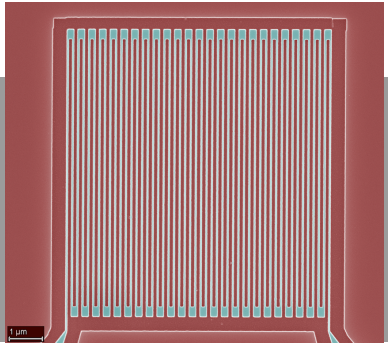
Superconducting Nanowire Detectors for the Electron Ion Collider



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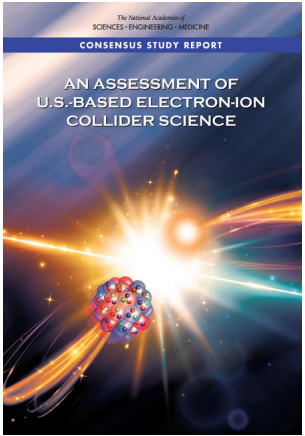
Overview

- Motivation
- Quick overview of SNSPDs
- SNSPDs in high magnetic fields
- Large area detector fabrication and readout
- Opportunities for the EIC
- Proposed R&D
- Milestones, Deliverables, and Budget
- Conclusion

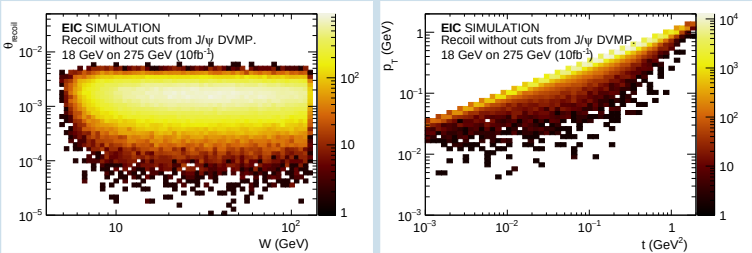
Motivation

Some of the big questions motivating the EIC [1]:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?



Deep exclusive processes



The left panel shows the recoil angle (in radians) as a function of W, while the right panel shows the recoil p_T as a function of the Mandelstam variable t.

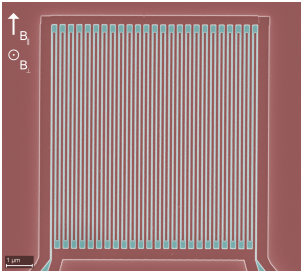
Forward hadron detection very important to EIC science.

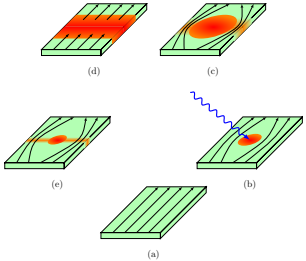
SNSPDs

Superconducting Nanowire Single Photon Detectors

SNSPD Construction and Operation

- Superconducting thin film (10 nm)
- Patterned with meandering wire pattern
- Wire width and pitch typically on the order of 100 nm
- Constant current biased ($\sim 10\,\mu$A to $25\,\mu$A)





Typical SNSPD Characteristics

- High quantum efficiency from visible to IR
- Excellent time resolution
- High rate operation with zero dark count

(a) Nanowire wire current biased below I_C

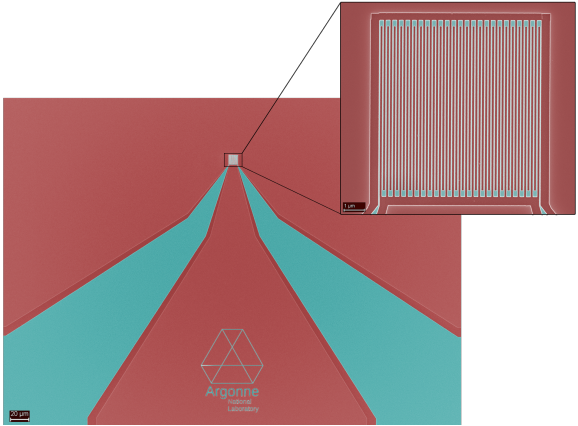
(b) Photon absorbed, breaking cooper pair

