D3.3 | THz detector

Author(s): Martino CALVO, Florence LEVY-BERTRAND and Alessandro MONFARDINI
Delivery date: 28.02.2023
Version: 1.0

Project Acronym:	SUPERTED
Project Full Title:	THz detector
Call:	H2020-FETOPEN-2016-2017
Topic:	FETOPEN-01-2016-2017
Type of Action:	RIA
Grant Number:	800923
Project URL:	https://superted-project.eu/

Editor:	Alessandro MONFARDINI, Institut Néel
Deliverable nature:	Report (R)
Dissemination level:	Public (PU)
Contractual Delivery Date:	28.02.2023
Actual Delivery Date :	28.02.2023
Number of pages:	29
Keywords:	Superconductivity, millimeter-wave
Author(s):	Alessandro MONFARDINI, Institut Néel Martino CALVO, Institut Néel Florence LEVY-BERTRAND, Institut Néel
Contributor(s):	Maria SPIES, CNR Pisa Elia STRAMBINI, CNR Pisa Clodoaldo ARAUJO, CNR Pisa Thibault GANDIT, Institut Néel

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 800923.

	Guillaume DONNIER-VALENTIN, Institut Néel Tero HEIKKILÄ, University of Jyväskylä Sanna RAUHAMÄKI, University of Jyväskylä
External contributor(s):	

Abstract

We present our efforts to elaborate a setup allowing us to test the SUPERTED detectors under mm-wave illumination in a dilution cryostat. We also present the options for enhancing the sensitivity of the SUPERTED NIS junctions to millimeter-wave illumination. We conclude presenting some recent testing results, including the evidence of a possible bias-less detection.

Acronyms:

CNRS = Institut Néel, Grenoble
CNR = National Research Council, Pisa
CSIC = Spanish National Research Council, San Sebastian
JYU = University of Jyväskylä, Jyväskylä
ADVA = Advacam

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 800923.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 800923.

Experimental setup

We describe here the requirements, the design and fabrication of the setup that we have prepared in order to illuminate the SUPERTED detectors with a sub-THz (millimetric) radiation.

Testing setup requirements and design

The SUPERTED detectors [1] are to be run in a dilution cryostat, delivering a base temperature lower than 100mK in a clean magnetic environment. Since the goal here is to demonstrate the sensitivity of these junctions under illumination with THz and sub-THz radiation, a clear optical path between room temperature and the coldest stages has to be implemented in the cryostat. For this reason, we have employed a modified millimeter-wave camera originally designed for astronomical application at millimeter wavelengths [2].

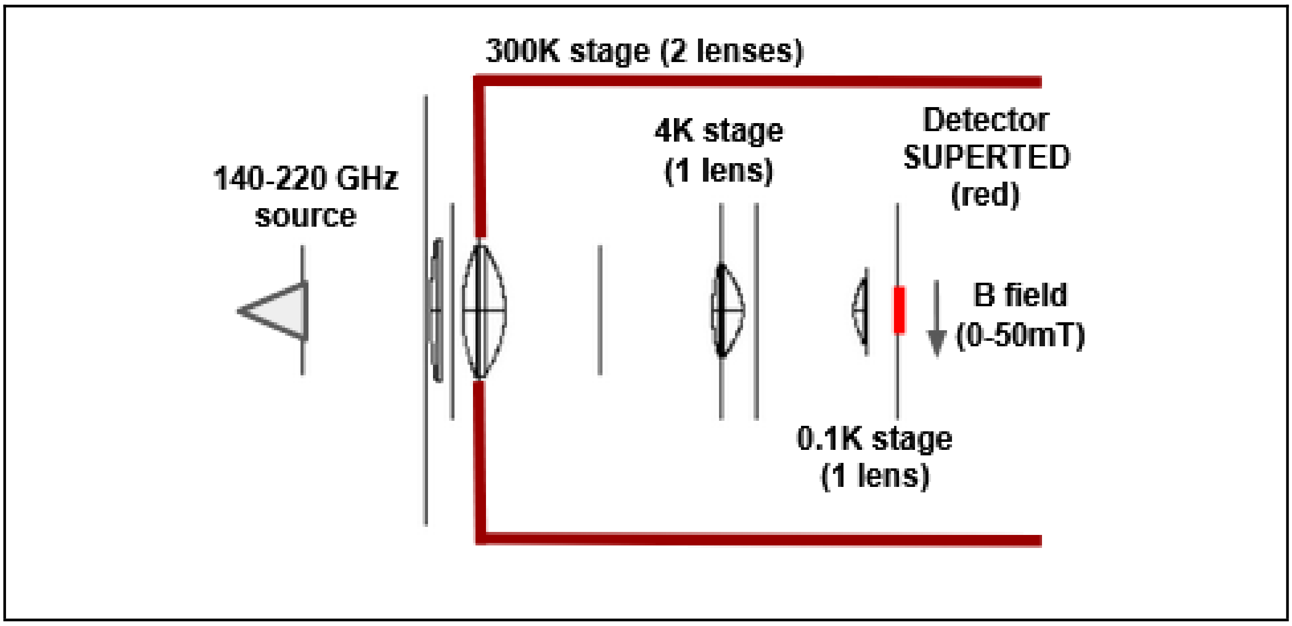


Figure. *Optics system adopted for the SUPERTED measurements in the so-called NIKA0 cryostat.*

A series of metallic multi-mesh filters are employed to allow only the interesting radiation (frequency comprised between 0 and 300 GHz) to reach the focal plane hosting the SUPERTED structures. The SUPERTED detectors are realized on standard Silicon substrates as shown in the next figure. The substrate is glued onto a copper plate equipped with kapton electrical circuits for

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 800923.

electrical connections (micro-bonding to the detector, Sn soldering to the wiring toward the readout).

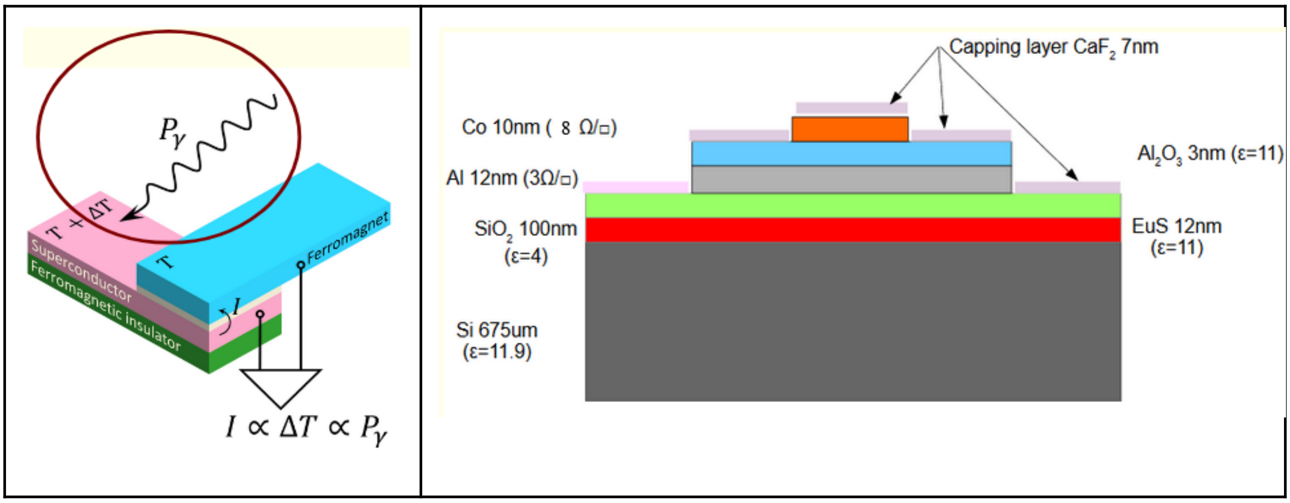


Figure. *Left: SUPERTED working principle [1]. Right: layers for the typical sample produced in CSIC and CNR.*

In order to run and test the SUPERTED detectors produced in the period 2020-2023, a uniform (at minimum over the SUPERTED chip area, thus of the order of $1 cm^2$) B field in the thin films plane of up to 50mT has to be applied. For diagnostic studies, this B field should be settable between 0 and 50mT during the phases of the cryostat cooldown.

