



First demonstration of an emulsion multi-stage shifter for accelerator neutrino experiments in J-PARC T60

Yamada, K. ; Aoki, S. ; Cao, S. ; Chikuma, N. ; Fukuda, T. ; Fukuzawa, Y. ; Gonin, M. ; Hayashino, T. ; Hayato, Y. ; Hiramoto, A. ; Hosomi, F...

(Citation)

Progress of Theoretical and Experimental Physics, 2017(6):063H02-063H02

(Issue Date)

2017-06

(Resource Type)

journal article

(Version)

Version of Record

(Rights)

© The Author(s) 2017. Published by Oxford University Press on behalf of the Physical Society of Japan.

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits...

(URL)

<https://hdl.handle.net/20.500.14094/90005110>



First demonstration of an emulsion multi-stage shifter for accelerator neutrino experiments in J-PARC T60

K. Yamada¹, S. Aoki¹, S. Cao², N. Chikuma³, T. Fukuda⁴, Y. Fukuzawa⁴, M. Gonin⁵, T. Hayashino⁶, Y. Hayato⁷, A. Hiramoto⁶, F. Hosomi³, T. Inoh⁸, S. Iori⁸, K. Ishiguro⁴, H. Kawahara⁴, H. Kim⁹, N. Kitagawa⁴, T. Koga³, R. Komatani⁴, M. Komatsu⁴, A. Matsushita⁴, S. Mikado¹⁰, A. Minamino¹¹, H. Mizusawa⁸, T. Matsumoto⁸, T. Matsuo⁸, Y. Morimoto⁸, K. Morishima⁴, M. Morishita⁴, N. Naganawa⁴, K. Nakamura⁶, M. Nakamura⁴, Y. Nakamura⁴, T. Nakano⁴, Y. Nakatsuka⁴, T. Nakaya⁶, A. Nishio⁴, S. Ogawa⁸, H. Oshima⁸, B. Quilain⁶, H. Rokujo⁴, O. Sato⁴, Y. Seiya⁹, H. Shibuya⁸, T. Shiraishi⁴, Y. Suzuki⁴, S. Tada⁴, S. Takahashi^{1,*}, M. Yokoyama³, and M. Yoshimoto⁴

¹Kobe University, Kobe 657-8501, Japan

²High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan

³University of Tokyo, Tokyo 113-0033, Japan

⁴Nagoya University, Nagoya 464-8601, Japan

⁵École Polytechnique, IN2P3-CNRS, Laboratoire Leprince-Ringuet, Palaiseau, France

⁶Kyoto University, Kyoto 606-8502, Japan

⁷University of Tokyo, ICRR, Kamioka 506-1205, Japan

⁸Toho University, Funabashi 274-8510, Japan

⁹Osaka City University, Osaka 558-8585, Japan

¹⁰Nihon University, Narashino 274-8501, Japan

¹¹Yokohama National University, Yokohama 240-0067, Japan

*E-mail: satoru@radix.h.kobe-u.ac.jp

Received March 13, 2017; Revised May 26, 2017; Accepted May 26, 2017; Published June 30, 2017

.....
We describe the first ever implementation of a clock-based, multi-stage emulsion shifter in an accelerator neutrino experiment. The system was installed in the neutrino monitoring building at the Japan Proton Accelerator Research Complex as part of a test experiment, T60, and stable operation was maintained for a total of 126.6 days. By applying time information to emulsion films, various results were obtained. Time resolutions of 5.3–14.7 s were evaluated in an operation spanning 46.9 days (yielding division numbers of $1.4\text{--}3.8 \times 10^5$). By using timing and spatial information, reconstruction of coincident events consisting of high-multiplicity and vertex-contained events, including neutrino events, was performed. Emulsion events were matched to events observed by INGRID, one of the on-axis near detectors of the T2K experiment, with high reliability (98.5%), and hybrid analysis of the emulsion and INGRID events was established by means of the multi-stage shifter. The results demonstrate that the multi-stage shifter can feasibly be used in neutrino experiments.
.....

Subject Index H16

1. Introduction

Neutrinos provide the only experimental evidence beyond the “standard model.” Therefore, a more thorough understanding of neutrino properties is important if we are to probe beyond our current understanding.

Nuclear emulsions, powerful tracking devices that can record the three-dimensional (3D) trajectories of charged particles to within $1\ \mu\text{m}$ accuracy, have already been used to make a number of key observations, such as the discoveries of the π meson [1] and the charmed particle [2], the first observation of tau–neutrino interactions [3], and the discovery of the $\nu_\mu \rightarrow \nu_\tau$ appearance [4].

In recent years, significant progress has been made in advancing emulsion techniques. Emulsion films now provide highly precise, completely uniform, refreshable, and mass-producible tracking devices [5], and their development and production is now feasible at the laboratory level [6,7]. Emulsion scanning is now automated, and achievable scanning speeds have been increasing exponentially [8–14]. In addition, multi-stage shifter techniques now allow track-timing resolution below the second scale with high reliability and high efficiency for large-scale and inaccessible emulsion experiments [15]. Therefore, it is clear that the latest emulsion techniques can open the way to innovative accelerator neutrino experiments with nuclear emulsions.

Among the studies currently being conducted at the Japan Proton Accelerator Research Complex (J-PARC) in Tokai, Japan, are the T60 [16,17] experiments, which use the emulsion detector for feasibility studies of precise measurements of ν –N interactions and strict validation of neutrino oscillation anomalies [18–26]. The emulsion detector can contribute to reducing uncertainties in the neutrino interaction kinematics, especially regarding hadron production and secondary interactions, which represent major systematic uncertainties in precise measurements of neutrino oscillations and other physics. An intense muon neutrino beam is produced by the 30 GeV proton synchrotron at J-PARC. The neutrino beam has an on-axis peak energy of approximately 1 GeV and a cycle of approximately 2.5 s. Specifically, a feasibility test was performed with a kilogram-scale target and month-scale exposure at the front of an INGRID module that had been positioned near the center of the module. INGRID, which is an on-axis detector composed of an array of iron/scintillator sandwiches, measures the neutrino beam direction and profile of the T2K experiment [27,28]. Using INGRID, we implemented the first ever use of a multi-stage shifter as an emulsion detector time stamper in an accelerator neutrino experiment. The multi-stage shifter has two or more emulsion films mounted on stages shifted by individual cycles. The combination of position displacement of the track between the stages can be taken and many independent time-dependent states are obtained. As a result, this setup can be used to achieve good resolution for longer time periods. By combining timing information, exceptionally clear full-event reconstruction can be achieved [29]. This means that events such as neutral current single π^0 ($1-\pi^0$) production can be reconstructed based on emulsion detection. It is difficult to reconstruct a $1-\pi^0$ production event without timing information. Event matching between the emulsion detector and INGRID can provide particle identification, especially for muons.

