VERTEX 2025 : 33rd International Workshop on Vertex Detectors

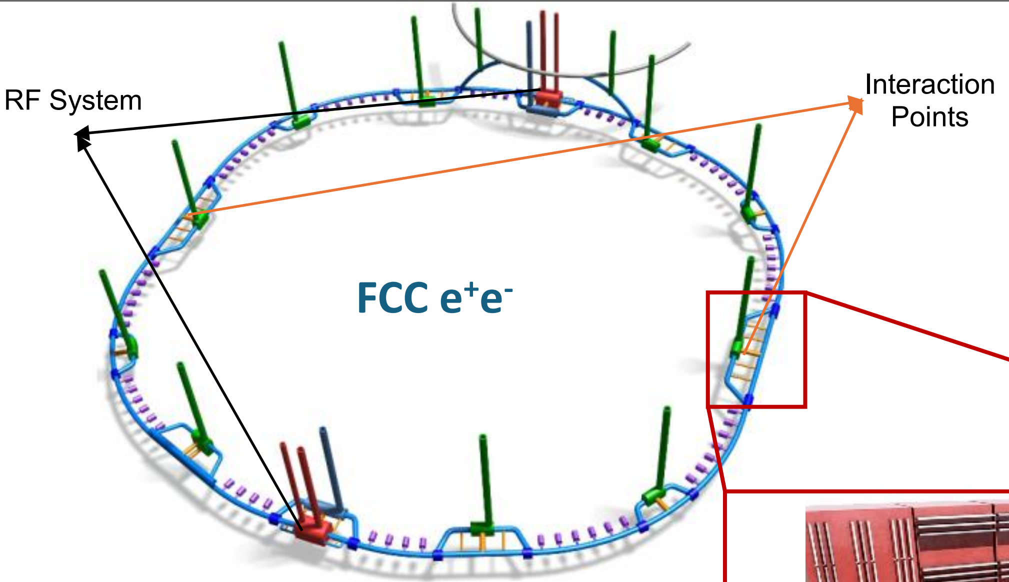
Knoxville, 28th August 2025

Tracking & timing performance of SNSPDs under 160 GeV SPS pion beams

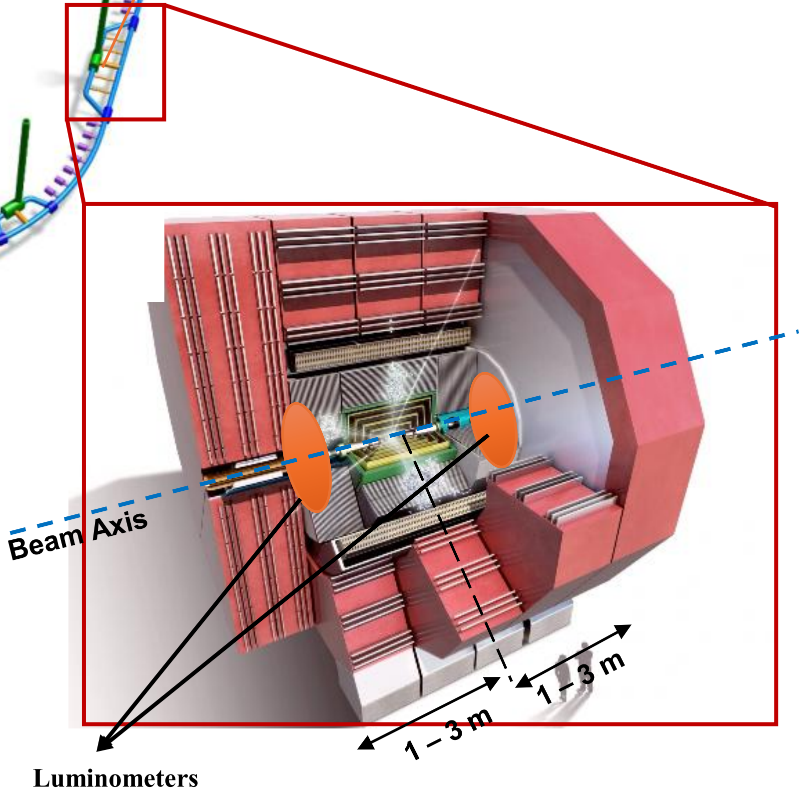
Evangelos – Leonidas Gkougkousis[1], Ilya Charaev[1], Anna Macchiolo[1], Alexandre Hennessy[1], Ben Kilminster[1]

1: University of Zurich

•Introduction and Scope



- ~100 km double ring collider
- 2 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

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

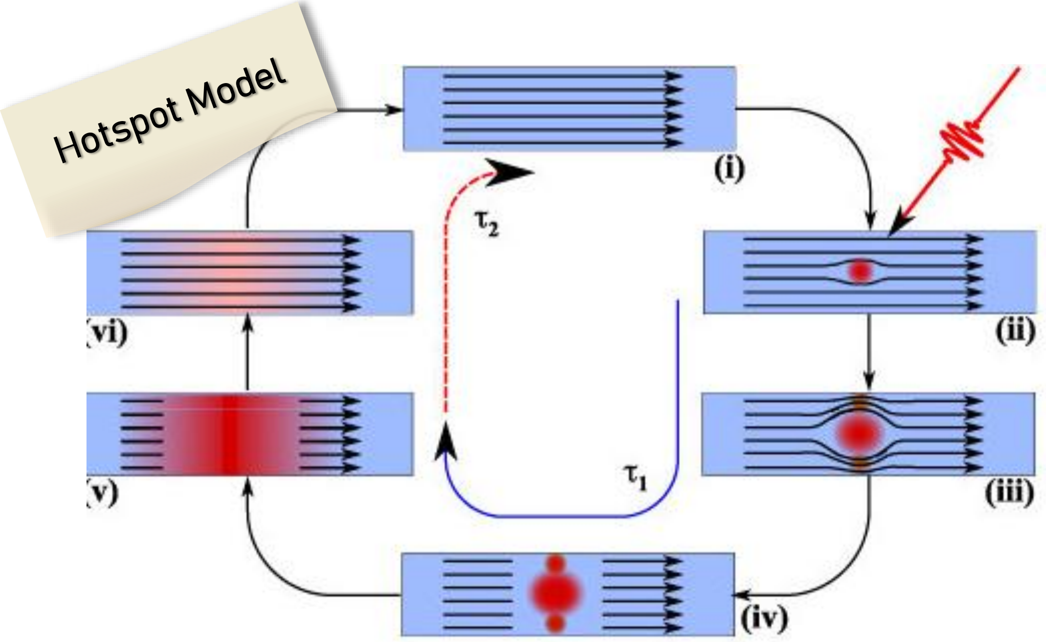
- ✓ Goal of 10^{-4} precision on absolute luminosity
- ✓ Readout at Bunch-crossing rates with < 20ns shaping time
- ✓ 1.5 MGray dose at Z pole
- ✓ Pile-up ~ 1E-3 / event
- ✓ σ(Z) ~ 40nb, σ(Bhabha)~14 nb

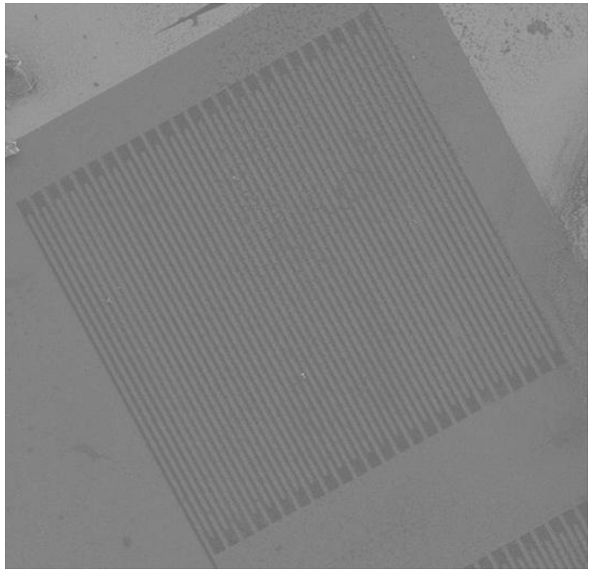
Current project:

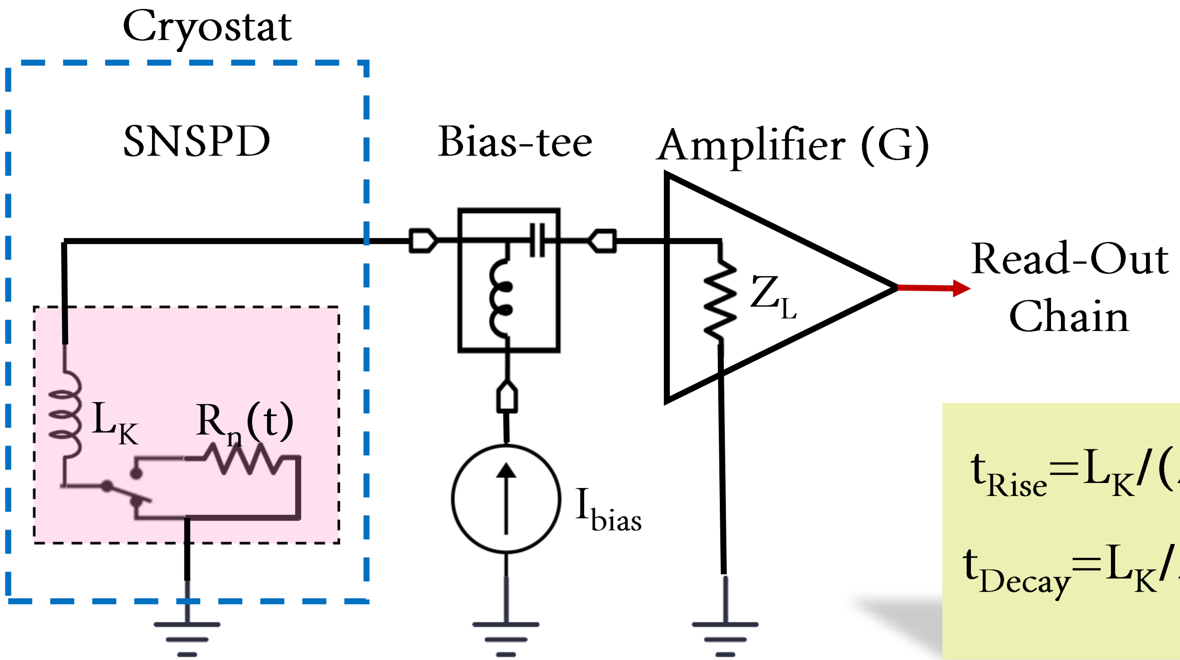
- ***Test pilot of MgB_2, MoSi, $La_{2-x}Sr_xCuO_2$, NbTiN as possible materials***
- ***Differentiate between poly- / mono crystalline and amorphous material response***
- ***Test different widths of nano-wire to characterise high-rate capability and recovery time***

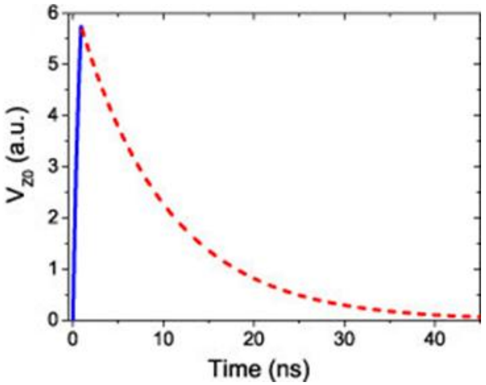
•Superconductive Nanowire SPD

- 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

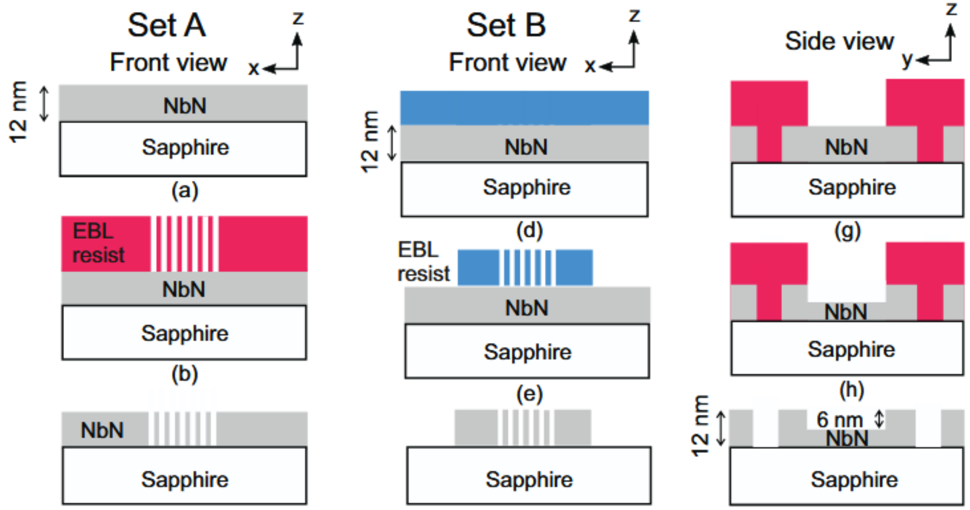
•Superconductive Nanowire SPD

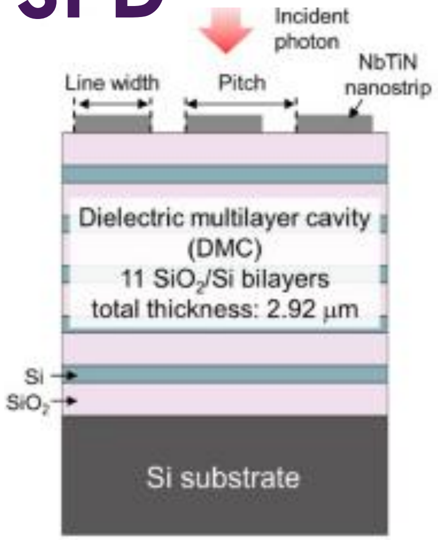
Film Growth

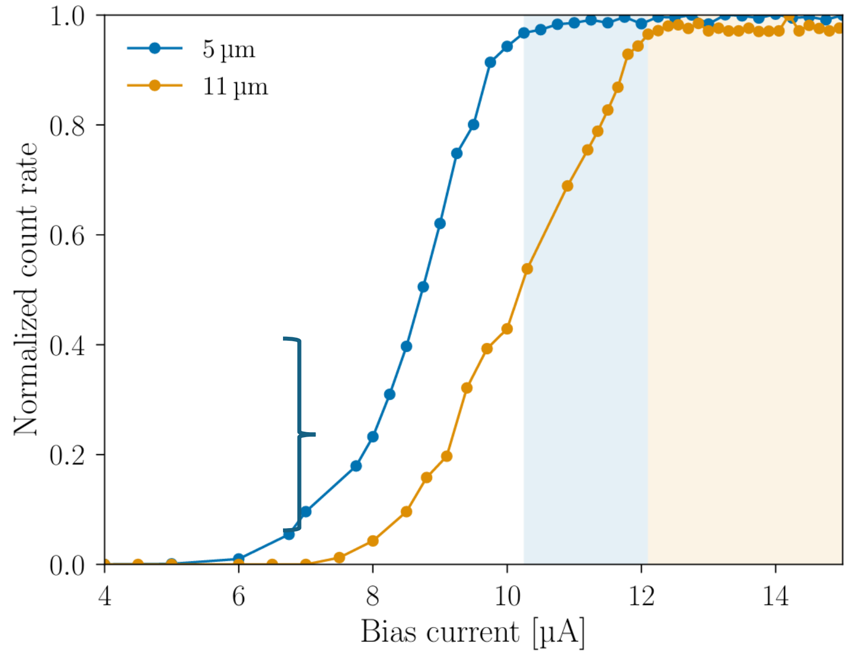
- Deposition with sputtering tools
- Growth by chemical vapor deposition
- Atomic layer deposition
- Molecular beam epitaxy
- Laser ablation (NbN)

Patterning

- EBL-Electron beam lithography
- PL-Photolithography
- CE-Chemical etching
- IBE-Ion beam etching
- FIB-Focused ion beam







(poly-) ccrystalline

$YBa_2Cu_3O_{7-\delta}$

Materials	NbN	NbTiN	WSi	TaN	MoGe	MoSi	NbSi	MgB_2	YBCO
Bulk T_c (K)	16	17	5	5	7.4	7.5	3.1	39	93
T_c (K) Thickness (nm)	8.6 (3nm)	9.6 (4.5nm)	3.7 (4.5nm)	8.3 (5nm)	4.4 (7.5nm)	4.2 (4nm)	2 (10nm)	39 (350nm)	85.5 (3unit cell)
Band gap $2\Delta o$ (meV)	4.9	5.17	1.52	1.52	2.2	2.28	0.94	11.86	28.29
Jc (MA/cm^2) Meas. Temp. (K)	2-4 (4.2K)	8 (2.9 K)	0.8 (250 mK)	4 (4.2 K)	1.2 (250mK)	1.1–2.5 (1.7 K)	0.14 (300mK)	1.1 (3 K)	14.4 (78 K)

