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Kinetic inductance neutron detector operated at near critical temperature

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Abstract: We previously succeeded in constructing and demonstrating the capability of a neutron imaging system based on a superconducting current-biased kinetic inductance detector (CB-KID). In the present work, we systematically studied the characteristics of the superconducting neutron detector to improve the spatial resolution and detection efficiency. We found that the number of neutron detection events with CB-KID remarkably increased when the detector temperature increased from 4 K to the critical temperature T_c . We observed systematic changes of neutron signals as a function of the detector temperature from 4 K to $T_{\rm c}$. We evaluated the detection efficiency of the CB-KID detector, and compared with PHITS Monte Carlo simulations, which modeled the sequential physical processes for the ${}^{10}B(n,\alpha)^{7}Li$ reaction, the transport dynamics, and the energy deposition by particles including neutrons, ⁴He particles, ⁷Li particles, photons, and electrons.

1. Introduction

Neutron beams can penetrate deeply into most materials except for some neutron absorbing/recoiling atoms, including hydrogen, lithium, and boron. Some substances are visible with neutron beams even though they are almost impossible to see with X-ray and gamma-ray imaging techniques. Therefore,



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neutron imaging has potential applications in non-destructive transmission imaging, tomography, darkfield image, visualization of magnetic-field distribution, various materials including intermetallic alloys [1,2], fuel cells [3], lithium ion batteries [4], cultural heritages [5], and others. In 1955, Thewlis [6] demonstrated the first neutron imaging by using a thin layer of boron or lithium to "convert" neutrons to α -particles which impinged on a fluorescent screen to draw an image on the photographic film. In recent decades, there have been active competing studies to achieve high resolution, energy-dispersive imaging and high-speed readout system. This has promoted the rapid development of neutron-imaging technology as well as the appearance of various different neutron detectors such as a photographic-film detector [7], a scintillator-and-storage-phosphor detector [8], a gas neutron detector [9,10], and a semiconductor (solid-state) detector [11]. To our knowledge, the highest spatial resolution of 2 µm was reported by using a gadolinium-oxysulfide-scintillator camera detector by performing center-of-gravity data processing of the optical readout points [12], and the color center formation in LiF crystals gave the resolution of 5.4 μ m [13]. We proposed a new superconducting neutron detector [14–16] called the delay-line current-biased kinetic inductance detector (CB-KID) system. We also succeeded in obtaining a neutron transmission image with a spatial resolution of 22 μ m and a detection efficiency of about 1% [17]. In order to improve the spatial resolution and the neutron detection efficiency of CB-KID, we further investigated the characteristics of our superconducting neutron detector. Koyama and Ishida [18] proposed a theory for the signal generation and propagation along a superconducting waveguide with an S-I-S structure within the framework of the London-Maxwell theory to explain an operating mechanism of the CB-KID system. We also used the Particle and Heavy Ion Transport code System (PHITS) to calculate the neutron transmission images and the neutron detection efficiency of CB-KID [19]. However, the PHITS simulations did not consider significant factors affecting the efficiency such as signal processing electronics, dead time, heat transfer within CB-KID, bias current, and detector temperature.

In the present work, we have studied systematic evolution of transmitted neutron signal, velocity of pulsed signal, and neutron detection efficiency with feeding bias currents as a function of the detector temperature [20,21].



Fig. 1. (a) Structure of superconducting neutron detector with a pair of X and Y CB-KIDs and a ¹⁰B layer convertor; (b) Schematic cross-sectional view of the X-Y CB-KID system.

2. Neutron detector and experimental details

2.1. Neutron detector

The structure of superconducting neutron detector consists of a pair of meanderlines (X- and Y-) [14–16] with an orthogonal stacking, and a ¹⁰B layer deposited on top of the X-, Y- meanderlines to convert neutrons to charged particles (**Fig. 1(a)**). The operating principle of CB-KID with orthogonal meanderlines is different from other conventional neutron detectors. When a neutron reacts with the ¹⁰B nucleus in the conversion layer, the nuclear reaction produces a ⁴He particle and a ⁷Li particle, of which one particle reaches the Nb nanowire to create a quasi-particle hot spot in a Nb stripline. This causes a

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rapid reduction of the Cooper pair density n_s locally at a tiny spot of the stripline with a length $\Delta \ell$ ($\ll \ell$), where ℓ is the total length of the meanderline. This yields a transient change in kinetic inductance (ΔL_k) as expressed by $\Delta L_k = m_s \Delta \ell / n_s q_s^2 S$ with the effective mass of the Cooper pair m_s , the local length of the hot-spot nanowire $\Delta \ell$, the electric charge of the Cooper pair q_s , and the cross-sectional area of superconducting nanowire S.

