Contact:
cgiganti@lpnhe.in2p3.fr, thorsten.lux@ifae.es

NP07: ND280 Upgrade project
-
SPSC Report

The T2K ND280 Upgrade Working Group

CERN-SPSC-2024-016 / SPSC-SR-347
26/04/2024

Abstract

The upgrade of the T2K Near Detector, ND280, has been approved by the SPSC in April 2019 and it is one of the Neutrino Platform projects (NP07). In this document, prepared for the SPSC Annual review, we summarize the main milestones, including the successfull installation of the detectors at J-PARC in Fall 2023 and the observation of the first neutrino interactions in the ND280 upgrade observed in December 2023.

Version 1.0
April 26, 2024

1 T2K and the ND280 upgrade project

The T2K experiment is a long-baseline neutrino oscillation experiment, currently ongoing in Japan. T2K has been the first experiment to detect the appearance of electron neutrinos in a muon neutrino beam and is now searching for CP violation in the leptonic sector by precisely measuring appearance probabilities of neutrino and antineutrinos. Such measurement requires both, larger statistics and a better understanding of systematic uncertainties. In order to improve both, an upgrade of the T2K Near Detector, ND280, is being conducted and is expected to significantly reduce the impact of systematic uncertainties on T2K oscillation analyses and, more in general, to improve the current knowledge of neutrino cross-section models.

The ND280 upgrade, shown in Fig. 1, consists in replacing one of the sub-detectors, the P0D, the most upstream inner detector of ND280, with two horizontal TPCs (HA-TPC) and a horizontal fully active carbon target in the middle (SuperFGD). Six Time-of-Flight (ToF) planes surround the HA-TPC and the SuperFGD.

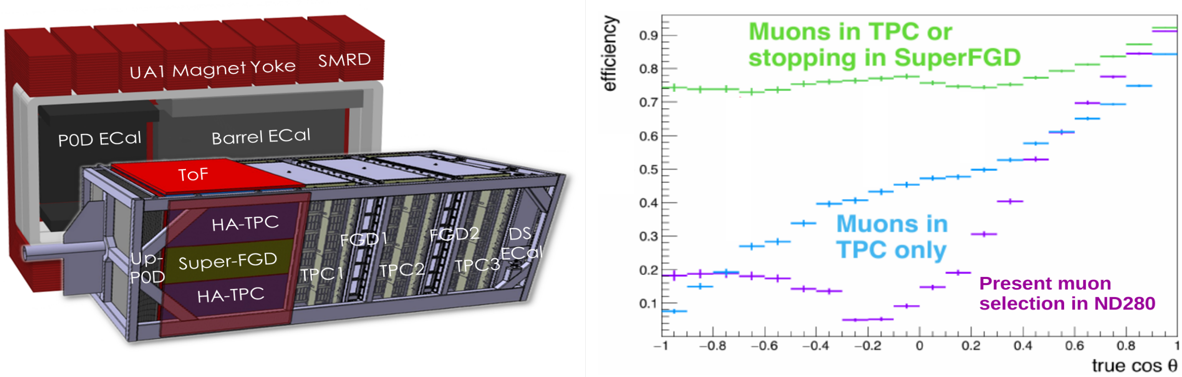


Figure 1: Left: Sketch of the ND280 upgrade project, including SuperFGD (green), HA-TPC (violet) and ToF modules (red). Right: ND280 upgrade efficiency in reconstructing muons (right) .

The main improvements that we expect to obtain thanks to the upgrade with respect to the current Near Detector configuration are:

- higher efficiency in reconstructing muons produced in neutrino interactions and emitted at high polar angle with respect to the neutrino direction, thanks to the two high angle TPCs. (see Fig. 1 right).
- higher efficiency in detecting low momentum protons and pions produced in neutrino interactions thanks to the high granularity and the 3D reconstruction capabilities of the Super-FGD.
- the ability to more reliably tag neutrons, and to measure their momenta using their time of flight from the neutrino interaction vertex thanks to the excellent position and timing resolution of the SuperFGD.
- improve selection of ν_e and $\overline{\nu}_e$ interactions thanks to the superior performances of the upgrade in distinguishing electrons produced in ν_e interactions from e^+e^- produced by γ conversions.

In this document we focus on the progress of the project since the last SPSC review in April 2023. For further details about the physics perfromances we refer to two recent publications [1, 2] as well the TDR describing the ND280 upgrade [3].

At the time of the previous SPSC report [4], the SuperFGD was being assembled at J-PARC while for the HA-TPC, after several tests done to understand an electrical issue we encoutered with the first Field Cage, we had just received at CERN the first half of what would have been the bottom HA-TPC and we had confirmed that it was properly working. The six ToF planes had also been assembled and tested at CERN and were ready to be shipped to J-PARC.

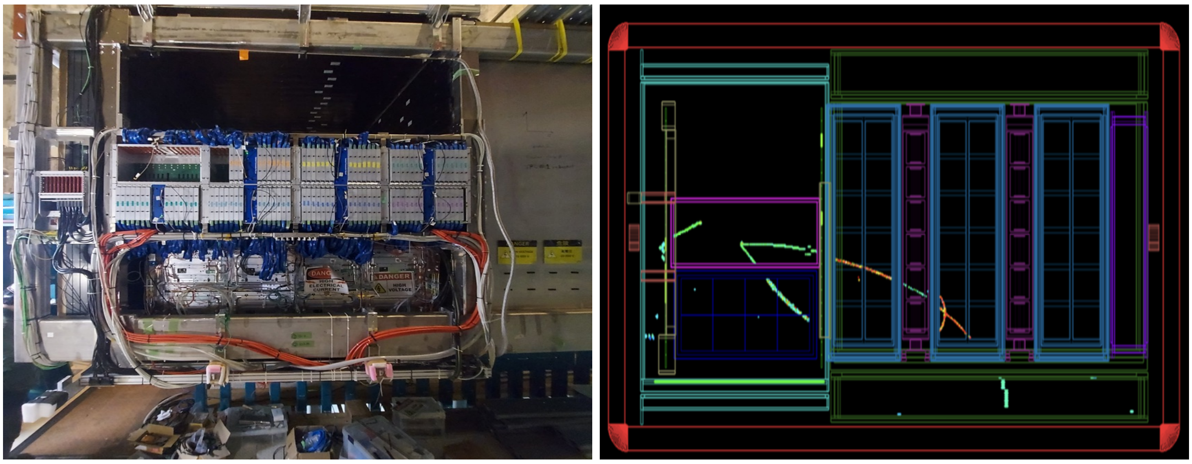


Figure 2: Installation of the ND280 Upgrade at J-PARC and first neutrino interactions observed in the Upgrade.

Since then, we have successfully assembled and shipped to J-PARC in August 2023 the bottom HA-TPC that has been installed in the ND280 basket in September 2023. The SuperFGD has also been assembled and tested on surface before installation in the basket in October 2023, and the 6 ToF planes have been shipped to J-PARC and four of them have been installed. The top HA-TPC has also been commissionned at CERN in March 2024 and has arrived at J-PARC on April 8th. It was installed in ND280 at the end of April 2024 and will be commissioned with neutrino beam in June 2024. The installation of the remaining ToF planes will follow.

The installed upgrade detectors (see Fig. 2) have been commissioned in the ND280 basket and successfully observed neutrino interactions in December 2023. We also had another run in February 2024 in which the ND280 Upgrade detectors have continuously taken data with the rest of the ND280 detectors.

The first physics run with the whole upgrade installed is expected for June 2024.

2 The SuperFGD

The SuperFGD [5] is a novel fully-active detector with fine-grained plastic scintillator (Fig. 3). It consists of about two million optically-independent 1 cm^3 cubes of plastic scintillator, read out along the three orthogonal directions by wavelength shifting (WLS) fibers, each one coupled at one end with a Multi-Pixel Photon Counter (MPPC). The active part consists of $192\times182\times56$ cubes. The total weight of the SuperFGD is about 2 tons, doubling the target mass and thus statistics compared to the existing ND280 tracker detector.

Detector assembly was completed in April 2023 and we detected cosmics using the assembled detector with 128-channel readout with commercial electronic boards. The design of the final electronics has been completed and validated with prototypes. The start of the mass production was also reported last year. In this section, we report the progress of the electronics production, commissioning on ground, detector installation, and initial operation of the detector.

2.1 Production of the SuperFGD electronics and commissioning on ground

The SuperFGD electronics for 55,888 readout channels requires 222 Front-End Boards (FEBs), 16 Backplanes, 16 Optical Concentrator Boards (OCBs), a Master Clock board, Low voltage supplies, a Water cooling system, and so on. Fabrication of the Backplanes, OCBs and MCB were completed in the US and those electronics were delivered to J-PARC by summer 2023. The production and assembly of

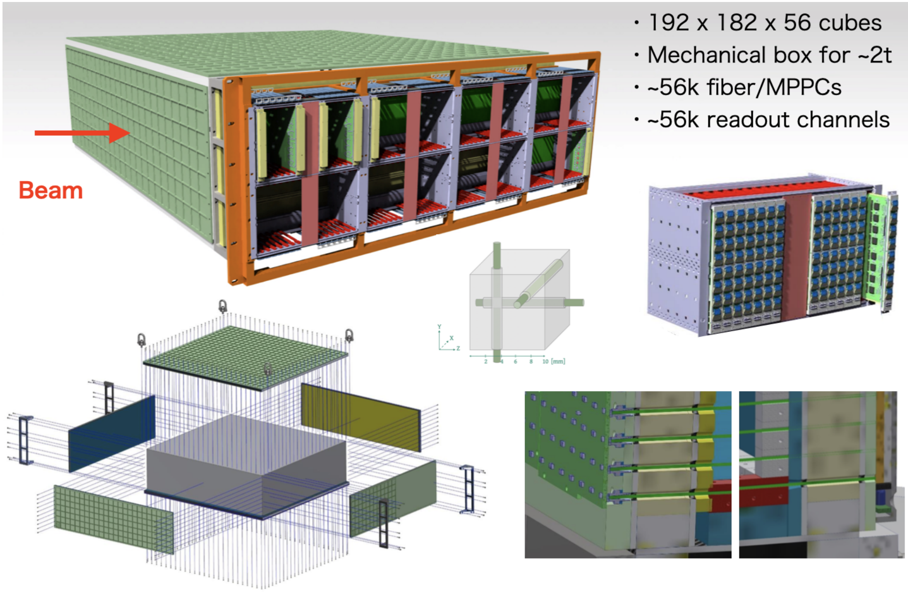


Figure 3: Detector design of the SuperFGD.

the Front-End Boards (FEB) took place in Europe. A total of 243 FEBs with associated cooling plates were produced by summer and FEB quality checks were sequentially performed using a dedicated test bench. Thanks to the mass quality test for all the FEB modules, we found initial failures that required fixes. A vertical slice test was also performed in Europe and J-PARC, which is an integration test of the full electronics chain including communications between MCB, OCB, backplane and FEBs.

Figure 4 shows a rough timeline for the FEB delivery, on-surface commissioning, detector installation and beam time. Good quality FEBs were delivered sequentially to maximize availability for the on-surface commissioning at J-PARC. Because it was not possible to address the repair of problematic FEBs and preparation of electronics firmware at the same time, we decided to focus on the firmware updates to ensure readiness for the first beam time in November/December, postponing the repair work. We integrated the available FEBs and operated the detector with 80% of readout channels during the technical run. All FEBs were successfully delivered to J-PARC in the middle of March 2024 and the detector was equipped with 100% readout channels by the end of March.

We performed detector commissioning in stages as also shown in Figure 4. Vertical slice tests for DAQ/electronics were started from May 2023 using 1 VME crate, 3 FEBs, a backplane, an optical concentrator board and a master clock board in J-PARC. Following the several deliveries of the electronics devices, we integrated more readout channels and proceeded with detailed commissioning. Using cosmics and the LED calibration system, we evaluated cable connectivity, DAQ system, Slow Control system, data unpacker, tuning of detector settings and so on. Following the delivery and installation of the last 50 FEBs, final commissioning with a full readout system is underway toward the next beam time.

