Mitigation of cosmic rays-induced errors in superconducting quantum processors

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***Abstract*—Environmental radioactivity and cosmic-rays have recently been identified as a source of decoherence in superconducting quantum bits (qubits). In particular, the absorption of cosmic-ray muons and gamma rays emitted by naturally occurring radioactive isotopes in the qubit substrate leads to correlated errors in superconducting quantum processors, posing significant challenges to quantum error correction. To enable quantum computing to scale, it is therefore necessary the development of mitigation strategies to prevent, or keep under control, error bursts due to particle impacts in the chip. While most environmental radioactive sources can be effectively suppressed using dedicated shielding, cosmic-ray muons, with their high penetration capability, can only be mitigated by moving the entire facility in a deep underground laboratory.**

This work explores the potential for developing a novel class of quantum processors equipped with an active veto system to protect superconducting-based quantum computers from the detrimental effects of atmospheric muons. Such a device would enable the identification of an atmospheric muon interaction within the processor and veto all operations performed during the occurrence of such an interaction. By demonstrating high detection efficiency and negligible dead time, we aim to establish that the future of quantum processors can be envisioned in above-ground facilities.

***Index Terms*—radioactivity, cosmic-rays, superconducting qubits**

I. Introduction

Macroscopic superconducting circuits are one of the most promising platforms for building fault-tolerant quantum processors. They offer a number of advantages, such as ease in design, fabrication, and operation, high fidelity, and fast gate times. Moreover, an increasing number of companies and research institutes have demonstrated the ability to inter-couple tens to hundreds of qubits using this technology [1]–[4], and this number is likely to grow rapidly in the coming years.

Currently, one of the main challenges is increasing the coherence time, i.e., the time in which the processor retains its quantum behaviour and can effectively process information. This value should be increased from tens of microseconds to hundreds of milliseconds or, in more ambitious programs, to seconds. Even though, today, environmental radioactivity is not the primary source of decoherence in superconducting qubits, there are evidences that it can hinder the achievement of a long coherence time [5]. Atmospheric muons, as well as the radioactivity of the laboratory environment, can release ionizing energy in the substrate, spoiling the performance of the qubits throughout the device [6], [7].

While environmental radioactivity can be mitigated by using dedicated shielding and radio-pure materials in the proximity of the qubits, benefiting from the experience of the scientific community developing low-radioactivity detectors for Particle Physics, cosmic-ray muons cannot be easily suppressed. Interesting studies have shown that shallow underground sites can provide good attenuation factors, ranging from 2 to a factor of 35 for depths of 10 meters and 100 meters, respectively [8]. In addition, it has been demonstrated in [8] using a specifically-built cosmic muon detector that, by orienting chips towards the horizon, the muon flux above-ground can be reduced by a factor of 1.6. However, to date, the only method to significantly reduce the muon flux is to operate quantum processors in deep underground laboratories [9], [10].

In this paper, we propose a novel strategy to protect quantum

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computers based on superconductors from the detrimental effects of atmospheric muons. We start introducing the different sources of radioactivity and their connection with superconducting qubits (Sec. II), with particular attention to cosmic-ray muons (Sec. III). In Sec. IV we describe our strategy for mitigating the catastrophic effects caused by muons interactions in the qubit substrate, focusing on the muon veto concept, its design, and the technology that will be used to build it. Finally, we comment on the expected performance of the muon veto in Sec. V.

II. Radioactivity and Superconducting Qubits

Radioactivity is a natural and omnipresent component of the Universe. It can have various origins and, in the field of low-radioactivity detectors, it is common to distinguish between "far" and "close" sources of radioactivity. The primary source of far radioactivity are radioactive decays of primordial radionuclides present in the laboratory environment, such as ^{40}K, ^{238}U, and ^{232}Th, which mainly produce γ-rays. In addition, there are cosmic rays and cosmic rays-induced processes, which produce mostly muons and neutrons. On the other hand, close sources of radioactivity consist of γ-rays emitted from primordial and cosmogenic radionuclides in materials that cannot be placed far away from the quantum device, such as cables, electronic components, and so on. As they are in proximity to the device or part of the device itself, close sources cannot be shielded. To suppress them, we need to select radio-pure materials and adopt strict protocols for the cleaning and handling of the various components constituting the setup. This is necessary to prevent the introduction of radioactive impurities on their surfaces.

