Project No. 13-4835

Microwave Readout Techniques for Very Large Arrays of Nuclear Sensors

Fuel Cycle Research and Development

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Executive Summary During this project, we transformed the use of microwave readout techniques for nuclear sensors from a speculative idea to reality. The core of the project consisted of the development of a set of microwave electronics able to generate and process large numbers of microwave tones. The tones can be used to probe a circuit containing a series of electrical resonances whose frequency locations and widths depend on the state of a network of sensors, with one sensor per resonance. The amplitude and phase of the tones emerging from the circuit are processed by the same electronics and are reduced to the sensor signals after two demodulation steps. This approach allows a large number of sensors to be interrogated using a single pair of coaxial cables. We successfully developed hardware, firmware, and software to complete a scalable implementation of these microwave control electronics and demonstrated their use in two areas. First, we showed that the electronics can be used at room temperature to read out a network of diverse sensor types relevant to safeguards or process monitoring. Second, we showed that the electronics can be used to measure large numbers of ultrasensitive cryogenic sensors such as gamma-ray microcalorimeters. In particular, we demonstrated the undegraded readout of up to 128 channels and established a path to even higher multiplexing factors. These results have transformed the prospects for gamma-ray spectrometers based on cryogenic microcalorimeter arrays by enabling spectrometers whose collecting areas and count rates can be competitive with high purity germanium but with 10x better spectral resolution.

Technical Results – Microwave Electronics

128 Channel Microwave Electronics

A photograph of the electronics hardware developed for this project is shown in Fig. 1. Tone generation and processing are performed using a Virtex 6 Field Programmable Gate Array (FPGA) chip. This chip is part of the so-called ROACH2 electronics developed by the CASPER radio astronomy consortium and adapted to this project. In addition to packaging the ROACH2 and its associated analog-to-digital/digital-to-analog (ADC/DAC) daughter card in an easy-to-use, low-noise enclosure, we developed custom intermediate frequency (IF) circuitry to mix tones generated at baseband up to GHz frequencies and then mix them back down again after probing the sensors.

Figure 1. The ROACH2 (at back) in its new case with the ADC/DAC (middle) and IF (front) circuitry inside the case, improved cooling fans, front panel SMA connections, and a lower noise power supply. The pictured IF circuitry was later replaced with better performing custom IF circuits.

We also developed firmware for the ROACH2 electronics that can generate and process microwave signals from up to 128 sensor channels per ROACH2 board. The firmware uses a polyphase filter bank to efficiently channelize different frequency bands after digitization. The architecture of the final firmware implementation is shown in Fig. 2 below.

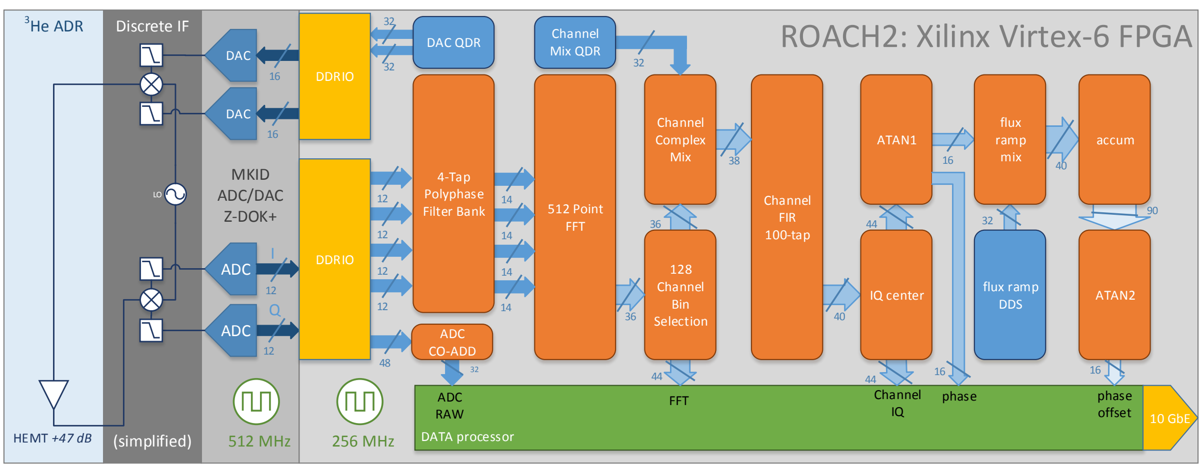

Figure 2. Firmware architecture for microwave tone generation and processing. Numbers in blue are the bit depth for each exchange of information.

The 128 channel firmware developed for the ROACH2 occupies only about 8% of the hardware resources on the central FPGA chip. Hence, there is abundant digital capacity to move to higher sensor counts. The vector network analyzer trace in Figure 3 shows the successful generation of 128 microwave tones that can be used to probe 128 sensor channels.

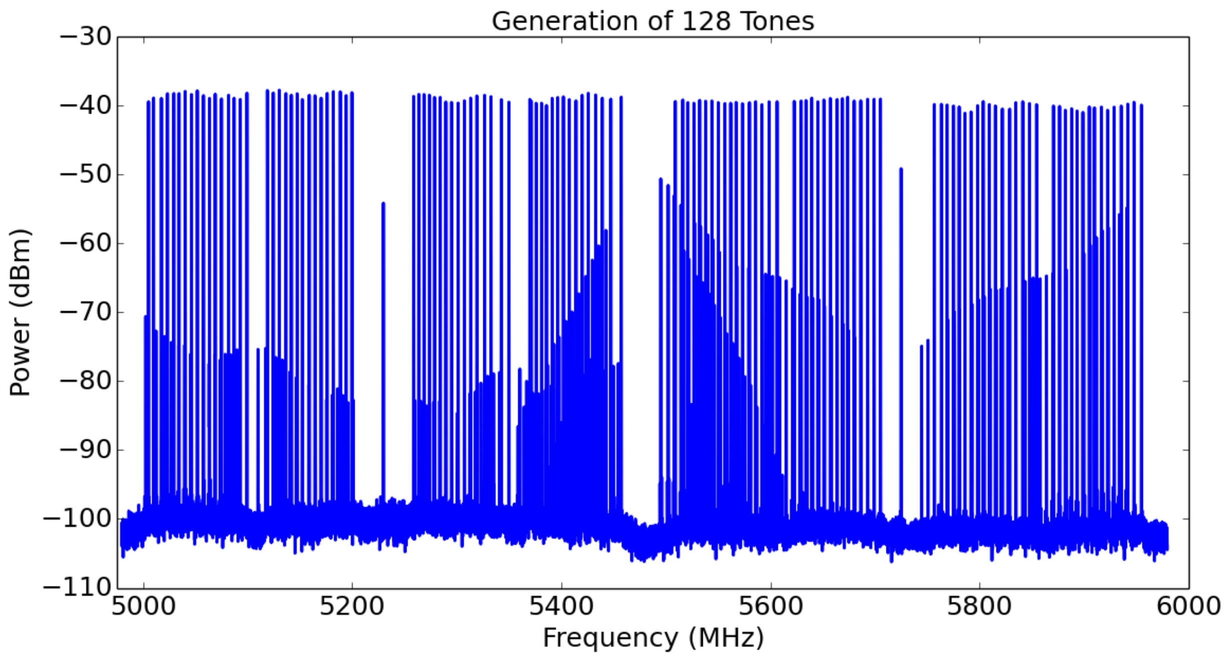

Figure 3. 128 microwave tones centered on 5.5 GHz produced by the ROACH2 electronics. The microwave tones are transmitted on a single shared coaxial cable and used to probe 128 sensor channels.

