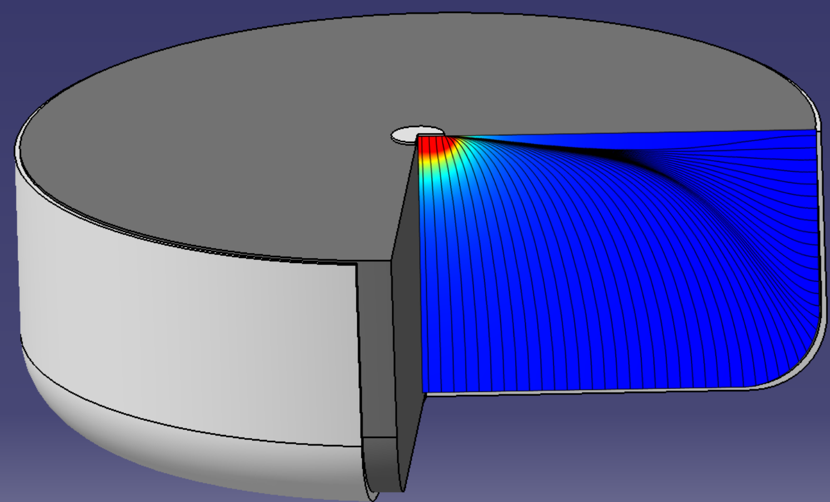
Projet émergeant **P2IO SUCRE**

Superconducting **C**harge **Re**adout device

Astroparticle Solid State Detector group (ASSD) – IJCLab
Stefanos Marnieros



Development of an innovative massive Ge bolometer with single-electron threshold

- 12 month P2IO project : jan-dec 2021
- 20 k€ P2IO funding

Applications :

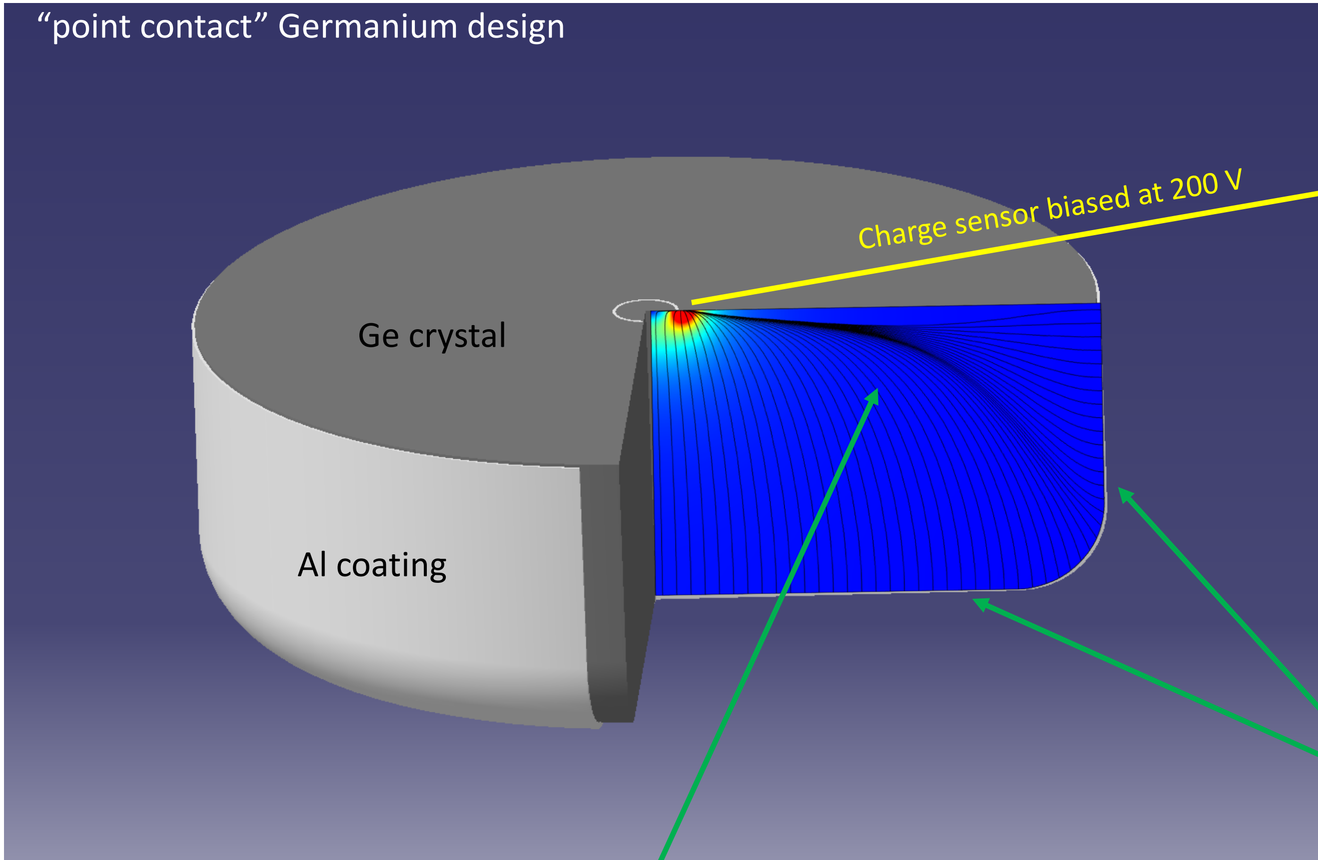
- light dark matter detection (EDELWEISS)
- neutrino-nucleus coherent elastic scattering (RICOCHET)

Continuation of the project - support by an ANR program (CRYOSEL : 2022-2025)

Physique des 2 Infinis et des Origines

Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

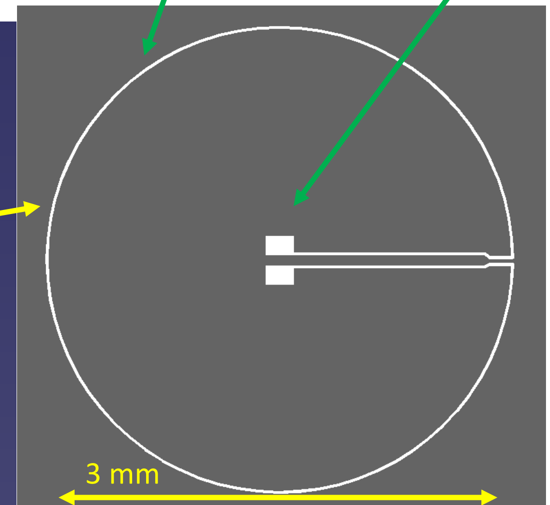
The SUCRE detector proposal



SSED sensor
(Superconducting Single Electron Device)