In this paper, the first implementation and demonstration of a multi-stage shifter used for accelerator neutrino experiments is described. In Sect. 2, the experimental setup, operation, and beam exposure are described. In Sect. 3, details of the emulsion track readout and reconstruction are presented. Using the information from the first stage of the multi-stage shifter (day-scale information), detections of a neutrino beam signature (Sect. 4) and a fading effect (Sect. 5) are described. Moreover, using information from the second and third stages of the multi-stage shifter (second-scale information), analyses based on timing and spatial information are described in Sect. 6. Detection of high multiplicity events (Sect. 6.1) and evaluation of the time resolution using such events (Sect. 6.2) are also described. In addition, the detection of vertex-contained events is reported in Sect. 6.3. Using such time information, the matching of emulsion and INGRID events is described (Sect. 7) for beam-induced muons (Sect. 7.1) and neutrino events (Sect. 7.2). Finally, a summary is provided in Sect. 8.

2. Setup, operation, and beam exposure

Figures 1 and 2 show the schematic layout and a photograph of the setup used in this experiment, respectively. The emulsion detector consists of an emulsion cloud chamber (ECC) for neutrino targets and a multi-stage shifter for the time stamper. The ECC has a $12.5 \times 10.0 \text{ cm}^2$ aperture area and a sandwich structure consisting of $500 \mu\text{m}$ -thick iron plates and $300 \mu\text{m}$ -thick emulsion films. The base is $180 \mu\text{m}$ thick and the emulsion layers installed on both sides have thicknesses of $60 \mu\text{m}$. For additional details about the ECC, see Ref. [30]. The multi-stage shifter is installed on the downstream side of the ECC within a 2 mm gap. The shifter, which has instrument dimensions of $44.0 \times 22.0 \times 6.0 \text{ cm}^3$ and an aperture area of $12.5 \times 10.0 \text{ cm}^2$, is composed of three stages on which doublet emulsion films are mounted. The stages are separated by 1 mm gaps. These films consist of the same type of ECC emulsion film. The power consumption is 7 W. A practical model of the multi-stage shifter was co-developed with Mitaka Kohki (Japan), based on the demonstration reported in Ref. [15] and used in the 2011 balloon experiment [29,31]. Additional details regarding the development of the multi-stage shifter can be found in Refs. [32–35]. In the balloon experiment, the multi-stage shifter was placed horizontally and operated on hour time scales. To expose the films perpendicularly to the neutrino beam, the multi-stage shifter had to be oriented vertically. In addition, since the exposure period of accelerator neutrino experiments is several months, long-term multi-stage shifter operation is required. To ensure that these diverse requirements could be met, we tested these components in various ways as regards their vertical driving and long-term operation prior to conducting our experiment.

The multi-stage shifter drive was started on 29 October 2014 and halted on 23 November 2014 to permit retreatment of the emulsion films. On 27 November 2014, the multi-stage shifter was restarted and operation continued until 22 December 2014. After a trial-and-error period for emulsion film handling, the emulsion detector was renewed in front of the INGRID module. The drive of the multi-stage shifter was started on 14 January 2015. Because of beam-period elongation, it was decided to modify the operation parameters from 13 February 2015 to extend the operation period. Operation of the multi-stage shifter continued until 1 April 2015. After beam exposure and shifter

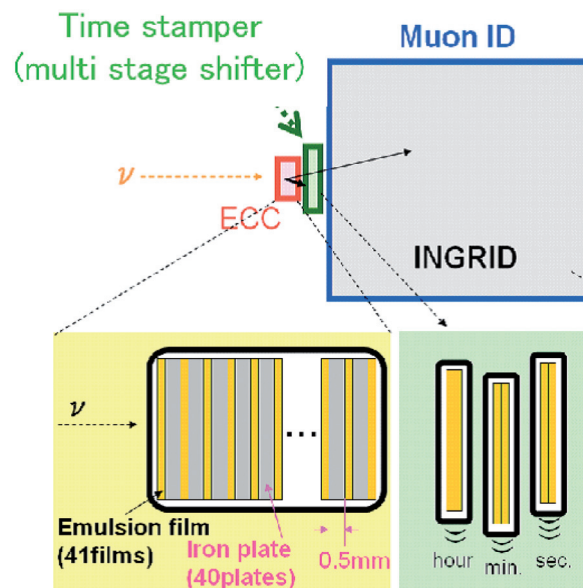


Fig. 1. Schematic view of the experimental setup.

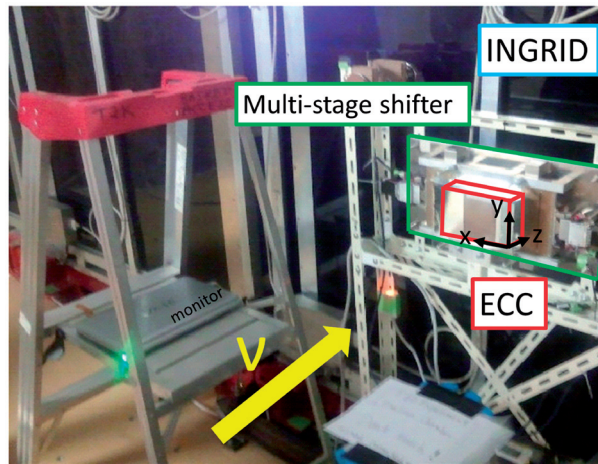


Fig. 2. Photograph of the experimental setup. The arrows located at the bottom right of the ECC show the detector coordinates. The gap between the multi-stage shifter and INGRID is approximately 15 cm. A monitor is used to check the status (stage position and number of pulses) of the multi-stage shifter.

operation adjustments, in situ exposure to cosmic rays was conducted from 1 to 8 April 2015 to permit pre-alignment of the shifter films.

Table 1 lists the operation parameters for the multi-stage shifter for each operation. For example, the $4\text{--}20\ \mu\text{m s}^{-1}$ third-stage velocity in the first operation corresponds to $1.25\text{--}0.25\ \text{s}$ time resolution with $5\ \mu\text{m}$ connection accuracy between the second and third stages. Figure 3 shows a timing chart for a portion of the fourth operation during which remote status monitoring (stage position and number of pulses) of the multi-stage shifter was performed. Figure 4 shows the reproducibility of each stage during operation. The stages of the multi-stage shifter were controlled by pulse motors. The third and second stages returned to the reference position for each cycle. The reproducibility was evaluated by checking the difference in the number of pulses between “go” and “return.” Root-mean-square (RMS) repeatability of 0.16 and $0.46\ \mu\text{m}$ was obtained for the third and second stages, respectively, for all operation periods. More specifically, we performed continuous, stable multi-stage shifter operation for 24.9, 24.8, 30.0, and 46.9 days for each period and achieved a total of 126.6 days of operation without encountering any problems with the multi-stage shifter. We achieved month-scale operation of the multi-stage shifter in a standing position.

3. Scanning and track reconstruction

The emulsion films exposed from 14 January to 8 April 2015 were recovered and developed. The emulsion films recorded cosmic-ray muons (majority) and tracks from neutrino interactions in the wall and the ECC. The emulsion films were scanned using the fully automated hyper-track selector (HTS) scanning system at Nagoya University, Japan [36]. These scans enabled us to obtain the recognized track information (which consisted of the tracks’ positions, angles, and darkness). The scan area and the accepted angular range were $105 \times 80\ \text{mm}^2$ (10 mm inside from the edge) and $|\tan \theta_x| \leq 1.8$ ($|\theta_x| \leq 60.9^\circ$), respectively, where θ_x is the projection angle on the x – z plane with respect to the z axis, and similarly for θ_y .

