The Construction of the sPHENIX Detector and Status of Its Commissioning

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Abstract. sPHENIX is the first new major detector at RHIC in over twenty years. It is designed for pioneering studies of the Quark Gluon Plasma and Cold QCD phenomena using high-p_T jet and heavy flavor probes with a broad kinematic reach and a capability to take large statistics sets of A+A, p+p and p+A data. sPHENIX construction was completed in April 2023. It was commissioned and took first Au+Au data in the RHIC 2023 Run. This paper describes the details of the detector design, challenges of sPHENIX construction, progress on the commissioning and first data from the RHIC 2023 run.

1 Introduction

sPHENIX is a large-acceptance, high-rate detector optimized to measure jet and heavy quark physics in Heavy Ion (HI) collisions by incorporating Hadronic and Electromagnetic Calorimetry (HCal and EMCal), a Time Projection Chamber (TPC), Silicon Pixel and Strip detectors, a Micromegas detector plus trigger detectors with a high rate Data Acquisition (DAQ)/Trigger and a 1.4 T solenoidal magnetic field. It is the first new major detector at the Brookhaven National Laboratory (BNL) Relativistic Heavy Ion Collider (RHIC) in over twenty years, and is a complete tear down and rebuild of the original PHENIX detector. sPHENIX utilizes a number of detector and infrastructure components of the PHENIX experiment and its associated support facilities, with the addition of eight new detector subsystems, a super-conducting central solenoid repurposed from the BaBar experiment, a high rate/high bandwidth DAQ/Trigger system and a full modernization of the experimental complex.

The concept for the sPHENIX detector began with the generation of the 2010 PHENIX Decadal plan [1]. The idea was to design and build a new, state of the art experiment at RHIC that could provide physics results which focused on jets and heavy flavor that complemented and overlapped with the HI physics results being generated by the experiments at the CERN Large Hadron Collider (LHC). The physics objectives described in the early sPHENIX proposal were identified in the 2015 US Nuclear Science Advisory Committee's (NSAC) Long Range Plan [2] as must do physics. The US Department of Energy identified the physics program described in the sPHENIX proposal as a US Nuclear Physics "mission need" and granted sPHENIX approval to begin conceptual design in the Fall of 2016. sPHENIX was approved to begin preliminary design, and make long lead procurements in the Fall of 2018, followed by an authorization to start construction in the Fall of 2019. The installation of the sPHENIX detector was completed in the Spring of 2023, including the completion of

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all ancillary support systems. sPHENIX was approved by BNL and DOE to begin routine operations in May 2023. The sPHENIX commissioning run with Au+Au collisions began within days of the DOE/BNL approval to operate. The importance of the sPHENIX physics program was once more emphasized in the Fall of 2023 with the release of the 2023 NSAC Long Range Plan [3] which stated, "To successfully conclude the RHIC science mission, it is essential to complete the sPHENIX science program as highlighted in the 2015 Long Range Plan."

During the period 2019-2023, which covered sPHENIX construction, installation and commissioning activities, a number of disruptive events took place. The COVID-19 pandemic shutdown much of the world, resulting in the total closure of BNL and numerous sPHENIX collaborating institutions followed by a long period of limited on-site activities. After the initial two to three month closure of many sPHENIX institutions in mid-2020, many institutions, including BNL only allowed on-site workforces to reach 25-50% of their normal levels for the following two years. A related impact, the global supply chain crisis, created multiple month delays especially in electronics components and equipment deliveries. International conflict created a huge shortage in neon gas, which was to be the main gas component for the sPHENIX TPC. An alternative gas needed to be identified that would be able to meet the TPC performance requirement. The sPHENIX beam pipe was lost while being transported between a vendor and a subcontracting machine shop due to a warehouse fire in the depot of a large transport company. Finally the sPHENIX commissioning run in 2023 was terminated many weeks early due to significant damage to a cryogenic feed-through in a RHIC accelerator cryo valve box. These combined events created significant schedule, budget and technical challenges for sPHENIX, though through extraordinary effort, sPHENIX was able to be completed on time, and on budget.

