



Full Length Article

Beam tests of the copper-based Dual-Readout calorimeter to measure electromagnetic performance for future e^+e^- colliders

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ABSTRACT

The Dual-Readout Calorimeter (DRC) is anticipated to deliver excellent performance for measuring the energy of both electromagnetic and hadronic particles by using both scintillation and Cherenkov light signals. The Korea DRC R&D collaboration has constructed two 2.5-meter-long modules using copper plates and two types of optical fibers. These DRC modules were tested with positron beams of momentum ranging from 20 GeV to 125 GeV at the H8 beam line of the CERN Super Proton Synchrotron, using a customized DAQ system with Domino Ring Sampler 4 chips. This paper presents the measured electromagnetic energy linearity and resolution of this DRC. The stochastic and constant term of the DRC energy resolution is measured to be 17.4% and 4% respectively, and the DRC response is linear within $\pm 2\%$.

1. Introduction

The Dual-REAdout Method (DREAM) is a calorimetry technique that enhances energy measurement performance by combining two independent readout channels. The primary challenge limiting the precision energy measurement of hadronic showers is the fluctuation of the shower's electromagnetic (EM) component fraction (f_{em}). The Dual-Readout Calorimeter (DRC) utilizes Cherenkov ($\check{C}$) and scintillation (S_c) optical fibers for each readout channel, where the $\check{C}$ fibers are

mainly sensitive to relativistic charged particles. Therefore, $\check{C}$ fibers have a larger EM-to-hadronic response ratio (e/h) than S_c fibers. The f_{em} can be measured by combining signals from each type of fiber on an event-by-event basis. This enables us to improve the energy resolution impacted by the fluctuation of f_{em} [1]. This method has been well established and verified through both experiments and simulations over the past 20 years [2–4].

Future e^+e^- colliders, such as FCC-ee and CEPC, require high-precision energy measurements of hadronic showers to meet their physics program goals [5,6]. Since the DRC demonstrates excellent

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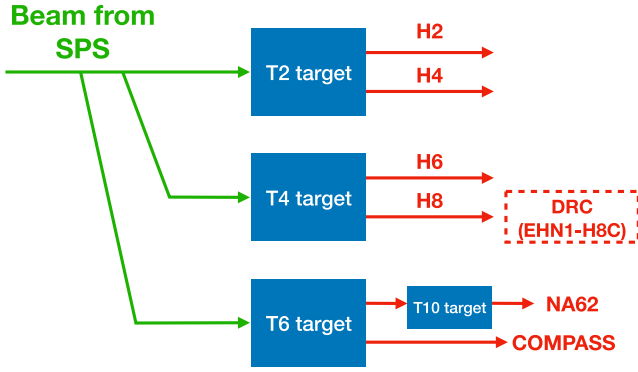


Fig. 1. Schematic layout of the CERN North Area beam lines. The DRC is located at the H8 beam line (EHN1-H8C).

hadronic energy resolution ($(30 \pm 2)\%/\sqrt{E}$ for single pions and protons) [1], it is a viable option for the calorimeter in these colliders. The IDEA (Innovative Detector for an Electron-positron Accelerator) detector concept, proposed as one of the detector candidates for the future e^+e^- colliders [5,6], contains a fiber-based DRC as the single calorimeter system to measure the energy of both EM and hadronic particles [7].

In this paper, we focus on the construction and testing of the fiber-based DRC fabricated by the Korea DRC R&D collaboration. The DRC used for the test is designed to be large enough to contain a sufficient amount of EM shower constituents. It was constructed in Korea in 2022 by stacking copper plates with two types of optical fibers alternately placed on the plates. The experiment was performed at the H8 beam line in the CERN North Area, using e^+ beams with energies ranging from 20 GeV to 125 GeV. The goal of the experiment was to measure the EM energy performance of the new DRC modules.

In Section 2, we introduce the experimental setup of the beam tests, including the detector modules and the brand-new data acquisition system (DAQ). Section 3 describes the experimental data and the analysis procedure. Finally, in Section 4 we present the EM energy linearity and resolution measured from the beam test.

2. Equipment and experimental setup

2.1. LHC beam line

The experiment was conducted at the H8 beam line in the CERN North Area [8]. Fig. 1 illustrates the beam facilities of this region. The beam originated from the Super Proton Synchrotron (SPS). A primary proton beam with an energy of 450 GeV is extracted from the SPS and directed to the CERN North Area. In the North Area, this primary beam is split into three, each directed onto different particle production targets: T2, T4, and T6. After striking one of these targets, secondary beams containing various types of particles are generated. By using additional targets, beam line magnets, and momentum slits, the secondary beam can be filtered to isolate a specific type of particle within a selected energy range [9]. The type and energy of the beam used for the test beam is explained in Section 3.1.

2.2. Detector setup

2.2.1. DRC modules

The DRC modules are situated in the experimental hall of the H8 beam line, specifically at EHN1-H8C. They are fixed onto an experimental table that can rotate and change height to adjust the beam impact point.

The DRC is composed of two modules, M1 and M2, each with a length of 2.5 m, corresponding to 10 nuclear interaction lengths. Both

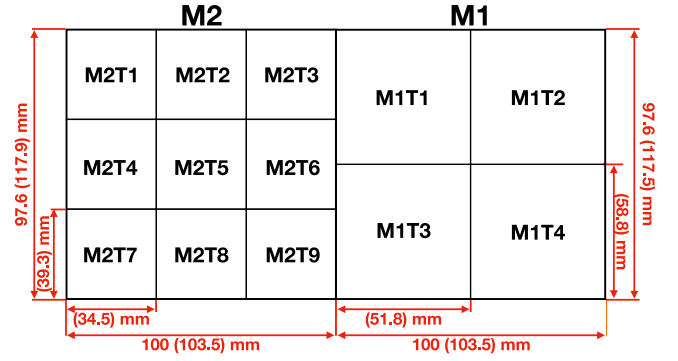


Fig. 2. The dimensions of the DRC modules and towers, as seen from upstream. The dimensions inside and outside the parenthesis are the measured values and designed dimensions, respectively. These values can differ due to distortion of the copper plate. 'M' represents the module, and 'T' stands for the tower. For example, M1T1 refers to the first tower of module number 1.

modules are divided into several towers, categorized by their readout system. M1 consists of 4 towers, while M2 comprises 9 towers. The measured and designed dimensions, as seen from the upstream side of the DRC, are illustrated in Fig. 2. Fig. 3 shows pictures of the DRC depicting (a) the installation on its base frame (b) the upstream side view.

Each module is constructed from a stack of copper plates (reused from the previous RD52 calorimeter [3]) with embedded optical fibers. Fig. 4 shows the designed dimensions of the plates and fibers of a single module. 61 plates are stacked to build one module with 61 fibers placed on each plate. The odd-numbered plates contain 31 $\check{C}$ fibers and 30 Sc fibers, while the even-numbered plates have 30 $\check{C}$ fibers and 31 Sc fibers.

Two different types of optical fibers, the $\check{C}$ and the Sc fibers, are used to generate their respective signals. The $\check{C}$ fibers are round-shaped with a diameter of 1 mm and have a single cladding [10]. Three different types of Sc fibers are installed in the DRC [11]. Square-shaped Sc fibers with cross section of $1 \times 1 \text{ mm}^2$ are installed in M1T1. Round-shaped Sc fibers with multi-cladding are used in M1T2. All other towers in the DRC use round-shaped Sc fibers with a single cladding layer. All round-shaped Sc fibers have a diameter of 1 mm. The details of the fibers are listed in Table 1.