10 µm wide SSED line

Bonding pads

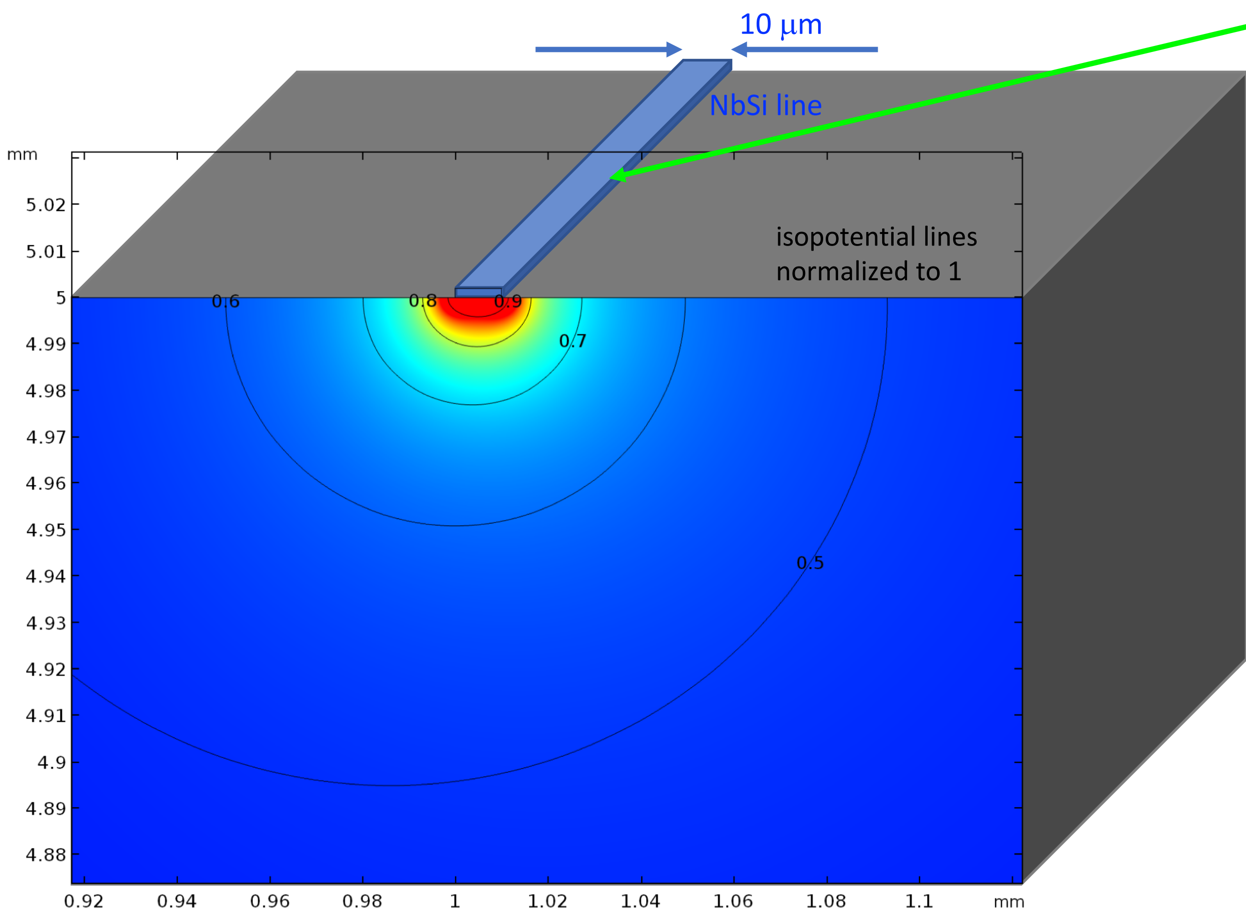


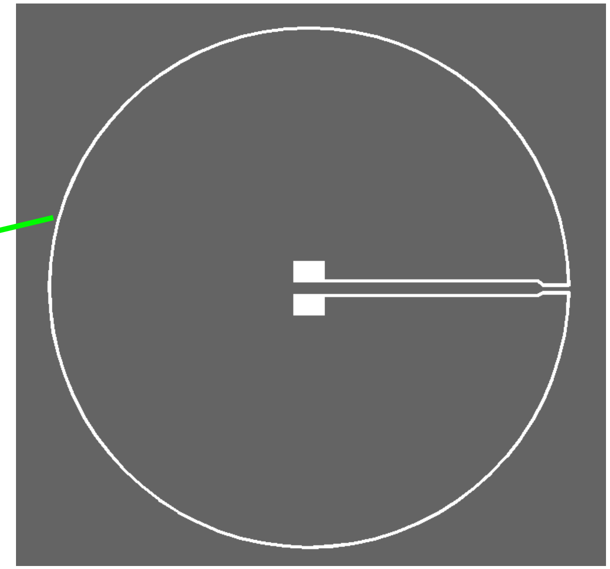
Thin superconducting line :
Nb_xSi_{1-x} film ($T_C \approx 30$ mK)

Bottom & side Al electrode
biased at 0 V

Electric field-lines in the Ge crystal:
electrons or holes are canalized towards the small charge sensor (SSED)

Neganov-Luke heating by the charge-drift in the Ge (Joule effect): athermal-phonons released below the NbSi line

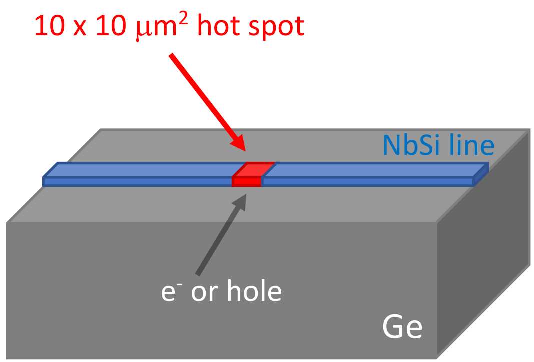




Very high E-field under the Nb_XSi_{1-X} line.

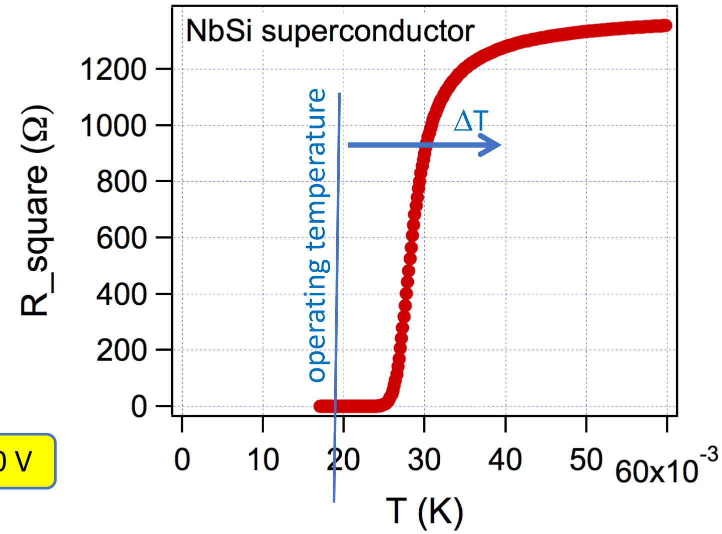
In the proposed PC SUCRE design, 20 % of the N.L. heating occurs just under the NbSi line (isopotential 0.8).

A single electron-hole event will create a hot spot into the NbSi line:



The Hot-spot temperature will rise above Tc for V_{LUKE} > 100 V

10 x 10 μm² NbSi resistivity behaviour



NbSi film operating below Tc

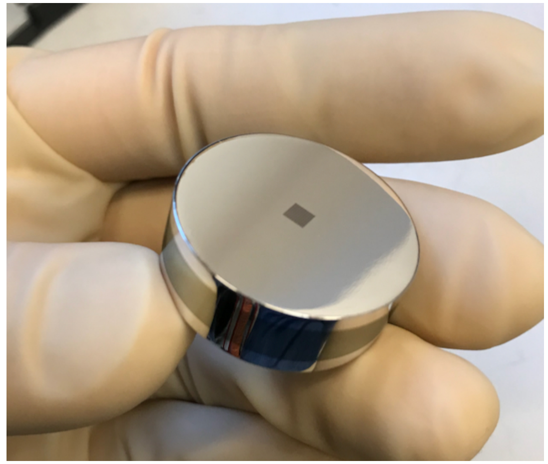
1 charge ≈ 1 kΩ pulse

Detector fabrication

First step of the SUCRE project was dedicated to the development of the detector fabrication process.
Preliminary tests were realized on thin substrates (Ge and Si wafers)

Ge high-purity crystals are commercially available (Mirion Technologies)

- Crystal purity : N_A-N_D < 2 10^{10} /cm^3
- 40 g crystals (d=30 mm, h=10 mm)
- Polished and chemically etched



IJCLab

- Aluminum e-beam evaporation
- Nb_XSi_{1-X} co-evaporation for the SSED sensor

C2N technological facility (PIMENT platform)

- Photo-lithography process (shaping of the deposited layers)
  UV photo-resist, aligners, lift-off, etching, laser lithography…

