Developments of the next-generation nuclear emulsion readout system " HTS2(Hyper Track Selector 2) "

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GRAINE project aims at precise observations of cosmic gamma rays from sub-GeV to GeV, especially on the Galactic plane or central region, using a balloon-borne nuclear emulsion telescope with a large sensitive area, high angular resolution, and polarization sensitivity. So far, the balloon experiments have been performed in 2011, 2015, 2018, and 2023. In the 2018 flight, we successfully imaged Vela pulsar with the highest angular resolution. In the 2023 flight, we employed a large sensitive area telescope, 6.5 times larger than in the 2018 flight. To increase the area and the number of flights for large statistics, one of the most important development elements is to speed up the readout system of nuclear emulsion. The nuclear emulsion records all charged particle tracks as analog images. The images should be readout by a microscope and analyzed using huge computer systems. We are currently developing a next-generation nuclear emulsion readout system, Hyper Track Selector 2 (HTS2). The designed scanning speed is 5 times faster than that of the previous system (HTS), which was developed as the fastest readout system in 2015. In this presentation, we will give an overview of the developments and features of HTS2. In addition, we will give the latest scan data obtained with HTS2.

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1. Introduction

The Fermi Gamma-ray Space Telescope, launched in 2008, has greatly advanced cosmic gamma-ray observations and opened up the field of gamma-ray astronomy. In recent years, observations of neutrinos and gravitational waves have been developed, and several relations between these physics events and cosmic gamma-ray observations have been suggested. Therefore, the importance of observing cosmic gamma rays as a multi-messenger observation is increasing. However, the difficulty of observing cosmic gamma rays in the tens of MeV to hundreds of GeV, which is the target of the Fermi Gamma-ray Space Telescope, makes the angular resolution several orders worse than that of observations in other wavelength. Since there are some problems to be solved, it is important to observe cosmic gamma rays with high accuracy.

Gamma-Ray Astro-Imager with Nuclear Emulsion (GRAINE) is a project aiming at precise cosmic gamma-ray observation using a nuclear emulsion, which has sub-micrometer spatial resolution. Especially from sub-GeV to GeV, it has higher angular resolution than the Fermi-Gamma Space Telescope, and it is the only experiment that can observe polarization observation. Nuclear emulsion have been a commonly used detector since the beginning of cosmic ray observations, but because they are photographic film, the observed tracks are recorded as analog data, and analysis has required many times.

Since the development of the world's first automatic track readout system of nuclear emulsion "Track Selector"[1], our F-Laboratory have been conducting research and development to improve the readout speed of nuclear emulsion(Figure 1). In 1998, the UTS (Ultra Track Selector) made it possible to detect tracks without specifying the angle, and achieved a readout speed of 1 cm^2/h/layer. Furthermore, a technique called NETSCAN[2] was established to reconstruct a large amount of tracks contained in nuclear emulsion by connecting the tracks between films. In 2006, S-UTS with a readout speed of 72 cm^2/h/layer was developed[3], enabling experiments using only nuclear emulsion without the need for scintillation counters. This led to the first GRAINE flight in 2011, and it was used for the analysis.

Later, the development of HTS in 2015[4], which dramatically increased the reading rate to 4,700 cm^2/h/layer, which made it easier to analyze the entire area of the nuclear emulsion, and it was used in the GRAINE2015 and GRAINE2018 flight experiments. In particular, the GRAINE 2018 flight experiment successfully imaged the Vela pulsar, achieving an angular resolution approximately 7.6 times better than that of the Fermi Space Gamma-ray Telescope.

GRAINE2023, which completed the flight from April 30 to May 1, 2023, used a nuclear emulsion with an effective area 6.5 times larger than that of the previous experiment in order to achieve large statistics. Therefore, it is essential to scan the large number of nuclear emulsion at even faster, and we are currently developing Hyper Track Selector 2 (HTS2), which aims to improve the readout speed by 5 times compared to HTS.

