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SPACEKIDS: kinetic inductance detectors for space applications

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SPACEKIDS: Kinetic Inductance Detectors for Space Applications


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ABSTRACT

SPACEKIDS, a European Union FP-7 project, has recently been completed. It has focused on developing kinetic inductance detector (KID) arrays and demonstrating their suitability for space applications at far infrared and submillimetre wavelengths. KID arrays have been developed for both low-background (typical of astrophysical applications) and high-background (typical of Earth-observation applications), based on performance specifications derived from the science requirements of representative potential future missions. KID pixel and array designs have been developed, together with readout electronics necessary to read out large numbers of pixels. Two laboratory demonstrator systems have been built and used for comprehensive evaluation of large-format array characteristics and performance in environments representative of both astronomy and Earth observing applications. We present an overview of the SPACEKIDS project and a summary of its main results and conclusions.

Keywords: far infrared, submillimetre, Kinetic Inductance Detectors, astronomy, Earth Observation, space instrumentation

1. INTRODUCTION

Superconducting detectors operating at sub-kelvin temperatures are currently the most sensitive detectors in the far infrared and submillimetre part of the spectrum. Instruments using transition edge superconducting (TES) sensors and kinetic inductance detectors (KIDs) are already in use in ground-based astronomical instruments, but have yet to be flown in space. SPACEKIDS was a European Union FP-7 project with the objectives of developing advanced KID arrays and demonstrating their suitability for space applications in both astronomy and Earth observing. SPACEKIDS completed its three-year programme in early 2016.

KID detectors [1, 2] are based on thin superconducting films. Sufficiently energetic photons can break Cooper pairs (paired electrons that form the ground state of the superconductor) into single particle excitations (quasiparticles) in the film. The superconductor exhibits the phenomenon of kinetic inductance due to the fact that flowing Cooper pairs have inertia, which any changing electric field must overcome. Pair-breaking changes both the Cooper pair and quasiparticle densities, hence modifying the kinetic inductance and resistance, so modifying the complex surface impedance of the film.

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In a KID, the superconducting film is part of a high-Q microwave resonant circuit which is coupled to a microwave feed-line. Absorption of photons in the film modifies the resonant frequency and Q-factor of the circuit due to the changes in the complex impedance, leading to changes in the transmitted phase and amplitude of a microwave readout signal at the resonant frequency. KIDs need to be operated at very low temperature \((T \sim T_c/10, \text{where } T_c \text{ is the critical temperature of the film}),\) to suppress generation-recombination noise due to thermally-generated pair-breaking.

Many hundreds of high-Q-factor KID resonators, each with a slightly different resonant frequency in the GHz region, can be coupled to a single feed-line excited by a comb of frequencies matched to those of the pixels, allowing all of them to all be read out simultaneously via frequency division multiplexing (FDM) with a single low-noise readout amplifier. The photon-induced changes in kinetic inductance in each pixel only affects the amplitude and phase of its own readout frequency. The readout can be based on either the phase or amplitude of the signal.

This high multiplexing factor is a major potential advantage of the KID concept for cryogenic space instrumentation. Up to \(~1000\) pixels can be read out using a single feed-line, so that a large-format array can be accommodated with a relatively small number of wires connecting the warm electronics to the cold focal plane.

Additional advantages of KIDs that make them eminently suitable for use in sensitive space instruments are: (i) they can achieve the high sensitivity levels needed to achieve photon noise limited performance in low-background applications; (ii) they have a high dynamic range; and (iii) they are relatively easy to fabricate, consisting of only a few patterned metal layers, making them robust, reliable and easy to manufacture as large-format arrays.