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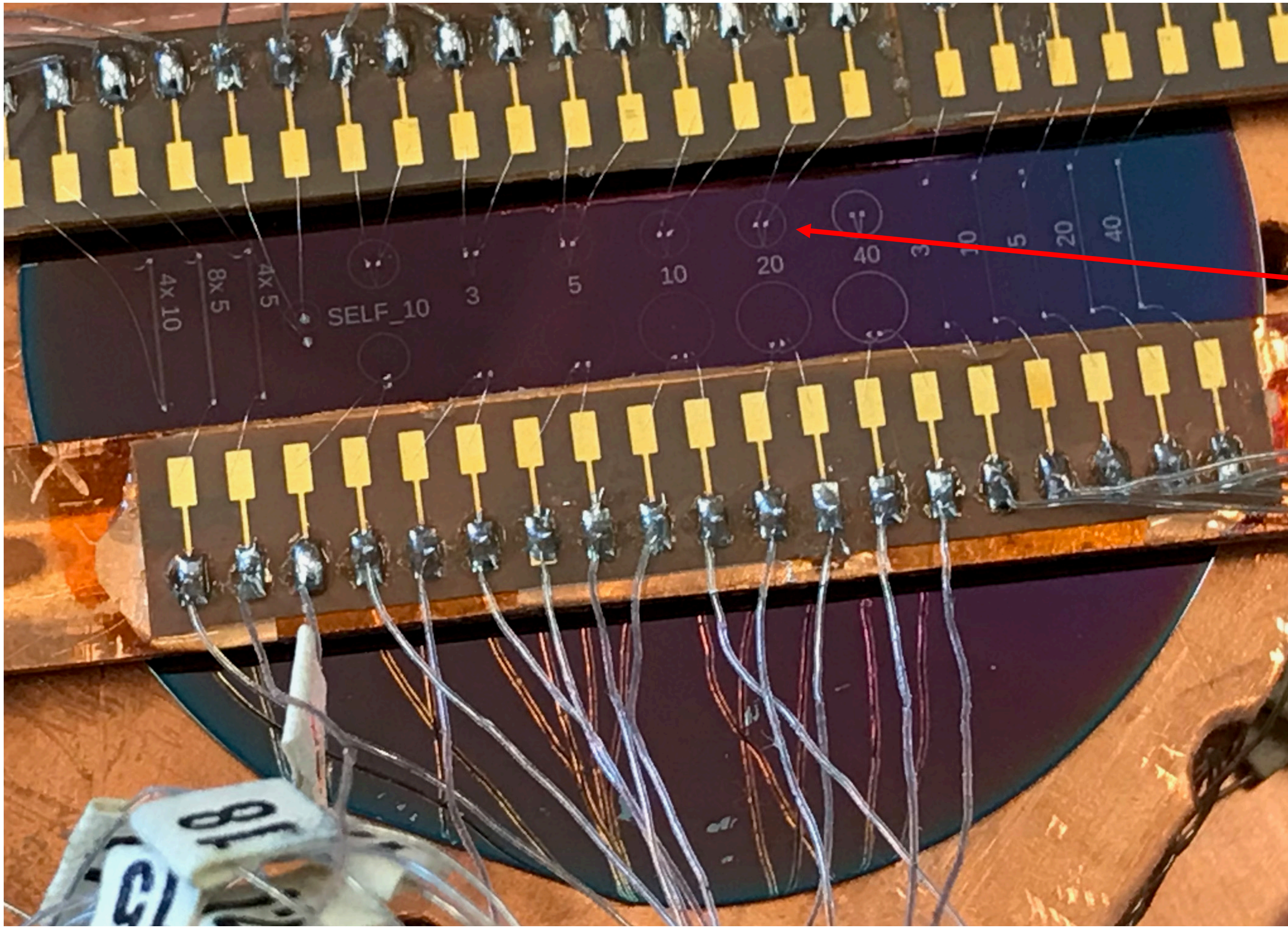
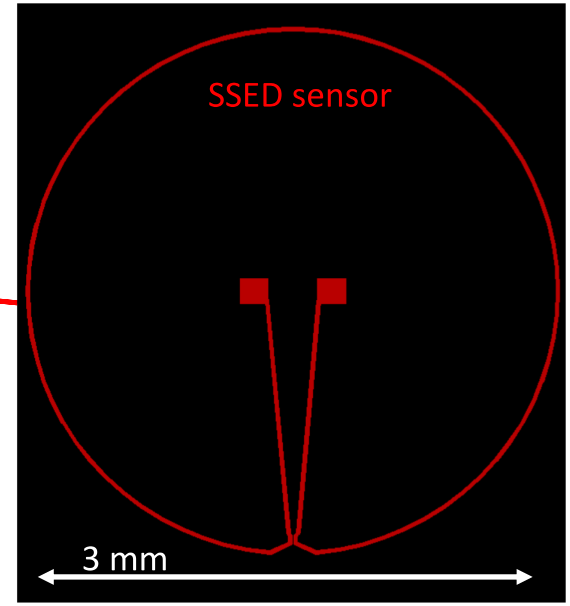
- Atomic Layer Deposition on Ge crystals (dielectric layers : HfO_2, Al_2O_3)

Test of SSED properties on thin substrates (Si or Ge wafers)

Test of the superconducting transition behaviour for various SSED geometries (film diameter, line-width, thickness)

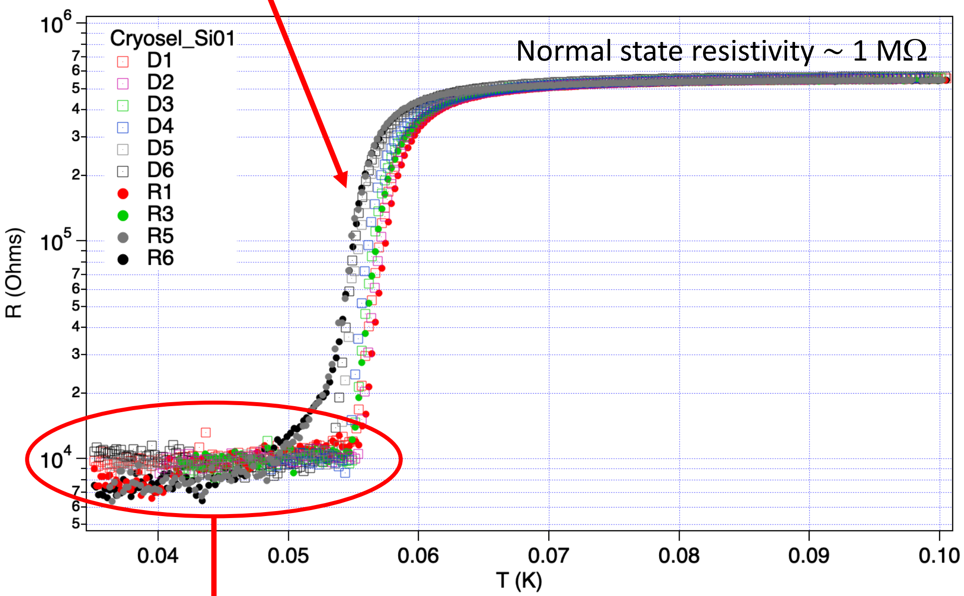




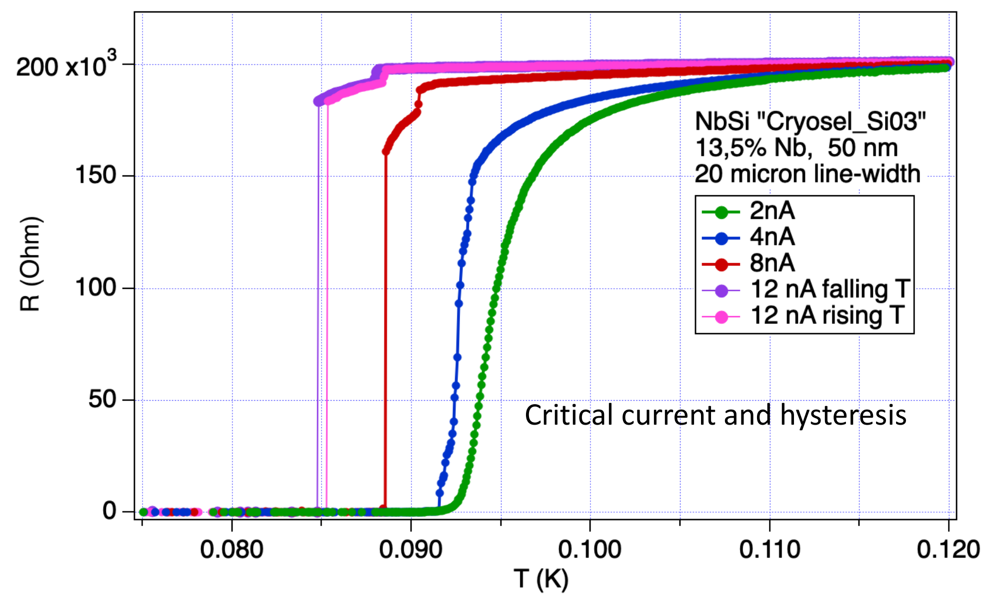
SSED optimization and critical points

The critical temperature of the Nb_XSi_{1-X} layer depends on :

