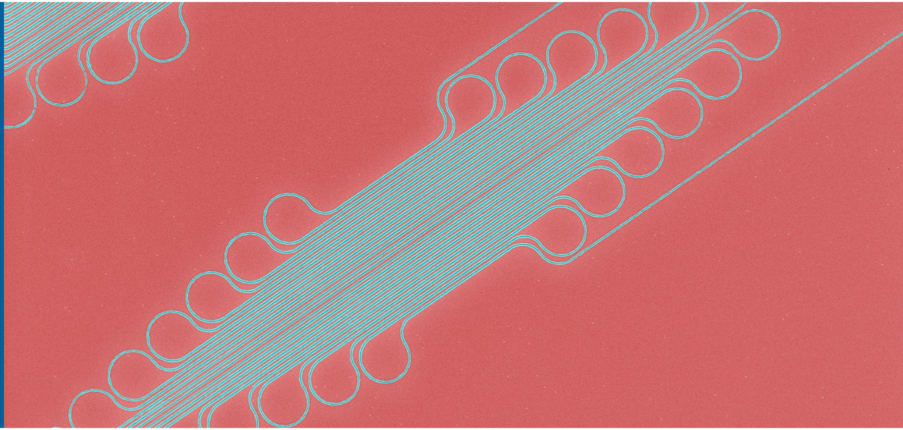
SUPERCONDUCTING NANOWIRES AS HIGH-ENERGY PARTICLE DETECTORS



TOMAS POLAKOVIC
Physics Division
Argonne National Laboratory
USA

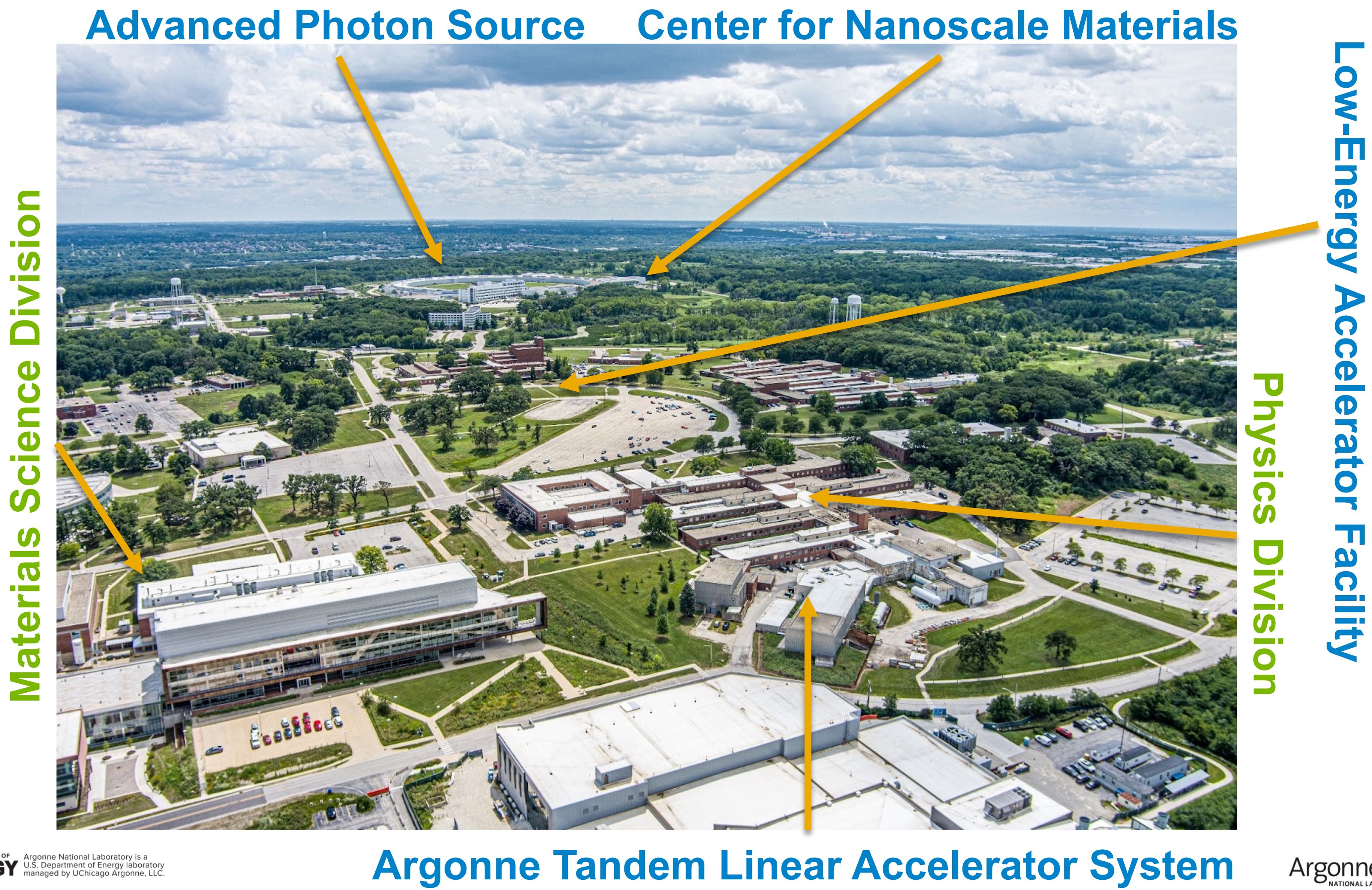
January 13th, 2025
QIS/NP&AMO, Boston

OUTLINE

So you know when to wake up…

- Superconducting detectors
  - Operating principle
  - Light detectors
  - Particle detectors
- Superconducting microelectronics
  - Fast timing switches
  - Supercurrent pre-amplifiers
- Other
  - Superconducting nanowire resonators
  - NV-center qubit readout
- Outlook

WHO WE ARE?