A pulsed voltage signal at the hot spot in the stripline of the detector under the bias current I_b is given by an electric relation $V = I_b \left(\frac{dL_k}{dt} + \frac{dL_m}{dt}\right) + (L_k + L_m) \frac{dI_b}{dt} \approx I_b \frac{dL_k}{dt} \approx I_b \frac{d\Delta L_k}{dt}$, where the magnetic inductance L_m is kept constant with time and $dI_b/dt \approx 0$ as far as the detector remains in the superconducting state. According to this equation, a pair of pulsed-voltage signals is generated which propagate as an electromagnetic wave pulse [18,22] along the stripline (meanderline) toward one of the end electrodes with an opposite polarity under the application of a DC bias current (**Fig. 2**). Ultra-low noise amplifiers are used to amplify the output signals from CB-KID, of which the output signals are connected to a time-to-digital converter (TDC) of the Kalliope-DC readout circuit [23] to evaluate the position (x,y) of neutron nuclear event. We can detect a correct position of neutron beam arrival at the ¹⁰B layer by combining the results obtained by two X and Y meanderlines as $x = \operatorname{ceil}\left(\frac{\Delta t_x v_x}{2h_x}\right)p_x$ and $y = \operatorname{ceil}\left(\frac{\Delta t_y v_y}{2h_y}\right)p_y$, where the origin of a coordinate is at the center of the detector, p_x, p_y are the

 $y = \operatorname{cen}\left(\frac{1}{2h_y}\right)p_y$, where the origin of a coordinate is at the center of the detector, p_x , p_y are the repetition pitches for the X, Y meanderline; v_x , v_y are velocities of neutron pulsed in x, y meanderline; h_x , h_y are the lengths of two single microstrip segments in the X, Y meanderlines; Δt_x , Δt_y are differences in time stamps in pulsed signals arrived at anode and cathode electrodes of the X and Y meanderlines. We designed CB-KID such that $p_x = p_y = p$ and $h_x = h_y = h$ to obtain a square sensitive area of the detector.



Fig. 2. The operating principle of the delay-line CB-KID with two orthogonal X and Y meanderlines and a ¹⁰B layer converter on a thermally oxidized silicon substrate. The schematic wave forms of the pulsed signals amplified by non-inverted and inverted amplifiers to produce output signals with positive polarity on the right-hand side of the figure.

We used computer-aided design (CAD) software (Layout Editor) to design our superconducting neutron detector and we fabricated the device at the Clean Room for Analog-Digital-Superconductivity (CRAVITY) at the National Institute of Advanced Industrial Science and Technology (AIST). The sensitive area of our detector is 15 mm × 15 mm (**Fig. 1(a**)). The nanowire width of the X (or Y) Nb meanderline is 0.9- μ m and the space between two neighboring nanowire segments is 0.6 μ m. This gives a 1.5- μ m repetition period with 10,000-times repetitions to reach 15-mm effective width and a total length $\ell = 151$ m of the meanderline. The CB-KID used for the present experiment is fabricated in a

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thermally oxidized Si substrate which is described sequentially as **Fig. 1(b)** from the bottom (1) a 300-nm-thick SiO₂, (2) a 300-nm-thick Nb ground plane, (3) a 350-nm-thick SiO₂ layer, (4) a 40-nm-thick Nb *Y* meanderline, (5) a 50-nm-thick SiO₂ layer, (6) a 40-nm-thick Nb *X* meanderline, (7) a 50-nm-thick SiO₂ layer, and (8) a ¹⁰B neutron conversion layer on top of the CB-KID.

