Superconducting Nanowire Particle Detectors for the EIC

EIC-related Generic R&D

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Massachusetts Institute of Technology

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JPL

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Jefferson Lab

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Overview

- Questions from the Assigned Readers

- Proposal
  - Overview
  - Progress Report
  - Applications at the EIC
  - Proposed Plans
  - Timeline, Deliverables, and Budget

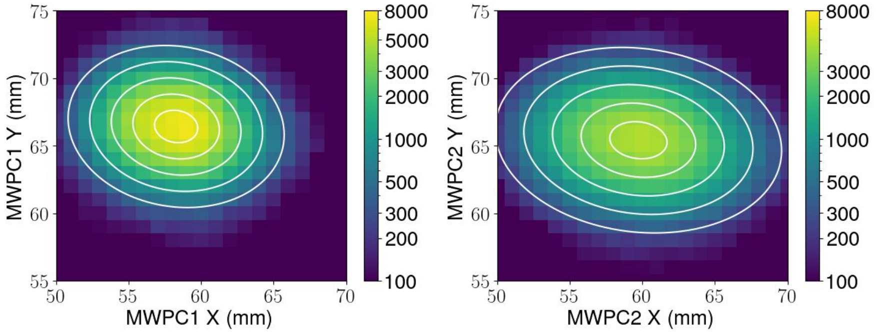
- Q&A

Questions from the Assigned Readers

Question 1. Details about the beam test at FTBF

What was the proton hit rate in the active area of the sensor in Hz?

- Beam
  - Typically, 1M proton per spill (maximum) requested and delivered.
  - Fermilab pulsed beam's spill is 4.2s long, and has 1 minute period.
- Acceptance
  - We used MWPCs that has $1/\sqrt{12}$ mm resolution in x and y, but the sampling rate of the device is too low to perform coincidence measurement.
  - The center of the beam was not controlled well enough to measure the absolute efficiency.
  - Unfortunately, MWPC3, closest to our cryostat didn't work properly.



- Active region is 30μmX30μm.
- Beam radius ~ 5.5 mm in X, 4 mm in Y.
- Rate ~ 1.6 Hz during the spill @ center

  ~ 0.5 Hz if off by 5 mm

  ~ 0.013 Hz if off by 10 mm.

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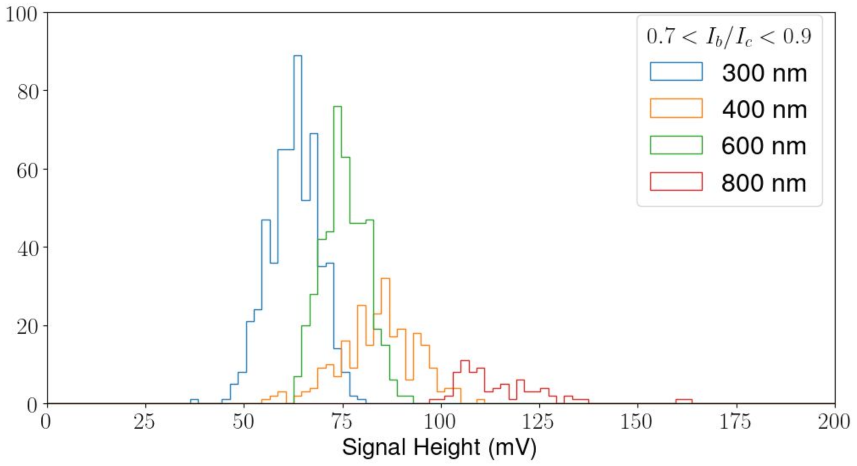
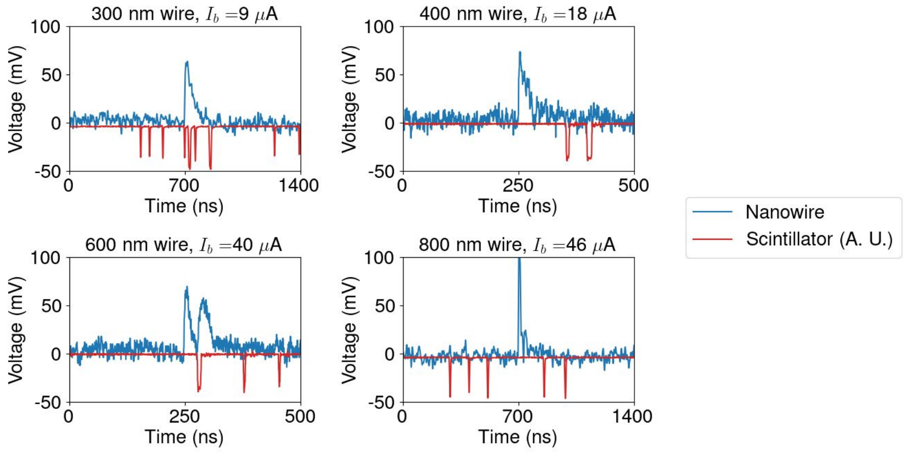
Question 1. Details about the beam test at FTBF

Please provide signal height/amplitude spectrum for proton hits

- The signal height spectrum depends on the wire size and the bias current.
- Left: histograms of signal heights for the same Ib/Ic range
- Right: An example of waveforms for each nanowire

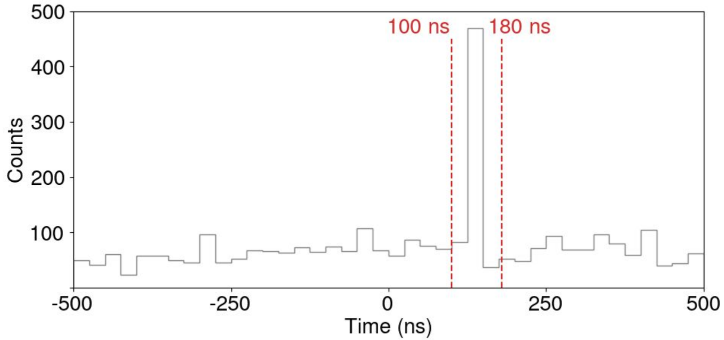


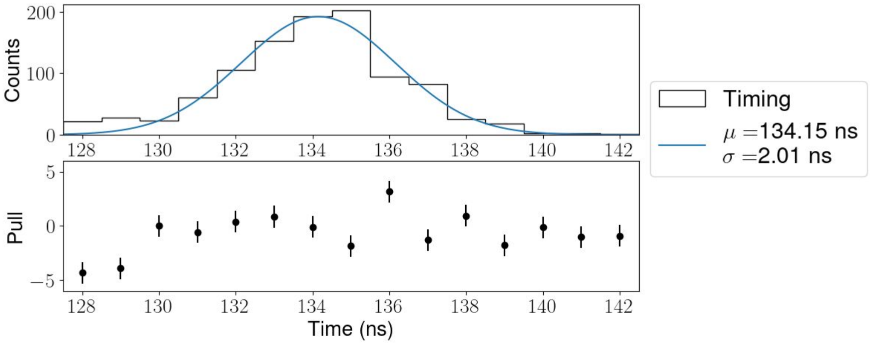


Question 1. Details about the beam test at FTBF

Is it possible to extract timing resolution from this data?
Could you measure the absolute detection efficiency in the future tests?

- The timing resolution was limited by the electronics for plastic scintillators, whose main purpose was to count the protons, not to provide the exact timing.
- As mentioned in the slide 4, there is a limitation in performing the single particle coincidence measurement.
- MWPC doesn't provide the timing.
- This motivated us to perform the next measurements with the silicon telescope or at the high rate tracking area.
- We are discussing the FY24 schedule of the FTBF with the facility managers.





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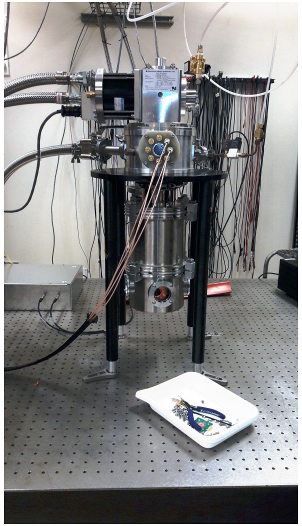
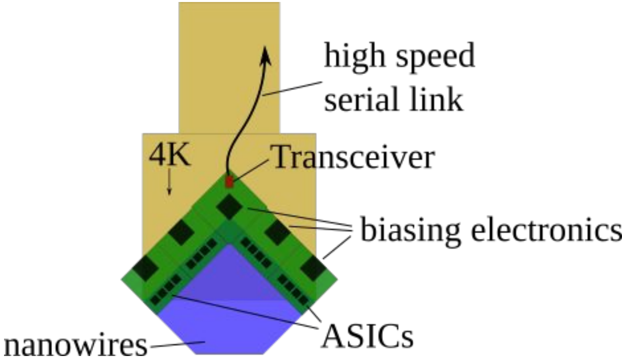
Question 2. Cooling infrastructure

In the windowless Roman pot detector application (Concept 1) and B0 tracker application (Concept 2), is there any concern for maintaining a 4K temperature, which includes beam-induced heating and synchrotron radiation absorption?

