STAR Time of Flight Readout Electronics, DAQ, and Cosmic Ray Test Stand

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***Abstract*– A novel Time-of-Flight (TOF) subsystem is under design for the STAR detector at RHIC. A total of 3840 Multi-gap Resistive Plate Chambers (MRPC) of 6 pads each are distributed over 120 trays. The total number of channels is 23040. Each TOF tray consists of 192 detector channels and three different types of electronic circuit cards, called "TINO", "TDIG", and "TCPU", listed in order of the data flow. Every 30 trays send their data to a "THUB" card that interfaces to the STAR trigger and transmits the data over a fiber to a fiber receiver which is part of STAR DAQ. The TINO contains the analog front end electronics based on the CERN/LAA NINO custom IC. The output of TINO is passed to the TDIG, where the data are digitized (using the CERN HPTDC ASIC). The TCPU formats and buffers the digital detector information. These formatted data are passed to THUB, which transmits it over an optical fiber to a data receiver in the STAR DAQ room.**

We have constructed a cosmic ray test system comprised of three plastic scintillators, 4 MRPC modules, and TOF prototype electronics in order to determine the timing resolution expected to be achieved with these electronics in the entire TOF system. Overall timing resolution of 80-110ps for cosmic ray events has been achieved.

I. The TOF Proposal

The main goal of the relativistic heavy ion program at RHIC is to produce a new form of matter, the Quark-Gluon Plasma (QGP), and to study Quantum Chromo Dynamics (QCD) in matter at high temperature. Initial experimental measurements of particle multiplicity and transverse momentum (energy) distributions indicate that the high energy density being reached in nucleus-nucleus collisions at RHIC is unprecedented. Recent RHIC results have offered a new view into nucleus-nucleus collisions with respect to studying the gluon dominated initial phase, partonic and hadronic evolution dynamics, and hadronic freeze-out scenarios.

A unique strength of the STAR detector at RHIC is its large, uniform acceptance capable of measuring and identifying a substantial fraction of the particles produced in heavy ion collisions. This large acceptance is central to STAR's scientific capability and has already resulted in new and intriguing physics results like the recent measurement of the suppression of back-to-back jets in central Au+Au collisions. Large acceptance detectors central to the STAR heavy ion physics program are the Silicon Vertex Tracker (SVT), the Time-Projection Chamber (TPC), and the Barrel Electromagnetic Calorimeter (BEMC), all having an acceptance covering 2π in azimuthal angle and $|\eta|\leq\sim1.5$ in pseudo-rapidity. STAR proposes a barrel Time-of-Flight (TOF) detector based on "Multigap Resistive Plate Chamber" (MRPC) technology, matching the acceptance of these existing detectors [1]. This upgrade will provide essential particle identification capability. Specifically, the percentage of identified kaons and protons will double to more that 95% of those produced within the acceptance of the TOF barrel ($|\eta|\leq\sim1$), greatly enhancing the discovery potential of STAR. This increase in particle identification efficiency over a large solid angle is especially important for measurements of multi-particle correlations since the feasibility of such measurements depends (on average) on the single particle efficiency raised to the power of the number of particles used in the correlation. The extended momentum range for particle identified spectra provided by the MRPC barrel TOF detector is crucial to understand the information contained in the large scale correlations and fluctuations being observed in Au-Au collisions at RHIC.

II. The Detector

Large acceptance TOF coverage has been an integral part of the proposed STAR detector since its inception. At that time, the TOF detector technology proposed was based on mesh-dynode phototubes and was deemed to be too expensive. The development of new, low-cost MRPC technology for the ALICE experiment combined with the parallel development of new electronic chips at CERN provides a cost effective means to fulfill the physics-driven requirements of the original STAR design. After extensive testing of MRPC technology at CERN and BNL in addition to its successful implementation in the HARP experiment, this technology is mature; a full-scale MRPC prototype tray with progressive versions of prototype electronics was installed in STAR for in-situ testing since the 2003 RHIC run.

