The STAR Heavy Flavor Tracker (HFT)

Joachim Schambach[1], *Eric Anderssen*[2], *Giacomo Contin*[2], *Leo Greiner*[2], *Joe Silber*[2], *Thorsten Stezelberger*[2], *Xiangming Sun*[3], *Michal Szelezniak*[4], *Flemming Videbæk*[5], *Chinh Vu*[2], *Howard Wieman*[2], *Sam Woodmansee*[2]

[1]University of Texas, 1 University Station, Austin, TX 78712, USA
[2]Lawrence Berkeley National Laboratory, Berkeley, CA 94720
[3]Central China Normal University (CCNU), Wuhan, China
[4]Institut Pluridisciplinaire Hubert Curien (IPHC), Strasbourg, France
[5]Brookhaven National Laboratory, Upton, NY 11973, USA

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The heavy quark hadrons are suggested as a clean probe for studying the early dynamic evolution of the dense and hot medium created in high-energy nuclear collisions. The Heavy Flavor Tracker (HFT) of the STAR experiment, designed to improve the vertex resolution and extend the measurement capabilities in the heavy flavor domain, was installed for the 2014 heavy ion run of RHIC. It is composed of three different silicon detectors arranged in four concentric cylinders close to the STAR interaction point. The two innermost layers are based on CMOS monolithic active pixels (MAPS), featured for the first time in a collider experiment, and the two outer layers are based on pads and strips. The two innermost HFT layers are placed at a radius of 2.8 and 8 cm from the beam line and accommodate 400 ultra-thin (50 μm) high resolution MAPS sensors arranged in 10-sensor ladders to cover a total silicon area of 0.16 m^2. Each sensor includes a pixel array of 928 rows and 960 columns with a 20.7 μm pixel pitch, providing a sensitive area of $\sim 3.8\ cm^2$. The sensor features 185.6 μs readout time and 170 mW/cm^2 power dissipation, allowing it to be air cooled, which results in a global material budget of only 0.5% radiation length per layer in the run 14 detector. A novel mechanical approach to detector insertion enables effective installation and integration of the pixel layers within a 12 hour shift during the on-going STAR Run. After a detailed description of the design specifications and the technology implementation, the detector status and operations during the 200 GeV Au+Au RHIC run of 2014 will be presented in this paper. A preliminary estimation of the detector performance meeting the design requirements will be reported.

1 Introduction

Results from experiments over the last decade at the Relativistic Heavy Ion Collider (RHIC) suggest that a hot and dense matter with strong collectivity has been formed in central Au+Au collisions with energies up to $\sqrt{s} = 200\ GeV$ [1]. The high temperatures and densities of nuclear matter generated in these collisions create conditions in which a phase of deconfined quarks and gluons, the so-called Quark-Gluon Plasma (QGP), should exist. Due to their mass, heavy quarks such as charm and bottom quarks, are only produced by hard processes early in the collision and not by thermal processes after the equilibration of the plasma, which makes mesons containing

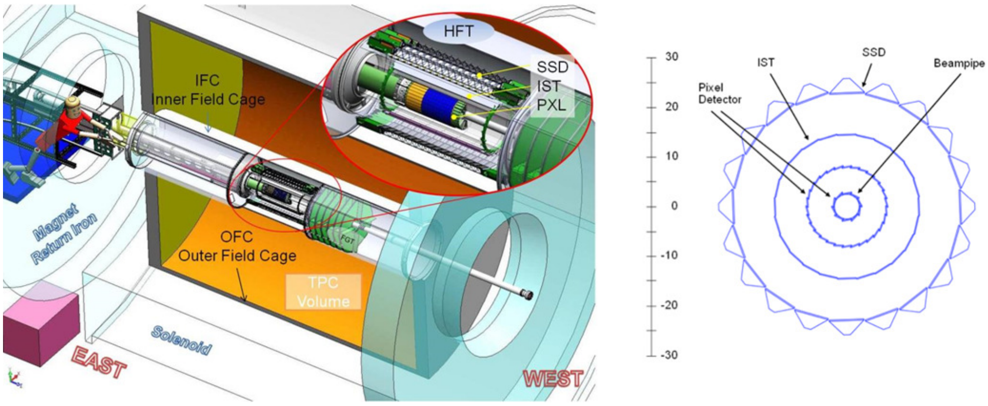

Figure 1: Schematic view of the HFT inside the TPC inner field cage.