2.2 Installation of the SuperFGD

After the bottom High-Angle TPC installation, the SuperFGD was installed in October 2023. Firstly, all the Front-End electronics and frames were dismounted for safe transfer. The detector together with the assembly basket were transferred from the Neutrino Assembly building to the Neutrino Monitor building using a rough terrain crane. The detector was temporarily placed with the assembly basket on the floor to switch to an indoor crane. Then only the detector was lowered by crane into the pit where the ND280 basket is located at the B1 floor (about 23 m underground). After inserting into the basket frame, the detector was fixed at four corners with brackets. Finally, the left and right electronics frames

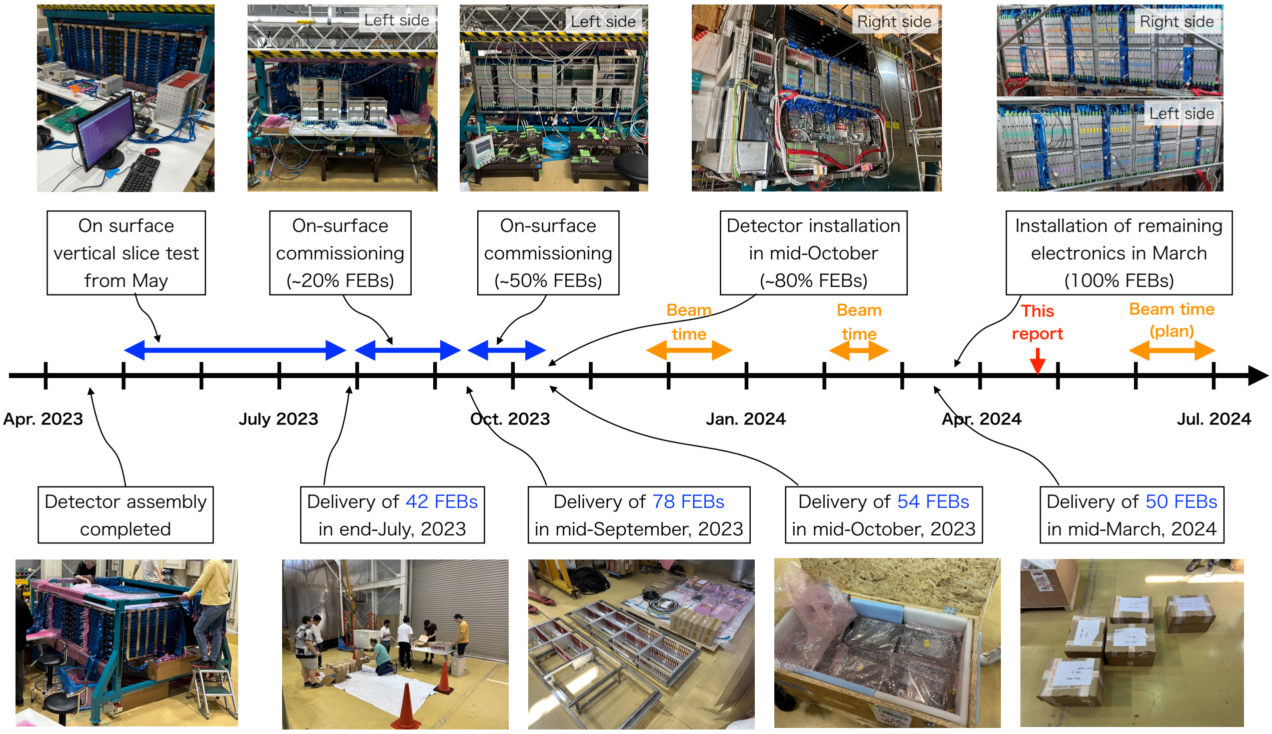


Figure 4: Rough timeline from April 2023 to July 2024. Electronics deliveries to J-PARC, progress of the detector commissioning, and the beam period are shown.

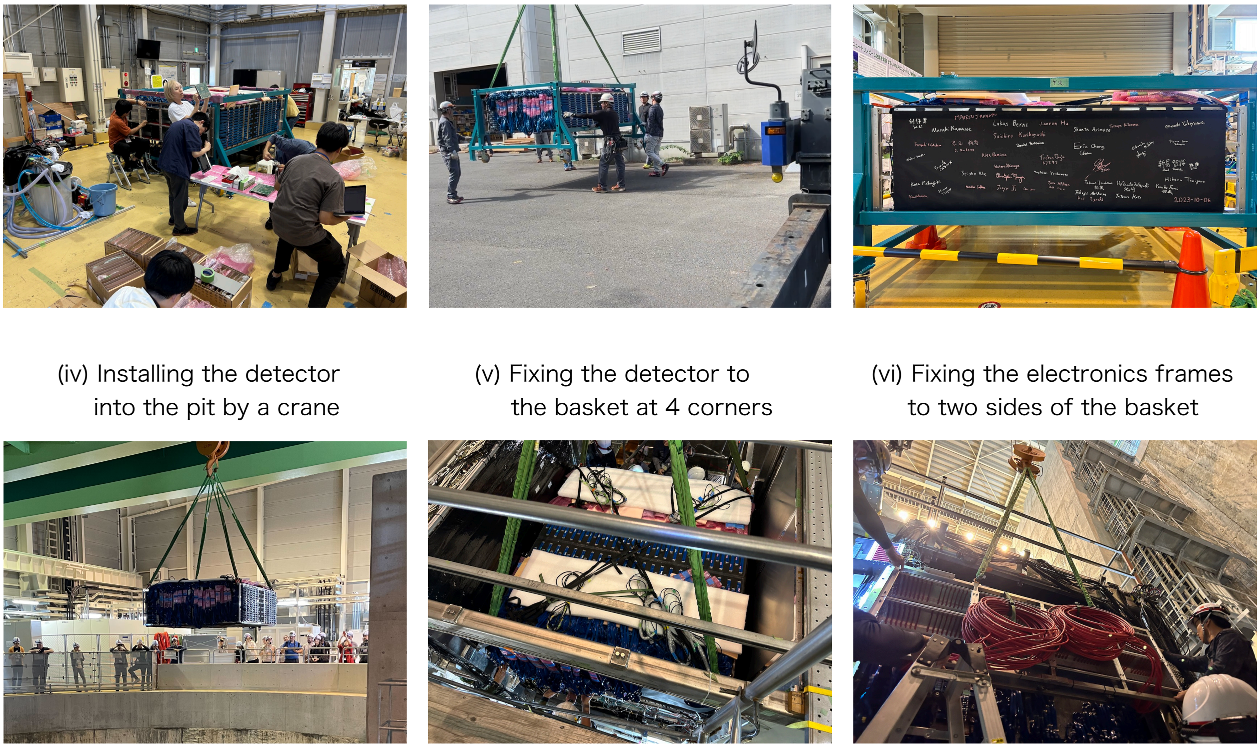
were fixed to the basket frame from outside. After the successful detector installation, we mounted the front-end electronics in 16 crates in the two electronics frames and connected 881 ribbon cables to the front panels of the FEBs. Other cabling such as low voltage, Ethernet, and calibration cables were carefully laid. Low voltage supplies, Back-End Electronics and LED drivers were also installed one floor below.

2.3 Initial SuperFGD operation results

Technical runs were conducted after the installation using cosmics, LEDs and beams. We performed many technical tests including DAQ stability, firmware/software debugging, DAQ integration with conventional ND280 detectors, establishment of MPPC gain calibration procedure. Cosmic, LED, and beam data were successfully collected. Immediately after the SuperFGD operation with beams began, we observed neutrino event candidates such as the one found in Figure 6.

Figure 7 shows the initial calibration results using the LED calibration data. The left figure shows an example of charge distribution that was obtained from the LED calibration data. Several photoelectron peaks can be clearly observed in the charge distribution. The right figure shows an example of the extracted gain for the whole detector in a certain period during the technical run. We established calibration methods and procedures, and optimized LED intensity, MPPC bias voltage, electronics gain, and electronics thresholds.

Initial evaluation of the detector response is in progress using cosmic and beam-induced muons. Figure 8 shows the initial results of the light yield and fiber attenuation. From a MIP peak from vertical cosmic muon events, observed light along a fiber direction was evaluated as a function of distance from MPPC. We found reasonable light yield from the plastic scintillator cube and attenuation length of the fiber. No major defect of the detector response was found so far thanks to thorough sanity checks in each detector construction stage. These evaluation results are important input for detector simulation and reconstruction. We will conduct more careful evaluations for better detector understanding.



(i) Dismounting the front-end electronics and frames
(ii) Transferring the detector from the assembly building
(iii) Last moment before installation into the pit
(iv) Installing the detector into the pit by a crane
(v) Fixing the detector to the basket at 4 corners
(vi) Fixing the electronics frames to two sides of the basket

Figure 5: Photos of some steps during the SuperFGD installation.

3 The High-Angle TPCs

In the period from April 2023 to April 2024 the two High Angle TPCs, respectively named Top and Bottom according to their location in the basket inside the ND280 detector, were assembled and commissioned at CERN and subsequently installed, integrated in the ND280 detector at JPARC. In particular the Bottom-HATPC, shipped from CERN in August 2023, was commissioned within the ND280 detector during a Technical Run with Neutrino Beam at JPARC in the period November-December 2023 and took data with Neutrino Beam again in February 2024. The Top-HATPC was installed in ND280 at the end of April 2024 and will be commissioned with Neutrino Beam in June 2024. In the following Sections we will report about the main steps which lead to the status of the project as of end of April 2024.

3.1 Assembly and Commissioning at CERN

The Bottom-HATPC was assembled in Bld.182 at CERN in the period March to June 2023, commissioned with Cosmic Rays in July 2023 and shipped to JPARC in early August 2023. The Top-HATPC was assembled and commissioned in the period December 2023 to March 2024 and shipped to JPARC at the beginning of April 2024. In the following, the main steps from assembly to shipment are illustrated

3.1.1 Field Cages acceptance, validation and setup

The overall field cage of each HATPC is made of two halves, which are named Field Cages (FC) and were build in Barcelona by the NEXUS company with design, supervision and validation at delivery by INFN. The lightweight and very thin-walled FCs are built with the electric field shaping electrodes

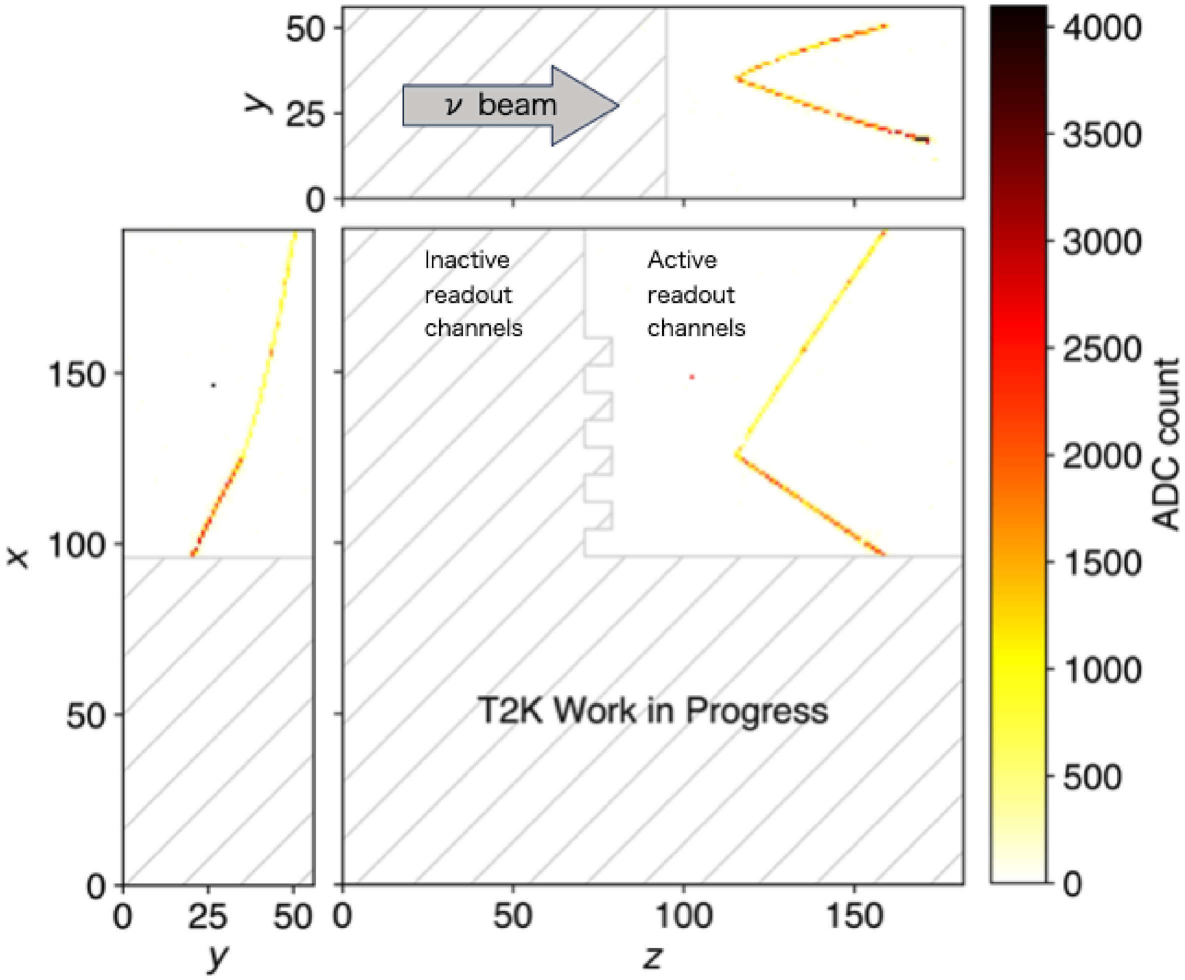


Figure 6: First event detected by the SuperFGD on 25 November 2023 during initial DAQ test. There are upstream (XY plane), top (XZ plane), and side (YZ plane) views. Two tracks emitted from the vertex initiated in the active volume were observed with excellent granularity.

