Construction and study of a micro-strips petalet prototype

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Abstract

As the HL-LHC (High Luminosity LHC) was proposed, the present ATLAS detector will be completely replaced to meet the challenges of operating at HL-LHC. The Inner Tracking System which is the inner most part of the ATLAS detector will be upgraded into an all-silicon tracker which can withstand the much harsher radiation and occupancy conditions of HL-LHC in 2024. The all-silicon Inner Tracker was proposed to have a structure which has pixel sensors at the inner radii surrounded by microstrip sensors. Both the pixel sensors and the microstrip sensors are arranged on cylinders and disks. In the center regions (barrel), sensors are arranged in cylinders, with 4 pixel layers followed by 3 short-strip layers then 2 long-strip layers, and the forward regions (end-caps) will be covered by 6 pixel disks and 7 strip disks. Multi-module structures used in barrel and end-caps regions were called "stave" and "petal" respectively. Small version of them are called "stavelet" and "petalet". This report will be mainly about the characteristic of a "petalet" in "bear" version.
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1 Introductions

1.1 The current inner detector of ATLAS

The Large Hadron Collider (LHC) at CERN has been acting as a frontiers of particle physics with its unprecedented high energy and luminosity. It has bunches of up to $10^{11}$ protons collided 40 million times per second, which will provide 14 TeV proton-proton collision at a design luminosity of $10^{34} \text{cm}^{-2}\text{s}^{-1}$.

The ATLAS Inner Detector (ID) is designed to provide hermetic and robust pattern recognition, excellent momentum resolution and both primary and secondary vertex measurements for changed tracks. The current ID layout is shown in Figure 1.

![vertex detector.png](vertex detector.png)

Figure 1: The baseline layout of the current inner detector of ATLAS

The ID consists of 3 independent but complementary sub-detectors: a Pixel detector and a Semi-Conductor Tracker (SCT) both implemented using silicon sensors, and a Transition Radiation Tracker (TRT) that uses ionization caused by charged particles in straw tubes filled with gas.

After the ten years of expected lifetime, and the propose of the High-Luminosity LHC, the Inner Detector need to be replaced completely.

1.2 The Inner Detector for ATLAS phase-II upgrade

The LHC is planed to have a major upgrade called Phase II Upgrade. After the upgrade, HL-LHC (High Luminosity LHC) will be operated in a luminosity of $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$. The extreme radiation level render the current Inner Tracker no longer suitable for long term operations. The new detector is requested should have higher granularity, higher radiation tolerance and novel powering solutions, it should also be able to reduce material, cable count, pitch size and cost.
An all-silicon tracker will be used as the Inner Detector of ATLAS detector in the HL-LHC. The baseline layout is presented below.

![Baseline layout of the all-silicon tracker](image)

Figure 2: The baseline layout of the all-silicon tracker

This proposed tracker layout is mainly based on requirements of excellent performance to fully exploit the new physics at HL-LHC and in particular to be able to cover the multi-TeV range[1]. The upgrade inner tracker can be divided into 2 part: the Barrel and the end cap. The barrel part consists of five full length cylinders that surround the pixel sensor barrel and a short stub barrel that covers the loss of acceptance between the end-caps and barrels. The end-caps part of the strip detector have seven disk on each side, and every disk is populated with 32 identical petals. For the barrel region the small structure is referred to as a Stave and for the end-caps region it is referred to as a Petal.

### 1.3 The petalet

As mentioned before, the upgrade strip detector consists of a central barrel region and 2 end-caps. The barrel part of the strip detectors was surrounding the pixel sensor barrel. The end-caps part of the strip detector have seven disk on each side, and every disk is populated with 32 identical petals.

Smaller prototype of the petal named petalet are under construction. From a mechanical point of view, a petalet consists of 3 strip modules per side, which are directly glued onto a 'bus tape' (a very thin, with multi-layered flexible circuit like the power and data transmission trace integrated in it under an aluminum shield, and several polyimide films, which remain stable across a wide range of temperatures(from $-268$ to $+400$°C). All of them are glued onto a low-mass carbon-based core with titanium cooling pipes embedded in it. Figure 3 shows the layout of a petalet of 'bear' version.
2 Thermal characterization of the core

There will be a lot of heat generated by the readout ASICs during operating, which will include a significant increase of the leakage current on the silicon sensor. This will translate in an increase of the electronic noise on the system, and a degradation of its performances. So we need to know how the cooling system is doing by analyse the thermal characterization of the core.

The way how we know the temperature distribution is by detecting the infrared radiation that emitted from the target, so we can know the temperature of the object according to the Planck's radiation law. But we need to get prepared before measuring the amount of infrared radiation, we will be explained in detail next.
2.1 The IR camera

The device we use to record the infrared radiation is called IR camera (Infra-Red camera) which forms an image using infrared radiation[4]. The temperature can be calculated according to Plank’s Law. The version of IR camera we use is VarioCAM hr (VarioCAM high resolution) which is a modern thermographic system for the precise, quick and non-contact measurement of surface temperatures of objects. It has been designed for universal use and can be applied as both a mobile and stationary system for measuring and saving temperature data. Its high measuring precision, precision lenses of extraordinary imaging quality and its universal interface design for taking real-time thermographic data permit the application of the VarioCAM hr in the most varied fields of research and development. Figure 4 shows a picture of the VarioCAM hr we used in this report.

