Superconducting Nanowire Particle Detectors

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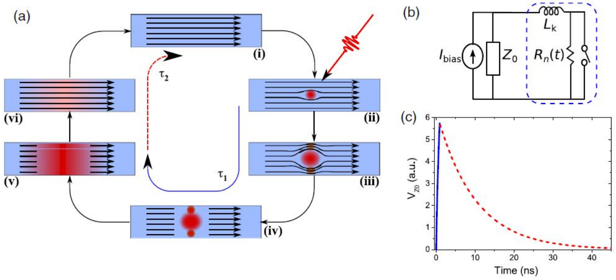
Overview

- Introduction to superconducting nanowire **particle** detectors
- Ongoing R&D at Argonne
- Proposed EIC-Related Generic Detector R&D
- Applications at the EIC
  - Far forward detectors
  - Superconducting magnet beamline detector
  - Neutral particle detector
  - Other uses at the EIC

SNSPD where "P" is Particle

- We do anticipate some change in the pulse shapes when comparing photons, low energy particles and high energy particle detection
- We are setup at the Fermilab Test Beam Facility and waiting for beam to test
- We intend on studying the degree to which the reset time changes using data from FTBF and the R&D proposed here



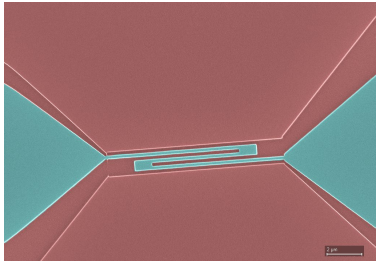
Particle	Energy	Approximate Energy loss in 100 µm silicon	Approximate Energy loss in 15 nm NbN	Detected
photon	UV-iR	all	all	✔
alpha	5 MeV	5 MeV	9.1 keV	
beta	1 MeV	15 keV	15.8 eV	
electron	100 MeV	100 keV	~100 eV	
proton	120 GeV	40 keV	24 eV	
pion /muon	10 GeV	30-45 keV	~20 eV	

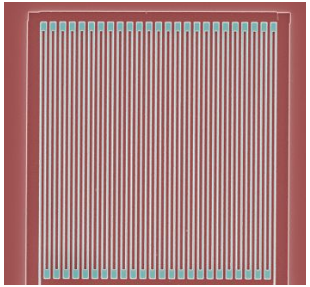
A single wire firing once injects about 2 fJ of energy into the system (or 124 keV)

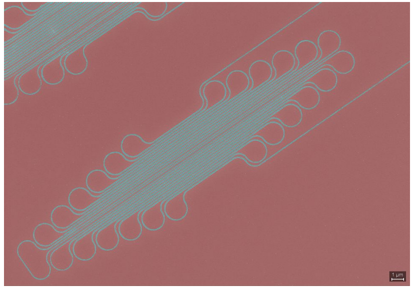
SNSPD Properties and Characteristics

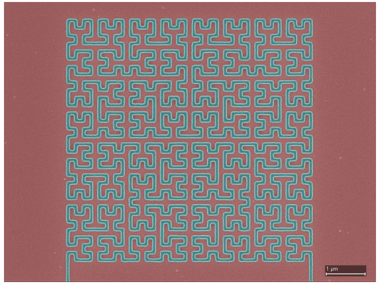
Quick Summary

- Photon energy thresholds as low as ~100 meV
- Timing jitter 20–40 ps easily achieved (current record of 3 ps)
- Reset times can be as low as 5-10 ns (potentially <1 ns in the future)
- Pixels on the order of 10x10 μm^2 to 30x30 μm^2
- Fast, granular, high-rate pixel detector → low occupancies
- Conveniently operates at LHe temperatures (T < 5K)
- Photon detection efficiencies >90%
- Expected to very radiation hard (more on this later)
- Can be fabricated with different geometry or pixel dimensions

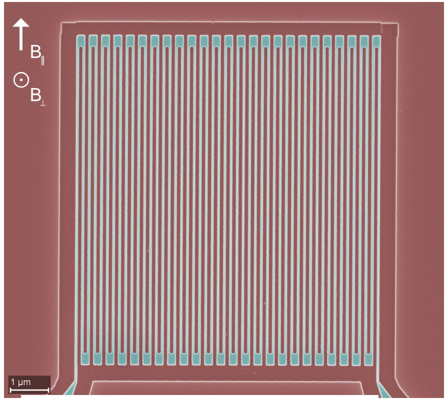


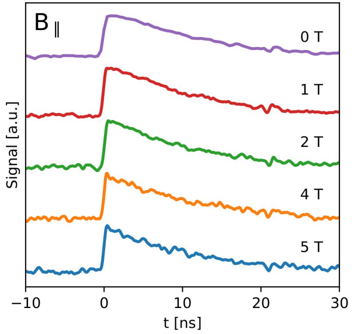


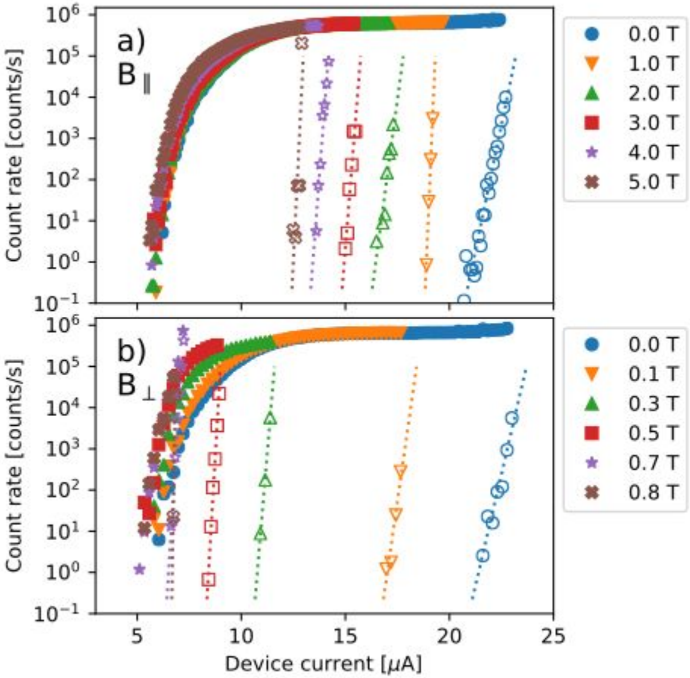


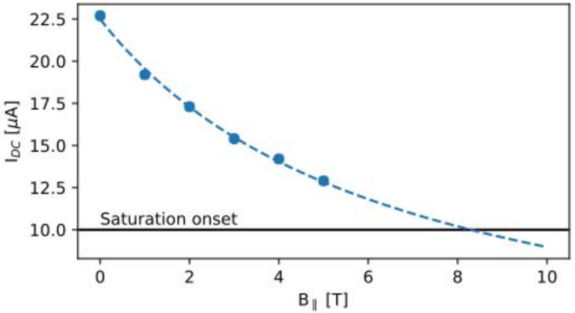


Strong Magnetic fields and high rates





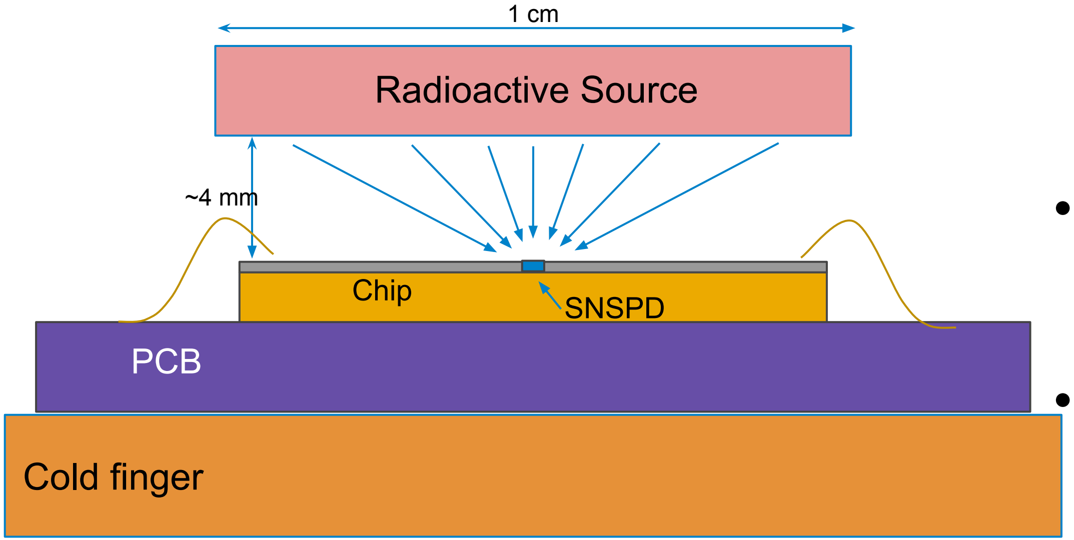




Can operate on strong magnetic fields with nearly zero dark count

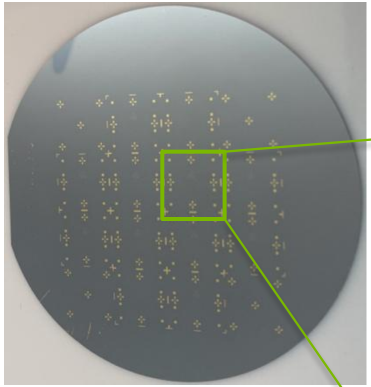
Ongoing Superconducting Nanowire R&D

Experimental Setup with Radioactive Sources

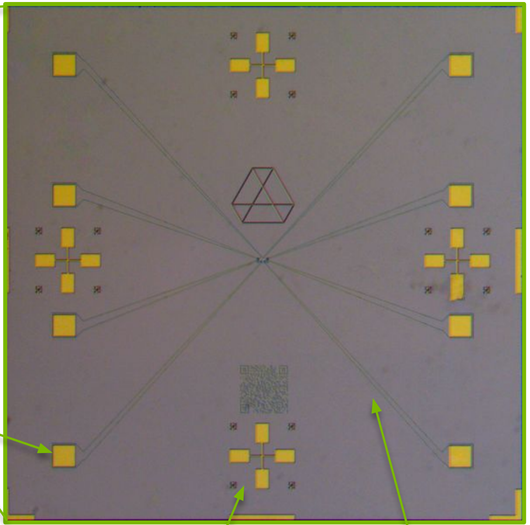


- Started with 0.1 μC ^{241}Am and ^{90}Sr sources
  - ^{241}Am is an α emitter
  - ^{90}Sr is a β emitter
  - Counting rate was roughly 2/min
  - Bias scans would take far too long time with these sources!
- 10 μC ^{241}Am arrived in October
  - Counting rate is now ~ 1/s
  - Bias scans slow but possible (2-3 hours for each I_b setting to get 1% statistical uncertainty)
- Ordered 100 μC ^{241}Am
  - Will take 20-30 min for each I_b setting

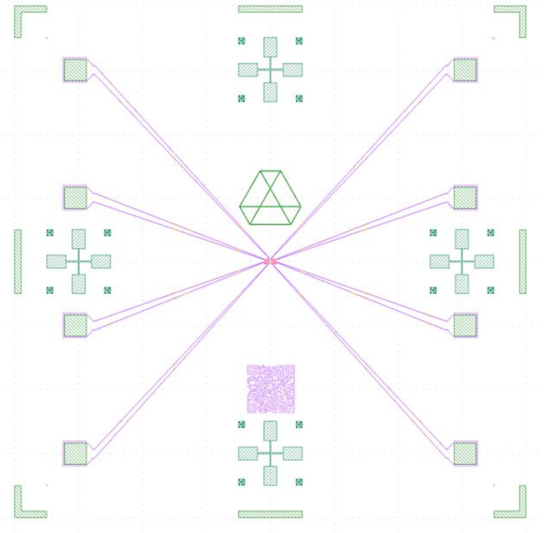
Nanowire devices for particle detection



Physical device (chip)



