Description de un Aparato de Carga Acoplada con sistema de lectura "Skipper"

(Description of Charged Couple Device with Skipper Readout system)

Trabajo de Fin de Máster
para acceder al

MÁSTER EN FÍSICA DE PARTÍCULAS Y DEL COSMOS

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ABSTRACT

This final degree project provides a detailed description of a Charge Coupled Device (CCD) setup with a Skipper readout system, used at IFCA (Instituto de Física de Cantabria). The setup is housed in a clean room and consists of a stainless steel vacuum chamber, a vacuum pump, and a cryocooler to accommodate the Skipper CCD (6544 x 1536 pixels, 15μm x 15μm x 670μm). The CCD is read out using a new electronic system based on the Low Threshold Acquisition (LTA) board, specifically designed for Skipper CCDs. The work thoroughly explains the experimental configuration, highlighting the roles of key components, especially in light of recent technological advancements.

The study also includes a comprehensive analysis of system manuals for the vacuum, cryogenics, and slow control systems, providing operational guidelines and best practices to optimize performance.

A significant part of the group research is focused on optimizing CCD configuration parameters, particularly improving charge collection, transfer, and readout efficiency. These efforts aim to better mitigate dark current and improve pixel readout noise estimations and it is collected in this report.

Furthermore, this project offers valuable insights into the operation of CCDs for the DAMIC-M experiment, specifically addressing the impact of electromagnetic noise on CCD performance.

Resumen

Este proyecto de fin de grado proporciona una descripción detallada de un sistema de Dispositivo de Carga Acoplada (CCD) con un sistema de lectura Skipper, utilizado en el IFCA (Instituto de Física de Cantabria). El sistema está instalado en una sala limpia y consta de una cámara de vacío de acero inoxidable, una bomba de vacío y un cricooler para alojar el CCD Skipper (6544 x 1536 píxeles, 15μm x 15μm x 670μm). La lectura del CCD se realiza mediante un nuevo sistema electrónico basado en la placa de Adquisición de Umbral Bajo (LTA), diseñada específicamente para los CCDs Skipper. El trabajo explica de manera detallada la configuración experimental, destacando el papel de los componentes clave, especialmente a la luz de los avances tecnológicos recientes.

El estudio también incluye un análisis exhaustivo de los manuales del sistema para el vacío, la criogenia y los sistemas de control lento, proporcionando pautas operativas y mejores prácticas para optimizar el rendimiento.

Una parte significativa de la investigación del grupo se centra en la optimización de los parámetros de configuración del CCD, mejorando especialmente la recolección de carga, la transferencia y la eficiencia de lectura. Estos esfuerzos tienen como objetivo mitigar mejor la corriente de oscuridad y mejorar las estimaciones de ruido en la lectura de los píxeles.

Además, este proyecto ofrece valiosos conocimientos sobre el funcionamiento de los CCDs para el experimento DAMIC-M, abordando específicamente el impacto del ruido electromagnético en el rendimiento de los CCD.

Contents

CHAPTER ONE
Introduction

This report will delve into the ongoing quest to uncover the mysteries of dark matter, the most prevalent yet enigmatic form of matter in the universe. Despite its abundance, dark matter remains largely unknown, eluding direct detection and challenging our understanding of the cosmos. Through this investigation, we aim to shed light on the elusive nature of dark matter, exploring the latest theories, experimental approaches, and technological advancements that are driving this critical area of research.

There are so many techniques that have been used to unveil the composition of this matter. One of them is the experiment that aims to detect dark matter particles through their interactions with normal matter in highly sensitive detectors. An example of this type of experiment is the DAMIC-M experiment which employs a silicon detector to interact with DM candidates, particularly the silicon charged couple device in its search for this matter.

Charged coupled devices (“CCDs”) are arrays of metal oxide semiconductor capacitors. Used in various fields such as digital cameras, camcorders, astronomy, medical imaging devices, and scientific research instruments. It was invented by Willard Boyle and George Smith in 1969. It was initially intended to be a memory storage unit but due to their ability to act as an ionizing image sensor, they are now used to acquire digital images. As of today CCDs are found in imaging technology that helps to produce high sensitivity and resolution. An improvement to the standard CCDs, the skipper CCDs, will be utilized in this research. This type of CCDs allows single electron resolution.

Skipper CCDs are an advanced type of CCD that offer extremely low readout noise, allowing for precise measurements. They are an evolution of the traditional CCD technology, designed to repeatedly measure the charge in each pixel to significantly reduce the uncertainty in the measurement. This process is called "skipping." Due to their ability to reduce noise in their various readout systems, they are thus employed in detection of dark matter.

1.1 Dark Matter

Dark matter was noticed by Fritz Zwicky in 1933 when he was studying the Coma galaxy cluster and realized that a large portion of the matter was not visible. He coined the name dark matter for this unseen matter.

In 1970 a US astronomer Vera Rubin in collaboration with Kent Ford confirmed the existence of an invisible matter, Dark matter, in her research on the galaxy rotation. Seeing that stars towards the edge of the galaxy move too fast to be held by the galaxy's luminous matter, she concluded that there is more matter than we see in the galaxies that aid to hold these stars in orbit.

Although it is said to take the larger part of the universe’s mass, the nature and composition of this matter is still a bit of a mystery. Unlike normal matter which is composed of baryons, the composition of dark matter is still uncertain. Most scientists think that dark matter is composed of non-baryonic matter, most scientists think that dark matter is composed of non-baryonic matter, for example a new particle, set of particles or new objects, there are many theories that try to explain what DM can be, and these theories give rise to many different possible candidates, varying from a huge range of masses, more than 80 orders or magnitudes.

The leading candidate of the predicted form of dark matter is WIMPS, and also Axions but lately there have been many other candidates or even hidden sectors. The quest for dark matter has persisted for more than eight decades. Unlike regular matter that are easily detected, dark matter is unaffected by electromagnetic force, meaning it doesn't absorb, reflect, or emit light, rendering it exceptionally challenging to detect. Dark matter is said to surpass visible matter by approximately six times, constituting around 27% of the universe. The presence of dark matter has been deduced solely from its gravitational impact on observable matter[1]. Dark matter is able to be detected through various experiments like direct, indirect detection and production at the collider. These experiments have been suggested to clarify dark matter, but its existence is highly validated by direct detection.

1.1.1 Indirect Detection

This method for detecting dark matter focuses on looking for the products obtained from dark matter interactions produced in the annihilation or decay of dark matter candidates, it is expected to be an anomalous flux of photons, neutrinos or cosmic rays. These products are mainly standard Model particles such as fermions, bosons, etc which are described by the forces of the standard model of particle. The detection is done by measuring the expected annihilation cross sections for weakly interacting massive particles which are detected[2]. Examples of these kinds of experiments are Fermilat, Pamela, Veritas, High altitude water Cherenkov experiment(HAWC), etc.

1.1.2 Production At Collider

It is one of the methods for identifying dark matter. The dark matter is produced at particle accelerators in different ways. This experiment seeks to create dark matter particles by simulating high-energy conditions similar to those just after the Big Bang. Due to the weakly interacting nature of dark matter, its creation in a particle accelerator could be detected by observing events where momentum or energy is missing. If the energy loss cannot be explained by standard model particles, it would be reasonable to infer that it escaped in the form of dark matter. The pursuit of dark matter through particle accelerators has significantly limited theoretical models[3]. Example of this type of collider is the Large Particle Collider which is located at CERN in Geneva Switzerland.

1.13 Direct Detection

This method of detection employs detection of dark matter itself by studying the interactions of dark matter directly with atoms. This experiment aims to detect dark matter particles through their interactions with normal matter in highly sensitive detectors e.g silicon detector. Experiments designed for direct detection operate on the premise that dark matter interacts with the nucleus or the electrons in the atoms of the detector and there will be a signal that can be interpreted as a DM. It is worth mentioning the most important candidates such as Axions, Dark photons, WIMPS, sterile neutrinos, etc. The leading candidate is WIMPS. Commonly employed method for detecting dark matter directly is the use of scintillating targets. This method relies on factors such as the density of dark matter in the vicinity of Earth and the properties of the selected materials[4]. Due to the fact that dark matter undergoes weak interaction with regular matter the experimental setup requires very low background noise interference to be able to detect signals from this interaction. For this reason the setup is located in deep underground laboratories which helps to minimize the arrival of cosmic rays to the detector[5]. Examples of these experiments include CDEX, SENSEI, OSCURA, DAMIC, DAMIC M, etc. The DAMIC at SNOLAB and DAMIC-M experiments utilize silicon sensors to detect ionization events.

1.2 Charged Coupled Devices

A prevalent technology in the realm of digital imaging is the Charged Coupled Device (CCD) that was invented by Willard Boyle and George Smith in 1969. This technology is used in various fields such as digital cameras, camcorders, astronomy, medical imaging devices, and scientific research instruments. It was initially intended to be a memory storage unit but due to their ability to act as an ionizing image sensor, they are now used to acquire digital images. A Charge Coupled Device (CCD) is a highly sensitive photon detector. It is constructed from semiconducting silicon, CCDs utilize the photoelectric effect, compton scattering and pair production to sense photons. Essentially, a CCD is divided up into a large number of light-sensitive small areas known as cells or pixels[6]. As of today CCDs are found in imaging technology that helps to produce high sensitivity and resolution images. It is present in some of the modern digital cameras that are used for specific science purposes that require very low intensity and noise, an example is the infrared camera.

Fig 1.1 shows a schematic diagram showing the processes in a CCD, from when a charge is collected, transferred along the surface by varying potential wells until it reaches the readout stage. A detector in the CCD is exposed to incoming radiation and the ionization process generates electron-hole pairs. The electric field propels holes towards the upper gate structure(potential wells), and they remain in the concealed channel until the transfer initiates. Simultaneously, electrons are guided towards the rear contact, where the bias voltage is implemented. Afterwards the transfer of charge begins sequentially for each pixel. A pixel comprises three gate contacts in a 3-phase CCD configuration. By manipulating the gate voltages, which can be independently switched from low to high or vice versa, it becomes feasible to transfer charge from one pixel to the next across the CCD through a process termed clocking. The clocks transferring charge across one column (i.e., in the row direction) are called parallel clocks. The clocks transferring charge across one row (i.e., in the column direction) are called serial clocks. Every pixel in a column shares the three gate voltages, and every column runs the parallel clock sequence. As a result, all pixels' charges are simultaneously transmitted in a parallel path. DAMIC CCDs have read-out amplifiers at the ends of the two outermost rows. For this reason, these rows are unique and are referred to as serial registers. The transfer gate is crossed by the final vertical transfer that introduces charge into the serial register.

The final vertical clock operation moves the charge from the active region into the serial register(SR), facilitated by the Transfer Gate. Charge transfer into the serial register occurs exclusively when this gate is at its low potential value. In this phase, charge undergoes horizontal clocking towards either side U (right side) or side L (left side). At the end, the charge is directed into an external circuit for the subsequent readout process. To ensure the orderly transfer of charge, it is imperative for the horizontal clocks to operate at a considerably higher speed than the vertical ones. This speed discrepancy guarantees that the charge from the next row is transferred through the Transfer Gate only after the entire row of the serial register has been emptied. As shown in figure 1.2. Every clock cycle and charge transfer process has the potential to lose charge back into the substrate. This loss is quantified by the Charge Transfer Inefficiency (CTI) which is a measure of the expected fractional loss during a transfer and is less than 1 part in ~10^−7 or better.

The CCD used in DAMIC-M experiment is an upgraded proposal for Janesick (search reference) in 1998 but not implemented successfully until 2017 by the A.Tiffenberg and his group (reference) to standard CCDs, known as Skipper CCDs. This readout allows a readout noise below 1 electron. It is valuable to note that precision measurements in traditional CCDs are limited by the readout noise of the CCD readout electronics, now the dark current and other electronic issues such as spurious charge become the limiting factors.

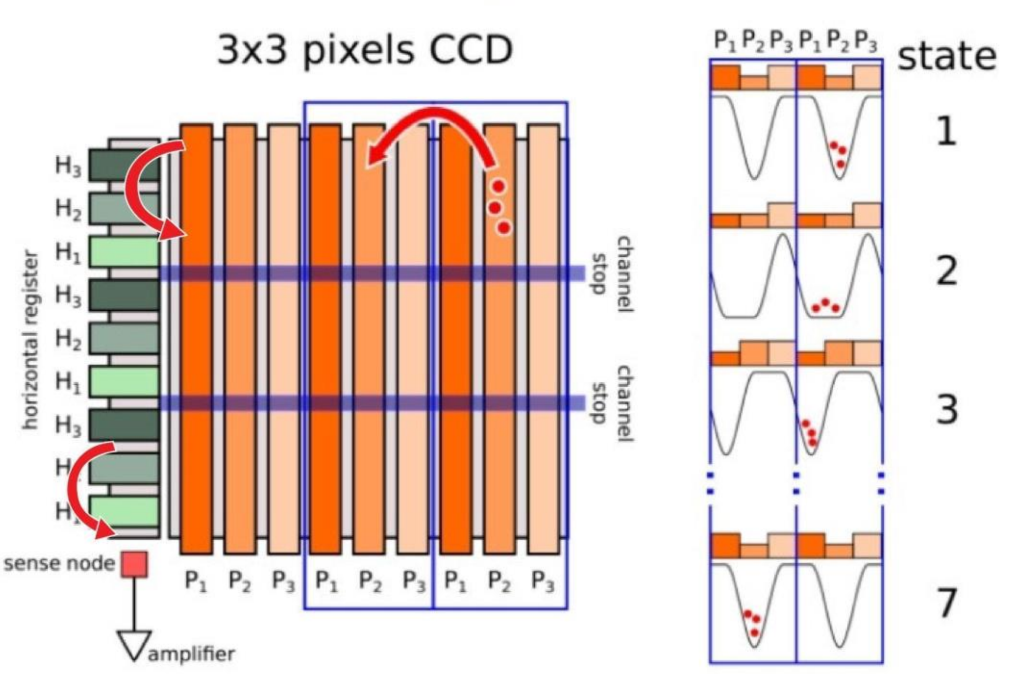


Fig1.1: Diagram of a CCD with a scientific readout system. At the right it can be seen the clocking sequence for transferring charge from one pixel to another. At the left is shown a put together picture of a CCD. Picture from [6].

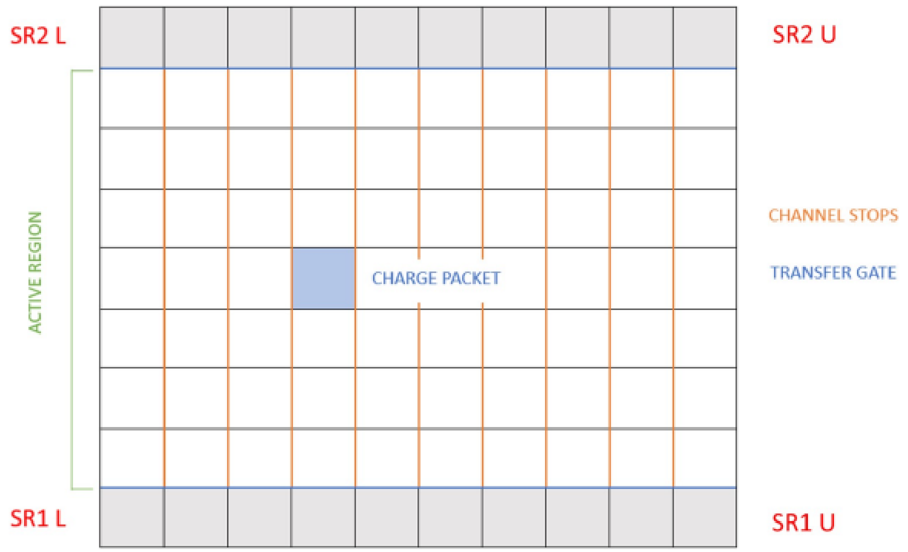


Figure 1.2:Diagram of the active region and serial registers (SR) of the CCD with labeled features.

1.2.1 Conventional Readout

These CCDs do not have the ability to reduce low frequency noise. Fig 1.3 shows an overview of the movement of the Charge packets for a conventional CCD. Here the charge packets are moved to the sense node, read and then discarded. The sense node is an active silicon (diffusion) region electrically isolated from all other nodes. The conventional CCD uses a sense node(floating diffusion gate) as a gate. Due to ohmic contact the charge is flushed out when the SN is set at VR and in consequence the SW and the OG can not change their values since the output gate in conventional CCDs is a fixed bias voltage. The figures below give a more vivid description of how this readout system works.

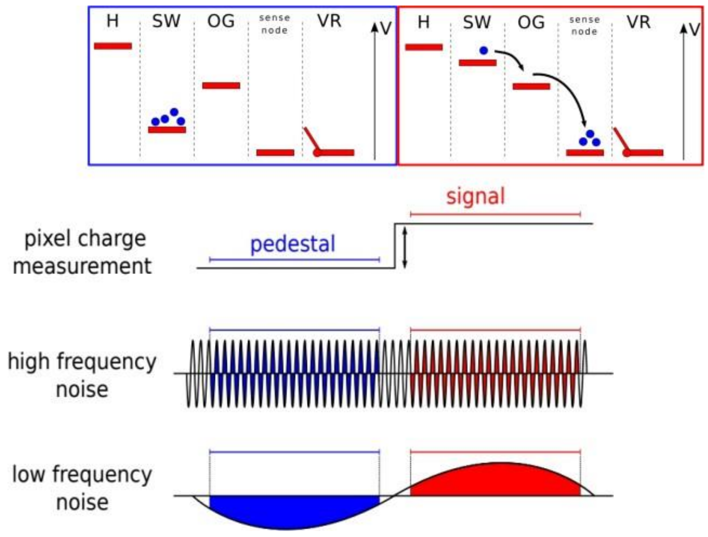


Fig 1.3: Showing pixel charge measurement of a conventional CCD. Figure from [6]

Figure 1.4 illustrates a schematic of the readout amplifier circuit. After the charge exits the serial register, it passes through the Summing Well gate (SW) and the Output Gate (OG) before being discharged into the Sense Node (SN), a capacitor responsible for measuring pixel charge. The charge transferred into the SN induces a change in the node's electrical potential, proportionate to the charge magnitude. This potential change is sensed, passed through the output JFET, and further amplified. The output transistor amplifies the signal, and a 16-bit analog-to-digital converter (ADC) digitizes it. By shutting the reset switch, which causes a pulse that the output amplifier detects, the charge in the sensor node is drained before the subsequent measurement. After a reset pulse, two measurements are always made. During the integration time, when the charge is still in the summing well, the first one is conducted. The second occurs when the sensory node is charged, likewise for a brief period of time called the integration time.

