Developing superconductive sensors for Particle Physics

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1 Introduction

With the emergence of the quantum era, many fields are converging on a central goal: developing detectors that can measure meV energy deposition depositions with sub picosecond timing resolutions at near 100% detection efficiency. Such performance has become increasingly important not only in quantum communication, but also in future particle physics experiments, where direct probing of heavy flavours and establishing limits only indirectly extrapolated is directly linked to breaking the picosecond timing barrier.

Superconducting Nanowire Single Photon Detectors (SNSPDs) are a well established technology in optics and quantum cryptography, with new applications in space telecommunications and atmospheric LIDAR experiments [1, 2], or even medical imaging [3]. Their instrumental success originates from very low dark rates, single photon sensitivity and excellent timing performance with time jitters demonstrated to be below 10 ps [4]. SNSPDs are meandering nanowires of superconducting films (7 nm). When operated with a bias current close to it's critical temperature, the wire exhibits essentially zero resistance. When a photon hits the nanowire, the locally deposited energy can break the cooper pairs responsible for the superconducting state. The externally applied bias current prevents quasi-particle recombination and leads to a growing hotspot of increased temperature, temporarily suppressing superconductivity. The short resistive section formed across the nanowire produces a measurable voltage pulse which is detected using an oscilloscope. The device subsequently recovers it's superconducting capabilities and is ready for a new particle to be detected. A detection diagram showing the theoretical pulse shape has been shown in *Fig. 1.*

In parallel, new physics increasingly relies on very sensitive timing measurements. Future detectors are expected to function in harsher environments while providing faster responses. In this context, SNSPDs represent a promising candidate for extending detection beyond photonics and towards high energy particle detection. However, this requires solving several physics and engineering limitations, the most important of which being the low expected energy deposited and detection efficiency due to the extremely thin films used in conventional SNSPDs.

For the purposes of high energy physics, this proposal aims to develop new superconducting detector technology optimized specifically for particle detection. This project combines a dedicated fabrication process with a full characterization workflow that simultaneously offers crucial information on the fabricated detectors while providing a feedback loop on the produc-

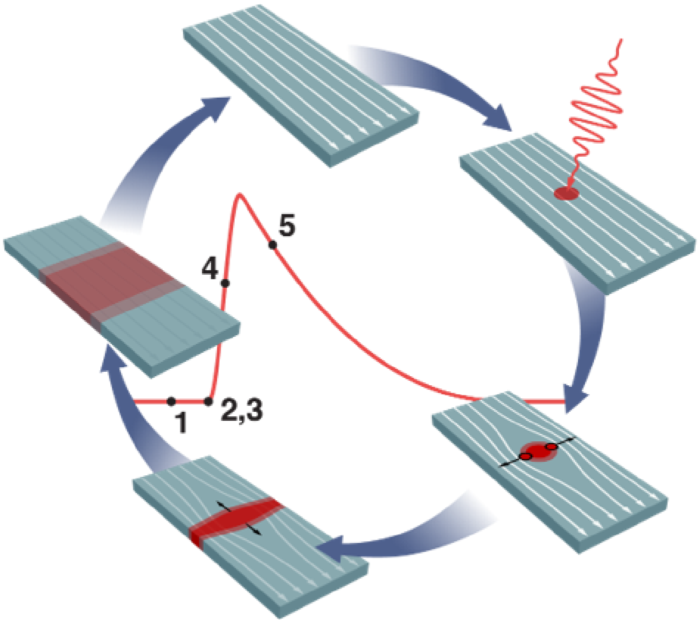


Figure 1: Detection mechanism of an SNSPD through an energy deposition from a photon. [5]

tion process. Implementing a parallel simulation effort using Synopsys TCAD [6] to carefully plan and describe the fabrication process will also provide information on the optimal parameters for the machines used and cutdown the learning curve required for new processes to be developed, enabling the creation of the first ever micrometer thick SNSPD directly etched into the substrate.

