PROCEEDINGS OF SCIENCE

MVTX: A MAPS Vertex Tracker for sPHENIX at RHIC

Ho San Ko[a,*]

[a] *Lawrence Berkeley National Laboratory, 1 Cyclotron Rd, Berkeley, U.S.A.*

E-mail: h-s.ko@lbl.gov

We assembled a MAPS (Monolithic Active Pixel Sensor) vertex tracker, MVTX, with 0.19 m^2 total silicon coverage and a pixel pitch of 27 µm. 48 staves, each comprised of 9 sensors thinned down to 50 µm thickness, are supported by carbon composite structures and organized into three concentric layers immediately surrounding the beampipe inside of the sPHENIX at RHIC of BNL. Reaching the designed resolution of MVTX is critical to the delivery of sPHENIX physics including heavy flavor studies. We present the construction and $\sim$ 20 µm-level mechanical alignment in the carbon composite support structure.

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*Speaker

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1. MVTX technical requirements and physics goals

The MAPS (Monolithic Active Pixel Sensor) vertex tracker, MVTX, is the innermost tracker of the super Pioneering High Energy Nuclear Interaction eXperiment (sPHENIX) [1]. The sPHENIX is located in Relativistic Heavy Ion Collider at Brookhaven National Laboratory in New York. One of the main physics goals of the sPHENIX is to probe the inner workings of strongly interacting quark-gluon plasma by resolving its properties at a femtometer length scale using jets and heavy-flavor observables. The main function of the MVTX is for heavy flavor hadron identification and reconstruction. The primary technical requirements of the MVTX are listed below.

1. Short integration time ($\leq 20\,\mu$s) window to minimize the event pile-up
2. Pixelation ($29.24 \times 26.88\,\mu m^2$) for good spatial resolution and low occupancy
3. Low material budget ($\leq 0.5\%\ X_0$) to minimize multiple-scattering track distortion
4. First detection layer as close (< 2 mm) as possible to the beampipe
5. Three layers for improved tracking and redundancy
6. Compact: all three layers within a radius of ~ 42 mm

2. MVTX detector composition

The MVTX consists of 48 staves. A stave is the basic detector readout unit that consists of 9 ALICE Pixel DEtector (ALPIDE) chips [2] supported by a Flexible Printed Circuit (FPC) substrate on top of a carbon-composite space frame. A schematic view of the stave is shown on the left side of Fig. 1. The ALPIDE chip is a CMOS MAPS sensor designed for ALICE ITS2 [3]. It streams data at 1.2 Gbps serially. The silicon is thinned down to $50\,\mu$m to minimize the material budget. Each chip contains 512×1024 pixels in a $15\,\text{mm} \times 30\,\text{mm}$ active area.

The 48 staves form three concentric layers surrounding the sPHENIX beampipe. The CAD model of half of the MVTX is presented on the right side of Fig. 1. The size of each layer and the distance from the beampipe are specified in Tab. 1.

	Layer 0	Layer 1	Layer 2
Radial position (min.) [mm]	22.4	30.1	37.8
Radial position (max.) [mm]	26.7	34.6	42.1
Active area length [mm]	271	271	271
Active area size [cm^2]	421	562	702
Number of pixel chips	108	144	180
Number of staves	12	16	20

Table 1: Physical properties of each layer of the MVTX.

