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Non-linearities in Superconducting Tunnel Junction Radiation Detectors and Their MCA Readout

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Abstract
The response of cryogenic high-resolution detectors to a short-pulse laser consists of a Poisson-distributed set of equidistant peaks that correspond to integer numbers of absorbed photons. Since the laser has a negligible intrinsic line width, the peaks can be used for detailed characterization of both the detector and the data acquisition system. We have characterized our superconducting tunnel junction (STJ) photon detectors in the UV and soft X-ray range with a pulsed 355-nm laser at rates up to 5000 counts/s. The observed peaks are described by a Gaussian to very high accuracy, with a width between ~1 and ~3 eV FWHM depending on the detector area and the absorbed energy. For high statistics, centroids can be determined with a precision of order 1 meV over an energy range of several 100 eV. This allows identifying and correcting for non-linearities in the digitizer that can otherwise limit the calibration accuracy.

Keywords Superconducting tunnel junctions · STJ radiation detectors · EUV detectors · MCA non-linearity · Integral non-linearity

1 Introduction

The calibration accuracy of high-resolution spectra is ultimately limited by the uncertainties of the calibration energies, the predictability of the detector response function and the non-linearity of the multi-channel analyzer (MCA) of the data acquisition system. Pulsed optical or UV lasers are good sources for detector calibration because they have negligible intrinsic linewidth, their wavelength can be

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measured with high accuracy and multi-photon absorption produces a distribution of equidistant peaks over a wide energy range.

We have used a pulsed 355-nm UV laser to measure the response of our superconducting tunnel junction (STJ) radiation detectors and determine their calibration accuracy in the extreme ultraviolet (EUV). This paper shows that an accuracy of ± 1 meV is attainable and discusses the limiting contributions.

2 Experiment

The detectors in these experiments were superconducting Ta–Al–AlOx–Al–Ta tunnel junctions with different areas fabricated at STAR Cryoelectronics [1]. They were operated at $T \approx 0.1$ K in an adiabatic demagnetization refrigerator (ADR) with liquid N_2 and He pre-cooling. The temperature was not regulated, since the STJ response is constant as long as the thermal quasiparticle density is negligible. The detectors were exposed to a pulsed frequency-tripled Nd:YVO_4 laser (Spectra Physics, model J40-B16-106Q) through an optical fiber. Its single-photon energy has been calibrated relative to the emission of a Hg vapor lamp as 3.49865 ± 0.00015 eV [2]. The STJ signals were read out with a custom 32-channel preamplifier, digitized with Texas Instruments AFE-5801 ADCs and processed on an FPGA with a trapezoidal filter with a 16-µs peaking time [3]. The preamplifier output from one of the STJs is split and available at an external port. It was fed into an analog spectroscopy amplifier (Ortec, model 627) with 10 µs Gaussian shaping and captured with a nuclear MCA (Ortec, model Aspec927 [4]), so that the same signals from one detector could be analyzed with two different amplifier chains. This allows separating detector non-linearities from MCA non-linearities.

3 Results

The spectrum of an STJ in response to a pulsed laser consists of a comb of Poisson-distributed peaks that correspond to the absorption of integer numbers of laser photons per pulse. Since the pulse length of ~ 5 ns is significantly shorter than the ~ 1-µs rise time of the STJ signal, the peaks are exactly equidistant. In addition, the pulse rate can be set to avoid pileup that distorts the spectra. Figure 1 (*top*) shows a 1-h spectrum of a midsize (138 µm)^2 STJ, taken with the Ortec shaper and MCA at a rate of 5000 counts/s. We fit the spectrum to a superposition of Gaussians to extract peak centroids and widths. The detector resolution varies between 1.7 and 2.5 eV so that the peaks are well resolved up to several 100 eV. Importantly, the energies of the peaks are absolute values whose accuracy depends only on the accuracy of the single-photon energy. The large number of equidistant Gaussian peaks with high statistics makes a pulsed laser an excellent tool to test STJ and MCA non-linearity.

We had noticed in the past that the calibration at low energies shows non-linearities that depend on the choice of the MCA. We therefore exclude the lowest 60 eV from the energy calibration where this effect is noticeable. At higher