2 SNSPD fabrication

SNSPD fabrication, and subsequent optimization, will be done at the user access Centre for MicroNano technologies (CMi) in EPFL, taking advantage of their broad knowledge and experience with nanofabrication. The development of such a process requires the use of multiple specialized tools and a well defined process flow. A simplified version of the latter is presented in *Table 1*, and below:

1. **Implementation of dicing and alignment markers:** Due to the low feature size, a 7 μm photolithography exposure of a negative resist is sufficient. After development, this step is followed by an isotropic deep reactive ion etch, necessary to define the 2 μm deep dicing and alignment markers which are mandatory to reach nanometer precision alignment with the future lithography and etching steps.

2. **Superconducting thin film deposition:** A superconducting material, either NbN or NbTiN, is deposited onto the wafer through magnetron sputtering, targeting a film thickness of 7 nm.

3. **SNSPD patterning:** Due to the nanometer feature size of SNSPDs, patterning of the

meander onto a negative PMMA resist is achieved with focused electron beam lithography, then etched into the film with reactive ion etching.

4. **Lift-off preparation:** A 10 nm gold surface is evaporated onto a lift-off resist previously exposed with photolithography using the bonding contact pads mask.

5. **Lift-off:** The resist is then removed taking away the unwanted material, leaving behind contact pads, device identifiers and exclusion regions made out of gold.

Process	**Instrument**	**Device geometry**
Resist coating	ACS200	
Photolithography	Heidelberg instruments MLA150	
Development	ACS200	
Deep reactive ion etching (DRIE)	SPTS Rapier	
Resist removal	ACS200	
Thin film deposition	Alliance concept DP650	
E-Beam resist coating	SAWATEC SM150	
E-Beam lithography	RAITH EBPG5000+	
PMMA development	Plade solvents wet bench	
Reactive ion etching (RIE)	Veeco Nexus IBE350	
E-Beam resist removal	Plade solvents wet bench	
Photoresist coating	SAWATEC SM200	
Photolithography	Heidelberg instruments MLA150	
Development	EVG150	
Gold deposition	Leybold optics LAB 600H	
Lift-off	Arias lift-off bench	

Table 1: Simplified process flow for the fabrication of conventional SNSPDs

The nanometer precision necessary for the lithographic steps described above, requires the generation of digital mask layers containing all the information used by the relevant tools. An example of the first wafer fabrication schematic can be seen in *Fig. 2.* It contains four duplicate quadrants with a total of 1600 SNSPD structures, as well as a small testing region where specific geometries are implemented to help understand wire proximity effects, wire width fidelity, thin film surface topology and damage during lift-off procedures.

Access and use of each tool requires meticulous preparation and organization, focused mainly on using the correct parameters for each machine and creating a coherent process flow that does not interfere with the meandering pattern or the superconducting capabilities of the material.

As of January 2026, the SNSPD fabrication process flow has been approved by CMi and training will begin shortly thereafter.

