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Improved acoustic instrumentation of the SIMPLE detector

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Abstract

The application of Superheated Droplet Detectors in dark matter searches by the SIMPLE project uses an acoustic instrumentation sensitive to the shock wave generated by the bubble nucleation of the refrigerant droplets. Previous instrumentation has been unable to distinguish between true nucleation and background noise events in the device, in particular microleaks associated with the escape of overpressuring nitrogen gas into the surrounding water bath. We here describe the development of an improved instrumentation which is shown to provide this discrimination capacity through a reduced noise level of the transducer amplification circuitry.

PACS: 43.58.+z; 29.40.−n; 95.35.+d

Keywords: Acoustic instrumentation; WIMP search; Superheated liquids

1. Introduction

A Superheated Droplet Detector (SDD) is a suspension of superheated freon droplets (~30 μm of radius) inside a viscous elastic gel, which undergo transitions to the gas phase upon energy deposition by incident radiation: each droplet behaves as a micrometric bubble chamber. The response of SDDs is described by the Seitz 'thermal spike' model [1]: if, within the metastable droplet, the energy deposition is: (1) higher than a critical energy E_c, and (2) within a critical distance s ($dE/dx > E_c/s$), the droplet vaporizes. Both thresholds are thermodynamic, and can be selected by varying the operating pressure and temperature to render the SDD insensitive to energetic muons, gamma-rays, X-rays, electrons, and other radiations depositing less than ~200 keV μm^{-1}: the SDD is essentially sensitive to only neutron and alpha recoil, and the detector has been widely used in neutron dosimetry [2,3] and spectrometry [4–6] for almost two decades. They have been shown to comply with ICRP 60 recommendations for accuracy of measurement, real-time response, low minimum detection threshold and, most importantly, a nearly similar dose equivalent response [7]. More recent developments include position-sensitive neutron spectrometers/dosimeters for application in radiotherapy [8], in energy and angle-differential neutron fluence measurements [9], in response enhancement to high-energy neutrons [10], and for registration of high and intermediate energy heavy ions [11].

Its application has recently been extended to dark matter (DM) searches, which rely on measuring the nuclear recoil produced by their elastic scattering off target nuclei, because of the intrinsic detector insensitivity to most backgrounds of such experiments. The SIMPLE project

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[12] is one of only two international DM searches (the other being PICASSO [13]) using SDDs.

Although the liquid-to-gas transition results in bubbles of millimetric diameters which can be easily observed, the rapid expansion of the bubble surface following nucleation is accompanied by an oscillating pressure pulse of <10 ms duration which can be acoustically recorded. Both SIMPLE and PICASSO have adopted this form of readout in instrumenting their detectors. In each case, the detector is monitored by one or more acoustic transducers, mounted either inside or outside the containment vessel.

The SIMPLE data acquisition is based on an inexpensive piezoelectric transducer (PKM 13EPY-4002-Bo) connected to a low-noise pre-amplifier (SSM2017) which couples through a wide bandwidth dual JFET input operational amplifier (TL082) to the input of an acquisition channel [14], as shown in Fig. 1. Mechanically the transducer is enclosed within a copper mesh acting as a Faraday cage, which is protected by a latex covering and installed in a glycerine layer overlying the gel in the detector. The transducer signal is amplified by a factor of 10^5, and recorded in a Labview platform together with the signals from other detectors, a wide-band hydrophone (Benthos AQ 4), and an acoustic monitor placed outside the bath/shielding.

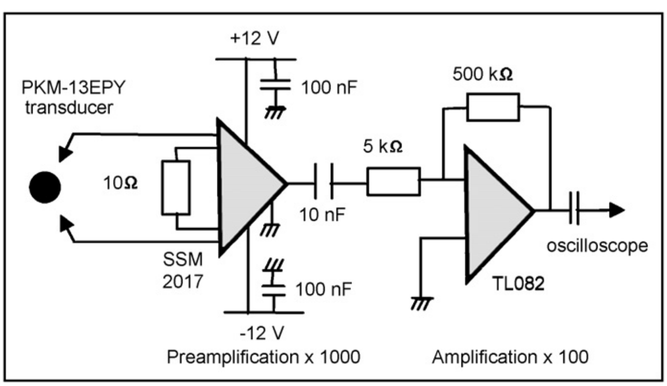

Fig. 1. Initial electronics for the PKM transducer.

Although the fast Fourier transform (FFT) of the transducer signal of a nucleation event, shown in Fig. 2(b), comprises a well-defined frequency response with a primary harmonic at ~5 kHz and a time span of a few milliseconds, the signal is accompanied by a relatively large (100 mV) noise level. Additional problems include: (i) an ungrounded copper mesh, (ii) an open transducer for the purpose of better signal pickup (generally resulting in its destruction), and (iii) unshielded, hard cabling interfaces between the electronics and DAQ (a small knock on the cable produces an event).