As described in Fig. 5, three different types of readout systems are used in this DRC. These readout systems create analog electric signals proportional to the number of incoming photons. Except for M1T3 and M2T5, all towers use square-shaped photomultiplier tubes (PMTs) [12]. For the three M1 towers, about 450 fibers are bundled by type within each tower and connected to a single PMT. The eight M2 towers are also bundled this way, with around 200 fibers per bundle connected to a single PMT. The M1T3 uses a microchannel plate photomultiplier tube (MCP-PMT) [13,14]. Like the other M1 towers, around 450 fibers are bundled by type and connected to the MCP-PMT. The M2T5 uses silicon photomultiplier (SiPM) [15] for high granularity. The M2T5 have 400 fibers, and each fiber is connected to a single SiPM channel. To prevent readout signal saturation, optical filters with a Wratten number 12 [16] are attached between the Sc fibers and readout systems. This filter reduces the number of photons from the Sc fibers. The details of the readouts are summarized in Table 2. The operational voltage settings for each readouts are listed in Table 3. Details of adjusting the operational voltage are explained in Section 3.2.

The EM energy performances are based on the measurements with M1T2 and M1T4. M1T4 contains round-shaped single cladding Sc fiber connected to square-shaped PMT for the readout, which is the standard fiber and readout configurations used in previous DRC studies. Therefore, the M1T4 is our reference tower ($tower_{ref}$), representing the baseline performance expected from the DRC towers. Its responses are

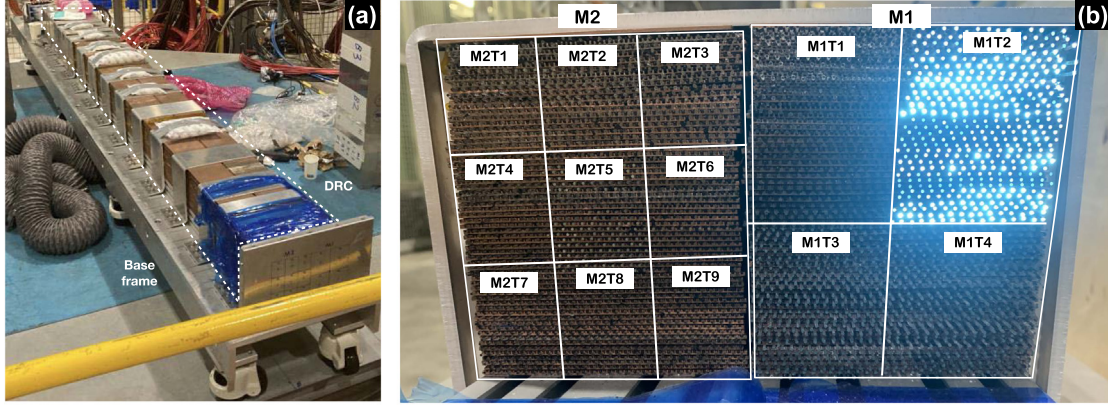


Fig. 3. (a) Picture of the DRC modules installed on their base. (b) Upstream side view of the two DRC modules, with the right module being M1 and the left module being M2. The blue lights on the M1T2 Č fibers are illuminated by a light source from the rear side. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

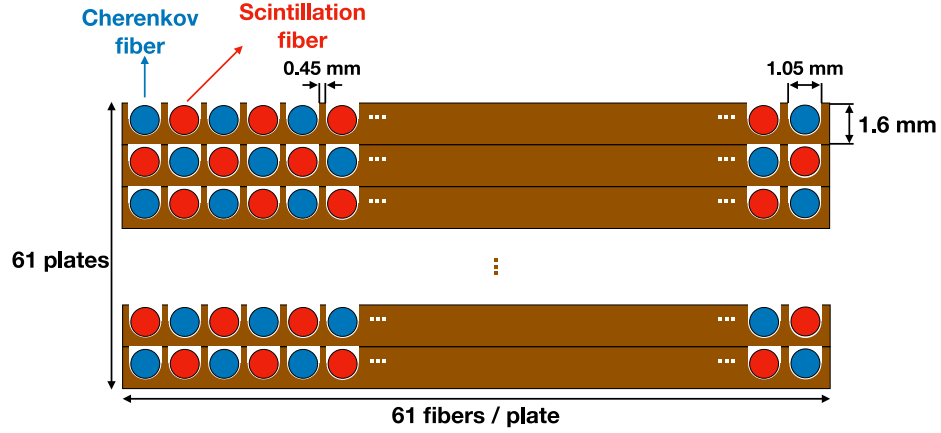


Fig. 4. Schematic design of a single DRC module with dimensions. The Sc and Č fibers are inserted into each copper plate.

Table 1
The list of fibers installed in the DRC and their properties.

Type	Shape	Cladding	Installed tower	Dimensions	Model	Materials
Č	Round	Single	All towers	Diameter : 1 mm Cladding thickness : 0.01 mm	SK-40	Core : PMMA Cladding : Fluorinated Polymer
	Sqaure	Single	M1T1	$1 \times 1\text{mm}^2$ Cladding thickness : 0.02 mm	SCSF-78	
Sc	Round	Multi	M1T2	Diameter : 1 mm Cladding thickness : 0.04 mm	SCSF-78M	Core : Polystyrene Cladding : PMMA
	Round	Single	All other towers	Diameter : 1 mm Cladding thickness : 0.02 mm	SCSF-78	

Table 2
The list of the readouts attached to the DRC.

Type	Channel	Installed tower	Number of channels	Model
MCP-PMT	Č	M1T3	1	PLANACON XP85112
	Sc	M1T3	1	PLANACON XP85012
SiPM	Č	M2T5	200	Hamamatsu S14160-1310PS
	Sc	M2T5	200	Hamamatsu S14160-1310PS
PMT	Č	All other towers	11	Hamamatsu R11265U-100
	Sc	All other towers	11	Hamamatsu R11265U-100

used to calibrate the DRC towers. Details of the calibration procedure are provided in Section 3.3. The M1T2 ($tower_{multi}$) has the same configuration as $tower_{ref}$, except for the Sc fiber which uses the round-shaped multi-cladding type. To study the performance of the standard tower configuration, and the relative performance of the multi-cladding Sc fiber compared to the single cladding one, the performances of $tower_{ref}$ and $tower_{multi}$ are investigated.

2.2.2. Auxiliary detectors

A set of auxiliary detectors is installed along with the DRC modules in the EHN1-H8C experimental hall. These auxiliary detectors include a delay wire chamber, trigger detectors, a pre-shower detector, and a muon counter. They are used to trigger, identify the beam particles, and analyze the beam quality. Fig. 6 illustrates the layout of the DRC

Table 3

The operational voltage of each readout. It is adjusted to avoid saturation of the readout signal, and to match the average signal magnitude of Sc and $\bar{C}$ equal.

Module	Tower	Readout	Operational voltage (V)	
			Sc channel	$\bar{C}$ channel
M1	M1T1	PMT	654	629
	M1T2		633	650
	M1T3	MCP-PMT	1808	2680
	M1T4	PMT	676	688
M2	M2T1	PMT	619	715
	M2T2		669	682
	M2T3		609	672
	M2T4		624	684
	M2T5	SiPM	46	46
	M2T6	PMT	683	653
	M2T7		664	664
	M2T8		614	667
	M2T9		669	674

M2			M1	
M2T1	M2T2	M2T3	M1T1 Square-shape	M1T2 Multi-cladding <i>tower_{multi}</i>
M2T4	M2T5	M2T6	M1T3 MCP-PMT	M1T4 <i>tower_{ref}</i>
M2T7	M2T8	M2T9		

Fig. 5. The upstream view of the DRC with configurations of each tower. The blue text shows the readout type, and the red text shows the type of Sc fiber. All towers without any specification on readout or Sc fiber use PMT and round-shaped single cladding Sc fiber. *tower_{ref}* and *tower_{multi}* are indicated with green text. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and the auxiliary detectors. The details of the auxiliary detectors are listed in Table 4.

The delay wire chamber (DWC) is a multi-wire proportional counter capable of detecting the position of incident particles in two dimensions. It has a spatial resolution of 0.2 mm [17]. Two DWCs (DWC1, DWC2) are installed upstream of the DRC.

Three plastic scintillator trigger detectors (Veto, TR1, and TR2) are installed between the two DWCs. The Veto scintillator has a circular hole at the center with a 10 mm radius. TR1 and TR2 consist of scintillators with a thickness of 2.5 mm, and are overlapped to make a cross-section of $4 \times 4 \text{ cm}^2$.

