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THE STAR FORWARD DETECTOR SYSTEM UPGRADE STATUS*

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The STAR Collaboration has successfully completed an upgrade of the forward detector system located between $2.5 < \eta < 4.0$. This upgrade comprises a Forward Calorimeter System, which contains an Electromagnetic Calorimeter and Hadronic Calorimeter, and a Forward Tracking System which consists of a Forward Silicon Tracker and Forward small-strip Thin Gap Chambers. The forward detector upgrade has excellent detection capability for neutral pions, photons, electrons, jets, and charged hadrons. A combination of soft and hard probes collected during 2023–25 will be used to probe the QGP's microstructure and will enable a unique forward physics program via the collection of high statistics Au+Au, p+Au, and pp data at $\sqrt{s_{NN}} = 200$ GeV. With the extended acceptance and the enhanced statistics, STAR will be positioned to perform correlation studies in heavy-ion collisions, *e.g.*, the pseudorapidity dependence of azimuthal correlations and the pseudorapidity dependence of global hyperon polarization. The STAR forward detector upgrade will also enable an extensive suite of measurements probing the quark–gluon structure of heavy nuclei. In this article, we will present the current status of the forward detector system and discuss its performance during data taking with cosmic-ray and pp collisions at $\sqrt{s_{NN}} = 510$ GeV during the 2022 RHIC run.

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1. Introduction

A prime motivation for the STAR forward upgrade is the exploration of cold QCD physics in the very high and low regions of Bjorken x [1]. The forward upgrade provides new detector capabilities at RHIC and STAR to explore the longitudinal structure of the initial state and the temperature-dependent transport properties of matter in relativistic heavy-ion collisions.

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The forward upgrade consists of four major new subsystems: a calorimeter system, which contains an electromagnetic calorimeter and hadronic calorimeter; a tracking system, formed from a silicon detector and a small-strip Thin Gap Chambers (sTGC) tracking detector. It has superior detection capabilities for neutral pions, photons, electrons, jets, and leading hadrons within the pseudorapidity range of $2.5 < \eta < 4$. A sketch drawing of the forward detectors can be found in Fig. 1.

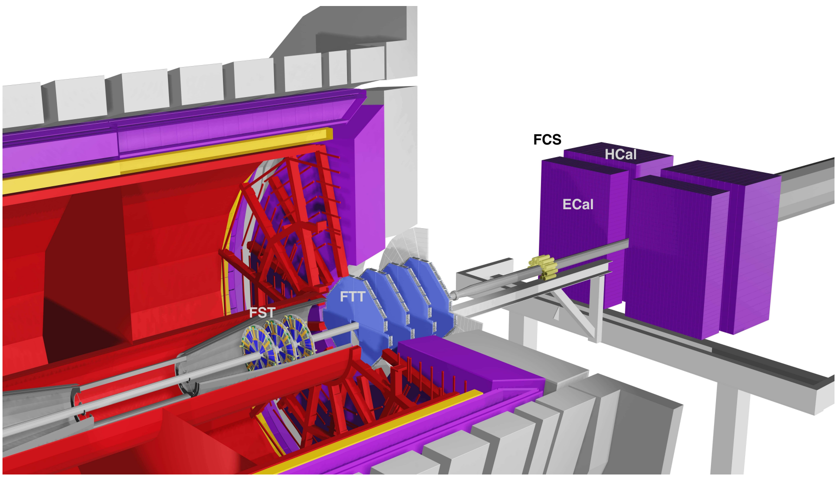

Fig. 1. 3D sketch drawing of the STAR forward upgrade detectors. From the inside out, the detectors presented are Forward Silicon Tracker (FST), Forward sTGC Tracker (FTT), and Forward Calorimeter System (FCS).

2. Forward Silicon Tracker

The Forward Silicon Tracker (FST) is built on the successful experience of STAR Intermediate Silicon Tracker (IST). Reusing the IST electronics, the DAQ, and the cooling system made the FST cost efficient. The FST consists of three identical disks located inside the STAR Time Projection Chamber (TPC) [2] cone on the west side of STAR. Each disk contains 12 identical modules. Each module has 3 single-sided double-metal silicon mini-strips sensors from Hamamatsu and is read out by 8 APV25-S1 chips [3]. The APV25-S1 chip has 128 channels each, with a charge-sensitive pre-amplifier, shaper, and 4 μs long pipeline. In total, 288 APV chips are needed to read out the 3 FST disks. The installation of the FST was completed in August 2021, and the detector was fully commissioned during the first few weeks of the Run 22. Fig. 2 (left) shows the FST installed in STAR and (right) the online display of p+p 510 GeV collisions recorded by the FST.