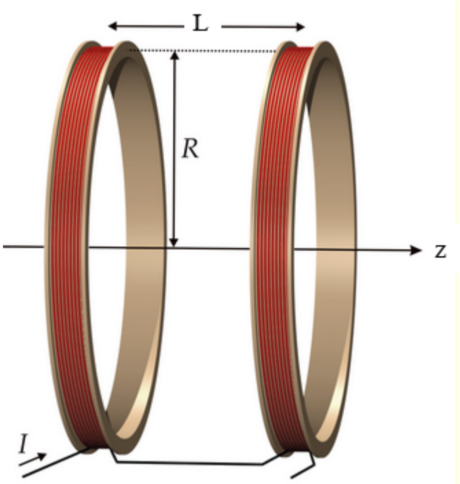


Figure. *The Helmoltz coil allows illumination of the focal plane and at the same time application of a relatively uniform magnetic field along the z direction.*

Both clear path for illumination and the required magnetic field are provided by our custom-made Helmoltz coil described in the figure above. The coil has to be mounted on the coldest stage of the

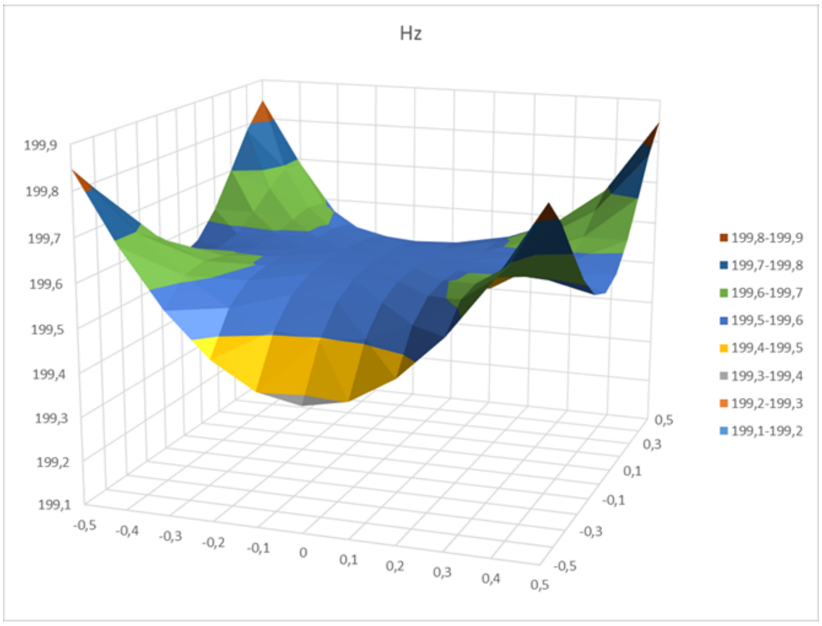
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 800923.

dilution cryostat, so a superconducting wire is required. We have chosen a commercial NbTi wire, superconducting below around 8K.

In order to achieve the needed performance, and account for the mechanical constraints of mounting the chips and fitting the whole device into the 100 mK stage of the NIKA0 cryostat, we have chosen the following parameters:

- internal coil support diameter: 51.8 mm
- external coil support diameter: 68.2 mm
- length of each coil (two in total) : 8.2 mm
- inner distance between each coil: 21.8 mm

To achieve the needed magnetic field, employing a current safely below the critical current of the wire, we would need around 7000 turns per coil, i.e. 14000 in total. This translates in a wire length of a bit less than 3 kilometers. We have simulated the behavior of such a device and found the results shown in the figure below. Across the 1x1cm of the active area we expect an homogeneity of 0.05 mT along the z axis (coil axis, as in the previous figure) and 0.025 mT along the radial direction. This is perfectly matching the requirements for SUPERTED.



This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 800923.

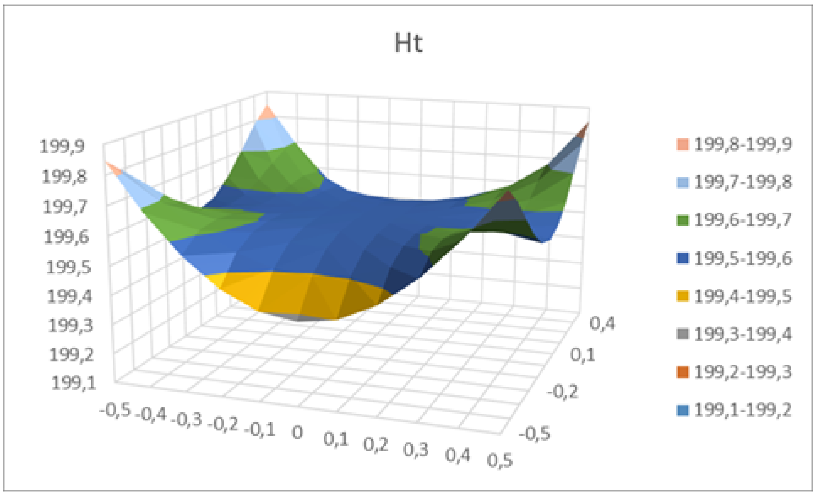


Figure. *Simulated magnetic field distribution along the z and t directions.*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 800923.

Fabrication of the testing setup

With the optical dilution cryostat already available, we have focused on the fabrication of the Helmoltz coil and the adaptation of the coldest parts of the cryostat to host it properly. The wiring of the coil is performed on the 4K stage.

The superconducting wire that we have selected has the following characteristics:

- SC-SW-18/10-0.10mm
- 18 filaments NbTi in Cu-10%Ni matrix
- CuNi:SC =1.5 : 1
- 0.10mm diameter bare
- 0.127mm diameter Formvar insulation

On the other hand the final physical characteristics coil are:

- Body material: Copper
- Dimensions of the mechanical support of the coil : 58.1mm
- Dimension external : 81.2mm
- Wire: dia.0.1/0.127 matrix Cupro SW-18
- Number of turns: around 7000 x 2
- Number of layers : 83
- Every layer with protective Epoxy resist
- Resistance : 103 kΩ @ 300K

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 800923.

Figure. *The fabricated Helmoltz coil, mounted on the 100mK stage of the NIKA0 system. Ready to be integrated into the cryostat. The small hole is where the optical beam is entering.*

The coil has been measured adopting standard procedure at 4K in a testing cryostat at the Institut Néel. The results of the B field along the axis show a good uniformity over a region larger than the original specifications. This will allow further measurements in the future over large detectors.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 800923.

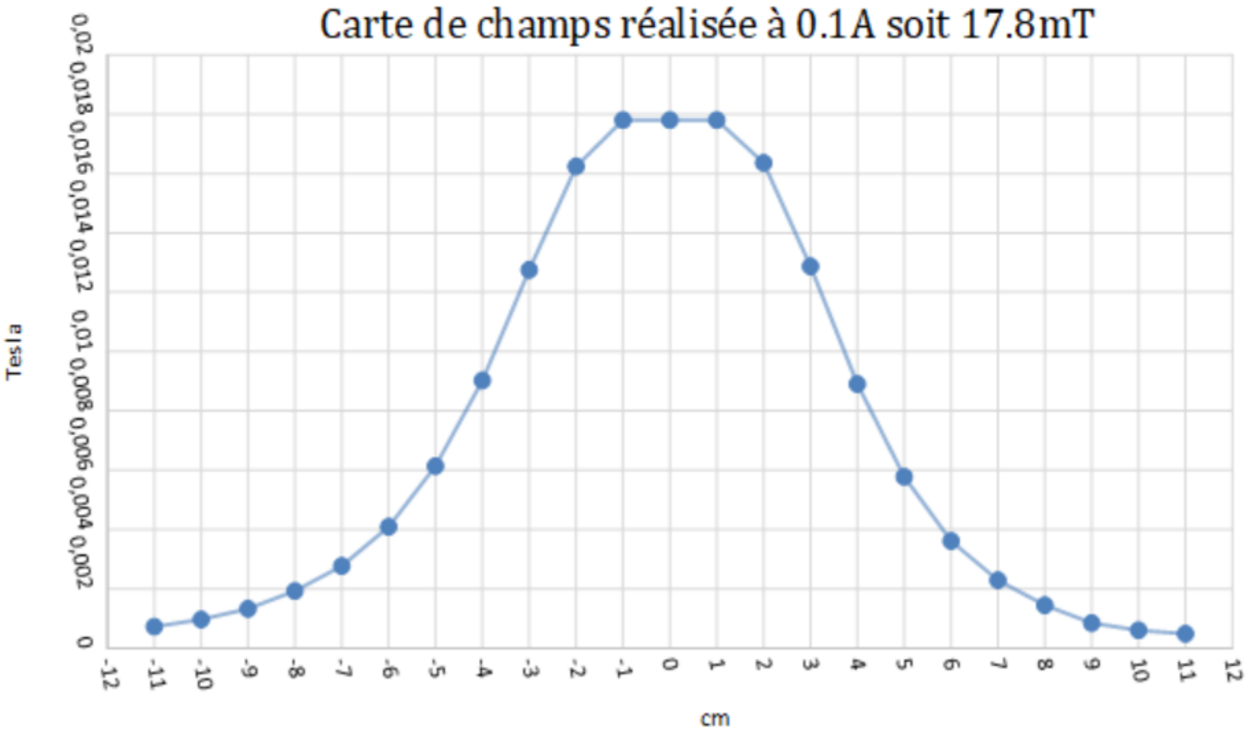


Figure. *B field measurement along the coil axis (z). The B field is very uniform across +/-1cm around the center, and is acceptable in the range +/-2cm.*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 800923.