•Electrical Characterization

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

Voltage Variation

Bias Current

Material Resistance

Temp. dependent resistance change

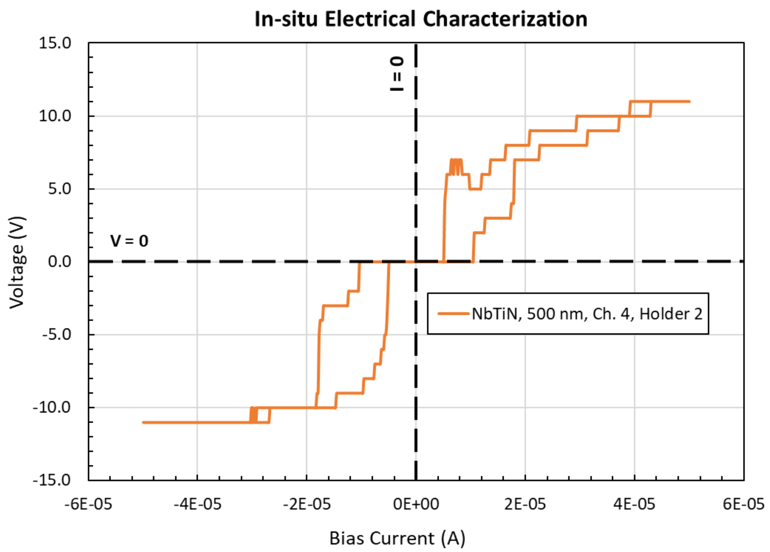
Temperature variation

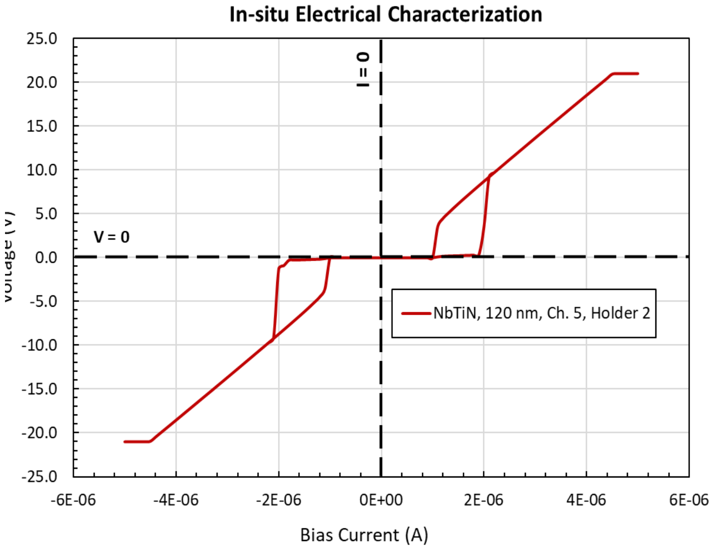
Positive sweep: Slow I_{bias} ramp-up until sharp voltage jump (I_c)

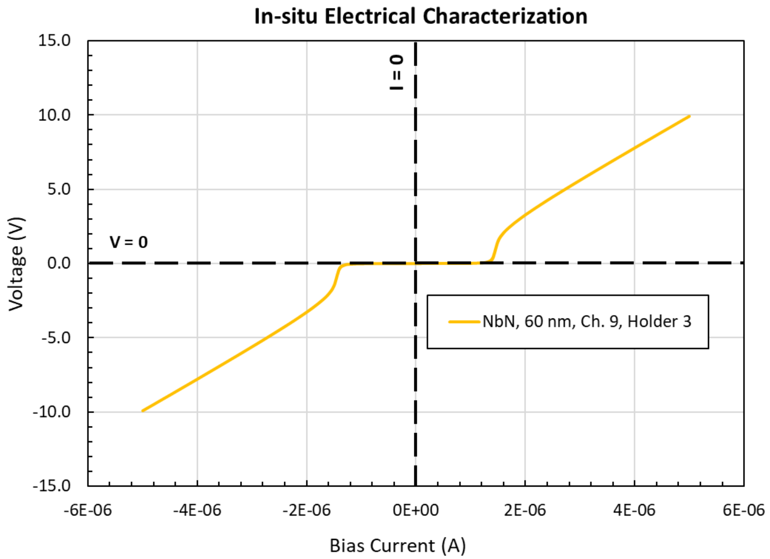
Retrace: Decrease I_{bias} until voltage drop to 0 (I_h)

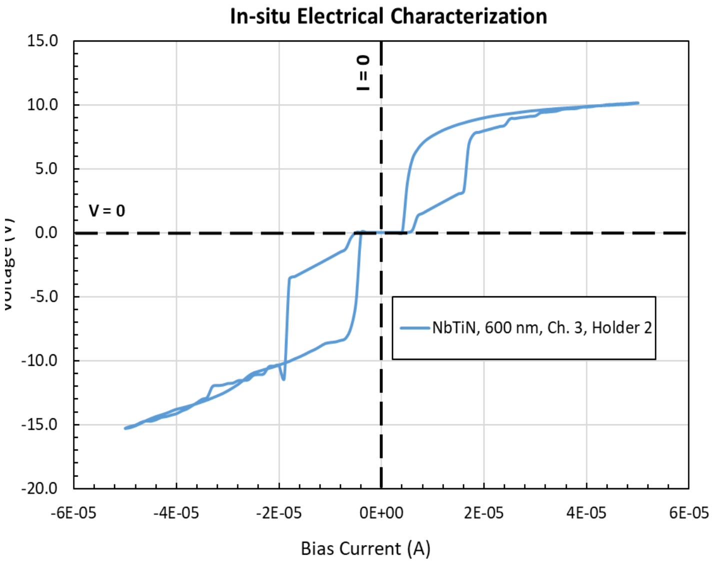
Negative sweep: Negative I_{bias} ramp to voltage transition ($-I_c$)

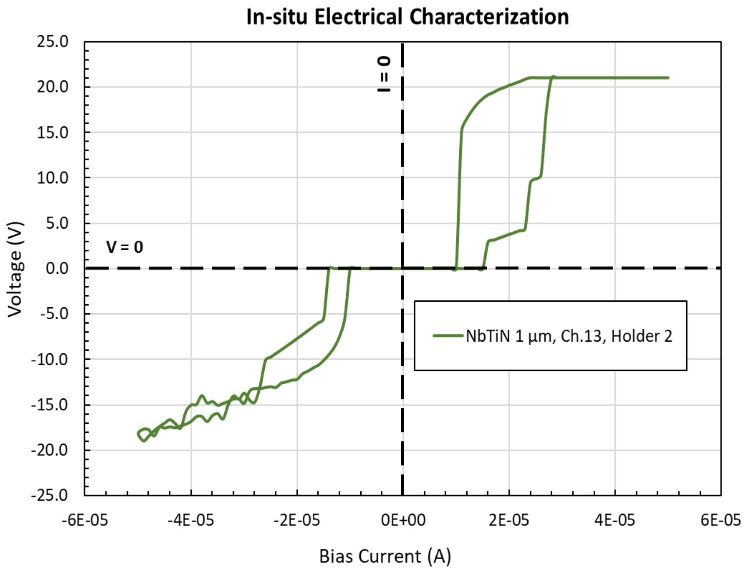
Retrace to 0: Decrease negative I_{bias} until voltage drop to 0 ($-I_h$)









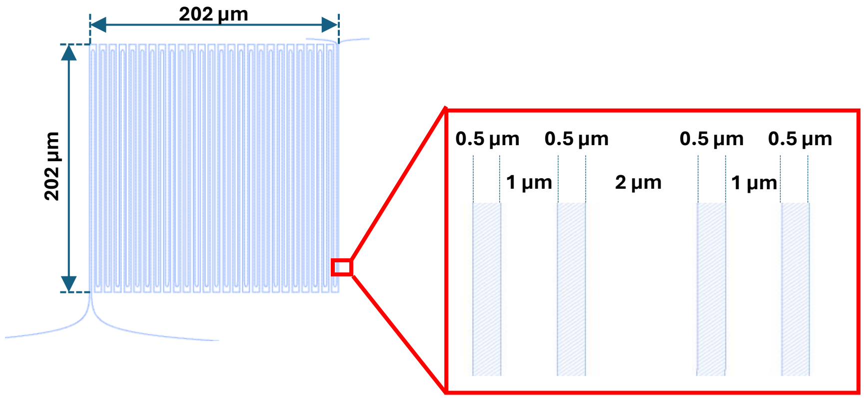


•Samples and Materials

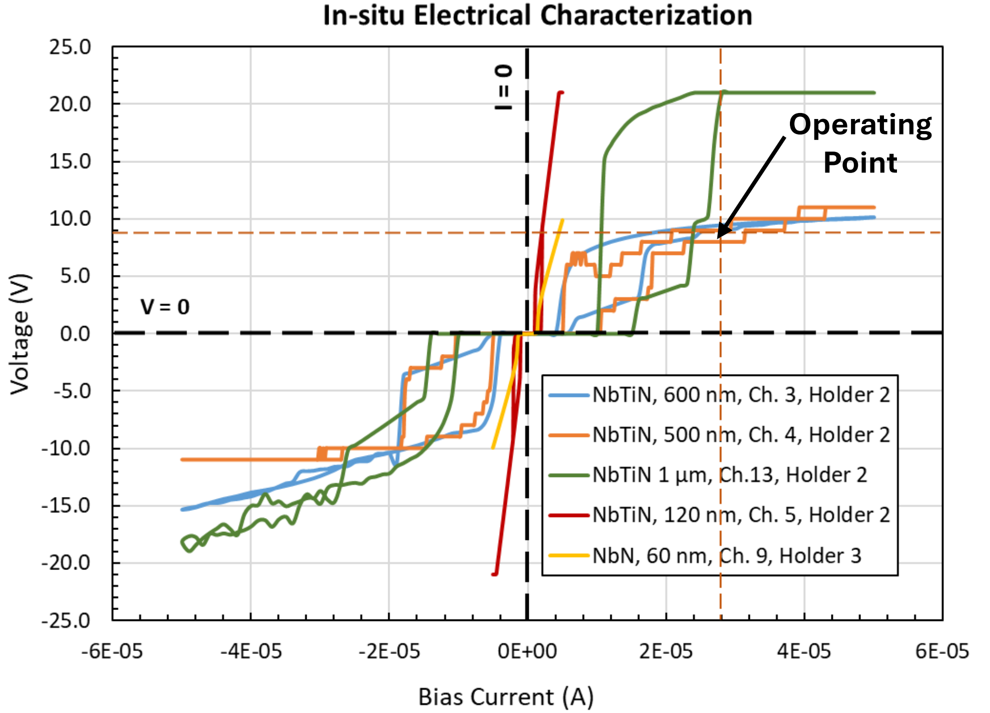
DUT Plane	Material	Wire Width	R (300 K)	Cryostat Channel	Super-conductive	Osc. Chan.	Particle Induced Signals
Holder no. 1 Last in beam direction	NbTiN	100 nm	123 kΩ	1	No	X	X
		100 nm	1.8 MΩ	2	No	X	X
		100 nm	590 kΩ	15	No	X	X
		100 nm	153 kΩ	16	No	X	X
Holder no. 2 Middle	NbTiN	600 nm	2.61 MΩ	3	Yes	Ch2, Osc1	No
		500 nm	1.58 MΩ	4	Yes	Ch3, Osc1	Yes
		120 nm	3.27 MΩ	5	Yes	Ch4, Osc1	No
		400 nm	1.01 MΩ	12	No	X	X
		1 µm	1.25 MΩ	13	Yes	Ch3, Osc2	No
		100 nm	1.9 MΩ	14	No	X	X
Holder no. 3 First in beam direction	NbN	110 nm	2.31 MΩ	6	No	X	X
		90 nm	770 kΩ	7	No	X	X
		120 nm	1.44 MΩ	8	No	X	X
		60 nm	1.71 MΩ	9	Yes	Ch2, Osc2	No
		80 nm	2.74 MΩ	10	No	X	X
		100 nm	2.8 MΩ	11	No	X	X

No temperature monitoring!!

- The 500 nm wire width NbTiN sample operated at 28 - 30 µA @ 9.3 V (5th metastable resistive state after I_c, phase slips, vortices, inhomogeneities)
- 600 nm wire width NbTiN sample operated at 14.0 µA @ 10 V (no particle induced signals, holder 2)



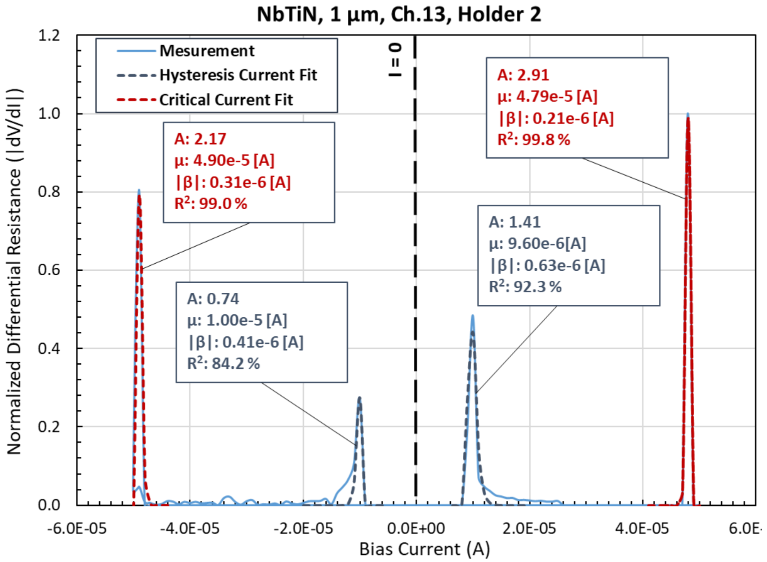
- Double loop geometry with 51 meandering branches
- 7 nm active layer thickness deposited on 400 µm Poly-Si substrate atop the native SiO_2 (2 nm)

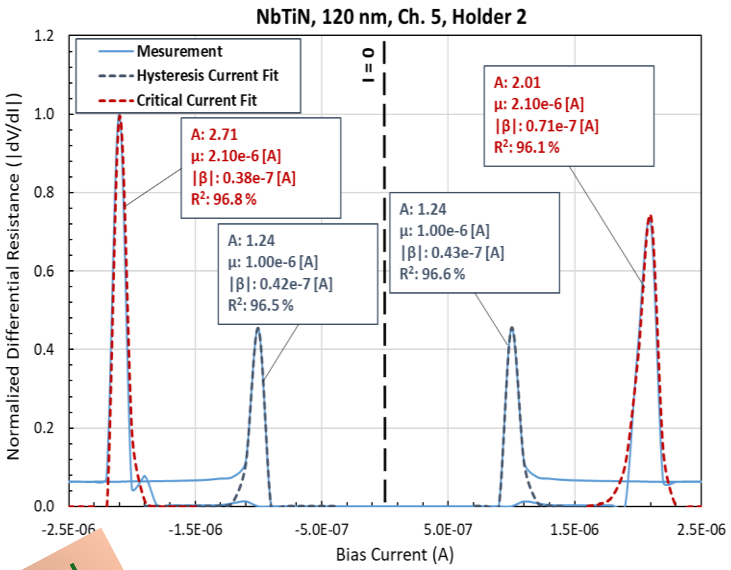


•Samples and Materials

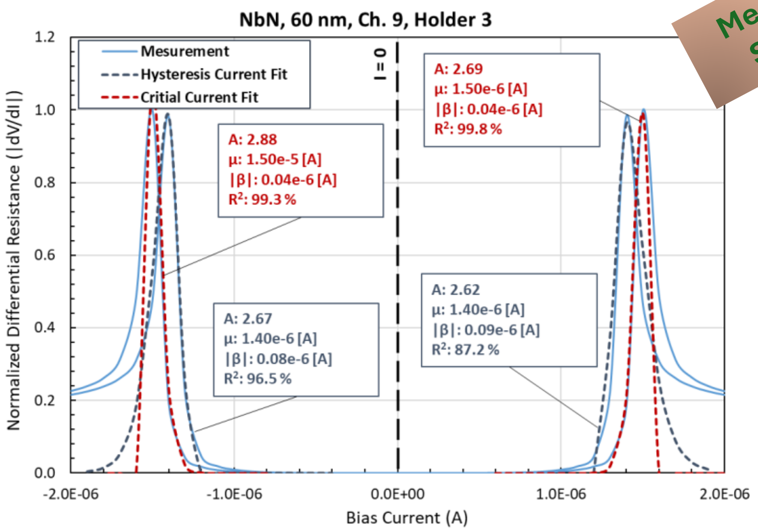
In-Situ characterization

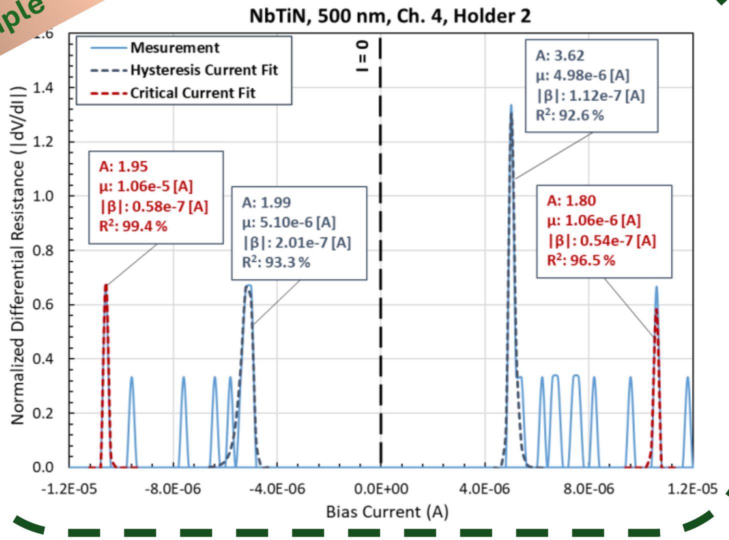
- Differential resistivity peaks at Critical / Hysteresis current
- Asymmetric distribution driven by stochastic effects and quantum phase slips
- Mirrored Gumbel PDFs, covariant matrix uncertainties

