PROCEEDINGS OF SCIENCE

Cooling Analyses of HV-MAPS detector in Compton Polarimeter in Hall A of JLab

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The Measurement of a Lepton-Lepton Electroweak Reaction (MOLLER) experiment anticipates new dynamics beyond the Standard Model. The measurements are acquired by the scattering of longitudinally polarized electrons off unpolarized electrons in a liquid hydrogen target using a set of detectors in Hall A at the Thomas Jefferson National Accelerator Facility (JLab) in Newport News, Virginia, USA. MOLLER will use High Voltage-Monolithic Active Pixel Sensors (HV-MAPS) in the Hall A's Compton polarimeter to monitor the polarization. The detector contains a quad-planar geometry and each plane has three HV-MAPS chips attached. Compton polarimeter requires the HV-MAPS to be placed inside the vacuum to allow for the detection of the scattered electrons. The chips generate heat during operation, and thus require an effective cooling system. The temperature measurement of the HV-MAPS in vacuum is essential to understand the thermal properties of the pixel detector and cooling needs. This project reviews the efforts towards the cooling strategies, structure modification, and thermal simulations to achieve an in-vacuum operation. Further, the prototyping and successful testing of the electron detector's cooling system (using a test version of HV-MAPS chips with equivalent heat load) in a local lab was performed, and computational fluid dynamics studies are compared with the collected data.

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1. Introduction

The primary goal of the MOLLER experiment is detecting new physics beyond the Standard Model. The experiment measures parity-violating asymmetry A_{PV} in the Møller scattering ($e^- + e^- \rightarrow e^- + e^-$), utilizing the upgraded 11 GeV beam in Hall A at the Thomas Jefferson National Accelerator Facility (TJNAF). The fractional precision of the measurement of parity violation asymmetry is expected to be 2.4%, representing more than a five-fold improvement as compared to the previous measurements achieved by the E158 experiment carried out at SLAC [1]. As the aim of the experiment is to extract the parity-violating asymmetry and consequently weak charge of the electron through the scattering of longitudinally polarized electrons off unpolarized electrons, it is important to accurately measure the polarization of incoming electron beam from the Continuous Electron Beam Acceleration Facility (CEBAF). Compton polarimetry (see section 2) is one of the most effective techniques used to achieve precise and continuous polarization measurements. For this purpose, High-Voltage Monolithic Active Pixel Sensor (HV-MAPS) technology (refer to section 2) is proposed as a key component of the detectors that will measure the polarization of incoming electrons. Compton polarimeter utilizes this detector assembly inside the vacuum, where heat dissipation is significantly constrained. Thus, effective thermal management is essential to ensure the detectors maintain best performance and accurate data collection ability within the magnetic chicane, and avoid damage due to overheating. This paper focuses on the thermal behavior of electron detector through Computational Fluid Dynamics (CFD) simulations, subsequently verified experimentally. This aims to ensure that the detectors operate within safe temperature limits, preventing any thermally induced degradation. By exploring and testing different cooling strategies with the help of thermal simulations, the objective is to fine-tune the design parameters of the HV-MAPS electron detector.

2. HV-MAPS technology for Compton Polarimeter

The concept of Compton polarimetry is based on the elastic scattering of polarized electrons by circularly polarized photons. The polarimeter is designed to achieve a polarization measurement precision of approximately 0.4%, while continuously monitoring for any significant fluctuations. The recent measurement conducted by CREX experiment at the JLab reported a higher precision measurement (0.36%) of electron beam polarization [2]. The MOLLER Collaboration members bring substantial expertise from their work in achieving these objectives [3]. One benefit of the Compton polarimeter is its ability to operate without altering the primary electron beam. Preserving the beam's polarization, orientation, size, and position as it exits the chicane is important because the unperturbed beam is essential for reaching and interacting with the target for the main experimental measurements of MOLLER. The Compton polarimeter is located in a 15 m long magnetic chicane. This chicane utilizes momentum analyzation technique to separate the Compton-scattered electrons from the primary beam (as depicted with blue line in Fig. 1), guiding them towards the electron detector for polarization measurement. The present electron detector setup at JLab consists of four silicon microstrip planes, each containing 192 strips. The current technology, although functional, suffers from a low signal-to-noise ratio, limiting precision of the measurement. Thus, there are plans to replace the setup with High-Voltage Monolithic Active Pixel Sensor (HV-MAPS) technology based electron detector [4]. These planes will be mounted on a motorized vertical stage that can be remotely controlled during operation to move the detector planes in/out of the beamline.

