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STAR PIXEL detector mechanical design

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ABSTRACT: A high resolution pixel detector is being designed for the STAR [1] experiment at RHIC. This device will use MAPS as the detector element and will have a pointing accuracy of ~ 25 microns. We will be reporting on the mechanical design required to support this resolution. The radiation length of the first layer ($\sim 0.3\%$ X_0) and its distance from the interaction point (2.5 cm) determines the resolution. The design makes use of air cooling and thin carbon composite structures to limit the radiation length. The mechanics are being developed to achieve spatial calibrations and stability to 20 microns and to permit rapid detector replacement in event of radiation damage or other potential failures from operation near the beam.

KEYWORDS: Particle tracking detectors; Instrumentation and methods for heavy-ion reactions and fission studies

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1 Introduction

An inner PIXEL detector is being designed and prototyped for the STAR experiment at RHIC. This is part of the STAR [1] Heavy Flavor Tracker (HFT) upgrade project. A main function of this detector is improved detection of D mesons through topological reconstruction within the high track environment of Au on Au collisions [2].

The mechanical design has been driven by the following design goals:

- Minimize multiple coulomb scattering, particularly at the inner most layer
- Locate the inner layer as close to the interaction region as possible
- Allow rapid detector replacement
- Provide complete spatial mapping of the pixels from the beginning

The first two goals, multiple coulomb scattering and minimum radius, set the limit on pointing accuracy to the vertex. This defines the efficiency of D and B mesons detection.

The third goal, rapid detector replacement, is motivated by recognition of difficulties encountered in previous experiments with unexpected detector failures. This third goal is also motivated by the need to replace detectors that are radiation damaged from operating so close to the beam. The fourth goal, complete spatial mapping, is important to achieve physics results in a timely fashion. The plan is to know at installation where the pixels are located with respect to each other to within 20 microns and to maintain the positions throughout the operation.

The PIXEL detector will be made of Monolithic Active Pixel Sensors based on standard CMOS silicon [3]. The silicon will be thinned to 50 microns and air cooling will be used to minimize multiple coulomb scattering.

Table 1. Some features of the HFT PIXEL design.

Pointing resolution	$(13 \oplus 19\,\mathrm{GeV/p{\cdot}c})\,\mu$m
Layers	Layer 1 at 2.5 cm radius Layer 2 at 8 cm radius
Pixel size	$18.4\,\mu$m $\times$ $18.4\,\mu$m
Hit resolution	$10\,\mu$m rms
Position stability	$6\,\mu$m ($20\,\mu$m envelope)
Radiation thickness per layer	$X/X_0 = 0.31\%$
Number of pixels	436 M
Integration time (affects pileup)	0.2 ms
Radiation tolerance	300 kRad