heavy quarks an ideal probe for studying the initial conditions of the produced QGP. Most of these heavy quarks produced in the collision end up in open heavy flavor particles that in the past were hard to detect in the STAR experiment due to their low abundance and the large combinatorial background. For that reason STAR installed a new micro-vertex detector for the 2014 heavy ion run at RHIC, called the "Heavy Flavor Tracker" [2], which allows the direct topological reconstruction of the decay vertices from open heavy flavor meson decays which happen close the primary collision vertex due to the small decay length of open heavy flavor particles.

2 HFT and PXL Design

The STAR experiment uses a Time Projection Chamber (TPC) inside a 0.5 T magnetic field as its main tracking detector. Using tracks found in the TPC, the primary interaction vertex can be resolved with a Distance of Closest Approach (DCA) pointing resolution of about 1 mm. Open flavor mesons that are produced at the collsion vertex have a decay length that is very small; for example the $c\tau$ of the D^0 meson is 120 μm. Thus, to be able to reconstruct these decay vertices, the primary physics requirements on the new "HFT" detector system is to provide vertex pointing resolution to resolve vertices displaced from the primary vertex by less than about 150 μm. The basic idea in the design of the HFT is to use tracks found in the TPC and add additional space points on these tracks towards the primary vertex with increasing resolution. The HFT therefore consists of 3 different silicon detector subsystems arranged in 4 concentric layers around the primary vertex as seen in Figure 1: the "Silicon Strip Detector" (SSD), the "Intermediate Silicon Tracker" (IST), and the "PIXEL" (PXL) detector.

The outermost Si detector system, the SSD is an existing detector consisting of double sided silicon strip modules with a 95 μm pitch at a distance of of 22 cm from the beam. The electronics for this detector was upgraded to achieve faster trigger rates compatible with other STAR detectors. The IST at 14 cm radius consists of single-sided double-metal silicon pad sensors with a 600 μm x 6 mm pitch. The SSD and IST detector layers redundantly guide tracks from the TPC to the two innermost layers of the HFT, the PXL detector.

The PXL detector, shown in Figure 2, consists of two layers at radii 2.8 cm and 8 cm using