In consequence, the device response was essentially that of a buzzer, and unable to discriminate true bubble nucleations from acoustic backgrounds such as microleaks arising from the escape of the overpressuring gas into the surrounding water bath, nor fracturing of the gel with bubble growth during the device use. The inability to discriminate microleak events imposed a serious constraint on the early SIMPLE measurements, since these accounted for the majority of the recorded events [12,14] as observed in freon-less SDD tests.

We here report improvements in the transducer circuity, which permit discrimination between nucleation and microleak events via significantly reduced levels of noise. Section 2 describes the modifications; Section 3, performance tests of the new instrumentation in the SIMPLE underground site, with an assessment provided in Section 4.

2. Revised data acquisition electronics

During the previous C_2ClF_5 measurements, refrigerant-free 'dummy' modules yielded signals indistinguishable from bubble nucleation events [14]. These were found to arise from pressure microleaks through the plastic SDD

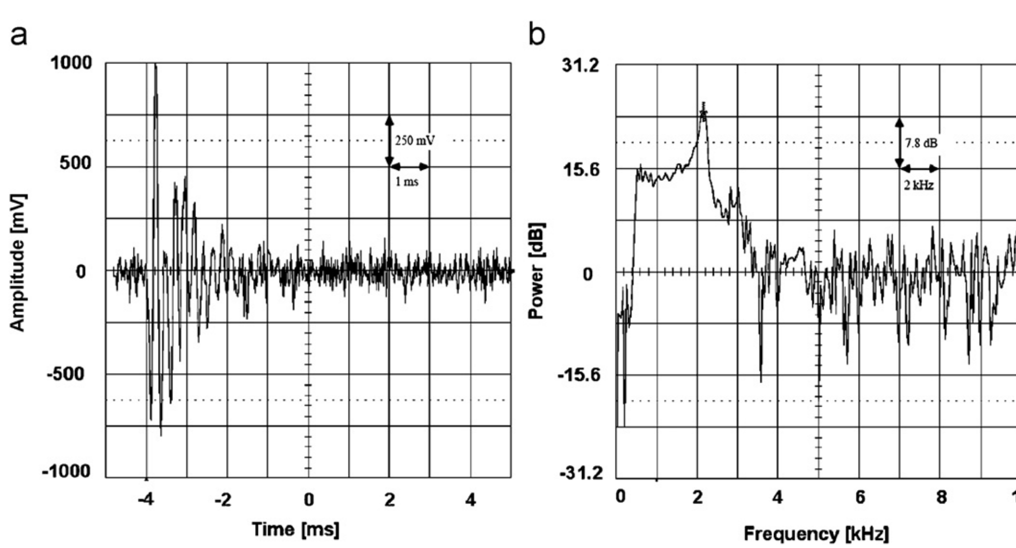

Fig. 2. Typical bubble nucleation event (a) and its FFT (b), as observed with the initial SIMPLE transducer electronics (from Ref. [14]).

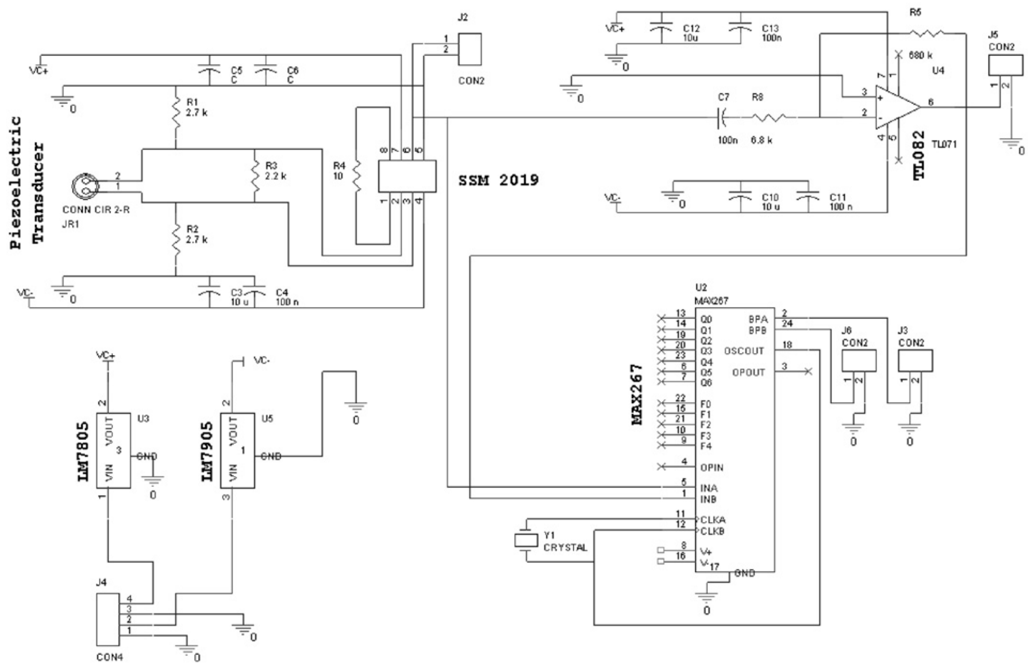

Fig. 3. Modified electronic circuit for the PKM transducer.

