A CRYOGENIC MUON VETO FOR SUPERCONDUCTING QUANTUM BITS

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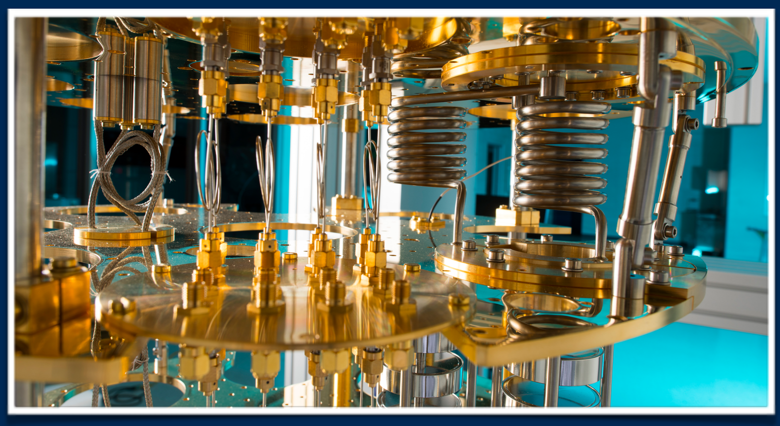
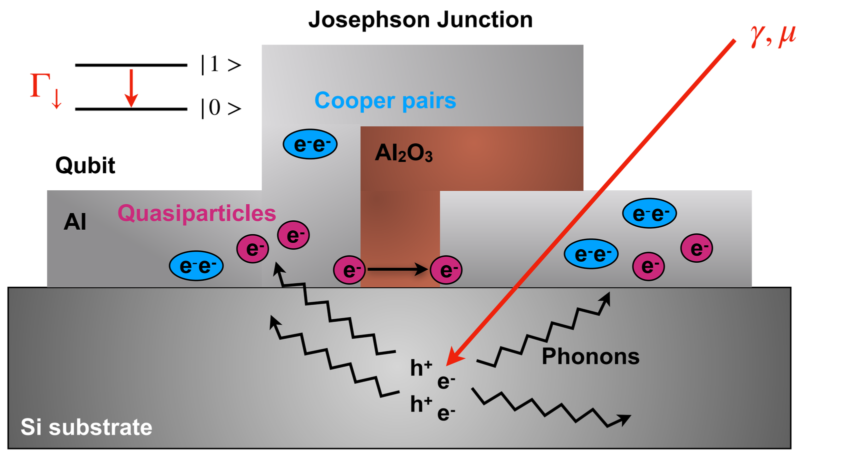


MOTIVATION

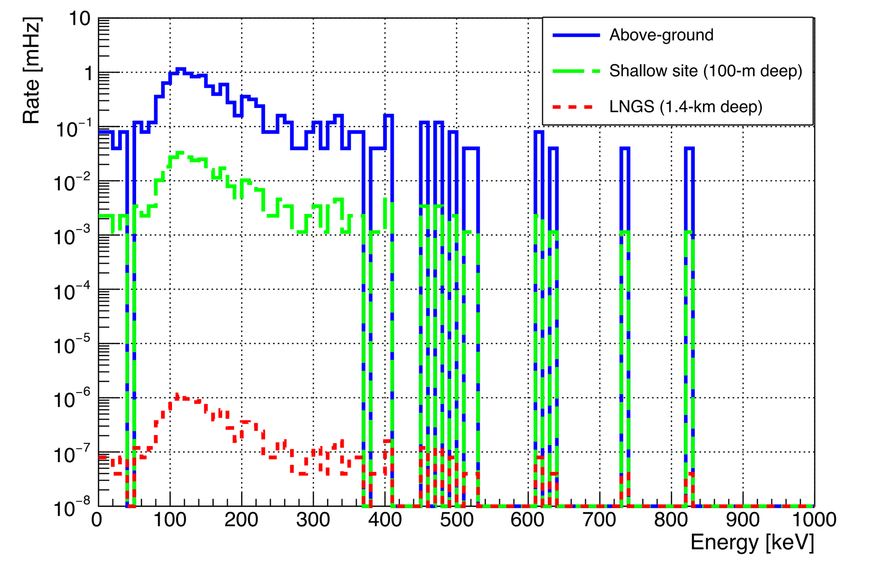
- **Radioactivity** and **cosmic rays** affect the performances of superconducting quantum circuits;
  [Cardani et al., *Nature Communications* (2021)]
- Absorption of **cosmic-ray muons** and **high-energy gamma rays** in the **qubit substrate** produces **correlated errors**, severely **limiting quantum error correction** algorithms;
  [Wilen et al., *Nature* (2021), McEwen et al., *Nature Physics* (2022)]
- The **major sources of ionizing radiation** in a typical qubit chip (~1 cm² surface area) operated **above-ground** are:
  1) Environmental gammas (~20 mHz); ⟶ Can be **significantly reduced** by using **lead shields** (<< 1 mHz).
  2) Cosmic-ray muons (~10 mHz). ⟶ Shallow underground sites offer effective attenuation factors (from 2 to 35 for depths between 10 and 100 m), but muons can be **drastically suppressed** only by operating superconducting qubits in **deep underground labs.**

[Cardani et al., *Eur. Phys. J. C* (2023), Bertoldo et al., *arXiv:2303.04938* (2023)]

We need a strategy to operate superconducting qubits in above-ground facilities.



