PSD14: International Conference on Position Sensitive Detectors

London, 2nd September 2026

University of Zurich UZH

Towards a superconductive luminometer for FCC

SD4HEP – Superconductive Detectors 4 High Energy Physics

DRD5

EURO-LABS EUROPEAN LABORATORIES FOR ACCELERATOR BASED SCIENCES

CMi

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(students in red)

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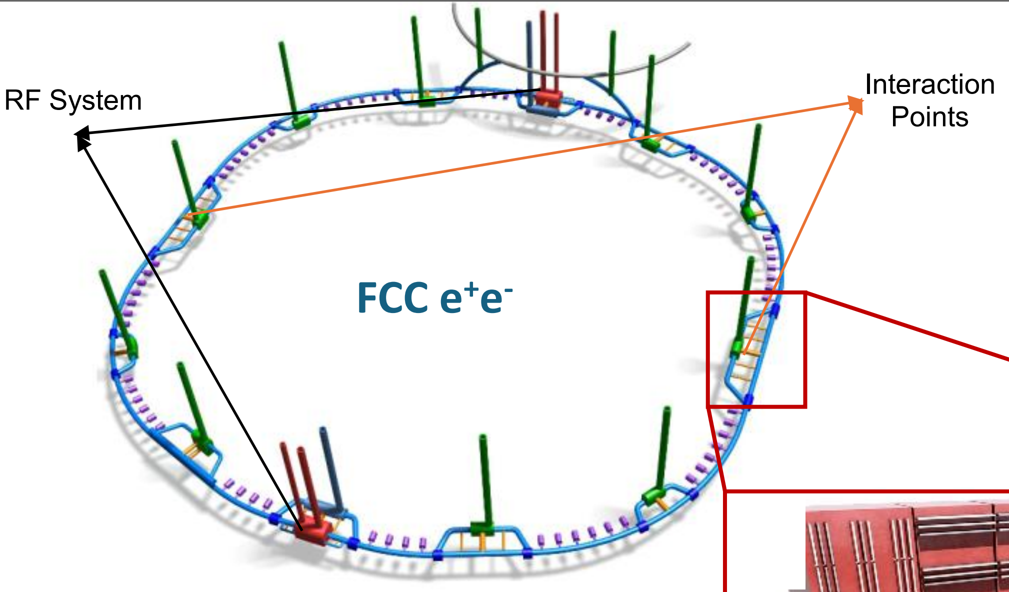
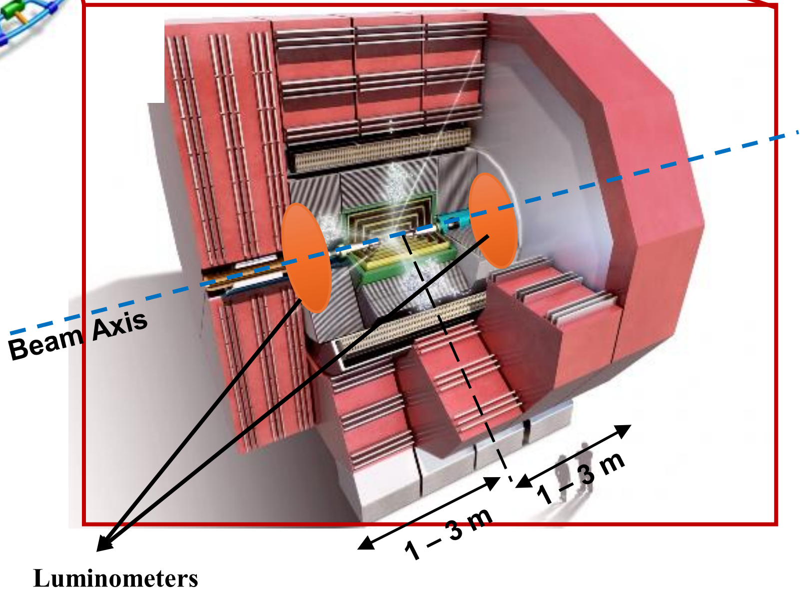
•Introduction and Scope



- ~90.7 km double ring collider
- 4 IPs with 30 mrad crossing angle
- 91 GeV (Z) – 365 GeV (ttbar)
- Luminosity: up to 500×10^{34} cm^{-2}s^{-1}



FCC Lepton detector (CLD) based on CLICdet

SN-SPDs based Luminometer

✓ Sub-per mill resolution through small angle Bhabha scattering

$$\sigma = \frac{16\pi\alpha^2}{s}\left(\frac{1}{\theta^2_{\min}} - \frac{1}{\theta^2_{\max}}\right)$$

✓ Goal of 10^{-4} precision on absolute luminosity

✓ Readout at Bunch-crossing rates with < 20ns shaping time

✓ 1.5 MGray dose at Z pole

✓ Pile-up ~ 1E-3 / event

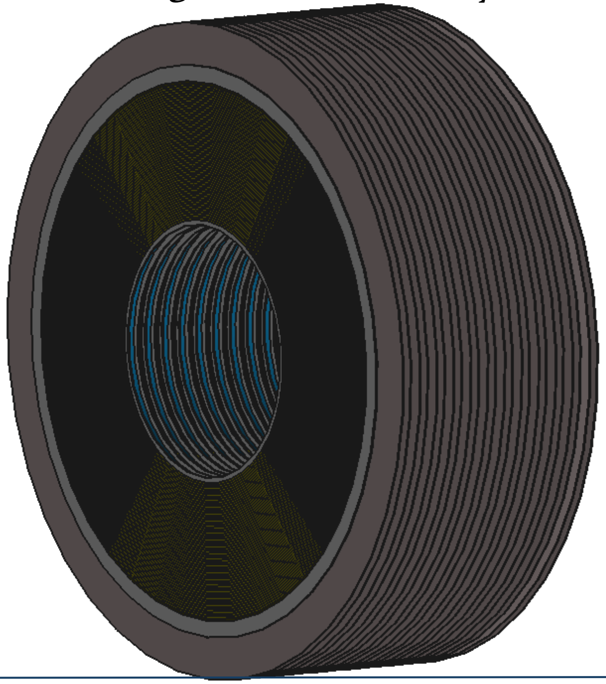
✓ σ(Z) ~ 40nb, σ(Bhabha)~14 nb

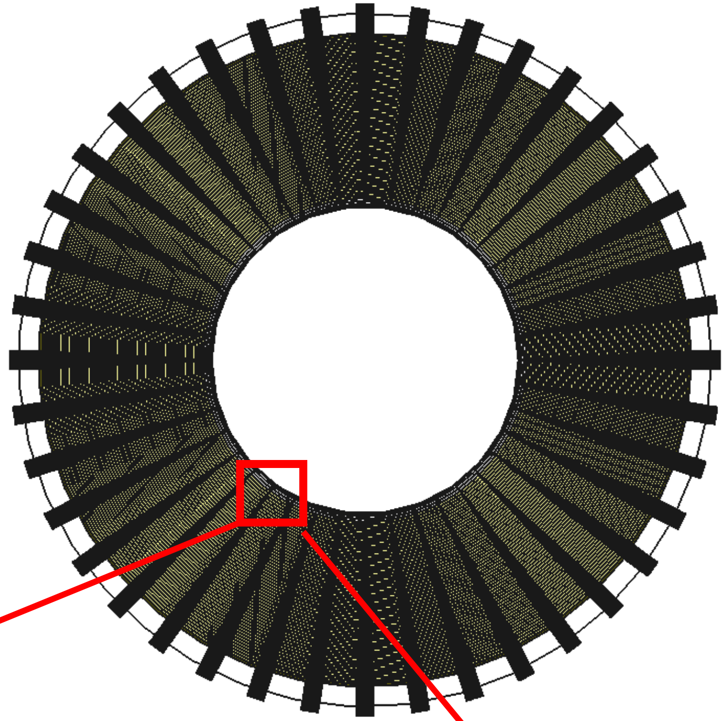
Current project:

- ***Develop NbN and NbTiN processing and transition towards MgB_2***
- ***Explore physical mechanisms integrating acustic (ballistic) phonon detection and lower effective detection threshold***
- ***Test different widths of nano-wire to characterise high-rate capability and recovery time***

•Introduction: Luminometer design

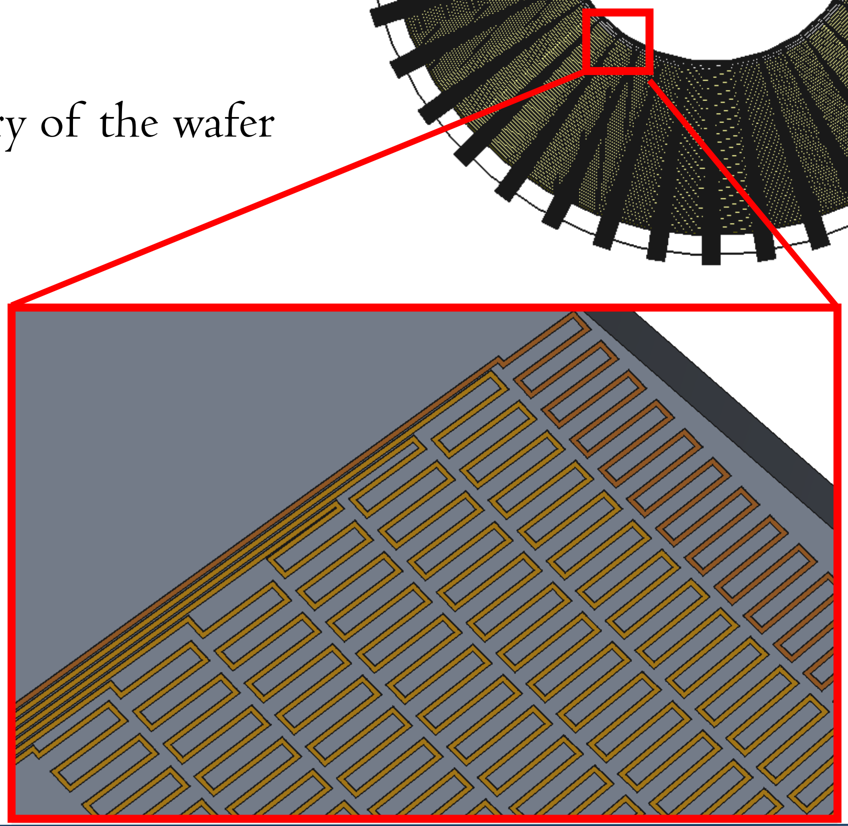
- 20 X 12” single wafers, 2 wafer per layer
- Sensors arranged in Tracks and Sectors
- 60 X 1 mm wide tracks spanning the perimeter of wafer from 54 mm to 114 mm
- 1 X Alignment track at the outer edge, R = 115 mm
- 40 Sectors, each with 9° angular coverage
- Radial readout corridors between sectors, 1 mm wide
- Readout region is inherently active as nanowire extends to the periphery of the wafer





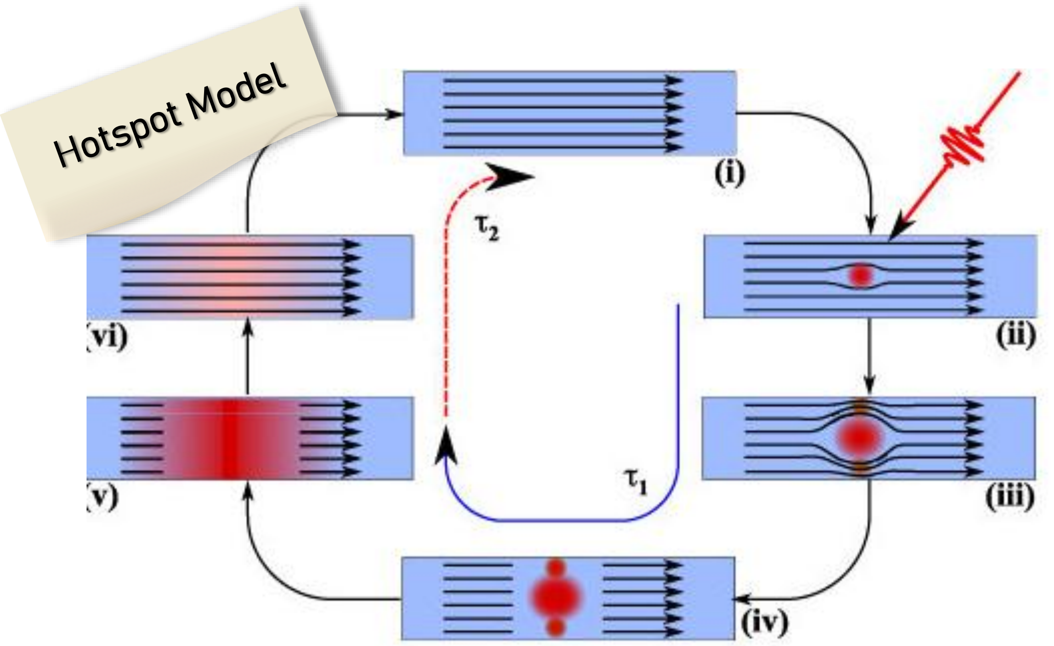
Sensor geometry: 100 % Fill Factor in multilevel staggered process

