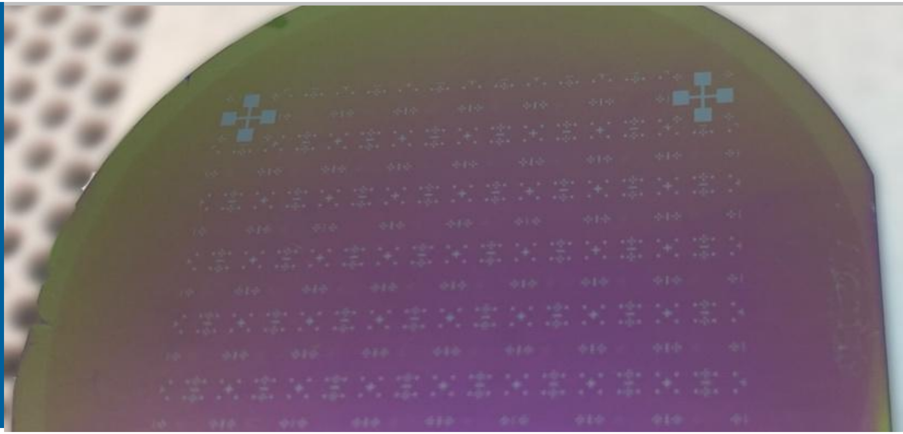
1st INTERNATIONAL WORKSHOP ON A 2ND DETECTOR FOR THE EIC

Superconducting Nanowire Particle Detectors



Whitney Armstrong
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U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

May 18, 2023

Overview

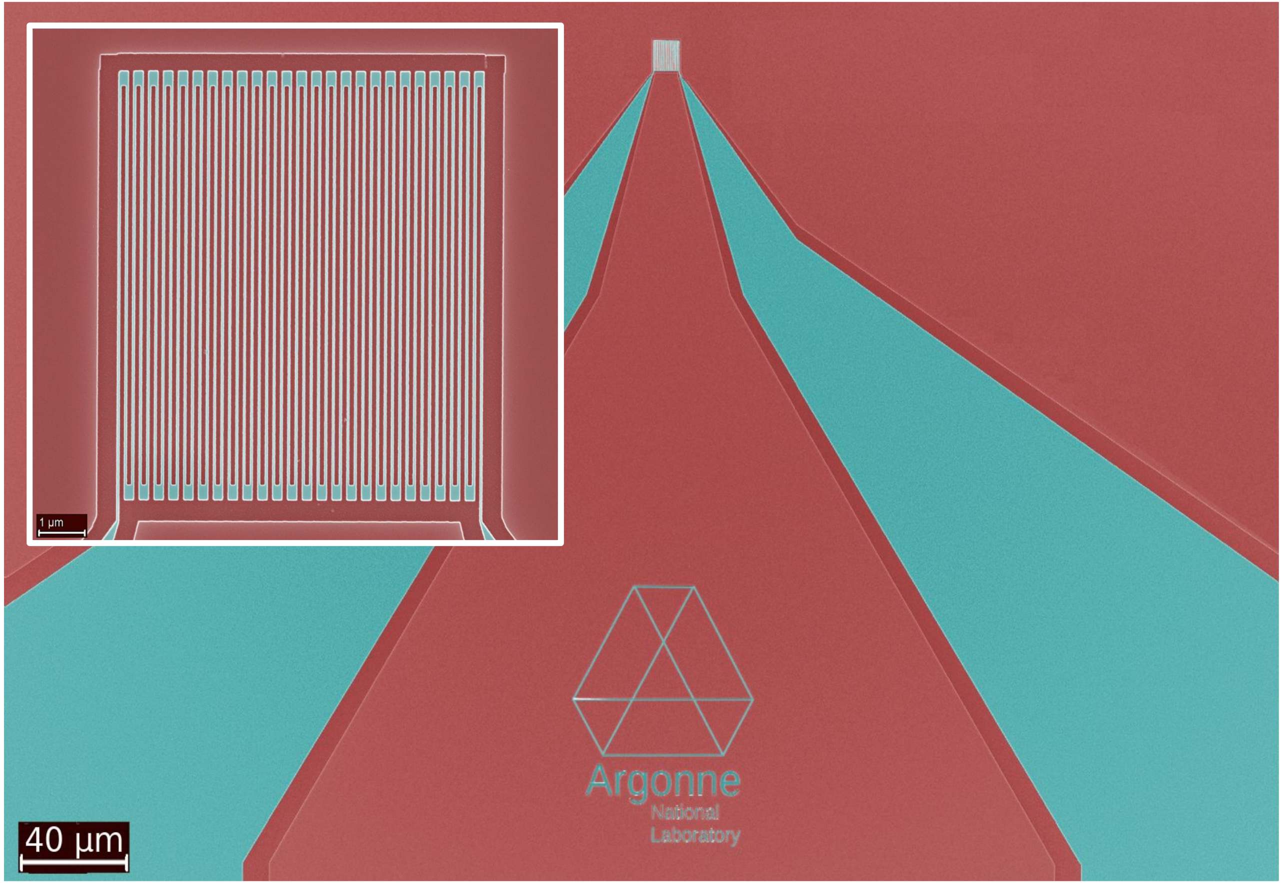
- Introduction to superconducting nanowire detectors
- Motivation for superconducting nanowires at the EIC
- Superconducting Nanowire Technology
  - Superconducting Nanowire Single Photon Detectors (SNSPDs)
  - Particle Detection
  - Superconducting Electronics and Cryogenic Readout
- Ongoing and future R&D
  - Current R&D
  - R&D needed to realize EIC detector
- What can be done for a second detector?
- Summary

Superconducting Nanowire Sensors

Superconducting Nanowire Single Photon Detectors

Typical device parameters

- Fabricated from ~10nm NbN film with T_c=15 K [1]
- Typical meandering geometry fills the pixel area
- 100 nm wide wire,
  100 nm spacing
- After etching device has
  T_c~ 5 K
- Current biased:
  I_b~ 10 - 40 µA



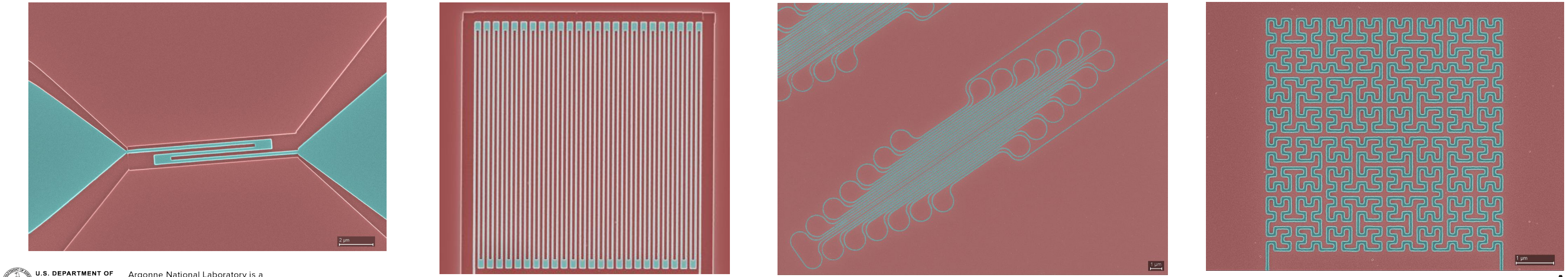
[1] *Room temperature deposition of superconducting Niobium Nitride films by ion beam assisted sputtering*. Polakovic et.al. APL Materials 6, 076107 (2018)

SNSPD Properties and Characteristics

Quick Summary

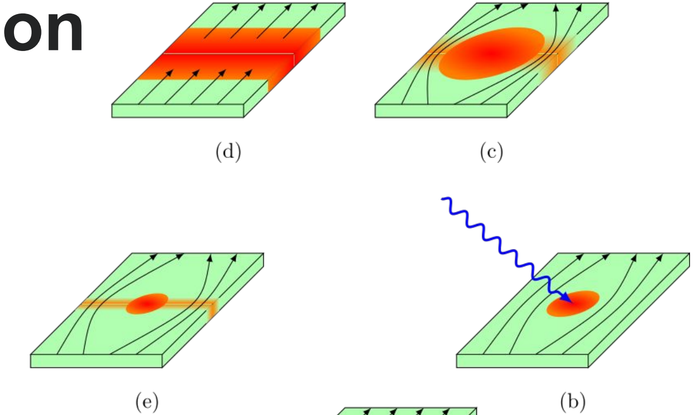
"Almost too good to be true"
T. Ullrich, Technology Inventory

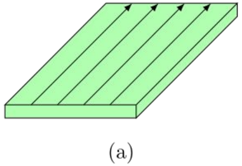
- Photon energy thresholds as low as ~100 meV
- Timing jitter 20-40 ps easily achieved (current record of 3 ps)
- Reset times can be as low as 5-10 ns (potentially <1 ns in the future)
- Pixels on the order of 10x10 μm^2 to 30x30 μm^2
- Fast, granular, high-rate pixel detector → low occupancies
- Conveniently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