2.2. Experimental details

In order to study the characteristics as a function of the temperature, the superconducting neutron detector was installed in a Gifford-McMahon (GM) refrigerator to conduct long-time measurements at a stable cryogenic temperature. The superconducting detector was cooled down to a temperature lower than 4 K, and the temperature of the CB-KID sensor was controlled and monitored by a temperature controller (Cryocon Inc., Model 44) through a heater and a Cernox thermometer which were installed in the neighborhood of the neutron detector via a LabVIEW program. We fed DC bias currents to X and Y meanderlines through bias resistors by using two adjustable DC voltage sources, which were supplied by an independent power source (NF Inc., Model EC1000SA) to minimize the effect of notable environmental noises induced from AC power line of the facility. We used low-noise amplifiers (NF Inc., Model SA-430F5) to amplify the voltage signal from neutron events on the meanderline and feed the TDC module of the Kalliope-DC readout circuit [23] and a 2.5-GHz sampling digital oscilloscope (Teledyne LeCroy Inc., Model HDO4104-MS) (Fig. 2). The neutron signal was tuned by adjusting the bias currents of the X and Y detectors to obtain proper amplitudes of pulsed voltages of neutron events to be measured by the high-speed digital oscilloscope, and the 5-bit variable attenuators (Hoshin Electronics Inc., Model N032) were used to tune the signal amplitude for the time-to-digital converter (TDC) of the Kalliope-DC readout circuit. To reduce noises, SMA connectors, MMCX connectors, and semi-rigid cables were used to transmit a signal pulse from the cryogenic temperature of CB-KID to the room temperature readout instruments in the cryostat. Our experiments were performed with the pulsed neutrons at the beam line BL10 in Japan Proton Accelerator Research Complex (J-PARC).



Fig. 3. The comparison of the propagation velocity as a function of temperature with a DC bias current and without a DC bias current. The fitting curve is obtained by the Koyama-Ishida theory [18].

3. Results and discussion

3.1. Propagation velocity under a DC bias current

The propagation velocity of neutron signal in the meanderline is an important parameter of the delayline CB-KID system in order to construct a high-resolution neutron transmission image. Therefore, the

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temperature dependent characteristics of propagation velocity of a superconducting neutron detector have been studied both theoretically and experimentally [18,20,24]. Our experiment confirmed that the theory of Koyama and Ishida [18] explains the appearance of the pulsed voltage signal and the propagation velocity of the signal along the meanderline as a function of temperature, successfully. While the temperature of the Nb-wire meanderlines was controlled from 3.8 K to 8.3 K, we did not feed a DC bias current to a superconducting Nb meanderline. In the present work, however, we conducted propagation velocity measurements under the DC bias currents to answer the question whether or not there is a change in the propagation velocity by feeding a DC bias current to the CB-KID when taking a neutron transmission image. We applied a bias current of $I_b = 50 \ \mu\text{A}$ and conducted the measurements of the propagation velocity as a function of temperature. Since, the velocity is very sensitive with the temperature, we also paid careful attention to keep the temperature stable. The errors of temperatures were estimated to be smaller than 10 mK when the temperature was controlled at a step of 0.1 K. Figure **3** shows the *T*-dependent propagation velocity as a function of the detector temperature together with the bias-current free velocity data, but we do not see an appreciable change when CB-KID is biased by a small DC current, and the experimental data points are in good agreement with the Koyama and Ishida theory [18]. The propagation velocity should be affected by larger DC bias currents that approach the critical current of the meanderline, as this will lead to the partial destruction of Cooper pairs. However, when the bias current is small, Fig. 3 shows there is basically no effect on the propagation velocity.



Fig. 4. The transmitted signals in the Y meanderline and the cross-talk signals from the Y-meanderline to the X-meanderline at the various different temperatures. We found that this behavior changes appreciably as a function of the detector temperature.

3.2. Temperature dependence of pulsed voltage profile

Our CB-KID works not only as a conversion system to generate a pair of the signals but also as a superconducting transmission line of the signals [22]. We noticed a difference in the velocities along the X-meanderline and the Y-meanderline. We consider that this is due to a different distance between each meanderline and the ground plane because the velocity is a function of this distance in the theoretical formula [18]. This results in a different spatial resolution for the *x*-direction and *y*- direction in the constructed transmission neutron images. Since a change in the distance between the meanderline and the ground plane would also affect the matching impedance of the signal transmission line, it would be better to develop a higher-speed readout circuit to enhance the spatial resolution further. We also have to pay attention to reduce the cross-talk signal between the X-meanderline and the Y-meanderline difference in the velocities may not be avoided in the real CB-KID system. We argue that it is very important to determine the propagation velocities for each CB-KID chip. In order to examine the extent

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of the cross-talk signals in our detector, we intentionally applied a pulsed signal to the Y-meanderline and measured the leaked signals appearing in the X-meanderline, and vice visa. We found that the amplitude of the cross-talk signal (to X), if any, should be smaller than 1% of the transmitted signal of the input channel (in Y) in Fig. 4. When the detector temperature approaches T_c , we noticed that not only the amplitude of pulse but also the noise floor decreases remarkably (Fig. 4). Since the Xchannel voltages change at the same time with that of the Y channel, we cannot rule out a possibility that a signal leakage to the X channel may



Fig. 5. An input-pulse to the electrode and the transmitted pulses from other end of the Y meander as a function of the detector temperature.

occur outside of the meanderline. At least, this finding indicates that the cross-talk signal in our detector is not so remarkable compared to the amplitude of the actual neutron signal. In the future, we will continue to refine the fabrication technique to realize a cross-talk free CB-KID detector for achieving reliable transmission neutron imaging.