(c) Hot spot begins to form

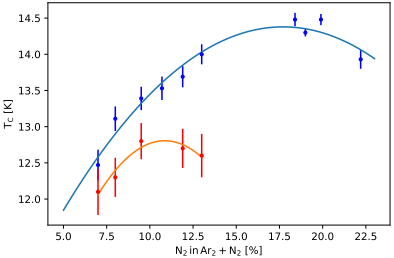
(d) Hot spot spans wire producing signal

(e) Superconducting state quickly recovers

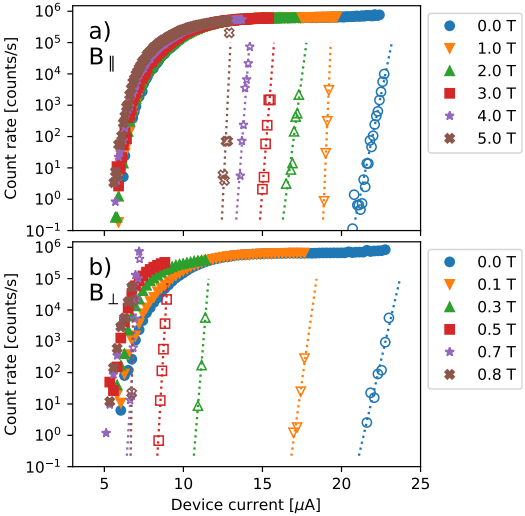
NbN SNSPDs made at Argonne

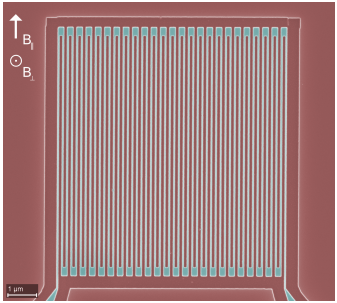


- Thin films prepared by ion beam assisted sputtering [2, 3].
- Sub-20 timing jitter [4]
- Near 100% quantum efficiency up to IR wavelength [5, 6]
- High rate (GHz) operation with almost zero dark count rate [7]
- Radiation hardened – short electron screening length material [8, 9]



Performance in Magnetic Field



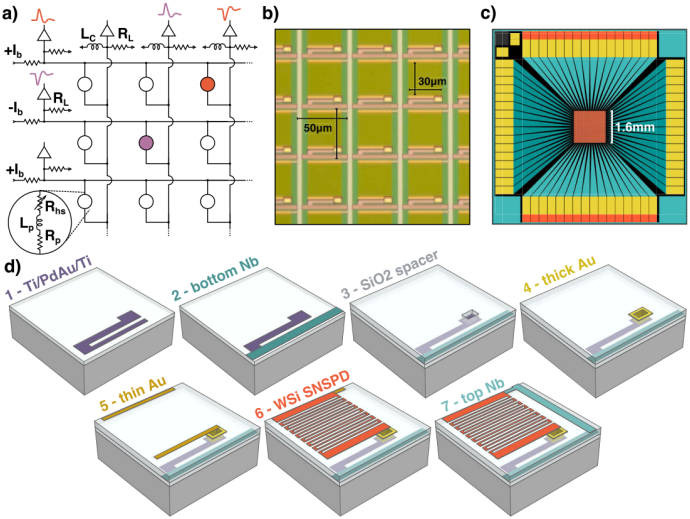


- Recent paper demonstrating high field, high rate operation [3]
- Test up to 5 T field.
- Full symbols indicate total count rate and empty symbols are dark counts.
- Note it is possible to find an operating point with zero dark counts and fully saturated detection efficiency.

Why Superconducting Nanowire Detectors for the EIC?

- Ultrafast timing, which has been demonstrated to be on the $\lesssim 20$ ps scale
- Small basic pixel size, allowing for $\mu\mathrm{m}$ position precision if needed.
- Efficient high-rate operation in high magnetic fields.
- 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. (Ongoing and future testing)