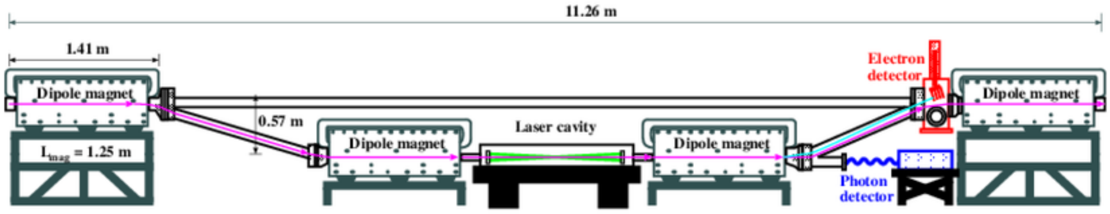

Figure 1: Compton Polarimeter in Hall A of the Thomas Jefferson National Accelerator Facility [5].

HV-MAPS are silicon diode arrays fabricated using HV-CMOS process [6]. These sensors enable efficient drift-based charge collection while integrating readout electronics directly onto the same chip. Due to their thin active regions, these sensors can be reduced to thicknesses below 50 μm, having a low material budget, making them ideal for tracking low-momentum particles at high rates. HV-MAPS integrate the strengths of both fast hybrid pixel detectors and thin monolithic active pixel sensors (MAPS), offering strong radiation tolerance and high precision, as evidenced by numerous studies [7–11], making them prime candidates for the tracking detector implementation. For the Compton Polarimeter, the electron detector has four planes, and each plane uses three HV-MAPS chips. These chips will be wire-bonded to a printed circuit board (PCB) to create a larger detection area for scattered electrons. The MOLLER experiment will use a version of MuPix, known as P2Pix. This chip operates within a voltage range of 60 to 120 V. Each chip is 2 cm $\times$ 2 cm, and when arranged together, they provide a total detection area of 6 cm × 2 cm per plane. Each chip contains 64,000 silicon pixel diodes of dimension 80 μm × 80 μm, each diode acting as an individual electron detector. Each individual pixel outputs a timestamp and its corresponding address where a particle is detected. The chip's high response rate reduces dead time and ensures high event rates. The chip generates 1 Watt of heat while operating. Most of the heat in MuPix Version of P2Pix HV-MAPS chips is generated by the state machine, which is concentrated at the periphery of the chip (refer to Fig. 2). For the purpose of our measurement in a local laboratory, we used plain silicon wafer chips (2 cm $\times$ 2 cm) and bonded Nichrome wire heaters to the top of the wafers to simulate a periphery/state machine on the dummy chip which is capable of depositing 1 watt of heat per chip. As this component dissipates power, and is kept under vacuum during operation, efficient thermal management at the chip's edges is crucial to prevent overheating and ensure steady operation. These chips must be kept below 70 ^{o}C to avoid data loss.

3. Results and Comparison

This section explores the design and implementation of HV-MAPS electron detector within the Compton polarimeter. The proposed detector design can be seen in Fig. 2. The HV-MAPS chips will be mounted on a 2-layered metal-core PCB adjacent to each other in a 3$\times$1 grid. The metal core is a 1.3 mm thick layer of copper, chosen to improve thermal conductivity. The PCB also works as the supporting structure for HV-MAPS and a platform for multiple electrical connections essential