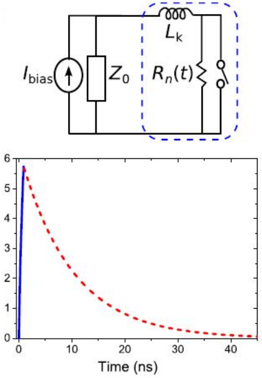


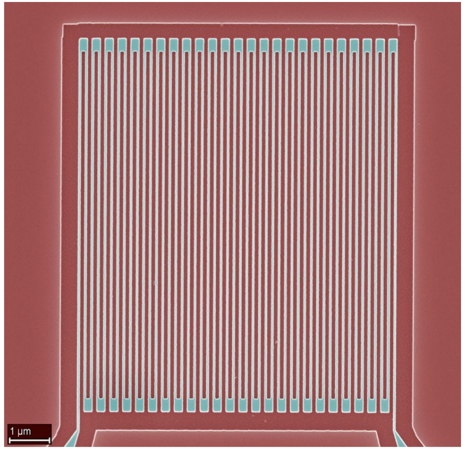
SNSPD Theory of Operation

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





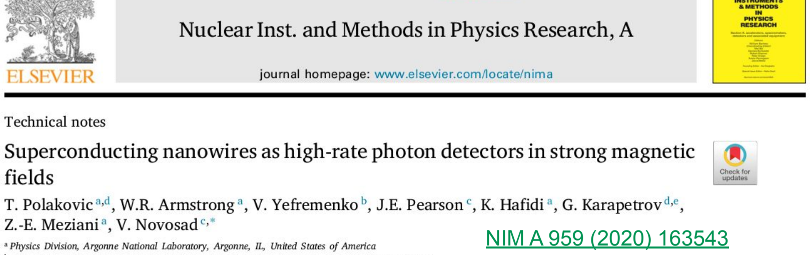




Strong Magnetic Fields

SNSPDs operated in fields up to 5T

- Sensors can operate in fields up to (at least) 7T with parallel field orientation
- Operate at high rates with **nearly zero dark count rate**.



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Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

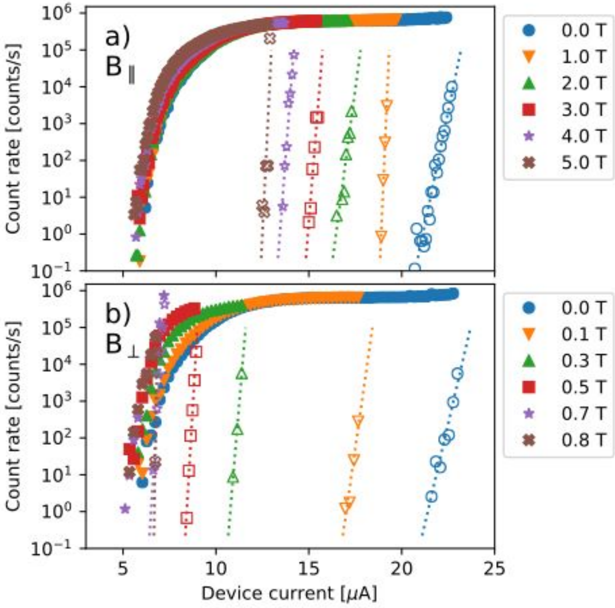
Technical notes

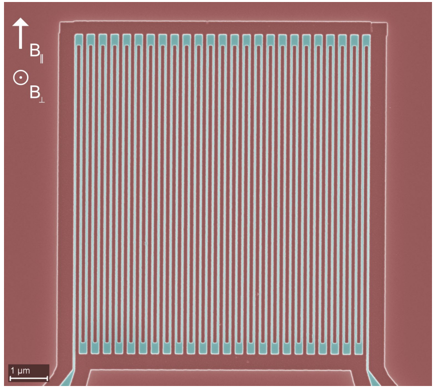
Superconducting nanowires as high-rate photon detectors in strong magnetic fields

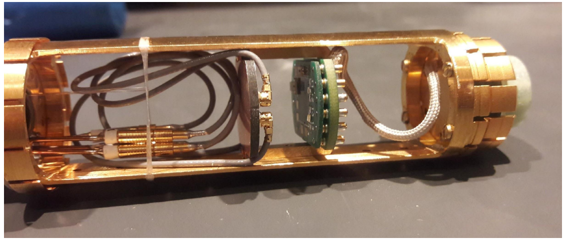
T. Polakovic [a,d], W.R. Armstrong [a], V. Yefremenko [b], J.E. Pearson [c], K. Hafidi [a], G. Karapetrov [d,e], Z.-E. Meziani [a], V. Novosad [c,*]

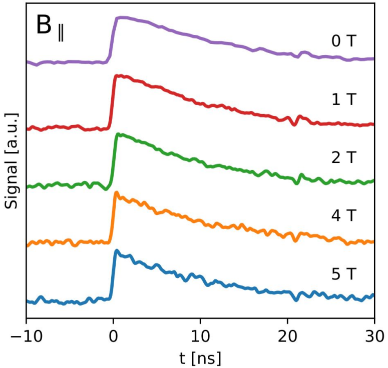
[a] Physics Division, Argonne National Laboratory, Argonne, IL, United States of America

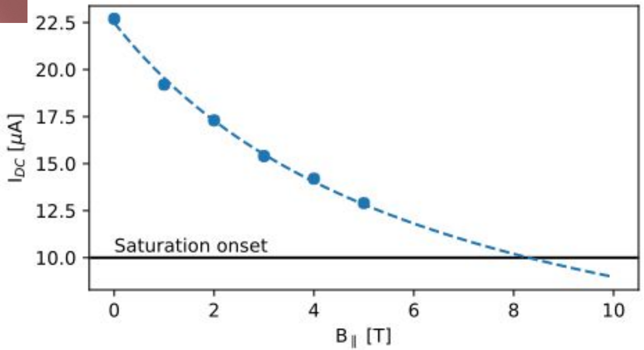
NIM A 959 (2020) 163543









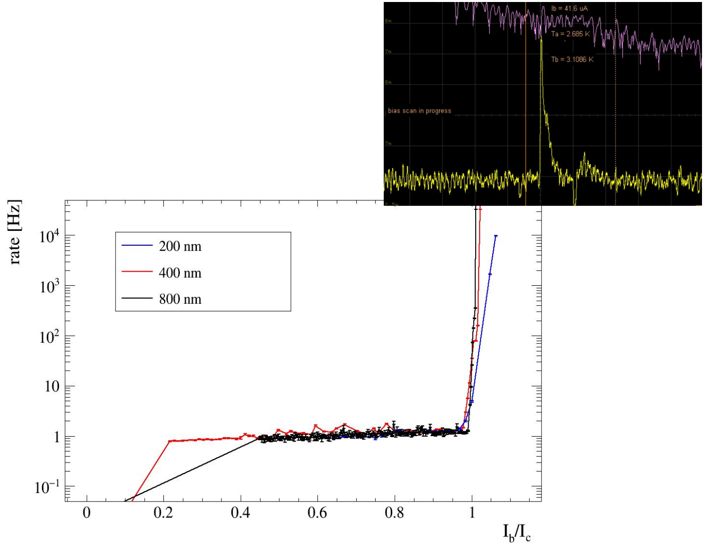


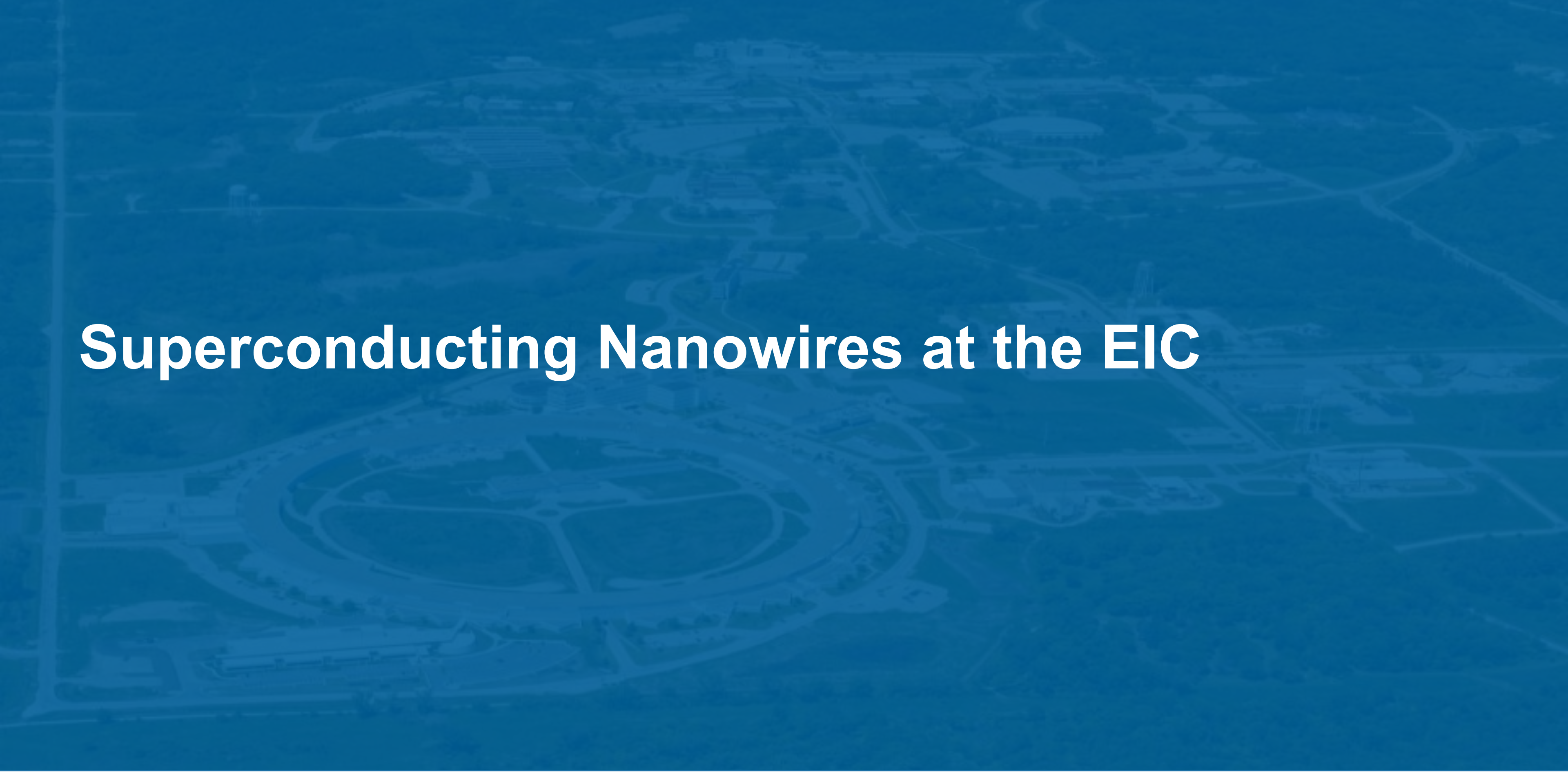
Particle Detection Status

- Note that the alpha particles deposit almost 10^3 more energy in NbN
- Demonstrating high energy proton detection is the key test needed for the EIC
  - No show stoppers expected…