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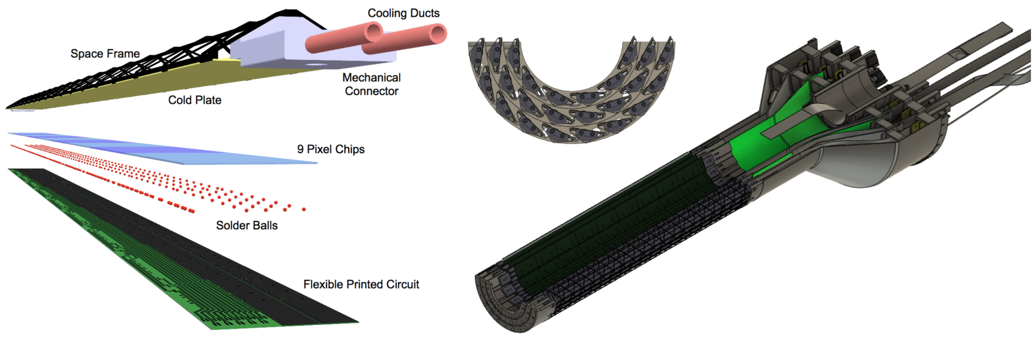

Figure 1: Left: 3D model of an MVTX stave. In the final design, the solder balls are replaced by wire bonds. Right: CAD model of half of the MVTX. The inset on the top-left shows the cross-section viewed along the main axis.

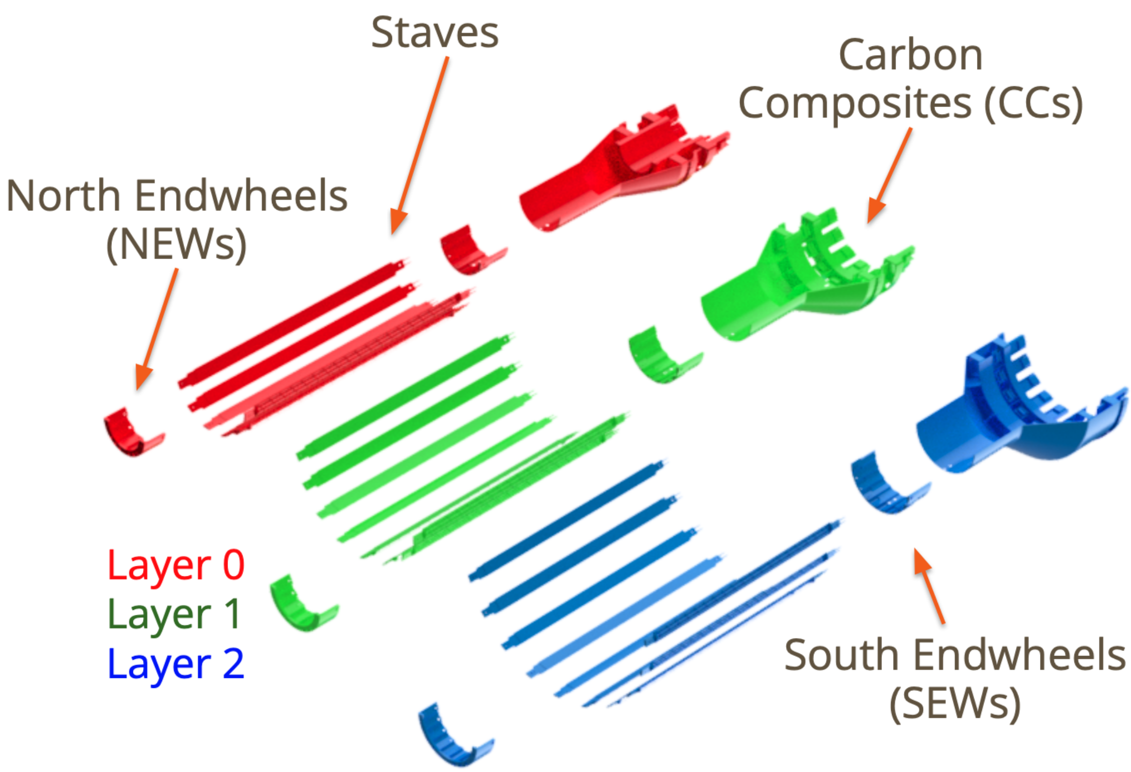

Figure 2: MVTX components. Each layer is shown in a different color.

