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Multigap RPCs in the STAR experiment at RHIC

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ABSTRACT

A large-area ($50\,m^2$) Time-of-Flight system has recently been installed in the STAR experiment at RHIC. The detectors are Multigap Resistive Plate Chambers (MRPCs) and are digitized using custom electronics based on the CERN "NINO" and "HPTDC" chips. Several different prototype systems were built and operated in STAR from 2002 to 2006. The design and performance of the prototypes and the $\sim 70\%$ installed final system during the 2009 RHIC Run will be presented. A possible future upgrade to the STAR experiment is the Muon Telescope Detector (MTD). This system will use very large MRPCs with double-ended read-out to identify via time of flight the muons that pass through steel back-legs of the STAR magnet. The design of this system and the performance of MTD prototype systems will also be presented.

1. Introduction

When it collides two ^{197}Au nuclei at the highest available energy of 100 GeV/*c*/nucleon, the RHIC facility at Brookhaven produces strongly interacting matter that is dense enough to quench jets yet flows like a nearly perfect fluid [1]. Of the two RHIC experiments now carefully studying this matter, the STAR experiment is unique in its wide and azimuthally complete acceptance defined by the Time Projection Chamber (TPC). STAR had, however, important "blind spots". STAR could not efficiently particle-identify (PID) the charged hadrons π and K (p) if their momentum was above $\sim 0.7(1.0)\,\mathrm{GeV}/c$. Roughly half of the total number of charged hadrons in a given event thus could not be directly identified. In addition, STAR has only an extremely limited ability to directly identify muons. To fill in these gaps in its PID capabilities, the STAR Collaboration has constructed and installed a large-area Time-of-Flight (TOF) system for charged hadron identification, and is developing another large-area system for muon identification. Both of these systems are based on Multigap Resistive Plate Chambers (MRPCs) [2].

A TOF system [3] with a total timing resolution of 100 ps in the STAR geometry, and for the tracking resolution of the STAR TPC, allows $\pi : \mathrm{K} : \mathrm{p}$ direct PID up to momenta of $\sim 1.7-1.9\,\mathrm{GeV}/c$ and $(\pi+\mathrm{K}) : \mathrm{p}$ identification up to $\sim 2.9-3.1\,\mathrm{GeV}/c$. Combining the particle identification capabilities of the TOF with those from the energy loss, dE/dx, in the TPC allows high efficiency particle identification over $\sim 98\%$ of the hadron spectra. The use of TOF to exclude "slow" tracks also allows a clean separation of electrons and pions based on the track dE/dx values. This dramatically extended PID capability will improve the signal-to-background ratios for ρ, $K^*(892)$, f^0, $\phi(1020)$,Δ,$\Sigma(1385)$,$\Lambda(1520)$,D^0, D^+, and D_s^+ particles by significant factors, in some cases allowing the measurement of complete spectra for these particles in single RHIC running periods for the first time. The TOF system is also seen as a particularly important component of STAR [4] for the RHIC beam energy scan ($5 < \sqrt{s_{NN}} < 39\,\mathrm{GeV/nucleon}$) to locate the Quantum Chromodynamic critical point which begins in RHIC Run 10. All observables of interest are improved by the presence of the TOF system. For example, the measurement of the K^+/π^+ ratio and its event-by-event fluctuations are improved by the suppression of both the π and K misidentification, and the otherwise large contributions to the dynamical fluctuations resulting from the finite counting statistics from the low efficiency of the TPC dE/dx PID.

An improved capability for the direct identification of muons will lead to large samples of identified J/ψ and Υ mesons and a unique measurement of $\mu-e$ correlations from heavy-flavor decays. A large-area system of muon detectors will thus allow the study of color degrees of freedom and the equation of state. For example, due to color screening, different quarkonium states will dissociate at different temperatures due to their different binding energies. The precise measurement of the transverse momentum distributions of quarkonia at different centralities and beam entrance channels will then provide a direct thermometer of the hottest stages of the collision. The MRPCs for the envisioned STAR Muon Telescope Detector (MTD) are much larger than those in the STAR TOF system and include the double-ended read-out of

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long strips. The basic approach of the MTD differs from conventional muon detectors that consist of multiple layers of absorbers and tracking. In the case of the STAR MTD, the STAR electromagnetic calorimeter and steel back-legs of the STAR magnet form a ~ 6 interaction length absorber between the TPC and the MTD. Tracks reconstructed in the TPC that result in hits in the MTD with the proper times and positions are identified as muons. Prototype MRPCs and MTD detectors have been studied in test beams and in STAR since RHIC Run 7.