Although KIDs are being increasingly adopted for ground-based submillimetre instruments \([e.g., 3, 4]\), they have yet to be adopted for any space application, given the high levels of reliability and technical maturity needed for any technology to be considered for use in space. The SPACEKIDS project was designed to address areas of KID development which are crucial for adapting this technology for use in space-based instruments: electromagnetic design of KID arrays to demonstrate the multiplexing ratio and uniformity of responsivity; optimisation of KID performance in the presence of cosmic ray flux representative of a space environment; optimisation of KID sensitivity and optical coupling for different levels of optical loading and wavelength coverage; and demonstration of wide band FPGA-based digital electronics coupled to large format KID arrays. There are two well-established KID architectures: antenna-coupled KIDS (also known as MKIDs) based on superconducting resonators formed by appropriate lengths of transmission line, and Lumped element KIDS (LEKIDs), based on an LC circuit formed by a capacitative and an inductive element (also acting as the absorber). Both architectures have been studied and developed in SPACEKIDS.

SPACEKIDS included the following objectives and activities

\(\text{(i)}\) review and analysis of the scientific requirements for future astrophysics and Earth observing missions, and derive key specifications for different applications;
\(\text{(ii)}\) development and evaluation of suitable pixel and array designs using both antenna-coupled and lumped-element KID (LEKID) architectures;
\(\text{(iii)}\) development and manufacture of broadband readout electronics suitable for use with kilo-pixel KID arrays;
\(\text{(iv)}\) fabrication and comprehensive testing, in representative laboratory test-beds, of prototype kilo-pixel arrays operating in both low and high photon background, in order to demonstrate some of the key performance parameters relevant to future space missions.

2. \textbf{SCIENTIFIC REQUIREMENTS OF POTENTIAL FUTURE SPACE MISSIONS}

A study of future mission requirements was carried out to define their ultimate detector performance requirements and to establish detailed specifications for the SPACEKIDS arrays and the demonstrator systems, including electromagnetic radiation bandwidth, background power levels, sensitivity (NEP), \(1/f\) noise, speed of response, crosstalk rejection, dynamic range and linearity. The demonstrator systems were not intended to demonstrate quantitative compliance with all of the performance requirements of these possible future missions, but to show significant advances with respect to the current state of the art and the potential for KIDs to be considered as the technology of choice for such future missions given plausible future technology development.
2.1 Astrophysics mission requirements

The ultimate detector requirements for astrophysical applications were examined through the analysis of three challenging mission concepts considered to be representative of any future mission in the FIR/submillimetre: (a) a double Fourier interferometer with two cold apertures, similar to the SPIRIT mission concept [5] and to options studied by the FISICA project [6]; (b) a large single dish telescope cooled to either 5 or 25 K and equipped with a wide field camera and/or a grating spectrometer, similar to the CALISTO [7] or Millimetron [8] concepts; and (c) a fourth-generation Cosmic Microwave Background (CMB) polarisation experiment such as CORE+ [9]. These concepts were intended to be indicative rather than definitive in that they generally cover the key performance parameter space. We assumed a sky background model [10] which includes contributions from the zodiacal light, the Cosmic Infrared Background (CIRB) and the cosmic microwave background (CMB). To derive the required ultimate sensitivity of detector arrays for the various mission concepts, we modeled the instruments with realistic parameters and approximations for the telescopes, the optics and the sky background.

Table 1 summarises the key assumptions and the background power levels per pixel and corresponding required detector NEPs, time constants and array sizes.

