Paper on americium calibration

BULLKID digest 27/03/2025

Matteo Folcarelli

About the paper

Data

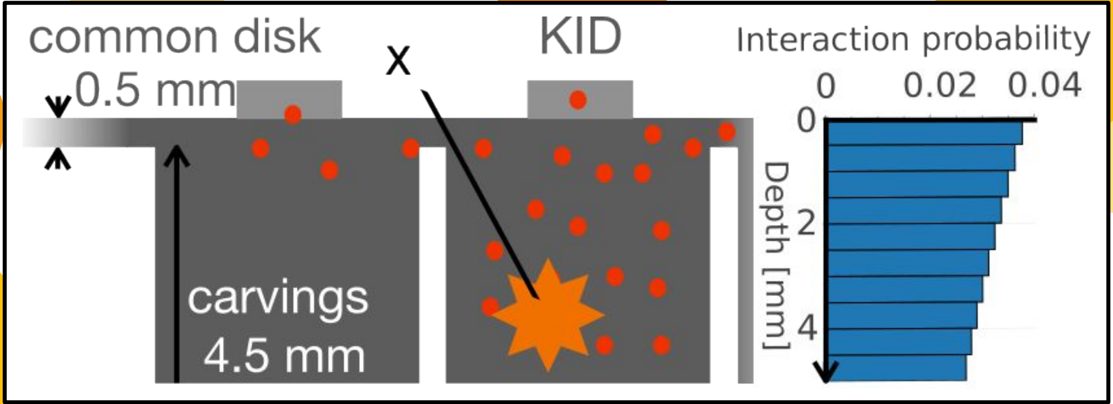
- Long run (36 h) acquisition of the 59.5 keV X-ray of an external americium radioactive source
- They are bulk events, i.e they penetrate deeply in the silicon dice

Aim

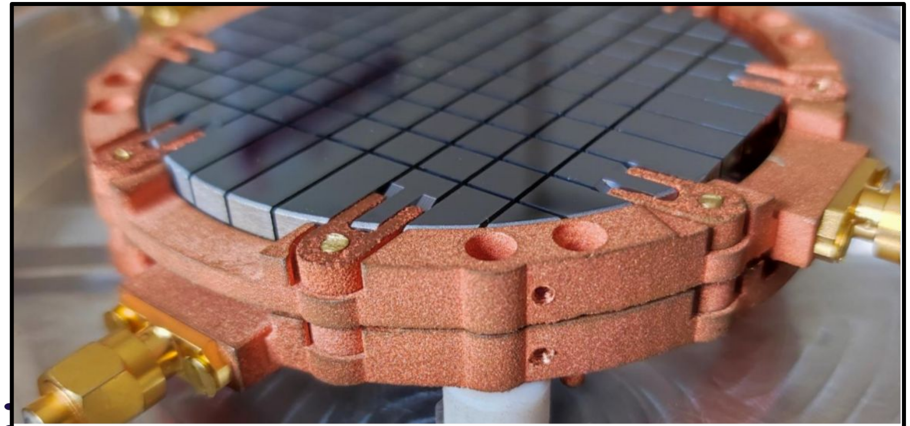
- Validation of the LED calibration for the bulk events of americium
- Probing of positional effects of bulk events trough neighbors analysis

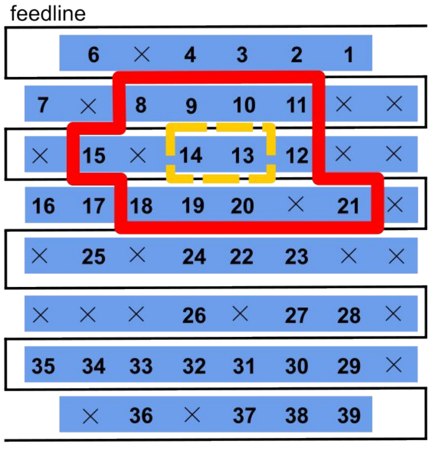
Outline

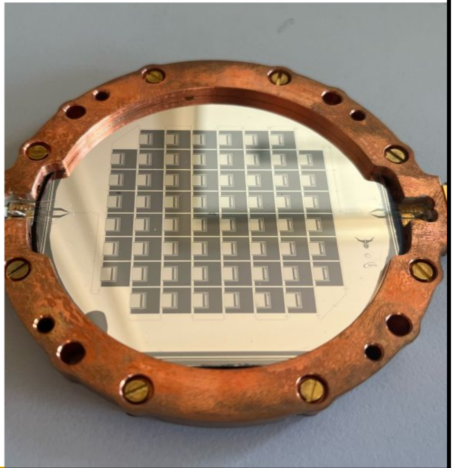
- Experimental setup
- LED calibration and corrections
- Detector stability
- Energy spectra (amplitude on the central dice)
- Neighbor analysis and improvement of the energy resolution
- Conclusions