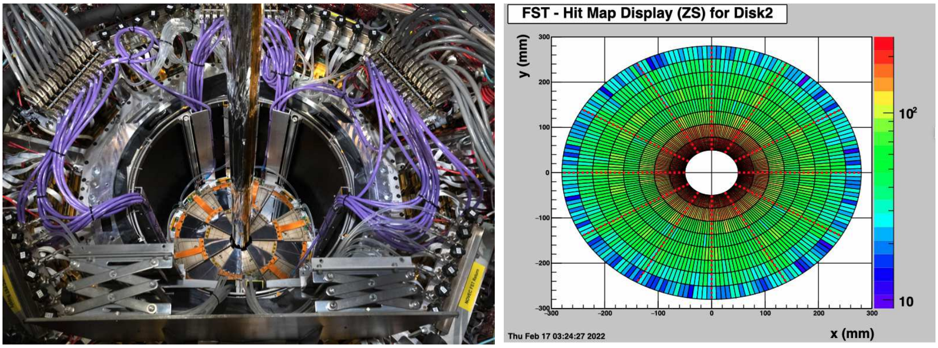

Fig. 2. Left: FST after installation; Right: event display for p+p 510 GeV collisions.

To find the optimal high voltage during operation, a voltage scan was performed during low-luminosity runs. The operational high voltage was set to 140V and 160V for inner and outer silicon sensors, respectively. The FST was commissioned with 3 time bins and a maximum DAQ rate of 4.5kHz.

The noise level of the FST silicon sensors is 10 to 20 ADC depending on the position of the silicon strip, and the average signal-to-noise ratio is about 25. Due to irradiation damage, the leakage current of the silicon sensors increased from 2 μA to around 10 μA (inner silicon sensor) and 15 μA (outer silicon sensor) after 4 months of p+p 510 GeV operation. This increase is consistent with expectations. There were 2 inner sectors and 2 outer sectors operating at a lower high voltage due to an abnormal bias current behavior. The FST readout chips are kept at room temperature by the cooling system, the same system was also used by IST, running 3M NOVEC. The leak rate of the whole cooling system increased from 0.6% per day to 0.9% per day at the end of Run 22. The coolant tank was refilled every 6 weeks by experts.

3. Forward sTGC Tracker

The Forward sTGC Tracker (FTT) has four identical planes, each with four identical pentagonal-shaped gas chambers [4]. These gas chambers are made of double-sided and diagonal strips that give x and y positions in each plane, and are located inside the pole-tip of the STAR magnet on the west side of the STAR.

The FTT chambers are operated with a quenching gas mixture of n-Pentane and CO_2 at a ratio of 45%:55% by volume at a typical high voltage of 2900 V. This gas mixture is flammable, and the n-Pentane is a liquid at normal atmospheric pressure and temperature. The maximum pressure tolerance for the sTGC chambers is about 4 mBar above atmospheric pressure and the gas flow rate is extremely low, about 50 cc/min per chamber. An independent binary gas analyzer was added during Run 22 to ensure that the gas mixture was stable. Since the gas mixture is flammable and liquefaction is possible inside the gas tubing, an independent redundant interlock system was designed and developed following industry standards. This system places the gas system in a safe state during any unforeseen situation such as a flammable gas leak, fire, pentane liquefaction, or if overpressure occurs inside the chambers.

The FTT uses the ATLAS VMM ASICs in the front-end electronics [5]. The FEE cards were directly mounted on the edge of the FTT modules. This location is subjected to radiation and the magnetic field, but the FEE cards performed exceptionally well during operation. To cool the FTT FEEs, 3D printed air ducts were integrated into the FTT assembly, where the air ducts direct cooled air onto each of 96 FEE cards in the FTT to ensure the cooling of the FEEs. The FTT was fully installed before the start of Run 22, and the detector was fully commissioned during the first few weeks of the run. Figure 3 (left) shows the FTT installed in STAR and (right) the event display of p+p 510 GeV collisions recorded by FTT.

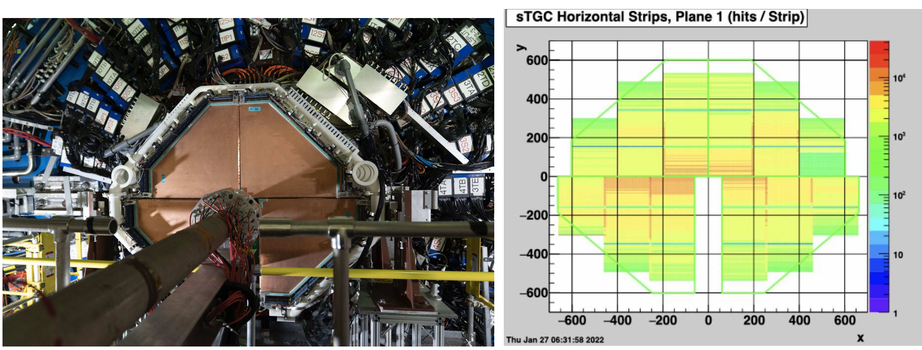

Fig. 3. Left: FTT after installation; Right: event display for p+p 510 GeV collisions.