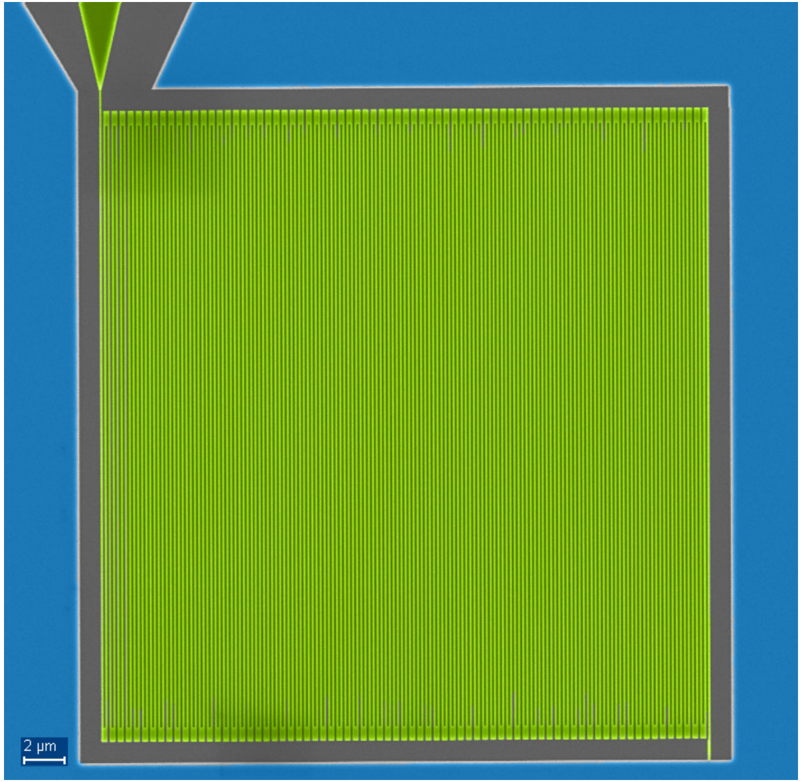

Advanced Photon Source
Center for Nanoscale Materials
Low-Energy Accelerator Facility
Materials Science Division
Physics Division
Argonne Tandem Linear Accelerator System

SUPERCONDUCTING DETECTORS

SUPERCONDUCTING NANOWIRE DETECTORS

At a glance

- Uses quasi-particle avalanche process inside a current biased superconducting nanowire to detect scattering/absorption of individual quantum excitations.
  - Analogous to operation of a bubble chamber, but in solid state system.
- Much faster and more sensitive than ionization avalanches in semiconductor detectors.
- The fastest and most precise “first-gen” quantum detector of individual particles.
  - Energy thresholds as low as ~100 meV
  - Timing jitter easily 20-40 ps (current record at 2.7 ps)
  - Reset times can be as low as 5-10 ns
  - Conveniently operates at roughly LHe temperatures
  - Can operate in magnetic fields of > 5 T



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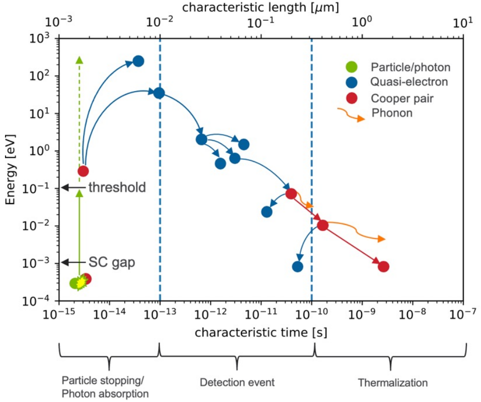
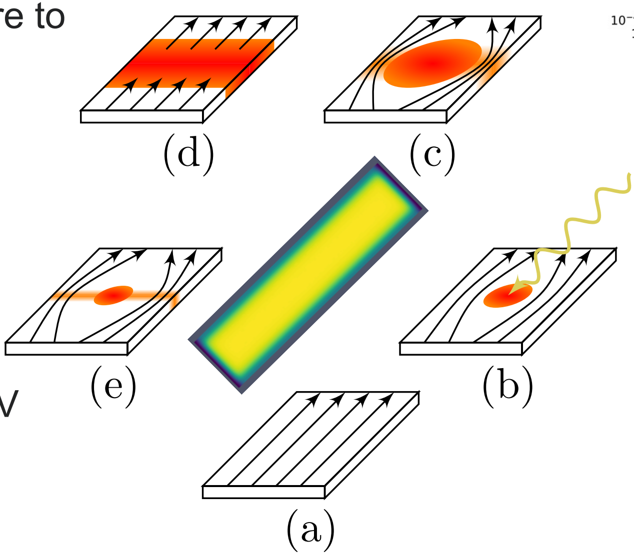
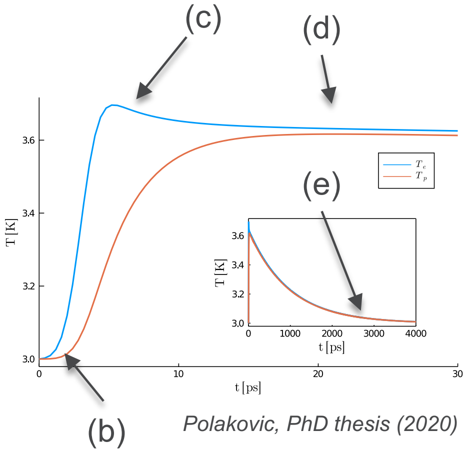
Polakovic, EIC FFWG meeting (2021)





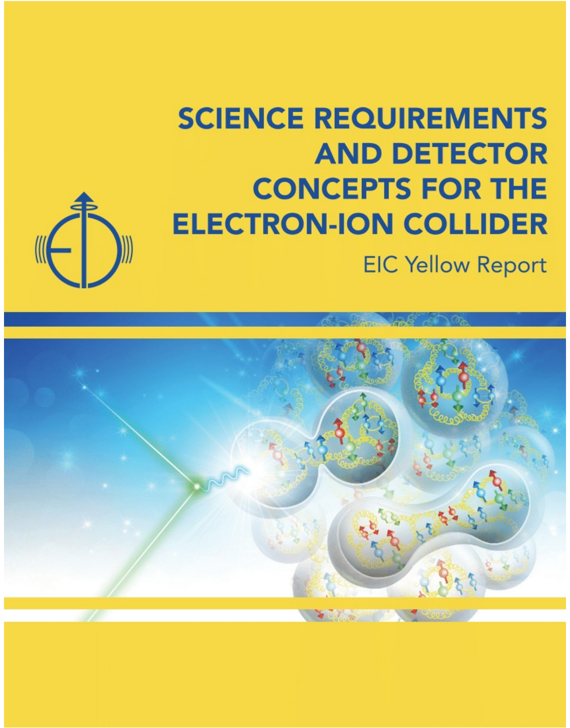


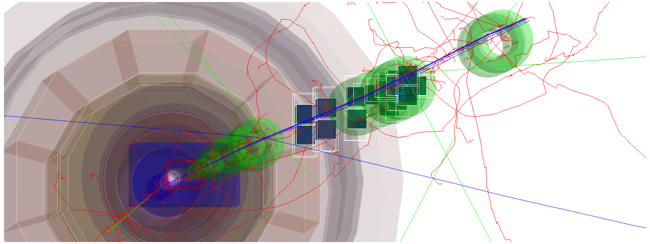
Polakovic, PhD thesis (2020)

SUPERCONDUCTING NANOWIRE PARTICLE DETECTORS

Modern solution for modern problems

- Design of nanowire meander sensors for charged particles.
- Leverage extreme time and position resolution for tagging, tracking, polarimetry, etc.
- Target HEP/nuclear physics experiments at particle colliders and other large-scale systems.