caps of the submerged devices. While the majority of these had been eliminated by coincidence between the detector microphone and the hydrophone, this problem was addressed through capping improvements: a preliminary test of new caps showed no microleaks in three weeks, yielding a 90% CL upper limit of ~0.11 microleaks/detector/day, corresponding to ~11 microleaks/kg/day for a 10 g/detector loading, versus the previous 0.5–1 microleaks/detector/day.

Apart from improvements in the device capping which significantly reduced the microleak rate, and cable replacement, it was decided to locate the new circuit together with the transducer inside the detector vessel, shortening the microphone-amplification distance towards reducing the noise levels. The circuitry was reconstructed in a Surface Mount Display (SMD), initially modified as seen in Fig. 3 to include voltage regulators (LM7805 and LM7905) to guarantee stability, and a pin-programmable universal and band-pass filter (Max267) introduced between the TL082 operational amplifier and the input of the acquisition channel. The MAX267 filter permitted selection of a desired region of operation for audio analysis, which was set to the range of 4–6 kHz.

Generally, the detectors were warmed to 35 °C to stimulate bubble nucleation events. These events were characterized, and cross-checked against events generated by irradiating the detectors using a quasi-monochromatic neutron beam of 54 keV obtained with an Si + S passive monochrometer filter at the Portuguese Research Reactor [16] to insure their validity. A typical measurement output is shown in Fig. 4(a), using a surface laboratory R-12 detector. Its FFT is shown in Fig. 4(b): the oscillating frequency lies within the ~4–6 kHz acceptance range of the band-pass filter, with further tests indicating this to depend somewhat on the composition of the detector and its size. The principal frequency response is at 4.8 kHz; the spikes at 21, 31, and 40 kHz correspond to parasitic signal from the power supply, PC monitor and oscilloscope, respectively; these were eliminated by reducing the acceptance window to 0–14 kHz. An FFT of only the noise signal yields a 5.5 kHz frequency spike, which is intrinsic to the PKM transducer.

A continuing high noise level (~100 mV), however, suggested that the second stage of amplification and/or the band-pass filter were either amplifying the noise level or introducing more. After an exhaustive experimental analysis of the circuitry, both were finally removed entirely to leave only the low-noise pre-amplifier (SSM2019) with its enhanced gain ($G = 100$) stability (Fig. 5).

Fig. 6 shows the final configuration of the circuitry, with the transducer located to the left, and the coupling to the external power supply and acquisition channel to the right. The typical signal outputs were similar to those of Fig. 4, with an accompanying noise level of ~1 mV.

A true bubble nucleation event validation routine was developed, which executes the following steps: (i) sets an amplitude threshold; (ii) identifies the beginning and ending of each spike, based on the previous threshold; (iii) amplitude demodulates the time evolution of the spike; (iv) measures the decay time constant (α) of the pulse; and (v) suppresses the pulses which exhibit time constants (α) below a given threshold.

The choice of the amplitude threshold is an interactive procedure, and can be set very low for the rejection of