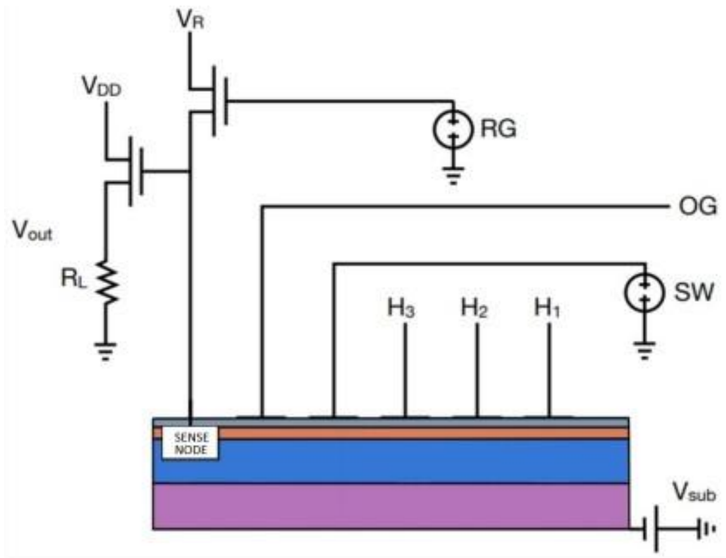


Figure 1.4: Circuit diagram of CCD readout. Picture from [7].

Following the signal measurement, the reset pulse is activated to discharge the charge, and this entire process is reiterated until the serial register is entirely read out. An example of a video output trace with pedestal and signal measurements is seen in Figure 1.4, pulses from the reset and summing well are visible. The reading system determines the charge level accumulated in a pixel by calculating the difference between the signal level and the pedestal level. The SW pulse locates the point of charge injection into the sensor node by using the correlated double sampling, or "CDS" technique. Reset pulse noise is subtracted by taking the difference between the signal (second measurement) and pedestal (first measurement). The CDS integration proves effective in compensating for high-frequency noise, primarily due to the central limit theorem. However, its efficacy is not adequate for reducing low-frequency noise, which persists in the CCD readout.

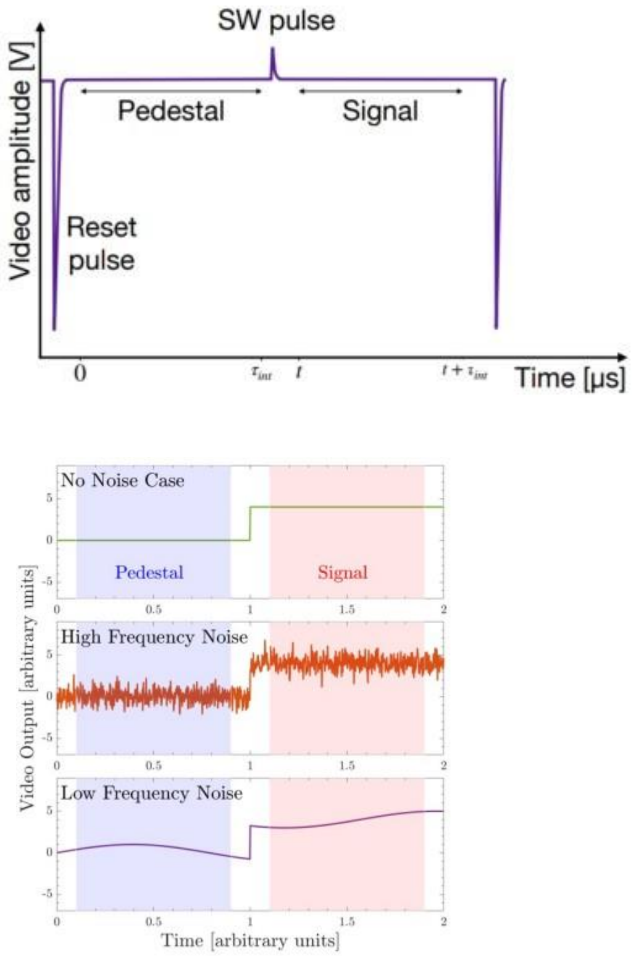


Fig 1.5: The top diagram shows a conventional CCD video output trace[7]. The down image shows a comparison of performing the CDS technique in a differential charge measurement in a case without noise, with high frequency noise components and a case with low frequency noise components[8].

CCD images record a compiled history of all ionization signals generated throughout the exposure time in a two-dimensional layout. If more rows are clocked in the y or x direction than the device contains, the resulting image becomes larger in the corresponding x or y dimension than the detector's size. These additional pixels, known as overscans, differ in vertical and horizontal overscans based on their pixel exposure time.

Horizontal overscans (x-overscans) occur when reading the serial register beyond the length of a row. Since this process is rapid, the extra pixels have minimal charge, serving as the baseline or pedestal for an image. This baseline corresponds to the Analog-to-Digital Unit (ADU) value representing zero charge in electron units (e−). On the other hand, vertical overscans (y-overscans) accumulate charge proportionate to the time required to read the entire CCD size. The SAOImageDS9((see the appendix section) visualization tool is commonly used for viewing these images.

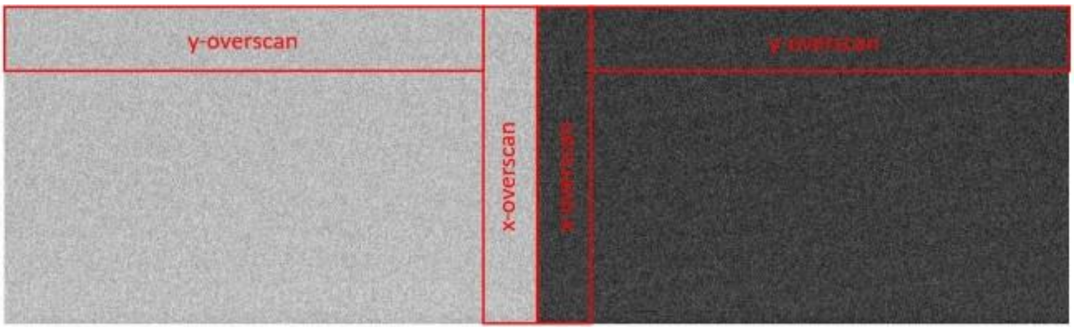


Figure 1.6: A non-skip image visualized with the “DS9” software. The left half side of the image has been taken with the left amplifier (L) while the right half side has been taken with the right amplifier (U). The x and y-overscans are labeled.

Figure 1.6 illustrates a CCD image displayed using "DS9," with both vertical and horizontal overscans clearly labeled. The pixels in this image have been sequentially read. As depicted in the figure, the baselines for the U and L amplifiers exhibit dissimilarities. However, this discrepancy does not indicate that one amplifier has a higher charge, as the charge is solely proportional to the pixel content after the pedestal subtraction process. This procedure is commonly known as equalization. The distribution of pixel values, post-pedestal subtraction, measured in Analog-to-Digital Units (ADUs) or electron units (e−), is termed the pixel charge distribution (PCD).

Figure 1.7 shows the several kinds of tracks that are frequently observed in CCD exposures, emphasizing the CCD's superior spatial selectivity as a particle detector. The images reveal ionization signals generated by alpha particles, electrons, and muons. Each of these events generates a unique track, enabling differentiation between them. Another category of events, known as point events, can be caused by particles like X-rays, gamma rays, or any other particle depositing a minimal amount of energy, including potentially dark matter candidates, neutrinos, or low-energy electrons.

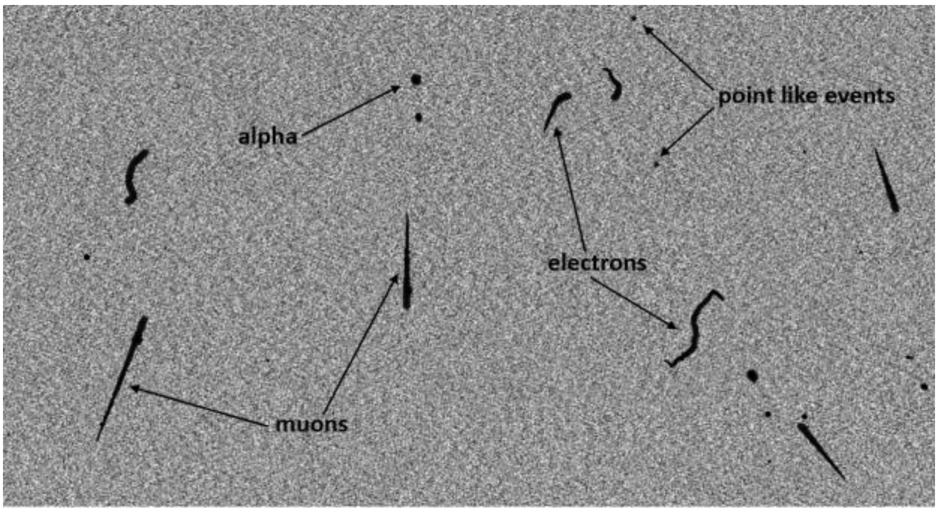


Figure 1.7: Diagram showing the image fraction visualized with “DS9” in which tracks produced by different types of particles are shown and labeled.

1.2.2 Skipper Readout System

This is an example of a specialized readout system that has the advantage for low noise applications. Early in the 1990s, Janesick et al. [reference] and Chandler et al. [reference] discovered that by taking advantage of the same principles that are fundamental to clocking charge in the rest of the CCD, one could create a non-destructive readout stage. This was how the skipper CCD was discovered. Utilizing this idea, Stephen Holland from the Lawrence Berkeley National Laboratory (LBNL) developed the first accurate single-electron counting silicon detector on a large-footprint. The fundamental idea of Skipper CCDs is to measure pixel charge several times nondestructively in order to achieve sub-electron resolution. We call these non-destructive charge measurements (NDCMs) simply "skips" and observe that noise can be reduced by the square root of the number N of NDCMs: $\sigma pix \rightarrow \sigma pix / \sqrt{N}$. This is achieved by averaging multiple charge samples from the same pixel. This results from using a readout-derived Gaussian white noise component in addition to representing pixel charge as the real induced ionization[9].

Low-frequency noise is reduced with Skipper reading, which is a significant result because each measurement's integration time is shortened as shown in Fig 1.8. Unlike the conventional CCDs here, the Skipper CCDs use floating gates; there is no ohmic contact compelling the charge to be flushed out when the sense node is set at VR. As a result, the Summing Well (SW) and the Output Gate (OG) can alter their potential values from high to low, facilitating the movement of charge back from the floating gate to the SW. This facilitates clocking between the SW and SN and it can be iterated a desired number of times. Also, the pixel charge can be measured a preferred number of times. The reset pulse specifically restores the Sense Node (SN) to VR after the charge has been read out.

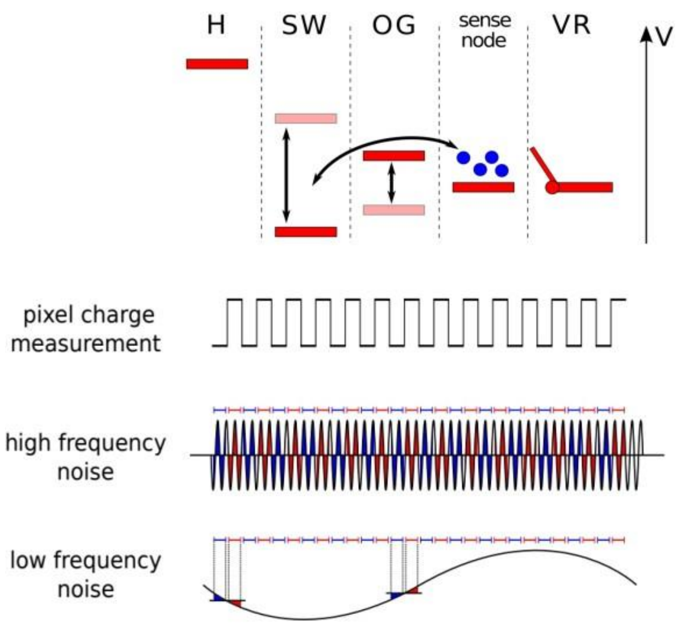


Fig 1.8: The pixel charge measurement of a skipper CCD. Here the low-frequency noise component is smaller. Figure from [6]

During the integration process the Dump Gate is maintained at a high level to prevent charge drainage. However, after the final measurement, this gate is lowered, allowing the charge to be cleared out. The entire process is better illustrated with fig 1.9.

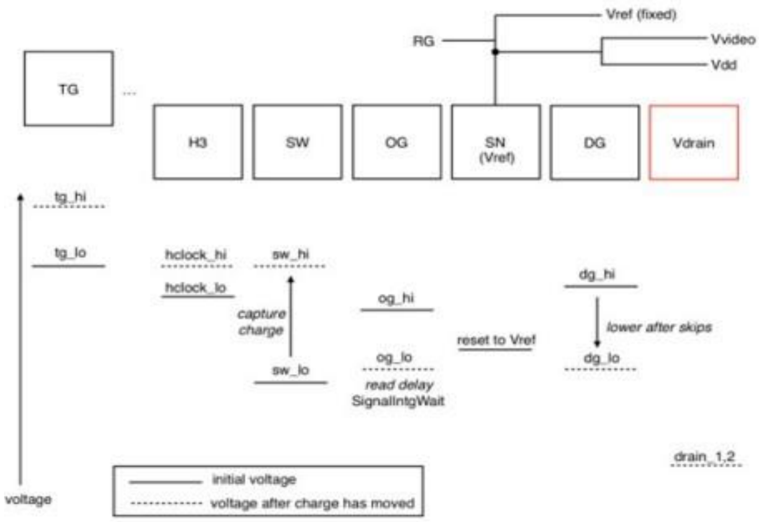


Figure 1.9: Diagram illustrating the structure of the output stage in a skipper CCD.

Skipper CCDs achieve sub-electron noise levels by statistically reducing uncertainty through averaging each pixel value across all the Non-Destructive Charge Multiplications (NDCMs).

1.2.2.1 Images for the Skipper CCDs

Information from each NDCM measurement is stored in a raw FITS file. Software like WADERS is used to average the NDCMs of each pixel inorder to generate an average image. WADERS (softWAre for Dark matter ExpeRiments with Skippers) is a Python3 based code used to process both simulations and real data. WADERS can be configured using a JSON file and handles all the passages required for the analysis of data. The FITS file format is used to provide the raw photos. The user can select the statistical algorithm that the code uses to compress a set of single skip measurements into a single image. Then, WADERS is used to clusterize charged pixels and subtract the pedestal value (row by row, column by column, using the overscan or active region). The code is also employed to keep an eye on the data quality[10]. Below is an explanation of how WADERS are used in the data analysis.

Figure 1.10 shows an evolution of the pixel charge distribution as the number of skips used to obtain the average image increases. It is seen that the electrons are better seen for a higher number of skips. Individual electron peaks are clearly seen better for a higher number of skips. The gain k can be extracted from the distance between the centroids of the first and second peaks. The 1st peak corresponds to the pixels that contain 0 e −, the 2nd peak refers to the pixels that contain 1 e − and the 3rd peak corresponds to the pixels that contain 2 e −. The term e − is technically a hole, it is used to refer to a single unit of charge.

Correct application of the clustering and masking techniques is necessary in order to detect and eliminate the clusters and precisely estimate the dark current. More specifically, the clustering method has conducted a systematic search of the image looking for pixels with charge larger than 3σ, where σ relates to the readout noise, in order to reconstruct the clusters (shown in blue) for the image corresponding to the dark current fit plot shown in Figure 1.11. Potential clusters are identified as pixels having charge above this pedestal threshold. A region can be categorized as clustered if it has at least one pixel in each of the probable clusters that has a charge higher than the specified threshold of 10σ. A cluster is eliminated correctly by applying clustering and masking processes.

The 2000 skips images are used to estimate and monitor the dark current level. For each run, one 2000 skips image is acquired. The charge distribution of pixels in the active area is characterized by a series of consecutive Gaussian peaks (G) with standard deviation equal to σ0, the readout noise. The k-th peak is centered in (k−1) e −. The first peaks are the result of the convolution with a Poisson distribution (P) with average λ, associated to the dark current induced charges. A fit is thus performed on the first two peaks to estimate the dark current rate (λ[ADU/pixel/image]), as well as the gain (g[ADU/e−]) and the readout noise (σ[ADU]):

$$\mathcal{N} \sum_{n=0}^{k-\text{peaks}} \left[\mathcal{P}\left(\frac{\lambda}{g}\right) \circledast \mathcal{G}\left(n - \frac{\mu_0}{g}, \frac{\sigma}{g}\right) \right]$$

where g is the conversion constant between ADU and e− and $\mathcal{N}$ is the normalization. When taking into account the charge distribution in ADU units, the former represents the separation between the centers of the 0 and 1 electron peaks. This is seen in fig 1.11. Note that this process is done using WADERS software.

