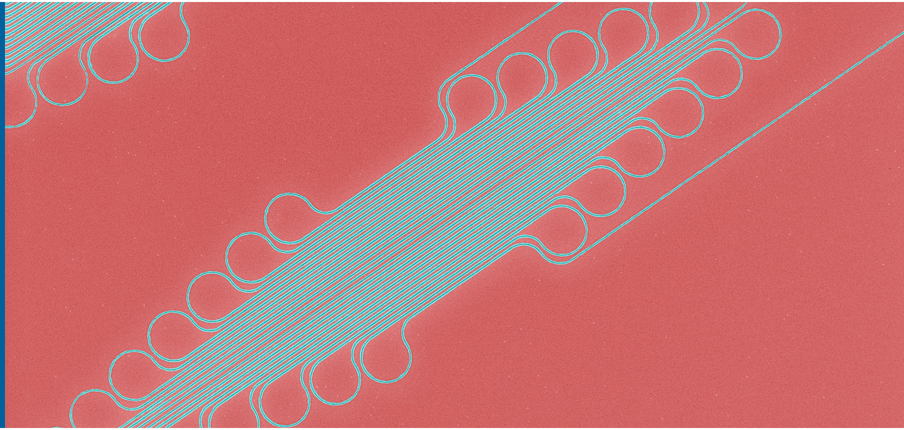
FROM SUPERCONDUCTING THIN FILMS TO HYBRID DEVICES AND QUANTUM SENSING



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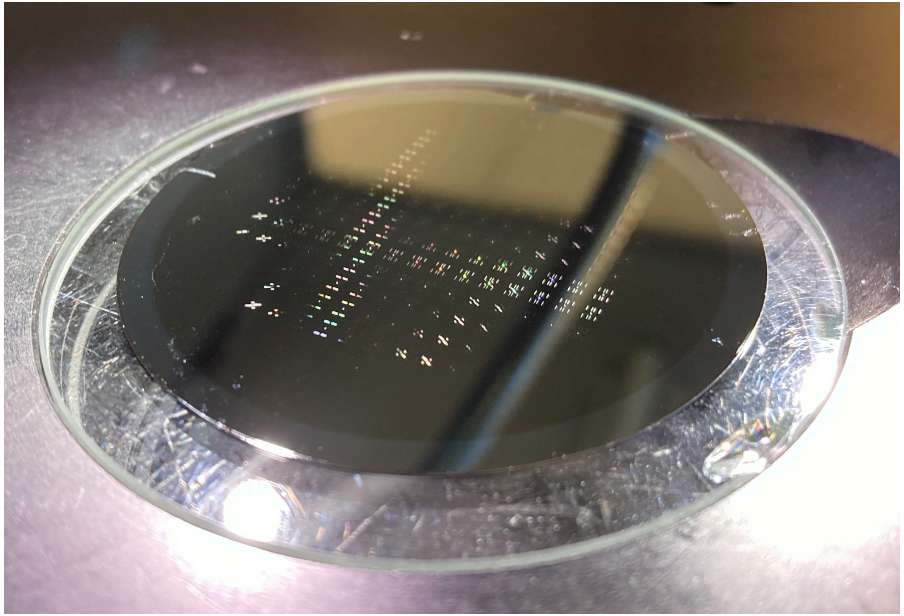
SUPERCONDUCTING THIN FILMS

Everywhere around us

- Superconducting devices are non-negotiable in many QIS technologies
- Requirements of the technologies have demands that might be hard to achieve concurrently with thin film deposition processes
  - Scalability
  - Reliability
  - Cost
  - Experimental conditions
  - Etc., etc., etc.,…

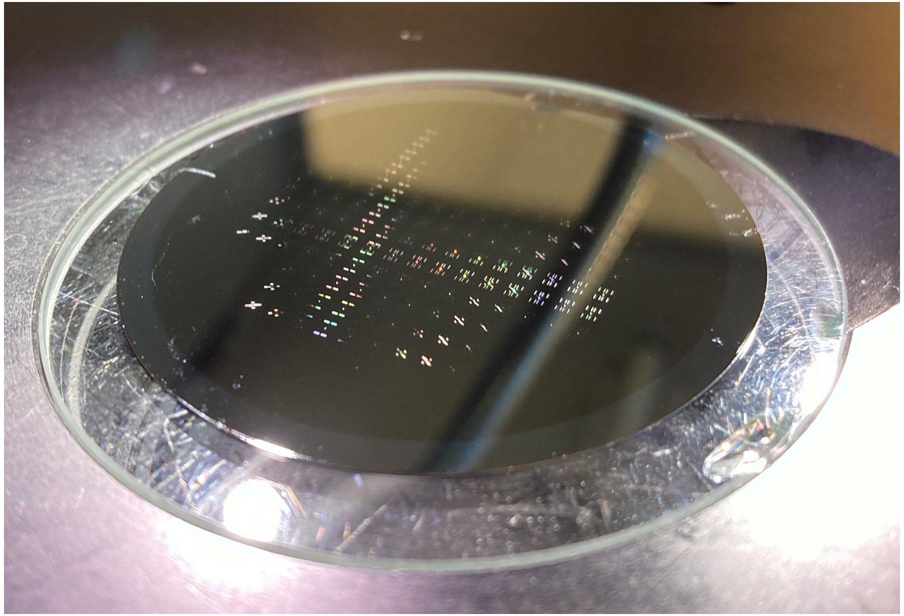


SUPERCONDUCTING THIN FILMS

Which ones?

- The decision with highest impact on results is the choice of base materials
  - Ceramics vs. metals
  - (poly)crystalline vs. amorphous
  - BCS vs. unconventional

- The naïve choice of “higher numbers equal more better” is almost always counter-productive
  - Example: We still can’t reliably make nanowire photon sensors out of MgB_2



SUPERCONDUCTING THIN FILMS

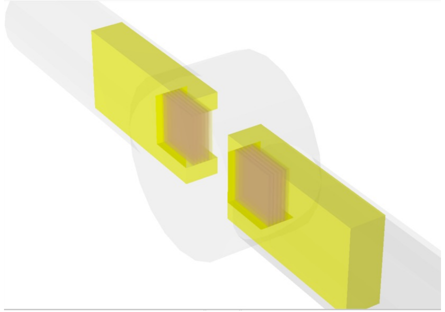
How to grow them?

