Superconducting Nanowire Particle Detectors for the EIC

EIC-related Generic R&D

November 16, 2022

Whitney Armstrong, Sylvester Joosten, Jihee Kim, Zein-Eddine Meziani, Valentine Novosad, Chao Peng, Tomas Polakovic, Marshall Scott, Junqi Xie, Maria Zurek
Argonne National Laboratory

Davide Braga, Farah Fahim
Fermi National Accelerator Laboratory

Karl Berggren, Alessandro Buzzi, Matteo Castellani, Reed Foster, Owen Medeiros, Sangbaek Lee
Massachusetts Institute of Technology

Matthew Shaw

JPL

Dave Gaskell, Ben Raydo, Holly Szumila-Vance

Jefferson Lab

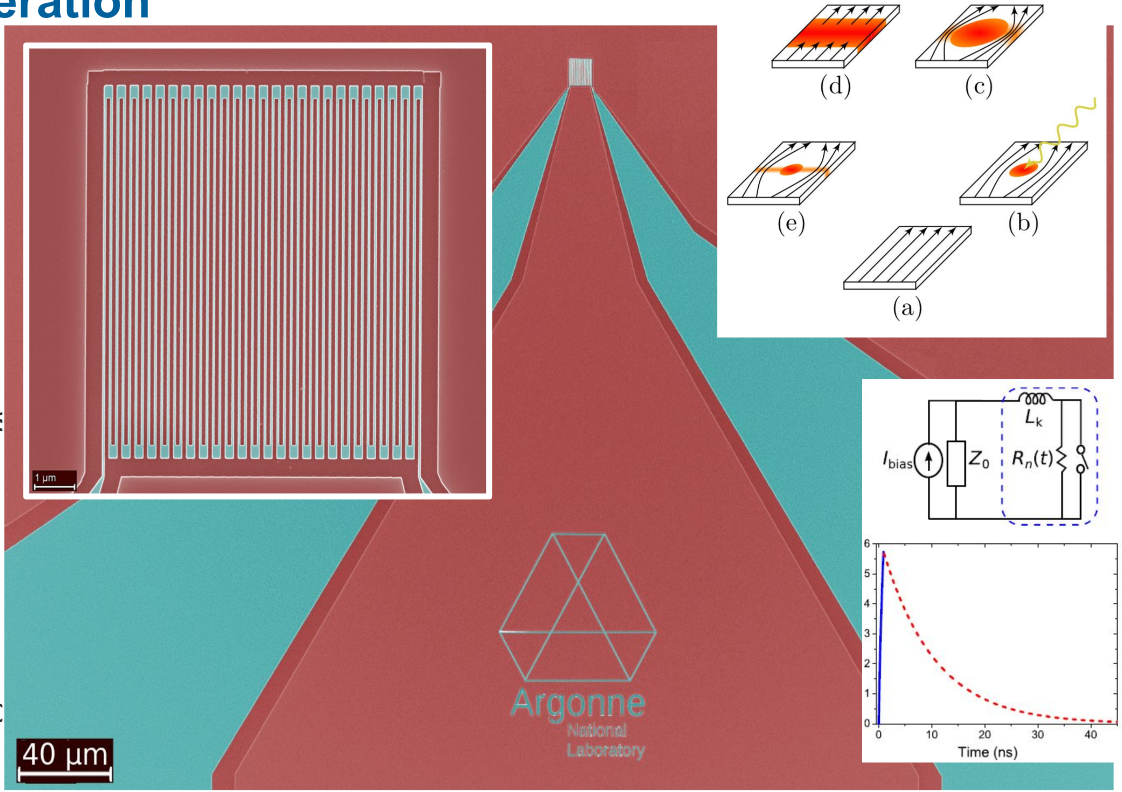
Overview

- Introduction to superconducting nanowire detectors
- Motivation for superconducting nanowires at the EIC
- Ongoing R&D related to EIC
- Proposed R&D
- Applications at the EIC
  - Far forward detectors
  - Superconducting magnet beamline detector
  - Neutral particle detector
  - Other uses at the EIC

Superconducting Nanowire Single Photon Detectors

SNSPD Construction and Operation

- Fabricated from ~10nm NbN film with T_c=15 K [1]
- Typical meandering wire fills pixel area.
- 100 nm wide wire with with 100 nm spacing etched to form pixel device with T_c~ 5 K
- Current biased: I_b~ 15 - 20 μA
- Photon breaks cooper pair (b), causes hot-spot to form (c), Joule heating causes normal conducting hotspot to grow to width of wire (d), current through wire is reduced (e), and superconductivity recovered (a).
- Voltage pulse has extremely fast rise-time, and the tail (d)→(e)→(a) is set by LR circuit, wire material/geometry, and other current shunts



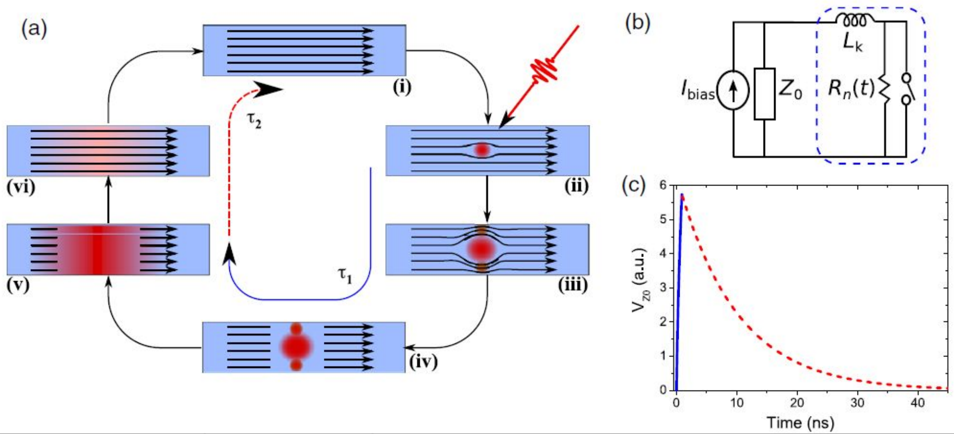
[1] Room temperature deposition of superconducting Niobium Nitride films by ion beam assisted sputtering. Polakovic et.al. APL Materials 6, 076107 (2018)

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)

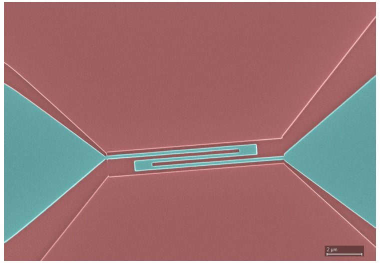


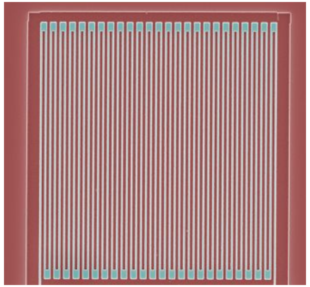
Particle	Energy	Approximate Energy loss in	
		100 um silicon	15 nm NbN
alpha	5 MeV	5 MeV	9.07 keV
electron	1 MeV	15 keV	15.8 eV
electron	100 MeV	~100 keV	~100 eV
proton	120 GeV	40 keV	24 eV

