DRD5 WP-3: Superconducting Quantum Devices — An Overview

Andrea Giachero

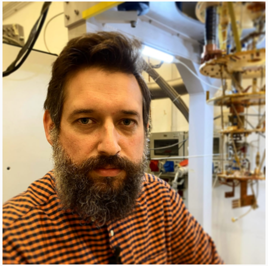
University of Milano-Bicocca

INFN Milano Bicocca

Bicocca Quantum Technologies (BiQuTe) Centre

DRD5 Quantum and Emerging Technologies

WP3 coordinators



Andrea Giachero

Associate Professor, Department of Physics, University of Milano-Bicocca

Research Associate, INFN Milano-Bicocca

Research Affiliate, University of Colorado Boulder

Board Member, Bicocca Quantum Technologies (BiQuTe) Centre

andrea.giachero@unimib.it

andreagiachero

Loredana Gastaldo NEW!!!

Associate Professor, Kirchhoff Institute for Physics, Heidelberg University, Germany

loredana.gastaldo@kip.uni-heidelberg.de

Sensors Based on Superconductivity

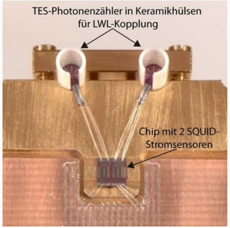
- **Superconducting Nanowire Single-Photon Detector (SNSPD)**
  Detects single photons by forming a resistive hotspot in a current-biased nanowire.
- **Transition Edge Sensor (TES)**
  Measures energy via resistance change at the superconducting transition temperature read out by a SQUID.
- **Magnetic Microcalorimeter (MMC)**
  Detects energy deposition through a temperature-induced change in magnetization of a paramagnetic sensor read out by a SQUID.
- **Superconducting Tunnel Junction (STJ)**
  Detects photons or particles through quasiparticle tunneling across a superconducting barrier.
- **Microwave Kinetic Inductance Detector (MKID)**
  Photon absorption changes the kinetic inductance of a superconducting resonator, shifting its resonance frequency.
- **Josephson Junction (JJ)–Based Detectors**
  Use the Josephson effect to sense microwave or terahertz photons via changes in the phase-current relation.
- **Hot Electron and Cold Electron Bolometer (HEB / CEB)**
  Absorbed radiation heats electrons in a superconducting element, changing its resistance or cooling rate.
- **Superconductor–Insulator–Superconductor (SIS) Mixer**
  Mixes high-frequency signals using nonlinear tunneling current between superconducting electrodes.
- **Superconducting Qubits (as Quantum Sensors)**
  Quantum two-level systems that detect extremely weak electromagnetic excitations.

Superconducting detectors (e.g., TES, KIDs, SNSPDs) require ultra–low-noise readout electronics operating at cryogenic temperatures.

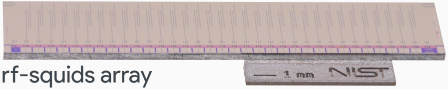
Typical readout components:

- **SQUIDs (Superconducting Quantum Interference Devices):** ultra-sensitive magnetometers that convert small changes in magnetic flux into voltage signals, enabling precise current amplification from superconducting sensors.
- **Microwave resonators:** superconducting resonant circuits that couple to multiple detectors, allowing frequency-division multiplexing and compact cryogenic readout architectures.
- **Parametric amplifiers (JPAs, KIPAs, JTWPA, KI-TWPA):** nonlinear superconducting devices that exploit the Josephson effect or kinetic inductance to provide near–quantum-limited amplification at microwave frequencies.

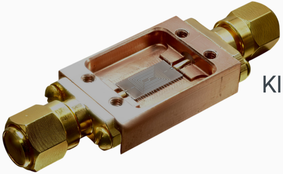
These devices preserve superconducting operation to minimize noise, dissipation, and signal loss.