![Vario CAM hr](image)

Figure 5: Vario CAM hr

2.2 The mechanical setup

The core we are going to record its thermal characterization will be placed into an aluminium box, and should be completely covered to avoid the light from outside incoming to the box, and we also need to hold the camera and wait for several minutes till the temperature level and distribution are stable enough to take a picture. Most of the time, we need to flush the box with nitrogen to avoid humidity. The setup includes a tripod and a black shading cloth which can be seen in Figure 6 and Figure 7. We hold the camera above the core and cover the camera and the box with the black shading cloth to set the proper mechanical setup.

But there are still some reflections in the thermal graphics.

2.3 To take a good thermal graphic

To take a good thermal graphic, not only the proper mechanical setup is needed, but also the calibration of the camera to site specific conditions. There are 3 things critical to the calibration:
Focus the camera;

Set the appropriate emissivity of the material of the surface that we are interested in using camera or software;

set the corresponding value of environment temperature using camera or software.

To understand the importance of the emissivity we need to first remind ourself of the knowledge about emissivity.

Emissivity is used to describe how well an object reflects radiation. The emissivity of the surface of a material is its effectiveness in emitting energy as thermal radiation. Quantitatively, emissivity is the ratio of the thermal radiation from a surface to the radiation from an ideal black surface at the same temperature as given by Stefan-Boltzmann law. The ratio varies from 0 to 1. For instance, objects which has the temperature above 0K, will emit infrared(thermal) radiation which isn’t visible to human eye. At room temperature, the surface of a black object emits thermal radiation at the rate of 418 watts per square meter, but real objects with emissivity less than 1.0 will emit radiation at a lower rates. The emissivity of an object is determined by its material and surface condition.

The IR camera can only detect the total amount of radiation received from an object. But the total amount of radiation is always bigger than the radiation emitted from the target. It always has 3 parts:

the first part is from the object itself, and second part is the reflected radiation reflect from the environment, which depend on the material’s reflectivity. In the case of transparent objects such as glass, there will be the third part radiation transmitted through the object to the camera, transmissivity describes the percentage of radiation can transmit through the object. And the detected amount of radiation \( \phi \) is the sum of the above
components. An equation describe that can be found below:

\[ \phi = \varepsilon \phi_B + \rho \phi_U + T \phi_H \]

\( \varepsilon = \text{Emissivity factor} \)
\( \rho = \text{Reflectivity factor} \)
\( T = \text{Transmissivity factor} \)
\( \phi_B = \text{Radiation from target object} \)
\( \phi_U = \text{Reflected radiation} \)
\( \phi_H = \text{Radiation from background} \)

The environment temperature is the reflected temperature, it is the infrared energy of our surroundings that being reflected off the object that we are trying to measure. Therefore, both the environment temperature and the emissivity are critical to our measurement. To calibrate the camera we need extra devices to measure the true temperature of the core and the temperature in the aluminum box:

- PT100(measure the true temperature of the core): Platinum resistance thermometers (PRTs) is a kind of platinum element whose resistance related to its temperature. The principle of operation is to measure the resistance of the platinum element then use the value to calculate its temperature. PT100 offers excellent accuracy over a wide temperature range(from -200 to +850°C), and it’s available from many manufactures with various accuracy specifications and numerous packaging options to suit most applications.

We used Kapton tape gluing the platinum element directly on the surface of the core, and connected it with a Mulimeter. The resistance of the cable and connector is 1.5364 ± 0.02ohm. we need to subtracting the resistance of them when we doing the calculation. There is an equation describing the relationship between the temperature and the resistance of the PT100:

\[ R_t = R_0[1 + At + Bt^2 + c(t - 100)t^3] \]
where $R_t$ is the resistance at temperature $t$

$R_0$ is the resistance at $0^\circ C$

$A = 3.9083e−3$

$B = −5.775e−7$

$C = −4.183e−12$(below $0^\circ C$), or $C = 0$(above $0^\circ C$)

- Thermocouple: A thermocouple is a device consisting of two dissimilar conductors or semiconductors that contact each other at one or more points, it produces a voltage when the temperature of one of the contact points differs from the temperature of another. Thermocouples are widely used type of temperature sensor.

We will put it into the box and it will be responsible for measuring the temperature in the box.
2.4 Thermal graphics

If we set the proper mechanical setup and successfully calibrate the IR camera, then we can start to take the thermal graphics. There are 3 parameters of the cooling system and we can change them to get different temperature distribution.

