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Design and performance of the data acquisition system for the NA61/SHINE experiment at CERN ☆

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ABSTRACT

This paper describes the hardware, firmware and software systems used in data acquisition for the NA61/SHINE experiment at the CERN SPS accelerator. Special emphasis is given to the design parameters of the readout electronics for the 40 m^3 volume Time Projection Chamber detectors, as these give the largest contribution to event data among all the subdetectors: events consisting of 8 bit ADC values from 256 time slices of 200 k electronic channels are to be read out with $\sim$100 Hz rate. The data acquisition system is organized in “push-data mode”, i.e. local systems transmit data asynchronously. Techniques of solving subevent synchronization are also discussed.

1. Introduction

NA61/SHINE is a large acceptance fixed target hadron spectrometer experiment at the SPS accelerator at CERN [1–5]. The main tracking system, i.e. the bending magnets and the five TPC detectors are inherited from the former experiment NA49 [6]. The physics program of NA61/SHINE is quite complex and covers the search for the critical point of strongly interacting matter, study the onset of deconfinement, the quantification of medium effects in strongly interacting matter, furthermore the measurement of hadron production spectra in hadron–nucleus collisions for cosmic ray and neutrino physics applications. These studies are carried out using the SPS beamline which is able to provide hadron beams in the 10–350 GeV/c, and ion beams in the 10–160 GeV/c/nucleon beam momentum range. The hadron beams are produced by the 400 GeV/c proton beam of the SPS accelerator hitting a beryllium production target and are tagged with their particle type using a differential Cherenkov detector trigger signal. Ion beams are either direct beams from SPS whenever compatible with the accelerator schedule, or are fragmented from a lead beam of the SPS using a beryllium fragmentation target with subsequent element tagging using a threshold Cherenkov detector or via scintillator response amplitude. The beam rate reaching the detector is up to 100 kHz, being the safety limit, out of which about 5–100% are the tagged useful beam particles with the selected type, depending on the actually used configuration. This beam hits a fixed target which is either liquid hydrogen or solid state material, depending on the reaction to be studied. The thickness of the target is adjusted in such a way that the collision probability of the selected beam particle type with the target material is around 0.1–3% in order to limit the contribution of secondary collisions within the target material. This setting provides $\sim$1–3 kHz collision event rate of the right type to be potentially recorded by the spectrometer downstream of the target.

The outline of the experimental setup is shown in Fig. 1. The ultrarelativistic particles produced in the collision within the target enter into the strong, $\sim$0.1–1.5 T, field of two

☆This paper is dedicated to the memory of our collegue, Dr. Ervin Dénes, coauthor of this paper, deceased in June 2015.

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superconducting bending magnets where the trajectories are deflected according to their momentum to charge ratio. The bending power of the magnet system is up to 9 T m. Within and downstream of the bending magnets, five large volume TPC (Time Projection Chamber) detectors record the charged particle trajectories in a 40 m^3 tracking volume. A set of ToF (Time of Flight) detectors aid the particle identification. The most downstream detector of the experiment is the PSD (Projectile Spectator Detector), a calorimeter used to measure the energy fraction of the piece of projectile nucleus which did not take part in particle production, providing a geometric measure of collision centrality.

Upon the start of the NA61/SHINE program, several new detectors were added to the original NA49 tracking setup. In addition, the available readout rate not greater than ~ 10 Hz in NA49 was insufficient for fully exploiting the available beam rates, and was also insufficient for completing the data taking schedule in a timely manner with the available 3–5 month of beamtime per year. Therefore a decision was made to design and produce a new readout system for NA61/SHINE in order to be able to record events at a rate ~ 100 Hz, along with incorporating new detectors into the readout chain. In this upgrade project the most elaborate part was a new solution for the TPC readout, as this detector component gives the largest contribution to the raw data. Therefore, this paper gives a special emphasis on the design requirements and description of the TPC readout part of the NA61 DAQ (Data AcQuisition) system.

The paper is organized as follows. Section 2 summarizes the requirements on the new TPC electronics as a main motivation. Section 3 describes the new TPC electronics, their firmware and working principle. Section 4 describes the integration of further subdetectors into the readout chain. Section 5 summarizes the signal and data flow lines within the experimental setup. Section 6 describes the solutions for guaranteeing the event synchronization in the parallel data channels. Section 7 describes the online software, mainly the Central DAQ. Section 8 outlines the structure of the raw data files written by Central DAQ. Section 9 summarizes the observed performance. Section 10 concludes the paper.