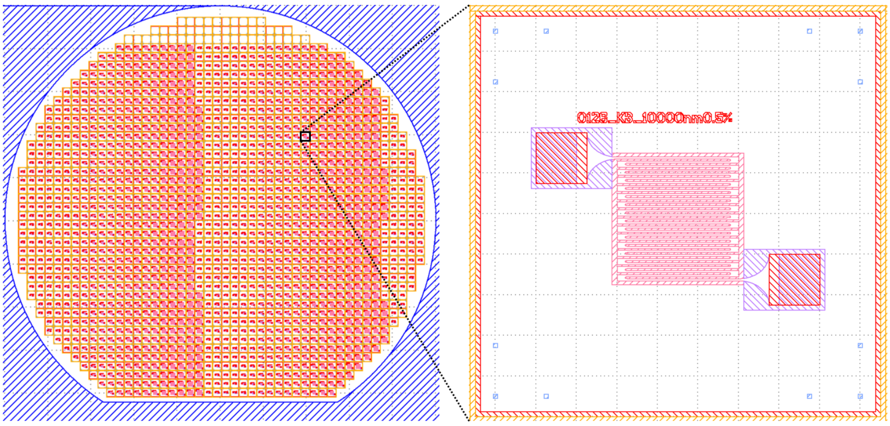


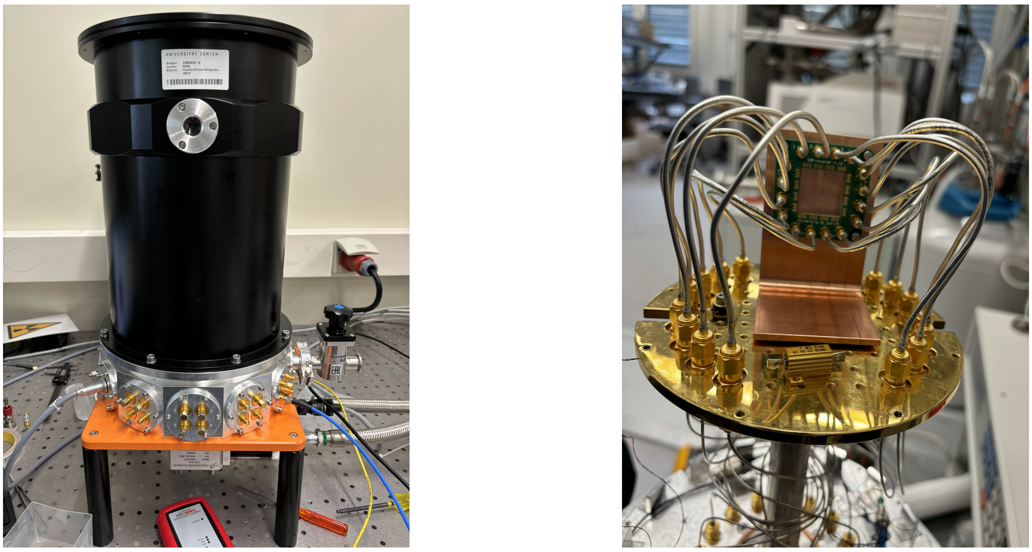
Figure 2: GDS schematic of a 4" Si wafer containing each mask required for fabrication (left). Example of a die containing an SNSPD (pink), gold contact pads, exclusion regions and identifier (red), dicing lines (yellow) and alignment markers (blue)

3 Measurements

The characterization of the devices produced is done through a three pronged workflow. The first step is to perform electrical testing and AFM/SEM picture analysis to assess the presence of defects during fabrication and the quality of the deposited film. The second stage involves a 2D mapping optical experiment through single photon injection to probe the response of the superconductive layer as well as the proximity effect of the wires. Finally, the charged particle measurements are split into two experiments, one done using a radioactive source in the laboratory, the second involves a test beam setup at CERN. The combination of both will provide crucial information on the response of superconductive wires to mid-to-high energy particles. All the tools and equipment required in the following experiments are readily available in the laboratory, with the optical characterization experiment being the only one that is still under development.

3.1 Electrical characterization

Particle detection in superconducting sensors is not only governed by the preservation of the superconducting state, but also by it's ability to maintain cooper-pair breaking after an initial depairing event through energy deposition. In this regime, the critical current (I_c) as a function of the temperature becomes a key parameter as low critical currents may enable quasiparticle recombination, which severely lowers the detection efficiency. On the other hand, the hysteresis current (I_h), which is linked to the thermal feedback of the detector after a transition to the normal state plays a key role in the recovery of the sensor after an event. For these reasons, a detailed mapping of both I_c and I_h as a function of temperature forms the very foundation of the electrical characterization. Additionally, these measurements also provide the fundamental material parameters such as the London penetration depth (characteristic length that a magnetic field can penetrate) and the coherence length (the size of the cooper pairs), which are essential to correctly understanding the response of the film used.