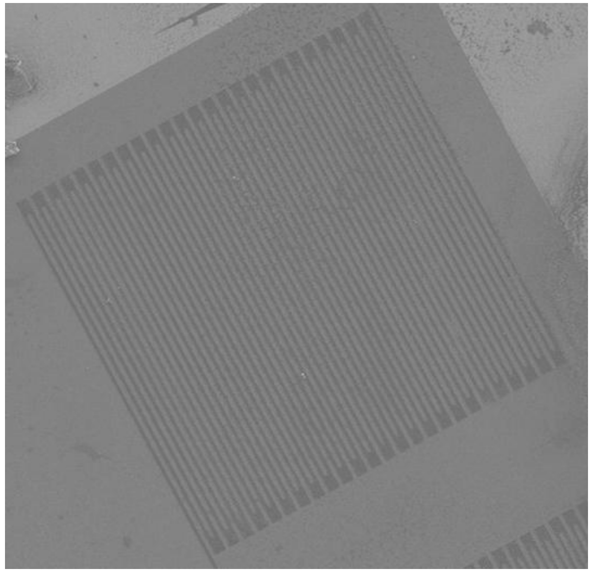
200 nm wide MgB_2 Film, 2 μm thickness

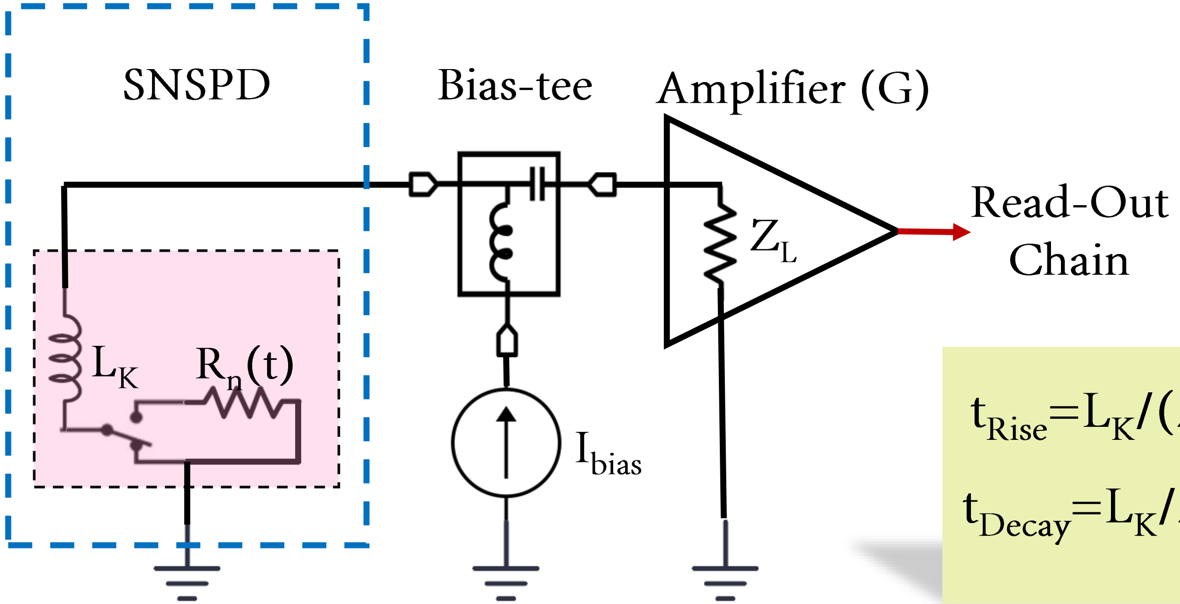


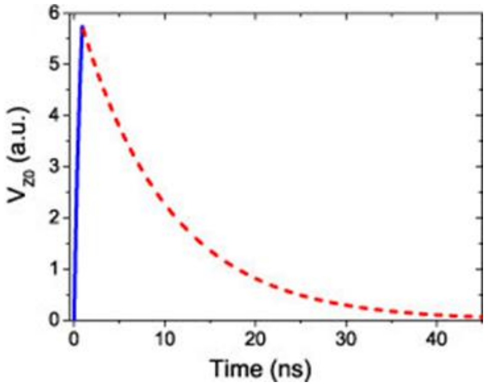
•Superconductive Nanowire SPD

- ultrathin, ~100-nm-wide superconducting strip on Si /SiN /SiC /sapphire/ diamond / substrate
- Current biased at a few K, operated just below it's transition point
- Single photon triggers brief resistive state, high efficiency at telecom bands, picosecond-scale timing, and ultra-low dark counts
- Absorbed photon locally breaks Cooper pairs forming nonequilibrium quasiparticle
- Current crowds around hotspot, exceeding the despairing current, resistive belt









$t_{Rise}=L_K/(Z_L+R_n(t))$

$t_{Decay}=L_K/Z_L$

Timing Characteristics

•Samples and Materials

- 500 nm width wire NbTiN sample operated at 28 - 30 μA @ 9.3 V (5th metastable resistive state after I_c, phase slips, vortices, inhomogeneities)
- Double loop geometry with 51 meandering branches
- 7 nm active layer thickness deposited on 400 μm Poly-Si substrate atop the native SiO_2 (2 nm)

$$\delta V = IR_0 \times \left[\frac{1}{R_0}\left(\frac{dR}{dT}\right)\right] \times \delta T$$

Voltage Variation; Bias Current; Material Resistance; Temp. dependent resistance change; Temperature variation

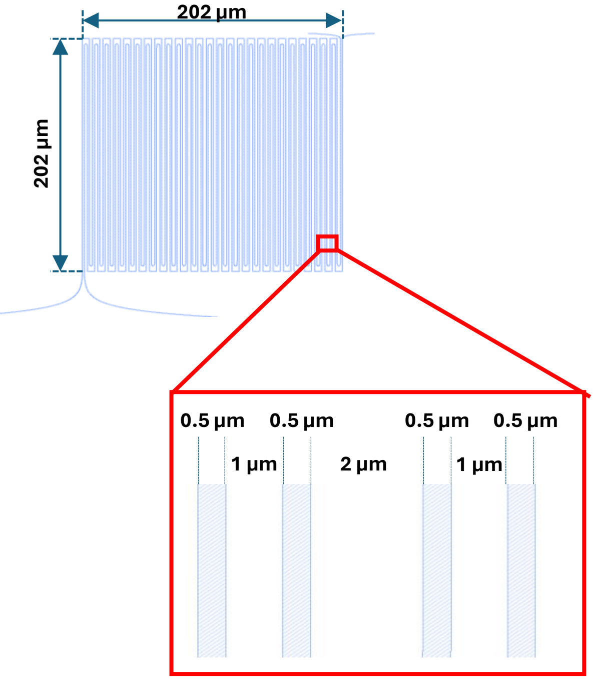
Sample	Critical Current [A]	Hysteresis Current [A]
600 nm, NbTiN	$(1.81 \pm 0.10) \times 10^{-5}$	$(4.04 \pm 0.49) \times 10^{-6}$
500 nm, NbTiN	$(1.06 \pm 0.01) \times 10^{-5}$	$(5.01 \pm 0.10) \times 10^{-6}$
120 nm, NbTiN	$(2.1 \pm 0.03) \times 10^{-6}$	$(1.00 \pm 0.03) \times 10^{-6}$
60 nm, NbN	$(1.50 \pm 0.03) \times 10^{-6}$	$(1.40 \pm 0.06) \times 10^{-6}$
1 μm, NbTiN	$(4.83 \pm 0.05) \times 10^{-5}$	$(9.87 \pm 0.52) \times 10^{-6}$

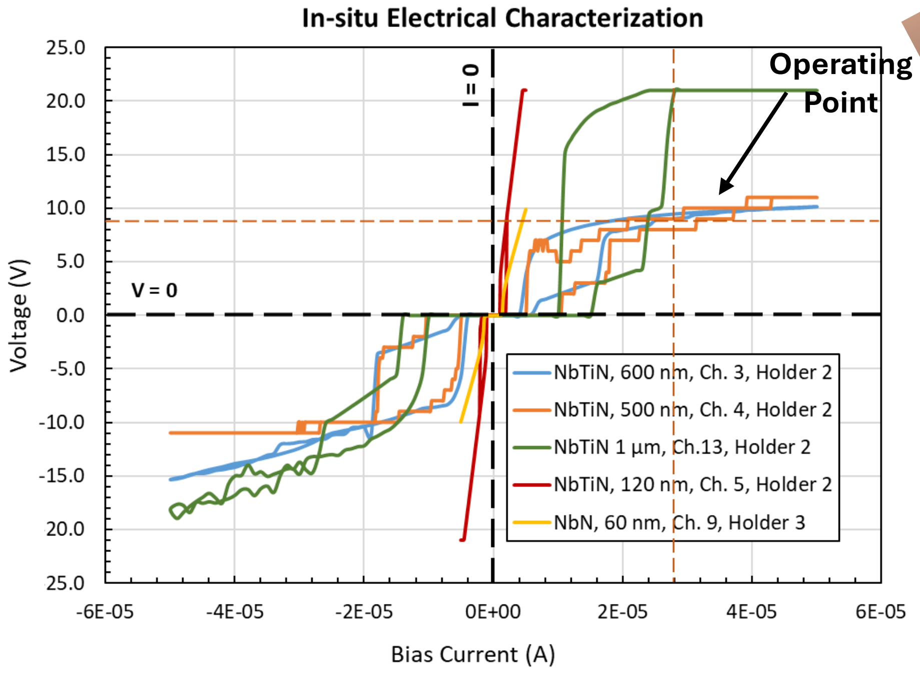
Positive sweep: Slow I_{bias} ramp-up until sharp voltage jump (I_c)

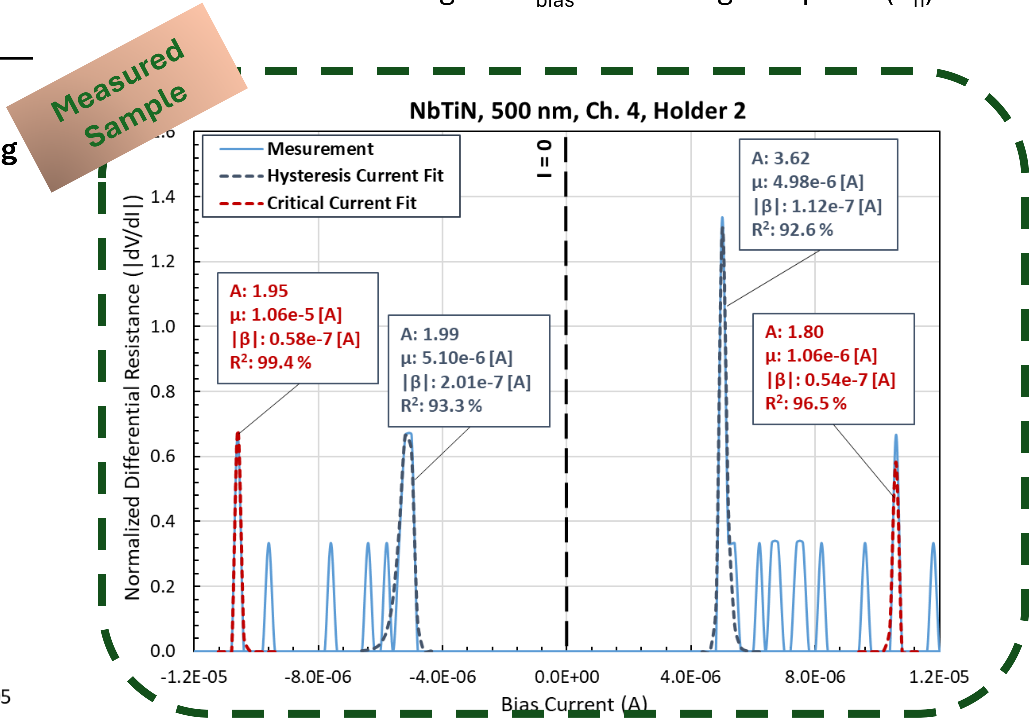
Retrace: Decrease I_{bias} until voltage drop to 0 (I_h)

Negative sweep: Negative I_{bias} ramp to voltage transition ($-I_c$)

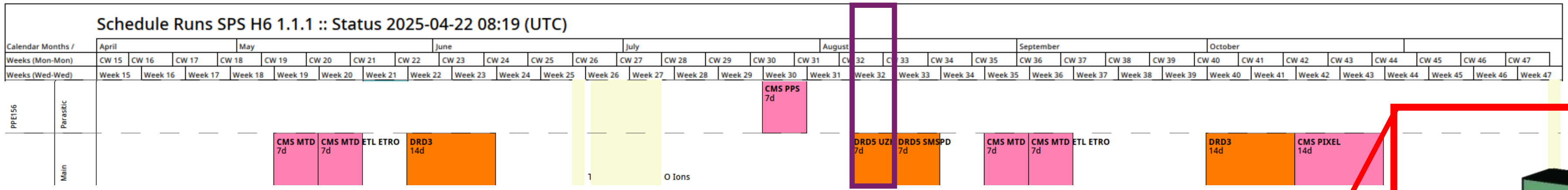
Retrace to 0: Decrease negative I_{bias} until voltage drop to 0 ($-I_h$)