2. Overview of HTS2

Hyper Track Selector (HTS2) is the successor to HTS, which has currently fastest readout system of nuclear emulsion at the world, and aims to achieve a readout speed five times faster than

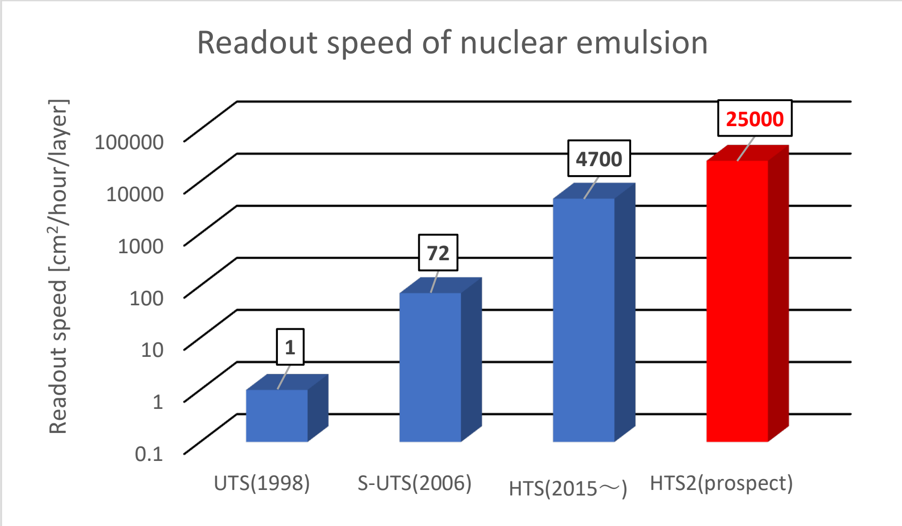

Figure 1: The readout speed of the Track Selector that has been developed in F-Laboratory and the target speed of HTS2.

that of HTS. Its appearance is shown in Figure 2. The basic structure is an enlarged version of an optical microscope, several hundred times larger than a general microscope.

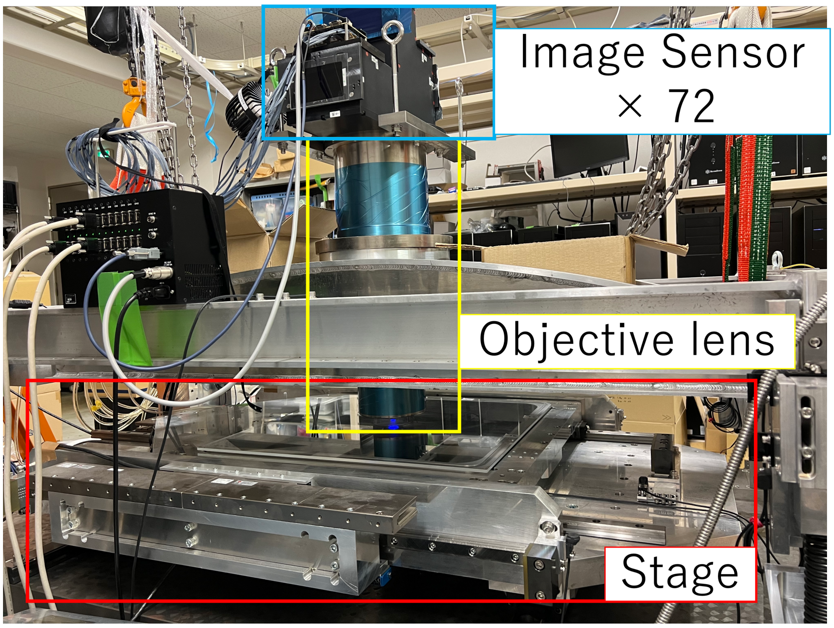

Figure 2: Appearance of HTS2

The stage that can be driven up to about 40 × 40 cm can be seen in the lower part of the figure. A nuclear emulsion is placed on the stage, and a objective lens, visible in the center, forms an image of an area of approximately 9 mm × 5 mm at a time. The formed image is divided into six directions, and a total of 72 sensors capture images. The captured images are analyzed in parallel by a group of 36 computers (each equipped with 2 GPGPUs). Compared to the HTS, the HTS2 has approximately twice the imaging area with a lower magnification. Furthermore, we aim to improve the drive speed by approximately 2.5 times by innovating the conventional image capturing method. Thereby, a total reading speed improvement about 5 times faster than that of HTS.