The functionality provided by the hardware and firmware developed for this project includes:

- Generation and summation of tones in MHz regime
- Up-mixing of summed tones to ~ 6 GHz regime
- Delivery of summed tones to resonators that can be coupled to sensors.
- Low noise measurement of summed tones emerging from microwave resonators
- Down-mixing of summed tones from GHz to MHz regime
- Digitization of summed analog MHz tones
- Channelization of tones, meaning separation into frequency bands that isolate each carrier frequency along with any signal embedded as perturbations to the carrier
- Extraction of sensor signals from the channelized tones using flux ramp demodulation.

All this functionality is performed in real time thanks to the processing power of the Virtex6 FPGA chip. Presently, the 128 tones must reside within a 500 MHz band due to the limits of the ROACH2 ADC/DAC hardware, but more modern ADC/DAC hardware will overcome this limit.

In addition to hardware and firmware development, we also wrote software to command the ROACH2 electronics and to make sense of and display the information returned from it. One example task performed by the software is to determine the frequencies for the microwave tones generated by the ROACH2; the correct frequencies correspond to the resonance frequencies of the thin-film resonators on the multiplexer chips in the cryostat. A screen shot from the software control environment is shown in Figure 4.

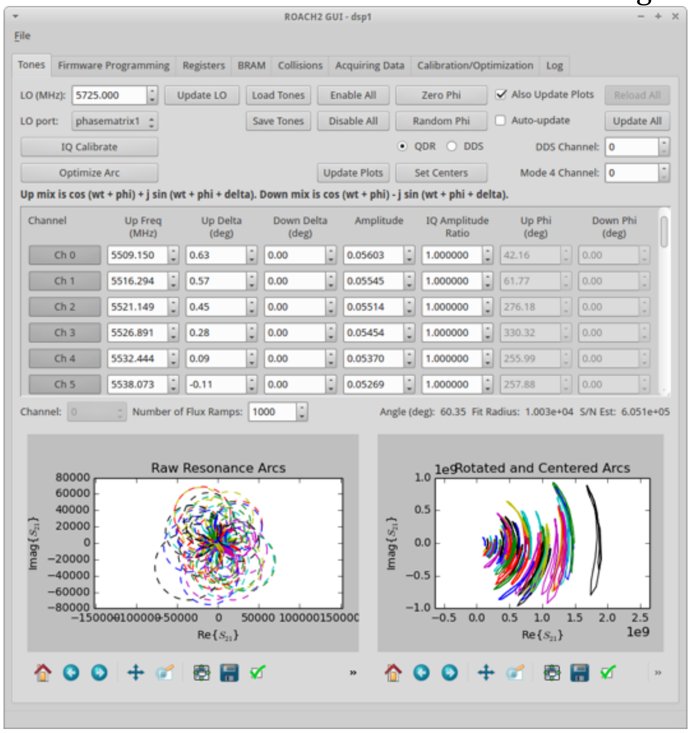

Figure 4. Screen shot of software control environment for microwave readout experiments. The plots at bottom are visualizations of the real and imaginary parts of the microwave transmission through the shared feedline for many sensor channels. These signals change in response to the state of the sensors.

Technical Results – Conventional Sensor Networks

An important goal of this project was to show that microwave readout can be used at room temperature to monitor networks of diverse sensor types. The use of microwave readout to monitor a sensor network has several attractions. Network complexity is transferred from the sensors to the central control electronics which could be advantageous in nuclear facilities where access to sensors after their installation may be very limited. All signals are carried on a single, simple coaxial cable so complex and expensive rewiring of a nuclear facility is not needed in the event of a change to the sensor network. Further, all sensors are monitored continuously using analog signals that have a clear connection to the physical state of the sensors. Such an architecture may be more robust to tampering than conventional digital networking.