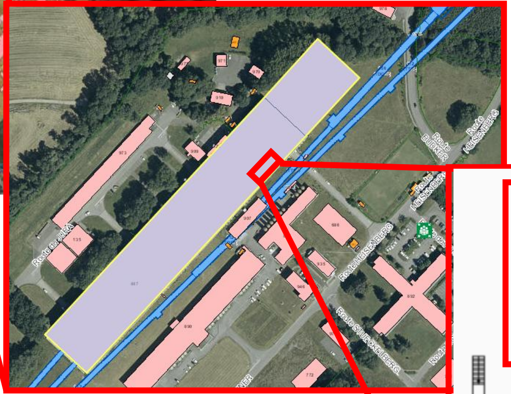


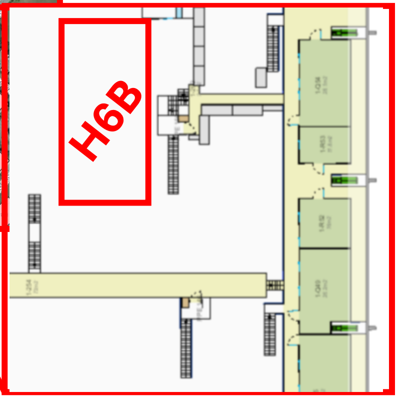
•General Information: H6B



CERN Prévessin

Building 887

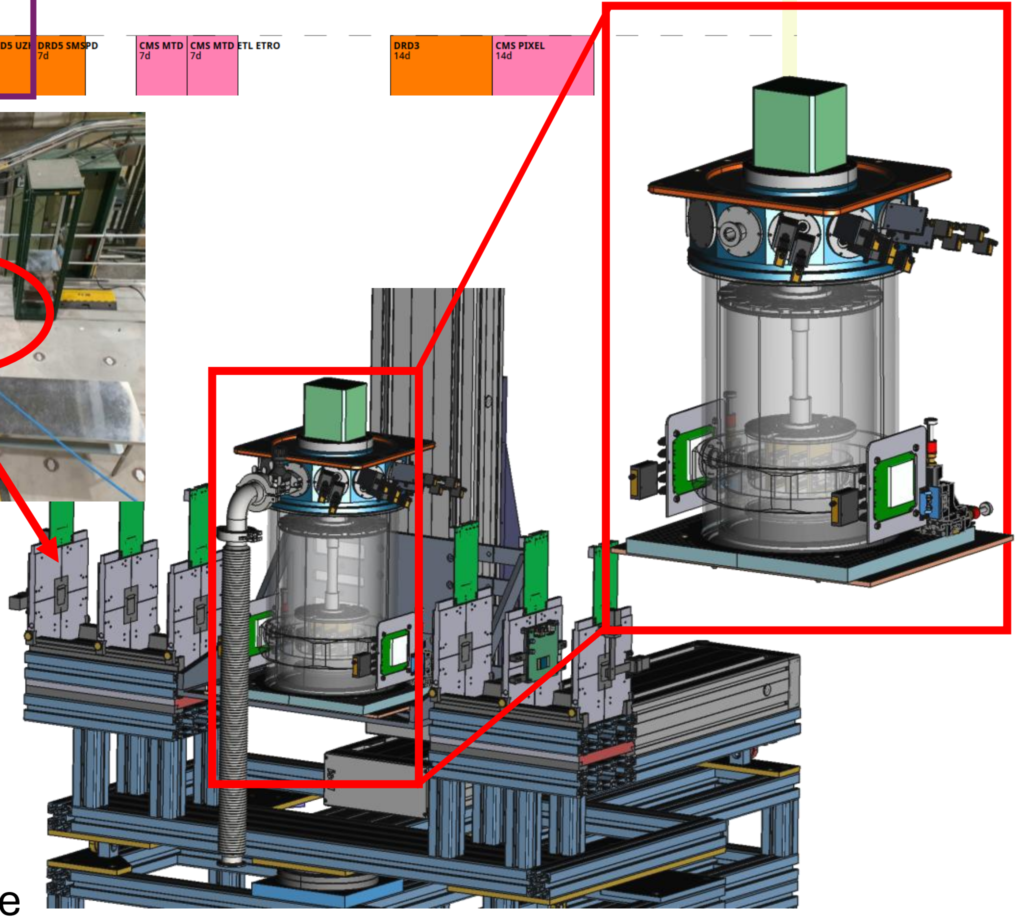




Area: SPS – North Area (NA)
Beam line: H6B
Access Door: PPE156
Counting Room: 887/1-Q54

AIDA Telescope in H6B Current setup

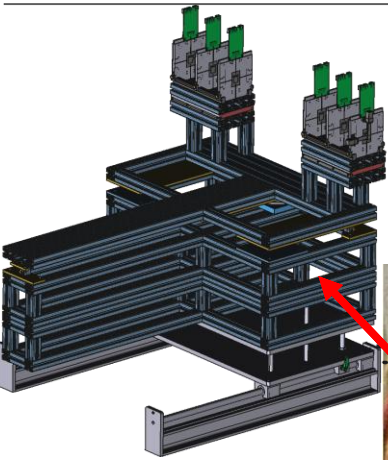
- 6 MIMOSA 26 planes
- One 2-axis ILE20 stage, up to 500 kg support



The Setup

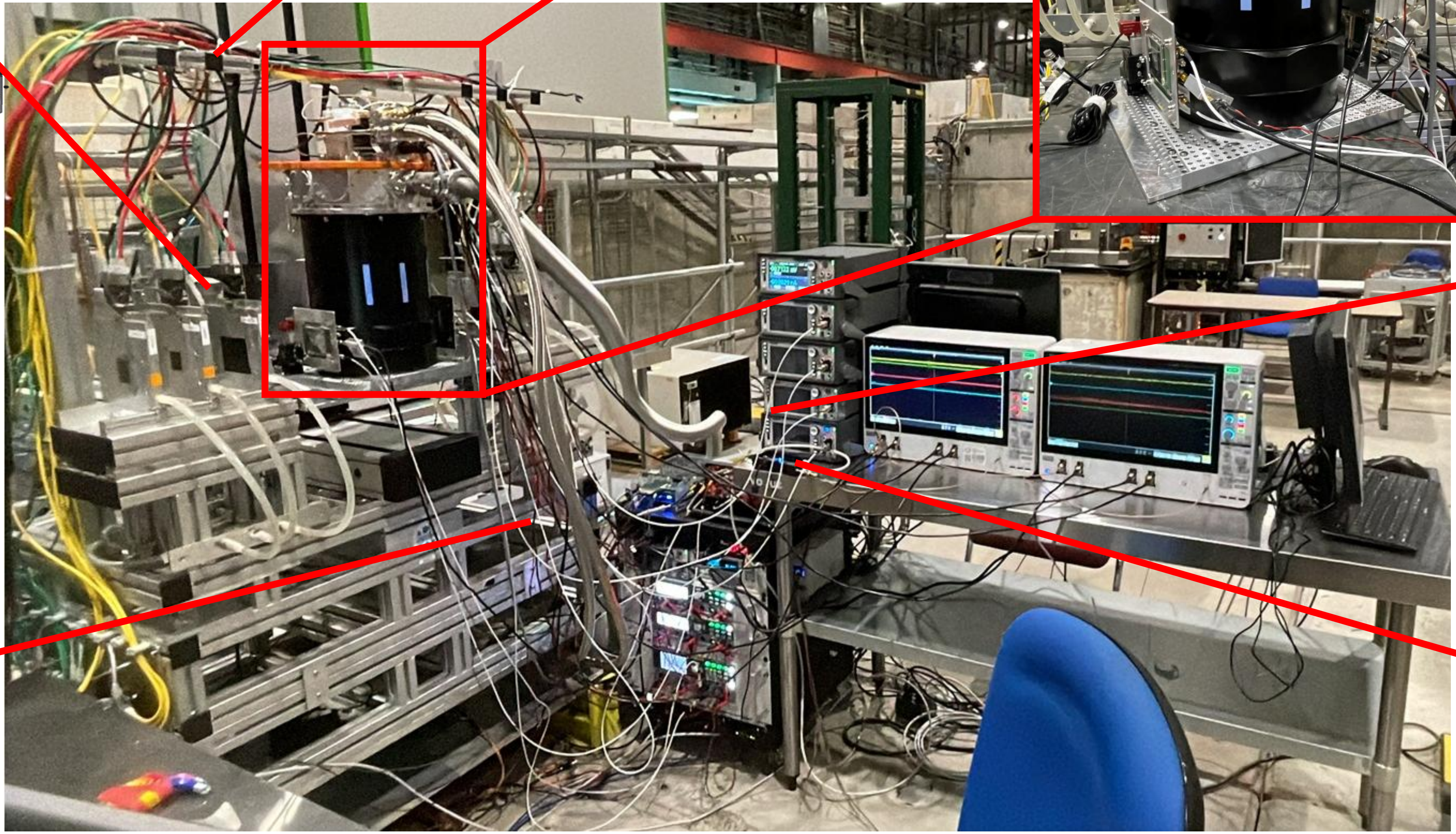
- AIDA Telescope
- Closed Cycle He Cryostat
- 2 x LGAD timing planes on UCSC single channel board
- Pixelated alignment & ROI plane

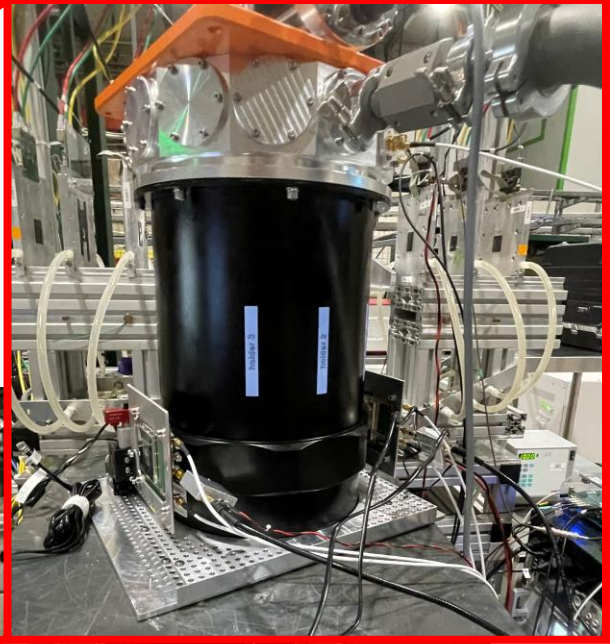
•Setup @ SPS



Modified telescope frame, 1.4 m back extension

New 500 Kg Stage Installation (part of AIDA WP2 project)

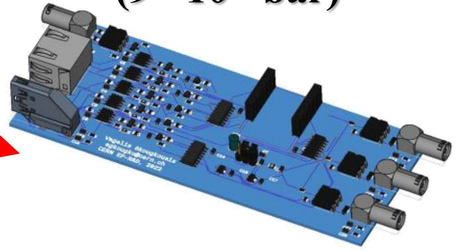




Instrumentation Rack

Turbo-Molecular vacuum pump (9×10^{-9} bar)

3-phase, He_2, water cooled Cryo-Compressor



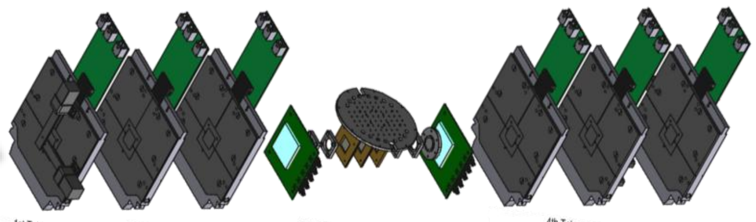
Dedicated Trigger & synchronization Board

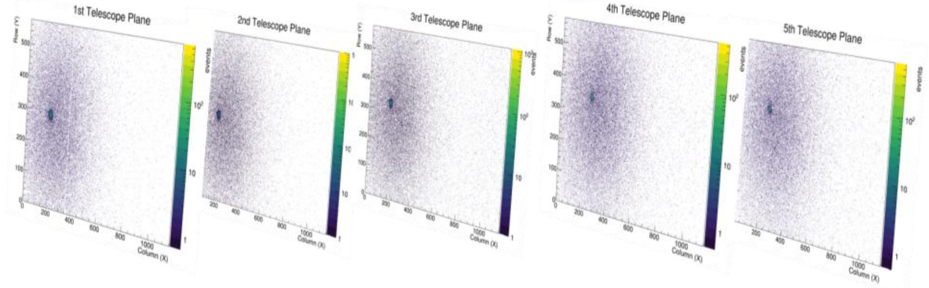
•2025 Test beam, 160 GeV $\pi^{0,\pm}$

2025 period (August)

- First ever particle detection with NbTiN and MbB_2 films
- 2.28 K operation within the AIDA telescope in H6B area
- 100 psec timing, 6 nsec rise times with 200 x 200 μm samples
- Very successful test period with article already submitted and under reviews, several Conference presentations (VERTEX 2025)

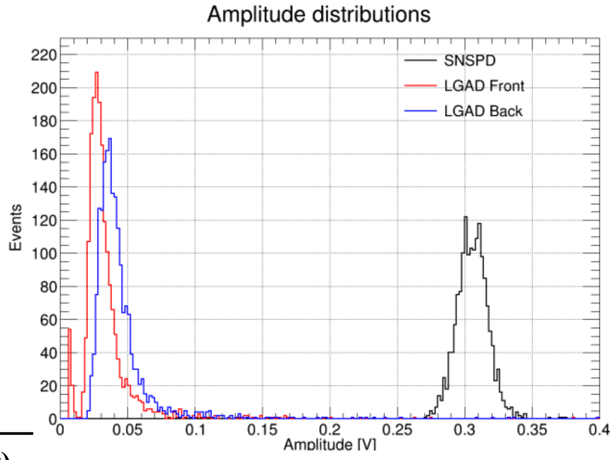
MIMOSA telescope

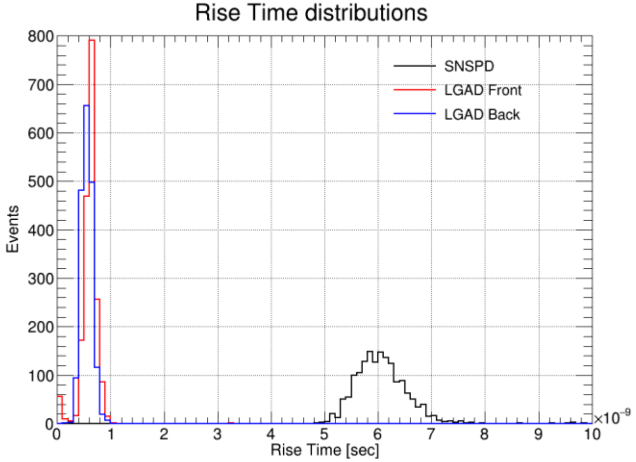




Samples & conditions

- Double loop geometry with 51 meandering branches
- 7 nm active layer thickness deposited on 400 μm Poly-Si substrate atop native SiO_2 (1.9 nm)
- operated at 28 - 30 μA @ 9.3 V (5th metastable resistive state after I_c)





Efficiency estimation

Run Configuration	No. of Events	I_{bisas} (SNSPD)	Rate (Hz)
DUT Trigger	2933	30 μA	0.000439
Tracing & Efficiency Run, RoI Trigger	6061	30 μA	0.011477
	6178	30 μA	0.011431
	7261	30 μA	0.011578
	7111	30 μA	0.010707

$$\eta = \frac{R_{DUT\ trigger}}{R_{area\ trigger}} \approx 3.89\ \%$$

•2025 Test beam, 160 GeV $\pi^{0,\pm}$

- End-to-end fully integrated simulation chain
- Propagation of fabrication related defects to DFT approach
- GEANT4 integration for energy deposition simulation
- Effective detection threshold extraction from TDGL approach

Energy Deposition
(GEANT 4)
ΔE to Q(x,y,z,t)
GEANT4 A SIMULATION TOOLKIT

Superconductivity Aware nanoscale simulation
(FEniCS)
- ***2-temperature model***
- ***quasiparticle diffusion / recombination***
- ***time-dependent Ginzburg - Landau model for hotspot***

Electronics
(LTSpice)
R(t, L(t))
LTspice

Device Fabrication
(Sentaurus Process - Slitho)
Parametrization of J_c, R, λ_L, D (diffusion)
SYNOPSYS

Material Properties
(QuantumATK, full DFT)
Electronics/ phonon properties, defect impact

•Geant4 Simulation

Differential x-section across different energy ranges

User defined **PAIMODEL+DL** is a custom implementation combining standard PAI with Drude-Lorenz

$$\left(\frac{d\sigma}{d\Omega}\right)_{total} = \begin{cases} \left(\frac{d\sigma}{d\Omega}\right)_{DL,NbTiN} & 0.8\ eV < E_{tr} < 10\ eV \\ \left(\frac{d\sigma}{d\Omega}\right)_{PAI,NbTiN} & E_{tr} \geq 10\ eV \end{cases}$$

ELF -> Energy Loss Function $ELF(E_{tr}, q) = Im\left[-\frac{1}{\varepsilon(E_{tr}, q = 0)}\right]$

$\varepsilon(E_{tr}, q)$ → Complex Dielectric Function
E_{tr} → Energy Transfer
q → Momentum Transfer (optical limit q = 0)

PAI Implementation of the energy loss function : $\left(\frac{d\sigma}{d\Omega}\right) \sim \frac{1}{E_{tr}} Im\left[-\frac{1}{\varepsilon(E_{tr})}\right]$

- Effective Energy threshold for NbTiN at 2.28 K with 30 μA bias current at ~0.8 eV engineered to be fully efficient at 1550 nm.
- This is not the de-pairing threshold, which is 2Δ and is typically in the meV range, it is the effective detection threshold defined by the film properties.