3. MVTX mechanical assembly

Each of the three layers of the MVTX contains four main components: the North Endwheel (NEW), staves, the South Endwheel (SEW), and a Carbon Composite structure (CC). As seen in Fig. 2, the staves are installed between the NEW and the SEW of each layer. To ensure optimal detector performance, the NEW and the SEW of each layer must be aligned within a tolerance of 20 μm.

Previous silicon trackers, such as the ALICE ITS2 and the STAR HFT [4], have utilized fiducial markers, such as reference balls, which are measurable during the assembly process. These markers allow for the immediate determination of the complete pose (position and orientation) of the detector parts. However, due to space constraints, the MVTX does not have dedicated fiducial markers or surface features that can be used to quickly determine its pose. As a result, the MVTX requires the measurement of multiple points on multiple faces of each part using a Coordinate Measuring Machine (CMM) and subsequent fitting to the corresponding Computer-Aided Design (CAD) model.

3.1 CMM survey for positioning

The pose of a part, such as an endwheel, is determined by performing a weighted nonlinear least-square fitting procedure [5] based on the data obtained from a CMM and the corresponding CAD model of the MVTX. The CMM has a precision of approximately 2 µm and the size of the probe is precisely known (2 mm in diameter). First, we measure multiple points on each face of the part and record the center coordinate of the CMM probe when it contacts a face. Where the CMM probe has touched the part of the piece is unknown at this point. Figure 3 shows an example of the CMM measuring procedure of the SEW of Layer 2 and a schematic drawing of the CMM probe touching the face of the endwheel.

From the CAD model (as depicted in Fig. 1 on the right), we extract information regarding the faces of the part, which consist of planes, cylinders, and spheres. This information is used to construct a 3D rigid object. With the CMM and model data, we perform the fitting. The set of CMM points is translated and rotated to find the closest fit to the multiple faces of the model simultaneously. The best-fit parameters of translation and rotation determine the measured pose of the part. Additionally, through the calculation of fit residuals, we determine the geometrical differences between the actual part and the CAD model.

A graphical representation of the residuals for one of the SEWs in Layer 2 can be found in Fig. 4. The numbered faces and their respective residuals are indicated in the figure. The overall shape of the residuals, in the form of an inverted "U", reveals that the SEW deviates from the CAD model by approximately 150 µm as a result of outward springing. This springing is pronounced in the SEWs, but remains negligible in the NEWs due to differences in structural rigidity. The numbered faces serve as the mounting surfaces for the staves. Therefore, the poses of these faces determine the poses of the staves and sensors, which are the most critical for performing the physics measurements.

3.2 Alignment

From the CMM measurements and fitting, we have determined the 6D pose (3D in translation and 3D in rotation) of each part (NEW and SEW) in the detector with a precision of 20 µm in translation and 20 µm / 50 cm in rotation. We then align the NEWs to the SEWs. The carbon composites (CCs) are epoxy bonded to the SEWs, and their poses are determined by the SEWs, hence the CCs are not aligned independently but rather fall into place naturally.

Our analysis of the CMM measurements and model fitting revealed that the CCs are springing inward compared to the model. However, the process of epoxy bonding the SEW and CC reduced the large outward springing of the SEW ($\sim$ 150 µm) to an inward springing of about 50 µm. This