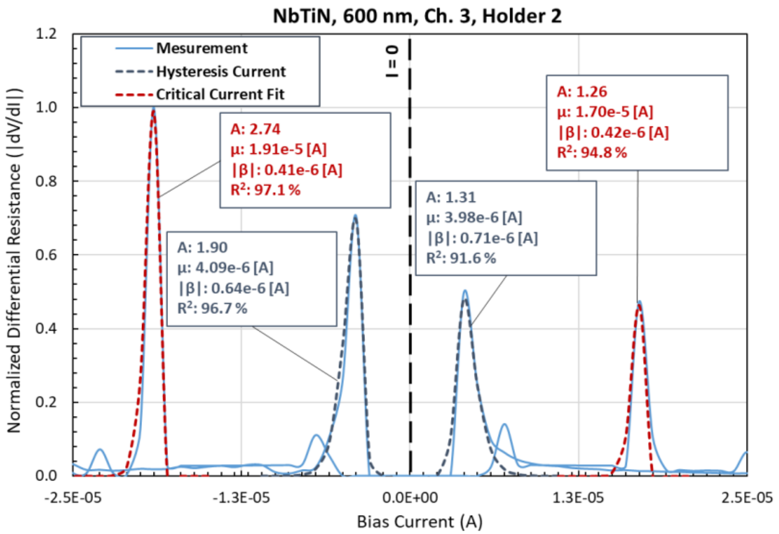




Measured Sample



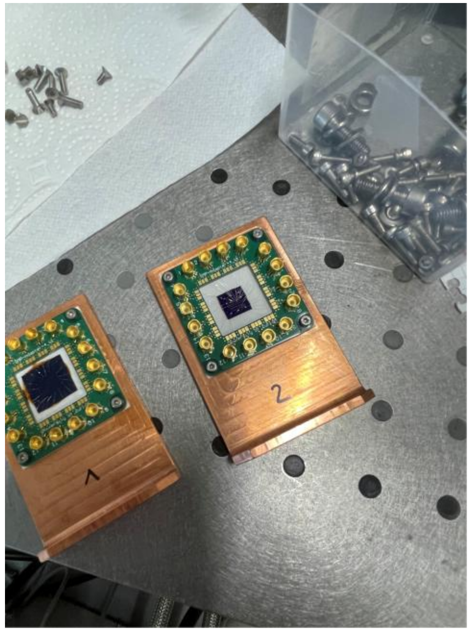


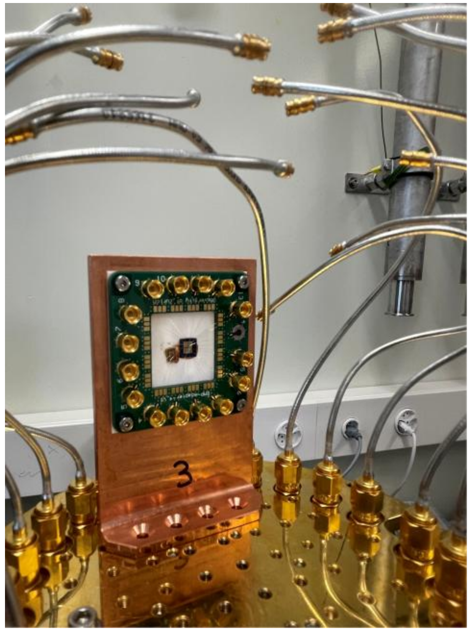


Sample	Critical Current [A]	Hysteresis Current [A]
600 nm, NbTiN	$(1.81 \pm 0.10) \times 10^{-5}$	$(4.04 \pm 0.49) \times 10^{-6}$
500 nm, NbTiN	$(1.06 \pm 0.01) \times 10^{-5}$	$(5.01 \pm 0.10) \times 10^{-6}$
120 nm, NbTiN	$(2.1 \pm 0.03) \times 10^{-6}$	$(1.00 \pm 0.03) \times 10^{-6}$
60 nm, NbN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

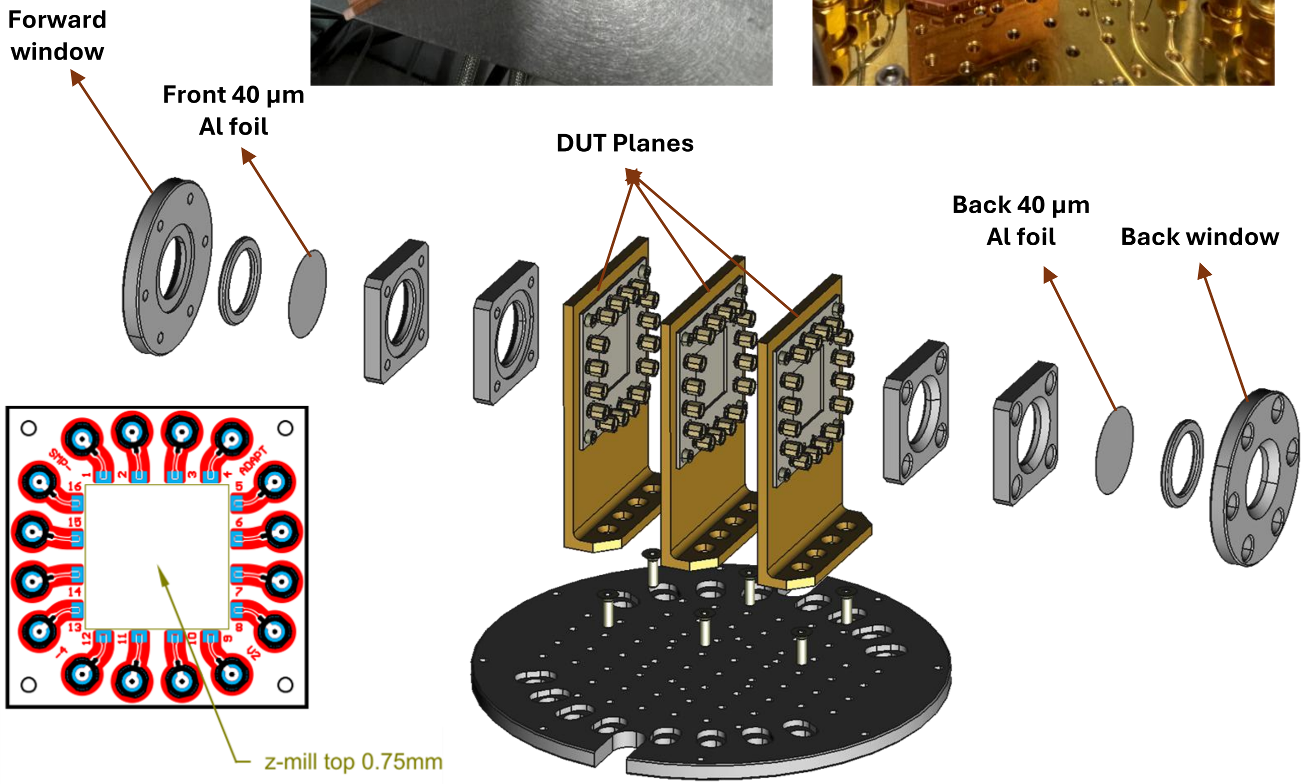
•DUT Holder & Assembly

Material	Density (kg/m^3)	Glass Transition (°C)	Melting Point (°C)	Electrical Conductivity $(\Omega \cdot m)^{-1}$	Volume Resistivity $(\Omega \cdot cm)$	Thermal conductivity W/(m·K)	Thermal expansion coefficient K^{-1}	Dielectric Strength (kV/mm)
Aluminum	2700	N / A	660.3	$\sim 3.5 \times 10^{7}$	7.2×10^{-5}	151–202	$16–18 \times 10^{-6}$	N / A
Stainless Steel A2	8000	N / A	1400 – 1450	$\sim 1.4 \times 10^{6}$	3.99×10^{-8}	14–17	23.6×10^{-6}	N / A
Nitril	1200	-29	250 - 300	$\sim 1 \times 10^{-8}$	$> 10^{15}$	0.25	170×10^{-6}	20 -30
AlN	3255	N / A	2200	$\sim 10^{-12}$ - 10^{-11}	10^{14}	> 170	$\sim 4.5 \times 10^{-6}$	15
Al_2O_3	3950	N / A	2.072	$\sim 10^{-14}$ - 10^{-13}	10^{15}	25 - 35	$\sim 7.5–8.5 \times 10^{-6}$	13 - 30
Silicon	2329	N / A	1412	0.005	2×10^{4}	150	2.6×10^{-6}	500 - 800
Capton	1420	360 - 410	500 decomposition	$\sim 10^{-16}$ - 10^{-15}	10^{17}	0.12	20×10^{-6}	150 - 300

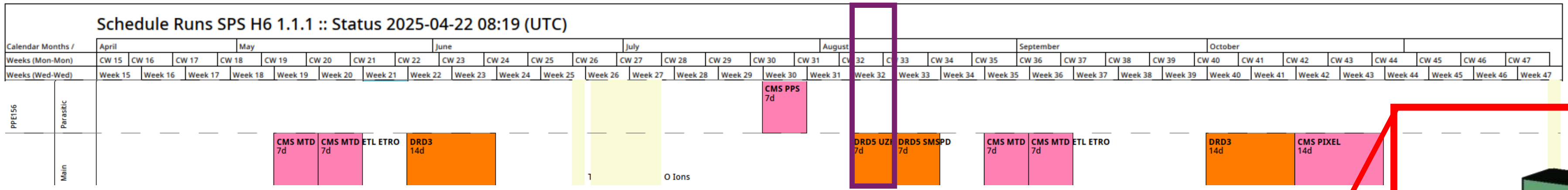




- FR4 PCB with 16 SMP high bandwidth connectors and a 2.0 x 2.0 central window
- Cu Sample holder with 2.0 x 2.0 cm center opening for beam passthrough and multiple scattering mitigation
- AlN sample support with 12 mm overlap with coper support on all sides and 750 um central thickness
- 40 um thick Al windows at entre/exit of the cryostat and no intermediate barriers for a total thickens of 2 x 40 um Al.