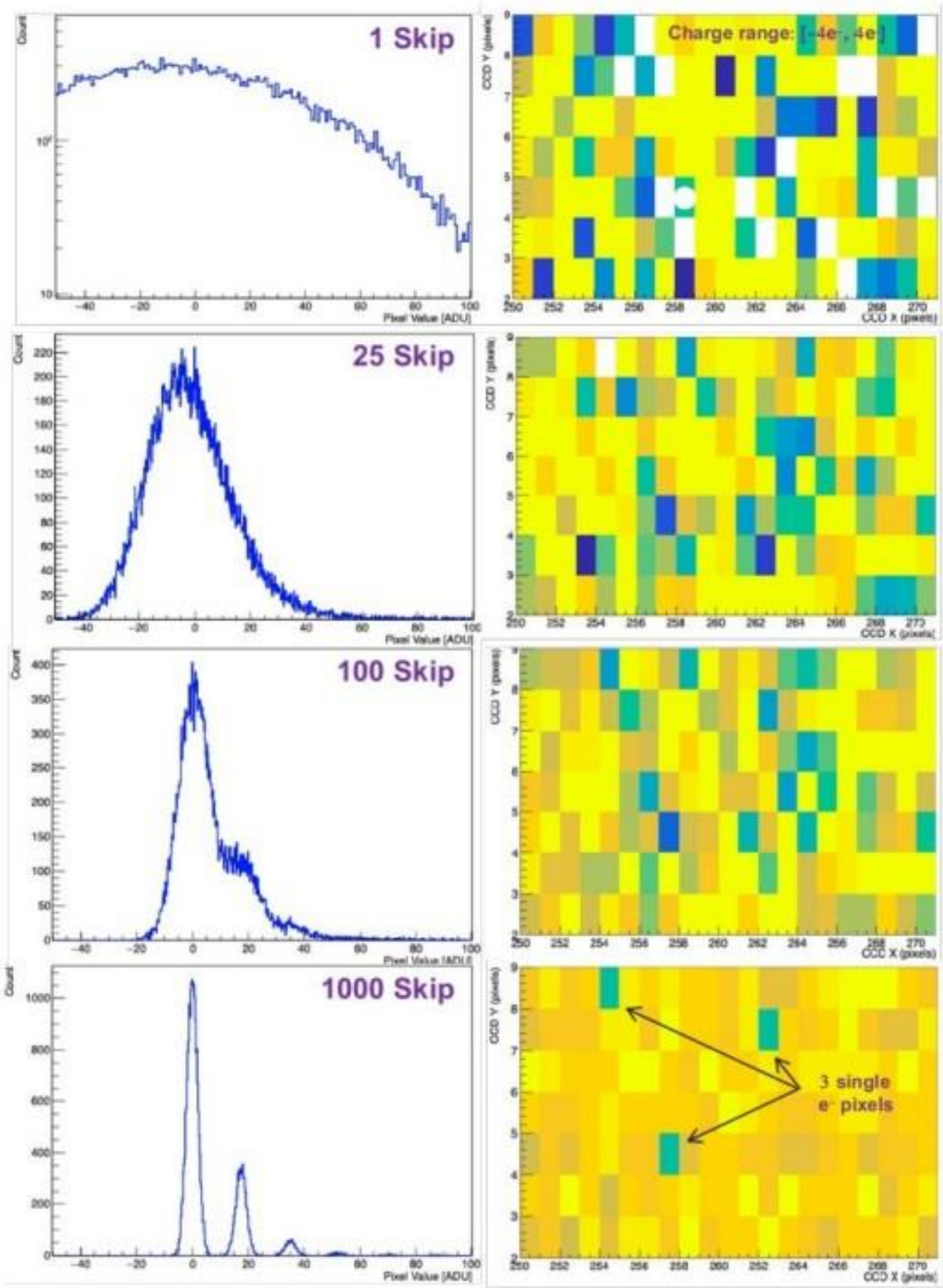


Figure 1.10: Evolution of the same Pixel Charge Distribution (PCD) and selected image region as the number of skips increases. One can see that as the number of skips increases, the PCD becomes more tightened and a discrete peak structure emerges while the noise per pixel is reduced on the image. Initially, the image region showed a wide range of potential charge values (limited to -4e − to 4e in terms of colors). After 1000 skips, the region contains only 3 occurrences of 1e events. Figure from [8]

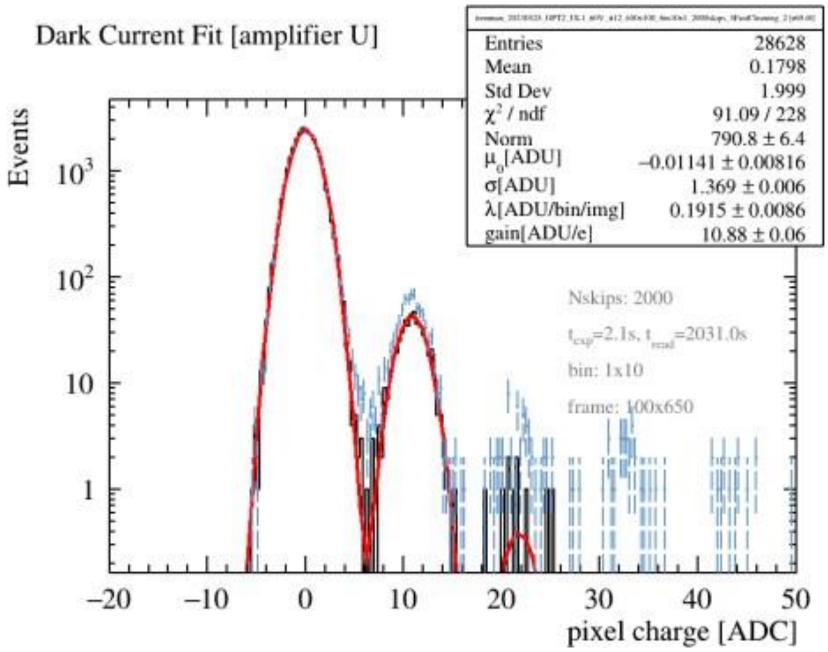


Figure 1.11: Dark current fit plot of an image taken with 2000 skips. The black histogram corresponds to the red histogram after the clustering and masking processes. The dark current rate λ (given in units of ADU per binning per image), the calibration constant k and the resolution (readout noise) σ are given by the dark current fit (red curve), i.e. the Gaussian-Poisson convoluted fit of the black histogram.

1.3 DAMIC-M Experiment

This experiment is used for direct detection of dark matter. DAMIC M simply means DAMIC at Modane. It is an experiment that will be done after the DAMIC at SNOLAB experiment. The experiment is designed to showcase a 1024×6176 pixel skipper CCD. The CCD features a three-phase polysilicon gate structure with a buried p-channel, a pixel size of 15×15 µm^2 , and a thickness of 675 µm. The bulk of the device is made of high-resistivity (10–20 kΩ cm) n-type silicon which can be fully depleted at substrate biases ≥40 V. For this measurement, the silicon bulk is fully depleted by a 95 V external bias, which also limits the lateral diffusion of charge carriers. The voltage biases, clocks, and video signals needed for the CCD operation are supplied via a kapton flex cable wire bonded to the device. The CCD is controlled and read out by commercial CCD electronics (Astronomical Research Cameras, Inc.). The CCD is housed in a copper frame within a stainless-steel vacuum chamber which is held at 10^−7 mbar and cooled to 126 K. Thin aluminum lids are placed on both the front and backside of the copper frame to shield the CCD from infrared radiation(IR) photons generated by the warm chamber walls. The dark current rate is thus reduced by an order of magnitude. A slow control system controls and monitors the operation of the various instruments. As seen in the previous section, the skipper CCDs utilizes non-destructive, repetitive measurements of pixel charge, enabling the precise detection of a single electron with high resolution. It is a kg-size detector with a depth of 1.7 km installed at the Laboratoire Souterrain de Modane in France, protected from cosmic rays by the rock overburden of the Alps.The DAMIC-M is being built for the sole purpose of enhancing the investigation of the hypothesis related to dark matter particles, particularly those associated with the "hidden sector," making substantial strides by several orders of magnitude. Hence this detector will help to significantly decrease background noise, enhancing sensitivity for detecting precise ionization signals resulting from nuclear and electronic recoils[11].

The DAMIC-M is currently in its development phase but a prototype named the Low Background Chamber (LBC), equipped with 20g of Skipper CCDs with low background, has been installed at the Laboratoire Souterrain de Modane and is actively collecting data[12].

1.4 Goals Of This Study

At IFCA (Instituto de Física de Cantabria), a clean room has been built up with an experimental setup for describing CCDs for the DAMIC-M experiment. CCDs are always used subterranean in the DAMIC-M experiment. Taking advantage of the fact that this setup is above ground, CCD images have been obtained by operating the CCD in a manner that approximates the kind of data that would be obtained from images captured by an underground CCD experimental setup.
This study will concentrate on explaining the experimental configuration and the roles played by each component like the cryostat and electronics, particularly in light of the recent advancements in electronics. It will also offer a thorough analysis of the manuals for every system that is being considered like the vacuum, cryogenics and the slow control. This work will also provide comprehensive instructions and operating recommendations to guarantee a full comprehension of each system's functionality and how to use it. These objectives will be developed in the following chapters.

Chapter two will focus on describing the experimental setup and the functions of each part of the setup especially since there has been an improvement in the electronics since the last studies.

In chapter three, I will provide an in-depth exploration of the manuals for each of the systems under consideration. This section will serve as a critical resource, offering detailed instructions and operational guidelines to ensure a thorough understanding of each system's functionality and how to effectively operate them.

Each manual will cover the key components, features, and configurations of the systems, outlining the operation, and maintenance. Additionally, I will include best practices to optimize performance and avoid common issues.

The exploration extends to the optimization of CCD configuration parameters in Chapter 4, with a primary goal of enhancing the efficiency of charge collection, transfer, and readout processes. This optimization is pivotal for mitigating and accurately calibrating dark current, thereby yielding more dependable estimations of pixel readout noise.

In a nutshell, this research makes a meaningful contribution to the analysis and comprehension of CCDs intended for the DAMIC-M experiment. It offers insights into the impact of electromagnetic noise on CCDs reading.

CHAPTER TWO

2. Experimental Setup

Understanding the properties of dark matter (DM) stands as a paramount objective in both particle physics and astrophysics today, with direct-detection experiments serving as pivotal tools in this quest. Exploring the realm of DM particles with masses considerably lower than that of protons, has become a crucial frontier gaining increased attention. As discussed in chapter one, direct-detection searches primarily focused on DM particles interacting elastically with atomic nuclei, thus exhibiting limited sensitivity to sub-GeV DM. Nevertheless, progress in enhancing sensitivity to dark matter (DM) masses significantly below the GeV scale has been made by studying signals triggered by inelastic processes. An inelastic interaction could be seen with the Skipper-CCDs designed to detect electron recoils originating from sub-GeV DM. Where the dark matter particles might excite the nucleus and make it break apart. This interaction will not only require higher energy, but it is also less likely to happen with the low-mass dark matter particle that DAMIC-M is targeting.

The Skipper CCDs aim to boast ultra-low readout noise and enable precise measurements of the number of electrons collected in each of their million pixels when a hit produces ionization, this charge is moved to the readout amplifiers with a charge transfer efficiency of about 99.9999%. These properties, coupled with a low background rate of Skipper-CCD experiments, establish the most stringent constraints to date within the domain of direct dark matter searches concerning sub-GeV DM-electron interactions. The groundbreaking results from this experiment aims for even more substantial detectors in the near future.

Characterizing and understanding the intrinsic background of the CCDs is a crucial task. CCDs readout Test-stand have been built in different institutions, such as the University of Chicago, University of Washington or LPNHE among others, also at IFCA, we have one. These Cryogenic test chambers are set up across institutions to conduct systematic CCD testing and design a selection process in view of DAMIC-M CCD production. A protocol is defined to establish detector grade and characterize detector performance. The test chamber constructed at IFCA will be additionally used to commission the instrumentation for a radiopurity service based on skippers CCDs located at the Underground Laboratory of Canfranc, Spain (LSC).

In the following we will described, in detail, the test-stand located at IFCA¨"

As stated above, the key purpose of the setup is for characterizing and background measurements of the CCDs for the DAMIC-M experiment and future experiments like Oscura. Which allows for evaluating single electron resolution, impact of electromagnetic noise on CCD images, study defects on the silicon net, dark current or spurious charger measurements among many other possible studies and also these effects can be studied at different temperatures. Below is a figure explicitly showing a Skipper CCD Test Chamber.

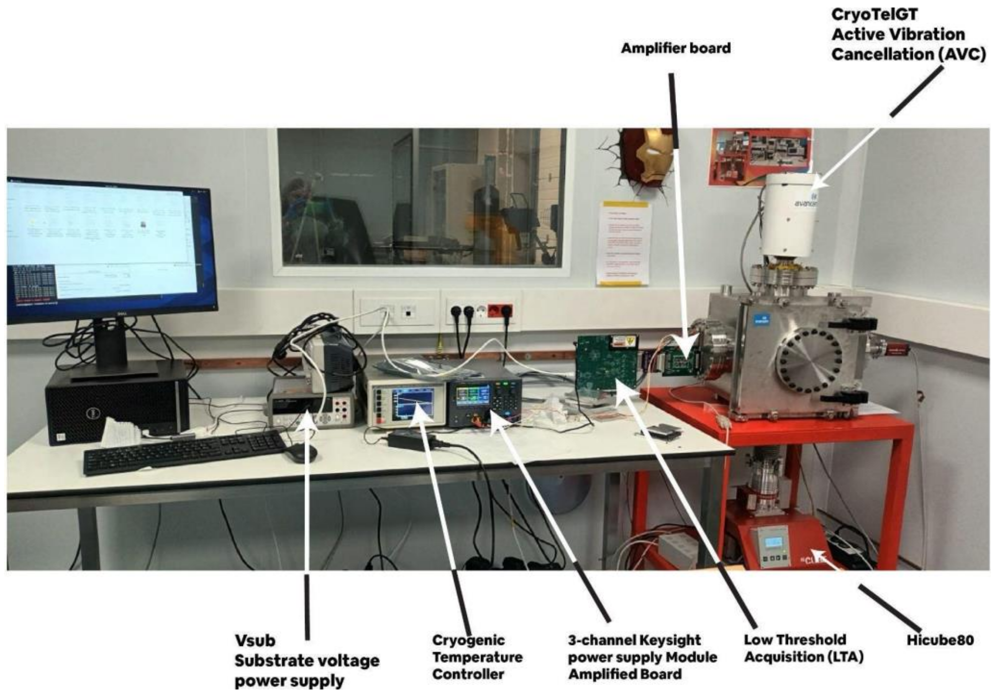


Figure 2.1: IRON MAN set-up for CCDs testing for DAMIC-M collaboration with labeled instrumentation.

2.1 Cryostat

The cryostat is a crucial part of the CCD setup because it protects the CCD from the environment and provides low temperatures that increase sensitivity and reduce noise. The cryostat is made up of the following Cryocooler, Vacuum Pump, Temperature Controller, Pressure Monitor and a Pressure Sensor with a DC power supply of 220V. The chamber contains the CCD and the kapton flex cable. The vacuum control system is made up of a HiCube 80 vacuum pump that regulates the air pressure inside the chamber through the CenterOne controller that monitors the pressure inside the chamber using a pressure gauge. The CCD box is supported inside the chamber by an L-shaped copper structure that is screwed to the cryocooler's cold head.The cryocooler, the cooling system mechanism, uses the copper support to lower the CCD's temperature. The cryocooler has an active vibration cancellation (AVC) system to reduce any mechanical stress and electronic noise caused by vibrations at the cold head. This technique guarantees steady CCD operation and successfully reduces vibrations. A temperature control system, such as the Cryogenic Temperature Controller (CTC100), is required for temperature regulation because the cryocooler (CryoTelGT) is unable to do so. This system also includes a temperature sensor and a power heater that ensures that the desired temperature is achieved. Specifically, the temperature is set at 120 K. The purpose of cooling a CCD is to reduce dark current, which can interfere with the signal-to-noise ratio of the CCD[12].

2.1.1 Cryogenic System

This is the most complex part of the cryostat. It is the part that helps with decreasing the temperature in a controlled way as well as stabilize the temperature and pressure inside the chamber.

2.1.1.1 The Cryocooler

The one used in this work is the Cryotel GT with controller Gen II v1.0.0, it is a free-piston, stirling cryocooler that consists of several integral components such as a cold finger, internal piston, pressure vessel, and a passive vibration absorber, etc. which was designed by Sunpower Inc. This cryocooler was designed to match the requirements of its user and it weighs about 3.1kg. On the surface of the external copper ring, which dissipates heat from the cooler, there is a stainless steel plate. This plate features four M3 threaded holes, allowing for the attachment of a NW50 or a customer specified vacuum flange. The test cap consists of a copper cap with two resistors, a through hole with ¼"-20 clearance for connection to the copper tip, and a copper clamp ring with M3 clearance holes to clamp temperature sensors around the circumference of the cold tip. This is done with an M3 screw in the 3mm drilled hole. A thin layer of Indium, Apiezon grease, or similar thermal grease is used between the sensor and the object to ensure proper thermal conduction. With a temperature sensor, a diode (25 Ω) in thermal contact with the CCD receives from the CTC enough power to control the temperature gradient and stabilize the CCD temperature over a long period of time either to expose the CCD or be in standby. Also the temperature sensor feedback also controls the cooler's power ramp-up. If the sensor is not installed properly, the cooling capacity of the cryocooler will be severely limited and temperature control will not function.

The NW50 flange has options of being either removable permanent to meet the requirement of the load(the object or area being cooled) being cold in the vacuum. When a mechanically generated vacuum flange is used it is usually sealed with an O-ring and clamp to eliminate possible loading of the cold finger from convection or condensation of elements in the atmosphere such as water vapor and nitrogen. This continues to maintain a vacuum inside the cryostat. The Controller measures the temperature inside the vacuum chamber by using a PT100 temperature sensor which is encased in a small copper slug.

The cryocooler operates by moving heat from the cold finger region to the heat rejection region, due to this it is built with either air-fin, water jacket or conductive cooling to aid proper heat rejection to prevent the cryocooler from overheating and getting damaged.
For the air-fin option, The air fins are attached to the heat rejector, transferring heat from the rejector to the fins. Forced air then absorbs and expels this heat from the system. To utilize the air fin option, it is required that there is no gap greater than 1 mm between the air fins and the shroud, guaranteeing the air passes through the fins rather than any gaps. A minimum airflow of 100 cfm is necessary for effective cooling. Sunpower provides both permanent and removable air fins.