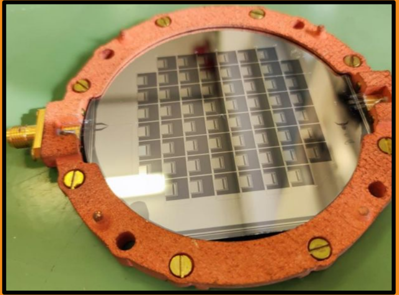


Experimental setup

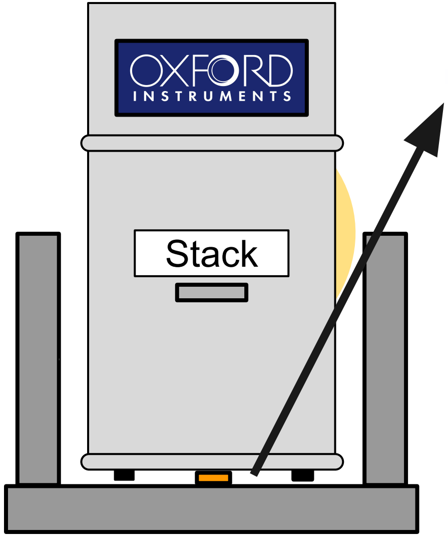


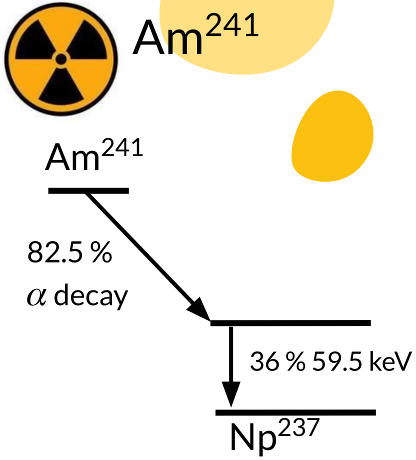






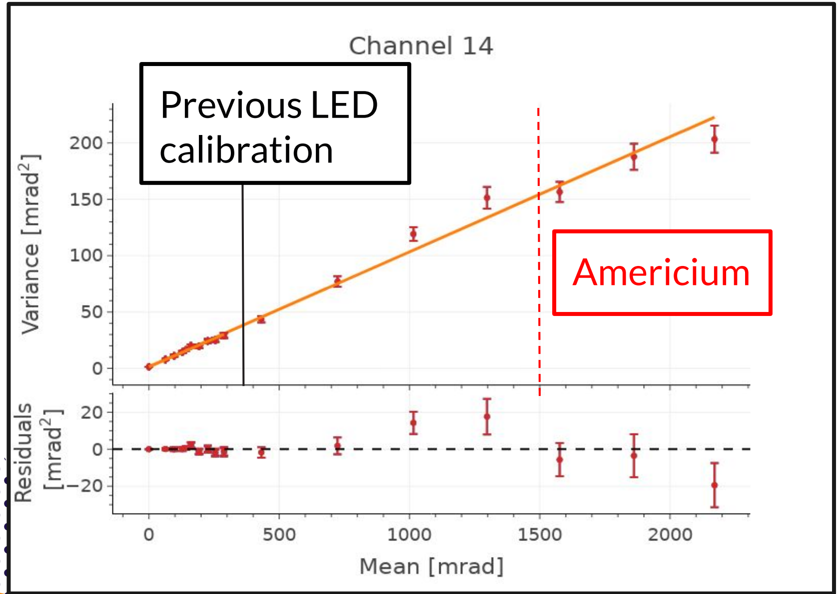
Stack-01: 60nm Al
38 working pixels out of 60
Quality factor (median) 185k

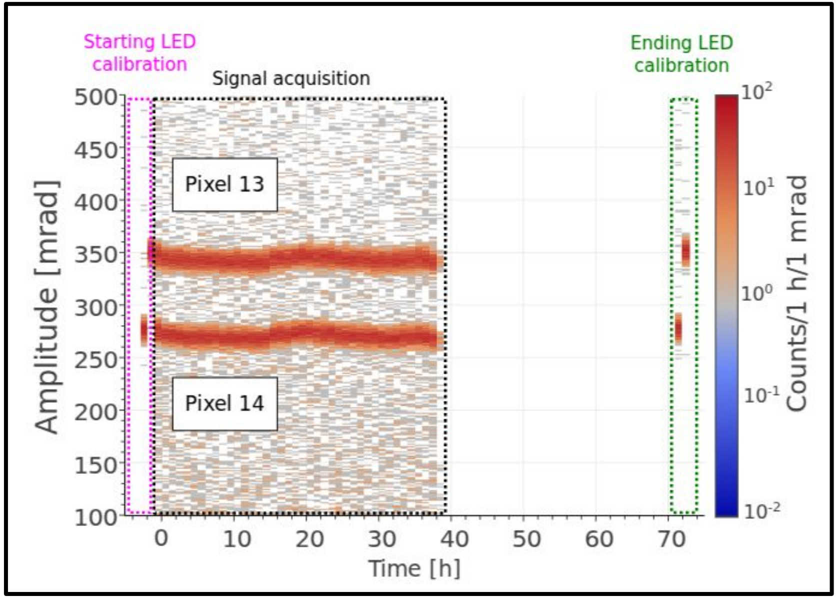




LED calibration and monitoring

At the beginning and at the end of the acquisition, a calibration with LEDs of 400 nm has been performed. During the entire acquisition, LED bursts were periodically sent for detector monitoring