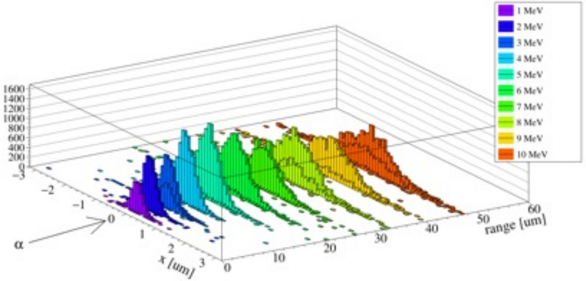


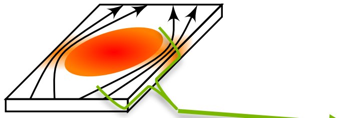


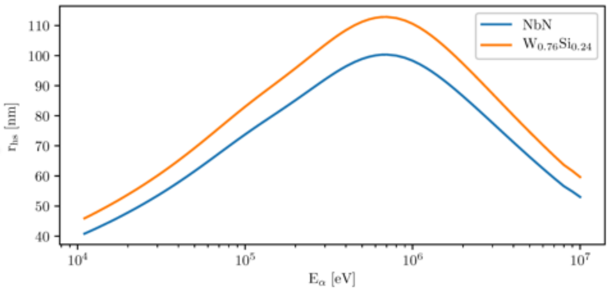
SUPERCONDUCTING NANOWIRE PARTICLE DETECTORS

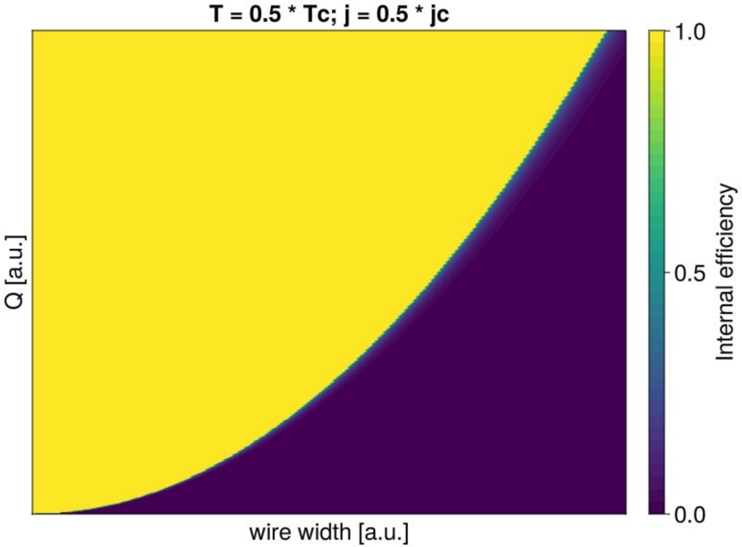
Modern solution for modern problems

- Inelastic collisions of charged particles with the lattice and electrons bypass the early stage of hot-spot formation
  - Very high detection efficiency even with wide nanowires







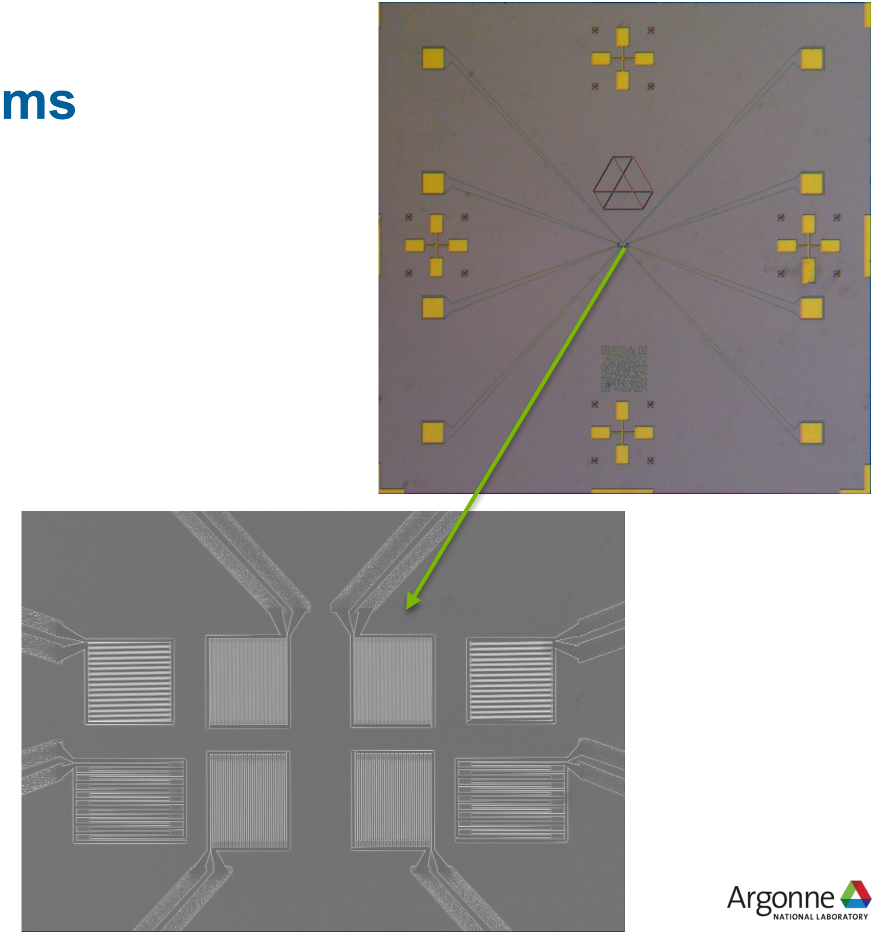


Polakovic, et.al.; *Nanomaterials* (2020)

SUPERCONDUCTING NANOWIRE PARTICLE DETECTORS

Modern solution for modern problems

- Detector performance tested in wide range of energies and conditions
  - Strong magnetic fields
  - VIS photons
  - Radioactive sources
    - 1-10 MeV α
    - ~100 MeV $\beta^{+/-}$
    - n^0 in the future?
  - Particle accelerators
    - 120 GeV protons



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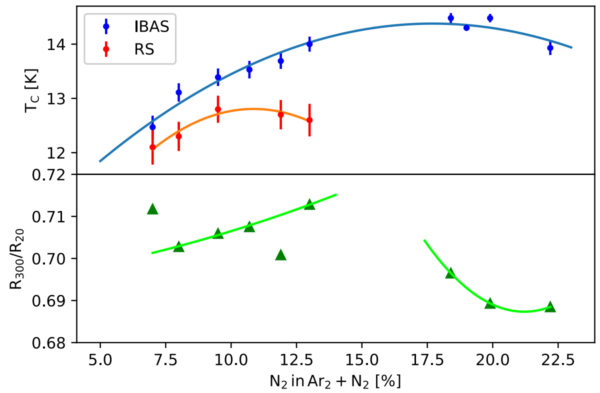