- Our nanowire detectors operate at LHe temperatures ~ 4 K
- We can tap into the upgraded 4.5 K and 2 K 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) it would load the cryosystem with ~0.5 W.
- We don't expect the Concept 2 that is using the cold mass suffers from the beam-induced heating.
- Concept 1 - the RP configuration will require a careful analysis and collaboration with the accelerator physicists



Conceptual layout of beamline detector

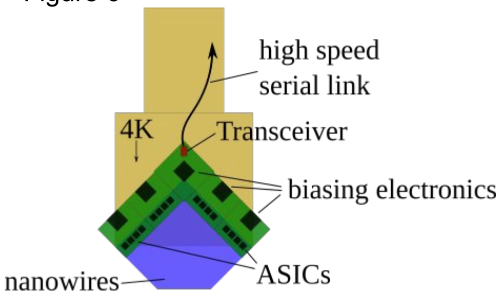


Question 3. Challenging steps in Integration

Assuming the proposed research is successful, please provide an envisioned technical-driven timeline and milestones toward a full-sized sensor as shown in Figure 6. Please comment on the most challenging step(s).

- We have provided the timeline for this proposal.
- Suppose that the prototype ASIC+nTron+shift register+nanowire sensor is successful, the path forward is packaging and integration in FY25.
- HYDRA collaboration has made main progress towards the realization of the full-sized sensor.
- Realizing a full-sized detector (Figure 6.) will require significant investment in scaling up fabrication areas. This is a known but solvable engineering challenge ($$)

Figure 6



1.	Purchase a cryostat to be installed at JLab in Hall C (or A)	Aug. 2023
2.	Prepare to operate the SNSPD with prototype cryoCMOS ASIC (v1)	Dec. 2023
3.	Install cryostat at JLab in Hall C (or A)	Jan. 2024
4.	Measure SNSPD background rate and dead time in high radiation environments. Measure the bit flip rate for the first prototype cryoCMOS ASIC in high radiation environments. Measure bit error rate for superconducting shift registers for a number of environments.	
-	Run LEAF to irradiate SNSPDs at a various intensities and accumulated dose.	Feb. 2024
-	Begin to run JLab High Radiation Environment testing	Mar. 2024
5.	Develop the design of the detector based on the sensors	May 2024
6.	Test the full system of ASIC, nTron, shift register, and nanowire sensor	Sep. 2024

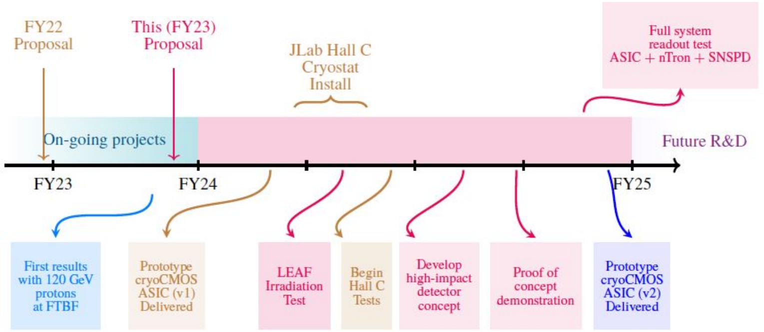
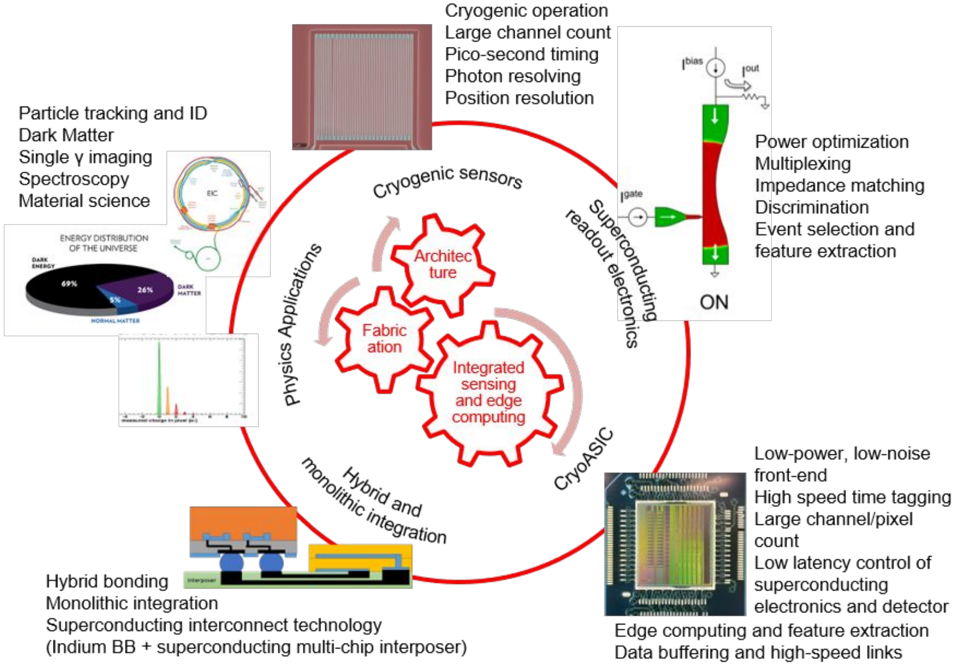


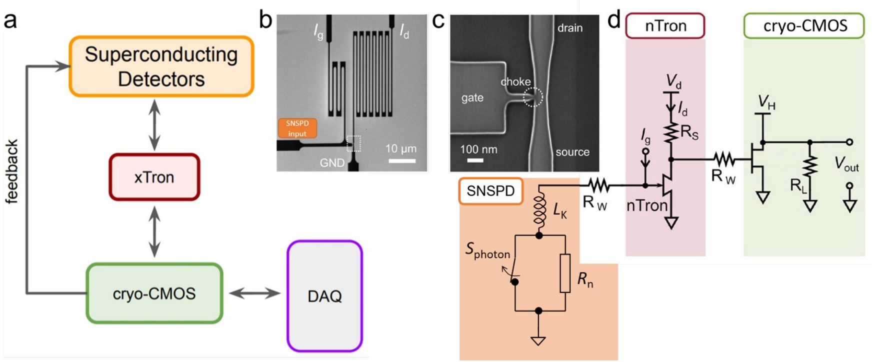
Figure 11: Timeline of proposed R&D projects for the FY23 cycle with some milestones from existing projects. Project milestones supported by FY22 and FY23 funding are color-coded in brown and red, respectively.

HYDRA: Hybrid Cryogenic Detector Architectures for Sensing and Edge Computing enabled by new Fabrication Processes (LAB 21-2491).

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



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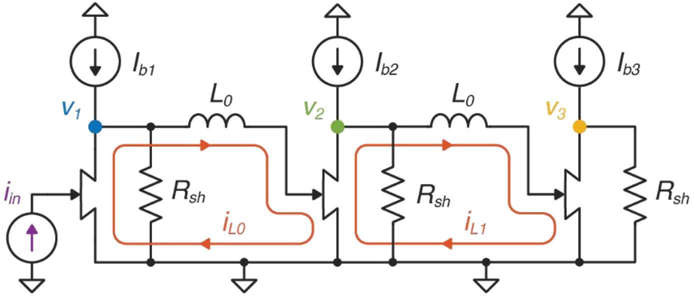
HYDRA: Hybrid Cryogenic Detector Architectures for Sensing and Edge Computing enabled by new Fabrication Processes (LAB 21-2491).

- FermiLab
  - 32 channel ASIC for SNSPD readout, tape out on 12/04, chips expected in March 2024.
  - $20k from FY22 EIC-related generic R&D helps the chips for the EIC-specific tests
- MIT
  - Major advances in cryotron logic and integration for large pixel arrays.
  - A. Buzzi et al., A nanocryotron memory and logic family (APL 2023)
  - R. Foster et al., A superconducting nanowire binary shift register (APL 2023)
  - M. Castellani et al., *A Nanocryotron Ripple Counter Integrated with a Superconducting Nanowire Single-Photon Detector for Megapixel Arrays* (arXiv 2304.11700)



From arXiv 2304.11700

Members of the Fermilab-led co-design team at their collaboration meeting in January 2023. From left to right: Adam Quinn from Fermilab; Whitney Armstrong and Sangbaek Lee from Argonne; Davide Braga and Kyle Woodworth from Fermilab; Owen Medeiros, Matteo Castellani, Reed Foster and Karl Berggren from MIT; and Matt Shaw from Jet Propulsion Lab. Photo: Lynn Johnson, Fermilab

