The Readout Electronics and Data Acquisition System of the MINOS Vertex Tracker

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***Abstract*–The MINOS (MagIc Numbers Off Stability) collaboration has developed a compact vertex tracker for in-beam gamma spectroscopy of very exotic nuclei. It comprises a cylindrical time projection chamber with a Micromegas amplification plane, a cylindrical tracker based on a curved Micromegas, and two off-the-shelf silicon detectors. In total, MINOS comprises ~5000 channels. Besides performance goals, the readout electronics system was designed to be versatile and upgradable with minimal effort. The hardware part consists of three types of custom-made cards. The Feminos is a small digital board that can read out a front-end card equipped with AFTER chips (originally developed for the T2K neutrino experiment), or AGET chips, a pin-compatible evolution designed by the GET collaboration. Multiple Feminos are synchronized by a board called the trigger clock module, and are connected to a data acquisition PC through a Gigabit Ethernet switch. System configuration, monitoring and data acquisition rely on a generic object-oriented framework based on the ICE middleware, a free software infrastructure for distributed computing.**

After a brief description of the detectors of MINOS, we present the design and performance of the readout and data acquisition system of this instrument, and show some of the results obtained during their validation in an in-beam test recently performed at HIMAC, Chiba, Japan.

I. INTRODUCTION

THE MINOS (MagIc Numbers Off Stability) collaboration was established in 2011 to develop a new instrument for in-beam gamma spectroscopy of very exotic nuclei [1] produced via hydrogen-induced proton knock-out reactions. MINOS is composed of a thick liquid hydrogen target (5 cm to 20 cm) to maximize the luminosity, surrounded by a cylindrical time projection chamber (TPC), and a cylindrical tracker. Both detectors use the bulk Micromegas technology [2] and are used to track fast recoiling protons with kinetic energy up to a few hundreds of MeV. A pair of double-sided silicon stripped detectors (DSSSDs) is used to measure the profile of the beam before and after the hydrogen target. For physics runs, MINOS will be placed in a gamma spectrometer, such as DALI2 which is available at the Radioactive Isotope Beam Factory (RIBF), RIKEN, Japan. This paper focuses on the development of the readout and data acquisition parts of MINOS. The instrument, except the liquid hydrogen target which was validated independently, was successfully tested at HIMAC, Chiba, Japan. Some of the results of these in-beam tests are presented here. MINOS has now just entered its exploitation phase, and the first physics experiments took place at RIBF in May 2014.

II. OVERVIEW OF MINOS SETUP AND DETECTORS

A mechanical drawing of MINOS with its support structure installed in DALI2 is shown in Fig. 1.

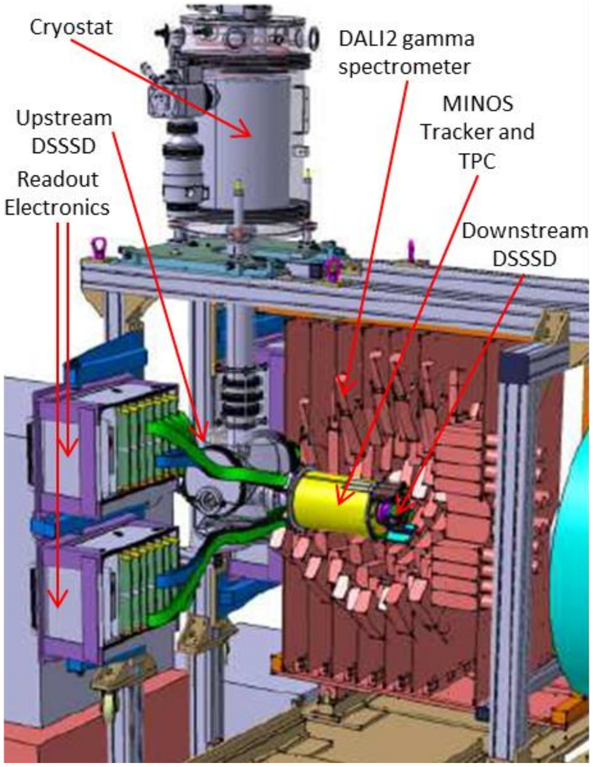

Fig. 1. View of the complete MINOS apparatus installed in the DALI2 gamma spectrometer. The 40 mm diameter liquid hydrogen target placed at the center of the TPC of MINOS is not visible.