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for data collection, and forms one plane of the detector. We utilize four of such planes. A copper cooling block will hold two planes on either side separated by a Thermal Interfacing Material (TIM) [4], requiring two cooling blocks for four HV-MAPS planes. The material chosen for the cooling blocks is Cu-110, a high conductivity grade of copper, making it efficient for rapid heat dissipation. Additionally, the heat exchanger/thermal block is sandwiched between the two cooling blocks at the top, as shown in Fig. 2. It supports a dual-method cooling strategy by incorporating both conductive and convective heat dissipation techniques: first, it adds on to the conductive cooling by simply increasing the conductive area in the detector setup through which heat can transfer, second, it introduces convective cooling by employing a top coolant pocket inside the thermal block that connects to the shaft. This pocket has a broad internal surface area, allowing incoming water to circulate effectively and absorb heat more efficiently before exiting, removing a significant portion of the accumulated heat. This creates a dynamic cooling loop that maintains the temperature within safe operating limits. In the present study, each chip periphery generates a thermal output of 1 W, while chilled water, which serves as a coolant, is introduced at different temperatures with flow rate of 7.5 L/min. The coolant is continuously circulated in a closed loop using a chiller, facilitating heat transfer from the chips to the coolant. To analyze the temperature distributions at multiple

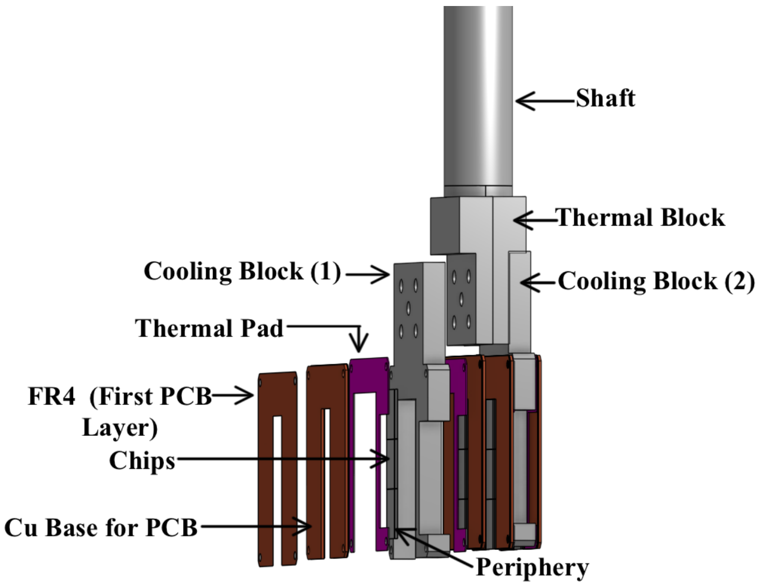

Figure 2: CAD Render of the HV-MAPS Detector Assembly (modelled by Nafis Niloy).

points in the detector assembly during operation, the highly sensitive silicon diodes are utilized as temperature sensors. The placement of these sensors is shown in Fig. 3. The tests were conducted inside the vacuum chamber. The CAD picture of the vacuum chamber with a prototype of the e-detector setup placed inside it is shown in Fig. 4. The results are compared at the specific sensor locations (shown in Fig. 3) for both the CFD analysis and local lab setup. For comparison, we selected the results from the setup where we introduced water at 12 °C, and applied 3 W of power per plane. The results of the computational simulation, run via CFD, are depicted in Figs. 5 and 6. On the other hand, the experimental results under similar conditions in the lab are shown in Fig. 7.

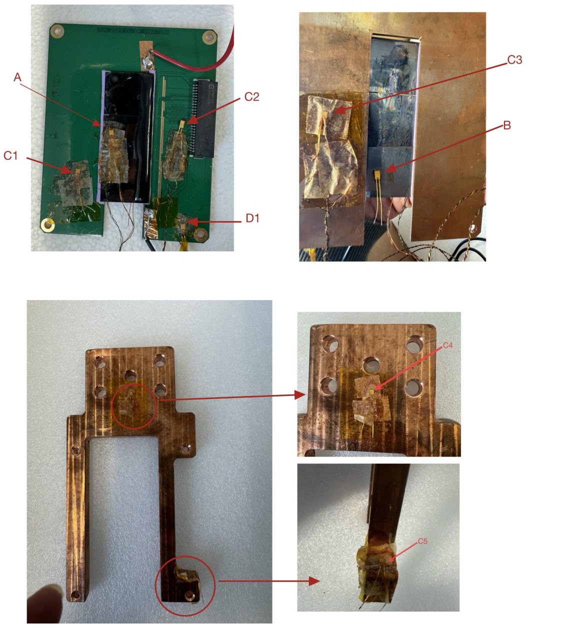

Figure 3: Placement Strategy of the Temperature Sensors.