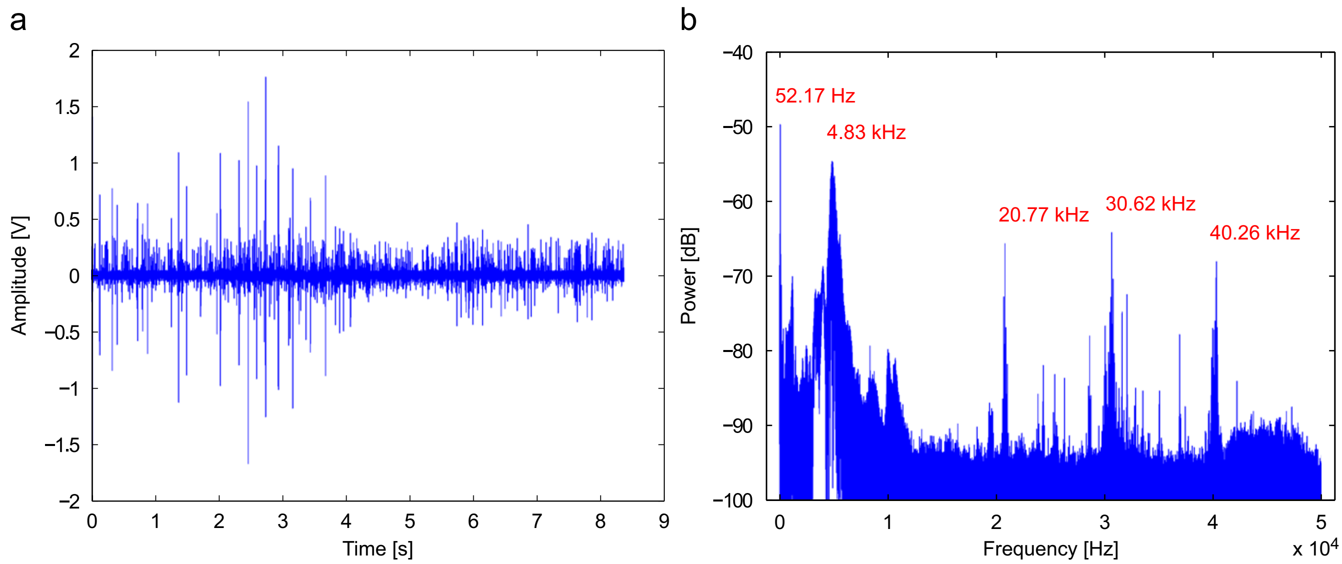

Fig. 4. Signal output (a) from the transducer for a detector warmed to 35 °C in a bath, and its FFT (b).

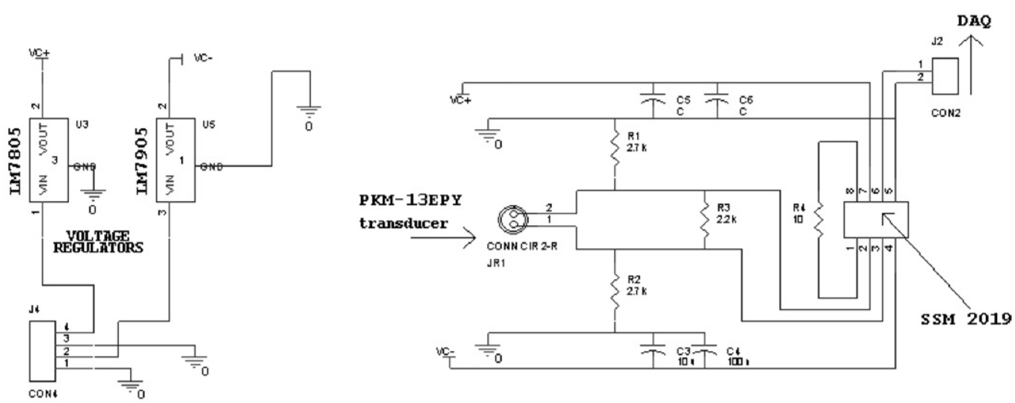

Fig. 5. Modified electronic circuitry for the PKM transducer.

spurious noise. The amplitude demodulation is achieved simply by performing the modulus of the Hilbert transform of the pulse waveform, $y(t) = |H\{x(t)\}|$. After the amplitude envelope has been obtained, the maximum and the minimum of the pulse shape are found to set the time window of the pulse that is used for evaluating α. The decaying part of the amplitude envelope is fit to an exponential, $h(t) = \mathrm{A}e^{\alpha t}$, by means of a linear regression after linearizing the envelope, $\ln(y(t)) = \ln(\mathrm{A}) + \alpha t + \mathrm{er}(t)$ where $\mathrm{er}(t)$ corresponds to the residual of the fit.

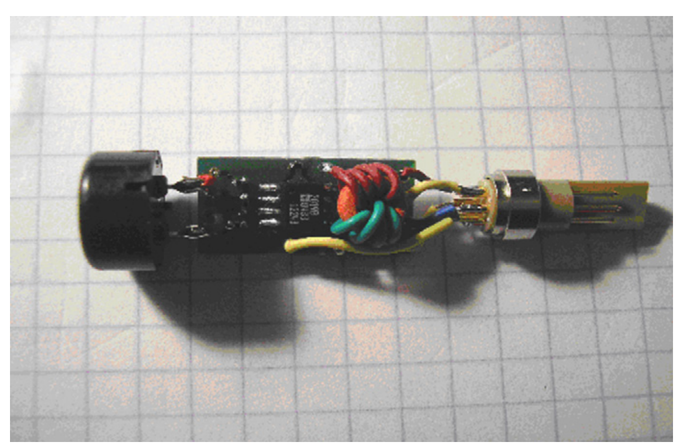

Fig. 6. Compact front-end electronics for the SDD.