The field cage of the TPC, 180 mm in the outer diameter and 300 mm in length, is a light structure composed of two concentric cylindrical walls made of 2 mm thick Rohacell on which Kapton foils with copper strips have been glued. A set of 788 resistors is soldered on both the inner and outer foils to define the internal electric field of the TPC. The end-cap downstream of the beam is the cathode of the TPC, while the upstream end-cap is an annular-shaped Micromegas detector. Pad planes with two different segmentations have been constructed. The “projective pad” geometry comprises 18 concentric rings of 256 pads each (i.e. 4608-channel in total). The “constant pad size” geometry is also composed of 18

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rings of pads, but the surface of each pad is made approximately constant. Inner rings have therefore fewer pads compared to outer rings, and the total number of channels in this configuration is 3604. The projective pad geometry brings the advantage of a regular mapping, but charge collection is non homogeneous among pads because central pads are smaller. The constant pad size geometry compensates for that dispersion at the expense of a more complex mapping.

Some of the common problems when operating a TPC are how to monitor electron drift velocity and determine the absolute position of the tracks along the drift coordinate. To address these aspects, MINOS uses a cylindrical tracker around the TPC. It is composed of two ~5 mm thick semi-cylindrical curved Micromegas detectors. Each detector shell is segmented into 128 strips which are perpendicular to the axis of the beam. Most of the detector area is covered by large strips (two regions of fourty-three 2.5 mm pitch strips), and two regions are segmented into twenty-one 1 mm pitch strips.

To read out the position of the projectile and ejectile event-by-event, a commercial 256-channel DSSSD (model BB18 from Micron Semiconductor) is placed in front of the liquid hydrogen target, and a second one is placed just behind the cathode of the TPC.

III. READOUT OF MINOS DETECTORS

As previously described, MINOS comprises three different types of detectors and totalizes ~5000 channels. The planning of the project did not allow to design and build a completely new system, and we decided to benefit from some earlier front-end ASICs, electronic boards, and generic software developments to provide a solution for the readout of MINOS.

A. *Interface to the Detectors*

MINOS is a compact size instrument, built with the lowest possible material budget. Not enough space is available to place the readout electronics directly on the detectors and we had to put it several tens of centimeters away. We compared two different technologies of interconnection between detectors and their electronics: cables made of flexible PCB and ribbons of micro-coaxial cables based on the FC-band® product manufactured by Hitachi Cable. The solution we retained uses Hitachi's KZ12-305 type of cable. It is composed of 0.35 mm diameter micro-coaxial cables bundled in flat ribbons of 64 units. The capacitance of the micro-coaxial product is only ~50 pF/m, while that of the flexible PCB option is ~80 pF/m. Lower capacitance cables bring less noise, which is a crucial aspect because we want to detect protons of energy close to the minimum of ionization.

B. *Readout Electronics*

The basic readout unit used for MINOS is the assembly of two cards shown on Fig. 2. The Front-End Card (FEC) is a board originally built for the T2K neutrino oscillation experiment [3]. It comprises four AFTER chips, and it can read out 288 channels. A pin compatible evolution of the AFTER chip, called AGET, has been built by the GET collaboration [4]. The AGET chip has 64 channels (72 in AFTER) and dead-time is reduced because only hit channels can be digitized. The AGET chip can self-trigger, and it is programmable for positive or negative input signals. Some other improvements and features are not exploited for MINOS. A FEC can be equipped with AGET chips instead of AFTER. The charge measurement range is selectable from 120 fC to 10 pC (600 fC with AFTER) and the peaking time can be set from 70 ns to 1 µs. The maximum sampling rate with both chips is 100 MHz. The depth of the switched capacitor array is 512 time-bins (511 with AFTER).

