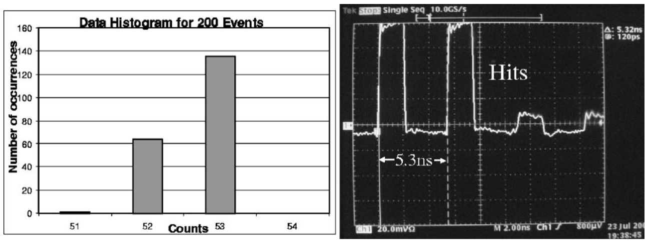

FIG. 2. At a TDC clock frequency (count rate) of 10 GHz, data is shown for 200 distinct events. We measured 52 and 53 counts, corresponding to 5.2 ns and 5.3 ns, respectively. Since the TDC clock and the hit signals are not synchronized, the 100 ps (one clock period) variation is expected.

ments are recorded on the number of counts accumulated in the counter between these events. Because the phase noise in our pattern generator is approximately 200 ps, it is difficult to accurately measure distinct events at high clock frequencies. To eliminate this time jitter and thus to verify correct TDC operation, we split each single event pulse and then recombined the pulse after a passive delay. Figure 2 shows the results for this experiment at a 10 GHz clock frequency/count rate (i.e., 100 ps time resolution).

To operate the digitizer as an ADC a high sensitivity superconducting quantum interference device (SQUID) front end was designed. The SQUID acts as a charge-to-flux converter, which is connected to the common digital counter described to create a flux-counting ADC. In this ADC, a 100:1 transformer coil amplifies an input current pulse, and this current is fed into the SQUID. The SQUID then produces a stream of SFQ pulses. The number per unit time (i.e., frequency) of SFQ pulses produced is proportional to the electrical charge applied at the input detector. By counting the number (N) of pulses over a specified time interval (sampling or integration time, T), a digital count is produced which is proportional to the charge in that time interval.

The major advantages of our implementation of this standard "counter-type" ADC are high sensitivity (4 nA/LSB at 100 M samples/s, corresponding to 4×10^{-17} C or $250e$) and the perfect proportionality between the charge (Q) and the magnetic flux ($Q\propto\Phi=N\Phi_0$, where $\Phi_0=h/2e=2.07\times10^{-15}$ Wb is a quantum of magnetic flux) of the SFQ pulse stream. The dc voltage output at the detector can be monitored directly while varying the input current in the coil to obtain the classic periodic transfer function of the SQUID [Fig. 3(a)].

As mentioned before, in ADC mode, the digital counter is used to count an asynchronous stream of SFQ pulses from the SQUID detector over a given integration time (T). If we vary the analog input current in the input coil, and measure the output at the counter, this experiment should reproduce the same $V-\Phi$ curves in digital count form as in Fig. 3(a). Figure 3(b) shows how this digital data is taken with a 200 ns counting period (5 MHz sampling rate). The results are shown in Fig. 3(c). Here, the measured digital "counts" (N) can be converted to the equivalent voltage using

$$V=\frac{N}{T}\Phi_0.$$

To verify that the ADC can be used to integrate the total charge in a pulse, we also performed a pulsed input test. A

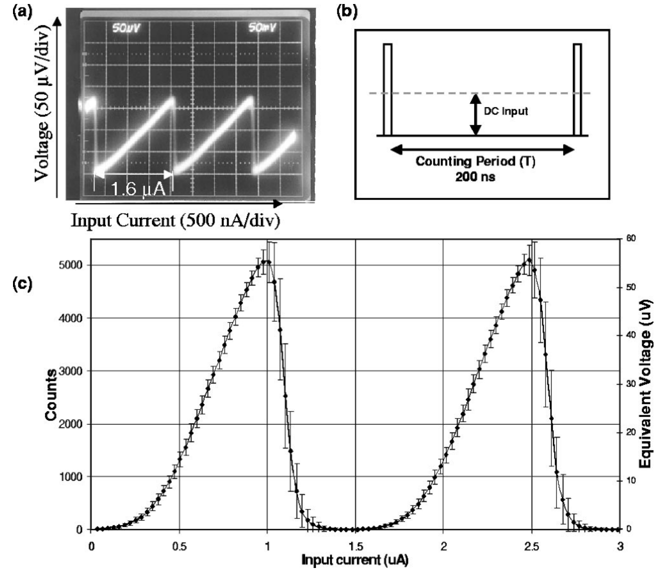

FIG. 3. (a) Periodic transfer characteristic of the SQUID front end. (b) dc input applied over a 200 ns counting period. (c) Reconstructed $V-\Phi$ curves from the counter.

current pulse of variable width ($T_{\text{pulse}}<T$) and amplitude (A_{pulse}) was applied. Here, the output of the counter represents the total charge of the pulse. Figure 4 shows the ADC output for three different pulse amplitudes, each for five different pulse widths. These results show excellent agreement with the theory. The linear curve fits through the count outputs for the same amplitude and different widths are also shown. This test confirms the ability to digitize the charge of a pulse.

The digitizer contains a parallel-to-serial converter, for the counter readout. This design element limits the number of samples to the buffer length. A new design that reads out the data in the counter in parallel has been developed. This version allows continuous ADC operation and will be installed at RIKEN (Institute for Physical and Chemical Research) in Japan to measure data from superconducting tunnel junction x-ray detectors.[7]

This dual-function digitizer has tremendous potential for applications in many areas requiring high speed, low amplitude digitization. Since ADC measurements are limited by SQUID noise in the front end, lowering operation tempera-

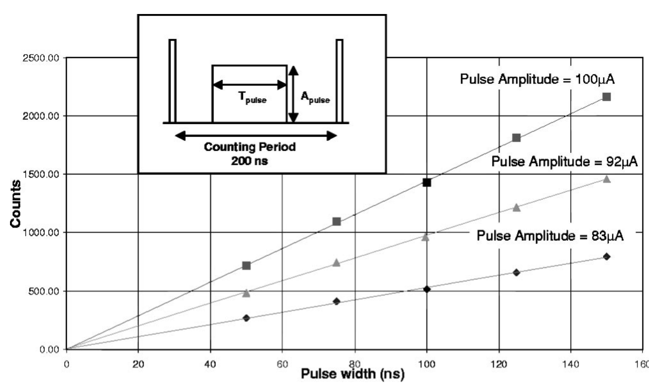

FIG. 4. Time integral of several current pulses of varying widths and amplitudes (without the amplification coil) were digitized. The linear fits for each data set corresponding to three different pulse amplitudes (A_{pulse}) are shown.

ture could further increase sensitivity. With this dual-function digitizer, it is now possible to create a multichannel system capable of measuring both charge and timing information simultaneously, with the option of switching any individual channel between the two functions in real time. If additional timing resolution is required in the TDC mode, an additional analog prescaler[8] can be integrated to the digital counter, which can increase time resolution to 5 ps.

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