3. Underground test results

Owing to the application, the modified electronic readout was tested in the electromagnetically shielded underground laboratory of the Laboratoire Souterrain Bas Bruit de Rustrel (LSBB), which is also the site of the SIMPLE experiment [15]. The main experimental area, at a 500 m depth, constitutes a Faraday cage isolated from mechanical vibrations: the shielding reduces the magnetic field to less than 6 μT, with a long time stability of better than 20 nT and fluctuations below $2.5\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ [15].

Three acquisition channels were tested in three SDDs, each of which contained a uniform dispersion of ~7 g of superheated droplets of C_2ClF_5 (R-115) suspended in ~11 of hydrogenated gel. A fourth channel was tested in a similarly fabricated but freon-less detector prepared to generate microleaks for identification and characterization. The instrumentation was coupled to a low cost 68 pin connector block (CB-68LP) via 6 m of shielded cable (SH68-68-EP), which interfaced with a low cost multi-function I/O & NI-DAQ board (NI PCI-6036E).

Each detector was overpressured to 2 bar, and submerged in a 700 l water bath at constant temperature of 9 °C, as is the case for a standard SIMPLE measurement [12]. In contrast to the surface measurements, bubble nucleation events were stimulated by the intrinsic warming of the detectors, which had been transported from their fabrication site at 0 °C. These events were characterized, and cross-checked against the surface neutron irradiation event characterizations to insure their validity.

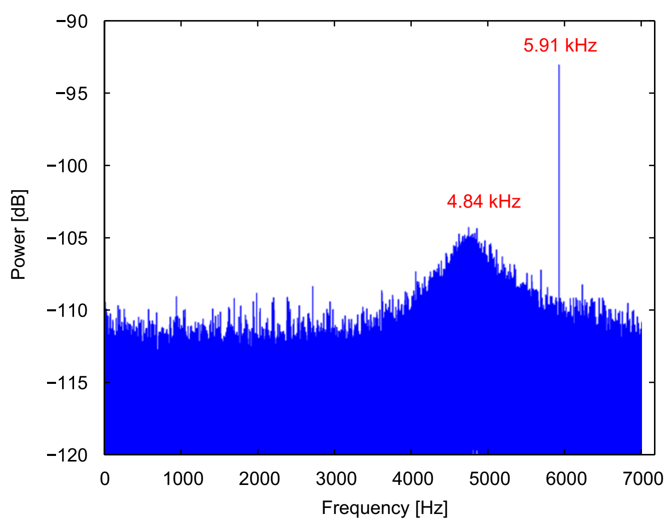

Fig. 7. A typical FFT for a full data run for the detector.

3.1. Detector response

The data for each trial was acquired in Matlab files of ~13 MB each, comprising 40 runs each of 2 min duration at a constant rate of 14 k samples per second. The total number of recorded events was 35.

All detector monitoring gave similar responses. An overall FFT from a typical run with the detectors is shown in Fig. 7, indicating the transducer spike at 5.9 kHz, a distribution of frequencies peaked at 4.8 kHz, and an otherwise flat power response. The data for the entire run gave an average noise level (RMS) of 0.97 mV.

Fig. 8 shows a typical FFT for a single bubble nucleation event, with a frequency distribution centered at 4.7 kHz and a power level peaked at ~60 dB. The transducer spike is hidden in the noise; the difference in power levels results from the averaging, which in the entire data run of Fig. 7 includes the noise.

3.2. Microleaks

The nitrogen used to overpressure the freon-less device was released by deliberately poorly sealing the cap of the SDD. Although the absence of freon insured that no true bubble nucleation events were recorded, the majority of events, were found to possess a pulse shape roughly the same as a nucleation event. The corresponding FFT, however, exhibited a plateau over 1.7–4.9 kHz with a power level of ~50 dB, as seen in Fig. 9. There is virtually no power in the region below 1 kHz. The noise level was 1.4 mV.

3.3. Mesh covering

An additional test was conducted in which the transducer was covered by a copper mesh as in the initial instrumentation, but this time grounded to the circuit.