- Nb concentration X
- film thickness
- annealing temperature of the sample



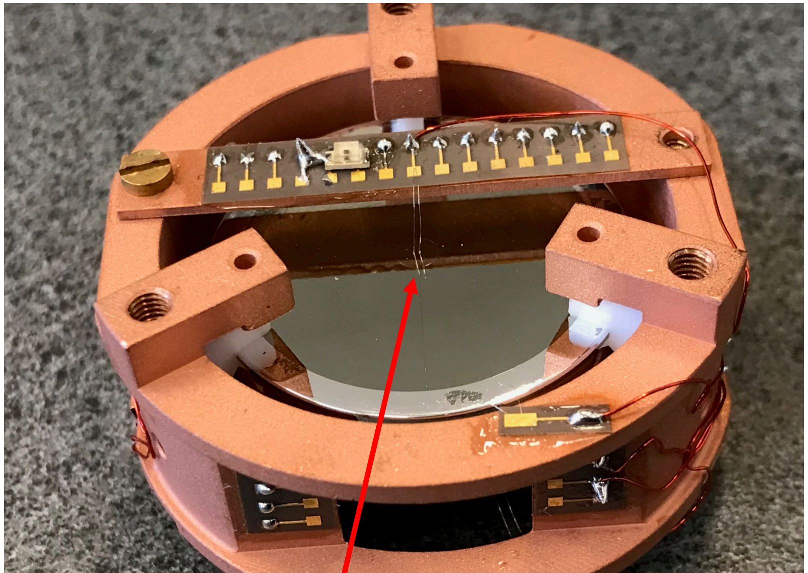
When the SSED is biased at high current we observe instabilities of the superconducting transition and hysteresis.

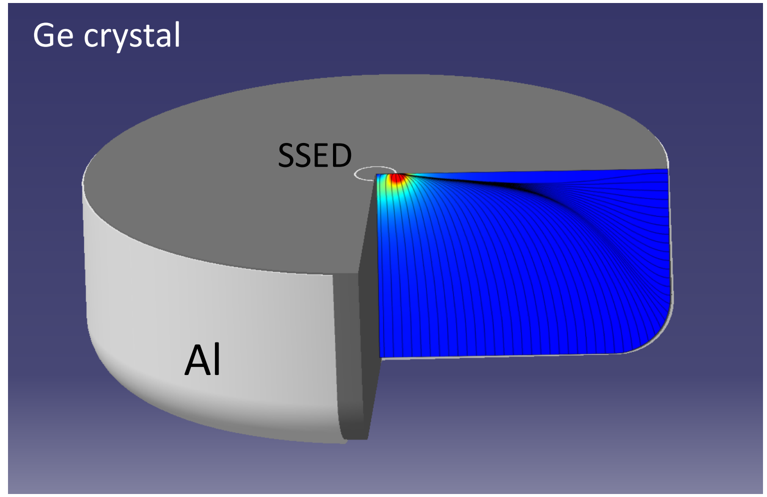


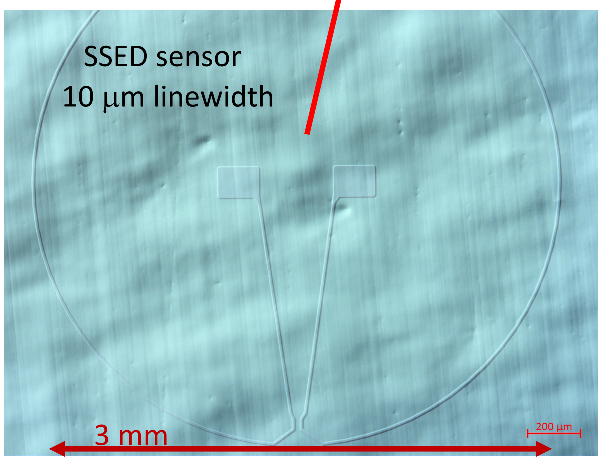
Due to its small size, the SSED sensor is very sensible to stray RF power.

If the readout electronics is not filtered conveniently, we observe a residual resistivity that may affect the detector performance.

First SSED detector prototype on a Ge crystal







Optical microscopy
(polarized light)

The first Ge detector prototype has been fabricated at the 6th month of the SUCRE project.

It was tested at IJCLab in a dilution refrigerator equipped with a low noise acquisition chain.

We encountered several problems on our first prototype :

- No superconducting transition of the SSED down to 15 mK.
- Onset of a strong leakage current in the Ge above 40 V (our target is 200 V)
- Accumulation of charges trapped at the Ge free surface, inducing degradation of the charge collection.

→ Upgrade of the detector design

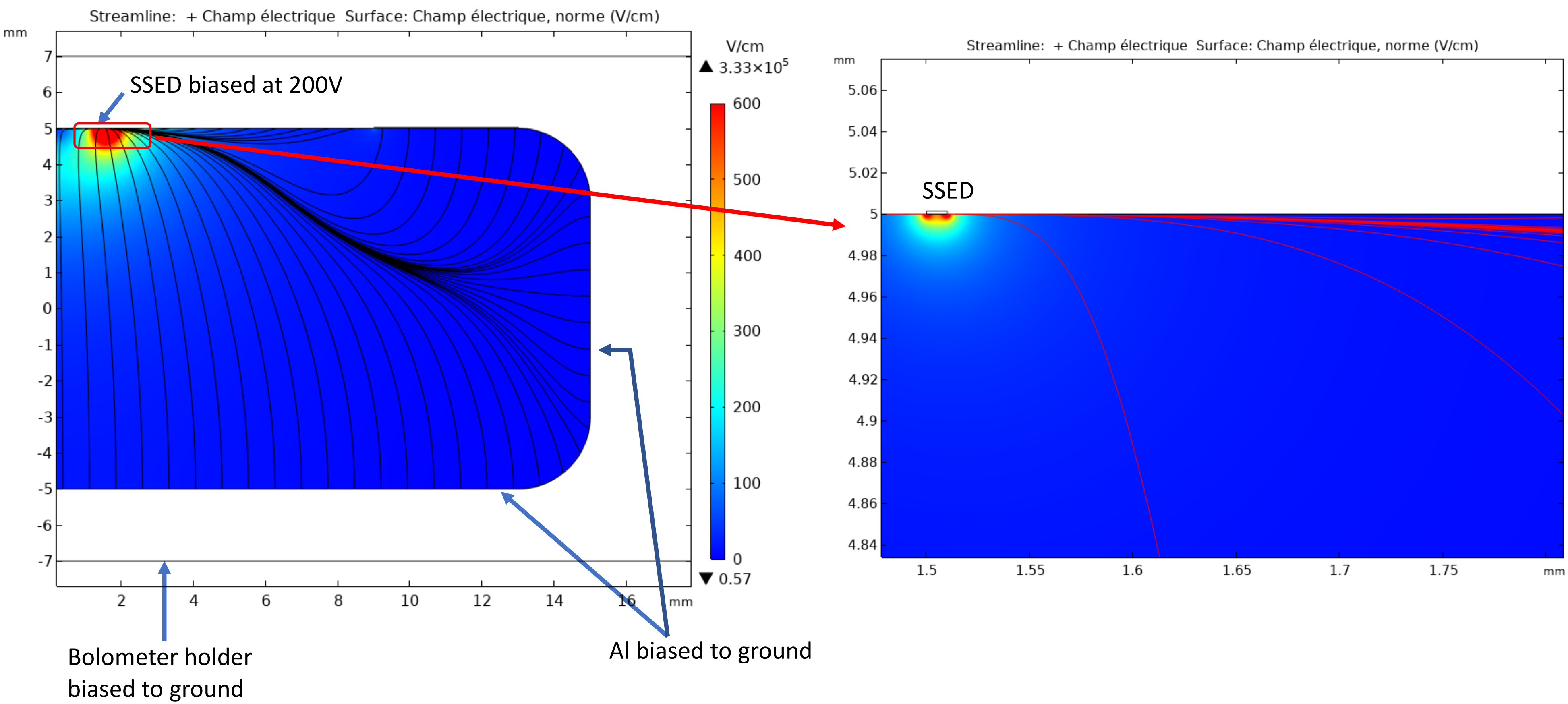
Simulation

Simulation of the SUCRE detectors using COMSOL finite element software.