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The propagation velocity changes primarily due to a reduction in the density of the Cooper pairs (or an elongated penetration depth) in the superconducting nanowire when the detector temperature increases. As seen in **Fig. 5**, the transmitted signal appears at a delayed time due to slowing down of the propagation velocity along the long meanderline. We also found that the amplitude of the transmitted signal gradually decreases as the temperature increases at temperatures from 8 K toward the critical temperature T_c . The width of the signal pulse also broadens as the detector temperature increases. This is caused by energy dissipation during signal transmission along the meanderline due to excess quasi particles at higher temperatures near the critical temperature. This behavior was observed for a test pulse, but a similar tendency can be seen for the signals from the CB-KID when detecting neutrons. To understand the characteristics of neutron pulse as a function of temperature, we investigated not

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only gradual changes of the voltage pulse amplitude but also changes in the width of neutron signal pulses. We investigated the behavior of the neutron signals at the beam line 10 (BL10) of Materials and Life Science Division (MLF) of the J-PARC Center, Japan Atomic Energy Agency (JAEA), where pulsed neutrons were produced at a rate of 25 shots per second. We utilized a pulse, called an MLF trigger, for specifying the generation time of each shot of pulsed neutrons. We obtained the systematic characteristics of the neutron signal by using the time-to-digital converter (TDC) of the Kalliope-DC readout circuit. The Y-meanderline was fed by a DC current of $I_b = 50 \mu A$ while the X-meanderline was not fed by a DC



Fig. 6. The histogram of the pulse width at the several different detector temperatures.

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current so as to produce no neutron signals from the X detector. The temperature was controlled from 4 K to 7.8 K. Figure 6 shows the histogram of the pulse width with changing the detector temperature. The time of threshold (TOT) data was taken by TDC as a pulse width at the preset threshold voltage by using the Kalliope-DC readout circuit. We found that the number of neutron events increased remarkably and the pulse width of the neutron signal also increased as a function of the detector temperature at temperatures lower than 6 K, but increased remarkably with temperature from 6 K to 7.8 K. We decided to limit the operating temperature of the CB-KID to lower than 7.8 K for the safety of the detector in the present measurements. However, we plan to investigate the characteristics of the neutron signal at higher temperatures to pursue improved detection efficiency of neutrons because the number of neutron-detecting events increased remarkably at temperatures near the critical temperature T_c .

3.3. Neutron detection efficiency

Neutron detection efficiency of a neutron detector is an important factor indicating the usefulness of the detector. It is influenced by the nuclear reaction rate of neutrons in the ¹⁰B conversion layer with neutrons, the structure of the neutron detector, and the operating conditions of the detector. We focused on the effect of the detector temperature on the detection efficiency in this work. In order to obtain the neutron detection efficiency of our detector as a function of temperature, we took the ratio of the number of neutron detection events as a function of wavelength (or ToF) with different temperatures from 4 K to 7.8 K against the direct beam flux estimated in PHITS simulations [25]. Figure 7(a) is the neutron detection efficiency of our detector at various detector temperatures from 4 K to 7.8 K. We found that the efficiency appreciably depends on the wavelength. The efficiency is the smallest at smaller wavelengths and increases to maximum value with a slight tendency of saturation up to the largest wavelength of ~ 10 Å. This primarily comes from the wave-length dependence of the neutron absorption cross section of the ¹⁰B converter. The behavior of the detection efficiency as a function of wavelength is very similar to that from PHITS simulations. We presume that the deficient behavior of the intensity in the regime from 7 ms to 15 ms is due to losses of the neutron counting in the Kalliope-DC readout circuit due to higher incident fluxes at this ToF regime. As a matter of fact, we found the deficient behavior weakened when the number of events becomes much smaller in Fig. 7(a). The nuclear reaction rate does not explain the temperature dependence of the neutron detection efficiency observed at temperatures near the critical temperature. We consider that further investigation on the effect of the



Fig. 7. (a) The detection efficiency of neutron detector at the several detector temperatures as a function of wavelength. The PHITS simulations for a 10 μ m-thick ¹⁰B conversion layer is also show (a modification factor of 1/2) [19]. (b) The absorption ratio (left axis) of the ¹⁰B layer with different thicknesses of 1 μ m, 10 μ m, and 100 μ m. The absorption cross-section (see a green line and right axis) is also shown as a function of wavelength.