The pre-shower detector (PS) is placed between the DWC2 and the DRC. The PS consists of a 5 mm thick lead plate followed by a 5 mm thick plastic scintillator, and is used to identify incoming particles. Particle identification (PID) is explained in Section 3.3.1. Together with the muon counter, the PS helps to select events with e^+ .

The muon counter (MC), installed further downstream of the DRC, is a scintillation detector with an area of $40 \times 80 \text{ cm}^2$ and a thickness of 3 cm. The MC is located about 28.3 m downstream from the DRC, after concrete blocks that absorb any possible punch through other than muons.

2.3. Data acquisition system

The customized DAQ system, built by NOTICE Korea, digitizes and records the analog signals produced by the readout systems. This system consists of 15 DAQ boards and one Trigger Clock Board (TCB).

It operates in conjunction with a DAQ control PC and a Nuclear Instrumentation Module (NIM) system for data acquisition. Fig. 7 shows photos of the DAQ and TCB boards. Each DAQ board has 32 channels. With a total of 15 DAQ boards, the system can process a total of 480 channels.

The DAQ digitizes the analog signal by help of the Domino Ring Sampler 4 (DRS4) chip [18]. The DRS4 chip has 1024 capacitors per channel, and the ADC digitizes the charges stored in the capacitors. The DAQ board digitizes 1 V is into 4096 ADC counts (12-bit) with 1024 time bins (10-bit). All 1024 ADC counts are recorded per event during the data taking. All DAQ boards are connected to the TCB board.

The NIM system is used to create the trigger logic signal. The signals from all three trigger detectors (TR1, TR2, Veto) are combined in this unit, and the trigger logic signal is produced if both TR1 and TR2 send a signal while the Veto does not (TR1 && TR2 && !Veto). Once the trigger is fired, it is sent to the TCB board.

The TCB board controls the data-taking process by synchronizing the multiple DAQ boards. When a trigger signal arrives at the TCB board, all connected DAQ boards simultaneously begin recording and digitizing the incoming detector signals.

The DAQ PC controls the DAQ system using customized software. The data recorded by the DAQ system is transferred to the DAQ PC. Fig. 8 shows a diagram of the data flow in the DAQ system.

3. Experimental data and analysis procedure

3.1. Experimental data

The test beam data was collected from August 19th, 2022, to August 23rd, 2022, at the SPS H8 beam line using e^+ with energy ranging from 20 GeV to 125 GeV. During this period, data was recorded for 5,066 min, capturing a total of 4,674,968 events, consisting of two run types: commissioning runs (67% of total events) and physics runs (33% of total events). The purpose and procedure of commissioning runs are described as follows: (1) to find the center of each DRC tower, (2) to optimize the high voltage (HV) of readout PMTs, (3) to calibrate each DRC tower. The 20 GeV e^+ beam is used for the steps. For physics runs to measure the EM performance, e^+ beams with energy of 20, 40, and 60 GeV are taken. Data with energy higher than 60 GeV have had very poor purity due to the CERN SPS operational conditions and almost negligible amount of events are selected after PID selection (therefore it is not used in this paper).

The digitized waveform signals from the readout systems are converted into the peak ADC count (*peakADC*) or integrated ADC count (*intADC*) to analyze the data. The *peakADC* is the difference between the pedestal and the minimum ADC count of the signal peak, which corresponds to the voltage. The *peakADC* is used for the readout operational voltage scan. All other analyses are performed using the *intADC*. The *intADC* is the area surrounded by the pedestal and the signal wave, which is analogous to integrated charge. Fig. 9(a) shows the example of the pedestal, *peakADC*, and *intADC*. Fig. 9(b) shows an example histogram of *intADC*.

3.2. Tower position and readout voltage scan

Before taking the physics analysis runs, the position scan is done to find the center positions of the DRC towers. It is important to find the tower center position since the calibration and performance measurement of the DRC is done with the beam steered to the center of the tower. Before starting the physics runs, a position scan is conducted to find the centers of the DRC towers since the calibration and performance measurement of the DRC are performed with the beam directed at the tower's center.

For the position scan, the *intADC* is measured for each tower while shifting the beam position in the vertical or horizontal direction. When the beam enters close to the center of a specific tower, the response of

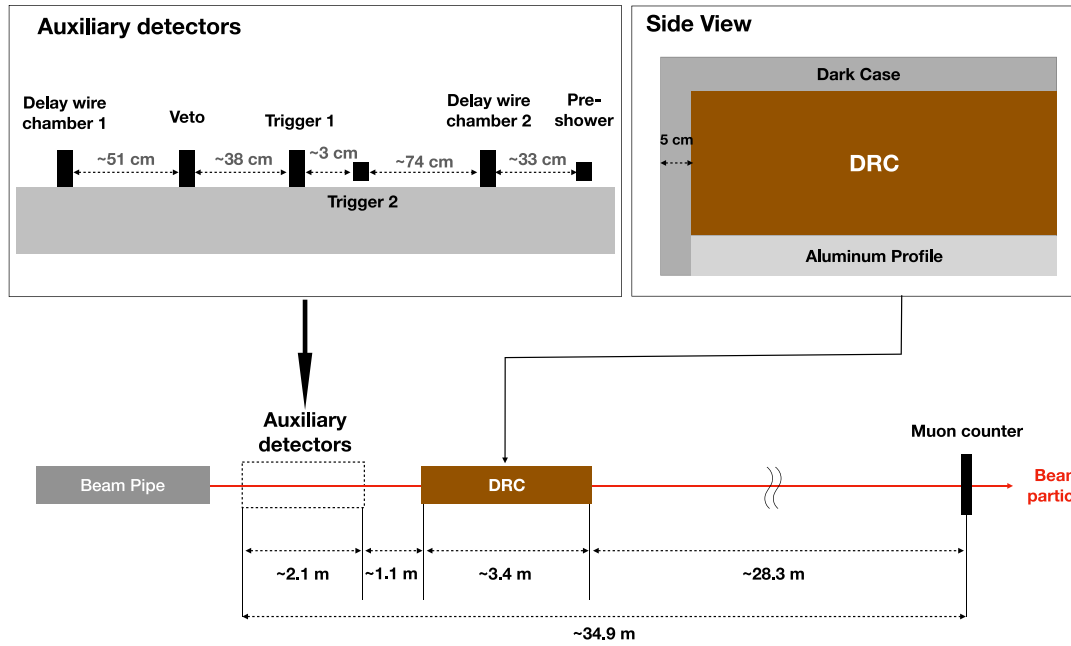


Fig. 6. Layout of the experimental setup with the auxiliary detectors. Beam travels from left to right.

Table 4

The list of auxiliary detectors installed in the experimental hall.

Position relative to the DRC	Name	Distance from DWC1 (m)	Type	Role	Operation voltage (V)
Upstream	DWC	0 (DWC1), 1.66 (DWC2)	Gas (Ar : CO ₂ = 1 : 1)	Beam position detection in 2D	2800 V (DWC1, DWC2)
	Veto	0.51			800 V
	TR1, TR2	0.89 (TR1), 0.92 (TR2)	Plastic scintillator	Trigger event taking process	1175 V (TR1), 1150 V (TR2)
	PS	1.99			750 V
Downstream	MC	34.9		Particle (e^+) identification	2600 V



Fig. 7. Photos of (a) The single DAQ board, and (b) the TCB board.

the tower is larger compared to its adjacent towers. As the beam moves to the boundary of the two towers, the response of each tower shows a similar value. When the beam crosses the boundary and moves to the next tower, the responses of the two towers are reversed. Therefore, the position where two towers show the same $intADC$ represents the tower boundary.

The position scan is initially performed in the vertical direction. Fig. 10 shows the position scanning direction. Since the beam pipe cannot be shifted, the DRC module is shifted to adjust the beam incident position. While shifting the vertical beam position in 1 cm steps from M2T4 to M2T7, the $intADC$ of two towers are measured. Fig. 11 shows the response of two towers with respect to the module's vertical position. As the beam moves from M2T4 to M2T7, the response of M2T4 reduces and M2T7 grows. When the beam crosses the border of two towers, the response of the two towers also gets reversed. The red dotted line represents the boundary of the two towers. From the measured boundary position and known tower size, the vertical center of each tower can be calculated.