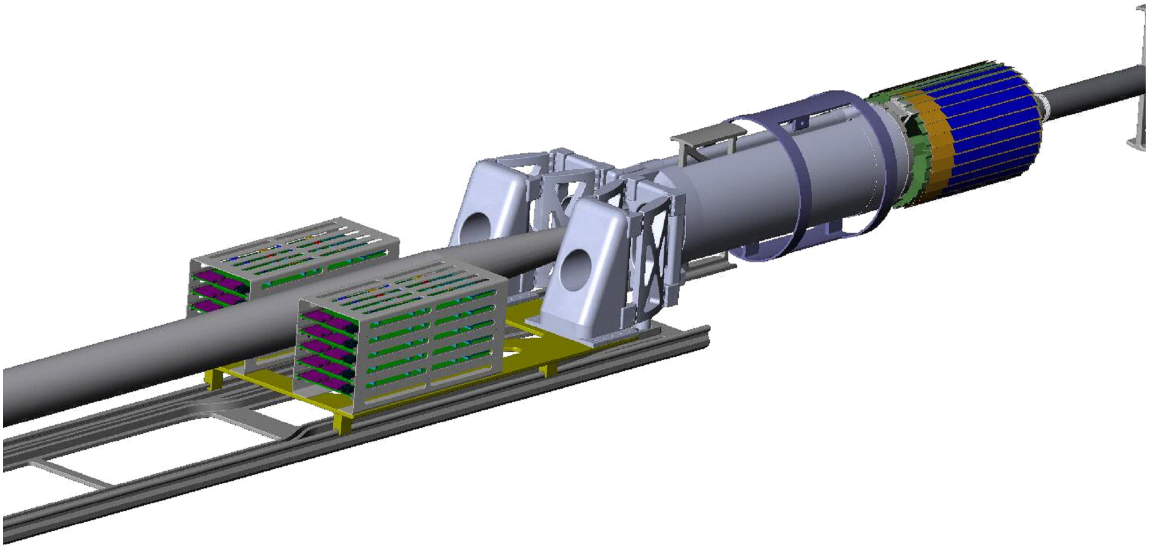

Figure 1. Pixel detector mechanics showing detector barrel, support structures and insertion parts plus interface electronics boards.

2 Mechanical design

The pixel detector (see table 1) consists of two concentric barrels of detector ladders 20 cm long. The inner barrel has a radius of 2.5 cm and the outer barrel has an 8 cm radius. The barrels separate into two halves for assembly and removal. In the installed location both barrel halves are supported with their own 3 point precision kinematic mounts located at one end close to the detector barrel. During installation, support is provided by the hinge structures mounted on a railed carriage. Some parameters of the design are listed in figure 1.

The pointing resolution indicated in table 1 is based on our original 30 micron pixel size and the specified radiation length. The stability requirement was originally set so as to not compromise pointing resolution when we were using the larger pixels. We have subsequently gone to a smaller pixel size to improve charge collection, but have not changed the stability requirement to be consis-

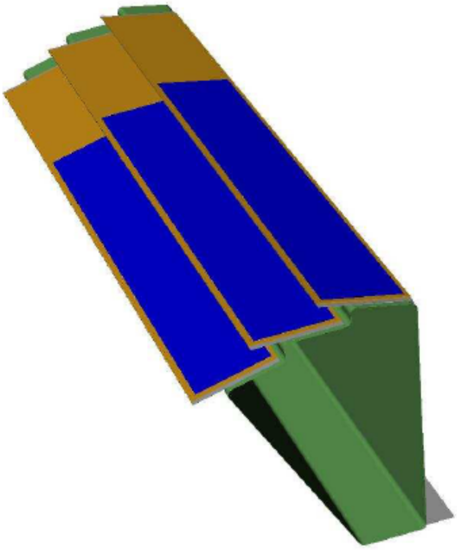

Figure 2. Thin wall carbon support beam (green) carrying a single inner barrel ladder and three outer barrel ladders. The beam in addition to supporting the ladders provides a duct for conducting cooling air and added surface area to improve heat transfer to the cooling air.

tent. The reason for this choice is that the multiple coulomb scattering term is the dominant factor and any attempt to improve the stability would have required increased mass, further compromising the multiple coulomb scattering term.

2.1 Silicon support design

The thinned silicon detector chips are arranged in ladders composed of a single row of 10 chips. The thinned silicon chips are bonded to a flex aluminum Kapton cable which is in turn bonded to a thin carbon composite structure. All electrical connections from the chips to the cable are done with a single row of wire bonds along one edge of the ladder. The carbon composite layer is quite thin. It's function is just to allow ladder handling and heat conduction. The primary stiffness and support of the ladders is provided by a thin carbon composite support beam which carries one inner ladder and three outer ladders as shown in figure 2. This beam which is an adaptation of the ALICE pixel detector design provides a very stiff support while minimizing the radiation length budget. Significant stiffness is required to control deformations from gravity, cooling air forces and differential expansion forces from both thermal and humidity variations. The composite beam carries a single inner ladder and three outer ladders. Ten of these modules form the two barrel layers. The beam in addition to its support function provides a duct for cooling air and adds cooling surface to increase heat transfer from the silicon chips. By making the beam from high strength and high thermal conductivity carbon fiber the wall thickness can be as thin as 240 microns and still satisfy strength and heat transfer requirements.