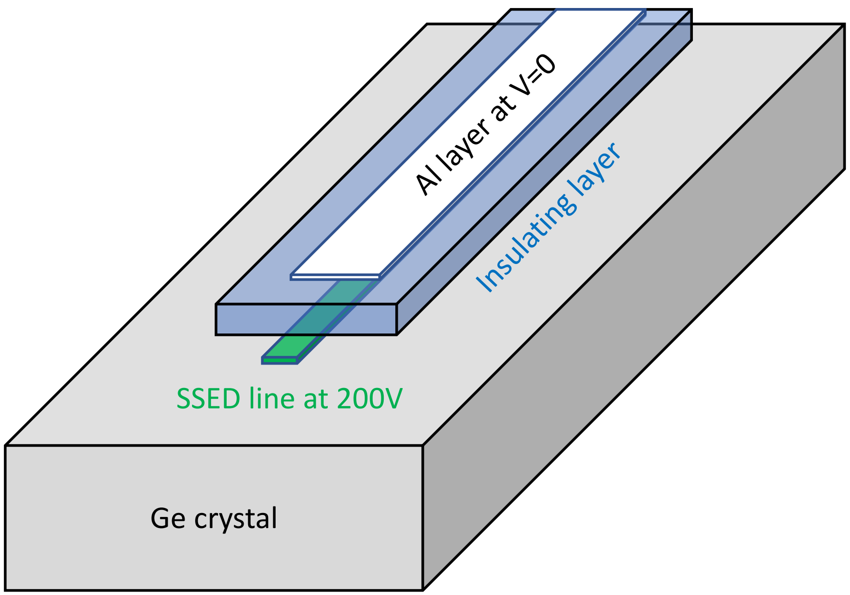
Focus on E field-lines and Neganov-Luke effect:

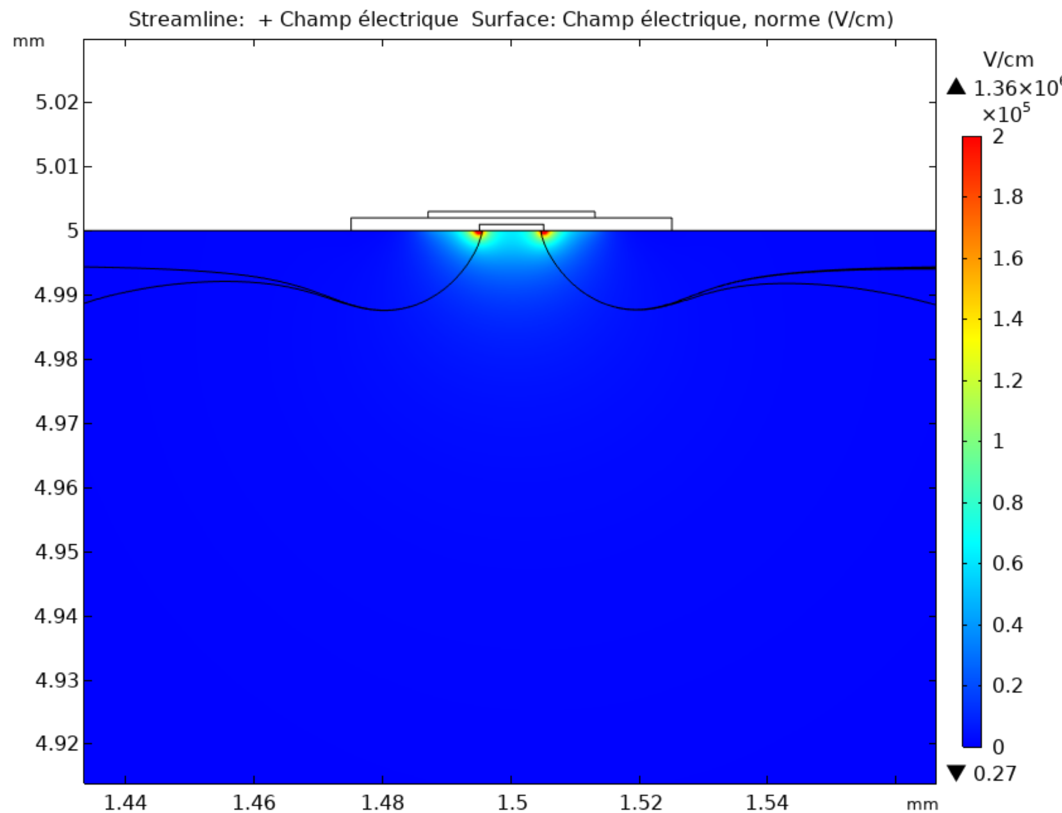
Problem due to charges drifting very close to the Ge free surface :

- High probability of being trapped.
- Incomplete Neganov-Luke heating. No heating under the SSED.



- Introduction of a grounded Al layer above the SSED : push the E field-lines to the Ge bulk
- “SU-8” epoxy photoresist for electrical insulation between the Al and SSED