The Feminos is a small-size digital board designed to read out one FEC equipped with AFTER or AGET chips [5]. The Feminos is based on an inexpensive commercial FPGA module, the Mars MX2 from Enclustra, housed on a custom-made carrier card. The FPGA (Xilinx Spartan 6) implements all the necessary logic to configure and read out a FEC. It contains an embedded MicroBlaze processor for communication with a DAQ PC over Gigabit Ethernet. Tests show that the maximum sustained data throughput of a Feminos is ~110 MByte/s.

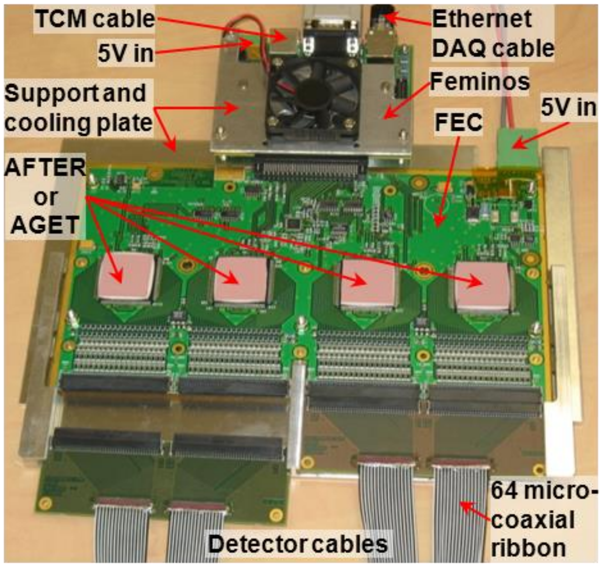


Fig. 2. Detector cables on a Front-End Card with its Feminos.

System scaling is achieved by deploying multiple FECs and Feminos. For global synchronization, an additional board is needed, the Trigger Clock Module (TCM). This board distributes to all Feminos via RJ45 cables an internally provided or externally supplied 100 MHz clock, common trigger information, and various synchronous signals (e.g. event time-stamp preset and event count clear). The TCM has 24 ports. Using one TCM, systems with up to 24 Feminos can be assembled (i.e. a maximum of 6912 channels).

IV. DATA ACQUISITION SOFTWARE

A. *Software Embedded in the Feminos*

The MicroBlaze processor implemented in the FPGA of the Feminos runs a standalone command interpreter program that executes the orders it receives from the data acquisition PC over Ethernet. Configuration commands and replies are formatted in ASCII while event data and monitoring information (pedestal histograms, channel occupancy histograms) are formatted in binary for coding efficiency. Communication with the DAQ PC uses UDP/IP.

B. *Backend Software*

The backend data acquisition software is based on a generic, object-oriented, C++ framework, called Mordicus, which is developed at the software engineering laboratory of IRFU on the basis of some earlier research [6]. Data acquisition with Mordicus consists of a number of processes that can run on the same machine or be distributed among several computers. Communication is based on the Internet Communication Engine (ICE) middleware, developed by ZeroC, which is freely available under GNU general public licence. Three types of processes can be distinguished in Mordicus: the Data Producers, the Data Processors and the Data Controllers.