(a) outside of the cryostat

(b) Inside of the cryostat with custom made copper sample holder

Figure 3: Pictures of the closed cycle cryostat used in the electrical characterization experiment

The electrical characterization of the devices will be performed in a closed cycle cryostat equipped with precise current biasing and voltage readout devices and an integrated PID control. Parallel to this, a 9T Physical Properties Measurement System (PPMS) will be used to accurately control the applied magnetic field, enabling the measurement of the London penetration depth, the zero temperature upper critical magnetic field as well as the coherence length. Both the PPMS and the cryostat have a base temperature of 2 K and a temperature stability down to 0.1 K.

3.2 Optical characterization

Once the intrinsic parameters of the sensor have been determined, the optical response of the SNSPD can be characterized using a calibrated laser source. By performing single photon transient measurements with precise timing and energy deposition, a two dimensional detection efficiency mapping of each device can be reconstructed. This map will provide critical information about non-uniformities and local defects related to the fabrication process, enabling an iterative optimization loop of the workflow. This setup requires a broadband laser source coupled to a wide-range monochromator combined with a 4 GHz oscilloscope for signal acquisition and precise timing measurements. To achieve the required spatial resolution, 30 nm stepper-motor scanning stages will be incorporated as well as zero order glass windows in a 4K liquid helium cryostat to minimize distortions.

3.3 Particle characterization

While the laser scanning experiment provides valuable information on the response map of the SNSPD, it is incapable of reproducing the deposition mechanism observed in high energy particles. To replicate the Landau fluctuations expected, a third experiment was created incorporating a 28MBq, ^{90}Sr radioactive source with a 2.3 MeV cutoff energy. Unlike in the laser characterization, the events are not fully controlled and make absolute efficiency measurements impossible. However, they provide crucial information on the timing resolution due to fluctuations in the deposited energy by the incoming particle. As with the electrical characterization, understanding the response curve of the device as a function of temperature is also instrumental in determining the overall stability of the device and the working range.

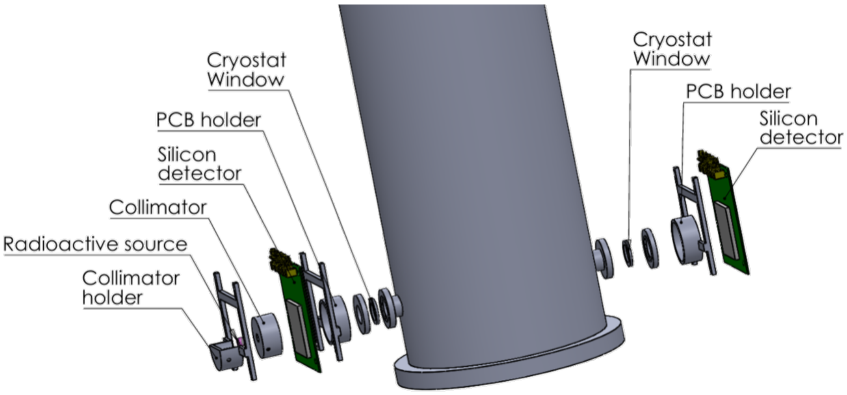


Figure 4: 3D model of the complete setup for the radioactive experiment with the liquid cryostat

Particle characterization also includes high energy particle detection through a dedicated setup [7] for the SPS test beam facility at CERN. The closed cycle cryostat was incorporated into the tracking telescope and installed onto motorized X–Y positioning stages for precise cryostat alignment. The system also contains six MIMOSA tracking planes with 3.2 μm intrinsic resolution over six detectors [8], and two LGAD timing planes with 20 ps time resolution [9], which are used for coincidence and detection efficiency measurements of the DUT.

Preliminary results have demonstrated the detection of 160 GeV pions with good agreement between measurement and simulation [7]. However, the overall efficiency remains low highlighting the necessity for new superconducting nanowire structures optimized for MIP detection.

While this represents a highly promising avenue of research, the coming year will focus on laboratory characterization, and device fabrication and simulation, targeting high energy particle detection, which will hereinafter be referred to as SD4HEP (Superconducting Detectors for High Energy Physics).