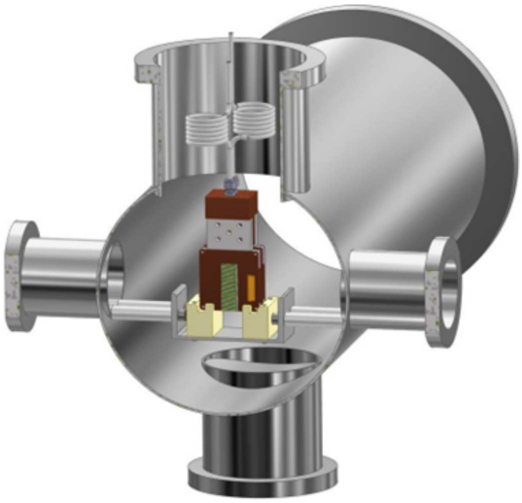

Figure 4: CAD Render of HV-MAPS Electron Detector Placed inside the Vacuum Chamber for Local Lab Setup.

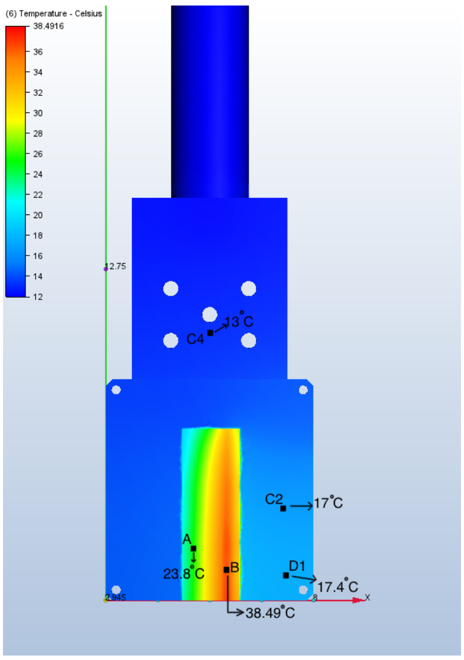

Figure 5: Computational Results of the Electron Detector with Water at 12 °C and 3 W of Power per Plane: Front View.

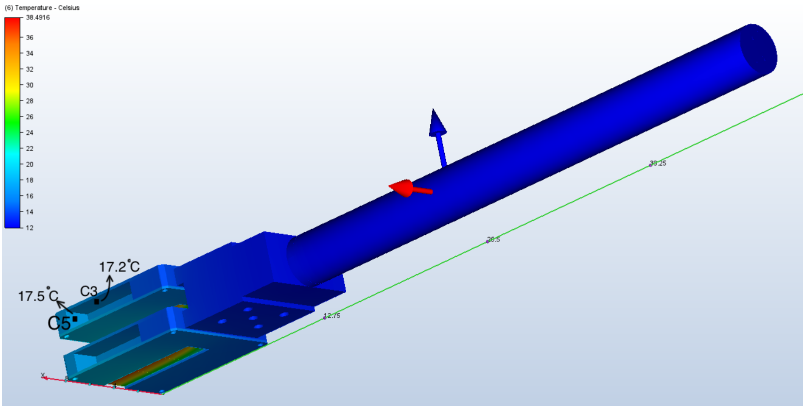

Figure 6: Computational results of the electron detector with water at 12 °C and 3 W of power per plane: side view.