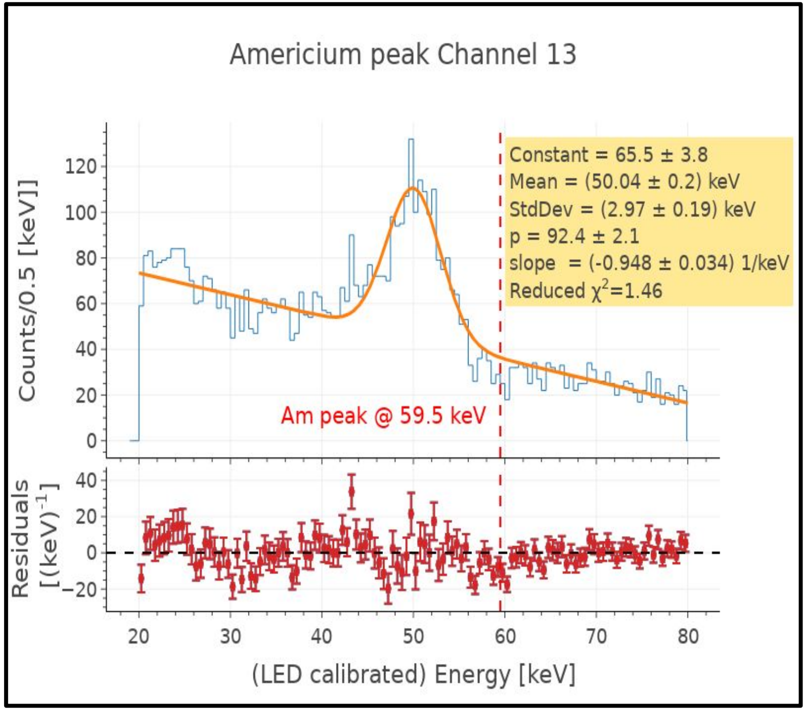


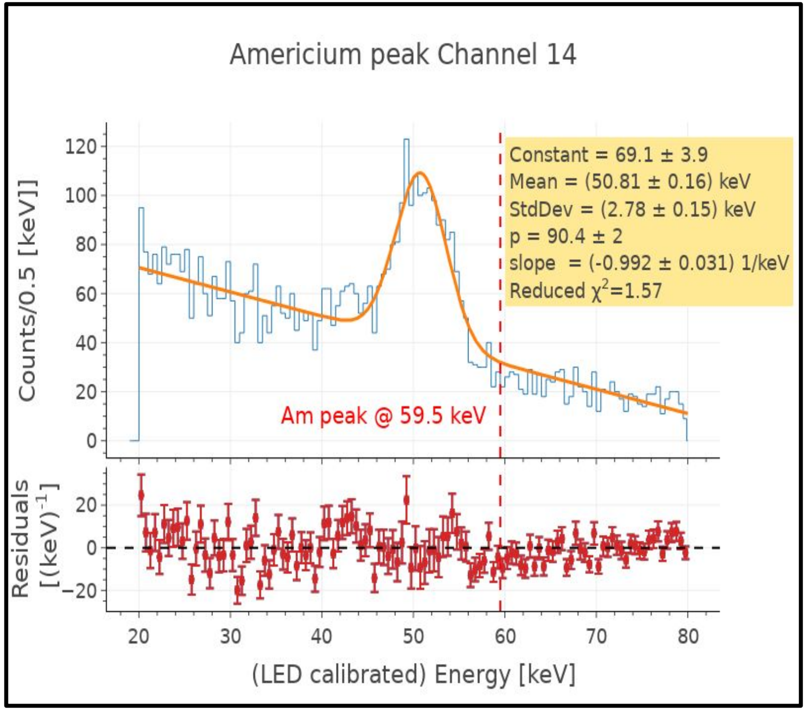


LED calibration considers the entire energy range and not only the low energy range

Detector stable for the entire data acquisition

Energy spectra





We are able to reconstruct the americium peak with a **mean shifted by -16%** with respect to the theoretically expected value and with a **resolution of 6%**

Neighbors analysis: leakage

Possible positional effects related to the bulk events of americium can be investigate by studying the phonon leakage from the central die to the neighboring dice.

It is evaluated as the ratio between the amplitudes in the two dice
(corrected for the quality factor of the resonators)

$$\boxed{R_n = \frac{E_n}{E_m}} = \boxed{\frac{A_n \cdot \left.\frac{dE}{d\phi}\right|_n}{A_m \cdot \left.\frac{dE}{d\phi}\right|_m}} = \boxed{\frac{A_n}{A_m} \cdot \frac{Q_m}{Q_n}}$$