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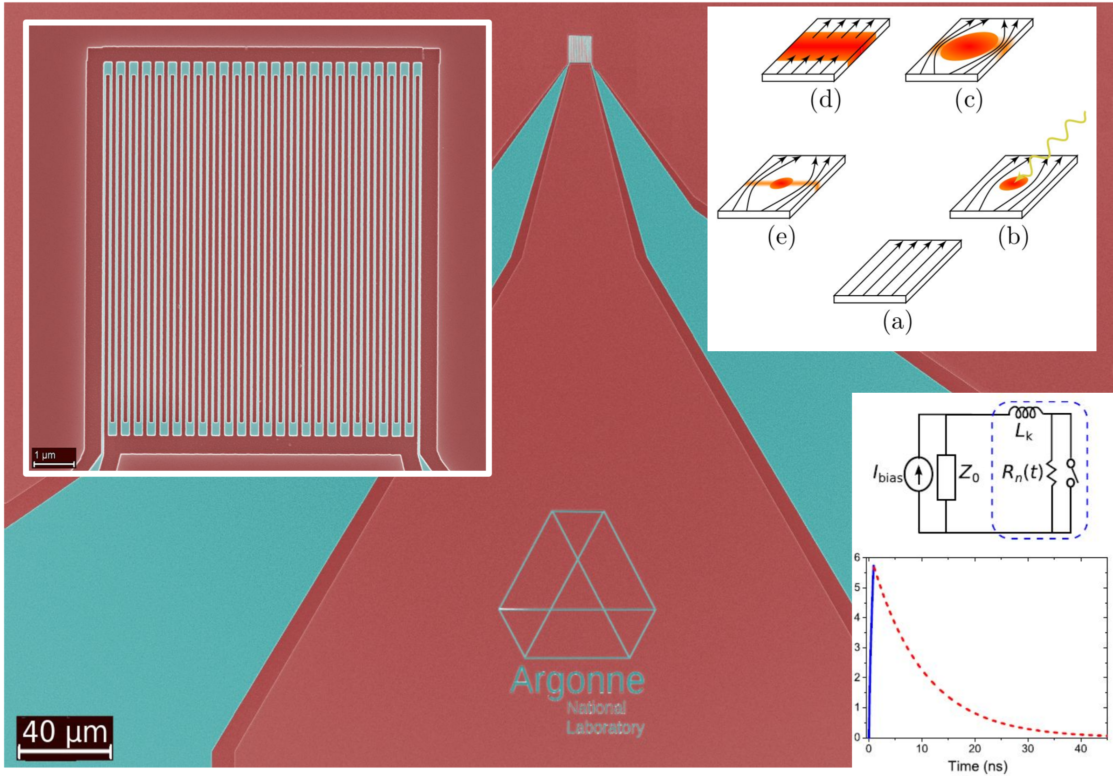
Proposal

Overview - SNSPDs as Particle Detectors

- Superconducting Nanowire Single Photon Detectors (SNSPDs) are well established as an ultra-fast and highly efficient single photon detector technology
- The superconductivity interfered by the interaction between the nanowire and the particle (photon) leaves a distinctive electronic signal
- Applications as a particle detectors have been studied [1, 2]
- Currently operational at 2–4 K with ~15-nm NbN film on SiN substrates with various widths [3]



[1] T. Polakovic, W. Armstrong et al., *Unconventional Applications of Superconducting Nanowire Single Photon Detectors, Nanomaterials* 2020
[2] T. Polakovic, W. Armstrong et al., *Superconducting nanowires as high-rate photon detectors in strong magnetic fields, NIM A* 2020
[3] T. Polakovic et.al., *Room temperature deposition of superconducting Niobium Nitride films by ion beam assisted sputtering*, APL Materials 2018

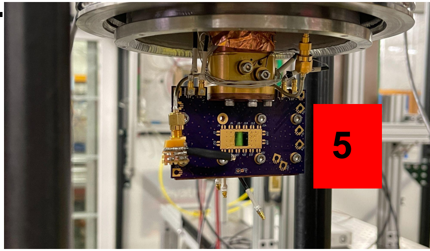
Overview - Current R&D Status

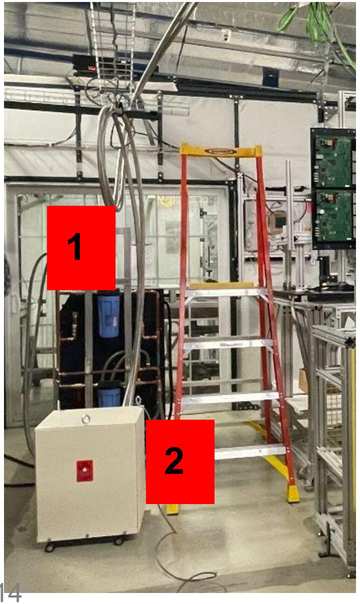
- This R&D project has been awarded the EIC-related Generic R&D in the FY22.
- Usage of R&D awards ($118,128)
  - ANL
    - Purchases of 2 AWGs (delivered) and a cryostat (purchase order initiated)
  - FNAL
    - the 32 channel ASIC tape-out on 12/04, chips expected in March 2024.
- Progress Report
  - ANL
    - **Particle detection tests with the high energy proton and radioactive sources**
  - FNAL
    - ASIC-based readout chip design
  - MIT
    - Studies of cryo-logic circuits
  - HYDRA collaboration, the DOE Microelectronics Co-Design Research Project
    - **2nd detector workshop (May 2023)**
    - Collaboration meeting (Jan 2023)
    - Superconducting electronics and detectors workshop at JLab (Nov 2022)
    - CPAD 2023 (Nov 2023)
- Continuation of the R&D
  - Radiation hardness test at LEAF and JLab.

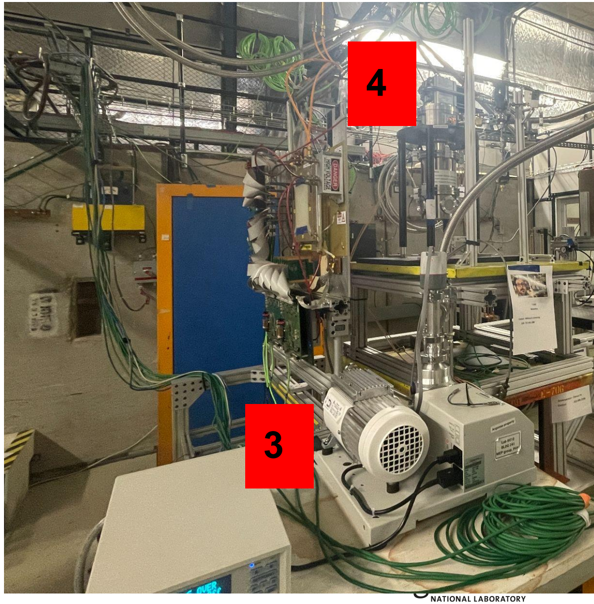
Progress Report - Beam Test Setup @ FTBF MT6.2

The G-M Cryocooler to maintain the operating temperature (< 4 K).
The entire setup was installed in the beam enclosure of MT6.2.

1. Water chiller
2. Compressor
3. Turbomolecular pump
4. Cryostat
5. Nanowire Sensor

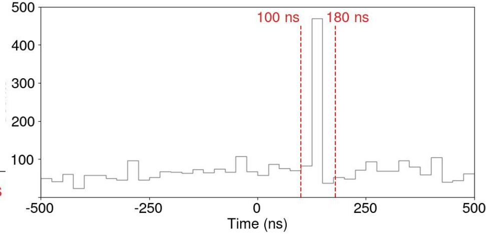


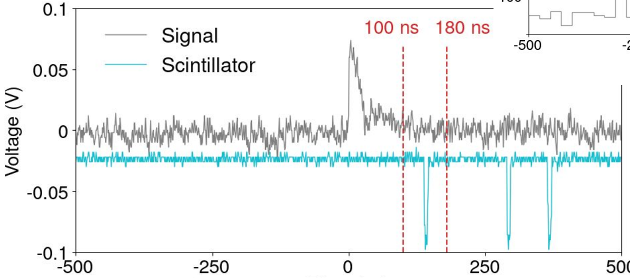


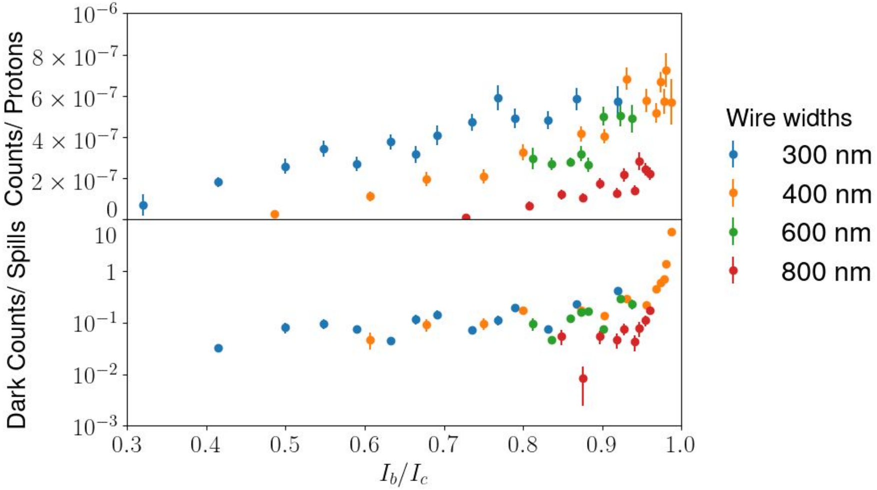


Progress Report - 120 GeV Proton Test Results

- We performed the bias scan with the nanowire sensors of various widths.
- Triggered on SNSPDs and looked at coincidence window with the plastic scintillators.
- FOM is the hit counts normalized to incident protons
  - the relative efficiencies.
  - statistical uncertainties only.
- Takeaways
  - First measurements w/ 120 GeV protons
  - Devices w/ smaller wires (~200 nm) will give the best performance and bias operating range