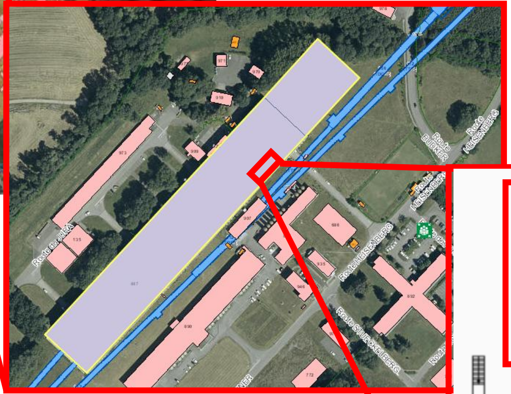


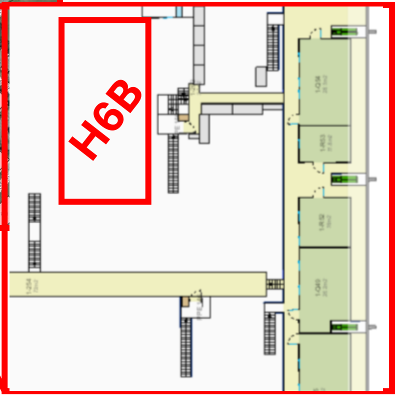
•General Information: H6B

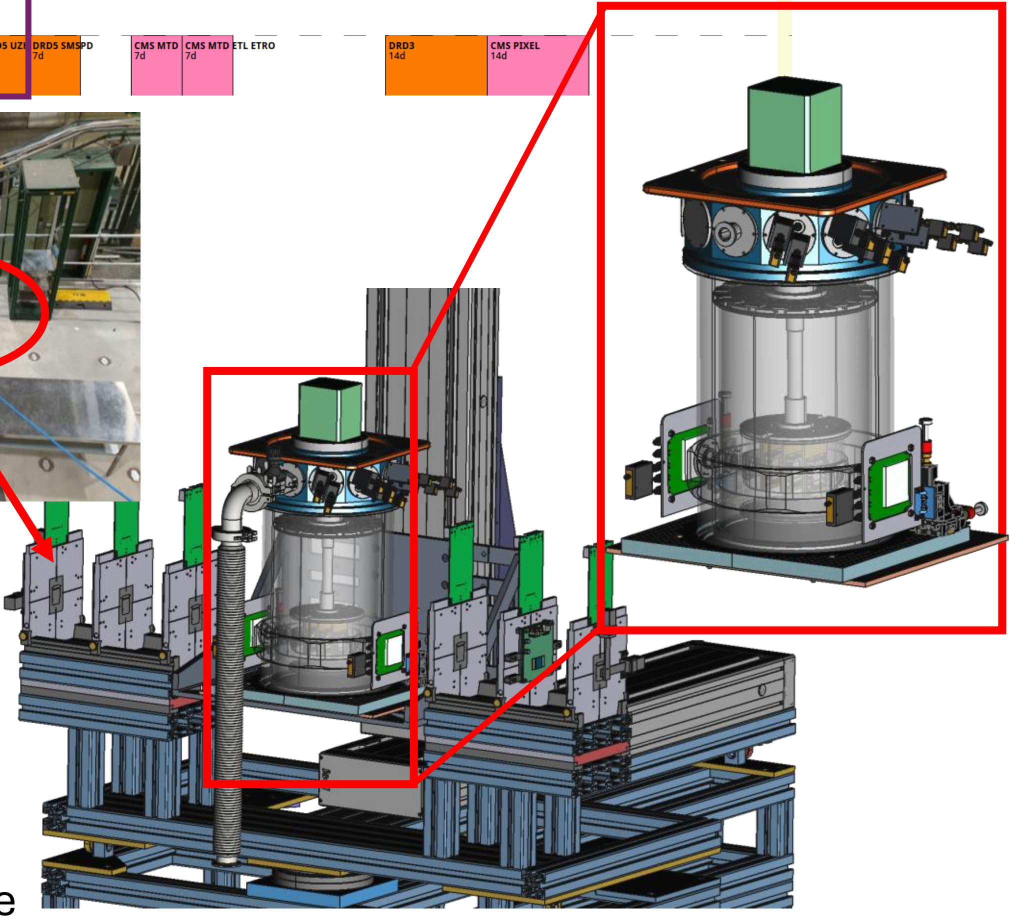


CERN Prévessin

Building 887







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

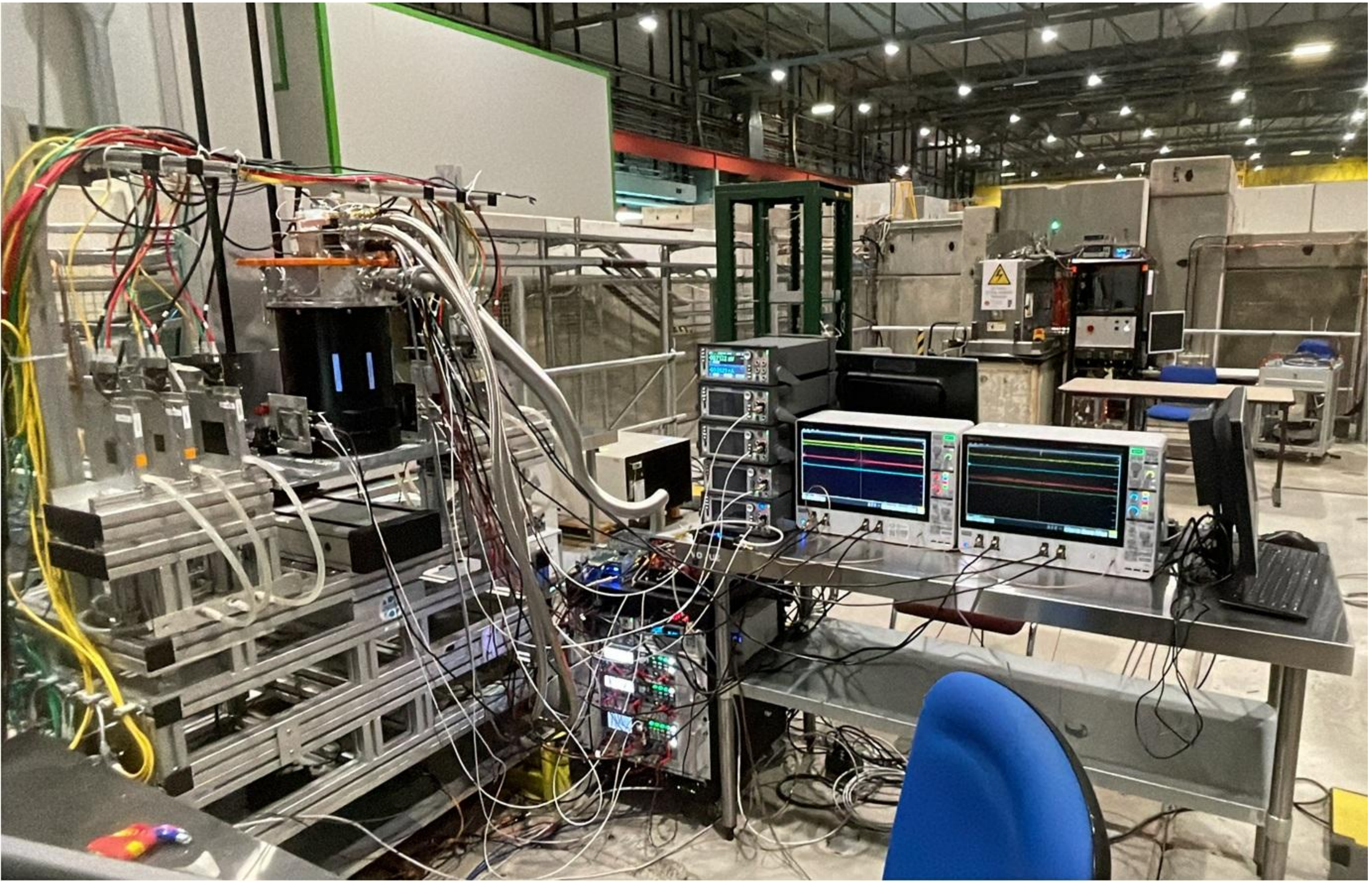
AIDA Telescope in H6B Current setup

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

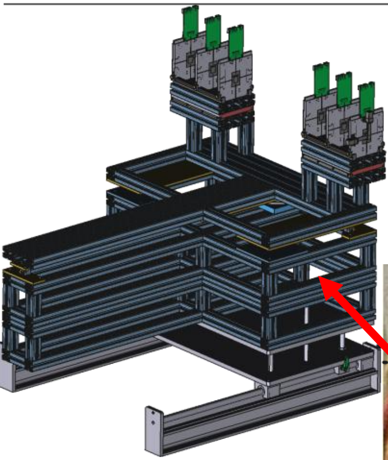
The Setup

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

•Setup @ SPS



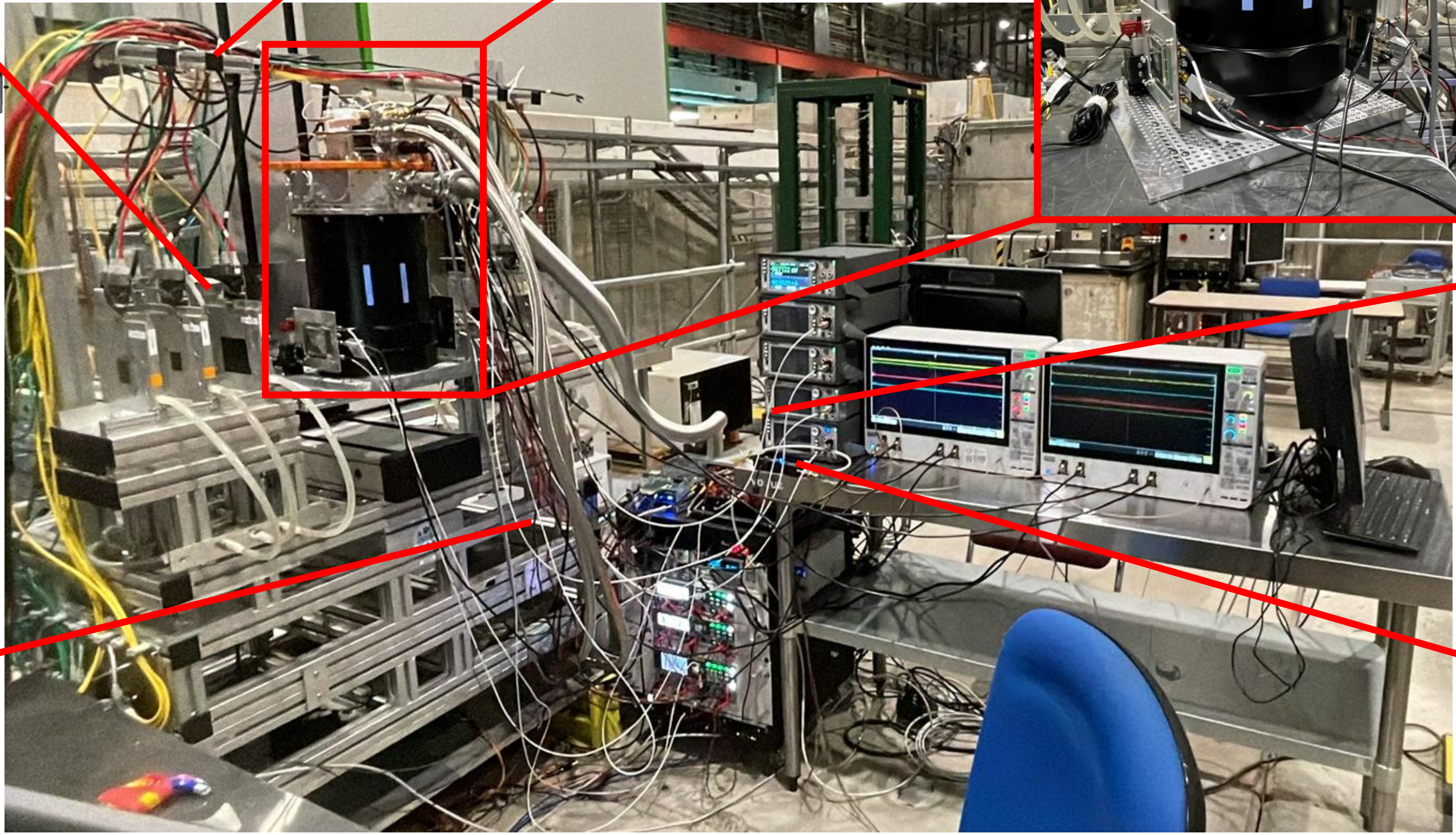
•Setup @ SPS

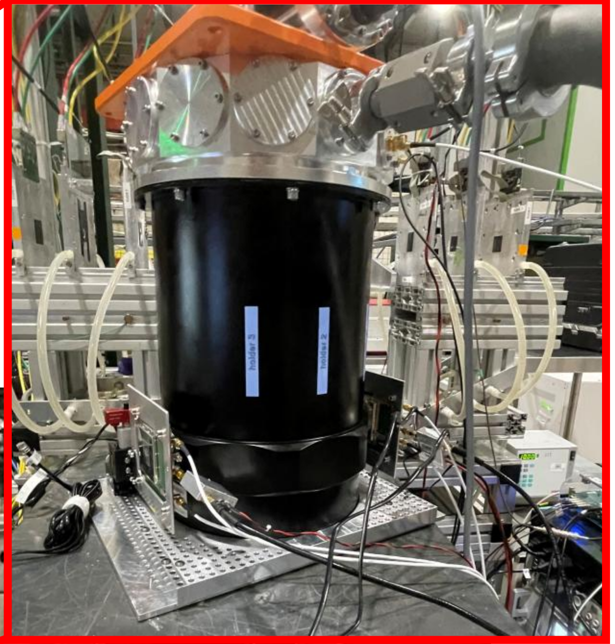


Modified telescope frame, 1.4 m back extension

3-phase, He_2 , water cooled Cryo-Compressor

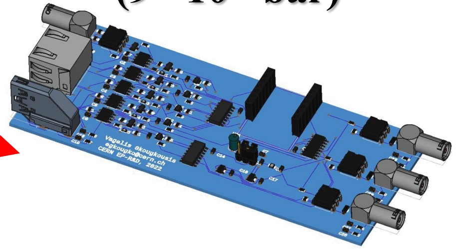
New 500 Kg Stage Installation (part of AIDA WP2 project)





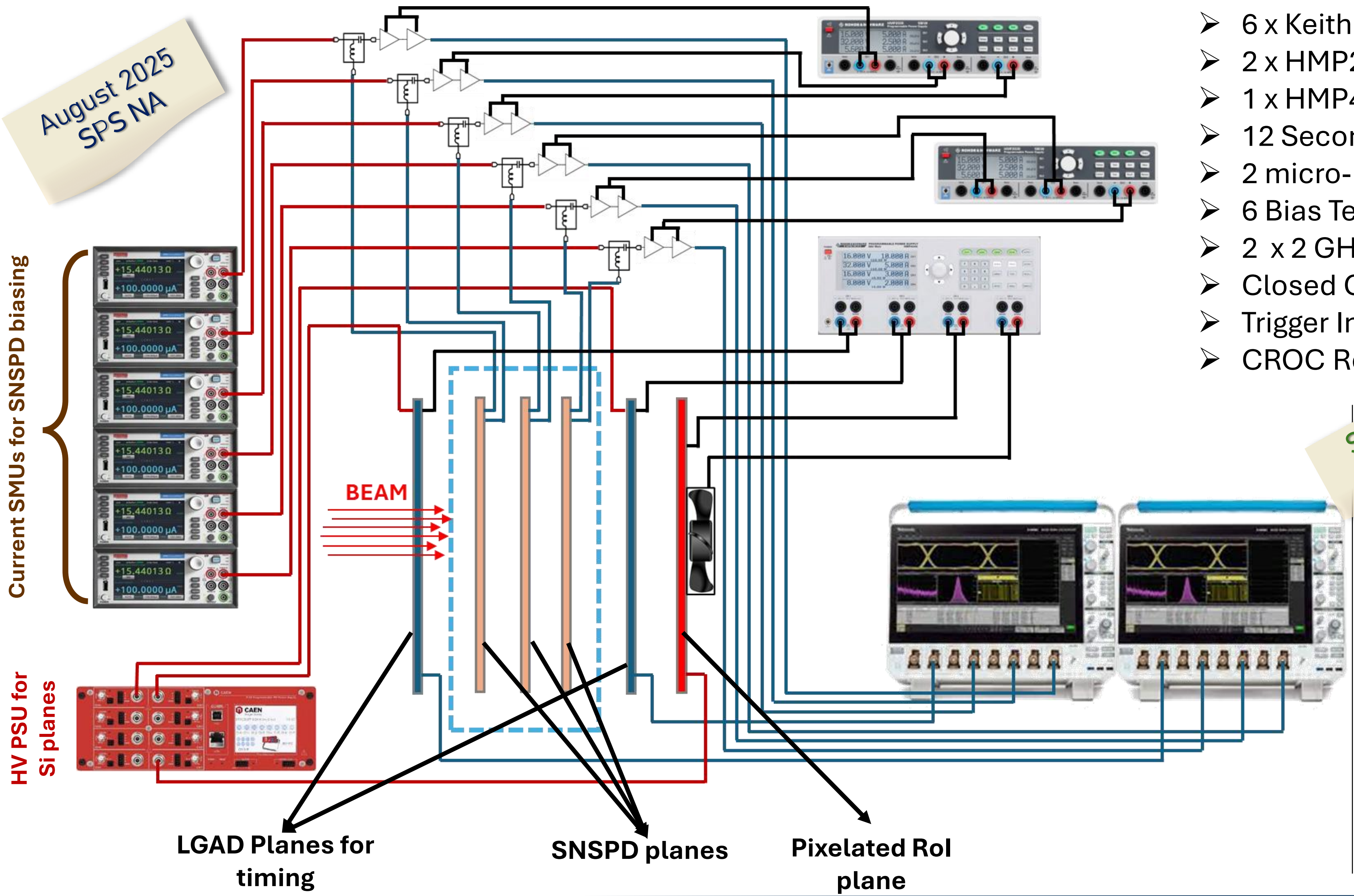
Instrumentation Rack

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



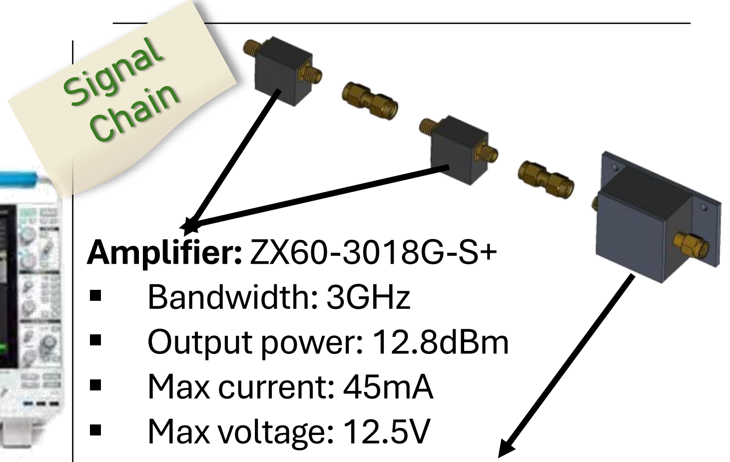
Dedicated Trigger & synchronization Board

•Instrumentation & Readout



Equipment

- 2 x 6 GHz Oscilloscopes (40 Gs/s)
- 6 x Keithley 2450 SMUs (10 pA resolution)
- 2 x HMP2030 LV PSUs
- 1 x HMP404 LV PSU
- 12 Second stage amplifiers (3 GHz)
- 2 micro-positioning stages
- 6 Bias Tees
- 2 x 2 GHz Bandwidth 2nd stage amplifiers
- Closed Cycle He CRYOSTAT
- Trigger Interface Board V2.0
- CROC RoI pixelated plane + FC7 Readout

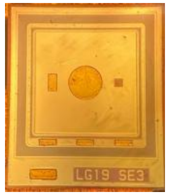


Amplifier: ZX60-3018G-S+
- Bandwidth: 3GHz
- Output power: 12.8dBm
- Max current: 45mA
- Max voltage: 12.5V

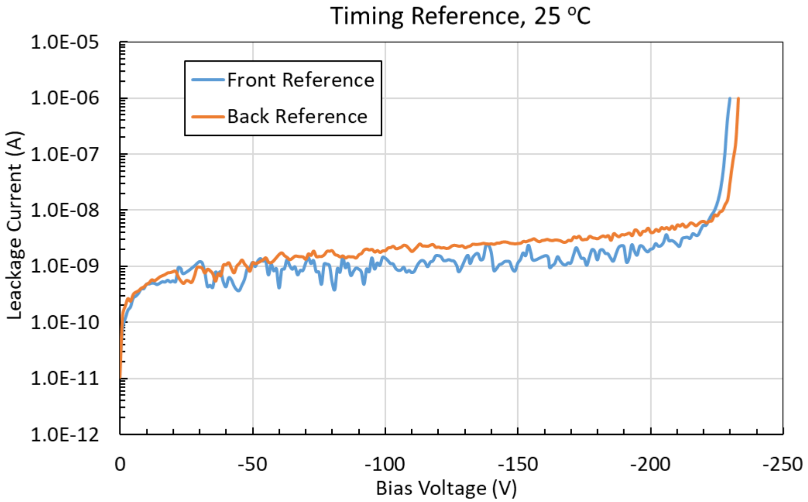
Bias Tee: ZX85-12G-S+
- Max voltage: 25V
- Max current: 400mA
- Insertion Losses: 0.6 dB
- Bandwidth: 0.2 MHz – 12 GHz

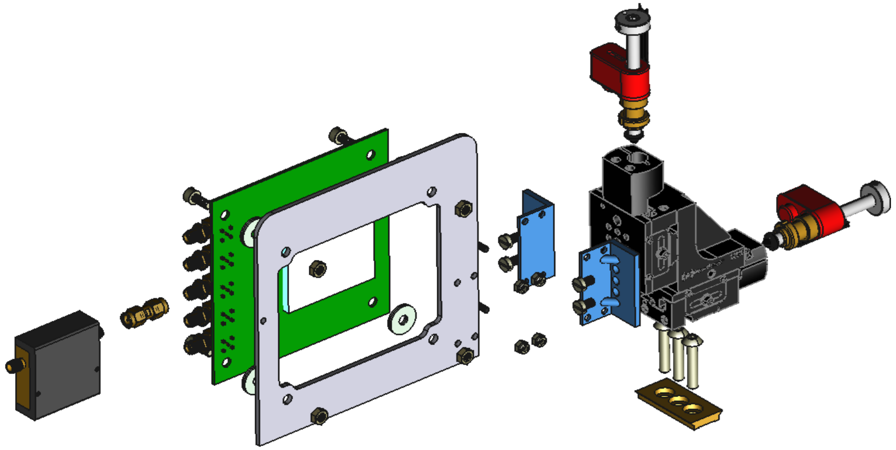
•Reference Timing Planes

Sensors



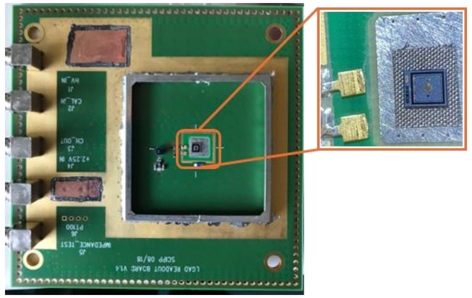
- 2 x 1 mm2, 50 um active thickness HPK LGADs (HPK-LGAD-L20-P3 front & HPK-LGAD-L20-P4 back)
- Breakdown ~ 230 V, depletion ~25 V
- Operated at fixed 150 V bias @ 25 C throughout the campaign
- One plane per oscilloscope for ps-level synchronization





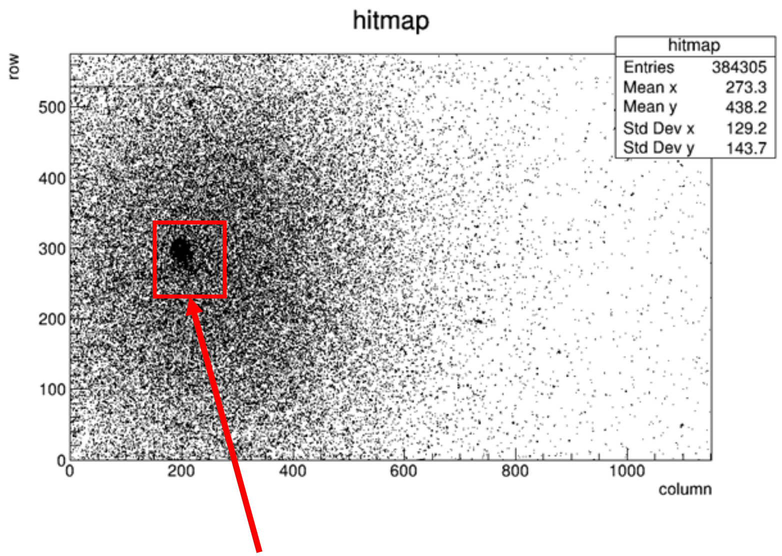
- 30 nm precision 2-axis (Y-Z) movement through piezo-electric stages
- Precision alignment within a 2 x 2 mm maximum range
- Geometric overlap between reference planes and DUTs for three object coincidence timing system

1st Stage Amplifier



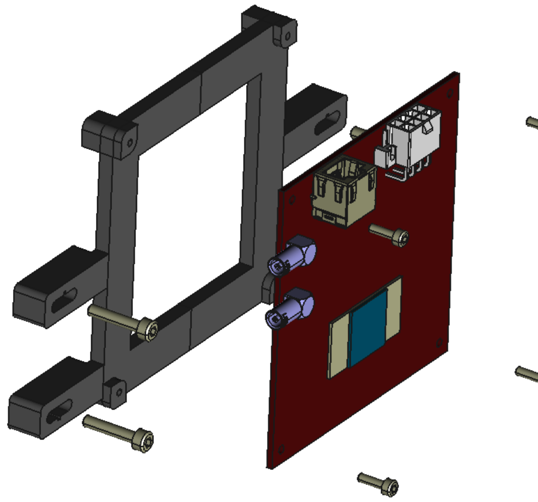
- High frequency SiGe (~12 GHz) common emitter first stage charge amplifier (470Ω trans-impedance)
- Fully enclosed faraday cage surrounding sensor
- RMS sensor + amplifier noise < 1.8 mV, gain of 10