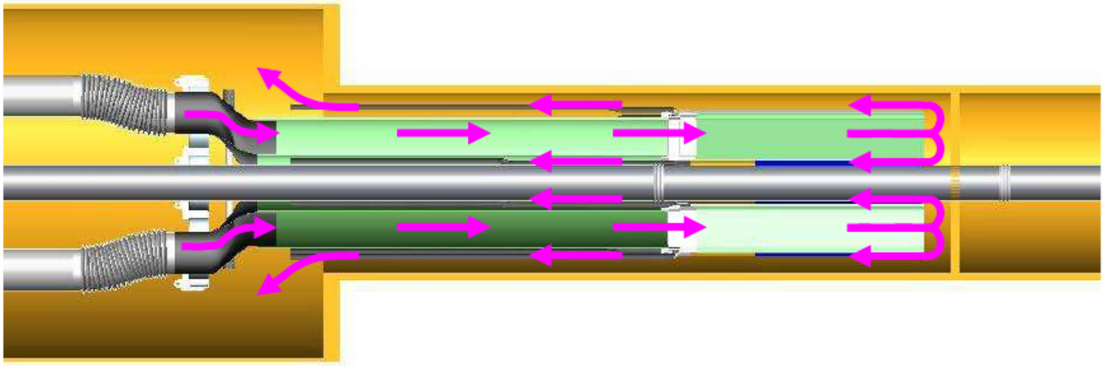

Figure 3. Pixel detector cooling air path. The air flows down the center of the sector modules and returns back over the detector ladders on the sector modules and into the larger ISC volume where it is ducted back to the air cooling unit.

2.2 Detector cooling

Cooling of the detector ladders is done with forced air to minimize radiation length. The pixel chips dissipate a total of 160 watts or 100 mW/cm^2 and an additional 80 watts is required for the drivers at the end of the ladders. In addition to the ladder total of 240 watts some fraction of this is required for voltage regulators and latch up electronics that are off the ladder but reside in the air cooled volume. Cooling studies (see next section) show that air velocities of 8 m/s are required over the detector surfaces and a total flow rate of 280 cfpm is sufficient to maintain silicon temperatures of less than 12 deg C above the air temperature. The temperature of the cooling air will be 24 deg C, slightly above the ambient temperature in the STAR experimental hall.

The detector cooling path is shown in figure 3. Air is pumped in through the support beam. A baffle in the Inner Support Cylinder (ISC) forces the air to return back over the detector surfaces both along the beam pipe and along the ISC.

3 Mechanical design simulation and analysis

A number of mechanical design studies have been carried out to find designs that can meet requirements of stability and cooling. The work reported here has been carried out by either ARES corporation or us.

3.1 Ladder support structure

The mechanical design of the pixel support system must meet stringent position stability requirements while also minimizing radiation length. The basic support design analyzed is pictured in figure 2.

The issues investigated are:

- Ladder backing stiffness required to hold thinned silicon flat against it's tendency to curl
- Support strength to control gravity sag

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- Support strength to control deformation from air flow pressures
- Control of thermal expansion induced deformation
- Control of moisture expansion induced deformation
- Support strength to handle insertion loads

We report on a subset of this list in the space allotted.

3.1.1 Control of gravity sag

The most critical component for controlling deformation from a variety of sources is the sector tube shown in figure 2. This structure is in the tracking path and thus requires the most attention to radiation thickness. Analysis of the sector tube control of gravity sag has been carried out by us and by the ARES corporation [4]. The ARES analysis, included details of the composite weave, and showed that a sector tube could be fabricated with a thickness of 120 microns that more than satisfies our 20 micron stability requirement giving a gravitational displacement of less than 6 microns. We have performed a similar analysis, but with an isotropic modulus representation of the composite. This work shows a 5 micron deformation for the detector elements, but adding an end lip reinforcement on the support beam reduces the gravitational detector displacement to 0.6 microns. These results show that gravity induced distortions are not a problem with this design.