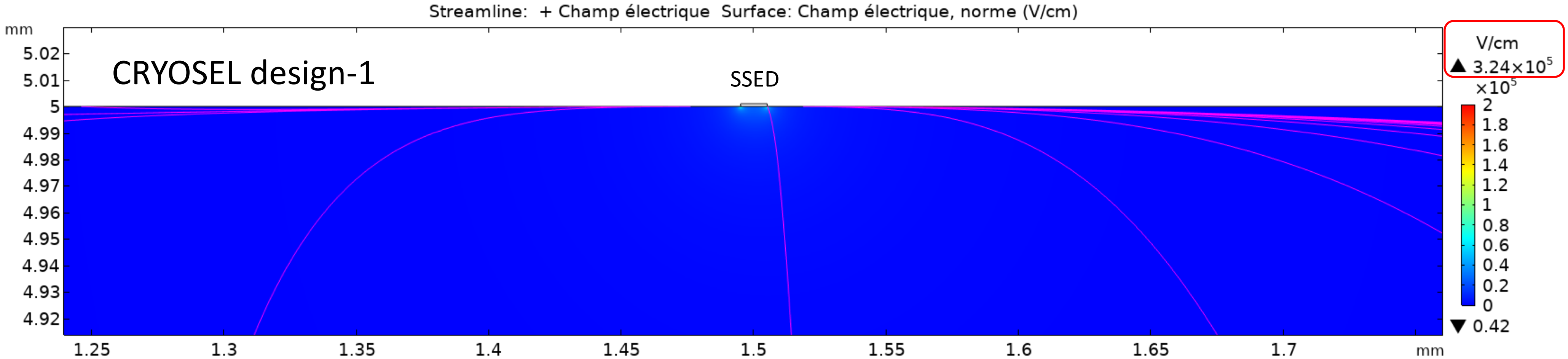


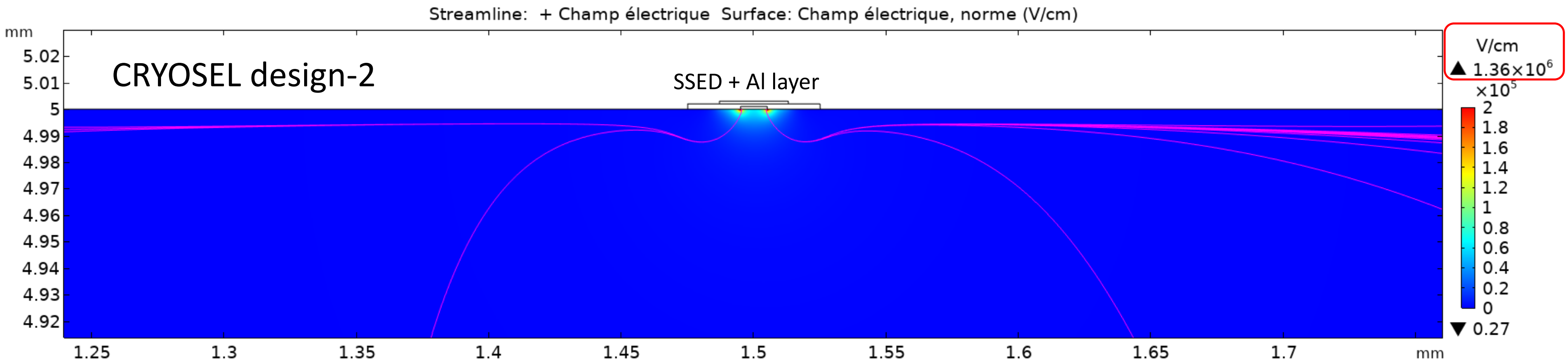
Design-2 upgrade :

Field-lines move > 5 µm below the Ge surface (less charge trapping)

N.L. heating occurs below the SSED : E field-lines arriving from the bottom and not from the side

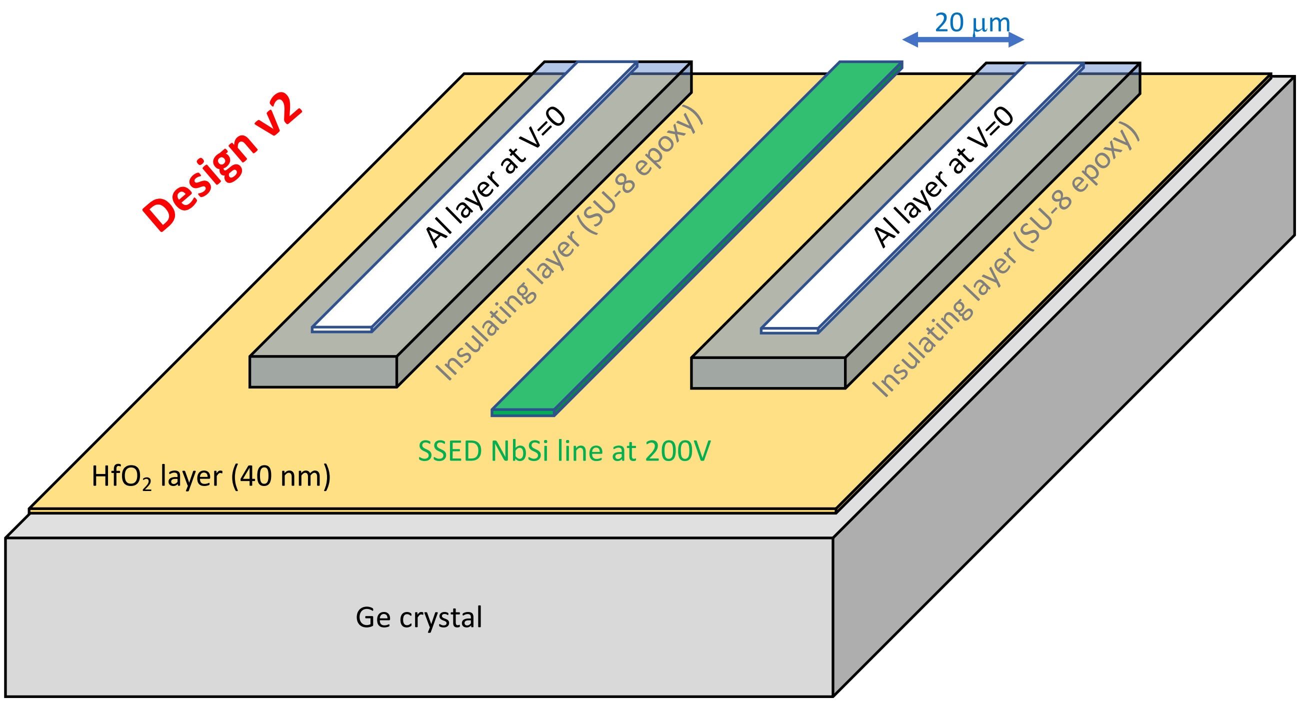
But the E-field under the SSED is increased by a factor of 4 and may induce a leakage current