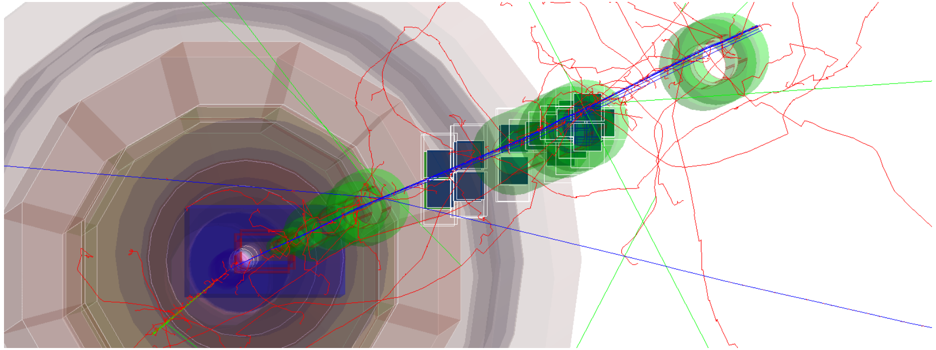
- Second highest-impact decision is on how to grow the materials
- Different techniques make trade-offs in different areas
  - Example: I can sputter multiple 6-in wafers in the time it takes me to do a single MBE growth, at the expense of film quality
- There is a big difference between the requirements of basic research/early-TRL projects and projects aiming towards applications or deployment.

SUPERCONDUCTING THIN FILMS

QIS/NP - Materials science with a purpose

- Initial motivator for our materials research was nuclear physics, specifically in superconducting nanowire detectors for particle colliders
- Immediate requirement for industrial-like processes and materials
  - Final product are multiple large-area detectors that need to operate within spec for years
  - The devices will operate in high-radiation, high-field environments, no colder than LHe temperatures





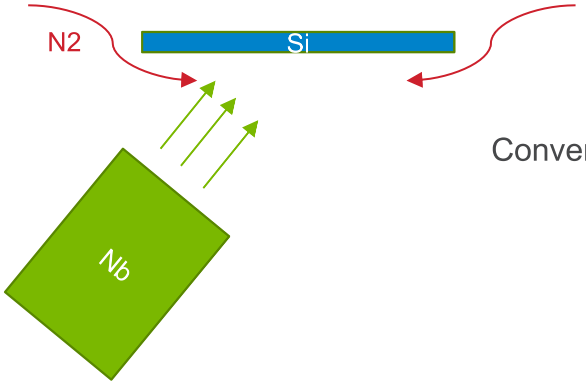
ION BEAM ASSISTED SPUTTERING OF NITRIDES

ION BEAM ASSISTED SPUTTERING OF NITRIDES

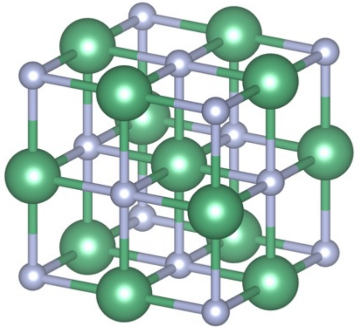
No surprises wanted

- Knowing the conditions and technology node, we opted for sputtering of Niobium Nitride
  - Sputtering enables us to grow large areas with good yield, and/or to hand off fabrication to industrial partners if needed
  - One of the most used materials for nanowire devices, well understood performance
  - Metallic, so it has short screening lengths and is robust against microstructural damage
  - Also a decently rad-hard material

- We happen to have an ion gun integrated into our deposition system, so let's check how much more performance can we materials science out of the material



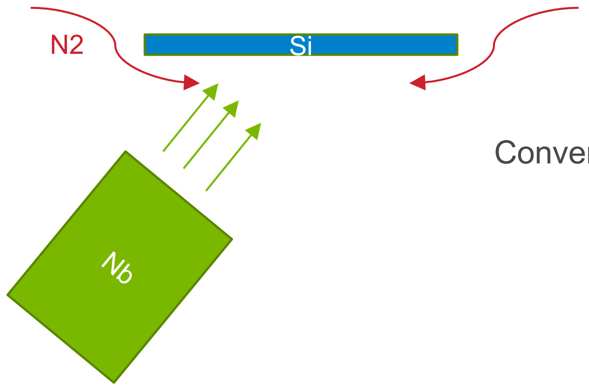
Conventional sputtering



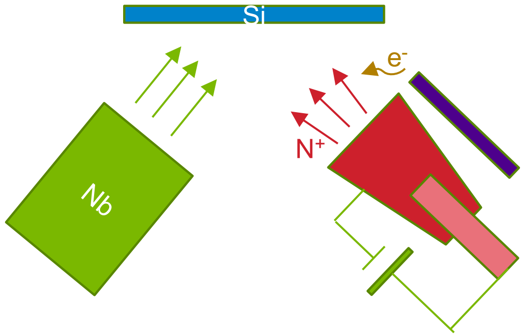
ION BEAM ASSISTED SPUTTERING OF NITRIDES

Making it better

- Conventional reactive sputtering process yields good films, but requires high temperatures
  - Limited process compatibility
  - Slow
- Increase in adatom kinematics is highly desired, if it can be achieved on a nominally cold substrate
- Solution: Directly inject excess kinetic energy into the system by means of an ion gun
  - US Patent 11,885,009



Conventional sputtering

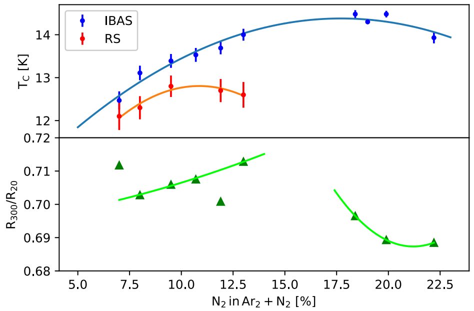


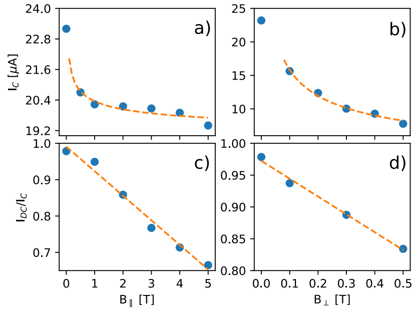
IBAS

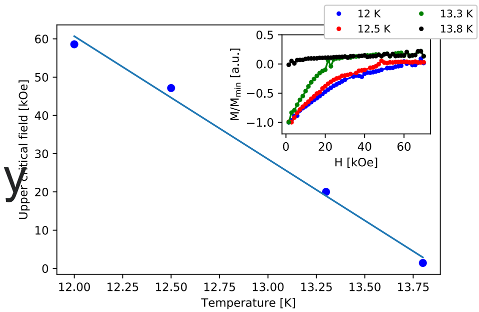
ION BEAM ASSISTED SPUTTERING OF NITRIDES

