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# Low noise electronics in practical applications

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ABSTRACT

The parameters essential to achieving low electronic noise are well established, but in practical applications many details are often ignored. A common challenge is to optimally use an existing IC in measurements for which it was not specifically designed, e.g. radiation damage tests where not just individual noise contributions, but also pulse shaping characteristics are affected. The relevant parameters must be evaluated to determine whether the change in signal-to-noise ratio originates in the detector, the electronics, or both. Another critical parameter in multi-electrode position sensing detectors is the input impedance, which sets the cross-talk between adjacent electrodes. Published data often do not include the required information, but to some extent the key electronics parameters necessary to derive changes in detector characteristics can be measured *in situ*. The paper discusses examples with differing requirements, such as detectors subject to radiation damage, long-strip position-sensitive systems, and—as an extreme example—ultra low-noise cryogenic bolometer arrays.

## 1. Introduction

Front-end integrated circuits for semiconductor detector tracking systems are usually designed for specific projects and their specifications are tailored accordingly. However, these devices are also used for detector R&D, for example to assess the effects of radiation damage in sensors. The problem is that these other applications involve different detector parameters and require more complete information to quantify the effects of sensor changes and isolate individual noise contributions.

The parameters essential to achieving low electronic noise are well established, but in practical applications many details are often ignored. The signal-to-noise ratio ($S/N$) after radiation damage depends not only on individual noise sources, but also pulse shaping characteristics. The relevant parameters must be evaluated to determine whether the change in $S/N$ originates in the detector, the electronics, or both. Another critical parameter in multi-electrode position sensing detectors is the input impedance, which sets the cross-talk between adjacent electrodes.

Unfortunately, most papers on IC performance do not explicitly present all important data. Sometimes it is possible to extract key characteristics from published information, e.g. plots of the final pulse shape, but it would be much more efficient if the designers and testers were to simply measure it and present comparisons with simulations. To some extent the required parameters can be determined *in situ*. The paper will discuss applications with differing requirements, such as detectors subject to radiation damage, long-strip position-sensitive systems, and—as an extreme example—ultra low-noise cryogenic bolometer arrays.

## 2. Signal-to-noise ratio and radiation damage

The signal-to-noise ratio depends both on the magnitude of the signal provided by the detector and electronic noise. High levels of displacement damage in the detector lead to critical levels of carrier lifetime, e.g. at fluences of $10^{-15}\,\mathrm{cm}^{-2}$ lifetimes are about 2 ns, so collection times must be reduced to comparable levels. Measuring the signal charge requires calibration of the electronics, which may be altered by radiation damage, so simply assuming pre-radiation calibration values can lead to wrong conclusions.

As shown in Fig. 1, if the impedance of the test capacitor $C_T$ is much larger than the impedances presented by the detector capacitance $C_d$ or the input impedance of the amplifier $Z_i$, the applied voltage step will be applied across the test capacitor and set the injected charge $\Delta Q = C_T \cdot \Delta V$. The injected current will distribute between $C_d$ and $Z_i$. For most efficient charge transfer from the detector to the preamplifier, $Z_i$ must be much smaller than the detector impedance $|X_C| = 1/(\omega C_d)$, where $\omega$ is determined by the shaping time. As long as this is the case the calibration will not be affected significantly by any change in detector impedance. However, if the magnitude of $Z_i$ is marginal, a change in detector parameters will affect both the charge calibration and charge transfer efficiency. The amplifier input

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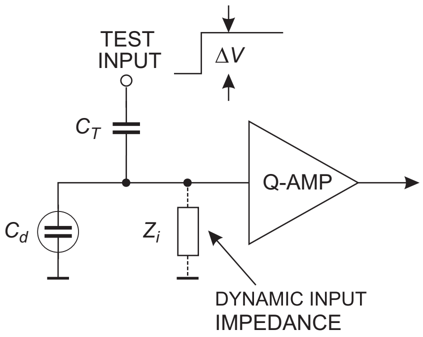

**Fig. 1.** If the parallel impedance formed by $C_d$ and $Zi$ is much smaller than that of the test capacitor $C_T$, the magnitude of the test pulse $\Delta V$ will be applied to $C_T$ and the injected charge is $\Delta VC_T$. The injected charge is distributed between $C_d$ and $Zi$, so any change in either $C_d$ or $Z_i$ will affect the charge calibration, unless $Z_i$ is sufficiently small.

impedance will be discussed in a subsequent section, but here the essential point is that the accuracy of charge calibration can be altered by changes in the detector and the electronics.