The STAR TOF MRPCs are discussed in Section 2, and the full-sized prototypes and the final system are discussed in Section 3. The MRPCs for the STAR MTD, and the status of the development of a large-area MTD system, are discussed in Section 4. The conclusions are presented in Section 5.

2. The multi-gap resistive plate chambers for STAR TOF

The MRPC technology was first developed by the CERN ALICE group [2]. Working closely with this group, we developed a variant for STAR and tested it in a CERN test beam [5]. Our TOF MRPCs are a stack of resistive plates (0.54 mm-thick float glass) with five 220 μm gas gaps. Graphite electrodes are applied to the outer surface of 1.1 mm-thick outer glass plates. A ~ 14 kV voltage difference is applied to these electrodes. The glass resistivity is $\sim 10^{13}\,\Omega$ cm and the electrode resistivity is $10^5\,\Omega/\square$. The read-out cells in each TOF MRPC are a single row of six $3.5 \times 6.1\,\mathrm{cm}^2$ pads read-out from one edge by traces that connect to two twisted-pair signal cables.

The MRPCs were operated in a gas that is 95% R-134a and 5% isobutane. The resulting signals are extremely small (~ 25 fC/hit). Thus, careful pre-amplification in the front-end electronics and careful shielding from external radio-frequency interference in the mechanical design is crucial. The "dark rate" is typically $\sim 1\,\mathrm{Hz/cm}^2$ (*i.e.* ~ 20 Hz/pad).

The detection efficiency (open circles), time resolution (solid circles), and average signal area (triangles) versus the voltage obtained from the CERN test-beam is shown in Fig. 1. The flux for these data was $200\,\mathrm{Hz/cm}^2$, which is the maximum rate expected for TOF in STAR during the RHIC-II era. One notices a wide voltage plateau leading to $>95\%$ efficiency, and a (pure-stop) timing resolution below 75 ps, which make these MRPCs viable for STAR TOF.

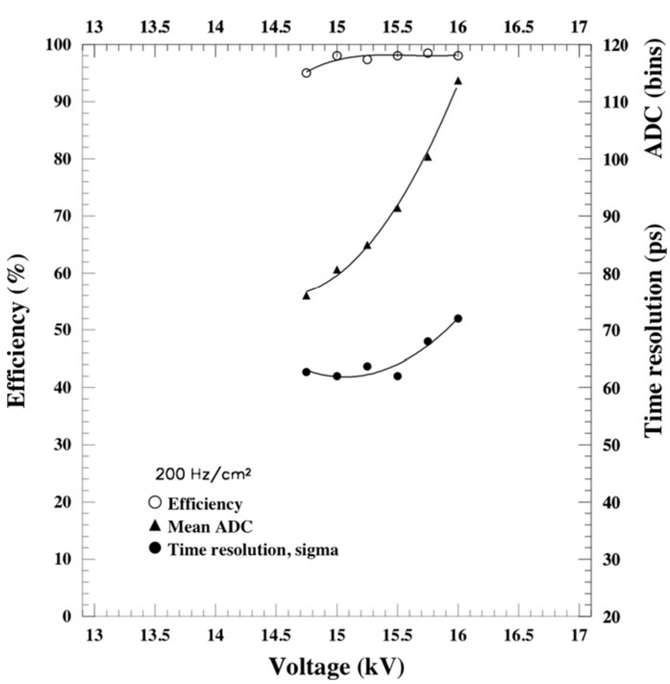

Fig. 1. The performance of the STAR MRPCs measured at a CERN test beam.