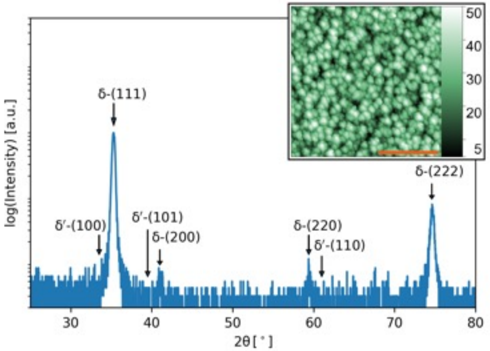
Making it better

- Solution: Directly inject excess kinetic energy into the system by means of an ion gun
  - US Patent 11,885,009
- The method yields films with higher critical temperatures and enhanced crystallinity
- Pinning due to meso-scale grain structure of the films also significantly enhances the upper critical fields
  - Exactly what we wanted!







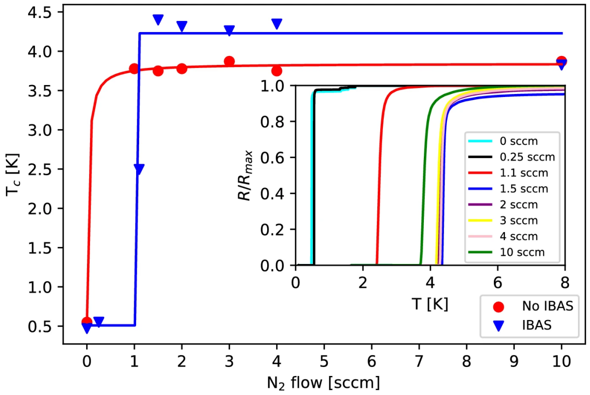


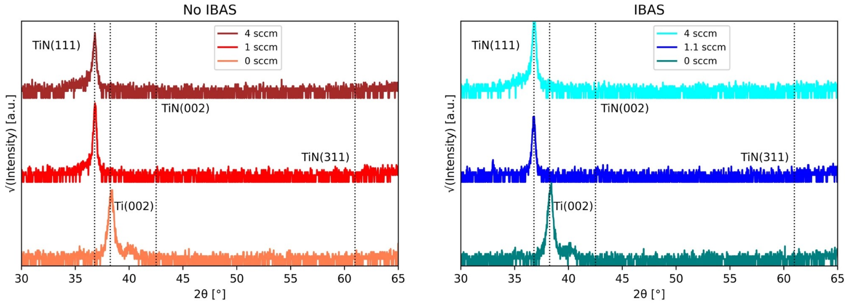
Polakovic, *et. al.*, APL Materials (2018)

ION BEAM ASSISTED SPUTTERING OF NITRIDES

Detour – Not everything is a nail just because you have a hammer

- Taken at face value, method has no reason to not work for any other metal nitride alloy
  - Kinematic enhancement should be universal
- We have published results with IBAS-grown TiN and internally evaluated MoN and TaN, with observed increase in film performance
- However, ZrN is proving to be a challenge to grow reliably even with IBAS
- Reiterates an important lesson to be learned: The materials are part of your experiment.





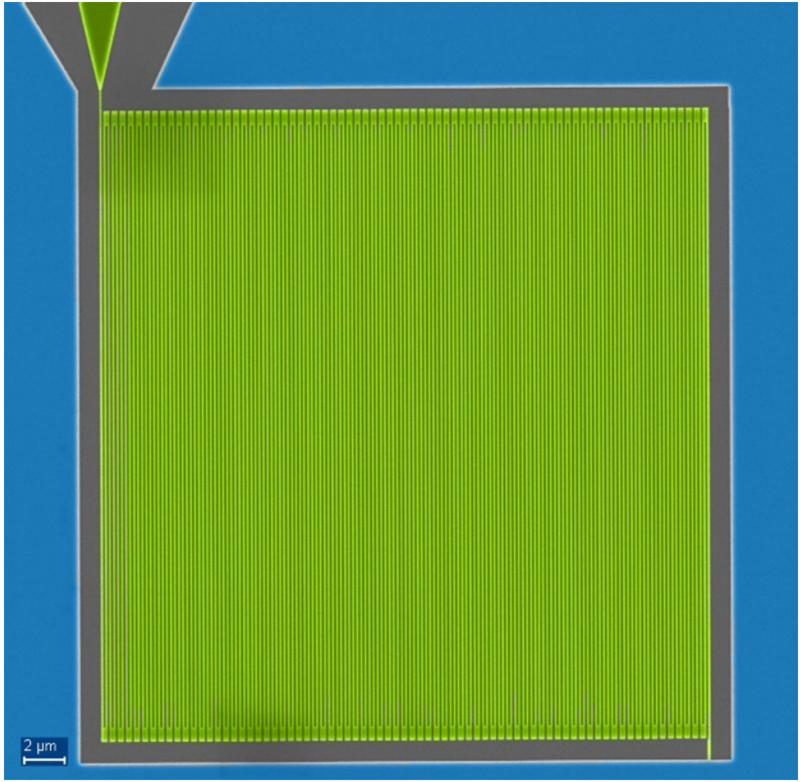
Draher, *et. al.*, Sci. Reports (2023)