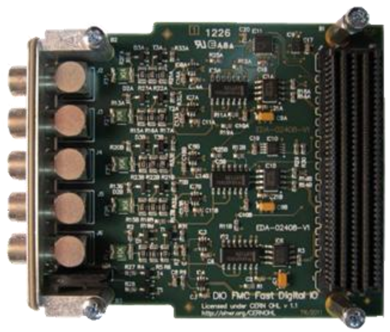
•Triggering Scheme & ROI



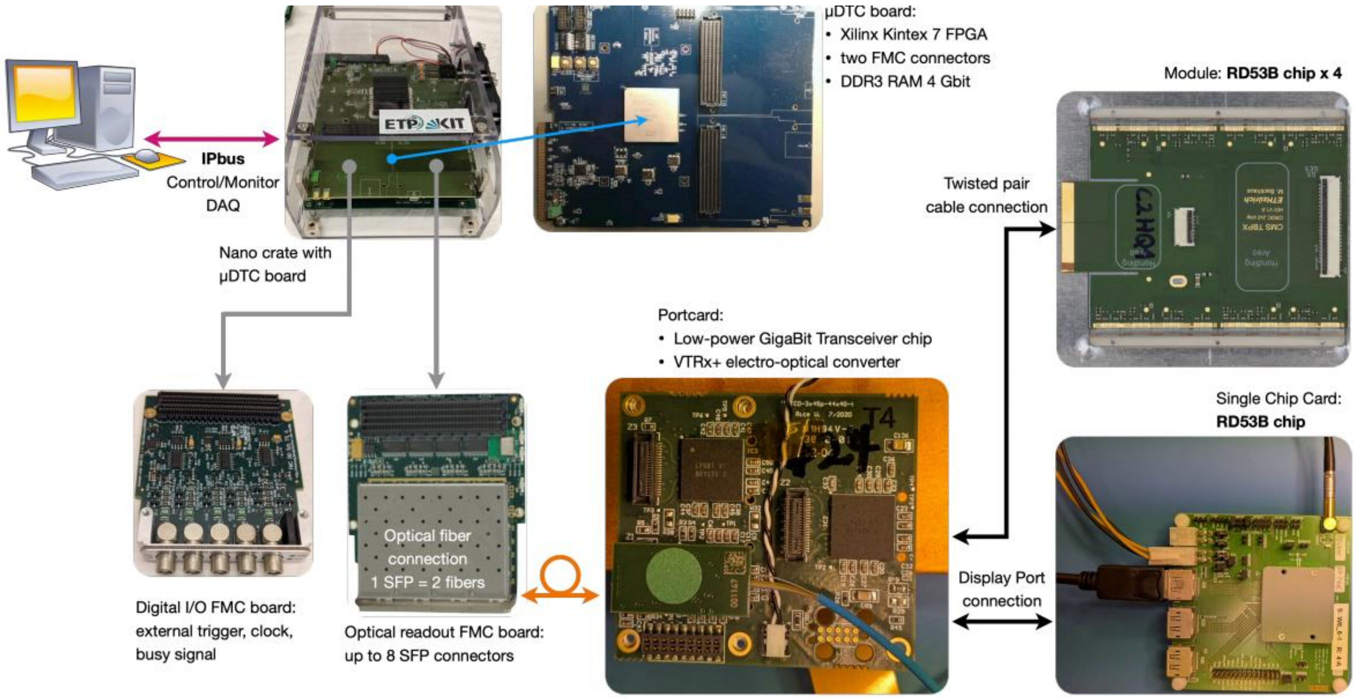
200 x 200 µm ROI

- Extremely small sensors, use of an ROI for triggering
- Trigger as coincidence of front scintillator and ROI Regio
- CROC + FC7 in combination with FDIO 5
- 16 - pixel mask in the CROC (4 x 4 region)
- Phase-2 Acquisition and Control Framework
- Have a look at Mauro's talk for details here



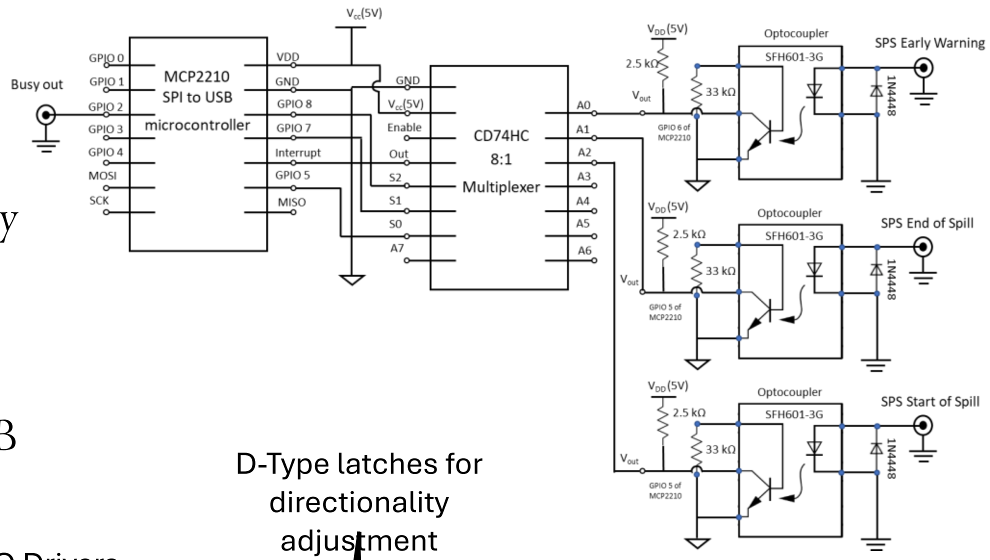


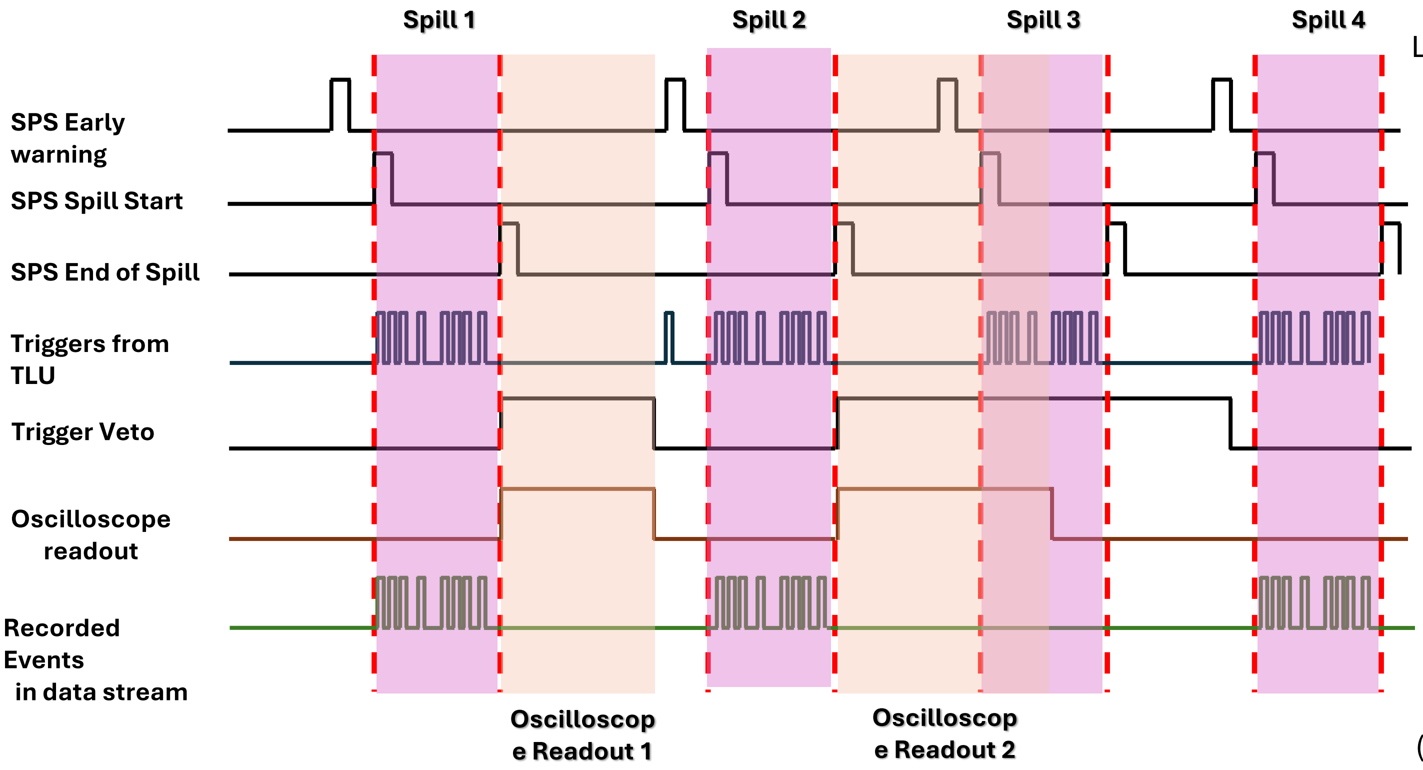
- FDIO 5 FMC Carrier

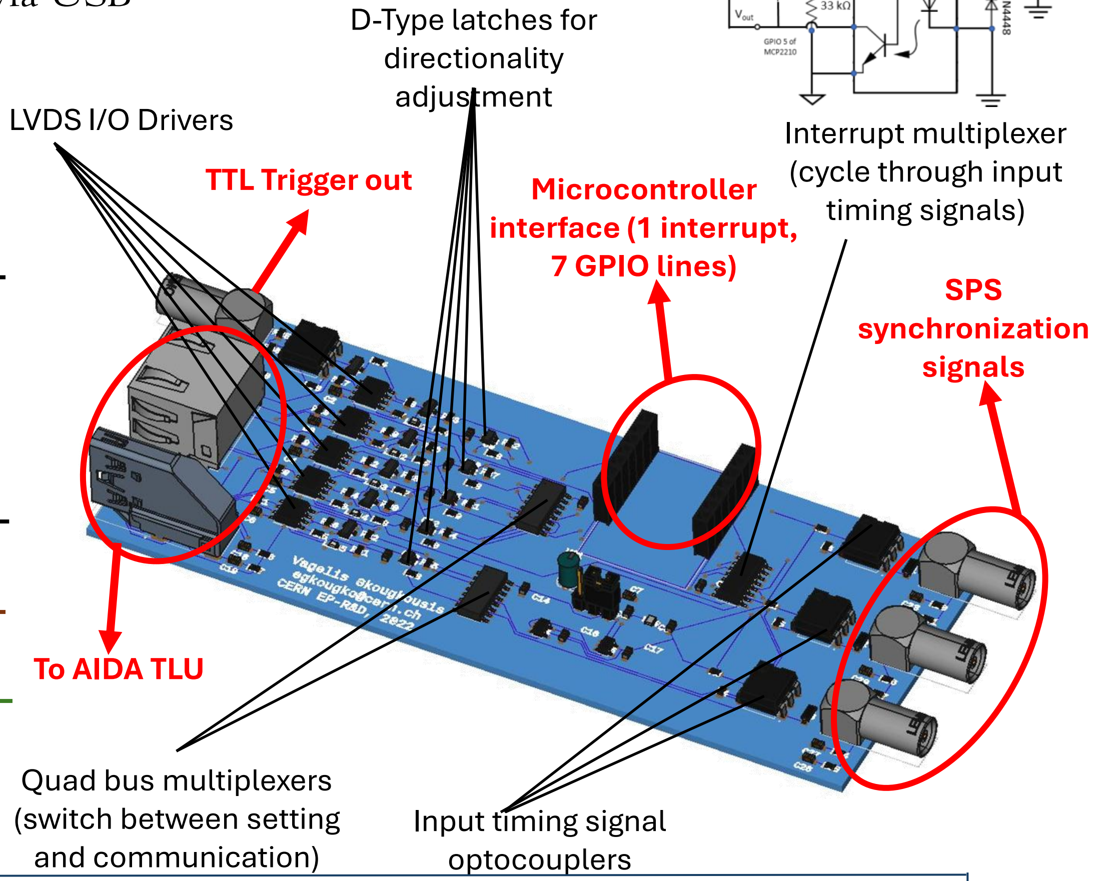


•Data Acquisition Scheme

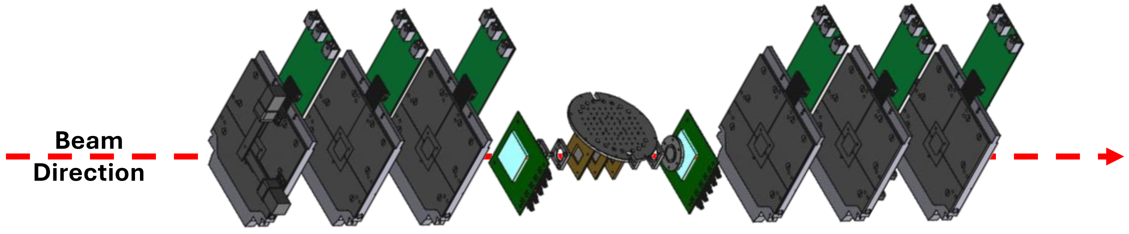
- Oscilloscope in fast readout mode with binary format
- Event readout only between SPS-spills or when event buffer full to increase efficiency
- TLU Synchronization by vetoing data taking during read-out
- RJ-45 or HDMI for EUDET TLU communication (EUDET 2 compatible)
- **Versatile design**, I/Os **Reconfigurable** and microcontroller **Reprogrammable** via USB