Validation of testing setup

In order to validate our testing setup we have fabricated an ad-hoc array (16 pixels) of Kinetic Inductance Detectors based on Aluminium planar resonators. We have also machined a mechanical interface allowing sliding this array (containing 16 pixels) into the SUPERTED Helmoltz coil. We have then cooled it down and measured the spectral response of the detectors as a function of frequency, for several values of the B field.

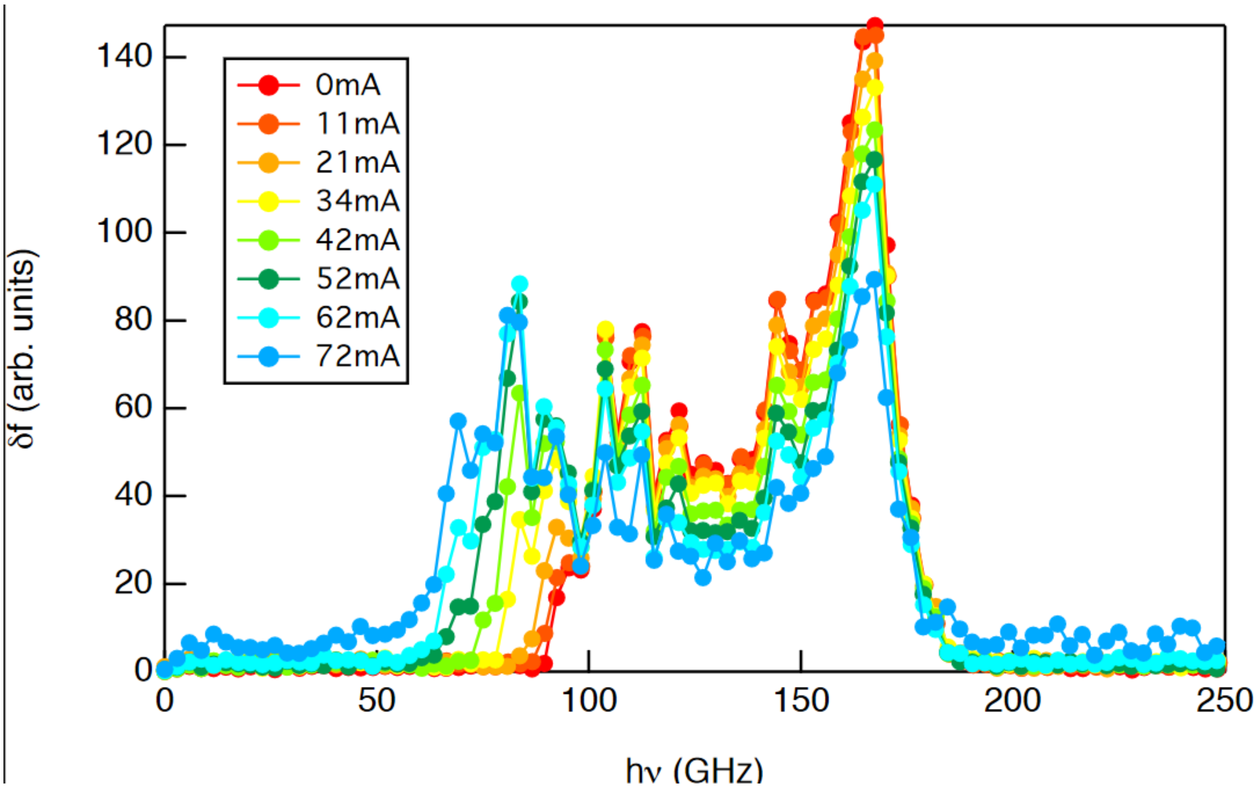


Figure. *200 nm thick Aluminium Kinetic Inductance Detectors (KID) tested under B field and mm-wave illumination. 100mA of current flowing corresponds to 18mT in the Helmoltz coil. The chip is tilted by 5 degrees in order to achieve a 10% B field projection perpendicular to the superconducting film.*

By sweeping the B field we were able to monitor and modulate optically the superconducting gap of Aluminium, confirming that the system is working and ready to be used on SUPERTED detectors. As shown in the figure, the superconducting gap of Al is modulated by the B field (up to about (72mA/100mA)*18mT*tan(0.1)=1.3mT in the direction perpendicular to the film). See [3] for more details.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 800923.

Detector design

We describe here the main arguments at the base of the detector design.

General THz detector considerations

We will define in this context the THz range as the range of frequencies between 0.1 and 3 THz. In terms of wavelengths this is equivalent to a range of 0.1 to 3 mm. This region of the electromagnetic spectrum is particularly interesting for present and future Astrophysics applications. In order to enhance the sensitivity of the SUPERTED NIS junctions to incoming THz radiation we have investigated several options. Among them, in decreasing order of fabrication complexity:

- implementing a higher gap superconducting (e.g. Nb) planar antenna, feeding the NIS sensor. From the fabrication point-of-view, this would have required adding a further metal layer (S2), and realize high-quality metal-on-metal contacts. On top of that, in order to properly match the typical antenna impedance with the NIS junction, a lithography and etching of the NIS structure would have been required.

- pattern the NIS junction into an impedance-matched absorber. The focusing of the THz radiation is achieved by adopting a micro-lens on the back of the silicon substrate. We stress that the dielectric substrate is transparent to THz radiation, allowing back-illumination. This approach is compatible with the existing layers, but would have required an additional, delicate lithography and etching of the NIS junction structure.

- based on the previously available shadow masks, post-patterning a non-optimised absorber in the existing S wire leading to the NIS junction. This only requires a lithography on the superconducting (Aluminium) wire, away from the NIS junction.

After some discussions, we have concluded that the safest option for a first proof-of-concept was the last. For this purpose, a photosensitive resist type S1805 is spinned on top of the chip and then baked. With UV lithography the pattern is subsequently realized. For both the development and the etching of the Aluminium, the developer solution MF319 is employed.

A picture of the NIS junction environment that has been fabricated and tested, together with the schematic of the optical cryogenics measurement setup is shown in the figure below.

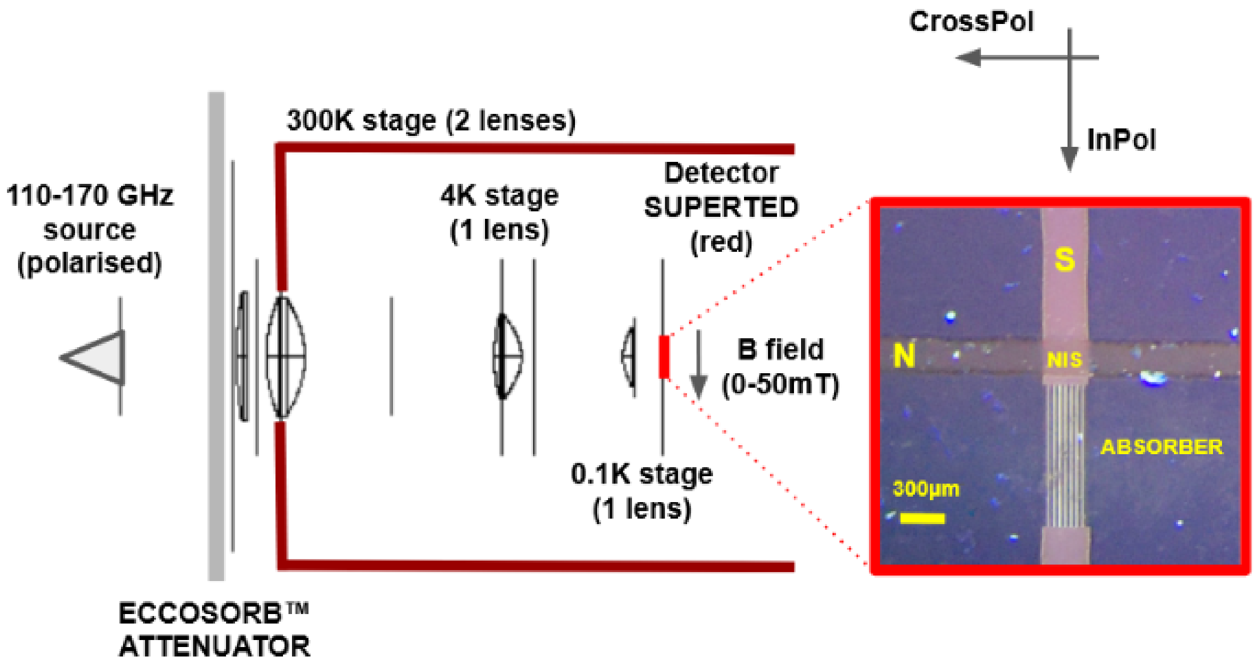


Figure: *Testing setup and positioning of the absorber.*

Antenna versus absorber

The mm-wave radiation is characterized by a wavelength non-negligible with respect to the size of the detector features. For this reason, we must implement an electromagnetic focussing system to produce the heat signal at the junction that has a size, for the current SUPERTED detectors, of 300x 300 microns. This optical coupling is usually achieved in one of two ways, using either an antenna or an absorber.