		Approximate Energy loss in		
Particle	**Energy**	**100 μmsilicon**	**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	✔

Preliminary Results with α Particles



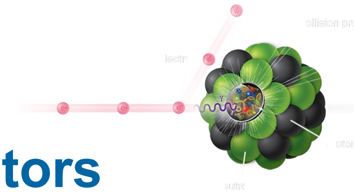


Superconducting Nanowires at the EIC

Electron-Ion Collider

Superconducting Nanowire Particle Detectors

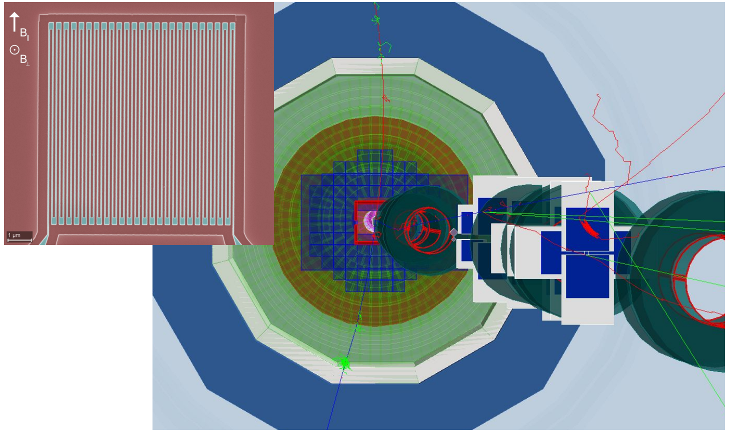
- Far forward/backward particle detection (<10 sigma)
- Superconducting magnet integrated tracker
- High resolution zero-degree tracking calorimeter
- High rate Compton polarimeter e/gamma detector
- Beam position and beam loss monitors

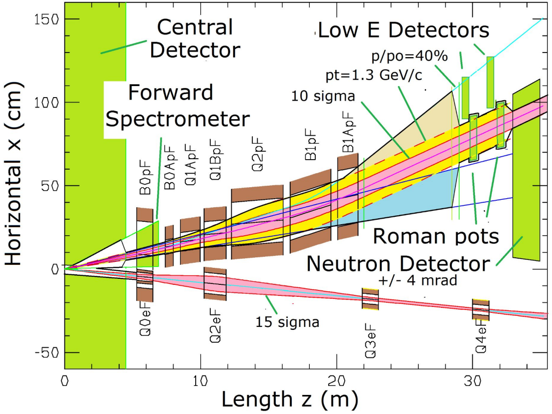


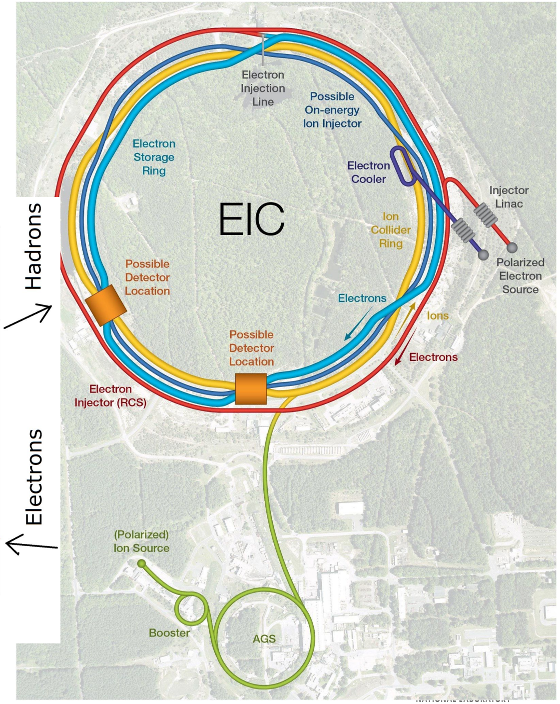
p/A → ← e^-

41 GeV, 100-275 GeV

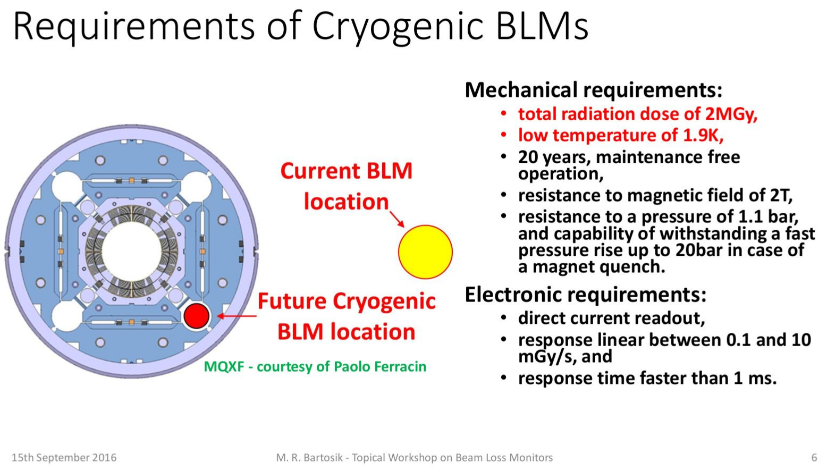
5 GeV - 18 GeV







Beam Loss Monitors at Accelerators



Requirements of Cryogenic BLMs

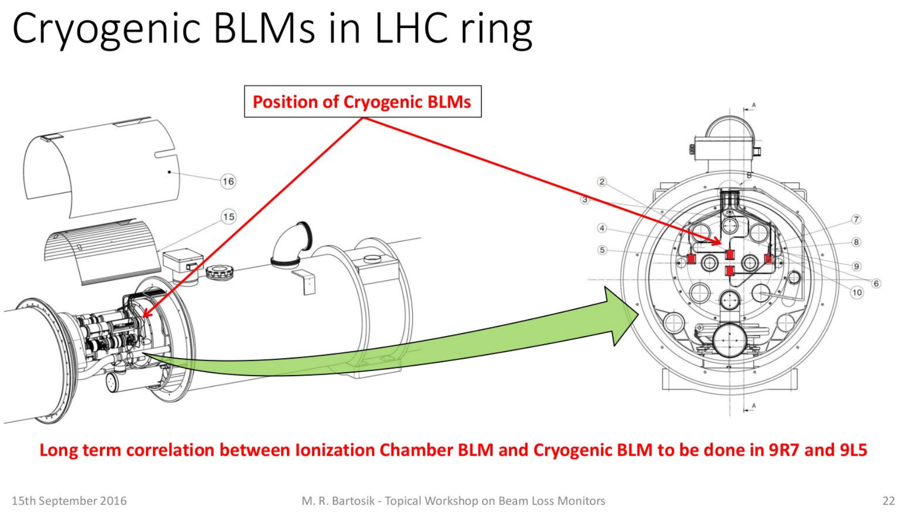
Mechanical requirements:

- 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

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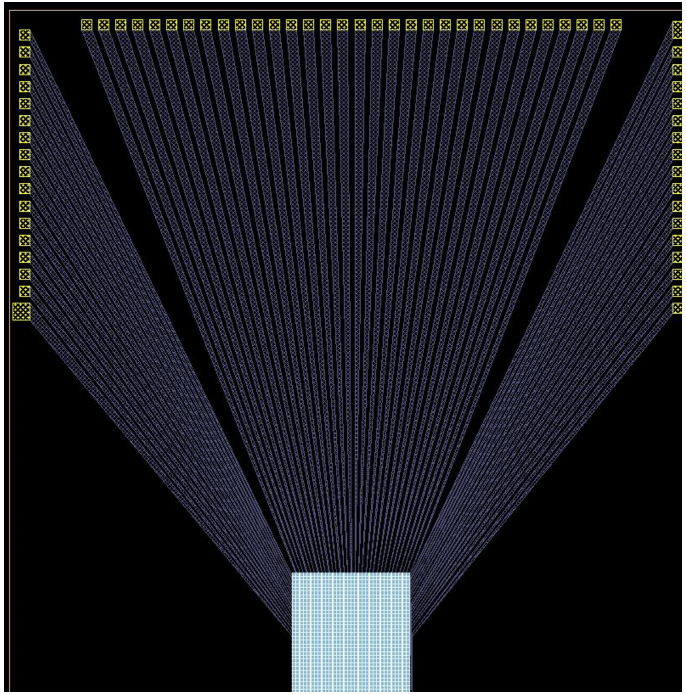
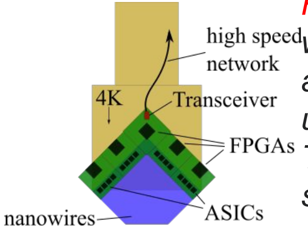
Anticipate similar applications at the EIC