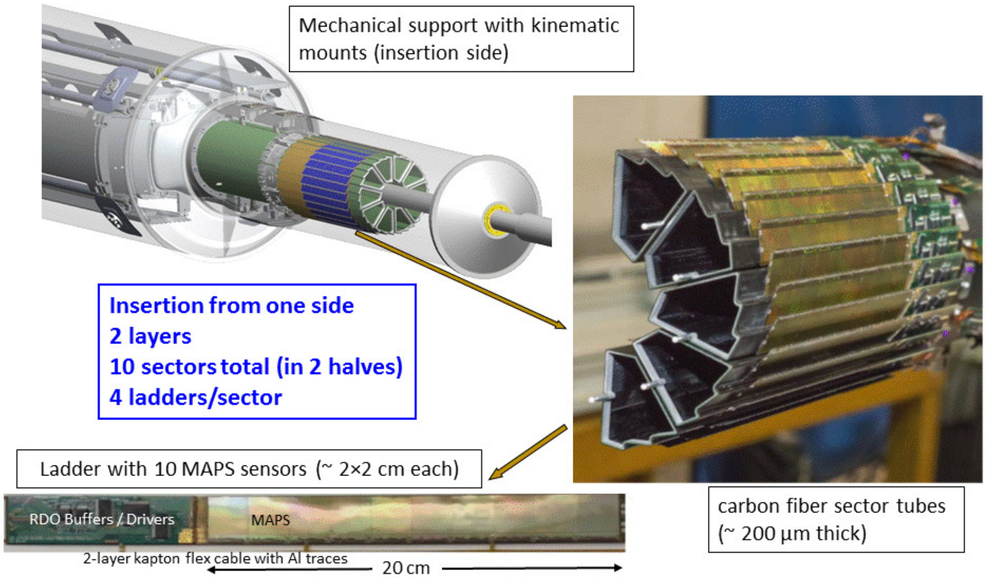

Figure 2: Schematic view of the PXL sub-detector system of the HFT.

state-of-the-art ultra thin CMOS Monolithic Active Pixel Sensors (MAPS) [3, 4, 5, 6]. Mechanically, the PXL detector is subdivided into 10 sectors, each consisting of a thin trapezoidal carbon fiber sector tube with four 10-sensor ladders mounted on each tube, one at the inner diameter, and 3 at the outer diameter. The sensors are thinned to 50 μm thickness, and are mounted on an aluminum conductor flex cable that provides the signal path to the electronics at the end of the flex cable containing the buffers and drivers for the sensor signals. This construction results in a total radiation length X/X_0 of as little as 0.4% per layer in the low-mass region.

The sectors are assembled into two halves on unique mechanical supports that allow for the insertion and retraction of the whole PXL detector from one side side of STAR in only about 12 hours, by pushing the detector halves along rails inside a support cylinder and locking them into a reproducible position with kinematic mounts. The sensor chip used for the PXL detector is the "Ultimate" sensor developed by IPHC in Strasbourg, France. These sensors use pixels with a pitch of 20.7 μm pitch arranged in a 928 (rows) by 960 (columns) array (a total of $\sim$ 890k pixels per sensor) on a 20.22 mm x 22.71 mm chip with a high-resistivity epitaxial layer for increased radiation hardness and increased signal-to-noise performance. Each pixel includes readout and correlated double sampling (CDS) circuitry for signal extraction and noise subtraction. The readout is done by reading each pixel row in parallel through programmable threshold discriminators at the end of each column. The resulting digital data are then passed through a zero-suppresion logic block located below the pixel array on the same chip, which delivers run-length encoded hit addresses for up to 9 hit clusters per row to on-chip memory for intermediate buffering. The memory is arranged in two banks of up to 1500 words each which allows simultaneous read and write operations. The data are read out bit-serially from one of these memory banks over two "Low-Voltage Differential Signaling" (LVDS) outputs per sensor, each running at 160MHz. The signal integration time of the whole sensor is

185.6 μs. Configuration by the JTAG protocol allows the control of many internal parameters and programming of internal test features. A power dissipation of only $\sim 170\ mW/cm^2$ allows these sensors to be operated at room temperature with just air cooling. The readout electronics for the PXL detector follows the mechanical segmentation of the detector and is divided into 10 parallel identical systems. After leaving the ladders, the sensor signals are transmited over $\sim 2m$ of thin twisted pair cables to "Mass Termination Boards" (MTB) at the end of the mechanical structure of the PXL system, which contain buffers and drivers for the signals, as well as latchup protected power supplies for the sensors. Each MTB services the 4 ladders of one sector, i.e. there are 10 MTBs in the PXL detector. Each MTB is connected to an FPGA-based Readout (RDO) board in the low radiation area of the STAR experimental hall with $\sim 11\ m$ of twisted-pair cable. The 10 RDO boards are mounted in a 9U-size crate; each RDO provides trigger based hit selection, buffers and formats the resulting data into event structures, and then sends it over 100 m optical fiber to one of two PCs in the STAR DAQ room, where the data are combined with the rest of the STAR data for event building and final storage. Control, configuration and monitoring of the PXL sensors is done from a control PC, which is connected via USB to the RDO boards. The control PC interfaces to the STAR Slow Controls system to provide monitoring and control of the PXL system to the STAR shift crew.

