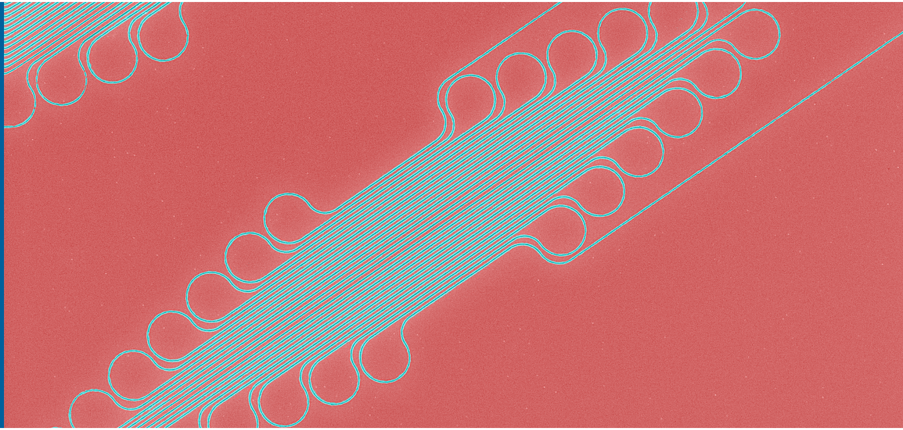
SUPERCONDUCTING NANOWIRE SINGLE PHOTON/PARTICLE DETECTORS



TOMAS POLAKOVIC
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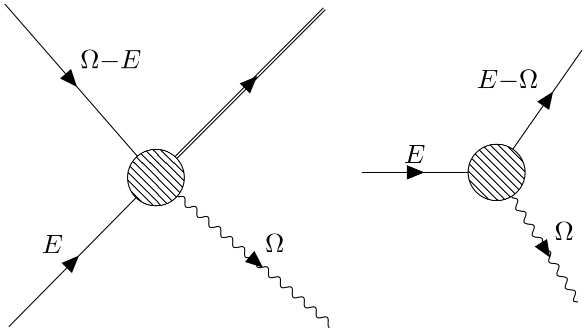
November 10th, 2020

EXCITATIONS OF A SUPERCONDUCTOR

The small picture

- Deposition of energy into the electron or phonon subsystem of the superconductor will lead to population of hot quasi-electrons



$$\begin{aligned}\frac{df(E)}{dt} &= I_{\mathrm{qp}}(E)\\
&-\tfrac{2\pi}{\hbar}\int_0^\infty d\Omega\alpha^2(\Omega)F(\Omega)\rho(E+\Omega)\left(1-\tfrac{\Delta^2}{E(E+\Omega)}\right)\{f(E)[1-f(E+\Omega)]n(\Omega)-f(E+\Omega)[1-f(E)][n(\Omega)+1]\}\\
&-\tfrac{2\pi}{\hbar}\int_0^{E-\Delta} d\Omega\alpha^2(\Omega)F(\Omega)\rho(E-\Omega)\left(1-\tfrac{\Delta^2}{E(E-\Omega)}\right)\{f(E)[1-f(E-\Omega)][n(\Omega)+1]-[1-f(E)]f(E-\Omega)n(\Omega)\}\\
&-\tfrac{2\pi}{\hbar}\int_{E+\Delta}^\infty d\Omega\alpha^2(\Omega)F(\Omega)\rho(\Omega-E)\left(1+\tfrac{\Delta^2}{E(\Omega-E)}\right)\{f(E)f(\Omega-E)[n(\Omega)+1]-[1-f(E)][1-f(\Omega-E)]n(\Omega)\}\end{aligned}$$

$$\begin{aligned}\frac{dn(\Omega)}{dt} = I_{\mathrm{ph}}(\Omega) - \frac{8\pi}{\hbar}\frac{N(0)}{N}\int_\Delta^\infty dE\int_\Delta^\infty dE'\alpha^2(\Omega)\rho(E)\rho(E')\\
\times\Big(\big(1-\Delta^2/EE'\big)\big\{f(E)\big[1-f\big(E'\big)\big]n(\Omega)-f\big(E'\big)[1-f(E)][n(\Omega)+1]\big\}\delta\big(E+\Omega-E'\big)\\
-\frac{1}{2}\big(1+\Delta^2/EE'\big)\big\{[1-f(E)]\big[1-f\big(E'\big)\big]n(\Omega)-f(E)f\big(E'\big)[n(\Omega)+1]\big\}\delta\big(E+E'-\Omega\big)\Big)\end{aligned}$$