The scanned tracks were connected in the following order: the most downstream of the ECC film $\rightarrow$ first stage $\rightarrow$ second stage $\rightarrow$ third stage. The tracks between films were reconstructed by using the position and angle coincidence of the tracks, which were extrapolated to the gap centers between

Table 1. Multi-stage shifter operation parameters for each operation.

Period	Duration (days)	First stage (100 μm step)			Second stage (100 μm step, 100 step stroke, 9900 μm stroke)				Third stage (5184 μm stroke)		
		Interval (hours)	# of steps	stroke (μm)	Interval (min)	# of steps	# of strokes	# of cycles	Velocity ($\mu\text{m s}^{-1}$)	# of strokes	# of cycles
2014 29 Oct 16:12 –23 Nov 14:04	24.9	14.4	42	4100	8.6	4150	41.5	20.8	10.0	4150	2075.0
2014 27 Nov 16:07 –22 Dec 10:38	24.8	7.2	83	8200	4.3	8252	82.5	41.3	20.0	8252	4126.0
2015 14 Jan 14:24 –13 Feb 13:39	30.0	11.5	63	6200	6.9	6240	62.4	31.2	12.5	6240	3120.0
2015 13 Feb 14:31 –1 Ap 12:54	46.9	36.0	32	3100	21.6	3127	31.3	15.7	4.0	3127	1563.5

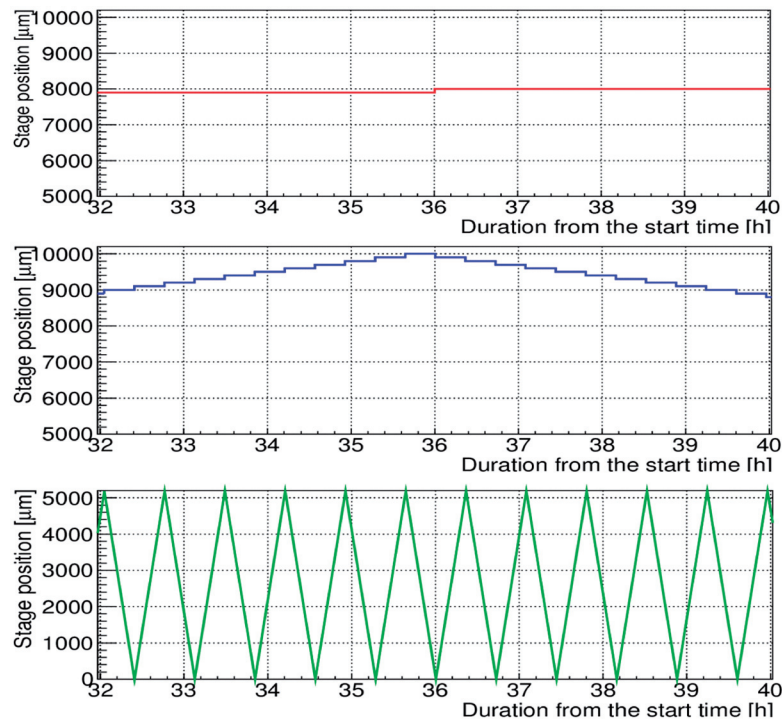


Fig. 3. Timing chart for part of the fourth operation (from 14 February 2015 at 22:31 to 15 February 2015 at 06:31). The top, middle, and bottom panels show the first, second, and third stages, respectively.

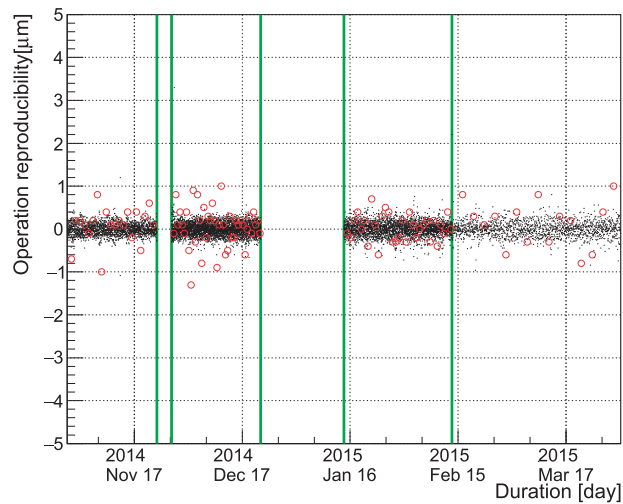


Fig. 4. Reproducibility of each stage during operation. The black dots and red circles represent the third and second stages, respectively.

stages. In this analysis, we focused on the $|\tan \theta_x| \leq 1.0$ ($|\theta_x| \leq 45.0^\circ$), $|\tan \theta_y| \leq 1.0$ ($|\theta_y| \leq 45.0^\circ$) range of angles. Using track reconstruction, the track displacements between the films at all stages were obtained. These displacements correspond to the stage positions for each time step. Using the combination of the stage positions, the track's incident time was obtained. In carrying out this analysis, we focused on the incident tracks for the period from 13 February to 1 April 2015, because the emulsion film condition is better for periods closer to the development date; small fading effects are described in Sect. 5.

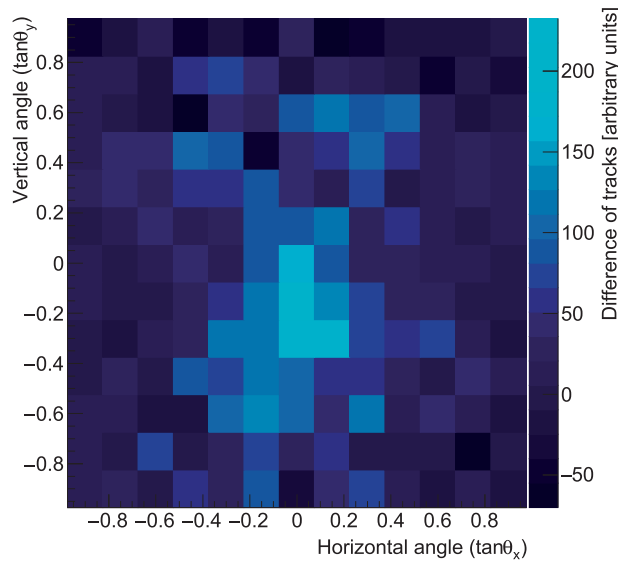


Fig. 5. Difference in track-angle distribution between the beam-on and beam-off periods (normalized by the beam-on period and assumed to be zero for $|\tan \theta_y| \geq 0.7$). For the vertical angle, positive numbers indicate upward trajectories and negative numbers indicate downward trajectories in the direction from the beam's upstream to downstream path (specifically, a positive direction for the z axis).

4. Neutrino-beam signature

From the position of the first stage (divided every 36 hr), the beam-on (31.5 days¹) and beam-off periods (7.0 days; pre-alignment period) can be distinguished. Figure 5 shows the difference in the track-angle distribution between the beam-on and beam-off periods. The beam excess (so-called “sand muons,” which are induced on a wall in front of the detector by the muon neutrino beam) was clearly detected in the center for the horizontal angle and in a slightly downward direction for the vertical angle owing to the beam's slightly downward projection. We used time information to find the neutrino beam's signature.