<table>
<thead>
<tr>
<th>Mission concept</th>
<th>( \lambda ) (( \mu \text{m} ))</th>
<th>( P_{\text{det}} ) (fW)</th>
<th>( \text{NEP}_{\text{det}} ) (W Hz(^{-1/2} \times 10^{-19} ))</th>
<th>Detector time constant (ms)</th>
<th>Array size</th>
<th>( 1/f \text{knee} ) (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Double Fourier interferometer</strong></td>
<td>25 – 50</td>
<td>0.029</td>
<td>2.8</td>
<td>&lt; 0.2</td>
<td>20 x 20</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>5-K telescope</td>
<td>0.5 ( \lambda/D ) pixels</td>
<td>50 – 100</td>
<td>0.022</td>
<td>1.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 – 200</td>
<td>0.018</td>
<td>1.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>200 – 400</td>
<td>0.83</td>
<td>4.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Single dish Broadband camera</strong></td>
<td>30</td>
<td>0.053</td>
<td>3.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>0.043</td>
<td>2.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>0.030</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>240</td>
<td>0.041</td>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \lambda/\Delta \lambda = 3 )</td>
<td>400</td>
<td>0.27</td>
<td>2.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Single dish Broadband camera</strong></td>
<td>30</td>
<td>0.053</td>
<td>3.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>0.043</td>
<td>2.4</td>
<td></td>
<td></td>
<td></td>
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<td>120</td>
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<td>1.5</td>
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<tr>
<td>( \lambda/\Delta \lambda = 3 )</td>
<td>400</td>
<td>0.27</td>
<td>2.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Single dish Grating spectrometer</strong></td>
<td>30</td>
<td>0.053</td>
<td>3.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>0.043</td>
<td>2.4</td>
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<td>240</td>
<td>0.041</td>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \lambda/\Delta \lambda = 1000 )</td>
<td>400</td>
<td>0.27</td>
<td>2.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Single dish Grating spectrometer</strong></td>
<td>30</td>
<td>0.053</td>
<td>3.9</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>60</td>
<td>0.043</td>
<td>2.4</td>
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<tr>
<td>240</td>
<td>0.041</td>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \lambda/\Delta \lambda = 1000 )</td>
<td>400</td>
<td>0.27</td>
<td>2.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CMB Experiment</strong></td>
<td>30</td>
<td>0.053</td>
<td>3.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>0.043</td>
<td>2.4</td>
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<td>1.2</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \lambda/\Delta \lambda = 1000 )</td>
<td>400</td>
<td>0.27</td>
<td>2.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In estimating the detector NEP, we assumed a maximum 10% detector/readout system contribution to the overall noise over and above the photon noise component. Telescope emissivity as taken to be 2% except for the CMB mission, for which 1% was adopted. For all cases a filter/mirror transmission efficiency of 0.45, a Lyot stop efficiency of 0.95, and a detector absorption efficiency of 0.8 and area fill factor of 0.81 were assumed. For the interferometer, and additional beam divider efficiency of 0.5 was included, and for the CMB instrument an efficiency factor of 0.5 was also adopted to represent the polarization sensitivity of the detectors.

The NEP values derived for the different mission concepts range from $4 \times 10^{-19}$ to $6 \times 10^{-21} \text{ W Hz}^{-1/2}$. The very low NEP required for detectors operating in a grating spectrometer with a cold aperture approaches photon counting performance (for example the photon rate corresponding to the required detector NEP of $1.6 \times 10^{-20} \text{ W Hz}^{-1/2}$ at 30 μm is only 2.4 photons per second). This is the most demanding mission concept and is out of reach of any current detector technology.

The requirement for the time response of the detectors depends on the application. For a grating spectrometer operating in pointed mode, a time constant of ~100 ms would be adequate to provide appropriate integration time and ensure ability to eliminate glitches due to ionizing radiation. For camera instruments operating in scan-map mode, a somewhat faster time constant of 30 ms would be appropriate to allow a reasonable scan rate. For a CMB instrument, which may operate with a faster sky scan rate, a time constant of ~5 ms is desirable. For a double Fourier interferometer, the need to sample both the spectrum and the UV plane sufficiently well in a single observation requires a time constant of ~200 μs or less. The largest numbers of pixels in the detector arrays required for the proposed mission concepts are ~$10^6$, usually arranged in a filled square with equal spacing between pixels. To simplify observing modes and to provide the best sensitivity to large-scale sky structure in scan-map observations, the 1/f knee of the detector system (after decorrelation of all common mode signatures) should be less than 0.1 Hz for all mission concepts, except an FTS-based instrument, which requires detectors with a 1/f knee < 1 Hz, given that the signal frequencies can be encoded at suitably high electrical frequencies through selection of an appropriate mirror scan rate.