$$\begin{aligned}I_{\mathrm{qp}}(E) \propto \frac{1}{4N(0)\Delta}\frac{E-\omega_0}{\sqrt{(E-\omega_0)^2-\Delta^2}}\left(1+\frac{\Delta^2}{E(E-\omega_0)}\right)[f(E-\omega_0,T)-f(E,T)]\theta(E-\omega_0-\Delta)\\
+\frac{1}{4N(0)\Delta}\frac{E+\omega_0}{\sqrt{(E+\omega_0)^2-\Delta^2}}\left(1+\frac{\Delta^2}{E(E+\omega_0)}\right)[f(E+\omega_0,T)-f(E,T)]\end{aligned}$$

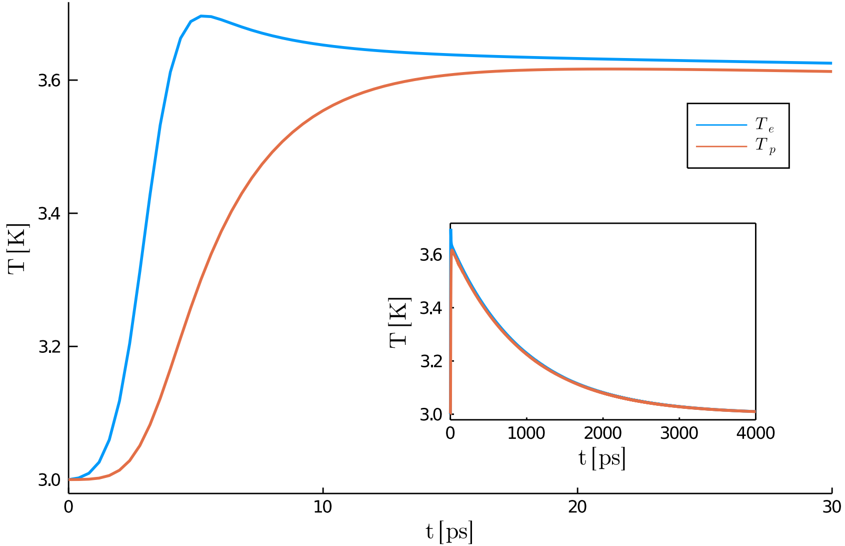
$$I_{\mathrm{ph}}(\Omega) \propto \int_{h\omega_D}^{\hbar\omega_0} dE\int_{\hbar\omega_D}^{\hbar\omega_0} dE'\alpha^2(\Omega)\big\{f(E)\big[1-f\big(E'\big)\big][n(\Omega)+1]-f\big(E'\big)[1-f(E)]n(\Omega)\big\}\delta\big(E'+\Omega-E\big)$$

Chang, PRB (1977)

EXCITATIONS OF A SUPERCONDUCTOR

The small picture

- Deposition of energy into the electron or phonon subsystem of the superconductor will lead to population of hot quasi-electrons
- This is a relatively fast process (generally still ~10 times slower than phase dynamics of the condensate itself)



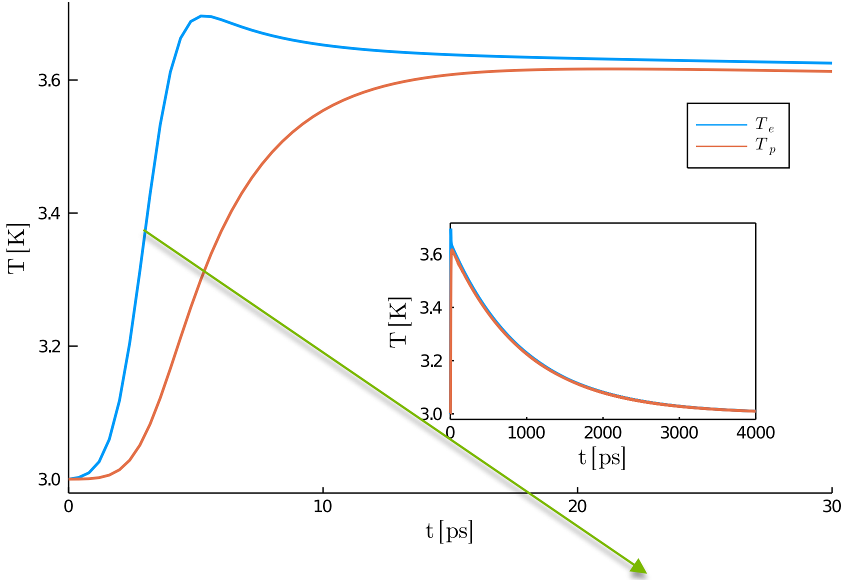
$$c_e \frac{dT_e}{dt} = -\frac{c_e}{\tau_{e-p}}(T_e - T_p) + P(t)$$