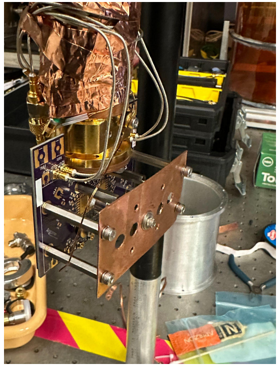


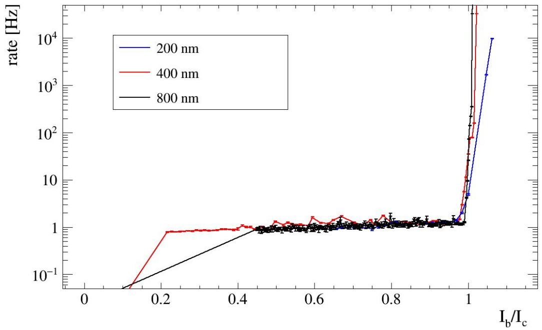


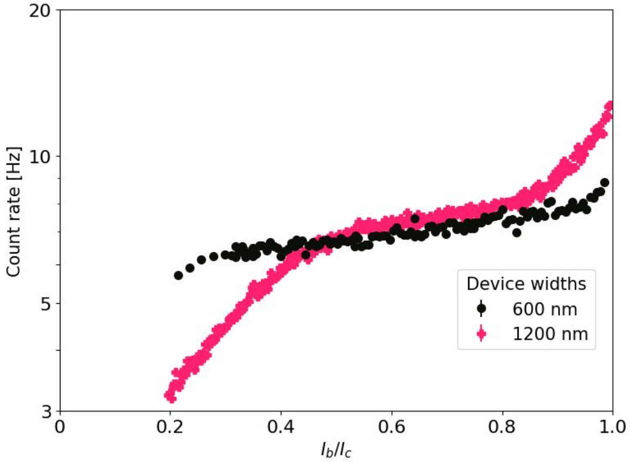


Progress Report - Radioactive Source Tests

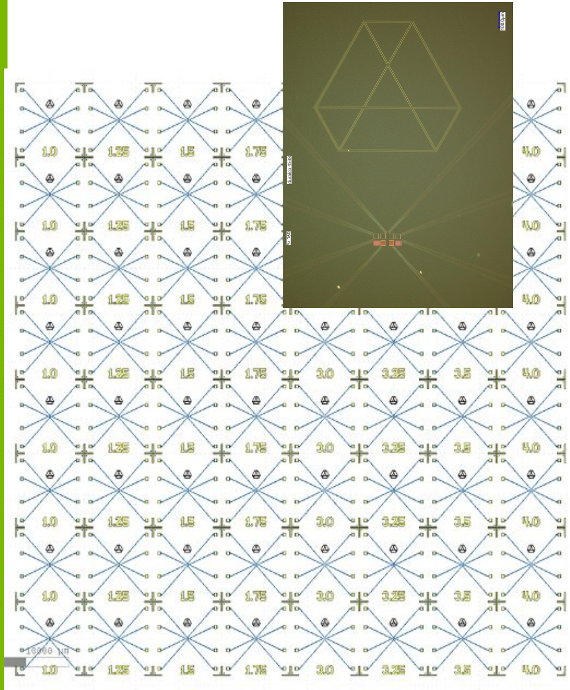
- Similarly, the bias scan with the alpha sources with the nanowire sensors of various widths.
- Above: included in the proposal
  Below: the recent measurements
- Minimized the systematic effects by the trigger threshold
- Takeaways
  - Alpha particle detected with the wider wires than the protons.
  - How far can we go?
  - Elbow at the count rate curve visible.

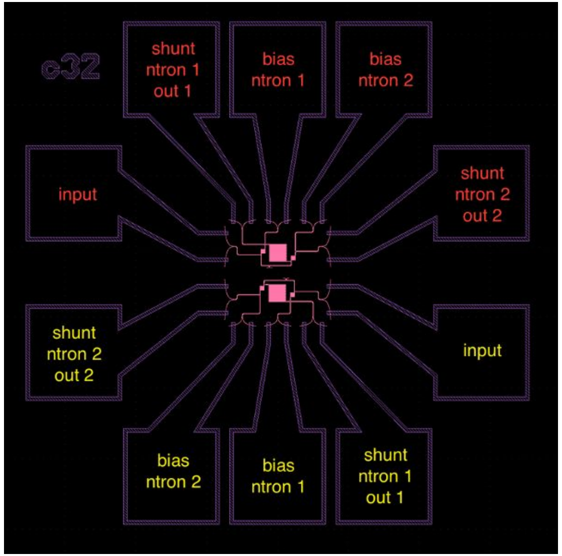


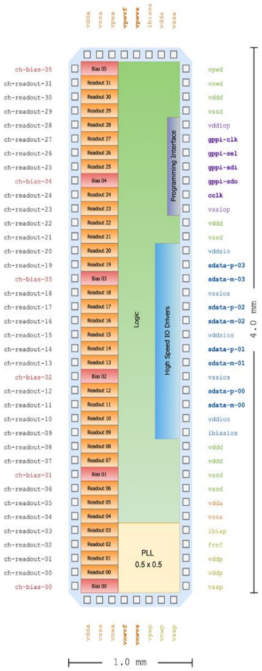


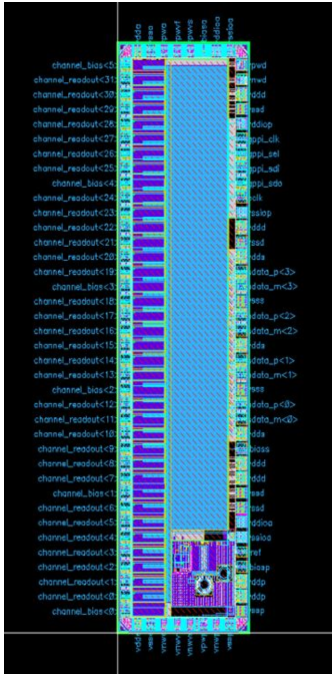


Progress Report - Hardware









Applications at the EIC
1. Particle detectors at the far-forward regions

- 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)

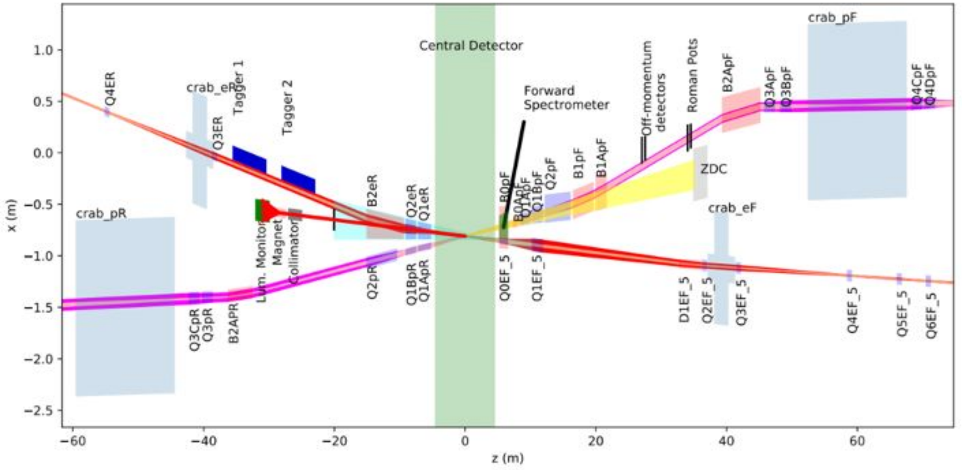


Figure 11.85 of YR

Applications at the EIC

2. 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

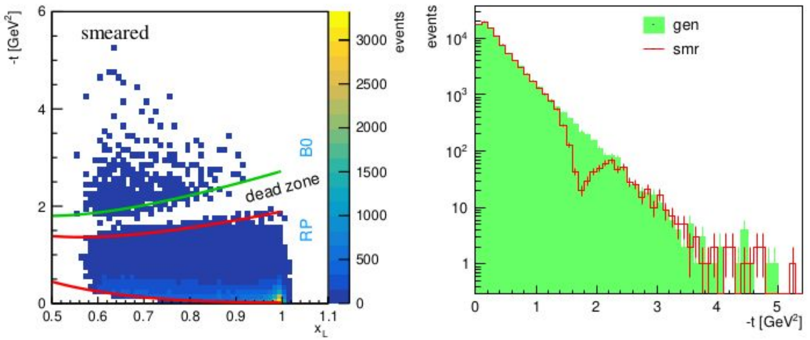


Figure 8.125 of YR

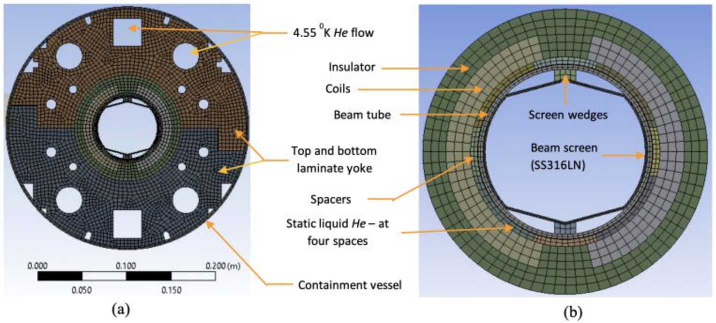


Figure 6.148: Finite-element model of (a) the RHIC arc dipole magnet cold mass cross-section and (b) close view around the beam tube.