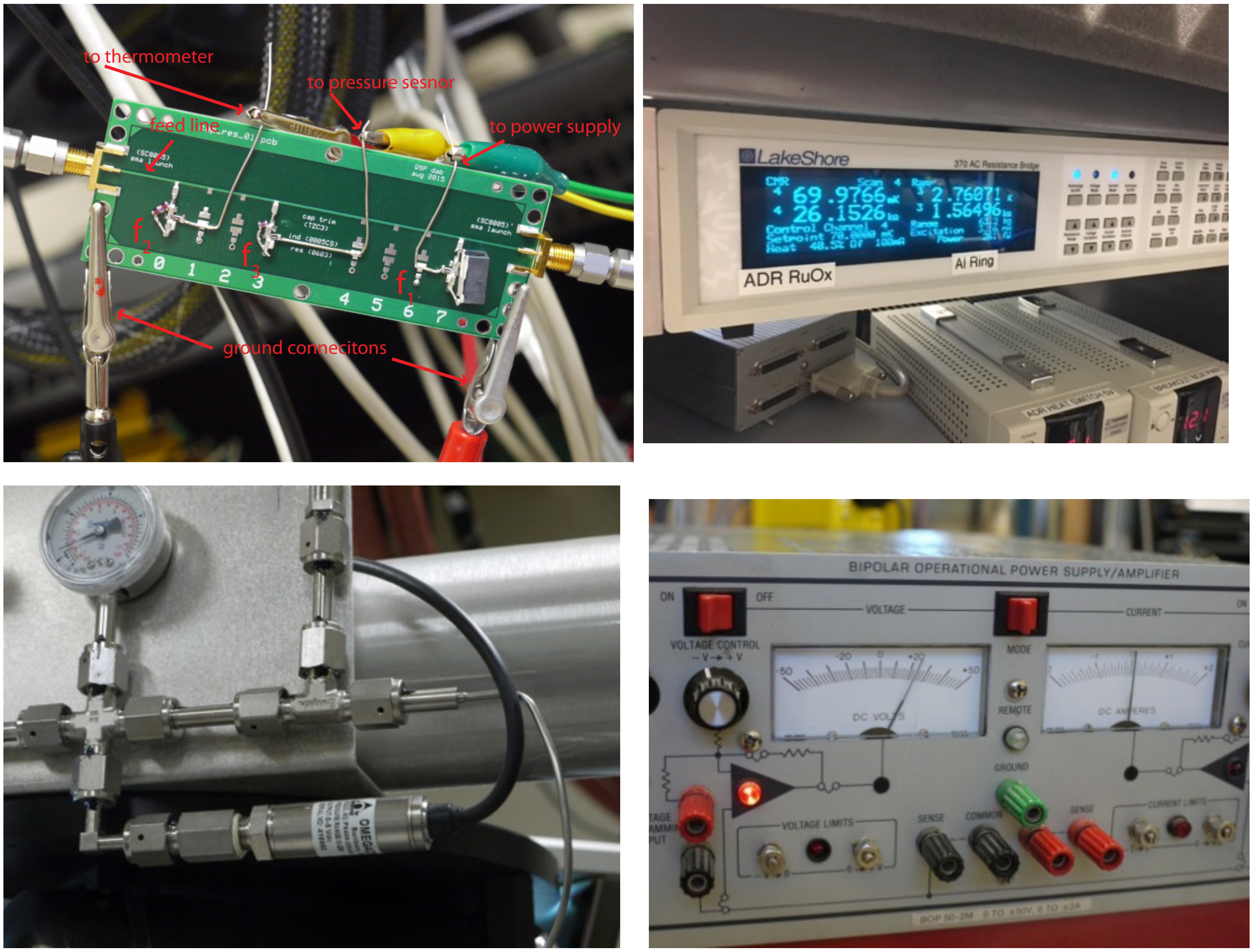

Figure 5. (Top left) Printed circuit board (PCB) containing microwave feedline and microwave resonators (labeled f_1, f_2, and f_3). Voltage signals from each element of a sensor network connect to the microwave resonators. Each voltage signal is connected to a voltage-controlled capacitor or varactor. The form factor of the PCB is not representative of how a sensor network for safeguards would be connected; it was chosen to be convenient for laboratory testing. (Top right) Commercial resistance bridge for temperature measurement used in the model sensor network. (Bottom left) Commercial pressure sensor used in the network. (Bottom right) Commercial voltage supply whose output was monitored using microwave readout.

Our key result in this technical area was demonstrating the use of microwave readout to monitor the state of a small network containing three very different pieces of electronics. These were (1) a commercial resistance bridge, (2) a commercial pressure sensor, and (3) a commercial voltage source (see Fig. 5). In all three cases, the state of the instrument is indicated by a voltage output which is transduced to a capacitance by means of an inexpensive, commercial varactor. The varactors are each embedded in room temperature microwave resonance circuits assembled from inductors and capacitors. Each resonance circuit has a unique identifying frequency and the three resonance circuits are monitored continuously using microwave tones from the ROACH2 electronics developed for this project.

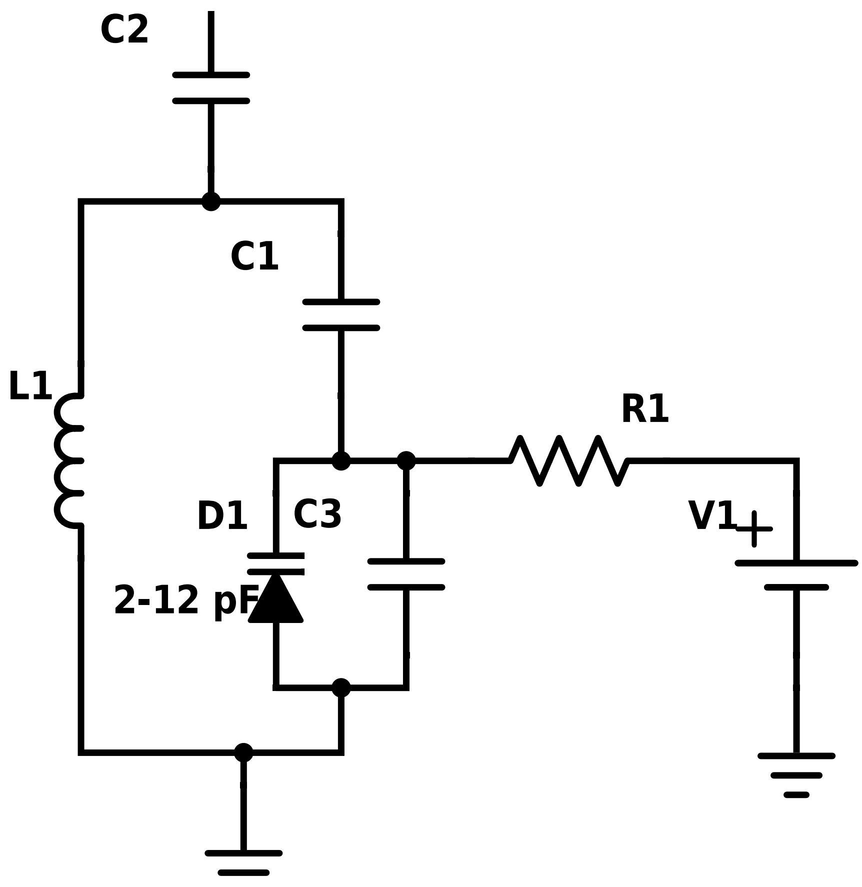

Figure 6. Electrical circuit for one microwave resonator. The input signal of interest is V1. The varactor (D1) is shown as a composite diode and capacitor. The capacitor C3 is used to keep the change of resonance frequency due to changing V1 to within a half bandwidth of the resonance. R1 is used for isolation of the signal voltage V1. C1 stops the current biasing the diode from being shorted to ground. C2 mostly controls the input coupling of the resonance circuit and limits the change in quality factor. L1 helps to create a circuit resonance at the target frequency and frequency width.

A detailed electrical circuit for one microwave resonator is shown in Figure 6. This circuit is replicated for each sensor in the network but with slightly different circuit values so that the resonance frequencies are nonoverlapping. All the resonators are connected to a single microwave feedline that is connected to the ROACH2 electronics. Microwave tones are injected at one end of the feedline and monitored at the other. For the present demonstration, the feedline was a trace on a PCB but in an actual safeguards scenario the feedline would be a coaxial cable or cables.