Design



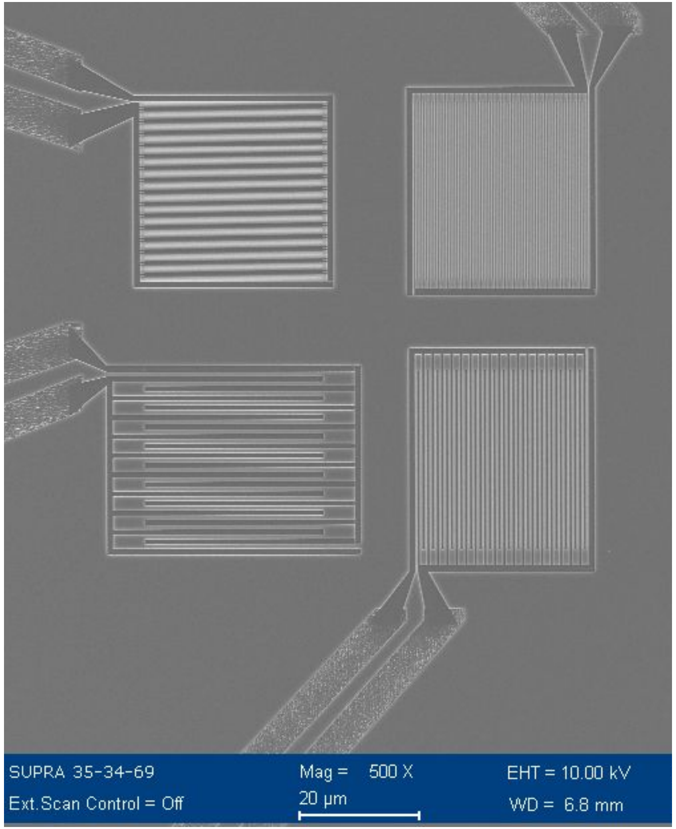
Wire bonding contact pad

Local alignment marks

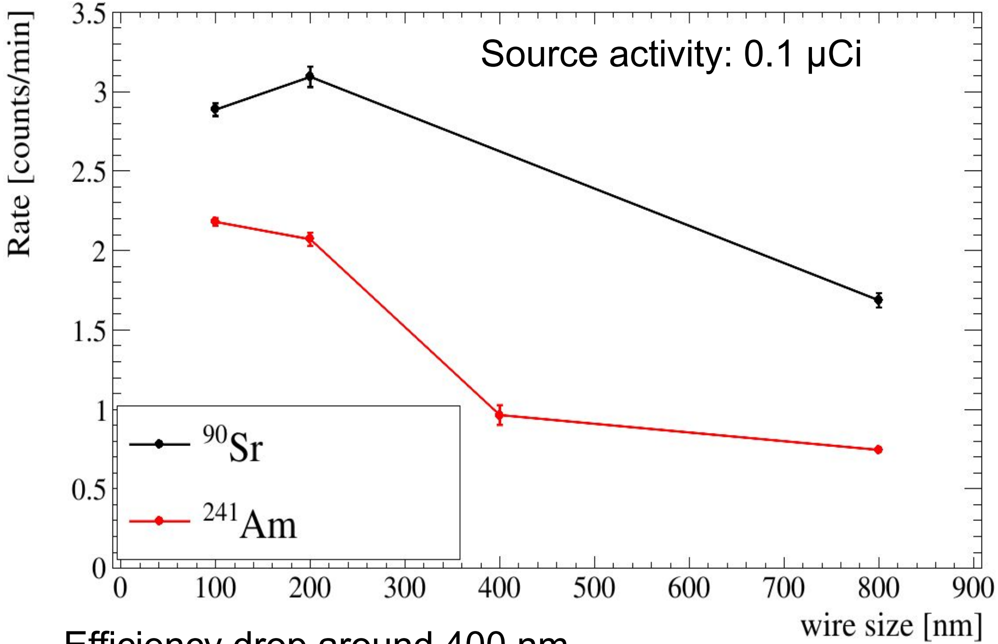
Contact lead

Fabricated by
Tomas Polakovic

Particle Detection with Radioactive Sources



Preliminary results looking at different pixel sizes with sealed sources



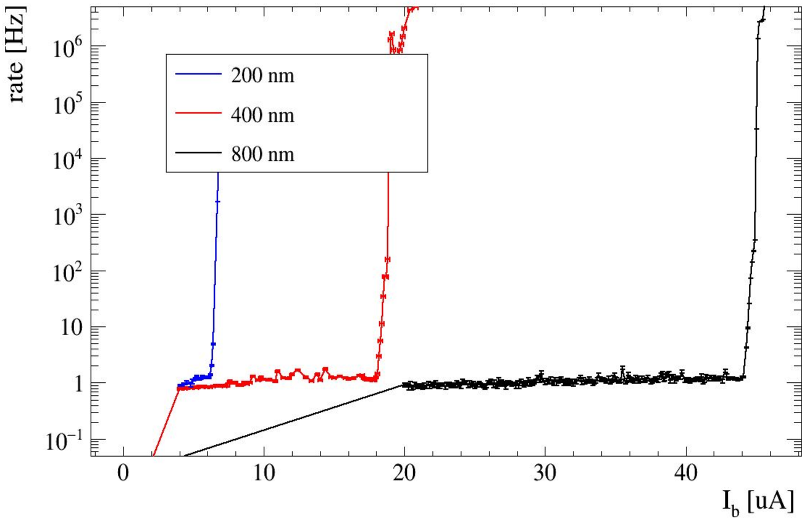
Efficiency drop around 400 nm.

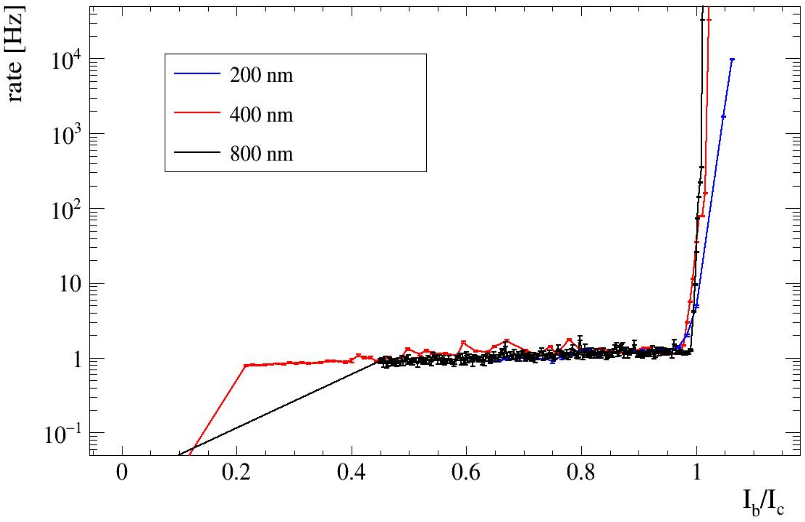
→ **Need to use higher activity source**

Preliminary Results with α Particles

Count rate vs. bias current

Source activity: 10 μCi



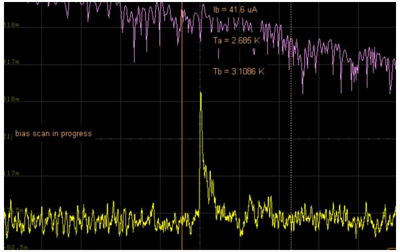


Limited by noise/interference at low bias currents → working to improve the SNR in this region
Should be able to detect α particles down low $I_b/I_c < 0.2$

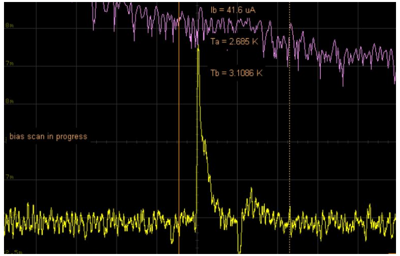
Preliminary Results with α Particles

A few different pulses with same bias current and 800 nm wire

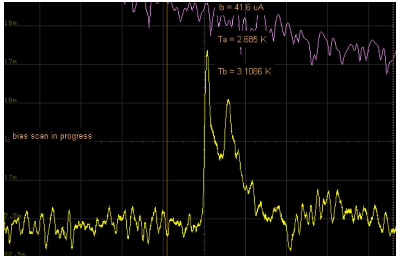
Dark count

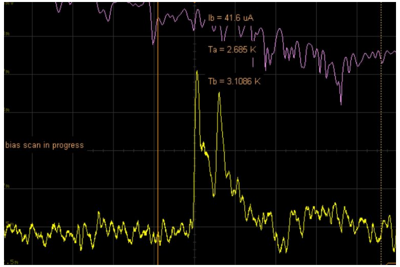


Large amplitude pulse

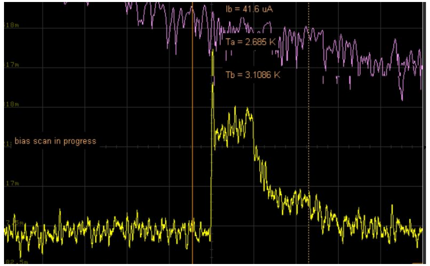


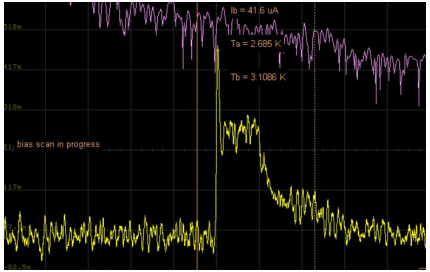
Double pulsing





Large pulse with tail

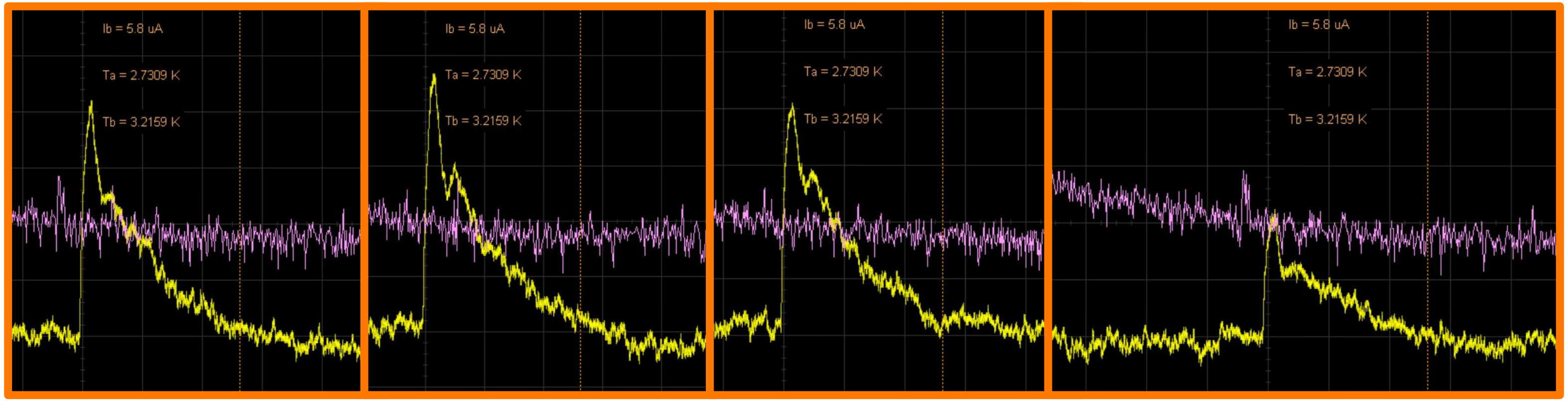




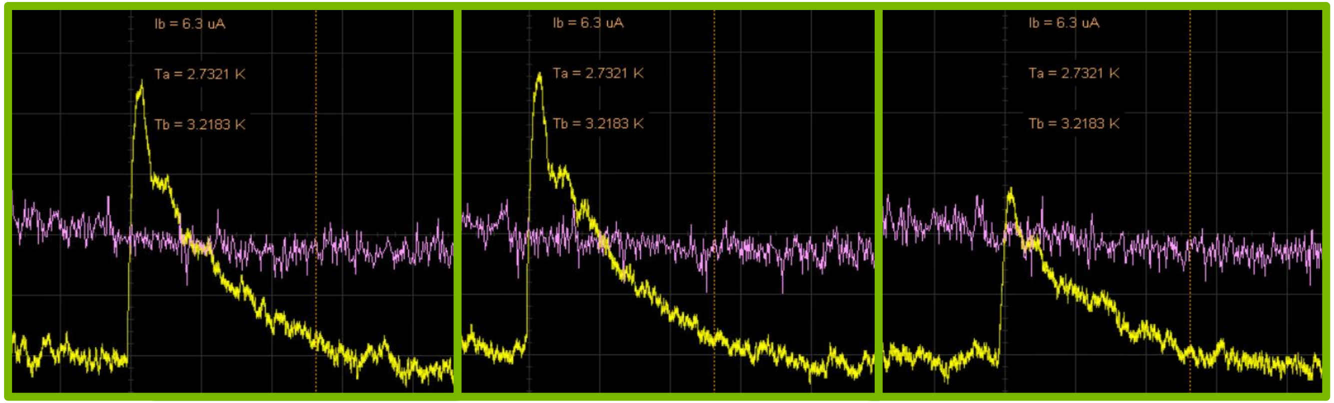
More Preliminary Results with α Particles