An MRPC is a stack of resistive glass plates with a series of uniform gas gaps. Electrodes are applied to the outer surface of the outer plates. A strong electric field is generated in each sub-gap by applying a 14 kV high voltage across these external electrodes. All the internal plates are electrically floating. The chambers operate in a highly electro-negative gas, primarily Freon r134a. A charged particle going through the chamber generates avalanches in the gas gaps. The induced signal on the pads is the sum of possible avalanches from all gas gaps. The electrodes are made of resistive graphite tape and are transparent to charge. Copper pickup

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pads are used to read out the signals. The graphite electrodes have a surface resistivity of 10^5 Ω and cover the entire active area. The outer and inner glass plates are 0.7 mm and 0.55 mm thick, respectively. They are kept parallel by using 0.22 mm diameter nylon fishing line as spacers. The signals are read out by an array of copper pickup pads. The pickup pad layers are separated from the outer electrodes by 0.35 mm of Mylar.

The primary mechanical structure of the system is a “tray.” These hold the detectors in three dimensions at specific positions and angles, support the on-detector electronics, and form all but one wall of the gas volume. A tray is an aluminum box with 50 mil (0.13 cm) wall thickness and welded corners. It takes 120 trays to cover the cylindrical outer radius of the TPC. The trays are arranged as two adjoining cylindrical shells of 60 trays each. Each cylindrical shell subtends approximately 1 unit of pseudo-rapidity. The detectors inside the gas volume are standard MRPC “modules,” 6 channels each, with detector channel dimensions of 3.3cm×6.1cm. It takes 32 modules to fill a tray. The “top” of the tray is a custom 1/8” thick electronics board called the “TINO” board (described below) which contains the TOF front end electronics. These TINO boards are simultaneously the “top” of the gas box, the signal feed-through mechanism, the actual FEE boards, and the mounting location of the TOF Digitization (TDIG) boards just above the TINO boards. Thus, the electronics exist as two layers, the TINO boards themselves are both the first layer of electronics and the tray top. Mounted above these is another layer of boards, TDIG, that perform the digitization. At the high-z end of the tray is one more electronics board, “TCPU”, which performs the communication of the digital data. A gas system provides a mixture of 95% Freon (R134a) and 5% Isobutane to the TOF chambers at atmospheric pressure.

III. Electronics Design

A TOF system measures time intervals, which are defined by independent electronic measurement of one “start time” and some number of “stop times” in each experimental event. In the proposed system, we will perform the timing digitization on-detector for about 23000 channels, with timing relative to a common clock to determine the stop time for a particle's flight. The start time, or time of the collision, is determined by the vertex position detector (VPD), scintillator-PMT detectors close to the beam pipe, which is digitized in the same way as the stop times. This information (and pulse width data for the rise-time or “slewing” correction) is transmitted digitally to the STAR DAQ for timing analysis:

$$TOF = t_{stop} - t_{start}$$

The total resolution after all corrections must be ≤100ps to achieve STAR's physics goals. For a start resolution of 50ps attained from the VPD, and a 30ps contribution from the timing corrections, a pure stop resolution of less than 80ps is dictated. The MRPC detectors developed for this project have demonstrated pure stop resolutions in the range from 50-70ps using prototype electronics very similar to that described later in this section.

The other basic performance requirement of the TOF electronics is to provide sufficient data buffering and transport capacity to deliver the TOF data to the STAR DAQ, within the constraints of hit rates, trigger (event) rates, and trigger latency.

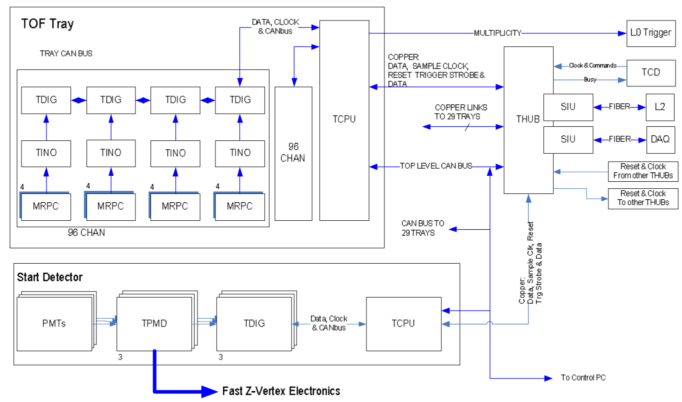

Fig. 1: The top-level diagram of the TOF electronics, showing the tray electronics containing the TINO, TDIG, and TCPU boards, the start detector electronics containing the TPMD, TDIG, and TCPU boards, as well as the off detector electronics board THUB, which interfaces to DAQ and Trigger.