•Geant4 Simulation

E_{tr} ≥10 eV: PAI Model

- Photon - Absorption Ionization (PAI) Model, was developed for ionization on gas and thin films, where E_{tr} is the energy transfer, σ_i - the ionization cross section, and σ_γ - the photon absorption cross section, with main structure [1]:

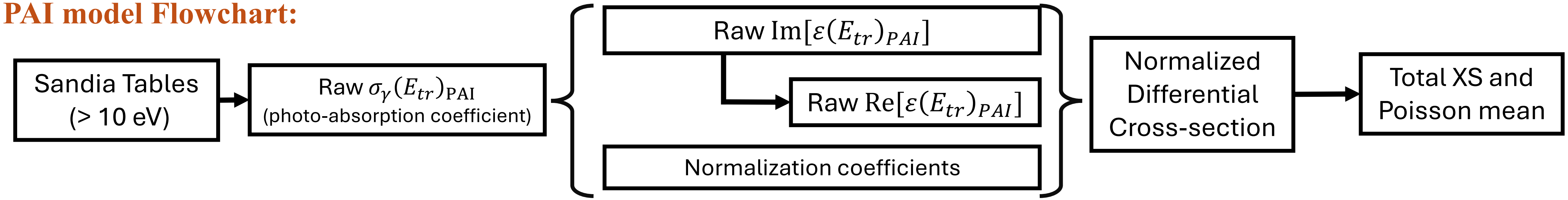
$$\frac{d\sigma_i}{dE_{tr}} = \frac{\alpha}{\beta^2}\left[\underbrace{\overbrace{\frac{\sigma_\gamma(E_{tr})}{E_{tr}|\varepsilon(E_{tr})|^2}}^{ELF(E_{tr},q)}\overbrace{\left(\ln\left(\frac{2m_e v^2}{E_{tr}|1-\beta^2\varepsilon(E_{tr})|}\right)+\ldots\right)}^{\text{Projectile Kernel }(1/E_{tr})}}_{\text{Energy loss}} + \underbrace{\frac{1}{E_{tr}^{\,2}}\int_{I_1}^{E_{tr\,max}}\left(\frac{\sigma_\gamma(E_{tr}')}{|\varepsilon(E_{tr}')|^2}\right)dE_{tr}'}_{\text{Delta electron tail}}\right]$$

- Expected yield is described by a Poissonian, of which mean is obtained from the integrated ionization cross section:

$$\mu = n\,\sigma_i\,l \quad \text{where} \quad \sigma_i = \int_{I_1}^{E_{tr\,max}} \frac{d\sigma_i}{dE_{tr}}\,dE_{tr}$$

where **μ**: Poissonian mean; **n**: electron density; **l**: step length
I_1: first ionization potential; **$E_{tr_{max}}$**: maximum transfer to free electron; **α**: fine structure constant (~1/137)
β: v/c; **m_e**: electron mass

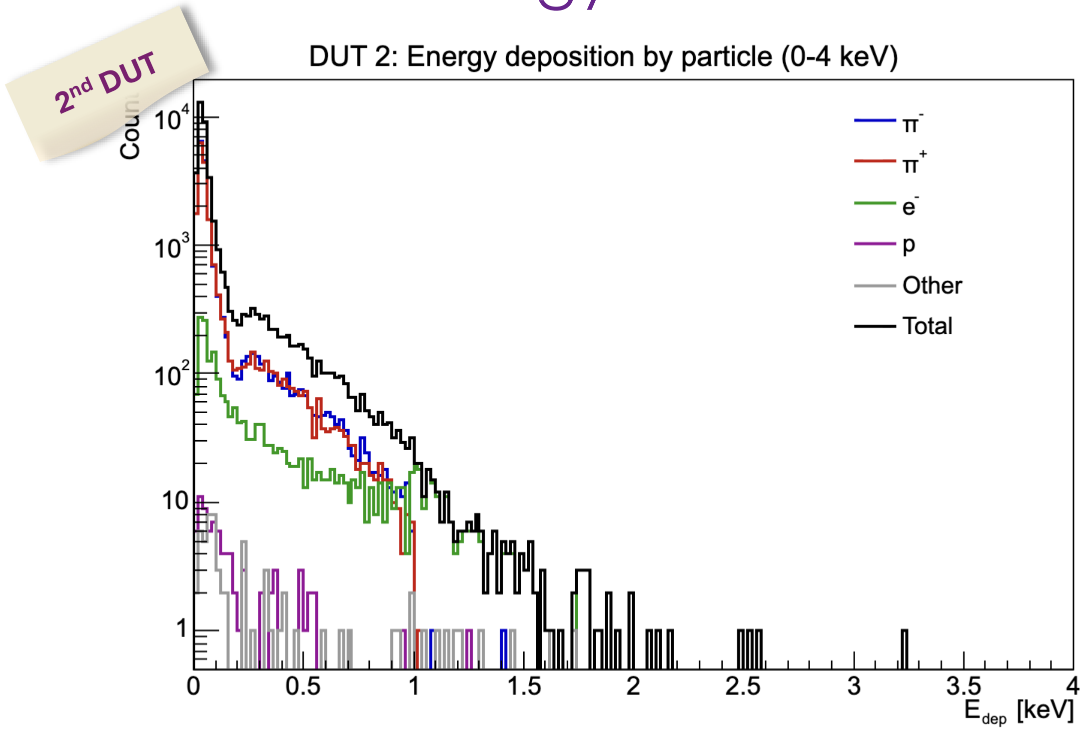
PAI model Flowchart:

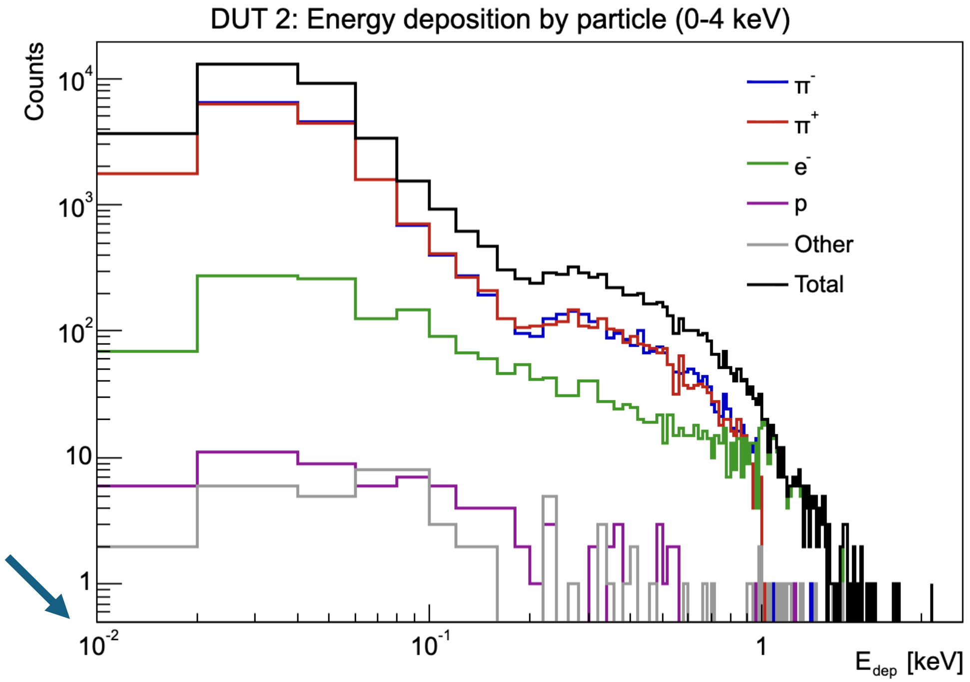


1. J. Apostolakis, Nucl. Instrum. Methods Phys. Res. A 453, 597–605 (2000)

•Geant4 Simulation

PAI Model: Low-energy limitations





Energy deposition spectra by particle type in a 7 nm $Nb_{0.7}Ti_{0.3}N$ film, simulated with G4PAI and shown in log-y and log-log scales.

- **Low energy limitation around 10 eV**
  - In GEANT4, the cross sections are constructed from data in `G4SandiaTable`
  - Sandia Table is limited at low energies, with the first available interval starting around 10 eV.
  - SNSPD detection threshold can be as low as ~800 meV

•Geant4 Simulation

E_{tr} <10 eV: Drude-Lorentz approximation

Approximate the collective and lattice effects as a sum of a single Drude and 2 Lorentz Oscillators

$$\overbrace{Re[\varepsilon(E_{tr})] + iIm[\varepsilon(E_{tr})]}^{\varepsilon(E_{tr})} = \varepsilon_\infty - \overbrace{\frac{E_{pu}^2}{E_{tr}^2 - i\Gamma_D E_{tr}}}^{\text{Drude Term}} + \underbrace{\sum_{j=1}^{n} \frac{f_j E_{0_j}^2}{E_{0_j}^2 - E_{tr}^2 + i\gamma_j E_{tr}}}_{\text{Lorentz Oscillators}}$$

$f_j E_{0_j}^2 \rightarrow E_{p_j}^2$

where $\mathbf{E_{tr}}$: energy transferred
$\boldsymbol{\varepsilon_\infty}$: background term
$\boldsymbol{E_{pu}^2}$: unscreened plasma energy (density of electrons)
$\boldsymbol{\Gamma_D}$: Drude broadening / scattering rate
$\mathbf{E_{0j}}$: Lorentz oscillator resonance energy
$\boldsymbol{f_j}$: Lorentz oscillator strength
$\boldsymbol{\gamma_j}$: Lorentz linewidth / damping factor

- Drude term: response of free or weakly bound electrons
- Lorentz term: response of bound-electron excitations

Parameters for 100 nm film

Parameter	Symbol	$Nb_{0.5}Ti_{0.5}N$(eV)	NbN(eV)	TiN(eV)
Background constant	ε_∞	1.896	1	3.558
Plasma energy	E_{pu}	8.67	10.58	7.44
Drude Broadening	Γ_D	0.954	3.222	0.416
Resonance Energy 1	E_{01}	6.158	5.666	4.802
Oscillator strength 1	f_1	5.547	2.291	3.819
Broadening 1	γ_1	4.525	2.03	2.4
Resonance Energy 2	E_{02}	2.254	3.035	2.024
Oscillator strength 2	f_2	0.224	7.174	0.997
Broadening 2	γ_2	1.71	5.5	1.617

Dielectric values from R. Bower et al., ACS Appl. Mater. Interfaces 12, 45444–45452, materials are all measured with 100 nm film deposited on Si substrate