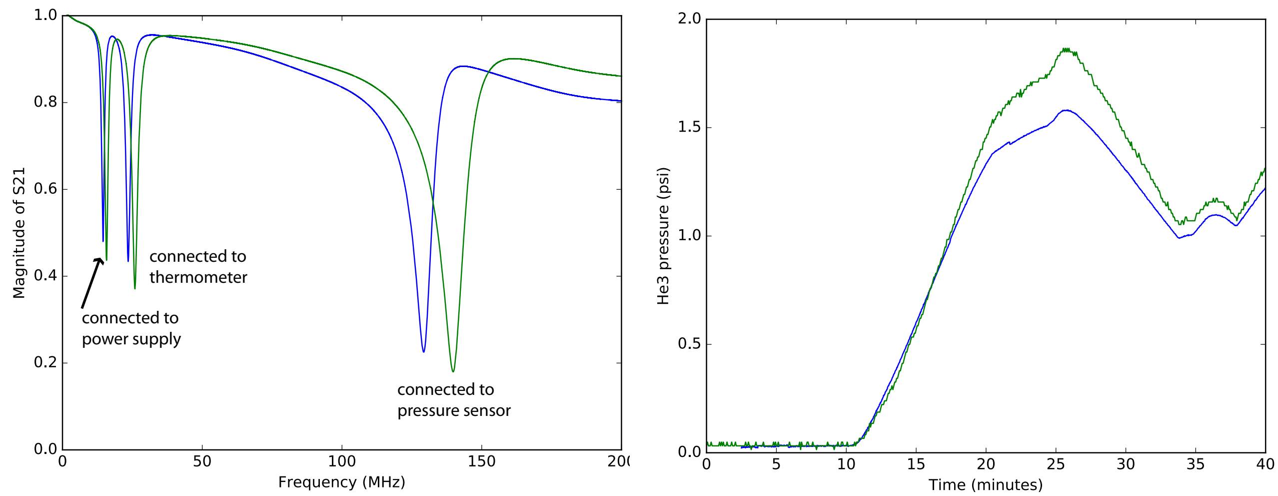

Figure 7. (Left) Measured microwave transmission through feedline vs frequency. The state of the three sensors affects transmission near their identifying resonance frequencies. The two curves (blue, green) show circuit behavior for minimum and maximum values of voltage applied to the varactors. (Right) Successful measurement of gas pressure performed using microwave techniques (blue) compared to conventional techniques (green). The amplitude discrepancies are due to an overly simple calibration scheme for the microwave readout.

Measured results for the sensor network of Fig. 5 are shown in Fig. 7 above. At left are measurements of microwave transmission through the feedline as a function of frequency. Frequencies as high as 8 GHz are accessible but 200 MHz is the highest value shown. Three microwave resonances are visible, one for each sensor. The two curves (blue, green), show the microwave response of the circuit when minimum (0 V) and maximum (10 V) signals are applied to the three varactors. The resonances shift in frequency, which changes microwave signals transmitted through the feedline. The frequency locations and widths of the resonances can be further optimized in the future. At right is a measurement of gas pressure vs time. The two curves show measurements performed using microwave techniques (blue) and conventional techniques (green). There is excellent qualitative agreement between the measurements and mediocre quantitative agreement. The quantitative discrepancies arise because the microwave technique assumes a simple linear correlation between pressure and transmitted microwave power; implementation of a nonlinear calibration curve is straightforward for the future. Similar comparisons have been successfully performed for the resistance bridge and the monitor output of the voltage supply.

The demonstration above used varactor diodes to transduce sensor voltages to capacitance changes in resonator circuits. However, our technique is considerably more general than just the use of varactors. Any physical change that can be transduced to a change in capacitance, inductance, or resistance can be measured. For example, physical displacements straightforwardly give rise to capacitance changes and therefore can be measured using the same technique. Also, the three sensors measured above were far from exhausting the 500 MHz of bandwidth available per ROACH2 unit so much larger networks of sensors are possible.

This work completed a M3 milestone scheduled for 9/30/2016 and fulfills one of the broad visions outlined in the original proposal.

Technical Results – Operation of Microcalorimeter Sensors

A second key goal for this project was to use microwave readout to measure signals from an array of gamma-ray microcalorimeter sensors. To review, these cryogenic sensors provide resolving powers 5-10x better than high purity germanium but the small size and slow response of individual devices necessitates the use of sensor arrays in practical applications. The largest array achieved before this work was 256 sensors measured using 8 amplifier channels, so that each amplifier was measuring the multiplexed signals from 32 sensors. This multiplexing was performed in the time domain and the bandwidth available per amplifier was only 5-10 MHz (D. Bennett *et al*, Review of Scientific Instruments, 2012). In what follows, we show that these earlier results have been decisively surpassed using microwave readout.

To read out microcalorimeter sensors, the current pulses from these devices are transduced to an inductance change using a specialized thin-film circuit called a RF-SQUID. Each RF-SQUID is embedded in a thin-film resonator that couples to a shared microwave feedline. We designed and fabricated these circuits as shown in Fig. 8. An important result was reducing the current noise of these circuits by a factor close to 4 compared to our proof-of-principle demonstration before this NEUP project. We successfully reduced the current noise to about 20 pA/rt(Hz) which is low enough to have negligible impact on the resolution of most microcalorimeter sensors.

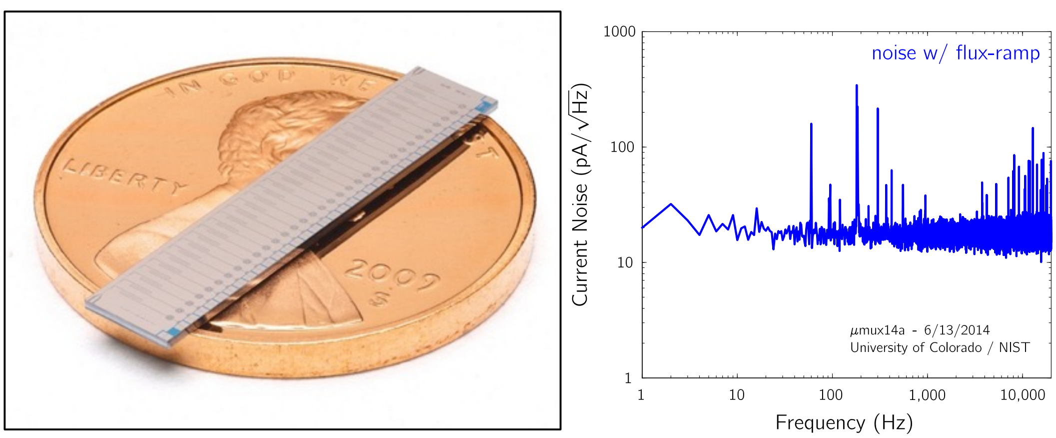

Figure 8. (left) Photograph of 33 channel RF-SQUID circuit with penny for scale. The shared feedline runs the length of the chip. The thin-film resonators can be seen as faint trombone-shaped structures spanning the width of the chip. (right) Measured noise spectral density from new RF-SQUID amplifiers. The noise is measured after flux ramp demodulation and is therefore representative of the noise that will be encountered by sensors coupled to the amplifier chips.

With RF-SQUID circuits and the microwave electronics in hand, we assembled the measurement circuit shown in Fig. 9.

