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Développement de détecteurs à inductance cinétique ultrasensibles pour l'infrarouge proche et le visible

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Acknowledgements

The past six months, during which I had the opportunity to complete my final-year project within the Galaxies, Stars, Physics, and Instrumentation (GEPI) laboratory at the Paris Observatory (OBSPM), have been a highly enriching experience and an excellent introduction to the world of research. I gained valuable knowledge by integrating into an open and people-centered laboratory, particularly alongside experts in a field I had previously only understood superficially: the use of electronics and superconductors for the astronomy of tomorrow.

I extend my heartfelt gratitude to Faouzi Bousaha, my internship supervisor, who trusted me, gave me his time, and provided invaluable advice throughout this project. I also wish to thank all members of GEPI, each of whom played a vital role in the project's success. I am very grateful to have been part of a team where mutual support, kindness, and communication are core values.

Finally, I thank all the supervisory staff at ENAC, especially Ms. Martineau, for her availability and support.

Abstract

The Paris Observatory (OBSPM), founded in 1667 by Louis XIV and run for over a century by the Cassini family, is dedicated to developing and operating astronomical instruments to advance terrestrial navigation. Today, the observatory operates three sites—Paris, Meudon, and Nancay—focusing its research on long-term observations in fields such as astronomy, geophysics, oceanography, and environmental science.

OBSPM is continually upgrading its technologies to extend and enhance its reach. It was here on the Paris site that Ole Rømer discovered the speed of light in 1676, and it may be here that the great mysteries of dark matter will be uncovered.

Currently, the GEPI laboratory is exploring the use of superconductors through an advanced photon detector known as the Microwave Kinetic Inductance Detector (MKID). Developed by scientists at the California Institute of Technology and the Jet Propulsion Laboratory in 2003, MKIDs detect photons impacting their superconductors, altering the properties of the MKIDs and allowing precise quantification of incoming photons—thereby advancing astronomical observation techniques.

Various MKID architectures are under study to enhance performance, with the aim of deploying them in large-scale projects like the SpectroPhotometric Imaging for Astronomy with Kinetic Inductance Detectors (SPIAKID). This is a 3.6-meter spectrophotometer equipped with 20,000 pixels, scheduled for installation on the 3.6-meter New Technology Telescope (NTT) in Chile between 2026 and 2028. SPIAKID will focus on the stellar population of ultra-faint dwarf galaxies in the Local Group to improve our understanding of galaxy formation and dark matter. Thus, Lumped Element KIDs (LEKIDs) will facilitate this MKID array, forming a matrix of 20,000 pixels.

Résumé

L'Observatoire de Paris (OBSPM), fondé en 1667 par Louis XIV et dirigé depuis plus d'un siècle par la famille Cassini, a pour mission de développer et d'exploiter des instruments astronomiques pour améliorer la navigation terrestre. L'Observatoire de Paris est aujourd'hui implanté sur trois sites : Paris, Meudon et Nancay et généralise ses recherches à des observations de longue durée dans le domaine des sciences de l'univers (astronomie, physique du globe, océanographie, environnement).

L'OBSPM renouvellement perpétuellement ses technologies afin de voir toujours plus loin et toujours mieux. C'est sur le site de Paris que la valeur de la célérité de la lumière a été découverte par Ole Røme en 1676 et c'est peut-être ici que les grands mystères de la matière noire seront découvert.

Aujourd'hui, le laboratoire GEPI étudie l'utilisation des supraconducteurs à travers un nouveau type de détecteur de photons appelé Microwave Kinetic Inductance Detectors (MKIDs). Ils ont été développés par les scientifiques de la California Institute of Technology et le Jet Propulsion Laboratory en 2003. Les photons incidents tappent les supraconducteurs du MKIDs, le phénomène a pour effet de modifier les caractéristiques du MKIDs. Ainsi le nombre de photons entrant pourra être déterminé avec précision et ainsi perfectionner les techniques d'observations de l'univers.