Ongoing and Future R&D

SUPERCONDUCTING NANOWIRE DETECTORS FOR THE ELECTRON ION COLLIDER

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

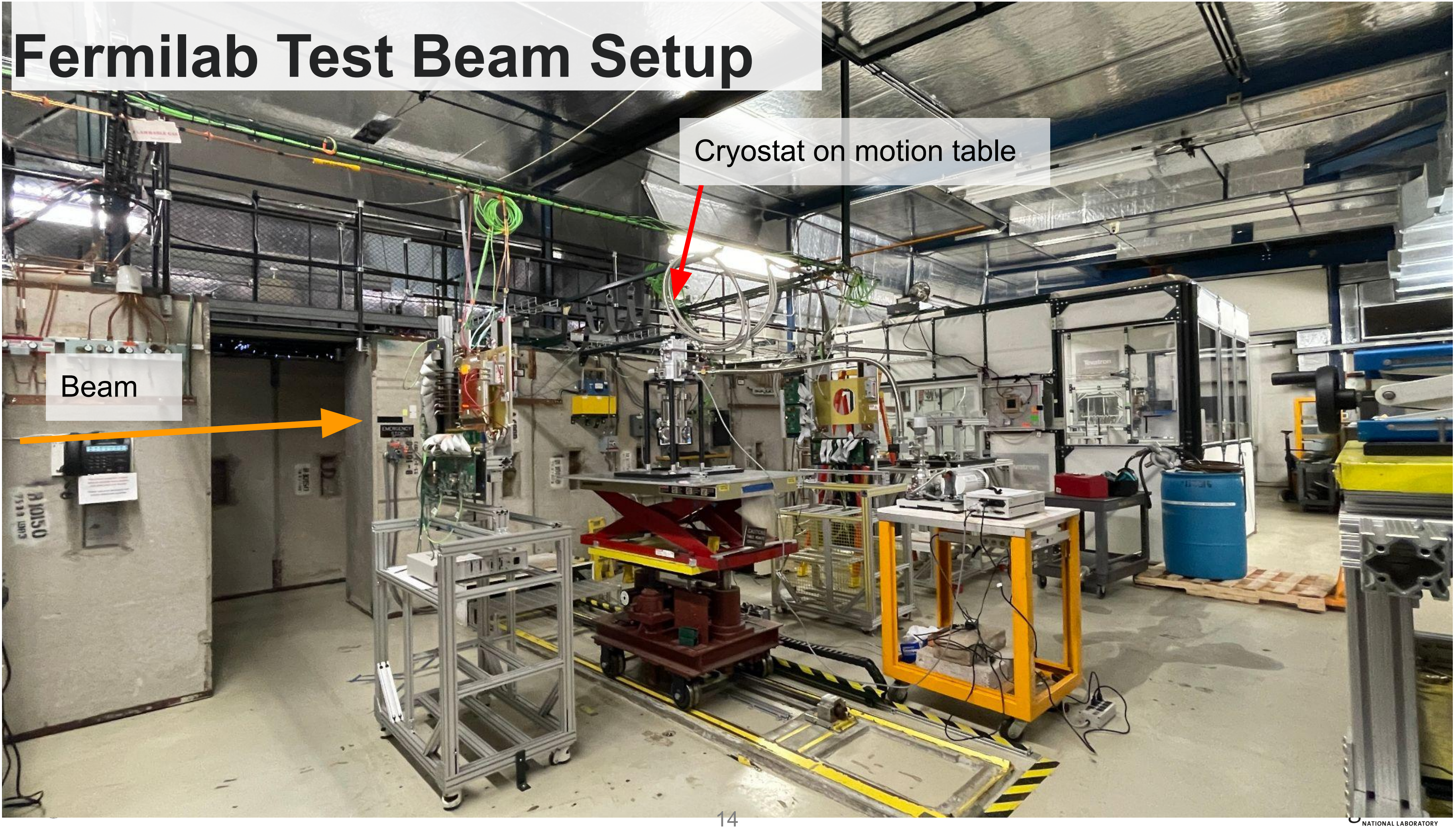




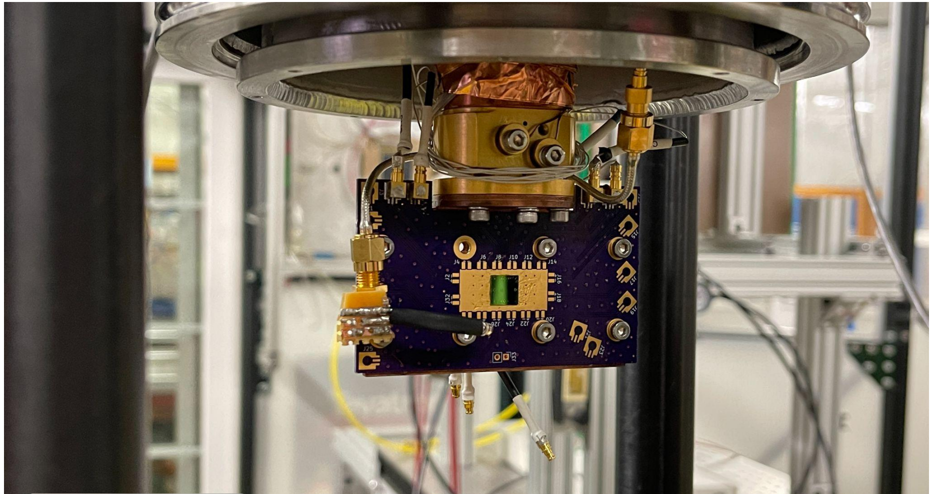
BNL EIC Detector R&D Committee:

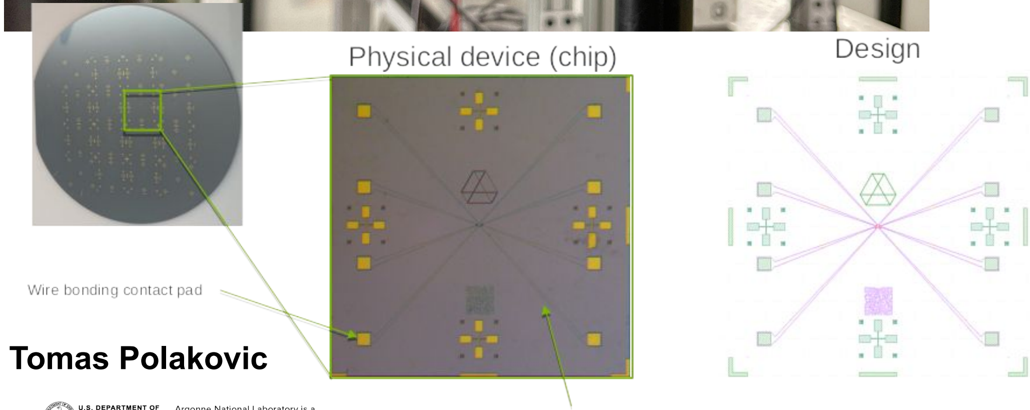
Superconducting nanowires have never been deployed in a particle or nuclear physics experiment to our knowledge. As such, this proposal represents a true spirit of detector R&D. This project will have to solve many issues before it would have a working detector as indicated above. There are interesting 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

Fermilab Test Beam Setup

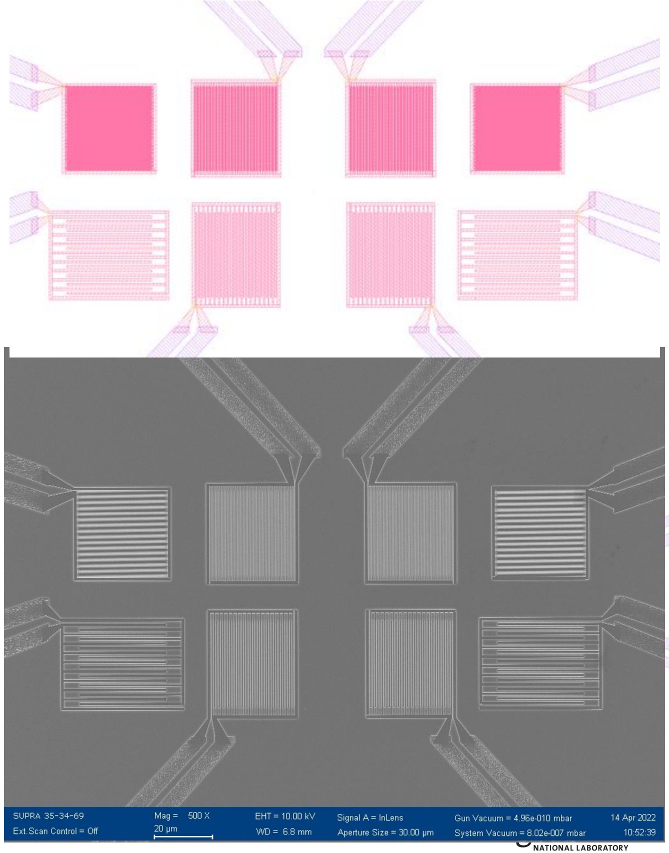


Fermilab Test Beam Facility - TSW1962





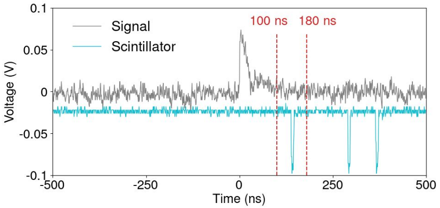
Tomas Polakovic

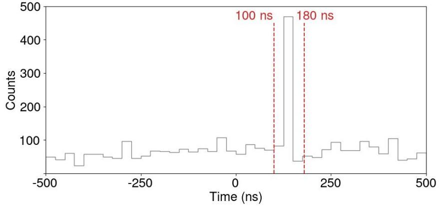


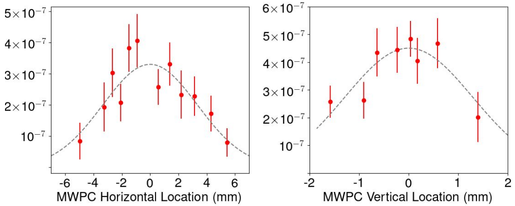
Preliminary Results with 120 GeV Protons