Next, moving the beam position horizontally in 1 cm steps from M2T7 to M1T3, the horizontal boundary position of the M2T9 and M1T3 is measured. Together with horizontal boundary position and measured tower sizes, the horizontal position of towers can be calculated.

After finding the tower positions, the operational voltage of the readout system is adjusted to make its signal have enough magnitude to be distinguished from other electrical noises, while not saturated. Also, the signal magnitude of the $\check{C}$ and S_c readout system is tuned to show a similar response when the beam with the same energy enters the DRC.

The HV of the readout system is tuned to a $peakADC$ of about 500 for a 20 GeV e^+ beam. The $peakADC$ of a tower with the beam entering its center is measured at various values of the readout HV. The readout gain, which is the response per voltage, increases exponentially with applied HV [12–14]. Fig. 12 shows the voltage vs. $peakADC$ graphs and the fitted functions for $tower_{ref}$. From this fitted function, the HV which produces 500 $peakADC$ for the S_c and $\check{C}$ channels is interpolated

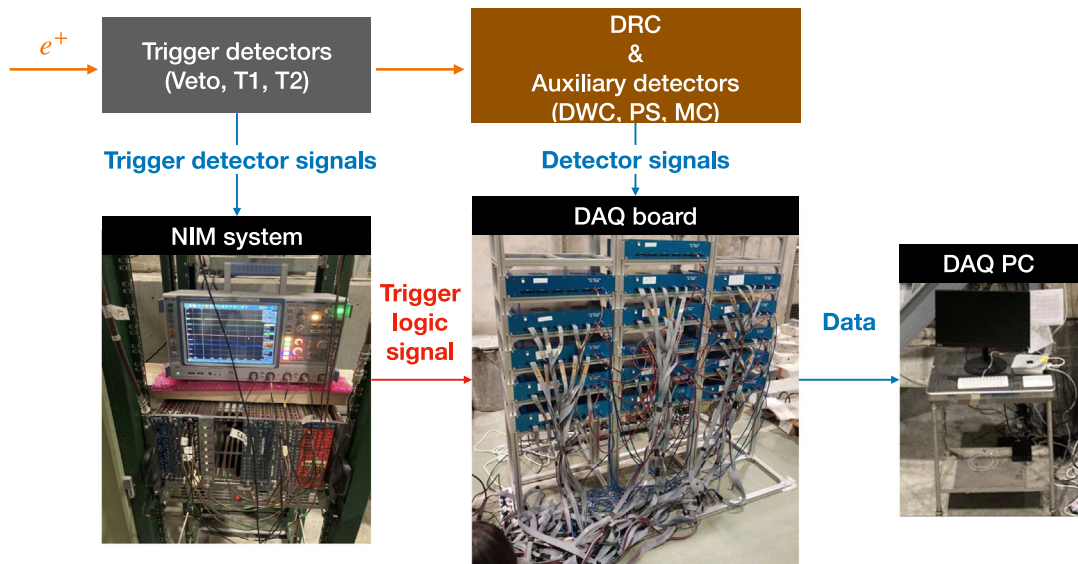


Fig. 8. The data flow diagram of the DAQ system.

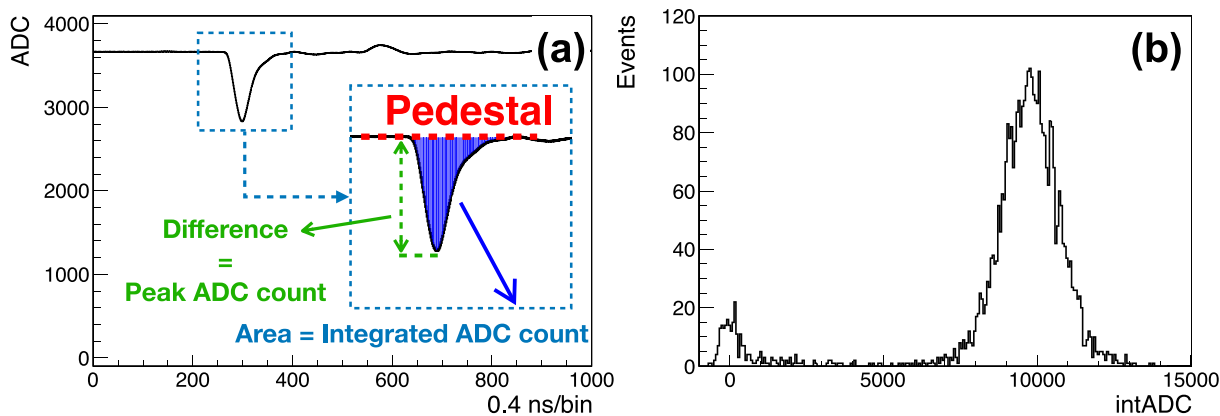


Fig. 9. (a) The signal waveform and pedestal of a single event. The black solid line represents the ADC signal. The red dotted line is the pedestal value. The *peakADC* is the difference of pedestal and the signal. The *intADC* is the area filled with blue between the pedestal and the signal. (b) An example of *intADC* histogram obtained by stacking the *intADC* event-by-event. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

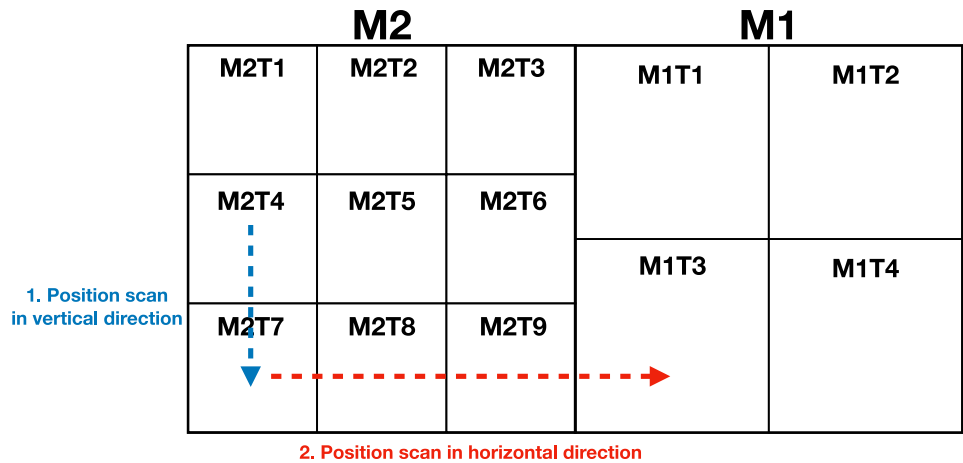


Fig. 10. Schematic of the position scan direction. First the scan in the vertical direction (blue) is done, and next the horizontal scan (orange) is done to find the tower center. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

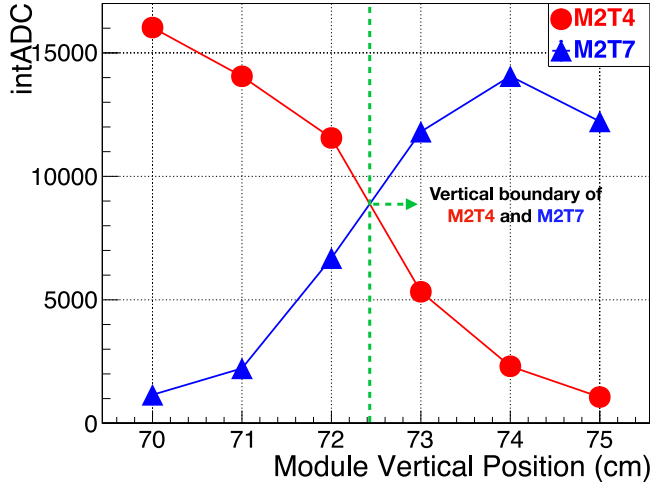


Fig. 11. The graph of tower response with respect to the module's vertical position. The beam incident position gets closer to M2T7 as the module's vertical position increases. The response of two vertically adjacent towers, M2T4 and M2T7, are plotted. The x-axis value of the crossing point represents the vertical position of the boundary of the two towers. Since the M2 towers have a size of 3.45 cm, the tower center position is 1.725 cm displaced from the boundary position. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to be 635 V and 650 V, respectively. After slight adjustments to match the S_c and $\check{C}$ channel response, the HV of 633 V (S_c) and 650 V ($\check{C}$) is used.