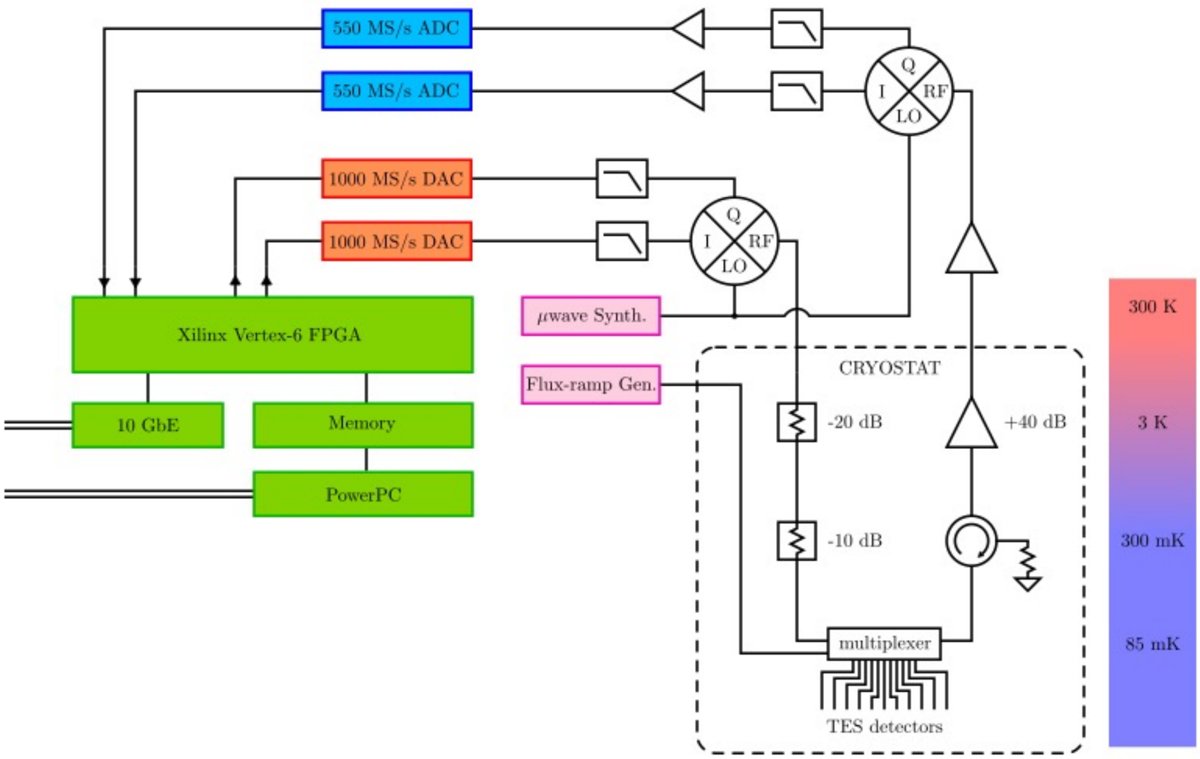

Figure 9. System diagram. The gamma-ray microcalorimeters use the resistive transition of a superconducting film to transduce deposited photon energy into a change in electrical current and are therefore known as Transition Edge Sensors (TESs). The multiplexer chip contains the shared microwave feedline, microwave resonators, and RF-SQUIDs which transduce TES current to a change in resonator frequency. The warm electronics functionality is provided by the hardware of Fig. 1 and the firmware of Fig. 2.

We also assembled a detector package containing gamma-ray microcalorimeters, RF-SQUIDs, and passive resistors and inductors. A photograph of the assembled detector package is shown in Figure 10. Microwave signals enter and leave the box on just four SMA connectors at the top and bottom walls of the package. The package is intended to have 256 microcalorimeter sensors although it can be seen in the figure that some are missing their Sn gamma-ray absorbers. This detector package and the measurement setup of Figure 9 are called **S**pectrometer to **L**everage **E**xtensive **D**evelopment of **G**amma-ray T**E**Ss for **H**uge **A**rrays using **M**icrowave **M**ultiplexed **E**nabled **R**eadout, or **SLEDGEHAMMER**.

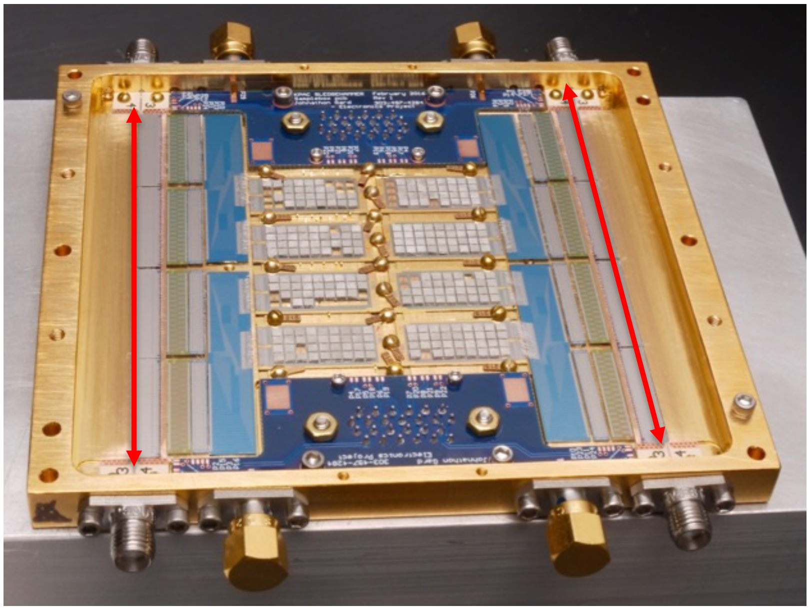

Figure 10. Complete SLEDGEHAMMER detector package with microcalorimeter sensors at center. Smaller silicon chips at sides contain the RF-SQUIDs, bias resistors, Nyquist inductors, and ancillary wiring. Red arrows indicate the two microwave feedlines that are coupled to the resonators and RF-SQUIDs. Each feedline is coupled to 128 resonators and RF-SQUIDs.

An important characterization measurement is shown in Figure 11 below. The figure shows the microwave transmission through four silicon chips containing a total of 128 RF-SQUIDs and thin-film resonators. The full SLEDGEHAMMER detector package contains eight silicon chips with a total of 256 RF-SQUIDs.

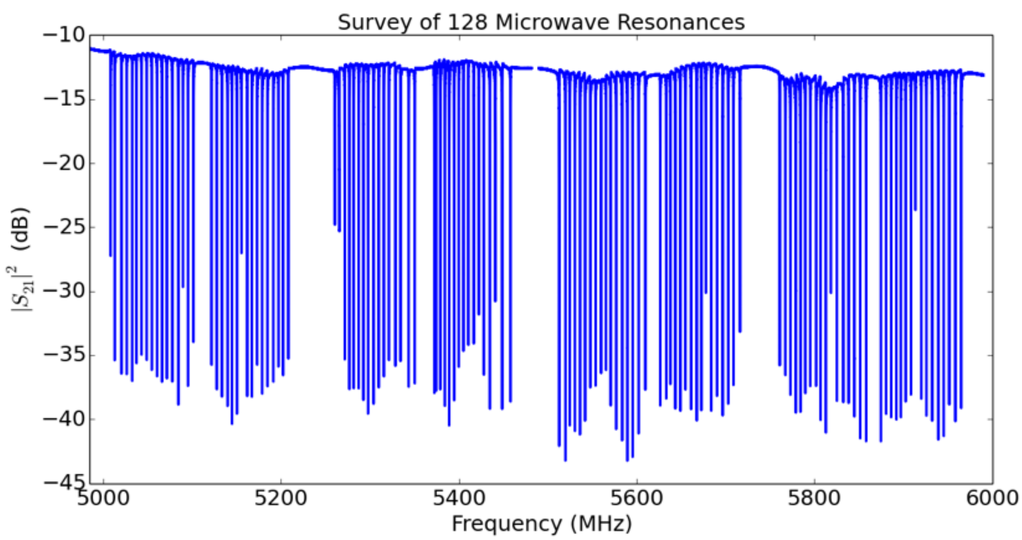

Figure 11. Microwave transmission through shared feedline with 128 coupled microwave resonators and RF-SQUIDs. The microwave tones of Fig. 3 are tuned to the resonances in order to probe the state of the sensors whose current is modulating the inductance of the RF-SQUIDs.