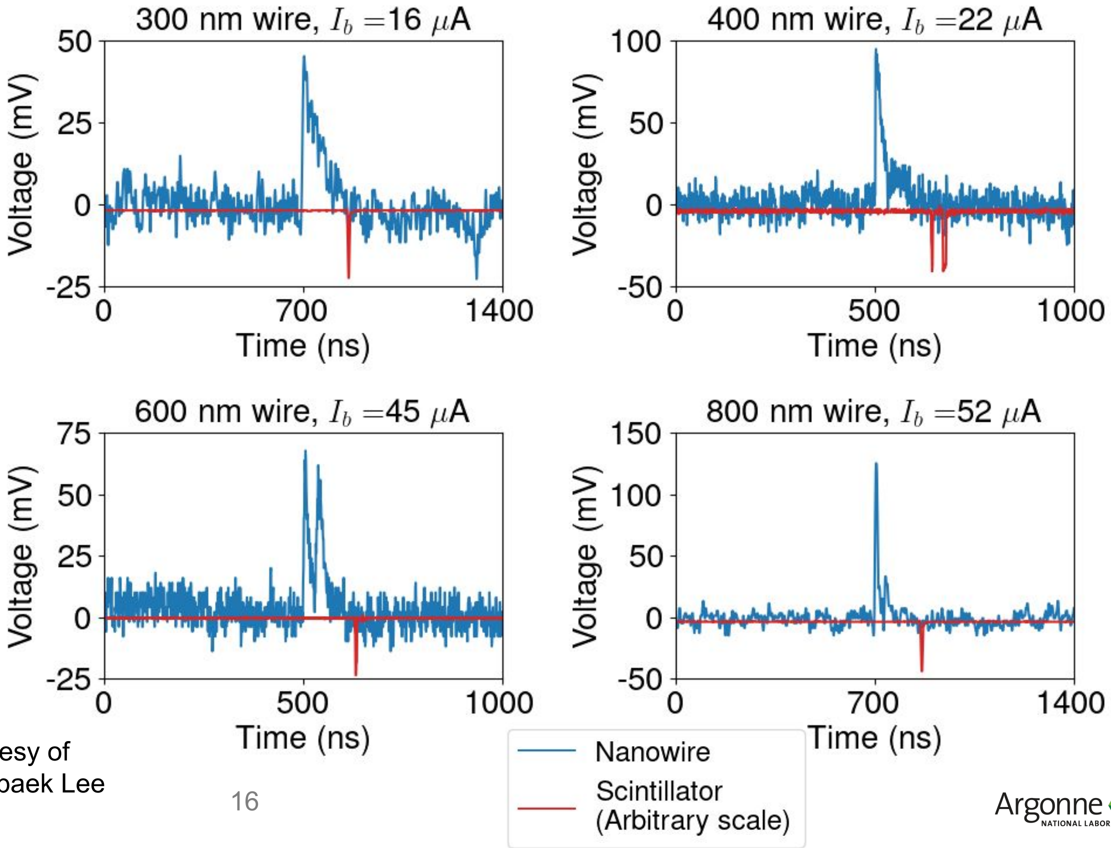
Raw waveforms in timing coincidence with the scintillator signal

Data taken with 120 GeV Protons at Fermilab Test Beam Facility.









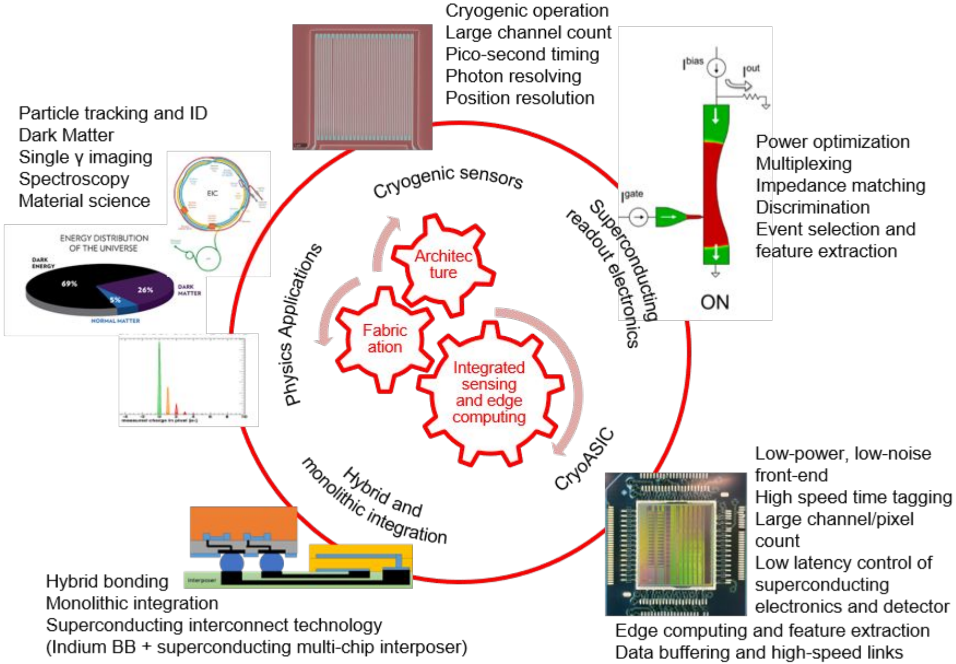
Courtesy of Sangbaek Lee

Cryogenic Readout and Scaling R&D

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

HYDRA
Project

HYDRA microelectronics co-design project



Cryogenic operation
Large channel count
Pico-second timing
Photon resolving
Position resolution

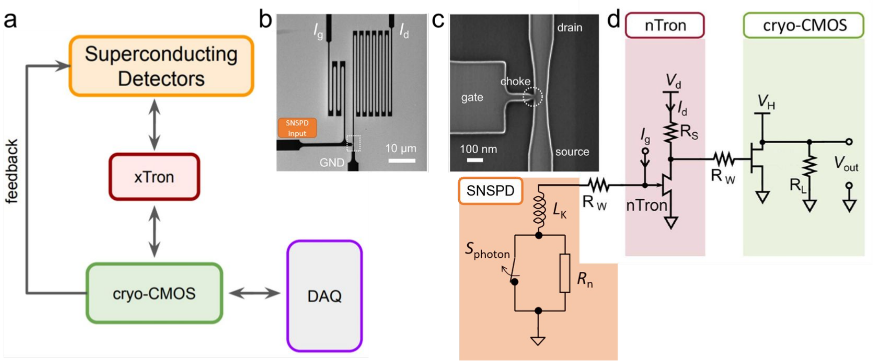
Particle tracking and ID
Dark Matter
Single γ imaging
Spectroscopy
Material science

Power optimization
Multiplexing
Impedance matching
Discrimination
Event selection and feature extraction

Low-power, low-noise front-end
High speed time tagging
Large channel/pixel count
Low latency control of superconducting electronics and detector
Edge computing and feature extraction
Data buffering and high-speed links

Hybrid bonding
Monolithic integration
Superconducting interconnect technology
(Indium BB + superconducting multi-chip interposer)

- 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

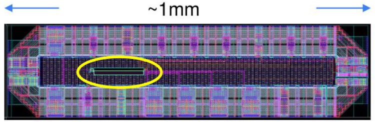
- Operation at <4K demonstrated in modern, state-of-the-art commercial processes (no special processing)
- Leverage low power, high performance ASICs for signal conditioning, time-tagging, data concentrator/edge computing, and serialization/readout
- Highlights:
  - SiGe HBT (high performance LNA)
  - 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

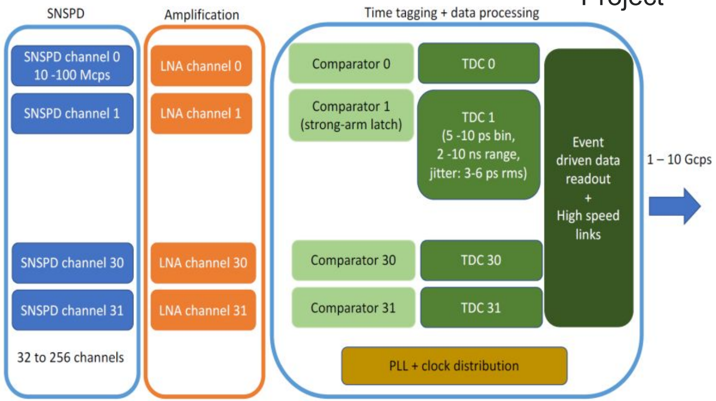
cryoASIC readout and control

- 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




SNSPD

SNSPD channel 0
10 -100 Mcps

SNSPD channel 1

SNSPD channel 30

SNSPD channel 31

32 to 256 channels

Amplification

LNA channel 0

LNA channel 1

LNA channel 30

LNA channel 31

Time tagging + data processing

Comparator 0

Comparator 1
(strong-arm latch)