3.3. Analysis procedure

The analysis is divided into three steps. First, a subset of the total events is selected to keep high-quality events only. After the event selection, calibrating the DRC towers and applying corrections are proceeded. Finally, the EM energy linearity and resolution are measured using the selected and calibrated events.

3.3.1. Event selection

The event selection is performed to collect events from the high-quality e^+ beams. Event selection consists of two steps. One is the geometrical acceptance selection using the Veto and the DWCs, which rejects the events with beam escaping DRC apparatus. The second is the PID selection using the PS and the MC.

For the particle beam in order to pass the geometrical acceptance selection, the beam has to be well-collimated to the center. The selection on beam collimation is applied by using the Veto. The poorly collimated beam will be spread out wider than the hole of the Veto and such events are rejected.

Even after passing through the Veto detector, a beam with an inclination relative to the beam axis can drift away from the DRC as illustrated in Fig. 13. Two DWCs are used to remove events with such tilted beams. A beam well aligned with the beam axis will pass similar position in DWC1 and DWC2. This implies that the beam position measured by the DWCs will be highly correlated in both the x - and y -axes if the beam is well aligned. Thus, by requiring the beam position on DWCs to have a difference smaller than 1.5 mm in both axes, the events with the beam escaping the DRC can be rejected. Fig. 14 shows the position correlation of beam particles in (a) x -axis and (b) y -axis between the two DWCs. Fig. 15 shows the position plots of DWCs before and after applying the geometrical acceptance selection.

Next, the PID selection is done with the PS and MC. To measure the EM energy performance of the DRC correctly, the events with only EM particles (e^+) need to be selected from the beam. The e^+ events are selected with the PS, and then events with muon contamination are rejected using the MC.

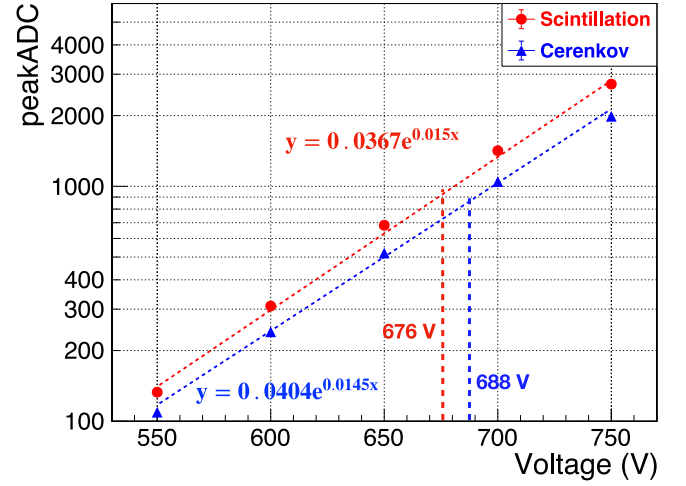


Fig. 12. The Voltage vs. $peakADC$ graph and its fitted function of the $tower_{ref}$. The red dot shows the graph of the S_c channel, and the blue dot is the $\check{C}$ channel. Fitted functions are represented with dashed lines. The vertical lines represents the HV value used for each channel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

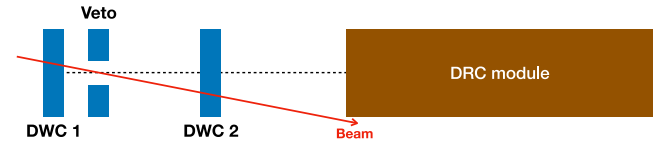


Fig. 13. Diagram of the installed DWCs, Veto and DRC. The red line indicates an example of a particle escaping the DRC even after passing the Veto. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The muons and hadronic particles in the beam hardly interact when entering the lead plate of the PS. Therefore, the muons and hadrons are likely shown as a single minimum ionizing particle (mip) signal inside the PS. In the $intADC$ distributions of the PS, muons and hadrons are located at the peak right after the pedestal peak (the peak near 0 $intADC$), called as one mip peak as indicated in Fig. 16(a).

On the other hand, the e^+ produces a certain signature in the PS compared to the other particles. The e^+ electromagnetically interacts with the lead plate of the PS with high probability and it produces a photon. The photon decays into $e^\pm$ (a pair production) and it results in two e^+ and one e^- (called as three electrons, with regardless of the charges). If two pair productions occur at the PS, five electrons appear at the PS. As a result, signals that are at least three (or five) times larger than the one mip peak are generated from the e^+ at the PS and they can be shown in the $intADC$ distribution as three (or five) mip peak.

Thus, choosing the events with PS $intADC$ higher than the three mip peak reduces a significant amount of hadron and muon contamination in the beam. By requiring a higher threshold, the purity of the beam is improved at the cost of the number of events left after the PID selection. 60,000 $intADC$, which is higher than the three mip peak, is used as the threshold for the analysis. Fig. 16(a) shows the $intADC$ of the PS with a 20 GeV beam enriched with e^+ . The single mip , three mip peak, and the PID selection thresholds are displayed in the figure.

The muon contamination is further removed by using the MC. Muons can survive in the beam even after the selection with the PS, since muons can also create showers in the PS, although this fraction is relatively small. Due to the large distance between the DRC and the MC, and together with the concrete blocks installed between them, the signal in the MC is mainly created by the muons. Hence, rejecting the events that show higher $intADC$ than the pedestal in the MC will reduce the muon contamination. Fig. 16(b) shows the MC detector response, and the corresponding selection threshold (2040 $intADC$).

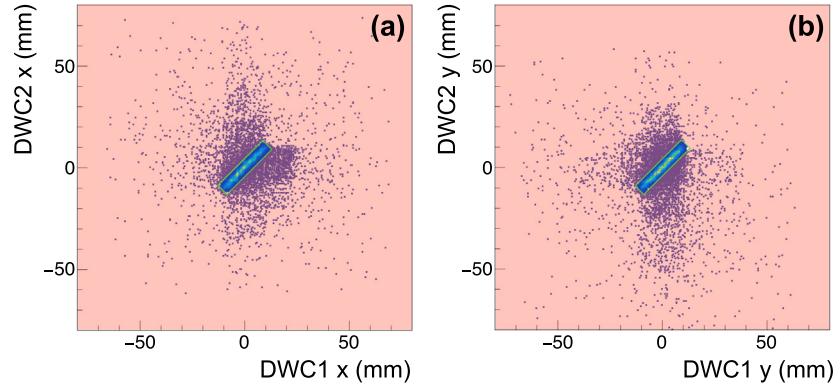


Fig. 14. The correlation plot between DWC1 and DWC2 with the (a) x - and (b) y -axis. The events at red region are rejected. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

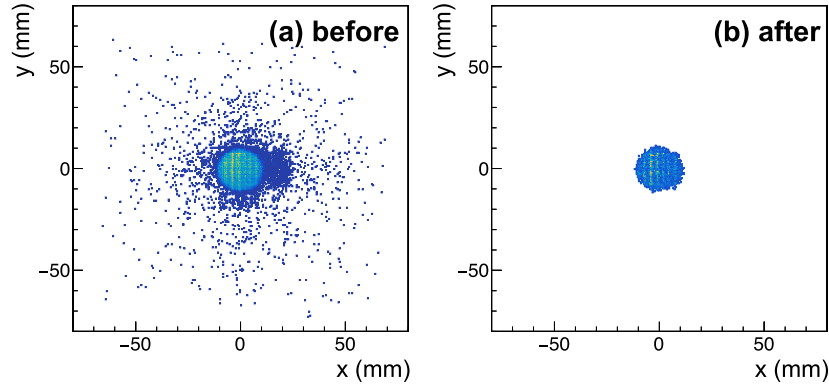


Fig. 15. The DWC1 position plot (a) before applying the geometrical acceptance selection, and (b) after applying the selection. The events placed far from the center of the DWC are removed after the selection.