•Geant4 Simulation

Drude Lorentz + PAI: Photo-absorption, Energy deposition

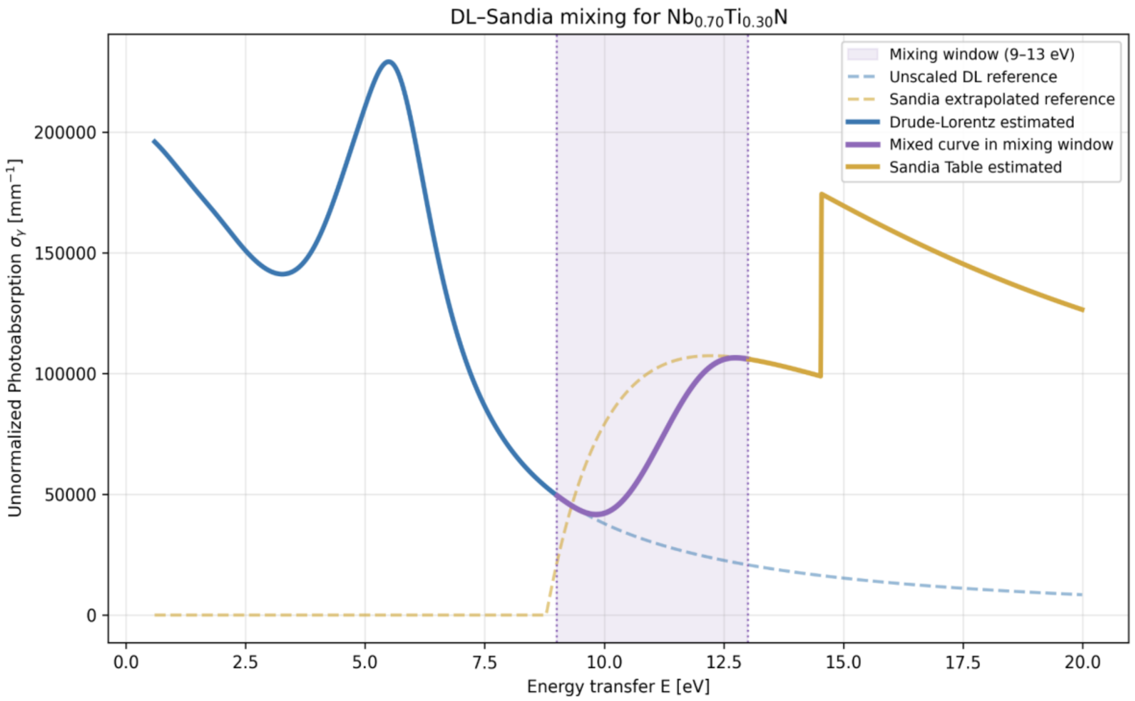
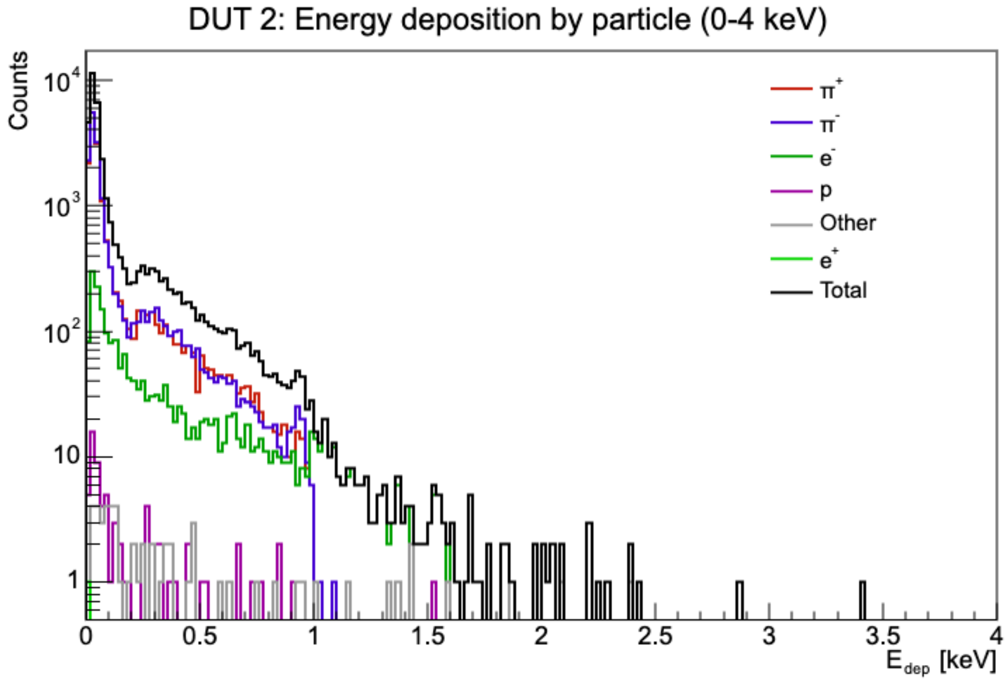


Photo-absorption cross-section of the extended PAI model for $Nb_{0.7}Ti_{0.3}N$, with a 9–13 eV blending window. The hump-shaped curve above 10 eV are shell structures from Sandia Table data.



Energy deposition by particle type $Nb_{0.7}Ti_{0.3}N$ using extended PAI model for a 7 nm thick film. Efficiency estimated in Per-Event level, with double count (back scatter / secondaries) rejection :

$$\varepsilon = \frac{[N_{prim.} \cup N_{secon.}]}{N_{\pi(+/-)}}$$

•Phonon Propagation in Si

Categories and thermalization

- Ballistic phonons: Created by e-h pairs through electron-phonon coupling

$$f_{max} = 21\ THz$$

Determined by the angular Debye frequency

- Thermal phonons: Created by ballistic phonon down-converting and lattice vibrations

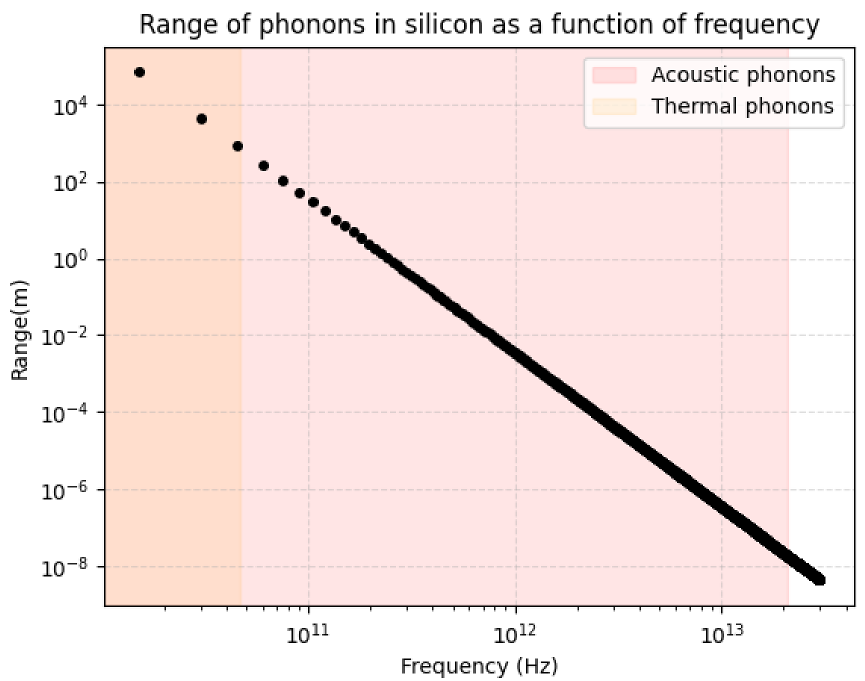
$$f_{max} = \frac{k_B T}{h} = 47\ GHz$$

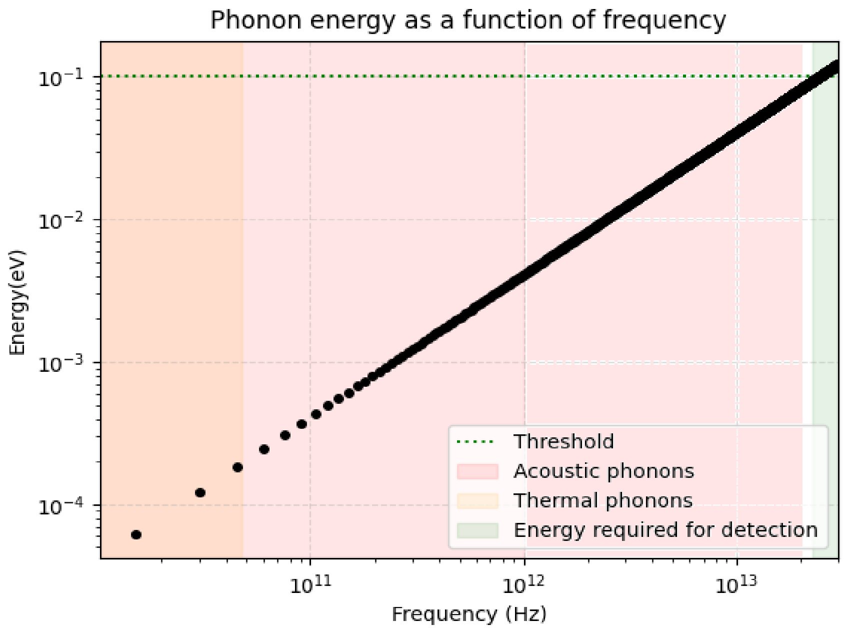
Determined by the Boltzman energy at 2.28K

- NTL (Neganov–Trofimov–Luke) phonons: Generated by charged carriers being displaced within an electric field (Not present here)

Tested sensor tunned for 1550 nm → 0.8 eV
Required phonon frequency > 21 THz

No detection of thermal or ballistic phonons





•TDGL Simulation

Time Dependent Ginzburg-Landau Model

- TDGL equation can be obtained from Ginzberg-Landau free energy, when order parameter is small (near T_c):

$$\underbrace{\Gamma\left(\frac{\partial\psi}{\partial t}+i\frac{q^*}{\hbar}\phi\,\psi\right)}_{\text{Time evolution term}}=\frac{\hbar^2}{2m^*}\underbrace{\left(\nabla-i\frac{q^*}{\hbar}A\right)^2}_{\text{Kinetic (vortex)}}\psi\underbrace{-\alpha\psi-\beta|\psi|^2\psi}_{\text{GL free energy potential}}$$

  - Order parameter ψ, scalar electric potential ϕ, and vector magnetic potential $\boldsymbol{A}$, were $0<\psi<1$ indicates the local "superconductivity", Γ is the relaxation constant (common value 5.79)
- The second TDGL equation is the Ampere's Law:

$$\underbrace{-\frac{4\pi\sigma_n}{c}\left(\frac{1}{c}\frac{\partial\boldsymbol{A}}{\partial t}+\nabla\phi\right)}_{\text{Normal Current}}+\underbrace{\frac{2\pi i e_s\hbar}{m_s c}\left(\psi^*\nabla\psi-\psi\nabla\psi^*\right)-\frac{4\pi e_s^2}{m_s c}|\psi|^2A}_{\text{Super Current}}=\underbrace{\nabla\times\nabla\times\boldsymbol{A}}_{\text{Total Current}}$$

- Can be numerically solved via: **Gauge choice** + **discretization (meshing)** + **numerical solver,** in dimensionless units:
- Length scales with coherence length or London penetration depth (depends on the simulation scales) :

$$r\rightarrow\xi_0\tilde{r},\ \nabla\rightarrow\frac{1}{\xi_0}\tilde{\nabla},\qquad r\rightarrow\lambda_0\tilde{r},\ \nabla\rightarrow\frac{1}{\lambda_0}\tilde{\nabla}$$

- Time scales with $\tau_0=\mu_0\sigma\lambda^2$:

$$t\rightarrow\tau_0\tilde{t}$$

- The dimensionless TDGL contains $\kappa=\lambda/\xi$, based on the length scaling, for example[1]:

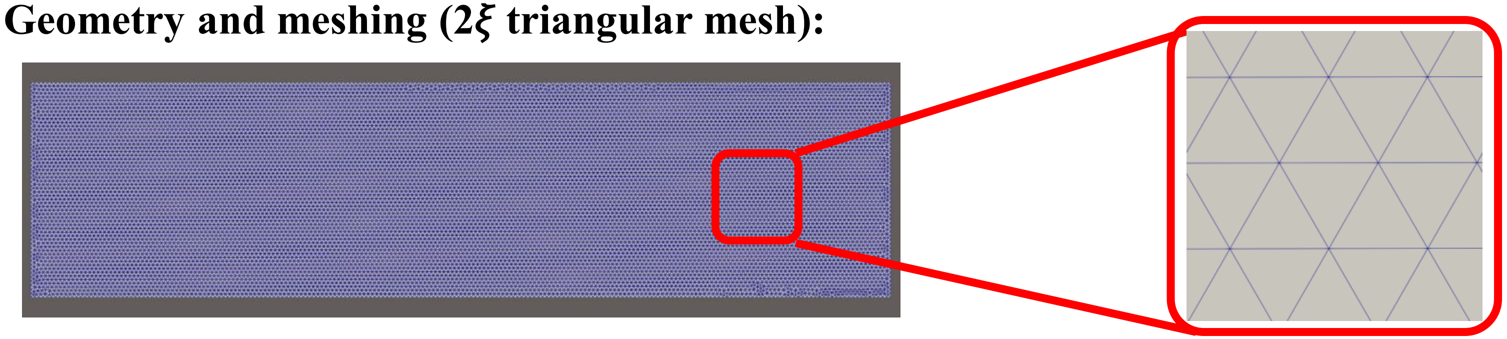
$$\gamma\left(\frac{\partial\psi}{\partial t}+i\kappa_0\phi\,\psi\right)+\frac{1}{\mu}\left(-\frac{i}{\kappa_0}\nabla-A\right)^2\psi+\frac{1}{\kappa}\nabla\frac{1}{\mu}\cdot\left(\frac{1}{\kappa_0}\nabla-iA\right)\psi-\alpha\psi+\beta|\psi|^2\psi=0$$

1. Harbick & Transtrum, Phys. Rev. B, (2025), doi:10.1103/q9h5-83fy

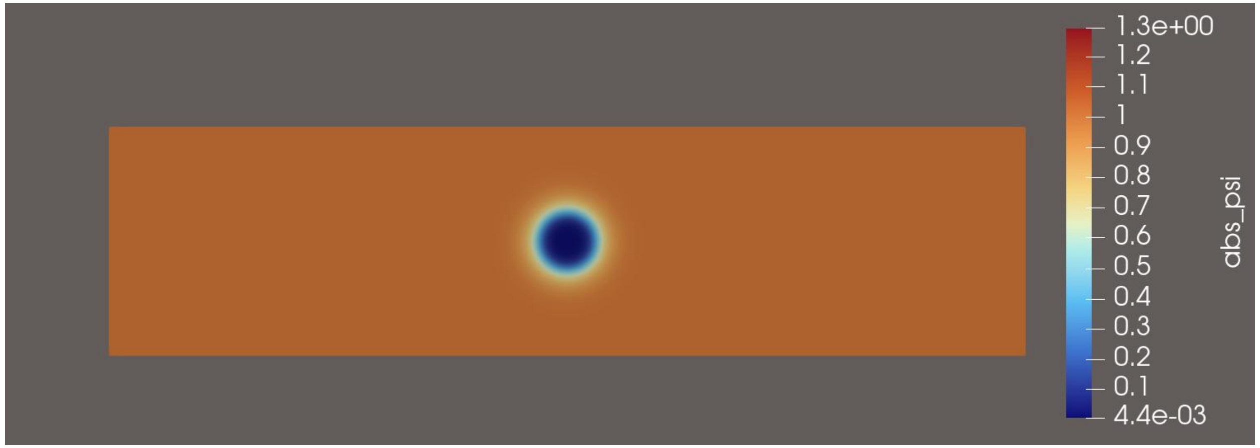
•TDGL Simulation

FEniCS TDGL Simulation: 2D run E-field Drive

- **Geometry and meshing (2ξ triangular mesh):**



- **Event simulation**



Meshing
Superconducting Region 2 ξ
Periodic boundary condition in x
No symmetry settings (for voltage)