Comparator 30

Comparator 31

TDC 0

TDC 1
(5 -10 ps bin,
2 -10 ns range,
jitter: 3-6 ps rms)

TDC 30

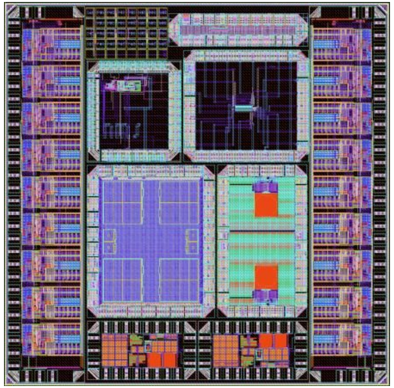
TDC 31

Event
driven data
readout
+
High speed
links

PLL + clock distribution

1 – 10 Gcps

Amplification could be done in either xTron or ASIC



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 (ntron) devices
- Fabricated with same NbN as SNSPDs.
- A preamplifier ntron is the simplest interface between sensor and cryo-CMOS
- Recently developed at MIT
  - A superconducting binary shift register for SNSPD readout (R. Foster)
  - Binary and Multilevel Counter (M. Castellani)
  - Building Blocks Design for Superconducting Nanowire Asynchronous Logic (A. Buzzi)
- More complex designs may exploit material's high kinetic-inductance in the future.

Sensor integrated superconducting electronics provides important/new capabilities:

- Pre-ASIC data reduction and processing
- Subsystem trigger or feature extraction
- Novel spiking neutral network architecture
- Edge/Neuromorphic computing possiblities

A superconducting binary shift register for SNSPD readout

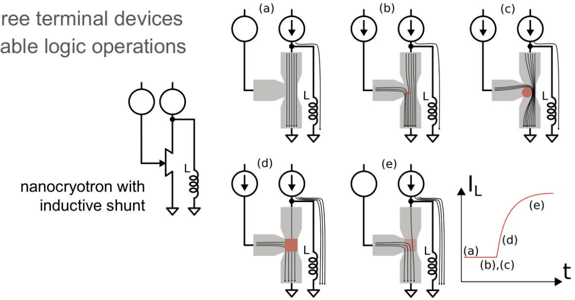
Reed Foster, Matteo Castellani, Alessandro Buzzi, Owen Medeiros, Marco Colangelo, Karl K. Berggren

WOLTE15 - Superconducting Electronics Nanowires
8 June 2022

Quantum Nanostructures and Nanofabrication
EECS, Massachusetts Institute of Technology

Superconducting nanocryotron operating principle

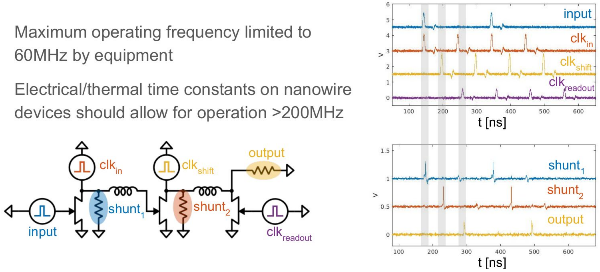
Three terminal devices enable logic operations



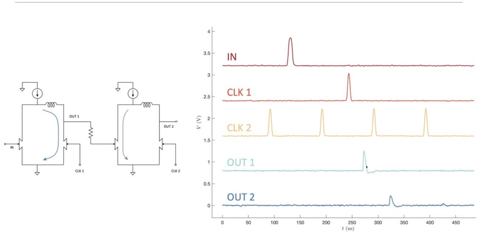
Demonstration of synchronous flux transfer

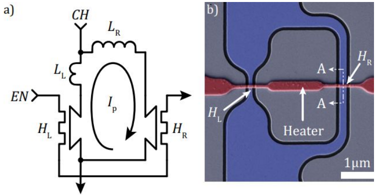
Maximum operating frequency limited to 60MHz by equipment

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

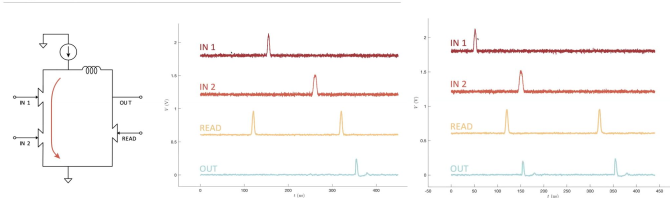


D flip-flop experimental results





OR gate experimental results



EIC-related Generic Detector R&D

EICGENRandD_2022_18

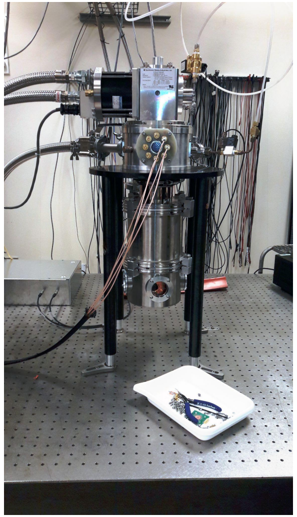
Submitted in July 2022

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

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

- 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)
- Quantify single event upset cross-section, displacement damage, and other cumulative damage
- Will monitor radiation exposure and produce estimates of the accumulated dose and scaled neutron fluence

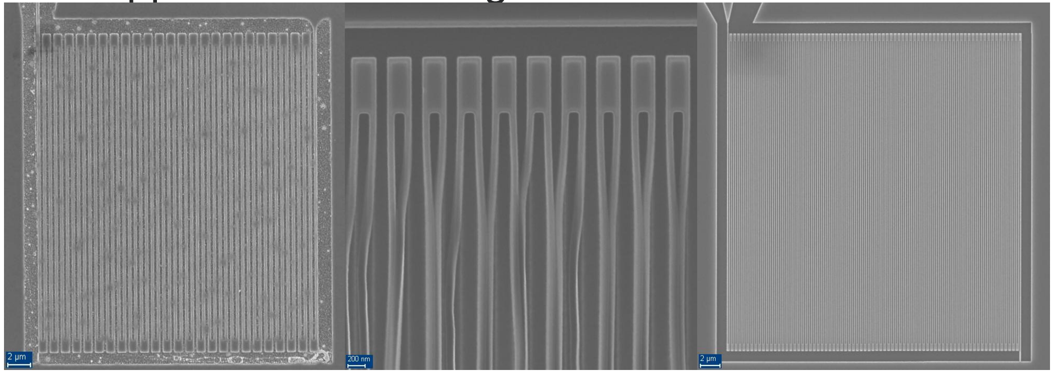


Delayed start due to arrival of funds

Scaling Fabrication for the EIC

Solving the technical barriers towards large-scale detectors

- State-of-the-art fabrication capabilities meet the current need of small scale devices for proof-of-principle devices and R&D but quickly reach their limits when scaling to wafer scale devices requiring high yields.
- Multi-institutional research proposal to be submitted responding to "*Accelerate Innovations in Emerging Technologies*" FOA aimed at superconducting nanowire technology at scale
- Wafer scale yields are needed to build the detectors needed for many future applications including the EIC



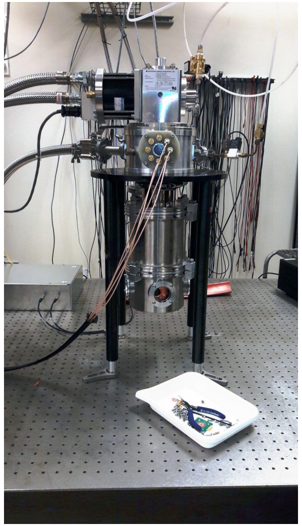
Example of tuning etching: Under, over, and good etching

- Many Materials and processes to explore
- Requires significant investment in basic research
- Need to bridge the gap between novel technology and large scale applications
- Broad applications far beyond the EIC and NP

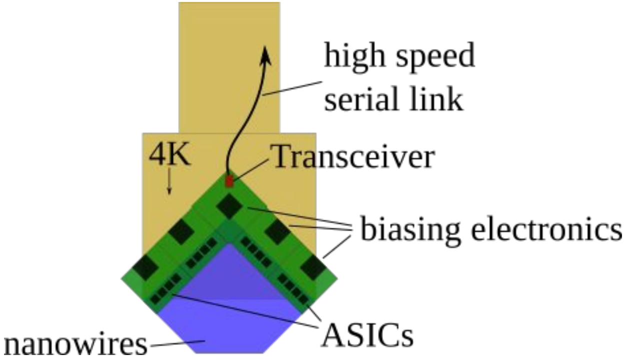
Applications at the EIC

Cooling infrastructure

- 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 state 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.