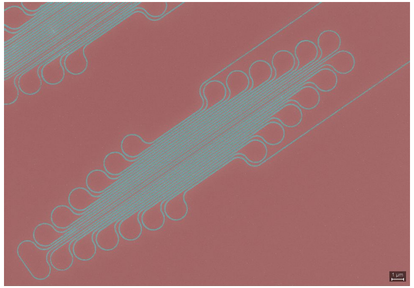
SNSPD Properties and Characteristics

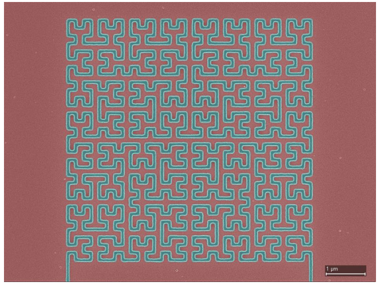
Quick Summary

- 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

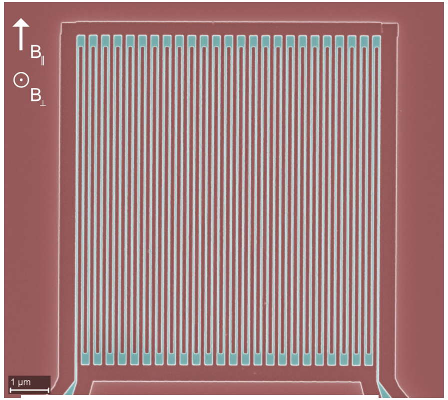


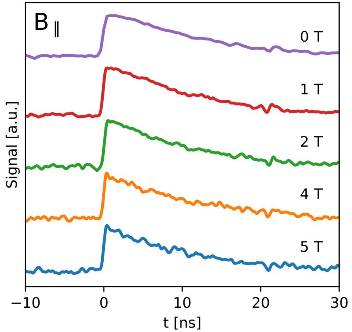


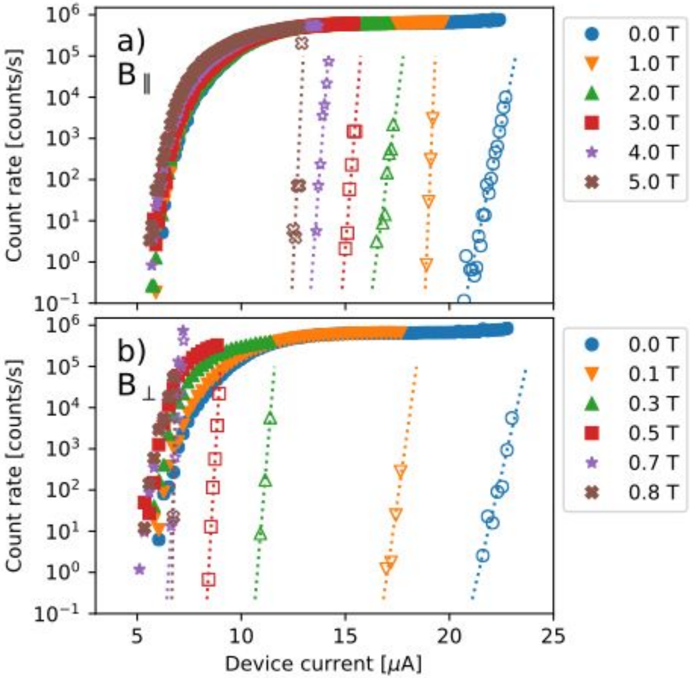


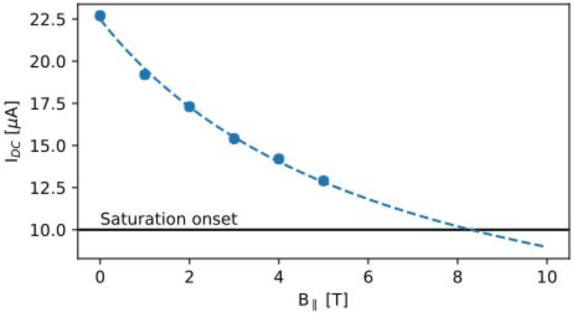


Strong Magnetic fields and high rates





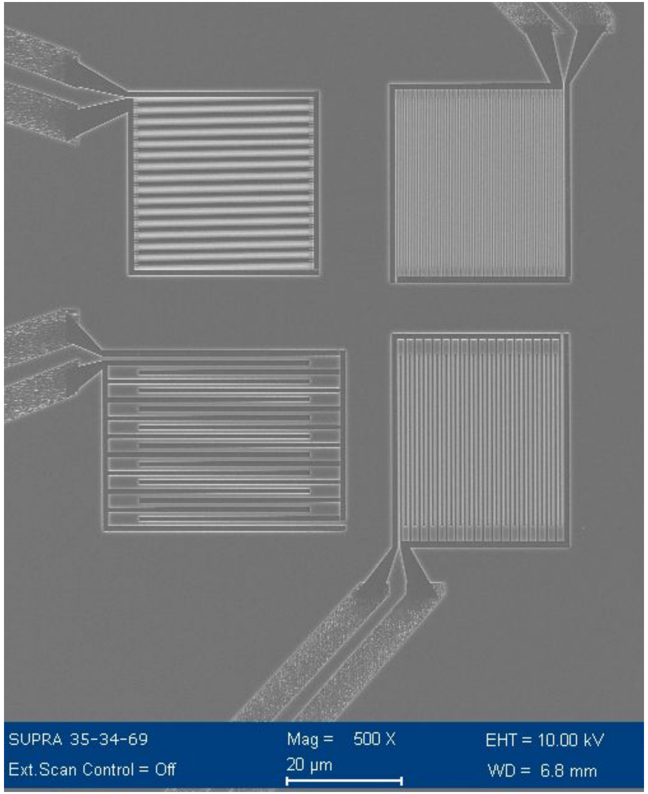




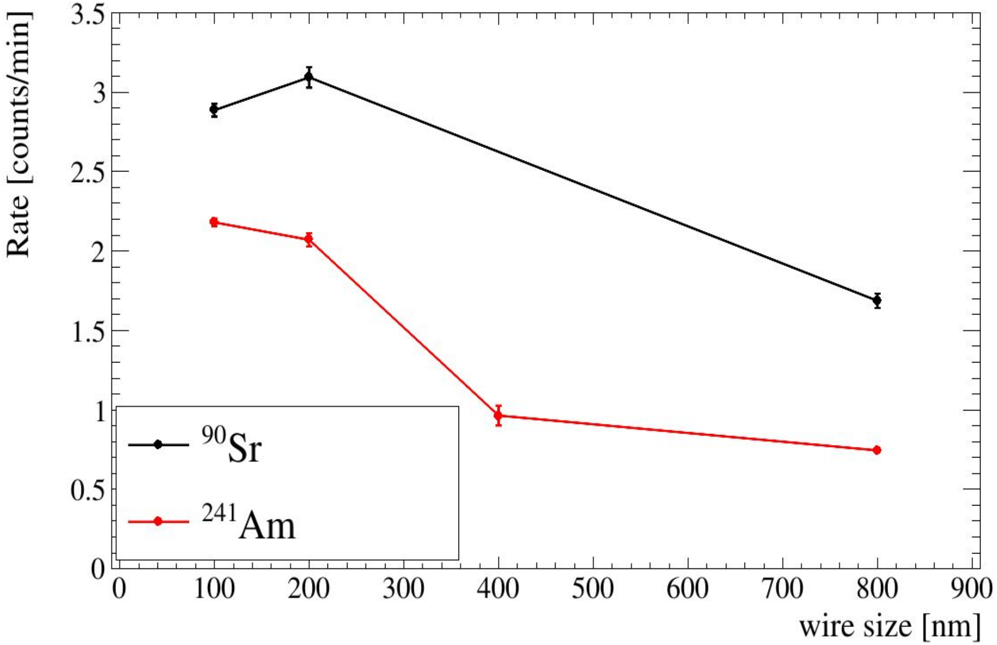
Can operate on strong magnetic fields with nearly zero dark count

Ongoing Superconducting Nanowire R&D

Particle Detection from radioactive sources



Looking at different pixel sizes with sealed sources

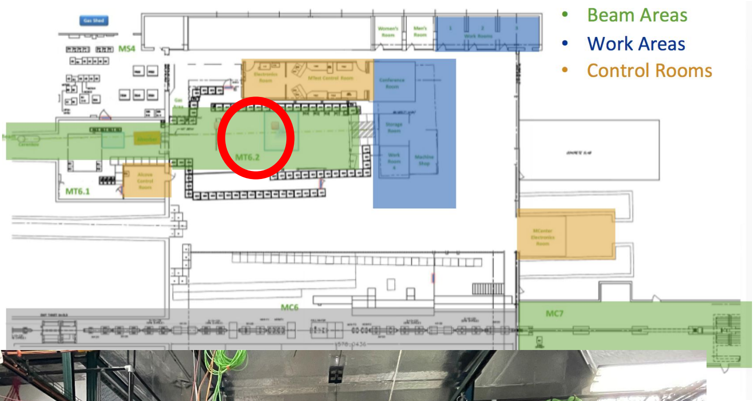


Efficiency drop around 400 nm.

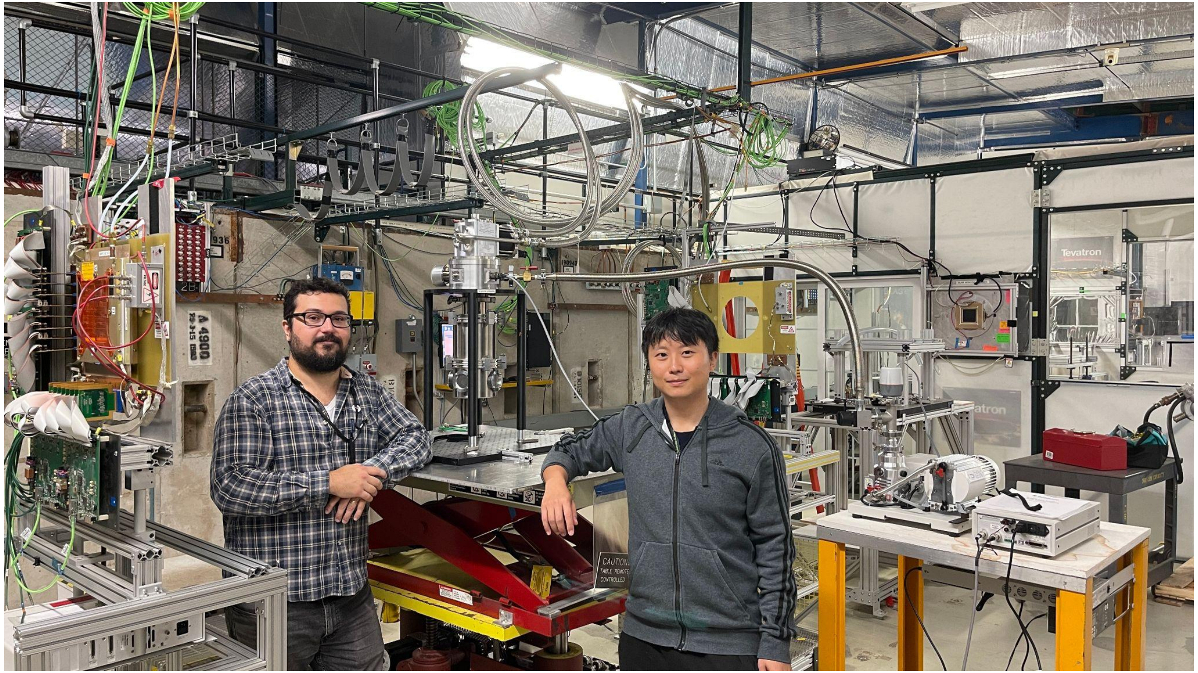
→ Need to use higher activity source

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.