We successfully cooled and operated the SLEDGEHAMMER instrument using our microwave readout electronics. A crucial metric for microwave readout is that the noise from the technique be much smaller than the intrinsic noise of the sensors under study. When this condition is met, energy resolution during gamma-ray spectroscopy will be set by the sensors, and not the readout. We measured the readout noise in all of the 256 sensor channels of the first SLEDGEHAMMER detector package. The noise data was acquired in two separate measurements of 128 channels but similar data will be acquired simultaneously in the future. Histograms of the average readout noise in the four quadrants of the detector package are shown in Figure 12. While this figure is rather undramatic, it tells a crucial story: that microwave techniques are enabling the undegraded readout of more sensor channels per amplifier (128) than ever before.

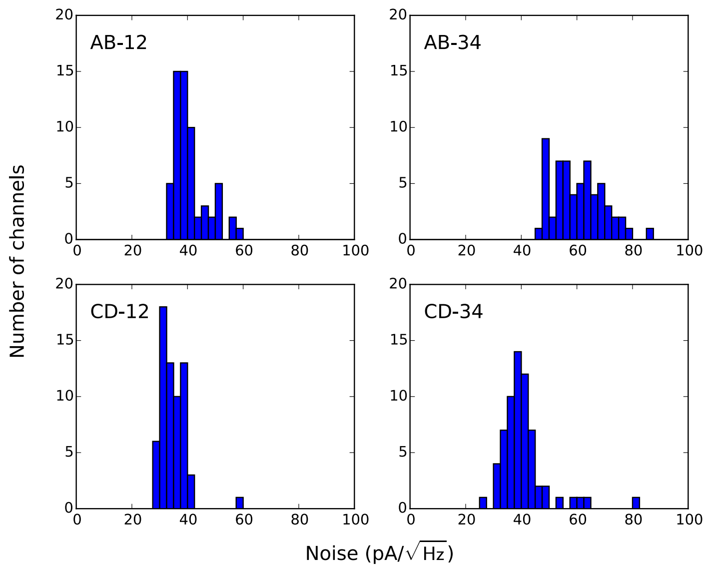

Figure 12. Histograms of average readout noise in 256 sensor channels divided into four quadrants. Typical values of sensor noise from a gamma-ray microcalorimeter are 100 pA/Hz$^{1/2}$, substantially larger than the values in the figure (in these units, noise terms add in quadrature). The average noise in quadrant AB-34 is higher than the other quadrants. This is due to less microwave power reaching the shared HEMT amplifier from the RF-SQUIDs in this quadrant.

The noise values in Figure 12 are mostly centered around 40 pA/Hz$^{1/2}$. In subsequent work, we determined that insufficient microwave power was reaching all the resonators. After remedying this problem, we obtained noise histograms centered around 20 pA/Hz$^{1/2}$, consistent with our expectations based on early results such as Fig. 8. While this additional noise margin isn't needed for gamma-ray sensors, it is desirable for other sensor types.

Having demonstrated full functionality of the readout system, we proceeded to acquire gamma-ray spectra from a ^{153}Gd radioisotope source using the first SLEDGEHAMMER detector package. The package contains 256 gamma-ray microcalorimeters on 8 separate silicon chips supplied by our collaborators at the NIST Boulder Laboratories. Unfortunately, more than half of the sensors contained defects. In total, only 89 sensors were sufficiently defect-free to be useful for high performance spectroscopy. Figure 13 shows output data streams from about 50 high quality microcalorimeter sensors. The traces illustrate both the time constant and signal-to-noise ratio of the sensors.

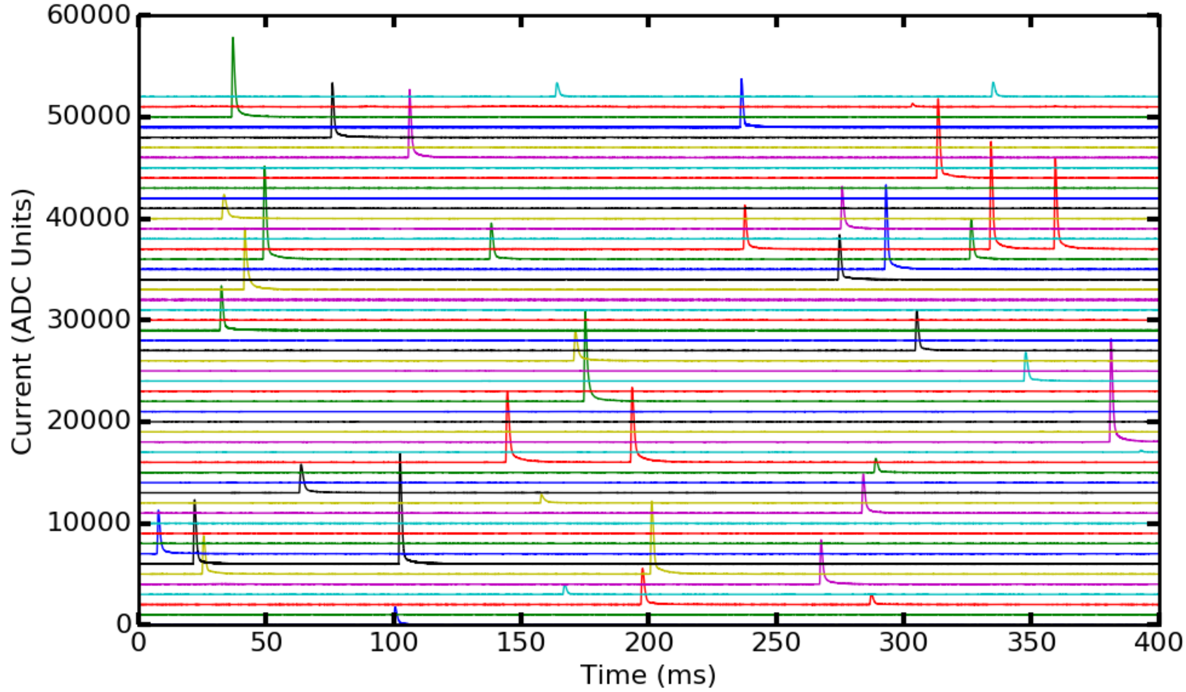

Figure 13. Output data streams from 53 microcalorimeter sensors under illumination from a ^{153}Gd radioisotope source. The displayed timespan is 0.4 seconds.