Shown in Fig. 1 is the top-level diagram of the electronics for the start and stop sides of the present system. The electronics chain on the start side is very similar to that on the stop side by design. The individual electronics boards seen in this figure are discussed in detail below.

The approach for the TOF readout electronics design uses on-detector electronics on the MRPC trays, with tray-level data buffering, and fiber-optics data communication with STAR DAQ. Each tray includes: 192 MRPC detector channels, 8 amplifier/discriminator circuit cards (“TINO”), with 24 channels each, 8 time-to-digital converter cards (“TDIG”), with 24 channels each, and 1 buffer card (“TCPU”) to store and forward data for all 192 data channels. On the start detector side, the TINO front-end card is replaced by a “TPMD” card, which contains level adapters and discriminators for the PMT signals. Provisions are made on the TPMD to split the PMT signals for use in additional electronics that will determine the position of the interaction vertex for triggering purposes. These electronics are, however, not part of the TOF electronics. Finally, the THUB card interfaces 30 TCPU cards to the STAR trigger and DAQ. Two of the THUB cards have an additional interface for the TCPU from the start detector electronics.

The TINO card is the interface between the MRPC tray and the TDIG read-out card. This card amplifies and discriminates the MRPC signals using the CERN/LAA analog ASIC “NINO” [2] which was developed for use with MRPC chambers in the CERN experiment ALICE [2]. The NINO chip has differential inputs to profit from the differential signals from the MRPCs; it contains a fast amplifier with less than 1 ns rise time and a discriminator with adjustable threshold. The slewing correction of the time measurements is accomplished by estimating the rise-time slewing of the signal with the Time-over-Threshold ("ToT") of the signal. To allow this measurement to be accomplished without the need for additional trailing edge TDCs, the NINO chip has the capability to add an additional fixed offset to the length of the output signal to provide for the finite dead time of the TDC. Each NINO chip handles 8 inputs; there are a total of 3 NINO chips on each TINO board. Each TINO board handles 4, 6-channel MRPC modules.

The TDIG card receives the input signals and records the signal times relative to a system-wide clock using the CERN High-Performance TDC chip "HPTDC" [3,4,5] developed for the experiments ALICE and CMS. The HPTDC uses a tapped delay line architecture to perform its time-sampling function. The 40 MHz input clock is multiplied on the chip to 320 MHz with a phase locked loop (PLL). This 3.125 ns clock signal is fed through a 32-tap delay locked loop (DLL) which is sampled at the arrival of the hits, resulting in a measurement with 97.66 ps in the least significant bit (LSB). Additionally, the chip samples the input signal 4 times with a small time interval between the samples achieved with a 4-tap RC network. By determining in which sample the rising edge of the reference clock comes out of a DLL tap, one can deduct the arrival time of the hit with a resolution equal to the sample interval. This final subdivision results in bin widths of 24.41 ps. The dynamic range of the measurement is increased with the use of a clock-synchronous counter that is recorded together with each time sample. Each channel of the HPTDC has a small FIFO associated with it to buffer the data. Time measurements stored in the channel buffers are passed to a data processing unit and, after proper encoding, they are written into 256-deep latency buffers while waiting to be serviced by a trigger matching unit. The extraction of hits related to a trigger is based on trigger time tags within a programmable time window. Extracted measurements are stored in a common 256-deep readout FIFO until they are read out via either a parallel (8 or 32 bit) or a serial bus. Additionally, the chip can also be operated in non-triggered mode, where every input hit is forwarded to the readout FIFO. There are 3 HPTDC chips on each TDIG card; each TDIG handles 24 signal channels coming from TINO. Each HPTDC channel records both the leading edge of the signal for timing, and its trailing edge to determine the ToT for slewing corrections. In addition to the HPTDCs, this card will have a slow serial interface (CANbus) for HPTDC and logic configuration, control of discriminator threshold and temperature monitoring. The TDIG card is mounted on top of its corresponding TINO card on the trays. A water channel between the TINO and TDIG cards provides cooling for these boards.