3. The STAR TOF prototypes and the full system

With our TOF MRPC design finalized in 2001, we then tested the technology in STAR in full-scale prototype "trays." The first, "TOFr," was used in Run 3, the second "TOFr′," was used in Run 4, and the third, "TOFr5," was used in Runs 5 and 6. Each of these TOFr prototypes was built "from the ground up" and included incremental improvements to the mechanical and electronic design to simplify the construction, improve the mechanical tolerances, and improve the overall performance. A few MRPCs were used in all three prototypes to search for possible aging effects-none were seen. TOFr was also tested extensively in an AGS radiation area [7].

Both TOFr and TOFr′ were digitized in CAMAC by the existing STAR TOFp subsystem [6] using long signal cables. For the subsequent TOFr5, the digitization was done on-board using the HPTDC [9] chip developed at CERN. The STAR TOF electronics were optimized over several years and final MRPCs, mechanical tray structures, and electronics were used for the first time in RHIC Run 8 (5 trays installed). In the final electronics, the MAXIM 3760 amplifier was replaced by the NINO [8] amplifier and discriminator, which was also developed at CERN. Ninety-four trays were installed before Run 9, and all 120 trays were installed before the on-going Run 10. The MRPCs were fabricated in China, and the trays were fabricated, assembled, and tested as complete units in Texas. The trays were then fully retested after arriving at Brookhaven.

The 120 trays of the full TOF system are arranged in two adjoining rings of 60 trays each immediately outside of the STAR TPC. Each tray covers a pseudo-rapidity interval of ~ 0.9, and 1/60th of the full azimuth. There are 32 MRPCs in each tray arranged nearly projectively for collisions occurring at the center of STAR. There are thus 3840 MRPCs, and 23,040 read-out channels, in total. The occupancy in central full-energy Au+Au collisions is approximately 12%.

The circuit boards used in the system are as follows [10].

- *TINO*—this board closes the gas box, feeds-through the differential MRPC signals from four MRPCs (24 channels) and inputs these into three NINO chips. The NINO chips amplify and discriminate the detector signals and also produce a voltage level if any of the eight channels are above threshold.
- *TDIG*—this board performs the time digitization of the signals from the TINO boards with respect to a 40 MHz clock using three HPTDC chips. The leading and trailing edges of a detector signal are digitized in the same channel of an HPTDC chip in "very high resolution" mode (~ 24.4 ps LSB). This "time-over-threshold" (ToT) information is the pulse-size metric used on the offline slewing corrections of the leading edge time stamps. The integral non-linearity (INL) of every one of the 23,040 HPTDC channels in the system was measured on the bench and included in the STAR database for use offline.
- *TCPU*—this board collects the digital information from the eight TDIG boards on each tray and formats and buffers it. It also collects the TINO multiplicity levels and outputs a digital multiplicity in the range of 0–24 for each tray that is used at the earliest level of the STAR trigger.
- *THUB*—the four THUB boards collect the digital timing information from 30 trays (240 TDIG boards) and send this information to a receiver in the STAR DAQ system via

SIU/RORC data links [11]. One THUB generates the master clock signal that is distributed to the other three THUB boards and trays.

The eight TINO, eight TDIG, and one TCPU board mounted on each tray draw ~100 W of electrical power in total. The resulting heat is quite efficiently (~90%) removed via a rectangular 1/4 in. × 3/8 in. copper cooling water loop that is in direct contact with the TINO layer below and the TDIG layer above. An aluminum cover is placed over the electronics layer on the top of each tray to provide mechanical protection and shield the electronics from radio-frequency noise.

The first five final trays ran stably throughout Run 8. The performance of these trays for particle identification in the p+p phase of this run is shown in Fig. 2. The stop-side calibrations required to achieve this performance include the HPTDC INL correction, channel-by-channel timing offsets with respect to the start time, and a standard leading-edge slewing correction based on the ToT values. Three-quarters of the full system was installed during the subsequent Run 9, which was also p+p. As the multiplicities are low in these collisions, the calibration was performed in groups of 24 channels (single TDIG boards). The total time resolution versus the board number is shown in Fig. 3. The system thus performed quite uniformly.