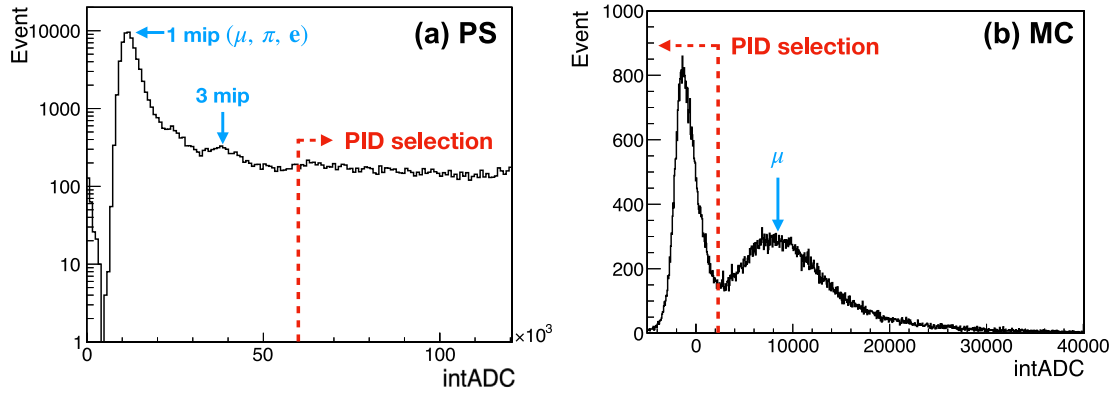


Fig. 16. (a) The response of PS and (b) the response of the MC. Events satisfying both $intADC$ of PS larger than 60,000 and MC smaller than 2040 are selected as e^+ candidates.

Fig. 17 shows the $intADC$ histogram of the DRC before and after the geometrical acceptance and PID selections.

The purity of the beam can be measured using the PID selection. Purity is defined as the fraction of the number of events left after the PID selection to the total number of events. For the 20 GeV e^+ beam, the purity is about 20%. As the energy of the e^+ beam increases, the purity decreases. The purity is about 5% for the 60 GeV beam, becoming insufficient for energies above 80 GeV. The measured purity of a single run for each energy point is listed in Table 5. Even though the data is recorded with positron beams with energy up to 125 GeV, only the 20, 40 and 60 GeV runs are used for the analysis due to lack of events over 80 GeV.

Table 5

The number of the events before and after the PID selection for e^+ beam with various energies measured within single run. Corresponding purity is also listed.

Energy (GeV)	# of events (Before PID)	# of events (After PID)	Purity (%)
20	50 028	11 394	22.78
40	10 150	787	7.75
60	10 050	500	4.98
80	10 060	394	3.92

3.3.2. Calibration and correction

The calibration of the DRC is essential to translate the $intADC$ into the actual energy. The calibration is done by two steps. First, the

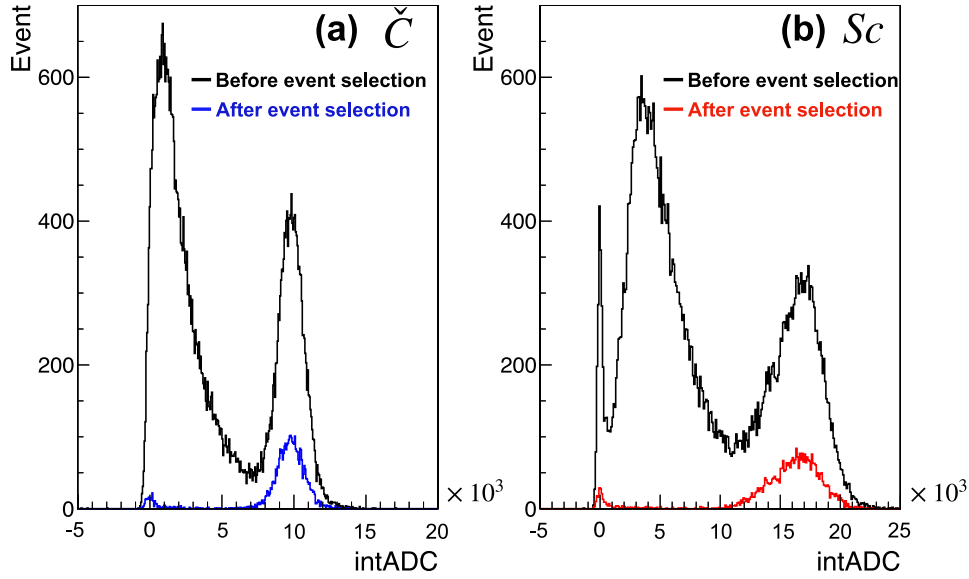


Fig. 17. The $intADC$ histograms of $tower_{ref}$ (a) $\check{C}$ and (b) Sc channel before and after the event selection. The black lines show distributions before the event selection, and the colored (blue for $\check{C}$, red for the Sc) lines are the distributions after the event selection. After the event selection, the events near pedestal are reduced significantly. The Sc channel has a peak next to the pedestal, which originates from the hadronic particles. This peak is also reduced after the selection. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

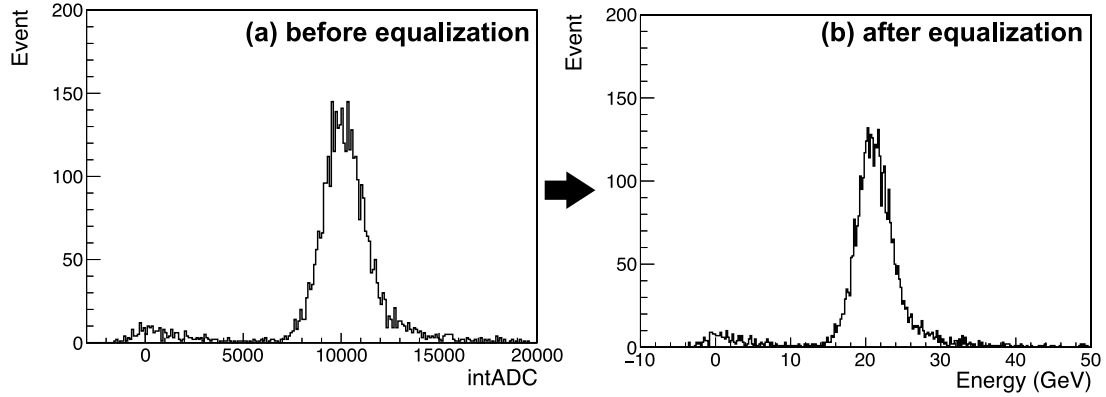


Fig. 18. The (a) $intADC$ of and the (b) equalized energy response of $tower_{ref}$ $\check{C}$ channel.

$intADC$ responses of each M1 tower, obtained using the 20 GeV e^+ beam, are equalized. Second, a scale factor is applied, which matches the sum of equalized energy responses of towers to the expected total energy deposit in the M1.

The equalization step matches the $intADC$ responses of different towers and converts them into energy units. For each tower, the $intADC$ is measured using the runs taken with a 20 GeV e^+ beam steered to the center of the tower. By dividing the energy of the beam, 20 GeV, with the mean value of the measured $intADC$, the equalization constant of the tower is calculated. Multiplying the equalization constant by the $intADC$ gives the response of the corresponding tower in energy units.

Fig. 18(a) shows $\check{C}$ channel $intADC$ of $tower_{ref}$ with a 20 GeV e^+ beam directed at its center. After applying the corresponding equalization constants, the equalized energy response of the $tower_{ref}$ $\check{C}$ channel is obtained as shown in Fig. 18(b).