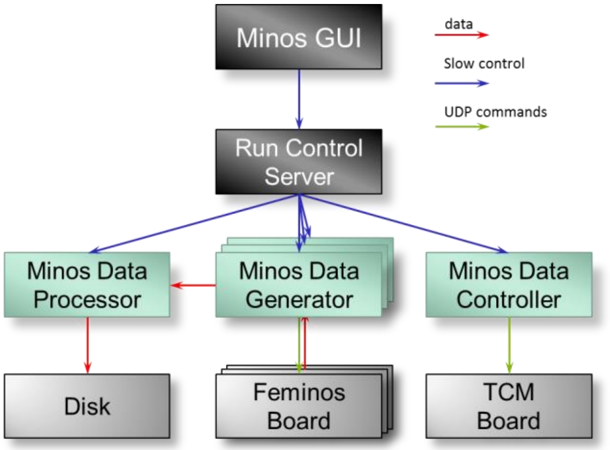
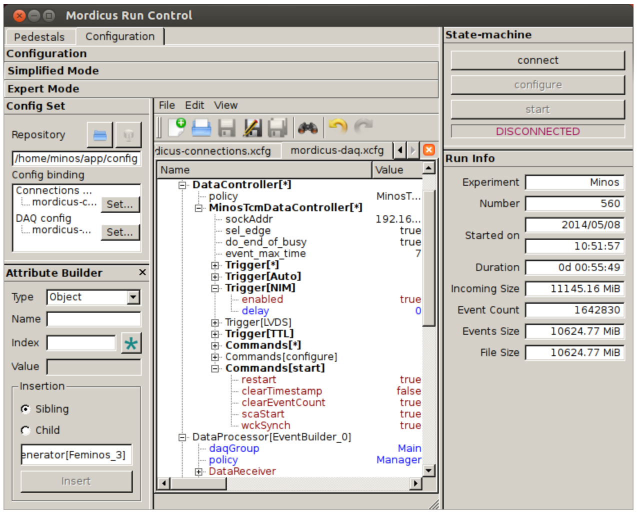


Fig. 3. Mordicus processes and their mapping to the readout hardware.

The Data Producers are the sources of data. There is a one-to-one correspondence between a Data Producer and a Feminos. The Data Processors receive data from the Data Producers, process and store them. The DAQ of MINOS uses only one Data Processor. It performs event building and storage. The Data Controllers handle physical components that do not generate event data. MINOS uses only one Data Controller which maps to the TCM. The different processes and their interactions are shown in Fig. 3.

All processes (~26 in total for MINOS) are orchestrated by a common Run Control Server process driven from a graphical user interface (GUI) where a logical view of the system is presented in a tree widget. Default values for the various parameters can be defined at the root of the configuration tree (e.g. setting a common value for the shaping time of all electronic channels), but it is also possible to override default values for the various branches of the tree so that changes only apply to the relevant subset of hardware. A picture of the latest version of the configuration and run control interface is shown in Fig. 4. Since the tests done at HIMAC, we have introduced a panel for non-expert users where only the most frequently used parameters are presented in more user-friendly widgets like pop-up menus and radio buttons. The complete configuration tree is accessible to expert users in a different panel.



Repository: /home/minos/app/config

Config binding
Connections ... mordicus-c...
DAQ config mordicus-...

Type: Object
Name:
Index:
Value:
● Sibling
○ Child
enerator[Feminos_3]

dicus-connections.xcfg | mordicus-daq.xcfg

```
Name                                   Value
⊟ DataController[*]
  policy                               MinosT...
  ⊟ MinosTcmDataController[*]
      sockAddr                         192.16...
      sel_edge                          true
      do_end_of_busy                    true
      event_max_time                       7
    ⊞ Trigger[*]
    ⊞ Trigger[Auto]
    ⊟ Trigger[NIM]
        enabled                         true
        delay                              0
    ⊞ Trigger[LVDS]
    ⊞ Trigger[TTL]
    ⊞ Commands[*]
    ⊞ Commands[configure]
    ⊟ Commands[start]
        restart                         true
        clearTimestamp                 false
        clearEventCount                 true
        scaStart                        true
        wckSynch                        true
⊟ DataProcessor[EventBuilder_0]
  daqGroup                              Main
  policy                             Manager
  ⊞ DataReceiver
```

DISCONNECTED

Run Info
Experiment: Minos
Number: 560
Started on: 2014/05/08 10:51:57
Duration: 0d 00:55:49
Incoming Size: 11145.16 MiB
Event Count: 1642830
Events Size: 10624.77 MiB
File Size: 10624.77 MiB

Fig. 4. Graphical user interface used for MINOS (expert mode shown).