SUPERCONDUCTING NANOWIRE DETECTORS

SUPERCONDUCTING NANOWIRE DETECTORS

At a glance

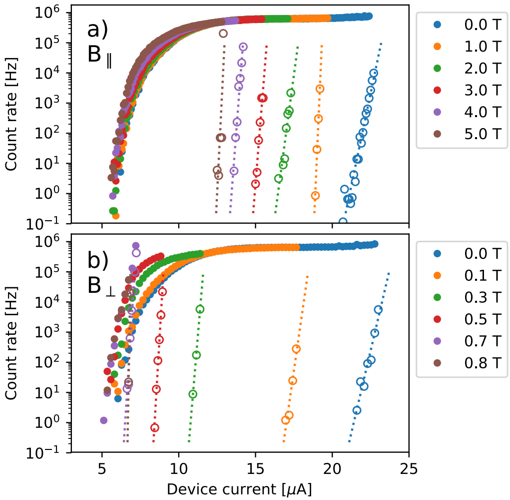
- Uses quasi-particle avalanche process inside a current biased superconducting nanowire to detect scattering/absorption of individual quantum excitations.
  - Analogous to operation of a bubble chamber, but in solid state system.
- Much faster and more sensitive than ionization avalanches in semiconductor 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



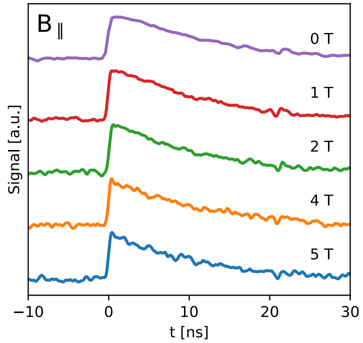
SUPERCONDUCTING NANOWIRE DETECTORS

Our best

- Deposition at room temperature
- Operation at 4 K
- Strong vortex pinning allows for relatively high critical currents
  - Good for high SNR and detection efficiency
- Demonstrated single photon counting in fields as high as 6 T
  - World record!



Polakovic, *et. al.*, NIM A (2020)

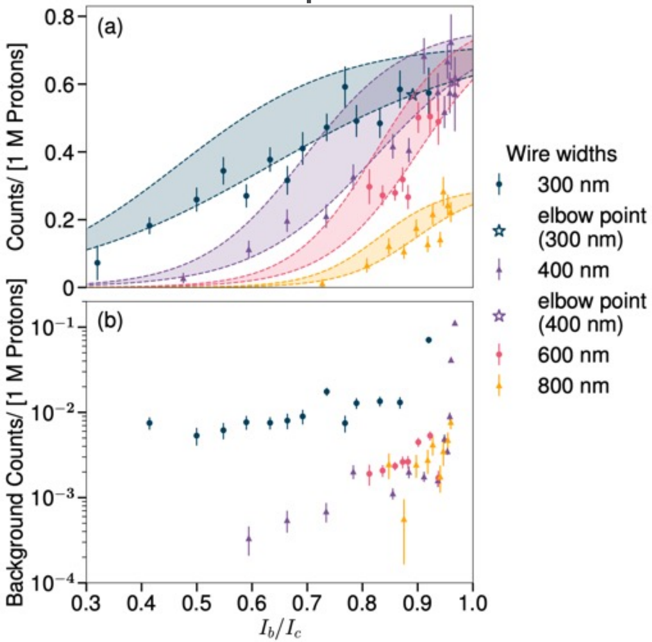


SUPERCONDUCTING NANOWIRE DETECTORS

Much to be done

- Further work is being done to convert this into a NP-related technology
  - Determination of physics that drives the process
  - Evaluation of radiation hardness of devices
  - Pushing the limits of scalability

120 GeV protons



Lee, *et. al.*, NIM A (2025)

SUPERCONDUCTING NANOWIRE LOGIC DEVICES

SUPERCONDUCTING NANOWIRE LOGIC

Cryotrons

- Scaling to large areas not feasible with single pixels
  - Outlook of 1-2 million sensors per detector
- Readout and instrumentation by millions of cables from the hot side won’t work
- Would be nice to have digital logic on-chip, within the process node of the sensors
- Solution: nano-cryotrons (nTrons)

1954

Albert Slade, photo: Dough Fairbarn

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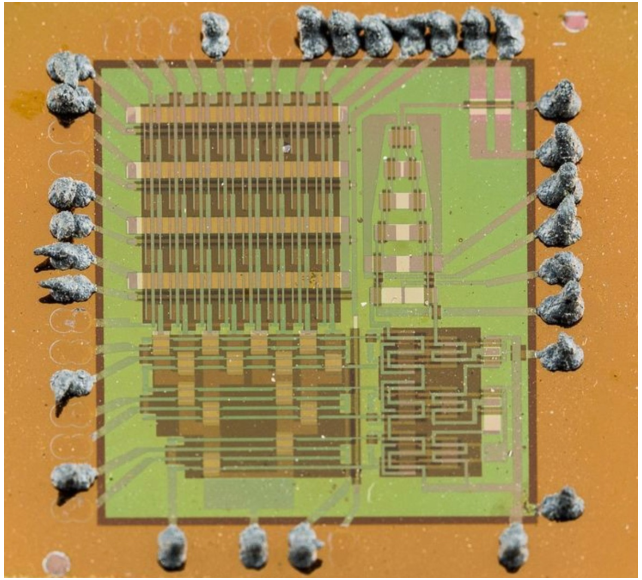
1965



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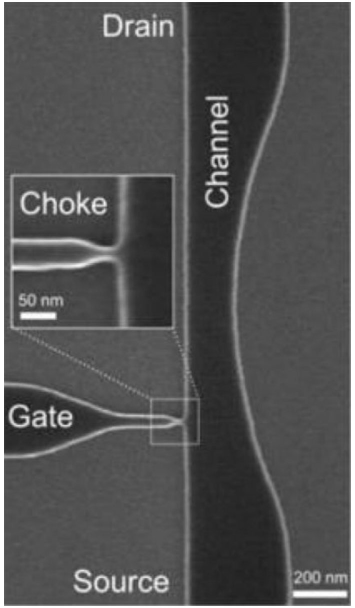
2014



McCaughan, *et. al.*, Nano Letters (2014)