Différentes architectures du MKIDs sont étudiées afin d'en perfectionner ses performances et de finalement de l'utiliser sur des projets à grandes échelles telle que le SpectroPhotometric Imaging for Astronomy with Kinetic Inductance Detectors (SPIAKID). Il s'agit d'un pectrophotomètre de 3.6m composé de 20 000 pixels qui sera déployé sur le New Technology Telescope (NTT) de 3.6m au Chili entre 2026 et 2028. SPIAKID s'intéressera à la population stellaire des galaxies naines ultra faibles du Groupe Local pour mieux comprendre la formation des galaxies ainsi que la matière noire.

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Internship environment

Company description

The Paris Observatory (OBSPM) is a public institution dedicated to fundamental and applied research, higher education, and knowledge dissemination in disciplines related to space sciences and astronomy. Today, it operates across three sites: Paris, Meudon, and Nancay, making it the largest astronomy research center in France.

OBSPM comprises 800 employees, including researchers, engineers, and administrative and technical staff. They contribute to theoretical studies, instrumental innovation, and observational services for major ground-based telescopes, metrology, and space missions. Leveraging its expertise, the Paris Observatory collaborates with leading international astronomy institutions.

As a major establishment within the Ministry of Higher Education, Research, and Innovation, OBSPM is organized into scientific departments and service units, which are affiliated with both the National Center for Scientific Research (CNRS) and PSL University.

Figure 1: Historic Perrault Building on the Paris Site

Vision and Values

OBSPM's vision is centered on advancing our understanding of the universe and training new generations of scientists in this field. The observatory upholds values of scientific excellence, rigor, innovation, and knowledge sharing, as well as a strong commitment to international research projects in space and astronomy.

Market

The Paris Observatory-PSL operates primarily in the research market of astronomy and astrophysics, covering fields such as cosmology, stellar physics, and planetary system observation. Its influence extends to public and private collaborations, engaging with cutting-edge markets in the space industry, observational technologies, and astronomical measurement systems.

Key Partners

OBSPM's partners are diverse, including space agencies (such as CNES in France and ESA at the European level), as well as major international observatories like the European Southern Observatory (ESO). The observatory also collaborates with prestigious academic institutions, such as universities and schools within the PSL (Paris Sciences et Lettres) alliance, and private entities on the development of space technologies and astronomical instruments.

These partnerships enable the observatory to play a key role in large-scale global scientific projects, fostering a dynamic environment of resource and expertise sharing.

Missions

OBSPM fulfills three main missions:

1. Conducting research to advance our understanding of the universe,
2. Providing initial and ongoing education,
3. Sharing knowledge with the public,
4. Engaging in international cooperation.

Organisational Structure :

Scientific departments and institutes :

GEPI : Galaxies, Etoiles, Physique et Instrumentation

IMCCE : Institut de mécanique céleste et de calcul des éphémérides

LERMA : Laboratoire d'Etudes du Rayonnement et de la Matière en Astrophysique

LESIA : Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique

LUTH : Laboratoire Univers et THéories

SYRTE : SYstèmes de Référence Temps Espace

Scientific services :

ORN : Observatoire Radioastronomique de Nançay

UFE : Unité de Formation et d'Enseignement

Laboratoires associés ou en partenariat :

OSUC : Observatoire des Sciences de l'Univers en région Centre

APC : Astroparticule et Cosmologie

LPP : Laboratoire de Physique des Plasmas

GEPI Laboratory

Le laboratoire GEPI est constitué de deux pôles, le pôle scientifique et le pôle instrumental auquel j'appartiens. Ce dernier a pour vocation la définition, la conception et la réalisation de grands projets instrumentaux de l'astronomie au sol et dans l'espace. Dans le cadre de collaborations internationales, une activité de Recherche & Développement (R&D) en amont des projets y est associée.