2 The Physics Program

sPHENIX will study Quantum Chromodynamics (QCD) phenomena discovered at RHIC with unprecedented precision. The studies of the microscopic structure of the Quark Gluon Plasma (QGP) will be performed using high statistic Au+Au and p+p data sets. The physics program will focus on hard probes including jet correlations and substructure, open heavy flavor production and correlations, quarkonia (Υ(1S, 2S, 3S)) suppression, as well as γ-jet and b-jet measurements. The detector's large solid angle coverage and high DAQ rate will also enable measurements of the bulk properties of hot nuclear matter with unparalleled statistics. sPHENIX results will complement those taken by the LHC experiments during the LHC Run-3. The sPHENIX measurements will have a sufficient kinematic reach to not only have a significant p_T overlap with the LHC data but to also access new, unexplored kinematic regimes where QGP effects are expected to be large. This will allow direct comparisons between QGP's formed at RHIC and the LHC with different initial conditions and expansion dynamics [4].

In addition to the hot QCD studies, sPHENIX has plans to take a transversely polarized data set to make many cold QCD measurements such as parton transverse-momentum dependent (TMD) effects. Single spin asymmetries will be measured using hadrons, jets, direct γ's and heavy flavor. Finally, once sPHENIX obtains sufficiently large Au+Au and p+p data sets, there would be significant interest in taking a p+Au data set with sPHENIX to study collective effects in jet, heavy flavor and hadron production [5].

3 The Detector

The sPHENIX detector is a large colliding-beam detector instrumented with calorimetry, tracking, and vertex detectors that cover 2π in azimuth and $-1.1 \leq \eta \leq 1.1$ in pseudorapidity [6]. It is the first RHIC detector with complete EMCal and HCal coverage at mid-rapidity. The sPHENIX tracking system combines a precision, compact TPC, a Micromegas-based Outer Tracker (TPOT), Silicon Strip Intermediate Tracker (INTT) and Monolithic Active Pixel Silicon Vertex detector (MVTX) with a 1.4 T central solenoid magnet to produce high precision momentum, vertexing and DCA measurements at mid-rapidity. Forward/Trigger detectors include a pair of fast-timing, quartz-crystal phototube arrays for Minimum Bias triggering (MBD), a pair of scintillator disks finely segmented in ϕ for Event Plane detection (sEPD), and a pair of Zero Degree Calorimeters (ZDC). The DAQ/Trigger system can record minimum bias A+A collisions, triggered photon, jet and Upsilon events in p+p and p+A, at 15 kHz with greater than 90% livetime. Figure 1 shows a schematic of the sPHENIX detector drawn as a vertical slice through the detector, and a photo of the completed detector.