$$c_p \frac{dT_p}{dt} = \frac{c_e}{\tau_{e-p}}(T_e - T_p) - \frac{c_p}{\tau_{\mathrm{es}}}(T_p - T_0)$$

EXCITATIONS OF A SUPERCONDUCTOR

The small picture

- Can be already (ab)used if we’re willing to measure resonant properties of superconducting oscillators
  - Changes of quasi-electron density translate to changes of inductance
  - Principle behind kinetic inductance detectors



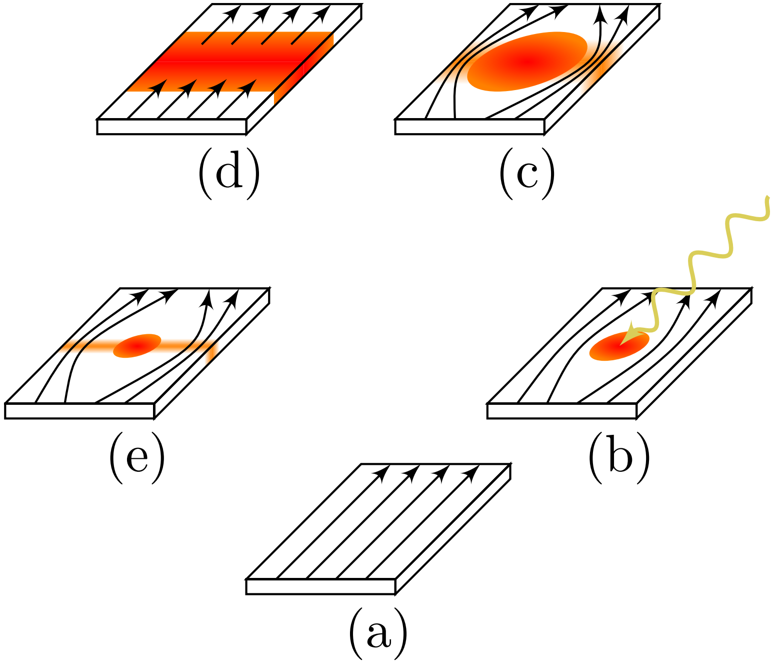
$n_s(T_e)$

$$\sigma(\omega) \approx \frac{m_n q_n^2 \tau}{m_n} + \frac{\pi n_s q_s^2}{m_s}\delta(\omega) + i\frac{n_s q_s^2}{\omega m_s}$$

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

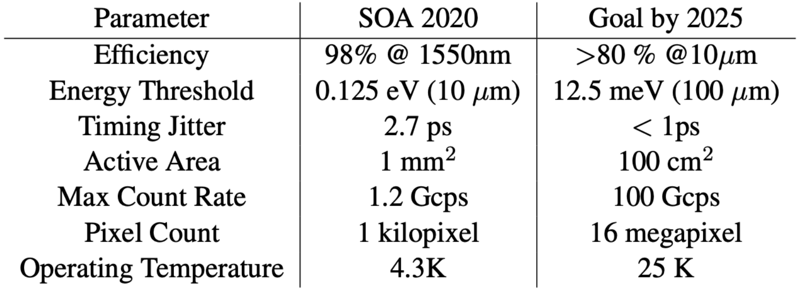


Polakovic, Nanomaterials (2020)

SUPERCONDUCTING NANOWIRE (SINGLE PHOTON) DETECTORS

Some metrics

- One of the fastest and most precise ways to measure interactions with individual quantum excitations
  - Energy thresholds as low as ~100 meV
  - Timing jitter easily 20-40 ps (current record of 3 ps)
  - Reset times can be as low as 5-10 ns (potentially <1 ns in the future)
  - Conveniently operates at roughly LHe temperatures