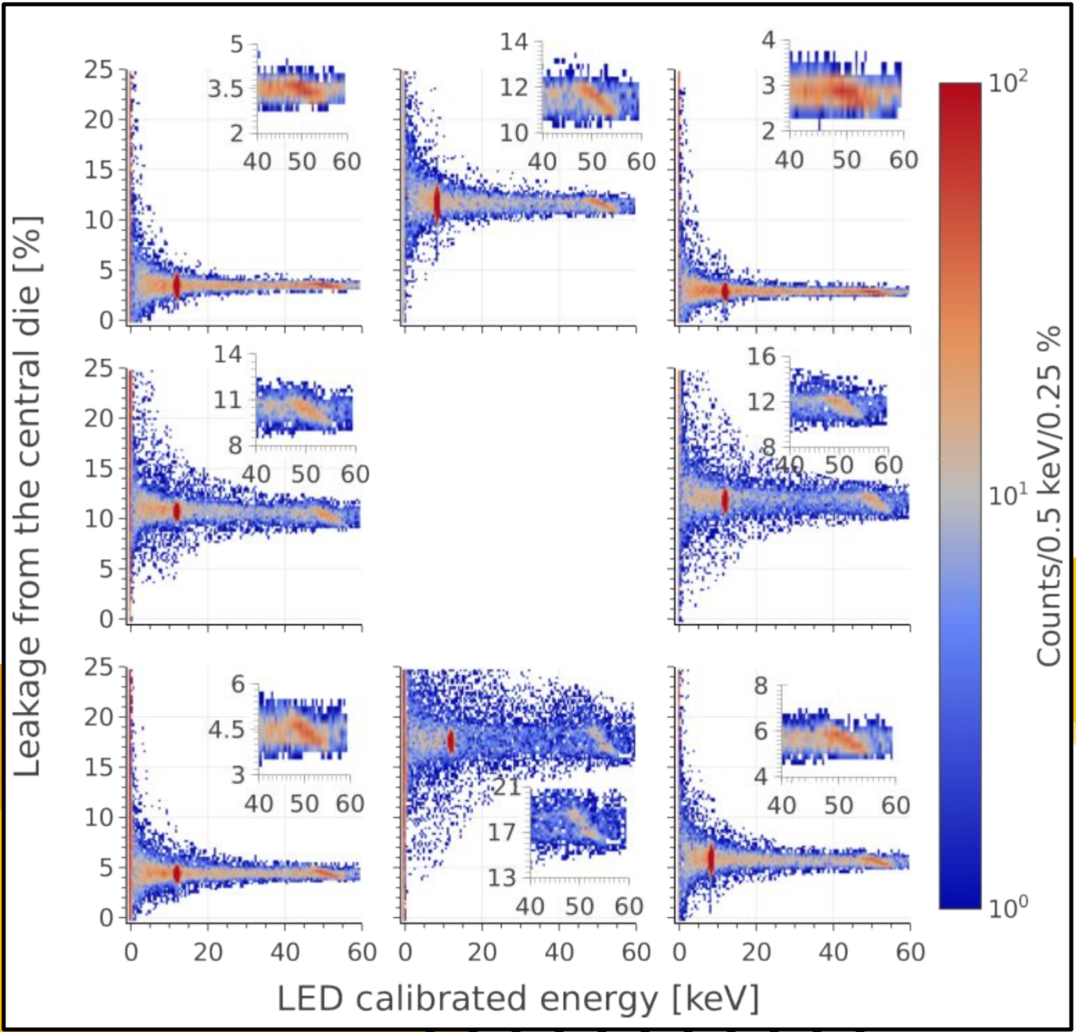
Definition

Evaluation

$$E = A \cdot \frac{dE}{d\phi}$$

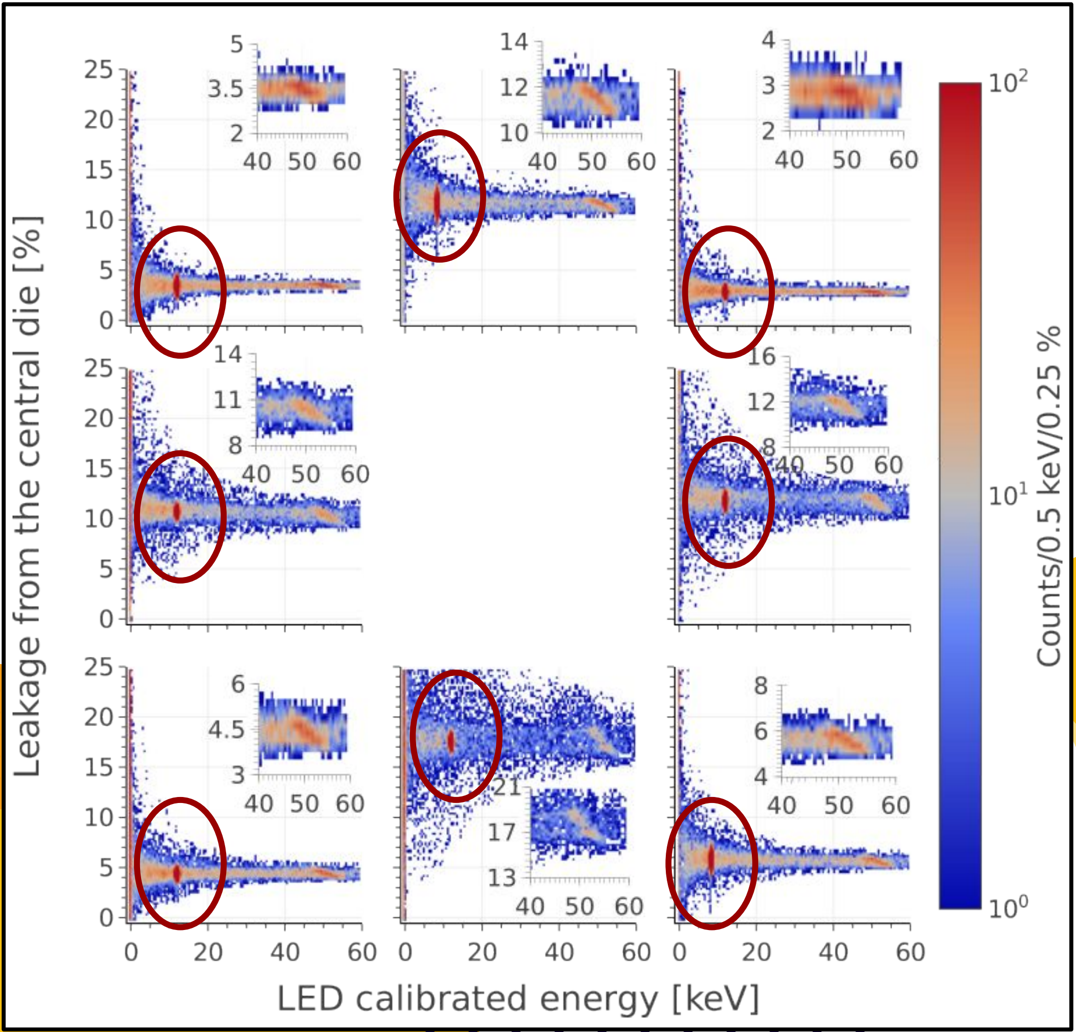
$$\frac{dE}{d\phi} = \frac{1}{Q} \frac{N_0 V \Delta_0^2}{\eta \alpha S_\phi(f_0, T)}$$

Neighbors analysis: leakage



- We observe a leakage constant in energy and equal for LEDs and americium events
- We observe and anticorrelation between the amplitude in the central die and the leakage in **all** the other dice