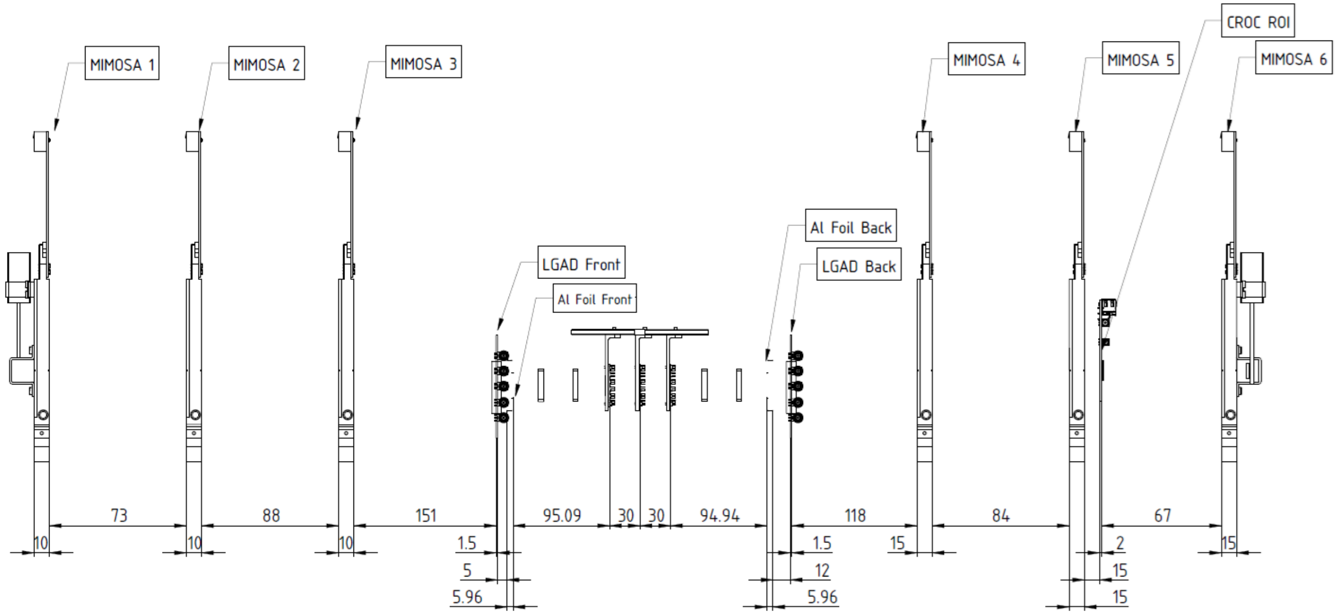




•Data & Track Reconstruction

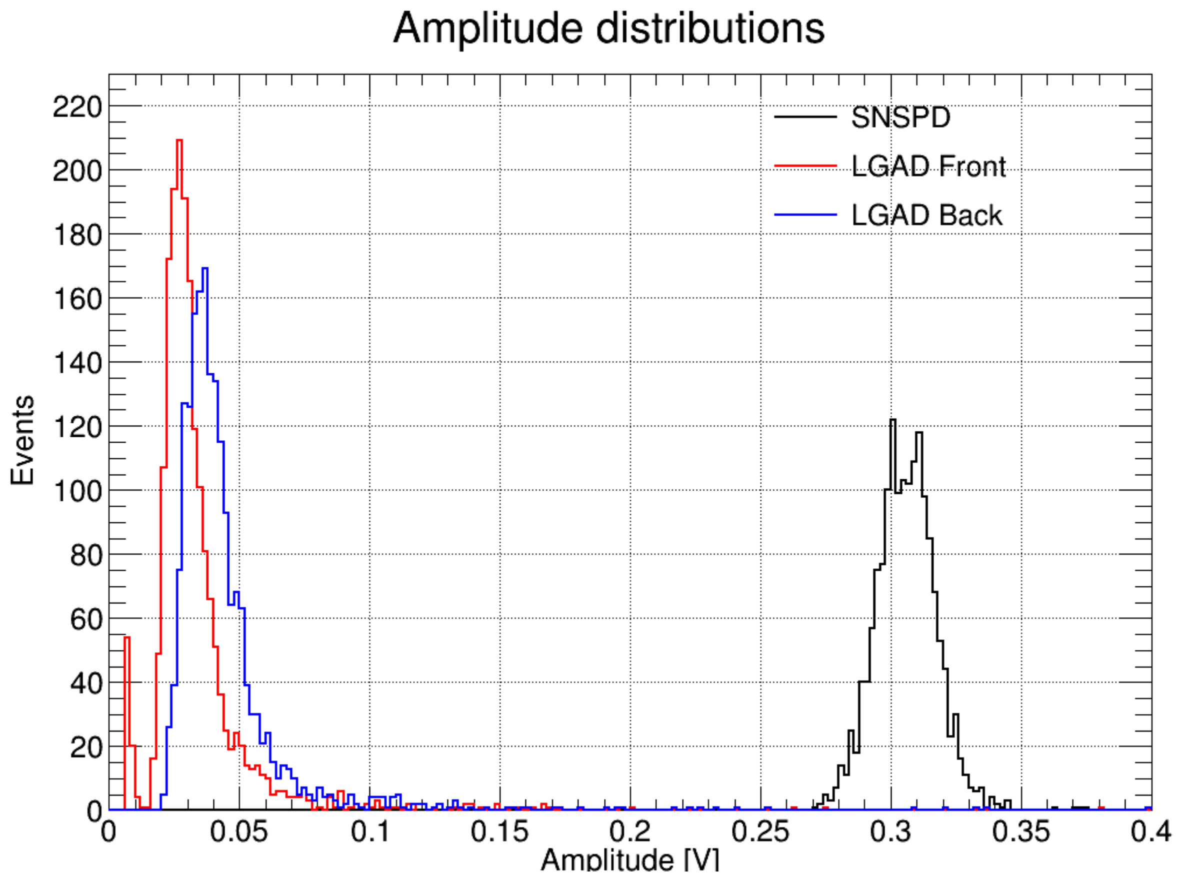


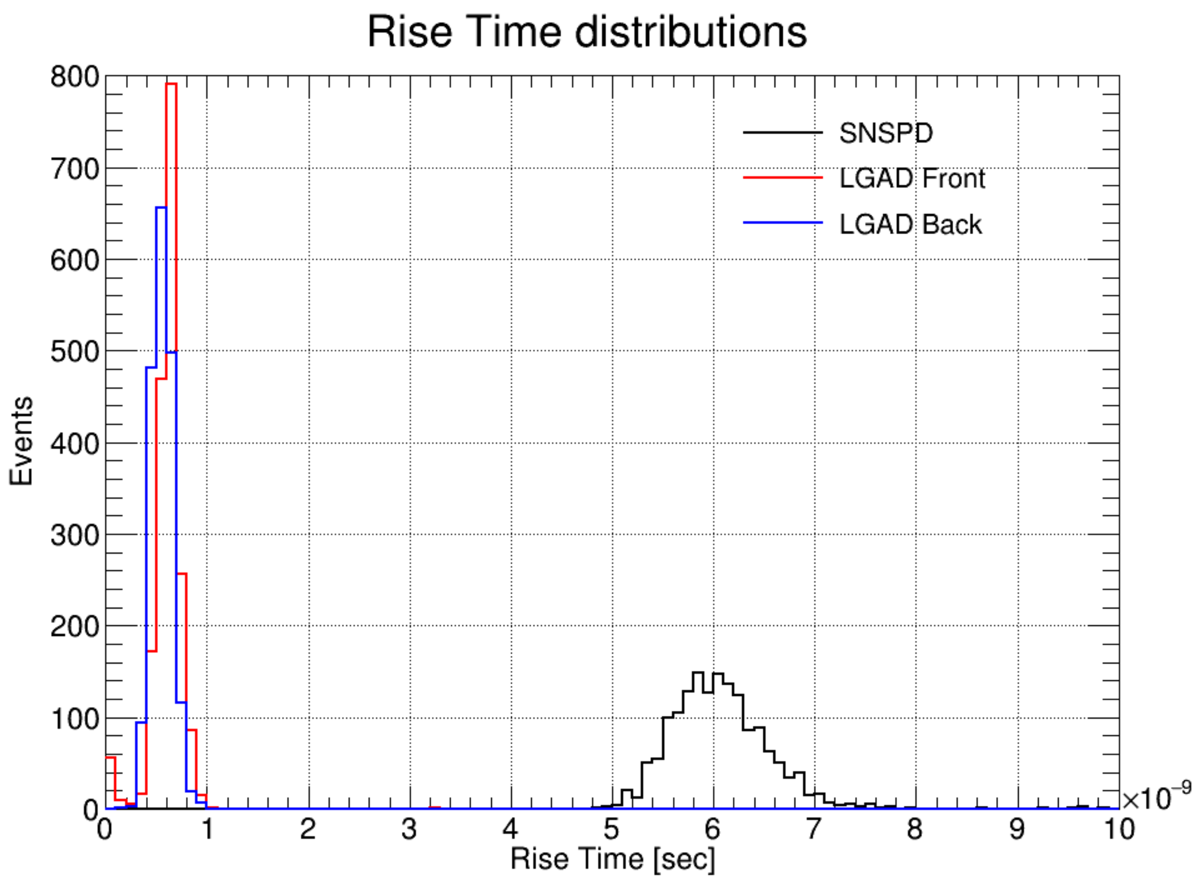
Run Configuration	No. of Events	I_{bisas} (SNSPD)	Rate (Hz)	LGAD Bias	Date
Timing Run Coincidence Trig.	2019	28 µA	0.000054	-150 V	10 / 8, 23:52
	2933	30 µA	0.000439	-150 V	10 / 8, 12:30
Tracing & Efficiency Run, RoI Trigger	6061	30 µA	0.011477	-150 V	12 / 8, 1:10
	6178	30 µA	0.011431	-150 V	12 / 8, 1:20
	7261	30 µA	0.011578	-150 V	12 / 8, 1:31
	7111	30 µA	0.010707	-150 V	12 / 8, 1:45
	568	30 µA	0.00529	-150 V	12 / 8, 9:51
	1942	30 µA	0.00343	-150 V	12 / 8, 10:26
	2560	30 µA	0.00343	-150 V	12 / 8, 10:38
	1928	30 µA	0.00343	-150 V	12 / 8, 10:50
Tracing & Efficiency Run, RoI Trigger SPS Sync.	51138	30 µA	0.004267	-150 V	12 / 8, 13:40
	59167	30 µA	0.00343	-150 V	12 / 8, 18:11
	186905	30 µA	0.009263	-150 V	12 / 8, 23:07
	110635	30 µA	0.007672	-150 V	13 / 8, 4:48
Total	**446406**	**(0.5 M events in 1.5 days)**			



- 5 Functioning MIMOSA26 CMOS planes (18.4 µm^2 pixel size, 115.2 µs readout time, 80 Mhz clock in rolling shutter mode)
- 1 x 150 µm active thickness CMS phase 2 Upgrade planar pixel module, 50 x 50 µm pixel, CROC readout, 2 x 50 µm active tickets LGADs
- Expected resolution @ 160 GeV with 5 planes ~ 5 µm

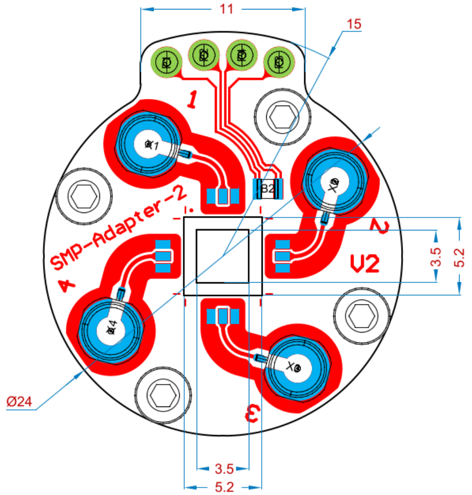
•Waveform analysis

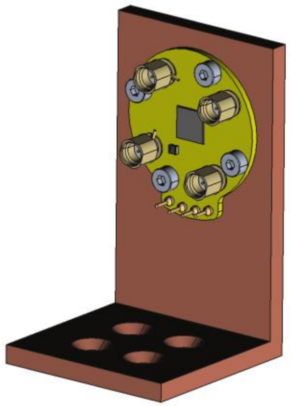


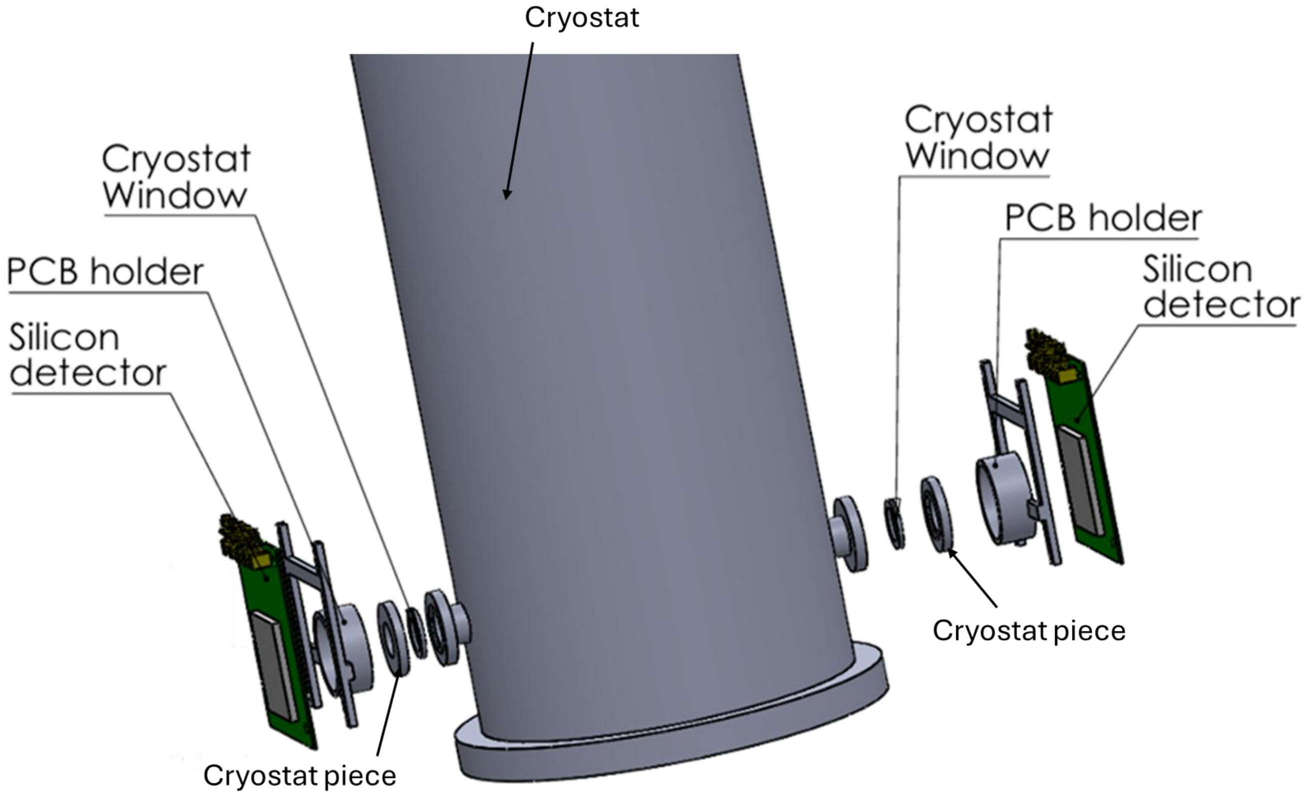


- ➢ Significantly higher amplitudes with respect to LGADs, ~ 300 mV (SNSPD Bias 28 μA)
- ➢ Gaussian distribution (no visible Landau tail as at the Vavilov / Landau Straggling limit)
- ➢ Rise time in the order of 6 nsec with respect to the 800 psec for the LGADs

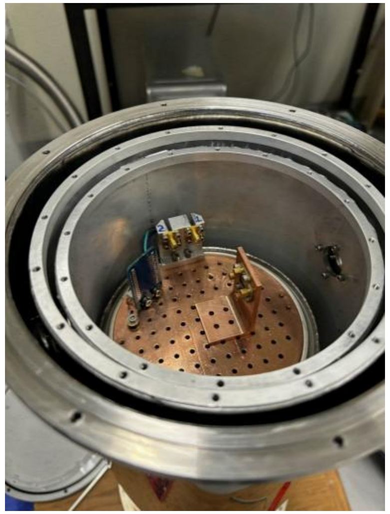
•β-particle measurements



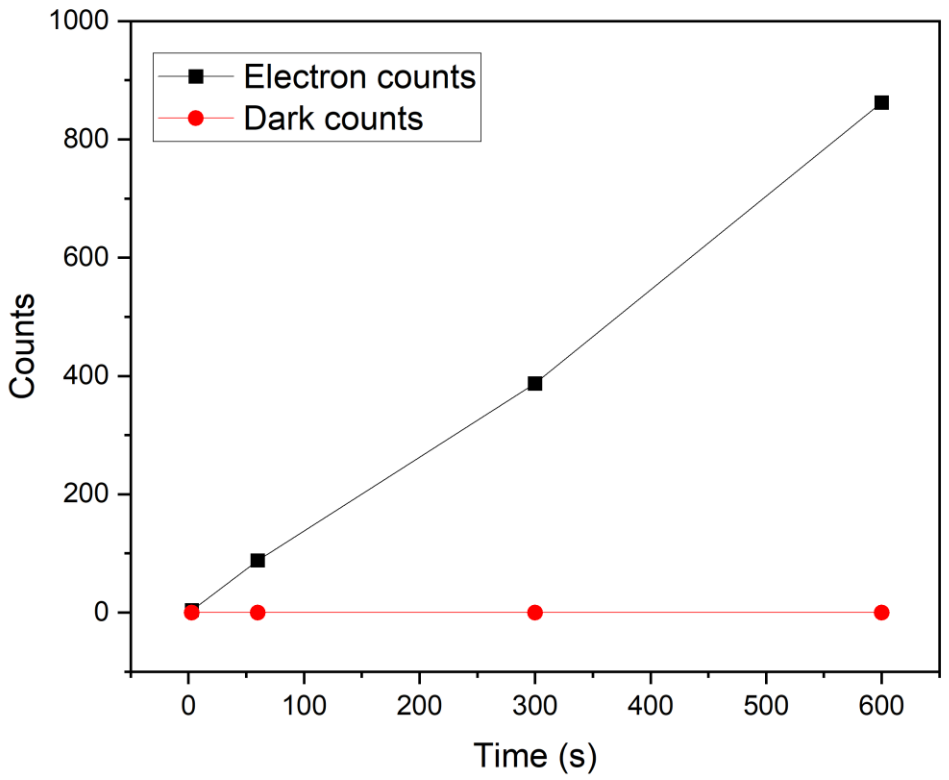


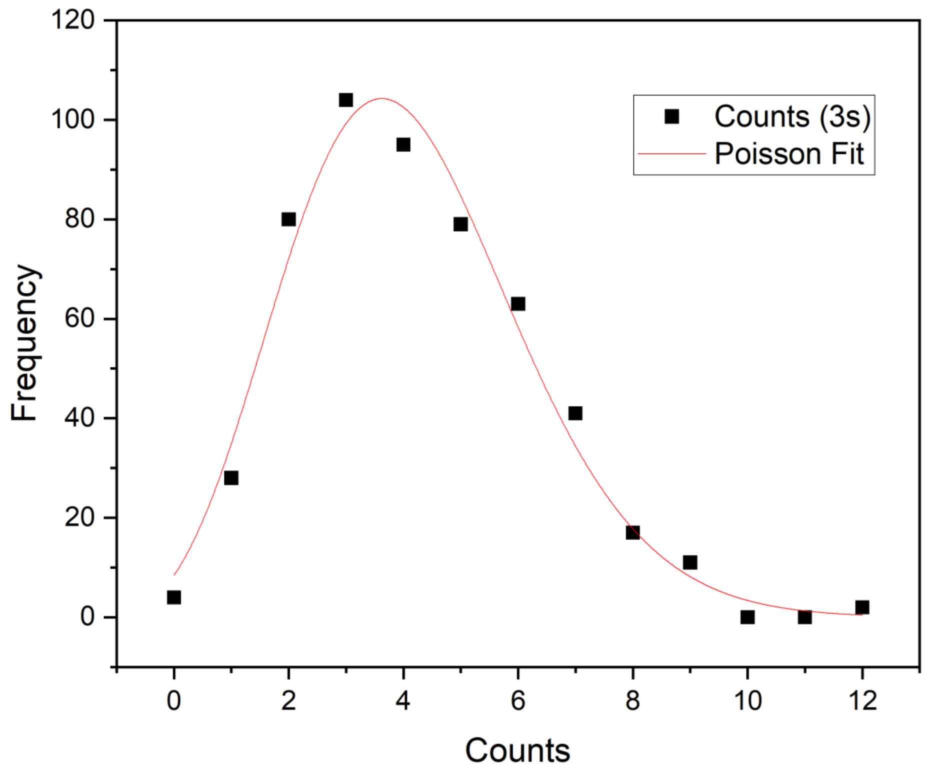


- AlN PCB with high thermal conductivity but low X_0
- Coper Sample holder with 0.5 x 0.5 cm opening behind the sample for beam passthrough and ,multiple scattering mitigation
- Aluminized Millar windows at both sides of the cryostat and intermediate barriers with a total thickens of 2 x 40 um Al.
- 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