200 nm wire biased just below I_c

I_b= 5.8 μA



I_b= 6.3 μA



Note: the scope was BW Limited at 20 MHz

Particle Detection Status

At Argonne we have detected photons, alphas, betas

Particle	Energy	Approximate Energy loss in 100 µm silicon	Approximate Energy loss in 15 nm NbN	Detected
photon	0.1 eV - 2 eV	all	all	✔
alpha	5 MeV	5 MeV	9.1 keV	✔
beta	1 MeV	15 keV	15.8 eV	✔
electron	100 MeV	100 keV	~100 eV	?
proton	120 GeV	40 keV	24 eV	?
pion /muon	10 GeV	30-45 keV	~20 eV	

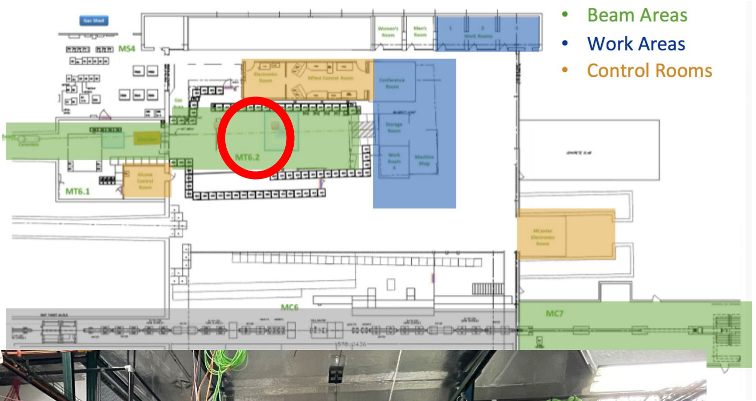
Demonstrating high energy proton detection is the key test needed for the EIC

No show stoppers expected…

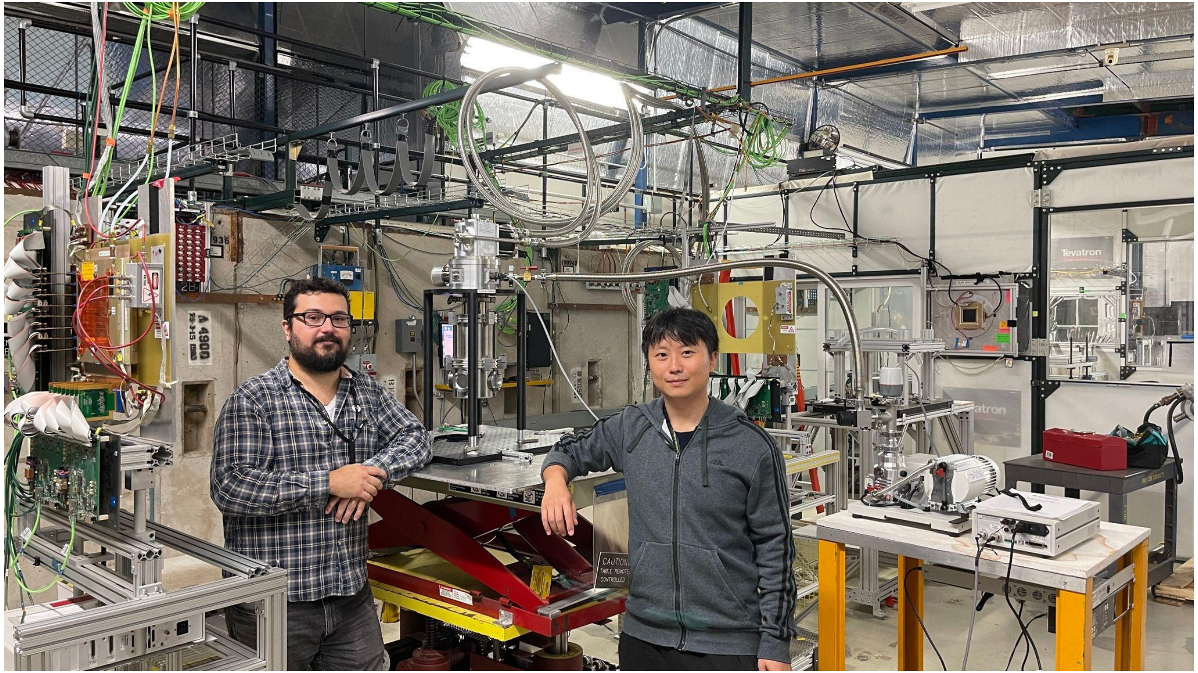
See Adam McCaughan's talk.

Fermilab Test Beam Facility

- We are ready to look at the 120 GeV proton as soon as they are ready to deliver beam
- Beam has been delayed until end of November.

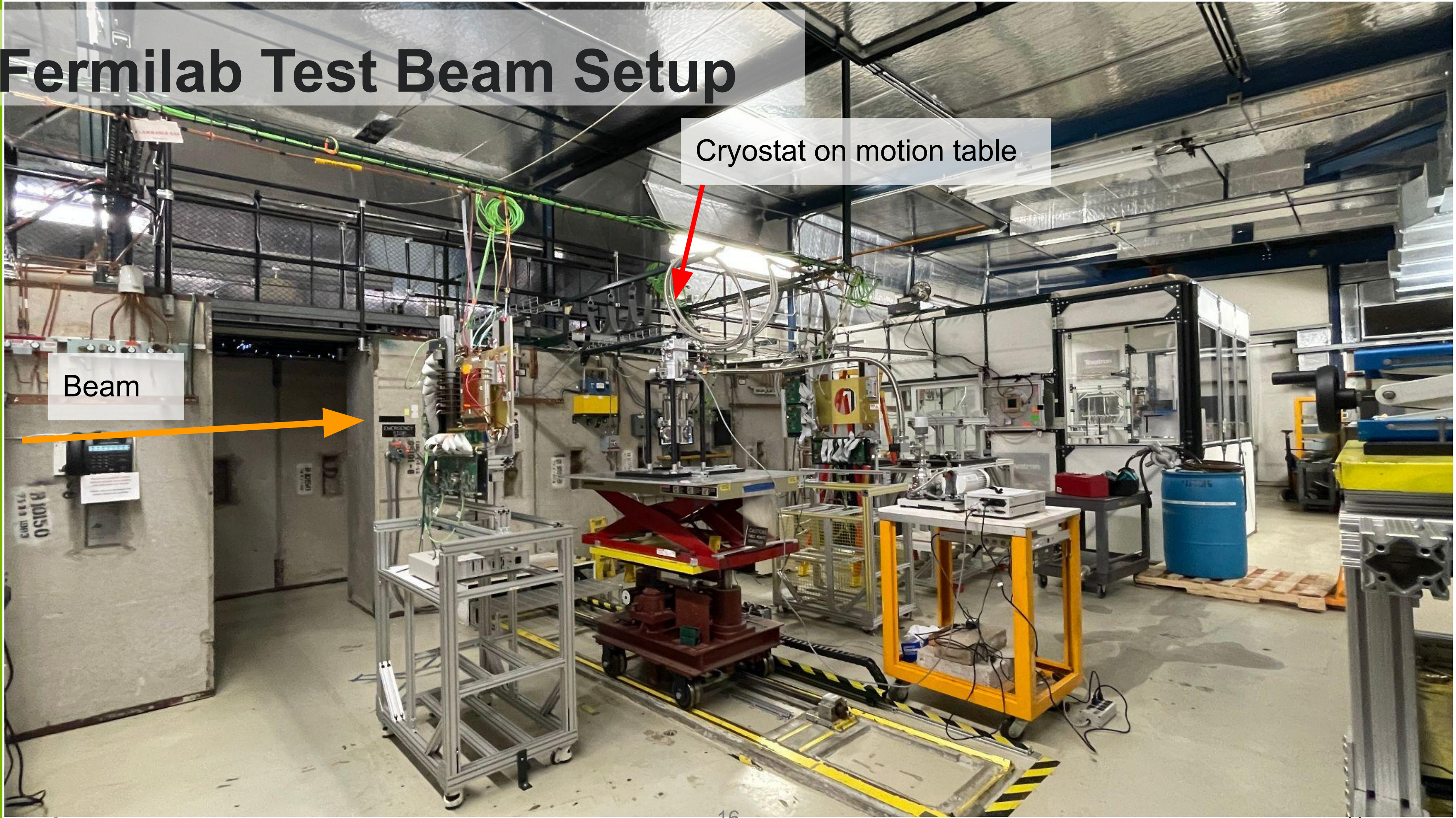


Setup for Operational Readiness Clearance (ORC)