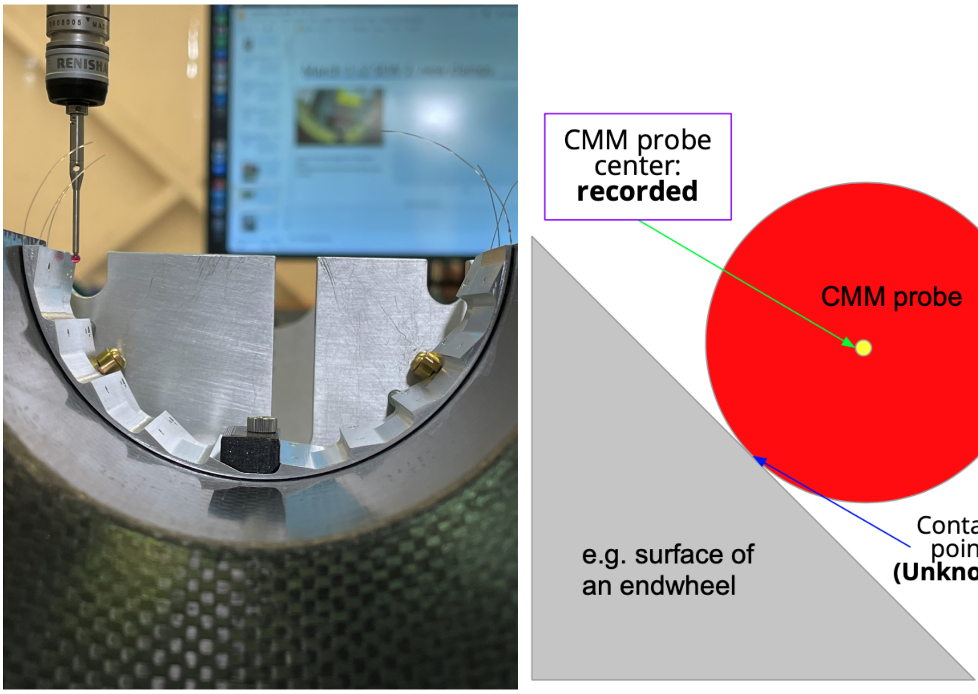

Figure 3: Left: CMM probing faces of the endwheel. Right: schematic of the CMM probe recording its position when it touches a face.

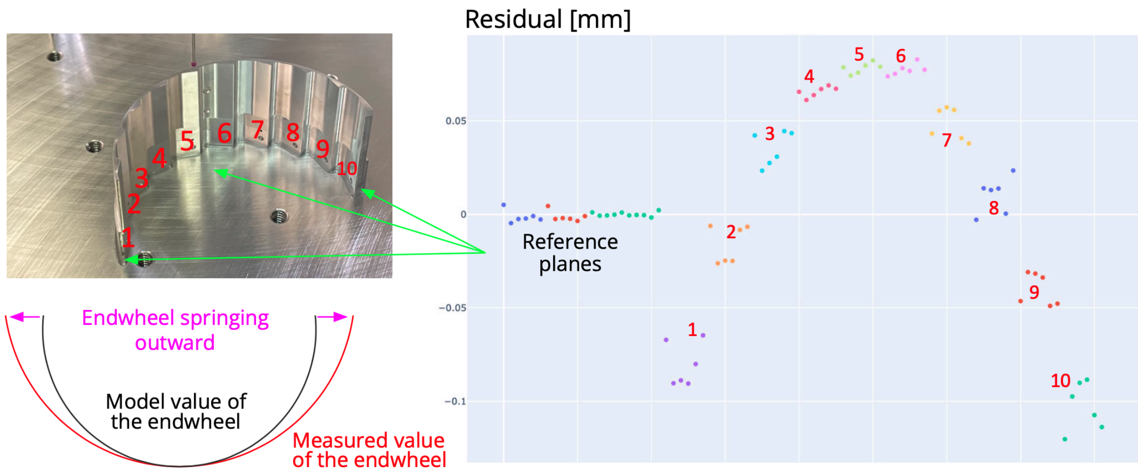

Figure 4: Residuals of one of the SEWs of Layer 2. Green arrows indicate measured faces used as references for a faster global pose determination. Numbers 1 to 10 show the measured faces and their corresponding CMM probe points residuals compared to the model.

inward springing does not compromise the hermeticity of the detector, which is of paramount importance for the design and assembly. Nevertheless, it does cause the staves to bend, requiring retroactive alignment of the pixels by software.