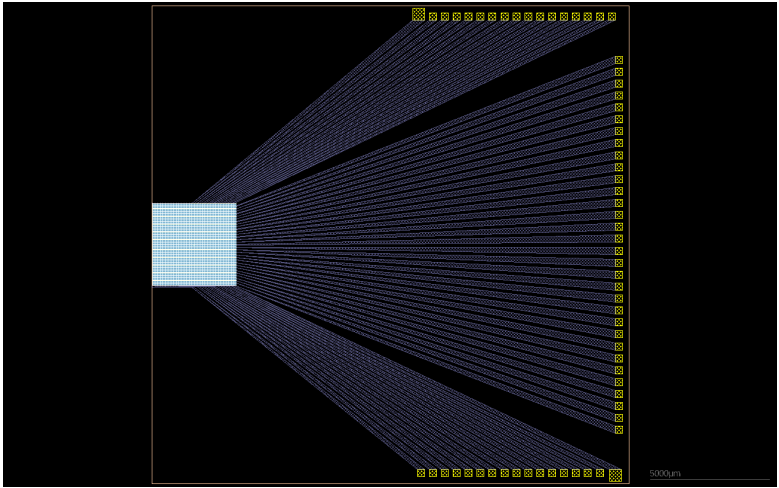
Large Area Arrays – Row Column Readout



A kilo-pixel array from Wollman, et.al. [10] (NIST group)

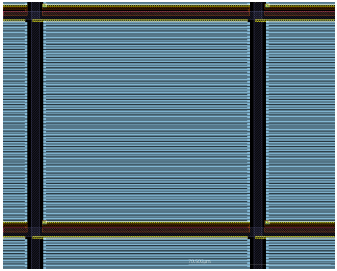
Double Ended Readout Prototype Design

- Potential kilo-pixel array
- A 3.5×3.5 mm sensor on a 2×2 cm chip
- 1024 pixels with 64 readout channels.

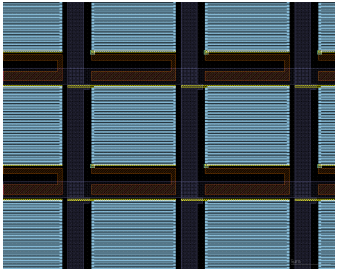


Pixel Size

- Pixel can be almost any shape
- Strips can be used to get fine position in one coordinate
- Pixel layer combined with strip layer can provide position/time correction for improved tracking



$100\,\mu m \times 100\,\mu m$

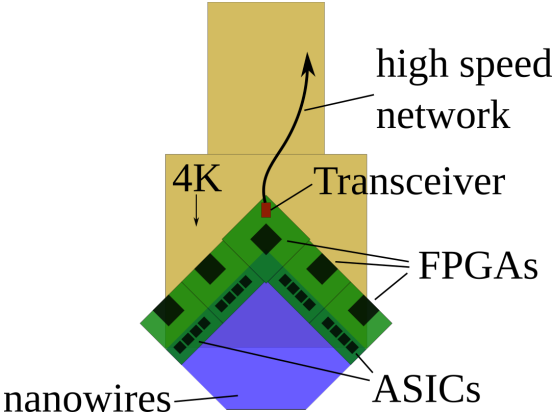


$10\,\mu m \times 10\,\mu m$

Cryogenic Temperature Readout Electronics

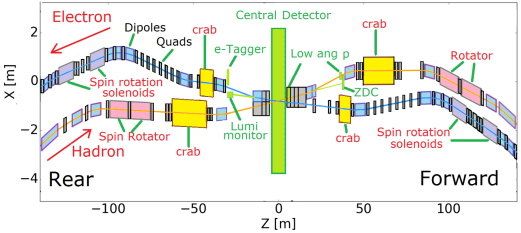
- Electronics have been tested for applications at 4 K [11, 12]
- FPGAs have been successfully operated at low temperatures [13, 14]
- Significant progress in cryo-CMOS for quantum computing [15, 16].
- We have reached out to partners in industry and plan on baseline testing current line of ASICs ahead of developing ASICs for nanowire readout.

A complete cryogenic read-out scheme for a Roman pot superconducting nanowire detector.