For the water jacket option which is the one used in our setup, The water jacket is installed over the heat rejection area, with water being circulated through the system. It uses a standard 1⁄4" Swagelok compression fitting for connections. It is also available in removable or permanent versions.

For proper functioning of the cryocooler, the internal components oscillate at 60Hz. This vibration can be reduced using the passive balancer/absorber. This device located in the out end of the cryocooler has an amplitude of 5 mm and is tuned to oscillate at 60Hz and absorb energy at this frequency. Another device that helps to reduce vibration in the cryocooler is the AVC(active vibration Cancellation) which has the same amplitude as the passive absorber but is slightly longer in size. The AVC system offers substantial active mitigation of the cryocooler's vibration by exerting an equal and opposing force to counteract the motion of its components. The controller in AVC supplies DC energy to the Cryocooler, measures the vibrations, provides instructions to the AVC balancer and communicates with the user through an RS-232 serial port on a computer.

Inside the cryocooler is also located a Pressure Vessel Cooling jacket that slips over the back end of the cooler and is attached to the water jacket. This helps to reduce temperature at the back end which results in improved cryocooler performance. Within the pressure vessel is a linear alternator transforming electrical power from the controller into linear motion for the piston. This motion generates an oscillating pressure wave that travels from the pressure vessel to the cold finger, inducing movement in the displacer housed within the cold finger. The pressure wave and the regenerator within the cold finger induce a temperature contrast, initiating a Stirling thermodynamic cycle. This cycle facilitates the transfer of heat from the cold tip to the heat rejector, consequently leading to a gradual decrease in the temperature of the cold tip. The heat rejection is done fairly through the walls of the pressure vessel but majorly by the copper fins which helps to direct air out.

The electrical pins on the metal plate at the end of the pressure vessel near the balance absorber are encased in glass, serving as an insulator to prevent helium leakage from the pressure vessel. This setup is known as a feedthrough. Due to the presence of the glass insulator, feedthroughs must be handled with care. The Cryotel GT is normally shipped with a power cable that attaches to the feedthroughs and the controller. This cable consists of orange and white 16 gauge wires with a molded plastic connector for the feedthroughs at one end and crimp sleeves to attach to the proper terminal block on the controller at the other end. The power cable is installed by aligning the cryocooler feedthrough pins with the holes in the cable connector and pressing down. Then a restraining screw is inserted to the connector and tightened.

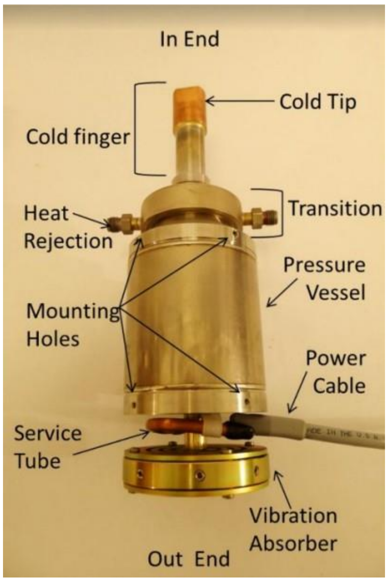


Figure 2.2: CryoTel GT Cryocooler

There are threaded holes on the outer diameter of the transition and end plate are designed for attachment of the cooler to an external mechanical structure for testing or integration into the application[13].

The precaution and the test of the cryocooler are discussed in the Appendix.

2.1.2 The Cryogenic Temperature Controller

The Cryogenic Temperature Controller (CTC100) is a device that can monitor and control temperatures with millikelvin resolution. The one used IFCA is 13 lbs in mass with dimensions 8.5" wide × 5" tall × 16" deep. It operates from an 88 to 264 VAC power source with a line frequency between 47 and 63 Hz. The CTC is packaged with three detachable power wires for connection to the power source and protective ground. On the back panel of the CTC is a power entry module(chassis grounding lug), labeled AC POWER , which provides connection to the power source and to a protective ground. The protective ground is usually a heavy duty ground wire, #12 AWG or larger, connected from the chassis ground lug directly to a facility earth ground to provide additional protection against electrical shock. A 10 A/250 V 3AB Slo-Blo fuse is used here to protect the device from overcurrent which can potentially lead to fire or damage of the equipment. It is important to note that all the covers and panels of the CTC are in place when in operation in order to prevent personal injuries to the user. The CTC has a minimum sampling rate of 1 Hz and a maximum of 50-60 Hz and the data logging rate is 10 samples/second/channel to 1 sample/hour/channel.

The CTC system consists of sensor inputs, two powered and four analog voltage outputs and up to six feedback control loops. It also has four general purpose analog and digital I/Os with auto tuning functions for setting PID parameters automatically[14].

Sensor Inputs

The sensor inputs consist of four temperature inputs. Each of the CTC100's four temperature inputs can read any type of resistive temperature sensor with a resistance below 300 kΩ, including RTDs, thermistors, ruthenium oxide, carbon glass, etc. Additionally, it can read diodes with a voltage drop below 2.5V. Provisions are made for connection of 2-wire or 4-wire thermistor, diode, or RTD using Two 9-pin D-sub sockets to the four temperature inputs. Each of these inputs has its own 24-bits ADC with eleven input ranges, and is equipped with its own independent excitation current source. Standard calibration curves for various sensors are provided and the user could input custom calibration curves with up to 400 points each. Each sensor input features high and low level or rate of change alarms. The sensor inputs can be low pass filtered or compared with another channel to minimize noise. Temperature sensors can be calibrated in three ways either by selecting one of the 33 preloaded calibration curves for common sensor types or by entering Steinhart-Hart, Callendar-van Dusen, or diode calibration factors or loading custom calibration curves with up to 400 (temperature, resistance) or (temperature, voltage) data points via a communication port or a USB memory stick.

Each sensor input has an alarm that triggers when the input exceeds a predefined limit. When activated, an alarm can play a sound, shut off a heater output, and/or trip a relay. Sensor inputs can be low pass filtered to reduce noise, have the value of a second input subtracted, and have the rate of change calculated.

Voltage outputs

The CTC100 has two heater outputs that are used with resistive heating elements with resistance between 10 and 250 Ω. It is preferable to use the 25 Ω heaters because they produce the most power, up to 100W. Heaters with higher or lower resistance will generate less power. Each heater output features a PID feedback loop that continuously adjusts the heater power to maintain a constant sensor temperature. The two sources are connected by #6 screw terminals. Accepts 12–22 AWG wire or #6 spade terminals up to 0.31" wide. Max torque 9 in-lb. Additionally, it has an output resolution of 16 bit and its accuracy depends on the range(±1 mA (2 A range), ±0.5 mA (0.6 A range), ±0.2 mA (0.2 A range)).

Analog I/O

As stated before, the CTC100 is packed with four voltage analog I/O channels, independently configurable as inputs or outputs. These four voltage analog I/O each of which supports PID feedback and custom calibration curves. These channels are connected using 4 BNC jacks. It has a voltage range of ±10 V, and its resolution is 24-bit for input and 16-bit for output. The ADC noise in these channels is 30 µVRMS which is equal to 10 µVp-p(at 10 samples per second).

Digital I/Os

It also has 8 digital I/O(opto isolated TTL lines) that are configurable either as 8 inputs or outputs which are connected by one 25-pin D-sub socket. It has four independent SPDT relays with maximum current of 5A that can interact with user programs. These relays are connected by One 12-pin 3.5mm header and they have a maximum voltage of 250 VAC. There are also three general purpose virtual channels that calculate values to be displayed, graphed, and logged.

Other Features CTC100 Include:

Graphical Touchscreen Display System

The CTC100 can display temperature measurements and heater outputs either numerically or on graphs. It can plot up to eight channels simultaneously, either on a single graph with a shared Y-axis or on separate graphs with individual Y-axes.

Data Logging

The CTC100 can store up to a million readings per channel in its internal memory. This data can be saved as a text file on USB memory sticks or hard drives. The readings per channel can be logged at intervals ranging from 0.1 seconds to 1 hour. This is done by using a Windows application for graphing CTC100 log files that can be downloaded from the SRS website.

The CTC100 can be controlled via USB, Ethernet, and either an RS-232 or an optional GPIB interface. Which enables the user to operate it through the slow control system. When using the USB interface, the CTC100 appears as a standard COM port on the computer and can be controlled by any software compatible with an RS-232 port. Also CTC100 functions can be scripted such that the User's program can add new capabilities.

2.1.3 The Pressure System

The vacuum system used is the Pfeiffer HiCube 80 ECO Dry Turbo Pumping Stations weighing about 50kg. This system usually comes with connection cables of different sizes, communication accessories, vacuum sensors. The turbo pumping stations are fully automatic pump units ready for connection. The turbo station consists of a portable vacuum pumping unit and a matched backing pump. The backing pump by a single-phase extended voltage range motors with reversible voltage range. This voltage range has to be placed correctly to avoid damage to the motor. The desired voltage range is set on the voltage selector switch using a suitable screwdriver. The backing pump is usually equipped with a transportation lock that helps to secure the entire vacuum system against damage during transportation. The HiCube 80 ECO has an electronic drive unit of the turbopump and its method of cooling is by forced air but in the case of excess temperature, the electronic drive unit helps to cool down the temperature of the drive automatically. The turbopump is fastened to a high vacuum flange which is usually of types IS0-KF or ISO-K, its load capacity depends on how the turbopump is used. There is also a counter flange, this flange is equipped with a splinter shield or protection screen that protects the turbopump from foreign bodies coming from the chamber thereby reducing the pumping speed of the pump. The evenness of the counter flange does not exceed 0.5mm maximum for the entire surface. The flange material is made up of Aluminium or stainless steel, and during operation, must be at least 170 N/mm^2. It also has a display control unit (DCU 002) which is used to control and monitor the pumping station. The DCU in this type of vacuum can be detached from the pumping station and used together with a connection cable M12 as a remote control. The LED on the DCU helps to show the operation condition of the turbopump. Where red indicates malfunction, yellow indicates warning(example improper assembling), green with rotation speed of <50min^-1 indicates that the pumping station is off and green with set rotation speed attained indicates that the pumping station is on[15].

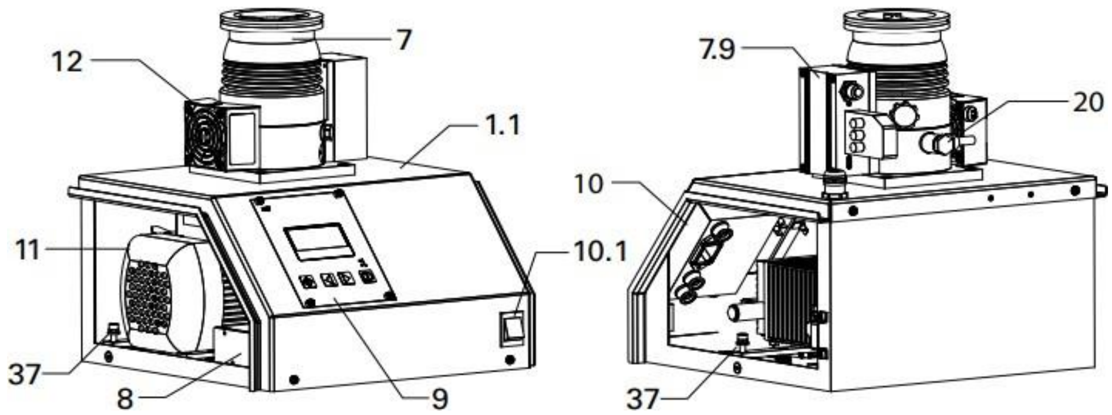


Fig 4: Components of the HiCube 80 ECO.

1.1	Casing	9	Display and control unit DCU 002 (option)	12	Air cooling unit
7	Turbopump HiPace 80			20	Fore-vacuum connection
7.9	Electronic drive unit TC 110	10	Relay box	37	Hexagon nut, transportation lock
8	Power supply pack TPS 110	10.1	Main switch		
		11	Backing pump MVP 015-2		

The connection between the vacuum and the mains supply is made possible through the relay box. This connection is done with a mains cable which comes with the system. Ensuring a safe connection with a protective earth conductor, the mains cable is plugged into the mains connection of the relay box. When doing this, the main switch is always placed at position “0”.

An adapter set is usually used with the HiCube in order to close the vacuum opening in the event that the pump is inadvertently turned on.

2.2 Data Acquisition("DAQ")

The data acquisition (DAQ) machines employed in the operation of the Skipper CCD are sophisticated pieces of equipment integral to the entire system's functionality. These DAQ machines serve multiple critical roles, primarily focusing on the control of the CCD's firmware, data transformation, and storage, ensuring that the Skipper CCD can operate at its highest potential.

One of the primary functions of the DAQ machines is to interface with the CCD to capture analog outputs, which are typically in the form of image FIT files. FIT (Flexible Image Transport System) files are a standard format used in astronomy and other scientific fields for storing, transmitting, and manipulating image data. The DAQ machines take these analog outputs and perform the crucial task of converting them into digital outputs. This transformation is essential because digital data can be easily processed, analyzed, and stored by computers, facilitating further analysis and ensuring that the data can be used for its intended scientific or research purposes.

To handle the large volumes of data generated during the operation of the Skipper CCD, each DAQ machine is equipped with significant storage capacity. Specifically, they are outfitted with two additional 8 TB hard drives. This substantial storage capacity is necessary to locally store the voluminous data produced during extensive and prolonged periods of operation. By having such a large storage capacity, the DAQ machines can operate efficiently without the immediate need for data offloading, thus reducing downtime and increasing productivity. Beyond merely capturing and storing data, the DAQ machines are also designed to play a pivotal role in data analysis. They come with advanced capabilities that allow for preliminary data processing and analysis directly on the machine. This feature is particularly useful for immediate diagnostic purposes and for ensuring the data integrity before it is transferred to long-term storage or further analyzed in more detail. Another critical function of the DAQ machines is the automated control they provide over the various operational tasks associated with the Skipper CCD, particularly in adjusting the voltage levels. Voltage adjustment is a delicate and precise task, crucial for the proper functioning and calibration of the CCD. The DAQ machines automate these adjustments, ensuring they are made accurately and consistently, which is essential for maintaining the reliability and quality of the data collected.

This automated control extends to various other tasks associated with the CCD's operation, reducing the need for manual intervention and thereby minimizing the risk of human error. This automation makes the system more robust and allows for continuous operation with minimal supervision, enhancing the overall efficiency of the data acquisition process[16]. This reading taken by the DAQ is obtained from the electronic component of the setup, which is the LTA.

The LTA board is produced by Astronomical Research Cameras (ARC). It comprises processing printed circuit boards (PCBs) that help to control the skipper CCD readout operations for clock sequencing, bias voltages, image dimensions, pixel binning and system gain. This system was recently updated to an LTA system. The LTA is a 7 by 8 inches single PC board hosting 4 video channels for readout, plus CCD bias and control. It has been optimized to work with thick, high-resistivity p-channel CCDs. The video channels utilize closely integrated low-noise differential amplifiers (LTC6363) and 18-bit, 15 Msps analog-to-digital converters (LTC2387) to capture video signals, employing digital correlated double sampling techniques.

The core part of the LTA is the Xilinx Artix XC7A200T FPGA. The Xilinx Artix XC7A200T FPGA is responsible for configuring programmable bias voltages, managing the clock signals that move pixel charge through the CCD array, handling video acquisition, telemetry, and transmitting data and status from the board to the PC. This fully digital approach to the data path enables the use of digital signal processing techniques for noise reduction in the video channels. A 40 channel DAC (AD5371), analog switches (ADG5234), and Op Amps (THS6072) produce the CCD clocks. A multi-channel adjustable potentiometer is created using the DAC. It lets you specify clock values with a dynamic range of up to 20 V within a ± 15 V range. An inherent offset controls the voltage range. Two DAC outputs are used by each CCD clock to identify its low and high states.

The clock signals are produced by the analog switches, which alternate each clock's low and high voltages. The required rise and fall time is provided by the Op Amps and related R-C network. Critical factors are output noise and clock shaping. ile the video readout shows stable clocks, during CDS integration times, there might still be some noise from the clock feed-trough. Reducing it at the generation point on the LTA board is crucial because that is not White Gaussian Noise (WGN). The video's noise level is already significantly reduced when 1 ppm of a 10 V clock is coupled in. The control and generation of power is another essential component of the LTA.

The LTA requires +12V DC input power supply,which can be provided using a typical AC/DC power switching supply. Even though any detrimental noise increase has not been observed when utilizing this type of supply, it is still necessary to keep the AC clean. AC lines are heavily contaminated with high noise associated with frequency switching, so either linear or switching AC/DC supply output is coupled to such noise. Therefore it is necessary to use an AC noise filter for measurements of very low noise. In order to prevent switching noise from affecting the frequency band of importance for the CCD readout, the DC switchers (LT3580) are run at 2 MHz. We achieved 100 µV of output noise RMS by using the ultra-low noise TPS7A33 with input and output filtering, as CCD bias is negative. In order to reduce the noise that couples to the onboard video inputs, the CCD, and the wires, the new line of ultra-low noise regulators is essential.

There are DC switchers which work with the frequency of 2MHz in the LTA and they help to switch noise away from the frequency band of interest in the CCD readout. Owing to the fact that the CCD bias voltage is negative, it aids the use of ultra-low noise TPS7A33 with input and output filtering to achieve 100µV of output noise RMS. This bias is usually adjusted using digitally controlled potentiometer.