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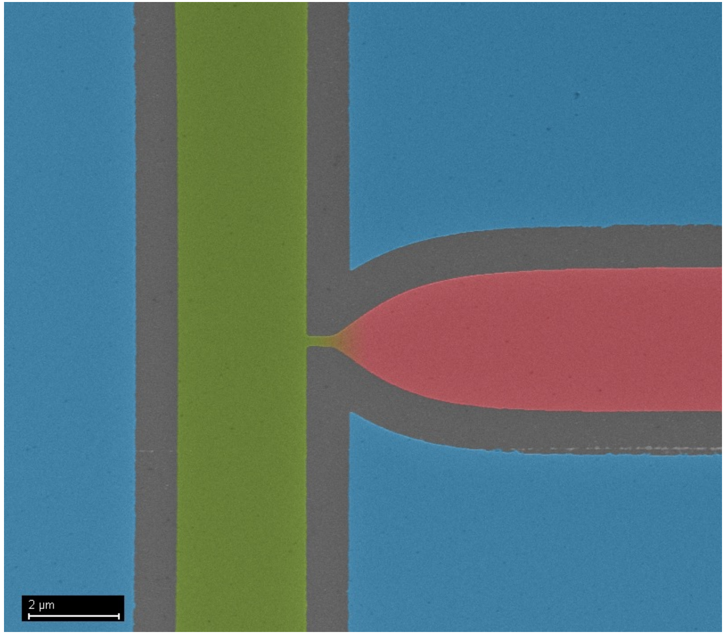
2023

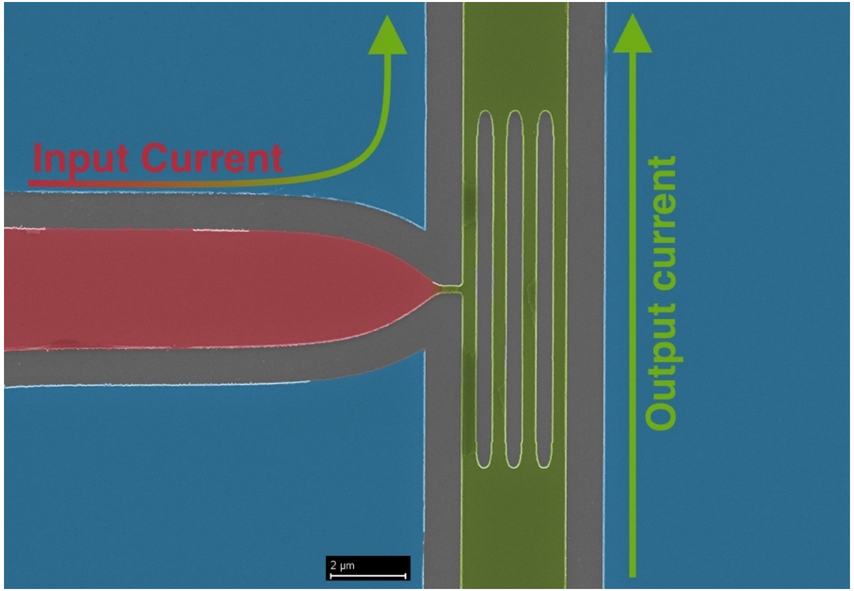


Draher, *et. al.*, APL (2023)

SUPERCONDUCTING NANOWIRE LOGIC

Cryotrons@ANL

- Additional optimization of device geometry allows for faster switching and operational electrical currents similar to SNSPDs.
- Benefits of strong field operation still present.



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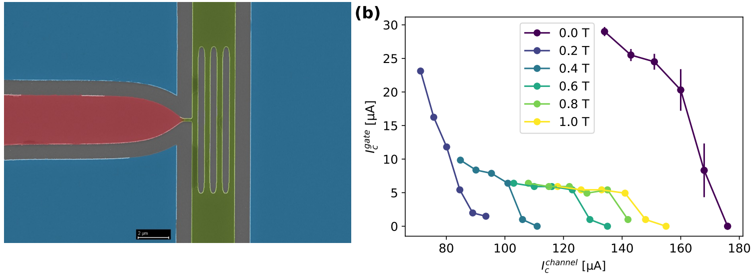
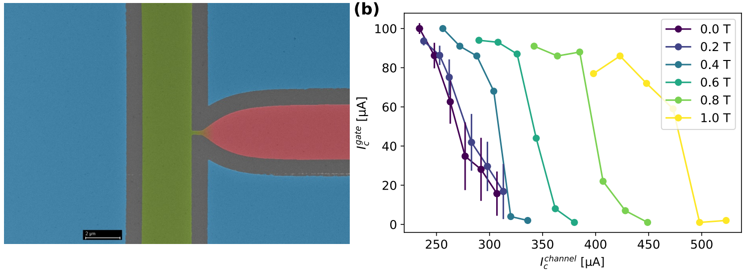