4 Outlook and proposed research

The long term objective of this project is to develop SD4HEPs optimized for MIP detection instead of the typical SNSPDs, aimed at photon detection. This requires three parallel efforts:

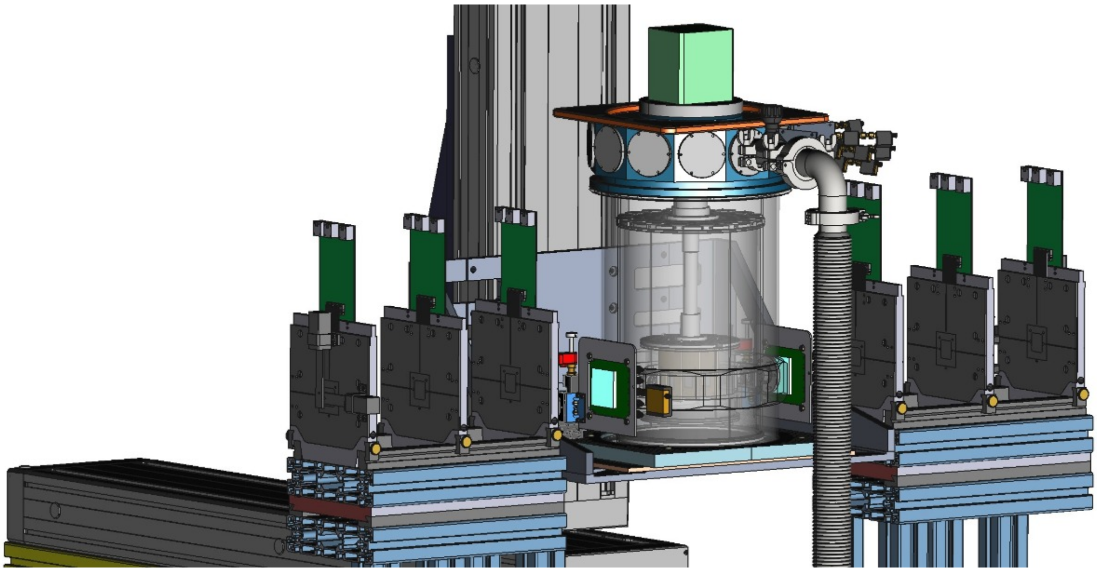


Figure 5: 3D model of the setup used during the 2025 test beam experiment at CERN with 160 GeV pions

the production of conventional control SNSPDs, in depth simulation of the fabrication processes and development of a novel SD4HEP detector fabrication process flow.

4.1 Conventional SNSPD fabrication

SNSPD fabrication will begin early in 2026 with plans to create the first functional detector within the year. The goal is to produce a well controlled, reproducible and optimized fabrication process for standard SNSPDs. These will act as a control group when attempting to fabricate new SD4HEPs with high aspect ratios, large active area, passivization film deposition, as well as new superconducting nanowire fabrication techniques.

A significant part of this section will focus on substrate-related effects that can critically impact superconducting nanowire performance and fabrication. This includes the investigation of phonon propagation within the substrate, the effect of surface imperfection associated with the native oxide layers, and the overall quality of the interface between superconducting materials and the wafer. One particularly important aspect is the choice of wafer, which can impact the quality of oxide layer growth, sputtering and deposition method and effect, as well as the different etching characteristics between $< 100 >$ and $< 111 >$ Si wafers. The choice must also be made between mono-crystalline and poly-crystalline substrates, leading to changes in thermal conductivity, stress impacts and surface topographies.