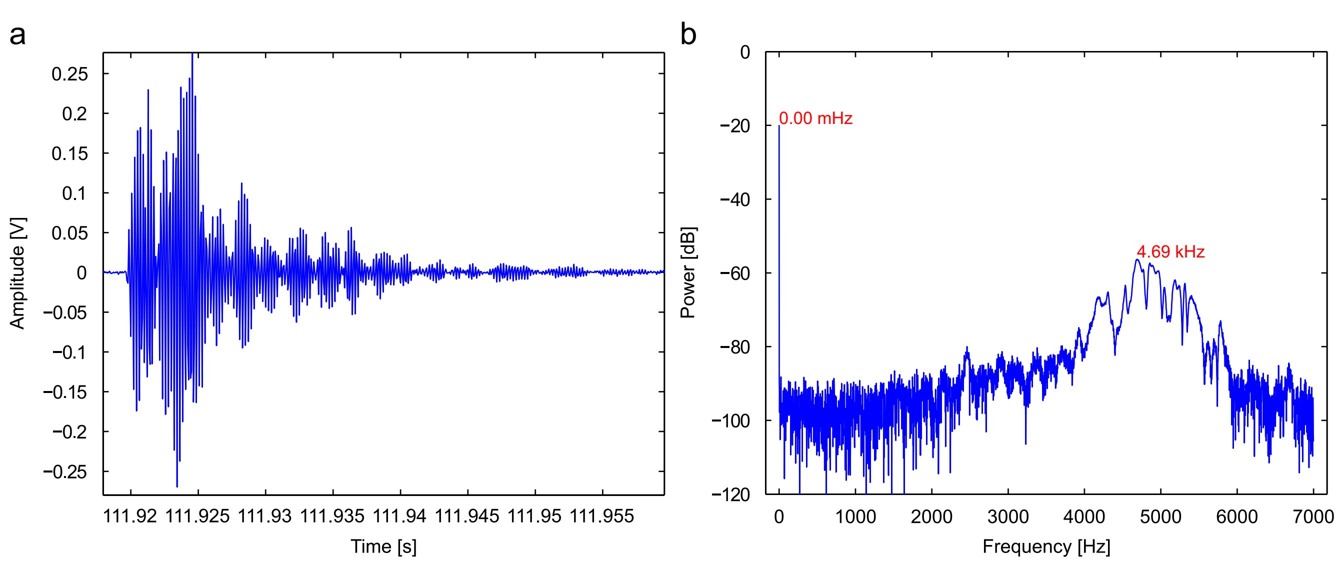

Fig. 8. A typical waveform (a) and FFT (b) for a single SDD nucleation event.

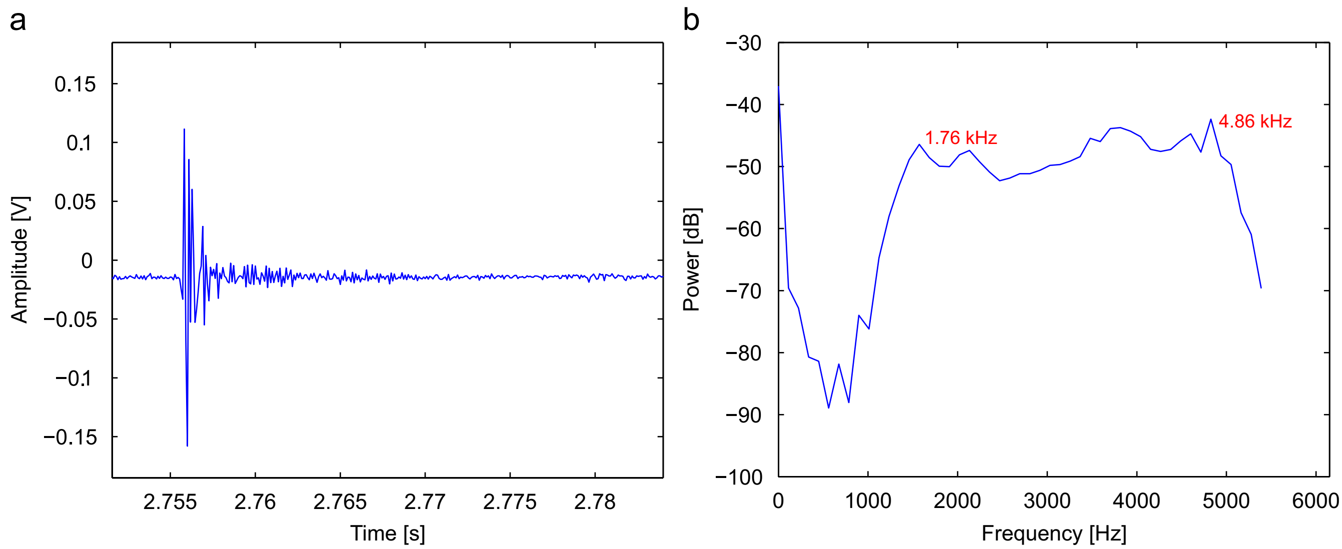

Fig. 9. A typical waveform (a) and FFT (b) of a microleak event.