Ce pôle regroupe une quarantaine d'ingénieurs et de techniciens de haute technicité ayant réalisé de grands instruments optiques pour le sol notamment les spectrographes GIRAFFE et X-shooter pour le VLT et participe actuellement à la construction de plusieurs instruments tels que CTA, MICADO, MOONS et WEAVE. Son rôle au sein de l'Observatoire de Paris est de renforcer le potentiel instrumental de l'établissement et de favoriser les actions interdépartementales par un regroupement des moyens lourds et des compétences. Ces compétences vont des techniques globales telles que l'organisation de projets, la simulation et la conception d'instruments, la fabrication, l'intégration et le test de systèmes complexes aux technologies associées telles que l'optique, l'électronique de commande et d'asservissement, la métrologie, les technologies du vide et les microtechnologies (micro-optique, microlithographie, micromécanique). Une équipe « qualité » intervient dans le travail de chacune des équipes « projet ».

Le rôle du Pôle Instrumental est majeur à l'observatoire de Paris où il représente l'essentiel des moyens « sol ». Grâce à son savoir faire et ses réalisations, l'organisation européenne d'astronomie (ESO) lui a confié de fortes responsabilités dans les études des instruments MOSAIC pour l'ELT (le télescope géant européen), qui ont vocation à être en première lumière.

Experts and referent people

Le laboratoire GEPI est constitué d'une équipe de recherche et de développement mixte dans le sens où elle appartient à la fois à l'observatoire de Paris mais également au CNRS. Au cours de mon stage, j'ai pu travailler et échanger avec Faouzi Bousaha, mon maître de stage. Au départ diplomé ingénieur en électronique, il devient ensuite docteur en astrophysique et instrumentation spatiale. Depuis 2010, il entretient des liens tout particuliers entre l'OBSPM et le Jet Propulsion Laboratory (JPL) de la NASA où il a travaillé plusieurs année. C'est ce même laboratoire qui, on le rappelle, a conçu pour la première fois un MKIDs fonctionnel en 2003. Les résultats obtenus au cours de mon stage seront donc d'un grand intérêt pour le JPL.

Mon stage a également servi à assister l'actuelle doctorante de Faouzi Bousaha. Maria Appavou travaille depuis déjà plus d'un an à l'amélioration des performances du MKIDs dans la cadre du projet SPIAKIDs en testant différentes architectures. Ces connaissances sur le sujet m'ont rapidement permis de comprendre les bases de la technologie.

I was hosted at the historic laboratory facilities of the Paris Observatory in the 14th arrondissement. The workspace is well-equipped, providing everything necessary to carry out my internship. I had access to the following equipment:

- **ISO 7 Clean Room**: The ISO classification of a clean room is determined by the concentration of airborne particles of a specified diameter. While ISO 7 is a relatively lenient standard, protective clothing is still required to avoid contaminating detectors during fabrication. I will describe the different machines used in the clean room in detail, parallel to the explanation of the MKID fabrication process, to clarify their functions.
- **CRYOMAT**: This platform is dedicated to material characterization at temperatures below one Kelvin. It is an exceptional piece of equipment and is available to many laboratories and industries in the Île-de-France region. It will be used to characterize the performance of LEKIDs (Lumped Element Kinetic Inductance Detectors), as these superconducting detectors must operate at temperatures below one Kelvin for optimal functionality.
- **IT Equipment**: A monitor, mouse, and keyboard set were provided.
- **Facilities**: Showers, restrooms, meeting rooms, and a cafeteria were accessible.

In terms of software, I used and became proficient with the following tools, which were essential for daily tasks:

- **AutoCAD**: A design software for drafting the technical components of MKIDs.
- **Sonnet**: A high-frequency electromagnetic simulation software for RF and microwave applications.
- **Google Suite**: Email, Calendar, Chat, Meet, Drive, and Slides for communication and documentation.

Internship Objectives

Contextualization and Description of the Broader Project

Due to the multiplexing capability of MKIDs, which enables the creation of multi-kilopixel arrays, this technology is at the forefront of new applications in astronomy. One of these applications is the **SpectroPhotometric Imaging for Astronomy with Kinetic Inductance Detectors (SPIAKID)** project, a 3.6-meter spectrophotometer equipped with 20,000 pixels that will be deployed on the New Technology Telescope (NTT) in Chile between 2026 and 2028. SPIAKID will focus on observing the stellar populations of ultra-faint dwarf galaxies in the Local Group to enhance our understanding of galaxy formation and dark matter.