### 2.1. Electronic noise charge

The electronic noise charge has two contributions, the first due to current noise, which increases with integration time, i.e. the pulse area, and the second due to voltage noise, which translates to charge through the total passive input capacitance $C$ and increases with the bandwidth of the shaper, so it increases with decreasing shaping time, i.e. higher frequency Fourier components. The equivalent noise charge

$$Q_n^2 = i_n^2 F_i T_S + e_n^2 F_v \frac{C^2}{T_S} + F_{vf} A_f C^2 \quad (1)$$

where $T_S$ is a characteristic time parameter, e.g. the peaking time of a pseudo-Gaussian pulse. The parameters $F_i$ and $F_v$ are determined by the pulse shape:

$$F_i = \frac{1}{2T_S}\int_{-\infty}^{\infty} [W(t)]^2\, dt \quad (2)$$

and

$$F_v = \frac{T_S}{2}\int_{-\infty}^{\infty} \left[\frac{dW(t)}{dt}\right]^2 dt. \quad (3)$$

Since both parameters are normalized to $T_S$, its definition is somewhat arbitrary, but it must perform the proper scaling for both current and voltage noise, so it must characterize both the pulse area and the derivatives, i.e. the rise and fall times.

The third term is the contribution of "1/$f$" noise. Typically an equivalent voltage source, its contribution increases with the total capacitance at the input, but is independent of $T_S$, as the total contribution of a 1/$f$ noise spectrum is determined by the ratio of the upper to lower cutoff frequency, rather than the bandwidth. For a given shaper configuration this ratio is independent of shaping time. The "1/$f$" contribution is typically significant at the optimum shaping time, where the current and voltage contributions are equal. However, when fast timing and increased shot noise due to radiation damage are important, the selected shaping time is usually smaller, so the second term dominates. Then the "1/$f$" noise contribution is usually negligible, as the components add in quadrature. It should also be noted that low frequency noise often does not have a 1/$f$ frequency dependence, but can have multiple components with a frequency dependence $dP_n/df = 1/f^{\alpha}$, where $\alpha$ is in the range 0.5–2 (see Ref. [1]).

The first two noise contributions are often called "parallel" and "series" noise, but viewing them in terms of physics quantities as noise current and voltage indicates their behavior. Current noise is due to statistical fluctuations in current flow, so the absolute fluctuations in charge increase with integration time, whereas voltage noise behaves like thermal noise, so its contribution increases with bandwidth and translates to charge through the total capacitance at the input. For a more detailed discussion see Ref. [1].

Minimizing noise involves a careful choice of shaping times. Radiation damage increases the detector leakage current, so reducing the shaping time will reduce its contribution. For a given peaking time, a symmetrical pulse yields a smaller current noise contribution, as the area will be smaller. Although short shaping times reduce the sensitivity to current noise, they increase the voltage noise contribution, as this increases the frequency range. The noise current typically originates from the detector leakage current, the base current of a bipolar input transistor, and the resistor shunting the feedback capacitor in the charge-sensitive amplifier. Both the detector leakage current and the base current are sensitive to radiation damage. The origin of the voltage noise is typically the preamplifier's input transistor, so if its operating point changes with radiation damage, the overall noise will also be affected.

Although short shaping times reduce sensitivity to current noise and improve time resolution, which can be quite desirable, if the peaking time is less than the width of the signal current pulse from the detector, part of the signal will be lost ("ballistic deficit"). If the overall peaking time of the electronics is comparable to the width of the signal pulse from the detector, a change in peaking time will change the charge response. Alternatively, if the detector pulse width is reduced by increasing the detector bias, the measured signal can increase, although the same charge was deposited in the detector.

Since the relative noise contributions depend on the shaper parameters $F_i$, $F_v$, and $T_S$ (when "1/$f$" noise is negligible), all three must be specified to characterize a pulse shaper. In circuits designed to reduce power dissipation the shaping times typically depend on the bandwidth of the preamplifier, which in turn depends on the load presented by the detector. Thus, simply specifying the noise level alone for a given configuration will not necessarily predict the results for another configuration. Furthermore, to assess the system's sensitivity to radiation damage, the individual noise contributions must be analyzed. Since changes in detector parameters or electronic operating points can affect all three shaper parameters $F_i$, $F_v$, and $T_S$, they should be characterized for various detector capacitances and electronics operating points. It is also important to verify amplifier stability, as "ringing" in the preamplifier can affect the signal's peak amplitude at the shaper output.

### 2.2. Noise parameter derivation in situ

If, as often encountered, the key parameters are not available, to some extent they can be derived *in situ*. Detector shot noise can be increased to make the first term of Eq. (1) dominate, for example by shining light on the detector and measuring the increase in bias current $I_b$. Then the spectral noise current density $i_n^2 \approx 2e \cdot I_b$ and

$$TF_i \approx \frac{Q_n^2}{2eI_b}. \quad (4)$$

In doing this measurement it is important to check that the front-end is operating in its linear regime, especially when the detector is DC coupled and the full bias current is flowing into the front-end.