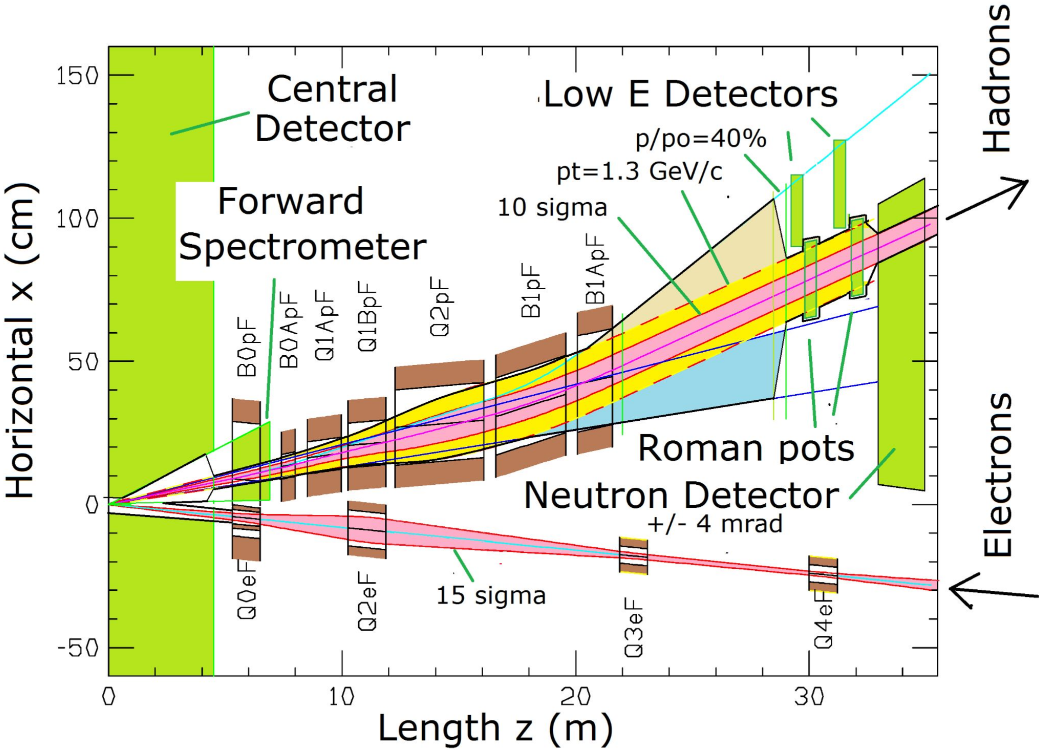


Conceptual layout of beamline detector



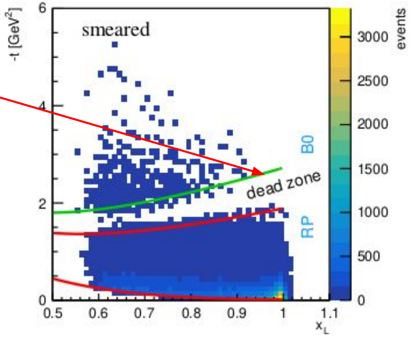
Far Forward Detector

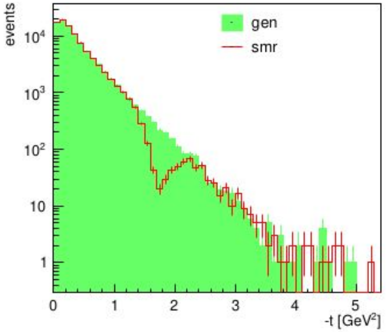
- We can use nanowire tracking detectors in a Roman pot configuration
- Ultrafast timing – demonstrated to be less than 20 ps
- Small basic pixel size, allowing for sub-μm position precision if needed.
- Edgeless sensor configuration – sensitive element positioned to within a few 100 nm of the substrate 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)



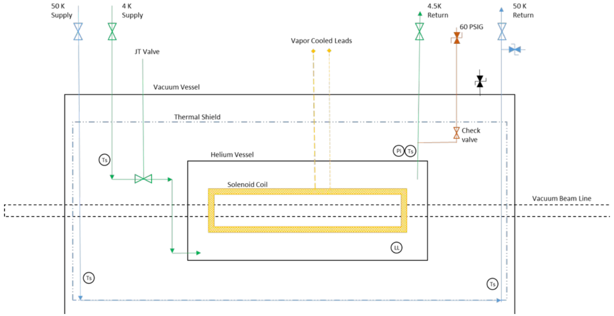
Superconducting Magnet integrated particle detector

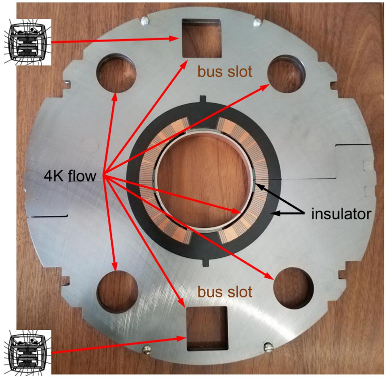
- Avoid the “dead zone” between roman pot detectors and B0 detectors
- Tie into superconducting magnets’ 4K supply
- Design a mechanical/thermal mounting location in the bore of the magnet





From Figure 8.125 of YR





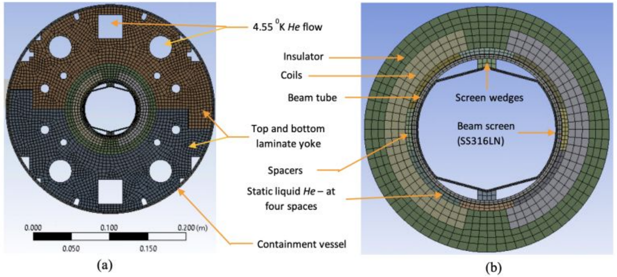
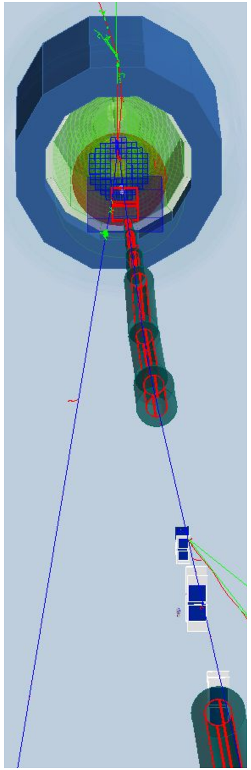


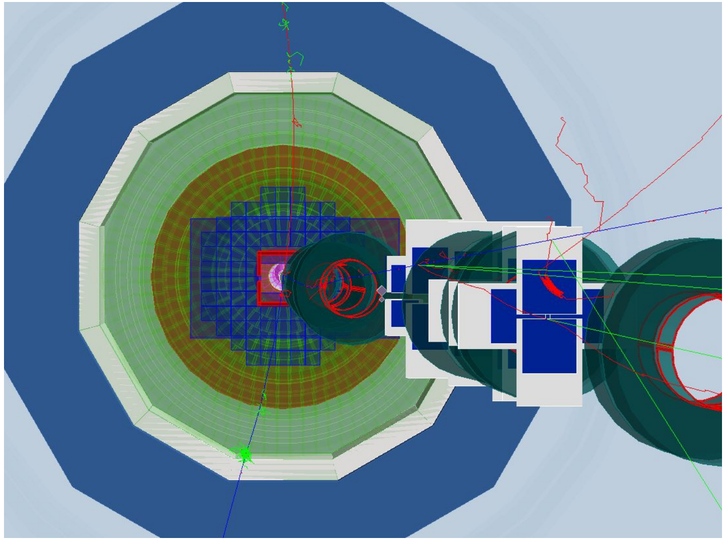
Figure 6.148: Finite-element model of (a) the RHIC arc dipole magnet cold mass cross-section and (b) close view around the beam tube.

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.





Unique opportunities for 2nd Detector

- Novel roman pot configurations leveraging unique capabilities (rad-hard, fast, sub-micron position, high B operation):
  - Low Q^2 far backward detector
  - Far forward ion detectors with secondary focus
  - PID of excited nuclear states (far-forward TOF)
- Superconducting magnet integrated detectors (cold mass coupled tracking detectors)
  - Fully hermetic tracking design from far-forward to far-backward.
- Likely more ideas for configurations to come…

Summary

- Superconducting Nanowire technology is “Almost too good to be true”
- **120 GeV proton detection has been demonstrated** at FTBF (no surprises)
- **Significant R&D effort tackling cryogenic readout** architecture is underway (HYDRA)
- Targeted EIC-related generic R&D efforts to understand radiation hardness and component-wise cryogenic readout operation
- Will address the scaling barriers with future R&D – the last piece needed to realize applications at the EIC

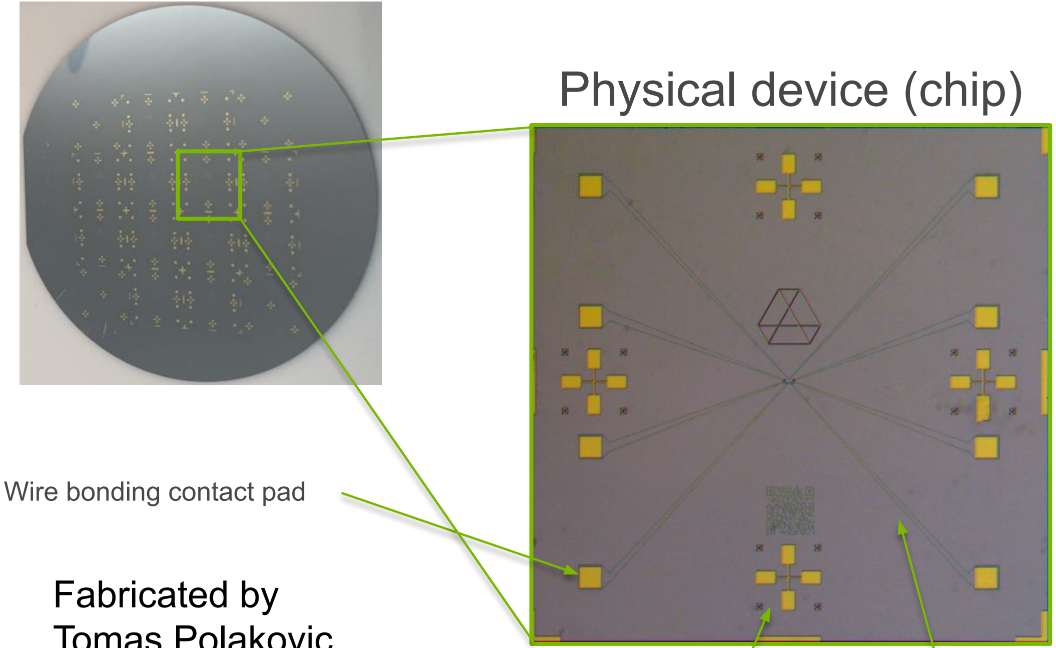
Indeed, superconducting nanowire detectors “Needs R&D”, but it is certainly not too futuristic.