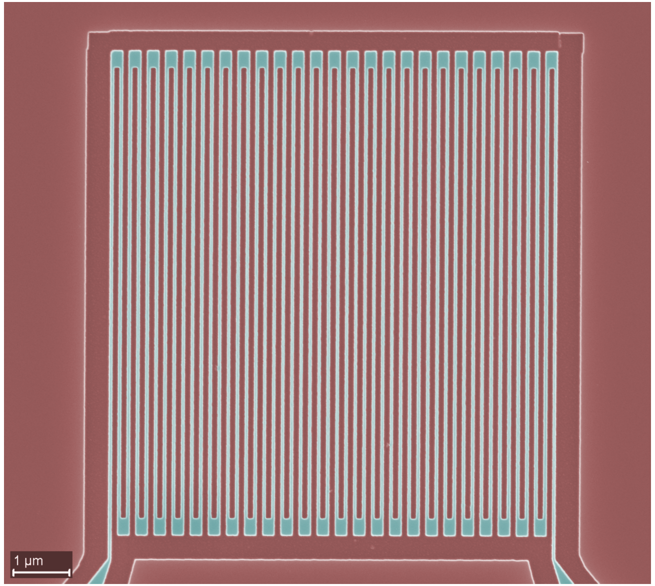
Parameter	SOA 2020	Goal by 2025
Efficiency	98% @ 1550nm	>80 % @10μm
Energy Threshold	0.125 eV (10 μm)	12.5 meV (100 μm)
Timing Jitter	2.7 ps	$<$ 1ps
Active Area	1 mm^2	100 cm^2
Max Count Rate	1.2 Gcps	100 Gcps
Pixel Count	1 kilopixel	16 megapixel
Operating Temperature	4.3K	25 K

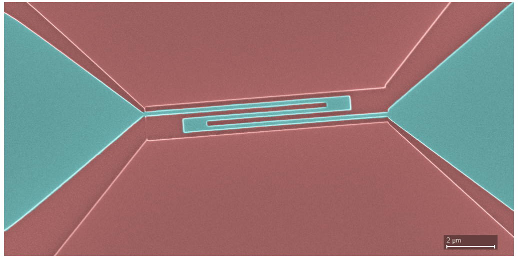
Snowmass2021 SNSPD LOI (2020)

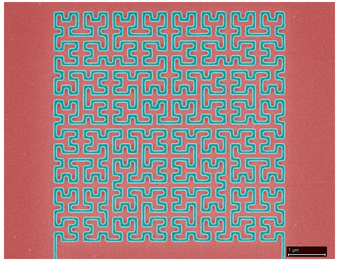
Polakovic, NIM A (2020)

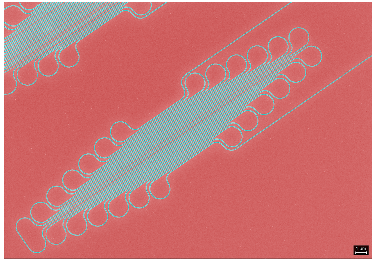
SNSPDS AT ARGONNE

- Ability to fabricate detectors with geometries and scales as necessary for the experiment
  - (Within budget constraints)