5. Measurement of the fading effect

The darkness of the emulsion tracks correlates with dE/dx for the incident particles and can be used for particle identification. The track darkness information is obtained during track recognition and is referred to as the pulse height (PH). When the scan system recognizes the tracks, 16 tomographic images are obtained in an emulsion layer. The PH is defined as the number of hit images. Figure 6 shows the PH—the sum of four emulsion layers' (most downstream of the ECC film and the first stage film) peak values—as a function of the time elapsed until development. Here, PH attenuation is clearly seen (8%). This can be explained as latent image fading. For the first time, we used time information to measure the precise fading effects using tracks recorded in the same emulsion film. These correspond to reasonably similar conditions in terms of the film characteristics, incident particles, elapsed environment, development effects, and scanning conditions. By measuring the fading effects, the PH can be corrected even if the tracks degrade. Thus, this also provides us with precise dE/dx measurements. In this exposure, the emulsion detector was maintained at a temperature

¹ Twenty-one steps were used.

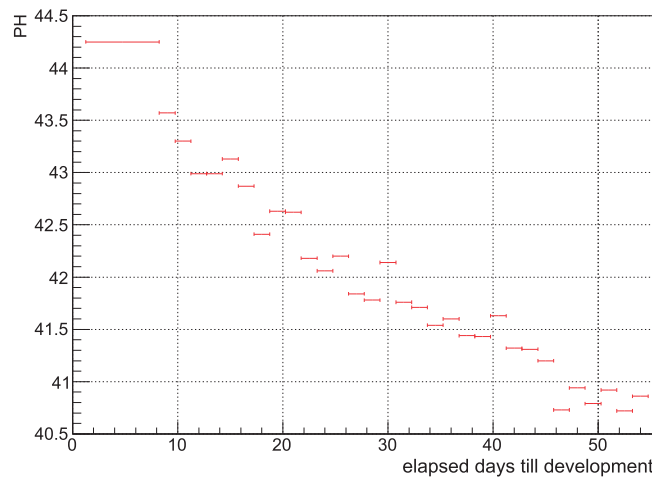


Fig. 6. Pulse height (PH), defined as the sum of four emulsion layers' (most downstream of the ECC film and the first stage film) peak values, as a function of elapsed time. The first point indicates the pre-alignment period. The other points indicate 36 hr periods. The emulsion films were kept refrigerated from recovery to development.

of approximately 22 °C. It is possible to suppress track fading by maintaining the emulsion films at a low temperature (10 °C or lower).

6. Measurement of the track rate

From the third-stage position, all incident tracks had associated time information at a time resolution of seconds. Figure 7 shows the number of tracks for 30 s intervals as a function of operation period. The number of tracks was basically constant during operation. For earlier periods, the number of tracks appears to decrease slightly because of fading effects. In addition, spikes appear on some tracks. Figure 8 shows a histogram of the number of tracks for 30 s intervals.

6.1. Detection of high-multiplicity events

We found some excesses in the number of tracks per 30 s (Fig. 8). Tracks localized in time were clustered. The clustered events had no tracks beyond 30 s from the event's timing edge. Figure 9 shows the multiplicity distribution after clustering. We found seven clear high-multiplicity events (≥ 7 tracks): 2 events with 7 tracks, and 5 single events with 8, 9, 13, 16, and 25 tracks. Figure 10 shows a vector map of the high-multiplicity event with 25 tracks. These tracks had similar incident angles, similarly to the other events. In addition, no events that matched with INGRID were found. It was expected that the events occurred during off-timing of the beam. Therefore, we assumed that the events were induced by cosmic rays.

6.2. Evaluation of time resolution

Tracks in the high-multiplicity events were expected to be recorded simultaneously. The time resolution of the multi-stage shifter was evaluated based on seven high-multiplicity events. For each event, an average incident time was calculated and the residual time between the average incident time and the incident time for the individual tracks was obtained. Figure 11 shows the residual time for tracks for each high-multiplicity event. From these, the standard deviation of the residual time, which was defined as the time resolution, was obtained. Figure 11 shows the standard deviation of the residual time for each incident angle. The evaluated time resolution of the multi-stage shifter in this operation

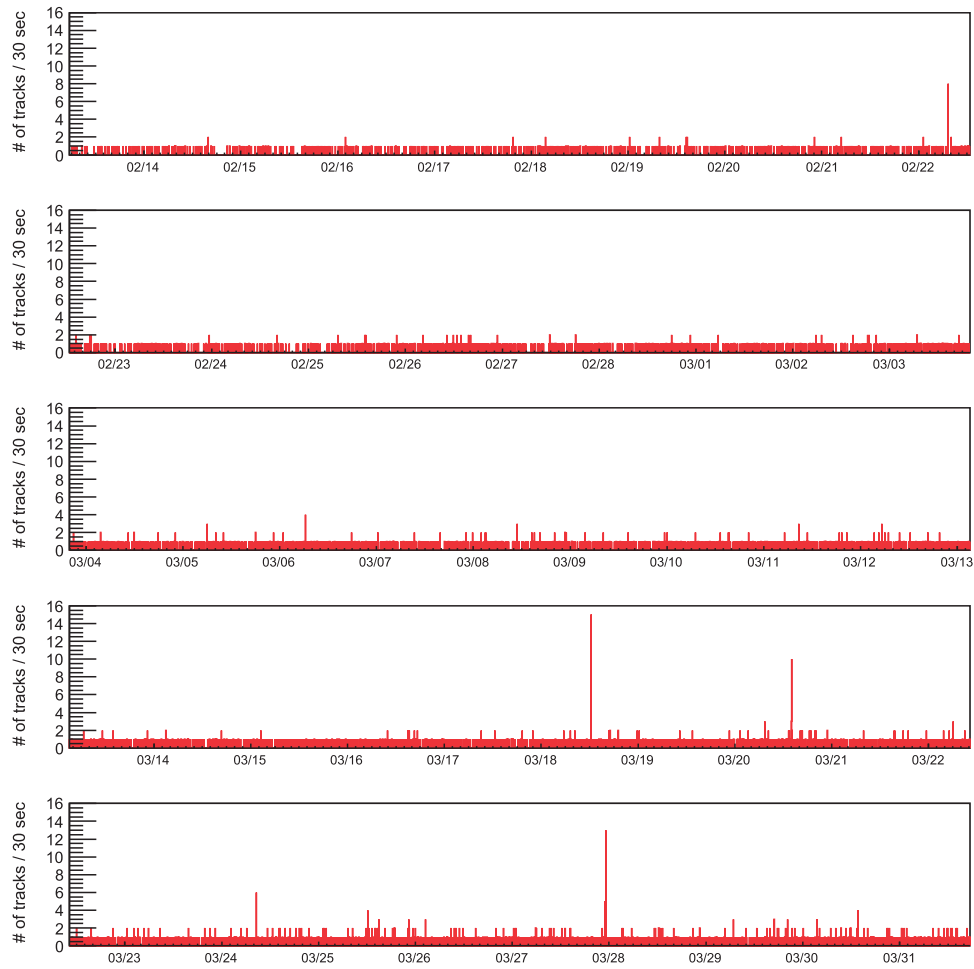


Fig. 7. Number of tracks for 30 s intervals as a function of operation period.