Susceptibility to ionising radiation is inevitably a major concern for any sensitive detectors operating in space. A reasonable requirement is that more than 80% of the observing time should provide useful data after appropriate treatment of ionising events (data editing and/or the application of a combination of experimental and modeling corrections), for a representative cosmic ray flux of 3 – 8 counts cm$^{-2}$ s$^{-1}$, characteristic of the L2 environment [11].

To ensure a high level of image fidelity, an additional important requirement for detector arrays is a low level of crosstalk between its pixels. The residual crosstalk between any pixels after implementing correction for known crosstalk, via a crosstalk correction matrix, should be better than 30 dB. An additional typical requirement for an individual observation is that the detector dynamic range be consistent with observing a source with a signal to noise ratio (SNR) of $10^4$ in the linear regime.

Any space instrument for FIR astronomy will be designed primarily for the observation of very faint objects, but must also be capable of observing brighter sources, and achieving a wide range of observable source brightness is always challenging. A reasonable maximum source brightness requirement, expressed as in-beam source flux density, is 1 Jy, with the stipulation that the detector should be able to function under the corresponding source power level while retaining its specified linearity requirements.

The SPACEKIDS demonstrator systems were not intended to achieve quantitative compliance with all of the performance requirements of these possible future missions, but to demonstrate significant advances with respect to current state of the art and the potential for KIDs to be considered as the technology of choice for such future missions with appropriate future technology development. In addition, requirements were designated as priority-1 for the test programme with others as priority-2. The requirements for the low-background demonstrator are summarised in Table 2.

### 2.2 Earth observation mission requirements

Measurements in the submillimetre range are particularly suited for measuring ice clouds [12]. To date such satellite instruments have been based on heterodyne radiometers which are complex and limited in bandwidth, and have only one receiver per frequency band. With this detection technique, some cross-track scanning is needed to obtain swath widths broader than a few detector footprints. Scanning is implemented by a rotation or cross-track scanning of the antenna main reflector, a technical solution that brings several drawbacks. The instrument configuration leads to very short
integration times – for a footprint size of 10 km and a 1000 km swath width, the integration time is in the order of 10 ms, which puts high demands on the receiver noise temperature – a particular problem at higher frequencies where heterodyne mixers have high noise temperatures. Direct detection based on KID arrays has the potential to enable novel instrument concepts, and could remove the requirement for scan mechanisms.

Table 2: Key requirements for SPACEKIDS low-background demonstrator test programme

<table>
<thead>
<tr>
<th>Test priority</th>
<th>λ (μm)</th>
<th>λ/Δλ</th>
<th>NEP (W Hz^{1/2} x 10^{-19})</th>
<th>Time const. (ms)</th>
<th>Detector absorption efficiency</th>
<th>Dynamic range</th>
<th>Cross-talk (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirement</td>
<td>850</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>500</td>
<td>-20</td>
</tr>
<tr>
<td>Goal</td>
<td>200</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>0.7</td>
<td>1000</td>
<td>-30</td>
</tr>
<tr>
<td>Test priority</td>
<td>No. of pixels</td>
<td>Array yield</td>
<td>Ionising hit dead time</td>
<td>Linearity</td>
<td>1/f knee freq. (Hz)</td>
<td>Max source power (fW)</td>
<td></td>
</tr>
<tr>
<td>Requirement</td>
<td>500</td>
<td>60%</td>
<td>&lt; 30%</td>
<td>5%</td>
<td>0.5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Goal</td>
<td>1000</td>
<td>70%</td>
<td>&lt; 10%</td>
<td>1%</td>
<td>0.02</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