Detailed Objectives

During my internship, I worked on a specific LEKID architecture (representing the array of MKIDs that form the desired spectrophotometer). This architecture, which will be detailed in the fabrication process, includes a component with vacuum-suspended parallel capacitors. My goal was to address the following research question:

How can the fabrication of this LEKID architecture be optimized within the SPIAKID project framework, and how do its performance metrics compare with existing architectures?

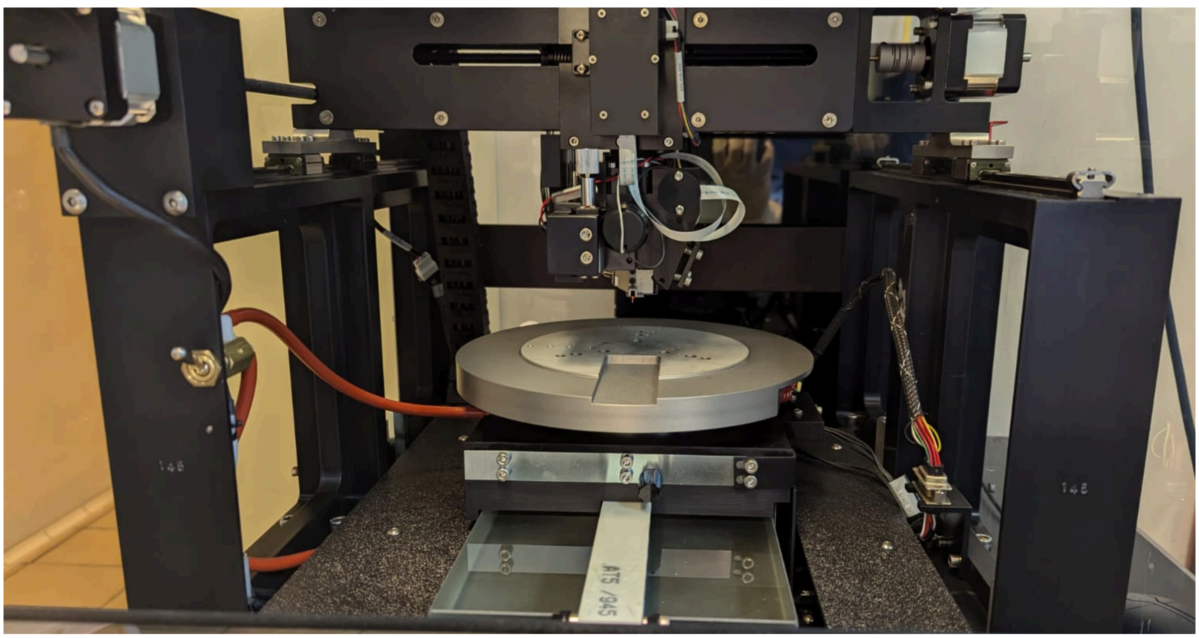
To answer this question, my internship was initially divided into the following tasks and deliverables:

1. **Understanding LEKID Functionality**: This included learning best practices for maintaining ISO 7 standards in the clean room and familiarizing myself with the equipment used by the research team through observing multiple hands-on operations.
2. **Optimizing Optical Parameters**: By analyzing the physical interactions of photons with the detector, I sought to fine-tune the optical performance of the detector.
3. **Optimizing Electronic Parameters**: I conducted simulations using Sonnet to optimize the electronic parameters of the detector.
4. **Fabrication of LEKIDs in the Clean Room**: This involved hands-on assembly of the detectors.
5. **Testing LEKID Performance at CRYOMAT**: This phase focused on evaluating detector performance in a low-temperature environment.

LEKIDs Fabrication

Several design constraints had already been identified at the beginning of the project. I will describe the equipment available in the clean room (which includes a darkroom area, often referred to as the "red room" due to its red lighting) in line with the step-by-step LEKID fabrication process. This will not only present the machinery but also provide an overview of the manufacturing sequence of these detectors.