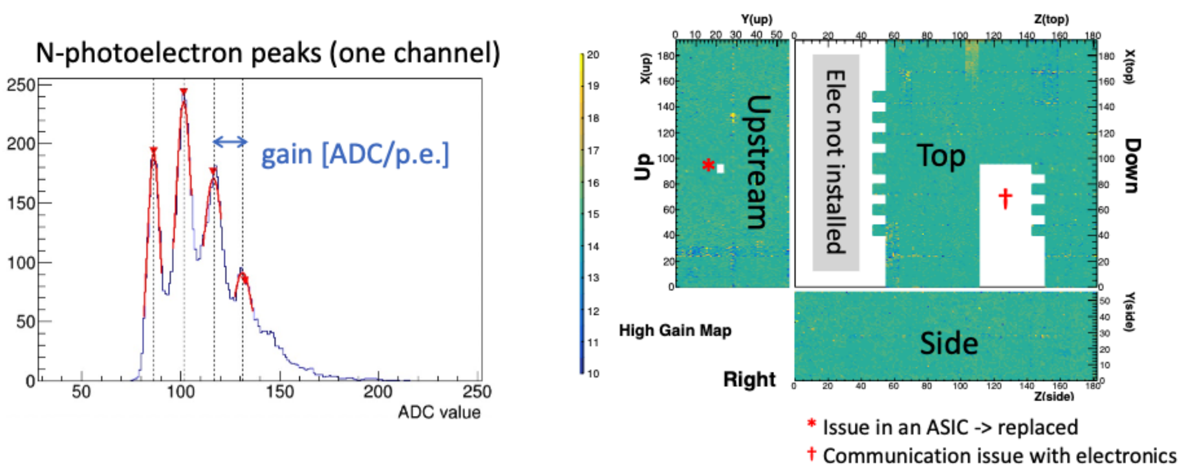


Figure 7: Initial results of the SuperFGD calibration. Several photoelectron peaks are clearly visible in the charge distribution from the LED calibration data (Left). Gains for all readout channels were calibrated using the established calibration method (Right). Issues found in the test were fixed.

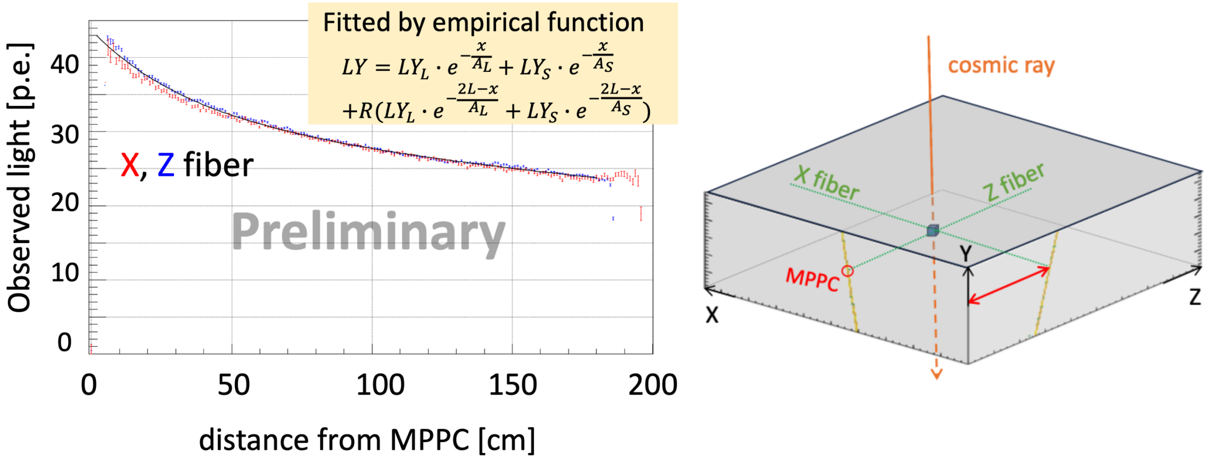


Figure 8: Initial evaluation of the detector response using cosmic events. Reasonable light yield per MIP from the plastic scintillator cube and attenuation length of the fiber were found.

(copper strips) directly supported (glued) onto the innermost surface of the walls. Tight mechanical tolerances, imposed by the electric field uniformity constraints, were respected by exploiting state of the art composite material techniques.

After delivery at CERN and accurate surface cleaning, each FC was validated concerning mechanical and electrical compliance within INFN specifications. Figure 9 illustrates the main validation steps. Mechanical tolerances, such as surface planarity at the level of O(100um/m), were verified through double-check metrology conducted at both NEXUS and CERN. We extend our appreciation to the CERN metrology service for their assistance in this regard. The electrical validation was assessed by verifying strip-to-strip and strip-to-shield insulation at high voltage, exceeding the O(Tohm) level. After closing both anode and cathode open sides with proper end-plates, gas tightness was verified by injecting some mbarg of He into the sealed volume and checking against localized leaks with a sniffer at $10{-}4\ mbar\ L/s$ level. Overall tightness was verified at level better than $10{-}3\ mbar\ L/s$ by injecting some mbarg Ar gas and monitoring for a few days the density inside the sealed volume.

The next steps consisted in preparing the FC for assembly, by soldering the resistors (selected with tolerance better than 10^{-3}) along the two parallel voltage dividers, and subsequently testing in the long term overall resistance and finally by preparing the supports for cathode fixation.

3.1.2 ERAM sensor modules validation and characterization

The production of ERAMs concluded at CERN by the end of January 2024, yielding a total of 40 modules. The X-ray test bench at CERN used for the ERAM characterization consists of an aluminium chamber with 3 cm drift distance and a robotic $x - y - z$ arm system on an optical breadboard of 120×60 cm^2 holding a 280 MBq ^{55}Fe radioactive source, housed inside a collimator. The results of the detailed characterization of the charge spreading in resistive Micromegas detectors (RC), gain and energy resolution are summarized in Figure 10. A detailed physical model has been developed to describe the charge dispersion phenomena in the resistive Micromegas anode. The model includes initial ionization, electron drift, diffusion effects and the readout electronics effects. The model provides an excellent characterization of the charge spreading of the experimental measurements and allowed the simultaneous extraction of gain and RC information of the modules. An energy resolution of 10% is obtained.

Figure 10 depicts the RC, gain, and energy resolution characteristics of all the produced ERAMs using candle plots. In each candle plot, the mean value (represented by a circle within the box) and variations within an ERAM (illustrated by the horizontal boundaries of the box and bars) are showcased. The lower and upper bounds of the box indicate the values corresponding to (Mean - 25%) and (Mean +

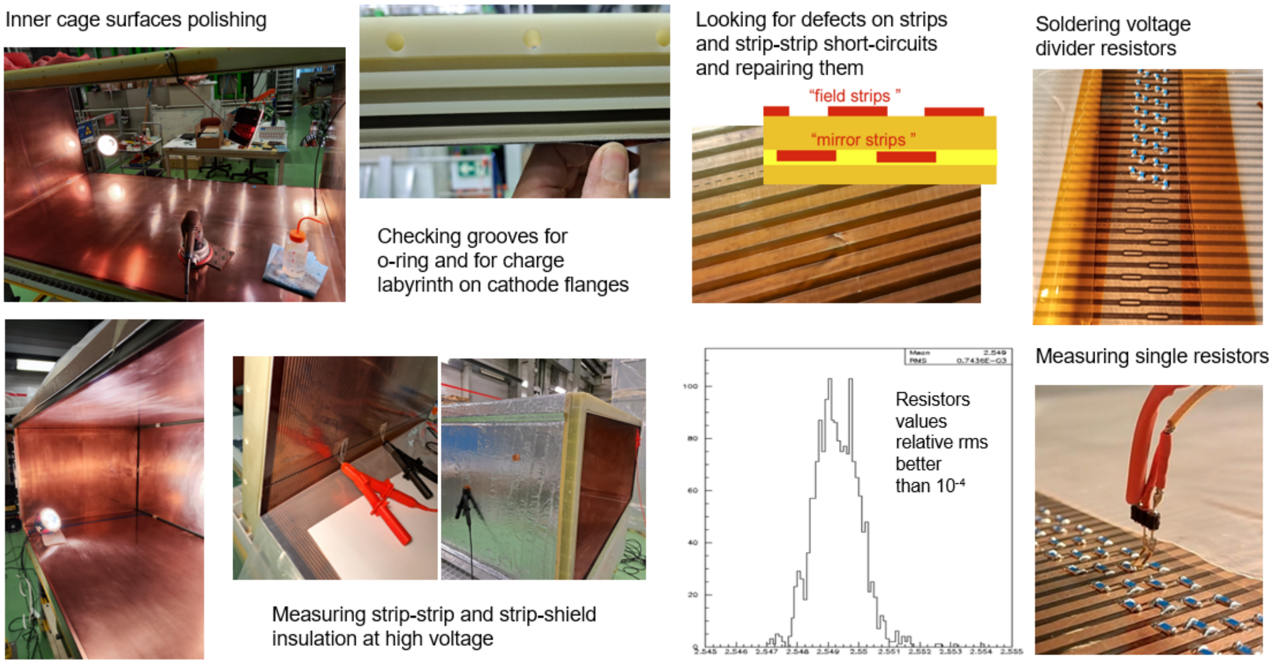


Figure 9: Photos of some steps during field cages validation and setup.

25%) of the distribution, respectively. Similarly, the lower and upper ends of the bars signify the values corresponding to (Mean - 49%) and (Mean + 49%) of the distribution, respectively. Consequently, the values within the upper and lower ends of the bars encompass 96% of all pads. The choice of a 98% fraction is deliberate, aimed at excluding damaged pads and a few extreme outliers. The width of the boxes holds no significance. These types of plots are invaluable for grouping ERAMs with similar mean or sigma of a particular characteristic for their installation in the TPC and for identifying defects or features in ERAMs.

3.1.3 TPC ASSEMBLY

The HATPC assemply was conducted at Bld.182 and consisted in two phases: 1) mechanical assembly of the two FCs with central cathode fixed on one of the two halves and with the two end-plates fixed to the respective FC and 2) assembly of the 16 ERAM modules (8 per end-plate) in Clean Room.

The cages were assembled in vertical position with end-plates and cathode planes oriented horizontally. Namely we assembled by piling-up a first FC with cathode fixed on its end-plate, and subsequently we fixed the second FC (with its end-plate already mounted) on top of the first FC where the two custom design silicone o-rings were preliminary placed into the cathode flange grooves.

We notice that the relatively large space available at Bld.182 and the use of the crane thereby were crucial to properly carry on the assembly. The "vertical procedure" resulted advantageous in terms of alignment of the two FCs. In particular matching the grooves onto the second FC with the o-rings already placed on the first FC was a most delicate step. Some steps of the procedure are illustrated in Figure 11.

The assembly of the ERAM modules was successfully conducted in the Bld.182 Clean Room (refer to Figure 12). Due to the ERAM's sensitivity to dust, a plastic tent measuring approximately $4 \times 4\text{m}^2$ was installed in front of the Clean Room's large entrance. This tent served as a grey anteroom, aimed at minimizing the infiltration of dust into the Clean Room when moving the HATPC inside the Clean Room trough the large entrance.