Since the track data recorded on the nuclear emulsion is three-dimensional information, the captured images must also be captured in three dimensions. Until now, an image capturing method called "stop-and-go" has been used in which a tomographic image is taken and then moved to the next X-Y coordinate position(Figure 3). However, with this method, an image cannot be captured during the time to move to the next X-Y coordinates and the time when the stage vibration after the movement stops. That time occupied about 60% of the total readout time, and was rate-limiting for the readout speed of Track Selector. Therefore, in HTS2, by tilting the imaging surface, images are captured while moving at a constant speed in the x direction. This enables to capture images in three dimensions without topping from end to end in the x direction(Figure 4). As a result, 2.5 times faster drive speed can be achieved.

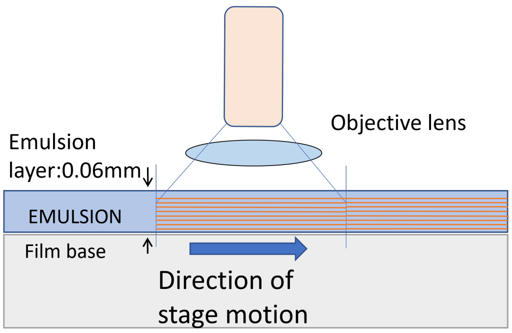

Figure 3: Conventional drive method: Move the z-axis to obtain a tomographic image, then move to the next xy-coordinate.

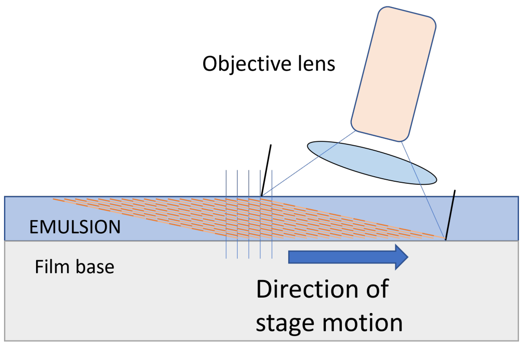

Figure 4: New driving method: The time when images cannot be acquired can be reduced by tilting the imaging surface.

3. Test scanned data by HTS2

As mentioned in §2, HTS2 has a lower magnification to expand the imaging area. There were also other hardware changes from HTS, such as a larger stage. To verify their influence, we did a test scan using one of HTS2's 72 image sensors.

The nuclear emulsion used for the test scan were used for rehearsal tests for the GRAINE 2023 flight experiment, and were placed near the summit of Mt. Norikura at an altitude of about 3,000 m for about a week to observe cosmic rays. A 3 cm $\times$ 3 cm section of that nuclear emulsion was scanned, and the tracks connected between the two films are shown in the Figure 5.

In the left figure, the position and angle detected per field of view are indicated by arrows. The right figure shows the position distribution for the all scanned area. Figure 6 also shows the angular distribution of the detected tracks. From this figure, it can be seen that there are many cosmic rays in the zenith direction observed near the summit of Mt. Norikura.

Next, we compared this data with the data of HTS. We scanned the same nuclear emulsion with HTS and compared its angular distribution and detection efficiency. However, the number of