The TCPU card concentrates the data from 8 TDIG cards and sends it to THUB. It also distributes the 40MHz clock to the TDIG cards, and sends multiplicity information from the TOF trays to the lowest level logic of the trigger system ("L0-trigger"). The 40 MHz system clock is received from the THUB card described below. A built in hardware handshake protocol allows all 12 HPTDC devices from four TDIG cards to share a 80Mbit/sec serial output port so that only 2 data cables are required per TOF tray (4 TDIG boards, 96 MRPC pads each). The TCPU is implemented as a combination of programmable logic and embedded CPU. It also contains a Serializer/Deserializer (SERDES) chip to receive control and trigger commands from THUB and to send digitized data to THUB.

The THUB card interfaces 30 or 31 TCPU cards to STAR trigger and DAQ. The data interface consists of a high-speed SERDES chip that transmits and receives data over twisted pairs in low-cost CAT-6 cables. The data from 4 SERDES channels is associated with fast memory chips through an FPGA. The memory is used to store the detector data until it can be transmitted to the DAQ system over a fiber-optic link described below. THUB creates a low-jitter 40-MHz clock for the HPTDC chips and distributes it to the TCPU card on the tray. One THUB card will take on the role of the master clock generator and distribute its clock to the other three THUB to provide a common clock throughout the system for the timing measurements. There are a total of 4 THUB cards for the TOF system, each in a chassis mounted on the magnet steel. Each THUB card has a custom daughter card developed by the CERN ALICE experiment ("Source Interface Unit" or "SIU"), that provides a dual-fiber half-duplex interface to STAR DAQ. The TOF DAQ receiver is a Linux PC with a PCI based optical interface card ("Read Out Receiver Card" or "RORC") and a Myrinet interface to the rest of STAR DAQ.

IV. Cosmic Ray Test Stand

To test the timing performance of MRPC chambers and to be able to test electronics performance, a cosmic ray test stand was constructed. The test stand consists of a gas box that can contain up to 4 MRPC modules, sandwiched between a 2 scintillators on top and one below the box that form a telescope which provides a trigger that a cosmic ray has traversed the MRPC modules in the gas box. A schematic of the setup is shown in Figure 2.

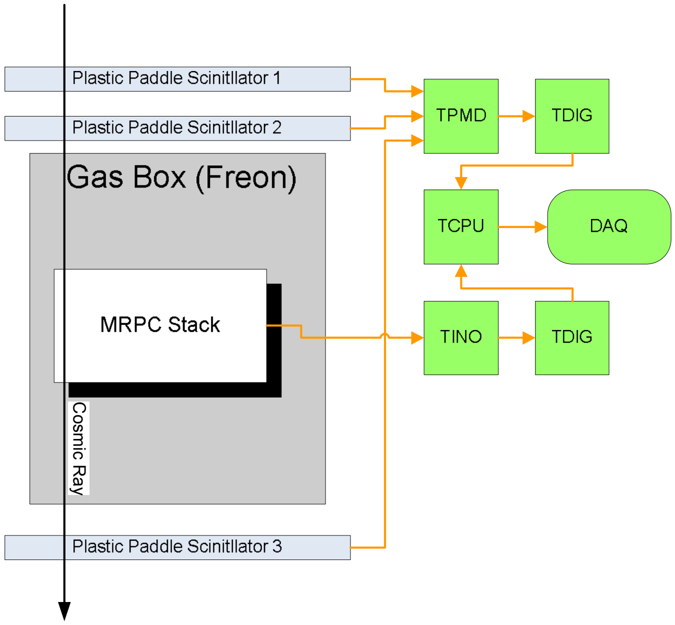

Fig. 2: Setup of the cosmic ray test stand and its associated electronics. Two scintillators on top and one scintillator on the bottom sandwich a gas box that contains up to four MRPC modules. Prototype electronics is used for readout and data acquisition.