Neighbors analysis: leakage



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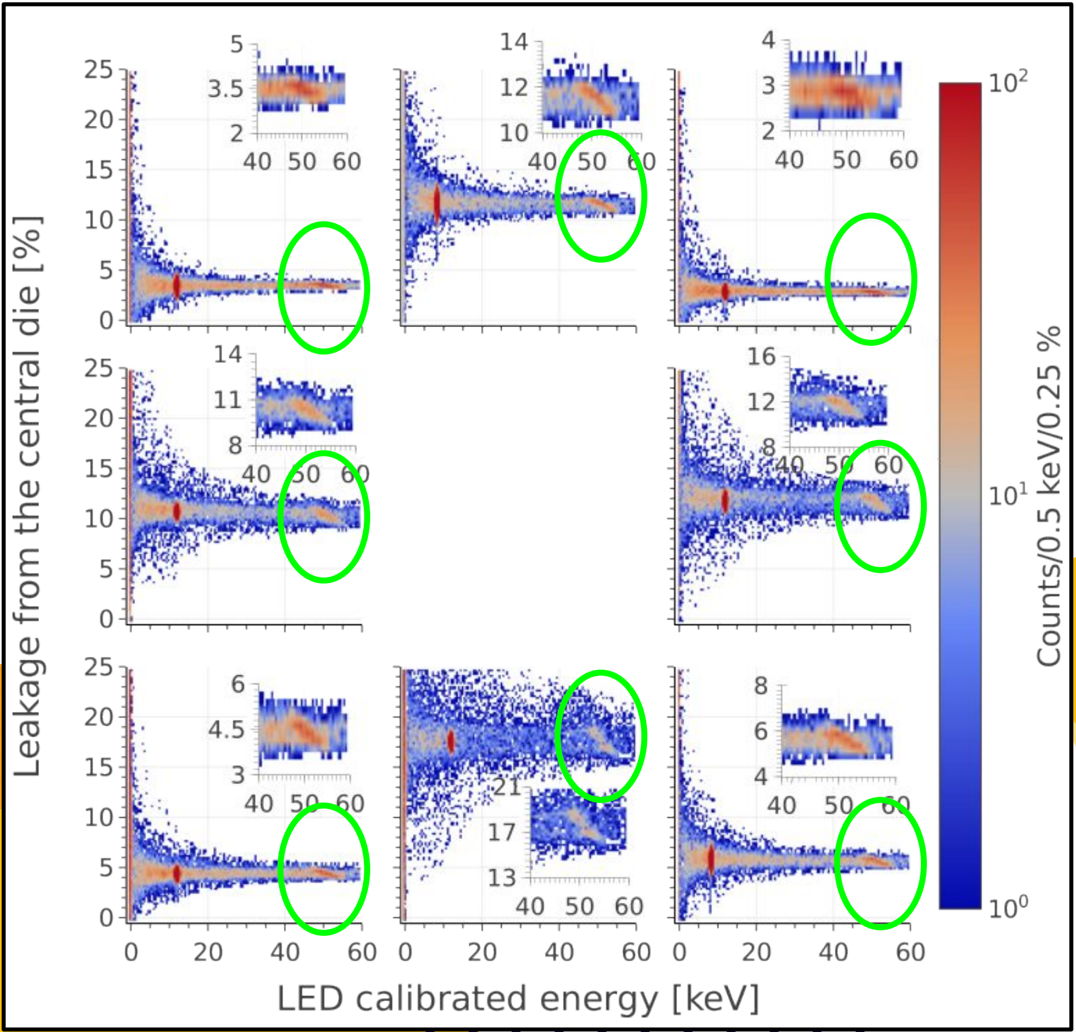

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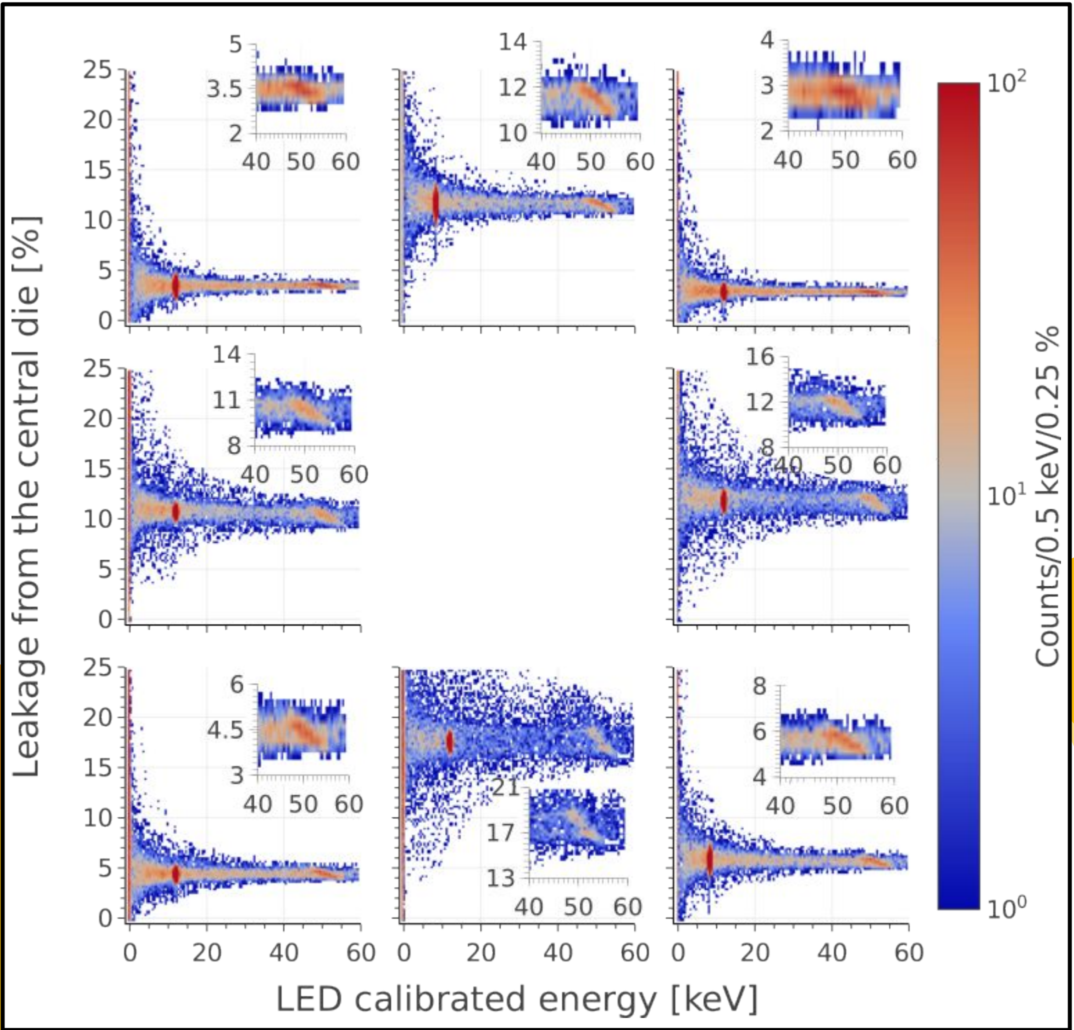