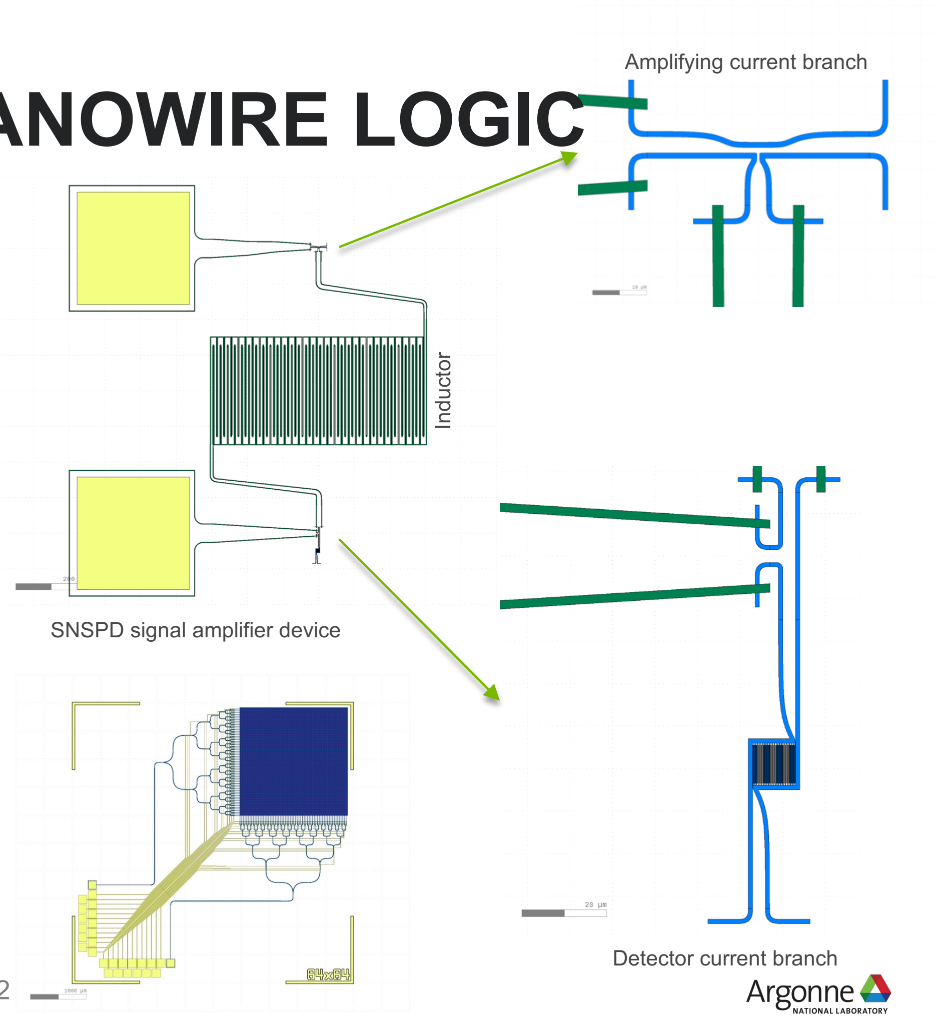


Draher, *et. al.*, APL (2023)

SUPERCONDUCTING NANOWIRE LOGIC

Cryotrons@ANL

- Additional optimization of device geometry allows for faster switching and operational electrical currents similar to SNSPDs.
- Benefits of strong field operation still present.
- Can now be used for more complex superconducting on-chip logic.

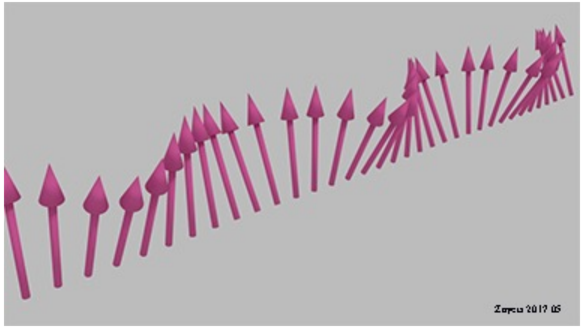


HYBRID MAGNONICS

HYBRID MAGNONICS

Modern solution for modern problems

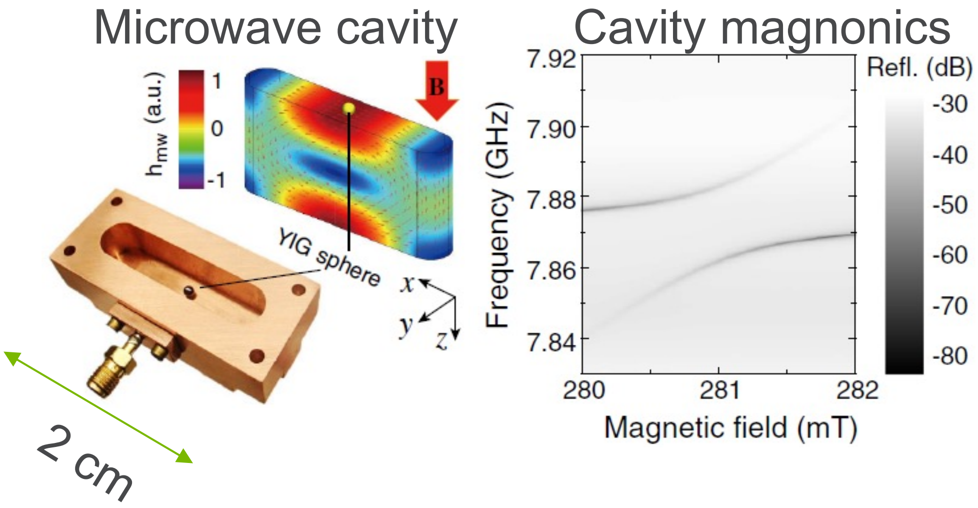
- Coherent transport and manipulation of spin and magnetization excitations interesting from computational perspective
- Robust and efficient, long life-times
- Can be, in principle, used for storage of quantum information
- Interference of excitation modes can be used for computation



HYBRID MAGNONICS

Modern solution for modern problems

- To leverage the good properties and bypass the drawbacks (like weak coherent transport), magnonic systems can be used in hybrid structures
- Common realization is cavity magnonics
  - Magnetic degrees of freedom of the material couple to EM excitations in a cavity.

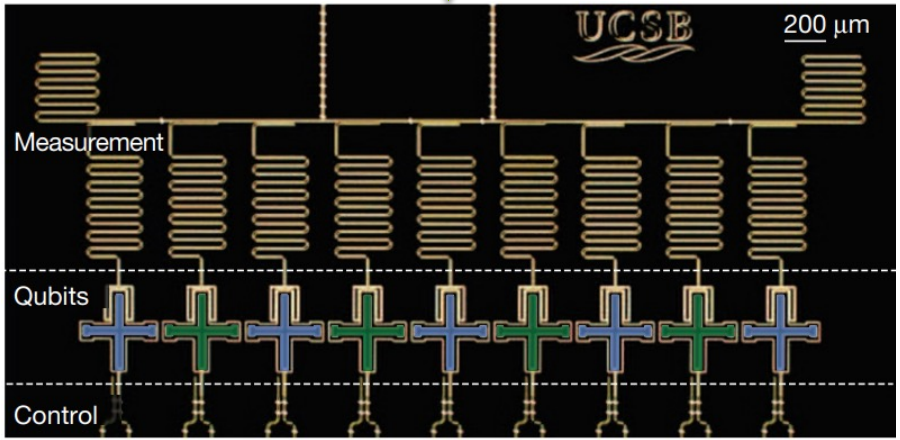


X. Zhang et al. PRL (2014)

HYBRID MAGNONICS

Modern solution for modern problems

- Macro-scale cavities work well, but are hard to integrate and next to impossible to scale-up
- Idea: Use superconducting micro-resonators
  - Small volume, efficient, integrates well with SC qubits
- Problem: Superconducting resonators do not like magnetic fields
- Solution: Use materials engineered for good field performance