The scintillators are read out on one side by Photo-Multiplier Tubes ("PMTs"). Signals from the PMTs are discriminated in a TPMD board (described above) and digitized by a TDIG board. The gas box contains up to 4 MRPC modules that are connected to a TINO board. The discriminated MRPC signals from the TINO board are digitized by the HPTDCs of a TDIG board. Both TDIG boards are connected to one TCPU board. In the cosmic ray setup we use the CANbus interface of the TCPU board to read out the digitized data to a PC, where the data are archived for later analysis. The PMT signals are split before they connect to TPMD and a second copy of these signals is then used to form a coincidence trigger to signal the traversal of a cosmic ray through the MRPC modules. One of the test inputs in the prototype TCPU board is used to provide this trigger to the programmable logic on TCPU which then initiates readout of the two TDIG boards in the test stand via their data cables. The only board missing from the readout chain shown in Figure 1 is the THUB board, which was deemed not necessary in this setup due to the low data rate coming from cosmic ray events.

Data from this setup allowed us to test all components of the proposed electronics in a realistic setup. Additionally, it allows us to test MRPC modules produced for their timing resolution. A time difference measurement is obtained by using one of the MRPC modules as a stop while the other MRPC modules provide the start of the timing measurement. We require that only pads in a single column are hit in a valid cosmic ray event. The analysis then proceeds to correct for the measured non-linearities of the HPTDC. Finally, leading-edge ("slewing") corrections are obtained by fitting the distribution of time differences versus ToT. A typical time difference distribution obtained by this setup and after all corrections have been applied is shown in Figure 3. The sigma of the time difference measurement distribution is used as a measure of the overall timing resolution. To obtain sufficient data to allow for measurement of the timing resolution takes a few days. Overall timing resolutions obtained from this setup vary from module to module and range from 80 – 110 ps.

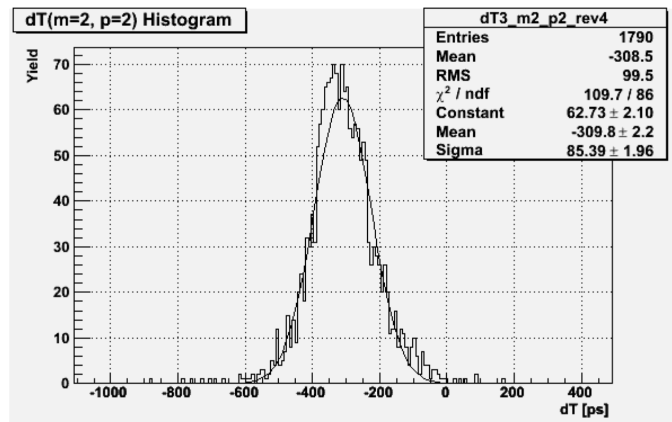

Fig. 3: Typical time difference distribution obtained with the cosmic ray test stand after all corrections have been applied to the data. Plotted on the x-axis is the time difference between the arrival time of a cosmic ray in one of the MRPC modules and the average of the arrival time in the other MRPC modules in the gas box. The sigma of this distribution is about 85ps.

REFERENCES

[1] http://www.star.bnl.gov/, and STAR TOF proposal: http://www.star.bnl.gov/STAR/tof/publications/TOF_20040524.pdf

[2] F. Anghinolfi, P. Jarron, A.N. Martemyanov, E. Usenko, H. Wenninger, M.C.S. Williams, A. Zichichi, "NINO : An ultra-fast and low-power front-end amplifier/discriminator ASIC designed for the multigap resistive plate chamber," Nucl. Instrum. Methods Phys. Res., A 533 183-187 (2004).

[3] http://micdigital.web.cern.ch/micdigital/hptdc.htm

[4] M. Mota, J. Christiansen, S. Debieux, V. Ryjov, P. Moreira, A. Marchioro, "A flexible multichannel high-resolution time-to-digital converter ASIC," 2000 IEEE Nuclear Science Symposium Conference Record , Volume 2 , 9/155 -9/159 (2000).

[5] M. Mota, J. Christiansen, "A high-resolution time interpolator based on a delay locked loop and an RC delay line," IEEE Journal of Solid-State Circuits, Volume 34, Issue 10, 1360 -1366 (1999).