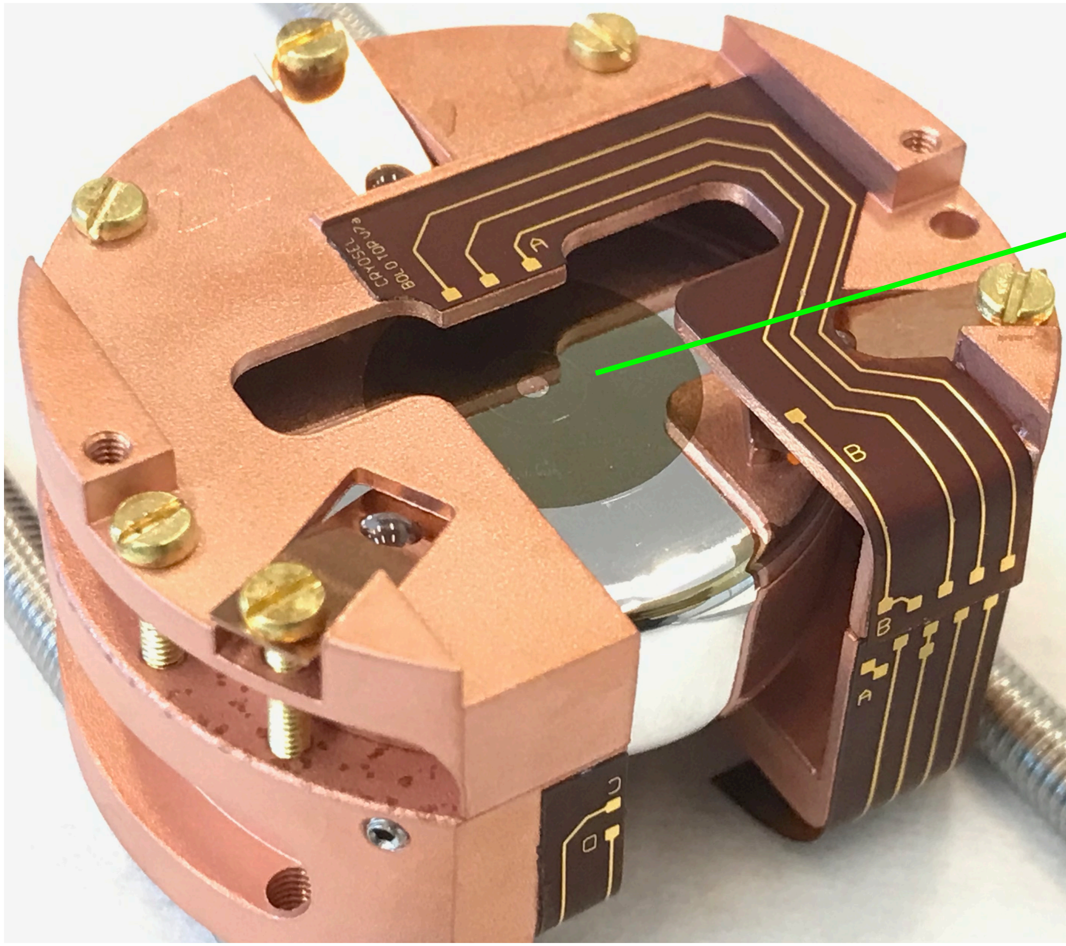
Cryosel design-v2 fabrication process

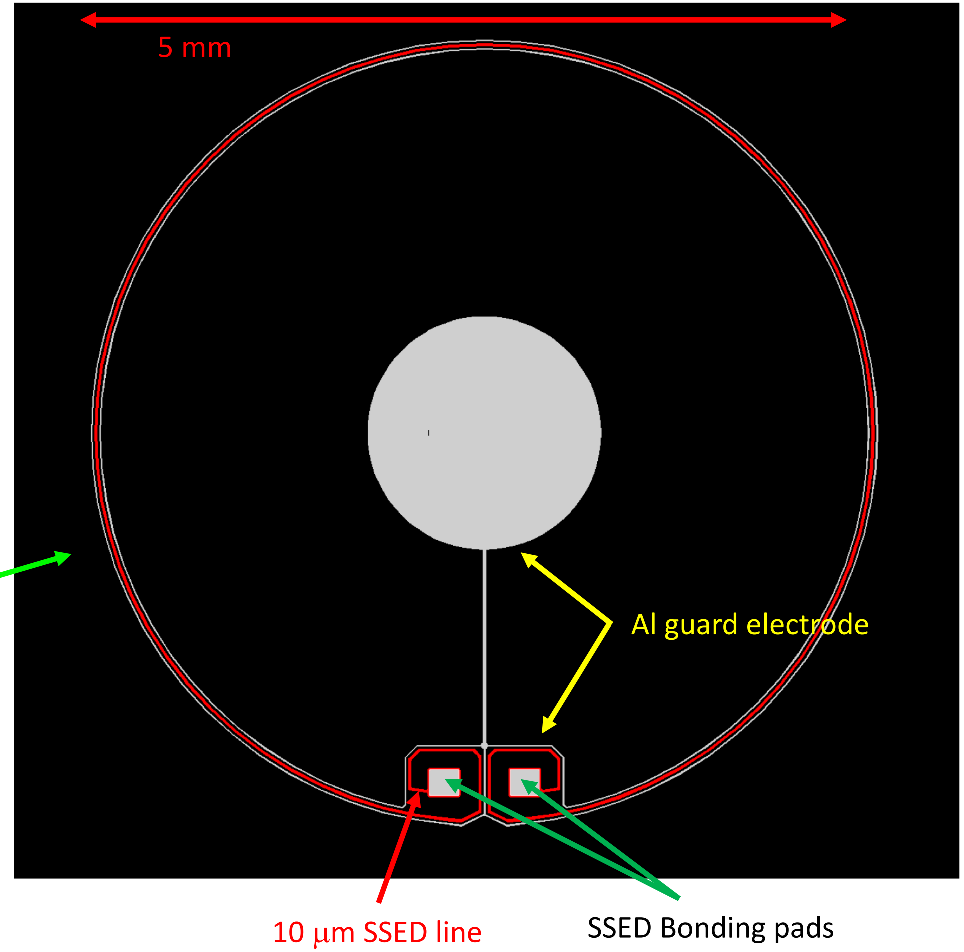
- HfO_2 dielectric layer
- SSED (NbSi + SiO protection)
- SU-8 epoxy photoresist
- Al electrodes (top, bottom, lateral side)



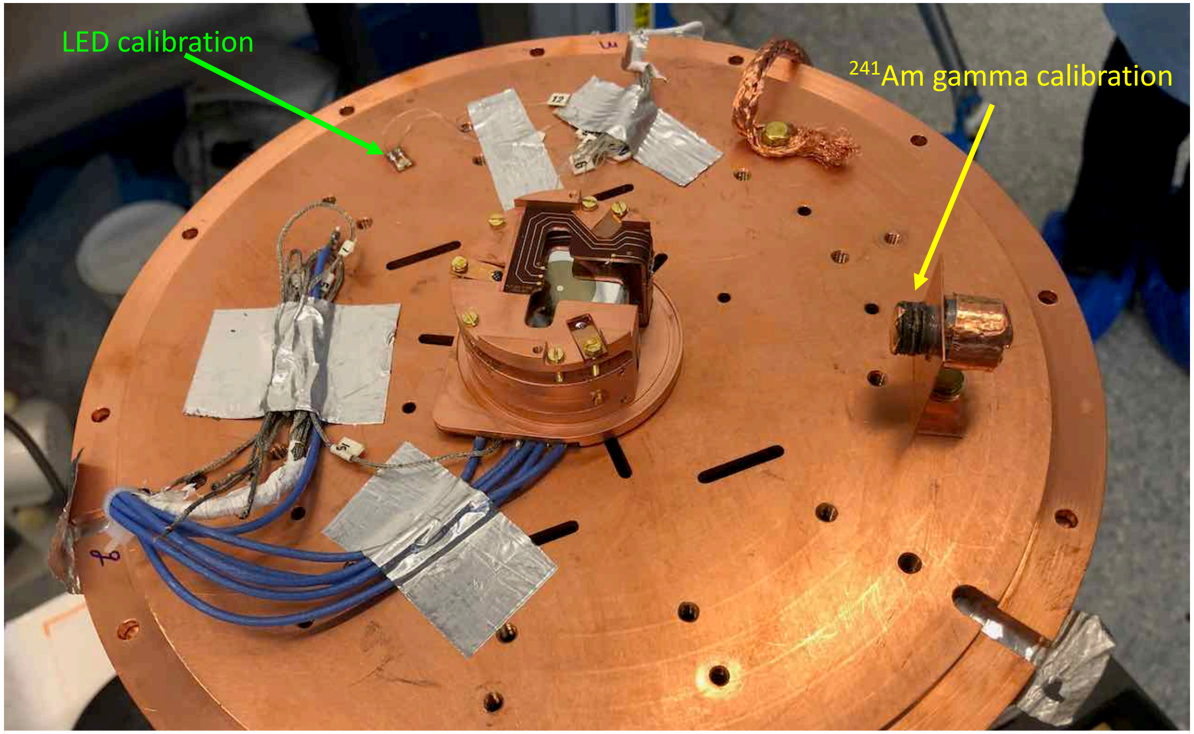
SUCRE Ge detector prototype design-2

- Upgraded SSED design
- Use of HfO_2 and SU-8 layers to avoid leakage currents
- Increased coverage of the Al electrode