A DAQ based on Mordicus can operate in standalone mode, or it can be coupled to some other DAQ system. Both modes are used in MINOS. In the coupled mode, the RIBF-DAQ developed at RIKEN [7] is the top level data acquisition system. It takes over the run control state machine of the Mordicus DAQ.

V. CHARACTERIZATION OF MINOS WITH IN-BEAM TESTS

The TPC and tracker of MINOS were tested in October 2013 at HIMAC (National Institute of Radiological Sciences), Chiba, Japan, to measure (p, 2p) reactions produced with a beam of ^{20}Ne at 350 MeV and 180 MeV per nucleon. Instead of the liquid hydrogen target, two 0.5 mm thick CH_2 targets (or one C target) were used.

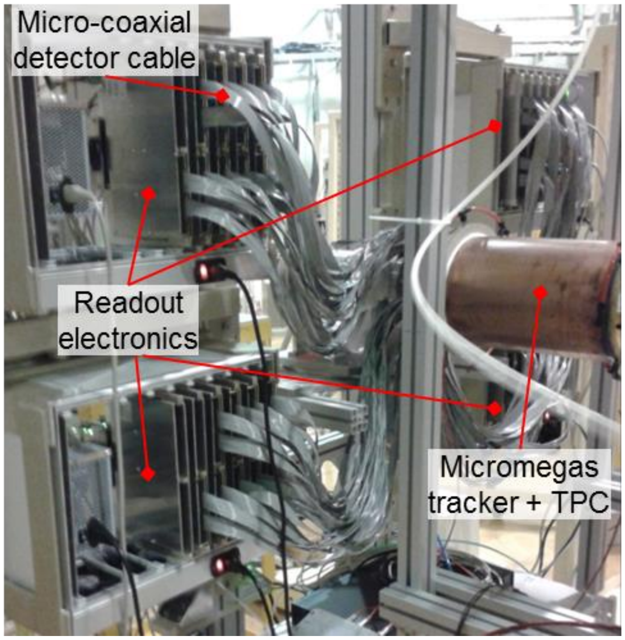


Fig. 5. Picture of the test setup at HIMAC.

Twenty one Feminos and FECs based on the AFTER chip were used to fully read out the TPC and the tracker. Besides

MINOS, the setup also included plastic scintillators, on the left and right side of the TPC, for triggering. Multi-wire drift chambers readout by VME-based electronics were used for beam measurements.

A picture of the test setup is shown in Fig. 5. The 21 readout cards and the TCM are housed in four custom-made crates placed in front of MINOS. Each crate contains a 5 V power supply composed of a standard PC ATX power supply mounted on an aluminum plate, two panel displays (voltage and current) and several plugs. The power supply of each crate and the power of each Feminos can be controlled remotely from a PC via an USB to 32-port (reed-relay) interface from Sea Level (model #8224). The global power consumption of the readout electronics in operation is ~50 A, i.e. 250 W in total or ~46 mW/channel.

The typical Equivalent Noise Charge (ENC) of FEC channels without cable and detector is ~750 e^{-} rms, at 100 MHz sampling rate and 200 ns shaping time. The complete noise map for the 5120 electronics channel available to read out the TPC is shown in Fig. 6.