3.1.2 Control of thermal expansion induced deformation

One of the greatest potential sources of deformation is differential expansion resulting from changes in temperature between powered on and power off. It is planned to spatially calibrate or map the detector structures in a vision coordinate machine with the power off and the structure should not deviate from the map while powered on during operation by more than 20 microns. This requirement was one of the main reasons for choosing the current design with its large moment of inertia and consequently large stiffness. In analyzing the ladder support beam it was found that the main issue requiring control is the bimetal thermostat effect from differential expansion. The problem is the result of the very large coefficient of thermal expansion (CTE) of the kapton cable compared to the rest of the structure. A thermal expansion analysis of ladders plus support [5] shows that by using a very compliant adhesive (3M 200MP) the Kapton cable is largely decoupled from the structure greatly reducing the thermal induced bending. Simulation results give a maximum deformation of 9 microns, well inside of the 20 micron requirement envelope.

3.1.3 Ladder cooling analysis

Air cooling has been chosen for the pixel detector in order to minimize multiple coulomb scattering and a number of studies have been carried out to optimize the air cooling design. Original tests [6] with a heated ladder in a fan driven air stream indicated that ladders with heat loads of 100 mW/cm^2 could be successfully cooled with a moderate air velocity. A study performed by the ARES Corporation found that an airflow velocity of 8 m/s through the sector beam was sufficient to limit the silicon temperature rise above ambient to 13 deg C. To accomplish this, however, additional cooling fins were required under the outer layer of silicon. These fins add mass and complicate construction, but it was found that by using air flow on both sides of the structure acceptable cooling can be

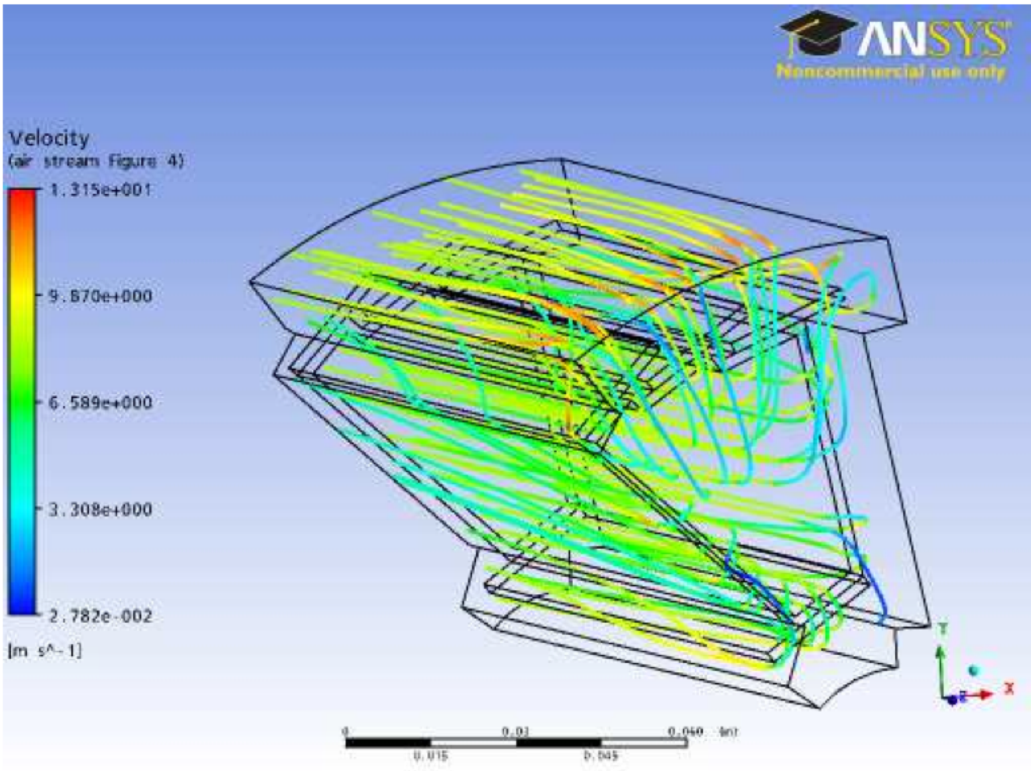

Figure 4. Stream lines showing the cooling air flow. The flow direction is from inside to outside. The color code shows air velocity.

achieved without added fins. We have done CDF modeling [7] to demonstrate the two flow cooling performance. The cooling simulation was run for one sector out of the 10 sectors in the complete pixel cylinder. The modeled air flow path is shown in figure 4.