After accumulating and filtering digitized pulses from the 89 good sensors, we generated the gamma-ray spectrum shown in Figure 14.

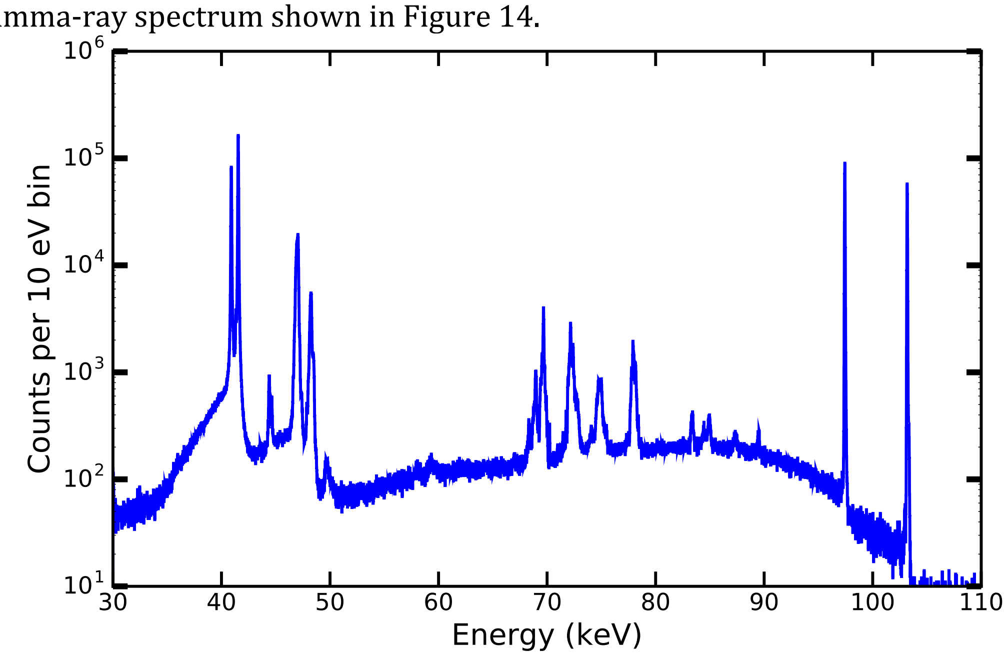

Figure 14. Gamma-ray spectrum of ^{153}Gd radioisotope source acquired using microwave readout and 89 microcalorimeter sensors. The two bright lines at 97 and 103 keV are gamma-rays from ^{153}Gd. Most of the features between 40 and 50 keV are x-rays from the

Eu daughter product. The features between 70 and 90 keV are x-ray escape events from the Sn absorbers and Pb fluorescence from the source packaging.

The peak-to-background ratio in Fig. 14 varies with energy, as expected, but is > 10^3 for the main Gd lines of interest. An expanded view of the 97 keV region is shown in Figure 15.

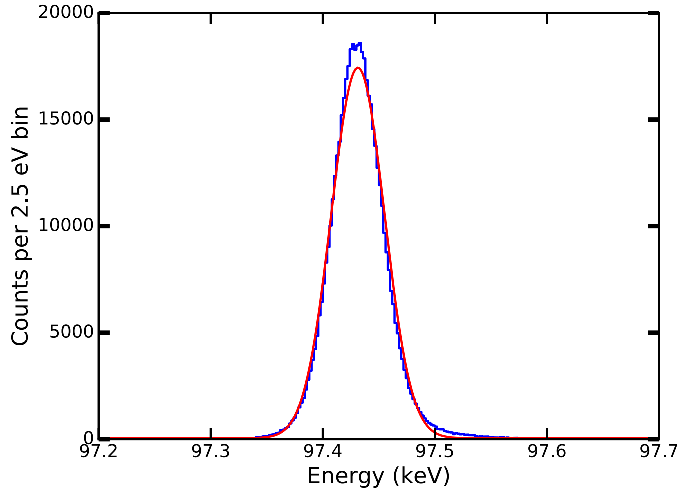

Figure 15. Zoomed view of 97 keV spectral region from Fig. 14 replotted with a linear vertical scale. The full-width-at-half-maximum of the ^{153}Gd gamma-ray line obtained from a Gaussian fit (red) to the data (blue) is 55 eV, almost 10 times narrower (better) than high-purity germanium. The spectrum was obtained by summing spectra from 89 individual sensors. The sum of a finite number of Gaussians with different widths is not itself a Gaussian which explains the difference between the blue and red traces.

These results comprise a fully successful demonstration of microwave readout with cryogenic sensors. We read out 128 sensor channels with one amplifier, a 4-fold improvement in multiplexing factor over previous work. Significant further increases in the multiplexing factor will be achieved in the near future. We have conclusively shown that the readout noise of our technique allows gamma-ray spectroscopy with almost 10x better resolution than high purity germanium. Finally, the use of microwave readout produces a large simplification of the spectrometer design as shown in Figure 16.

This work completed a M2 milestone scheduled for 12/31/2016 and fulfills the second broad vision outlined in the original proposal.

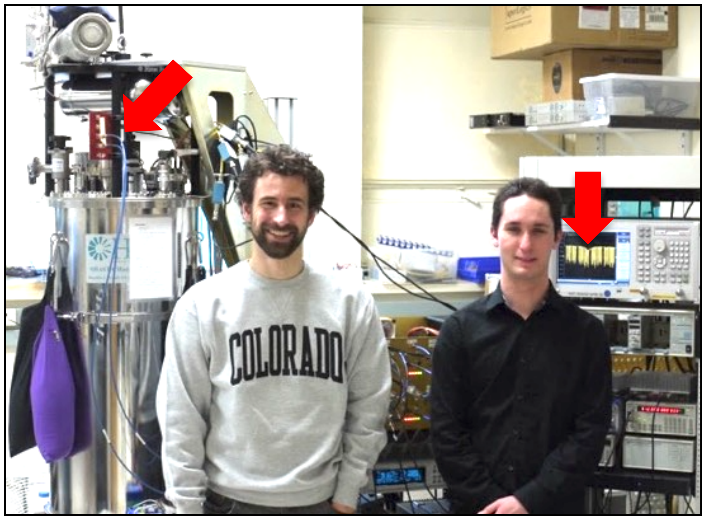

Figure 16. Project researchers Ben Mates (left) and John Gard (right) standing by the SLEDGEHAMMER spectrometer. The red arrow at left indicates two blue coaxial cables that carry all the signals used to read out 128 sensors. Previous readout schemes required many 10s of cables. The red arrow at right shows measured microwave transmission through the readout circuit.