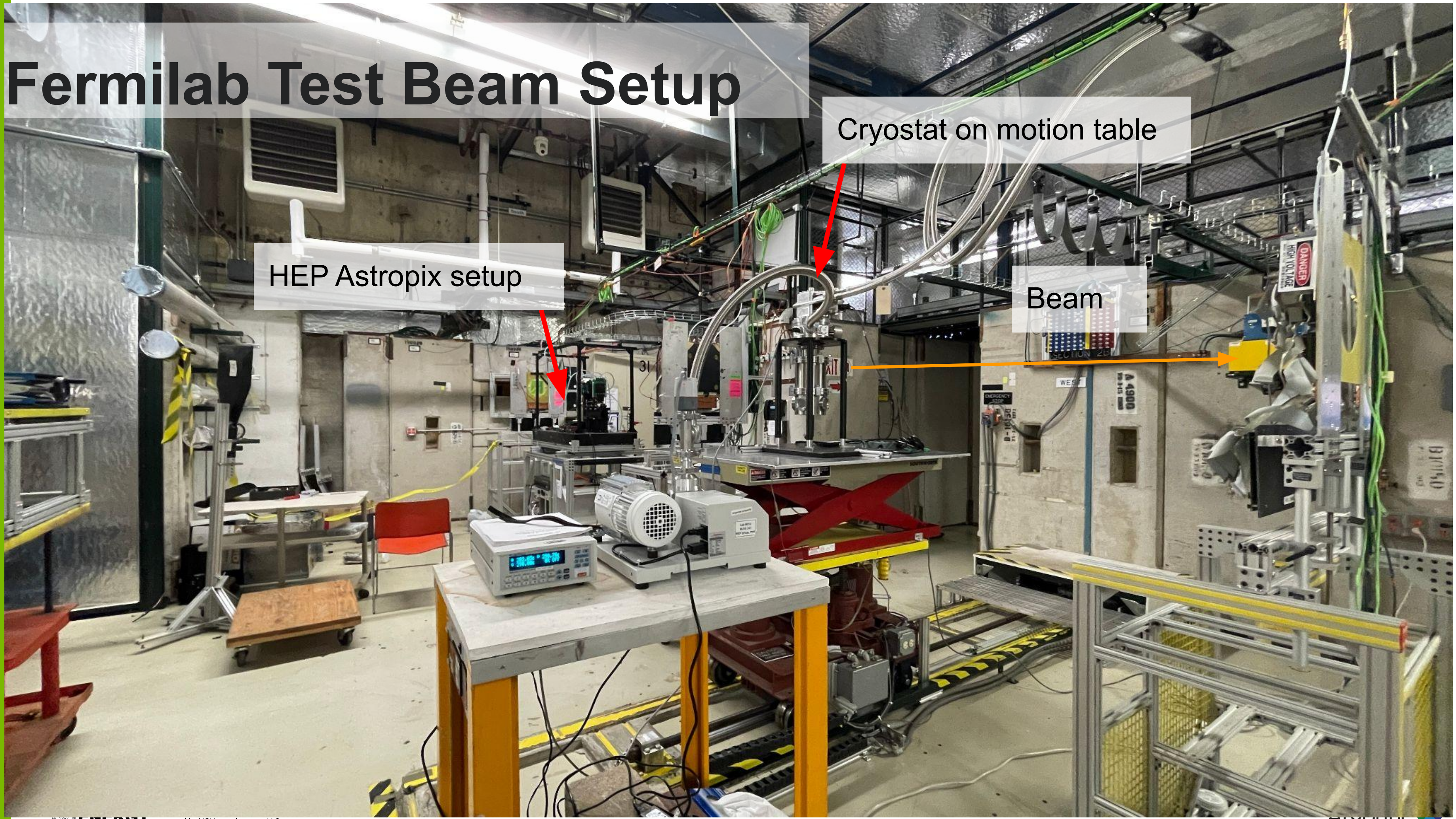


Sangbaek Lee is a new postdoc
at Argonne work on this R&D

Fermilab Test Beam Setup

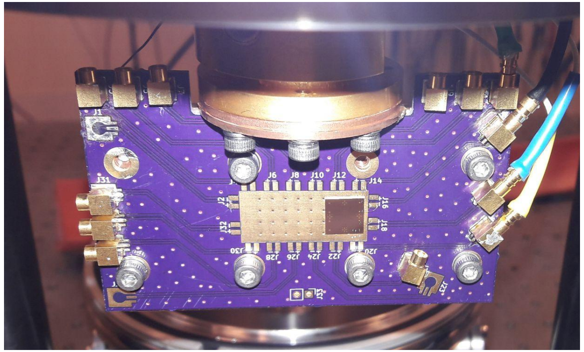


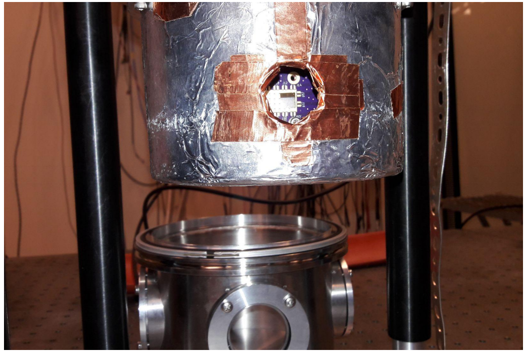
Fermilab Test Beam Setup

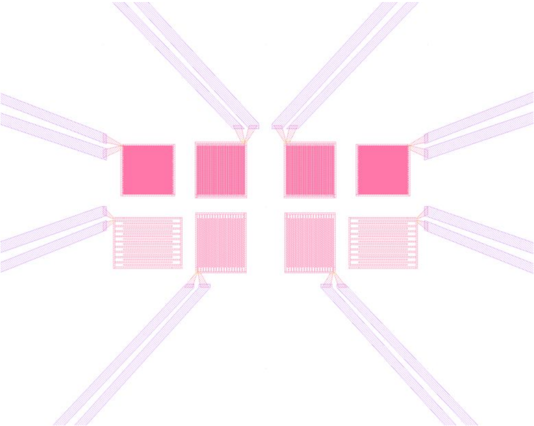


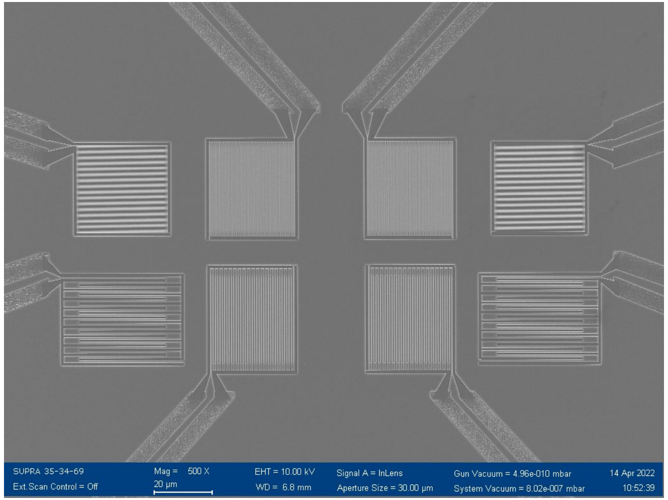
Test Devices

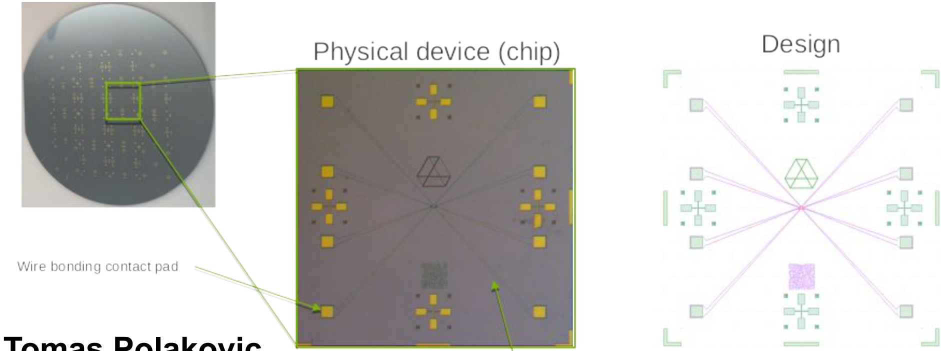
Device cold finger mounting PCB







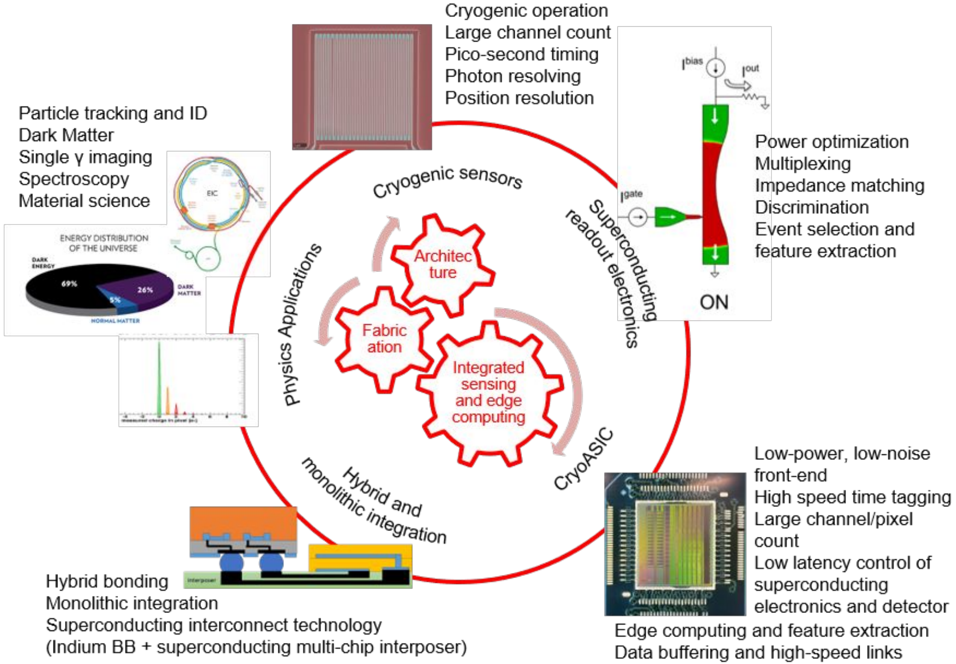




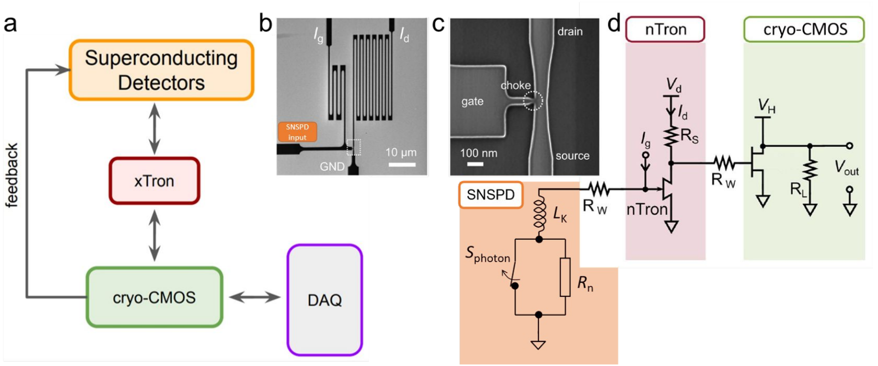
Tomas Polakovic

Hybrid Cryogenic Detector Architectures for Sensing and Edge Computing enabled by new Fabrication Processes

A microelectronics co-design project

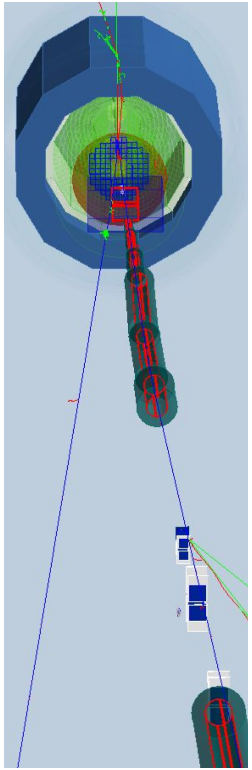


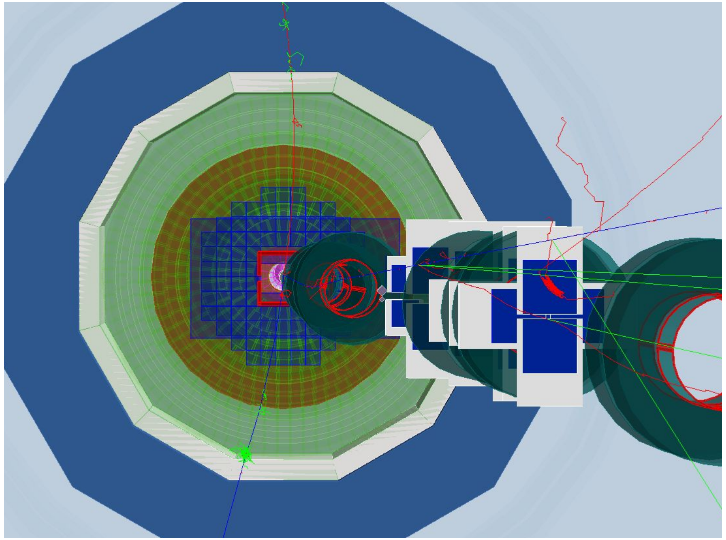
- Timely microelectronics R&D focused on cryogenic sensors and readout
- Project will produce first Cryo-CMOS ASIC for high channel count detectors at the EIC
- Fermilab is developing a cryo-CMOS ASIC architecture
- MIT is leading the development of superconducting electronics
- Argonne is leading the particle detector thrust
- JPL is investigating new interfacing technologies



SUPERCONDUCTING NANOWIRE DETECTORS FOR THE ELECTRON ION COLLIDER

Successful proposal (2020) for EIC Detector R&D at BNL: eRD28

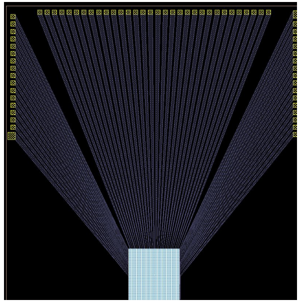


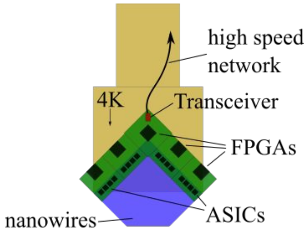


BNL EIC Detector R&D Committee:

Superconducting nanowires have never been deployed in a particle or nuclear physics experiment to our knowledge. As such, this proposal represents a true spirit of detector R&D. This project will have to solve many issues before it would have a working detector as indicated above. There are interesting synergistic activities with other projects under this program such as the polarimetry measurement. The idea to test a device in the Fermilab test beam and study the response to protons, electrons and pions is a very worthwhile exercise and would provide new information. We strongly recommend that at the least this aspect of the project is supported, funding permitting

- Will demonstrate the detection of low energy particles from radioactive sources at high rate and in high magnetic field.
- Fabricate a small pixel array for high energy particle detection



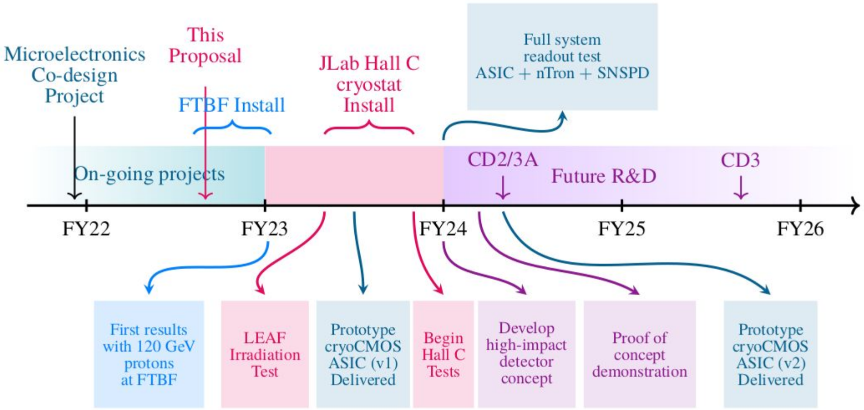


EIC-related Generic Detector R&D

Submitted in July 2022

- Proposed R&D radiation hardness tests of SNSPDs, superconducting electronics and cryo-CMOS

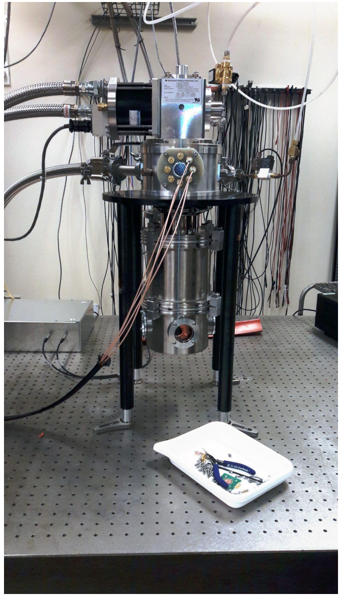
1. **Irradiation at LEAF (total of 1 week)**
   a. Radiation hardness of SNSPDs
   b. Measure onset of change in performance
   c. Identify upper limit for the onset of defects and device failure.



2. **JLab test-bed**
   a. Baseline background error rate for superconducting shift registers
   b. SNSPD efficiency in high radiation environment
   c. Single Event upset cross-section for prototype cryo-CMOS ASIC

High Radiation Environment Testing at JLab

- Establish cryogenic testbed at JLab (similar to one at FTBF).
- Located in Hall C near beam height, with 10 m Helium gas lines will connect to a water-cooled Helium compressor
- Will test SNSPDs, superconducting electronics devices, and cryo-CMOS prototype (if available)
- We look to quantify single event upset cross-section, displacement damage, and other cumulative damage
- Will monitor radiation exposure using SiPMs calibrated against neutron dosimeters and opti-chromic rods to produce estimates of the accumulated dose and scaled neutron fluence
- Run parasitically with location depending on running experiment environment



Irradiation at Argonne’s Low-Energy Accelerator Facility (LEAF)

Establish upper for radiation hardness

- Establish upper limit where significant radiation damage can be observed
- Determine at what neutron fluence do defects form in the NbN devices
- How do these defects change the critical currents and at what levels do devices fail?

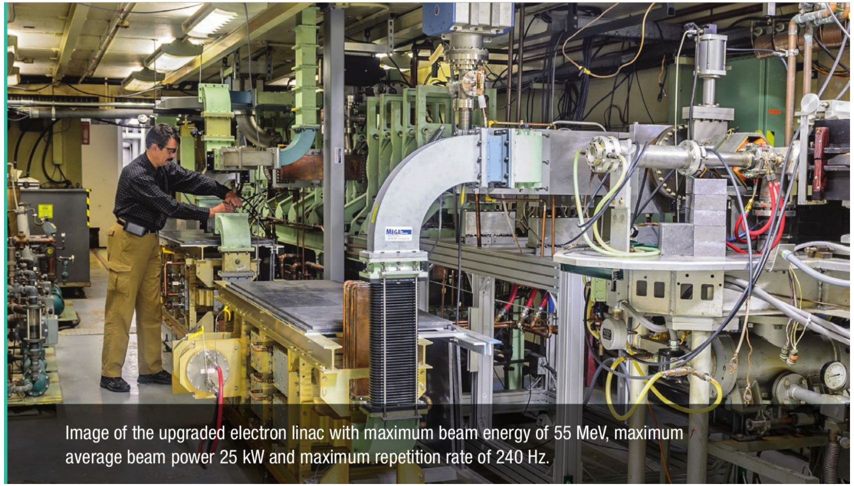


Image of the upgraded electron linac with maximum beam energy of 55 MeV, maximum average beam power 25 kW and maximum repetition rate of 240 Hz.

Year 1 Project Milestones

1. Install cryostat at JLab in Hall C (or A)
2. Run LEAF to irradiate SNSPDs at a various intensities and accumulated dose
3. Measure SNSPD background rate and dead time in high radiation environments
4. Measure bit error rate for superconducting shift registers for a number of environments
5. Measure the bit flip rate for the first prototype cryo-CMOS ASIC in high radiation environments

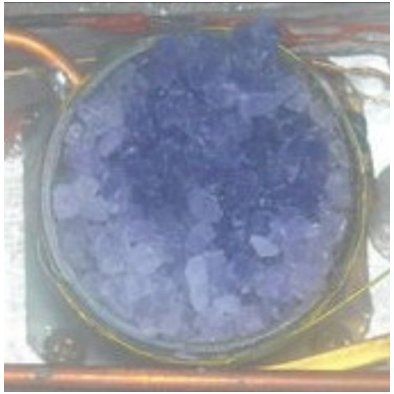
Deliverables

- Radiation hardness of SNSPDs characterized with upper limit for the onset of defects and device failure.
- Single Event upset cross-section for prototype cryoCMOS ASIC
- Bit-error rate for superconducting logic, counters and/or memory in high radiation environment
- SNSPD efficiency in high radiation environment

Applications in Nuclear Physics

An Active Polarized Target at JLab

Look at the figure of merit for a polarized target



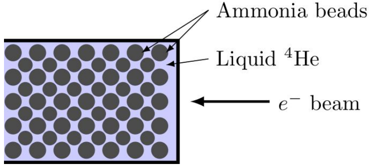
Time needed to measure an asymmetry with statistical uncertainty □A

$$t \propto \frac{1}{{P_T}^2}\frac{1}{f^2}\frac{1}{\delta A^2}$$

$$F.o.M. = f^2 P_T^2$$

$$df(W,Q^2) = \frac{N_p\sigma_p(W,Q^2)}{N_p\sigma_p(W,Q^2) + \sum_i N_i\sigma_i(W,Q^2)}$$

- F.o.M. depends on target polarization Polarized ND_3 and the target dilution factor
- Dilution factor is the ratio of cross sections from polarized target material to everything else.
- Typical dilution factor is on the order 15 - 30% depending on how you slice it
- Active target is designed to identify events scattering from polarized material → f = 100%
- F.o.M. improved by a factor of 25 to 80!



Measuring the Neutron Spin Structure Function

The polarized EMC effect for the neutron g_1^n

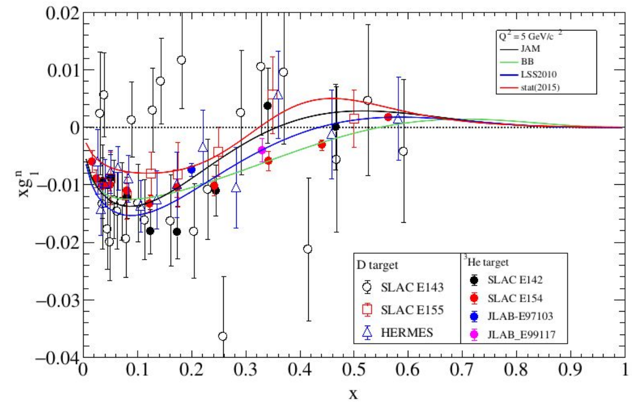
The polarized EMC effect in the neutron is challenging:

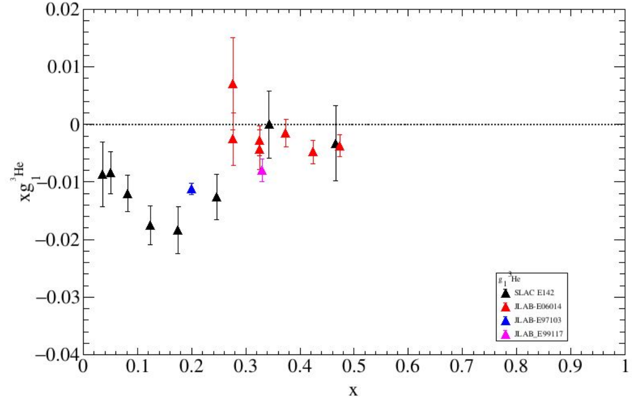
- Sign change in g_1^n (x), location of zero crossing not well constrained.
- Extraction of g1n from ^{3}He and D is very different.
- D has a large subtraction of g1p, ie:

$$g_1^n \simeq \frac{2}{1-1.5\omega_D} g_1^d - g_1^p$$

- ^{3}He spin is dominated by polarized neutron but is more deeply bound nuclear system:

$$g_1^n = (g_1^{^3He} - 2P_p g_1^p)/P_n$$
$$P_n = 0.879 \text{ and } P_p = -0.021$$

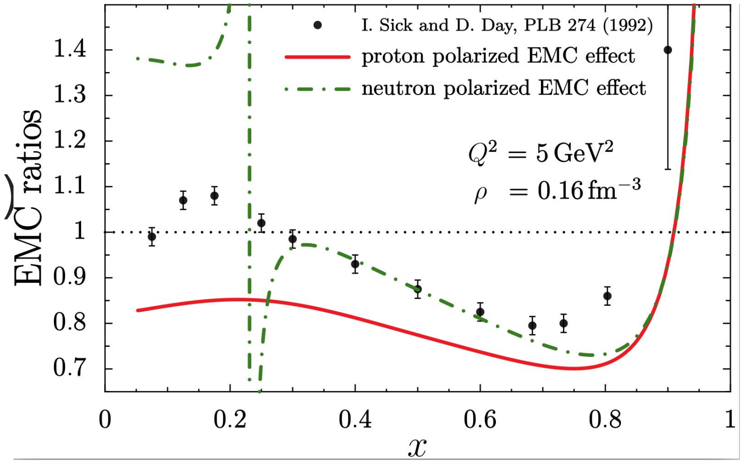


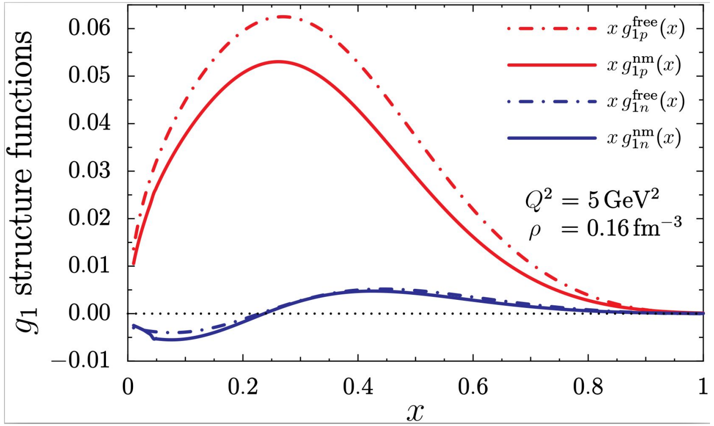


Polarized EMC effect

Looking at the neutron

- Active polarized neutron target complements polarized ^{3}He target in CLAS12 (C12-20-002)
- Measure the best "free" neutron spin structure function with the deuteron
- Form the pEMC ratio with the ^{3}He in numerator
- Is the zero crossing of g_1^n useful to measure?
- Sensitive to non-nucleonic degrees of freedom