A correction should be applied to the energy obtained from the equalization step. The lateral size of each tower is not sufficient to fully contain the shower, and thus the energy deposited in each tower should be smaller than 20 GeV. From Geant4 version 10.05.p01 simulations [19], a 20 GeV e^+ beam is expected to deposit 89.5% of its energy in a single DRC M1 tower, which corresponds to 17.9 GeV. The scale factor is given by dividing 17.9 GeV by the mean value of the measured tower energies sum. The proper energy deposit in DRC M1

is determined by multiplying the scale factor to the measured energy. Fig. 19 shows the corrected energy of $\check{C}$ and Sc channels with 20 GeV e^+ beam for the $tower_{ref}$.

3.3.3. EM energy linearity and resolution

The energy distribution obtained from the calibration and correction, as described in previous sections, is fitted with a Gaussian function in order to obtain the calorimeter response. The calorimeter response is determined by dividing the mean value of the fitted results by the incident beam energy. Fig. 20 shows an example of the calorimeter response measured for the $tower_{multi}$ using 20 GeV e^+ . The calorimeter response of the combined channel ($Sc + \check{C}$) is also measured by summing up the $\check{C}$ and Sc energies and dividing the summed energy by two times of the incident beam energy in same event.

As the DRC response should be proportional to the incident beam energy, it is crucial to show a linearity of the calorimeter response as a function of e^+ beam energies. The linearity of $tower_{multi}$ and $tower_{ref}$ is studied using e^+ beam with energy of 20, 40, and 60 GeV.

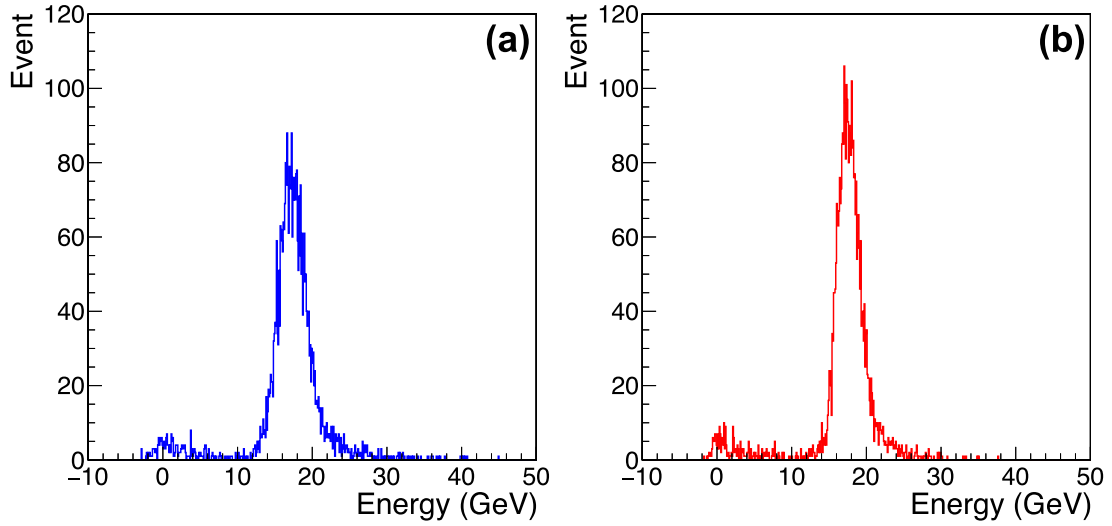


Fig. 19. Scaled energy measured from $tower_{ref}$ (a) $\check{C}$ and (b) Sc channel. Since the single M1 tower contains about 89.5% energy against the 20 GeV e^+ beam, signal responses of both channels are scaled to match the mean value of 17.9 GeV.

The energy resolution $\sigma/\sqrt{E}$ is determined using the measured calorimeter response, by dividing the standard deviation of the measured energy by its mean value. Fig. 20 also shows the example of calculating the energy resolution of the $tower_{multi}$ using a 20 GeV e^+ beam. The resolution of the combined channel ($Sc + \check{C}$) is also calculated by summing up the energy distributions of the Sc and $\check{C}$ channels. This summed energy distribution is also fitted with a Gaussian function. The standard deviation of the fit result divided by its mean value gives the energy resolution of the $Sc + \check{C}$ channel. It is well known that the resolution scales by $1/\sqrt{E}$, so that it can be written as $\sigma/E = \alpha/\sqrt{E} \oplus \beta$ [20]. The α is the stochastic term of the resolution, while the β is the constant term. The stochastic term shows the resolution itself, and the constant term represents the effects originating from the impact point of the beam. Using the same physics runs for calculating the linearity, the energy resolution is measured per energy point for both $tower_{multi}$ and $tower_{ref}$. A linear fit is performed to estimate the stochastic and constant terms.

4. Results and discussion

Fig. 21 shows the linearity plots of $tower_{multi}$ and $tower_{ref}$. For both towers, the Sc channel shows response proportional to beam energy within $\pm 1\%$, and the $\check{C}$ is proportional within $\pm 2\%$. Also, the $Sc + \check{C}$ channel shows the best linearity, with a value about $\pm 0.75\%$. Therefore, the calorimeter responses of each channel of the DRC and its combination are consistent up to $\pm 2\%$ within beam energy of 20 GeV to 60 GeV.

Fig. 22 shows the plots of the measured EM resolution of the $tower_{multi}$ and the $tower_{ref}$. The Sc channel, $\check{C}$, and the $Sc + \check{C}$ channel are plotted for each energy point respectively. The $tower_{multi}$ shows a stochastic term of 16.2% for the Sc channel and 35.2% for the $\check{C}$ channel. For $tower_{ref}$, the stochastic term of Sc is 15.6% and 31.4% for the $\check{C}$ channel.

Both results showed a lower stochastic term in the Sc channel compared to the $\check{C}$ channel. The $\check{C}$ channel only responds to relativistic e^+ , while the Sc channel produces photons with e^+ as well as other particles. It results in much higher light yields in the Sc channel. The stochastic term of the resolution is strongly dependent on the standard deviation of light yield (σ_{ly}), and therefore the Sc channel with higher light yields is expected to show a lower stochastic term than the $\check{C}$ channel [1,3], same as our results.

The constant term of $\check{C}$ shows smaller results than the Sc channel. For $tower_{multi}$, the Sc channel constant term is 4.8%, whereas the $\check{C}$

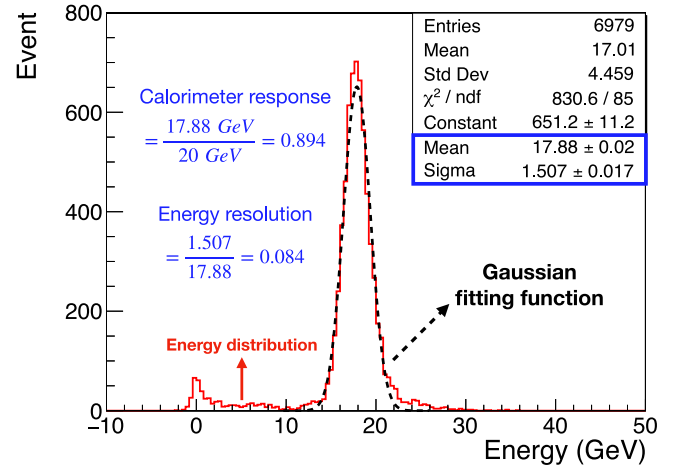


Fig. 20. The measured energy distribution (red line), Gaussian fitting result (black dotted line) and calorimeter response and resolution of the $tower_{multi}$ obtained (written by blue color). It is measured from the Sc channel only by using the 20 GeV e^+ . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

channel shows a smaller value of 3%. The $tower_{ref}$ Sc channel constant term is 5.3% and for the $\check{C}$ channel it is 4.1%. The constant term represents the effects regarding the impact point of the incident beam. Since $\check{C}$ photons are mainly produced by the particles around the shower maximum [1], $\check{C}$ is more robust to the effects of the beam impact point. Therefore, the $\check{C}$ is likely to show a lower constant term compared to the Sc channel, as shown in our results.