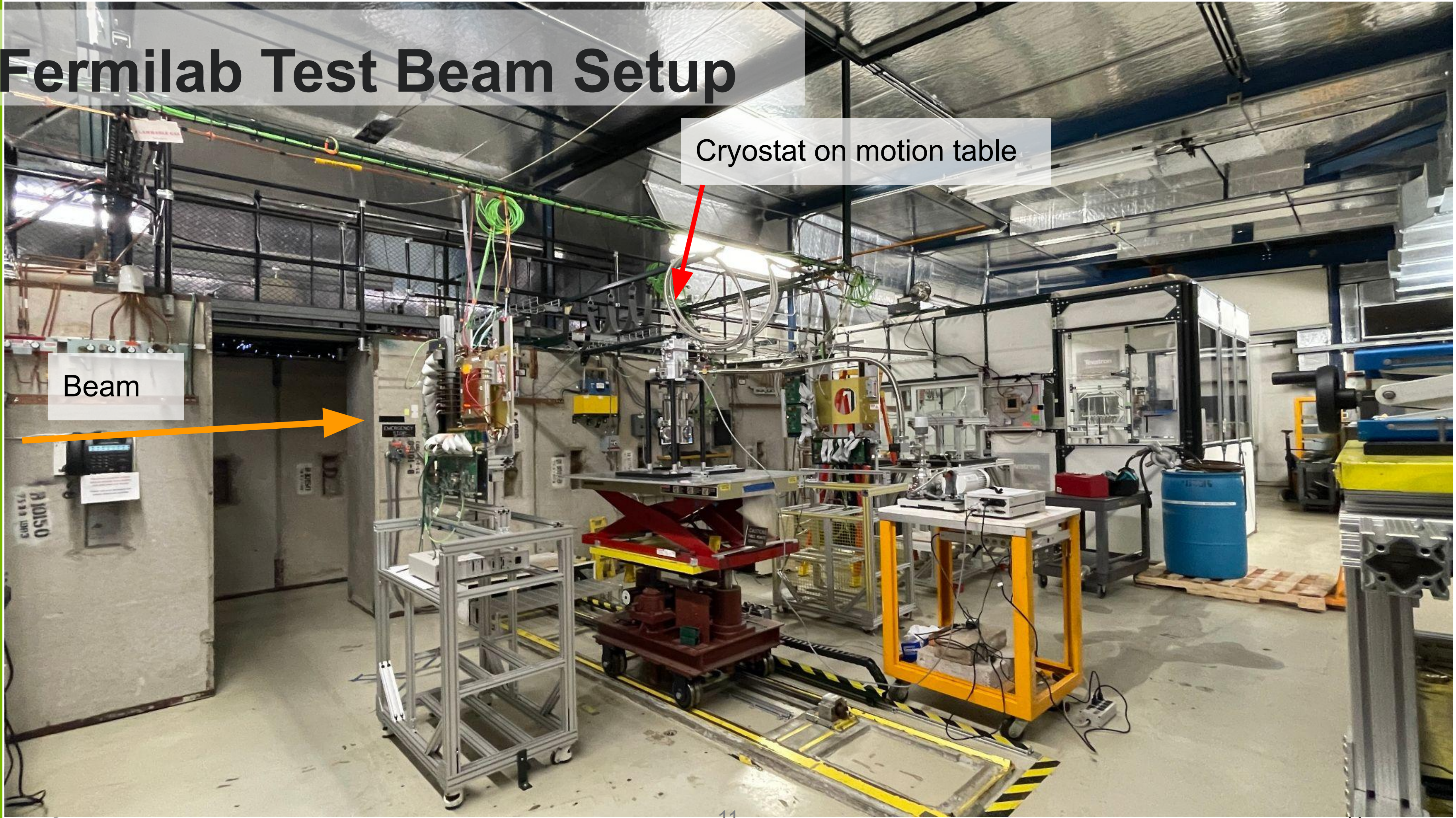


Setup for Operational Readiness Clearance (ORC)