↓

Current Drive
- Phase vector drive
- **Electric field drive**
- Source-drain drive

↓

Split-step simulation
Remove hotspot, converge to initial state

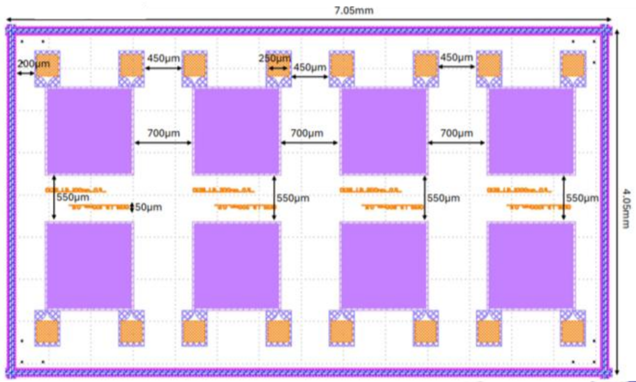
↓

View Results
Save xdmf file and view in Paraview

•Fabrication Run

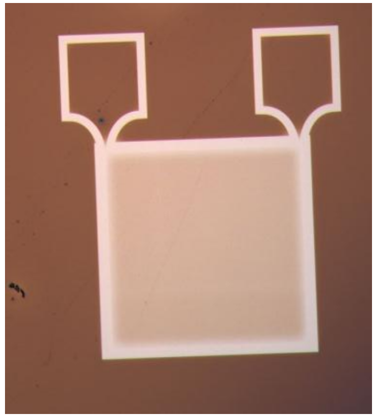
Full wafer layout (BETTY)

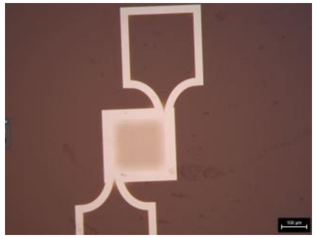
Second SNSPD layout for pixels <500μm



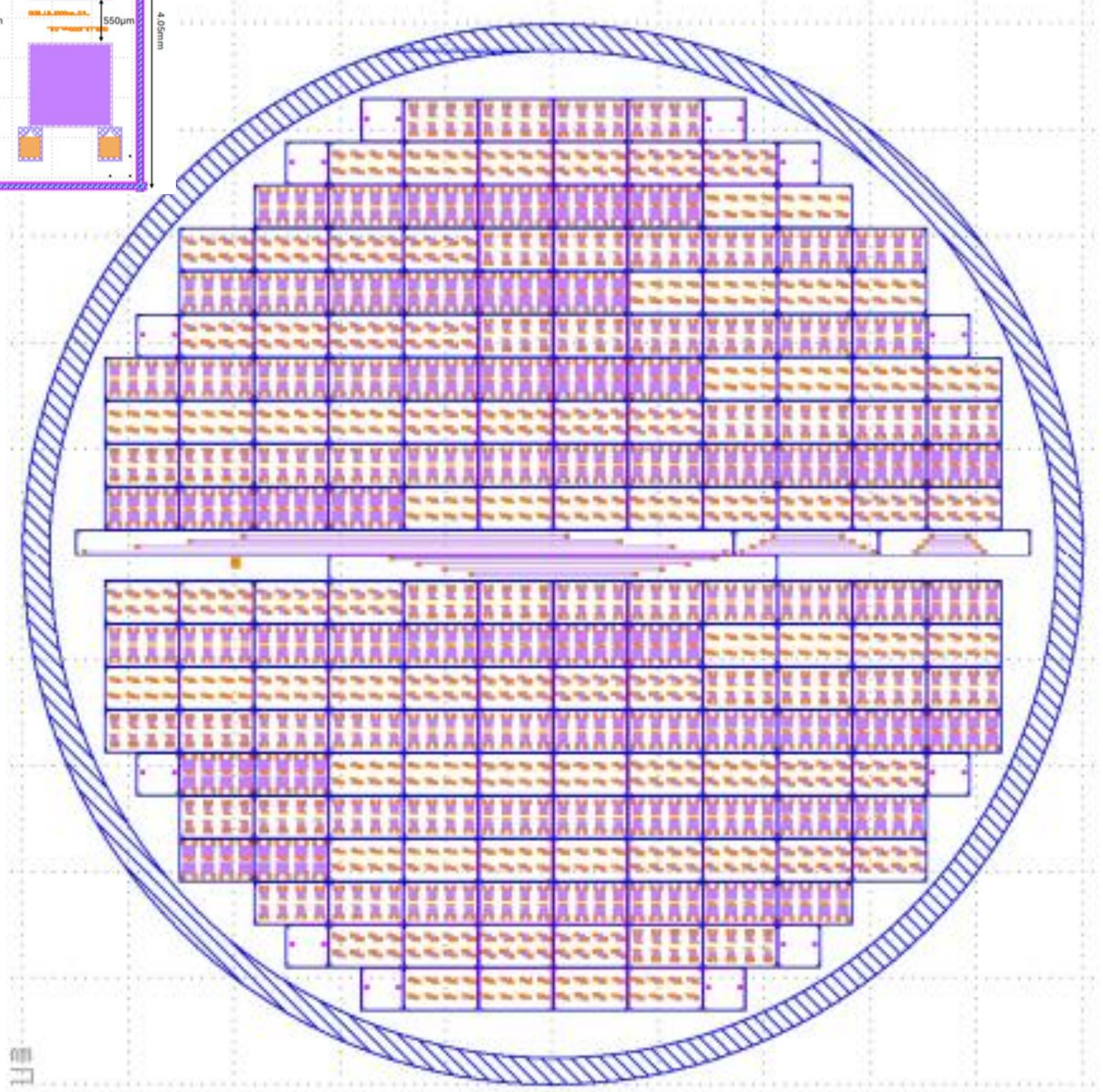
Layout information:
- 160 unique SNSPDs
- 47 SNSPD die and 18 test structures
- 7 duplicates with variable relative positions
- 50μm dicing lines
- 50μm marker width

Key differences:
- Bigger chips with 8 SNSPDs instead of 1
- Less photolithography required

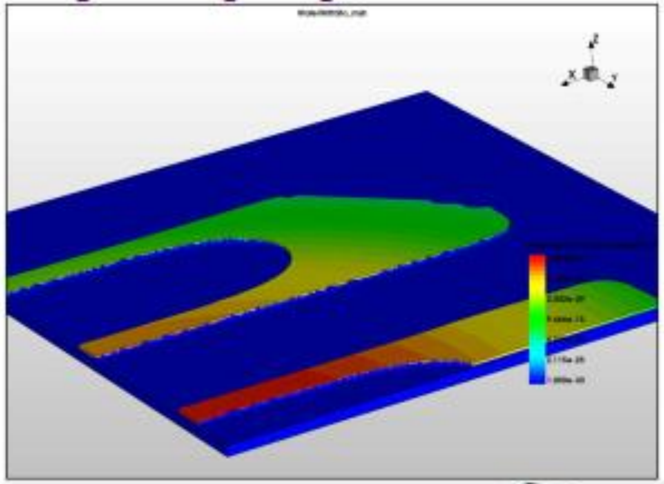


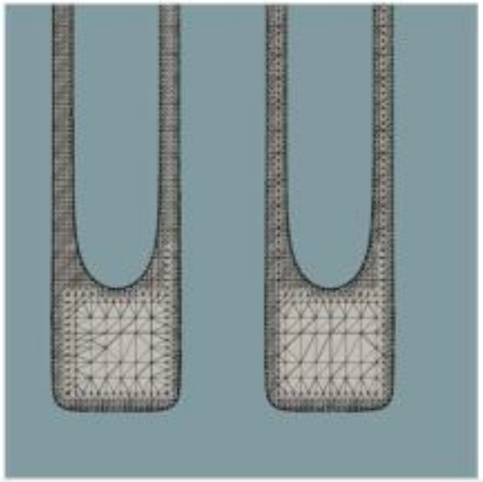


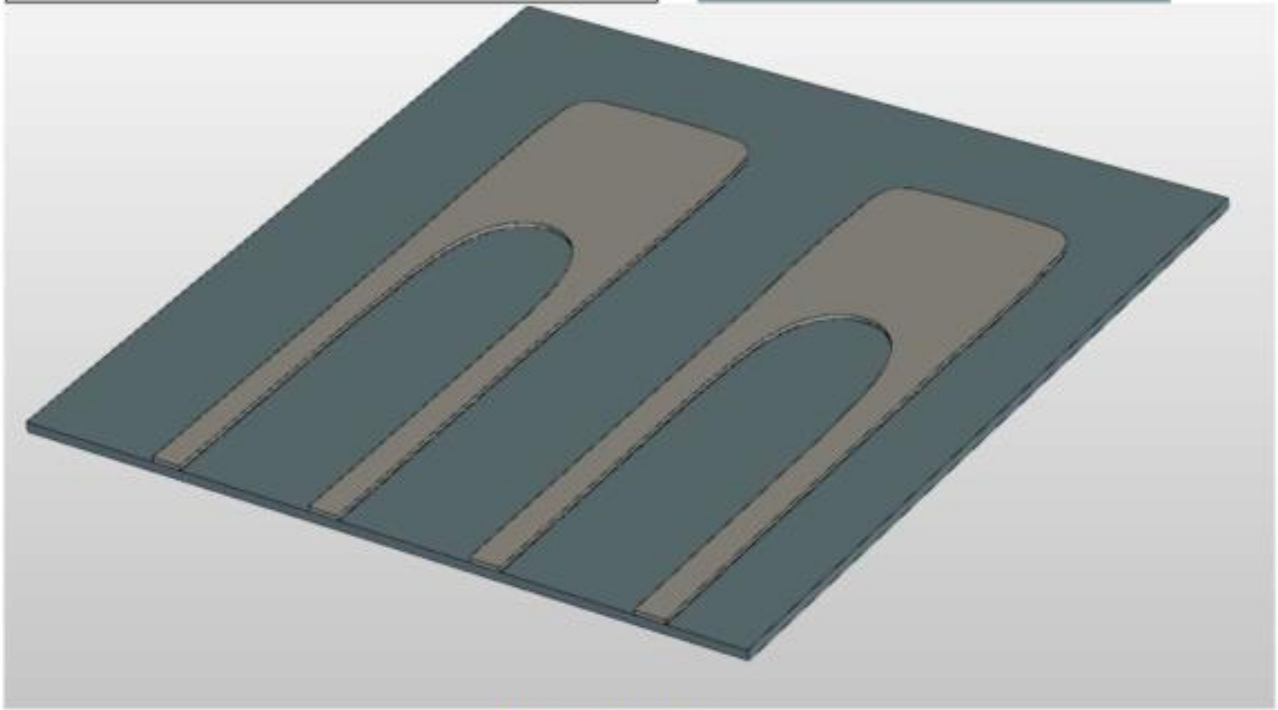
Silicon wafer:
- Monocrystalline Fz Si
- <100> or <111> orientation
- 4" diameter
- 525μm thickness
- Double sided polish
- P-type boron doping
- 10KOhm.cm



Synopsys Simulation







Full simulation result

Simulation steps (e-beam lithography):

- Si <100> 525 μm substrate **Sprocess**
- Spin coating of resist (PMMA) **Slitho**
- Pre-baking **Slitho**
- E-beam lithography emulation through **Slitho**
- Resist development **Slitho**
- Reactive ion etching **Sprocess**

Full simulation process flow in the silicon workbench package

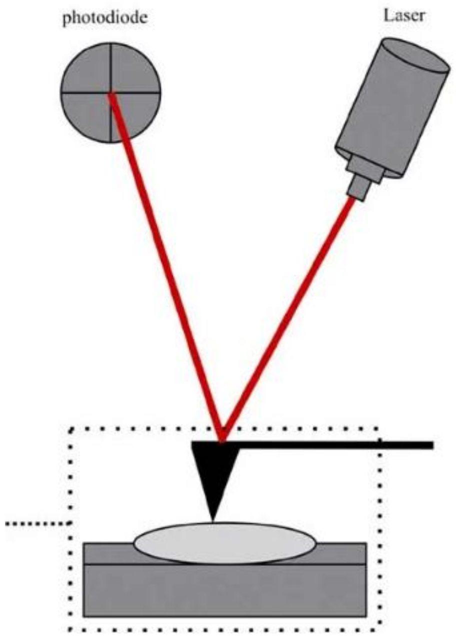
- Adaptive meshing done around the RIE edge
- Doping field used to emulate defects within the structure of the thin film