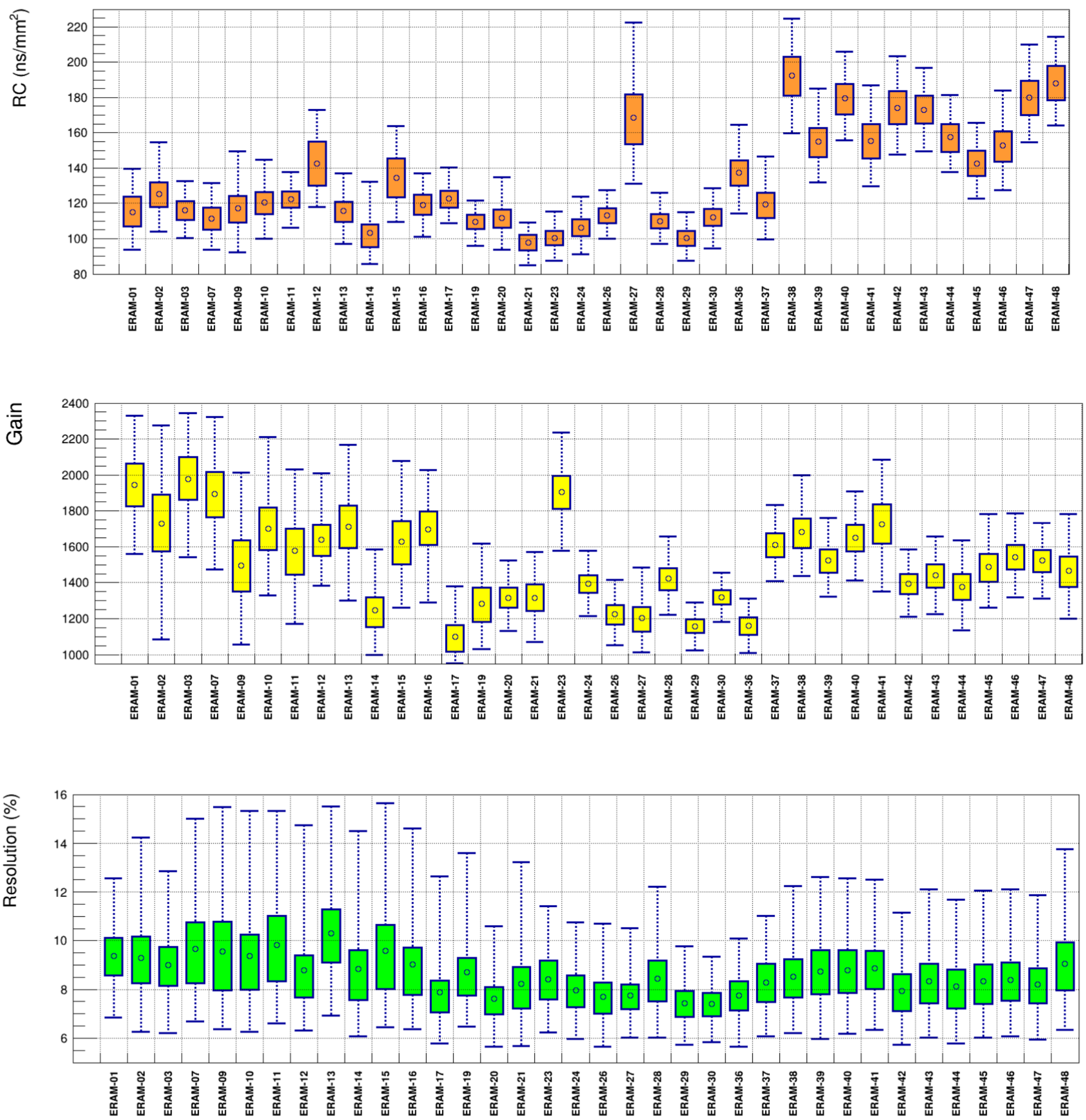


Figure 10: Mean value and local variation in RC (top), gain (middle) and energy resolution (bottom) for all analyzed ERAMs using X-rays at CERN.

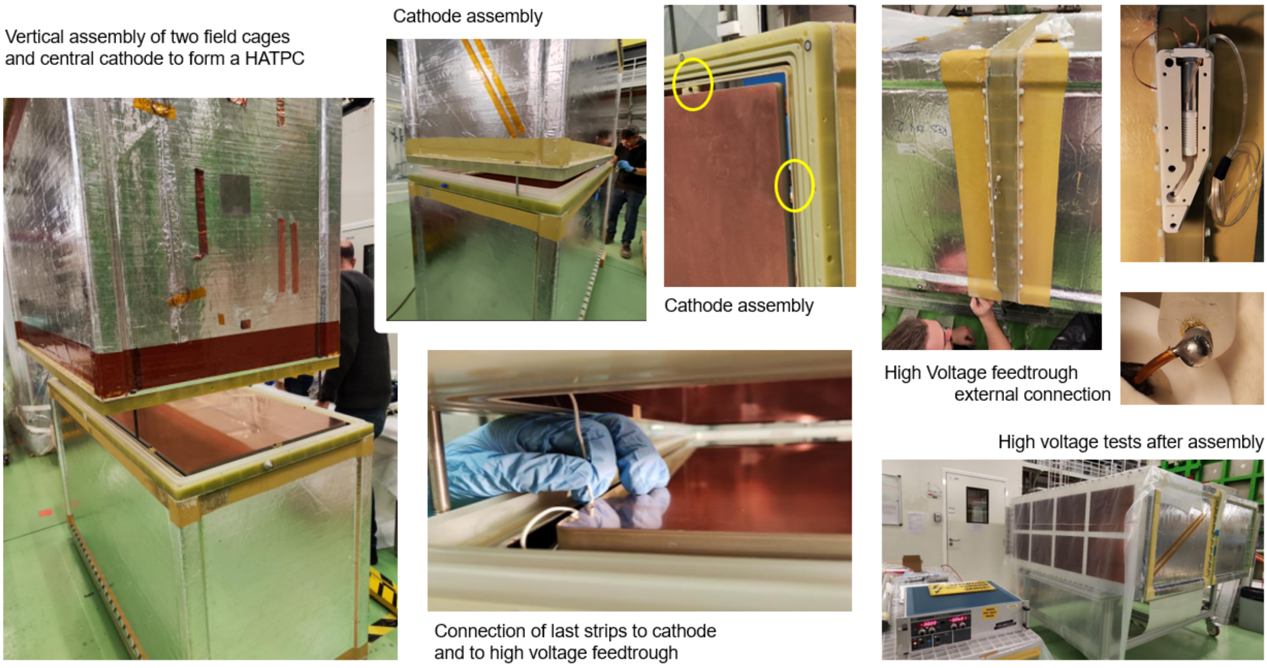


Figure 11: Photos of some steps during HATPC assembly.

Figure 12: Photos of some steps during HATPC assembly.

3.1.4 HATPC Characterization

Metrology of the assembled FCs was carried on before assembling the ERAM modules in order to access the inner TPC surfaces and to verify the overall alignment or perpendicularity of the relevant inner surfaces including both end-planes and cathode surfaces and the 8 surfaces where the strips are located. We acknowledge the CERN metrology service for their assistance, particularly for providing access to a comprehensive 3D laser-based scanning system. This system is capable of accurately reconstructing and comparing surfaces over very large volumes at a precision level surpassing O(100um). The HATPC metrology is illustrated in Figure 13.

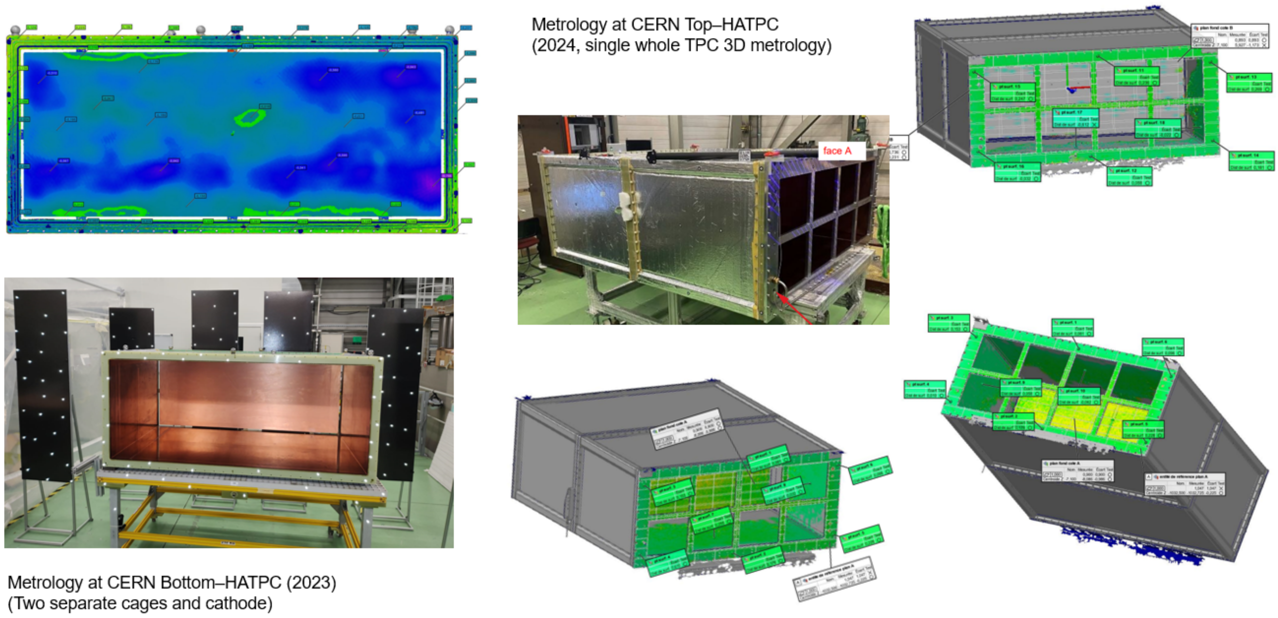


Figure 13: CERN Metrology of HATPC field cages

Mechanical characterization of the assembled FCs was carried on before assembling the ERAM modules by various kinds of load tests. A very fair comparison was found with a detailed Finite Element Model of the cage accounting for the composite materials specifications building procedure. We kindly acknowledge Rémi Boullon and Fabrizio Rossi for the implementation of the Model. HATPC mechanical characterization is illustrated in Figure 14.

3.1.5 Commissioning with Cosmic Rays at CERN

Each HATPC was commissioned at CERN with Cosmic Rays. The goal of such commisioning is to ensure that the HATPC is fully working before shipping. For this purpose, a dedicated gas system has been made to supply gas but also check for gas quality. Each ERAM modules were readout by the final electronics composed of two FrontEnd Cards (FECs) and one FrontEnd Mezzanine Card (FEM). The data were then transferred via optic fiber to the Trigger and Data Concentrator Module (TDCM) and saved on the DAQ and slow-control PC. The trigger was made using four scintillator panels of around one meter side. Two were positioned on the top of the HATPC and the other two on the bottom ensuring a great coverage of the active area. The trigger rate was about 100Hz. After acceptable contamination level of Oxygen and Water moisture inside the TPC was reached, we took 3 weeks of data for the Bottom HATPC and a few days of data for the Top HATPC. We have checked that all ERAM modules can sustain nominal voltage (350V) and all pads are responding as expected. Moreover some spatial resolution and ERAM alignment studies have been performed with those data ensuring the performance of the HATPCs before their shipment. The Cosmic setup is illustrated in Figure 15 together with some images of tracks from the monitoring Event Display application.

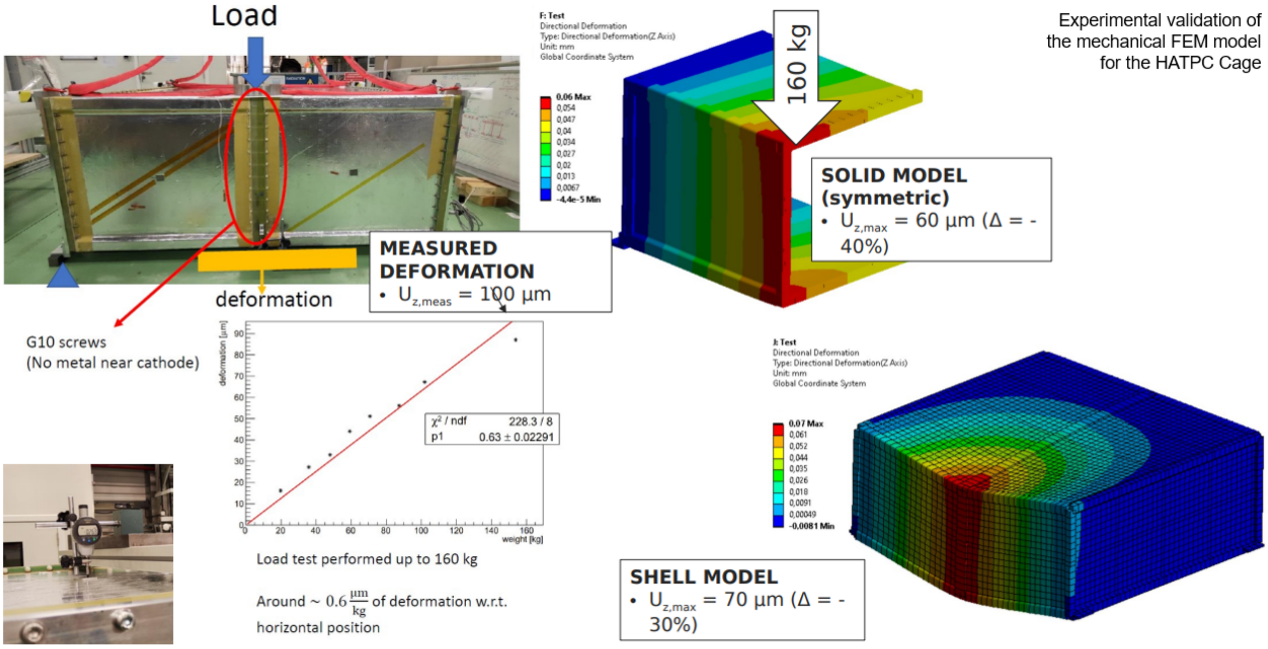


Figure 14: HATPC mechanical characterization

For the commissioning with the Cosmic Rays setup, the HATPCs were fully instrumented with the final hardware and software configuration ensuring this way the readiness for a prompt installation in ND280 at JPARC.