Thank you!

Backup

Nanowire devices for particle detection

Physical device (chip)



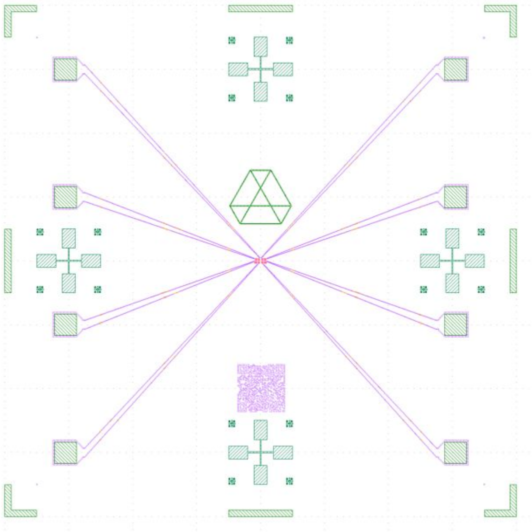
Wire bonding contact pad

Local alignment marks

Contact lead

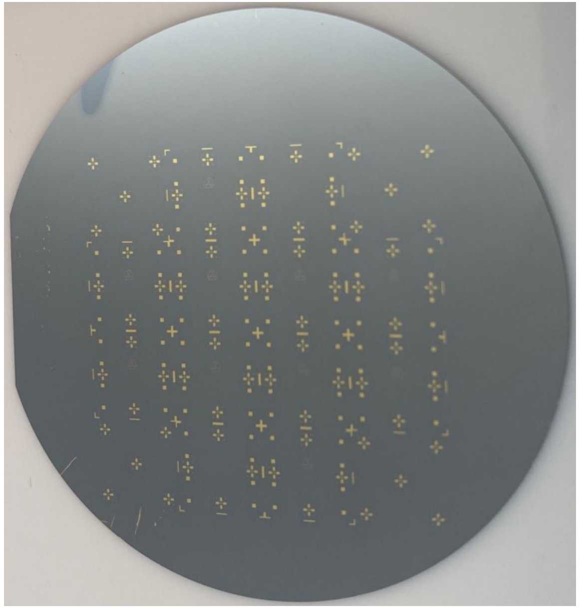
Fabricated by
Tomas Polakovic

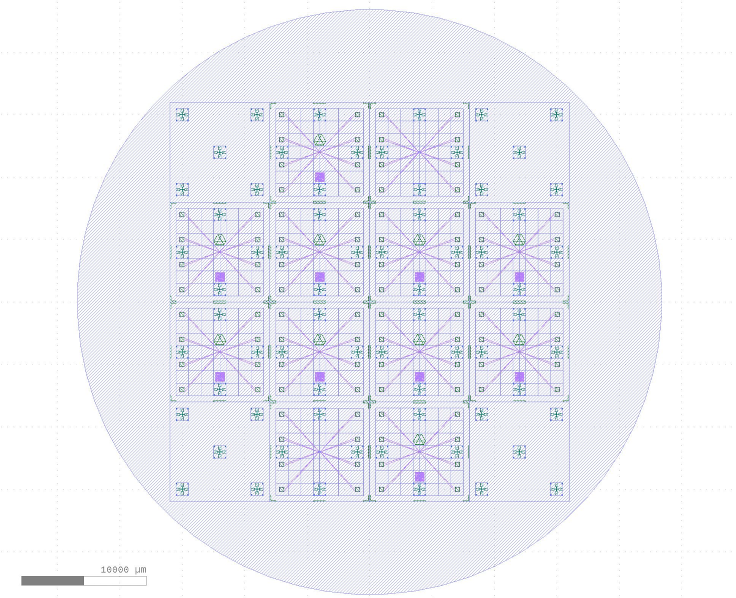
Design



2-inch wafer

8 mm chips

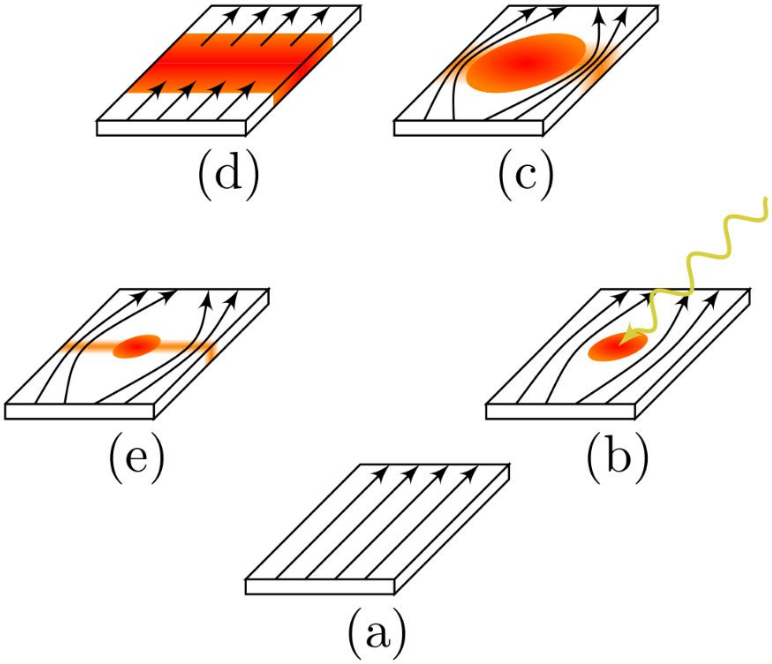




SUPERCONDUCTING NANOWIRE (SINGLE PHOTON) DETECTORS

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

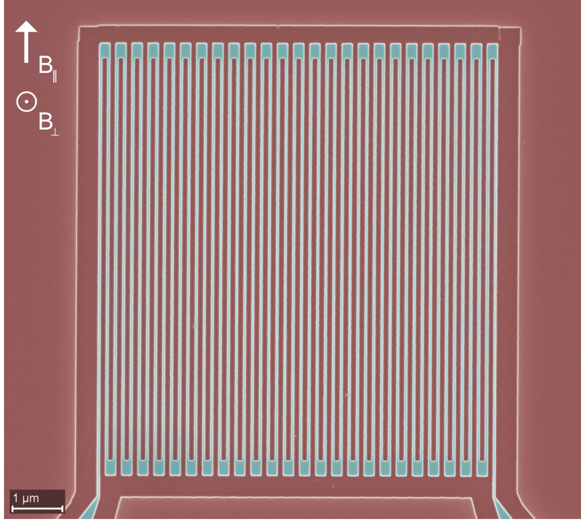


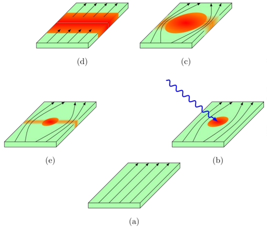
Polakovic, Nanomaterials (2020)

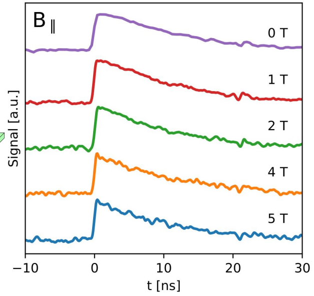
SUPERCONDUCTING NANOWIRES

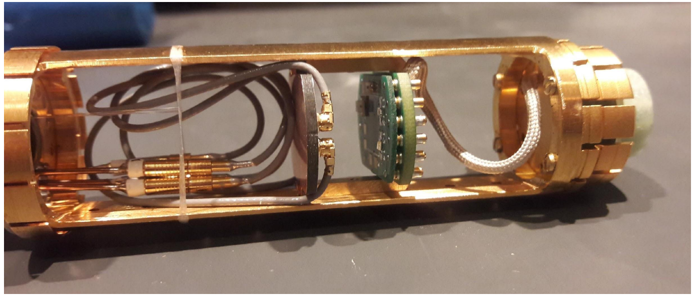
Overview of Nanowire Detectors

- Sensors can operate in fields up to (at least) 7T, can operate inside of cold bore of superconducting magnets (T< 5 K).
- Novel concept for high-resolution rad-hard detectors based around superconducting nanowires (early R&D stage)
- Near-beamline detectors for tagging low energy electrons (low Q^2) and in the far-forward region.









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.