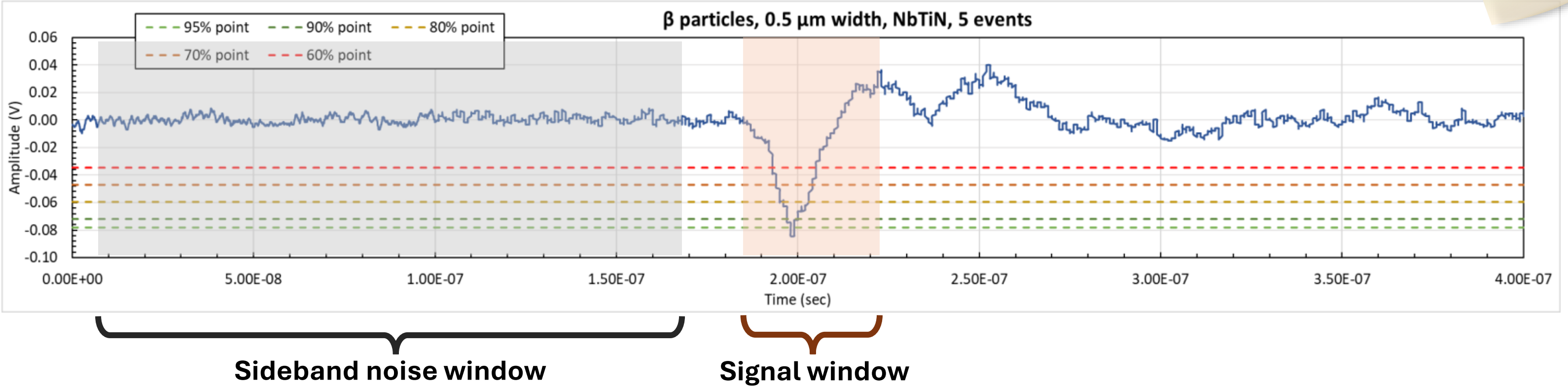
•β-particle measurements

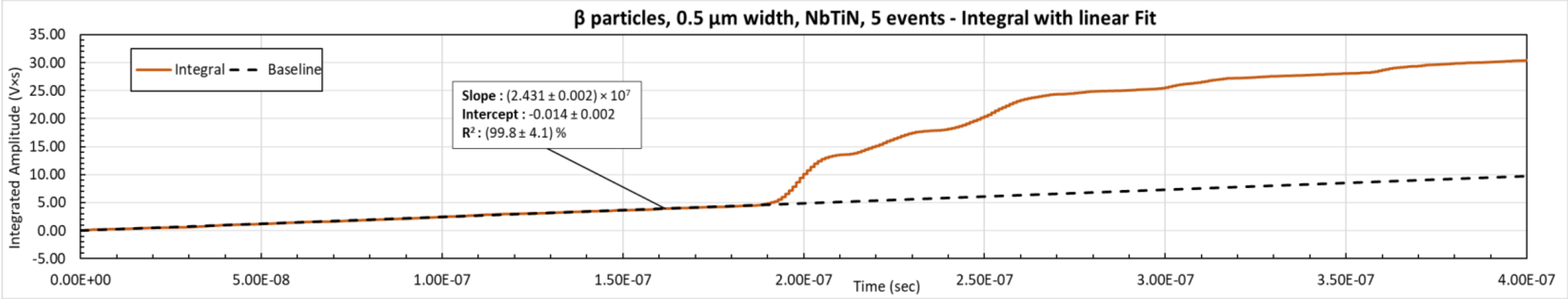


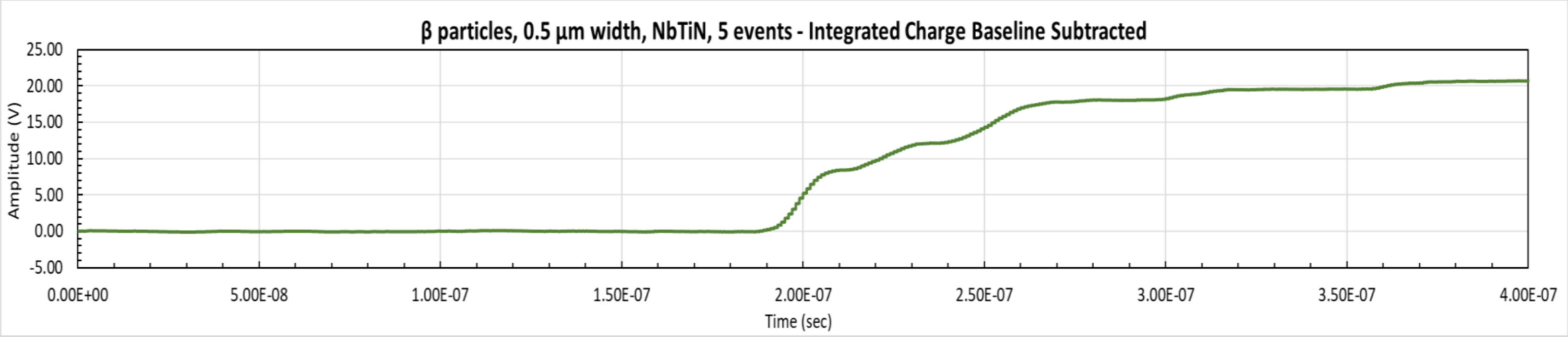


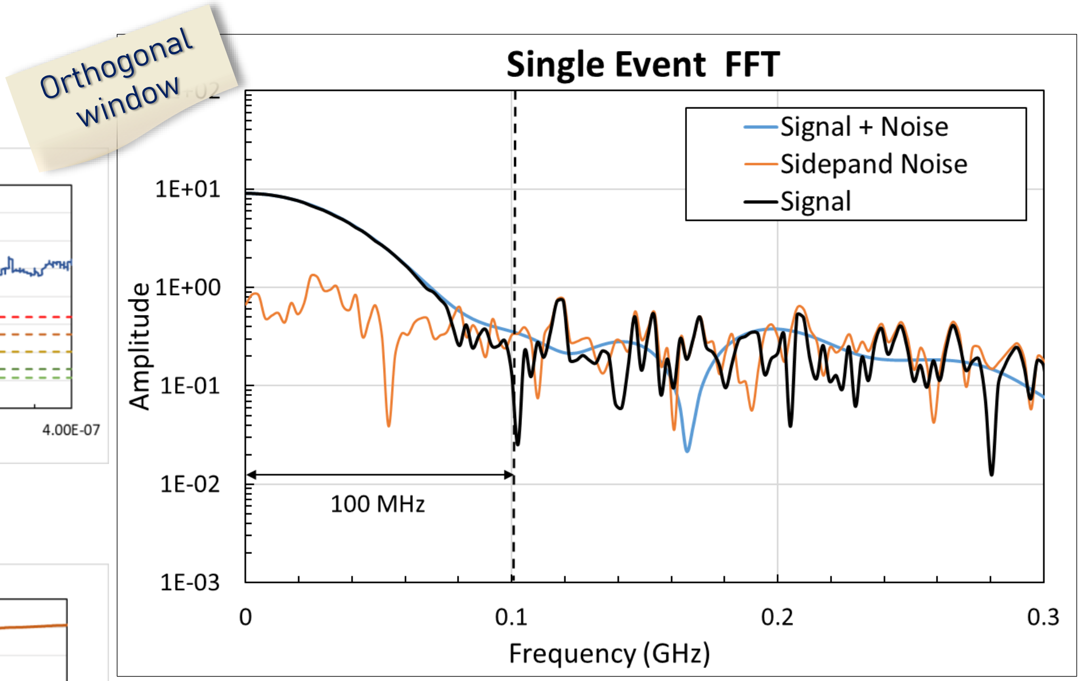
- ➢ Measured rates in the lab to verify functionality
- ➢ Poissonian distribution of frequency of counts
- ➢ Mylar windows with cooper support holder, similar response to test bema

•β-particle measurements









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

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

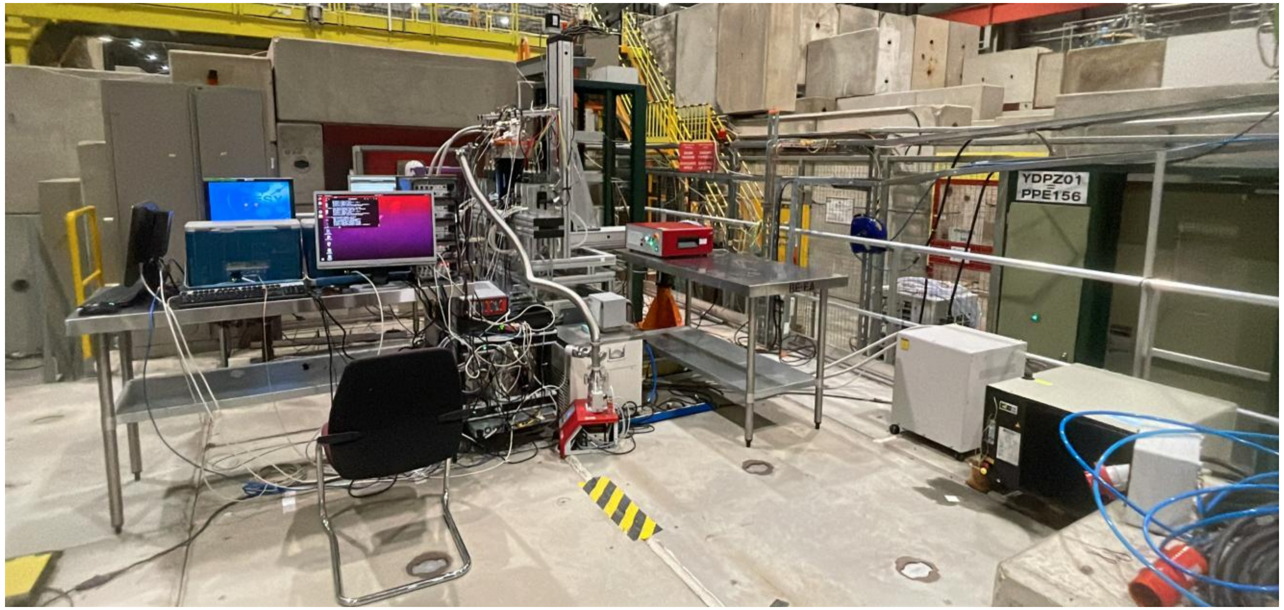
50 Ω Chain

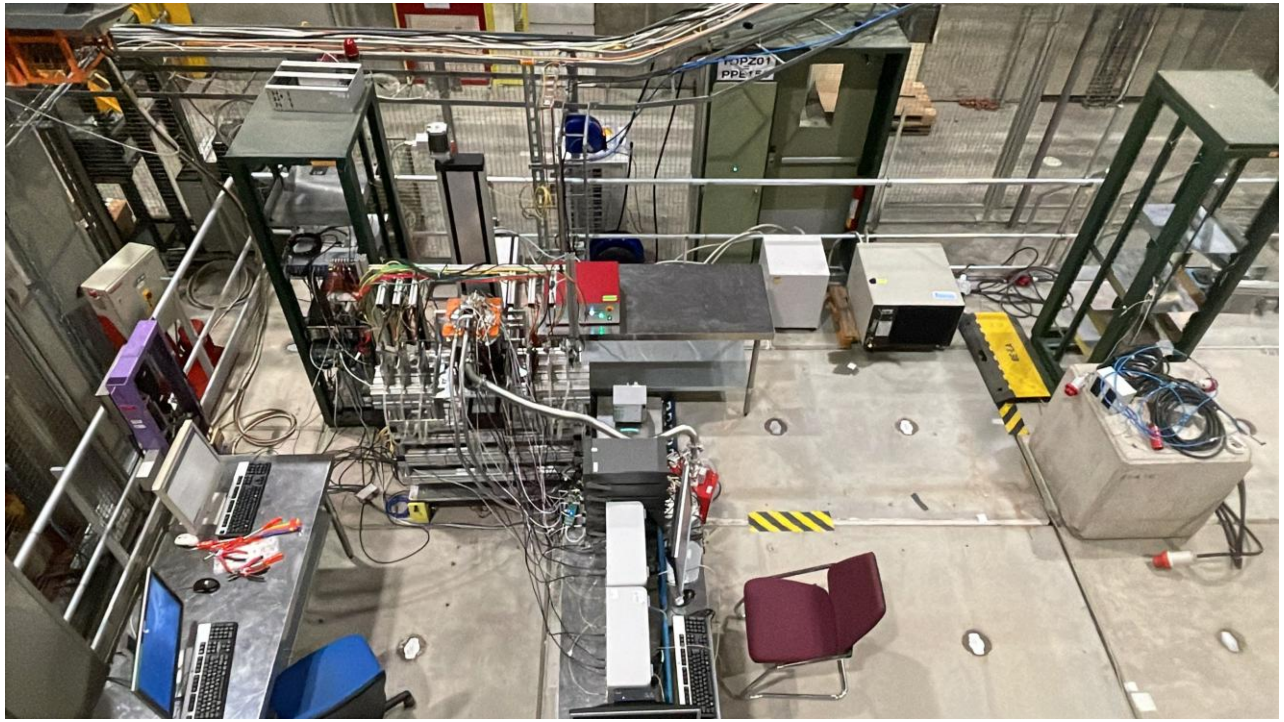
•Conclusions & Outlook

- First Test of NbTiN and Nb N samplers in test beam proved operating principal
- Temperature issues to be resolved in the upcoming three-week period (19 September – 1 October)
- Tracing analysis on-going, first results encouraging but demonstrate slow signals
- Simulations under way with Synopsys QuantumATK and quantum seaport algorithms (PARCS) in combination with GEANT4 to understand substrate implication
- Future target higher temperature materials (MgB_2)
- Design optimization for faster signals and higher fill factors