3.1.6 Transport from CERN to JPARC

We decided to ship the HATPCs by air cargo instead of boat cargo, due to a much shorter transport duration (few days compared to aout 40 days), to better Temperature, Pressure and Humidity conditions during the transport (confirmed by monitoring them) and lower cost (by a factor of two).

The Bottom-HATPC departed from CERN on August 7th 2023 and arrived at J-PARC on August 25th 2023. The Top-HATPC departed from CERN on March 27th 2024 and arrived at J-PARC on April 8th.

We acknowledge the CERN Import-Export service for their assistance concerning the transport and the customs related documentation. We acknowledge Dr. Tsunayuki Matsubara (with KEK) for his support related customs clearance in Japan and delivery to JPARC.

3.2 Installation and Integration at JPARC

After delivery at JPARC, quality control tests, encompassing Cathode HV, ERAM HV, and Gas tightness evaluations, were successfully conducted at surface level. Subsequently, the HATPCs were deemed ready for installation in the basket, which took place on September 8th 2023 and on April 25 2024 respectively for the Bottom and the Top HATPC (refer to Figure 16)

The HATPCs integration with the new Gas System at JPARC, with the ND280 cooling system for the electronics, with the ND280 DAQ system, with the High Voltage system and other parameters' slow control systems proceeds for about one month after the installation.

3.3 Early Operations inside Magnet and with Neutrino Beam

Cosmics data taken at J-PARC in end of 2023 were used to study the TPC performance. Example of cosmic ray events recorded with a trigger provided by the first 2 TOF panels are shown in Figure 17.

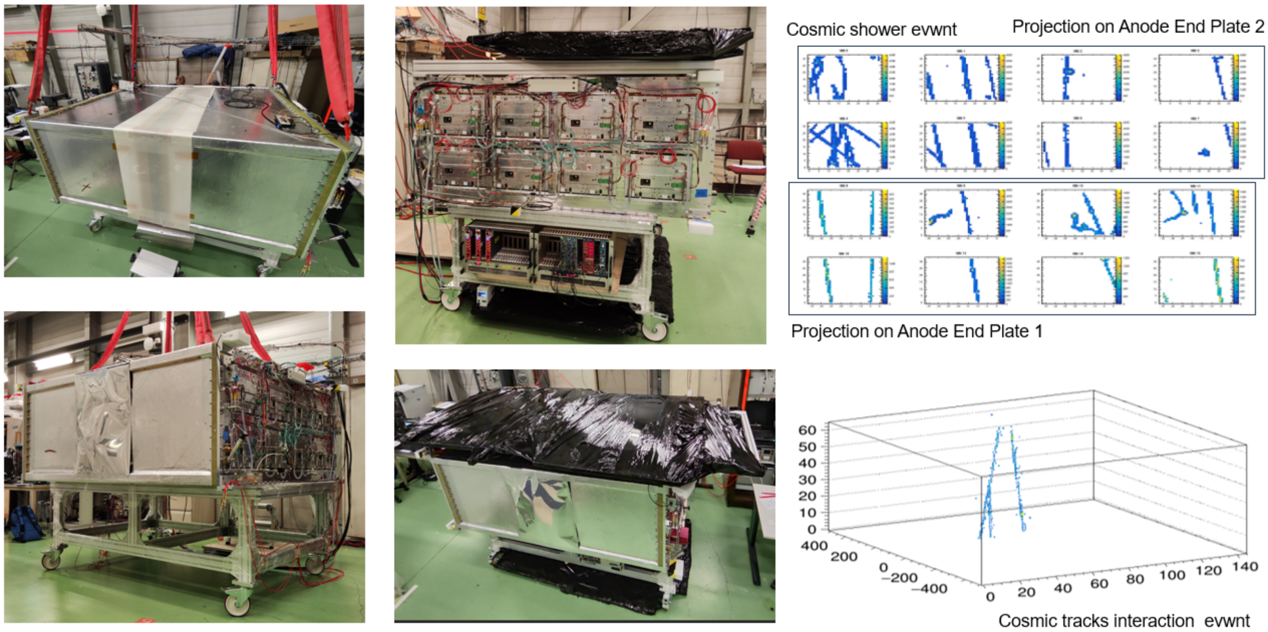


Figure 15: Cosmic Rays Setup for commissioning at CERN with Cosmic Rays and some reconstructed events

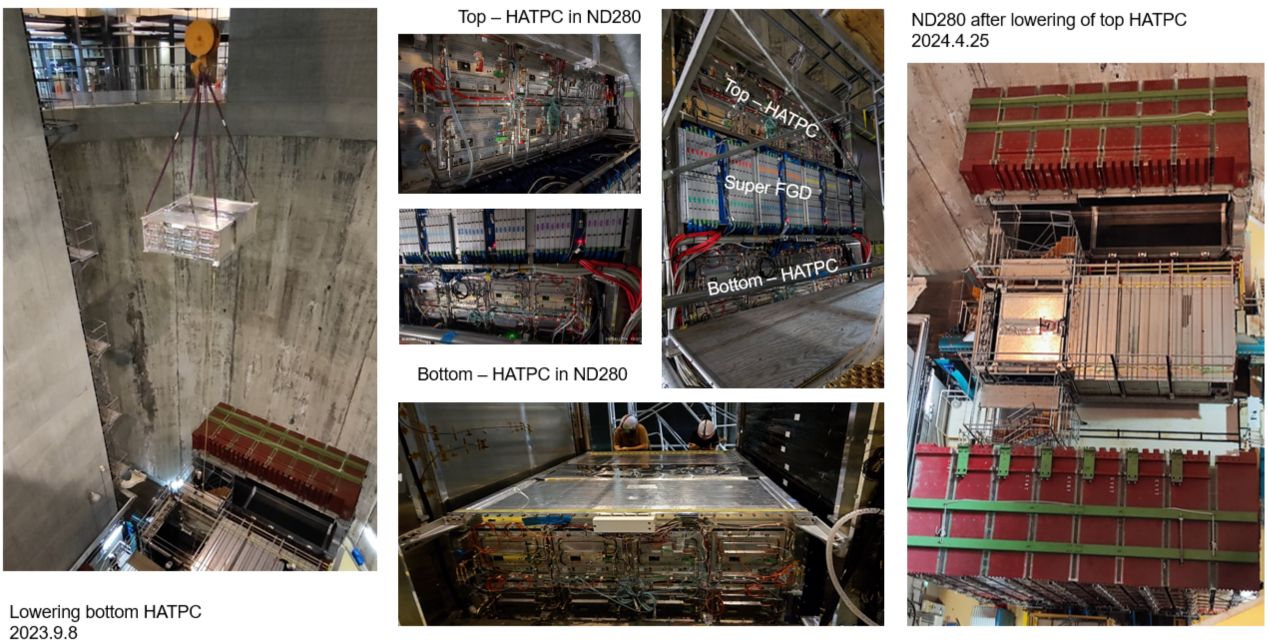


Figure 16: Photos of some steps during installations in ND280.

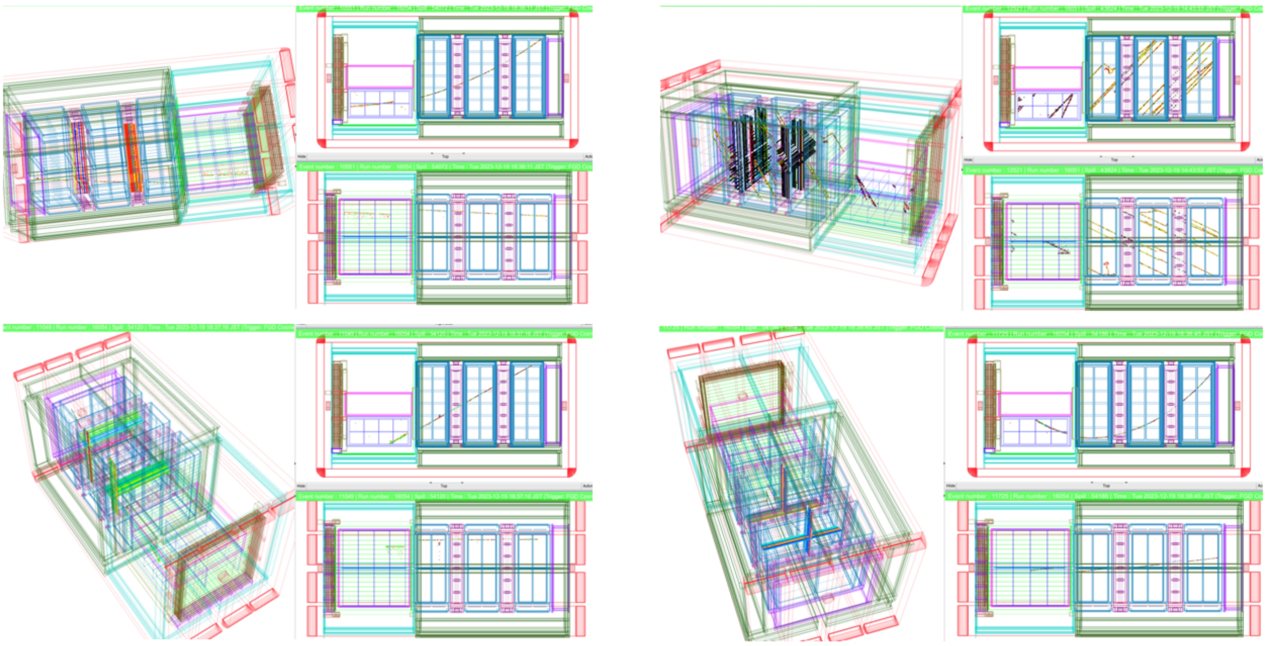


Figure 17: Cosmic Rays tracks magnetic field on

A spatial resolution of 500μm (about 10% momentum resolution) was obtained in both data and simulation. A dE/dx resolution of the order of 10% has been measured in a wide range of momenta as shown in Figure 18.

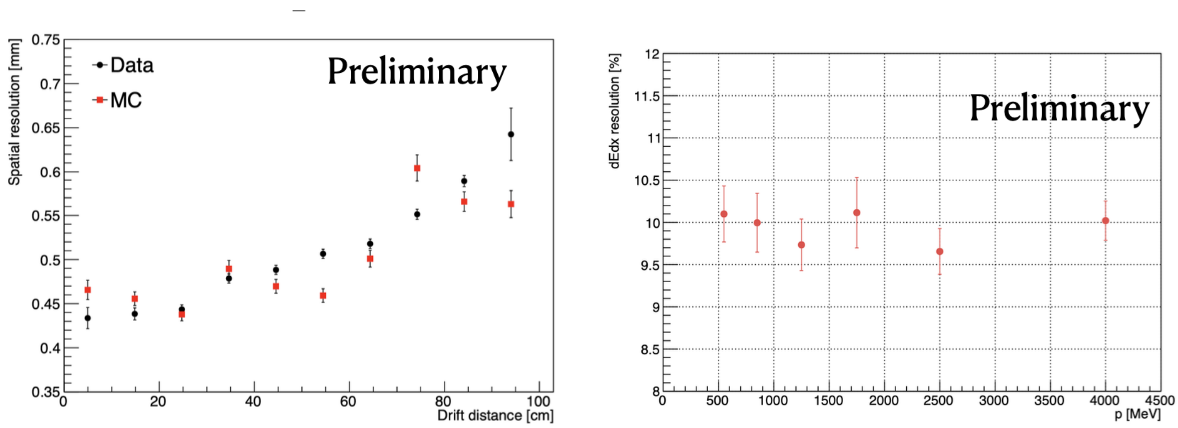


Figure 18: Spatial resolution (left) and dEdx resolution (right) obtained with cosmics data at J-Parc.