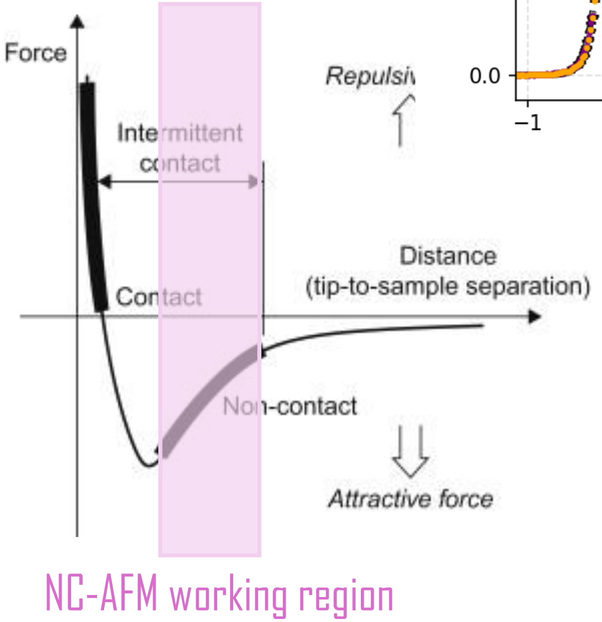
•Sample Characterization

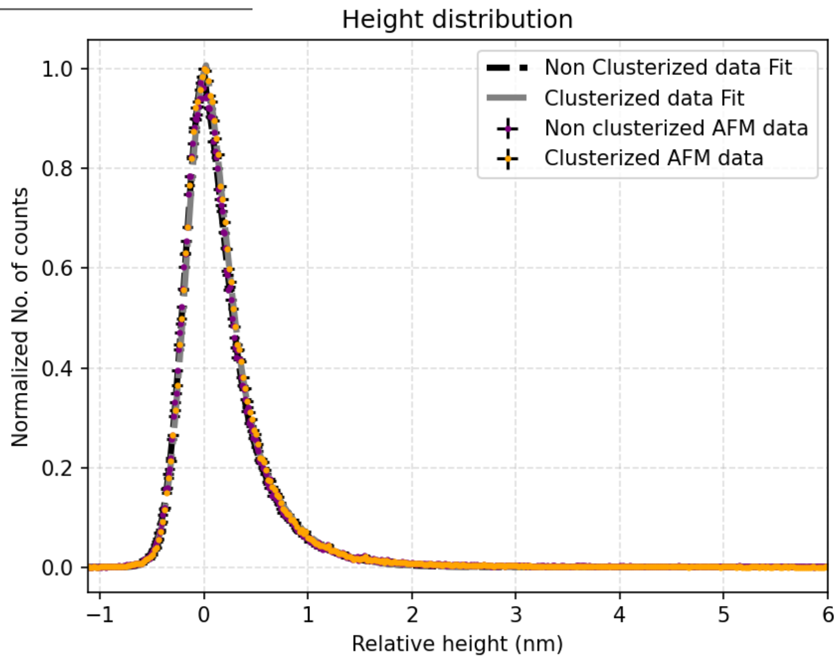
Atomic Force Microscopy

What we can reach:

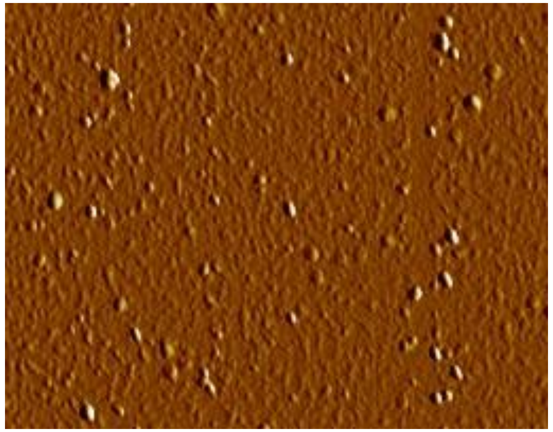
- 0.05 nm height precision
- 5 nm x 5 nm pixel resolution
- Several μm vertical deflection







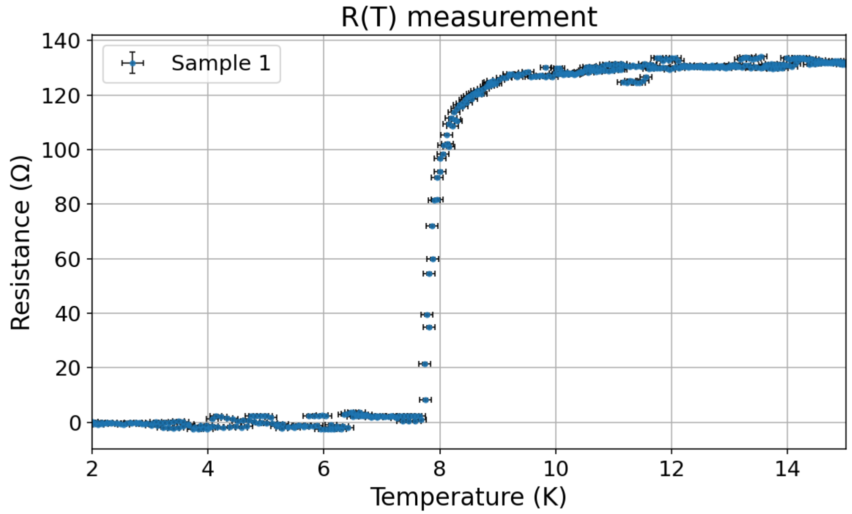
Data	Clusterized	Non-Clusterized
Gaussian amplitude	0.35 ± 0.016	0.35 ± 0.0052
Gaussian mean	1.103 ± 0.007	1.11 ± 0.002
σ	0.191 ± 0.005	0.192 ± 0.0017
Poisson amplitude	0.722 ± 0.009	0.680 ± 0.003
λ	0.093 ± 0.0035	0.098 ± 0.0012
X^2	5.76	15.9

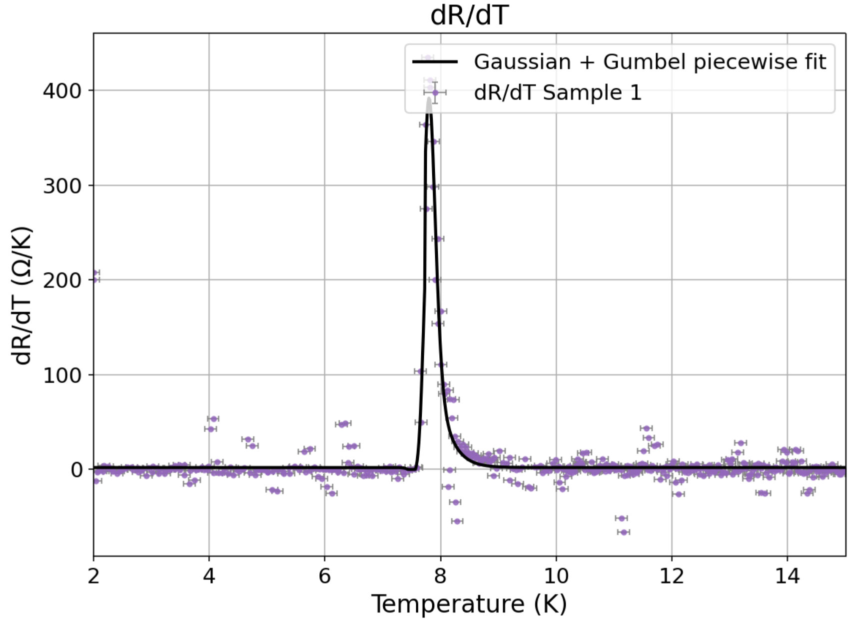


- Clusterization algorithm removes ~4% of the data
- Current wafers: Test grade wafers: 1-2 nm roughness, low resistivity, CZ growth, SSP, P or N type doping
- Topsil wafers: Research grade, 0.2 nm roughness, High resistivity 1500 Ohm-cm, SSP, P type boron doping

•Sample Characterization

Electrical Characterization – R(T)





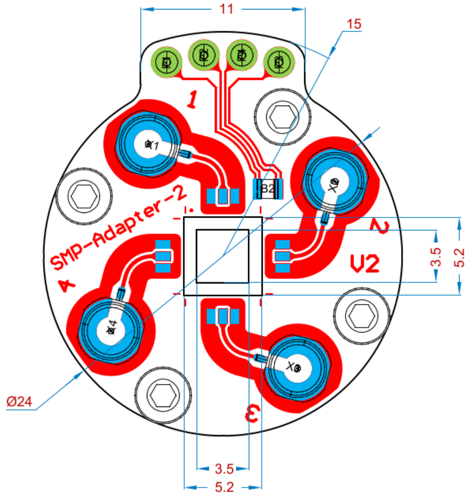
- dR/dT fit done with an asymmetric **Gauss + Gumbel distribution**.
- Gumbel used to describe the **high temperature tail**.

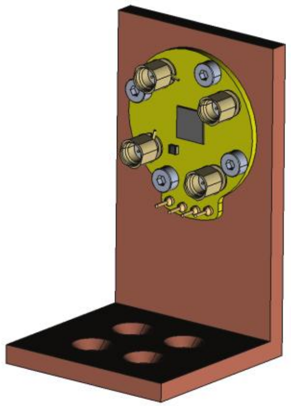
- Mathematically, a Gumbel distribution models the **distribution of maxima events in a series of distributions**.
- Physically, the influence of local non uniformities lead to **out of order local superconducting breakdown**, which the Gumbel distribution captures correctly.

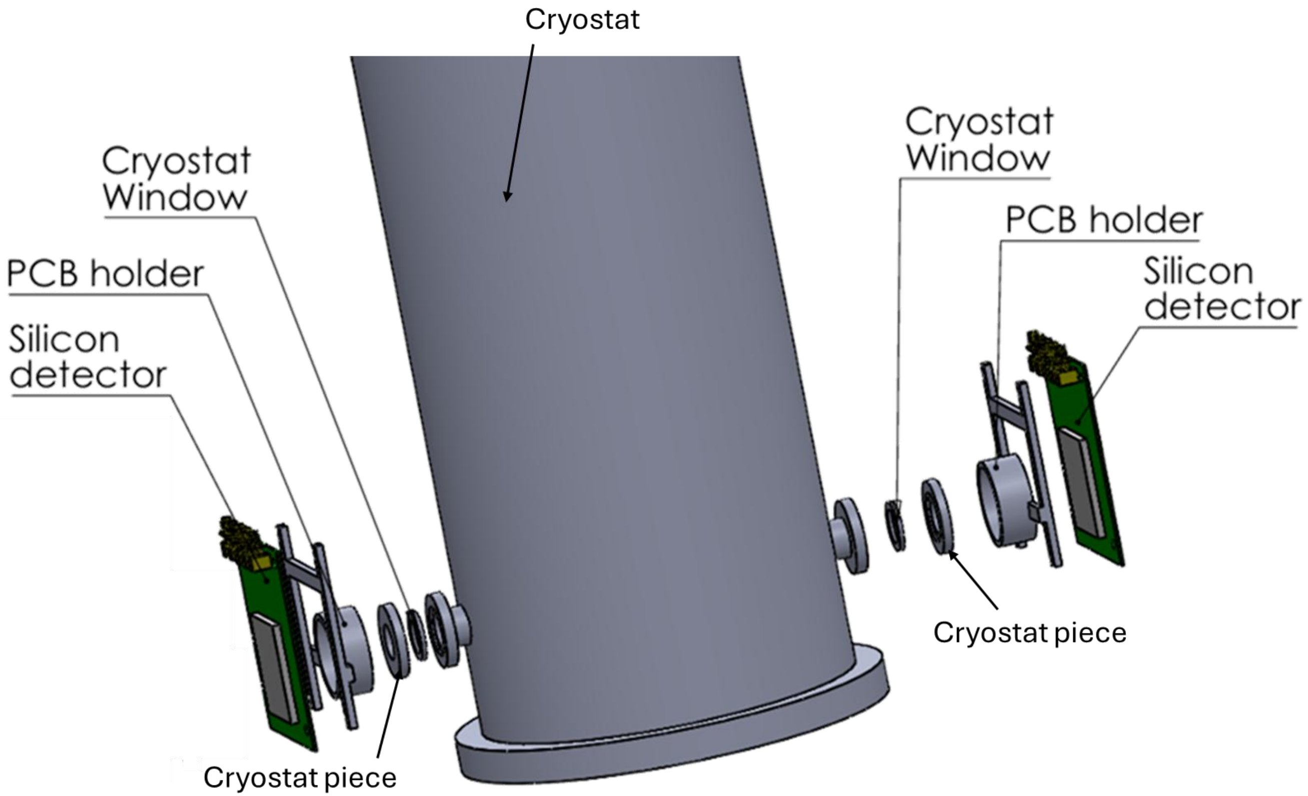
The values we need for afterwards are the Critical temperature and FWHM:

Sample number	T_c	ΔT
1	7.73 K	0.23 K
2	7.81 K	0.3 K

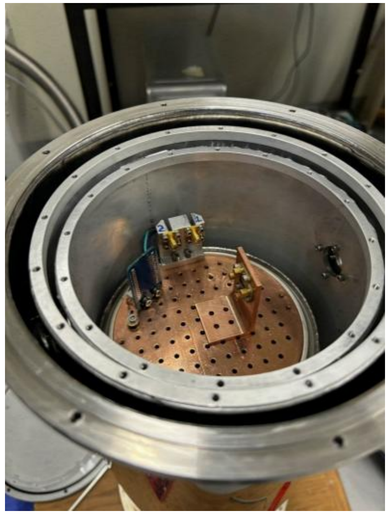
•β-particle measurements



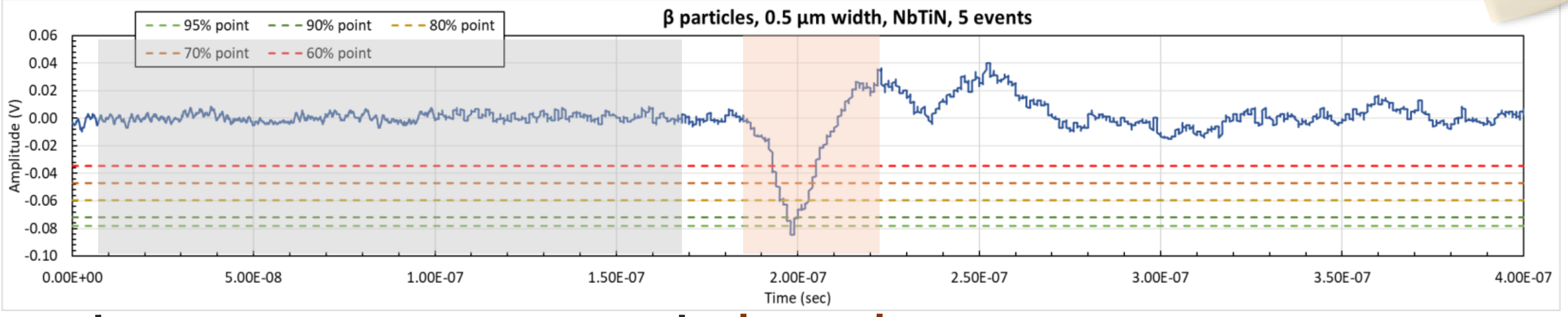




- AlN PCB with high thermal conductivity but low X_0
- Coper Sample holder with 0.5 x 0.5 cm opening behind the sample for beam passthrough and ,multiple scattering mitigation
- Aluminized Millar windows at both sides of the cryostat and intermediate barriers with a total thickens of 2 x 40 um Al.
- Open cycle cryostat with no active temperature control
- 2 GHz oscilloscope at 5 Gs/s with 28 Mbq (± 15%) ^{90}Sr beta source
- 3 GHz MiniCircuits voltage amplifiers in a 2-stage configuration



