Quantum Device Radiation Reliability: from Testing to Algorithmic Solutions

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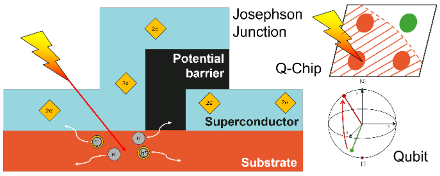
INTRODUCTION

Quantum Computing

Quantum Computing (QC) is the most promising solution to the imminent bound to the miniaturisation of classical chips. QC exploits quantum properties of matter (superposition and entanglement) as a computing resource rather than suffering them as an interference. Information is stored in quantum bits (qubits) being the analogous of the classical bits.
Many different physical implementations of qubits exist. Among all, **superconducting qubits** are the most promising technology. They rely on the ability of certain metals to conduct current without resistance when cooled down below their critical temperature (Tc) and on the Josephson effect. The core part of a superconducting qubit is the Josephson junction.

Radiation Reliability Problem

The bottleneck for large-scale adoption of QC is represented by **reliability problems**. Exploiting quantum mechanics for computational advantage inherently introduces the challenge of quantum state decoherence, either intrinsic or due to external agents, in particular **radiation**.



Main shreds of evidence related to radiation-induced events on quantum devices:

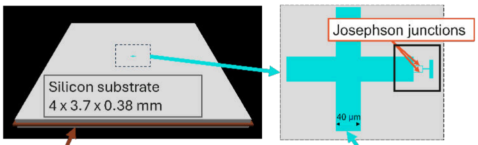
- faults persist up to hundreds of seconds (vs the fast SEU in classical electronics) [1, 2, 3, 4, 5];
- faults spread logically and physically through the devices and corrupt multiple qubits [6, 7, 8, 9];
- there is no activation energy to alter the state of a qubit [5, 10, 11].

Aim

Characterise the radiation response of quantum devices through simulations and beam experiments to develop physical mitigation strategies and computational error correction solutions.

MONTE CARLO SIMULATIONS

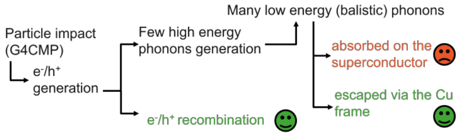
Employing Geant4 and G4CMP, we characterise both the interaction of particles on the device and the propagation of secondaries within the substrate [12]. We consider the deposition of energy directly on the superconductor. We perform 17 different physical simulations: **neutrons** (1, 10, 100 MeV), muons (0.1, 1, 10 GeV), gamma rays (0.1, 1, 2 MeV) and **alpha particles** (1, 3, 5, 7, 10 MeV).



Copper enclosure. Hypotetical support for the substrate and escape path for phonons

Aluminum Xmon qubit: the large cross shape is capacitively coupled to other aluminium parts. Thickness 380nm

We employ $QGSP\_BIC\_EM$ physics list that resolves ionising, indirect ionising (for neutral particles) and non-ionising processes. G4CMP physics list allows for the ultralow temperature ($T \ll 1K$) events such as e^-/h^+ generation, phonons production, phonons downconversion and Luke phonon emission.


Particle impact (G4CMP)
e⁻/h⁺ generation
Few high energy phonons generation
Many low energy (balistic) phonons
absorbed on the superconductor
escaped via the Cu frame
e⁻/h⁺ recombination

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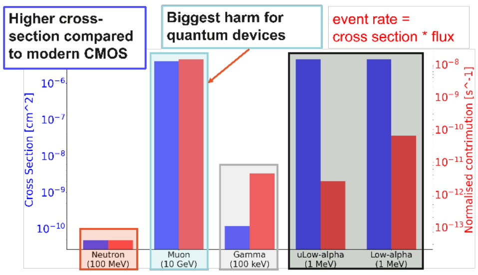
Different Particles Contribution

We identify which kind of particle is more likely to corrupt a qubit. We measure the cross-section of the worst-case event for each particle species and then normalise the contribution according to the respective flux at sea level.


Higher cross-section compared to modern CMOS

Biggest harm for quantum devices

event rate = cross section * flux

Neutrons, biggest concern for CMOS, represent a **small** contribution

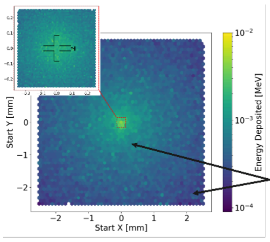
Muons are **extremely interacting** and they are **really abundant**

Gamma rays, despite being **less interacting,** are the **most abundant**

Alpha particles contribution even from ultra-low alpha materials is significant

Energy Propagation

Simulations for 25000 10 GeV positive muons (the most likely cause for qubit errors). We study muon interactions both with the substrate and with the superconductor, and energy propagation within the substrate.