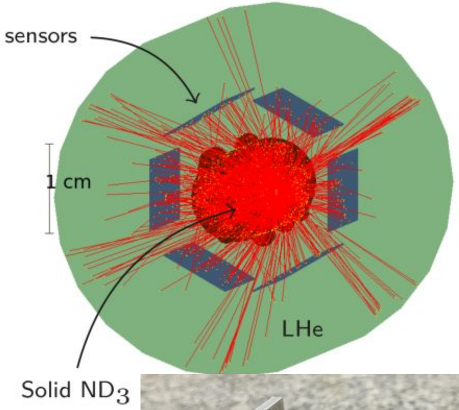
$$R_{As}^{^3\mathrm{He}} = \frac{g_1^{^3\mathrm{He}}}{P_n g_1^n + P_p g_1^p}$$

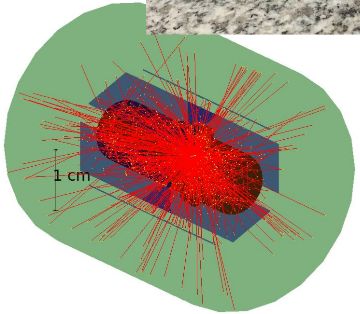
I. C. Cloet, Wolfgang Bentz, and Anthony William Thomas. EMC and polarized EMC effects in nuclei. *Phys. Lett. B*, 642:210–217, 2006.

An Active Polarized Neutron Target Concept for CLAS12

SNSPDs are the enabling technology for concept

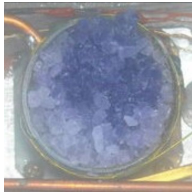
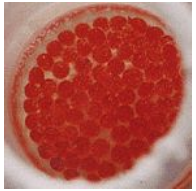
- Detect the recoil spectator proton in polarized deuteron: eliminate large dilution
- Only photon detectors needed
- Challenge: Optical properties of polarized target material
- Previous attempts at Mainz struggled to detect a few photons guided out of the cryostat
  - Was both a detector and target material challenge
  - SNSPDs solve the cryogenic detector problem
- Can we use the standard material for JLab: ND3
- Replace walls of target cup with SNSPD devices
  - Can a 5 MeV proton recoiling in the standard ND_3 target produce enough photons to escape to the cup permeter?
  - Range in LHe is about 0.5cm
  - Would introduce little new material to the RGC target.



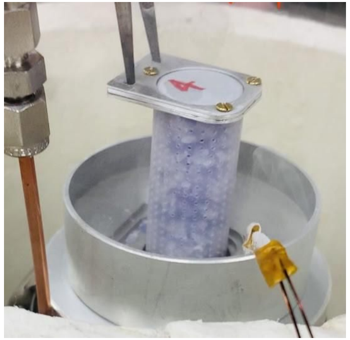


Polarized Target Material

Finding the best material

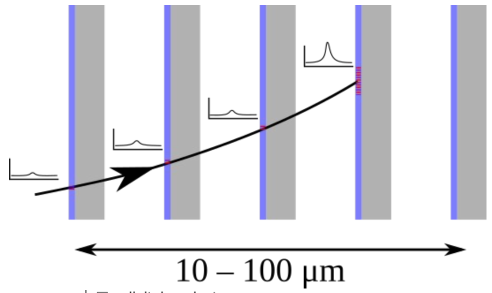




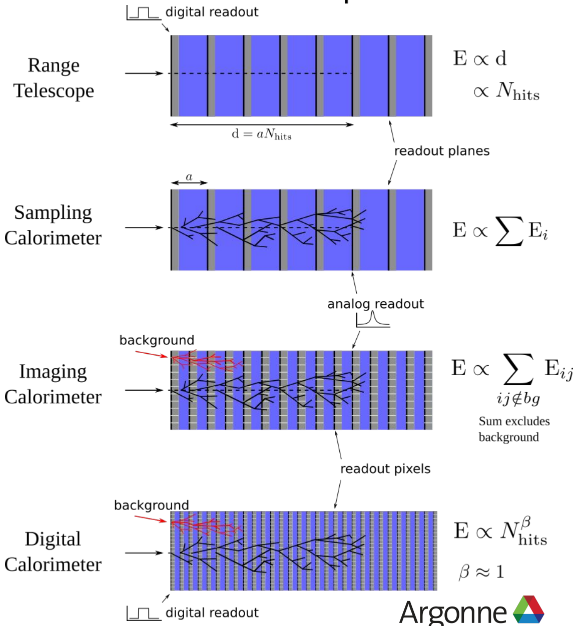
Material	Pros	Cons
ND_3	Used for RGC	beads and optical properties not well understood
d-Butanol	easy to polarize	radiation damage
d-Polyethelene	mechanically sound, easy to polarizem,optical properties favorable	radiation damage unknown
LiD	Easily formable, radiation hard	relatively opaque

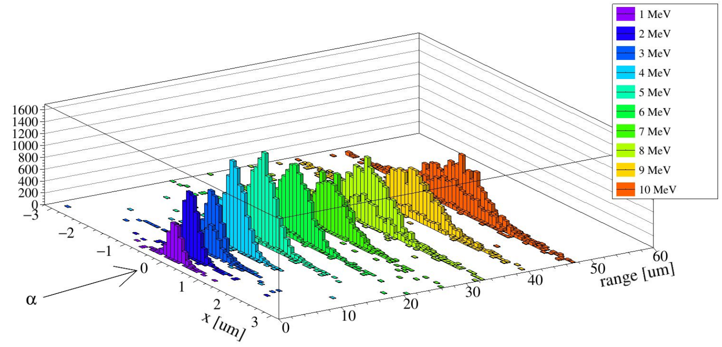


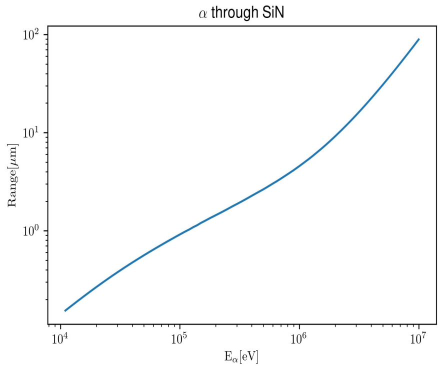
Micro Range Telescope for Active LHe Target

- Measure kinetic energy of recoils
- # layers, material thickness and size depend on application
- Alpha recoil: low density, few um spacing
- Low energy proton recoil: few 10s um spacing
- Vertexing/tracking for higher energy particles
- Alternatively, leverage scintillation properties of LHe and excellent SNSPD time resolution to create ultrafast photon TPC









Motivation of building Nanowire Particle Detector

- GPD physics requires the momentum transfer $|t|/Q^2$ to be small.
- Lower limit determined by

  (1) $|t| > |t_{min}|$: physical threshold

  (2) the detector acceptances

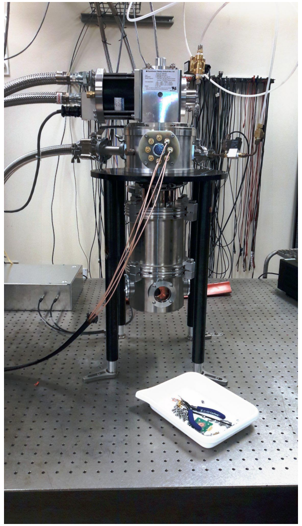
- Scattered protons
  - p_T > 0.2 GeV/c is equivalent to $|t| > 0.04$ GeV^2

- Scattered nuclei (coherent DVCS and DVMP)
  - Larger room between $|t_{min}|$ and the detector acceptance limit

- Aligned with Roman Pot requirements reported in YR
  - Fast timing
  - Radiation hardness
  - Fine position resolution

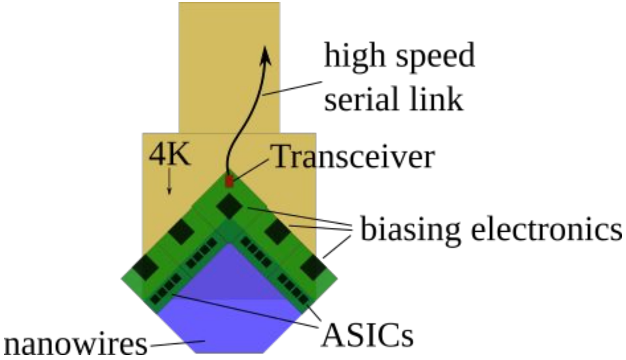
Cooling infrastructure

Please provide some idea of the infrastructure that would be needed to cool the detectors to superconducting temperatures without interfering with the primary beam.



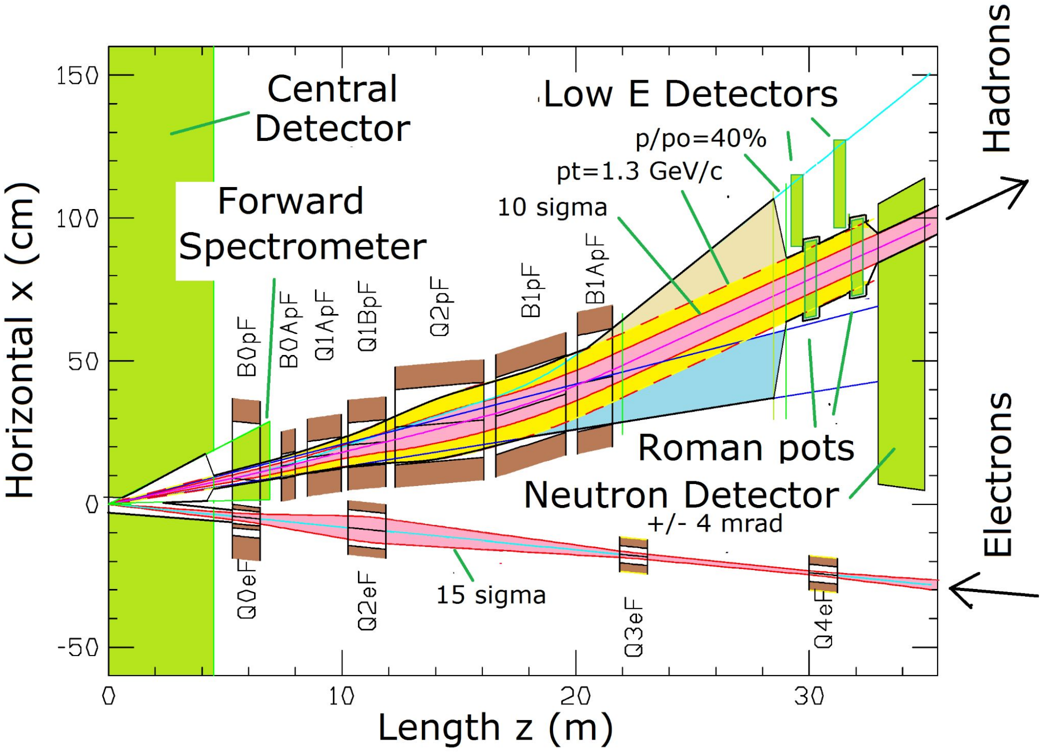
- Our nanowire detectors operate at LHe temperatures ~4K
- We can tap into the upgraded 4.5K and 2K cryosystems for the EIC at BNL
- A conservative estimate for a wire is roughly 20 nW when it is latched – normal conducting with most current going through shunt resistor
- The total power of the sensors does not necessarily scale with area – it is set by the number of wires
- With a detector area of 25cm x 10cm, if all sensors latched (a malfunctioning detector with 100% occupancy), the cryosystem would see a load of ~0.5 W.

