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Development of a mono-energetic positron beam line at the Kyoto University Research Reactor

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ABSTRACT

Positron beam facilities are widely used for solid state physics and material science studies. A positron beam facility has been constructed at the Kyoto University Research Reactor (KUR) in order to expand its application range. The KUR is a light-water-moderated tank-type reactor operated at a rated thermal power of 5 MW. A positron beam has been transported successfully from the reactor to the irradiation chamber. The total moderated positron rate was greater than 1.4×10^6/s while the reactor operated at a reduced power of 1 MW. Special attention was paid for the design of the in-pile position source to prevent possible damage of the reactor in case of severe earthquakes.

1. Introduction

Mono-energetic positron beams are uniquely used for a wide variety of experiments in solid state physics and material science, such as obtaining spatially resolved maps of plastically deformed or irradiated metals [1–4], non-destructive investigation of thin layers [5], and observing the annealing behavior of defects or free volumes in polymers [6]. In addition, they can be used for studying the Fermi surface and the topmost atomic layers of materials [7]. The main positron sources employed in the generation of a positron beam are β^+ radioactive isotopes, such as ^{22}Na. In these positron beam facilities, vapor-deposited cryogenic rare gas solids, such as solid Ne, are used to achieve a high positron moderation efficiency. For example, the positron moderation efficiency of solid Ne is as high as about 1% [8], while that of a thin-film W moderator is of the order of several 10^{-4} [9], and strongly depends on its prior heat treatment. A ^{22}Na source of 1.85×10^9 Bq can produce 10^7/s moderated positrons using a Ne moderator. However, the disadvantage of using ^{22}Na is that the delivery of the source is long. In addition to the β^+ radioactive isotopes, linac-based positron sources can also deliver higher beam intensities [10,11], where positrons are generated in a high-Z target bombarded by electrons with energies of several tens of MeV.

It has been reported that highly energetic γ-rays, with energies higher than the threshold energy for pair production (1.022 MeV) produced by a reactor can be used as positron sources because positrons are naturally generated by pair production [12,13]. Furthermore, the intensity of the γ-radiation can be increased with the reaction ^{113}Cd (n, γ) ^{114}Cd, and it was previously used in the NEPOMUC facility at the FRM II at the Technische Universität München, which is the facility that delivers the world's highest positron beam intensity, and in the positron beam facility at the North Carolina State University [14].

In order to promote the research application of the Kyoto University Research Reactor (KUR), an old and less frequently used irradiation facility has been removed. In its place, a high-intensity positron beam facility has been designed and constructed. In this paper, the design specifications and the main characteristics of this reactor-based positron beam are described.

2. Outline of the KUR

The KUR is a light-water-moderated tank-type reactor operating at a maximum thermal power of 5 MW. The cross-sectional view of the reactor is shown in Fig. 1. The reactor core consists of plate-type fuel elements (U_3Si_2–Al) using about 20% enriched uranium and graphite reflector elements. The maximum and average thermal neutron flux is 8×10^{13} and 3×10^{13} n/cm^2 s, respectively. Criticality of the KUR was first achieved in 1964. The KUR

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has been widely used for experimental studies in physics, chemistry, biology, engineering, agriculture, and medicine for over 50 years. Therefore, some experimental facilities became outdated and their use was infrequent. In order to expand the use of the reactor, the construction of the positron beam facility, which does not depend on the isotope market supply and has many prospective users, was planned 4 years ago. The large irradiation hole is ideal to deliver high-intensity positron beams because the production of positrons is proportional to the area of the converter. The largest irradiation hole B-1 shown in Fig. 1, which has a diameter of 20 cm, was selected to construct the in-pile positron source. As the first stage of the in-pile positron source, the converter was set at a position 12 cm away from outer plug of the B-1 hole to decrease the temperature increase generated by γ-radiation. The thermal neutron flux and the γ-ray flux at the positron source position are about 1.5×10^{12} n/cm^2 s and 10^5 Gy/h, respectively, at 5 MW.

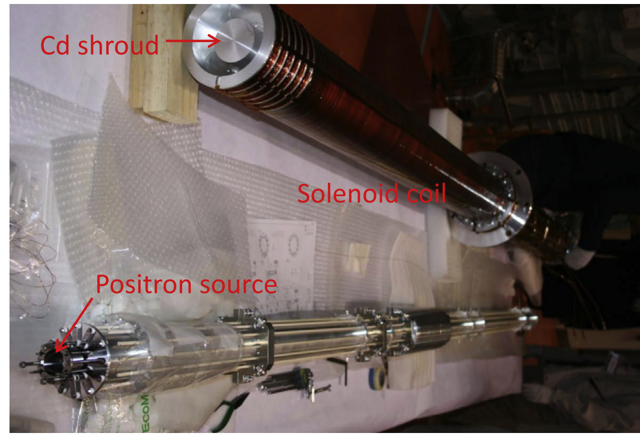

Fig. 2. Components of the positron beam line located inside the reactor.