In the case of the antenna, the incoming radiation couples to the adopted geometry. The antenna itself is made by a low resistivity (ideally, lossless) material, so that the induced signal can be guided towards the detector, where it is then dissipated. A simple and effective design, which could be used for SUPERTED, is the diabolo antenna. This consists of two triangular patches of metal that are joined at one vertex. The incoming electric field induces a current that is concentrated where the two triangles touch, where the SUPERTED detector should be placed so as to dissipate the power at the junction.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 800923.

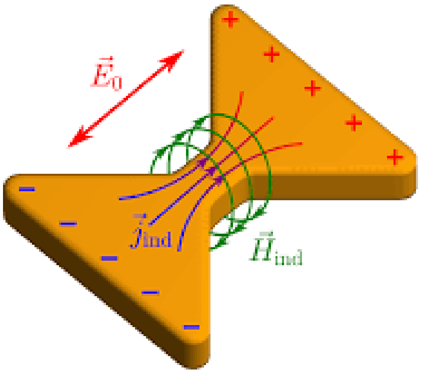


Figure: *sample diabolo antenna design. From Hrtoň et al, Phys. Rev. Applied 13, 054045.*

For an absorber, the design is chosen so as to get an impedance as close as possible to that of the incoming wave, and the absorbed optical power is dissipated in the absorber itself. If the surface resistivity of the material used is too small, as it is often the case (typical values are in the *Ohm/sq* range, to compare to a free space impedance of *377Ohm*), one solution is that of patterning the absorber so as to interleave the metallic surface with empty spaces. If the patterns are small compared to the wavelength, then the effective impedance of the absorber will be given by the material impedance divided by the filling factor. In the case of a parallel lines absorber, given w the width of each line and s the separation between two lines, we get

$$Z_{eff} = Z * (w+s)/w$$

In this design, the absorption is polarization sensitive, being very small for light polarized perpendicular to the absorber lines and maximal in the perpendicular direction.

Design considering the SUPERTED fabrication constraints

In the framework of the SUPERTED project, the solution adopted for coupling the THz radiation to the detector has been driven mainly by consideration on the ease of fabrication, rather than on overall optical efficiency. In fact, the fabrication of the junctions for SUPERTED is in itself challenging and has needed a great effort to reach a good maturity level. Adding steps in the process requiring extra masks and deposition of additional metallic layers would have likely decreased the overall detector yield, for an increase in optical efficiency that is not the key point for a demonstrator device.

To minimize the impact of the optical coupling system on the current fabrication steps, we decided therefore to adopt a solution that 1) did not require modifying the mechanical masks currently used for the SUPERTED detector, and 2) did not require depositing additional materials. Considering these constraints, the best option was that of adding a parallel line absorber in the Aluminum bars. This can be achieved by a simple etching of the Aluminum, that can be done after the detector has been completely fabricated and, if desired, even cooled down and tested to check the quality and performance of the barrier in the dark.

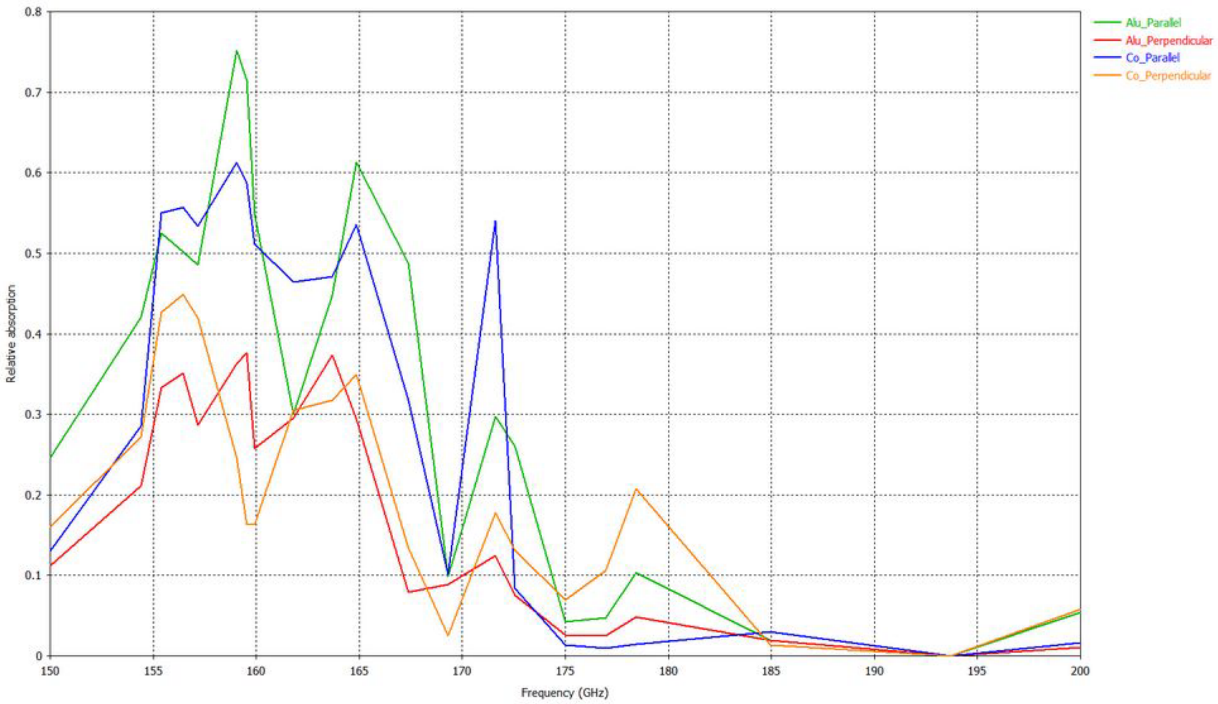


Figure. *Simulated absorption using CST Microwave studio of the real mask adopted in CNR to realize the absorbers. The simulation has been carried out in the frequency domain, with a limited number of points. This explains the fact that the spectral features are not fully resolved. Not very relevant for this case.*

Given the constraints:

1) direct absorption in the normal metal electrode is not avoidable

2) the polarization selectivity is present but not very good (only a factor 2)

BUT the optics absorption, despite not optimized, should be OK for a proof of concept.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 800923.

Fabrication of the first detectors prototypes (absorbers)

In the case of the SUPERTED project, the fabrication of the junctions is made using mechanical shadow masks in CSIC. The original design was made with perpendicular wires (N and S) with a width of 300 microns. The resolution of the shadow mask process being of the order of 100 microns, it was not possible to realize the smaller structures needed for the antenna or the absorber, as described in the previous section.

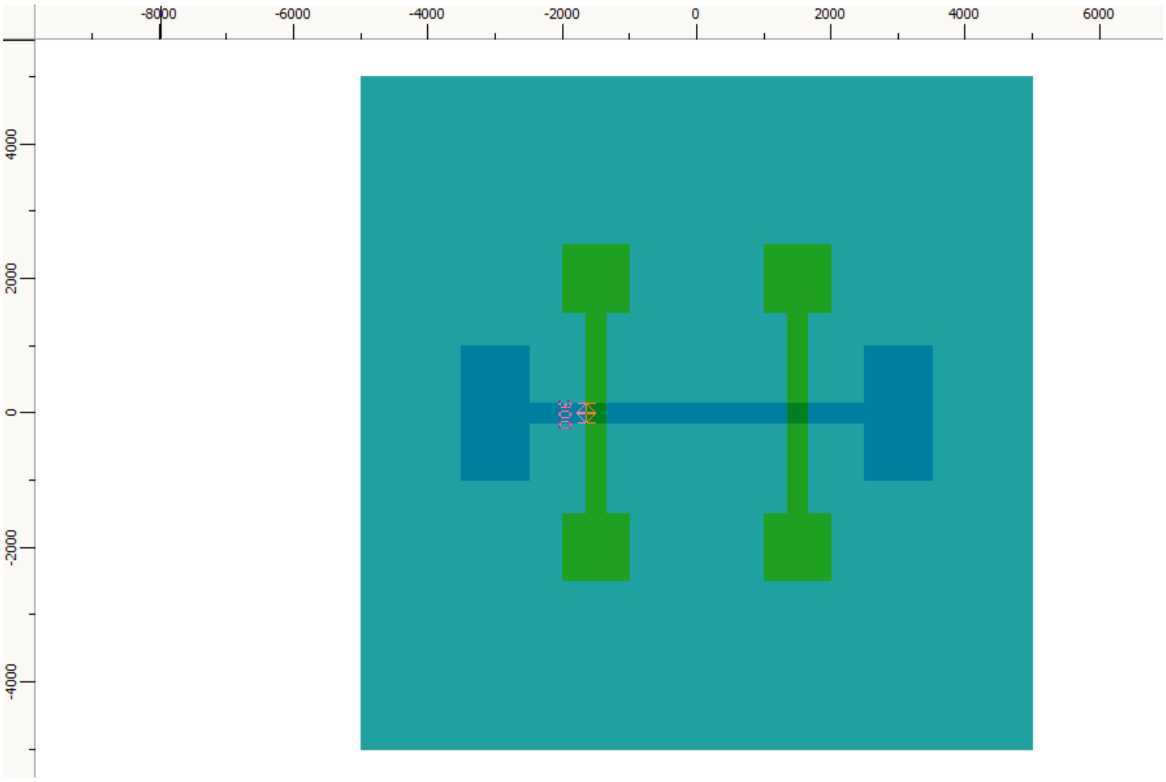


Figure. *SUPERTED original design (CSIC), with a chip of 10x10mm2 and two 300x300 microns junctions. Green is Aluminium, Blue is Cobalt.*

The sheet resistance of the metals (N and S) for the SUPERTED detectors is of the order of a few Ohms per square. It is thus not suitable for direct coupling to incoming radiation (absorber). On the other hand, for the antenna the feed connecting the two sides should have been realized to match the impedance of the antenna itself. That would have required designing a specific geometry for the NIS junction, which was considered too risky for the junction itself.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 800923.