In the first room, there is a **profilometer**, which is used to verify the surface quality of a substrate. Given the nanoscale of the detectors, even minor manufacturing defects could lead to severe issues. The profilometer performs surface roughness tests, as any surface irregularity could result in significant deformations when applying a thin metal layer via sputtering or when depositing the resin. The substrate is placed on a circular platform, and a stylus scans the surface to measure its roughness.



In the darkroom area, which is lit with actinic (non-photoactive) lighting to avoid photo-chemical reactions, components are cleaned using basic and acidic solutions, especially the substrates used as a base for photon detector fabrication.

The second room of the clean room includes a **sputtering machine**, which applies thin metal layers onto substrates. These thin layers will later be covered with resin.

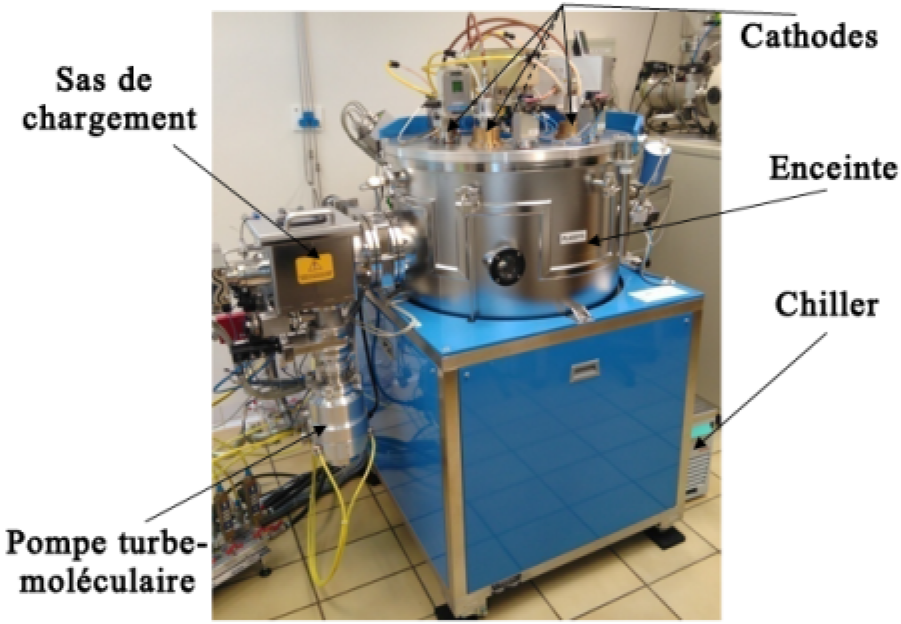
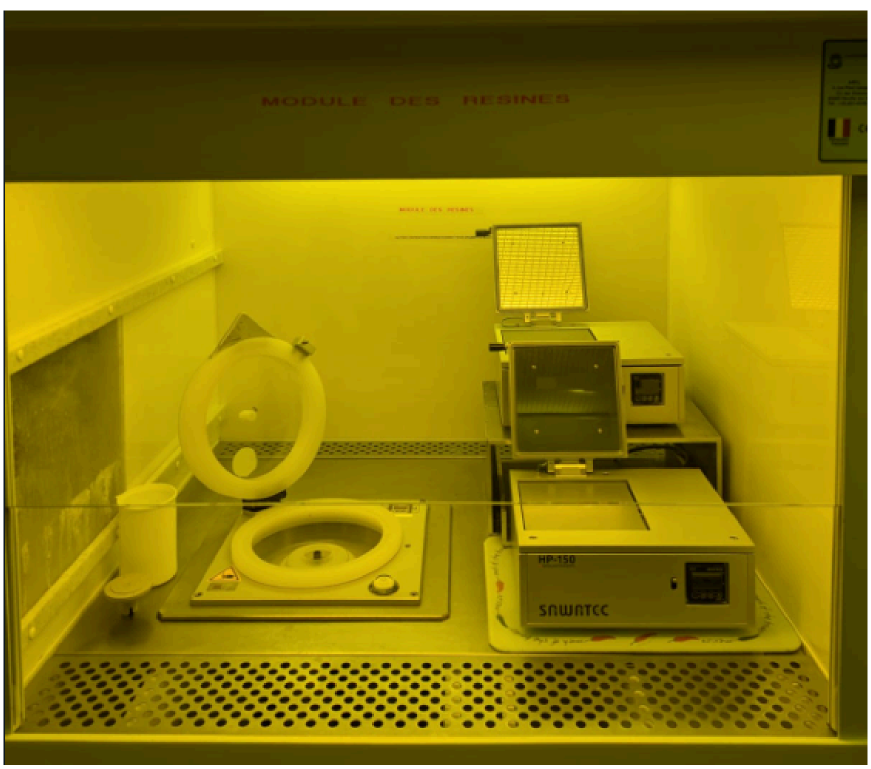