The interaction between the user and the LTA board is made possible through the aid of a single Ethernet port which allows for sending and receiving commands and also data. A soft-core µBlaze CPU powers the initial configuration and the sluggish speed management of every block. The application is a lightweight, stand-alone C program that utilizes internal FPGA memory with a maximum memory requirement of 256 kbytes. The CCD's clock signals must be controlled with exact timing. In order to do this, the sequencer module (Seq) is developed in hardware to guarantee exact synchronization between the processing of ADC samples and clock signals during the CCD reading. ADC samples are normally supplied into the Digital Correlated Double Sampling (CDS) block, which calculates the sample average. The sequencer is responsible for managing the integration window. In order to transmit raw data, the user can also send ADC data into the Smart Buffer block. It should be evident that a complete image cannot be stored for later analysis in the internal memory of the FPGA, and real-time data transfer is not feasible given the raw data stream's speed of 15 MSPS with 18-bit. These restrictions lead to the Smart buffer storing the raw data in a regulated way. Because it was designed to function as an integrated oscilloscope, the user can set this block to record one, two, or all four raw video channels. It also supports continuous or single capture. An added feature is the ability to save data samples at exact times by routing signals from

the sequencer to the buffer and using them as external triggering. The user can set the Ethernet interface to send data at a lesser speed once they've decided to do so. The Smart Buffer stores data for this purpose. When it comes to finding issues in the video chain or maximizing readout speed and noise performance, this oscilloscope mode is quite crucial. Normally, the Packer module wraps the pixel data coming out of the CDS block with additional control information before sending it to the Eth module for external transmission.
The Tele module is in charge of gathering telemetry data from clocks and bias voltages, whereas the Clks and Bias blocks govern how clocks and bias voltages are configured. Additionally, the LTA enables simple scaling to an infinite number of parallel CCD operations. The boards are wired together and set up in slave mode for this reason. The CCD clock sequence is synchronized for the entire group while only one of them operates in master mode. Crosstalk noise from clock transitions is reduced with a synchronized readout. A JTAG port connectivity is added for easy programming and debugging [17].

The C++ code for the LTA software uses open-source libraries for IP connectivity. Its foundation is a client-server architecture in which commands, telemetry, and data collection are handled by a local daemon. Through the terminal, users communicate with the software through a request-response mechanism to carry out sequencer uploads, readout and telemetry requests, and LTA board configuration.
The computer's giga-etherner port is used only for UDP over IP transmission of data and commands, and the program uses the hard drive as a buffer to prevent needless RAM utilization. The program generates final images in FITS and other formats after completing a coherency check on the data.
Numerous Linux distributions, including Ubuntu, Scientific Linux, Rasp-bian, Ubuntu over Windows WSL, and OpenSuse over Windows WSL, can compile the code. It can run on various Linux distributions with few changes.

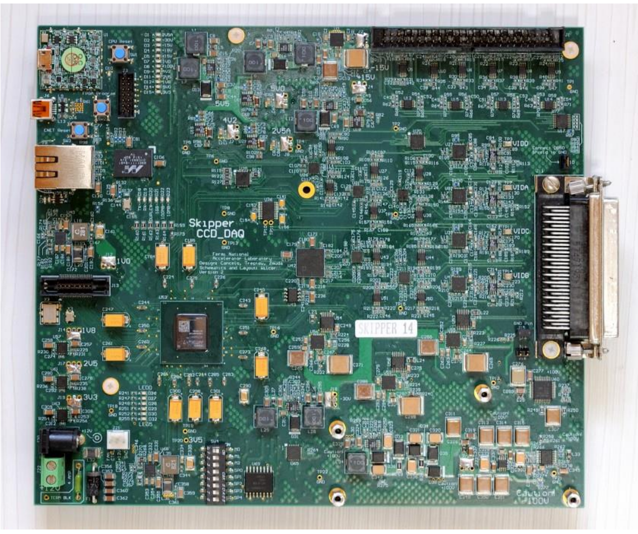


Figure 1: Low Threshold Acquisition Electronics(LTA). Picture from [17]

2.3 CCD Detector

As mentioned before, the Skipper CCD (Charge-Coupled Device) is meticulously mounted inside a vacuum chamber on a sturdy metal base, which incorporates an L-shaped copper bar for enhanced stability and thermal management. This strategic design ensures that the Skipper CCD remains securely positioned and properly cooled during operation, which is crucial for maintaining the precision and sensitivity of the readings. The Skipper CCD is equipped with four read-out amplifiers, strategically arranged to optimize the device's reading capabilities. Specifically, there are two amplifiers located in the upper region, referred to as the U-amplifier region, and two in the lower region, known as the L-amplifier region. These amplifiers are integral to the device's functionality, as they enable the collection of data either independently or in a coordinated manner, depending on the requirements of the experiment or detection process. However, there is a notable limitation in the current setup: the absence of four dedicated readout systems to fully utilize each amplifier individually. To work around this constraint, the system has been configured such that two of the amplifiers are simultaneously utilized by a single readout system. This approach, while not ideal, allows for the continued operation of the Skipper CCD and ensures that data collection can proceed without significant interruptions. The connectivity between the Skipper CCD and the external readout electronics is facilitated by a Kapton cable, which is chosen for its excellent electrical insulation properties and flexibility. This cable features 50-pin male and female connectors, ensuring a reliable and secure connection that is essential for transmitting the delicate signals from the CCD to the readout system[18].

Temperature control within the vacuum chamber is another critical aspect of the Skipper CCD's operation. The chamber's temperature is carefully regulated, typically set within the range of 120K to 140K. This controlled environment is necessary to reduce thermal noise and enhance the performance of the CCD. The system is considered ready for detection once the temperature stabilizes at approximately 135K, at which point the thermal conditions are optimal for achieving high sensitivity and accurate measurements.

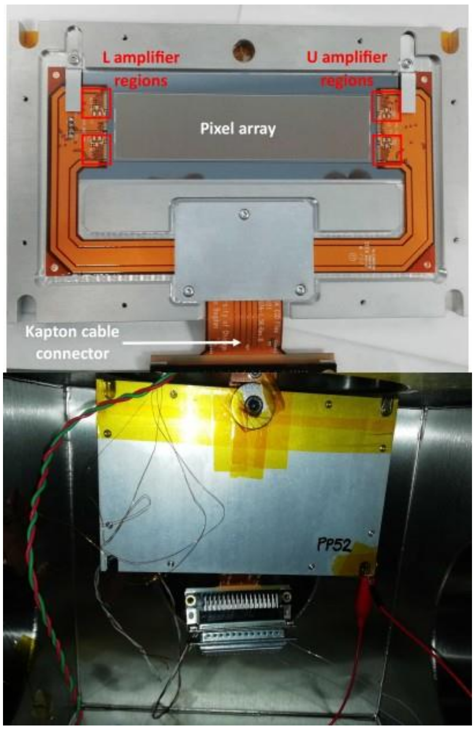


Fig 2: showing the inner and outer parts of the skipper CCD. Figure from[18].

2.4 Control Systems

This comprises the slow control and the data acquisition machines which are used to control parameters and collect data.

2.4.1 Slow Control

It is a Dell machine which was setup in collaboration with the University of Chicago to aid the monitoring and access of the component of the CCD test chamber even outside the clean room. A php web interface is used for monitoring and controlling the experimental telemetry. This is used to perform functions like plotting, low-level analysis, logging, etc. For monitoring and control done outside the clean room, different physical ports like ethernet and serial and protocols like TCP/IP, modbus and serial are utilized to facilitate communication between devices and a server situated on the local computer within the Clean Room through a physical network. The SC has fields for storing user-related data, access timestamps, data acquired from the Cryogenic Temperature Controller (CTC), the devices installed, and their corresponding IP addresses. All of these are monitored by the SC except for the vacuum pump which has not yet been introduced into the SC system. The SC offers the capability to manage user access and their permissions for executing tasks with the connected devices. Tasks such as switching or adjusting instruments. For root users, they have the authority to regulate permissions for other users, oversee data monitoring activities, and introduce new devices to the Slow Control system. On the other hand, guest users are restricted to monitoring data solely for the cryogenic temperature controller.

If the user wishes to access the SC solely for data monitoring purposes, modifying the SC settings, such as adding a new device or toggling the operation of certain apparatus, a password is also necessary[19].

CHAPTER THREE

3.CONTROL SYSTEMS

This chapter is dedicated to the control systems that help to control parameters and receive data.

3.1 Remote Management Of Operational Settings

As mentioned earlier the control system is made up of the Slow control system and the Data acquisition system(DAQ).

3.1.1 Slow Control

The slow control (SC) system is flexible and requires low-cost equipment such as a linux computer with decent RAM/storage, network switch, serial device servers, and ethernet cables. The backbone of the slow control are the C programs that establish how the network should interface with each individual instrument and allow to send/recieve the adequate commands to either get the information needed to keep the control or to give orders to the instruments to change the working parameters or turning them on/off. These programs need to be compiled against the slow control library. The C programs are used for the instrument backed, MySQL to store data, and PHP to provide the web interface.

Through the SC web interface, the Slow Control system enables remote operation and monitoring of critical parameters and equipment involved in the CCD setup. This sophisticated system provides real-time status information accessible remotely via the internet, ensuring that researchers and technicians can maintain oversight and control over the CCD setup from, hopefully, any location. The SC system employs MySQL for robust database administration. It is architecturally composed of a C backend and a PHP frontend.

The C processes are responsible for populating a master MySQL database for every instrument connected to the system, ensuring that all data is systematically organized and readily accessible. This backend process is crucial for maintaining the integrity and reliability of the data, as it continuously updates the database with the latest information from each instrument.

In addition to the core database functionalities, the SC system incorporates a range of procedures that makes its operation easier for the user, such as automated alerts. These alerts can notify users of any critical changes or anomalies in the system, allowing for prompt intervention and troubleshooting. This feature is particularly valuable in maintaining the operational integrity of the CCD setup, as it ensures that potential issues are addressed swiftly before they can escalate.

The PHP web interface serves as the primary platform for experimental telemetry monitoring and control. This user-friendly interface provides a comprehensive suite of features, including logging, low-level analysis, and charting. These tools enable users to perform detailed analyses of the collected data, track historical trends, and visualize real-time data through various graphical representations.

Instrument control and monitoring are meticulously set up on a private internal network, ensuring secure and reliable communication between the host computer and the various instruments. These connections are facilitated through a variety of physical ports (serial and Ethernet) and protocols (TCP/IP, modbus, and serial), which are chosen based on the specific requirements and compatibility of each instrument. This setup allows for seamless integration and control of a diverse array of instruments within the CCD setup.

In our case, the CTC 100, CryoTel GT, Keysight E36312A, and Center One controller can be powered on and off, and their operational parameters can be adjusted as needed. The temporal evolution of various parameters can be observed through graphical representations, providing a clear and intuitive way to monitor changes over time.

The SC page presenting the sensor values for each instrument under its control is depicted in Fig. 3.1. For all LBC users, this page is reachable by visiting the address "http://185.26.226.123:5880/SC_web/slow_control_plots.php". When this is done the webpage in 3.1 is seen. As can be seen from the image, the output power is 120 W and it is kept at this level to guard against harm to the instrumental setup. When the cryotel's reject temperature rises by roughly 30°C, an alert is set off to draw the user's attention and stop the cryotel from being damaged. On the amplifier board, two voltages and currents may also be detected. Their rates differ greatly, despite the fact that the currents are nearly identical. These can also be seen with identical voltages that change at different rates every second. The cold head's temperature remains constant at 93.67 degrees Celsius with no change in the rate. To avoid damage, the CTC is maintained at a constant temperature of 120 K. It is significant to remember that the yellow sensor data are older than ten minutes.

Guest users can only access the text page and the plots, but full privilege users gain full access to the SC page. These include: users, alarms, config, control , logBook , cams, plots, MPlot, scatter, text, Sys Log, Runs.

As previously mentioned, Plots and Text are useful for comparing trends of different quantities; 2D scatter plots of selected parameters can be generated in the Scatter section; Sys Log records all user activities; Runs can be used as an engine search for information about various runs as specified in LogBook; Users allows slow control administrators or users to input their data, select a password, and change their shift status as necessary; Alarms provides a comprehensive list of low and high alarms whose values can be chosen, and that can be (de)activated for all monitored parameters; config allows for the addition of new instruments and their sensors as well as, crucially, the ability to reset instruments in the event that there is a problem with the monitoring and control of the parameters. Control is the process by which instruments are turned on, setpoints are selected, etc. In LogBook, notes regarding an acquisition run or a cryogenics test can be made, indicating the run and category. The cameras mounted to monitor the setup are housed in the Cams section; this feature is currently not available[20].

It should be noted that system administrators and authorized users alone are responsible for managing the installation, deletion, and modification of alarms, as well as the turning on, off, and shifting of instruments and setpoints.

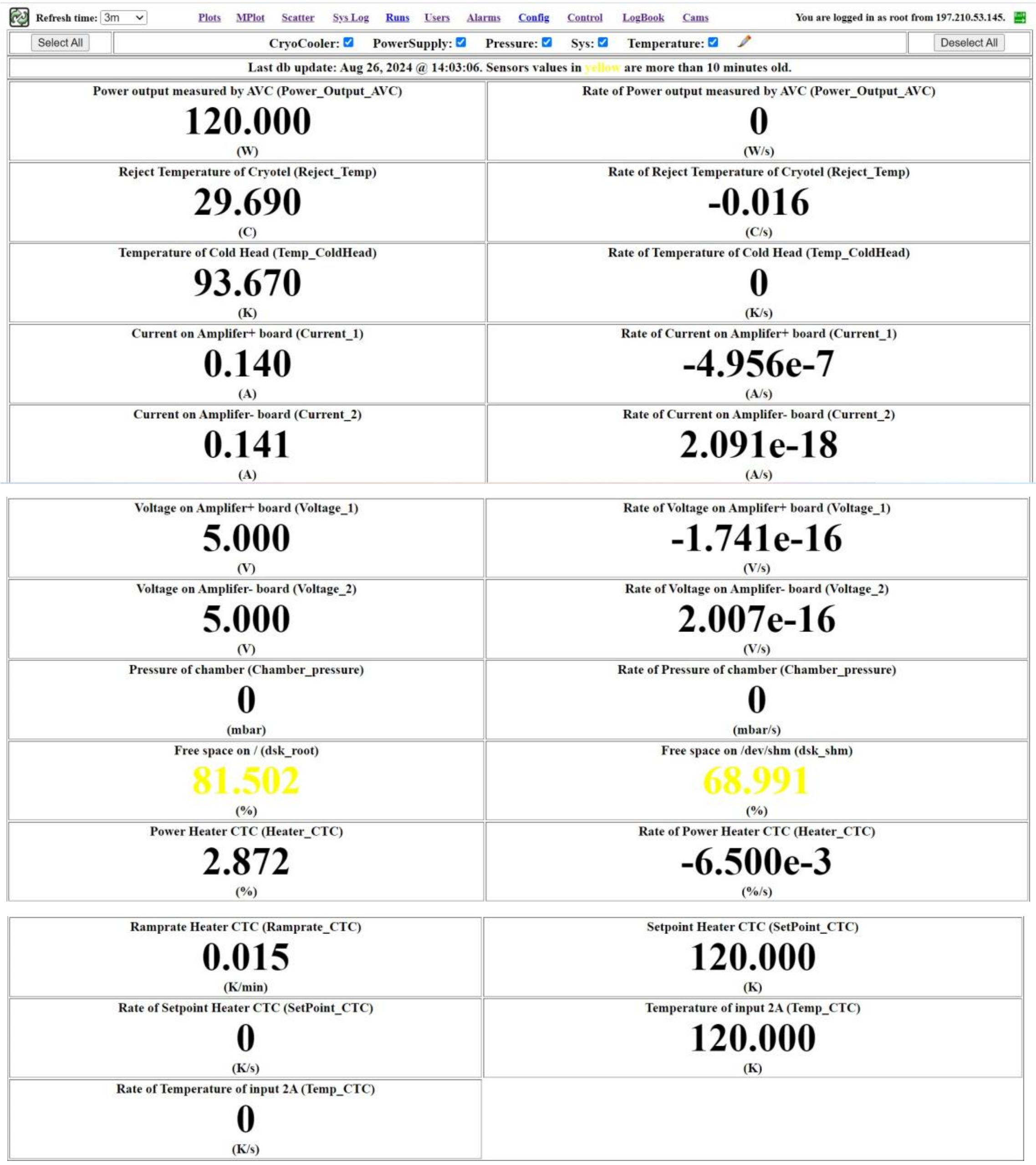


Fig 3.1 Showing the text page for the values of the controlled parameters of the SC.

Most of the instruments are connected using an Ethernet to serial conversion, technically, Ethernet networks are serial in the way they transmit data, but they are called “Ethernet networks” not “serial networks” because they have many more uses and protocols associated with them ensuring efficient and reliable communication. They can be used to connect multiple devices to the same local network. Here in IFCA we are concerned with Ethernet networks that use fiber optic” or “wireless” variants. The major advantage of Ethernet over others is that it can be used over very long distances. The only exception is the vacuum pump, which is connected using serial protocols. This approach to connectivity ensures that all instruments can communicate effectively with the host computer, facilitating smooth operation and monitoring.

The slow control private network and other blue cryostat external electronics devices are systematically arranged to ensure optimal performance and ease of access. This configuration is depicted in Fig.3.2, illustrating the intricate network of connections and the integration of various components within the CCD setup. The UPS provides backup power during outages, ensuring critical equipment like CCDs stay operational. It is integrated with the slow control network for real-time monitoring and management. As seen, all the instruments are powered by the UPS. The CTC100 is remotely controlled via its Ethernet port that connects it with the SC by sending ASCII text commands, with macros that can be stored and executed immediately. Only one client can issue commands at a time, and the Ethernet interface requires IP configuration. The Cryotel cryocooler works in conjunction with the slow control system to regulate the temperature of the CCDs, ensuring they operate within the required thermal range. The slow control system continuously monitors the temperature and adjusts the Cryotel's settings as needed to maintain a stable environment below 140 K. This precise temperature control is essential for reducing noise and ensuring the sensitivity of the CCDs during data acquisition, which is crucial for detecting low-energy events like potential dark matter interactions. Pressure is monitored with a CenterOne controller, which measures the pressure inside the chamber with a pressure gauge. The connection of the HiCube to the SC allows for it to remotely switch on/of pressure gauges. This is all that can be done in our setup for now because we have not successfully connected the vacuum to the RS232. The Keysight E36312A power supply interacts with the slow control system in the DAMIC-M experiment by providing precise and stable voltage and current necessary for powering various components of the experiment, such as the readout electronics of the CCD detectors. Its role is crucial in maintaining the operational integrity and accuracy of the highly sensitive equipment involved in detecting dark matter interactions within the CCDs. The Low Threshold Acquisition (LTA) system works closely with the slow control system to ensure precise synchronization and monitoring of the CCDs' operation. The LTA is responsible for the low-noise readout of the CCDs, capturing detailed data on low-energy events. In turn the slow control system manages the overall operation of the experiment, including environmental controls and system diagnostics. The interaction between LTA and slow control is crucial for maintaining stable conditions and accurately processing the data collected by the CCDs.