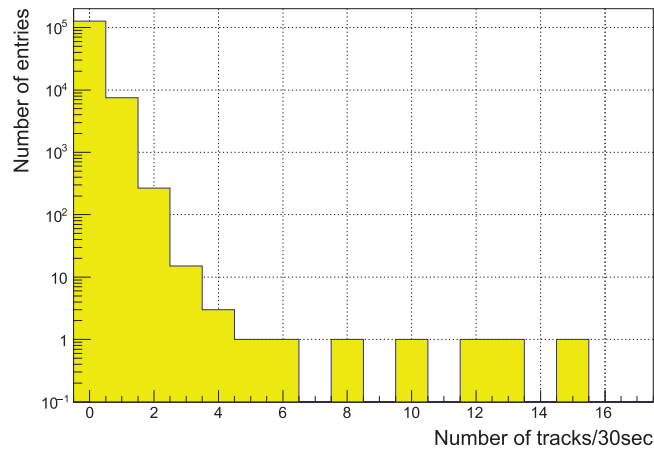


Fig. 8. Histogram showing the number of tracks for 30 s intervals.

was 5.3–14.7 s. We evaluated the time resolution by using the observed high-multiplicity events and performed an evaluation up to the largest incident angle used in this analysis. The time resolution is determined by the track-connection accuracy divided by a final-stage velocity. The connection accuracy is determined by the gap, the track-angle accuracy, and the alignment accuracy between stages.

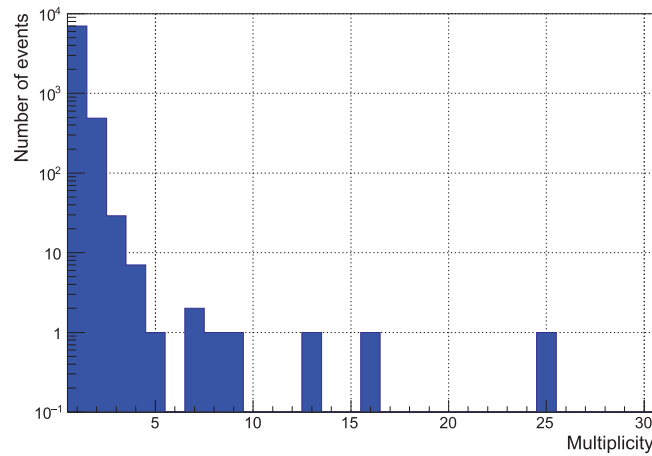


Fig. 9. Multiplicity distribution after clustering.

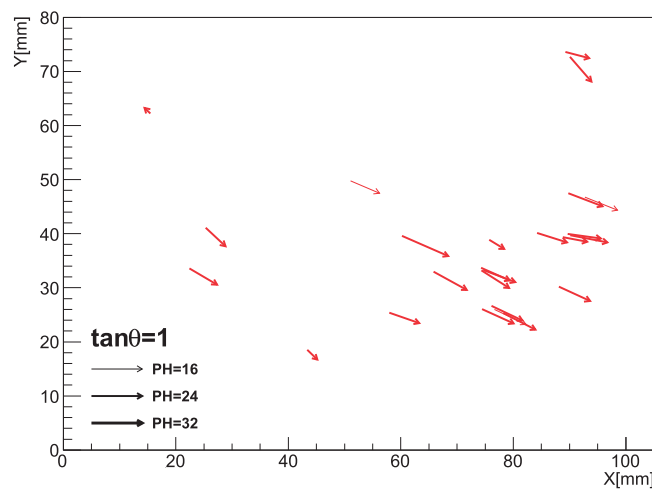


Fig. 10. Vector map of a high-multiplicity event (25 tracks). Horizontal and vertical ranges show the scanned area of the most downstream ECC film. The starting point of the vectors indicates the positions of the tracks on the same film. The lengths and directions of the vectors indicate the sizes and directions of the incident angles of the tracks, respectively. The end points of the vectors indicate the positions of the tracks extrapolated onto the third-stage film of the multi-stage shifter. The vector widths indicate the PH (the sum of the two emulsion layers most downstream of the ECC film) of the tracks. The vectors (black) located at the bottom left-hand side of the vector map indicate the angle and PH scales.

In this configuration, the time resolution was 5.3–14.7 s for a stage velocity of $4.0 \mu\text{m s}^{-1}$, corresponding to a connection accuracy of 20–60 μm (more correctable). In this operation, to extend the operation period owing to the beam-period elongation, the third-stage velocity had to be reduced. By increasing the velocity and improving the connection accuracy, the time resolution can be improved. Moreover, by decreasing the gaps between the stages and increasing the number of stages, the time resolution can be improved by several orders of magnitude. For example, in this configuration, by adding a stage with a shorter cycle, a 100 times better time resolution can be achieved (approximately 0.05 s time resolution). This allows one to distinguish between beam-on/off timing (cycles of approximately 2.5 s).

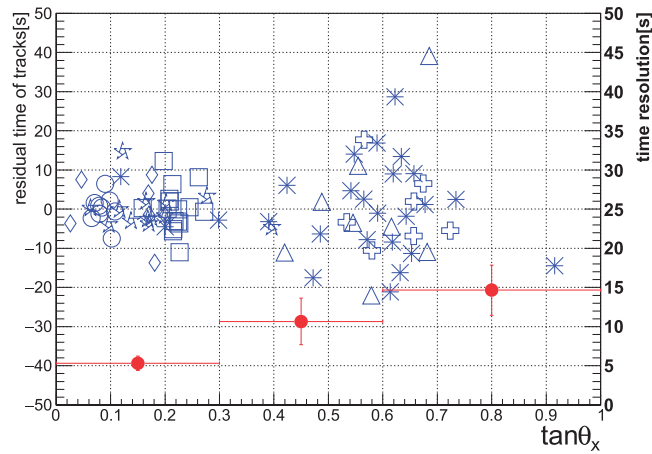


Fig. 11. Data points using different symbols without error bars indicate the residual time (left-hand vertical axis) for tracks for each high-multiplicity event. The filled circles and error bars indicate the corresponding standard deviations (right-hand vertical axis).

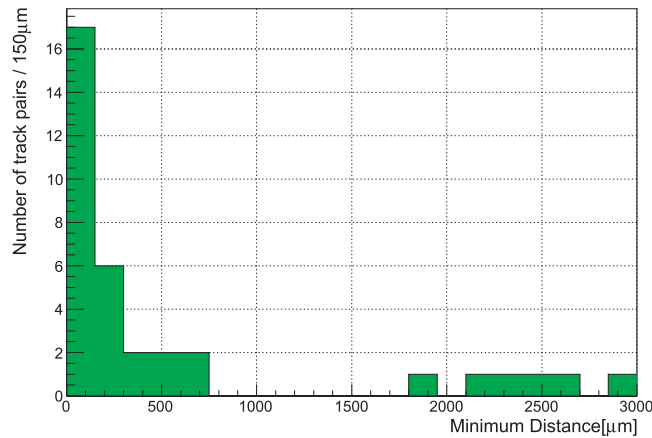


Fig. 12. Distribution of minimum distances.