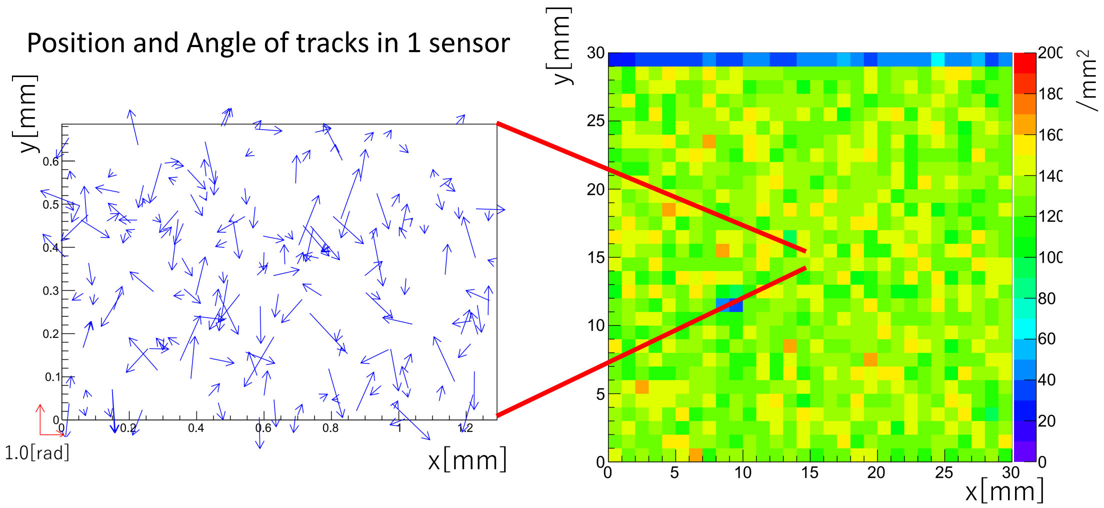

Figure 5: Position distribution of tracks detected by HTS2. In the left figure, the position and angle detected per field of view are indicated by arrows. The right figure shows the position distribution for the all scanned area.

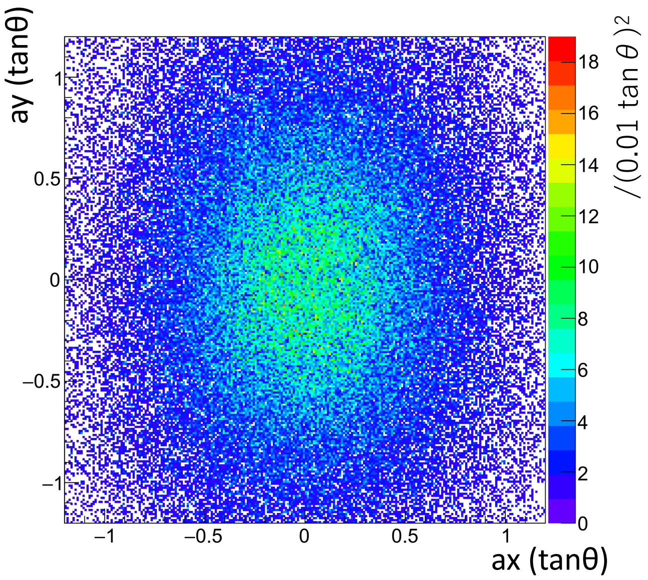

Figure 6: Angular distribution of tracks detected by HTS2

statistics differs from the HTS2 test scan data because we scanned approximately 12 cm × 10 cm by HTS, the maximum area that can be scanned at one time. Therefore, when making comparisons, we scaled the histogram by the total number of detected tracks. Figure 7 shows a comparison of the angular distribution of tracks detected by HTS/HTS2. From this figure, it can be seen that

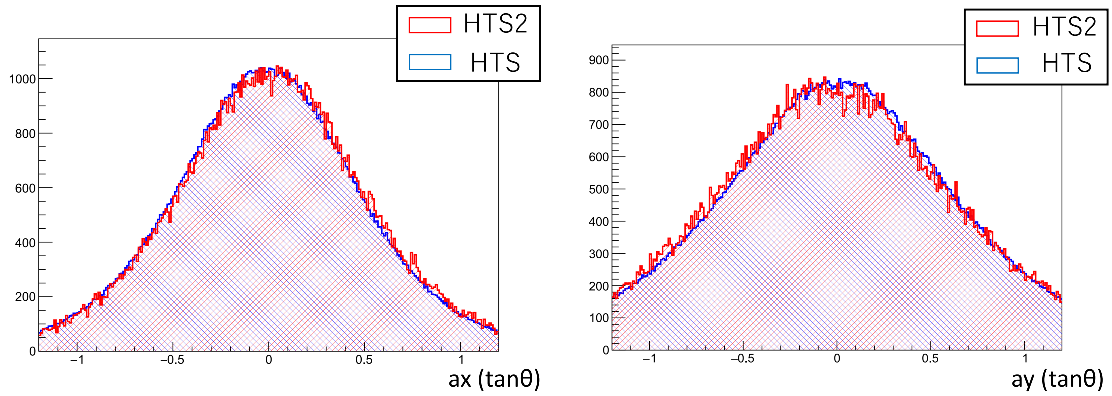

Figure 7: Angular distribution of tracks detected by HTS/HTS2. HTS data is scaled.

the angular distribution of the detected tracks is very well matched. Next, we discuss detection efficiency. The detection efficiency was calculated using three adjacent nuclear emulsion, with the number of tracks connected by the outer two nuclear emulsion as the denominator and the number of tracks connected by all three as the numerator. The result is shown in Figure 8. Because the scan