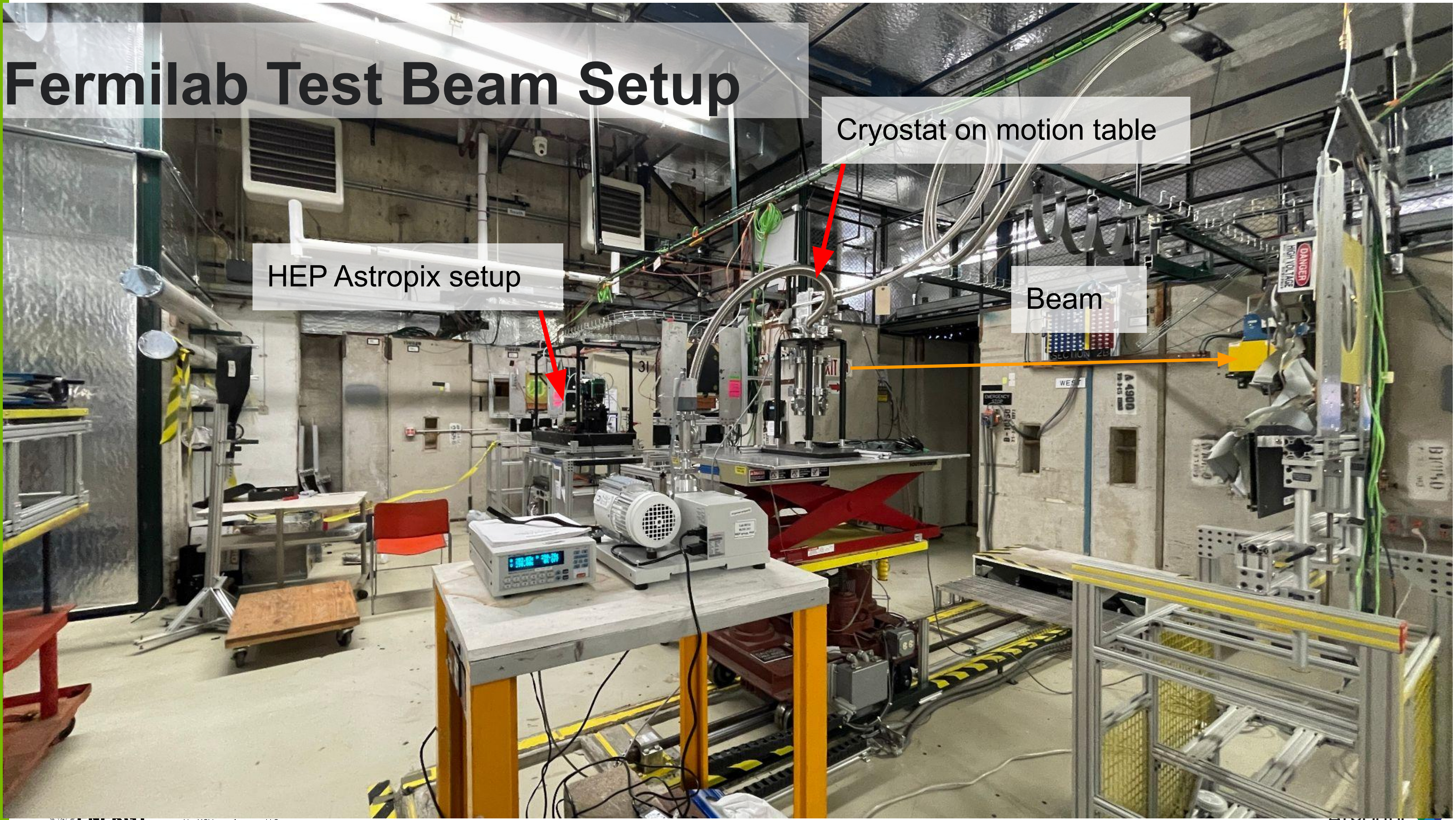


Sangbaek Lee is a new postdoc
at Argonne work on this R&D

Fermilab Test Beam Setup

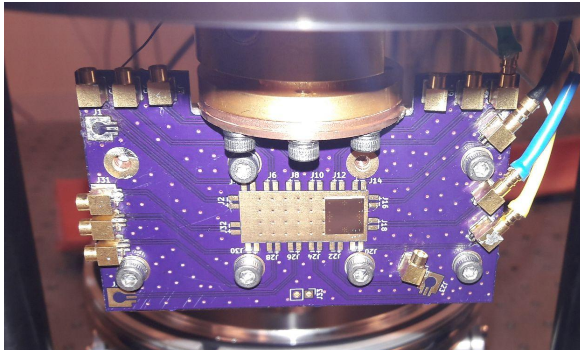


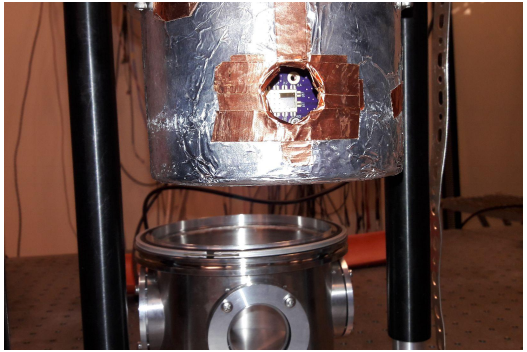
Fermilab Test Beam Setup

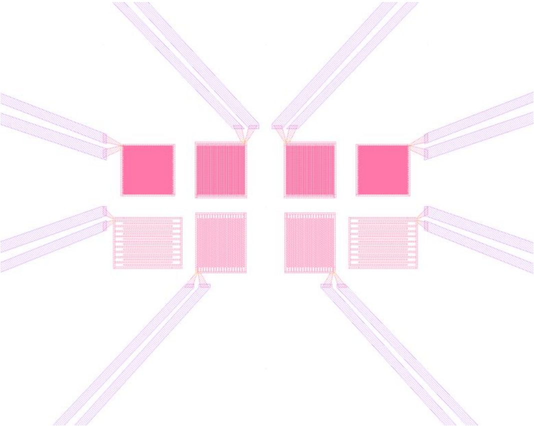


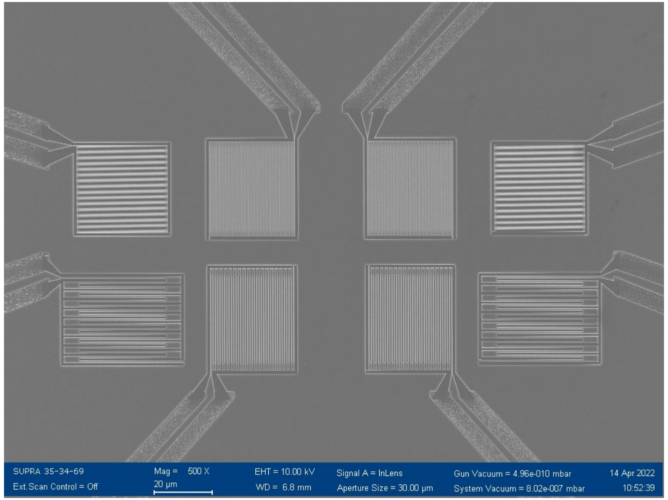
Test Devices

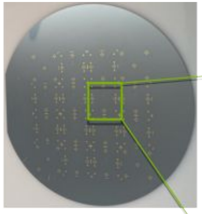
Device cold finger mounting PCB



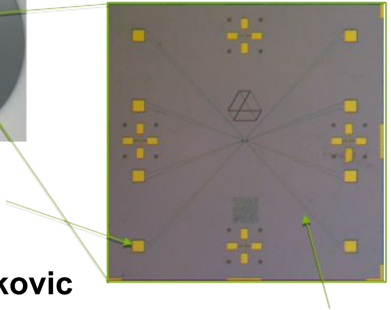




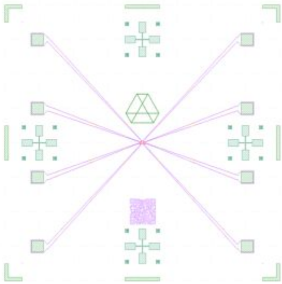




Physical device (chip)



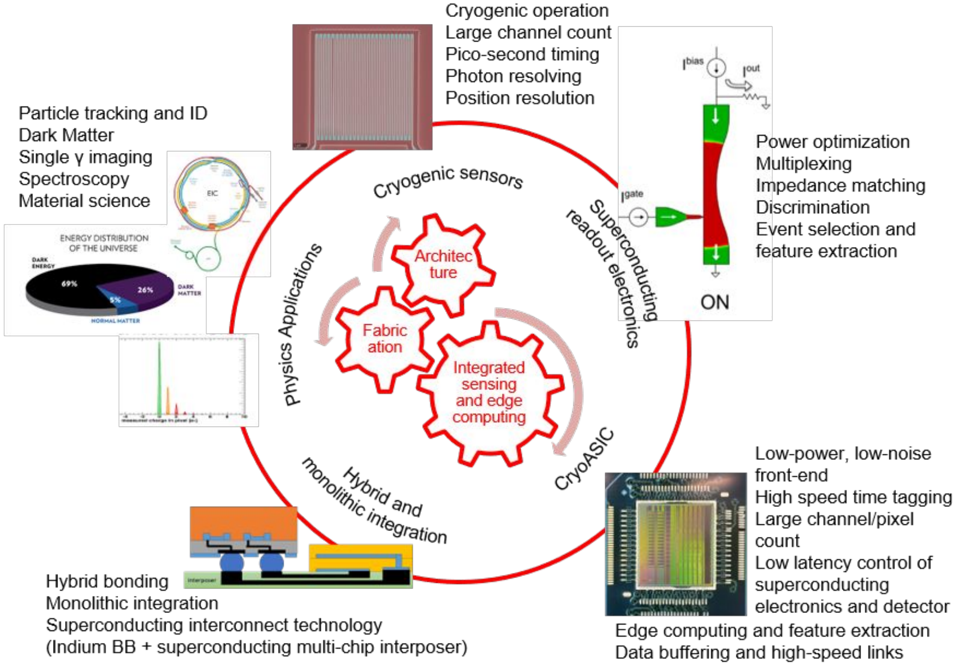
Design



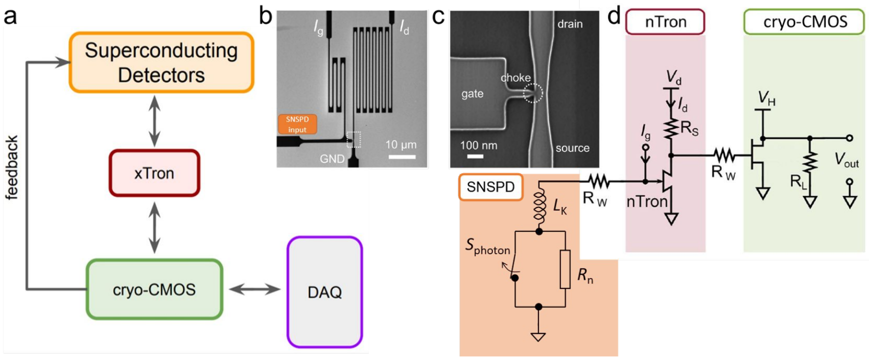
Tomas Polakovic

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

A microelectronics co-design project

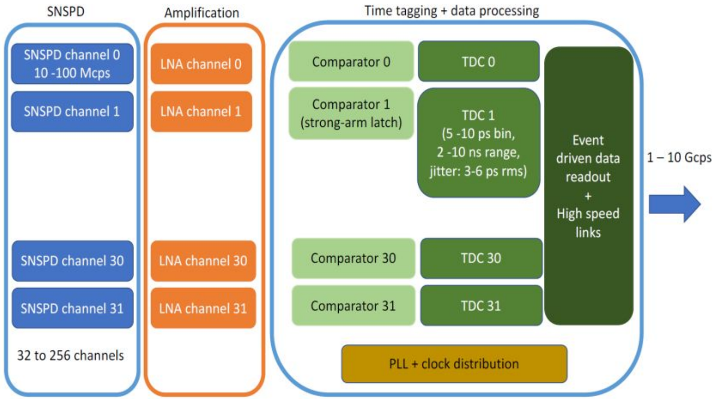


- Timely microelectronics R&D focused on cryogenic sensors and readout
- Project will produce first Cryo-CMOS ASIC for high channel count detectors at the EIC
- Fermilab is developing a cryo-CMOS ASIC architecture
- MIT is leading the development of superconducting electronics
- Argonne is leading the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



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



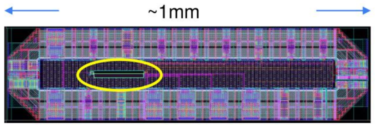
Amplification could be done in either xTron or ASIC

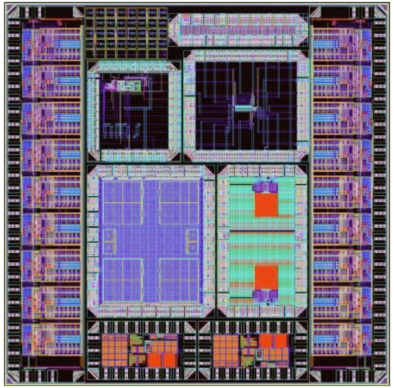
cryoASIC readout and control

- 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

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

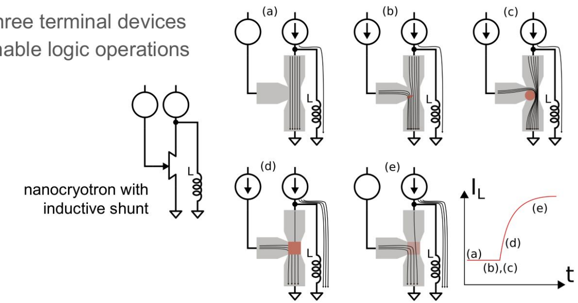
Reed Foster, Matteo Castellani, Alessandro Buzzi, Owen Medeiros, Marco Colangelo, Karl K. Berggren