The operating point of the high voltage was scanned for optimum efficiency. The gas chambers were stable at the desired operational high voltage and at the high luminosity; also the leakage current is well within the operational limits. At the chosen high voltage of 2900 V with a VMM chip gain of 1 mV/pC, the FTT exceeded the designed hit efficiency of 97%. Four chambers were lost during the run and the reason(s) for losing the chambers are still under investigation.

4. Forward Calorimeter System

The Forward Calorimeter System (FCS) consists of an Electromagnetic Calorimeter (ECal) with 1486 towers, and a Hadronic Calorimeter (HCal) with 520 towers [6]. The ECal, which was installed in 2019, and the HCal, which was installed in 2020, sit on the west platform at STAR. All SiPM sensors, front-end electronics boards, and readout and triggering boards, called DEP, were fully installed, commissioned, and calibrated during Run 21. Signal splitter boards for the west Event Plane Detector (EPD) were installed before Run 22 to allow using the west EPD used as pre-shower detector in the electron triggers. The FPGA code for the FCS triggers was developed in fall 2021, and a total of 29 triggers, including triggers for di-electron (J/Ψ and Drell–Yan), jets, hadrons, and photons were commissioned and verified within a few days of RHIC starting to deliver stable p+p collisions, and then used for data taking throughout Run 22 successfully. Figure 4 (top left) shows the FCS installed in STAR and (bottom left) the event display during the p+p 510 GeV collisions recorded by the FCS.

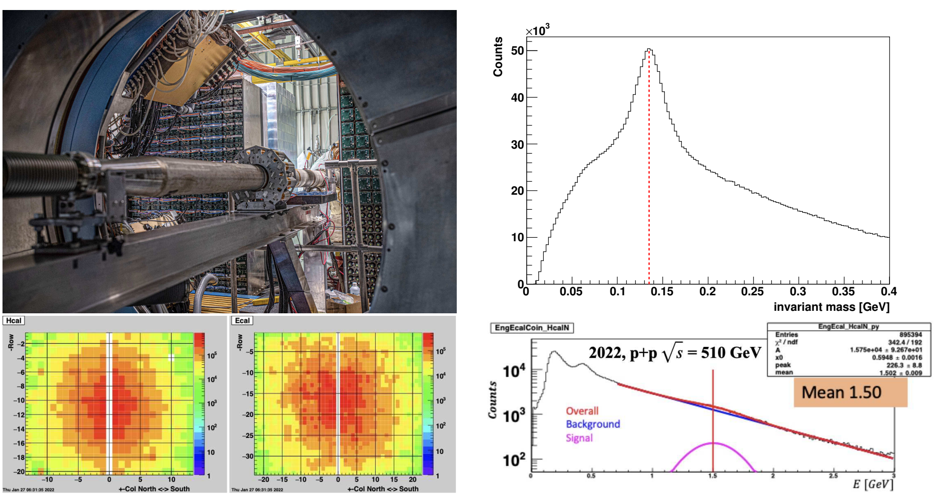

Fig. 4. Top left: FCS installed in STAR; Top right: Invariant mass distribution and π^0 peak reconstructed with ECal from p+p 510 GeV collision; Bottom left: event display for p+p 510 GeV collisions; Bottom right: MIP peak in HCal from $< 1\%$ of charged hadrons that did not start hadronic shower in HCal from p+p 510 GeV collisions.

The calibration of the ECal was accomplished by using π^0 reconstruction, Fig. 4 (top right). The HCal calibration was done by using the MIP peak from $< 1\%$ of the hadrons from p+p collisions, which did not start to shower in the HCal, together with cosmic muon signals if the HCal modules have been oriented vertically outside STAR, Fig. 4 (bottom right).

FCS operations during Run 22 were successful and smooth. All 1486 channels of the ECal worked flawlessly, and the HCal had only a couple of dead channels. Radiation damage to the SiPM sensors due to the beam was within expectations. There was an unexpected loss of signal amplitudes of $\sim 20\%$ per week in the ECal near the beam, which turned out to be radiation damage in one component of the front-end electronics boards.

5. Summary

All four new subsystems of the forward upgrade were fully installed, instrumented, and commissioned before/during the 2022 RHIC running period. Note that the entire construction, installation, and commissioning of the four systems were completed during the pandemic. Enormous efforts were made to keep the forward upgrades on schedule. During Run 22, despite all the difficulties of the collider operation, the forward upgrades performed exceptionally well and took data smoothly throughout the run.

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