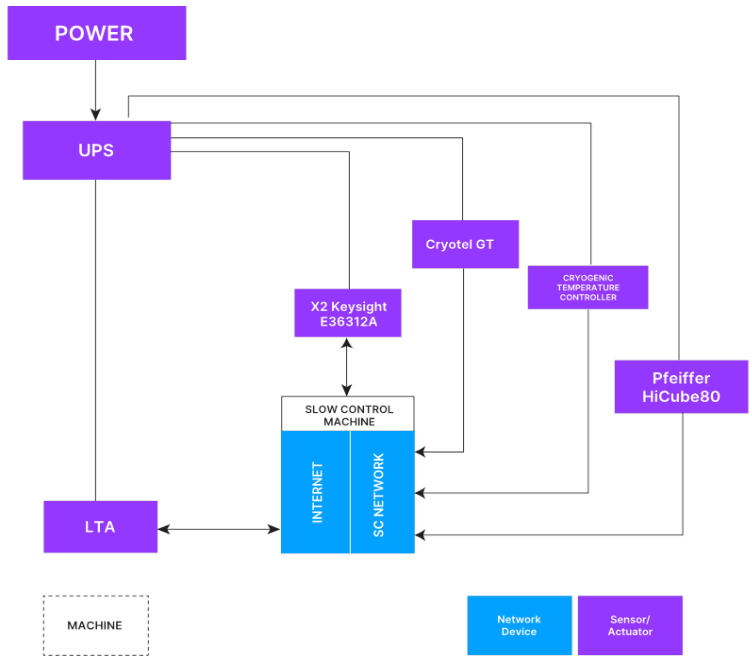


Fig 3.2 Schematics of the current configuration of the IFCA air-side electronics.

Additionally, the instruments within the CCD setup include essential components such as the uninterrupted power supply (UPS). This device plays a crucial role in ensuring the continuous and stable operation of the CCD system, particularly in scenarios where power stability and management are paramount.

3.2 Integration of the Instruments In The SC

The integration of instruments into the slow control (SC) system in the DAMIC-M experiment ensures centralized monitoring and control of all critical components. Each instrument's operational parameters, such as voltage, temperature, and data acquisition, are continuously monitored by the SC. With the SC system, real-time adjustments to maintain stable operating conditions, optimize performance, and ensure precise synchronization across all devices can be made.

3.2.1 The SC and the UPS

The UPS is an uninterruptible power supply designed to provide backup power in the event of a power outage. The UPS is a locking cord adapter of about 15 ft in length. It is equipped with a battery that takes over instantaneously when a power loss is detected, ensuring that critical instruments continue to operate without interruption. This capability is vital for maintaining the integrity of ongoing experiments and for protecting sensitive equipment from the potential damage that can result from sudden power loss. The UPS ensures that instruments such as the CCD, its control systems, and other vital components remain powered, allowing for a controlled shutdown or continuation of essential operations during power interruptions.

The integration of the UPS into the CCD setup provides a robust layer of protection and reliability. The UPS not only guards against data loss and equipment damage but also allows researchers to continue their work with minimal disruption, even in the face of power stability issues. This level of continuity is essential in scientific research, where even brief interruptions can compromise the integrity of an experiment and the quality of the data collected.

The UPS system is integrated into the slow control network, which facilitates centralized management and monitoring of these power devices. Through the slow control web interface, users can remotely monitor the status of the UPS, including real-time information on power consumption, load balancing, and battery health. This remote monitoring capability is invaluable for ensuring that the power management systems are functioning correctly and for diagnosing any potential issues before they escalate into more significant problems.

In addition to real-time monitoring, the slow control system enables automated alerts related to the power status. For instance, if the UPS switches to battery power due to a power outage, an immediate alert can be sent to the relevant personnel, allowing them to take necessary actions swiftly. The UPS also sends notifications if there are any abnormalities in the power status of the vacuum pump or other connected devices. These alerts enhance the responsiveness of the system to power-related issues, thereby safeguarding the operation of the CCD setup. Therefore we could say that alarms are a crucial part of the slow control system which help to prevent damage to CCDs and instruments, keep stable operation and safely shut down when needed. These alarms are usually set by the user with the permission of a system administrator.

An illustration of alert management using the SC interface is shown below. An alarm is set off when the reject temperature rises above 56°C for a longer duration than the grace period.

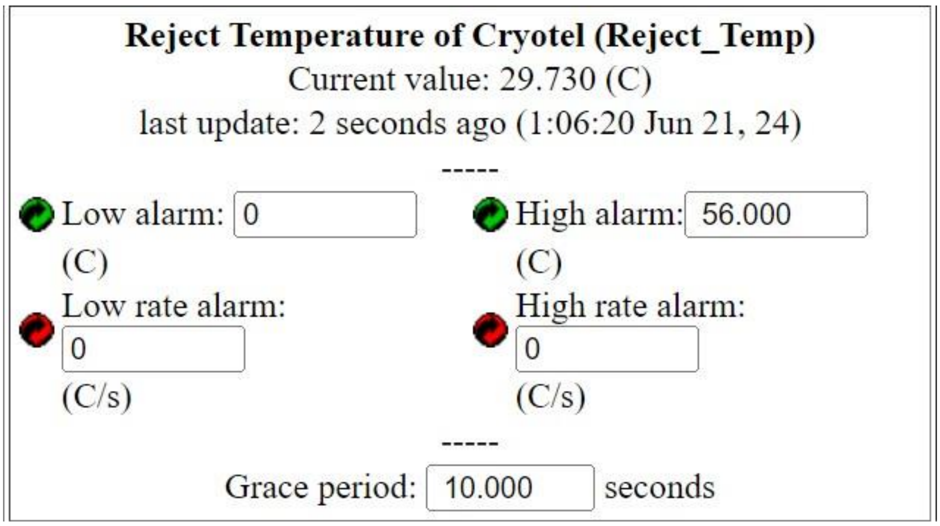


Fig 3.3 Example of an alarm management box in the slow control web interface. An alarm is issued when reject temperature is greater than 50°C.

3.2.2 The Slow control and the CTC100

An Ethernet port is used to remotely control the CTC100. This is done by sending lines of ASCII text to one of the CTC100's ports. Responses gotten from the CTC100 after the text is sent always terminate with a carriage return and a linefeed. Since every line of text transmitted to the CTC100 is interpreted as a macro, it is possible for it to contain repeated blocks, conditional expressions,

and one or more instructions. The macro launches right away, and if it takes a while to finish, the Program page allows you to track its progress. Additional macros can be delivered to the CTC100 while it is operating. The Program screen displays only the first four of the up to ten macros that can run concurrently. Macros can be stored as text files on a USB memory device, which can be plugged into the CTC100. The macro can be run from the Program window or called from other macros, just like a saved macro. Each macro can have up to 4096 characters, while individual instructions or arguments can have up to 1024 characters each. Both instructions and arguments can be separated by one or more whitespace characters, as well as by special characters like parentheses, brackets, equals signs, etc. Moreover, macros can be kept on a USB memory stick as text files. The macro can be called from other macros or launched from the Program window when the USB device is inserted into the CTC100, just like any other macro. Since large macros can include several lines and comments when saved as text files, editing them is made easier.
Macros have the ability to be named and stored, and they can call other macros that have been saved by name; however, they are not allowed to call themselves again. When two commands have the same name and are saved under different ones, the macro that was saved first gets priority if the command is issued with a capital letter, and the instruction takes precedence if the command.
The CTC100's Ethernet port can receive remote commands via the following techniques. The mode of operation is automatically detected by the CTC100.

• Sending text in ASCII to port 23 via a raw TCP/IP stream.
• Sending UDP packets with ASCII text on port 23
• A telnet port 23 connection

The Ethernet interface cannot be used until the IP address is configured. There is only one client that can issue commands to the CTC100. The CTC100 ignores commands from other clients until the System.IP after receiving a command addressed to port 23. When you press the close button, the instrument reboots, the client ends the connection, or the connection times out for lack of use. It is not required to use an Ethernet connection in order to access the building's network; CTC100 can be connected directly to your computer with a standard Cat 5 cable.

The CTC at IFCA operates at an input temperature of 120K for a current of 2A. This temperature has to be maintained in order to prevent damage to the instrument. A change in this temperature usually indicates a fault in the instrument. Below is a figure showing the temperature of the CTC over a period of time.

The figures below show the fluctuation of the CTC input temperature over four months. From the graphs it is seen that the instrument maintained the input temperature of 120K from May 17th until the 22nd when rose up to 296.29 and then started to increase slowly again until May 29th when it fell to about 294 K then rise again to about 302 K then fell to the constant value of 120 K. the rise in temperature of about 180 K more than the normal value from May 22th to 31th may suggest that the instrument might be faulty or an issue in the instrumental setup.

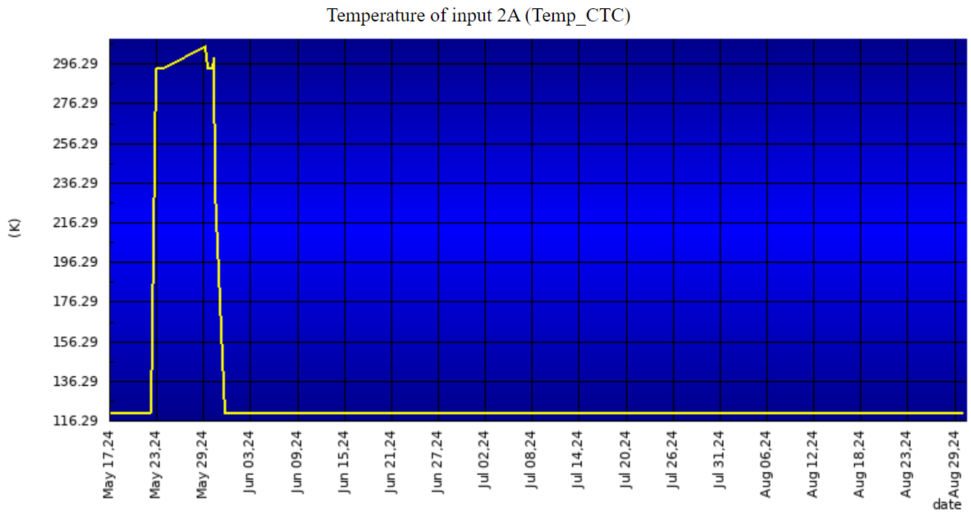


Fig 3.4 Graph showing the performance of the CTC for about four months.

3.2.3 The Slow control and the CryoTel GT

The Cryotel GT provides users with two distinct control options: temperature control mode and power control mode, each serving a unique purpose in the operation of the cryostat. The power control mode is initially employed to bring the cryostat's internal cold components down to a temperature below 140 K. This is done with the aid of a heater. This mode is particularly effective in achieving rapid cooling, efficiently reducing the temperature of the cryogenic system's components to the desired low levels. Once the temperature of the cold components has been sufficiently reduced using the power control mode, the system transitions to the temperature control mode. This mode allows for precise regulation and fine-tuning of the temperature within the cryostat, ensuring that the cooling rate is controlled and stable. The temperature control mode provides the operator with the ability to maintain a specific target temperature, making it essential for applications that require stringent thermal management. By utilizing these two control modes, the Cryotel GT offers a versatile and reliable method for managing the thermal environment within the cryostat, making it suitable for a wide range of cryogenic applications.

Fig 3.5 shows the reject temperature of the cryotel for the period of seven and fourteen days. The "reject temperature" of a Cryotel system typically refers to the temperature at which the heat generated by the cryocooler is expelled or "rejected" to the surroundings. This is a key parameter because it influences the efficiency and performance of the cryocooler. The reject temperature is usually higher than the cryogenic temperatures maintained within the cryostat itself and is often dependent on the cooling system used to dissipate the heat, such as air or water cooling. The trend of the reject temperature for about four months fluctuated between 28.59 and 29.59 celsius from 17th to 21ist of May when there was an abrupt drop in the temperature to about 10 degree celsius. Then there was a fluctuation between 19.59 to 21.59 degree celsius till the 26th of May when there was a swift increase in the temperature to almost 31.29 degree celsius then after this there is fluctuation about 29.59 degree celsius with no notable discrepancy except for between 29th of July and 2nd of August where there was a little spike in the reject temperature. This discrepancy suggests that the instrument might be faulty or there was a system failure at that point.

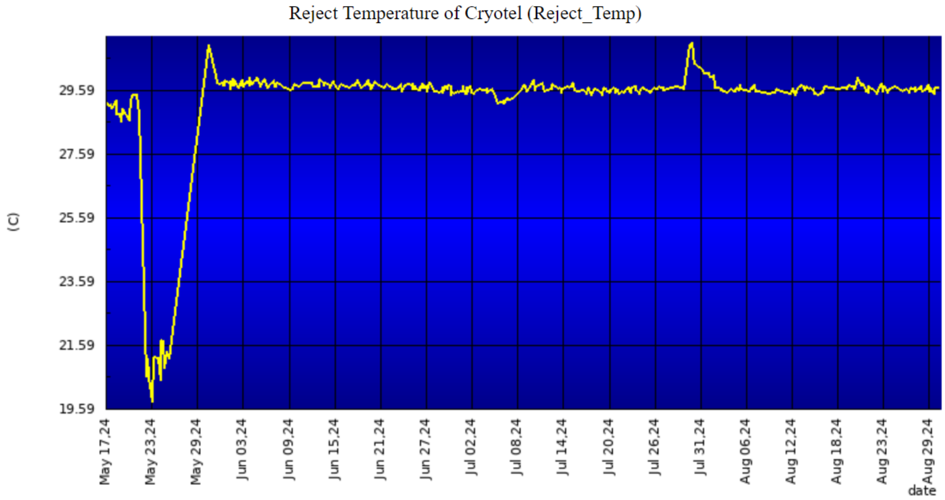


Fig 3.5 Reject temperature trend for different periods of time.

The figure below shows the temperature trend of the cold head. The cold head is the component that directly cools the target object or environment, and it achieves these cryogenic temperatures to maintain or control the temperature of the system it's integrated with. The cold head temperature is carefully regulated to reach and maintain very low temperatures suitable for applications it is required for. The precise temperature achieved by the cold head depends on the operational parameters set by the user, such as the cooling power and temperature control settings.

From Fig 3.7 it is seen that the temperature fluctuated between 93.43 and 93.46 from 20-21 of July and then after there was decrease to 93.40 from 21- 22 and then it started to increase until 30 of July then it started to decrease and increase until 5th of August.

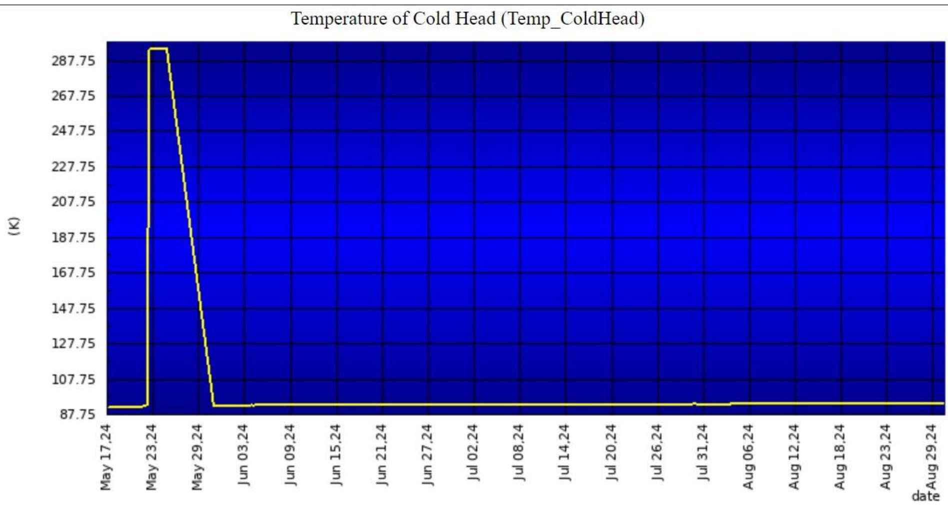


Fig 3.7 Graph showing the temperature of the cold head over a period of time.

3.2.4 The Slow control and the HiCube

The HiCube must be outfitted with the adapter set so that the vacuum opening can be closed even when the pump is accidentally turned on. The adapter is usually the M12 to DB9 adapter which has ADAM RS-485 serial server attached to it to enable the conversion to series. This connection is done with a short ethernet cable attacher to the series server and plugged to the network switch.

The issue in the pump slow control processes that triggers the alarm occurs at the startup or reset of the slow control process, where a wrong value is sent to the pump. Because these processes are critical, users are usually advised to let the system administrators perform it.

Instabilities have not yet been observed during the monitoring of the HiCube at IFCA. because the vacuum pump can not be turned on/off, the speed rotation of the pump can not be recorded. Although this can not be done yet, we are able to take the gauge reading which is zero in every case.

The SC makes it possible to switch ON/OFF the pressure gauges remotely. When the gauge is switched off, the SC probes the pressure controller which provides the last measured values for both sensors. This process usually takes up to 10 minutes and the value goes yellow when it is done.

Fig 3.8 shows the trend of the pressure for about four months, from the graph it is seen that there is a yellow line which maintains a constant value of zero until there was a brief increase in the pressure to over 980 mbars then it dropped to zero again. Indicating that the pressure gauge was OFF until a slight change which might be due to faulty instrument or the gauge was briefly turned on.