Table 1: Different setup to the cooling system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling liquid temperature(°C)</td>
<td>0,5,10,15</td>
</tr>
<tr>
<td>Pump flux</td>
<td>Max, Min</td>
</tr>
<tr>
<td>Nitrogen core</td>
<td>With/without nitrogen filling in the box</td>
</tr>
<tr>
<td></td>
<td>Before/after bus tape glued</td>
</tr>
</tbody>
</table>

we can take thermal graphics about the core under different setup of the cooling system. Every time we change the setup of cooling system, we need to wait for several minutes till the temperature of the core be steady. The thermal graphics we get are always like the figure below:

Figure 11: Thermal graphic of a core on the side without bus tape glued on
2.5 Results

There are several important results we can get from comparing the thermal graphics or the histograms:

- The function of filling the box with nitrogen: prevent moisture on the surface of the core;

![Figure 12: Thermal graphic of a core on the side with bus tape glued on](image)

![Figure 13: The image on the left was cooling with nitrogen on, the one on the right was cooling without nitrogen flush in the box. The ambiguous area in the centre of core on the right is moisture](image)

- comparing the temperature distribution histograms below we can get that the pump flux has the biggest effect to the cooling effect;
Figure 14: This histogram shows the temperature distribution of a core with the pump flux setted at max

Figure 15: This histogram shows the temperature distribution of a core with the pump flux setted at min

- the most important result: the kapton bus tape acts as a thermal block making the core warmer about 3.5°C

Figure 16: Histograms of the temperature distribution of the surface of a core with/without the bus tape

3 Gluing modules on the core

3.1 Infrastructure

To glue the modules on the core, we need a series of devices: pickup tools, Microscope, Mounting Frame, X-Y stage, Micrometer stand, PC. A picture of the Infrastructure can be seen below.

3.2 Steps

There are a several steps required to glue the modules on the core:

- Setting origin of coordinates on a fiducial on the mounting frame;
Figure 17: The Infrastructure to glue modules on the core

- Locate modules on a Gel-Pak pad (releases with vacuum) and place the pad on the micrometer stand;
- Look for fiducial on Si and re-align them with the micrometers to a known location (in the origin of coordinates created);
- Double-check location with plexiglass dummy pickup tool and readjust;
- Pickup tool holds the modules under vacuum (by switching on vacuum on pickup tool, then switch off vacuum on Get-Pak);
- Repeat above steps to glue next module;
- Place pickup tool with the modules on ”parking” position;
- Place core on mounting jig: the PT will fit precisely into this mounting jig;
- Stencil on core, deposit SE4445 glue (thermally conductive, electrically insulating) and spread it uniformly;
- Place 120µm fishing line to determine glue thickness and glue spread;
• Place Ag epoxy (TRA-DUCT 2902)(electrically conductive) on the HV contacts of the core;
• Places modules with PTs(Pickup Tools), lower them until they reach fishing lines;
• Wait about 6 hours for glue to cure, maintaining the vacuum;

4 Electrical testing

4.1 Description

For electrical testing, we use SCTDAQ to analysis the performance of the petalet. The SCTDAQ software used in the tests is based on the SCTDAQ software that was used for the system tests of the current SCT. It has been modified to support the new HSIO system and to handle multiple modules.

The value we are interested in is the input noise of each module which can be calculated using:

\[
\text{Input noise} = \frac{\text{output noise}}{\text{gain}}
\]

we need to first do some configuration to BCCs and ABCN25s aim to adjust the delays coming from cabling, interface, and internal calibration capacitors.

Also, the strobe delay which is a kind of calibration of the timing(delay) of an injected calibration pulse with respect to the arrival time of the command to actually issue that pulse need to be down as well. The calibration consists of 2 parts: a threshold scan at 2fC first, followed by the actual scan through the strobe delay. The strobe delay(0.25) was called here, which means the optimal strobe delay setting is set at 25% of the working region.

After that, we will run 3-point gain(1fC) which is performing threshold scans at three different injected charges(0.5fC, 1fC, 1.5fC). The output noise is the distribution of the threshold for a particular injected charge, and the gain will be the derivative calculated from a linear fit of the three threshold scan points.

4.2 Results

The Input Noise of the petalet can be found in the output file, and the plots of Input Noise can be found in Figure 14. The plots of Input Noise of a non-embedded petalet can be found below for comparison with the embedded petalet.
Figure 18: The Input Noise of the upper modules and the lower modules of the embedded petalet

Figure 19: Input Noise of the non-embedded petalet

The result we got by comparing the two figures is the average input noise of an embedded petalet is higher than that of a non-embedded petalet by $\sim 100$ ENC in upper modules and $\sim 120$ ENC in lower modules, cause the embedded fan-ins modules in our petalet[5], which introduced a parasitic capacitance effects between the 1st and 2nd metal layer makes the noise larger.

5 conclusion

In this summer program, I gained a lot knowledge about:
• Elementary knowledge about modern silicon particle detector for high energy physics (HEP);

• The way to use the IR camera;

• The thermal characterization of cooling structures;

• Knowledge about assembly of multi-module silicon micro-strip prototypes such as the petalet;

• The electrical characterization of fully functional multi-module prototypes was tested using fast, differential signals across support structures.
Reference