Figure 6.148 of CDR 2021

Applications at the EIC
3. 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.

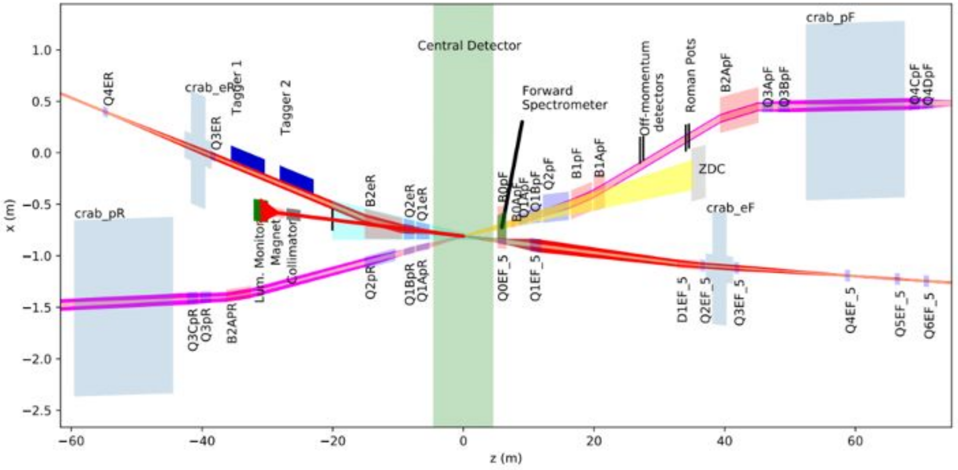


Figure 11.85 of YR

Applications at the EIC
4. Beam Loss Monitors

- A cryogenic BLM was proposed for the LHC upgrade to reduce the risk by distinguishing quench-provoking beam losses from the normal operation.
- The proposed cooling idea is to put the detector inside the cold mass of the magnet.
- When a similar cryogenic BLM is desired for the EIC, the nanowire easily satisfies the requirements.

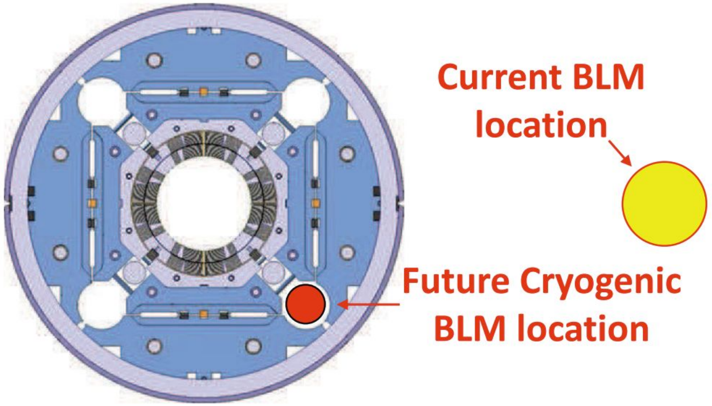
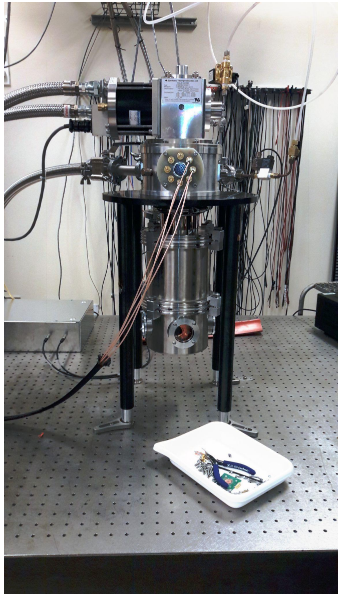


Figure 2: Cross section of a large aperture superconducting insertion magnet (MQXF) foreseen for HL-LHC with the current BLM and the future Cryogenic BLM locations shown.

M. R. Bartosik et al., Proceedings of IBIC2015

Proposed Plans - Irradiation 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



Proposed Plans - Irradiation at Argonne Low-Energy Accelerator Facility (LEAF)

Establish 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?

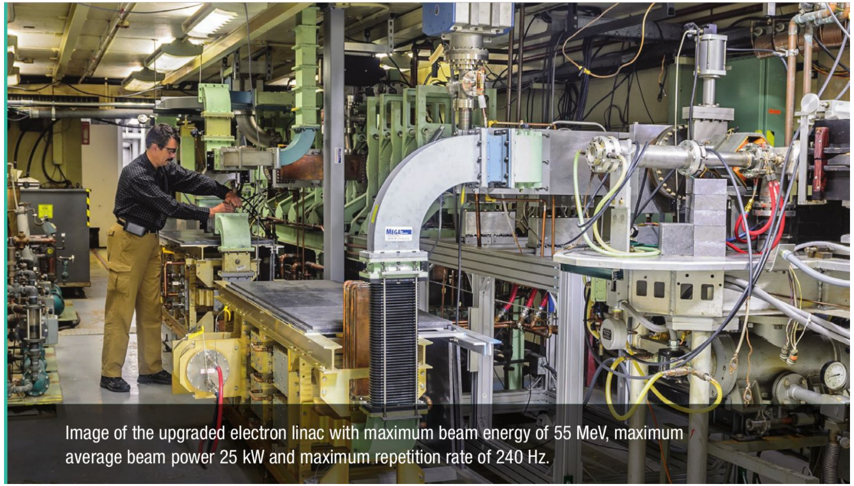


Image of the upgraded electron linac with maximum beam energy of 55 MeV, maximum average beam power 25 kW and maximum repetition rate of 240 Hz.

Timeline, Deliverables, and Budget

Table 2: Breakdown of individual budget items and the corresponding institutions.

Item No.	Description	Institution	Cost
1	One week of LEAF machine time	Argonne National Laboratory	40k
2	Purchase of Electronics	Argonne National Laboratory	10k
3	Travel	All	10k

A Realistic Nominal Budget (Baseline Budget)

1. Perform the radiation hardness testing of the board at LEAF without operation of the sensor.
2. Verify the operation of the nanowire sensors at LEAF.
3. Perform the operando radiation hardness testing at LEAF.
4. Purchase $\sim$ 10 bias boards for the nanowire sensor testing and the micro coaxial cables and connectors.
5. Test the full operation with shift registers, nTrons, and ASICs.

1.	Purchase a cryostat to be installed at JLab in Hall C (or A)	Aug. 2023
2.	Prepare to operate the SNSPD with prototype cryoCMOS ASIC (v1)	Dec. 2023
3.	Install cryostat at JLab in Hall C (or A)	Jan. 2024
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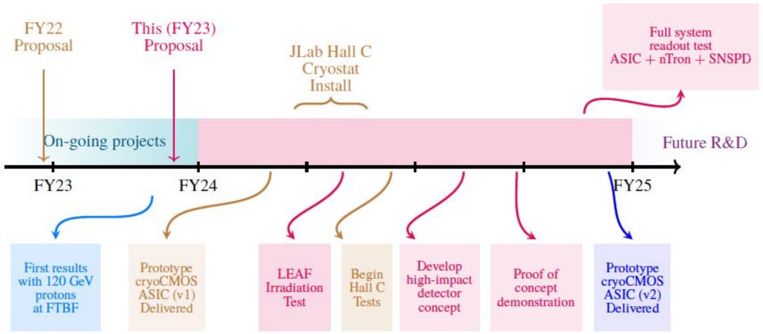
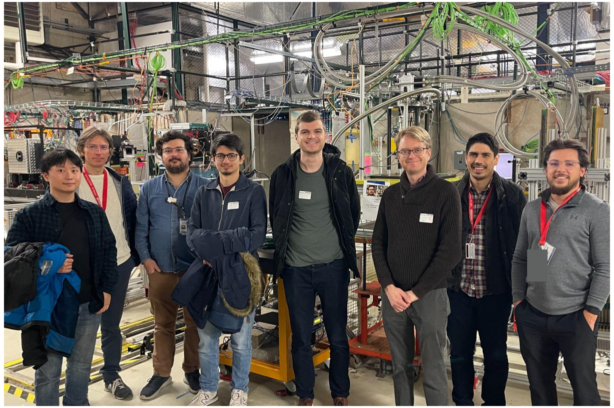


Figure 11: Timeline of proposed R&D projects for the FY23 cycle with some milestones from existing projects. Project milestones supported by FY22 and FY23 funding are color-coded in brown and red, respectively.