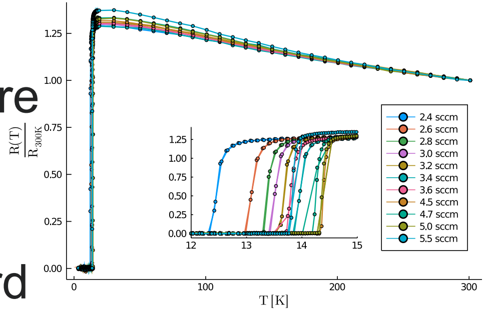


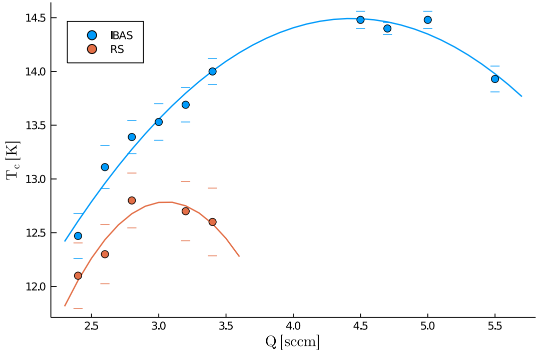


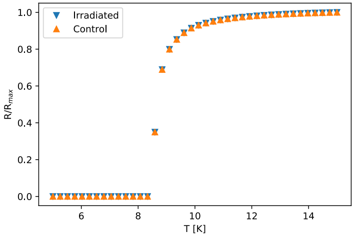


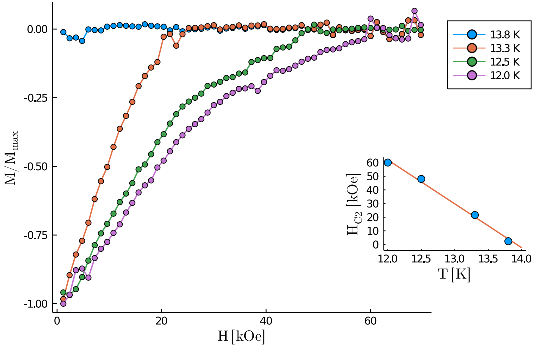
SNSPDS AT ARGONNE

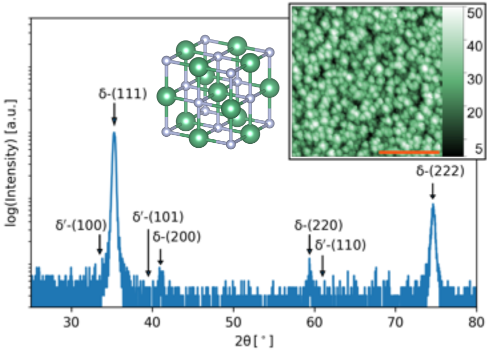
- Process works at room temperature and on Si substrates
- Preliminary results show that material (and devices) are rad-hard
  - At conditions of ATLAS at ANL









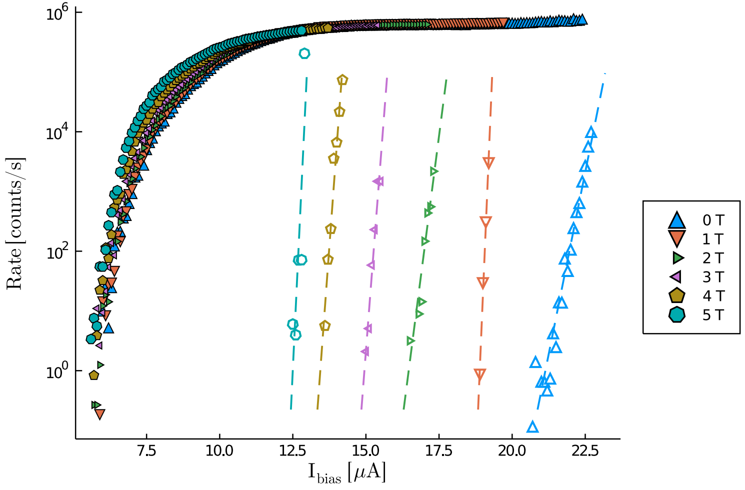


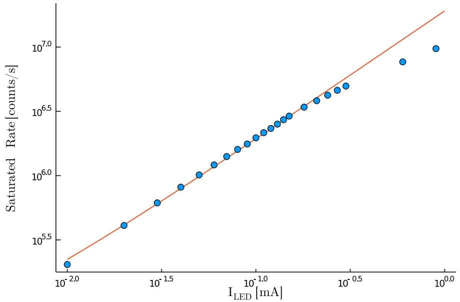
Polakovic, APL Materials (2018)

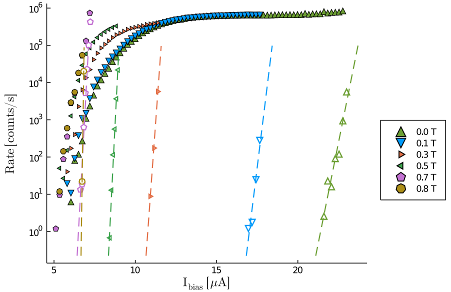
SNSPDS AT ARGONNE

Photons

- Current characterization focus on visible-UV photons
- Detectors capable of single-photon detection with saturated QE in fields up to 8 T
- Operational temperatures of 4-6 K
- Detection rates as high as 100 MHz with 0 dark counts







Polakovic, NIM A (2020)