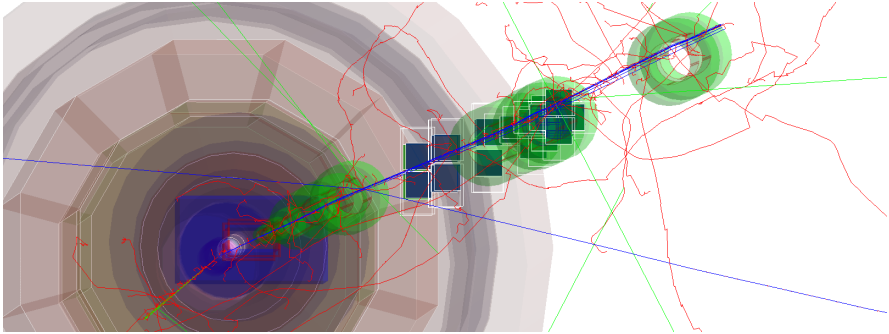


State-of-the-art Instrumentation Opportunities at the EIC

1. Novel Forward Detectors
2. Superconducting nanowire detector and superconducting magnet integration
3. Neutral particle detector at zero degrees



Forward Hadron Beamline and Detector Simulation



- Simulation visualization of the forward hadron beam line extended up to the last quad before the spin rotator, located roughly 100 m downstream of the IP.
- Extended magnets based on a recent accelerator design [17].

Proposed R&D

- Fabricate small pixel array. (Each with separate readout)
- Test the response to photons and particles from radioactive sources (α and β emitters) in high magnetic fields.
- Characterize the response to 120 GeV protons at Fermilab test beam.

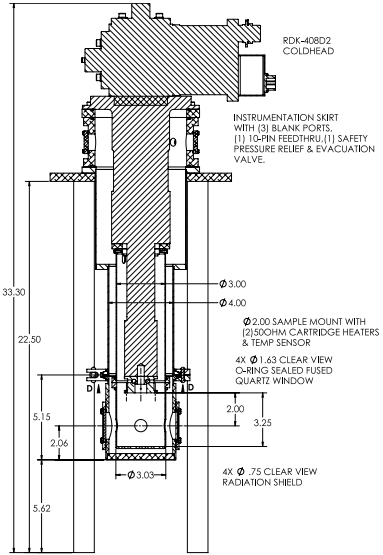
R&D Goal: detection of high energy ions

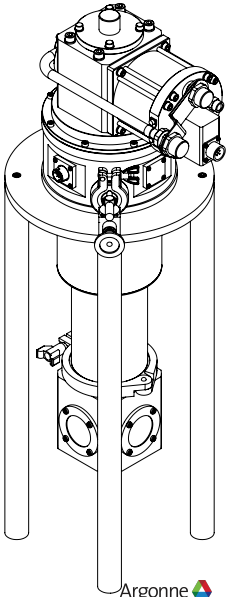
Characterize the detector's response to high energy protons and identify the key differences (if any) from photon detection.
What are the optimum nanowire parameters for high energy ions?

Test Beam Cryostat

- Portable optical cryostat for laser and beam tests.
- Cold finger coupling and detector mount designed as part of proposed work
- First design of magnet integration strategy.

Cryostat arrived April 2020.





Milestones and Deliverables

Project milestones:

1. Fabricate 4×4 pixel array covering roughly $1\,\mathrm{mm}^2$ on a thin substrate. (January 2021)
2. Characterize detector with a pulsed light source and radioactive sources in strong fields. (March 2021)
3. Design vacuum chamber windows and cold finger coupling mount for test beam measurements. (May 2021)
4. Test read-out of pixel array in optical cryostat. (July 2021)
5. Conduct in-beam pixel array test at the Fermilab Test Beam Facility using high energy protons. (August 2021)

FY21 Deliverables

1. Fully instrumented and tested pixel array readout
2. Characterized array performance with pulsed light source and low energy particles from α and β emitting sources
3. Pixel array test with high energy proton beams at Fermilab.

Budget Scenarios

Item	Scenario 1	Scenario 2	Scenario 3
Test beam engineering Support	10k	10k	10k
Nanowire bias/read-out electronics	25k	17k	9k
M&S	5k	5k	5k
total	40k	32k	24k

- Reduced funding scenarios have fewer number of channels instrumented with readout electronics.
- Resources for engineering support and other M&S remain fixed.

Quantum Opus Bias/Readout

Conclusion

- Superconducting nanowire detector technology worth considering in special cases where the detector area is not too large but the conditions are harsh requiring a detector with ultimate performance in timing resolution, position resolution with high magnetic field and radiation immunity.
- With the proposed work we intend to demonstrate that such a detector offers a unique capability for forward hadron detection in an EIC.

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