3 PXL Status and Performance

Two complete PXL detectors and 40 spare ladders have been fabricated by the fall of 2014, and the first PXL detector was installed before the 2014 heavy ion run of RHIC. Because of production issues only 2 of the inner ladders were produced with Aluminum-conductor flex cables, while the rest of the ladders were constructed using alternative Copper-conductor flex cables. This resulted in an increase of the radiation length from the design value of 0.4% to 0.5%. The SSD and IST detectors were installed into STAR during the fall of 2013, while the PXL detector was installed in January of 2014, shortly before the beginning of the 2014 heavy ion run of RHIC. The PXL detector was inserted and cabled into the STAR TPC inner flied cage and operational within a 2 day installation. At the time of the first PXL detector installation all 400 sensors of the PXL system were tested to be working properly with less than 2000 bad pixels out of more than 365 million total. The discriminator thresholds were adjusted to give a fake hit rate of $\sim 1.5 * 10^{-6}$ for all sensors based on an automatic scan of noise rates versus discriminator threshold.

Before the beginning of the heavy ion run the PXL and IST detectors were included in a STAR cosmics run. This run was used for commisioning and integration of the PXL readout electronics with the existing STAR DAQ, Trigger, and Slow Controls systems. Data from this cosmics run were used for alignment and efficiency studies of the PXL detector. The efficiency of the PXL detector was obtained from these data by finding (straight) cosmics ray tracks in the TPC with hits on 3 PXL sensors, and looking for hits on a fourth sensor at the position of a straight-line fit through these three hits extrapolated to the fourth sensor. The analysis of these data were done before normal beam operation and before detector operation optimization was complete. Nevertheless, the average efficiency over all sensors was determined to be 97.2%.

During construction all pixel positions on the sectors as well as the position of the sectors within a detector half were measured in a coordinate measurement machine (CMM). The different parts of the PXL system were then aligned using these same cosmic ray data by looking at the residuals resulting from comparing hit positions to the track projections and adjusting

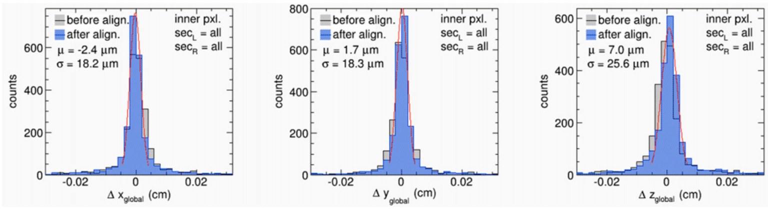

Figure 3: PXL hit residual to cosmic track before and after PXL sector-to-sector alignment.

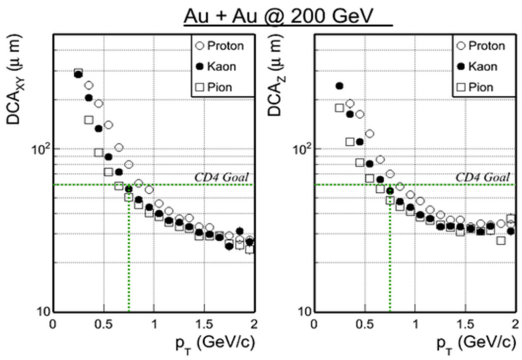

Figure 4: DCA resolution in x-y (left panel) and z (right panel) for TPC tracks with 1 IST hit and hits in both layers of PXL vs. transverse momentum.

the positions of the sensors in order to minimize these residuals. Gaussian fits to these residuals after the alignment was done result in a $\sigma \leq 25\ \mu m$ (see Figure 3), which exceeds the PXL design goals.