Summary and Outlook

- Superconducting Nanowire Particle Detectors for the EIC has been proposed, driven by strong motivations for the scientific mission of the EIC.
- The nanowire is an advanced technology that is supported by the ANL PHY, MSD division and the HYDRA, microelectronics co-design project.
- Particle detection with the nanowire has been tested for 120 GeV protons and alpha particles. We are continuing our efforts toward further demonstrations and co-design of the full-size detector.
- We are requesting funding to continue this R&D to test radiation hardness.

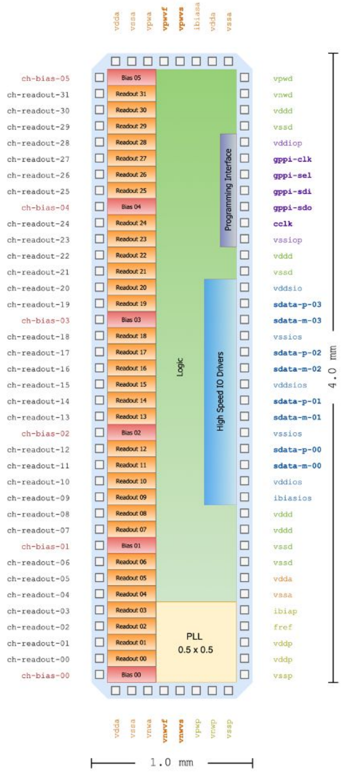


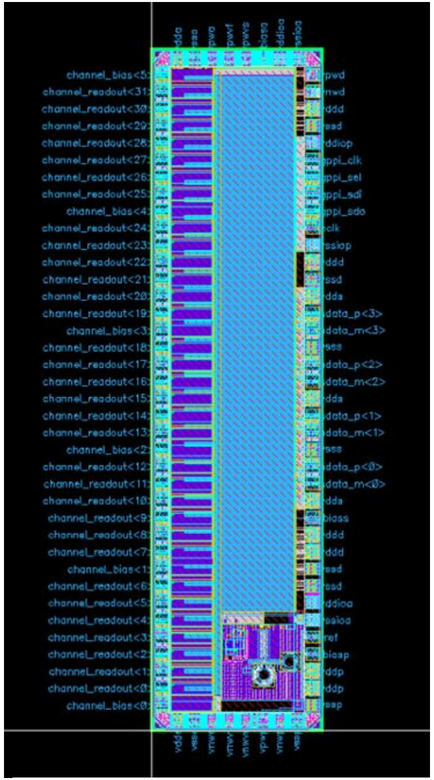
- Open Q&A time

Backup

SUNROCK cryoCMOS ASIC (v1)

- 32 channels, each including amplification + biasing + termination discriminator + fast time tagging (~5ps)
- Suitable for both SNSPD (internal gain) or nanocryotron (external gain) readout
- High performance on-chip PLL
- Additional DAC biasing channels for global biasing
- 22nm CMOS, operation at 4K
- Tape out in 12/04/23, chips expected from fabrication in March 2024





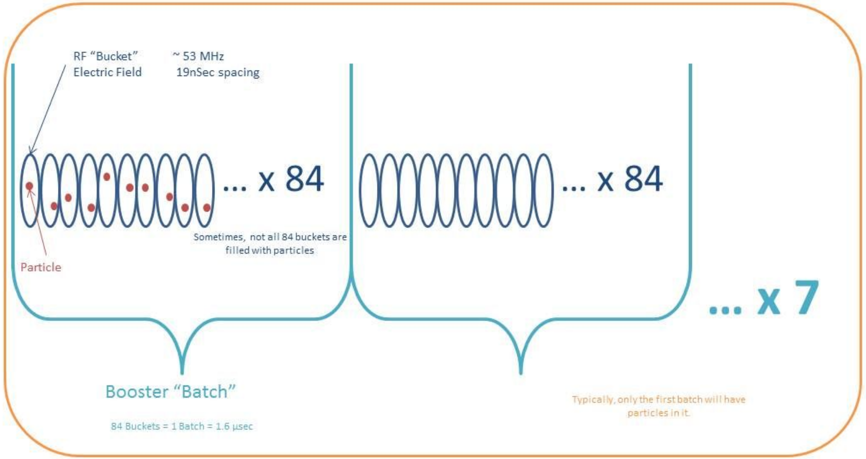
Fermilab

Erratum

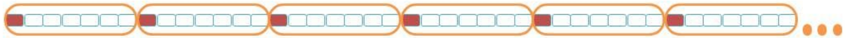
- Authors
  - Added J. Fredenburg at FNAL
- P. 19
  - in-operando → operando
- P. 20
  - 8 nm → 8 mm

Counters and AWGs Arrived at Argonne

FTBF Proton Beam Overview

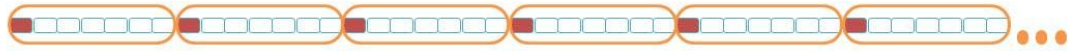


7 Batches = 1 MI Cycle = 11.2 microSec



Beam is resonantly extracted over 375,000 MI Cycles, to create a 4.2 second Spill.

If beam were smoothly extracted, 100 kHz or less would imply 1 particle per MI rotation (1 particle every 11.2 microsec) would occur.
Beam extraction is not smooth, resulting in up to 35% double occupancy per MI rotation



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From https://ftbf.fnal.gov/beam-delivery-path/

Argonne NATIONAL LABORATORY

Irradiation at FermiLab ITA

- We prioritize our beam time at FTBF for the detection efficiency tests.
- Testing the radiation hardness at ITA is one possibility.

Superconducting electronics connecting detector and cryo-CMOS

Lead by Karl Berggren's group at MIT

- Developing digital electronics components using superconducting nano-cryototron devices
- Fabricated with same NbN as nanowire detectors.
- Nanocryotrons are simplest interface between sensor and cryo-CMOS
- Recently developed at MIT
  - A superconducting binary shift register for SNSPD readout (Reed Foster)
  - Binary and Multilevel Counter (Matteo Castellani)
  - Building Blocks Design for Superconducting Nanowire Asynchronous Logic (Alessandro Buzzi)
- A lot of interesting ideas and possibilities to explore for data reduction and detector readout

A superconducting binary shift register for SNSPD readout

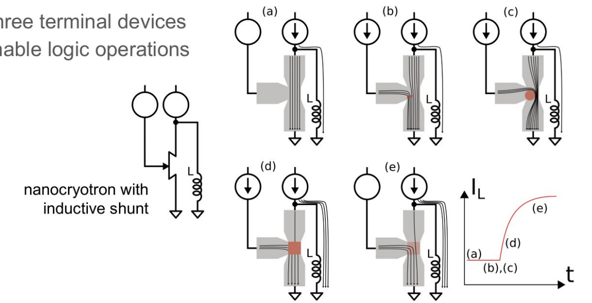
Reed Foster, Matteo Castellani, Alessandro Buzzi, Owen Medeiros, Marco Colangelo, Karl K. Berggren

WOLTE15 - Superconducting Electronics Nanowires
8 June 2022

Quantum Nanostructures and Nanofabrication
EECS, Massachussetts Institute of Technology

Superconducting nanocryotron operating principle

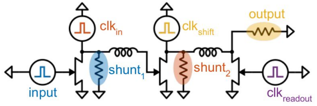
Three terminal devices enable logic operations

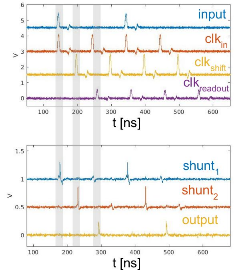


Demonstration of synchronous flux transfer

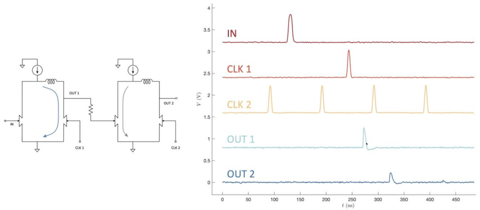
Maximum operating frequency limited to 60MHz by equipment

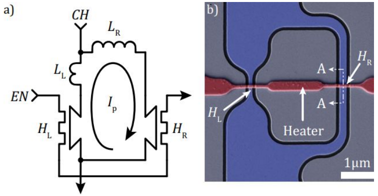
Electrical/thermal time constants on nanowire devices should allow for operation >200MHz