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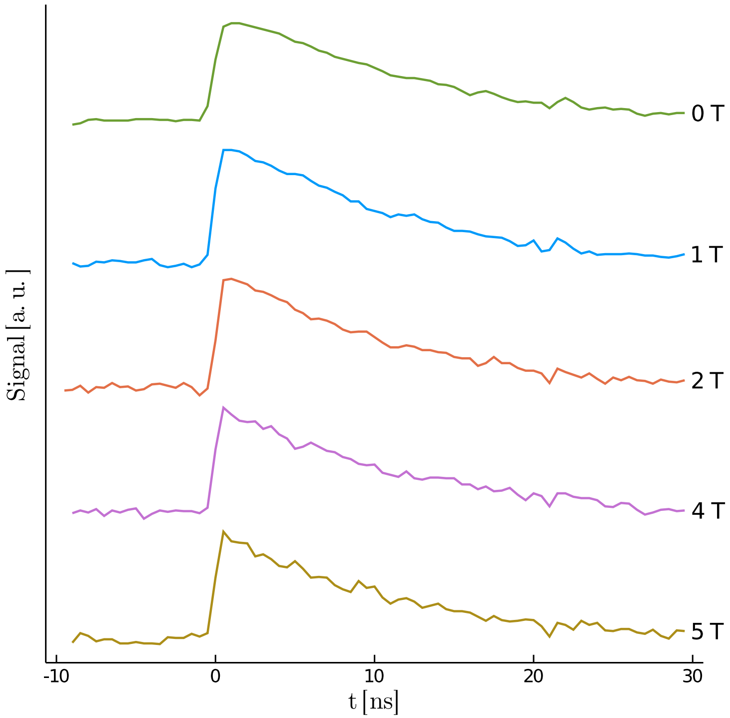
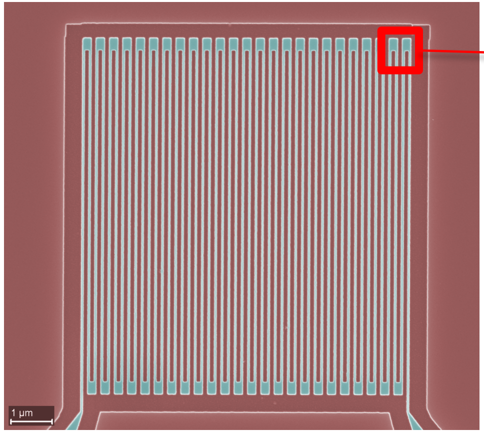


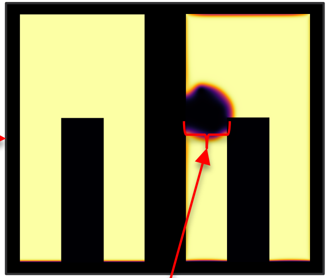
Polakovic, NIM A (2020)

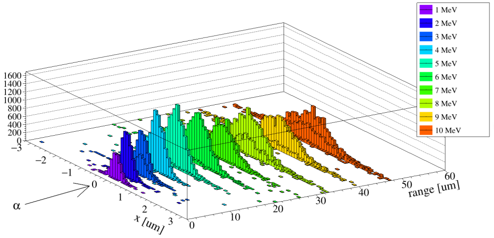
SNSPDS AT ARGONNE

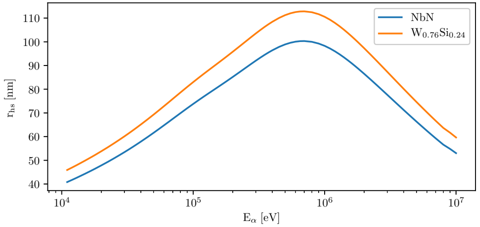
Particles

- Particle detection at E ~ 1-5 MeV works as well as with visible photons
- Current focus on detection of higher energy particles
  - Outlook positive
- Calorimetry using nanowires (hopefully) in very near future