For the Earth-observing (high background application) we have therefore adopted a new instrument concept, based on the science requirements for the approved Ice Cloud Imager (ICI) radiometer instrument on the MetOp-SG satellite [13], to characterise the detector needs. The instrument concept is based on a ~25° field of view compact range antenna with 10 or more photometric bands between 90 GHz and 1.5 THz. Each wavelength band has a linear array of detectors perpendicular to the along-track scan direction, obviating the need for cross-scanning. The corresponding requirements for the high-background demonstrator are listed in Table 3. A characteristic frequency of 350 GHz was adopted for the test programme. As for the astrophysics case, the detector NEP contribution is required to contribute no more than an additional 10% over the photon noise contribution. The tie constant requirement is dictated by the rate at which ground scene changes (integration time per pixel). The observation bandwidth, typically 1 – 5%, is assumed to be set by filtering prior to the detector.

Table 3: Key requirements for SPACEKIDS high-background demonstrator test programme

<table>
<thead>
<tr>
<th>Test priority</th>
<th>Frequency (GHz)</th>
<th>NEP (W Hz^{1/2} x 10^{-17})</th>
<th>Time const. (ms)</th>
<th>Detector absorption efficiency</th>
<th>Dynamic range</th>
<th>Cross-talk (dB)</th>
<th>Background Power (pW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirement</td>
<td>350</td>
<td>3.8</td>
<td>15</td>
<td>0.5</td>
<td>2</td>
<td>-20</td>
<td>1.8</td>
</tr>
<tr>
<td>Goal</td>
<td>350</td>
<td>1.2</td>
<td>7</td>
<td>0.7</td>
<td>10</td>
<td>-30</td>
<td>0.2</td>
</tr>
<tr>
<td>Test priority</td>
<td>No. of pixels</td>
<td>Array yield</td>
<td>Ionising hit dead time</td>
<td>Linearity</td>
<td>1/f knee freq. (Hz)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Requirement</td>
<td>500</td>
<td>60%</td>
<td>&lt; 30%</td>
<td>5%</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goal</td>
<td>1000</td>
<td>70%</td>
<td>&lt; 10%</td>
<td>1%</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. KID PIXEL AND ARRAY DEVELOPMENT

The main objectives of the SPACEKIDS development KID pixels and arrays were

(i) Characterisation of thin superconducting films (Al and TiN) with a goal of selecting the best material suitable for use as in broad-band LEKID detectors.

(ii) Minimisation of the susceptibility of kilo-pixel KID arrays to ionising radiation so that such an array could be operated in space with an acceptable level of data loss

(iii) Minimisation of the microwave crosstalk between array pixels, enabling 1000 resonators within a 2-GHz bandwidth to be operated with < 5% microwave crosstalk below 5%.

(iv) Design of efficient broadband optical coupling schemes for antenna coupled MKIDs and absorber coupled MKIDs.

(v) Design, fabrication and testing of both antenna coupled and LEKID arrays for the Earth observation or astrophysics applications.
All of these objectives have been achieved. Through modelling and experimental verification, it has been demonstrated that KID arrays can be produced with negligible cross-coupling between pixels.

**Superconducting film material:** Theoretically, based on film resistivity, critical temperature and other parameters, a TiN LEKID would be expected to achieve NEP values of $\sim 1 \times 10^{-19} \text{ W Hz}^{-1/2}$ [14], which would fulfil all detector requirements for SPACEKIDs. However, a problem was found with TiN KIDs, in that their sensitivity is lower than model predictions. Comparison of the sensitivity at 350 GHz of TiN and an Al KIDs showed that Al KIDs can reach background limited performance with good optical efficiency down to power levels of $\sim 100$ aW. But for a TiN KID the NEP was found to approach the theoretically expected level only for levels of absorbed power much higher than the values appropriate for low-background space applications. Other groups have found similar results with TiN films [15]. For this reason the programme subsequently concentrated on the use of Al-based devices, using 40 – 50 nm films for MKIDS and 15 – 25 nm films for LEKID designs.