SNSPD fabrication is inherently prone to defects and artifacts arising from lithography resolution, proximity effects, indirect process damages and the fragile nature of superconducting films, making perfect device production impossible. This becomes especially detrimental when developing new methods to construct innovative devices and fabrication procedures. To mitigate these issues, process simulations using Synopsys TCAD with the s-litho package will be utilized to model and optimize every step of the workflow. The most important open questions include

Step 1: Oxide layer growth (up to 3um) with the *Centrotherm furnaces*

Step 2: Meander well creation using *E-beam lithography* and *Deep reactive ion etching*

Step 3: Thin film deposition *(Magnetron sputtering)* and photoresist coating for lift-off (This step should be modified)

Step 4: Lift-off at the using SVC14

Step 5: Gold pad deposition with evaporation and Lift-off at the using SVC14

Figure 6: Simplified workflow of the SD4HEP fabrication process

the resist choice and deposition/development method, oxidization parameters, material deposition including gas concentrations and ionizing currents, and etching. These simulations will provide detailed 3D representations of the process flow, enabling detection of defect formation mechanisms and subsequent removal by iteratively tuning the tool parameters.

The first milestone will be to build a complete simulation framework of the conventional SNSPD fabrication process, which will in turn be used to modify the current fabrication process. Creating several iterations of this parallel workflow will drastically decrease the formation of defects in SNSPDs as well as provide key information for the SD4HEP fabrication process.

4.2 Particle oriented nanowire detectors

Historically, conventional SNSPDs have been exclusively used for photon detection, where thin films and narrow wires are instrumental to achieve near 100% efficiency [10]. However, for MIP detection, the primary limitation is the low detection probability due to the limited amount of energy being deposited into the nanowire which is directly related to the low film thickness. Increasing the thickness of the SNSPD mitigates this issue and has become a central research direction in this project.

By modifying the original manufacturing process incorporating thick and narrow wires, the SNSPD would become unstable and warp, or even collapse due to low stability. Any contact with the wire, even for lift-off procedures would lead to irreversible damage to the structure making it unusable. The solution proposed hereinafter ensures great structural stability for the SNSPD while fulfilling the thick and narrow design required for MIP detection.

The fabrication process consists in etching deep, micrometer scale trenches into the silicon wafer or an oxide layer grown on top of it, then depositing the superconducting material inside. The remaining steps then become trivial and identical to the ones introduced for conventional SNSPD fabrication and do not risk the stability of the SD4HEP. Considering this solution has yet to be tested, simulating the complete process will once again be instrumental in understanding what the various roadblocks and pitfalls of this process are. A simplified version of the process is presented in *Fig. 6*.

5 Timeline

Period	**Milestones**
August 2026	Commissioning of the scanning laser transient characterization setup and upgrade to the electrical characterization infrastructure.
September 2026	First iteration of the SD4HEP fabrication simulation and characterization of initial SNSPD samples
October 2026	Creation of the SD4HEP process flow and continued lab characterization efforts
November - December 2026	Modifications to the SD4HEP process flow from results obtained on the SNSPD characterization and first run / analysis of the SD4HEP fabrication process with SEM/AFM imaging and electrical characterization
January - February 2026	Full lab characterization of SD4HEP fabricated samples
March - April 2026	Simulation iterations for SNSPD and SD4HEP devices
May 2026	Presentation of initial results at the CMi annual review meeting
May - July 2026	Final optimization of the SNSPD fabrication process and feedback on the SD4HEP process flow

6 Summary

This proposal outlines a one year research plan to develop, simulate and characterize a novel fabrication process for superconducting nanowire sensors oriented at particle detection. This research line is motivated by the limited detection efficiency of high energy particles observed during the 2025 test beam at CERN with 160 GeV pions [7]. Towards that objective, a key milestone is to establish a robust and optimized fabrication process for baseline SNSPDs. Produced devices will be studied through a three pronged laboratory process, including electrical measurements, optical response characterization with 2D surface mapping using transient laser injection and particle response studies with 2.3 MeV electrons from a ^{90}Sr beta source.

Upon understanding of the performance and fabrication effects, simulation and optimization of a new fabrication process towards SD4HEP devices will be the implemented, by investigating substrate-related effects and iterative tool parameter optimization with Synopsys TCAD and related packages.

Finally, the goal will be to use feedback loops between simulation and fabrication to create a reproducible and optimized workflow for SD4HEP structures.

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