ARTICLE IN PRESS

Nuclear Inst. and Methods in Physics Research, A ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

The STAR MAPS-based PiXeL detector

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ARTICLE INFO

Keywords:
MAPS
Pixel
Vertex detector
HFT
STAR
RHIC

ABSTRACT

The PiXeL detector (PXL) for the Heavy Flavor Tracker (HFT) of the STAR experiment at RHIC is the first application of the state-of-the-art thin Monolithic Active Pixel Sensors (MAPS) technology in a collider environment. Custom built pixel sensors, their readout electronics and the detector mechanical structure are described in detail. Selected detector design aspects and production steps are presented. The detector operations during the three years of data taking (2014–2016) and the overall performance exceeding the design specifications are discussed in the conclusive sections of this paper.

1. Introduction

We describe the pixel detector system (PXL) for the STAR experiment at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory. The STAR PXL detector is the first large-scale application of the state-of-the-art thin Monolithic Active Pixel Sensors (MAPS) technology in a collider environment. PXL is a part of a 3-detector system called Heavy Flavor Tracker (HFT) that has been added to the pre-existing STAR apparatus just before the 2014 RHIC Run to significantly improve the impact parameter resolution of STAR tracking and to enable the direct topological reconstruction of hadronic decays of heavy flavor mesons and baryons in the heavy ion collision environment. After introducing the HFT physics motivations in this section, the paper describes the PXL detector design requirements in Section 2 and gives an overview of the HFT system in Section 3. The detector characteristics are discussed in detail in the following sections, focusing on the MAPS sensor (Section 4), electronics (Section 5), mechanics and cooling (Section 6) respectively. Section 7 describes the PXL detector production process and Section 8 summarizes the detector integration and operations during the three years of data taking (2014–2016). The detector performance measured in the 2014 Run data is finally shown in Section 9. Selected lessons learned from the PXL project are summarized in Section 10. The conclusions and an outlook on future particle physics applications of the MAPS technology are presented in Section 11.

1.1. Physics motivations

One of the main goals of the STAR experiment at RHIC is to study p + p, p + Au, d + Au, and Au + Au collisions at several energies up to $\sqrt{s_{NN}}$ = 200 GeV for A + A and up to 500 GeV for p + p collisions with the aim to reproduce and characterize the QCD phase transition between hadrons and partons [1]. Heavy quark measurements are a key component of the heavy ion program for the systematic characterization of the dense medium created in heavy ion collisions, the so-called Quark–Gluon Plasma (QGP). Due to their mass, heavy 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 heavy quarks (e.g. charm, *c*) an ideal probe for studying the initial conditions of the produced QGP. The main tracking detector used in the STAR experiment is a Time Projection Chamber (TPC), with $|\eta| \leq 1$ and full azimuthal coverage, operated inside a 0.5 T magnetic field. With its 1 mm pointing resolution, the TPC is not able to resolve the decay vertices of short-lived particles, like $D^0(c\bar{u})$ mesons ($c\tau \sim 120$ μm) and Λ_c(udc) baryons ($c\tau \sim 60$ μm), from the collision

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https://doi.org/10.1016/j.nima.2018.03.003
Received 27 September 2017; Received in revised form 10 January 2018; Accepted 2 March 2018
Available online xxxx
0168-9002/Published by Elsevier B.V.

Please cite this article in press as: G. Contin, et al., The STAR MAPS-based PiXeL detector, Nuclear Inst. and Methods in Physics Research, A (2018), https://doi.org/10.1016/j.nima.2018.03.003.

primary vertex. Introducing the HFT detector inside the TPC Inner Field Cage significantly improves the system track pointing resolution. The HFT and its 4 layers of silicon detectors with graded spatial resolution enable tracking inwards from the TPC and achieving a track pointing resolution of the order of 30 μm for 1 GeV/c or larger momentum particles at the vertex.

1.2. HFT system overview

The Heavy Flavor Tracker (HFT) in STAR consists of 4 concentric cylindrical silicon detector layers with three different sensor technologies [2]. The outermost layer at 22 cm radius from the beam line is called the Silicon Strip Detector (SSD) [3]; it is based on double-sided silicon strip sensors with 95 μm inter-strip pitch and 35 mrad relative P–N-side stereo angle inclination. The SSD silicon and front-end chips were part of an existing past STAR detector and have been equipped with new, faster readout electronics to match the increased readout speed (>1 kHz) of the upgraded STAR experiment. The SSD consists of 20 ladders, each with 16 sensors for a total ladder length of 106 cm. The total number of channels in the SSD is approximately $5\cdot10^5$. The detector is air-cooled, which allows for a low radiation length of approximately 1% X_0. Inside the SSD, the Intermediate Silicon Tracker (IST) layer is placed at a radius of 14 cm. It is based on single sided silicon pad sensors with a 600 μm × 6 mm pitch. The IST is composed of 24 ladders, each equipped with 6 silicon pad sensors and a readout chip, for a total sensitive ladder length of 50 cm. The total number of channels in the IST is just above $1.1\cdot10^5$. The IST is liquid cooled with aluminum cooling tubes integrated into the ladder structure, which results in a total material budget smaller than 1.5% radiation length. The two innermost layers at 8 and 2.8 cm radii constitute the PiXeL (PXL) detector, based on state-of-the-art CMOS Monolithic Active Pixel Sensors (MAPS). A total of 400 MAPS sensors are distributed over 40 ladders (10 at the inner PXL layer radius and 30 at the outer radius) and cover a surface area of 0.16 m^2 with 356 M square pixels. A more detailed description of the PXL detector is provided later in this paper. Equipped with this new micro-vertex detector, STAR is able to provide a distance of closest approach (DCA) pointing resolution of less than 50 μm for 750 MeV/c kaons, which enables the topological reconstruction of decay vertices of heavy flavor particles, like D^0 mesons ($c\tau \sim 120$ μm), in the high-multiplicity environment typically produced in Au–Au collisions at 200 GeV. This resolution is achieved by tracking inwards from the TPC, which provides a pointing resolution of approximately 1 mm, through the SSD and IST, with pointing resolutions of 250–300 μm, to the PXL detector, that can point at secondary vertices with the resolution of a few tens of micrometers.