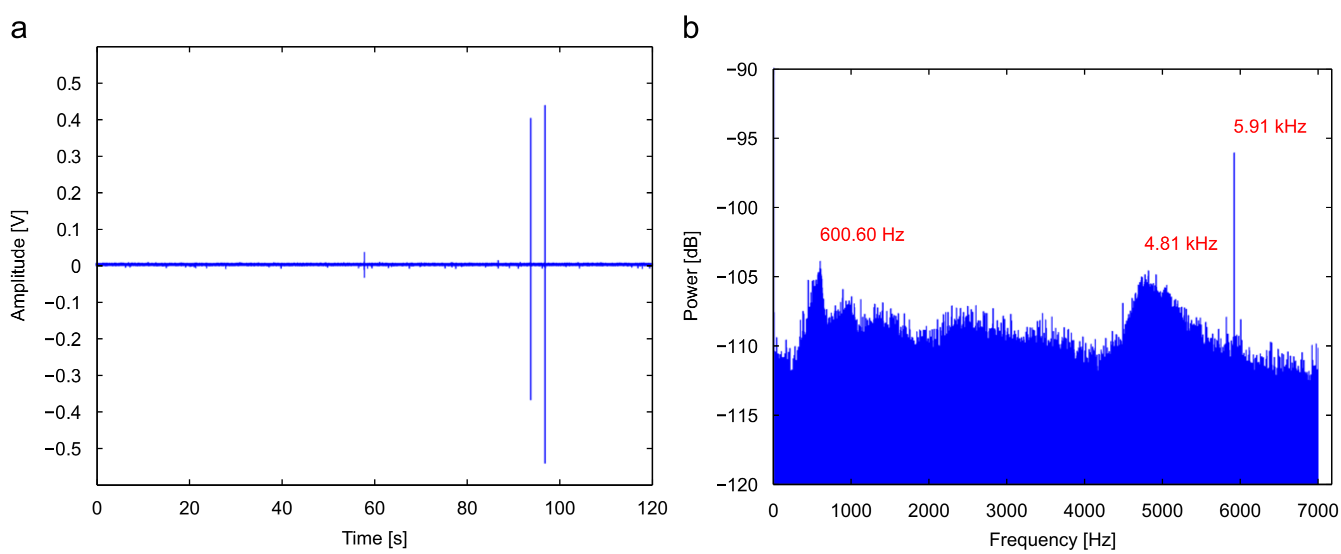

Fig. 10. A typical signal output (a) and FFT (b) of an entire SDD data run, with the transducer shrouded in a copper mesh.

Runs of 30 min duration gave an average noise level (RMS) = 0.94 mV. The number of recorded events was 43. Fig. 10 shows the FFT for an entire data set, which above 4 kHz is similar to that of the detector without mesh in Fig. 7, exhibiting the transducer spike at 5.91 kHz and power distribution peaked near 4.8 kHz. Below 4 kHz, however, there is a significant power increase, and a spike at ~600 Hz with about the same power level as the signal events at 4.8 kHz.

Analysis of the individual events indicates a variety of responses and severe differences among the various FFTs, which can be grouped into two typical classes as shown in Fig. 11(a) and (b). These are characterized by almost equivalent power densities at 4.8 kHz, independent of the distribution at lower frequencies resulting from the mesh. This peak is absent in the event of Fig. 11(c), which was provoked by a gentle tapping of the SDD capping, indicating the event origin to be other than a bubble nucleation. The noise is, however, the same as in the other SDDs, and the 5.91 kHz transducer spike is again masked.

4. Discussion and conclusion

The overall test results are shown in Table 1, which summarizes the frequencies and power levels associated with the responses in each of the tests, as well as their respective noise levels.

Lowering of the noise level of the previous SIMPLE circuitry reveals significant and measurable differences between true bubble nucleation and microleak events, with the former characterized by a power spectrum peaked at 4.8 kHz and virtually no power into the region below