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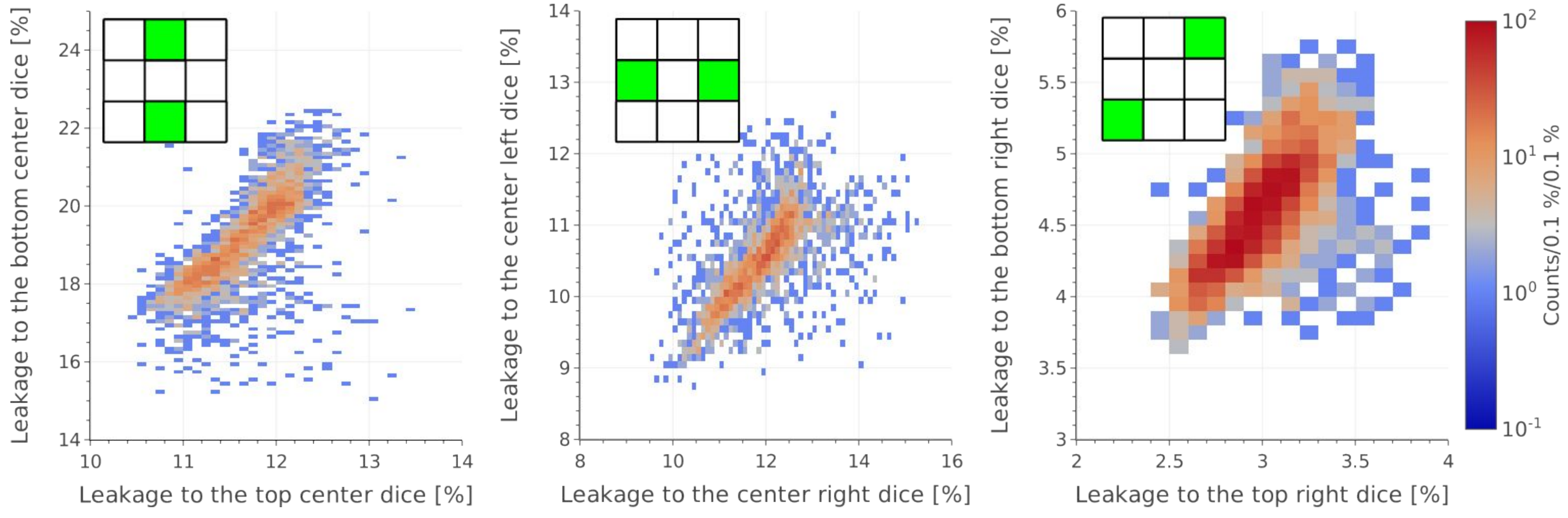
Neighbors analysis: leakage



- We observe a correlation between the leakage of all the dice

Calorimetric energy and its calibration

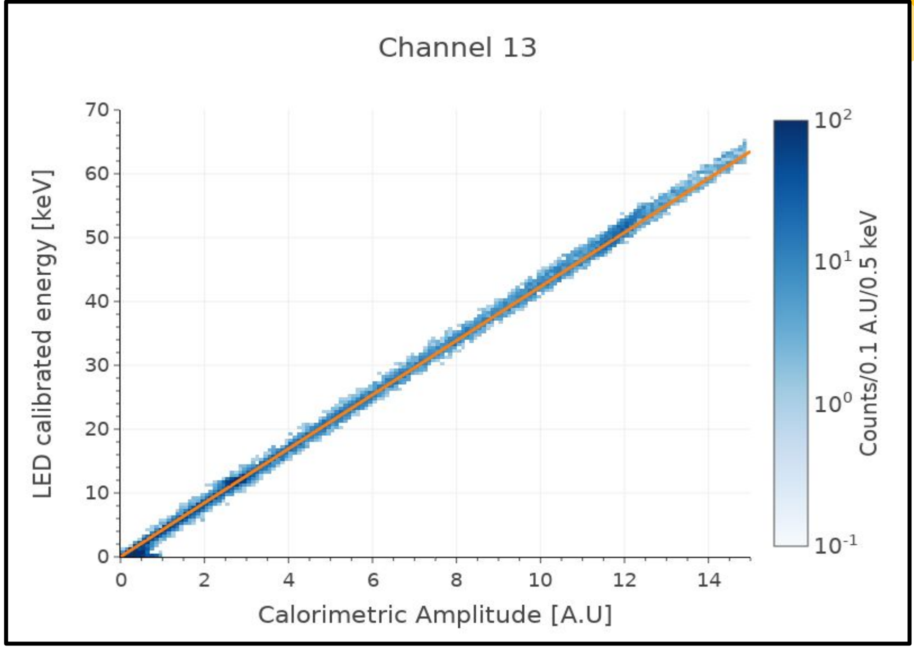
Model

Americium events are mono-energetic, hence the more phonons leak in the neighbors, the less are absorbed by the main pixel and an anticorrelation is expected.

