been investigated using PHITS, a Monte Carlo transport simulation code. While the photoneutrons produced in range of intermediate and fast neutrons uniformly distribute in the target area, electrons and photons that are also created can be suppressed by lead shield. The hole for mounting a neutron detector is able to detect such neutrons. In order to obtain cleaner test neutrons with lower background, magnetic field could be introduced to filter secondary electrons. A detector sensitive to neutron will later be installed to confirm production and the number of photoneutrons.

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Figure 7. Flux of neutrons, protons, electrons, and photons as a function of energy. Data is recorded at the detector hole where radius is between 24.0 - 25.0 cm, angle is between 160 - 200 degrees, longitudinal position is 45.0 - 50.0 cm.
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