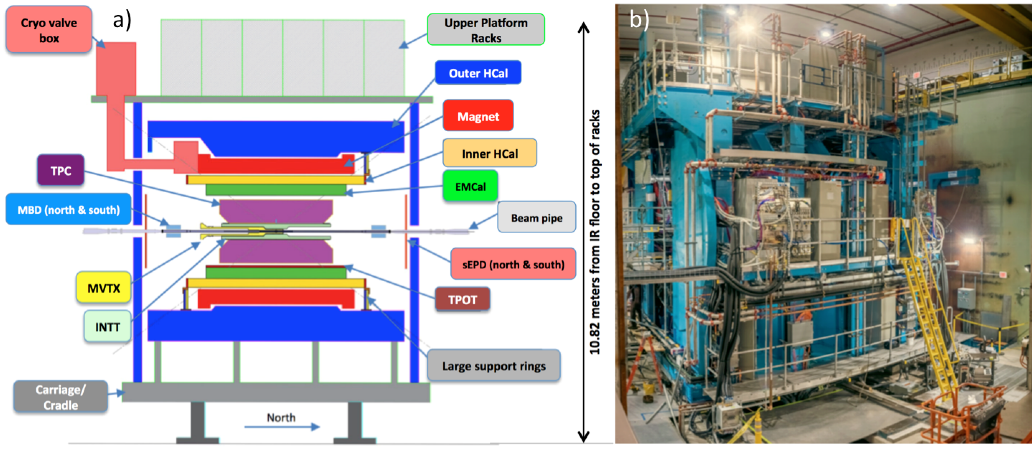

Figure 1. a) Schematic of vertical slice through sPHENIX. b) Photo of the sPHENIX Detector.

The hadronic calorimeter is built in two radial rings. The Outer HCal (OHCal) is located outside the cryostat of the sPHENIX central magnet. It is composed of interleaved steel plates and scintillating tiles oriented in a tilted-plate geometry. The OHCal doubles as the barrel portion of the magnet flux return. The Inner HCal (IHCal) is located just inside the inner radius of the central magnet cryostat. It is composed of interleaved aluminum plates and scintillating tiles oriented in a tilted-plate geometry. The IHCal also serves as the mechanical support for the EMCal. The scintillating tiles for both the OHCal and IHCal are different shapes depending on their position along the z-direction (axial) so that they are projective to the vertex point at the center of the collision diamond. The EMCal is built from calorimeter blocks in a Spaghetti Calorimeter (SPACAL) geometry. Each EMCal block contains 2500 longitudinally oriented-scintillating fibers encased in a tungsten power-epoxy composite. The blocks are positioned to be projective to the collision vertex in both η and ϕ. The OHCal, IHCal and EMCal are all readout with silicon photomultipliers (SiPMs). The interaction depth of the HCal+EMCal+Magnet cryostat system is 4.7 λ_I. The EMCal is 18 X_o. The average electromagnetic energy resolution $=13.3\%/\sqrt{E} \oplus 3.5\%$ [7]. The average jet energy resolution for the full calorimeter system $< 150\%/\sqrt{E}$.

The TPOT consists of eight identical Micromegas modules, two detectors/module, grouped in three sectors. The three sectors are mounted to the EMCal at the bottom of the TPC. Each TPOT module measures a space point of charged tracks passing through sPHENIX. Its function is to provide tracking distortion correction-information for the TPC. The TPC is a compact cylindrical tracking detector, 2.1 m in length with an outer radius of 80 cm and a total gas volume of ~4 m^3. The TPC operates with an Ar-CF4 60/40 gas mixture. The TPC field cages are constructed from kapton-carbon fiber. The device is readout on each end with quad-GEM modules each containing four layers of GEM foils plus a cathode pad plane. There are 36 quad-GEM modules on each end of the TPC. The TPC makes high precision measurements (space point resolution $< 200\ \mu$m) of the momenta of all charged tracks passing through sPHENIX at mid-rapidity. The INTT is a two-layer silicon-strip detector for tracking and vertex determination. It is radially located between the TPC and MVTX. The INTT interpolates tracks between the extremely fine pitch of the MVTX and the coarser spatial resolution of the TPC and provides single-beam-crossing timing resolution. The MVTX is a three-layer silicon pixel detector located just outside the sPHENIX beampipe [8]. The MVTX measures the collision vertex, the displaced vertex of charged tracks, and contributes to the overall tracking resolution of sPHENIX. The MVTX sensors are MAPS-based with a position resolution of 5 μm and a 2D-DCA resolution of 30 μm. It is a copy of the inner three layers of the ALICE Inner Tracking System (ITS).