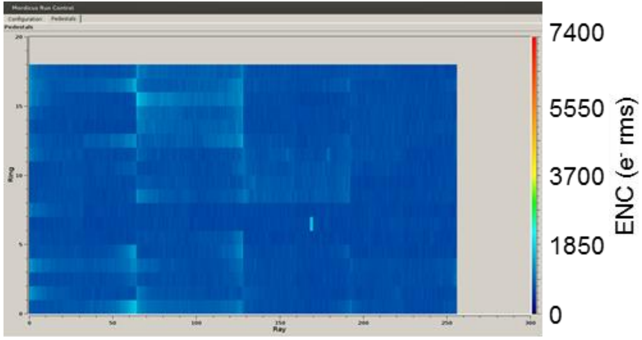


Fig. 6. Floor noise map (i.e. no detector, no cable) of the 256 × 18 readout channels of the TPC. Some of the board and ASIC boundaries can be distinguished as well as one isolated noisy channel.

When connected to the TPC via 80 cm long cables, the ENC is roughly doubled. This is shown on Fig. 7 for the constant pad size geometry TPC.

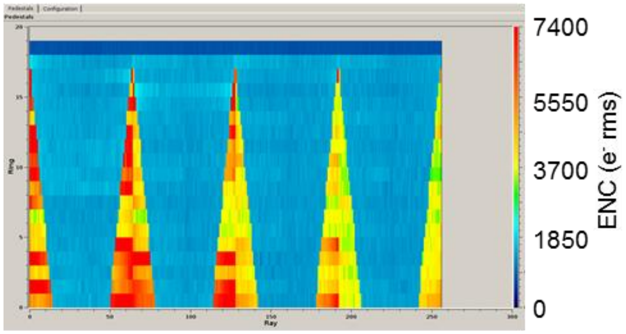


Fig. 7. Noise map of the constant pad size TPC. All electronic channels are shown but only those in light blue map to detector pads. Unused electronic channels are either floating (dark blue area) or grounded on the detector side. The effective load of these channels is the 220 pF AC coupling capacitor of the FEC and consequently, their noise is increased. This is not an issue because these channels are masked during readout.

For the tracker, cables are 1.5 m long and detector strips have a higher capacitance than TPC pads. The measured ENC is ~3500 e^{-} rms, with some channels having higher values as shown in Fig. 8. This abnormal behavior could not be understood and given the limited available time, priority was given to the work on the TPC. Consequently, almost no exploitable data from the tracker was collected during the campaign. This detector is hopefully not a critical component of MINOS. At present the drift velocity of electrons in the TPC is estimated by an indirect measurement method.

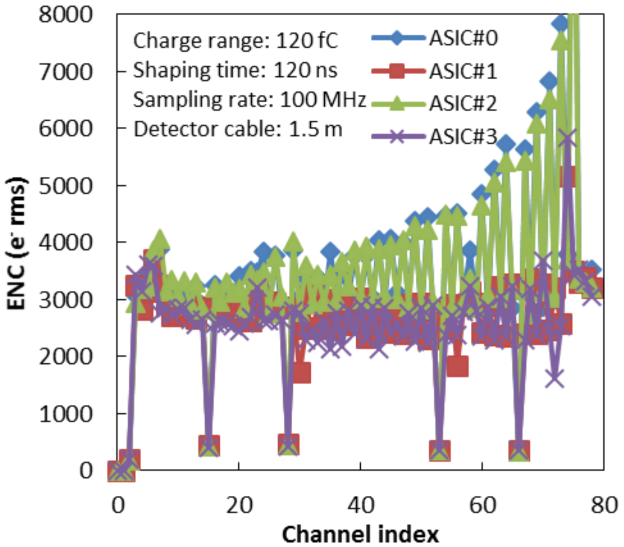


Fig. 8. ENC of Tracker channels. Points below 1000 e^{-} correspond to non-instrumented channels in the AFTER chips. Most channels show the expected – although rather high – noise level, but some channels seem to oscillate.

Global data acquisition is controlled by the RIBF DAQ system that merges the events received from the DAQ of MINOS with the events acquired from the beam monitors. Merging events from the two sources is done on the basis of matching event numbers.