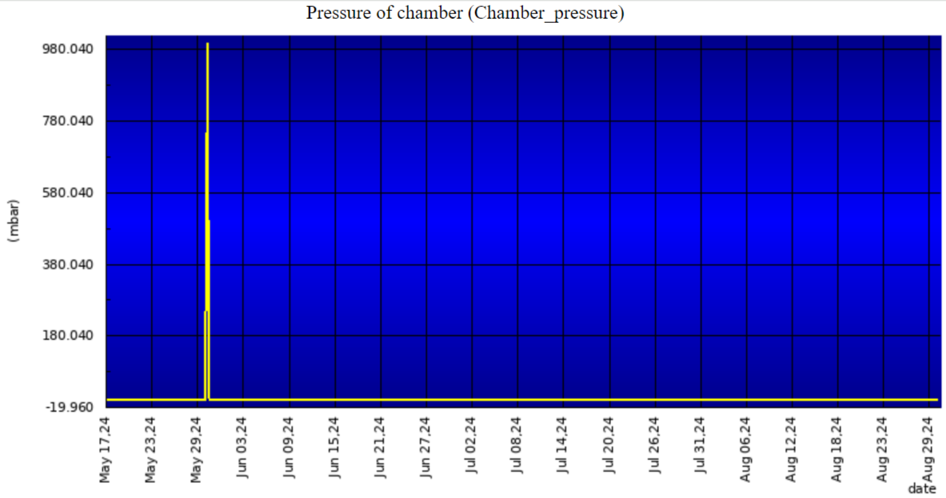


Fig 3.8 Pressure trend for the period of seven days

CHAPTER FOUR

4 IMAGES TAKEN AT IRONMAN SETUP

4.1 1.5k x 6k CCDs and Test Setup

From a batch of Skipper CCDs constructed and used in DAMIC-M R&D efforts are 1537×6144 pixels diced from the larger circular wafer, we got the CCD PP52-U. This CCD was tested to check the amplifiers at University of Washington were sent here for optimization and testing of the full Ironman setup. The setup has been discussed in the previous Chapters. These CCDs are instrumented with 4 amplifiers, split across 2 serial registers. The PP52 used was a 678 μm thick fully-depleted CCD, of the back-illuminated type, i.e., the back side of the device is exposed to incident radiation and then the generated charges migrate to the opposite side, where they are collected by the potentials generated by the tracks on the back side. The dead zone at the back of the CCD was composed of three layers: a ~ 20 nm layer of indium stannous oxide, a ~ 38 nm layer of zirconium dioxide ($ZrO2$) and a final ~ 100 nm layer of silicon di-oxide ($SiO2$). The CCD was divided into four quadrants, called OHDUs, with an output amplifier in the corner of each quadrant, allowing simultaneous readout of all quadrants. Each quadrant consists of 768 rows and 3072 columns, and each pixel has a dimension of 15 μm × 15 μm.

The CCD is equipped with a short flex wire bonded and has a 50-pin D-Sub female connector on one end to send all the voltages, clocks and receive the video signal from the CCDS . To establish a connection between the CCD and the feedthrough vacuum side, a Kapton flex cable with 50-pin male (CCD) and female (feedthrough) connectors is utilized (see Figure 2.4 of the CCD)

CCD PP52-U configuration parameters to achieve an efficient charge collection, transfer and readout using the LTA; which consequently leads to an improvement of the electronic noise. Has been done in previous works from other TFM students In order to determine the optimal configuration parameters, the integration time was initially varied, which resulted in finding that the CCD Test Chamber installed at IFCA presents a high sensitivity to electromagnetic noise. This discovery prompted an investigation into how this electromagnetic noise visually impacts the images, the pixel readout noise and the dark current fit plots.

4.2 Data Acquisition

The characterisation involves studying the values of the voltages of the horizontal and vertical clocks, and also the different voltages needed in the final reading process, as well as the time in which we are in each configuration of the movement of the rows and columns as well as in the reading process.

These changes are done through different files that are read by the LTA. We will explain how this readout is done [22].

Figure 4.1 shows the structure of the data acquisition software, in conjunction with the LTA. A daemon runs in the background during the entire operation, taking care of powering up the LTA and initializing it so it can do the same for the CCD skipper. The daemon runs as a terminal-compiled executable written in C/C++. Data acquisition begins by executing the Data acquisition script, illustrated in Figure 4.1. First of all, the Initializer is called by the Data acquisition script in order to create the data acquisition environment (file names, write directories, etc.), read modes, timeout between voltage application, integration times for the signal and the pedestal, among others. The

Voltage configuration is in charge of pre-configuring the voltages for the signal and the pedestal, among others.
to pre-configure the voltages to be used in each of the CCD gates when operating the CCD. Some examples are the upper and lower voltages of the active area pixels (V1, V2 and V3) or of the horizontal register (H1, H2 and H3) or the voltage of the Vdrain where the charge of a pixel is transferred for its final discard after being read in the SN.
Finally, the sequencers used for data acquisition are loaded. These codes are in XML format and detail step by step the reading of the CCD after power-up.
This goes from the first vertical transfer to the reading of the last pixel of the image. Additionally, there are sequencers for the cleaning phase or special data acquisition routines that require skipping the reading of certain rows/columns, cleaning between rows, changing the vertical/horizontal transfer direction of the loads, among other reading variants. The LTA board will use the sequencers to tell the gates in each pixel how, when and for how long they should change their electrical potential. The Data acquisition script is in charge of encapsulating the execution of these codes and of organizing the reading of the detector both by modifying some of the parameters previously configured by the Initializer and the Voltage configuration and by establishing other parameters such as the exposure time or the number of images to be read, among others. All these processes are better explained below.

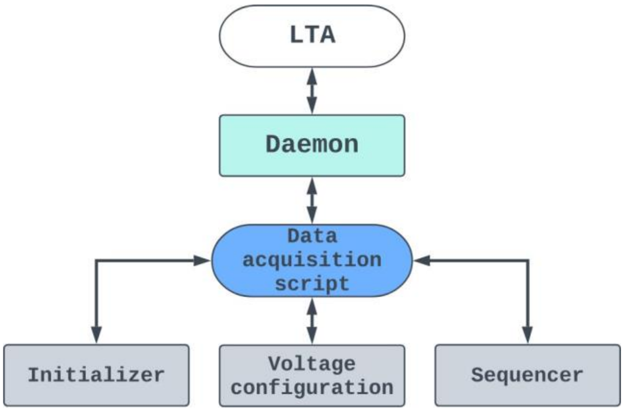


Fig 4.1: Block diagram of the main software components in the LTA.

The Low Threshold Acquisition (LTA) readout electronics presented in this work, is specifically designed to meet the requirements of growing demand of the technology. As said in the previous chapter, This system was recently updated to an LTA system, which is a 7 by 8-inch single PC board hosting 4 video channels for readout, plus CCD bias and control. The LTA board is produced by Astronomical Research Cameras (ARC). It consists of processing printed circuit boards (PCBs) that help to control the skipper CCD readout operations for clock sequencing, bias voltages, image dimensions, pixel binning, and system gain. The LTA is best run on Ubuntu 20.04, but it can also be run on Ubuntu 18.04, RHEL/CentOS/SL 6+7, and Debian 10. The LTA scripts are only compatible with the bash shell; some configurations may use csh or tcsh by default. You can check your shell preference by running ps in any terminal. You can use chsh to set your default shell to /bin/bash, or you can run bash in the terminal before executing the LTA scripts. GCC version 4.7 or newer is required for compiling the LTA daemon, which is compatible with the majority of current Linux distributions. The LTA Daemon has dependencies like Root, CFITSIO, and Basic software development tools. After the LTA daemon is set, it is connected to the LTA through the ethernet port then the ethernet connection is configured to the board. The configuration is successful if you are able to “ping 192.168.133.7”. When the configuration of ethernet connection is complete, a terminal and the daemon is started with the command “./configure.exe”. This terminal should remain visible to you in the background. It will give you import color coded messages, warnings (yellow), errors (red). Then after the runvariables.sh script in ltaDaemon which carries information about the image folder, sequencers, nsamps, voltage file, etc. is edited and then run with the code “source runvariables.sh”. The LTA is initialized after this with the code “source skp_init.sh” and then erased and purged with the code “source skp_erase_and_purge.sh” ; these commands help to erase and purge charges from the CCD. The “runseq” command is used along with the command so the charge can run through the CCD without being read. Inorder to take an image, the charge is read with the command “lta read” and then viewed with the command “ds9” images/image_lta_1.fits” as outlined in the previous chapters[23].

4.2.1 LTA Command Lines

To interact with the Low Threshold Acquisition (LTA) system in the DAMIC-M experiment, specific commands can be sent via a script named lta.sh. Before executing commands, you must initialize the LTA by entering the command “source setup_lta”.sh. Once initialized, commands are sent using the format “lta <command>”, where <command> represents the specific instruction you wish to execute. These commands can include starting and executing a sequencer, modifying variables, reading charge values, and more. Detailed command lines and instructions are thoroughly outlined in the appendix of the experiment's documentation.

This setup allows for precise control and monitoring of the LTA system, which is crucial for maintaining the integrity and accuracy of the data collected during the experiment. Each command plays a vital role in managing the functions of the LTA, ensuring that the CCDs operate under optimal conditions and that any changes in the environment are promptly addressed. The appendix provides comprehensive guidance on using these commands effectively, making it an essential resource for operators.

4.2.2 The LTA Sequencer

The sequencer in the DAMIC-M experiment plays a crucial role in controlling the Charge-Coupled Devices (CCDs) by determining the precise sequence of states that the CCDs should move through during operation. It consists of three key components:

1. Defining States and Variables: This involves specifying the different states the CCD can be in, as well as the variables that will govern transitions between these states. States may include various operational modes like initialization, data acquisition, or standby. For the state, One particular pin on the LTA DB50 pin connection is represented by the arrangement of zeros and ones. Here, we are assigning a "name" to each pin and thereafter, we delineate states, which consist of binary combinations of the "pins". Just like this

<state name="V1A" val="00000000000000000000000000001"/>
<state name="V1B" val="00000000000000000000000000010"/>

<state name="STATE_12" val="V1A | V1B | "/>

Variables could be parameters such as voltage levels, timing intervals, or environmental conditions that influence the CCD's behavior. Here "NROW" and "NCOL" specify the dimensions of the image you'll capture per quadrant. "CCDNROW" and "CCDNCOL" refer to the physical size of the entire CCD and do not affect the image dimensions. When capturing a binned image, "NBINCOL" and "NBINROW" define the bin sizes, where the final image dimensions are "NROW" and "NCOL." The total rows and columns read from the CCD are calculated as NROW*NBINROW and NCOL*NBINCOL. Example

```
<var name="NROW" val="50"/>
<var name="NCOL" val="250"/>
<var name="NBINCOL" val="1"/>
<var name="NBINROW" val="1"/>
```

The delay times is also defined as a variable. This times tells you how long to stay in each state when executing a recipe. The units are in slots of 15 MHz each, therefore to get times we have to divide the value by 15MHz.

```
<var name="delay_H_overlap" val="20"/>
<var name="delay_Integ_Width" val="380"/>
```

2. Recipes: Recipes are predefined sets of instructions or actions that the state will execute. These can be thought of as the "instructions" for the CCD, outlining what should happen at each stage. A recipe might include commands to adjust voltages, control timing signals, or read out data from the CCDs. Recipes ensure that the CCDs perform consistently and according to the experimental requirements. We remain in each state for the allotted period of time in which the recipe is carried out.

```
<recipe name="skipper">
<step state="STATE_8" delay="delay_RG_after"/>
<step state="STATE_8B" delay="delay_Integ_Width"/>
<step state="STATE_9" delay="delay_SWhigh"/>
<step state="STATE_10A" delay="delay_integ_after_SW_high"/>
<step state="STATE_10A" delay="delay_Integ_Width"/>
<step state="STATE_10RB" delay="delay_og_low"/>
<step state="STATE_10RG" delay="delay_RG_Width"/>
</recipe>
```

The skipper recipe instructs the CCD to use STATE_8 for a delay_RG_after total time, STATE_8B for a delay_Integ_Width total time, and so on.

3. Sequence: The sequence is the order in which the states and recipes are executed. It dictates the flow of operations, ensuring that the CCDs transition smoothly from one state to another in the correct order. This sequence is vital for the coordinated functioning of the CCDs, as it ensures that all processes occur in the right order and at the right time, minimizing errors and optimizing data quality. The sequence is what will be executed when we tell the lta to read, runseq, or startseq.

Together, these three components allow the sequencer to manage the CCDs efficiently, ensuring that they operate according to the precise needs of the DAMIC-M experiment. The sequencer's ability to define states, recipes, and sequences ensures that the CCDs are not only controlled accurately but also adaptable to different experimental conditions.

There are different sequencers that carry out different functions.

4.2.2.1 Idle Sequencer

The LTA will enter "idle mode" thanks to this sequencer. When this sequencer is operating, charges will be constantly moved from the CCD to the drain until it receives a stop command. Three for loops are used to accomplish this process, which could take longer than a human lifetime. To initiate this type of sequencer, we type in the following

foo@bar:~$ lta sseq $idleSeq
foo@bar:~$ lta startseq

It is crucial to start this command with the startseq command rather than the read or runseq commands. If not, you will have to restart the daemon in order to stop it, as it will never cease.
To stop the idle mode type, we used the command “foo@bar:~$ lta readoff”. Prior to sending any further commands to the LTA, make sure you have completed the readoff command. Because if you do not, what will occur in the other case is unpredictable.

4.2.2.2 Clean Sequencer
This sequencer clears the CCD of any residual charge in a methodical and gradual manner. It works by slowly transferring all the accumulated charge within the CCD to one of its corners, where the charge is then directed to the drain. This approach, though deliberate and unhurried, ensures that the CCD is completely cleared of charge without rushing the process, reducing the likelihood of errors or incomplete drainage. The method is effective for thoroughly resetting the CCD, preparing it for subsequent operations or data collection.

4.2.2.3 Exposed and Binned Sequencer
This sequencer is designed to expose the CCD to external environmental conditions for a specified duration, known as **EXPOSURE** seconds. During this time, the CCD's sensitive surface is deliberately left open to its surroundings, allowing it to collect data based on ambient conditions. The duration of this exposure is critical, as it determines the amount of environmental data the CCD captures. This process is essential for CCD to gather information such as light or radiation, from its environment for a precise and controlled period. After the exposure time elapses, the sequencer transitions the CCD back to its standard operational mode.

4.2.3 LTA Scripts
Just like any other script, the LTA scripts are sets of instructions written in a programming language that automate specific tasks or processes on a computer. They were developed to streamline the workflow and simplify routine tasks within the DAMIC-M experiment. Script like “run_variables.sh”, is used to initialize and set up the essential run variables before an experiment begins. This script defines several critical parameters, including the directory where the captured images will be saved, the naming convention for these images, the specific sequencers that will be employed during the run, and the configuration file used to initialize the voltages for the Low Threshold Acquisition (LTA) system. Script like the “skp_init.sh” helps in initializing the Charge-

Domain Sampling (CDS) variables of the LTA, this is crucial for preparing the LTA to capture an image. The CDS variables control the precise timing and voltage settings required for reading out the charge from the CCDs accurately. By setting these variables correctly, the LTA system is configured to operate under optimal conditions, ensuring that the image data captured is both accurate and reliable. Script like the “skp_erase_and_puprge.sh” helps to remove and clear any residual charge from the LTA system. However, due to a small bug in the firmware, performing the erase and purge operations causes the VSUB voltage to reset unintentionally. To address this issue, it is necessary to manually reconfigure the VSUB voltage each time after the erase and purge actions are completed, ensuring that the system is correctly set up for subsequent operations. Script like “ skp_get_image.sh” helps to take an image with the proper integration widths. Script like “skp_idle_mode.sh”, places the CCD in "idle mode" and loads the idle sequencer onto the LTA. The “voltages/voltages_setup.sh” script sets up the operating voltages of the LTA and the CCD. All of these scripts assist the user in getting a grasp on things.

4.2.4 LTA Probes

There are two points which can be probed on the LTA. First, you can probe the clock voltages (H1A, V1, etc.) using the 64-pin connector located in the upper right corner (blue box).
Second, there are four probes to examine the video signal directly behind the DB50 pin connector (red box). The fourth, first, third, and fourth quadrants of the output fits file are corresponding to these probes, which are called VIDD, VIDA, VIDC, and VIDB, respectively. These two ways aid debugging the system during use.
You should be able to read a Skipper-image by using an oscilloscope to probe the video signal and observe the image on the right.

4.3 Images taken with the setup

For the images, we have taken different configurations to try to get the least noise. As has been proven by other colleges at this point, we have not been able to take high quality images in order to carry out a physical analysis mainly due to the glowing and defects in the CCDs. However, significant progress in reducing electromagnetic noise, particularly thanks to the improvements in grounding and studies of the parameters were obtained.
The setup has now been moved to the LSC at Canfranc for radiopurity studies. Additionally,
new scientific CCDs like the ones installed in the LBC setup will be sent by the collaboration to us for future characterization, with the expectation of acquiring scientific-grade CCDs similar to those installed in the LBC.

We have some basic parameters to that we have modified to take some images:

Parameter	High Value [V]	Low Value [V]	Width [µs]	Overlap Width [µs]
Horizontal Clocks	2	-0.5	1.25	1.25

Vertical Clocks	4.5	1.5	30	20
Transfer Gate	4	1.5		
Summing Well	-3	-10	0.24	
Output Gate	-4	-9	0.24	
Dump Gate	-4	-8	0.24	
Reset Gate	5	3	0.24	

Parameter	Voltage [V] Time [µs]
PSAMP, SSAMP	12.5
PINIT, SINIT	2.5
VR	-7
Vdd	-19
Vdrain	-22
Vsub	50

Table 4.3: Showing the fixed values for the 6k x 1.5k CCD PP52-U parameters.
For the horizontal and vertical clocks, Overlap Width refers to the duration during which two gates are set to the same low potential value, while Width indicates the time duration of a gate when it is not overlapping with another gate. The parameter values represent fixed voltage and timing settings used across all the tests. The pedestal wait time refers to the delay before the start of pedestal integration, while the signal wait time indicates the delay before the start of signal integration. Vsub is the bias voltage, VR is the reference voltage, Vdd is the amplifier voltage, and Vdrain is the drain voltage.