2. Requirements on the TPC readout electronics

The 40 m^3 TPC chamber system produces the largest and most complicated subevent data of the experiment: for each triggered event the charge deposit on each of the 182 784 readout pads needs to be acquired throughout the 51.2 μs drift time in 256 or 512 samples, where the charge deposit is measured in 1 Byte ADC counts. This means 50 or 100 MByte per event in the 256 or 512 time sampling mode, respectively. In normal data taking, the 256 timebin mode is used, the 512 timebin mode is needed only during short and rare periods of gain calibration runs with radioactive krypton gas in the TPC volumes. During normal beam data taking 50 MByte per event needs to be transported at a ~ 100 Hz event rate, which would result in ~ 5 GByte/s data rate. However, the TPC detector data is zero dominated, since detection signal in the TPC volume only appears where particle trajectories traverse it. Therefore, it is evident that some kind of data compression method can and should be applied.

The original NA49 FEE (Front-End Electronics) cards of the TPC chambers [8,9] provided a minimal dead time of 11.7 ms when read out. This already allows 86 Hz readout rate without modification of the 5712 pieces of FEE cards. A trade-off between the needed readout rate and the development time and costs motivated the re-usage of the NA49 FEE cards in the new system without modification, and the redesign of the readout electronics upstream of them. The electronic units reading out the FEE cards are called MotherBoards. They perform the steering of the readout

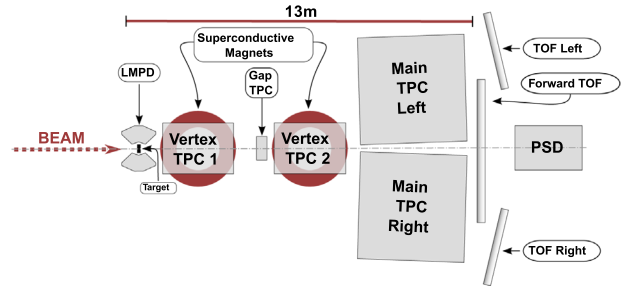

Fig. 1. The setup of the NA61/SHINE detector. A set of trigger and beam counters are placed on the beamline, followed by the fixed target. A large acceptance magnetic spectrometer setup with 40 m^3 tracking volume is placed downstream of the target. The spectrometer setup consists of two large superconducting magnets and TPC (Time Projection Chamber) volumes. The setting is completed by a set of ToF (Time-of-Flight detectors) along with a calorimeter in the beamline, called PSD (Projectile Spectator Detector). In some of the runs the target is surrounded by a special detector, called LMPD (Low Momentum Particle Detector) [7], which is a small TPC chamber using the same readout as the large ones.

process of the FEEs, the data compression before transfer, and subsequent serial transmission of the processed FEE data. Because of geometrical and data density constraints, the MotherBoards were designed to read out up to 24 FEE cards, and therefore 248 MotherBoards were used in the complete system.

Due to the extended size of the full experimental setup, event data need to be transmitted to large distances, about 50 m, from the detectors to the location of the Central DAQ in the control room. This means a high risk for accidental introduction of ground loops in the system, and therefore galvanically decoupled transmission lines were needed. Our choice fell to the relatively cheap and well understood large bandwidth DDL (Detector Data Link) system [10,11] for long range optical data transfer, also used in the ALICE experiment working at the LHC accelerator at CERN.

In order to minimize the number of optical links toward Central DAQ, an intermediate serialization stage was needed in between the MotherBoards and the Central DAQ. These units were called the ConcentratorBoxes and were designed to serialize data of up to 32 MotherBoards onto a DDL line. Short distance data transfer between the MotherBoards and the ConcentratorBoxes used relatively inexpensive LVDS (Low Voltage Differential Signal) connections. These connections, being differential, are noise tolerant and although they do not provide galvanic isolation, can work with up to ± 1 V common mode mismatch between the transmitter and the receiver side.

3. The TPC readout electronics

Motivated by the requirements discussed in Section 2, the NA61 TPC readout system [12] has four main components as shown in Fig. 2.

The main parts of the assembly are:

1. Front-End Electronics [8]: these cards perform the analog sampling of TPC pad charges, the analog storage of these and subsequent digitalization. Upon trigger arrival, one FEE card samples the preamplified and shaped pad charges over 51.2 μs time duration in 256 or 512 timeslices using an SCA (Switched Capacitor Array) [9]. The pertinent sampling clock is derived from a centrally generated 25 MHz oscillator in order to avoid phase ambiguity. Following the sampling period the, stored charges of each timeslice are digitized to 9 bits using Wilkinson ADCs. One FEE can handle 32 TPC detection pads. Due to historical reasons, each FEE is built up of two equivalent halves