First neutrino interaction events were recorded with Neutrino Beam during the Technical Run in November 2023. A new data taking was carried on in February 2024 with Neutrino Beam, which was useful for further understanding and characterizing the upgraded Near Detector. Some Neutrino Beam events with tracks detected by the bottom-HATPC are shown in Figure 19. A new data taking is foreseen in June 2024, for commissioning the recently installed Top-HATPC.

3.4 Activities at CERN in 2024-25

Due to the presence of a poor insulation layer buried in the full scale prototype FC walls, we had to change our HATPC production schedule in 2022. After understanding and solving this HV insulation related issue we had to promptly start the HATPC production in late 2022 and skip some whole HATPC

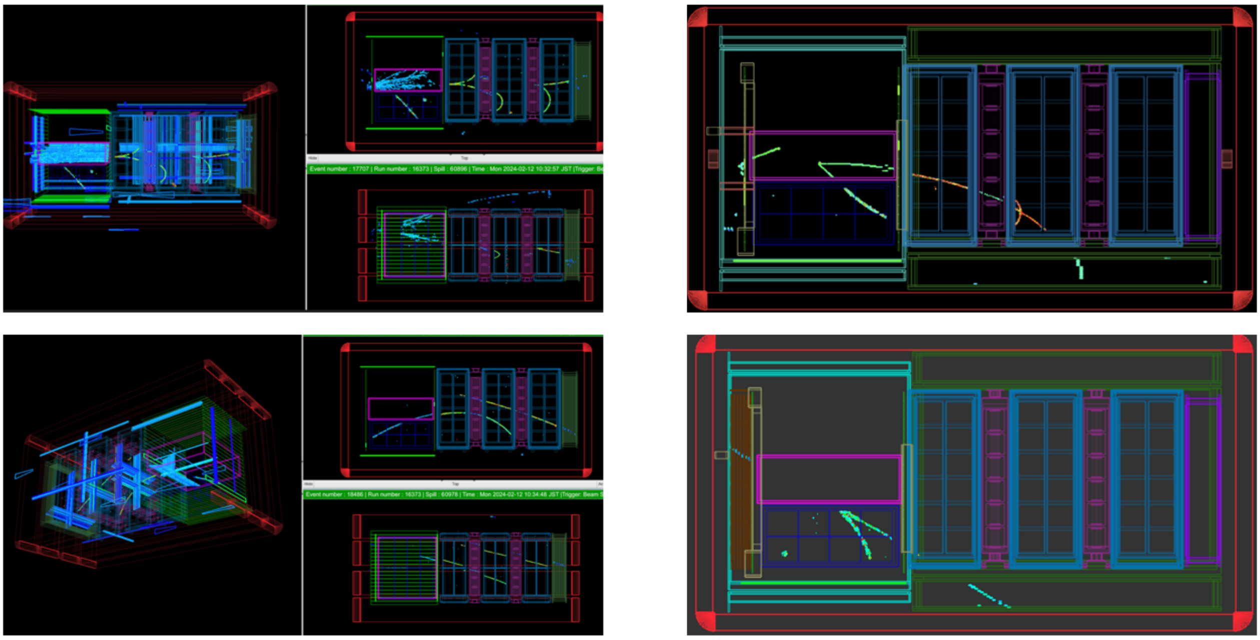


Figure 19: Neutrino interactions

charaterization process, including a test Beam with low energy (about 1GeV/c) hadrons and electrons at the CERN PS.

After the completion of the commissioning of the two TPCs at JPARC in Summer 2024, the HATPC is planning to resume a detailed characterization campaign of the TPC at CERN. To this purpose we already started to recover the full scale FC prototype where we removed the resistive layer which was accidentally formed underneath the strip layer. The full recovery of the FC will take place in Summer 2024, when we will glue on to the inner surface of the FC a new strip foil.

After recovery of the FC we will install a new anode End-Plate supporting 8 ERAMs and a cathode on the opposite side, covered by an End-Plate made of insulating material (G10). This "Half-HATPC" will be then ready to be exploited for full characterization at CERN, by means of a Test Beam and of the injection into the active volume a laser beam according.

At the moment we are carrying on all the needed procedures for being allowed to implement a Q-switched UV laser setup in Bld.182. With the laser we planned to characterize the HATPC space resolution and the dE/dx resolution and to assess the electric field non-uniformity of the cage in Winter 2024. We are planning to assess dE/dx resolution with charged particles and space resolution at a Test Beam at CERN PS in Spring 2025. Our Test Beam setup will include a silicon pixel tracker.

To the purpose of this extended and final characterization campaign we will need space at Bld.182 and access to the Clean Room therein until Spring 2025.

4 The TPCs gas system

4.1 Requirements

Each V-TPC module consists of an inner volume (TPC) containing the drift space for the primary electrons, and an outer volume (Gap) to insulate the grounded outer box from the high-voltage field-cage. The gas system has to provide an insulating gas (CO_2 in this case) to the Gap volumes, and the standard T2K mix to the inner ones. The new H-TPC modules do not have a Gap volume, so that only T2K gas has to be provided. In total, the gas system (GHS) has to serve 5 lines of T2K gas mixtures, and in addition 3 lines of insulating gas. Expanding the previous gas system proved impossible, and a completely new one was designed and provided by CERN.

To reduce gas operating costs, the GHS recirculates and purifies most of the gas flow. Typical flow rates are adjusted to insure 3 to 5 volume changes per day in each TPC, leading to a total recirculation rate approaching $3m^3/h$.

The system must insure a stable chamber pressure even during rapid atmospheric pressure changes; in this region they be as fast as $10mbar/h$. The previous system had to respect this requirement making use of a steady flow of fresh gas input. One of the achievements of the new system is that, thanks to large gas buffers, it is able to compensate the pressure changes with minimal input; w.r.t. previous operations, the gas consumption has been reduced by a factor 3, with additional improvements possible in the near future.

The new GHS was received from CERN on April 28, 2023, as shown in figure 20b. Since then, an intense activity allowed to properly install, commission and optimize the system.

4.2 Mixing and Purification block

The mixer module receives fresh Ar, CF_4 and iC_4H_{10}, mixes them in the desired concentration, and provides the resulting mixture to the recirculation loop. Gas returning from the TPCs first goes through the Purification module, before joining the fresh gas input. Both modules are located in the so-called *Mixing Room* located at the surface of the experimental site (see figure 21a).

4.3 Distribution and Pump block

The recirculation loop bring the purified gas to the *Service Level*, just below the detector, where the Distribution module (as shown in figure 21b) splits the flow to intependent lines, one per TPC, and operates PLC-controlled valves to stabilize their operating pressure. The gas returning from the TPCs enters the new Pump module; it is equipped with two *oil free* high capacity pumps, one in operation and one in standby, and a PLC-controlled valve to stabilize the differential pressure between the TPC return and the recirculation loop. From the Pump module the gas is pushed back to the Purifier module in the *Mixing Room*.

4.4 Gas Analysis modules

Several analysis points are available in the system both in the *Mixing Room* and closer to the detector. Each analysis module is capable of measuring the gas composition and the concentration of contaminants. The capability of automatically switching between different inputs allows to monitor the gas parameters independently from each TPC and in several key locations of the recirculation loop.

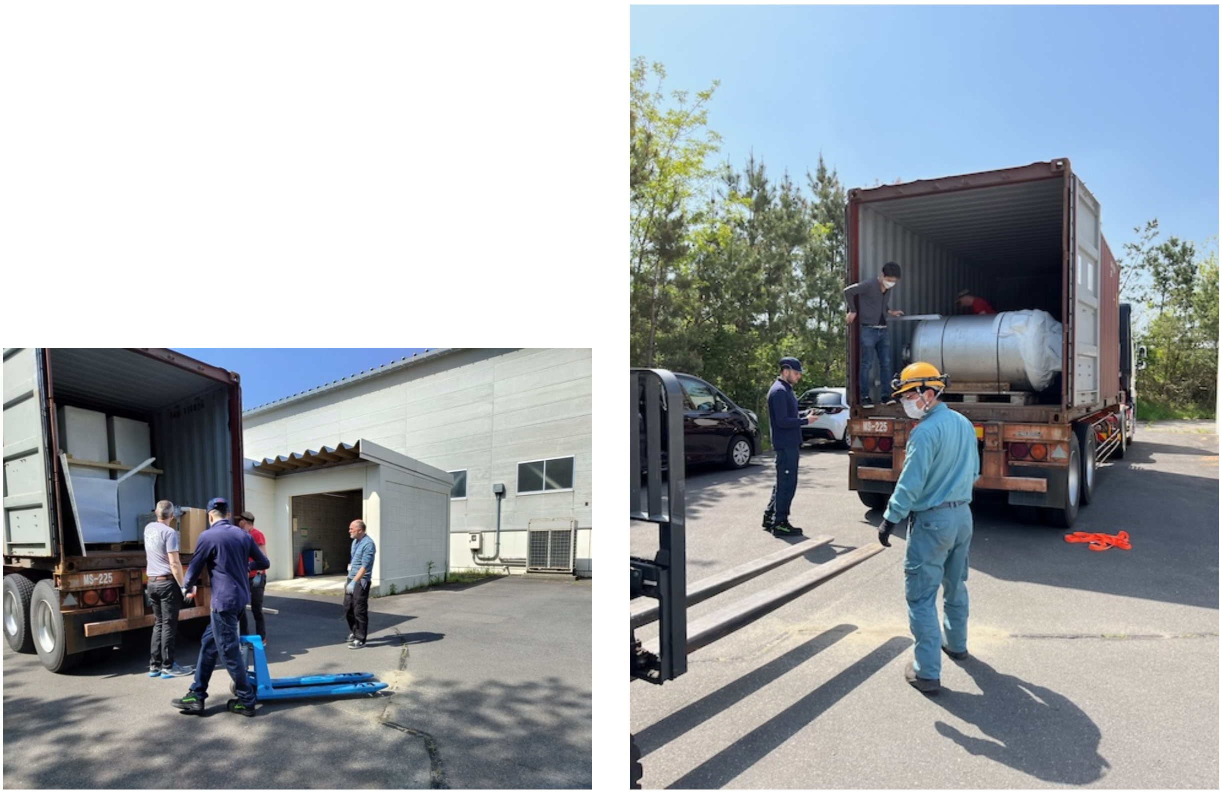
4.5 Interface to the detector DCS

All data necessary to monitor the status and relevant for TPC calibrations are forwarded to the detector slow control system for proper storage and further processing. A few simple configuration files allow to add performance parameters without the need for complicated software coding.

4.6 Commissioning, Operation and Performance

The new GHS started commissioning with the delivery of the first H-TPC in the fall of 2023. It has since then successfully and stably operated during the data taking at the end of 2023, and again in February this year. It is now in the phase of commissioning the part serving T2K mix to the *top* H-TPC.

The present performance is in line or better w.r.t. the previous system. As shown in figure 22, a record O_2 concentration below the ppm level was reached in February 2024 in the gas provided to the distribution input.



(a) (b)

Figure 20: GHS racks (a) and gas buffers (b) being delivered and unloaded from the container at J-Parc.

More optimizations are the in works: additional measurement points for temperature and pressure, to help TPC calibrations, and modifications to further reduce the fresh gas consumption, both to lower the operating cost and to minimize the rejection in the atmosphere of fluorinated and greenhouse gasses.

5 The Time Of Flight detector

The Time of Flight (ToF) detector, composed by six modules of 20 scintillator bars each read by arrays of SiPM at each edge, has been commissioned at CERN since September 2022. The detector is designed to provide the particle track direction (inward or outward) to help to reduce the background due to interactions outside the detector fiducial volume. The detector is able to provide an cosmic trigger signal which can be used by the other upgrade detectors for calibration purposes.

5.1 Installation in Japan

The ToF detector has been extensively commissioned at CERN dunring Spring 2023. in late May 2923 it has been packed and shipped together with its supporting electronics to JPARC in Tokai. The six modules have been hanged vertically on a dedicated Aluminum frame structure and packed one by one with sagex to protect them against chochs during the transportation by cargo plane. The detector arrived to JPARC on June 22nd and it has been unloaded and unpacked into the supporting NA building, just aside of the building where the ND280 pit is. Figure 29 shows the arrival of the detector at JPARC.

Before installation into the pit, the six modules have been tested in surface to ensure any damage occurred to the panels nor to the electronics during the transport. For integration reasons the six modules of the ToF detector have been installed at various stages of the overall setting up of the ND280upgrade. The Upstream and Bottom modules have been installed as first just few days after the arrival of the detector at JPARC. The installation procedure foreseen to move the supporting structure with a forklift

(a) (b)

Figure 21: GHS racks installed in the dedicated mixing room building (a) and at the *Service Level* close to the detector, with gas pipes from the TPCs connected on top of the racks.