WOLTE15 - Superconducting Electronics Nanowires
8 June 2022

Quantum Nanostructures and Nanofabrication
EECS, Massachussetts Institute of Technology

Superconducting nanocryotron operating principle

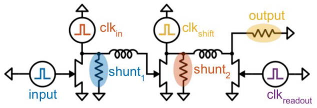
Three terminal devices enable logic operations

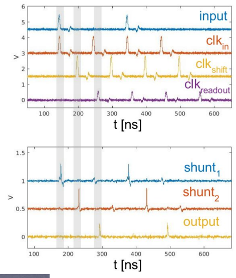


Demonstration of synchronous flux transfer

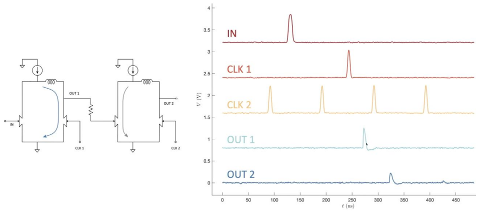
Maximum operating frequency limited to 60MHz by equipment

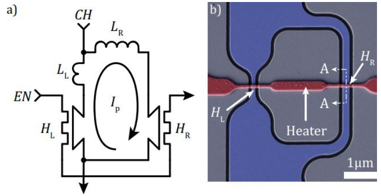
Electrical/thermal time constants on nanowire devices should allow for operation >200MHz



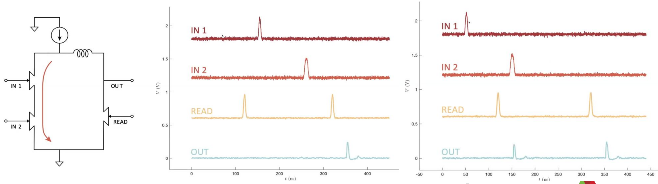


D flip-flop experimental results





OR gate experimental results



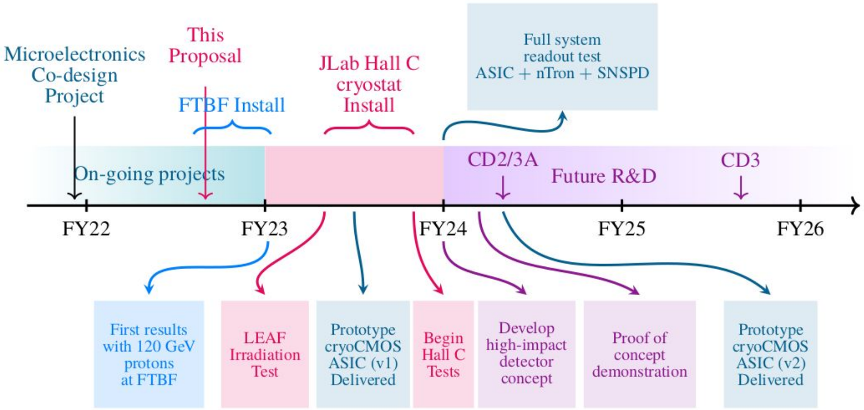
The Proposed R&D Plan

EIC-related Generic Detector R&D

Submitted in July 2022

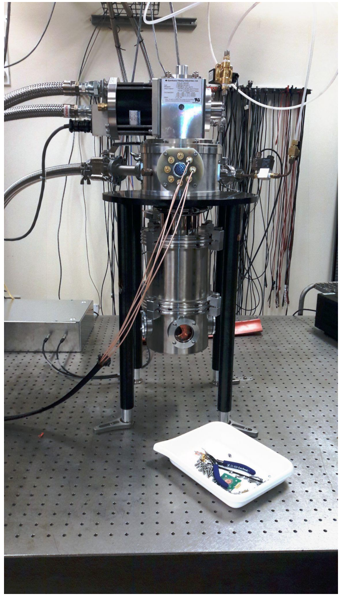
- Proposed R&D radiation hardness tests of SNSPDs, superconducting electronics and cryo-CMOS

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?

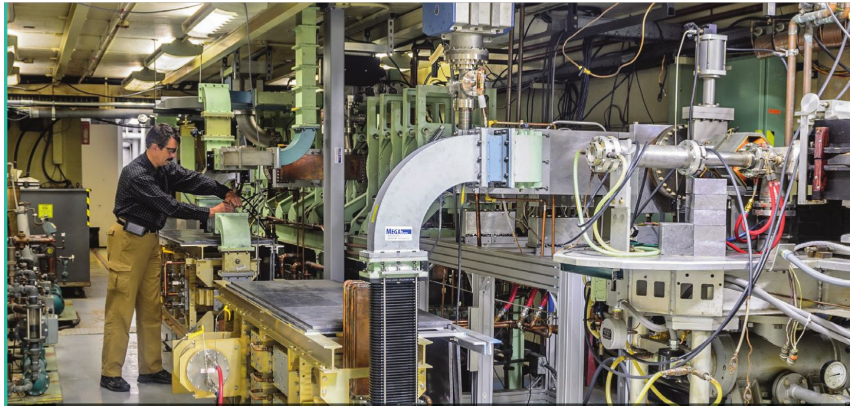


Image of the upgraded electron linac with maximum beam energy of 55 MeV, maximum average beam power 25 kW and maximum repetition rate of 240 Hz.

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
- Background error rate for superconducting shift registers
- SNSPD efficiency in high radiation environment

Applications at the EIC

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

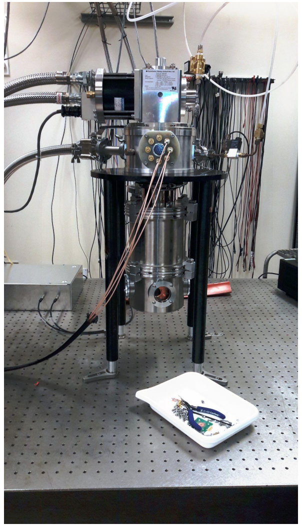
- Scattered nuclei (coherent DVCS and DVMP)
  - Larger room between $|t_{min}|$ and the detector acceptance limit

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

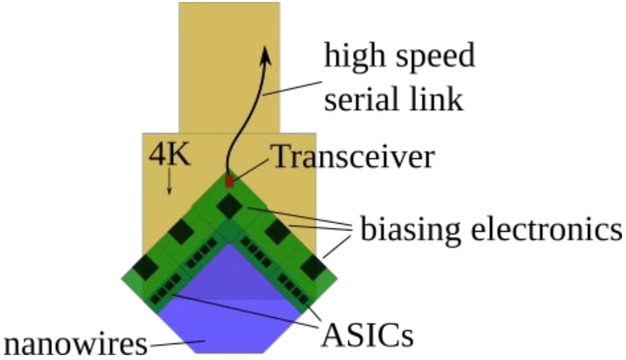
Cooling infrastructure

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) it would load the cryosystem with ~0.5 W.

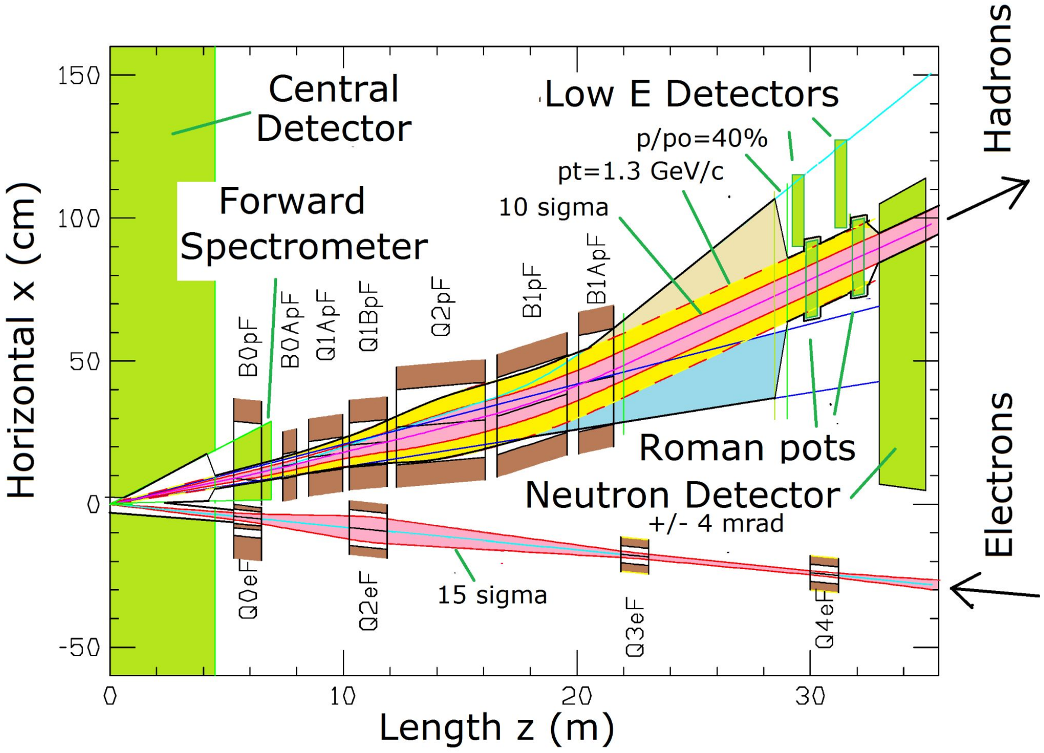


Conceptual layout of beamline detector



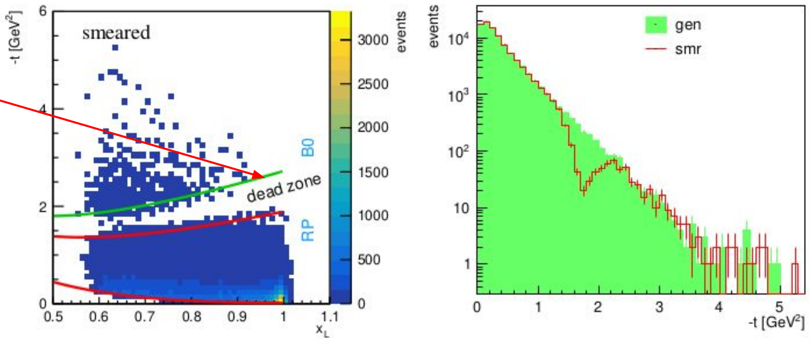
Far Forward Detector

- 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)