Conceptual layout of beamline detector



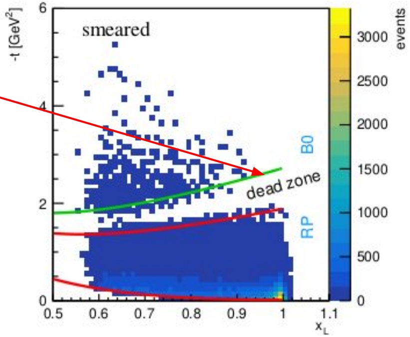
Far Forward Detector

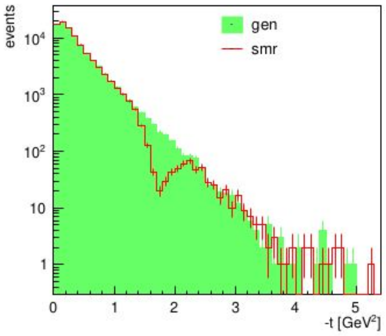
- We can use nanowire tracking detectors in a Roman pot configuration
- Ultrafast timing – demonstrated to be less than 20 ps
- Small basic pixel size, allowing for µm position precision if needed.
- Edgeless sensor configuration – sensitive element positioned to within a few 100 nm of the substrate
- edge, eliminating detector dead zone.
- Wide choice of substrate material – the detectors can be fabricated on membranes as thin as few 10 µm, cutting down on material thickness.
- Radiation hardness – operate in close proximity of the beam and interaction regions with long lifetime. (A focus of the proposed R&D)



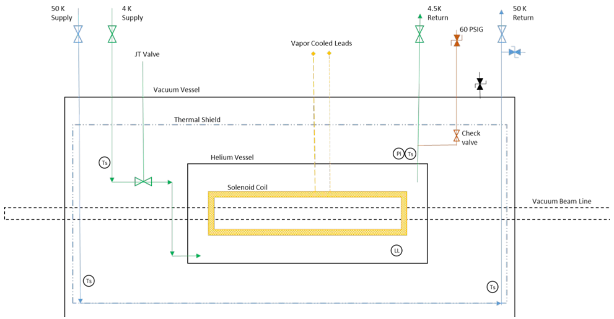
Superconducting Magnet integrated particle detector

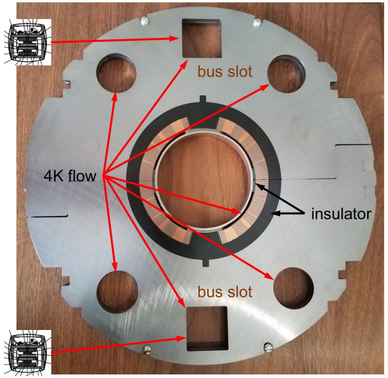
- Avoid the “dead zone” between roman pot detectors and B0 detectors
- Tie into superconducting magnets’ 4K supply
- Design a mechanical/thermal mounting location in the bore of the magnet





From Figure 8.125 of YR





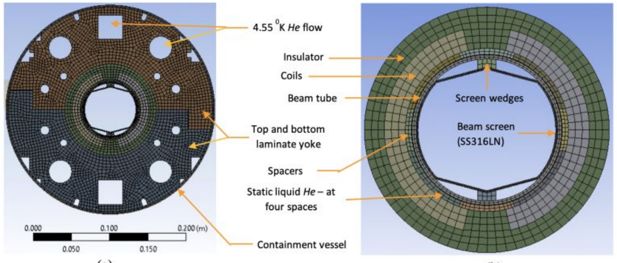
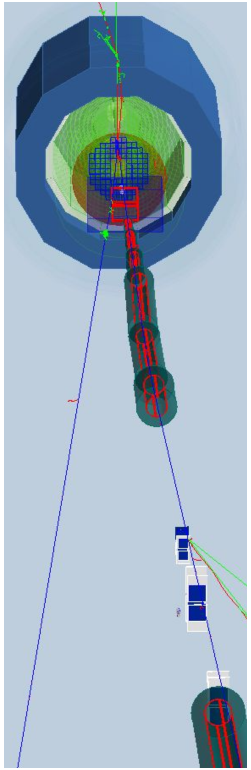


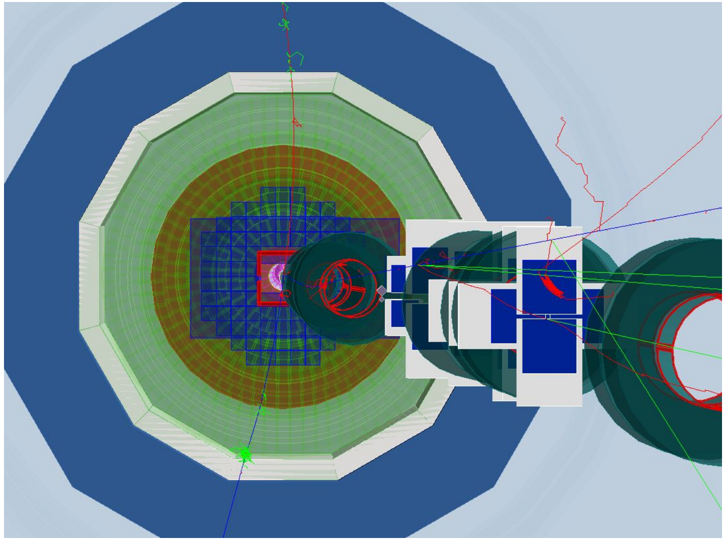
Figure 6.148: Finite-element model of (a) the RHIC arc dipole magnet cold mass cross-section and (b) close view around the beam tube.

SS Vacuum Pipe Beam Screen - Copper liner (coated with carbon to reduce secondary electron yield)

Neutral particle detector

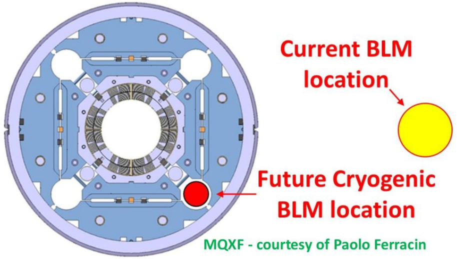
- A radiation hard pixel detector could provide useful tracking for the ZDC
- Also a photon (or electron) detector for compton polarimeter which can operate at high rate and last the lifetime of the EIC.





Beam Loss Monitors at Accelerators

Requirements of Cryogenic BLMs



Mechanical requirements:
- total radiation dose of 2MGy,
- low temperature of 1.9K,
- 20 years, maintenance free operation,
- resistance to magnetic field of 2T,
- resistance to a pressure of 1.1 bar, and capability of withstanding a fast pressure rise up to 20bar in case of a magnet quench.

Electronic requirements:
- direct current readout,
- response linear between 0.1 and 10 mGy/s, and
- response time faster than 1 ms.

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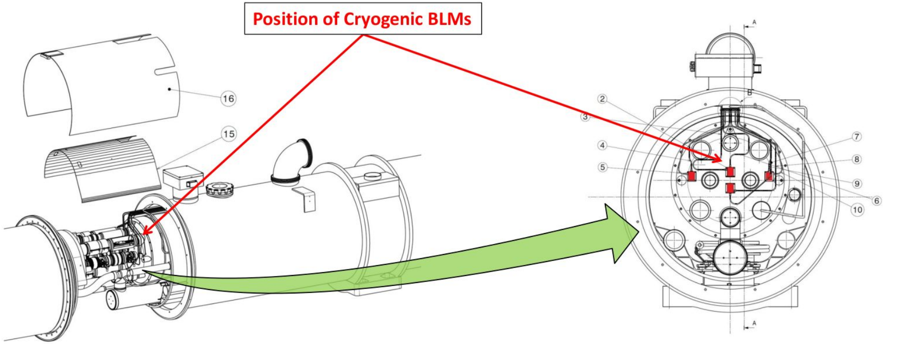
Cryogenic BLMs in LHC ring



Long term correlation between Ionization Chamber BLM and Cryogenic BLM to be done in 9R7 and 9L5

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Anticipate similar applications at the EIC

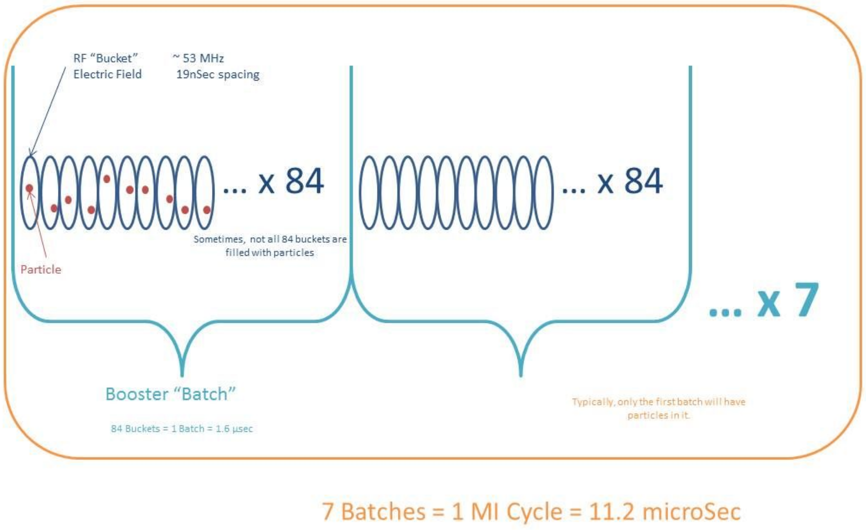
Summary

- Particle detection testing is underway
- First Fermilab test beam results expected very soon
- Working towards EIC physics applications
- Just the start of SNSPDs in NP!

Thank you!

Backup

FTBF Proton Beam Overview



Creating the beam

750keV H-minus ions are extracted from the source into the Linac. The Linac accelerates the ions to 400MeV, and then extracts them to the Booster Accelerator. As the ions are injected into the Booster, the electrons are stripped off leaving 400MeV protons to circulate in the Booster.

The Booster captures the protons into 84 bunches (1 batch) and accelerates them to 8GeV. Each of these bunches is 19 nsec long. Typically, 8 – 30 of these bunches are extracted to the Main Injector for Test Beam operation (a process known as partial-batching.) At the injection total energy of E = 8:938 GeV, the **Main Injector has a circumference in time of T0 = 11:13 µs**, which is exactly 7 booster batches long.

The Main Injector accelerates the beam to 120GeV at a frequency of **53 MHz**, at which point a process called Resonance Extraction is started and a fraction of the beam is resonantly extracted in a slow spill for each Main Injector rotation.