Preview of Future Results

Tremendous performance gains are now within reach. Each ROACH2 unit of our microwave electronics can manipulate 500 MHz and our budget allowed us to purchase 2 ROACH2 units corresponding to 1 GHz of active bandwidth. However, the HEMT amplifier that we are using provides 4 GHz of potential bandwidth. There is no technical obstacle to buying more ROACH2 units to use the full 4 GHz. In addition, we are now discussing yet more capable electronics with a commercial supplier wherein a single unit can manipulate 4 GHz. We have used resonators with 6 MHz spacing so far but have already demonstrated that 3 MHz spacings are realistic. With 4 GHz of bandwidth and 3 MHz resonator spacings, 1300 sensor channels can be measured using a single amplifier. For comparison, previous, non-microwave techniques only allowed 32 gamma-ray sensors per amplifier. The results obtained during this project have transformed the potential for large arrays of cryogenic sensors. This advance has resulted in considerable recognition. Dr. Ben Mates has been invited to speak at an upcoming international conference and similar readout work has been initiated at Los Alamos, Argonne, NASA Goddard, and SLAC laboratories. All these programs are using RF-SQUIDs designed by our team at the University of Colorado.

Summary

We successfully developed hardware, firmware, and software that enabled the full demonstration of microwave readout techniques. We demonstrated that these techniques can be used to measure signals from networks of diverse conventional sensors as might be used for safeguards or process monitoring in a large nuclear facility. We also demonstrated that microwave readout techniques can enable a substantial increase in the size of arrays of cryogenic sensors. We have assembled a unique gamma-ray spectrometer based on cryogenic microcalorimeters with microwave readout and demonstrated 10x better energy resolution than possible with high purity germanium sensors.

Publications

- D. A. Bennett, J. A. B. Mates, J. D. Gard, A. S. Hoover, M. W. Rabin, C. D. Reintsema, D. R. Schmidt, L. R. Vale, J. N. Ullom, "Integration of TES microcalorimeters with microwave SQUID multiplexed readout," *IEEE Transactions on Applied Superconductivity,* 25 (2015) 2101405.
- J. A. B. Mates, D. T. Becker, D. A. Bennett, J. D. Gard, J. P. Hays-Wehle, J. W. Fowler, G. C. Hilton, C. D. Reintsema, D. R. Schmidt, D. S. Swetz, L. R. Vale, J. N. Ullom, "Simultaneous readout of 128 gamma-ray transition-edge microcalorimeters using microwave SQUID multiplexing," in preparation for *Applied Physics letters*.
- J. D. Gard, D. Becker, D. A. Bennett, J. D. Fowler, G. C. Hilton, J. A. B. Mates, C. D. Reintsema, D. Schmidt, D. Swetz, J. N. Ullom, L. R. Vale, J. Hays-Wehle, "A scalable readout for microwave SQUID multiplexing of transition-edge sensors", in preparation for *Journal of Low Temperature Physics*.

Presentations (including by NIST collaborators on joint work)

- "Microwave Multiplexed Readout for Large Arrays of TES Microcalorimeters", D.A. Bennett, J.A.B. Mates, J. Brevik, J. Gao, J.P. Hays-Wehle, J.W. Fowler, J. Gard, G.C. Hilton, C.D. Reintsema, D.R. Schmidt, L.R. Vale, J.N. Ullom, R. Winkler, A.S. Hoover, M.W. Rabin, oral presentation at the Symposium on Radiation Measurement and Applications, June 2014, Ann Arbor MI.
- "Microwave Multiplexed Readout for Large Arrays of TES Microcalorimeters", D.A. Bennett, J.A.B. Mates, J.P. Hays-Wehle, J.W. Fowler, J. Gard, G.C. Hilton, C.D. Reintsema, D.R. Schmidt, L.R. Vale, J.N. Ullom, O. Noroozian, R. Winkler, A.S. Hoover, M.W. Rabin, oral presentation at the 2014 Applied Superconductivity Conference, Aug. 2014, Charlotte NC.
- "Microwave Multiplexed Readout for Large Arrays of Cryogenic Sensors", D.A. Bennett, D.T. Becker, J.D. Gard, J.A.B. Mates, C.D. Reintsema, J.W. Fowler, G.C. Hilton, D.R. Schmidt, L.R. Vale, and J. N. Ullom, Astronomy Signal Processing and Electronics Research Workhop, Jan. 2016, Capetown South Africa.
- "Advances in Microwave SQUID Multiplexers", J. A. B. Mates, D. T. Becker, D. A. Bennett, J. D. Gard, J. P Hays-Wehle, G. C. Hilton, C. D. Reintsema, L. R. Vale, J. N. Ullom, oral presentation at the Applied Superconductivity Conference, Sept. 5-9, 2016, Denver CO.
- "Firmware Development for the Read-out of High-bandwidth Sensors Using Microwave SQUID Multiplexers", J. D. Gard, J. A. B. Mates, D. Becker, J. N. Ullom, D. A. Bennett, G. C. Hilton, J. W. Fowler, C. D. Reintsema, L. R. Vale, poster presented at the Applied Superconductivity Conference, Sept. 5-9, 2016, Denver CO.
- "Maximizing Multiplexing Factors for High-Sampling-Rate Microwave SQUID Multiplexers", D. Becker, D. Bennett, J. Gard, G. Hilton, J. A. B. Mates, C. Reintsema, D.

Schmidt, D. Swetz, J. Ullom, L. Vale, poster presented at the Applied Superconductivity Conference, Sept. 5-9, 2016, Denver CO.

- "SLEDGEHAMMER: a microwave multiplexed transition edge sensor array for nuclear non-proliferation applications", D. Schmidt, D. Bennett, D. Becker, J. Gard, G. Hilton, V. Kotsubo, J. A. B. Mates, C. Reintsema, D. Swetz, L. Vale, J. Ullom, M. Croce, A. Hoover, M. Rabin, L. Sexton, J. Wilson, oral presentation at the Applied Superconductivity Conference, Sept. 5-9, 2016, Denver CO.
- "Microwave SQUID multiplexer development", J. A. B. Mates, invited oral presentation at the 17th International Workshop on Low Temperature Detectors, July 17-21, 2017, Kurume Japan.
- "Firmware Development for Microwave SQUID Multiplexer Readout", J. D. Gard, D. Becker, D. A. Bennett, J. D. Fowler, G. C. Hilton, J. A. B. Mates, C. D. Reintsema, D. Schmidt, D. Swetz, J. N. Ullom, L. R. Vale, J. Hays-Wehle, poster presentation requested at the 17th International Workshop on Low Temperature Detectors, July 17-21, 2017, Kurume Japan.
- "A large-scale demonstration of microwave SQUID multiplexing: the SLEDGEHAMMER TES gamma-ray microcalorimeter instrument", D. Becker, D.A. Bennett, J. D. Gard, J.P. Hays-Wehle, J.D. Fowler, G.C. Hilton, J.A.B. Mates, C.D. Reintsema, D.R. Schmidt, D.S. Swetz, L.R. Vale, and J.N. Ullom, oral presentation requested at the 17th International Workshop on Low Temperature Detectors, July 17-21, 2017, Kurume Japan.