The MBD is a pair of fast photomultiplier arrays with quartz radiator windows located at forward rapidity in sPHENIX. It is the repurposed PHENIX Beam-Beam Counter with new electronics. The MBD system timing resolution is 50 ps. The sEPD is a pair of disks of scintillating tiles finely segmented in ϕ with readout into SiPMs located at forward pseudorapidity. Its role is high-resolution event plane determination. The ZDC is a pair of hadronic calorimeters located in the RHIC tunnel on either side of the sPHENIX Hall. It is interleaved layers of tungsten and PMMA optical fibers readout with phototubes. The ZDC measures forward neutrons for centrality triggering, and integrated luminosity.

4 Accomplishments During the 2023 Commissioning Run at RHIC

The primary goal of sPHENIX in the 2023 RHIC run was to commission the detector. Commissioning objectives included simultaneously reading out the full complement of detector subsystems, maintaining the consistent and smooth operation of every detector subsystem and ancillary support system, confirming the synchronization of event data among subsystems, checking basic energy measurements and tracking performance, establishing detector monitoring procedures, and measuring initial throughput and rate performance of the Data Acquisition system. Significant progress was made on all the commissioning objectives, however the early termination of the RHIC run prevented the completion of the full commissioning program. Examples of the progress made in sPHENIX commissioning can be seen in the following figures. Figure 2 shows comparisons of the tower energy from the IHCal and OHCal, as well as the π^o mass peak (ADC scale only) from the EMCal. Figure 3 shows the correlation between a) TPOT clusters and MBD charge, and b) sEPD energy and MBD charge. Figure 4 shows a) a cosmic ray event containing data from the MVTX, INTT, TPC and TPOT, and b) a comparison of vertex finding from the INTT and MBD. Figure 5 shows a) TPC tracks from a central Au+Au collision, and b) a dijet event seen in the EMCal, IHCal and OHCal.

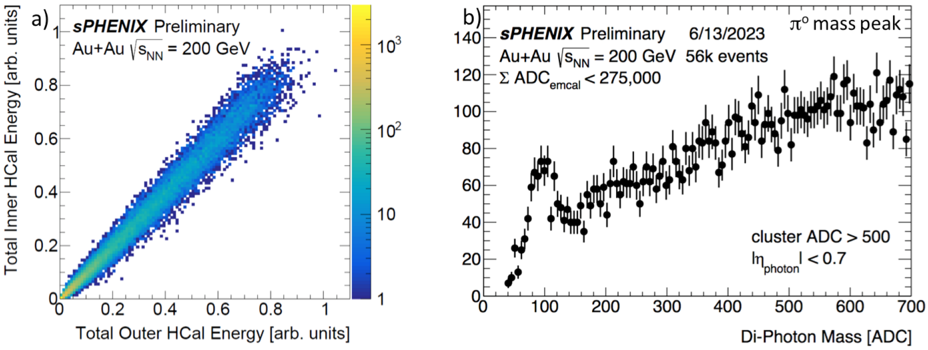

Figure 2. a) Correlation between the tower energy in the IHCal and OHCal from Au+Au events. b) Pair mass of energy clusters (ADC units) in the EMCal from Au+Au collisions showing a π^0 mass peak.

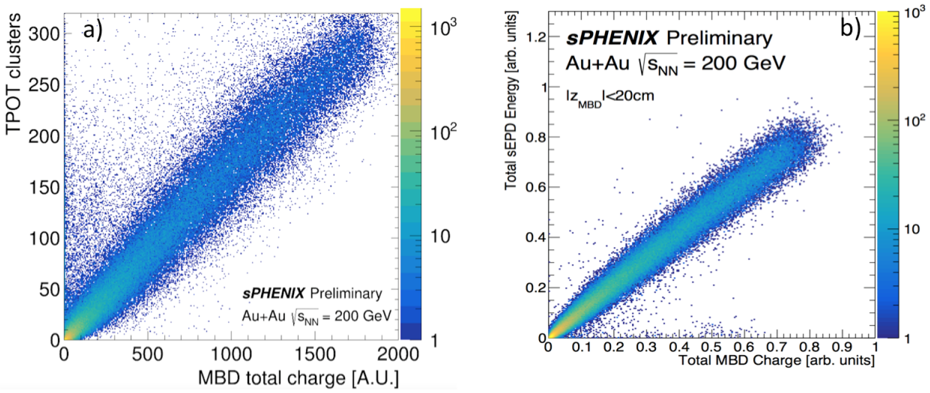

Figure 3. a) Correlations between the number of TPOT clusters and the MBD total charge on an event-by-event basis in Au+Au events. b) Correlations between sEPD total energy and MBD total charge on an event-by-event basis in Au+Au events.