dc-SQUID, PTB

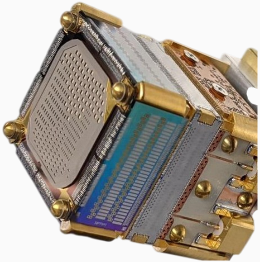


rf-squids array
NIST



KI-TWPA, NIST

- Single-photon detection (optical/IR) – **SNSPDs, TES, MKIDs**
- X-ray spectroscopy / high-resolution calorimetry – **TES, STJ, MMC**
- Submillimeter / millimeter astronomy – **MKIDs, Bolometers**
- Microwave / THz detection – **JJ Detectors, SIS Mixer, Superconducting Qubits**
- CMB and infrared radiation measurement – **Bolometers, TES**
- Dark matter searches / axion detection – **TES, MMC, Superconducting Qubits, Quasiparticle Traps**
- Neutrino measurement and double beta decay searches – **TES, MMC, Bolometers**
- Magnetic field sensing / biomagnetism – **SQUID, MMC**
- Phonon detection – **TES, MKIDs, MMC, recently superconducting qubits**
- Quantum communication / optical quantum computing – **SNSPDs, TES, MKIDs**
- High-frequency signal mixing / radio astronomy – **SIS Mixer, Josephson Junction Detectors**



TESs, NIST

MKIDs, UCSB

Superconducting detectors are quantum-limited sensors:

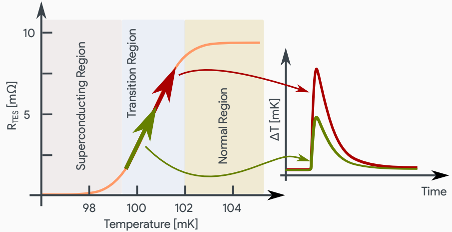
- Not based quantum mechanics (superposition, entanglement, interferece);
- Operate as quantum-limited devices:
  - Sensitive to the minimum energy allowed by quantum mechanics, the quantum of energy $\hbar\omega$;
  - Performances approache the fundamental quantum limits (e.g., set by quantum noise or pair-breaking energy 2Δ).
- Based on quantum materials (superconductors, Josephson junctions, etc.);
- Examples: TES, SNSPD, MKID, STJ, MMC, bolometers, SIS mixers.
  - They detect classical quantities (energy, temperature, current, flux) using quantum effects in the material;
  - They rely on quantum physics, but do not manipulate quantum states.

Quantum-Enabled devices

- Use coherent quantum states (superposition, entanglement, and phase coherence) as the basis of their sensing:
- Examples:
  - Superconducting qubits used as quantum sensors (for dark matter, axions, microwave photons);
  - Josephson or Kinetic Inductance Parametric Amplifiers used in quantum readout chains;
  - Interferometric SQUIDs when operated in regimes where quantum phase coherence is exploited.

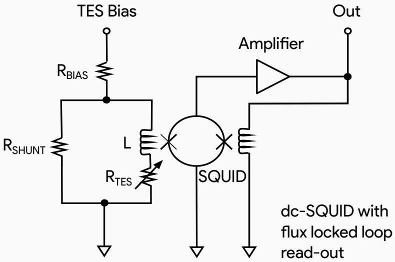
TES Operation: measure small ΔT using a superconducting circuit:

- operates in the sharp superconducting-to-normal transition region;
- Small temperature change produces a large resistance change;
- Thermal fluctuations and readout noise limit sensitivity;
- Absorbed energy may break Cooper pairs, but TES is fundamentally a thermal detector



Readout via SQUIDs:

- dc and rf SQUIDs enable multiplexing for large TES arrays;
- operate at millikelvin temperatures with very low noise and minimal added amplification;
- dc SQUID requires a flux-locked loop for stable linear operation
- rf SQUID uses flux-ramp modulation and linearization for accurate readout

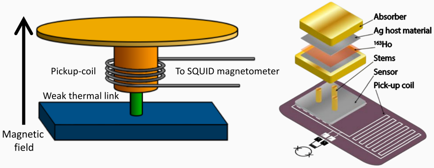


Large TES arrays have been successfully used in astroparticle and particle physics experiments (e.g., neutrino and dark matter searches)

For more details, see talks by Daikang Yan and Sebastian Kempf.

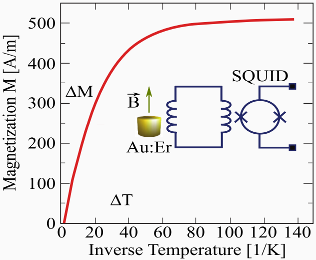
MMC Operation: measure induced change in magnetization:

- uses a paramagnetic sensor weakly coupled to a thermal bath;
- energy absorbed in the sensor raises its temperature, changing magnetization;
- very high energy resolution, limited by thermal and readout noises;
- fully thermal measurement; no direct pair-breaking is required



Readout via SQUIDs:

- SQUIDs measure tiny changes in magnetic flux due to sensor magnetization;
- Can be multiplexed for large arrays using rf SQUIDs (like TESs;
- Requires careful thermal and magnetic design to achieve optimal sensitivity



MMCs have been successfully used in X-ray spectroscopy and rare-event searches (e.g., neutrino mass, double beta decay)

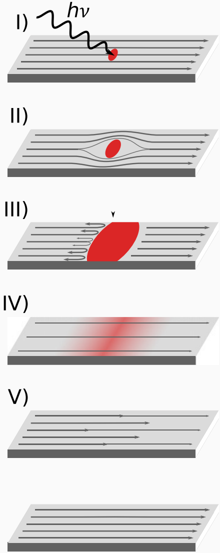
For more details, see talks by Sebastian Kempf.

Superconducting Circuit (Nanowire) or Pads (Chicane)

- Absorbed quanta of energy (photons or phonons) break Cooper pairs and generate a localized non-superconducting region (hotspot);
- Enables extremely low energy threshold and ultra-fast response (tens of picoseconds or better);
- Applications: quantum-pixel arrays, ultra-sensitive particle tracking, detection of milli-charged particles;

Recent Achievements

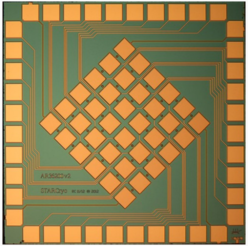
- Operate at higher temperatures (1–4 K), using compact cryocoolers and no need dilution refrigerators;
- Micron-scale devices providing larger active areas while maintaining single-photon sensitivity;
- Commercial systems are available for quantum communication applications;
- Recent experiments have demonstrated the detection of charged particles;



For more details, see talks by Adi Bornheim

Superconducting Tunnel Junctions (STJ)

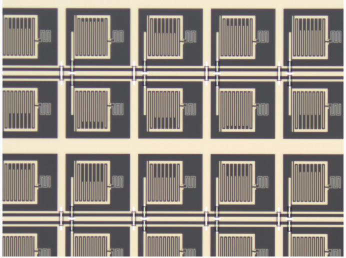
- Exploit quantum tunneling in a junction of two superconductors;
- Direct tunnel current measurement (non-heterodyne)
- Enables simultaneous fast photon counting and spectroscopy in IR, visible, and UV bands;



STJ, StarCryo

Microwave Kinetic Inductance Detectors (MKIDs)

- Energy quanta (photon or phonon) absorption creates quasiparticles, shifting the phase of an LC resonator;
- Read-noise free, with easy multiplexing for large arrays (∼10k pixels);



MKIDs, UCSB

Superconductor-Insulator-Superconductor (SIS) receivers

- Enabling technology for sub-millimeter astronomy;
- Superconducting circuits allow phase-coherent downconversion from THz to GHz;

Qubits act as highly sensitive two-level quantum systems whose states can be perturbed by extremely weak classical or quantum fields;

Examples of target signals:

- Microwave signals (photons) induced by axions or dark photons;
- Phase shifts generated by gravitational waves;
- Transition frequency shift induced by vibrational quanta (phonon);

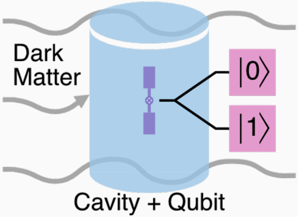
Example: Dispersive qubit readout coupled to a resonator tuned to the axion conversion frequency.

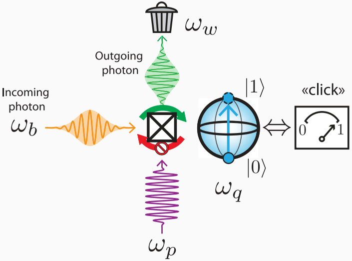
Measurement based on the effective Hamiltonian:

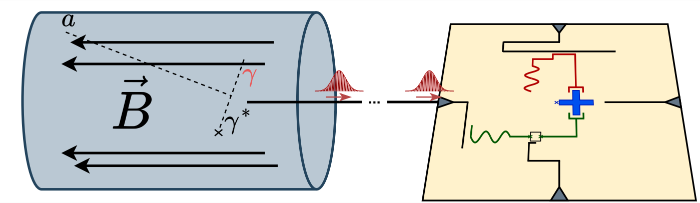
$$H = \frac{1}{2}\hbar\omega_q\sigma_z + \hbar g\, a^\dagger a\, \sigma_z \xrightarrow{\text{quanta}} \delta\omega_q = g\langle a^\dagger a\rangle$$

where the signal alters the average photon number $\langle a^\dagger a\rangle$, shifting the qubit frequency.