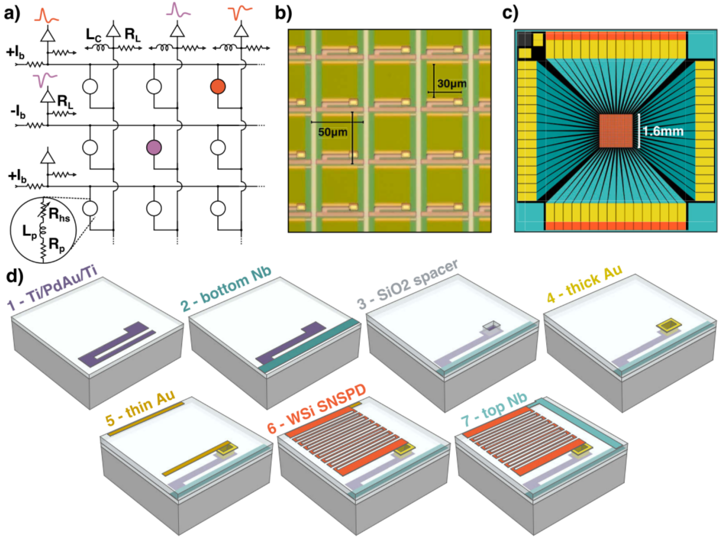
Polakovic, Nanomaterials (2020)

SNSPDS AT ARGONNE

Towards real detectors

- Segmented, multiplexed readout
- Applicable for special cases within EIC, where areas are not too large, but conditions are not hospitable for conventional technologies (high fields, radiation) and timing is resolution is crucial

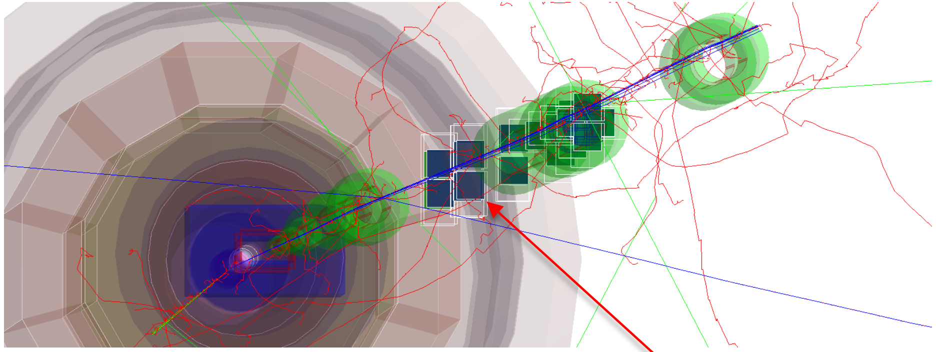
- Compton polarimeter (for electrons, photons maybe?)
- Forward Roman Pot Tracking
- Cold bore magnet integrated tracking
- Precision vertex tracking

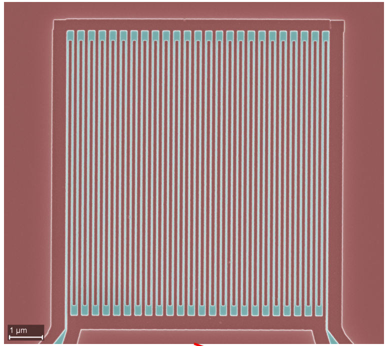


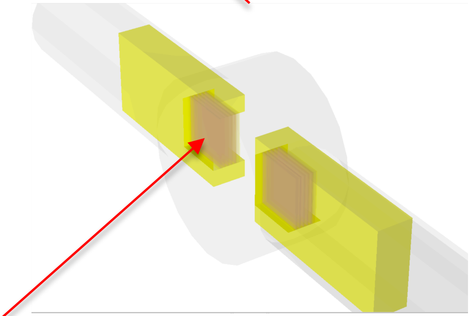
Wollman, Opt. Express (2019)