Max. rates at adjacent 'bucket'

- 53 MHz

Realistically,

- 8 – 30 protons in 1 batch (84 buckets)
- ~ 20 MHz

Beam size ~ 1 cm

Flux ~ 0.2 Hz/ µm^2

Rates (pulsed) for 30x30 µm^2 ~ 200 Hz

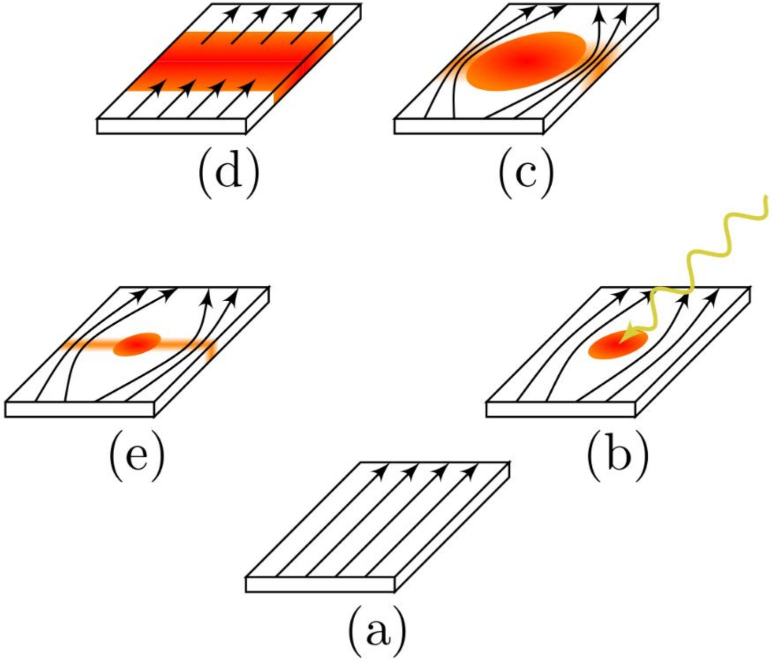
Rates averaged over spill ~ 30 Hz

Rates averaged over time ~ 2.1 Hz

SUPERCONDUCTING NANOWIRE (SINGLE PHOTON) DETECTORS

A modern take on the bubble chamber

- Excited pair of quasi-electrons has a massive amount of excess kinetic energy
- Rapid scattering on other (condensed) electrons and the lattice will spread the energy and heat up the system locally -> there's a high-concentration region of quasi-particles
- Quasi-particles diffuse outwards and scatter, creating a secondary population of quasi-electrons which suppresses the superconductor across the structure
- Eventually, current density becomes too large and the superconducting state collapses
- Electrical resistance of the detector changes from 0 Ω to ~1 M Ω
  - This can be easily measured by a two-wire measurement

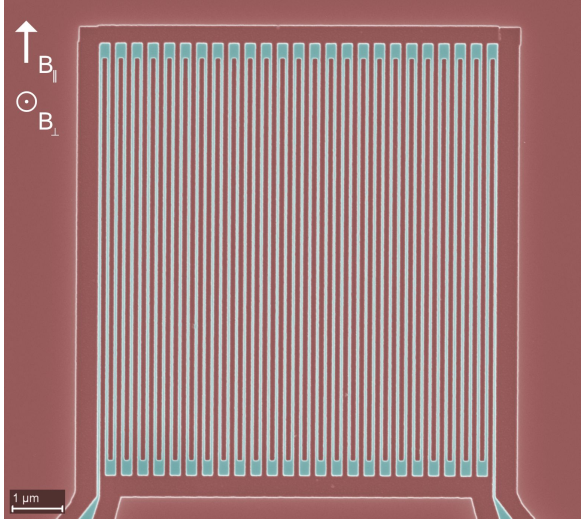


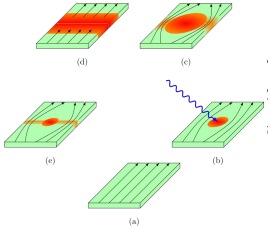
Polakovic, Nanomaterials (2020)

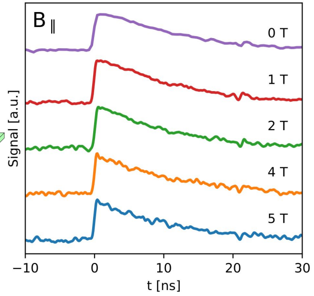
SUPERCONDUCTING NANOWIRES

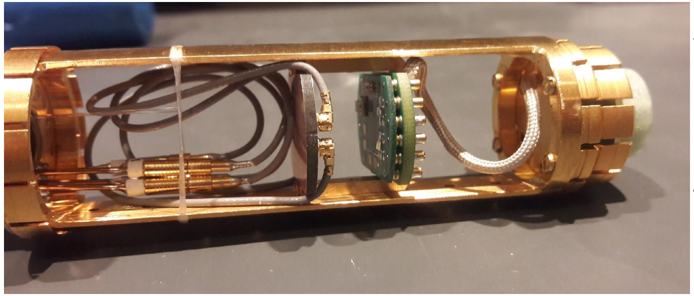
Overview of Nanowire Detectors

- PHY-MSD Collaboration supported by DOE-NP (FWP-32537.2)
- Sensors can operate in fields up to (at least) 7T, can operate inside of cold bore of superconducting magnets (T< 5 K).
- Argonne nanowire sensors fabricated on-site.
- Novel concept for high-resolution rad-hard detectors based around superconducting nanowires (early R&D stage)
- Near-beamline detectors for tagging low energy recoils (Jlab) in the far-forward region (EIC).
- Developing readout electronics for cold environments





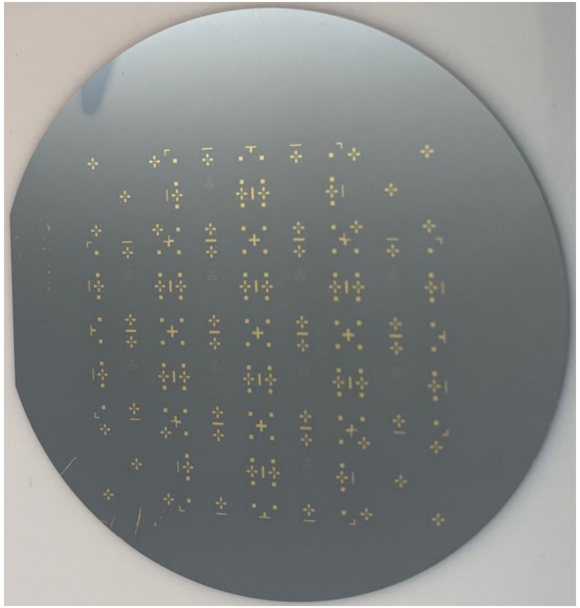


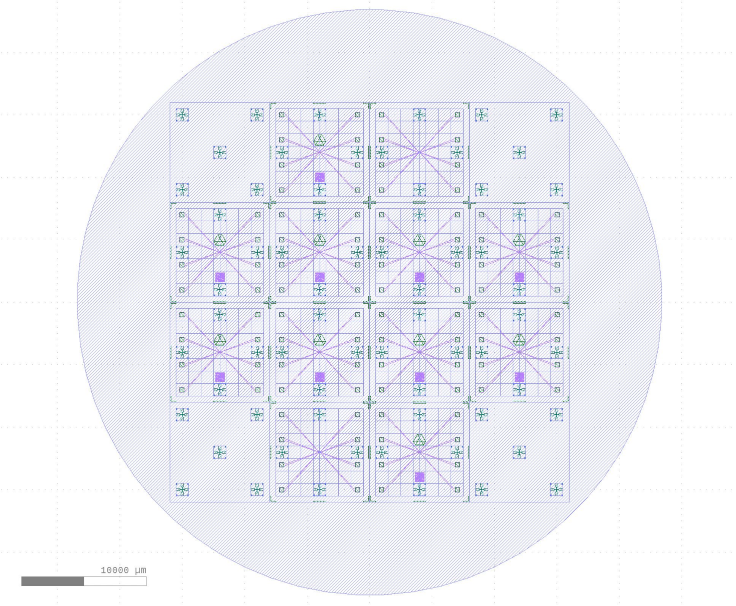


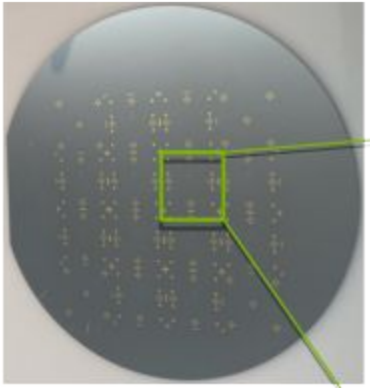
1) *Room temperature deposition of superconducting Niobium Nitride films by ion beam assisted sputtering*. APL Materials 6, 076107 (2018)
2) *Superconducting nanowires as high-rate photon detectors in strong magnetic Fields*. NIM A 959 (2020) 163543
3) *Unconventional Applications of Superconducting Nanowire Single Photon Detectors*. Nanomaterials (2020), *10*, 1198.

2-inch wafer

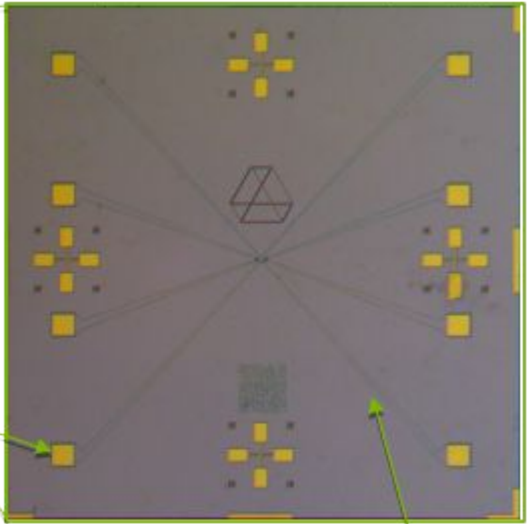
8 mm chips



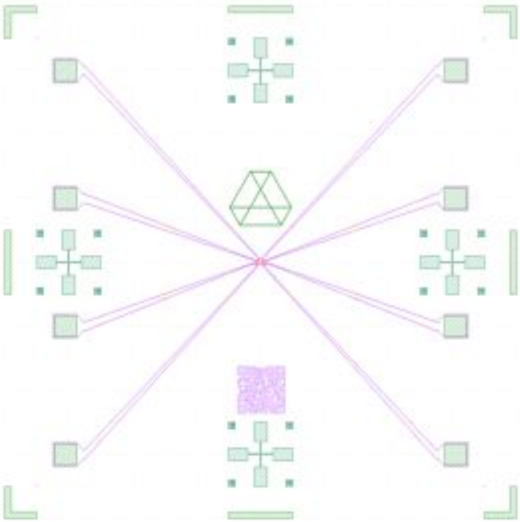




Physical device (chip)



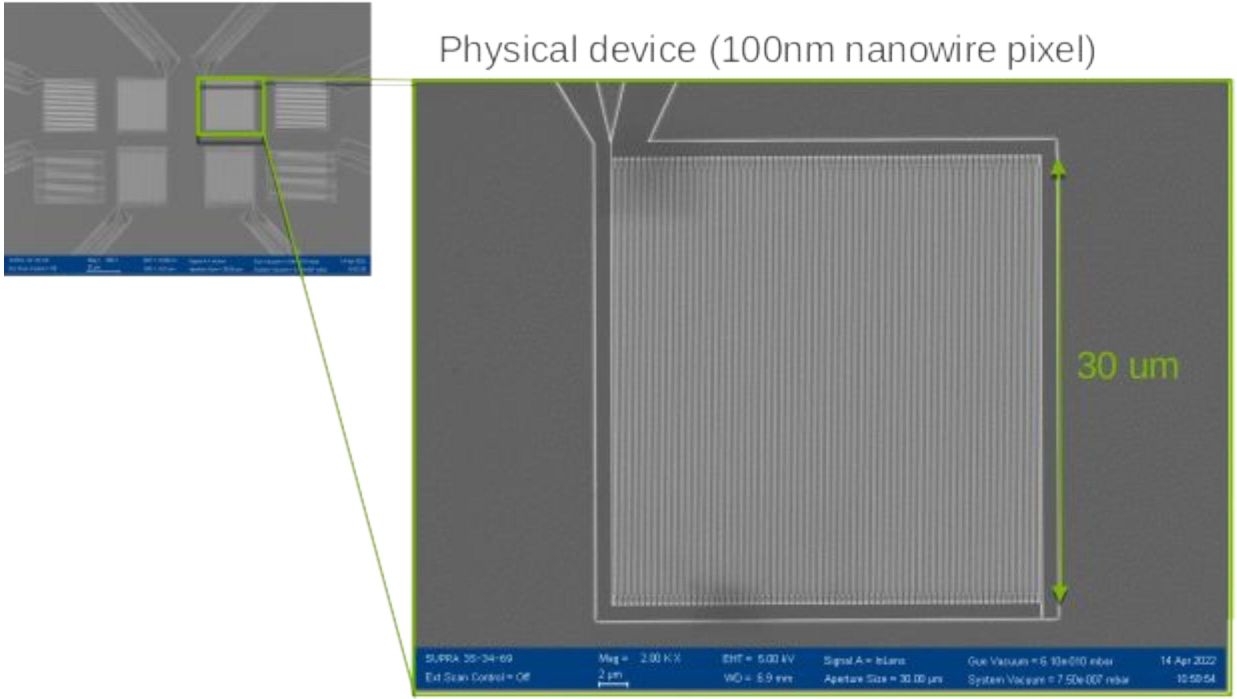
Design



Wire bonding contact pad

PROJECT OUTCOMES

Physical device (100nm nanowire pixel)



Design