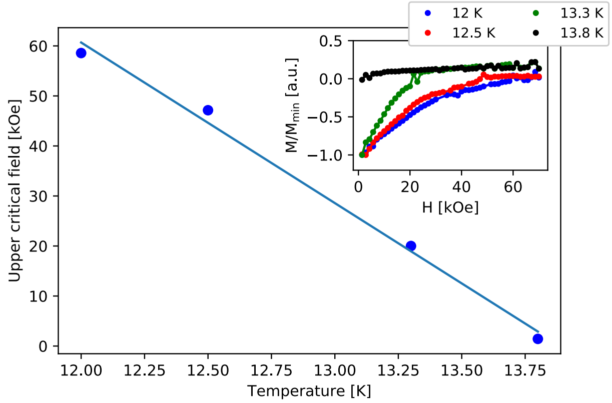

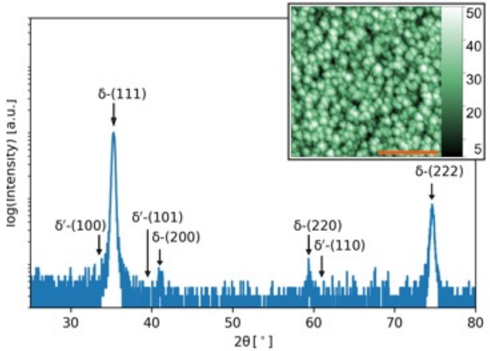

Polakovic, *et. al.*, APL Materials (2018)

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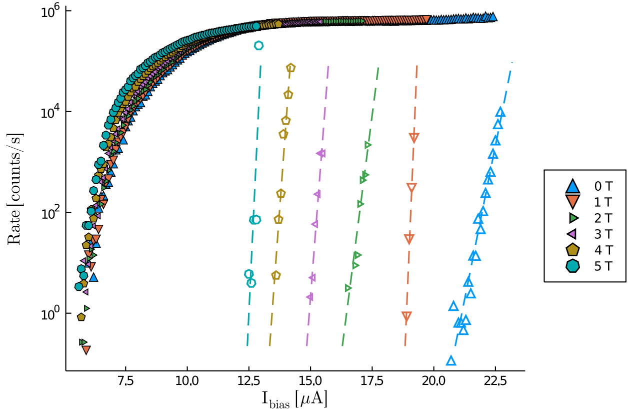

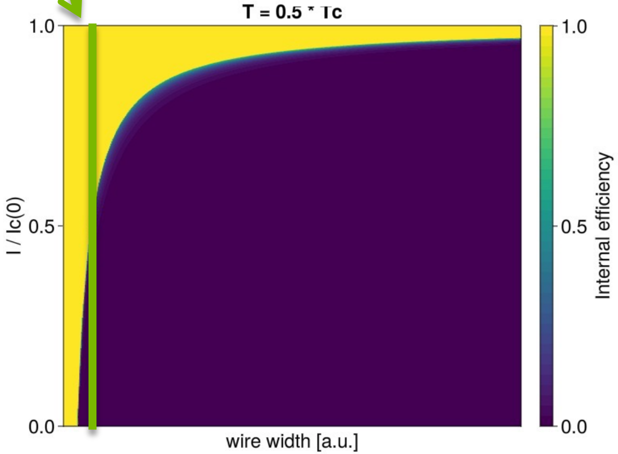

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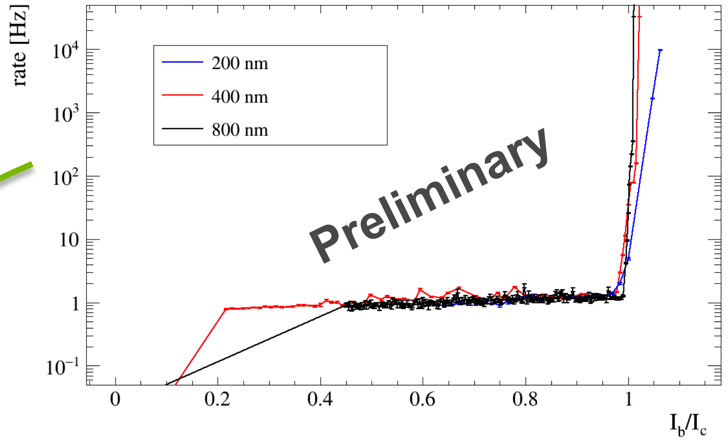

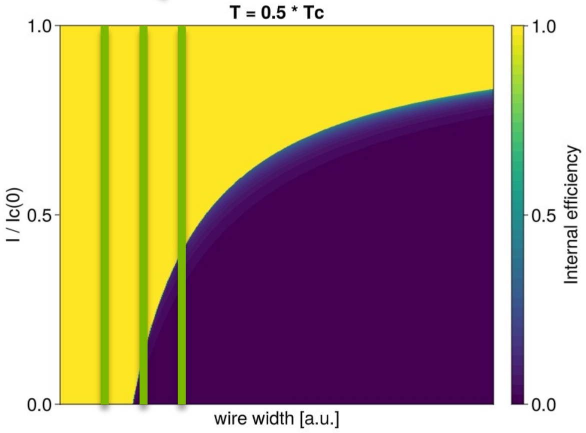

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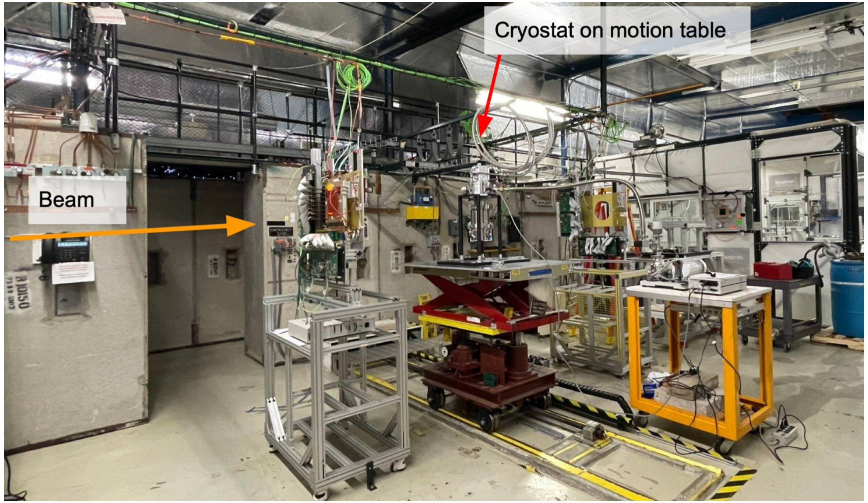