6.3. Reconstruction of vertex-contained events

Next, we searched among the clustered events for vertex-contained events with low multiplicity (2–5 tracks). To accomplish this, the minimum distance between any two tracks in a clustered event was calculated. Figure 12 shows the distribution of the minimum distances. We found events localized around small minimum distances. Here, 29 track pairs with minimum distances of less than 1 mm were selected. Chance coincidences were estimated at less than 2.0 track pairs from the event density for large minimum distances (1–3 mm). By improving the time resolution, we found that chance coincidence could be reduced. After track-pair clustering for 29 track pairs, 23 clustered events (vertex-contained events) were reconstructed. Of these 23 vertex-contained events, 20 events had 2 tracks and 3 events had 3 tracks. A major component of the 20 events with 2 tracks was an electron-pair candidate, which has a topology characterized by close positions and a narrow angle between the two tracks owing to the small opening angle of an electron pair. Some of the events were confirmed as electron pairs by checking the two tracks starting from the same position in the ECC. Figure 13 shows a vertex-contained event that was confirmed as a neutrino interaction by checking the tracks starting from the same position in the ECC. Figure 14 shows an ECC display of that

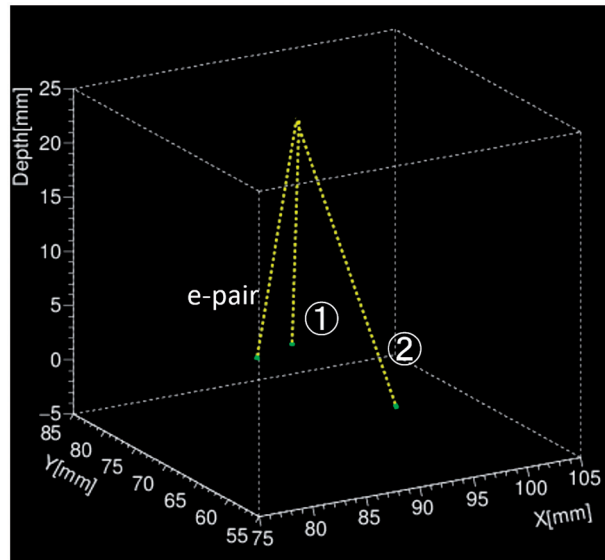


Fig. 13. Example of a vertex-contained event. The solid lines (green) show track segments in the most downstream of the ECC film. The dashed lines (yellow) show the lines extrapolated to the vertex point. The tracks labeled “1” and “2” were confirmed as charged particles, and the other track, labeled “e-pair,” was confirmed as an electron pair in the ECC.

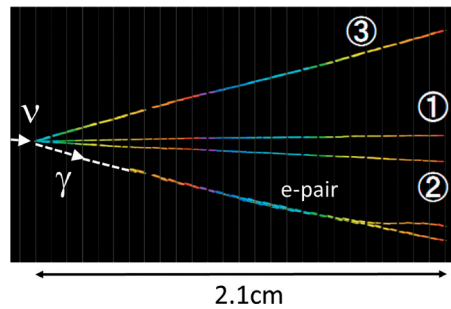


Fig. 14. ECC event display. The tracks labeled “1,” “2,” and “3” were charged particles, and the other track, labeled “e-pair,” was an electron pair.

specific event. We reconstructed the neutrino interaction with timing and spatial information using the multi-stage shifter. In addition, we detected a γ -ray associated with the neutrino interaction. These results show that inclusive event reconstructions, including γ -ray and neutral-particle events, can be achieved. Moreover, by detecting an event with two γ -rays using timing and spatial information, the $1-\pi^0$ production event could also be reconstructed.

7. Matching of emulsion and INGRID events

7.1. Sand muon matching

We used emulsion tracks time-stamped to the third stage to perform event matching to INGRID events. The efficiency of time-stamped application to emulsion tracks was approximately 80% in the track base obtained from neutrino event time-stamping, as shown in Sect. 7.2. The time-stamp inefficiency was consistent with the fading effect. Since two emulsion films are mounted on each stage, taking both into consideration permits the time-stamp efficiency to be improved. Moreover, by suppressing the fading effect, the time-stamp inefficiency can be reduced.

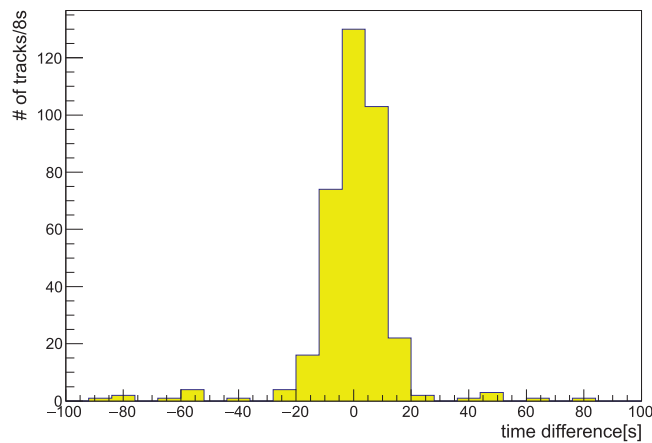


Fig. 15. Time differences between emulsion-track and INGRID events.

The following criteria were required for selection of INGRID events: use of beam-on timing; at least one track with three or more hits in each projection; and a hit on the most upstream plane. The INGRID events were mainly sand muons, and the hit efficiency for sand muons was 98%. In this analysis, the average INGRID event rate was 14.1 events per 200 s. INGRID events were selected in a ± 100 s time window for the time stamp of each emulsion track. Of these, events with position and angle differences within 3σ were used. In this analysis, the position difference σ s obtained were 1.7 cm for both projections. The angle difference σ s were 0.057 rad and 0.047 rad for both projections, respectively. These σ s were dominated by the track position and angle accuracy of INGRID. Figure 15 shows the time difference between the emulsion track and the INGRID event. We obtained a clearly matching peak and a fitted σ of 7.9 s, which corresponds well to the absolute timing resolution of the multi-stage shifter for 46.9 days in this operation. The result is also consistent with the time resolution evaluated in Sect. 6.2. The time resolution can be improved as described in Sect. 6.2. By constraining the time difference within 3σ and using a chance coincidence density of greater than 3σ , a matching reliability of 98.5% was obtained. We can thus confirm that emulsion track matching to INGRID events with high reliability was achieved using the multi-stage shifter.

7.2. Neutrino-event matching

We detected neutrino events with the ECC in a pilot analysis (events with downward-starting tracks from a vertex in the ECC, except for events such as single electron pairs using the opening angle and dE/dx information) and followed them down to the most downstream of the ECC films (three events and five tracks). Of these five tracks, four tracks in three events were time-stamped. One track showed a time-stamp inefficiency that was consistent with the fading effect. The time-stamp efficiency can be improved as shown in Sect. 7.1. In addition, we detected neutrino events by reconstructing vertex-contained events with the multi-stage shifter, as shown in Sect. 6.3, and confirmed neutrino events in the ECC (three events and eight tracks). By combining the neutrino events detected with the ECC and the multi-stage shifter, we confirmed four events and nine tracks:² two events with three tracks, one event with two tracks,³ and one single track event. Track time stamps for each event were consistent with the timing resolution. We time-stamped neutrino events using the average track time

² Two events and three tracks overlapped.