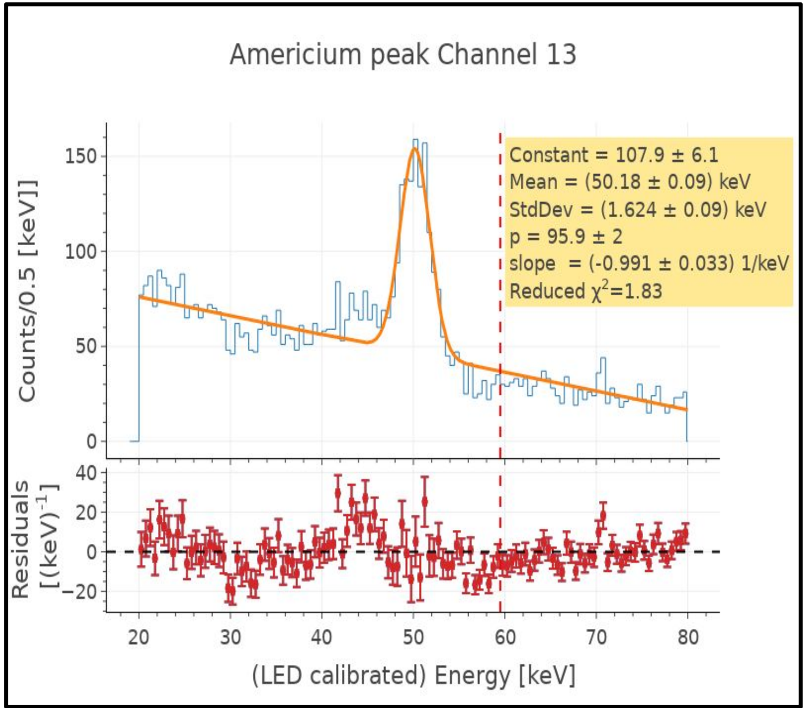
Since the neighbors are correlated it seems to be a positional effect related to the depth of the event