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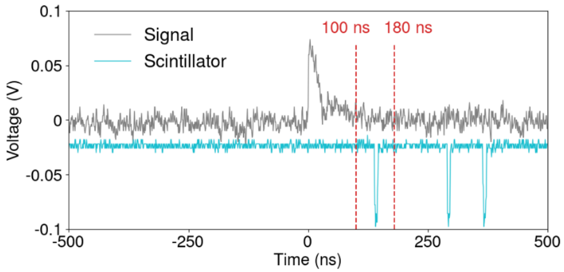

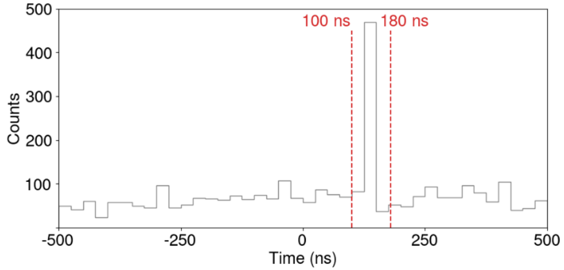

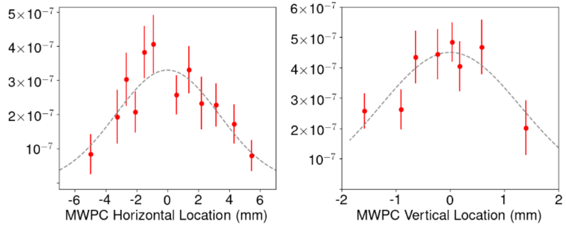

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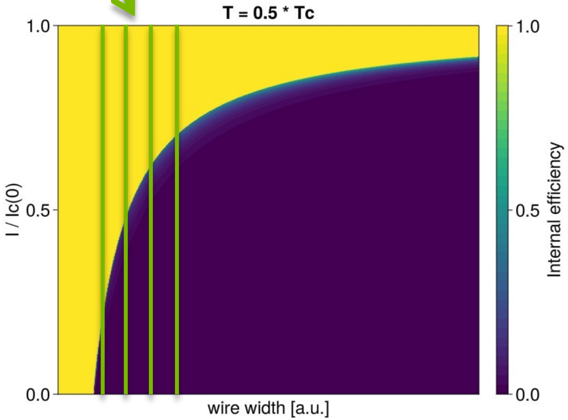

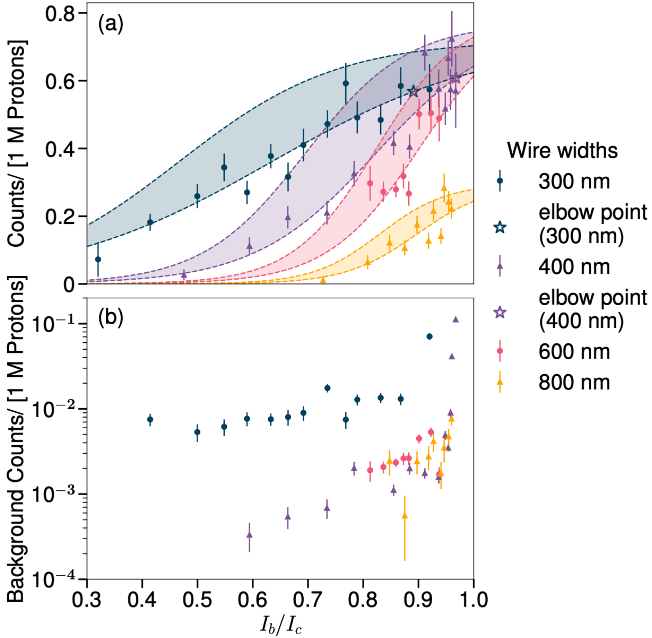

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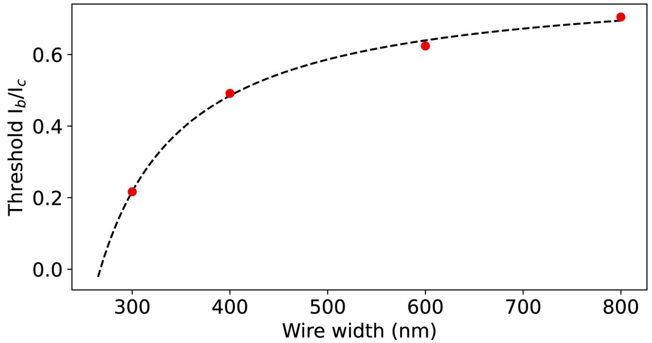
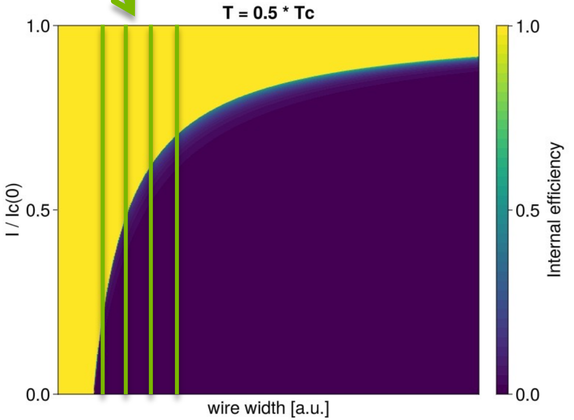
Lee, et. al.; NIM A (2024)