5 Outlook and Summary

sPHENIX is fully installed and was operational in RHIC Run 2023. Numerous challenges were presented and successfully overcome during the detector construction and installation from 2019-2023. sPHENIX was completed on-time and on-budget. It will carry out a comprehensive jet and heavy flavor HI physics program, make measurements of the global and local properties of the nuclear medium created at RHIC, as well as conduct a cold QCD program. The detector performed very well in the 2023 commissioning run and the experiment is poised to commence physics data-taking in the RHIC Run 2024. sPHENIX is looking forward to a long p+p run in 2024 and a long Au+Au run in 2025.

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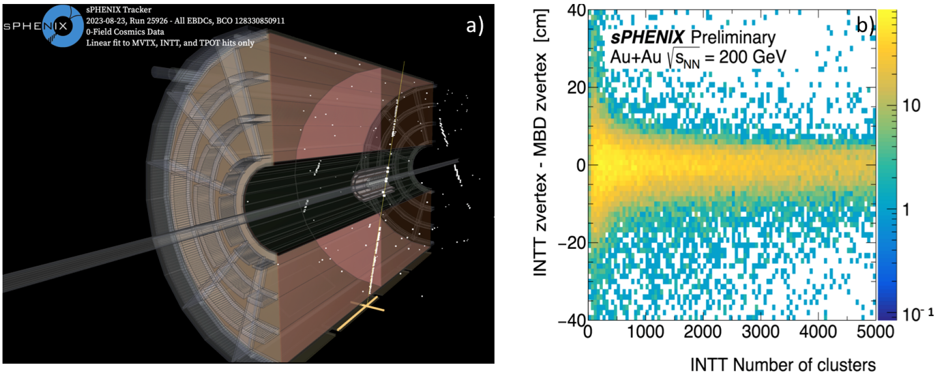

Figure 4. a) A cosmic ray event recorded by the TPC, INTT, MVTX and TPOT. b) The RHIC collision vertex difference measured by the INTT with tracklets and the MBD via timing difference vs. the number of INTT clusters.

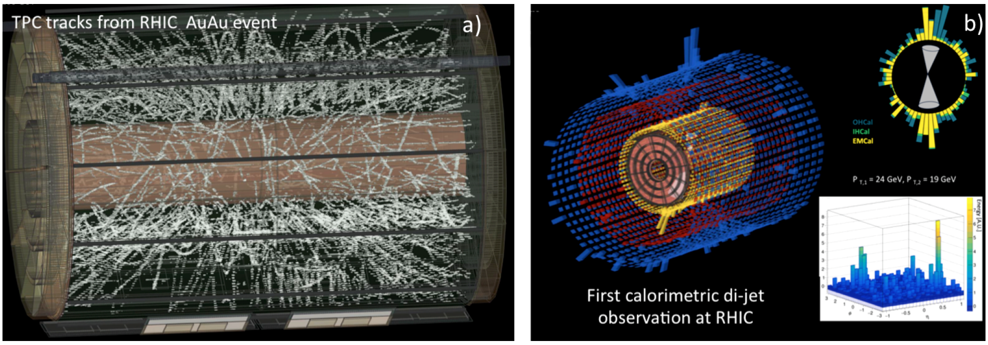

Figure 5. a) TPC tracks from a Au+Au event, B-field on. b) Dijet event from Au+Au collisions seen in the HCal and EMCal.

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