³ Not an electron pair, since we detected more than two tracks from the primary vertex.

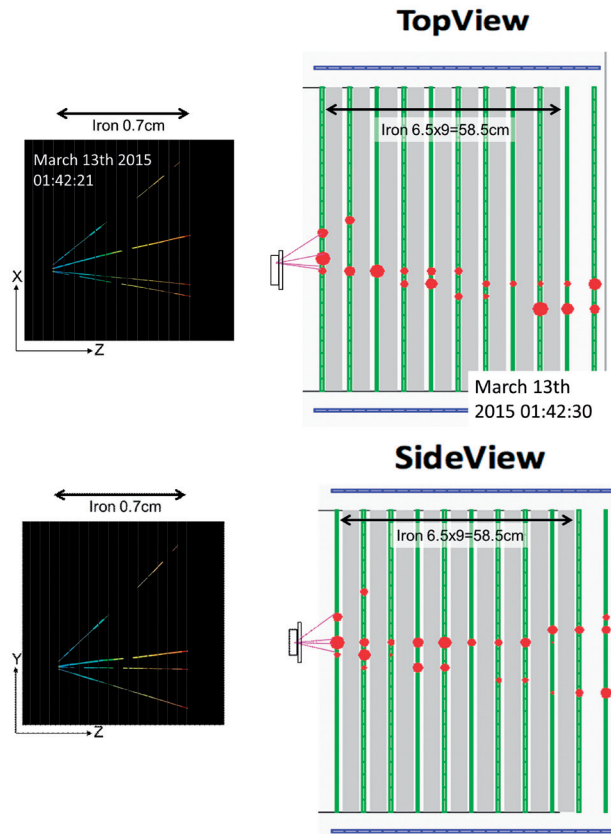


Fig. 16. Matched event #1. Event displays of (left) ECC and (right) INGRID. The top and bottom panels show the top and side views, respectively.

stamps, and then attempted neutrino-event matching with INGRID. INGRID events were selected using event-timing differences, track positions, and angles within 3σ . These are the same criteria as used for sand-muon matching in Sect. 7.1.

Of the four events, three were uniquely matched with INGRID events. The matched events had reasonable timing differences. Figures 16, 17, and 18 show the ECC and INGRID events. In addition, the matched events were topologically and kinematically compatible. This result shows that we succeeded in event matching with INGRID and established a hybrid analysis by using the multi-stage shifter. A single event with one track was not matched with an INGRID event. The track in this event was a black track and not a minimum ionization particle (a high- dE/dx particle). Using measurements of multiple Coulomb scattering, $p\beta$ was $22 \text{ MeV}/c$ at the multi-stage shifter. Here, p and β are the momentum and velocity in units of light speed, c , which corresponds to a kinetic energy of less than 12 MeV . The energy loss in a 6.5 cm -thick steel plate with a plane in the INGRID module is 74 MeV for a minimum ionization particle. Since INGRID events are required to have tracks with more than three-plane hits, it is likely that this track is not identified as an INGRID event.

8. Summary

In this paper, we reported on J-PARC T60 experiments using an emulsion detector for feasibility studies of the precise measurement of ν -N interactions and strict validation of neutrino-oscillation anomalies. In our accelerator neutrino experiments, a multi-stage shifter was implemented with vertical and month-long time-scale operation, for the first time, and stable operation (0.16 and

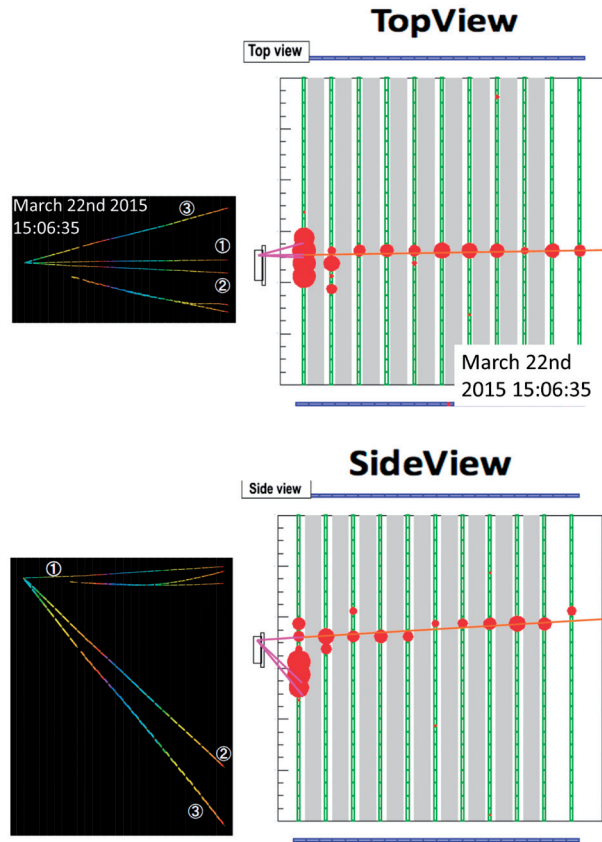


Fig. 17. Matched event #2.

0.46 μm reproducibility for the third and second stages, respectively) was achieved for a total of 126.6 days.

Emulsion films exposed from 14 January to 8 April 2015 were scanned ($|\theta_{x,y}| \leq 60.9^\circ$), and operations spanning the period from 13 February to 1 April 2015 were analyzed ($|\theta_{x,y}| \leq 45.0^\circ$).

Using the first-stage position, the neutrino beam's signature was clearly detected. In addition, fading effects were measured for the first time using tracks recorded in the same emulsion film. These correspond to quite similar conditions in terms of film characteristics, incident particles, elapsed environment, development effects, and scanning conditions. By precisely measuring fading effects, the PH could be corrected even if tracks exhibited such effects. The results provide us with dE/dx measurements.

From the track rate measured using the third-stage position, high-multiplicity events were clearly identified. Using these high-multiplicity events, a time resolution of 5.3–14.7 s was evaluated for a 46.9-day operation period (4.05×10^6 s). This result corresponds to time-resolved numbers of $(1.4\text{--}3.8) \times 10^5$ $\left(= \frac{4.05 \times 10^6}{(5.3\text{--}14.7) \times 2}\right)$. By increasing the stage velocity, improving the connection accuracy, decreasing the gap between the stages, and increasing the number of stages, the time resolution can be improved by several orders of magnitude. As a result, beam-on/off timing (cycles of approximately 2.5 s) could be distinguished.