3. Mono-energetic positron beam line at the KUR

The positron beam line consists of two parts: one part is located inside the reactor (shown in Fig. 2), and the other is located outside the reactor (Fig. 3). The first part is composed of two tubes with the positron source set on the top of the smaller-diameter tube. The other tube consists of a solenoid having a highest magnetic field of 7 mT, which guides the positrons to the outside the reactor. Positions are generated by pair production from high-energy γ-rays. The positron source in the present study is composed of a converter and a moderator, which moderates the positrons with high energy. The converter consisted of a 1-mm-thick and 3-cm-diameter Tungsten, while a 50-μm-thick meshed structure was used as a moderator [15]. In order to enhance the positron generation, a 1-mm-thick Cd shroud covered with an Al plate was mounted on the top of the magnetic field to cap the *W* converter and moderator as shown in Fig. 2, because high-energy γ-rays are generated by the ^{113}Cd (n, γ) ^{114}Cd reaction. The cross-section of thermal neutron capture in ^{113}Cd (the abundance of ^{113}Cd in natural Cd is 12.22%) is up to 26,000 barns, on average, 2.3 photons with energy above 1.5 MeV are emitted per captured neutron [15]. In addition, seven independent solenoids made Al wires coated with Al_2O_3 were placed at the same side of the tube to enhance the positron beam. A cross-section view of the in-pile positron source is shown in Fig. 4. In order to reduce the background due to the fast neutrons and the γ-radiation generated in the reactor core, the beam line outside the reactor forms a chicane embedded in shields of polyethylene, concrete, and lead block. The former two materials act as fast-neutron moderators, while the lead is used to shield the γ-radiation. Fig. 5 shows a draft of the positron beam line at the KUR [16]. The positrons are accelerated up to 30 keV just before injection to samples.

In order to prevent possible damage of the reactor during a severe earthquake, the beam line is designed according to the Japanese seismic guidelines [17]. Because of the presence of the positron source, the part of the beam line inside the reactor is fixed

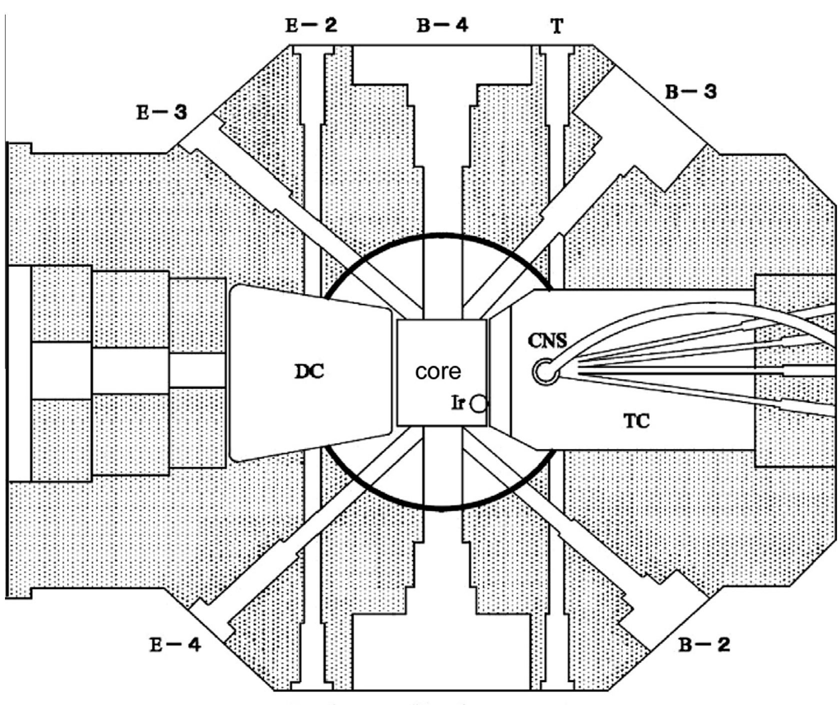

Fig. 1. Cross sectional view of the KUR.