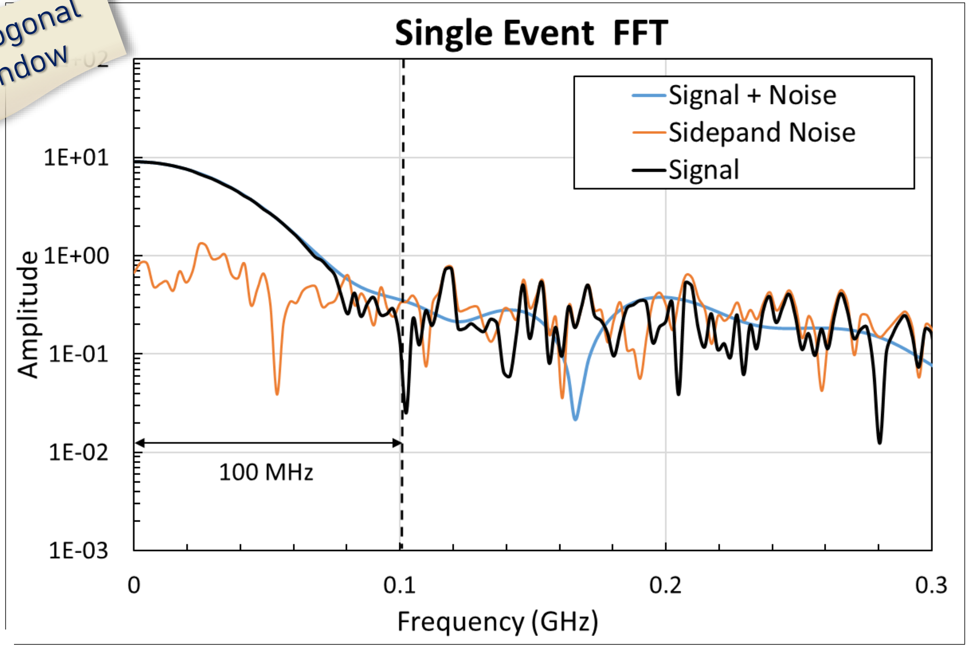
• β-particle measurements

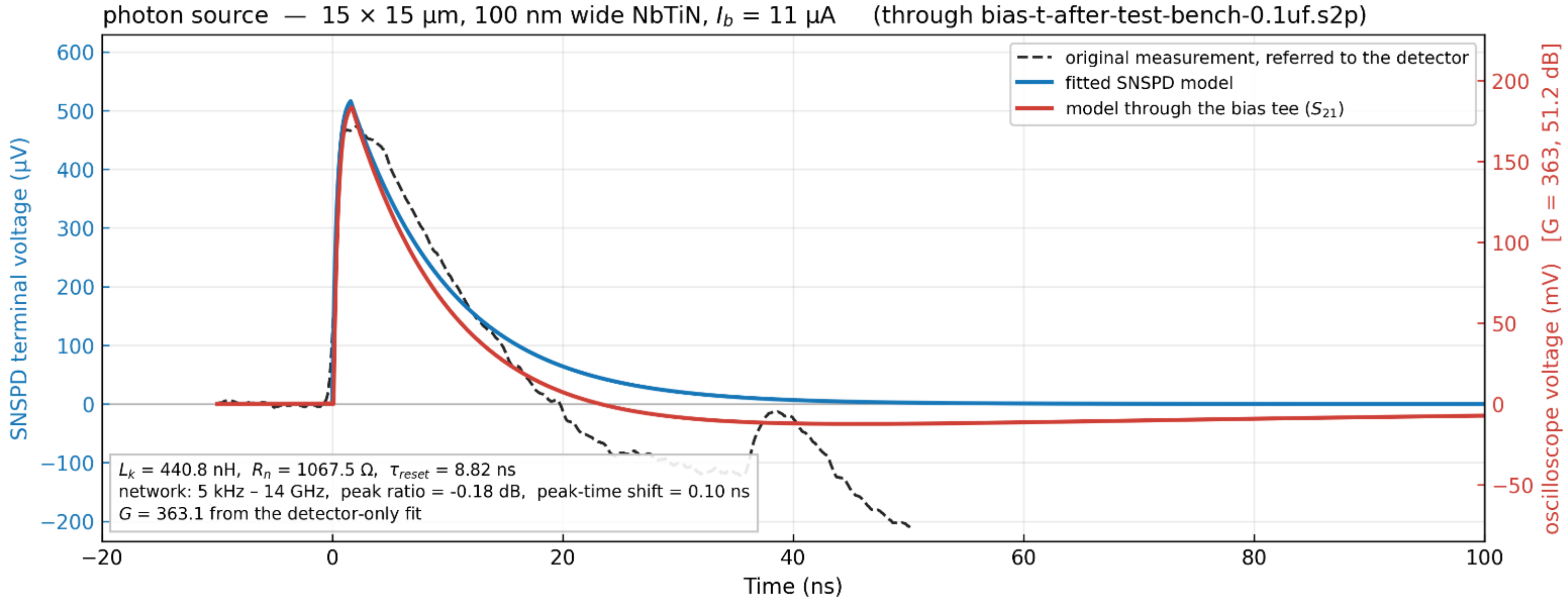


Sideband noise window

Signal window

Orthogonal window





$$A_{sig}(f) = \sqrt{\max\left(A_{meas}(f)^2 - A_{noise}(f)^2, 0\right)}$$

Signal Caractéristiques	
Min Voltage	- 40 mV
Max Voltage	084.3 mV
Baseline	3.6 mV
RMS noise	3.9 mV
Rise Time	9.7 nsec
Signal Duration	36 nsec
Integrated Charge (22.4^2 gain @ 100 MHz)	2.88×10^{-11} Q

50 Ω Chain

• Cryogenic Electronics

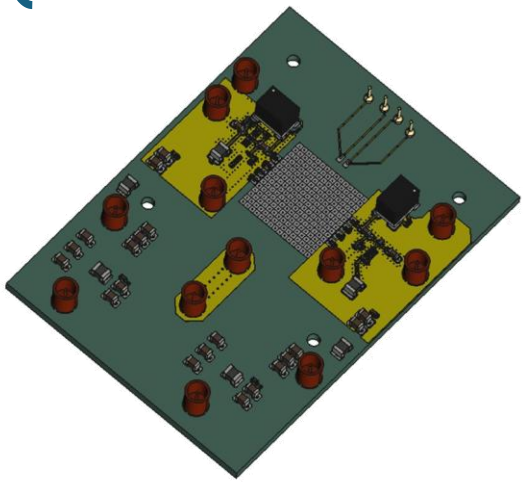
Target

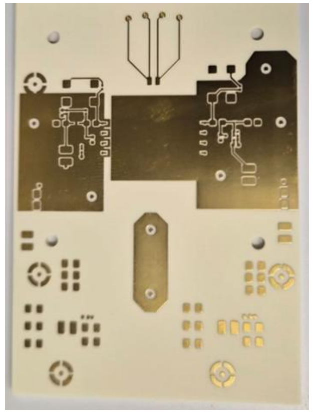
- 2-stage voltage amplifier with 2.2 - 20 K operation
- Integrated bias Tee (SNSPD current biasing)
- AlN substrate PCB with SMP connectors
- 16 readout channels
- < 100 mV heat dissipation total (~ 8.2 mV / channel)

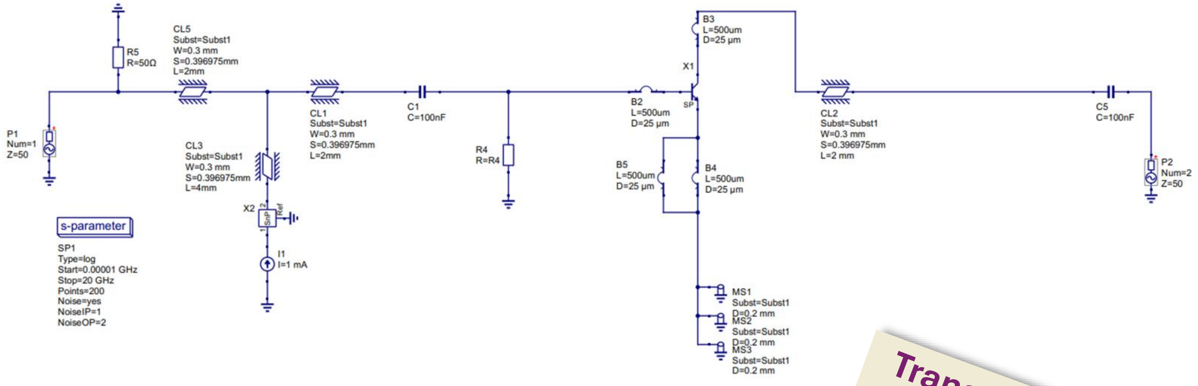
High Electron Mobility Transistors (HEMPs)

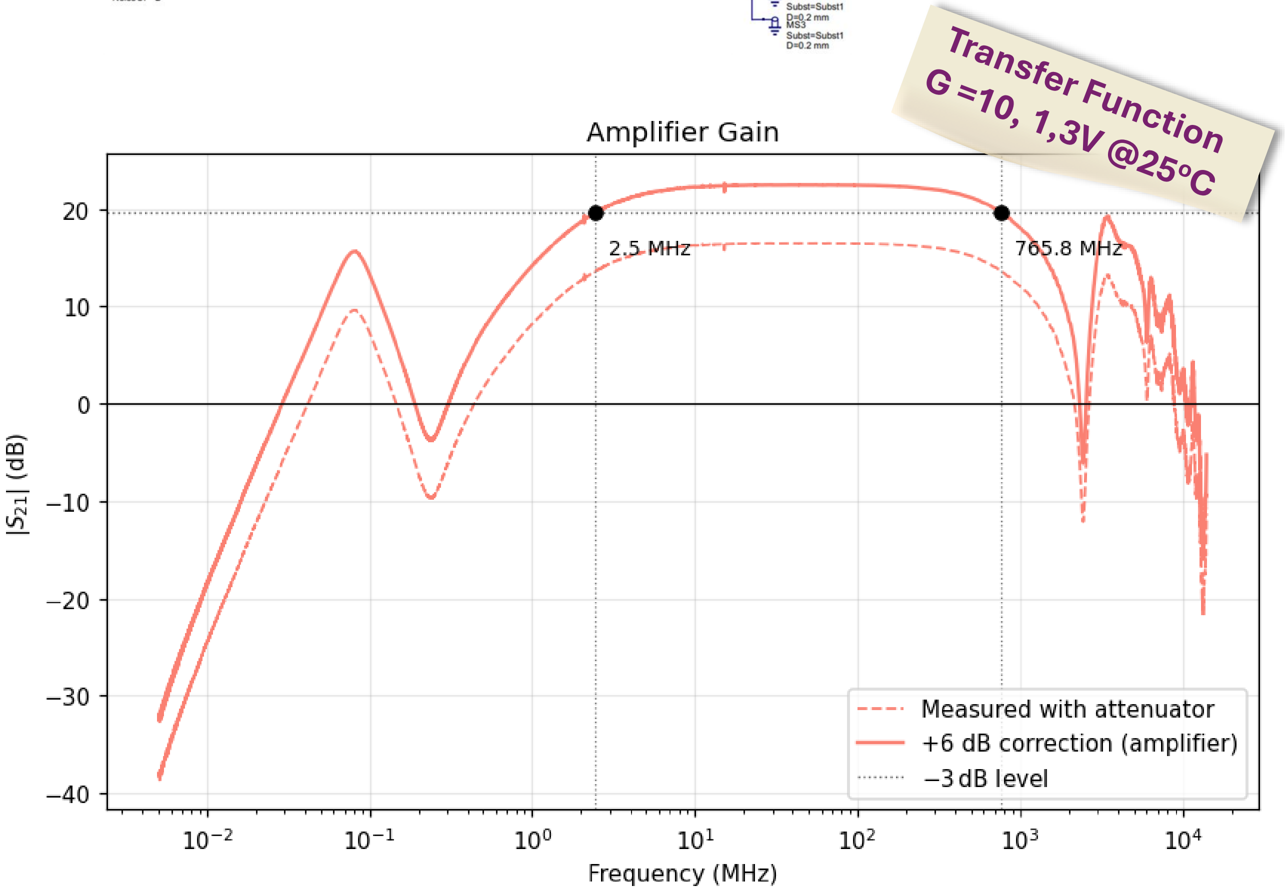
1. **Diramics pH-100:**
   - Indium Phosphate, 100 nm gate width
   - > 0.1dB Noise @ 10 K
   - 40 GHz bandwidth

2. **Infineon SiGe BFR840:**
   - Standard elektronisch CompuNet
   - RF NPN Transistor up to 76GHz
   - CMOS Syn-crystallization









•Conclusions & Outlook

- First Test of NbTiN and Nb N samplers in test beam proved operating principal
- Efficiency understood with GEANT4 simulations with custom model developed for low energy depositions, below atomic level states
- First in-house production run designed and currently at patterning stage, films show excellent performance
- Synopsys simulations on-going for process optimization
- Electronics design based on High Electron Mobility Transistors and SiGe on Rogers 4K substrate
- Time Dependent Ginzburg Landau Simulations for optimization of effective detection threshold