The cosmic ray run was followed by a run period of Au+Au collisions at 14.5 GeV from mid February until mid March 2014, which was used to optimize the sensor performance and minimal data taking during stable beam operation. The next 14 weeks were devoted to 200 GeV Au+Au collisions during which a total of $1.2B$ mimimum bias events with PXL included were recorded. Daily PXL noise runs with beam collisions were taken to reassess the sensor status, find hot or not-working pixels, and to verify the noise levels. Periodic threshold-vs-noise scans were performed to readjust the discriminator thresholds. During the final ^{3}He+Au run of RHIC, PXL was only occasionally turned on for further performance and sensor damage studies.

After the survey and preliminary alignment corrections described above were completed, the 200 GeV data were used to estimate the pointing resolution of the PXL detector to the interaction vertex. The DCA resolution for tracks found in the TPC which include 1 IST hit and 1 hit in both layers of PXL as a function of transverse momentum p_T for protons, pions and kaons are shown in Figure 4. For kaons with $p_T = 750 MeV/c$ this DCA resolution exceeds the design goal of 60 μm, in fact, for p_T larger than 1.5 GeV/c, the DCA resolution is better than 30 μm. A more detailed deterimination of the alignment corrections is still ongoing which will further improve these results.

During the 14.5 GeV Au+Au run and into the first two weeks of the 200 GeV Au+Au run first indications of sensor damage manifested itself that seemed to be related to the STAR radiation environment. The sensor damage took on many different forms: increased digital current, damaged or total loss of pixel columns, damaged configuration registers, loss of full or partial sub arrays, etc. Most of the damage occured in the sensors of the innermost layer of PXL, but even some sensors in the outer layer displayed these kind of damages. After several changes to the operational parameters of the running detector when this damage was detected, further damage to the installed detector for the rest of the run was greatly reduced or stopped. These methods included: turning on the PXL sensors when the collision rate started to fall below a certain threshold, power-cycling the sensors and reloading the sensor configutration periodically, and, most importantly, reducing the threshold at which the power supplies would over-current closer to the normal operational current of the sensors. A total of 15 of the 400 sensors in the PXL detector were damaged, which still allowed us to complete the physics run successfully. We plan on implementing these operational methods from the beginning of the 2015 RHIC run, thus hopefully limiting damage to the PXL sensors in the future. Further investigations of the cause of the observed damage is ongoing.

4 Conclusions

The new HFT micro-vertex detector at STAR enables or enhances open heavy flavor measurements at STAR, thus allowing us to study the early dynamic evolution of the dense and hot medium created in high-energy heavy ion collisions at RHIC. As part of this detector, state-of-the-art MAPS technology was used successfully for the first time in a collider experiment in the PXL subdetector. All three sub-detector systems of the HFT were installed and commisioned during the 2014 RHIC heavy ion run, and more than 1.2 billion Au+Au 200 GeV minimum bias events were recorded with the IST and PXL detectors included. Preliminary studies of the DCA pointing resolution performance show that the detector meets or exceeds the design goals. A second PXL detector was constructed during the summer of 2014 and will be installed in STAR before the 2015 RHIC run. The PXL ladders with damaged sensors were replaced after the 2014 run, and this detector was shipped to STAR to serve as a hot spare. Sensor damage related to the radiation environment in STAR was observed, but seems to be very limited by implementing operational methods.

Acknowledgments

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References

[1] J. Adams *et al.*, Nucl. Phys. A, vol. 757, 102 (2005).

[2] D. Beavis *et al.*, *The STAR Heavy Flavor Tracker Technical Design Report*, available at: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0600 (2011).

[3] C. Hu-Guo, *et al.*, Nucl. Instr. And Meth. **A623** 480 (2010).

[4] A. Dorokhov *et al.*, Nucl. Instr. And Meth. **A624** 432 (2010).

[5] A. Dorokhov *et al.*, Nucl. Instr. And Meth. **A650** 174 (2011).

[6] L. Greiner *et al.*, Nucl. Instr. And Meth. **A650** 68 (2011).