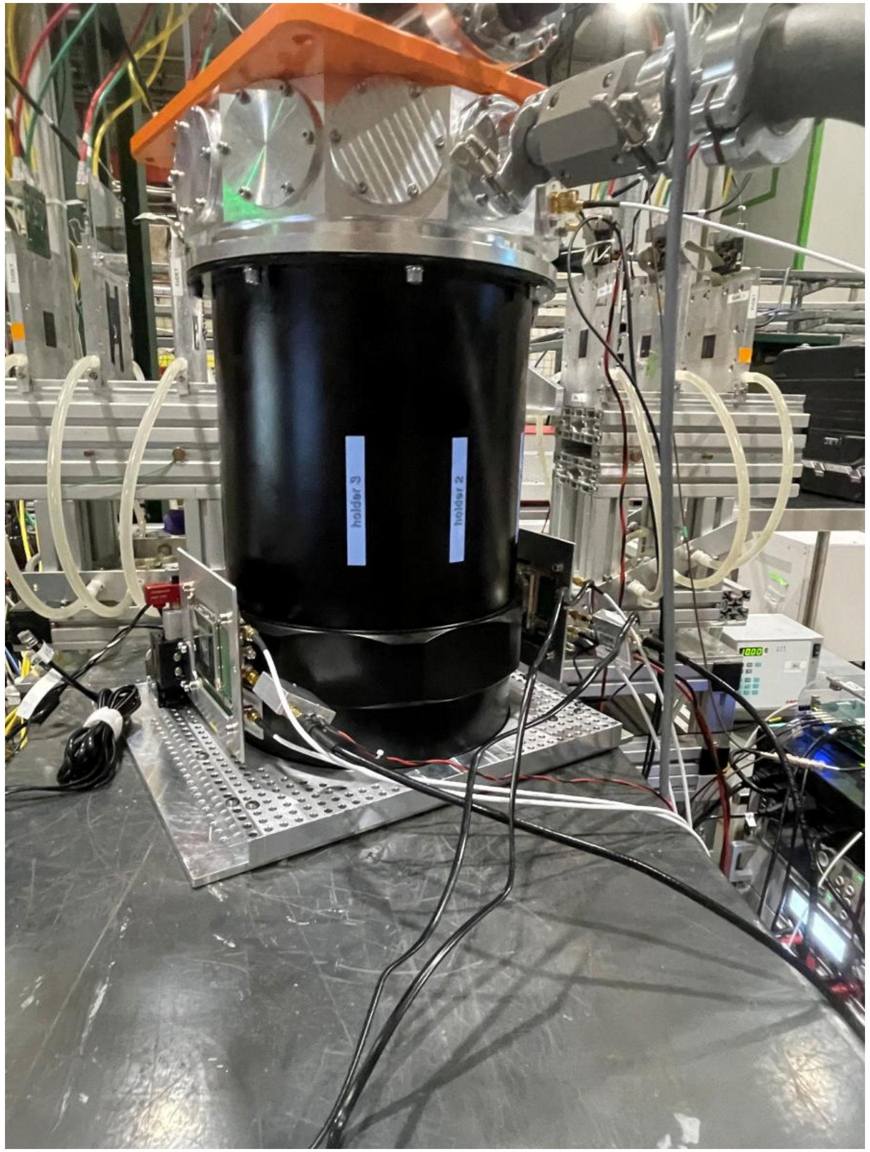
•Backup

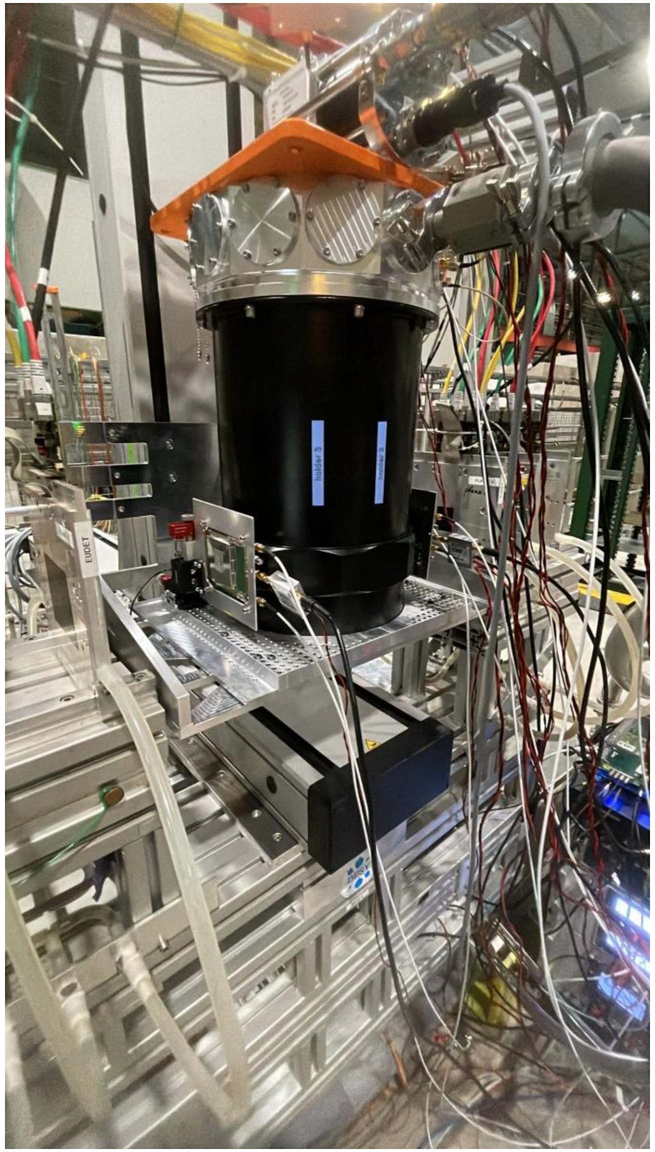
•Timming planes Assembly





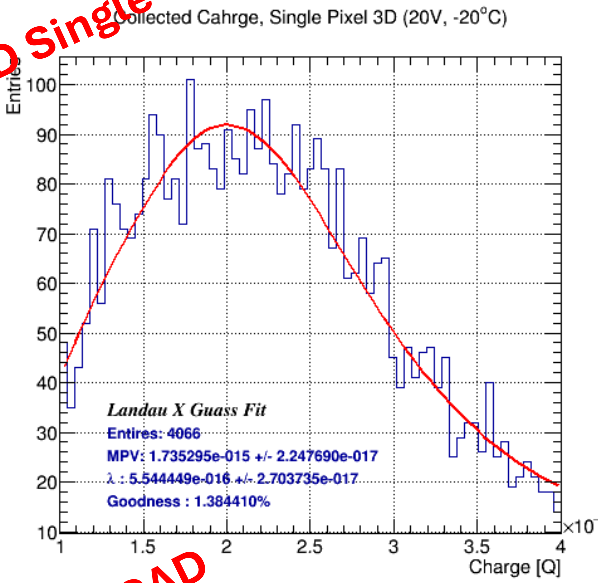
•Timming planes Assembly

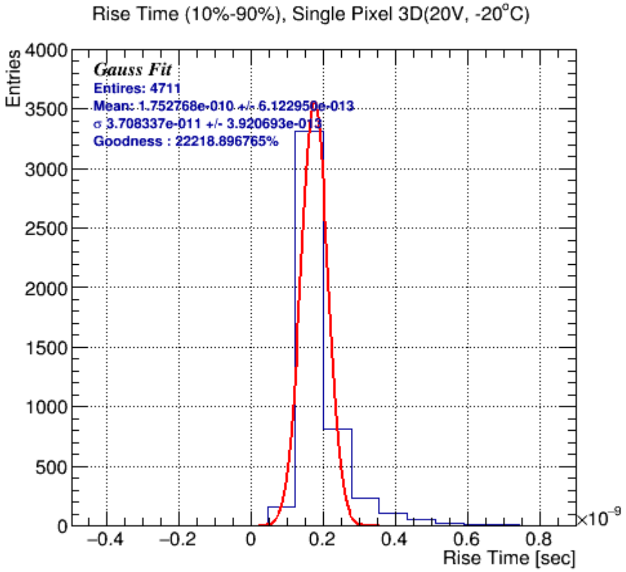




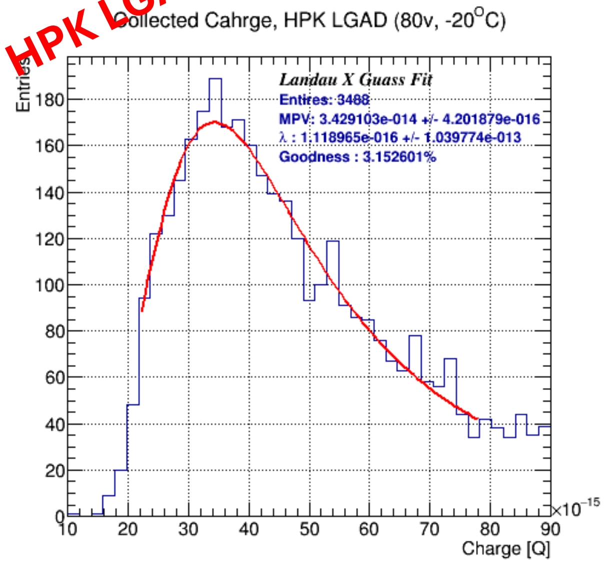
•Timing Reference

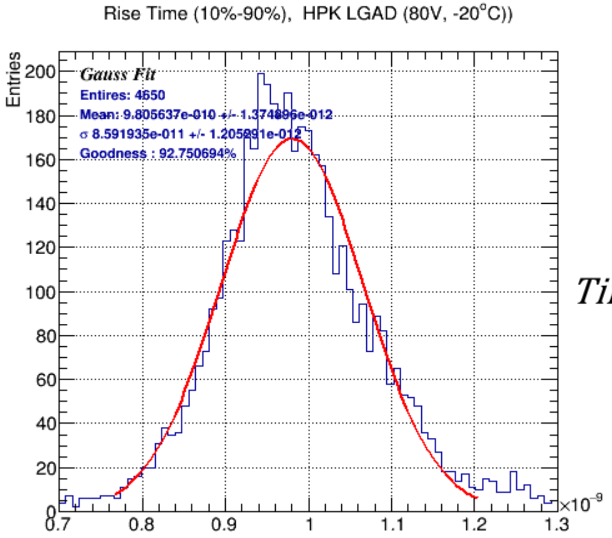
3D Single Cell





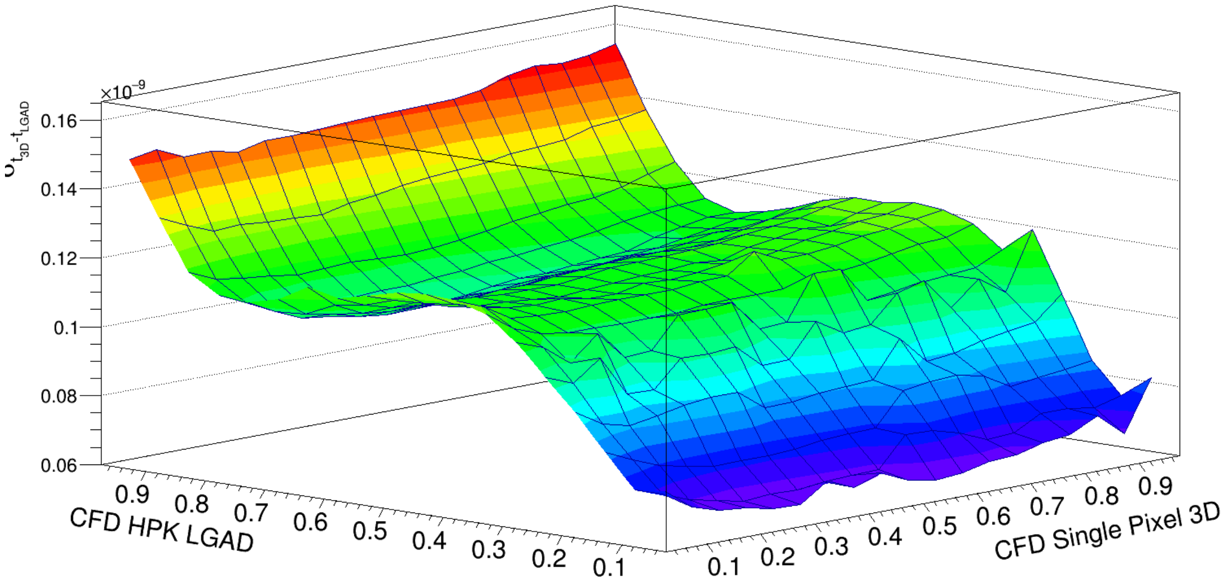
HPK LGAD





$$(\sigma_{\text{Dut}})_{CFD_{ij}} = \sqrt{(\sigma^2_{\text{Tot}})_{CFD_{ij}} - (\sigma^2_{\text{Ref}})_{CFD_i}}$$

CFD Map, LGAD - Single Pixel 3D (-20°C, 20V)



2D optimization plot – 0.5% binning

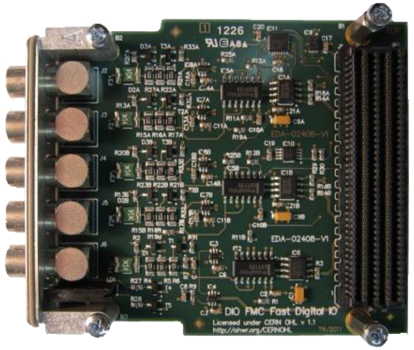
Time Resolution: $\sigma^2_{tot} = \sigma^2_{timewalk} + \sigma^2_{jitter} + \sigma^2_{conversion} + \sigma^2_{Clock}$

- $\sigma^2_{timewalk}$: $\sigma^2_{Dist.} + \sigma^2_{Landau}$
- σ^2_{jitter}: $\left(\frac{t_{rise}}{S/N}\right)^2$
- $\sigma^2_{conversion}$: $\left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2$
- σ^2_{Clock}: *Fixed Term ~ 5-7 psec*

•ROI trigger – CROC

FMC DIO 5ch TTL a

CERN Open Hardware Project



Product Name	Company	Contact
fmc dio 5chttla	iNCAA Computers	sales@incaacomputers.com
FMC DIO	Sundance Technology	sales@sundance.com
FMC DIO 5CH TTL A	Creotech	kontakt@creotech.pl

Plane	Distances (mm)	
	Interplane	Relative
MIMOSA 1	0	0
MIOMSA 2	83	83
MIMOSA 3	98	181
LGAD Front	157.5	338.5
Holder 3	106.05	444.55
Holder 2	30	474.55
Holder 1	30	504.55
LGAD Back	112.36	616.91
MIMOSA 4	125.5	742.41
MIMOSA 5	99	841.41
CROC	24.5	865.91

$$\frac{dy}{dx}(I) = A \times \exp\left(-\frac{I-\mu}{\beta} - e^{-(I-\mu)/\beta}\right)$$

$$\frac{dy}{dx}(I) = A \times \exp\left(+\frac{I-\mu}{\beta} - e^{(I-\mu)/\beta}\right)$$

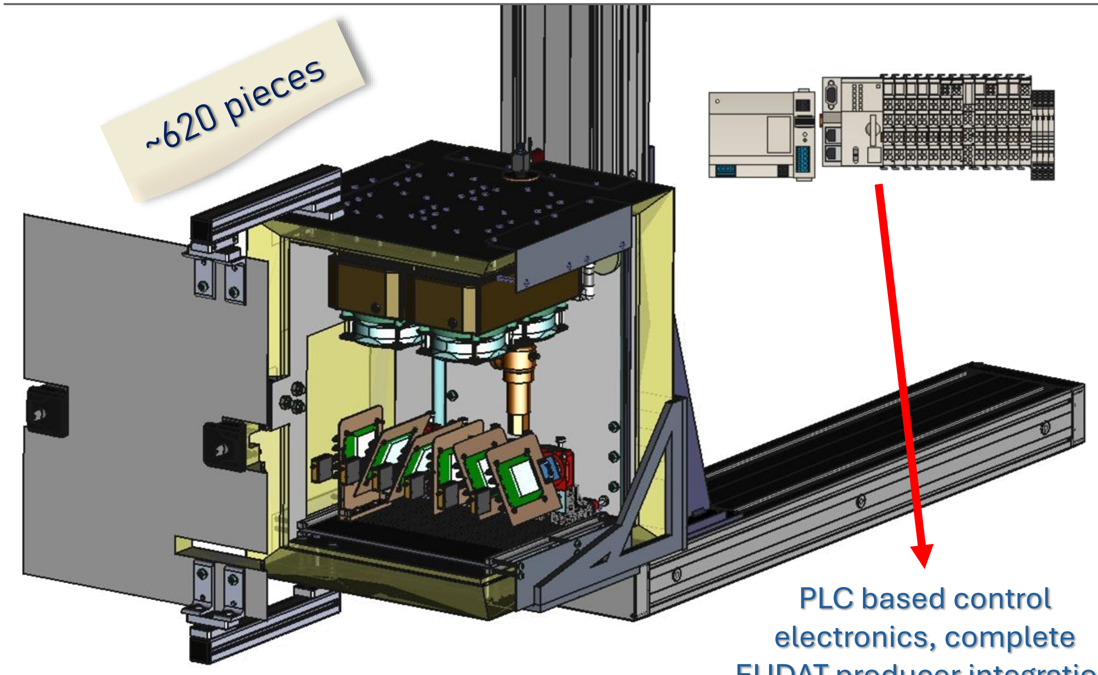
β : asymmetric skew parameter
measures spread of switching events

μ : x- axis location parameter
most probable switching current

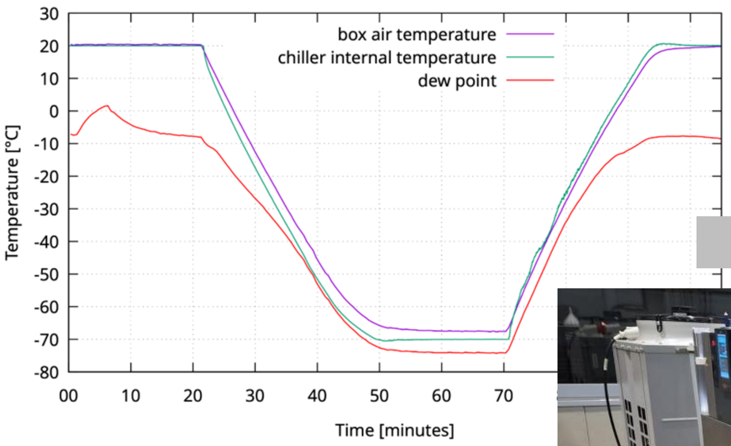
A : amplitude scaling parameter

https://docs.google.com/spreadsheets/d/1vLE-evXXKtkaPMSj6GC_cAlBCw8hYmCW9g4qIiC3hTk/edit?usp=sharing

•Infrastructure upgrade @H6B

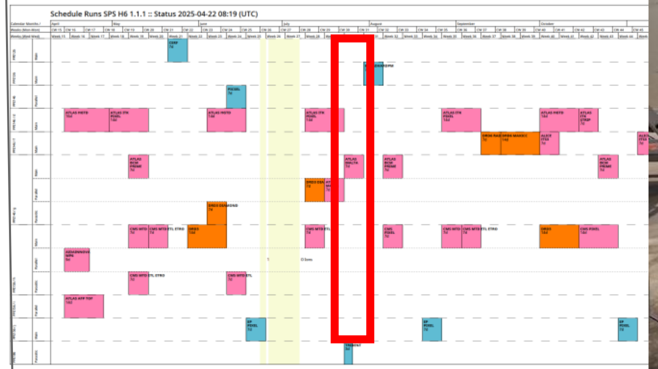


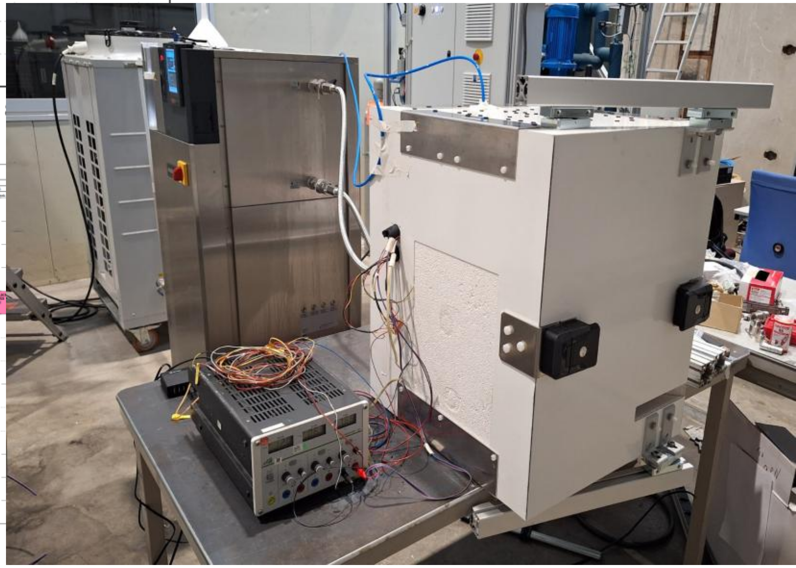
PLC based control electronics, complete EUDAT producer integration



Team: Vagelis Gkougkousis
Andre Rummler
Dominik Dannheim

More info at Vagelis AIDA Innova prestation





- - 80 °C with ethanol cooling
- 20% ^{0}X for pions using aluminum clad XPS fly-ash reinforced-core wall, 8 % in beam region
- Carbon fiber hydraulic pass-through, conductive
- 5 plane X - Y DUT translation stages
- Independent DUT rotation up to 35°

Complete drawings and step files:
https://github.com/VGkougkousis/VBox/tree/main

- ✓ Chiller / stages / box delivered end of 2024, acceptance test complete
- ✓ Setup currently in Building 180, Transfer to H6B end July
- ✓ Installation foreseen for the week of August 3rd, fist user CMS Pixel
- ✓ Services to be finalized (water supply / power infrastructure / safety)
- ✓ Universal software integration with **ALL** available LV / HJV units to a single framework (Unified infrastructure producer)

Cryostat window minimum thickness

Minimum window thickness equation:

$$S_{max} = \frac{KD^2P}{4T} = \frac{F_a}{Sf} \qquad T = D\sqrt{\frac{SfKP}{4F_a}}$$

- K : 0.75 (empirical factor accounting for the clamping method)
- D : Diameter
- P : Pressure difference
- Fa : Rupture modulus
- Sf : Safety factor taken as 4
- T : Window thickness
- S_{max} : Maximum force

Material	Aluminium Nitrite	Aluminium Oxide	Aluminium	Plexiglass	Silicon
Density (g/cm^3)	3.255	3.98	2.7	1.18	2.38
Rupture Modulus (MPa)	367	800	280	72	200
Minimum Thickness (mm)	0.26	0.3	0.18	0.58	0.35

To chose optimal window material, need to analyse the individual stopping power of each material, and the post window beta spectrum

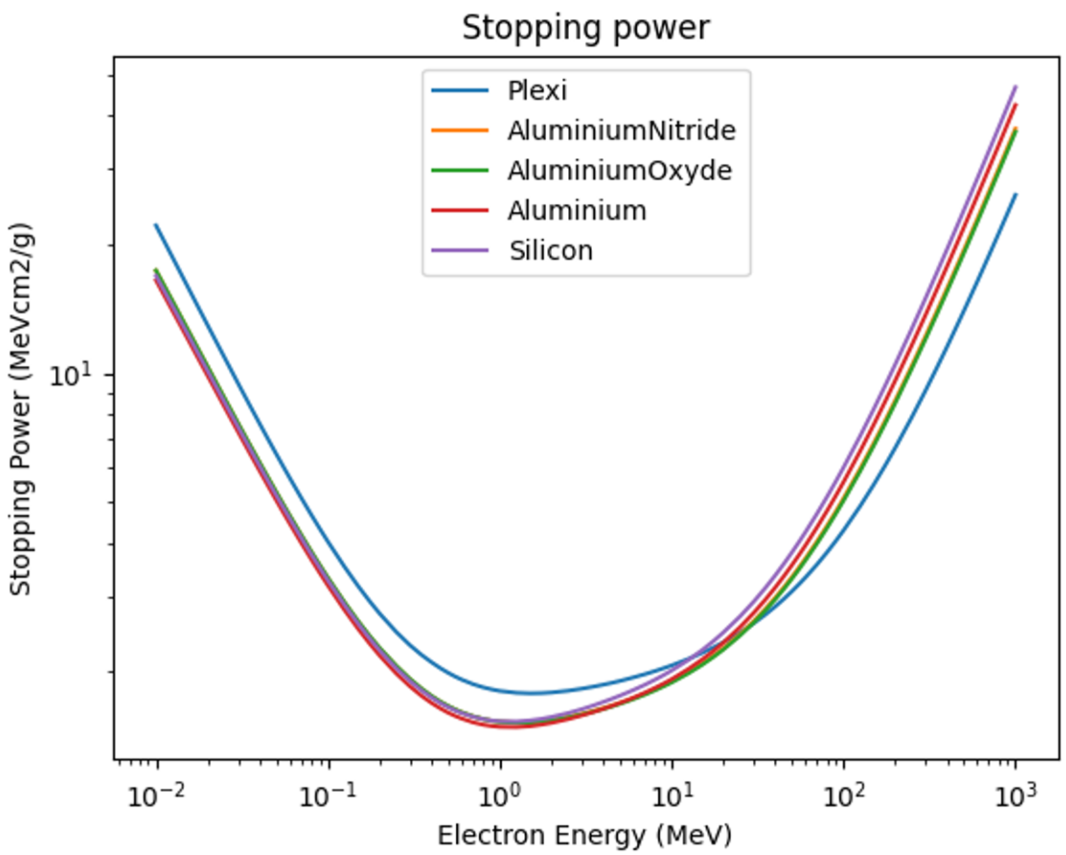
Stopping power analysis

Bethe Bloch equation:

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2} ln\left(\frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2}\right) - \beta^2 - \frac{\delta}{2}\right]$$

- T_{max}: Maximum kinetic energy
- K: Constant
- A: Atomic mass of medium
- Z: Atomic number of medium
- m_e: Electron mass
- $\beta = \frac{v}{c}$
- δ: Density effect correction
- z: Electron charge
- I: Average excitation energy

Considering the Stopping power for the selected materials is relatively close, we needed an analysis of the Beta Spectrum to make an educated choice



The data was taken from the NIST ESTAR database

estar
stopping-power and range tables for electrons