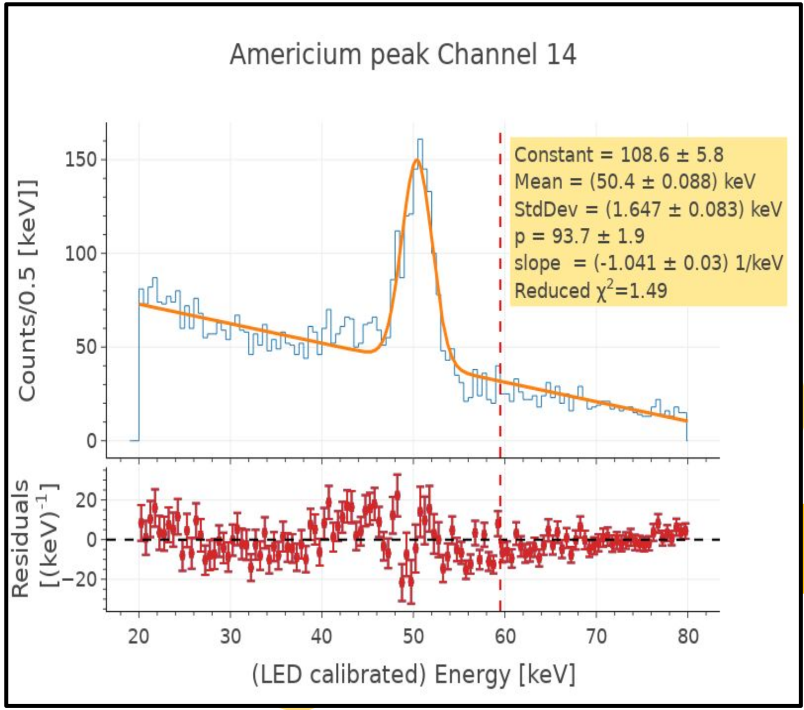
Definition of a new variable

$$A_{\mathrm{cal}} = A_m/Q_m + \sum_{\mathrm{neigh.}} A_n/Q_n$$



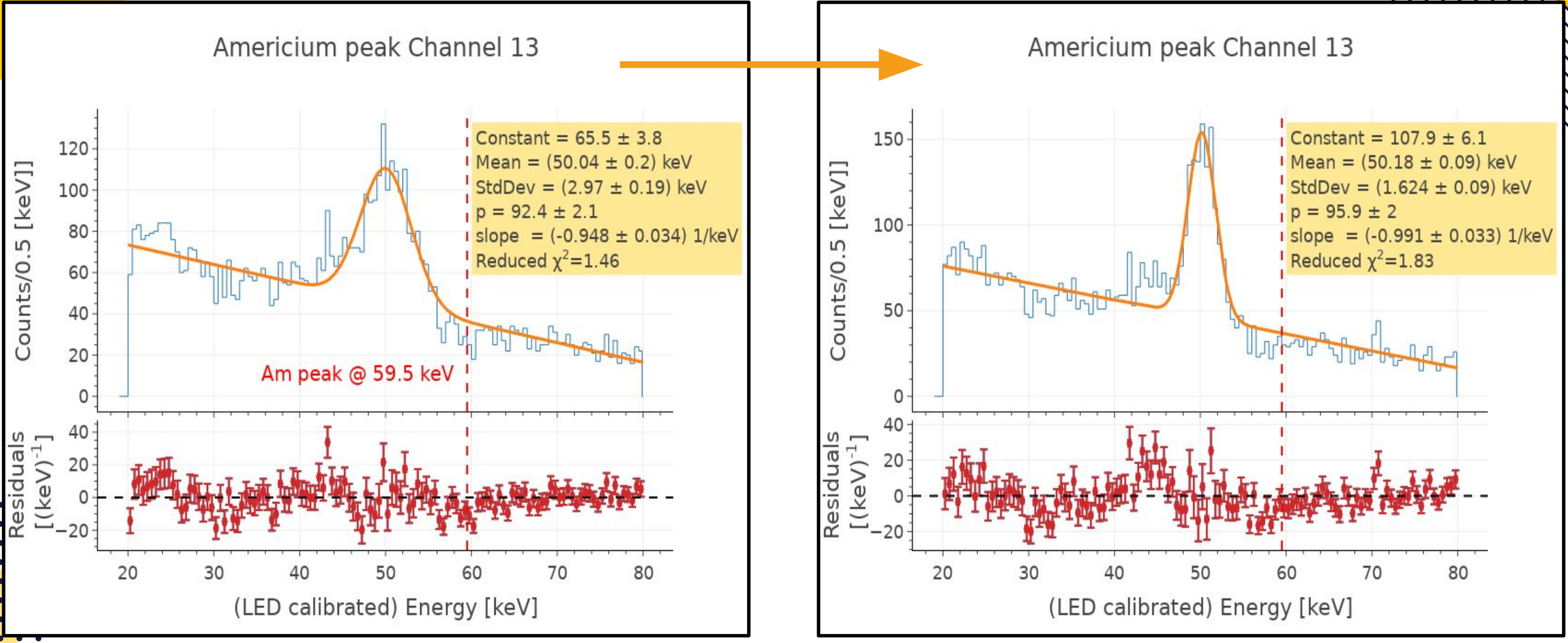
Energy spectra of calorimetric amplitude





We are able to reconstruct the americium peak with a **mean shifted by -16%** with respect to the theoretically expected value and with a **resolution of 3.3%**

Conclusions of the analysis



LED calibration validated with an accuracy of -16%
Resolution of bulk events improved from 6% to 3.3% through the calorimetric amplitude

Status of the paper

Article drafted and a preliminary version will be ready soon

EPJC is the journal target for the paper

We are thinking on repeating the data acquisition with more pixels thanks to the new wafer available

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(will be inserted by the editor)

Calibration of bulk events in the BULLKID detector

Matteo Folcarelli[a,1]

[1]Sapienza university of Rome, Piazzale Aldo Moro, 5, 00185 Roma RM, Italy

Received: date / Accepted: date

Abstract BULLKID is a cryogenic, solid-state detector designed for direct searches of particle dark matter candidates, with mass ≤ 1 GeV/c^2, and coherent neutrino-nucleus scattering. It is based on an array of dice carved in 5 mm thick crystals, sensed by multiplexed Kinetic Inductance Detectors. In previous works, the detector was calibrated with bursts of optical photons, which are absorbed in the first micrometers of the substrate and behave as surface events. In this work, we present the reconstruction of bulk events through the 59.5 keV X-ray induced by an ^{241}Am source, which resembles more closely the interaction of Dark Matter and neutrinos particles with respect to optical photons. The peak resolution is (2.8 ± 0.2) keV σ and its mean is shifted by -16 % with respect to the optical calibration. The resolution is further improved by a factor ~ 1.7 combining the signal from neighbors dice. These results confirm the performance of the detector in view of the physics goals of the BULLKID-DM experiment.

1 Introduction

BULLKID [2, 5, 7] is a monolithic detector composed of a fully-active wafer of crystal, without inert materials, carved in dice of $5.4 \times 5.4 \times 5.0$ mm^3 and sensed by phonon-mediated cryogenic kinetic inductance detectors (KIDs). It is designed for the detection of sub-keV energy release of particles interacting in the crystal, making it suitable for experiments of direct dark-matter detection and coherent neutrino-nucleus scattering. The energy calibration in such energy range is a major challenge and the BULLKID collaboration adopts a technique based on bursts of 400 nm optical photons [3, 8]. The validation of such approach is of prime interest, in order to corroborate the performances evaluated for the detector. In this paper we present such validation through the reconstruction of the 59.5 keV X-ray peak of a radioactive ^{241}Am source by a BULLKID made of silicon. Moreover, such X-rays are enough energetic to penetrate the entire dice of the wafer ($\lambda_{abs} = 13$ mm) [9], while optical photons are fully absorbed on their surface ($\lambda_{abs} \sim 0.082\,\mu$m) [6], allowing the investigation for different responses between bulk and surface events (Fig. 1).

[a]e-mail: matteo.folcarelli@uniroma1.it

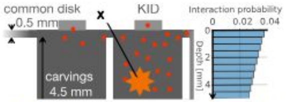

Fig. 1 On the left a scheme of a particle releasing energy in a die of BULLKID. The athermal phonons generated are mostly absorbed by the KID (main) corresponding to the interacting die. The rest of the phonons leak to the nearby dice through the commond disk inducing a signal in the corresponding resonators. On the right the interaction probability density function of the 59.5 keV X-rays of ^{241}Am in function of the penetration in the silicon die.

2 Experimental setup

The BULLKID detector, adopted in this measure, is a stack of two silicon wafers, of 3″ in diameter and 5 mm thick, carved in 60 silicon dice (Figure 2 Top). The carvings leave intact a 0.5 mm thick common disk that acts as both the holding structure of the wafer and as substrate for the aluminum lithography of the KIDs that, in this way, are fully multiplexed [2]. Figure 2 (Bottom) shows a picture of the top wafer and a map of its resonators. This is the wafer used during the measurement, as it is suitable for optical calibration. We evaluate a total number of 38 working pixels out of 60, due to production issues, with a median quality factor of

Thanks for the attention

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