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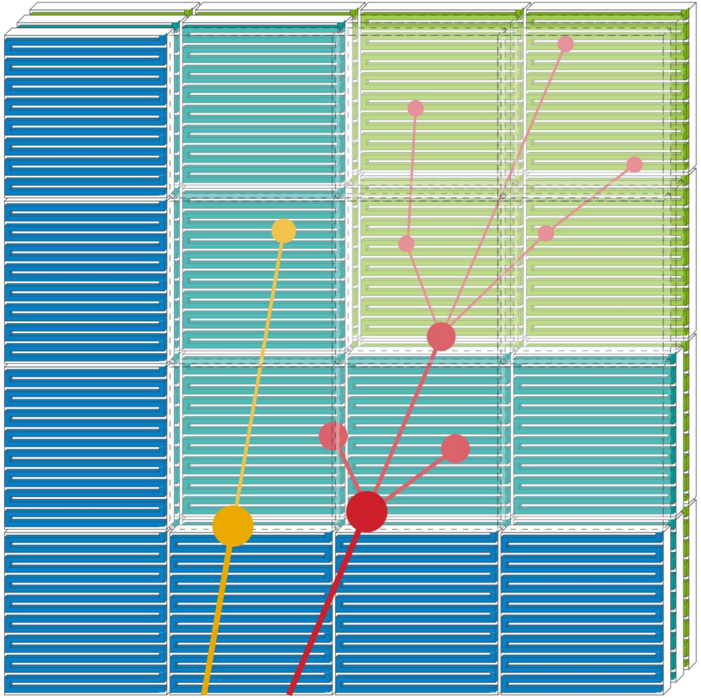
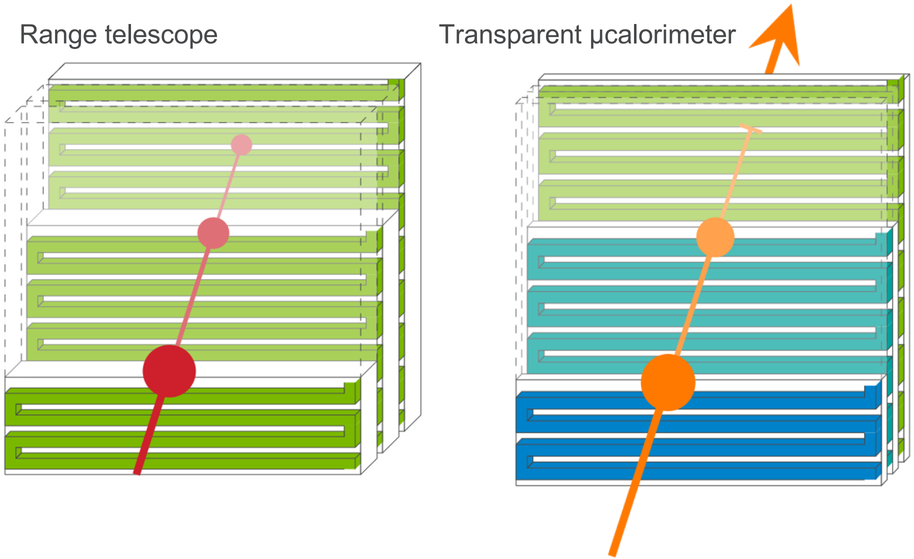


Digital calorimeter

Range telescope

Transparent µcalorimeter



- **Faster and more precise** than any other NP-used technology, real or conceptual
- **Enhancing NP science mission and enabling new** experiments

SUPERCONDUCTING NANOWIRE PARTICLE DETECTORS

Modern solution for modern problems

Particle	Energy	Approximate Energy loss in 100 µm silicon	Approximate Energy loss in 15 nm NbN	Detected
photon	0.1 - 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	?

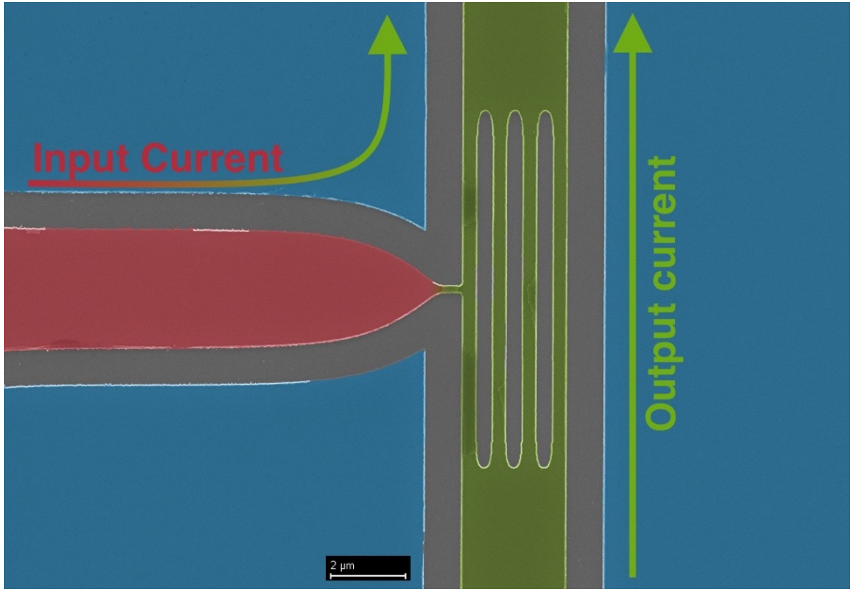
SUPERCONDUCTING MICROELECTRONICS

NANO-CRYOTRONS

Superconducting electronics

- A fast-operating superconducting switching device.
  - ~1 ns switching time.
- Can be used for amplification of weak supercurrents.
- Ability to dissipate persistent current loops "on demand" – useful for (S)FQ logic.
- Functionality of a NAND gate – can be used directly in digital logic.

Draher, et. al.; APL (2023)



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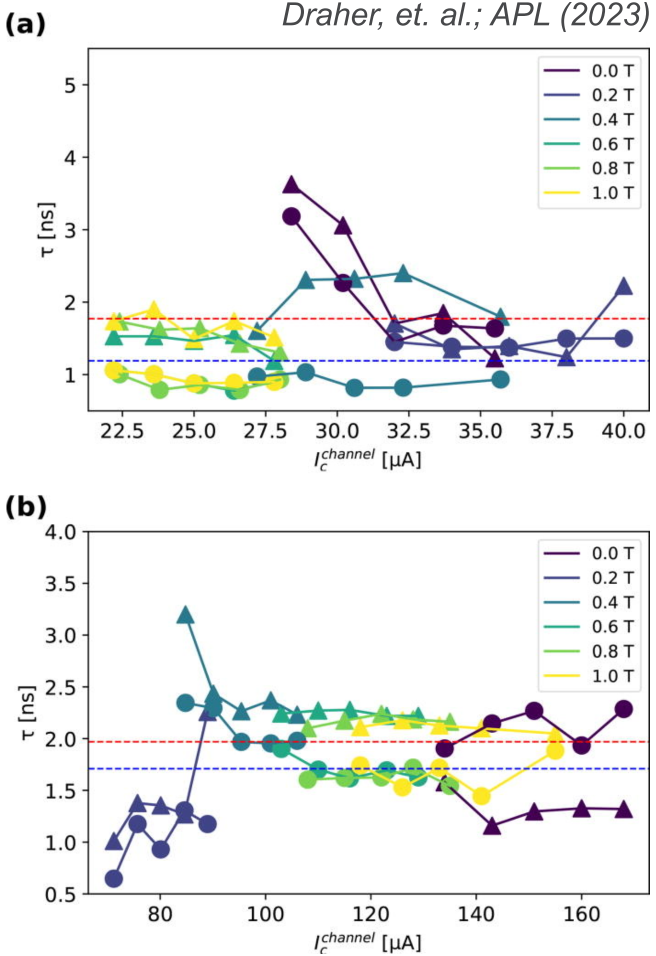