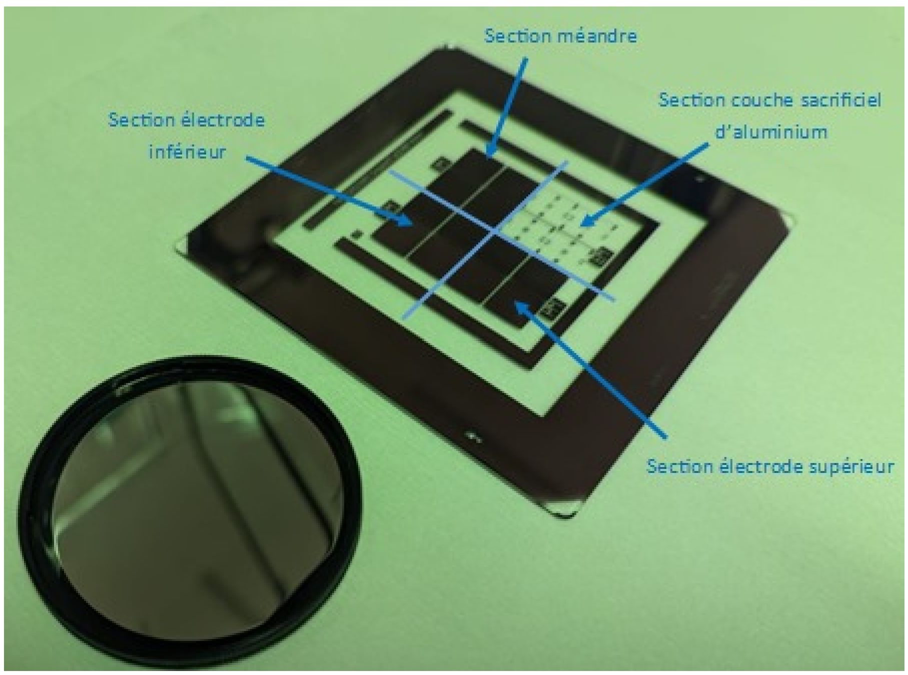
Figure 4.1.2: Banc Plassys MP700s de pulvérisation cathodique à magnétron.