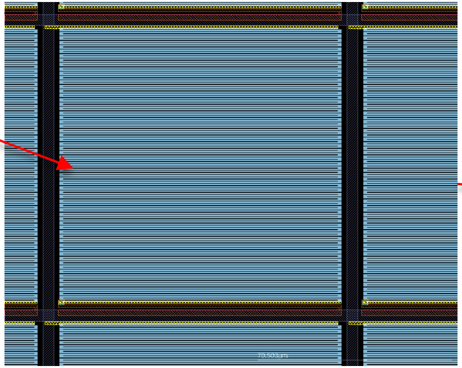
SNSPDS AT ARGONNE

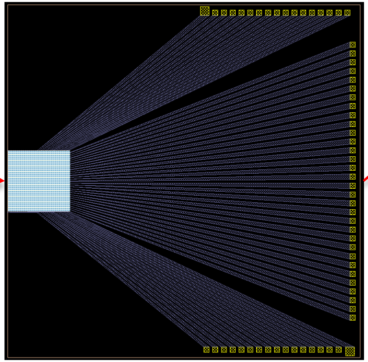
Towards real detectors







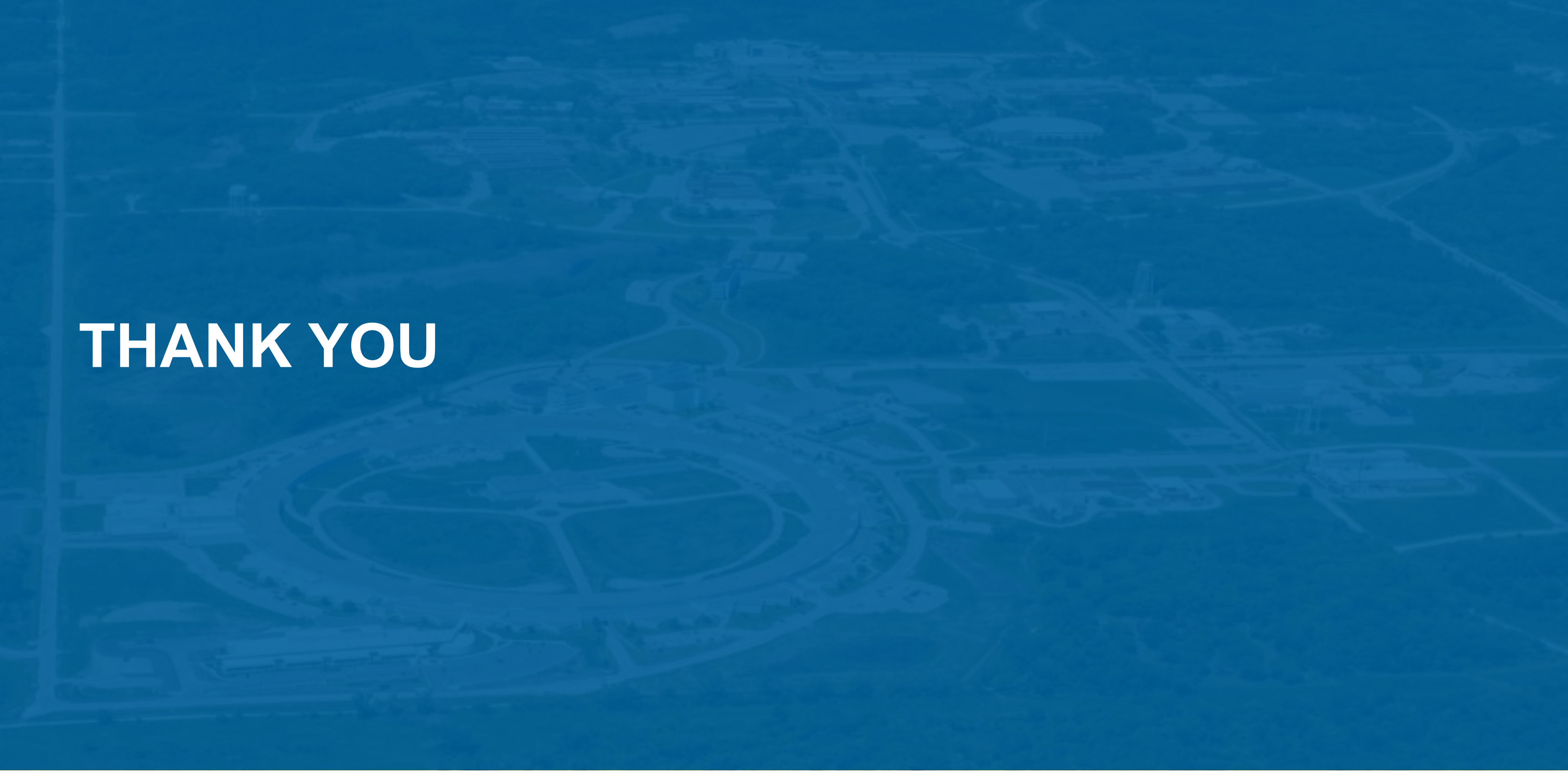




eRD28: Superconducting Nanowire Detectors for the Electron Ion Collider

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.



THANK YOU

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