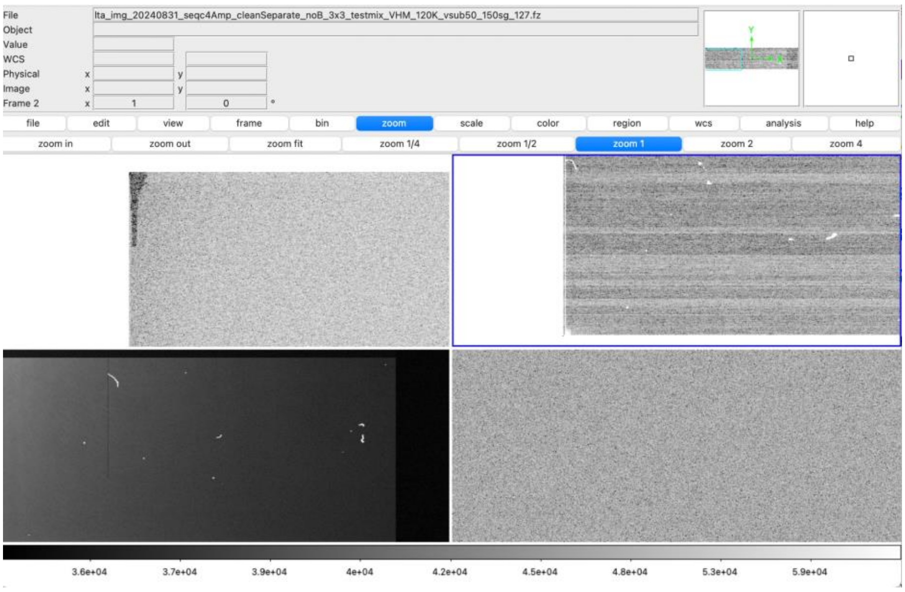
The CCD configuration parameters shown in Table 4.3 are the starting points to optimize the device. Regarding the substrate voltage, a value of 50 V is enough to fully deplete the CCD [24], so CCD images are not significantly impacted by this parameter as long as it exceeds 50, images were generally taken with a substrate voltage of 50 V.

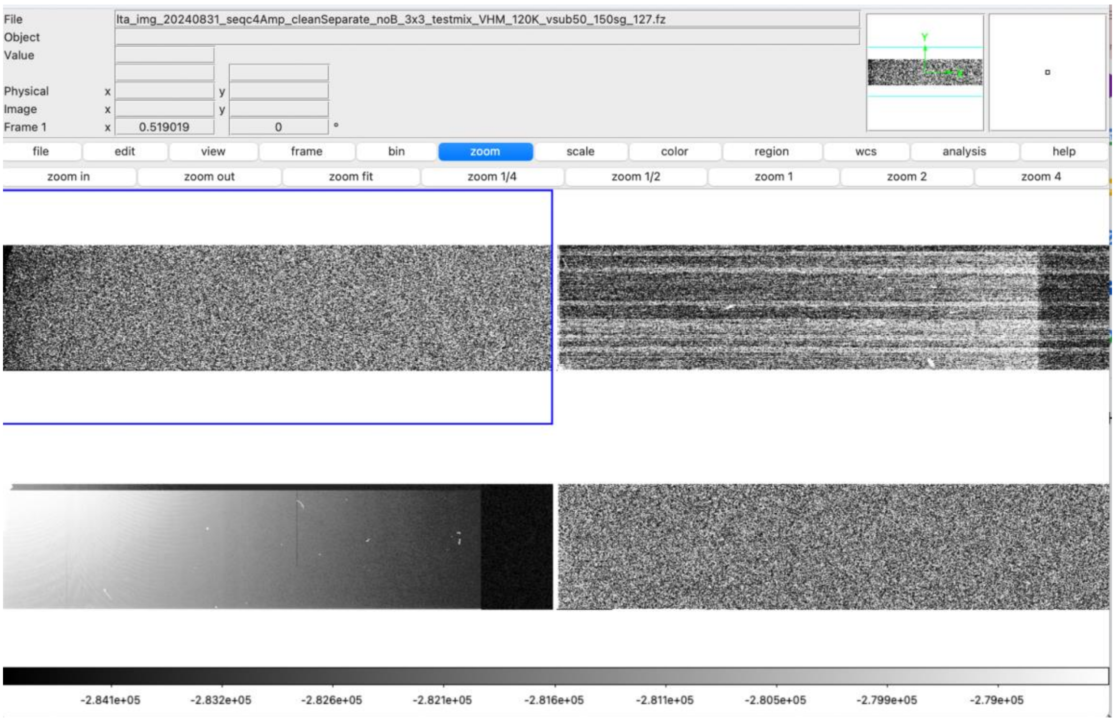
4.3.1 Noise Sources For The CCD

There are various sources of noise that can interfere with a CCD charge measurement. In the DAMIC-M experiment, sources of noise can be categorized as electronic and non-electronic. Electronic noise are unwanted variations in an electrical signal that compromise the functionality of electronic systems. In the DAMIC-M experiment, electronic noise arises from various sources. For example: readout noise, 1/f noise, clock induced charge noise, shot noise, dark current noise.

Non-electronic noise sources are noise sources that are not related to the electronic components of the CCD. This type of noise can significantly impact the sensitivity and accuracy of the experiment. Some sources of non-electronic noise include: Radiation effect, environmental factors and charge transfer inefficiency.
Noise in CCD images is a critical factor that affects image quality. Images produced could be skip or non-skip images. As the name implies, Non-skip images refer to images where all the pixels in the CCD array are read out and processed, without skipping any rows or columns. In other words, every pixel in the sensor is included in the image, providing full resolution and detail whereas skip images are the opposite of this.

4.3.1.1 Non-skip Images
The three non-skip images below were obtained by varying the integration time parameter; the first two were taken on August 31, 2023, and the third on August 13, 2024, using the instrumental setup at IFCA. The four display portions of each image correspond to the four amplifiers used. The first image shows a portion of the three-amplifier image with high correlated noise visible as patterns; the down left portion has a clear trace of ionized particles and a lighter part which may be due to the incident of light; the top right portion and the down left portion have peculiar dark parts, more visible in the down left portion, which could be caused by a hot pixel or hot column, or it could even imply that the CCD might be defective.
The second image features a white area on both the left and right sides that could indicate a light incident on the CCD. The left top portion has a small dark patch that could indicate a hot pixel or a defect. The top right portion shows traces of ionized particles similar to the down left portion.
Then, the down right portion just displays noise patterns. The top left and the down right portions of the third image display discernible noise patterns. The top right and the bottom left both have traces of ionized particles, and the bottom left has a white area that might indicate a light incident.
All of these indicate that the CCD is unfit to be used for readings and that the values obtained might not be suitable for analysis.





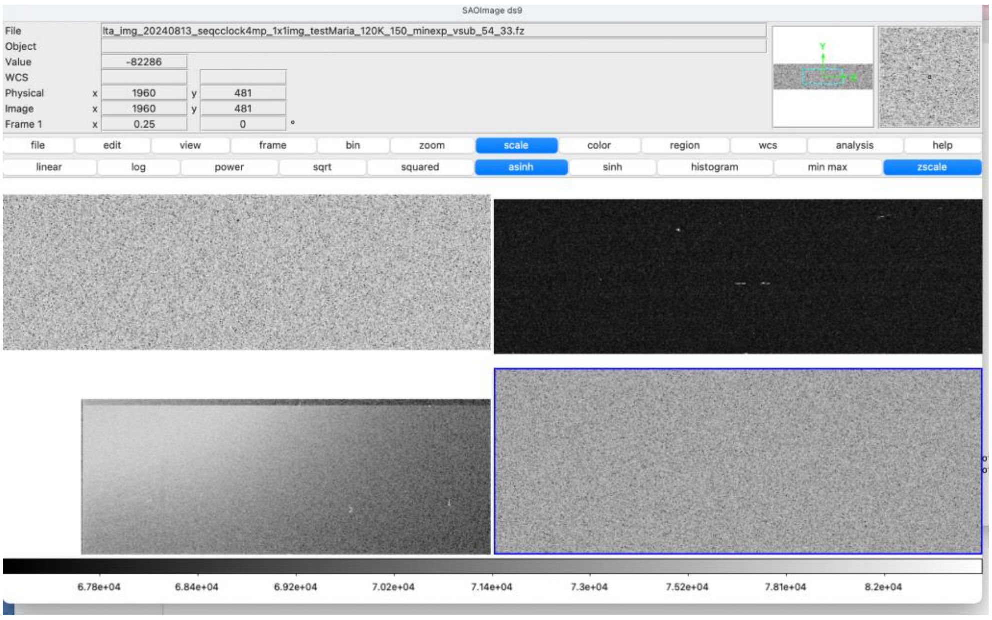


Fig 4.4:CCD images obtained by the setup at IFCA showing different tracks/ signatures for different ionizing particles in a CCD. A straight track (cosmic ray muon), large blob (alpha particle), "worm" (straggling electron) and small round clusters (low-energy X-ray, nuclear recoil, DM candidate)

5. Conclusion

In conclusion, this research at IFCA (Instituto de Física de Cantabria) marks a significant step forward in the description of CCDs for the DAMIC-M experiment. By utilizing an above-ground setup, the study has successfully simulated and obtained valuable data that approximates the conditions of subterranean CCD operation. Through a detailed examination of the experimental configuration, including advancements in electronics and system components, this work provided a comprehensive framework for understanding and optimizing CCD functionality.

The study not only offered in-depth analyses and practical guidelines for system operations but also focused on critical areas such as improving the efficiency of charge collection, transfer, and readout. By addressing the optimization of CCD parameters and mitigating factors like pixel readout noise, this work enhances the accuracy and reliability of CCD data for the DAMIC-M experiment.

Ultimately, the research contributed to a deeper understanding of CCD performance in the presence of noise and offered a solid foundation for future experiments, ensuring that CCD systems are optimized for the demanding conditions of underground operations. This work is poised to significantly impact the ongoing advancements in CCD technology and its application in low-background experiments like DAMIC-M.

5.1 Future Work

This work has given a vivid insight to the instrumentation of the DAMIC-M setup and how they are best used. Some recommendations can be made from this study. First of all, further optimization of CCD parameters, including charge collection, transfer, and readout, is needed to minimize noise and improve integration times for both skip and non-skip images. Secondly, exploring noise reduction techniques and advanced calibration methods will enhance data accuracy, while incorporating next-generation electronics could improve readout efficiency. Additionally, long-term stability studies will ensure reliable CCD performance in extended-duration experiments. All of these efforts will contribute to better data quality and the overall success of the DAMIC-M experiment.

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Appendix A

Setting Up The Cryocooler

A.1 Testing The Cryocooler

After preparation the cryocooler is tested by using these outlined procedures:

1. Prepare the CryoTel GT for testing as described in chapter two of this work.
2. Connect the cryocooler power cables for the CryoTel GT to the controller's power terminal block.The orange wire should be connected to pin 2 (OUT +). The white wire should be connected to pin 1(OUT -). orange power cable wires are positive and white wires are negative.
3. Connect the controller with the right polarity to a 48V DC power outlet. This is connected to the power terminal block pin3 (IN+).
4. Allow cold tip temperature to stabilize at desired cold end temperature.

To shut the Cryotel GT system down,the following procedures is used:

1. Turn off the controller.

NB: allow the cold tip to reach a temperature above 60K before shutting down to prevent the cooler from energizing and becoming an engine.

2. Allow the cold tip and the rest of the cryocooler temperature to rise to room temperature before opening the vacuum in order to prevent the vapor outside the cryostat from condensing and freezing on the cold tip.

Note: Applying a heat load to the cold tip during the warming process reduces the time needed to reach room temperature.

There are two led light that help to indicate whether the cooler is in the set point temperature or if the cooler is still in cool down mode. The red LED indicates the cooler has not reached the setpoint temperature. But once the cooler reaches its setpoint temperature within the desired temperature range, the green LED will turn on. The default temperature band is 0.5K. When the cooler is at the set point temperature the digital output is 5V but when it is not the output is 0V. It is also important to note that when the two led lights are flashing at once then the controller is reporting an error. This error is usually resolved in two ways:

1. Issuing The ERROR<CR> command
2. Counting the number of LED flashes

When the ERROR<CR> command is issued, any error present is indicated with a "1" hence it is easily detected and resolved.

To check an error code using the LEDs, count the number of flashes. Both the red and green LEDs will flash simultaneously. You'll observe a series of short flashes followed by one long flash, with the long flash indicating the end of the sequence. The total flash count includes both the short and the long flash. If multiple errors occur, only one will be displayed by the LEDs. After the long flash, the red and green LEDs will flash rapidly back-to-back, indicating that there are additional errors not currently displayed.

A.2 Precaution Of Use For The Cryocooler

Because the cryocooler can be damaged if not handled properly when removed from the package or when in use, there are few do’s and don'ts to aid proper handling.

It should be noted that before modifying the cryocooler, Sunpower has to be consulted for guidance. It is also very important to ensure that the controller is properly cooled if placed in an enclosure. When testing the cryocooler in a lab with heaters providing the thermal load to the cold tip, install interlocks to prevent the heaters from operating unless the cryocooler is running, to avoid accidental overheating.

Notable things to avoid while using the cryocooler, avoid handling the cryocooler by the cold finger or placing it on the cold tip. Avoid denting the cold finger, and do not drill, puncture, or modify the pressure vessel. Ensure proper cooling during operation and prevent damage to the copper service tube. Avoid stressing the electrical feedthroughs and do not mount the cooler by hanging it from the absorber mounting bolt or apply clamping pressure to the pressure vessel. Use a flexible method for mounting the absorber stud and do not remove or impact the protective cover on the copper service tube. Avoid controlling power by connecting or disconnecting leads, and do not use an external automatic control system to adjust the cryocooler's set points.

The cryotel GT is normally used with adequate cooling at the heat rejection site to avoid overheating. In order to achieve this adequate cooling the cryocooler is first prepared before it is used. Attach the application apparatus or test cap assembly to the cold tip of the cold finger, applying a thin layer of Apiezon thermal grease or Indium to enhance thermal conductivity. If a vacuum is needed, connect the customer-provided cryostat appropriately. Route wires from the temperature sensor and other measuring devices through the Dewar feedthroughs, ensuring they do not touch the Dewar walls to avoid increased heat loading. Seal the cryostat vacuum, leaving the connection to the vacuum pump open if using a vacuum. Securely attach the cryocooler assembly to the provided mounting device and connect the cryostat feedthroughs to the test and measurement devices. Connect the cold tip temperature sensor to the controller's connector. Finally, attach and start the vacuum pump, allowing it to reach a vacuum of 10 or better.

Appendix B

LTA COMMAND LINES

B.1 Starting The LTA

To begin with the lta command, type

foo@bar:Setup_lta.sh ~$ source

To send commands to the LTA:type foo@bar~$ lta <command>

To add a sequencer based on XML to the LTA

foo@bar:~$ lta sseq

To add a sequencer based on text files to the TLA

foo@bar:~$ lta seq

To name your output fits file foo@bar, specify it as follows:~$ lta name
foo@bar~$ lta name images/test1/run1/lta_img_2_

The image in the second line will be saved as a file called lta_img_2_1.fz in the directory ltaDaemon/images/test1/run1, where the last number represents the total number of photographs taken since ltaDaemon was turned on.

To create a fits file by reading an image from the CCD:
foo@bar~$ lta read
To change the value of a variable that was defined in the sequencer
foo@bar:~$ lta <variable name> <value>
E.g foo@bar:~$ lta NSMAP 1000

To change the value of a variable inherent to the LTA.
foo@bar:~$ lta set <variable name> <value>
E.g foo@bar:~$ lta set v1ah 2

psamp = number of pedestal samples
ssamp = number of signal samples

To get the voltage of all the clocks type
foo@bar:~$ lta get telemetry all

To get the voltage of a specific clock type
foo@bar:~$ lta get telemetry
E.g foo@bar:~$ lta get telemetry vdd

In summary the different command and description are below:

Command	Description
sseq <sequencer>	Load a xml based sequencer
seq <sequencer>	Load a txt based sequencer
<var> <val>	Change the value of a sequencer variable
set <var> <val>	change the value of lta variable
name <name>	set the name of the output file
get telmetry <clk>	Get voltage of a certain clock
get telmetry all	Get all the voltages in the LTA
read	run the sequencer and produce an image
runseq	run the sequencerbut do not produce an image
startseq	start the sequencerbut do not end it
readoff	stop a sequencer from runningcan only be used with startseq

B.2 LTA Scripts

```
#!/bin/bash
#where images will be saved
imgFolder=images/sample/
runName=Run_1
name=$imgFolder/lta_img_

# Sequencers that we will use
#imageSeq=sequencers/clock2L_UW1611S/expose_binned.xml
imageSeq=sequencers/example/sequencer_expose_binned.xml
idleSeq=sequencers/example/idle.xml cleanSeq=sequencers/example/sequencer_clean.xml

# voltage variables
 voltage_setup=voltages/voltage_setup.sh

# cds variables
# Integration width = (cdsSAMP+cdsSINIT+seqSIGEXTRA)/15 in units of microseconds
cdsSAMP=200                    #ssamp and psamp for signal and pedestal samples
cdsSINIT=30
cdsPINIT=30
seqPEDEXTRA=5
seqSIGEXTRA=5
cdsout=2                       # 3 for differential-Amp, 2 for Op-Amp only

# dimensions of the CCD that you want
skpNSAMP=1
 skpNROW=800
skpNCOL=1100
skpNBINROW=1
skpNBINCOL=1

# Substrate voltage
VSUB=45
```