The total, pure-start, and pure-stop timing resolutions of the TOF prototypes and final system trays are summarized in Table 1. On-board TDIG-based digitization was used starting in Run 5 and the slewing corrections were then based on the ToT values. For earlier runs, the slewing corrections were based on the signal area using CAMAC ADC values. The start detector was also changed before Run 8. The resolution results shown for Runs 9 and 10

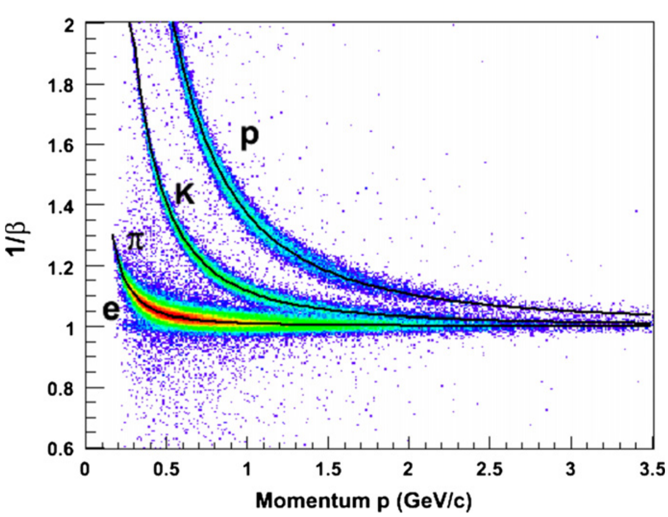

Fig. 2. The PID performance of the first five final TOF trays that were installed during RHIC Run 8.

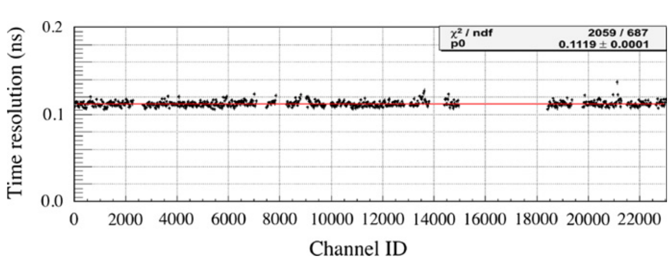

Fig. 3. The total time resolution from the $\frac{3}{4}$–installed STAR TOF system during RHIC Run 9.

Table 1
The time resolution results obtained for the various TOF prototype and final trays during operation in STAR during RHIC runs.

RHIC run (year)	Beams and $\sqrt{s_{NN}}$ (GeV)	Start (ps)	Total (ps)	Stop (ps)
3 (2003)	d+Au, 200	85	120	85
	p+p, 200	140	160	80
4 (2004)	Au+Au, 62	55	105	89
	Au+Au, 200	27	86	82
5 (2005)	Cu+Cu, 200	50	92	75
	Cu+Cu, 62	82	125	94
8 (2008)	p+p, 200	83	112	75
9 prelim. (2009)	p+p, 500	85	115	78
	p+p, 200	81	111	74
10 prelim. (2010)	Au+Au, 200	30	87	82

(presently in progress) are preliminary. The Runs 9 and 10 results shown were obtained from the initial "fast-offline" data production and are hence based on small subsets of the available data and/or an incompletely calibrated TPC. Additional improvements of ~10 ps or so are thus possible. Nonetheless, the pure-stop resolution of the final system trays (Run 8 and later) is in the range of 74–82 ps, and the total resolution in the full-energy Au+Au in Run-10 meets the required sub-100 ps total resolution requirement to meet the physics goals.

Of the 94 trays installed before Run 9, eight developed problems. The LV cable sense wires became disconnected from two trays, five HV cables were improperly installed or damaged by the STAR magnet pole-tips, and one tray had a bad TCPU card. All of these problems were repaired after Run 9. In Run 10, only one tray is not functional due to a single intermittently bad HV cable that is in a difficult to reach location. This will be repaired during the upcoming shutdown period. There are only three dead read-out channels in the system.