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superconducting properties is needed to explain the strong dependence of the detection efficiency on the detector temperature. Maximum neutron detection efficiency at 10 Å is 5 % at the temperature of T= 7.8 K. According to the PHITS simulations by Malins *et al.* [19], the neutron detection efficiency of a CB-KID was expected to reach 16% at the wavelength of 10 Å with the 10-µm thick ¹⁰B layer. Since the PHITS simulations did not consider the effects of signal processing electronics, dead time, heat transfer within CB-KID, bias current, and detector temperature, we regard the PHITS results as the upper-limit of the detection efficiency for the envisaged geometry. In **Fig. 7(b)** with the ¹⁰B thickness of 10 µm, the maximum absorption ratio can be over 90% at 10 Å. Note that we did not consider the covering ratio of the line-and-spacing of the superconducting meanderline in **Fig. 7(b)** while the event of simultaneous detections both in the X and Y detectors were considered in the PHITS simulations [19]. We argue that it is more important to consider the superconducting properties to optimize the operating conditions of the CB-KID system in the future.

4. Summary

We systematically studied the characteristics of the neutron signals from our superconducting neutron detector CB-KID when the temperature of CB-KID approaches the critical temperature. We conducted experiments to investigate the characteristics of the CB-KID by using the beam line (BL10) of Materials and Life Science Experimental Facility (MLF) of J-PARC. We did not see an appreciable difference of the propagation velocity between the cases of a bias current of 50 μ A and no bias current. In both cases, there was in good agreement between the experimental points and the prediction derived from the Koyama-Ishida theory. As characteristic features of the signal, the pulse height decreased with temperature-dependence of the CB-KID. We argue that further understandings of the temperature-dependence of the CB-KID. We argue that further understandings of the temperature-dependent features are required to improve the efficiency, the sensitivity, and the resolution of our superconducting neutron detector.

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References

- [1] Kardjilov N, Manke I, Hilger A, Strobl M and Banhart J 2011 Neutron imaging in materials science *Mater*. *Today* **14** 248–56
- [2] Tremsin A S, Rakovan J, Shinohara T, Kockelmann W, Losko A S and Vogel S C 2017 Non-Destructive atudy of bulk crystallinity and elemental composition of natural gold single crystal samples by energy-resolved neutron imaging *Sci. Rep.* 7 40759
- [3] Satija R, Jacobson D L, Arif M and Werner S A 2004 In situ neutron imaging technique for evaluation of water management systems in operating PEM fuel cells J. Power Sources 129 238– 45
- [4] Siegel J B, Stefanopoulou A G, Hagans P, Ding Y and Gorsich D 2013 Expansion of lithium ion pouch cell batteries: Observations from neutron imaging *J. Electrochem. Soc.* **160** A1031–8
- [5] Kockelmann W, Frei G, Lehmann E H, Vontobel P and Santisteban J R 2007 Energy-selective neutron transmission imaging at a pulsed source *Nucl. Instrum. Meth. Phys. Res. A* 578 421–34
- [6] Thewlis J 1956 Neutron radiography Br. J. Appl. Phys. 7 345-9
- [7] Pugliesi R and Andrade M L G 1997 Study of cracking in concrete by neutron radiography *Appl. Radiat. Isot.* 48 339
- [8] Lehmann E H, Frei G, Ku G and Boillat P 2007 The micro-setup for neutron imaging : A major step forward to improve the spatial resolution *Nucl. Instrum. Meth. Phys. Res. A* **576** 389–96

32nd International Symposium on Superconductivity (ISS2019)