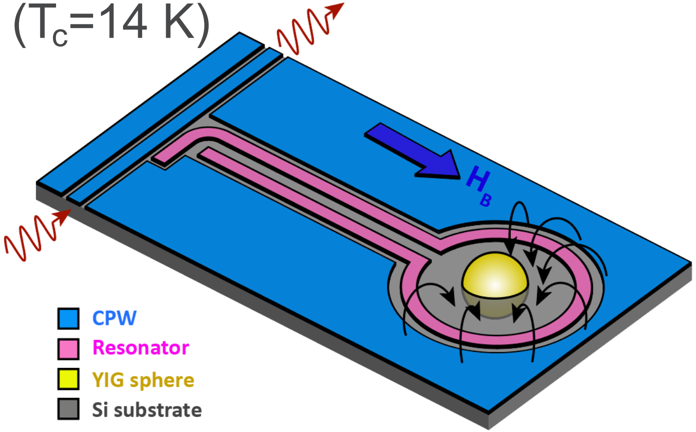


Kelly, et al. Nature (2015)

HYBRID MAGNONICS

Hybrid Magnonics@ANL

NbN Superconducting resonator (T_c=14 K)



Y. Li, et al. PRL (2022)

YIG sphere mounting

Before mounting

After mounting

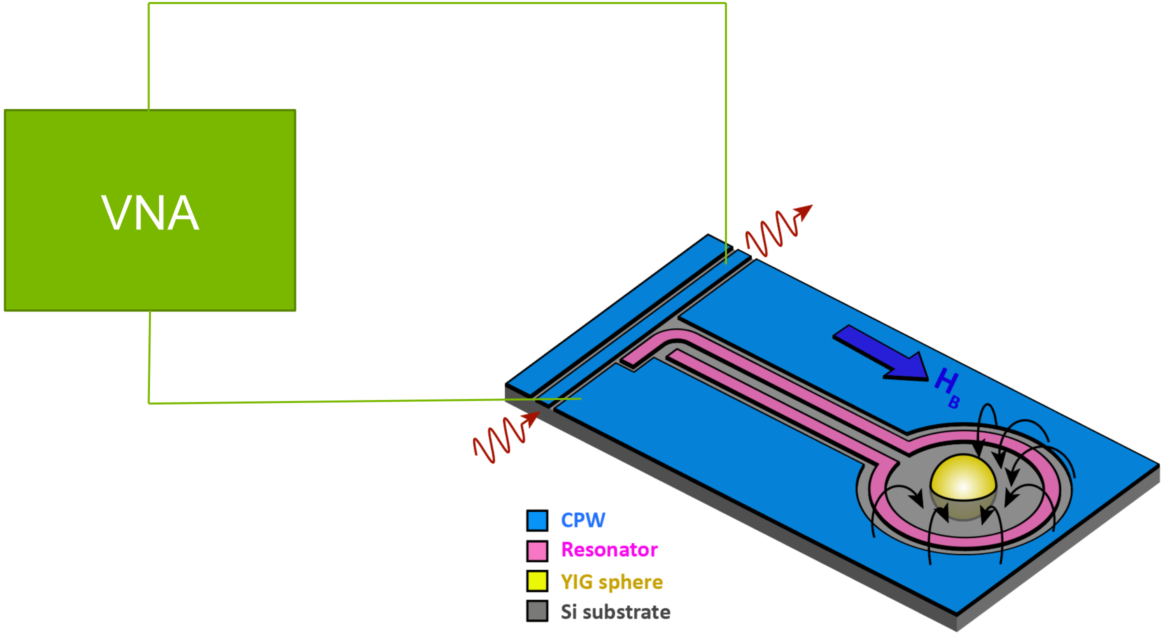
Si etching:

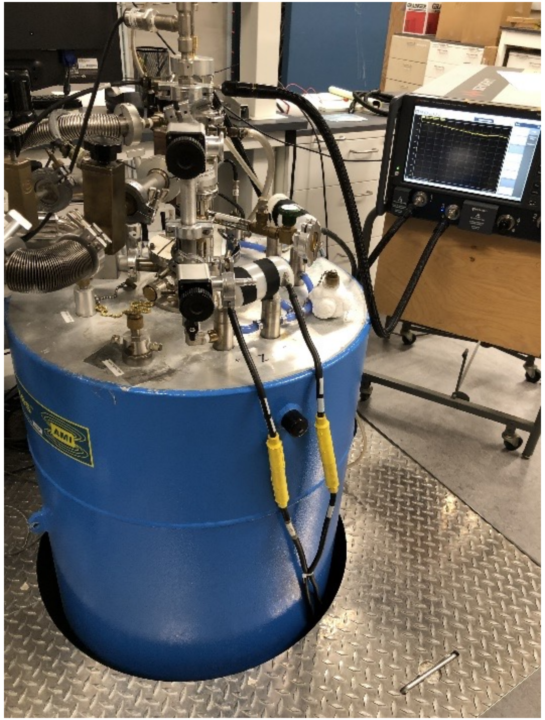
- Deep RIE
- Depth: 125~150 um
- Roughness: <5 um

Tom Cecil, Vlad Yefremenko, Margarita Lisovenko, Ralu Divan

HYBRID MAGNONICS

Hybrid Magnonics@ANL



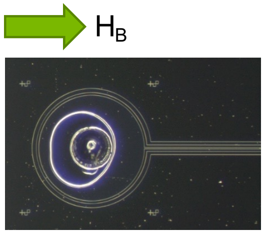


Yi Li

HYBRID MAGNONICS

Hybrid Magnonics@ANL

- We can achieve robust resonator performance with the photon mode being independent of the magnetic field
- Strong coupling between modes
  - $g_0/2\pi$ = 0.63 Hz, ~20x stronger than reported coupling of a magnon qubit + 3D cavity
  - Tunable with field strength