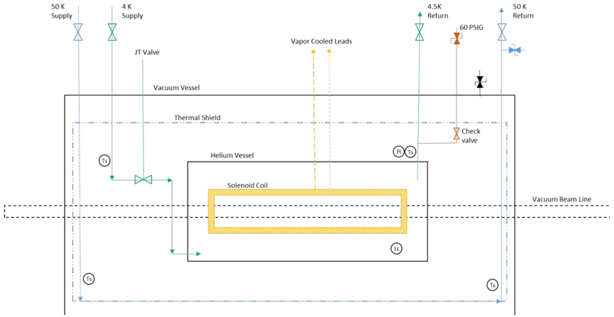


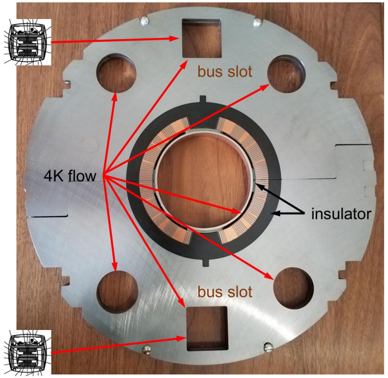
Superconducting Magnet integrated particle detector

- 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





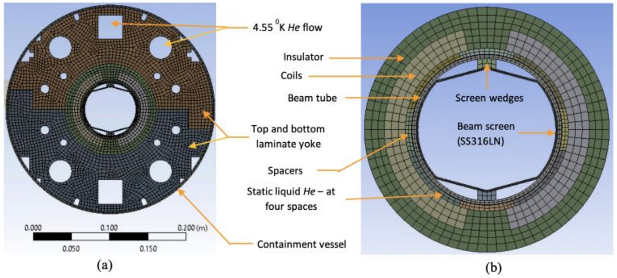
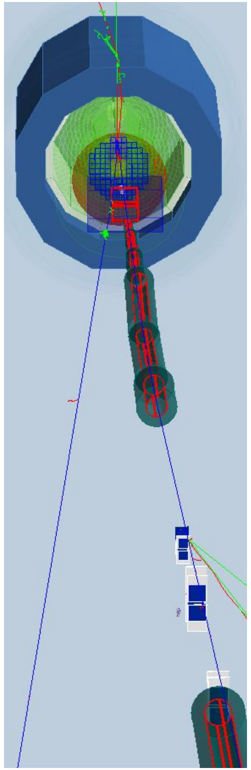


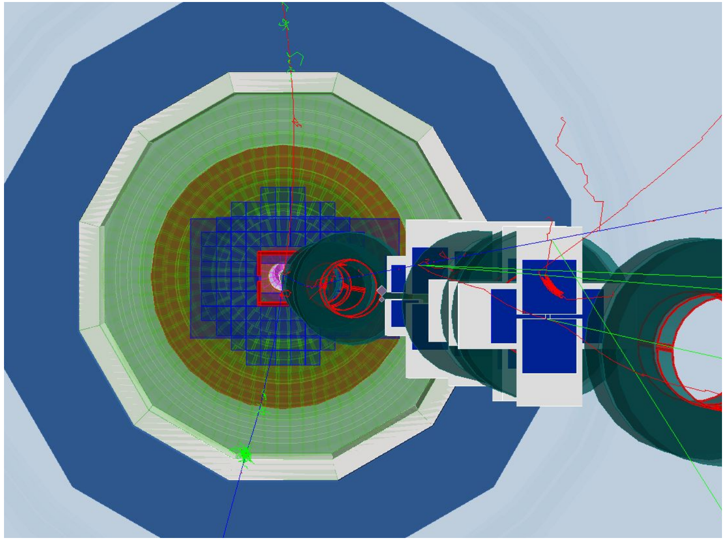
Figure 6.148: Finite-element model of (a) the RHIC arc dipole magnet cold mass cross-section and (b) close view around the beam tube.

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.



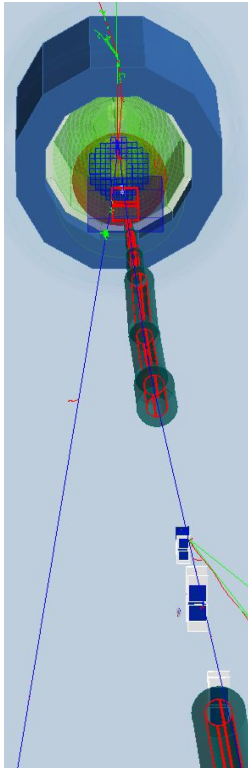


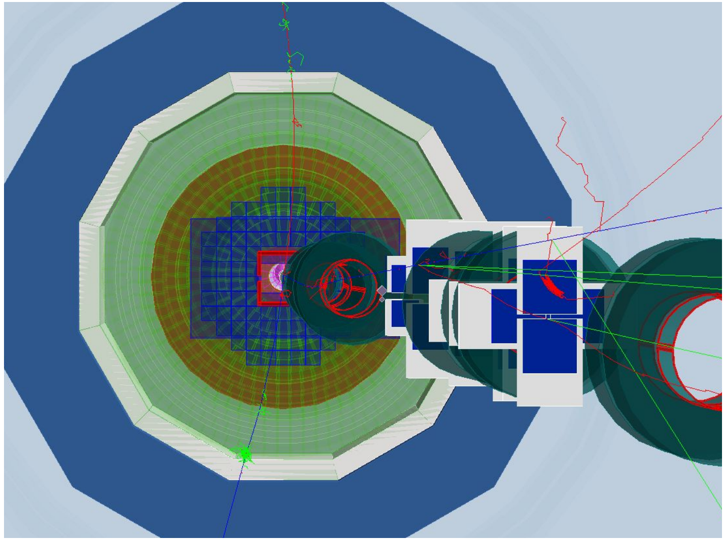
Thank you!

Backup

SUPERCONDUCTING NANOWIRE DETECTORS FOR THE ELECTRON ION COLLIDER

Successfulproposal for EIC Detector R&D at BNL: eRD28

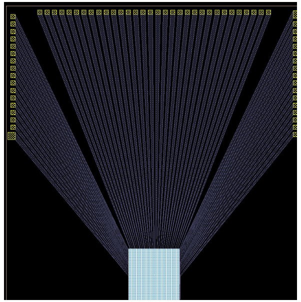


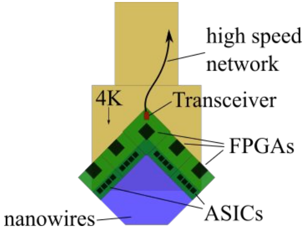


BNL EIC Detector R&D Committee:

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

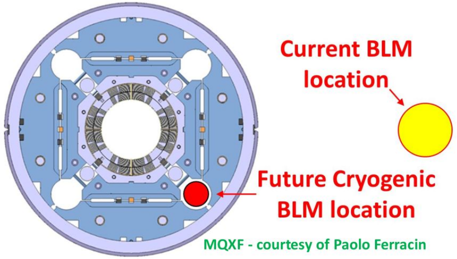
- Will demonstrate the detection of low energy particles from radioactive sources at high rate and in high magnetic field.
- Fabricate a small pixel array for high energy particle detection





Beam Loss Monitors at Accelerators

Requirements of Cryogenic BLMs

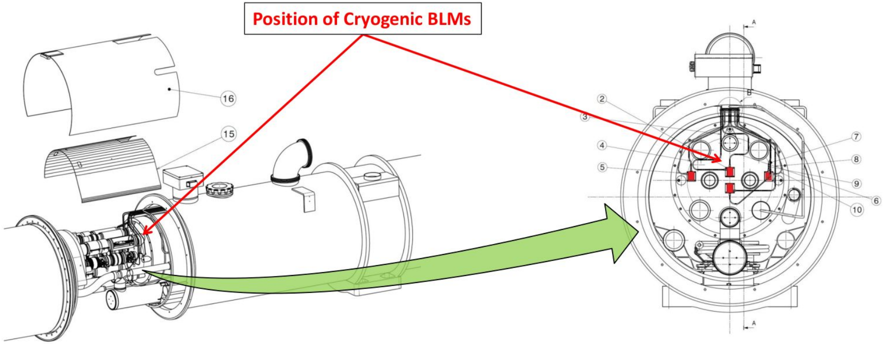


Mechanical requirements:
- total radiation dose of 2MGy,
- low temperature of 1.9K,
- 20 years, maintenance free operation,
- resistance to magnetic field of 2T,
- resistance to a pressure of 1.1 bar, and capability of withstanding a fast pressure rise up to 20bar in case of a magnet quench.