IOP Publishing

Journal of Physics: Conference Series

1590 (2020) 012036 doi:10.1088/1742-6596/1590/1/012036

- [9] Korff S A and Danforth W E 1939 Neutron measurements with boron-trifiuoride counters *Phys. Rev.* **55** 980
- [10] Batchelor R, Aves R and Skyrme T H R 1955 Helium-3 filled proportional counter for neutron spectroscopy *Rev. Sci. Instrum* **26** 1037-47
- [11] Kumashiro Y and Okada Y 1985 Schottky barrier diodes using thick, well-characterized boron phosphide wafers *Appl. Phys. Lett.* **47** 64-66
- [12] Hussey D S, LaManna J M, Baltic E and Jacobson D L 2017 Neutron imaging detector with 2 μm spatial resolution based on event reconstruction of neutron capture in gadolinium oxysulfide scintillators *Nucl. Instrum. Meth. Phys. Res.* A 866 9-12
- [13] Matsubayashi M, Faenov A, Pikuz T, Fukuda Y and Kato Y 2010 Neutron imaging of micronsize structures by color center formation in LiF crystals *Nucl. Instrum. Meth. Phys. Res. A* 622 637–41
- [14] Ishida T, Nishikawa M, Fujita Y, Okayasu S, Katagiri M, Satoh K, Yotsuya T, Shimakage H, Miki S, Wang Z, Machida M and Kano T 2008 Superconducting MgB₂ thin film detector for neutrons J Low Temp Phys 151 1074–9
- [15] Shishido H, Miyajima S, Narukami Y, Oikawa K, Harada M, Oku T, Shishido H, Miyajima S, Narukami Y, Oikawa K, Harada M, Oku T, Arai M, Hidaka M, Fujimaki A and Ishida T 2015 Neutron detection using a current biased kinetic inductance detector *Appl. Phys. Lett.* 107 232601-4
- [16] Yoshioka N, Yagi I, Shishido H, Yotsuya T and Miyajima S, Fujimaki A, Miki S, Wang Z and Ishida T 2013 Current-biased kinetic inductance detector using MgB₂ nanowires for detecting neutrons *IEEE Trans. Appl. Supercond.* 23 2400604
- [17] Shishido H, Miki Y, Yamaguchi H, Iizawa Y, Dang V T, Kojima K M, Koyama T, Oikawa K, Harada M, Miyajima S, Hidaka M, Oku T, Soyama K, Suzuki S Y and Ishida T 2018 High-speed Neutron imaging using a current-biased delay-line detector of kinetic inductance *Phys. Rev. Appl.* 10 044044-(10)
- [18] Koyama T and Ishida T 2018 Electrodynamic theory for the operation principle of a superconducting kinetic inductance stripline detector Electrodynamic theory for the operation principle of a superconducting kinetic inductance stripline detector J. Phys. Conf. Ser. 1054 012055
- [19] Malins A, Machida M, Vu T D, Aizawa K and Ishida T 2020 Monte Carlo radiation transport modelling of the current-biased kinetic inductance detector *Nucl. Instrum. Meth. Phys. Res. A* 953 163130
- [20] Vu T D, Iizawa Y, Nishimura K, Shishido H, Kojima K M, Oikawa K, Harada M, Miyajima S, Hidaka M, Oku T, Soyama K, Aizawa K, Koyama T and Ishida T 2019 Temperature dependent characteristics of neutron signals from a current-biased Nb nanowire detector with ¹⁰B converter *J. Phys. Conf. Ser.* **1293** 012051
- [21] Miki Y, Yamaguchi H, Iizawa Y, Shishido H, Kojima K M, Oikawa K, Harada M, Miyajima S, Hidaka M, Oku T, Soyama K and Ishida T 2018 Neutron signal features of Nb-based kinetic inductance detector with ¹⁰B converter J. Phys. Conf. Ser. **1054** 012054
- [22] Swihart J C 1961 Field solution for a thin-film superconducting strip transmission line J. Appl. Phys. 32 461-9
- [23] Kojima K M, Murakami T, Takahashi Y, Lee H, Suzuki S Y, Koda A, Yamauchi I, Miyazaki M, Hiraishi M, Okabe H, Takeshita S, Kadono R, Ito T, Higemoto W, Kanda S, Fukao Y, Saito N, Saito M, Ikeno M, Uchida T and Tanaka M M 2014 New μSR spectrometer at J-PARC MUSE based on Kalliope detectors J. Phys.: Conf. Ser. 551 012063
- [24] Iizawa Y, Yamaguchi H, Miki Y, Nishimura K, Shishido H, Kojima K M, Oikawa K, Harada M, Miyajima S, Hidaka M, Oku T, Soyama K, Koyama T and Ishida T 2018 Physical characteristics of delay-line current- biased kinetic inductance detector J. Phys. Conf. Ser. 1054 012056
- [25] Harada M, Maekawa F, Oikawa K, Meigo S, Takada H and Futakawa M 2011 Application and validation of particle transport code PHITS in design of J-PARC 1 MW spallation neutron source *Prog. Nucl. Sci. Technol.* 2 872–8