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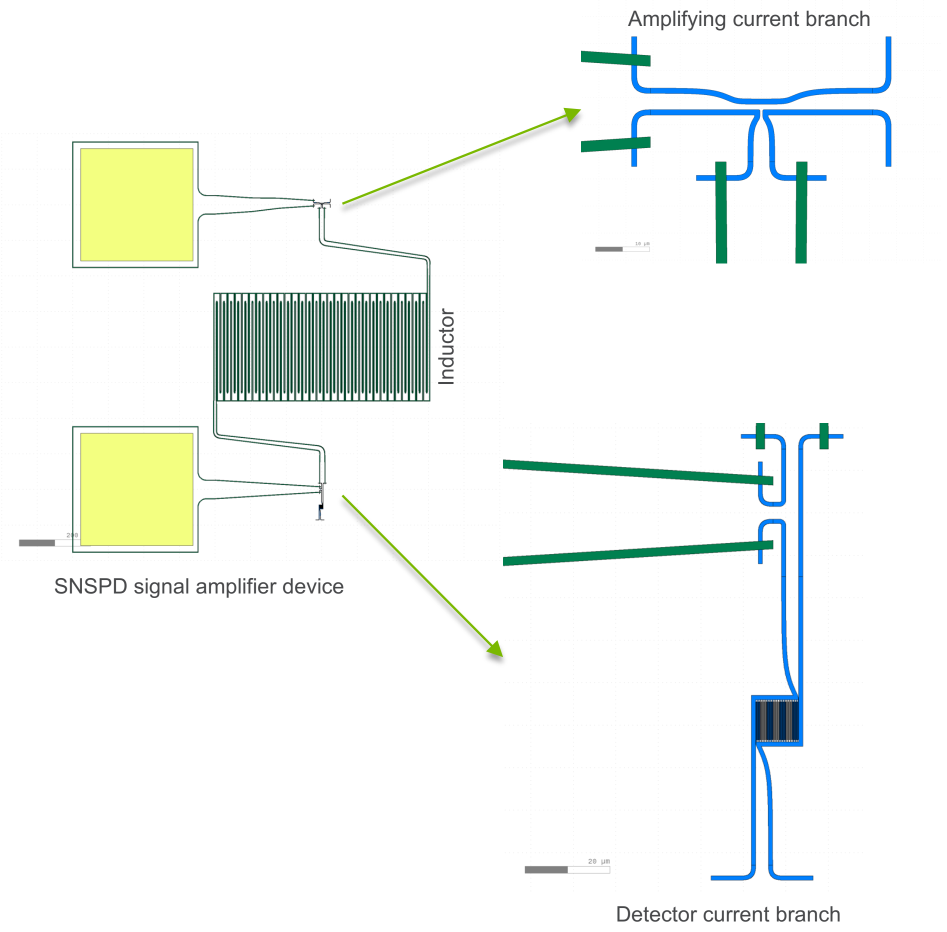

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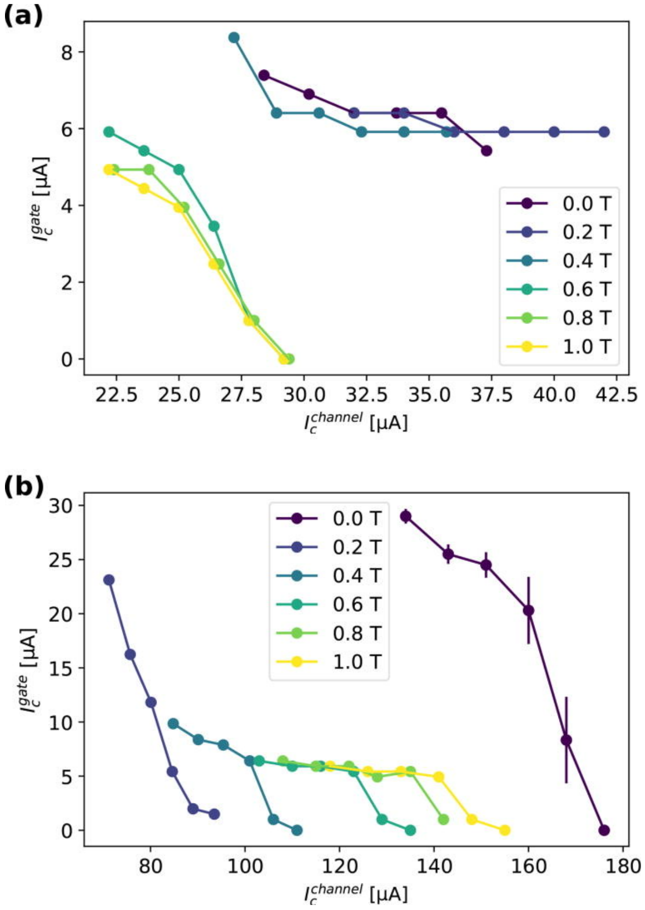
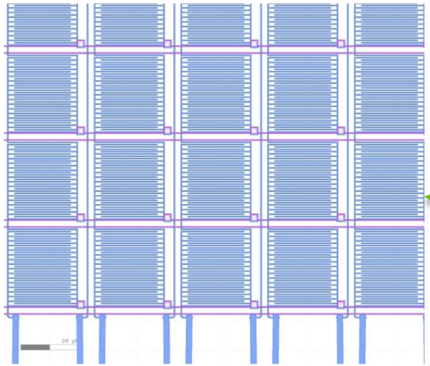
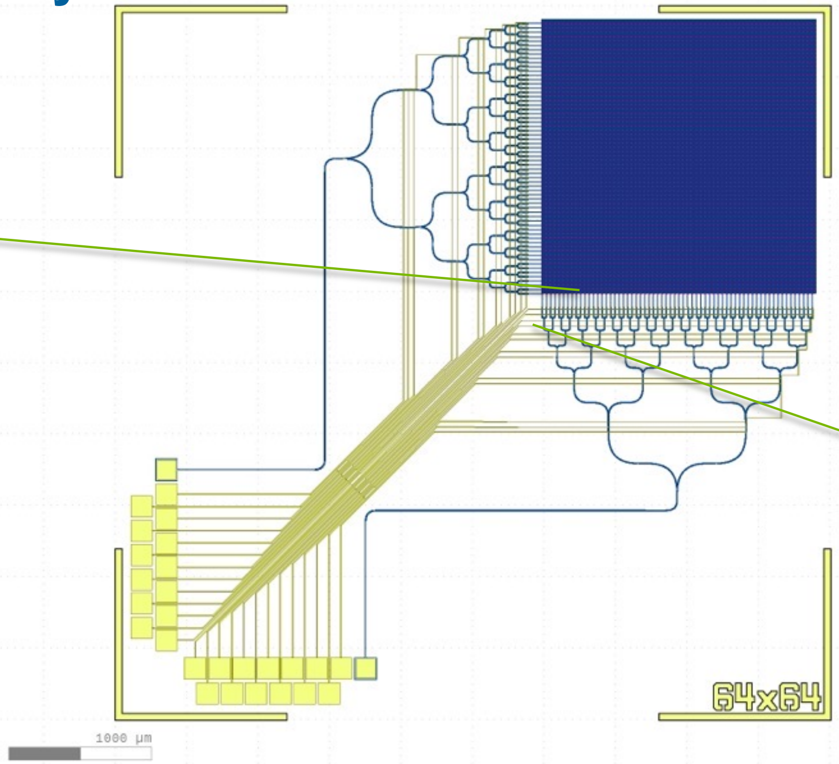
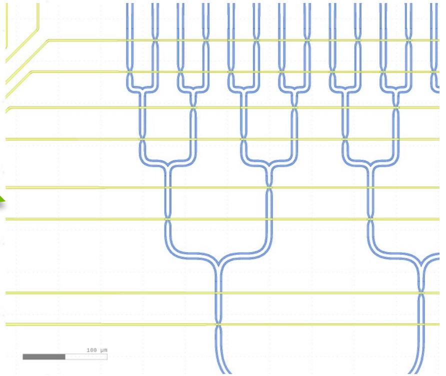