The best energy resolution is achieved by the combined channel ($Sc + \check{C}$) as expected. The energy resolution of the $Sc + \check{C}$ channel is 17.4% and 4% for the stochastic and constant term respectively for $tower_{multi}$. Results in 60 GeV show larger fluctuations, which originates from low statistics due to poor purity of the incident beams. The DRC uses both $\check{C}$ and Sc fibers, which are designed to have independent sampling structures. Thus, improvement in the resolution is promising by combining the photons produced from both types of fibers. The energy resolution terms for both towers are summarized in Table 6.

Overall, the results of $tower_{multi}$ and $tower_{ref}$ agrees well with the expected behavior. The Sc channel shows a lower stochastic term compared to the $\check{C}$ channel, while the constant term is the opposite. Also, the $Sc + \check{C}$ channel shows best resolution for each energy point.

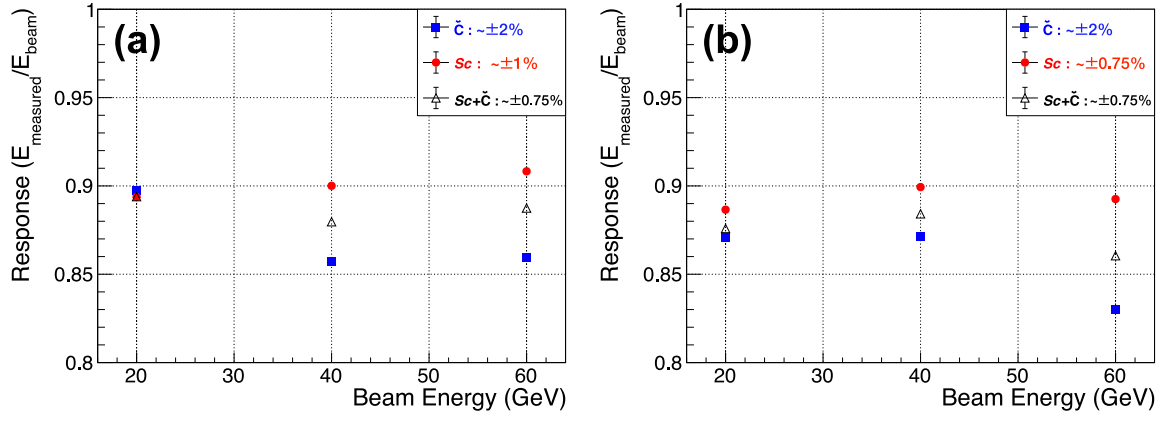


Fig. 21. DRC response as a function of incident beam energy for (a) $tower_{multi}$ and (b) $tower_{ref}$. The blue, red, and black mark represents the $\tilde{C}$, Sc , and $Sc+\tilde{C}$ channel respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

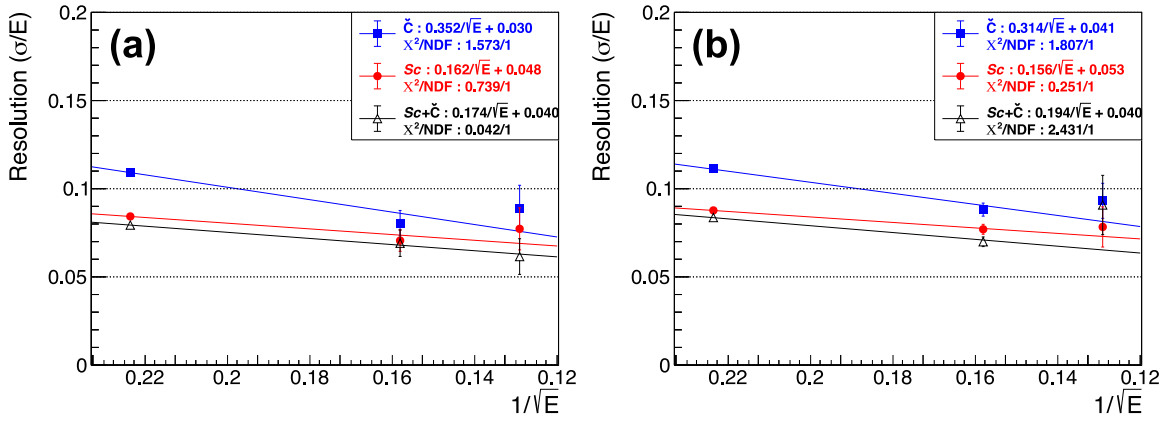


Fig. 22. The EM resolution of (a) $tower_{multi}$ and (b) $tower_{ref}$. The x-axis is scaled by $1/\sqrt{E}$. The blue line represents the $\tilde{C}$ channel, the red line represents the Sc channel, and the black line represents the $Sc+\tilde{C}$ channel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 6

The stochastic and constant terms of $tower_{multi}$ and $tower_{ref}$, for each channel.

Tower	Channel	Stochastic (%)	Constant (%)
$tower_{multi}$	$\tilde{C}$	35.2	3
	Sc	16.2	4.8
	$Sc+\tilde{C}$	17.4	4
$tower_{ref}$	$\tilde{C}$	31.4	4.1
	Sc	15.6	5.3
	$Sc+\tilde{C}$	19.4	4

5. Summary

The Korea DRC R&D collaboration has built two DRC modules with a length of 2.5 m (10 nuclear interaction length) and performed test beam studies at the CERN SPS H8 beam line facility to measure its EM performance. The DRC modules are assembled with stacks of copper plates with two types ($\tilde{C}$ and Sc) of optical fibers installed on copper plates. A customized DAQ system, which consists of the DAQ boards based on DRS4 chips and the TCB board, is adopted together with the NIM system and DAQ control PC to take the data.

To ensure the high-quality data, event selections for geometrical acceptance and the PID are performed. After selecting high-quality events, the DRC towers are calibrated to measure the energy, and corrections are applied to match the expected energy estimated by the Geant4 simulation. Two DRC towers, $tower_{ref}$ and $tower_{multi}$, are used to measure the EM performance. The $tower_{ref}$ is used to measure the performance of the most general configuration among the DRC towers,

which uses a round-shaped single cladding Sc fiber and a square-shaped PMT. The performance of $tower_{multi}$ is measured to find out the performance of the multi-cladding Sc fiber. The energy of 20, 40, 60 GeV e^+ beams are measured, and the linearity and resolution of the energy measurements are calculated for both towers. Overall, the results of the two DRC towers show the expected EM performances and good agreements.

CRediT authorship contribution statement

Guk Cho: Investigation. **Sungwon Kim:** Writing – original draft, Software, Investigation. **Joonsuk Bae:** Investigation. **Soocho Chae:** Investigation. **Byunggu Cheon:** Resources. **Suyong Choi:** Resources. **Yuji Enari:** Investigation. **Changgi Huh:** Investigation. **Jieun Hwang:** Investigation. **Kyueong Hwang:** Software, Investigation. **Haeun Jang:** Investigation. **Seoyun Jang:** Investigation. **Beomkyu Kim:** Investigation. **Bobae Kim:** Investigation. **Dongwook Kim:** Investigation. **Dongwoon Kim:** Investigation. **Minsuk Kim:** Investigation. **Tongil Kim:** Investigation. **Yongjun Kim:** Investigation. **Sanghyun Ko:** Software, Investigation. **Hyejin Kwon:** Investigation. **Nahye Kwon:** Investigation. **Hyungjun Lee:** Investigation. **Jason Lee:** Investigation. **Junghyun Lee:** Investigation. **Sehwook Lee:** Methodology, Investigation. **Yunjae Lee:** Investigation. **Sanghoon Lim:** Investigation. **Minseok Oh:** Investigation. **Hyebin Park:** Investigation. **Hyesung Park:** Investigation. **Jaehyeok Ryu:** Investigation. **Ian James Watson:** Investigation. **Yun Eo:** Investigation. **Seungkyu Ha:** Writing – review & editing, Project administration, Investigation.

Min Sang Ryu: Writing – review & editing, Methodology, Investigation. **Hwidong Yoo:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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