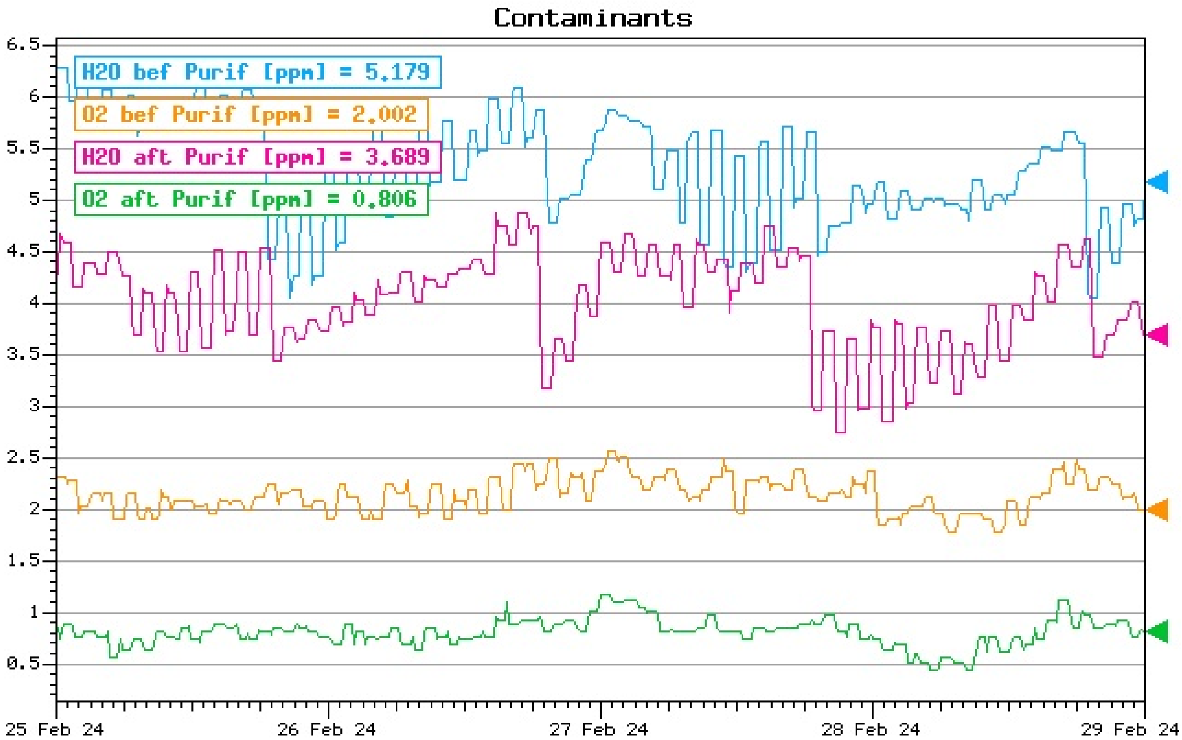


Figure 22: H_2O and O_2 as measured in the gas supply line to the TPCs (after purification) and in the return line (before purification); O_2 (green line) to the TPCs is consistently below the ppm level. Data from the last run (Feb 2024) as received by the ND280 Slow Control system.

(a) (b)

Figure 23: (a): ToF detector arriving at JPARC. (b)): ToF detector just out of the box. The six modules are standing on a dedicated supporting structure.

from the NA to the NM building just aside the pit and lift down one module after the other. The Upstream module has been installed first and hanged to the basket structure. Similarly was done for the bottom module with the difference that this module has to be rotated horizontally to be inserted into the basket. This delicate operation was done using the crane and pivoting the module from one end. The insertion went very smooth and the two modules were installed in one working day. The modules have been therefore connected to the ToF slow control system and successfully re-commissioned. The next two modules, the Downstream and the Top modules have been instead installed in early November after the installation of the bottom-HAT and of the superFGD. Also in this case the installation went very smooth even for the top module that, as for the bottom module, has to be put horizontally. Figure 24 shows some pictures during the installation of these first modules. Figure 25 shows all four panels installed together with the superFGD and the bottom-HAT.

The last two modules (Right and Left - called with respect to the beam direction) will be instead installed only after the installation of the top-HAT TPC (end of May 2024).

5.2 Slow Control system

The ToF slow control system has been integrated in the general ND280 control system prior to the data taking in October. Figure 26 shows the slow control Front End from there the system can be operated and monitored. Monitoring plots are indeed available for many interesting quantities as the voltage and current of the power supply or the temperature registered by our sensors located either on the ToF panels (3 sensors per panel-side) or on the slow control board themselves. Plots are updated every few minutes and help to check the status of the system in near real time. Warnings and alarms are set and actions are taken to safely secure the detector in case of problems.

5.3 First data, first physics results

With the first data collected, the detector has been re-commissioned showing since the very first days stable conditions and good data quality. Figure 27 shows occupancy of the detector for all modules installed for beam data and cosmic rays data. A preferred directional of the events is clearly visible: for neutrino events, the Upstream (U) and Downstream (D) panels are the most populated. For cosmic rays data instead events are more likely to cross the Top (T) panel as expected and eventually go through to the Bottom (B) panel. Figure 28 shows the 2-dimensional distributions for key quantities of the recorded waveform as the maximum Amplitude, the rising time and the Time over Threshold (ToT). The same two-dimensional plots are done for the three trigger conditions available. From top to bottom, each row

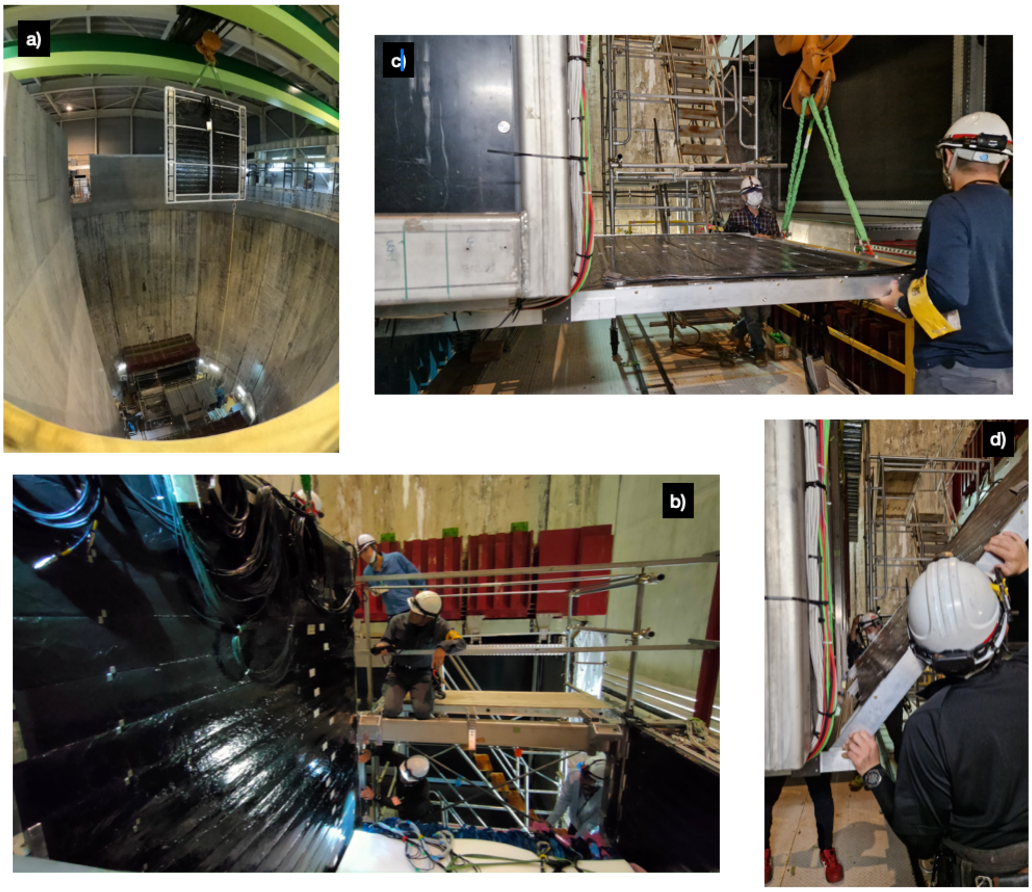


Figure 24: Installation of the ToF modules. (a) Lowering of the Upstream module into the pit. (b) Insertion of the Downstream module on the basket. (c) Rotation procedure of the Bottom module prior to the insertion into the basket. (d) Insertion of the Bottom module into the basket.

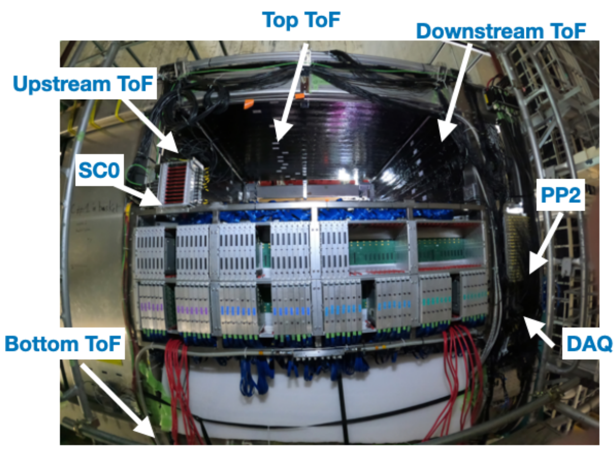


Figure 25: Four modules over six of the TOF detector installed in the pit together with the bottom-HAT and the superFGD.

of the figure shows the distributions when each channel trigger independently (no HLT); coincidence conditions are applied either on the two bar edges (High Level Trigger 2); coincidence conditions are applied on opposite modules (High Level Trigger 3). It can be appreciated that signals from electronic noise characterized by low amplitude and high ToT values, can be easily identified and removed either

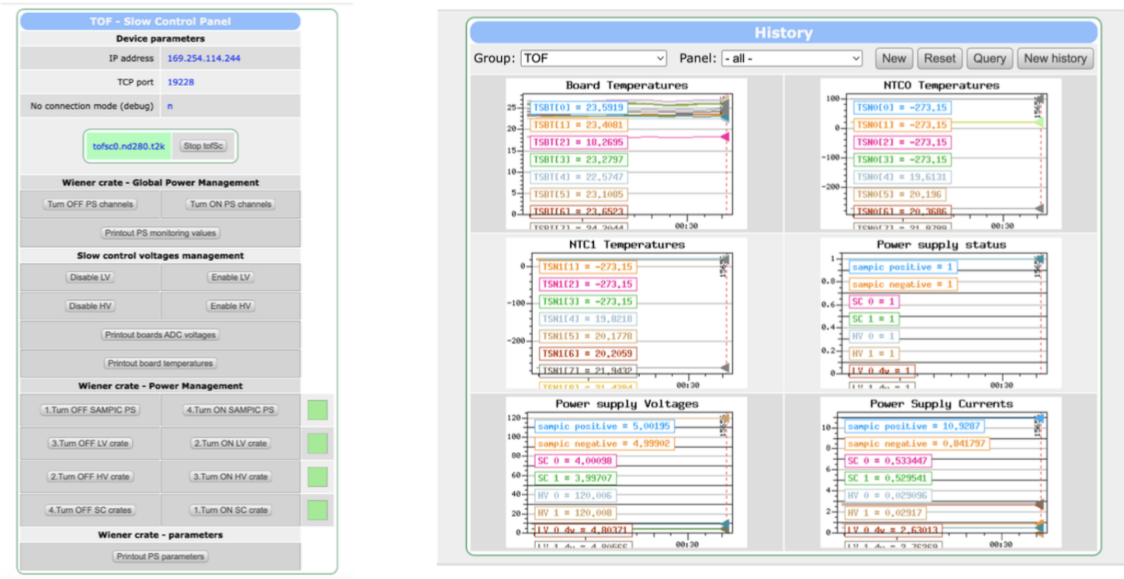


Figure 26: Left: ToF slow control Front End. From this Front End panel the ToF detector is controlled. Right: ToF Slow Control history plots to monitor in almost real time the status of the detector. The monitoring is done by reading every few minutes voltages and currents from the power supplies. Temperatures are also read from the sensors mounted both on the panels and on the Slow Control boards.

applying high trigger conditions or by simple selection.

With the fist data we also had some first phisics results. Figure 29a show a very preliminary time resolution we achieved looking just to raw data : no correction are applied and a very basic selection is performed just to require hits on two opposite panels. The time resolution achieved is of 0.63 ns which is corresponding to a 0.45 ns per plane. This current time resolution is larger than the expected value of 0.30 ns but we consider this can be achieved once a proper data analysis will be performed. Figure 29b shows the capability of the ToF detector to easily resolve the beam structure just looking at the hits time. The average bunch width is of 19 ns which is very close to the expected 12 ns. This figure shows therefore the additional capability of the ToF detector to perform studies on the beam structure.