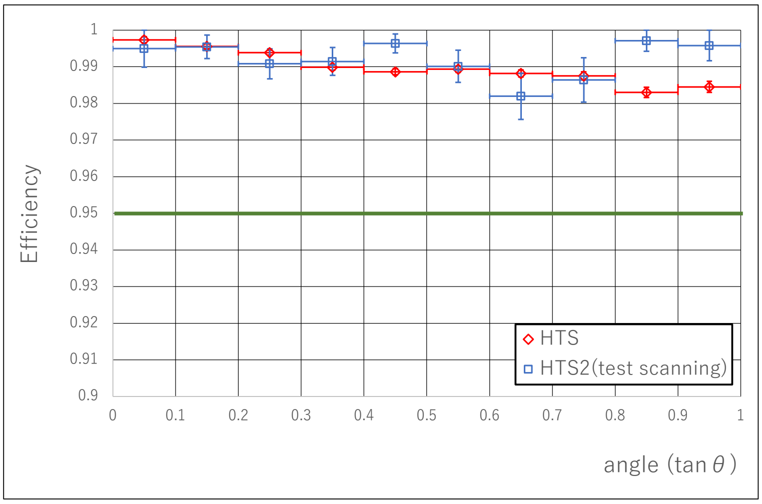

Figure 8: Detection efficiency of HTS/HTS2 respectively. The target value is to be more than 95% within tanθ<1.

area is smaller than HTS, the statistical error is larger, but the target accuracy of greater than 95% within tanθ<1 has been achieved.

From the above results, it was shown that a test scan using a single image sensor can perform scanning comparable to the current model HTS.

4. Track data of GRAINE2023 by HTS2

As mentioned above, the GRAINE 2023 flight was successfully completed from 4/30 to 5/1, 2023, with a total area of 250 m^2 of nuclear emulsion. Currently, the nuclear emulsion used for that flight experiment have been returned to Japan and are being developed in sequence. HTS2 will analyze the GRAINE2023 flight film as its first operational installation. Therefore, the nuclear emulsion used in this experiment were scanned using the "stop and go" method with a single HTS2 image sensor. The results are shown in Figure 9. It can be seen that many cosmic rays are observed

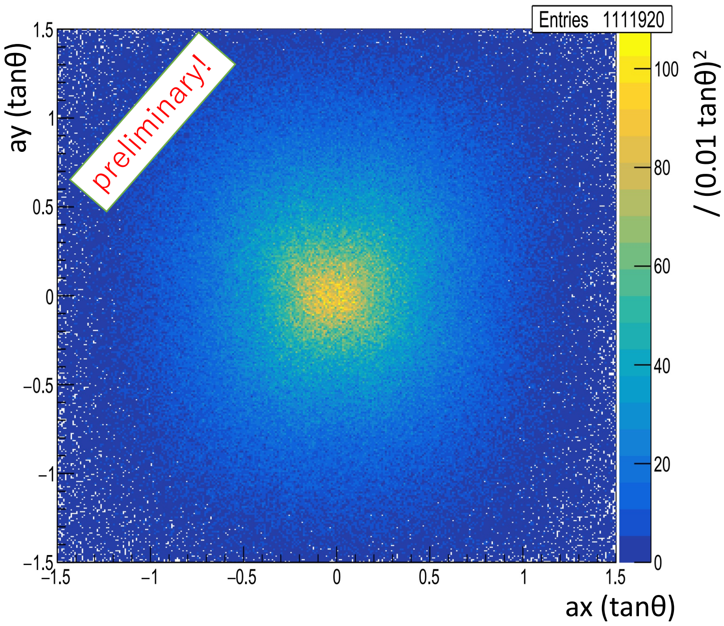

Figure 9: Angular distribution of the nuclear emulsion used for the GRAINE2023 flight by HTS2

from the zenith direction. Since this data contains all tracks for approximately five months from the time the nuclear emulsion were made to the time they were developed, we will closely examine what kind of tracks they contain in the future.

5. Outlook

The above results show that HTS2 can scan nuclear emulsion successfully. The next goal is to implement the HTS2-beta mode, which is twice as fast as HTS by using all 72 image sensors. After that, we will establish an image analysis method when the imaging surface is tilted, and finally aim for a readout speed of 25,000 cm/h/layer, which is five times faster than HTS.

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