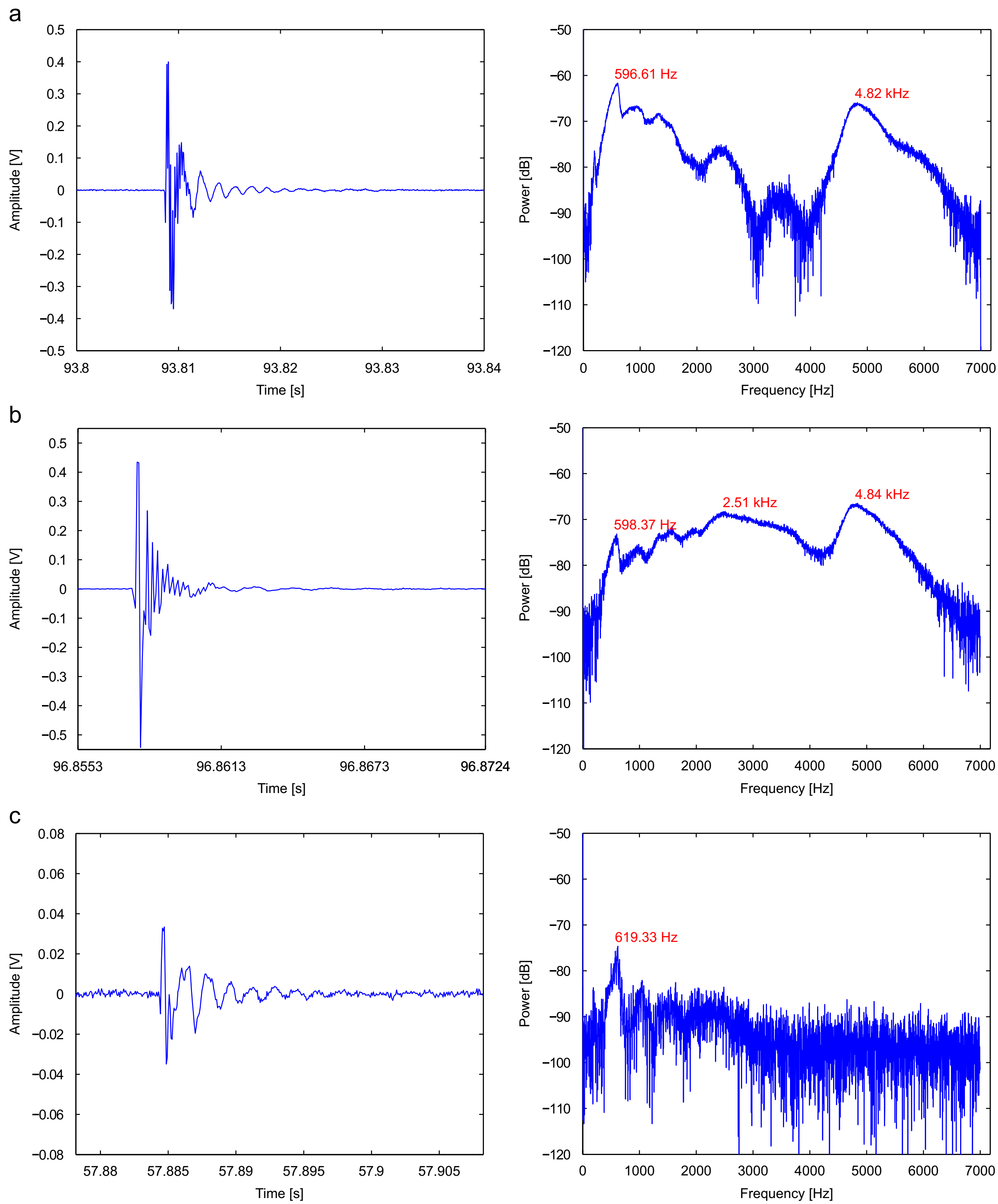

Fig. 11. Examples of characteristic waveforms and FFT types in the mesh-covered transducer; (a) and (b) correspond to true bubble nucleation events, whereas (c) results from a tapping on the SDD capping.

3 kHz. Acoustically, the ~10% power differences are not significant, and can be attributed to mechanical differences between the acquisition channels.

The improved transducer instrumentation, without mesh, was recently used in a 4 day test of a new SIMPLE 6 g CF_3I-based, 1 l SDD prototype, which recorded 33 total

Table 1
Results of the LSBB tests of the modified instrumentation

	Noise level (mV)	Frequency (kHz)	Power (dB)
Without mesh	0.97	4.5–5.5	-58 ± 6
With mesh	0.94	0.6, 4.5–5.5	-64 ± 6
Without freon	1.40	1.7–4.9	-52 ± 6

events registered prior to FFT filtering, and corresponded to the events visually observed during the detector removal from the water bath following the test. Twelve events survived the FFT filtering, none of which survived the pulse shape verification. These were later attributed to the fracturing of the gel during the measurement because of the high solubility of CF_3I gas which expands into microscopic gas pocket cavities causing a visible and audible crack (as tested with a SDD made by dissolving all the refrigerant inside the gel, which produced cracks within 24 h).

The addition of a grounded copper mesh surrounding the transducer results in a significant power increase into the low frequency region of the FFT, which appears to originate in the electronics itself. Its effect is to modify severely the FFT of true bubble nucleation events, the why of which is not yet understood. The differences do not appear to arise from differences in the actual events, e.g., whether the event occurs in the detector bulk or at the glass–gel interface, nor droplet–bubble size, etc.

Discrimination of the microleaks provides a significant improvement in the SIMPLE DAQ, alone improving the measurement sensitivity by a factor of 30 for the same exposure, improving the limit in the spin-independent sector by a similar factor and that in the model-independent spin-dependent sector by $\sim$3. The overall results provide strong motivations for the development of a true microphone-based instrumentation. This has been initiated, with the results to be reported in a forthcoming paper.

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