During data taking with the beam, the measured dead-time of MINOS readout system is ~1.6 ms. This corresponds to the time required for the digitization of the 72-channel (in fact 79 channels because the 4 non-instrumented channels and the 3 overhead channels must also be accounted for) × 511-time bin SCA matrix at 25 MHz. Because zero-suppression is applied and channel occupancy and noise level are low, events are of relatively small size (a few kBytes). Data transfers to the DAQ and storage are not the limiting parts and system dead time is primarily determined by the time required to digitize the SCA matrix of the AFTER chips. The measured average inter-event time for accepted triggers is 2 ms, i.e. the event taking rate is 500 Hz. Missed triggers were not counted but given that the readout system has an almost fixed dead time of 1.6 ms (i.e. a maximum event service rate of 625 Hz), it can be estimated that only ~50% of incoming events could accepted at 625 Hz input rate, or ~90% at 62.5 Hz (using Erlang B formula). Although this was not a limitation in these tests, lower dead-time is expected with AGET because only hit channels will be digitized.

Some system instability – Feminos card re-initialization – was caused by sparks occurring on the cathode of the TPC after a gas feed through was accidentally broken. The appropriate corrections were made in the final design of the cathode.

A typical event associated to a (p, 2p) reaction with two proton tracks observed in the TPC is shown in Fig. 9. Data analysis show that the position of the two CH_2 targets placed within MINOS can be reconstructed with a resolution better than 4 mm (FWHM) which is compatible with our requirements.

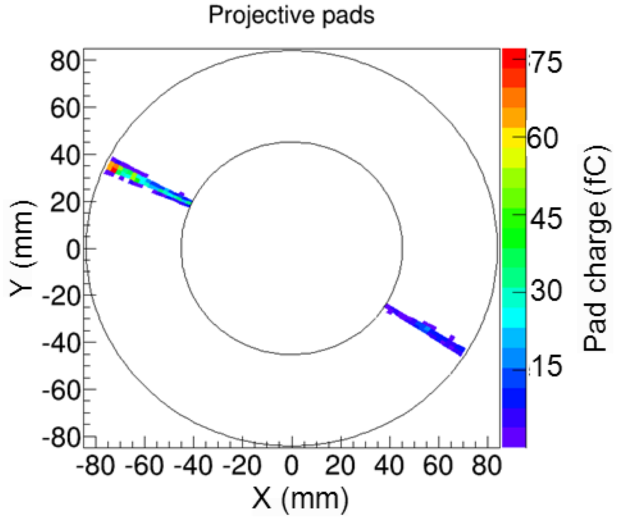


Fig. 9. Event display of the TPC: two proton tracks from a (p, 2p) reaction.

VI. CONCLUSION AND CURRENT STATUS

We reported the design of the readout electronics and data acquisition software of the MINOS experiment. We re-used the front-ends card based on the AFTER chip that were built for the T2K neutrino experiment to validate the TPC in an in-beam test at HIMAC in fall 2013. New front-end cards populated with the pin-compatible AGET chip have now been produced. We designed the Feminos, a versatile readout card capable to read out both types of chips. This allowed us to validate MINOS detectors with existing AFTER electronics until the AGET chip became available.

We based the data acquisition software of MINOS on our generic object-oriented framework called Mordicus. We demonstrated its operation in standalone mode and in coupled mode with RIBF DAQ system.

The success of the in-beam tests at HIMAC showed the readiness of the apparatus for physics runs. The first experiments with MINOS coupled to the DALI2 gamma spectrometer have been completed at RIKEN RIBF in early May 2014. The configuration of MINOS included the liquid hydrogen target, the TPC and the upstream silicon detector. The readout system was composed of 22 Feminos, each coupled to an AGET FEC. The DAQ system was running in coupled mode with the RIBF DAQ. Detailed analysis of system operation and performance during this campaign will be reported in a coming paper.

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