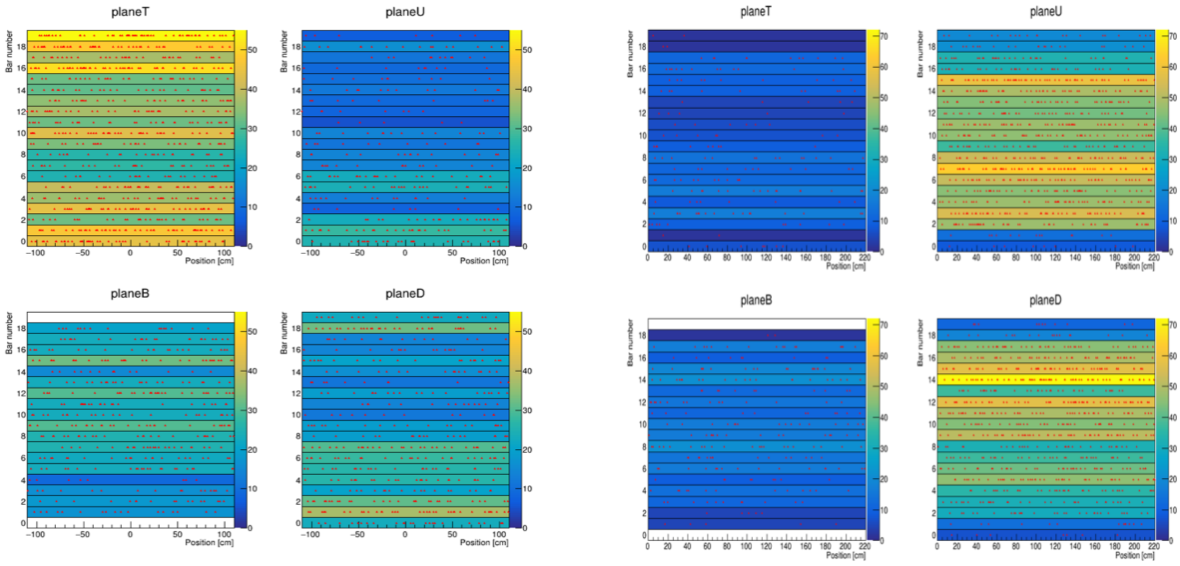
The main effort is now focused on the data analysis and on the understanding of the detector simulation response. A first very promising data-MC comparison has been performed using data coming from a test setup which consider only one bar from a ToF module crossed by particle at given position selected by an external trigger. Figure 30 shows this first comparison. The dependency of the resolution from the distance is well understood. It depends on the shape of the waveform which are modulating depending on the amount of direct and reflected light collected by the SiPM arrays at the bar edges.

6 ND280 Integration

As mentioned in the previous sections, the integration of the new detectors have been successfully accomplished in Fall 2023 and first data have been taken in December and in February 2024.

During the run in February, the upgrade detectors stably took data with the rest of the ND280 detectors in the global DAQ and the data are being used for commissioning, calibration, and understanding of the detectors.

Currently also the upgrade detectors that had not yet been installed in the ND280 magnet have been shipped to J-PARC. The top HA-TPC is expected to be installed on April 25th and the remaining ToF planes will also be installed in May. We expect to take neutrino beam data with the full upgrade detector installed in the month of June.



(a) (b)

Figure 27: (a): Events display for neutrino beam data (left) and cosmic ray data (right) for the four ToF panels installed. As it is shown, for neutrino data events are more likely to be on Upstream (U) and Downstream (D) planes, while for cosmic data events are more likely to populate Top (T) and Bottom (B) ToF planes. A limited statistics is used to produce these plots.

7 Future plans

While in 2024, the main activity is shifted from CERN to J-PARC, we would like to request to keep the space currently occupied by the TPC group in building 182, at least partly. It would be also necessary to access the clean room punctually in 182. This request is motivated by the fact that field cage 0 (FC0) will be still at CERN and it is foreseen to use it for testbeam measurements in 2024. This would be very useful to understand better the TPC performance we obtain at J-PARC.

References

[1] L. Munteanu et al. “A new method for an improved anti-neutrino energy reconstruction with charged-current interactions in next-generation detectors”. In: (2019). arXiv: 1912.01511.

[2] S. Dolan et al. “Sensitivity of the upgraded T2K Near Detector to constrain neutrino and antineutrino interactions with no mesons in the final state by exploiting nucleon-lepton correlations”. In: *Phys. Rev. D* 105.3 (2022), p. 032010. arXiv: 2108.11779.

[3] K. Abe et al. “T2K ND280 Upgrade - Technical Design Report”. In: (2019). arXiv: 1901.03750.

[4] C Giganti and T Lux. *NP07: ND280 Upgrade project SPSC Report 2023*. Tech. rep. Geneva: CERN, 2023.

[5] A. Blondel et al. “A fully active fine grained detector with three readout views”. In: *JINST* 13.02 (2018), P02006. arXiv: 1707.01785.

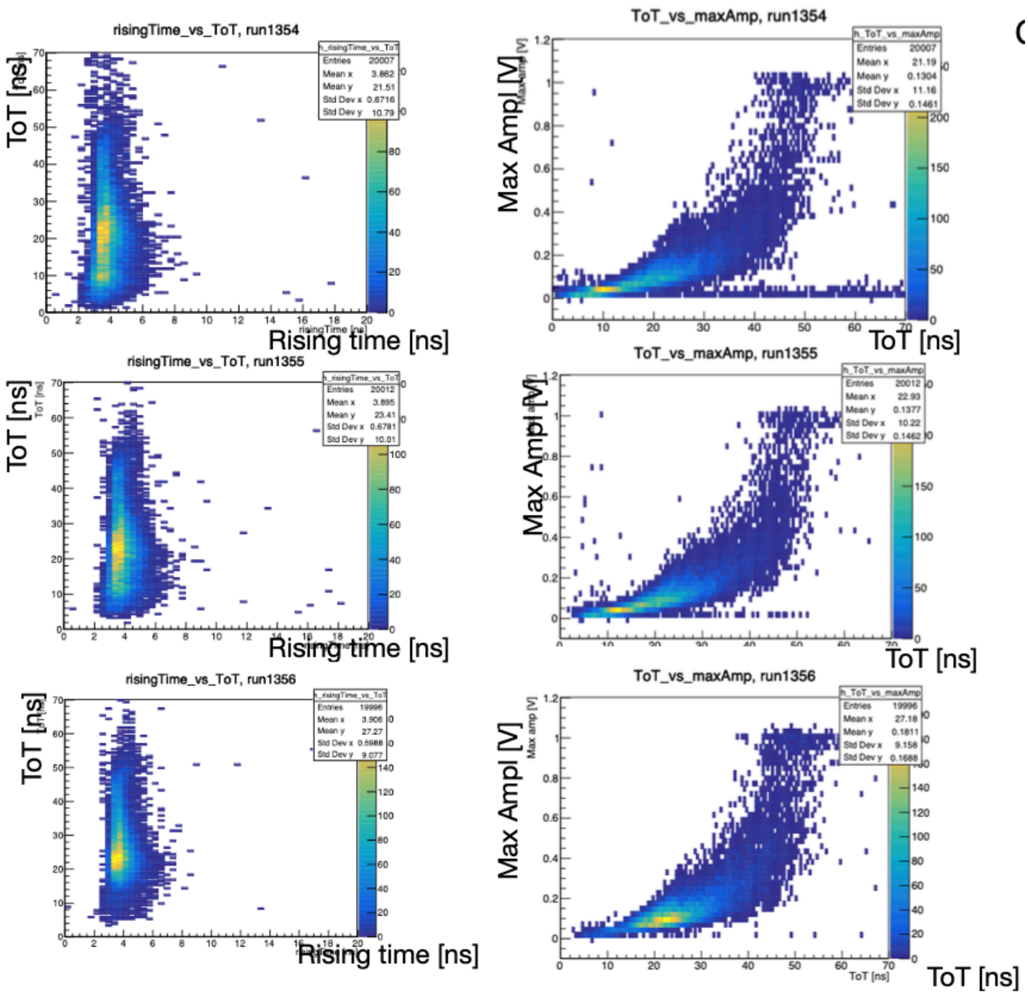
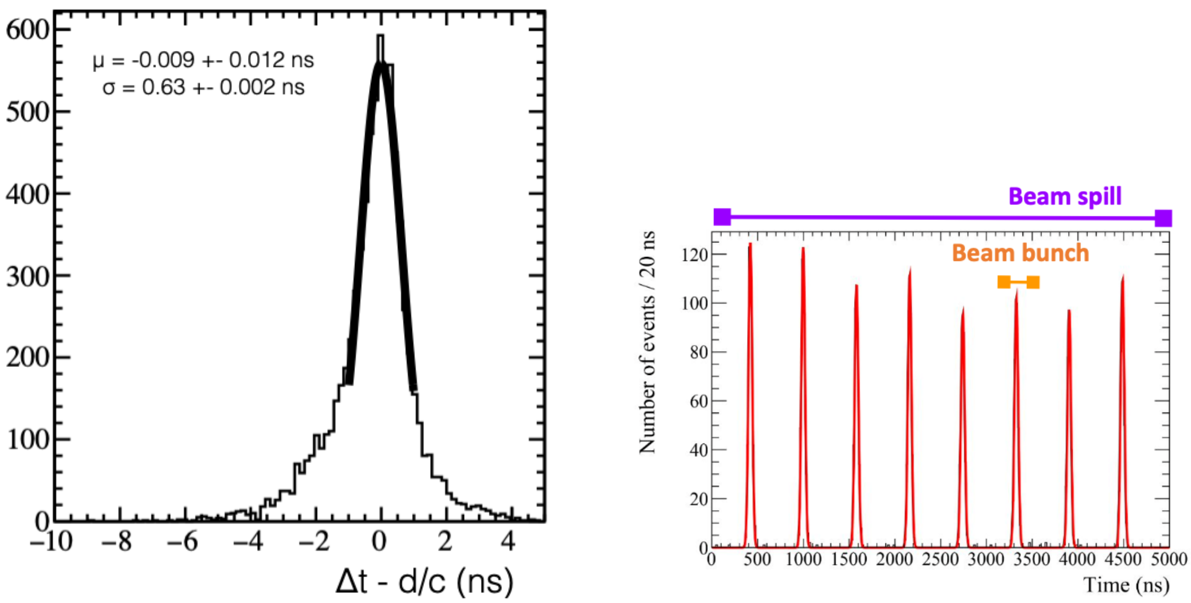


Figure 28: 2-dimensional distributions for key quantities of the recorded waveform as the maximum Amplitude, the rising time and the Time over Threshold (ToT). Plots are shown for the three trigger conditions: either each channel is triggering independently (first row) or coincidence conditions are applied either on the two bar edges (second row) or on opposite modules (third row).



(a) (b)

Figure 29: (a): Preliminary time resolution from the Upstream and Bottom module installed in the pit. From raw data (no correction applied) the achieved time resolution is of 0.63ns, which corresponds to a 0.45ns per plane, a very promising result. (b): Neutrino beam structure seen by the ToF with raw data. The measured beam bunch width is of about 19 ns, very close to the expected 12 ns.

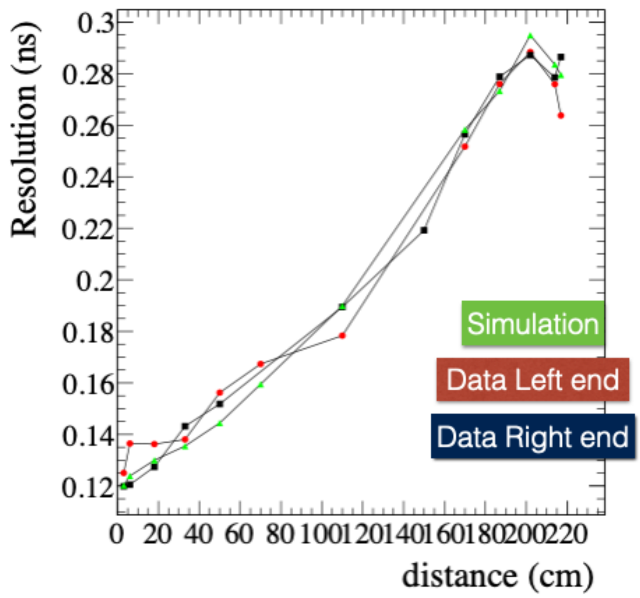


Figure 30: First preliminary data - MonteCarlo comparison for ToF data collected in a test setup. An external trigger has been used to select the position of the cosmic particle passing through.