In this case an input air velocity of 8 m/s was used. This results in a maximum silicon temperature rise of 12 deg C above the 24 deg C ambient temperature (see figure 5) which is acceptable. It is interesting to note that the inside ladders next to the beam pipe cool more effectively than the outside ladders. This is because the surface area of the support beam sides provides a significant fraction of the cooling.

The total air flow in this case for the full pixel detector barrel is ~ 280 CFPM and the temperature rise in the air for the total power of the ladders, 240 W, is 1.5 deg C. This is a very modest and acceptable rise in the air temperature.

The rapid air velocity, 8 m/s, has the potential of vibrating the detector structure as well as static deformation which could compromise position resolution. At the original time of this presentation we were working on a wind flow test to investigate this issue. These tests have since been completed using a capacitive probe to measure vibration and displacement. We observed multiple vibration modes peaking at around 135 Hz with an RMS amplitude of 7 microns. This is right at the limit of our position stability requirement.

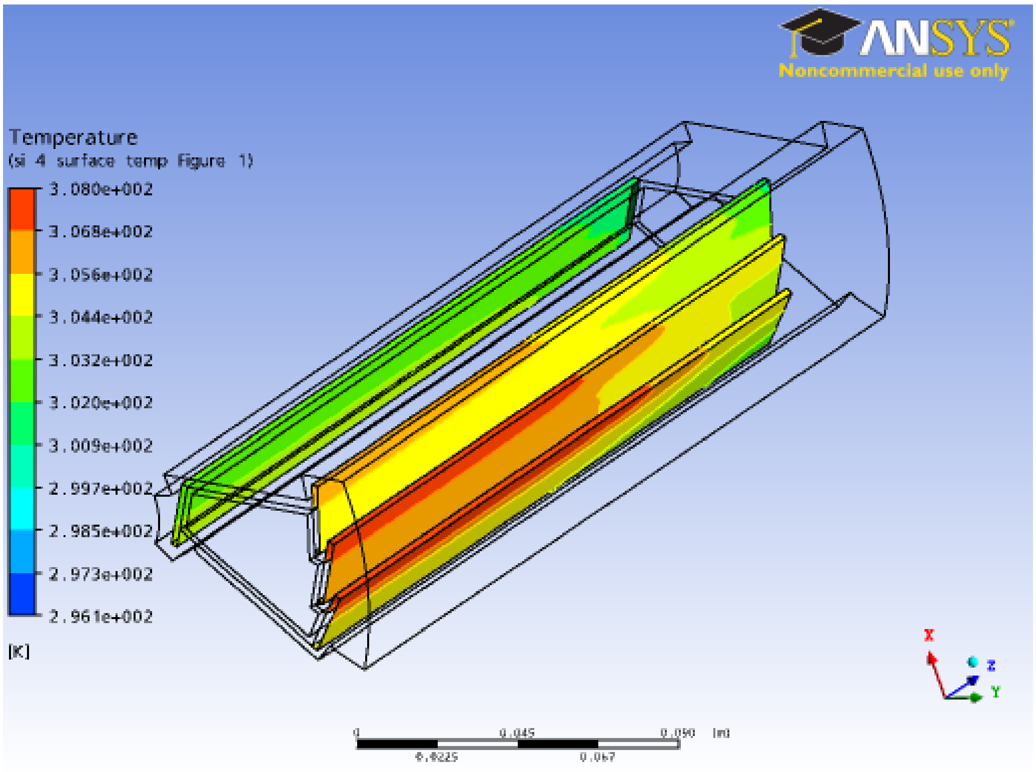

Figure 5. Surface temperature of silicon ladders. The maximum temperature increase above ambient is 12 deg C. The cooling air flows across both the inner and outer surfaces. The air enters from the left on the inside of the support beam, turns around at the right and exits on the left.

4 Conclusion

We have a workable mechanical design for a very low mass inner pixel detector for STAR which has been shown through analysis to meet requirements of stability and cooling. Prototype work is proceeding.

Acknowledgments

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[6] http://www.lbnl.leog.org/ladder_thermal_imaging.pdf.

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