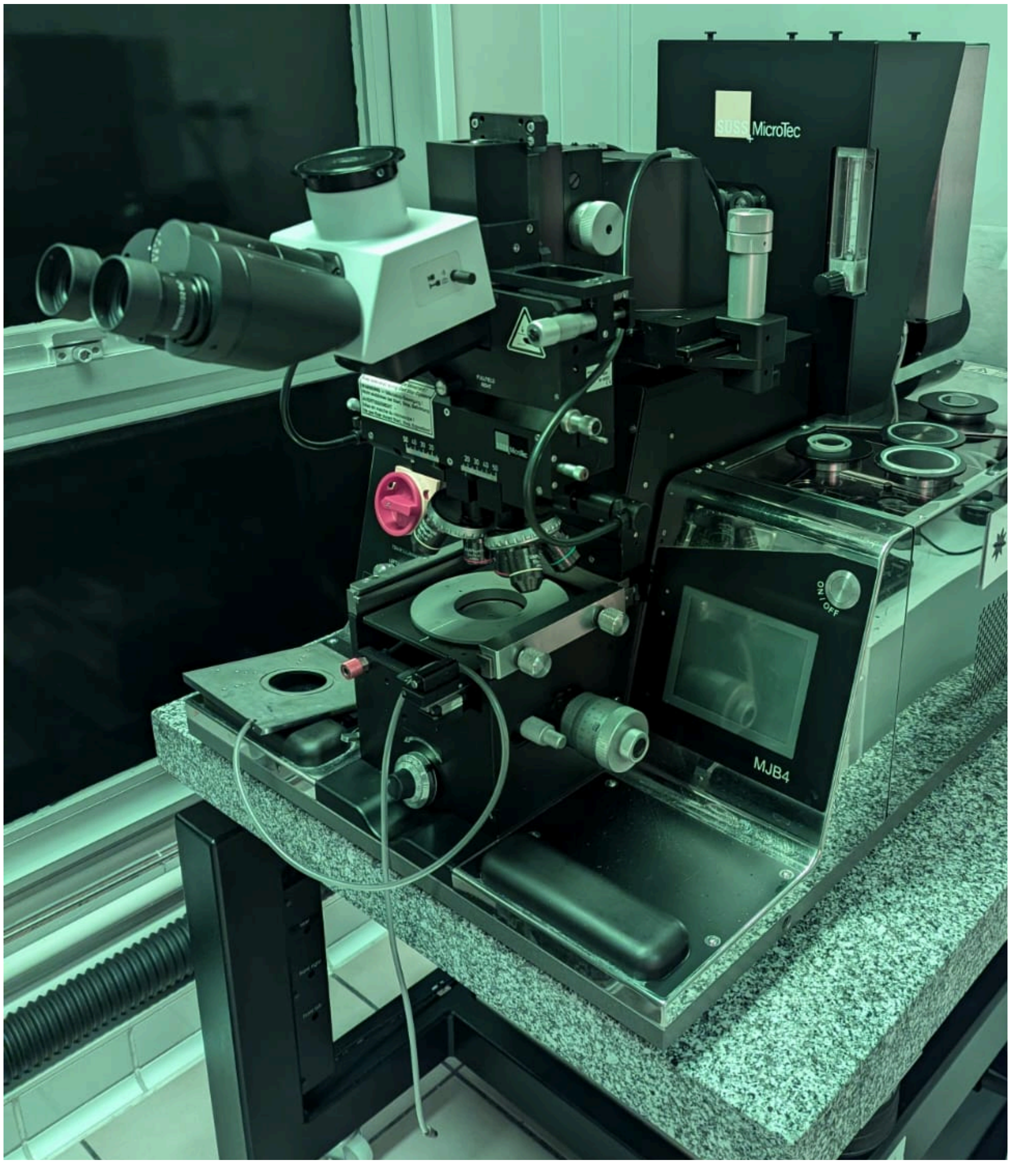
Returning to the first room, which is known as the "red room" due to its red lighting that limits UV propagation, photolithography is conducted here. This process involves printing on a flat surface using light, and the red lighting helps control UV exposure. Through a mask, light is directed onto the resin, fixing it only in areas allowed by the mask configuration.