Figure. *First proposal, calling for a lithography of the NIS junction. This solution has been considered too risky for the junction itself.*

In order to find a solution for a proof of concept, feasible (i.e; without changing the original CSIC shadow masks) and not risking to destroy the NIS junction (i.e. without applying a lithography+ etching process to the NIS junction) we have proposed to realize a multi-wire absorber on both sides of the NIS junction, purely etching in the S wire and without affecting the junction, in order to better match the vacuum impedance of 377 Ohms. This was considered possible by the CNR group, and the processing was realized there by Maria Spies. The design of the mask has been made in collaboration between CNRS and CNR. We have designed, taking into account the design rules imposed by the lithography (minimum linewidth = 10 microns), we have designed two sections of absorbers on both sides of the NIS junction. The incoming millimetric radiation (above-gap) is thus better matched by these structures, and is able to increase the electron temperature in the S wire (heating), generating a thermo-current into the N electrode. An alternative view is that quasi-particles are created (from Cooper-pair breaking) in the S wire. These quasi-particles migrate in the S wire until meeting with the NIS junction and eventually tunnel into the N electrode and being detected by the readout electronics.

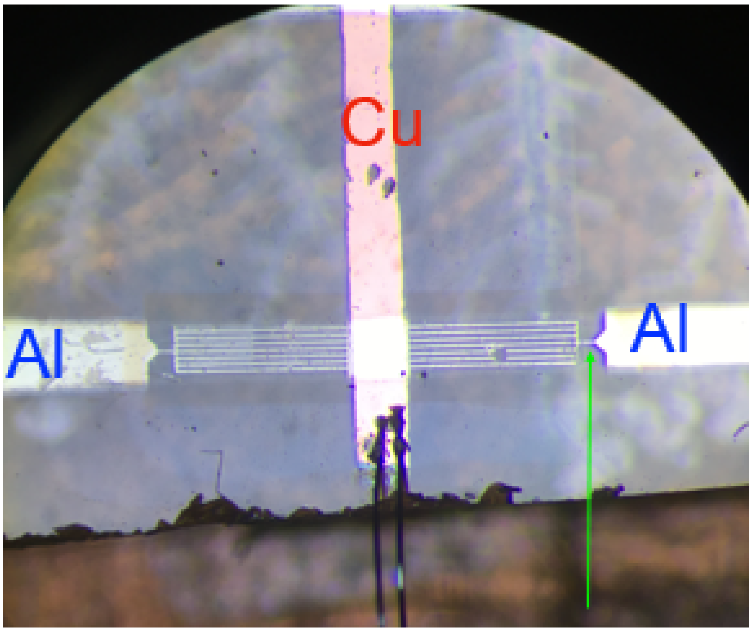


Figure. *Ideal configuration of the THz detector (based on absorbers, and avoiding any litho on the junction), including two portions of absorbers on both sides of the NIS junction.*

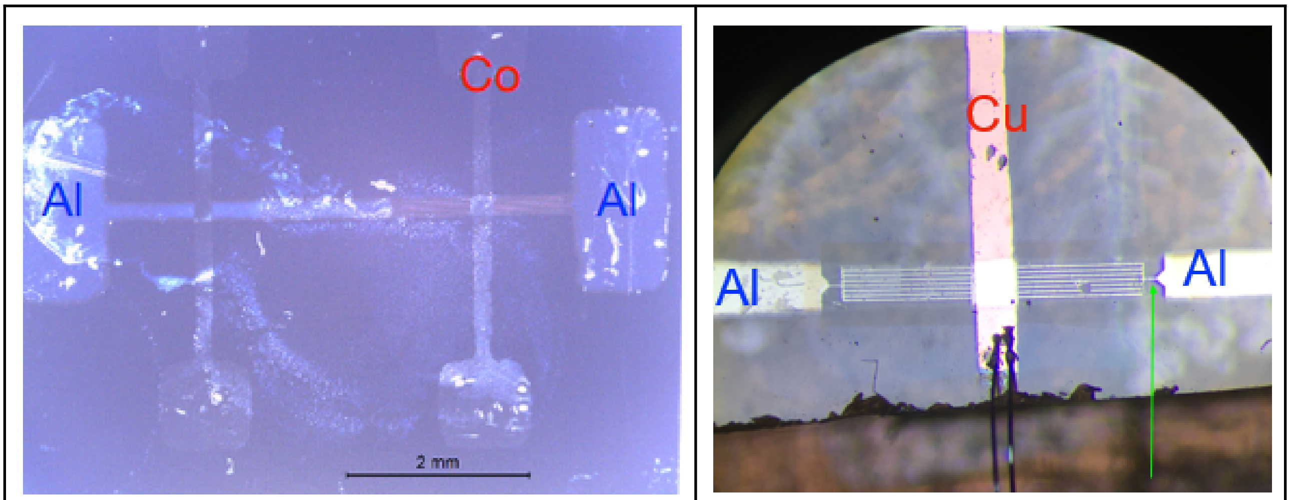


Figure. *Left: a CSIC SUPERTED chip, following the design shown previously. Right: Moodera sample.*

We present here a number of pictures taken on samples that we have received from CSIC and the CNR and that we have micro-bonded (using a 17 microns Aluminum superconducting wire) and tested in the cryostat described in [2].

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 800923.