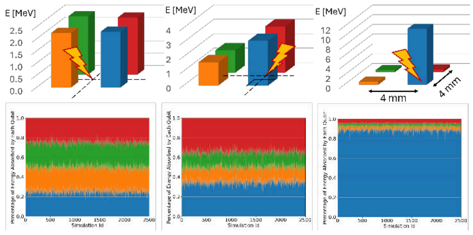


Measure of the particle impact distance on the substrate that can lead to a Cooper-pair breaking absorption by the superconductor

Impacts closer to the qubit have a higher probability to induce faults, but even impacts 2 mm from the qubit can modify the state

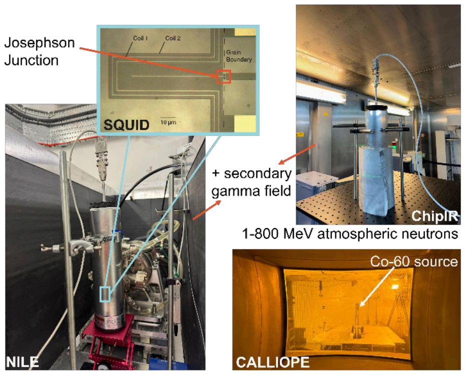
Multi Qubit Corruption

To observe how deposited energy diffuses in the substrate, we consider four equally spaced qubits on the substrate and run three simulations (2500 injection each) employing 100 MeV positive muons injected in three different positions.



BEAM EXPERIMENTS

To understand how a qubit responds to radiation exposure, we study the effect on a **SQUID (Superconducting Quantum Interference Device)**: an analog device that can be controlled at low-level.
We perform experiments with **neutrons** and gamma rays (muons to come) in different facilities:



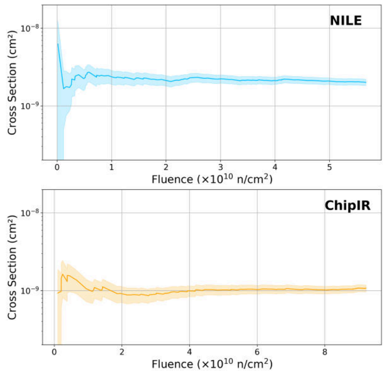
1-800 MeV atmospheric neutrons

14 MeV mono-energetic neutrons

1.25 MeV mono-energetic gammas

Cross Section

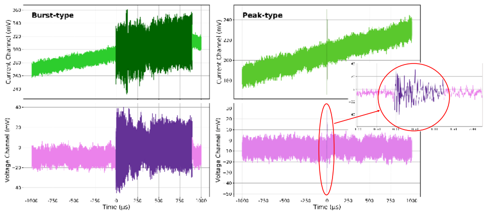
- Compatible observations at NILE and ChipIR, considering the difference of the sources.
- No cumulative effects.
- No events recorded at CALLIOPE.



Fault Identification

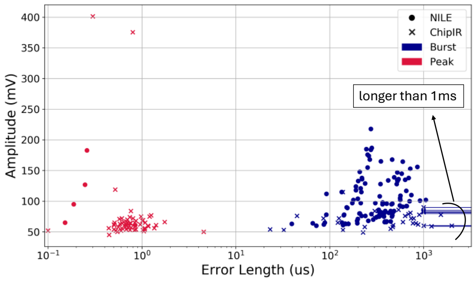
The SQUID is extremely sensitive to external stimuli: background radiation fields and electromagnetic fields. We identify faults by comparing measures with beam off characterisation. Faults

- affect both the voltage and current channel;
- are safely larger than the set trigger.

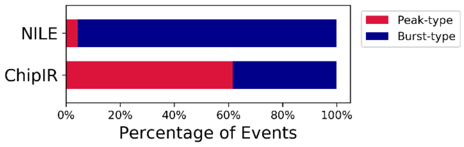


Fault Classification

2 macro-categories can be identified, according to the time lengths of the faults: burst-type [O(100 µs)] and peak-type [O(100 ns)] errors.



Peak type and burst type faults recorded in different facilities show analogous characteristics ⟹ manifestations of the same phenomenon.



Different ratio between peaks and bursts at NILE and ChipIR. Considering that the gamma-to-neutron ratios differ significantly (1:10 at NILE and 1:1 at ChilR), it is likely that peak-type faults faults are induced by gamma rays, while **burst-type faults** are caused by neutrons.

SUMMARY

- Muons are the most harmful particles for quantum devices.
- No safe radius exists. Even energy depositions far from the active unit can affect the qubit state.

- Neutrons affect the output of the SQUID, causing $100\mu s$ long bursts.
- Gamma rays are likely to alter the SQUID output, causing short $(100\ ns)$ spikes.