**Ionising particle susceptibility:** An ionising particle impact on a KID device produces a cascade of non-thermal phonons, which can cause a glitch in the time trace of the detector and a consequent loss of usable data. Phonons with energy below the superconducting gap will not be sensed. The decay of a glitch is determined by the quasiparticle recombination time in the detector and by the conversion of the non-thermal phonons to thermal phonons. Both phenomena occur on timescales below a few ms (faster than is typical for bolometric detectors). However, with KID arrays being manufactured using a single wafer, steps must be taken to prevent ionising hits being registered as spikes by multiple detectors as the non-thermal ballistic phonons propagate across the wafer. In the case of a basic array, with no particular measures implemented to reduce susceptibility, it was found that each glitch is observed on multiple pixels, even if they are separated by more than 20 nm. The phenomenon of multiple pixel glitch response can be greatly reduced by the addition of a layer of superconducting titanium on the rear side of the detector chip. Non-thermal phonons incident on this surface are absorbed, breaking Cooper pairs in the Ti film. The resulting quasi-particles then thermalize their energy very rapidly before eventually recombining to form a new Cooper pairs with the emission of phonons with typical energy close to the energy gap of the Ti. Thus, the Ti layer acts as a fast thermalisation channel for the non-thermal phonons produced by the ionising hit, preventing their large-scale propagation. It was found that with this additional feature, only nearest-neighbour pixels see ionising particle hits [16].

**Crosstalk:** KID-KID cross-coupling can occur due to overlaps in the resonant response profiles of the individual pixels, leading to undesirable crosstalk in the overall array response. SPACEKIDS has quantified the degree to which this depends on inter-pixel distance and on the characteristics (frequency gap and Q-factor) of the pixel resonances, leading to the development and verification of an array design strategy (based on large pixel-pixel distances for pixels that are close in frequency and a large frequency difference between spatially closely spaced pixels) which minimises the effects. Experimental validation has shown that KID arrays can be made with negligible cross coupling.

**Optical coupling:** A number of designs for broadband optical coupling of both antenna-coupled (MKID) and absorber-coupled (LEKID) array configurations have been produced and evaluated. The pixel configuration designed for Earth observation applications is based on a double slot antenna coupled to a silicon lenslet. This design works well over a bandwidth of around 25%. For cases in which a broader bandwidth is needed, an alternative design based on a lenslet-coupled leaky-wave antenna has been developed. A dual polarisation version of this design provides well-defined and symmetric patterns with high aperture efficiencies over a bandwidth of more than an octave [17]. The combination of LEKID pixels with lenslets has also been modelled, showing that bandwidths greater than an octave can be achieved [18, 19].

The design for the low background 850-GHz demonstrator is based upon a hybrid antenna coupled MKID fabricated on a sapphire substrate [20]. It is based on a NbTiN resonator fed by a twin slot antenna at its end. A thin aluminium strip (40 nm thick, 2 µm wide, 1 mm long) located close to the antenna acts as the radiation sensitive material. Aluminium, with a gap frequency of 80 GHz, is lossless at the readout frequency, but capable of absorbing the 850 GHz. For efficient radiation coupling and beam definition the antenna is coupled to a 1.6-mm diameter Si lenslet with a $\lambda/4$ parylene anti-reflection coating. A linear array of four pixels was used for testing. For the 350-GHz high-background testing, a similar design was adopted, with two key differences: the antenna was optimized for the lower frequency and the lenses were made from alumina rather than silicon (to reduce costs). Both of these devices have frequency response.
and beam pattern in excellent agreement with electromagnetic modelling. The limiting sensitivity was only measured for the 850 GHz device, giving an NEP of $4 \times 10^{-19}$ WHz$^{1/2}$. These two device geometries were used for the main demonstrators of the in kilo-pixel arrays.