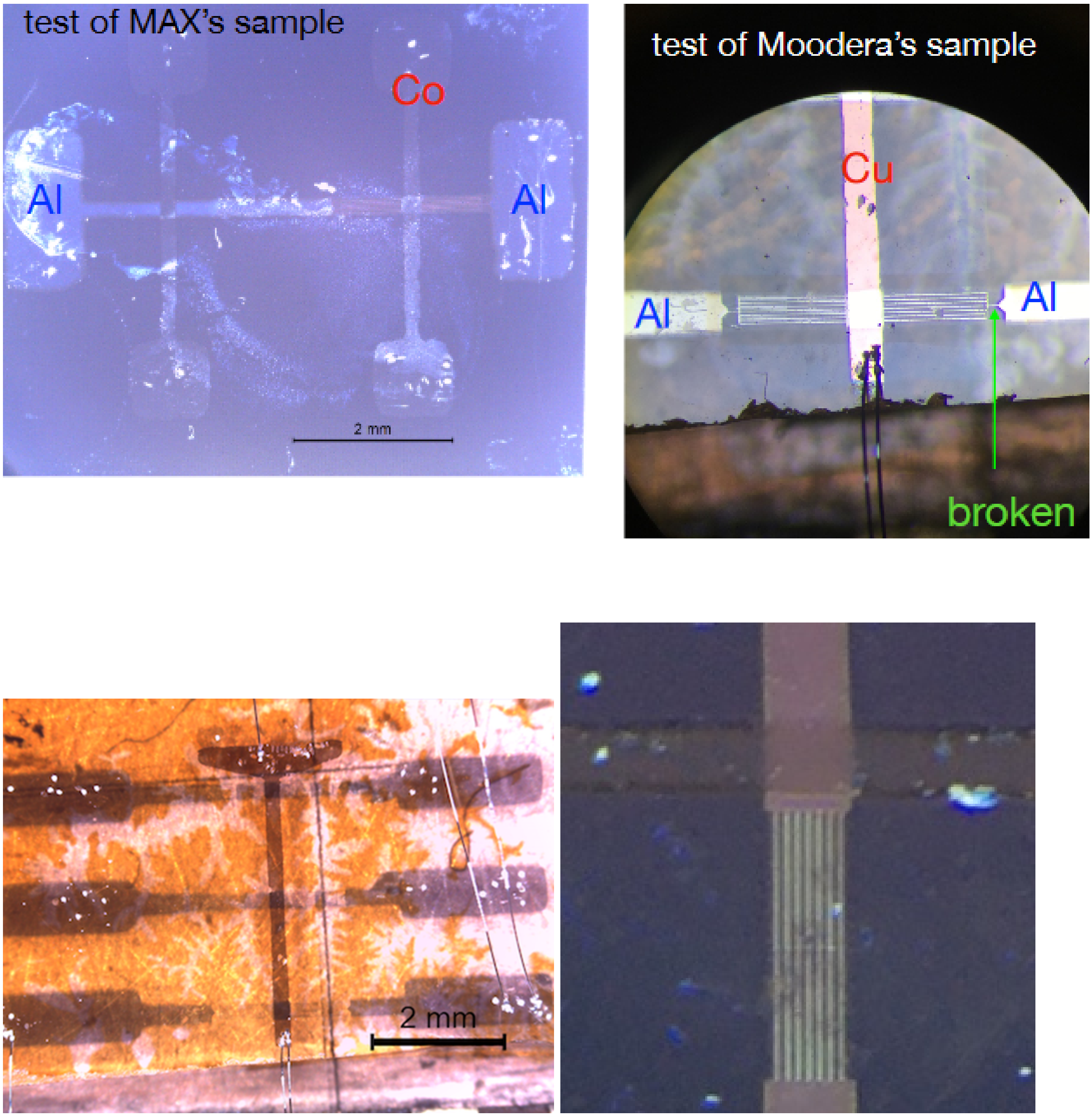


Figure. *From top-left in clockwise direction: a) one of the first CSIC ("Max") samples with absorbers realized on both sides; b) an MIT sample from Moodera with lithography (but broken) realized in CNR; c) picture of the whole Moodera sample realized on a transparent glass substrate; d) the CSIC sample tested in January 2023 and showing the first possible bias-less detection (see below).*

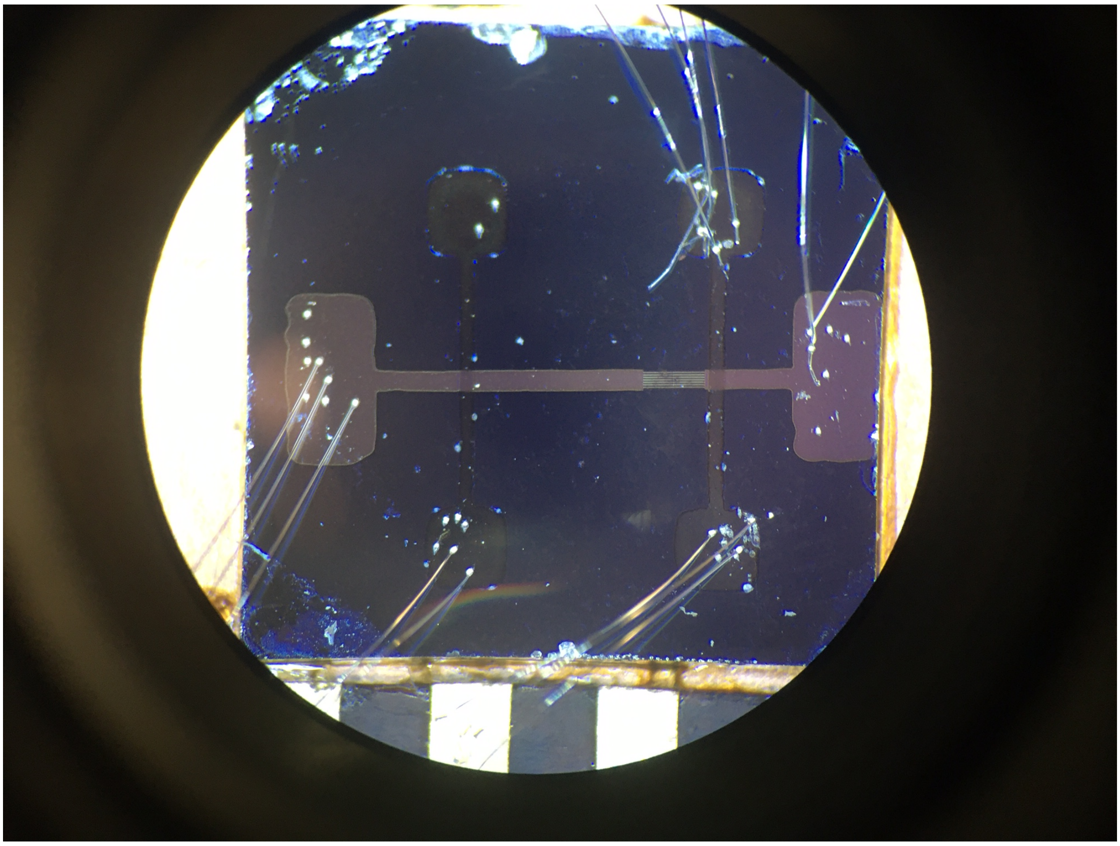


Figure. *Full sample from CSIC (optical measurements results described in paragraphs below), with one single absorber on one side of one of the junctions. Horizontal: Aluminium (S) electrode. Vertical: Cobalt (N) electrodes. Two NIS junctions with size 300x300 microns are shown.*

Preliminary measurements

We describe here the first measurement carried out on specific chips fabricated in CSIC or MIT (mechanical masks) and CNR (lithography of the absorbers).

Readout electronics

For the proof of concept of the THz detection, we have adopted standard instrumentation, following the recipes given by the experienced CNR group. In particular we have adopted:

- FEMTO DDPCA-300 current amplifier for standard measure (self-polarized detector and current generation)
- Keithley 2636A digital multimeter and source for IV (diagnostic) measurements
- Stanford Research System - Model SRS830 DSP Lock-in Amplifier to reduce the noise on the I-V characteristics curves at low bias
- AMC-05 (140-220GHz) and E8257DS06 (110-170GHz) millimeter wave sources

We have adopted 60-Ohm (in total) resistivity constantan wires, running all the way from 300K down to base temperature, properly thermalised on all the cryostat stages, i.e. 100K, 50K, 4K, 1K, 0.1K, and used low-pass EM filters at 300K. This readout is noisy due to the lack of cold/proximity electronics, and cannot be scaled up to large arrays (no multiplexing possible). But it was needed to achieve the first detection (see below).

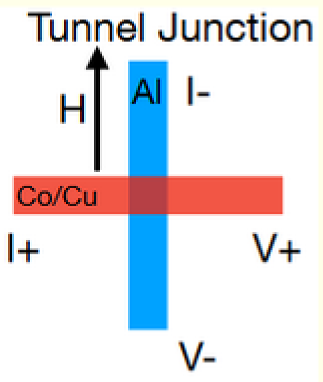


Figure. *Configuration for I-V measurements. Each electrode is connected to a 30-Ohms Constantan wire running up to 300K and connected to the readout electronics.*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 800923.

An alternative readout that we have proposed for the future is the iKID, allowing in principle the multiplexing of hundreds of SUPERTED detectors in the frequency domain. The concept is based on the effect on the non-linearity of the kinetic inductance versus the current flowing into a planar high-quality-factor resonator.

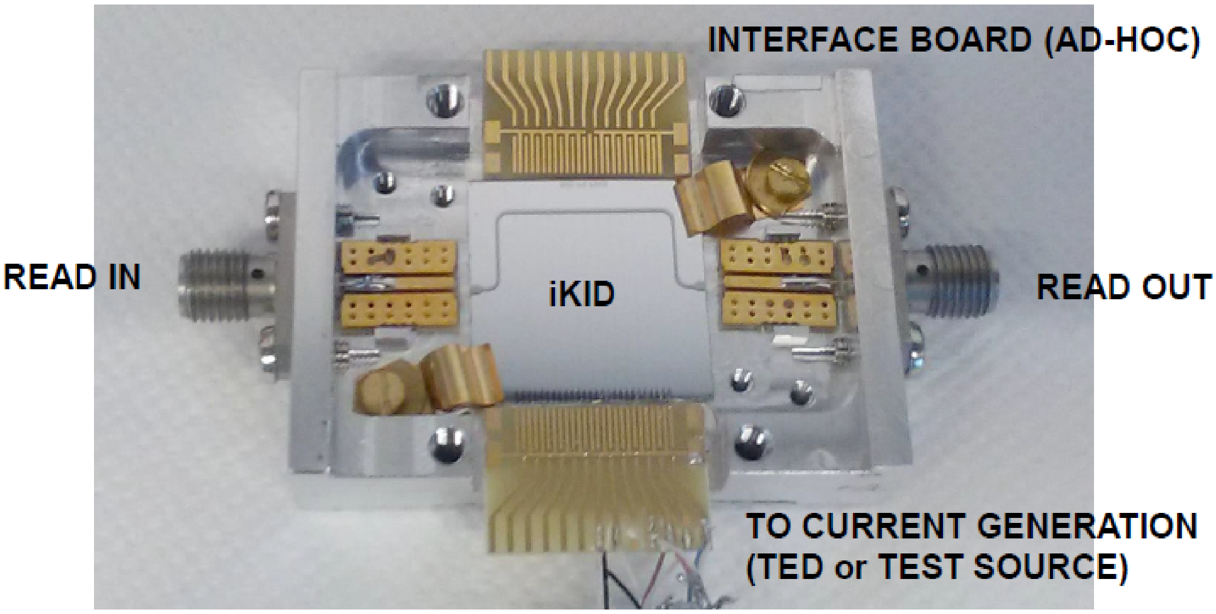


Figure. *Prototype iKID multiplexed readout realized in collaboration with KIT.*

During the SUPERTED project, we didn't produce iKID devices with satisfactory performance, but we made progress in identifying a possible design. A first design, based on two flavors of granular Aluminium highly-inductive (low-pass) wires is shown in the figure. For the future generations, we are now more oriented toward lumped-element low pass filters based on parallel-plate capacitors.