Requires quantum-limited amplifiers (e.g., JPAs, TWPAs) for high-fidelity readout of extremely low-energy excitations.







- The axion field a, interact with the magnetic field $\vec{B}$ inside the haloscope;
- The interaction produces a real photon γ and a virtual photon γ^*;
- The real photon is absorbed by a tunable storage cavity (shown in green);
- The photon presence induces a phase precession in the qubit (shown in blue);
- Repeated photon detection is achieved via parity measurements through the readout resonator;
- Activity funded as exploratory R&D within INFN (Qub-IT and QUART&T project);

Comparison of Superconducting Detectors

Detector	STJ	MKID	MMC	TES
Mechanism	Tunneling current proportional to number of quasiparticles	Quasiparticle density influences the resonant frequency of LC circuit	Magnetic flux change in paramagnetic material	Resistance change due to photon heating
ΔE (soft X-ray)	$\sim$ 2 eV	$\sim$ several 10 eV	$\sim$ 1 eV	$\sim$ 1 eV
ΔE (hard X-ray)	Detector material too thin, low absorption	Rarely developed	10 eV @ 60 keV	5 eV @ 17 keV
Advantage	High count rate (10^4/s)	Large array multiplexing	High energy resolution; large energy range; very good linearity	High energy resolution; well-developed multiplex technique
Disadvantage	Low energy resolution; small energy range	Low energy resolution; small energy range	Hard to multiplex	Energy range smaller than MMC

Detector	Microwave	Submillimeter	Far Infrared	Optical	High Energy
	3 cm-3 mm	3 mm - 300 μm	300 μm - 30 μm	2 μm - 300 nm	UV, X-Ray
	10-100 GHz	100 GHz-1 THz	1 THz-10 THz		
	0.04-0.4 meV	0.4-0.04 meV	4-40 meV	few eV	1 eV - 100 keV
Transition Edge Sensor (TES)	😐	😊	😊	😊	😊
Magnetic Microcalorimeters (MMC)		😊		😐	😊
Kinetic Inductance Detector (KID / MKID)	😐	😊	😊	😊	
Superconducting Nanowire SP Detector (SNSPD)			😐	😊	
Hot-Electron Bolometer (HEB)			😊		
Cold-Electron Bolometer (CEB)		😊			
Superconductor–Insulator–Superconductor (SIS)		😊			
Travelling-Wave Parametric Amplifier (TWPA)	😊	😐			
Josephson Parametric Amplifier (JPA)	😊				

Mission: Achieve orders-of-magnitude improvements in the sensitivity of high-TRL superconducting sensor technologies, enabling breakthroughs across a broad range of fundamental physics experiments.

In general, following suggestions from Stafford Withington (former WP3 coordinator):

- **Identify synergies:** Map out the most promising collaborations within and beyond DRD5 to align scientific goals with the most suitable technologies, accelerate TRL advancement, and enable science-grade experiments.
- **Connect communities:** Unite currently separate groups inside and outside DRD5 to share expertise and drive progress in quantum-enhanced experimentation.
- **Explore hybrid approaches:** Develop and assess compatible technologies for realizing hybrid sensors, looking toward a 10–20 year horizon.
- **Shape the ecosystem:** Engage policymakers and funding agencies to establish major R&D programs, instrument-construction efforts, and shared infrastructure—supported by clear evidence of scientific impact.

What Can WP3 of DRD5 Actually Do?

- **Host** a series of web-based seminars, discussions, and workshops focused on targeted technical and scientific challenges;
- **Form** small, focused study groups to provide expert analyses of up to five key challenges—producing white papers or full research publications as sub–work packages;
- **Invite** overview talks from leading experts outside our immediate community to broaden perspectives and foster cross-disciplinary collaboration;
- **Support** training and skills development for practitioners—PhD students, early-career experimentalists, and engineers (electronics, cryogenics, systems) from outside the quantum technologies domain;

- A good example is the sub–work package on the development of SNSPDs for charged particle, initiated in parallel with development of the CERN Test Beam Platform for Quantum Technologies (indico.cern.ch/event/1580512)
- Recent COST Action submitted through WP6 coordination represents a strong example of networking and next-generation education across EU groups;