A novel broadband leaky-wave lens-coupled antenna was also developed, and a fabrication and integration scheme for a silicon lenslet array developed and tested [21]. Successful fabrication and operation of a 1.4 – 2.8 THz single polarisation leaky-wave antenna-coupled MKID was achieved. Beam pattern and frequency response agree very well the model calculations and the device is background limited down to 0.05 fW incident power (corresponding to an NEP of $2 \times 10^{-19}$ W Hz$^{-1/2}$).

4. READOUT ELECTRONICS DEVELOPMENT

SPACEKIDS included the design, construction, validation and use of electronics for the read-out of a large KID array with high or low Q-factor. Two readout systems were developed, one for 2-4 GHz and one for 4-8 GHz. The 2-4 GHz system was used for a high background absorber-coupled (LEKID) detector array option [22]. Both the 2-4 GHz and 4-8 GHz readout systems were used with the system demonstrators. Requirements included provision of up to 2200 simultaneous readout tones and an output data rate of 160 or 1280 Hz.

5. DEMONSTRATOR SYSTEMS AND TEST RESULTS

5.1 Low-background demonstrator

The essential features of the low-background test set-up are shown in Figure 1. The system allowed arrays cooled to 100 mK to be tested under varying background and with careful control of radiation filtering and stray light. Most of the tests were carried out on a 961-pixel array of 850 GHz twin slot antenna-coupled MKIDs, coupled to an 18x18 element (324 pixel) lenslet array allowing full dark testing and partial optical testing. A new feature of the array was the use of a stray light absorbing layer of TiN, patterned as a low pass filter structure, and deposited on the rear side of the wafer, so located between the chip and the lens array. This layer was implemented to absorb surface waves induced by in-band radiation that does not couple to the antenna, which would otherwise lead to optical cross-talk between pixels. It thus ensured efficient absorption of 850 GHz stray light without affecting the MKID performance or the associated readout signals. To allow the lens-antenna system to work, effectively, ~1-mm diameter holes in the TiN layer were centred at the antenna positions, so coinciding with the lenslets.

Figure 1. Schematic diagram of the low-background demonstrator set-up.
Key test results, with respect to the specifications in Table 1 are:

**Bandwidth:** $\lambda/\Delta\lambda = 2.2$ (broader than the requirement of 3)

**Sensitivity:** The average dark NEP was $3.3 \times 10^{-19}$ W Hz$^{-1/2}$ for 818 detectors in the array, exceeding the requirement of $3.3 \times 10^{-19}$ W Hz$^{-1/2}$.

**Absorption efficiency:** 75% coupling efficiency, referred to one polarisation with single mode throughput and a $1-F\lambda$ sampling. Measurements on the full array compared to results for a smaller test chip imply that the larger array suffered from a non-optimal gap between the lens and the array itself, resulting in poorer absorption efficiency by a factor of approximately 2, something that can be addressed in the future by improving the manufacturing process.

**Time constant:** An average quasi-particle lifetime of around 1.2 ms was measured for the array. This value is the dominant time constant for each the detector and is well within the required 5-ms time constant requirement.

**Dynamic range and maximum source power:** The dynamic range (the range of powers that can be measured with photon noise limited performance for a fixed readout tone tuning) was shown to be roughly 0.1 – 100 fW demonstrating an instantaneous dynamic range of 1000 and meeting the goal. The upper limit of 100 fW also meets the requirement for maximum source power.

**Crosstalk:** performance has still to be fully evaluated but preliminary results indicate that this requirement is also met.

**Array yield:** The array yield (defined as the number of pixels meeting the NEP and time constant requirements) is 82%, exceeding the goal of 70%.

**Cosmic ray dead time:** Using an extremely aggressive approach of disregarding all data from the array in the event of a cosmic ray being registered in any pixel, and scaling to the L2 radiation environment, the dead time for the array is estimated to be around 30%, meeting the requirements of the demonstrator.

Further details of the low-background test programme and results are given in [21] and [23].