2. PXL detector design requirements and choices

2.1. Detector requirements

The PXL detector has been designed in order to achieve the physics goals described in Section 1.1. The track pointing resolution is primarily determined by the two innermost measurements of the track position. This resolution is improved by placing the first detection layer as close to the beam line as possible, minimizing the material budget to reduce the multiple-scattering track distortion for low-momentum tracks, and selecting the sensor segmentation that maximizes the intrinsic single-layer spatial resolution of the reconstructed track points. Fine segmentation and a short integration time window are needed to minimize the event pile-up and keep the detector occupancy low. The PXL design is also constrained by the existing STAR detector layout and environment. The PXL is designed to match the TPC acceptance in η and φ, and the beam pipe radius (20 mm) provides a mechanical limit for the minimum radius of the innermost PXL layer. The detector has to survive the radiation level expected in STAR. On the basis of these considerations and of extensive simulations, the PXL Detector has been designed in order to meet the following requirements:

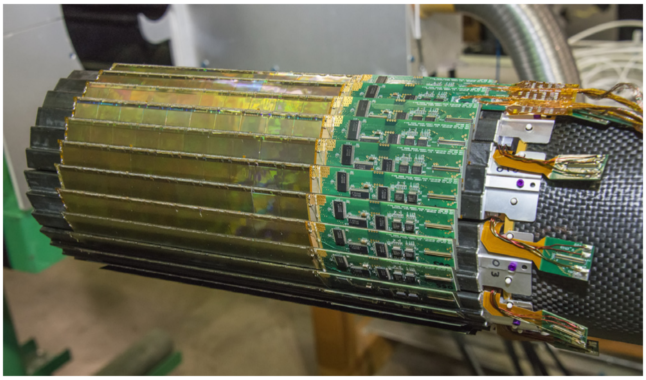

Fig. 1. The HFT PXL detector (*photography by Roy Kaltschmidt - Berkeley Lab*).

- $|\eta| \leq 1$ and full azimuthal coverage
- DCA pointing resolution $\leq$ 60 μm required for 750 MeV/c kaons
  - Two or more layers with a separation of >5 cm
  - Pixel size of ≤30 μm
  - Radiation length ≤0.5% per layer, including support structure, with 0.37% per layer as goal
- Integration time of <200 μs
- Sensor efficiency ≥99% with accidental rate $\leq 10^{-5}$
- Radiation tolerance up to 90 kRad/year and $2\cdot10^{11}$ to 10^{12} 1 MeV $\text{n}_{eq}/\text{cm}^2$.

2.2. Technology choices

The technology and architecture have been chosen in order to meet these requirements and are reflected in our detector design. These design choices include:

- MAPS technology, providing low power dissipation and short integration time
- thinned sensors and low-mass cable with low radiation length
- air-cooling, to minimize the material budget
- support mechanics designed for quick detector installation or replacement
- pixel positions fully mapped.

The implementation of these choices in the PXL design is described in the next section.

3. System overview

3.1. Global layout

The PXL detector, shown in Fig. 1, consists of two cylindrical layers of CMOS Monolithic Active Pixel Sensors (MAPS) located at radii of 2.8 and 8 cm. The total of 400 MAPS sensors covers the surface area of 0.16 m^2 with 356M pixels and pixel pitch of 20.7 μm.

Mechanically, the PXL detector is subdivided into two detector-halves attached on one end to a set of unique cantilevered mechanics, which allows for the fast insertion and retraction of the detector while preserving the pixel positional stability at the level of 20 μm, as described in detail in Section 6. The same mechanical support serves as air delivery and extraction ducts for the detector air cooling system. The PXL detector has been designed as a highly parallel system [4], where each half consists of 5 sectors mounted to a detector half shell using precision machined mounts. A sector represents the basic unit in terms of powering and readout. Each sector consists of a trapezoidal, thin (250 μm) carbon fiber sector tube supporting four 10-sensor ladders,

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