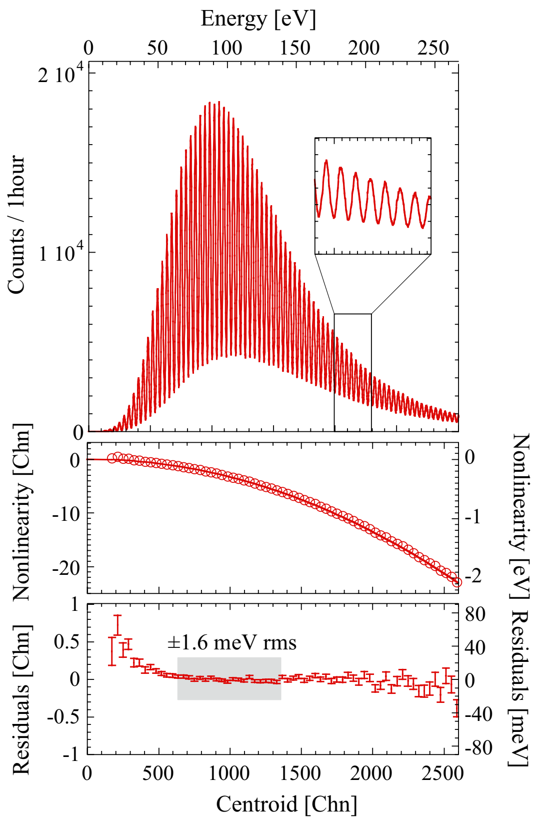

Fig. 1 (*Top*): The response of an STJ detector to a pulsed 355-nm laser consists of a Poisson-distributed set of peaks that correspond to integer numbers of absorbed photons. (*Middle*): This STJ detector has a non-linearity of ~ 0.01/eV in this run. (*Bottom*): For a 1-h spectrum at 5000 counts/s, the calibration accuracy of the spectrum is ± 1.6 meV rms in the region of high-count peaks, consistent with statistical fluctuations (Color figure online)

energies, the STJ response follows a second-order polynomial to high accuracy, with a non-linearity of ~ 0.01/eV (Fig. 1, *middle*).

Figure 1 (*bottom*) shows the residuals between the measured peak centroids and the quadratic energy calibration. They are consistent with zero for most of the energy range, except at energies below 60 eV where the MCA non-linearity dominates. This suggests that the STJ response can be described by a second-order polynomial to very high accuracy. In the energy range around 100 eV where the peaks contain the maximum number counts, the residuals fluctuate by ± 1.6 meV around zero, or roughly 1 part in 10^5. This is consistent with the expected statistical fluctuations.

This high calibration accuracy is achieved through a process called *sliding scale linearization* that is used in certain MCAs for nuclear spectroscopy such as the Ortec Aspec 927 to reduce intrinsic fluctuations in channel width [4, 5]. The process relies on adding a random but known analog voltage to each input signal, so that signals with the same initial amplitudes fall into different channels of the MCA. After digitization, the digital value of the analog voltage is subtracted so that signals with the same amplitude produce the same digital value. This process averages out fluctuations in the width of individual channels and improves the linearity of the MCA.

The sliding scale linearization breaks down for the first and last channels of an MCA where the addition of a random voltage can cause the signal to exceed the MCA input range. This causes the linearity to degrade for small signals and is responsible for the increase in the residuals for energies below ~60 eV (Fig. 1, *bottom*).

Since the preamplifier output from one of the STJ detectors is available at an external port, we can feed the exact same signals into two separate amplifier chains to compare their performance. Our standard setup feeds the signals from our custom 32-channel preamplifier board directly into a matching digital pulse processing board. It uses a Texas Instruments (TI) AFE-5801 chip which contains eight variable-gain amplifiers and eight 12-bit 65-MHz analog-to-digital converters (ADCs) [6]. The TI AFE-5801 ADCs connect in pairs to two field-programmable gate arrays (FPGAs) to process the 32 signals with a 16-μs trapezoidal filter, provide timing information and check for pileup. The TI AFE-5801, which was developed for ultrasound imaging, was chosen because of its low input noise density of 5.5 $nV/\sqrt{Hz}$ and its compact eight-ADC design that allows integrating 32 STJ signal processing chains on a single 3U PXI board.

The second amplifier chain, which was used to capture the data in Fig. 1, consists of an analog amplifier (Ortec, model 627) with 10 μs Gaussian shaping, followed by a commercial nuclear MCA (Ortec, model Aspec927). Both amplifier chains are controlled by the same data acquisition computer.

Figure 2 (*top*) shows the energy resolution of the exact same data from the same STJ preamplifier but processed with the two different shapers and MCAs. The resolution varies between 1.5 and 2.5 eV FWHM in the energy range up to 250 eV, better for smaller and worse for larger STJs [1, 7]. The resolution is consistently better when the STJ detectors are measured with our custom digitizers. This implies that the secondary Ortec amplifiers still contribute somewhat to the broadening of the lines, most likely because the Model 727 shaper is optimized for the readout of high-purity Ge detectors and only provides filtering with a maximum shaping time of 10 μs, or because its input noise density exceeds that of the FET at the input of the AFE-5801 ADC.