A reconstruction of vertex-contained events was performed using timing and spatial information, from which neutrino events were identified. In addition, a γ -ray event associated with the neutrino

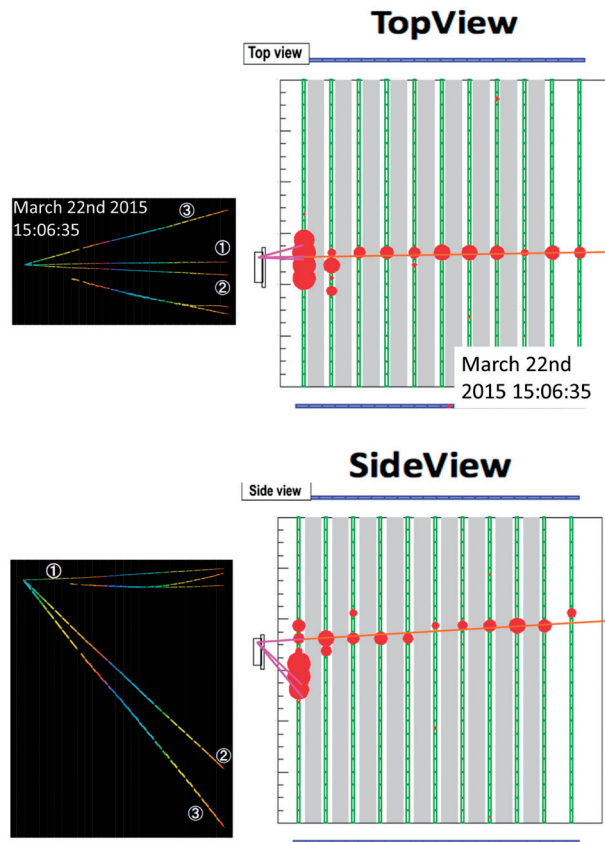


Fig. 18. Matched event #3.

event was found. Thus, it was clarified that event reconstruction including γ -ray and neutral-particle events could be performed, and that a $1-\pi^0$ production event could be reconstructed.

Emulsion track matching to INGRID events was performed with high reliability (98.5%). By using the matching peak, we obtained an absolute time resolution of 7.9 s, which is consistent with the time resolution evaluated based on the high-multiplicity events. In addition, neutrino events were time stamped and clear neutrino-event matching with INGRID events was performed. Furthermore, hybrid analysis was established using the multi-stage shifter.

Finally, the results show, for the first time, the feasibility of multi-stage shifter use with accelerator neutrino experiments.

Acknowledgements

The authors thank J-PARC and the T2K Collaboration for their support. This work was supported financially by the Japan Society for the Promotion of Science (JSPS) KAKENHI (grant numbers 20244031, 25105001, 25105006, 25707019, 26105516, 26287049, 26800138, and 16H00873).

References

- [1] C. M. G. Lattes, H. Muirhead, G. P. S. Occhialini, and C. F. Powell, *Nature* **159**, 694 (1947).
- [2] K. Niu, E. Mikumo, and Y. Maeda, *Prog. Theor. Phys.* **46**, 1644 (1971).
- [3] K. Kodama et al. [DONUT Collaboration], *Phys. Lett. B* **504**, 218 (2001).
- [4] N. Agafonova et al. [OPERA Collaboration], *Phys. Rev. Lett.* **115**, 121802 (2015).
- [5] T. Nakamura et al., *Nucl. Instr. and Meth. A* **556**, 80 (2006).
- [6] N. Naganawa and K. Kuwabara, Abstracts for SPIJ's Fall Conference in 2010, pp. 10–11 (in Japanese).

- [7] K. Ozaki et al., JINST **10**, P12018 (2015).
- [8] K. Niwa, K. Hoshino, and K. Niu, Proc. Int. Cosmic Ray Symp. High Energy Phenomena, Tokyo, p. 149 (1974).
- [9] S. Aoki et al., Nucl. Instr. and Meth. B **51**, 466 (1990).
- [10] T. Nakano, Ph.D. Thesis, Nagoya University, Japan (1997) (in Japanese).
- [11] T. Nakano and K. Morishima, J. SPSTJ. **72**, 229 (2008).
- [12] K. Morishima and T. Nakano, JINST **5**, P04011 (2010).
- [13] T. Fukudaa, S. Fukunagaa, H. Ishidaa, K. Kodamab, T. Matsuoaa, S. Mikadoc, S. Ogawaaa, H. Shibuyaa, and J. Sudoa, JINST **8**, P01023 (2013).
- [14] T. Fukudaa, S. Fukunagaa, H. Ishidaa, K. Kodamab, T. Matsuoaa, S. Mikadoc, S. Ogawaaa, H. Shibuyaa, and J. Sudoa, JINST **9**, P12017 (2014).
- [15] S. Takahashi et al., Nucl. Instr. and Meth. A **620**, 192 (2010).
- [16] S. Aoki et al., KEK/J-PARC-PAC 2014-17.
- [17] S. Aoki et al., JPS Conf. Proc. **8**, 023004 (2015).
- [18] C. Athanassopoulos et al., Phys. Rev. Lett. **75**, 2650 (1995).
- [19] C. Athanassopoulos et al., Phys. Rev. Lett. **77**, 3082 (1996).
- [20] C. Athanassopoulos et al., Phys. Rev. Lett. **81**, 1774 (1998).
- [21] C. Athanassopoulos et al., Phys. Rev. C **58**, 2489 (1998).
- [22] A. Aguilar et al., Phys. Rev. D **64**, 112007 (2001).
- [23] A. Aguilar-Arevalo et al., Phys. Rev. Lett. **98**, 231801 (2007).
- [24] A. Aguilar-Arevalo et al., Phys. Rev. Lett. **102**, 101802 (2009).
- [25] A. Aguilar-Arevalo et al., Phys. Rev. Lett. **105**, 181801 (2010).
- [26] A. Aguilar-Arevalo et al., Phys. Rev. Lett. **110**, 161801 (2013).
- [27] K. Abe et al., Nucl. Instr. and Meth. A **659**, 106 (2011).
- [28] K. Abe et al., Nucl. Instr. and Meth. A **694**, 211 (2012).
- [29] S. Takahashi, S. Aoki, K. Kamada, S. Mizutani, R. Nakagawa, K. Ozaki, and H. Rokujo, Prog. Theor. Exp. Phys. **2015**, 043H01 (2015).
- [30] T. Fukuda et al., [arXiv:1703.03659](https://arxiv.org/abs/1703.03659) [hep-ex] [[Search INSPIRE](#)].
- [31] H. Rokujo, S. Aoki, S. Takahashi, K. Kamada, S. Mizutani, R. Nakagawa, and K. Ozaki, Nucl. Instrum. Meth. A **701**, 127 (2013).
- [32] S. Takahashi et al., Ionizing Radiation **40**, 127 (2015) (in Japanese).
- [33] F. Mizutani et al., Proc. Balloon Symp., ISAS/JAXA, isas14-sbs-005 (2014) (in Japanese).
- [34] S. Takahashi and S. Aoki, J. SPIJ. **78**, 228 (2015) (in Japanese).
- [35] S. Takahashi et al., Prog. Theor. Exp. Phys. **2016**, 073F01 (2016).
- [36] M. Yoshimoto, T. Nakano, R. Komatani, and H. Kawahara, [arXiv:1704.06814](https://arxiv.org/abs/1704.06814) [physics.ins-det] [[Search INSPIRE](#)].