Some results from electrical measurements

In this paragraph we show some results of electrical measurements on some SUPERTED structures produced either by the CSIC group or at MIT (Moodera). These measurements further confirm that our setup was able to perform good measurements (mostly thanks to the lock-in amplifier), and delivering the good magnetic field (right direction and intensity) and that our electronics setup is good enough.

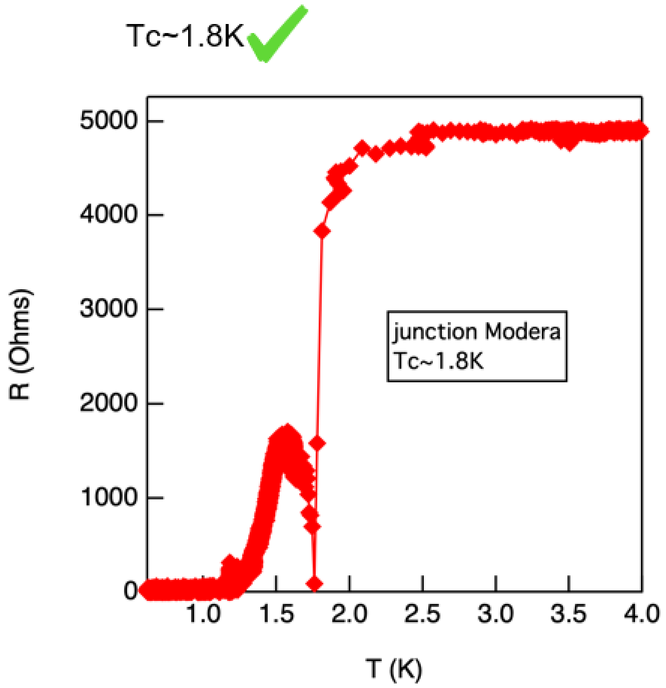


Figure. *Moodera sample critical temperature measurement. We measure around 1.8K for the very thin Aluminium (few nanometers only) deposited by Moodera.*

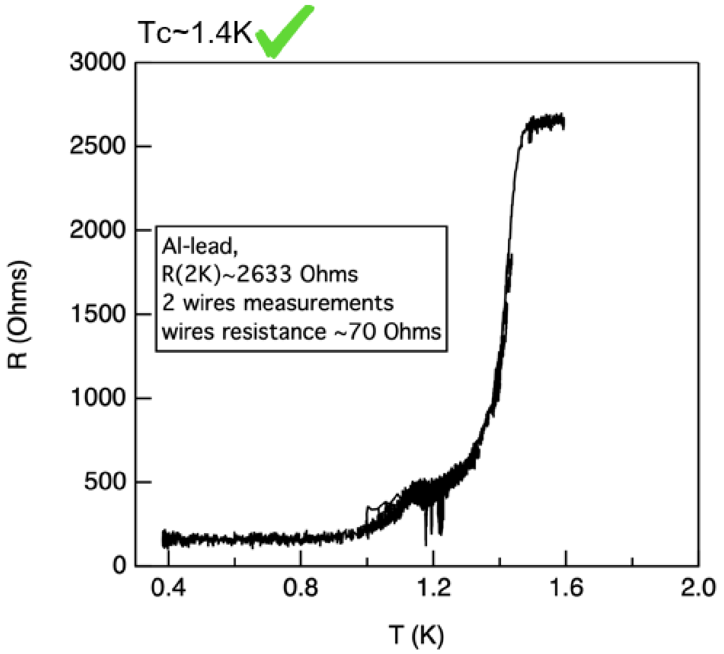


Figure. *"Max" (CSIC) sample critical temperature measurement. We measure, as expected, around 1.4K for the Aluminium S electrode.*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 800923.

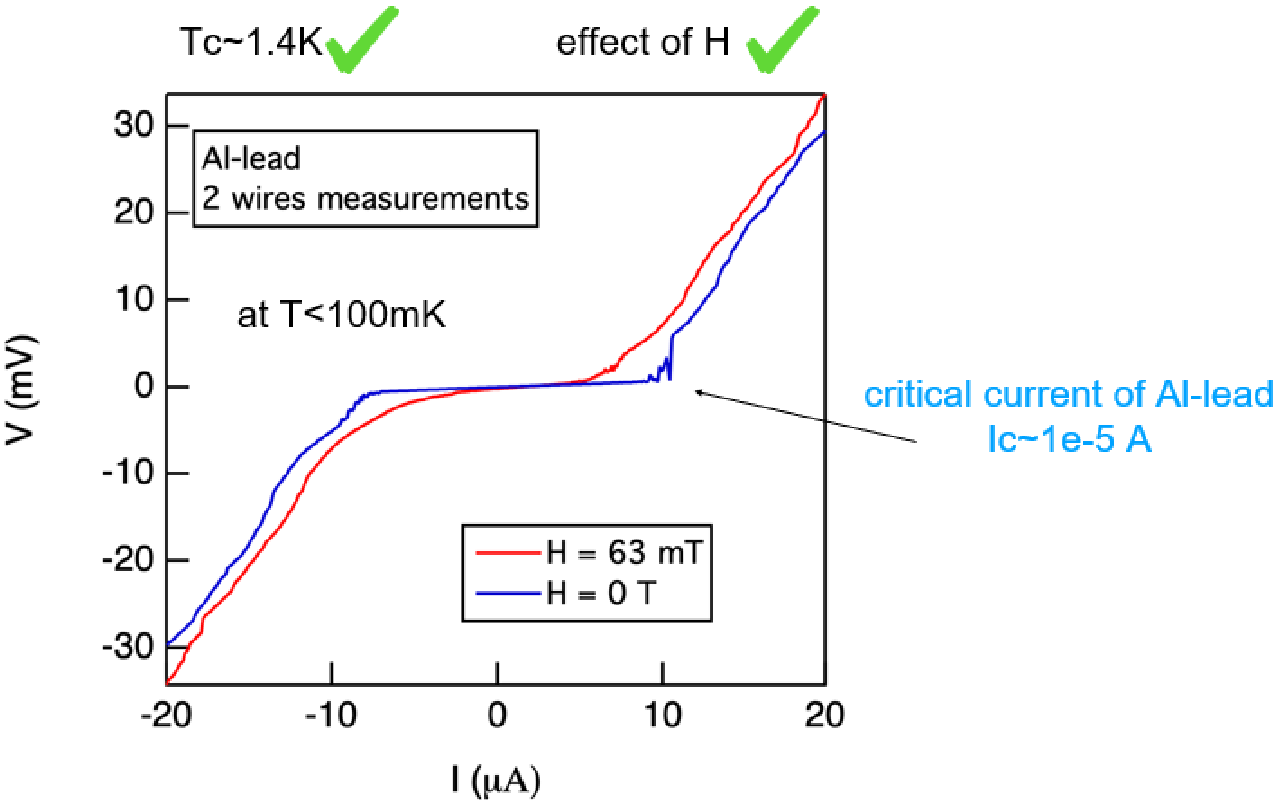


Figure. *Max sample critical current measurement. The effect of the B field on the critical current is clear. On top of that, we have measured the critical temperature that is, as expected, around 1.4K.*

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 800923.