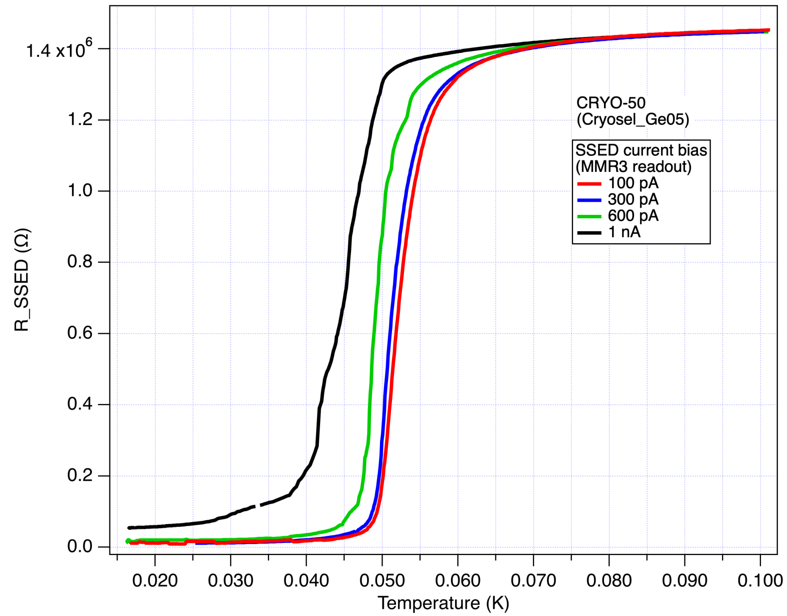


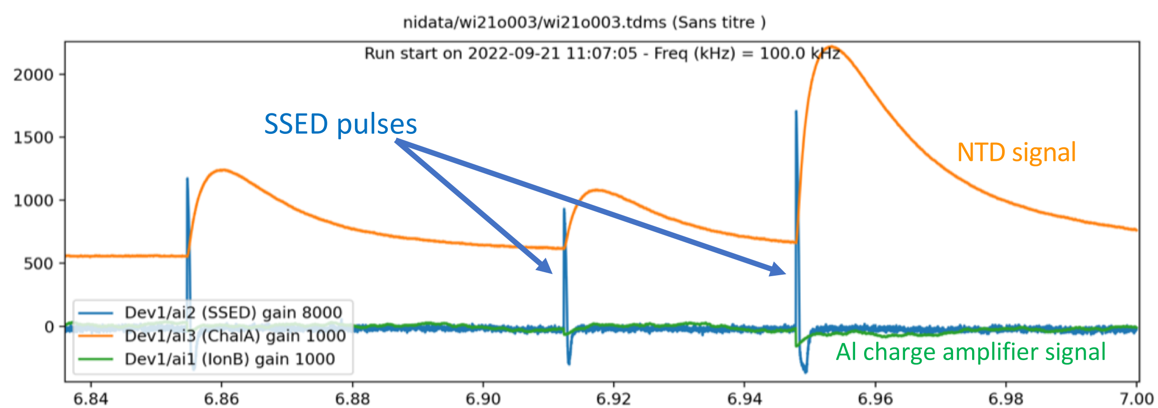


SUCRE prototype-2 : test and calibration (sept. 2022 run)



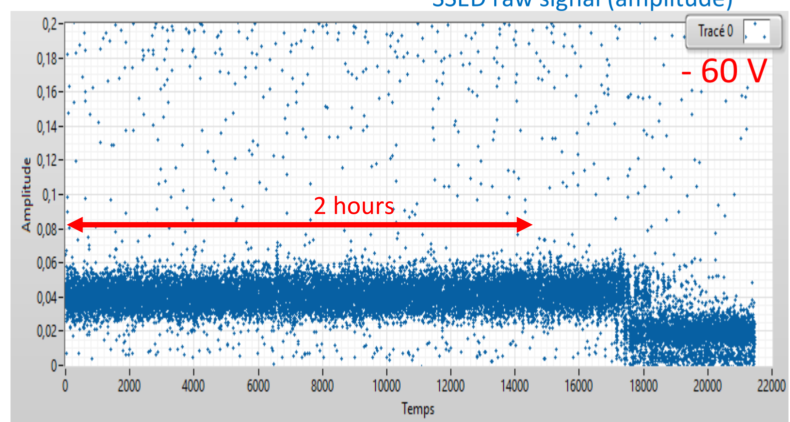
NbSi - SSED superconducting transition at 50 mK



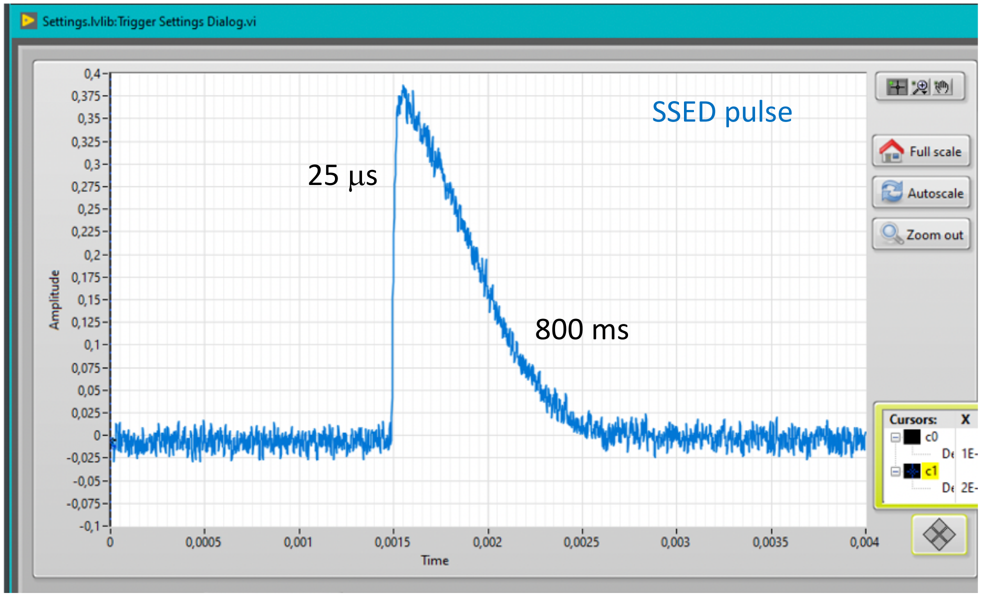


SSED signal stability

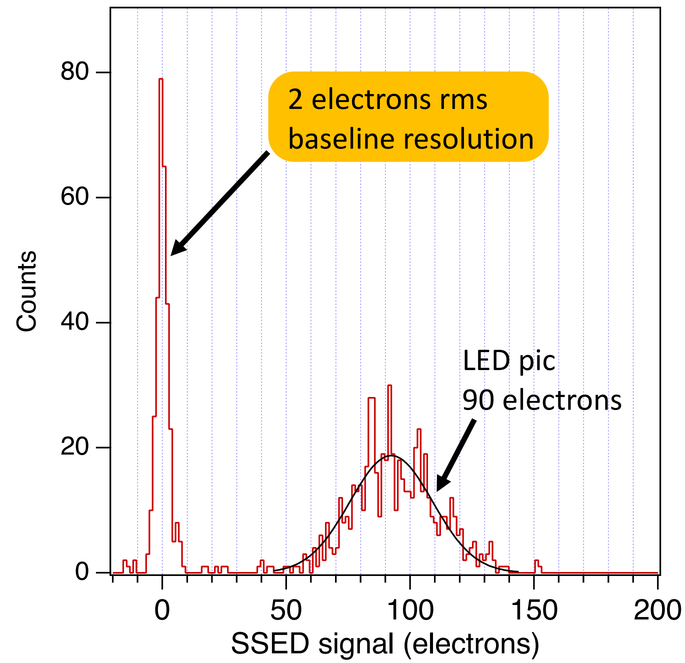
90 electron events – LED 2 Hz
SSED raw signal (amplitude)



SSED signals – prototype 2

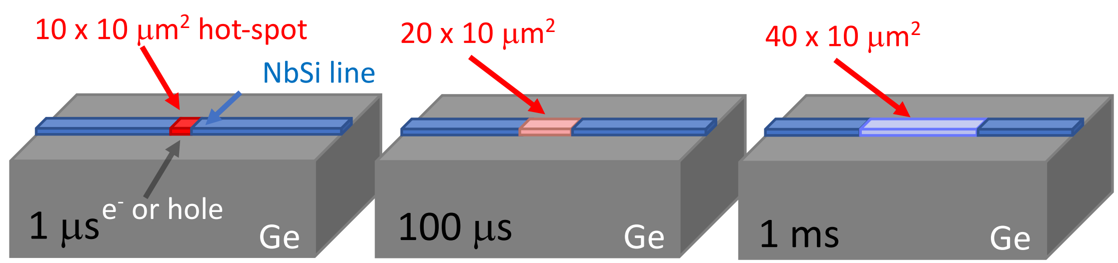


SSED detector performance at 50mK



SSED behaviour is well understood

- Sensitivity :
  3 % of the athermal phonons from the N.L. heating are directly absorbed by the SSED
- Rise-time :
  - $R_{SSED}C_{gate}$ (limited by readout)
- Decay-time :
  - Thermal diffusivity in the NbSi
  - NbSi electron-phonon coupling



Evolution of the hot-spot over time – NbSi thermal diffusivity

Conclusion – perspectives

- The SUCRE P2IO funding allowed us to demonstrate the proof of concept of an innovative low-threshold Ge detector
- Two SSED Ge detector prototypes were fabricated and tested at low T
- 2 electron rms baseline resolution (estimated threshold ~ 10 electrons)

- The project is currently ongoing with support by the CRYOSEL-ANR program (2022 – 2025) and IN2P3
- Further development and design upgrade is in progress to achieve single-electron threshold
- In the frame of the EDELWEISS dark-matter project we plan to install and operate several SSED-Ge detectors at LSM (coupled to the 2023 installation and deployment of the BINGO experiment at LSM)