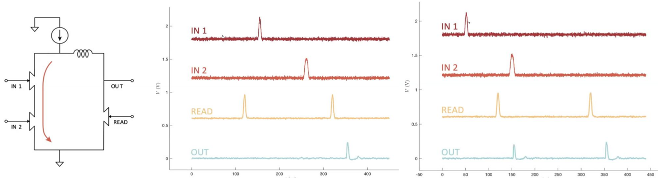


D flip-flop experimental results



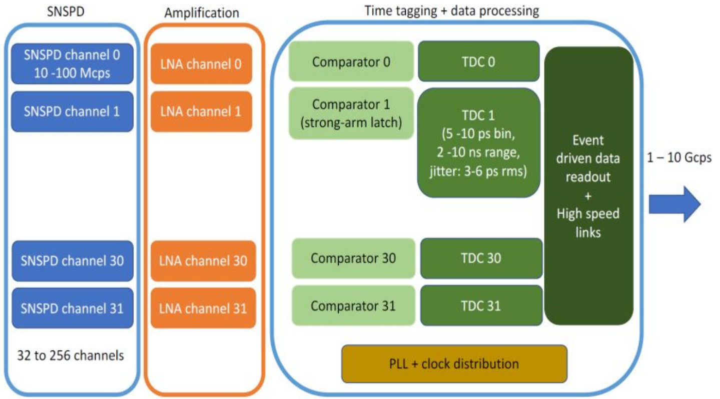


OR gate experimental results



Cryo-CMOS ASIC Development

- Operation at <4K demonstrated in modern, state-of-the-art commercial processes (no special processing)
- Leverage low power, high performance ASICs for signal conditioning, time-tagging, data concentrator/edge computing, and serialization/readout
- Highlights:
  - SiGe HBT (high performance LNA)
  - FDSOI with backgate control to compensate for threshold increase at cryo
- Fermilab and EPFL currently collaborating on EAD-compatible cryo-electronic models for Global Foundries' 22nm FDSOI



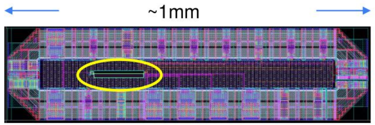
Amplification could be done in either xTron or ASIC

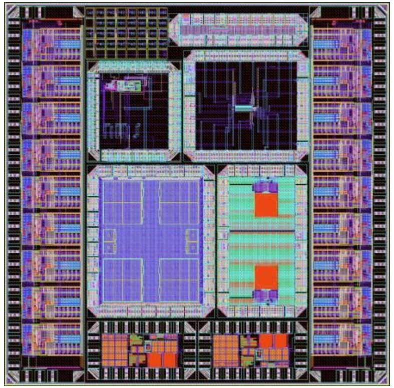
cryoASIC readout and control

- xTron driving directly comparator for binary readout
- Active quenching biasing from ASIC can reduce the deadtime of the nanowires

Prasana Ravindran, Risheng Cheng, Hong Tang, and Joseph C. Bardin, "Active quenching of superconducting nanowire single photon detectors," Opt. Express 28, 4099-4114 (2020)

- CryoCMOS allows for fine resolution TDCs for time tagging
- Fermilab prototyped a 22nm cryo TDC for 5ps resolution and >10ns range (7b fine, 10b coarse), <0.5mW
- Digital readout:
  - Event driven, serializer, line drivers, etc.
- Feature extraction:
  - Correlation between detector layers
  - Event selection/reconstruction
  - DNN





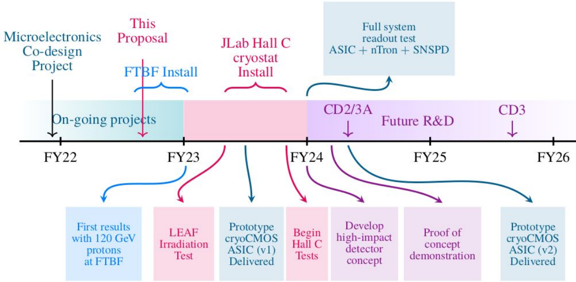
Fermilab's 22nm prototype

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



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

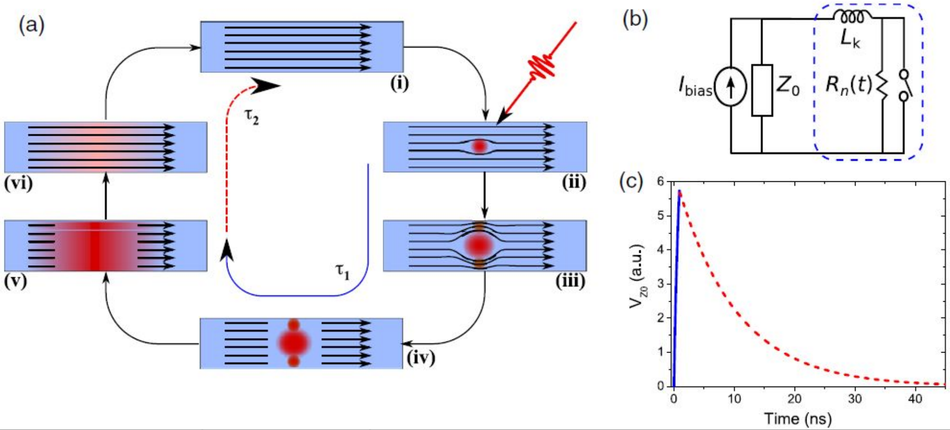
- Radiation hardness of SNSPDs characterized with upper limit for the onset of defects and device failure.
- Single Event upset cross-section for prototype cryoCMOS ASIC
- Background error rate for superconducting shift registers
- SNSPD efficiency in high radiation environment

SNSPD Reset time

The reset time was presented as being O(10)ns in the context of single photon detection. For charged particles, is the reset time expected to be longer (given the several orders of magnitude larger local heat deposition)?

- The reset time is essentially determined by the LR circuit
- 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

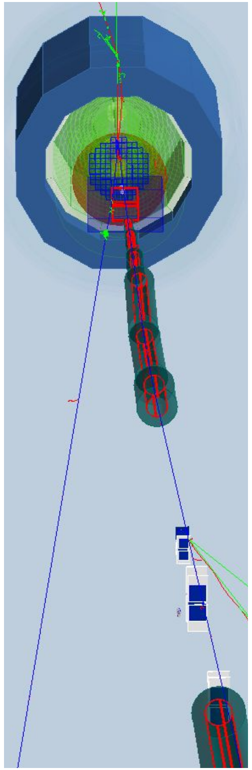
A single wire firing once injects about 2 fJ of energy into the system (or 124 keV)

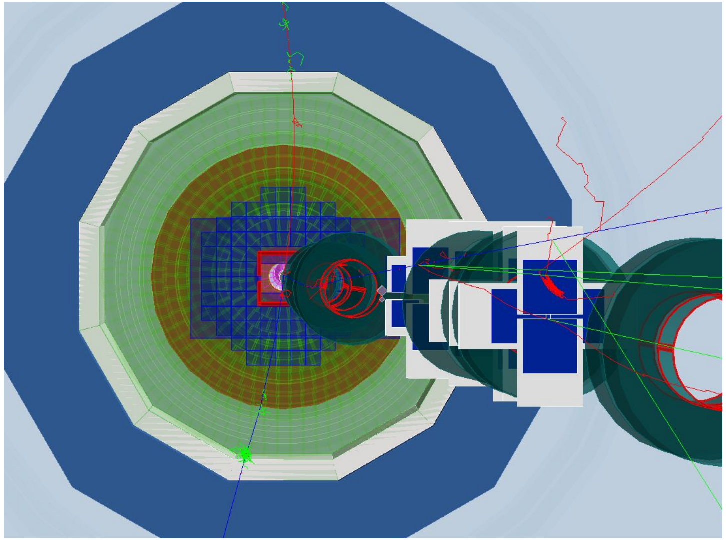


Particle	Energy	Approximate Energy loss in	
		100 um silicon	15 nm NbN
alpha	5 MeV	5 MeV	9.07 keV
electron	1 MeV	15 keV	15.8 eV
electron	100 MeV	~100 keV	~100 eV
proton	120 GeV	40 keV	24 eV

SUPERCONDUCTING NANOWIRE DETECTORS FOR THE ELECTRON ION COLLIDER

Successfulproposal for EIC Detector R&D at BNL: eRD28

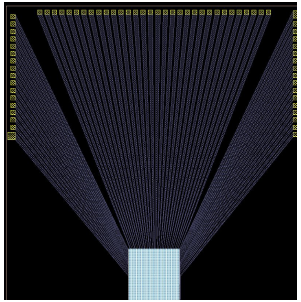


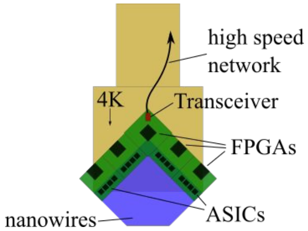


BNL EIC Detector R&D Committee:

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

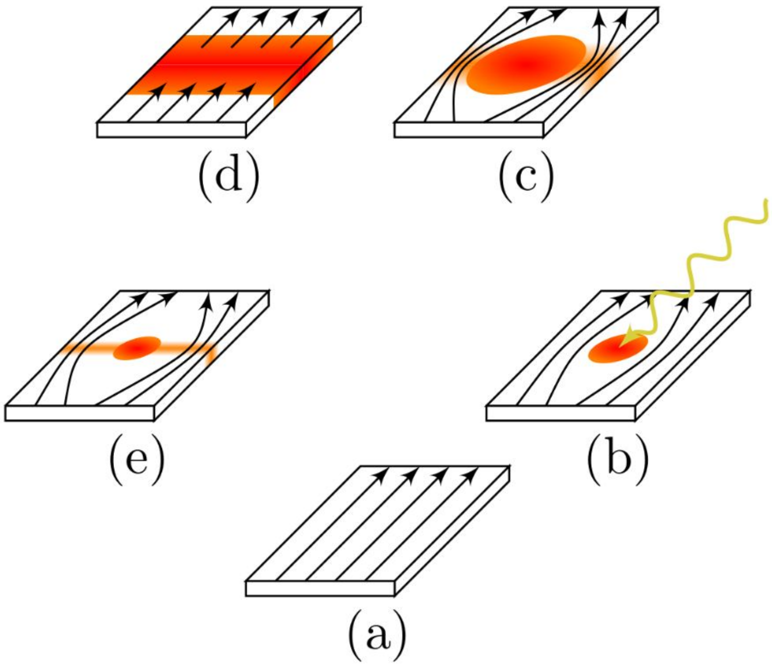




SUPERCONDUCTING NANOWIRE (SINGLE PHOTON) DETECTORS

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

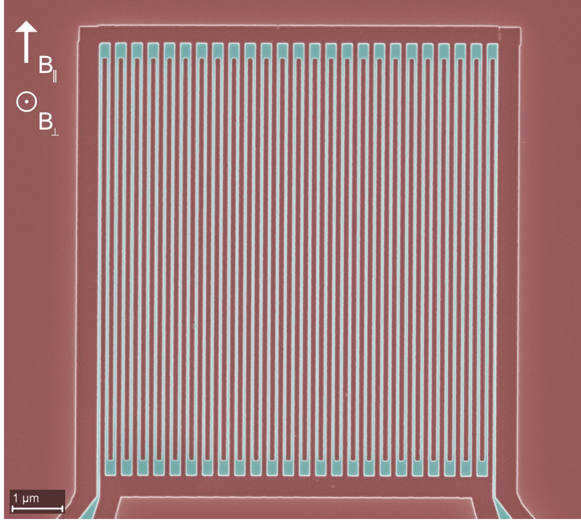


Polakovic, Nanomaterials (2020)

SUPERCONDUCTING NANOWIRES

Overview of Nanowire Detectors

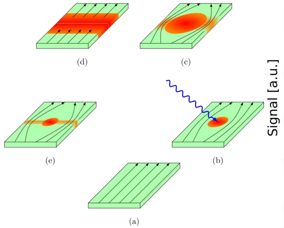
- PHY-MSD Collaboration supported by DOE-NP (FWP-32537.2)
- Sensors can operate in fields up to (at least) 7T, can operate inside of cold bore of superconducting magnets (T< 5 K).
- Argonne nanowire sensors fabricated on-site.
- Novel concept for high-resolution rad-hard detectors based around superconducting 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

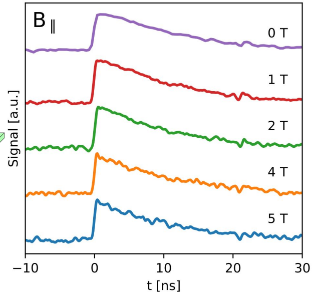


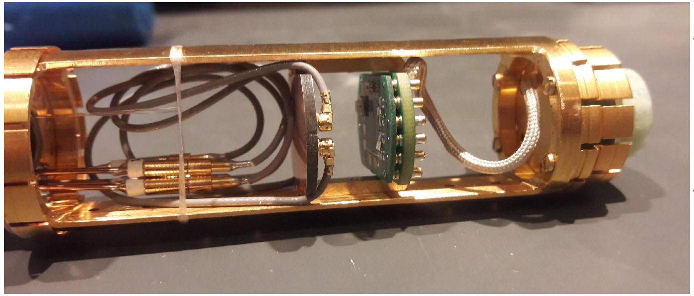
1) *Room temperature deposition of superconducting Niobium Nitride films by ion beam assisted sputtering*. APL Materials 6, 076107 (2018)

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.

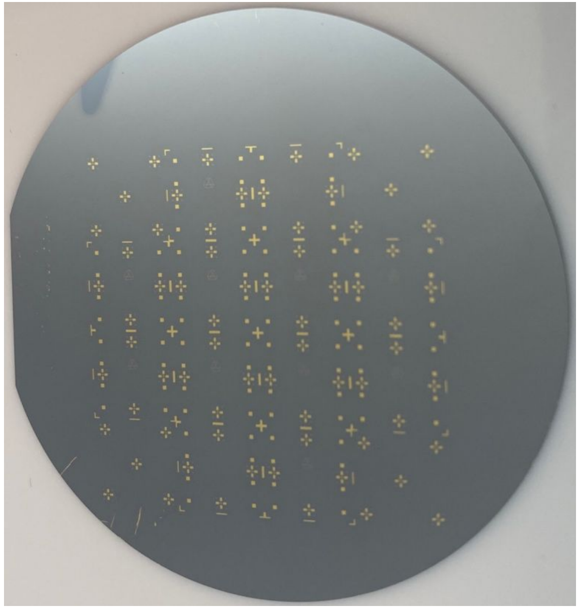


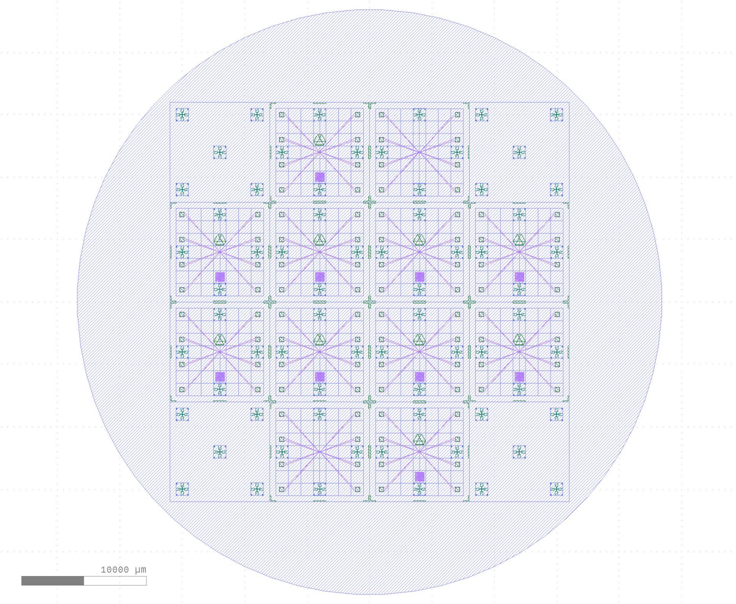


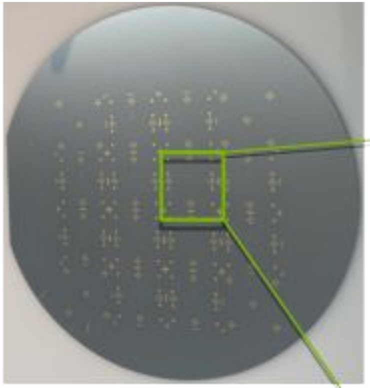


2-inch wafer

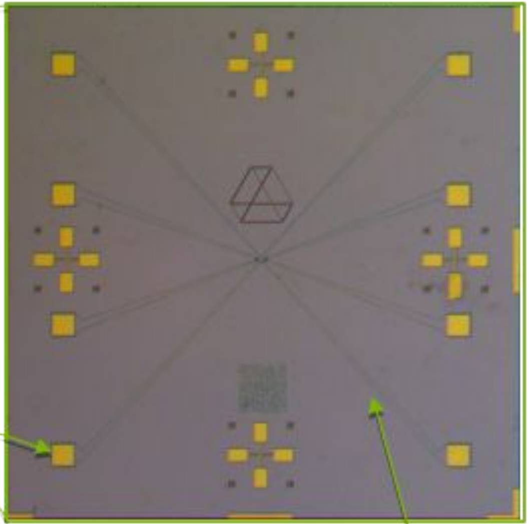
8 mm chips



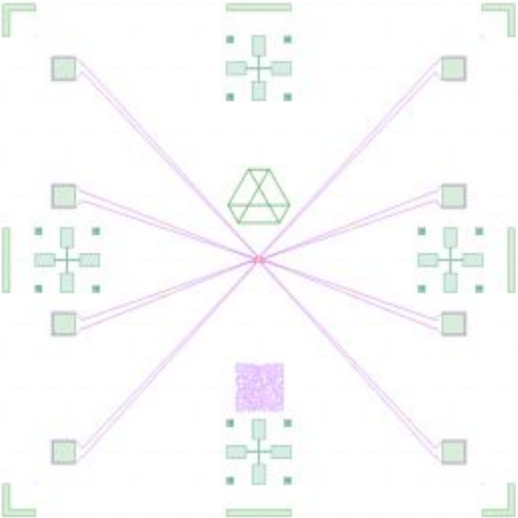




Physical device (chip)



Design



Wire bonding contact pad

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