MUON RATE EXPECTED FOR VARIOUS FACILITIES

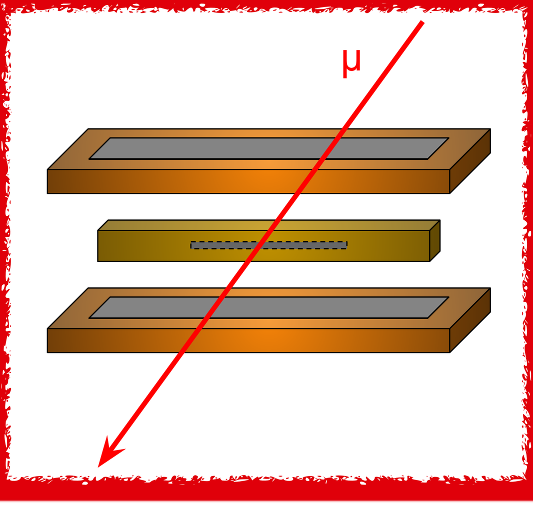


THE IDEA

WHAT:
Develop a new class of quantum processors equipped with a **muon veto.**

WHY:
Protect quantum computers based on superconductors from the detrimental effects of atmospheric muons.

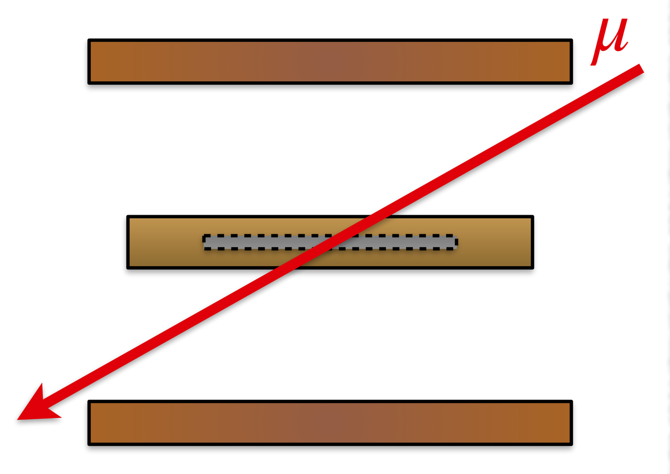
HOW:
Tagging muons (instead of suppressing them) to identify and reject/ correct operations done while these particles are crossing the chip.



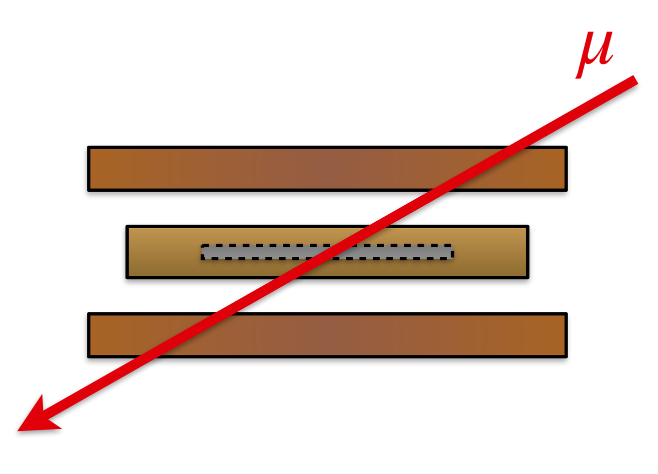
- Qubit chip enclosed within two identical particle detectors (**muon veto system**).
- A muon is identified by the presence of a signal in both the particle detectors within a certain time interval (**AND condition**).

THE MUON VETO DETECTOR - REQUIREMENTS

1) High **(geometrical) veto efficiency**
   - The probability to successfully identify a muon when passing through the quantum device has to be **at least 90%**;
2) Low **dead-time**
   - "Idle" of the muon veto detector as a result of an interaction has to be **less than 1%.**



Low efficiency, low dead-time

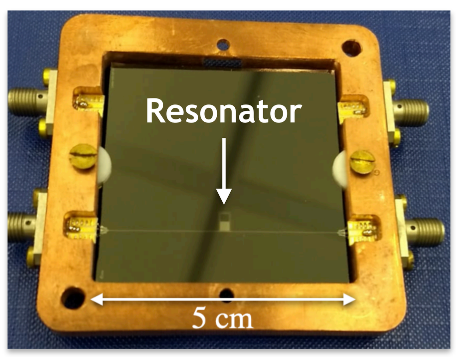


High efficiency, low dead-time

The muon veto detector must be as close as possible to the chip and must work at the operation temperature of qubits (tens of mK).