Cosmic rays, as well as γ-rays emitted by naturally occurring radioactive isotopes in the laboratory and sample materials, can interact with the qubit chip, releasing energy of the order of hundreds of keV in the substrate [6], [11]. These energy deposits produce a sizable fraction of free charges, which diffuse and create phonons. Phonons can be absorbed by the superconductor, breaking Cooper pairs into dissipative quasiparticles, which propagate throughout the chip strongly suppressing coherence in superconducting qubits [12]–[14]. Since phonons have a large spatial footprint, they can affect multiple qubits on the same chip, leading to correlated errors [6], [7]. This severely undermines quantum error correction algorithms, which rely on the assumption that errors across qubits belonging to the same matrix are uncorrelated in space and time. Furthermore, recent studies indicate the existence of an interaction between ionizing radiation and the dominant qubit loss mechanism, i.e., two-level systems (TLSs) [15]–[18]. According to [19], radiation impacts can cause frequency jumps in multiple TLSs, inducing fluctuations in the qubit lifetime and limiting the stability of the device.

Nowadays, an increasing number of strategies have been proposed to mitigate the effects of radioactivity in superconducting qubits. The "easiest" approach consists in the suppression of all sources of radioactivity using methods well-established in Particle Physics [9], [10]. Additionally, there are solutions that require modifications to the qubit or chip design, such as the development of "traps" surrounding the qubit to protect it from travelling phonons [20], [21]; the deployment of qubit arrays on decoupled chips to reduce correlated errors [22]; and the implementation of an assisted fault mitigation through the use of sensors located near physical qubits [23].

III. The Case of Cosmic-Ray Muons

Muons are very energetic and highly penetrating ionizing particles, produced by the interaction of a primary cosmic ray in the upper atmosphere. They travel on average tens of kilometers, and arrive at sea level with a typical flux of about 1μ/cm^2/min [24]. In deep underground laboratories, the muon flux drops almost exponentially with the thickness of the rock overburden above the laboratory, resulting in a suppression of the muon flux by several orders of magnitude [25].

Concerning above-ground facilities, in [11], we determined that the rate of impacts in a typical qubit chip ($\sim$1 cm^2 325 μm-thick silicon wafer) is dominated by γ-rays originating from the natural radioactivity of the laboratory, contributing to an overall rate of approximately 20 mHz. This rate can be reduced by up to two orders of magnitude using lead shields. The second most significant contribution comes from muons, with a rate of about 10 mHz. Despite their lower rate, cosmic-ray muons are more troubling than gamma particles, as they can produce long tracks that potentially affect multiple qubits on the same chip [6].

Today, the most effective approach to significantly reduce the detrimental effect of cosmic-ray muons on superconducting qubits is to operate them in deep underground sites. As an example, the cryogenic facility at the Laboratori Nazionali del Gran Sasso (LNGS), in Italy, which is covered by a rock overburden of 1.4 km, provides a reduction factor of about 1 million for the muon flux [26], [27]. Nonetheless, as shown in [8], effective suppression factors can also be achieved in shallower sites (up to a factor of 35 for depths of 100 meter). Fig. 1, illustrates the rate of muon impacts as a function of the energy that they deposit in a typical qubit chip ($\sim$1 cm^2 surface area), obtained through a Geant4-based Monte Carlo simulation. The plot differentiates the expected results for above-ground laboratories, a shallow site (100-meter depth), and the deep underground LNGS facility (1.4-kilometers depth).

It is worth noting that other research groups are proposing alternative methods to mitigate the devastating effects of muons at the chip level by suggesting new distributed error correction schemes [28].

IV. The Muon Veto Detector

An alternative strategy may consist of tagging muons (instead of suppressing them) to identify and reject operations performed while these particles are crossing the chip. If successful, this approach would enable the operation of quantum processors even in above-ground facilities. Muon tagging, along with the rejection of their associated signals, is the main

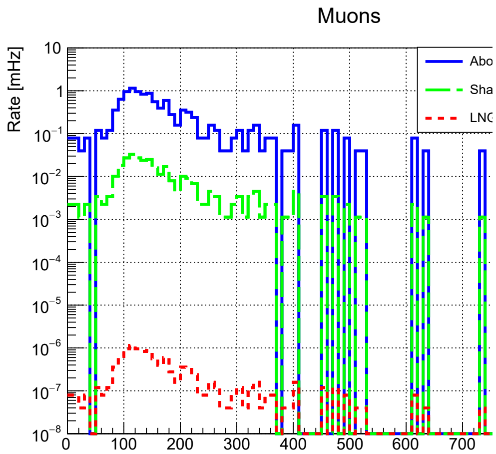

Fig. 1. Rate of impacts due to cosmic-ray muons repor the energy that they deposit in a silicon chip with an appr of 1 square centimeter. These results were obtained thro Monte Carlo simulation. The different lines represent the in: a typical above-ground facility (blue solid line); a 1 site (green dashed line); the 1.4-km deep LNGS undergr line).