The measured second-order non-linearity (Fig. 2, *middle*) is very similar for the two amplifier chains as expected, because it is set by the non-linearity of the STJ detector. This non-linearity changes slightly between runs and tends to be higher in runs with larger ADR currents during the cooling cycle. This suggests that at least some of the quadratic non-linearity in STJs is due to different amounts flux trapping during the ADR cycle, which creates trapping sites where signal-induced excess quasiparticles recombine with one another. This process is known as "self-recombination," depends on the square of the number of excess quasiparticles and therefore produces a quadratic non-linearity in the STJ response.

Higher-order non-linearities (Fig. 2, *bottom*) differ noticeably between the two amplifier chains for the same set of data. Aside from the energy region below 60 eV, the Aspec927 MCA appears highly linear, in agreement with its specified integral non-linearity of $<0.025\%$. In contrast, the TI AFE-5801 ADC shows higher-order non-linearities of up to an integral value of half a channel width. This is not be unexpected given that the TI AFE-5801 ADC was developed and optimized for

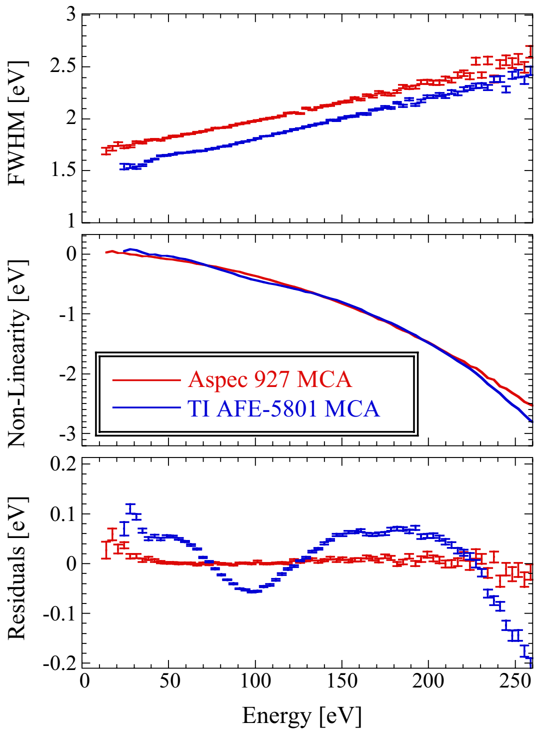

Fig. 2 Comparison of the exact same STJ laser signals processed with two different amplifier chains: One (red) uses an Ortec 627 shaper and 927 MCA [4] and the other (blue) a custom amplifier with a TI AFE-5801 ADC [3]. (*Top*): The custom STJ amplifier provides higher resolution than the Ortec 627. (*Middle*): The second-order non-linearity is similar for both amplifier chains because it is set by the non-linearity of the STJ detector. (*Bottom*): The Aspec 927 MCA provides higher linearity because of its sliding scale linearization algorithm [5] (Color figure online)

ultrasound imaging and does (to our knowledge) not linearize its response with the sliding scale algorithm. On the other hand, the higher-order non-linearities of the AFE-5801 vary only slowly as a function of channel number, and they can therefore be corrected by the measured STJ response to a pulsed laser. For the highest calibration accuracy, the AFE-5801 should also be operated at maximum gain so that the integral non-linearity of half a channel translates into a smaller energy non-linearity. Under these circumstances, we expect to be able to calibrate out STJs with a precision of order ± 1 meV in the energy range of high statistics peaks even when read out by our custom 32-channel digital processing board. Achieving an absolute calibration accuracy of 1 meV will require more accurate measurements of the single-photon energy of our calibration laser.

4 Conclusions

A pulsed laser is a powerful instrument to test the linearity and the calibration accuracy of cryogenic detectors and their MCA readout, because it produces a set of exactly equidistant peaks with negligible intrinsic linewidth. For STJs, the laser spectrum can be fit to a superposition of Gaussian functions to extract centroids with a statistical precision < 1 meV. In addition, the calibration accuracy can also be affected by the non-linearity of the MCA readout. For the highest accuracy, MCAs with sliding scale linearization are desirable, which can achieve an integral non-linearity < 0.025% [4]. Alternatively, a high-accuracy STJ spectrum from a pulsed laser can be used to correct for non-linearities in the MCA, because the STJ response at low energies follows a second-order polynomial to better than one part in 10^5 and the integral non-linearity of MCAs varies slowly with channel number. At present, our calibration accuracy is limited by the 0.15 meV uncertainty of the single-photon energy of our 355-nm calibration laser. This can be further improved, so that an absolute calibration accuracy < 1 meV for energies up to several 100 eV is possible.

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