PUTTING IT ALL TOGETHER

Next-gen Detector systems







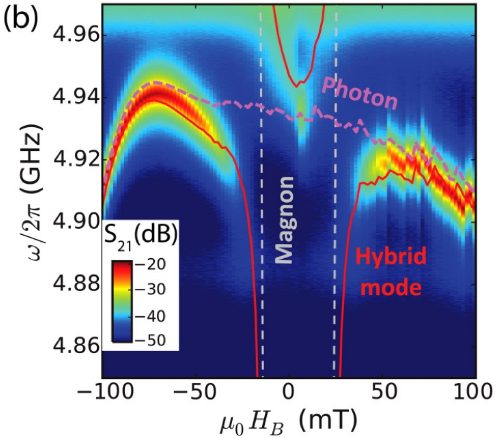
A complex, 7-layer, fully-multiplexed 4096-pixel array with 2 RF signal channels and 28 DC channels.

AND MUCH MORE

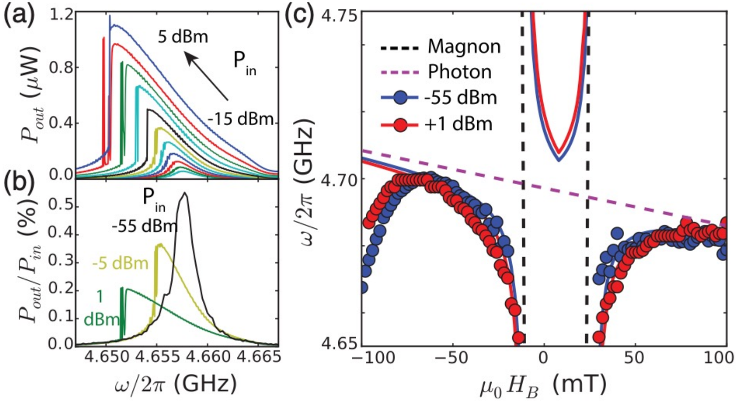
SUPERCONDUCTING NANOWIRE RESONATORS

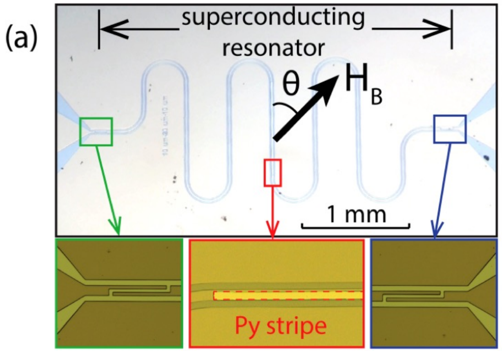
A new option for quantum communication

- Synergy through R&D of field-resistant superconducting devices
- Magnon-photon transducers
- Parametric amplifiers



Li, et.al., *PRL* (2019)

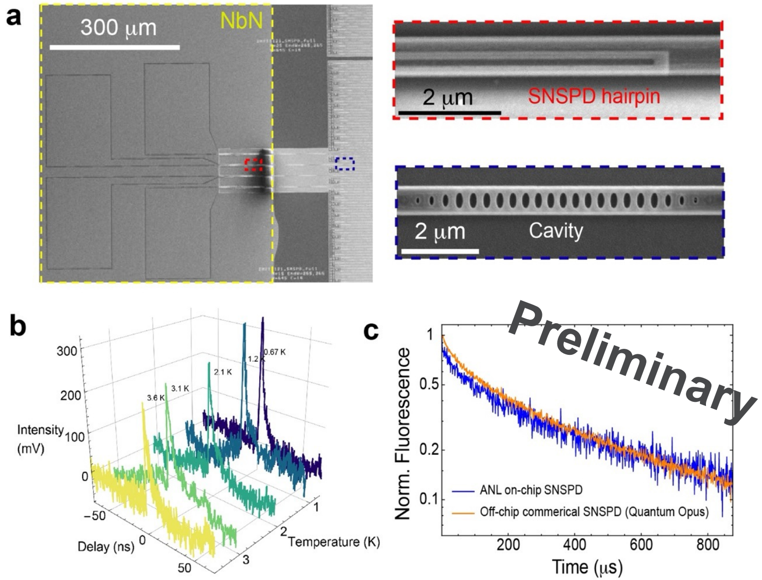




QUBIT READOUT

Integration with QIS

- Monolithic, on-chip integration to detect single photons from NV-center photoluminescence.
- Ability to fine-tune detector performance for specific photon emitters.
- Already competitive with off-chip commercial solutions.
  – At less than 20% of the cost



Characteristic pulse shapes from current gen devices.

Comparison of commercial and in-house design SNSPD performance.

OUTLOOK

There's no conclusion to research

- Superconducting nanowires are state-of-the-art solution for detection of (almost) any excitations down to SQL
  - IR-VIS-UV photons
  - 1 MeV – 100 GeV charged particles
  - Unparalleled timing and resolution
- Superconducting nanowires enable manufacturing of discrete and analog microelectronics
  - Compatible with other nanowire technologies and SFQ designs
  - Can serve as an "interposer" between superconducting and conventional (CMOS) components
- R&D of superconducting nanowires for strong-field and large-scale applications has synergy with QIS and other microelectronics efforts

JOIN US!

We’re looking for students and postdocs

tpolakovic@anl.gov or novosad@anl.gov

THANK YOU FOR YOUR ATTENTION!