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

15th September 2016 M. R. Bartosik - Topical Workshop on Beam Loss Monitors 6

Cryogenic BLMs in LHC ring

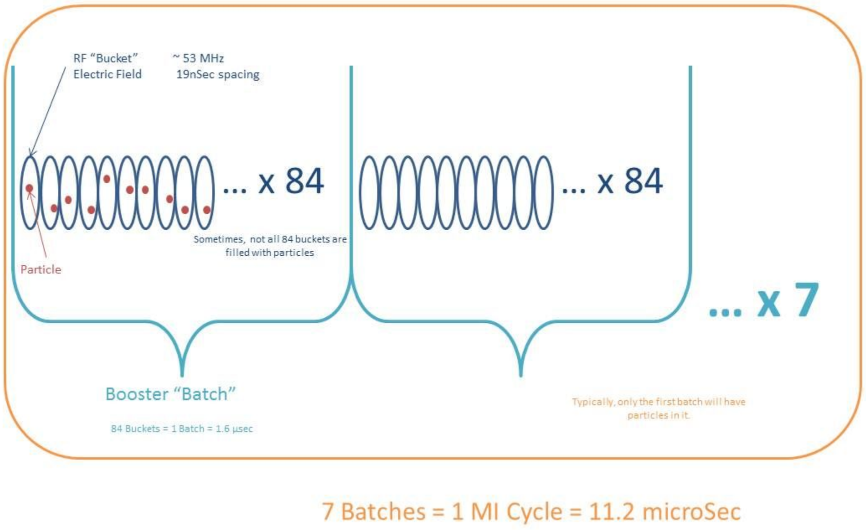


Long term correlation between Ionization Chamber BLM and Cryogenic BLM to be done in 9R7 and 9L5

15th September 2016 M. R. Bartosik - Topical Workshop on Beam Loss Monitors 22

Anticipate similar applications at the EIC

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

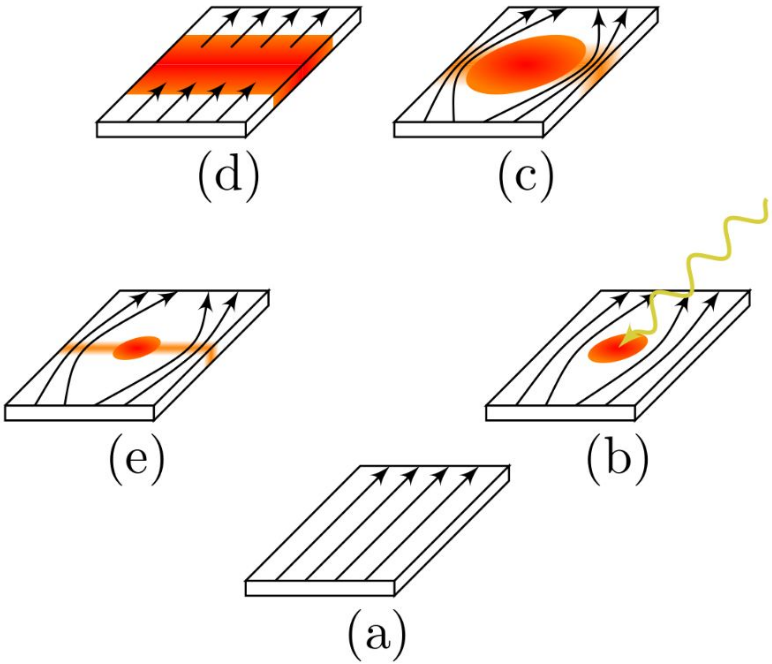
Rates averaged over spill ~ 30 Hz

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

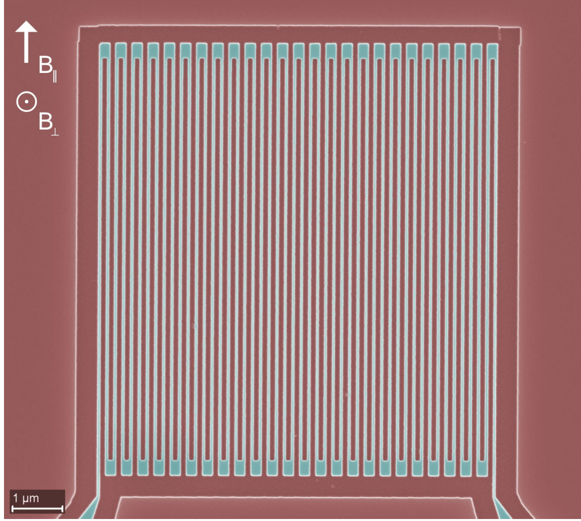


Polakovic, Nanomaterials (2020)

SUPERCONDUCTING NANOWIRES

Overview of Nanowire Detectors

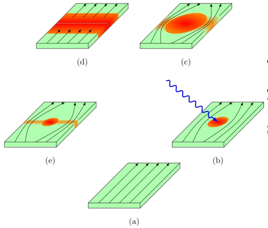
- PHY-MSD Collaboration supported by DOE-NP (FWP-32537.2)
- Sensors can operate in fields up to (at least) 7T, can operate inside of cold bore of superconducting magnets (T< 5 K).
- Argonne nanowire sensors fabricated on-site.
- Novel concept for high-resolution rad-hard detectors based around superconducting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

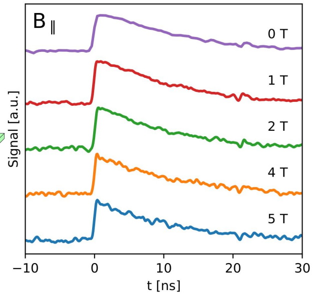


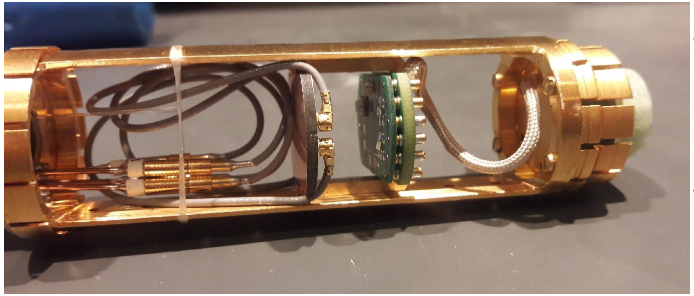
1) *Room temperature deposition of superconducting Niobium Nitride films by ion beam assisted sputtering*. APL Materials 6, 076107 (2018)

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.