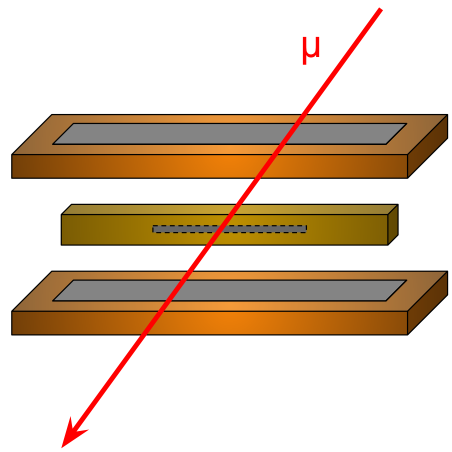

Fig. 2. Schematic conceptual design of the muon veto system. The quantum processor is enclosed between two identical particle detectors, and the passage of a muon will be identified by the presence of a signal in both the particle detectors within a specific time interval.

task of the muon veto detector, commonly used in Particle Physics experiments [29].

A. Concept

To reduce the error rate due to muon interactions in the chip and its surroundings, we propose to perform active muon tagging by means of a muon veto detector. Fig. 2 shows a schematic conceptual design of the muon veto detector to illustrate its working principle. In this setup, the quantum processor is enclosed between two identical particle detectors, which constitute the muon veto system. A muon passing through the quantum processor chip will be identified by the presence of a signal in both the particle detectors within a certain time interval (coincidence window).

Consequently, the muon veto system would enable fast and proper identification of a muon interaction within the chip, allowing all calculations performed during the period of time in which the quantum processor may have been subject to simultaneous errors to be discarded. The duration of this time interval, known as *veto gate*, depends on the timescale associated with the dynamics of a particle impact in the chip. In [7], it was shown that high error rates resulting from a high-energy interaction in a Google Sycamore processor are initially confined to a small number of qubits but gradually spread throughout the device over the course of the event. The number of errors increases rapidly in a timescale of tens of microseconds, and then returns to a baseline value following an exponential decay with a time constant of about 25 ms. This number may vary depending on the specific characteristics of the processor, particularly its architecture, making it a crucial factor to take into account when designing the muon veto system.

B. Design

There are two important specifications that should be kept in mind when designing a muon veto:

- *(Geometrical) veto efficiency*, namely the probability to successfully detect a muon when passing through the device. It depends on the geometry of the setup and has to be as high as possible (at least 90%);
- *Dead-time*, i.e., the interval of time when the muon veto detector is "idle" as a result of an interaction. It should be kept low ($< 1\%$).

In order to meet these requirements, we need to make a compromise between the surface area of the muon veto detector and its distance from the qubit chip. In particular, the surface area should be wide enough to ensure high geometrical efficiency, but not so wide as to significantly increase the interaction rate, and consequently, the dead-time. The drawback of an efficient muon veto placed outside the dilution refrigerator and operated above-ground is that, due to its dimensions, it would feature a trigger rate as high as hundreds of Hz [29]. Hence, we plan to use a more sophisticated approach, building a cryogenic muon veto to be placed extremely close to the chip. This solution would guarantee a similar efficiency by reducing the detector's size. As a result, the trigger rate, and consequently, the associated dead-time, would decrease. In addition, since the rate of impacts in typical qubit chips due to environmental radioactivity is at the level of 20-30 mHz (to be compared with 10 mHz from muons), their mitigation is mandatory to ensure such a low dead-time. To this aim, we will design a heavy shielding made of lead and/or copper to suppress all sources of environmental radioactivity other than muons, that cannot be shielded, to a negligible level (below 1 mHz).

C. Technology

To ensure a minimal amount of dead-time, the muon veto detector must work at the same operation temperature of qubits (tens of mK), with high efficiency and fast signal response. Furthermore, its readout should be easy to integrate with the one of qubits.