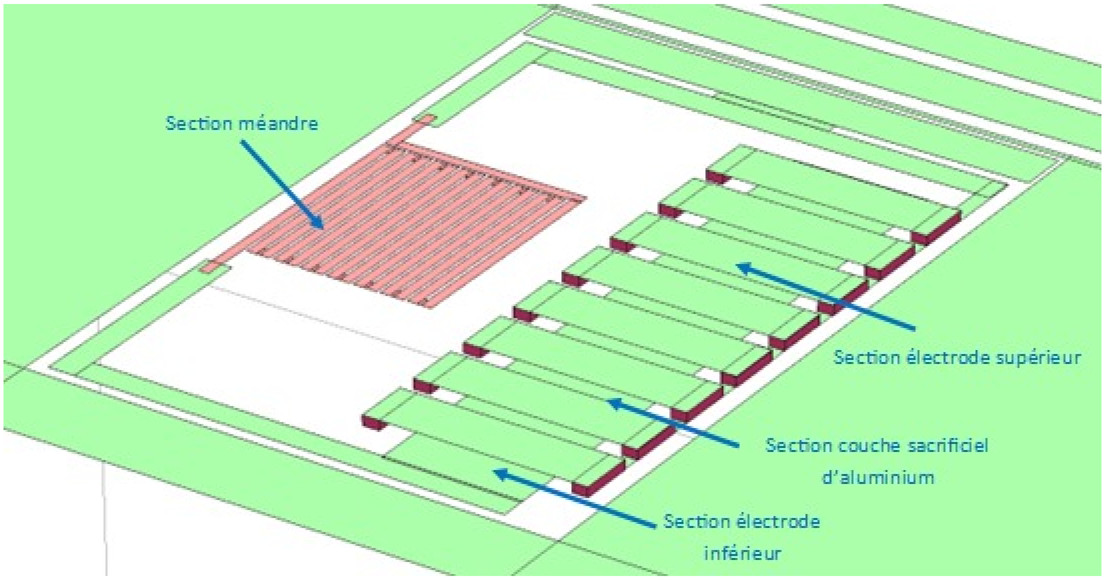
This photo shows the module where resin is applied to the substrate. Actinic lighting (light with a wavelength that does not contain UV) is used here to prevent interference during the resin treatment process by photolithography.

The next photo displays a sapphire substrate after it has passed through the magnetron sputtering machine (covered with TiN metal, as detailed in the section on superconductors). Its reflective surface indicates low roughness. To the right is a mask containing several sections. For economic reasons, different assembly steps for the detector are consolidated on the same mask. I will provide a 3D representation obtained using the Sonnet software, positioning each of the four sections for better visualization, before continuing with the fabrication process and introducing the various machines I used during my internship.





The etching phase involves removing the thin metal layer deposited on the substrate, leaving only areas protected by resin. This process enables precise cutting, such as the creation of meanders.



Technical Environment

Software Utilized

I extensively used **AutoCAD** for designing the four-section masks and **Sonnet** for simulating the electrical behavior of the detector. AutoCAD allowed for detailed design adjustments and enabled high precision in the mask layout, which was crucial for accurate detector fabrication. Sonnet provided a robust platform for simulating RF and microwave properties of the LEKID circuits, allowing us to predict performance parameters and refine the design before physical fabrication.

Analysis of Difficulties

The primary challenges encountered during this project were technical and operational in nature:

1. **TLS Losses**: The Two-Level System (TLS) losses in superconducting detectors present significant issues by contributing to energy dissipation. Reducing these losses was crucial for ensuring optimal detector sensitivity.
2. **Critical Temperature**: Another key challenge was maintaining a critical temperature for superconductivity. This parameter is essential for the LEKIDs' performance, as exceeding it can impair their effectiveness.
3. **Key Circuit Values (f_res, Q_i, and Q_c)**: Fine-tuning the resonant frequency (f_res), internal quality factor (Q_i), and coupling quality factor (Q_c) required precision and a clear understanding of their interplay in the detector's electronic circuit.

Solutions Implemented

To address these difficulties, the following strategies were employed:

1. **TLS Loss Reduction**: To reduce TLS losses, we adjusted the fabrication process and refined the surface treatment of substrates to minimize energy dissipation at the detector's nanoscale level.
2. **Maintaining Critical Temperature**: By optimizing cooling protocols and employing ultra-low-temperature environments like CRYOMAT, we maintained the LEKIDs below their critical temperature, ensuring stable performance.
3. **Optimizing Key Circuit Values (f_res, Q_i, and Q_c)**: Using Sonnet simulations, we carefully adjusted circuit design parameters to achieve the desired resonant frequency and quality factors, optimizing the detector's response to incident photons.