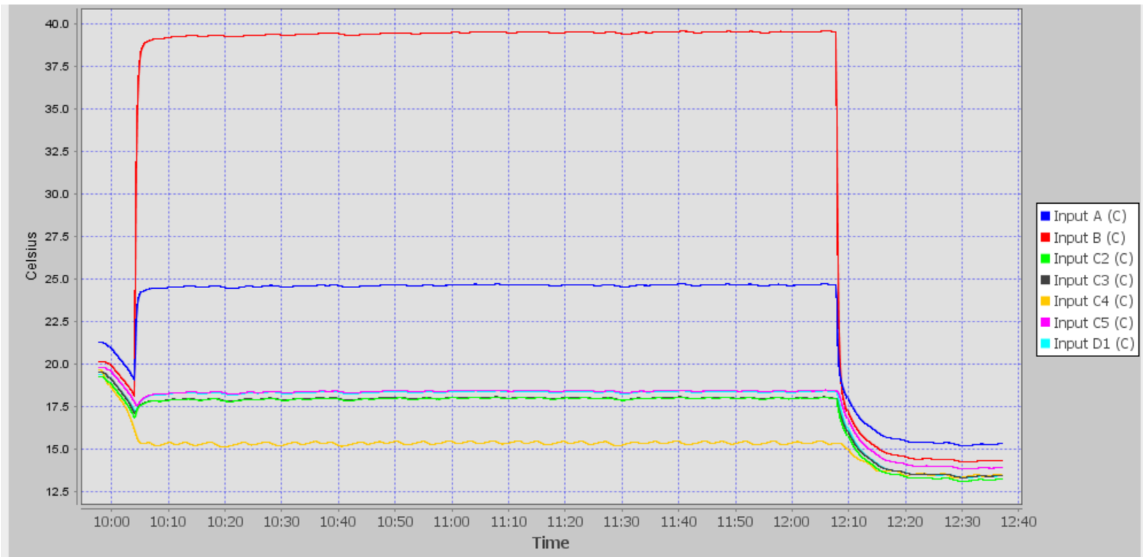

Figure 7: Results from the Local Lab Setup, where all the Sensors labelled on the Side with Colors, indicating the Temperature recorded.

Tab. 1 summarizes the comparison of temperature at various sensor positions of the prototype operating inside the vacuum, alongside the computationally modeled thermal simulations of the same model. Similarly, we performed tests across a range of temperature settings (4 °C, 8 °C, 12 °C, 16 °C) and varying power levels (6 W, 12 W, 15 W) applied to all planes of the detector. The corresponding results are presented in the Tab. 2. For the present study, dummy chips have been used and a nichrome wire is assembled on them to simulate a heat load. The simulation results confirm that the electron detector remains within a safe operating temperature of 70 °C, demonstrating the effectiveness of our cooling system. To further validate the design, a final prototype incorporating the HV-MAPS (MuPix 11) is currently underway and will undergo a subsequent round of comprehensive testing in the near future.

Table 1: Comparison of Temperature Results at diffrent Sensors Locations for both the CFD Analysis and Experimental Setup, for this specific Case: Coolant Temperature: 12 °C, Flow Rate: 7.5 L/min, Power per Plane: 3 W.

Sensor Location	Experimental Results [°C]	CFD Results [°C]
B	39	38.5
A	24.5	23.8
C2	17.5	17
C3	18	17.2
C5	18.5	17.5
D1	18	17.4
C4	15.3	13

Table 2: Comparison of the Experimental (Lab) Results with the Computational (CFD) Results.

Power [W]	Temp. of the Coolant [°C]	Measured Temperature at the Sensor B [°C]	Simulated Temperature at Sensor the B [°C]	Difference [°C]
6	4	20.8	17.3	2.8
6	8	24.1	21.3	2.8
6	12	27.7	25.2	2.4
6	16	33	29.2	3.7
12	4	33.5	30.5	3
12	8	36	34.4	1.6
12	12	39	38.5	0.5
12	16	47	42.5	5
15	4	43	37.1	5.9
15	8	46	41.1	4.8
15	12	49	45.1	3.8
15	16	55	49.1	5.9

4. Summary and Conclusions

The MOLLER experiment is an effort to explore the dynamics of the electroweak interaction, focusing on the measurement of parity violation in electron-electron scattering. The polarization of the incoming beam is necessary to be observed. HV-MAPS sensors emerge as a promising candidate for this purpose for various reasons. While working under vacuum conditions, the detector dissipates a significant amount of heat. Thus, Cooling is necessary for proper operation of theses detectors under vacuum environments. This paper demonstrates the in-vacuum suitability of these chips as electron detectors, supported by both computational simulations and experimental data. Thus, confirming the detector's capability to maintain temperatures below 70 °C, ensuring consistent performance throughout the experiment. The next steps are to replace the dummy version of chips with the real HV-MAPS (Mupix 11) chips, and run the similar tests within a beamline facility.

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