The ideal device to implement such a muon veto has already been developed in the field of Particle Physics, within the CALDER project [30]. CALDER (Cryogenic wide Area Light Detectors with Excellent Resolution, 2014-2020), aimed at designing wide-area ($5\times5\,\mathrm{cm}^2$) photon detectors for cryogenic applications [31]. The last prototype of this project [32] consisted of a $5\times5\,\mathrm{cm}^2$, 650-μm thick silicon substrate, sampled by a microwave resonator made of a three-layer aluminum-titanium-aluminum (Al 14 nm / Ti 33 nm / Al 30 nm [33]). The working principle of this detector is rather simple: an energy deposit in the silicon substrate produces phonons; phonons travel through the substrate until they are absorbed by the resonator, breaking Cooper pairs into quasiparticles; and thus, the microwave signal transmitted past the device changes. By monitoring the changes in frequency and phase of the transmitted signal, it is possible to reconstruct the interaction with exceptional energy and time resolutions. The final CALDER prototype achieved a rise-time of 120 μs and a noise resolution of $\sim$90 eV RMS (that, without a particularly aggressive trigger algorithm, can be translated into an energy threshold of about 500 eV). Moreover, such performance remained stable within the temperature range of 10-100 mK.

We thus propose to exploit two CALDER-like prototypes to implement the muon veto. This choice is particularly suitable for our application, and brings the following advantages:

- The chosen technology is compatible with cryogenic operations and remains stable over a wide temperature range, thus not demanding for specific thermal stabilization;
- The choice of a sensor based on microwave resonators allows the sharing of entire electronics and readout with superconducting qubits. Both systems can be operated using the same RF cables, circulators, insulators, filters, cold amplifiers, etc. Furthermore, the natural multiplexing of microwave resonators allows the coupling of the two detectors used for the muon veto to a single readout line, reducing the need for major modifications to the existing cryogenic apparatus;
- The wide surface area of over 20 cm^2 guarantees high geometrical efficiency;
- The fast time development ($<$1 msec) ensures a negligible dead-time. More sophisticated analysis algorithms could also exploit the rise-time of the pulses alone (rather than the entire pulse) to define a coincidence in the muon veto. The fast rise-time of microwave resonators (120 μs for the CALDER prototype) allows for further reduction of the dead-time if required.
- A muon passing through this device would release a minimum energy of tens of keV, well above the energy threshold of 0.5 keV, leading to a detection efficiency of $\sim$1.

V. Expected performance

The aim of our project is to build and test a cryogenic veto for cosmic-ray muons, that can be easily integrated with quantum processors to reduce correlated errors and prevent chip-wide failures. We will demonstrate the potential of this technology using a quantum device provided by the Superconducting Quantum Materials and Systems (SQMS) Center, which is one of the five Department of Energy (DOE) National Quantum Information Science Research Centers focused on advancing quantum science and technology. However, it is important to note that the simple architecture and readout of the muon veto system will allow us to couple it to any processor based on superconducting circuits as well.

Our prototype is expected to have a lifetime ranging from tens to hundreds of microseconds and will consist of multiple qubits (at least four). A long lifetime will ensure that other decoherence effects remain under control, and the presence of multiple qubits will allow us to investigate any (detrimental) correlated errors induced by atmospheric muons.

Based on our design for the muon veto detector, we expect to achieve a (geometrical) efficiency greater than 90% and a dead-time significantly lower than 1%. Our goal is to demonstrate that, unlike what has been observed in the past, moving the quantum device to the deep underground Gran Sasso National Laboratory does not further improve the performance guaranteed by the muon veto in a shielded facility above-ground.

VI. Conclusions

Radioactivity can undermine the achievement of a long coherence time in superconducting qubits. Specifically, high-energy interactions in the chip produce bursts of quasiparticles that spread throughout the device, causing correlated errors that spoil the performance of quantum processors. Several tech companies are therefore starting to worry about the detrimental effects of cosmic-ray muons which, producing long tracks, can potentially affect multiple qubits belonging to the same chip. In contrast to γ-rays, these highly penetrating particles cannot be suppressed simply by using copper or lead shields. As a result, the only significant improvements in the performance of quantum devices to date have been obtained by moving them to deep underground laboratories.

Instead of attempting to suppress muons, we propose a novel device consisting of a quantum processor equipped with a muon veto, which will allow us to identify a muon interaction in the chip and discard all the operations performed during such an interaction. The muon veto system, constituted by two kinetic inductance detectors, is designed to operate at cryogenic temperatures, ensuring easy integration with quantum processors based on superconducting circuits. We will test our prototype using a quantum device provided by the SQMS Center. By demonstrating a veto (geometrical) efficiency grater than 90%, and a negligible dead-time ($<1\%$), we expect to reduce correlated errors by at least an order of magnitude, consequently improving both coherence and frequency stability of the device. If successful, this technology will enable the operation of quantum processors even in above-ground facilities.

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