4. The multi-gap resistive plate chambers for STAR MTD

The MRPCs for the STAR MTD are both much larger than those in the STAR TOF system and the read-out is double-ended. Prototype systems were operated in STAR in Runs 7–10 using "Long MRPCs" (LMRPC) [12]. The "MTD7" prototype used two LMRPCs end-to-end, while the "MTD9" prototype used three LMRPCs side-by-side, two of which were in the MTD7 prototype. The signal processing for the MTD7 prototype used simple FEE [13] and long cables before the digitization on the platform using STAR trigger system electronics. The MTD9 prototype used the same on-board electronics as is used in the STAR TOF system.

An LMRPC module consists of a double-stack of resistive glass plates resulting in a total of ten 250 μm-wide gas gaps. They are operated at a potential of 12.6 kV for each 5-gap stack and the detector gas is the same mixture of 95% $C_2H_2F_4$ and 5% isobutane as is used in STAR TOF system. Each LMRPC has six copper read-out pads with dimensions of $87 \times 2.5\,cm^2$. In the range of $12.5 < HV < 13.0$ kV, the efficiency was above 95% and the timing resolution was about ~70 ps in cosmic ray and beam tests [12]. The spatial resolution along the strips from timing was <1 cm. The timing performance of the MTD7 prototype in STAR was about 300 ps due to the long cables and specific electronics used [14]. The analysis of the Runs 9 and 10 data is in progress.

For the final MTD system, much wider MRPCs, "WMPRCs," are planned. There will be a total of 117 of these detectors in the full system, and each will be single-stack, five-gap, detector with outer dimensions of $91.5 \times 58.0 \times 3\,cm^3$. Each WMRPC has twelve $87 \times 3.8\,cm^2$ strips, with 0.6 cm gaps between strips, read-out at

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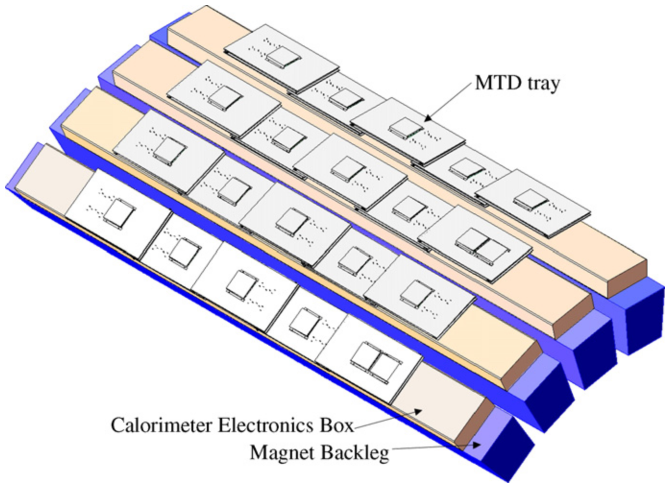

Fig. 4. The planned arrangement of MTD trays on the outside of STAR.

both ends by STAR TOF electronics. Three such detectors will be installed before Run 11. A schematic drawing of five MTD trays per magnet back-leg mounted to the outside of STAR is shown in Fig. 4.

5. Conclusions

STAR has embraced the MRPC technology and is employing it both for charged hadron identification via time-of-flight inside the STAR magnet (STAR TOF) and for muon identification outside the magnet (STAR MTD). Numerous prototype detectors for both types of systems were operated in test beams and in STAR and work well. The prototype "TOFr" systems were the first use of MRPCs in a collider experiment and they demonstrated the viability of the technology. These detectors also resulted in the first physics results [15] obtained from an MRPC-based TOF system. The construction of the large-area TOF system was completed in late 2009 and the system is now operating successfully in RHIC Run 10.

Next-generation prototypes of the STAR MTD system, which will increase STAR's physics reach by directly identifying muons in a large acceptance, will be installed for RHIC Run 11. We hope to complete the large-area MTD system in advance of RHIC Run 13.

Acknowledgments

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