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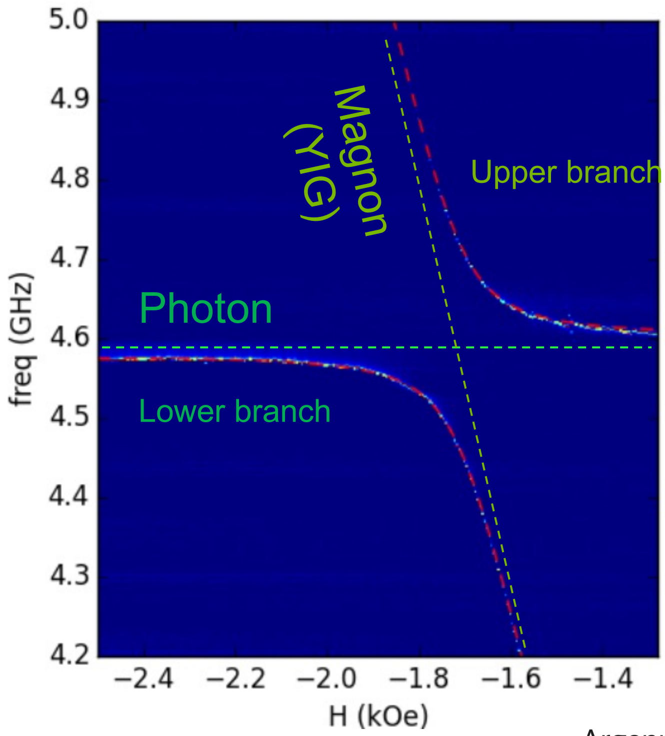
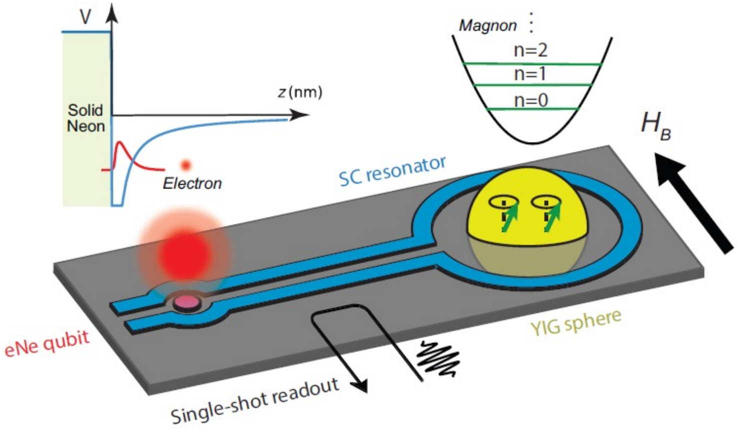


HYBRID MAGNONICS

Hybrid Magnonics@ANL

- The demonstrated system is rich in applications
  - Study of entanglement between two coherent (magnon) qubits
  - Hybrid magnon networks for classical information processing



X. Zhou, et al. Nature 605, 46 (2022)

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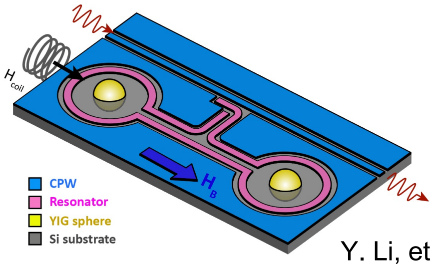
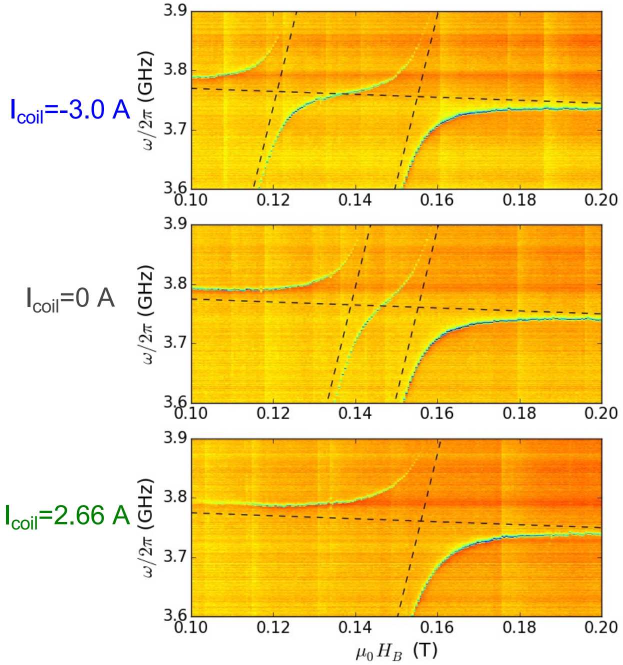


Y. Li, et al. PRL (2022)



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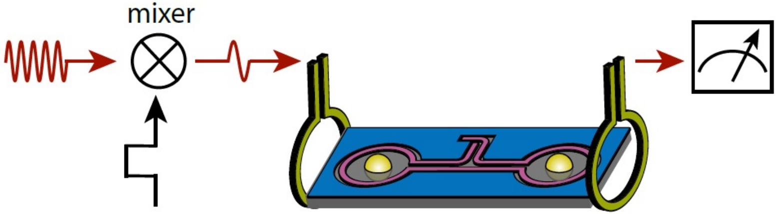

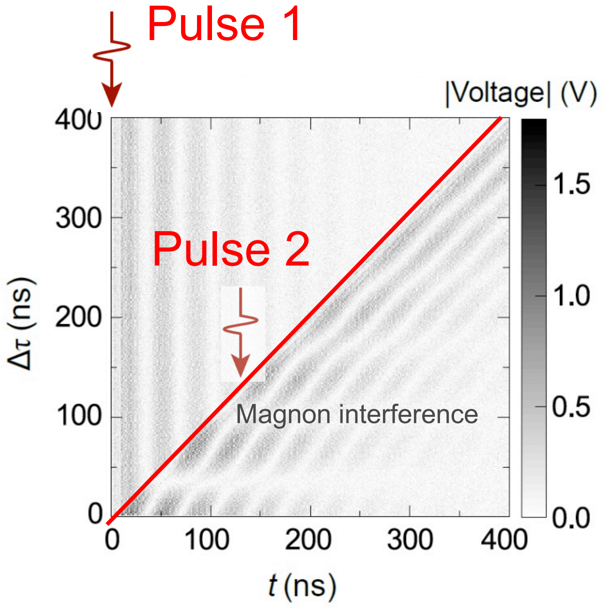

M. Song, et al. Nature Commun. 16, 3649 (2025)

CONCLUSION

CONCLUSION

- We have developed a technology and set of processes for large-area growth of superconducting films designed to operate in strong magnetic fields
- Film performance is on par with conventional techniques, making it a drop-in replacement in most processes
- The processes have been used in multiple QIS(-adjacent) applications, with more to come
  - Photonics in strong-field environments, particle detection, discrete logic devices, micro-cavities, hybrid quantum structures,…

THANK YOU FOR YOUR ATTENTION!