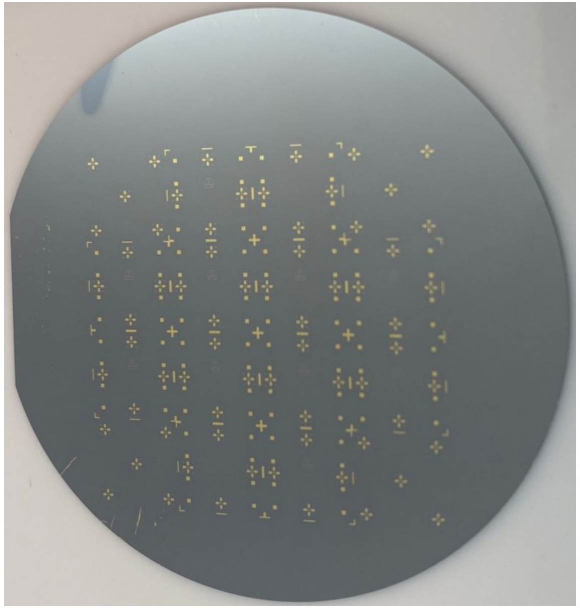


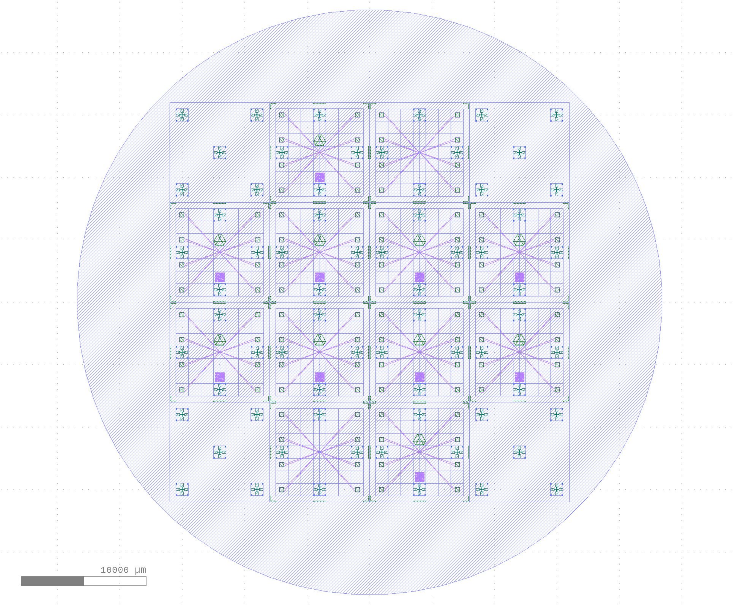


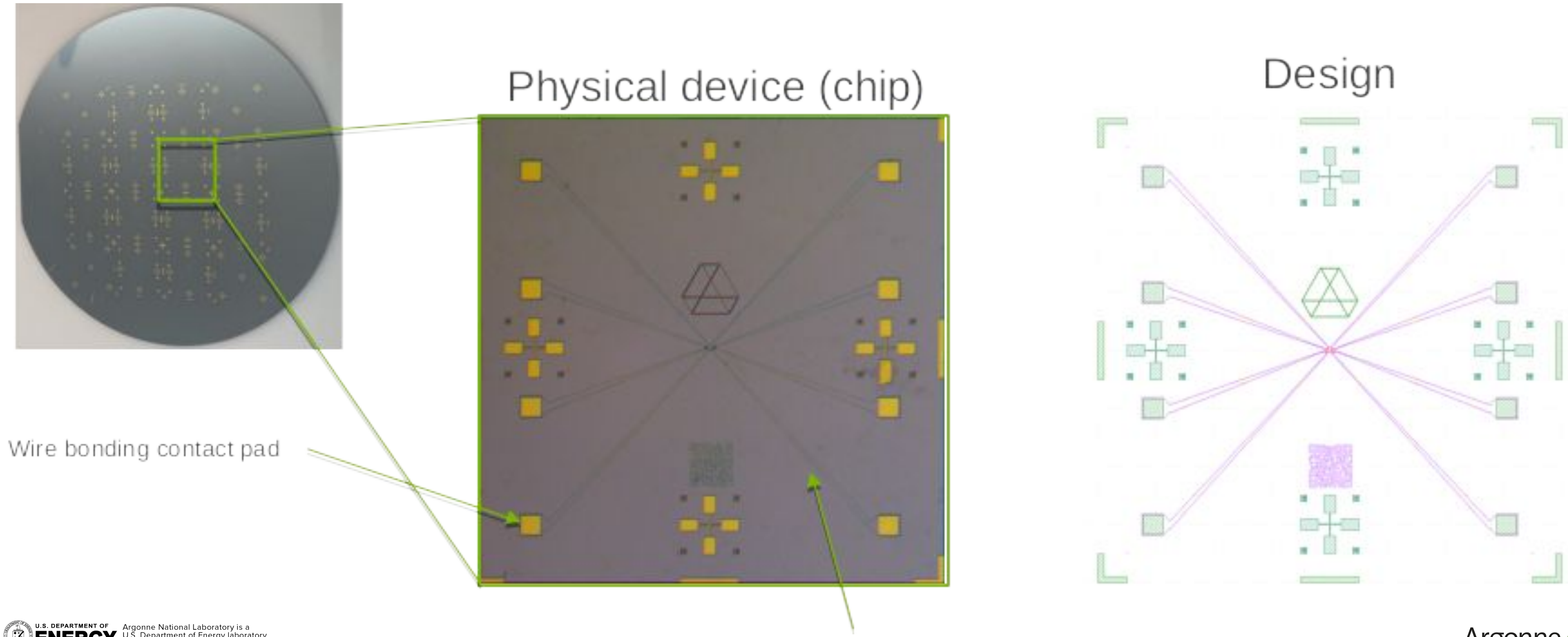


2-inch wafer

8 mm chips



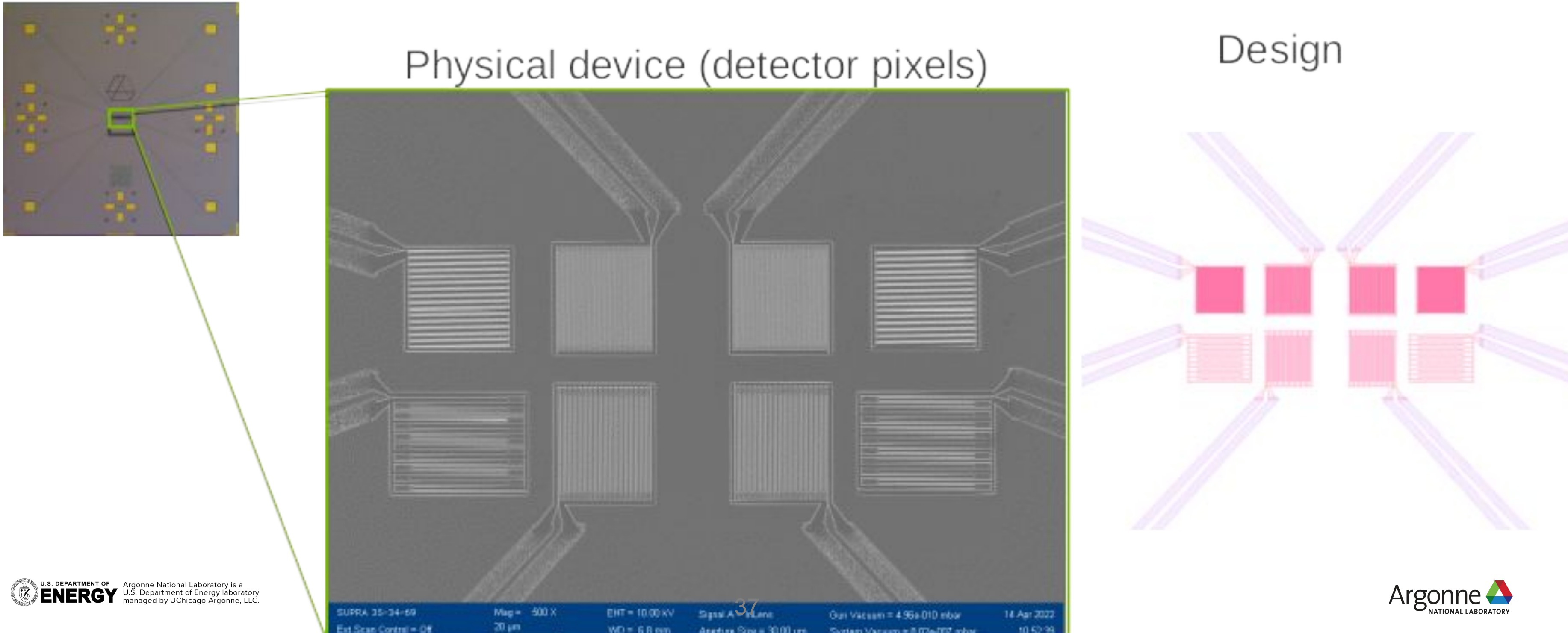



Physical device (chip)
Design
Wire bonding contact pad

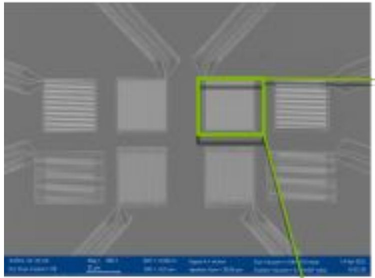
PROJECT OUTCOMES

Physical device (detector pixels)

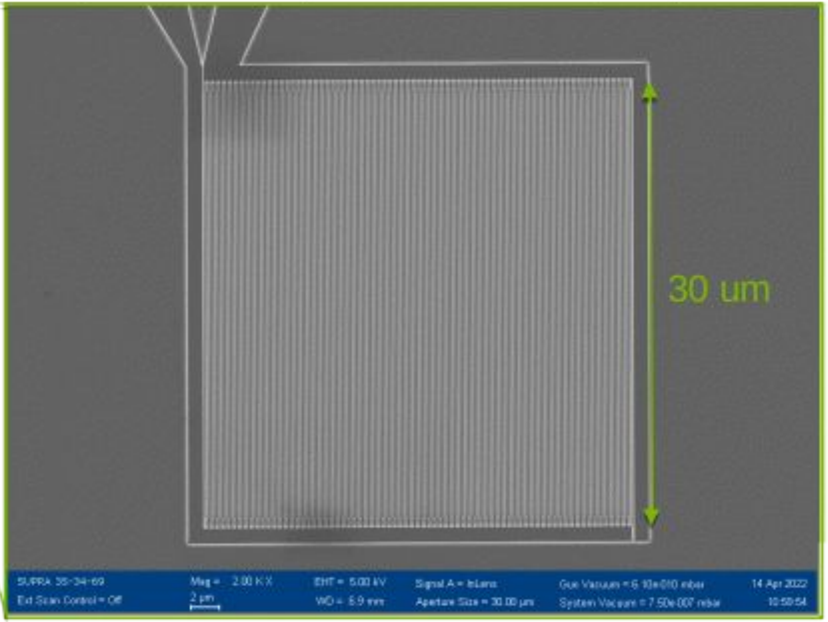
Design



PROJECT OUTCOMES



Physical device (100nm nanowire pixel)



Design