THE MUON VETO DETECTOR - TECHNOLOGY

Ideal device already developed within the CALDER (Cryogenic wide Area Light detectors with Excellent Resolution) project (2014-2020).



[N. Casali et al., Eur. Phys. J. C 81, 636, (2021)]

CALDER prototype:

- 5x5 cm², 650-μm thick **silicon substrate**, sampled by a microwave resonator made of a three-layer Al-Ti-Al (**KID, Kinetic Inductance Detector**);
- 6.4x6.4 cm², 4-mm thick copper holder.

We will use **two CALDER-like prototypes** to implement the muon veto: **KID** deposited on a **4.5x4.5 cm², 650-μm thick silicon substrate.**

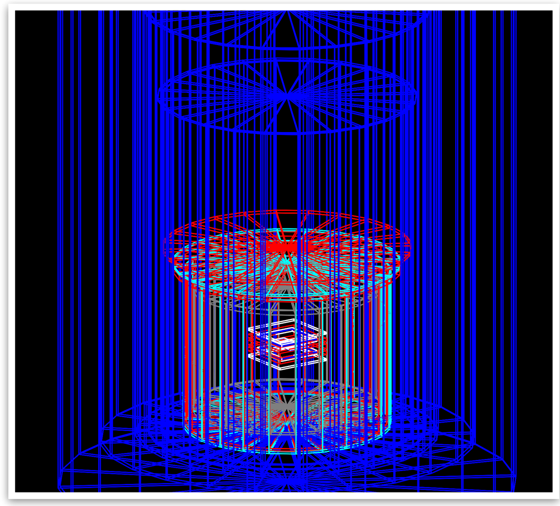
- Production by STAR Cryoelectronics foreseen by the end of September 2023.

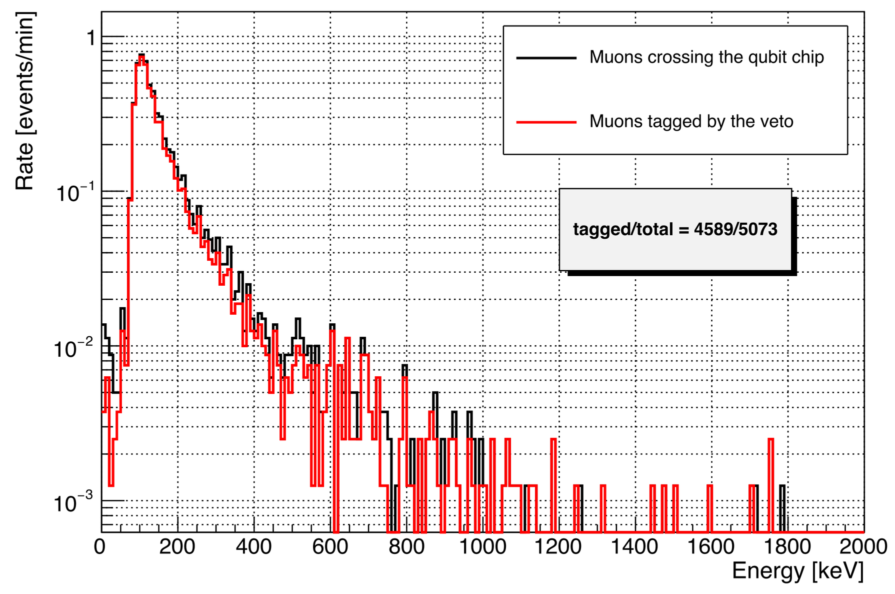
PROS:

- Compatible with cryogenic operations;
- Ease of integration, both in terms of hardware and readout;
- High (geometrical) efficiency thanks to the wide surface (>20 cm²);
- Fast time development (<1 ms) ensures negligible dead-time;
- Extremely high detection efficiency (~1 for muons).

MONTE CARLO SIMULATION

We developed a **Geant4-based** Monte Carlo (MC) simulation to study the muon veto detector performance and optimize its design.



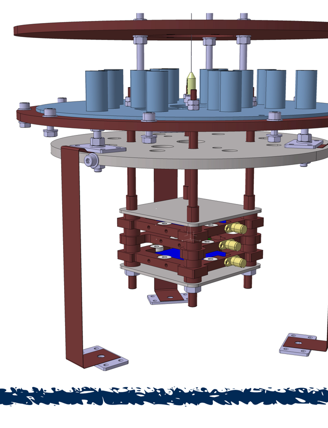


- Two 4.5x4.5 cm² , 650-μm thick silicon substrates with copper holders (muon veto system);
- One 4x2 cm², 325-μm thick silicon chip into a 5-mm thick copper box.

RESULTS:
- Veto efficiency: ~90%;
- Gamma-induced dead-time: ~0.02%.

FUTURE PLANS

1) **Optimization** and **test** of a **cryogenic muon veto** that can be easily integrated with superconducting quantum devices;
2) **Commissioning** of a high performing **superconducting quantum chip** (lifetime T1 >100 μs) **equipped with muon veto**;
3) **Measurement** of the **qubits lifetime** and **study** of **correlated errors** with and without the use of the muon veto system.



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