### 5.2 High-background demonstrator

The baseline design tested in the high-background set-up was an array of 880 twin-slot hybrid MKIDs tuned to absorb 350 GHz radiation, coupled to an antireflection-coated monolithic lenslet array, and operating at 240 mK. A CAD model of the optical setup is shown in Figure 2 together with photographs of the test array.

The ‘static’ blackbody radiator provides a controllable ($3 – 70$ K), fixed power load, providing several orders of magnitude difference in incident power at 350 GHz. A 3-mm hole in the centre of the radiator allows a modulated signal from a faster blackbody source to be applied.

Key test results, with respect to the specifications in Table 3 are:

**Bandwidth:** $\lambda/\Delta\lambda = 2.2$ (broader than the requirement of 3).

**Sensitivity:** An average NEP of $6 \times 10^{-18}$ W Hz$^{-1/2}$ was achieved across 648 detectors in the array, exceeding the goal of $1.2 \times 10^{-17}$ W Hz$^{-1/2}$.

**Absorption efficiency:** Optical NEP measurements for pixels in the array using a single pixel readout demonstrate that the array is working as expected with an optical efficiency of 93%.
**Time constant:** The average quasi-particle lifetime for a few selected resonators across the array was found to be \( \sim 40 \mu s \). This value is the dominant time constant for each the detector and is well within the required 7-ms goal.

![Schematic diagram of the high-background demonstrator set-up.](image)

**Dynamic range and maximum source power:** Photon noise limited sensitivity has been demonstrated for the array over a range of background powers spanning both the requirement and goals set out in Table 3.

**Crosstalk:** 53% of the pixels in the array are below the required cross-talk level of -20 dB.

**Array yield:** All detectors are well within the goal time constant of 7 ms. 648 of the 880 detectors are below the required NEP of \( 1.2 \times 10^{-17} \text{ W Hz}^{-1/2} \) (this includes some “well behaved” clashed resonators that can be tracked by the readout electronics, corresponding to 73% yield).

**Cosmic ray dead time:** As for the low-background case, using the aggressive approach of disregarding all data from the array in the event of a cosmic ray being registered in any pixel, the dead time for the array is estimated to be around 30%, meeting the requirements of the demonstrator.

### 6. CONCLUSIONS

Based on a review of future potential mission concepts for astrophysics (low photon background) and Earth observation (high photon background) applications, representative specifications for the large-format demonstration arrays were derived. Electronics capable of reading out kilo-pixel KID arrays with 2-4 and 4-8 GHz bandwidths were developed and utilized in low- and high-background test systems. Through modelling and experimental verification, SPACEKIDS has demonstrated that KID arrays can be produced with negligible cross-coupling between pixels. While TiN KIDs have lower sensitivity than model predictions, aluminium detectors can achieve the photon-noise limit at low background. Broadband optical coupling methods have been developed for both MKID and LEKID arrays. Sensitivities needed for low-background instruments were measured with antenna-coupled KIDs, with photon-limited performance down to
background powers of 100 AW. Successful methods of minimizing the effects of in-band stray light and ionising radiation hits on the arrays have been developed and proven. High- and low-background large format arrays have been produced, and fully characterised in dedicated test facilities, with all priority-1 tests successfully carried out, meeting the requirements in all respects, and the goals in most cases.

SPACEKIDs has demonstrated that large KID arrays an be made that comply with the strict requirements needed for a space-borne instruments. A roadmap for further technological development has also been drawn up outlining the necessary next steps to produce fully qualified and flight-ready KID-based detector systems, with particular emphasis on development of low-power readout electronics, space qualification of KID arrays, and efficient sub-K cryogenic systems.

The technical progress made by SPACEKIDS will enable new scientific research in astronomy and Earth observation through the maturation of a novel detector technology suitable for future space-borne observations with advanced imaging and spectroscopic instruments.

REFERENCES