To attain 20 µm alignment accuracy between the NEW and the SEW, which are separated by a distance of ∼ 30 cm, we secure the SEW. We then utilize CMM measurements to determine the pose of the SEW and align the NEW relative to the SEW through the use of kinematic mounts. These

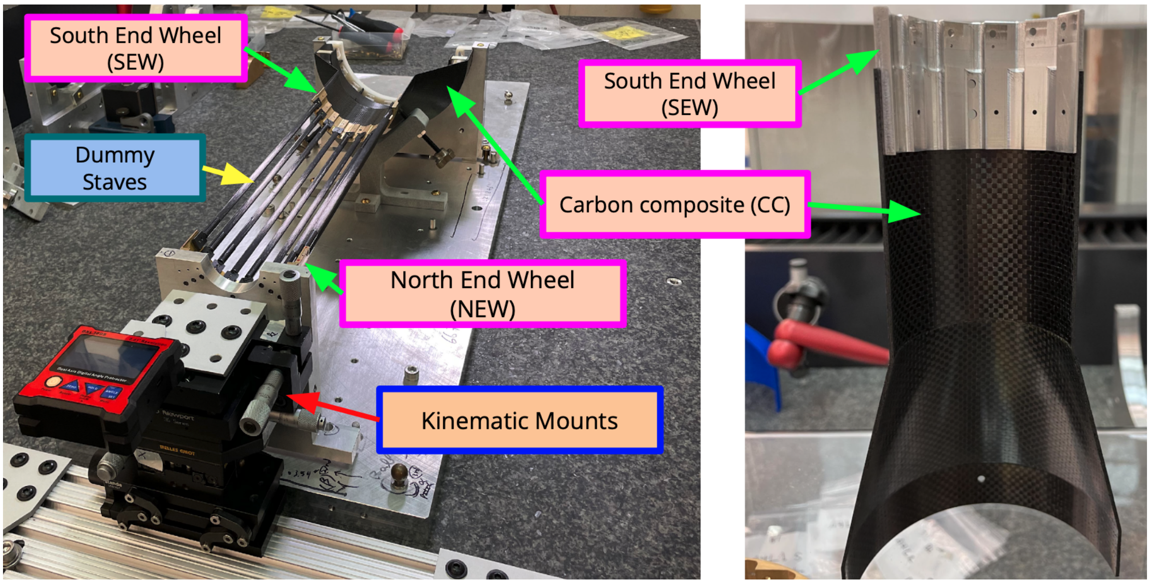

Figure 5: Left: Layer 2 on the assembly jig, aligned. Right: SEW and CC of Layer 1.

commercially available mounts allow us to precisely control each of the six degrees of freedom within a few microns. Once the pose of the NEW is fixed, we proceed with the installation of the staves. As depicted in the left side of Fig. 5, one of the Layer 2 components is shown after successful alignment. To ensure the stability of the alignment, we employ the use of dummy staves to fix the pose between the NEW and SEW during the installation of the actual staves. By combining CMM measurements and model fitting to determine the part poses and utilizing kinematic mounts for alignment, we can efficiently assemble a single half-layer within a few hours and a full three-layer half-MVTX detector within a week.

4. Summary

The MVTX is the innermost vertex tracker of sPHENIX, with a total silicon coverage of $0.19\,\mathrm{m}^2$. It consists of 48 staves, each made up of 9 ALPIDE chips, arranged in 3 concentric layers around the beampipe. The precise alignment of the MVTX is essential for the accurate reconstruction of heavy flavor tracks.

As the MVTX had limited space for reference points, we relied on global alignment using a CMM. The CMM measurements revealed that the SEWs were springing outward, which was reduced through epoxy bonding with the CC. However, the alignment of each pixel in the MVTX is still necessary, which would be accomplished through software alignment. Kinematic mounts were used to control the six degrees of freedom, with a resolution of a few microns, enabling us to achieve an alignment accuracy of $20\,\mu\mathrm{m}$ over $\sim 50\,\mathrm{cm}$. With this assembly method and setup, we successfully assembled the entire MVTX detector in a few weeks.

References

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