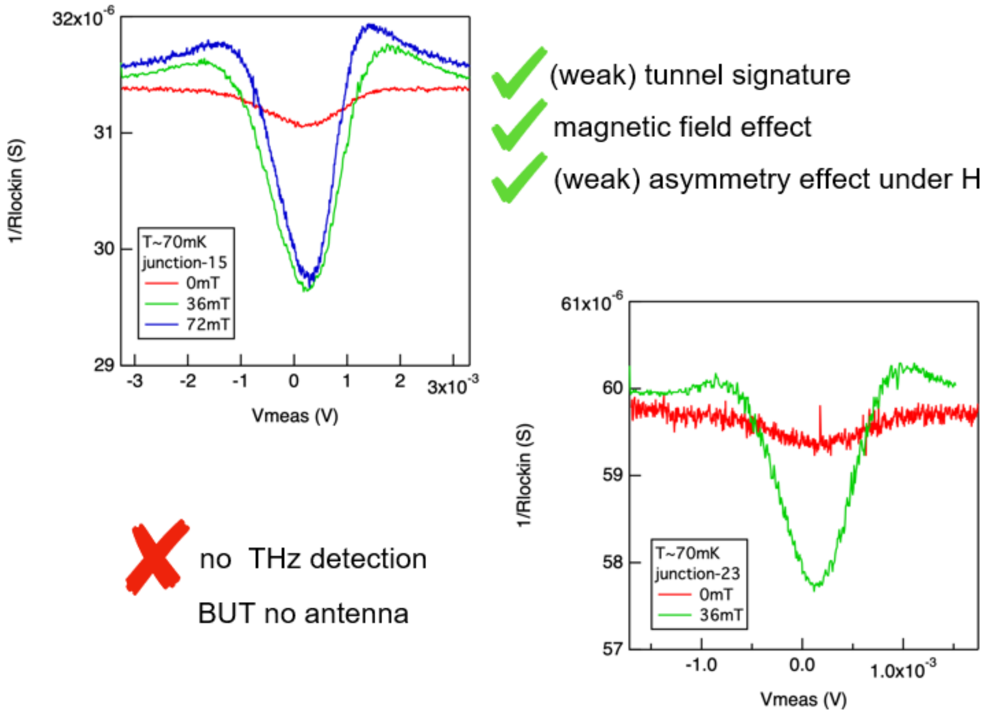


Figure. *Signature of the tunnel junction on a Max sample realized without the absorbers lithography. We see clearly the effect of the application of a magnetic field.*

Some results from optical measurements

In this paragraph we will show some results obtained from a chip made in CSIC that has been tested under illumination.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 800923.

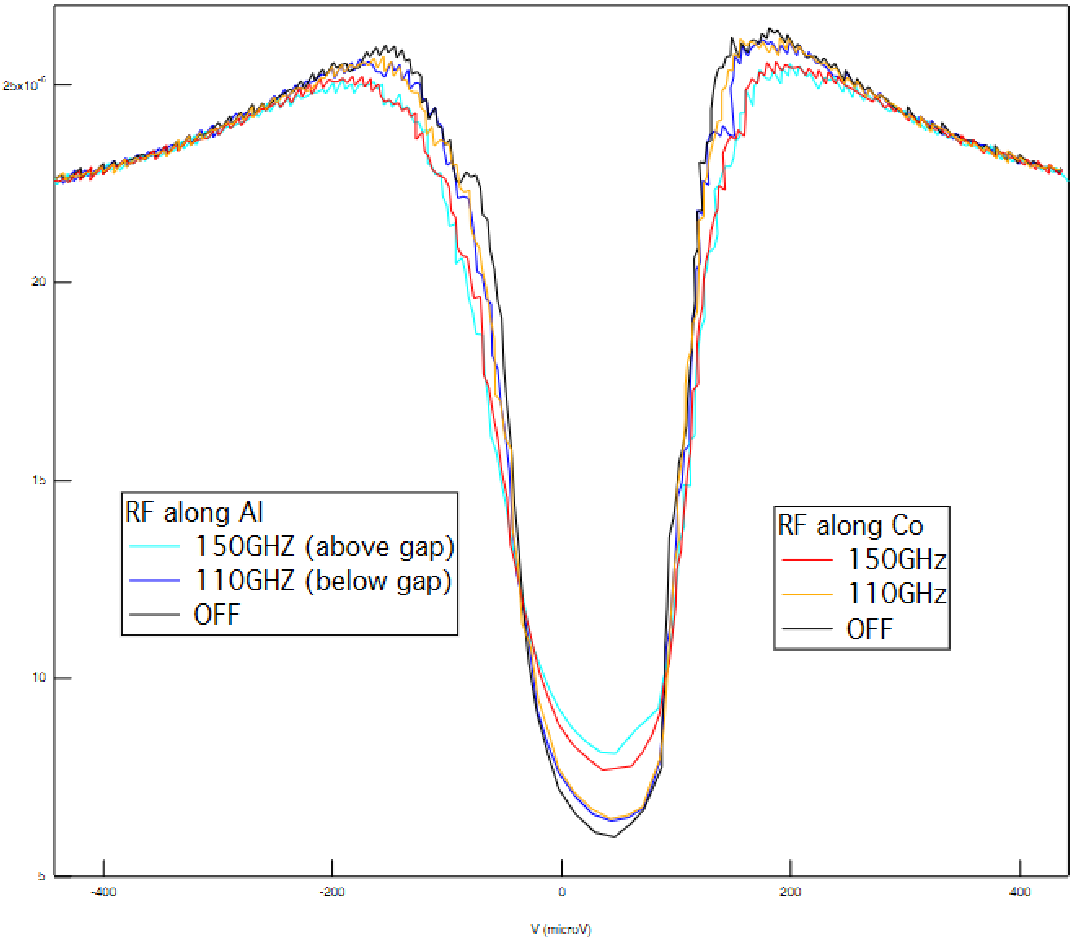


Figure. *Tunnel spectroscopy under mm-wave illumination. For two different polarisations and for two incoming photons frequencies. The resistance at large bias, thanks to the tunneling, is around 45kOhms, while at low (smaller than the superconducting gap, no tunneling) bias it increases to 166kOhms.*

We have first measured the junction characteristics by sweeping the voltage and measuring the conductivity between the S and N electrodes (with the I layer in between). This has been done after having applied a B field of around 20mT parallel to the thin films composing the structure. We show this measurement in the figure above. The effect of the mm-wave illumination is clearly visible.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 800923.

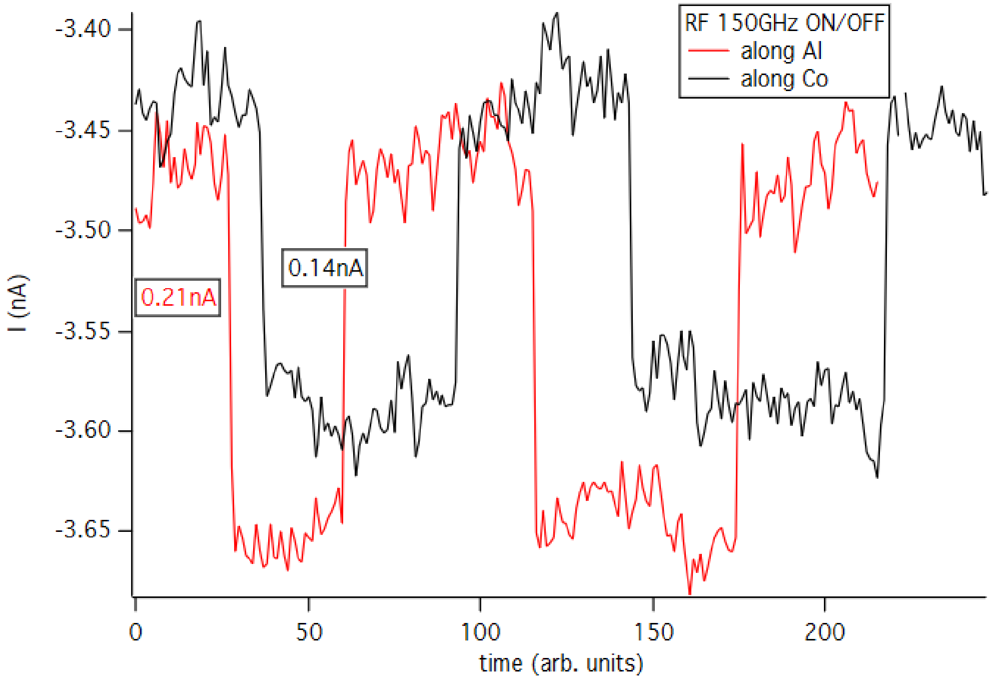


Figure. *First bias-less detection of 150 GHz photons for a SUPERTED structure. By switching ON/OFF the external mm-wave source, we could detect a signal in current from an unbiased SUPERTED structure.*

In a second experiment, we have left the junction unbiased and measured, using the FEMTO DDPCA-300 amplifier, the current that establishes into the N (Cobalt) electrode. As shown in the figure above, we detect a signal in correspondence of the switching ON and OFF of the millimeter wave source, operating at 150GHz. The sensitivity of this detection is pretty poor; a large optical power has been applied, but this corresponds to a relatively small S/N (or the order of 10). The NEP that we estimate is worse than 10^{-11}W/Hz$^{0.5}$.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 800923.

Conclusions

Based on this first tentative detection, and despite the bad sensitivity for now, the SUPERTED detector, after decisive optimisations, might have the potential to compete with the existing cryogenic sensors operating at THz frequencies, i.e. Kinetic Inductance Detectors (KID), Transition Edge Sensors (TES), high-impedance bolometers and others. Among the potential advantages of SUPERTED, is the fact that the detector is producing a thermo-electric current without external polarization.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 800923.

Bibliography

[1] T. Heikkila et al., Physical Review Applied, Volume 10, Issue 3, id.034053 (2018)

[2] A. Monfardini et al., The Astrophysical Journal Supplement 194, Issue 2, 24 (2011)

[3] F. Levy-Bertrand, in preparation (2023)

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 800923.