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CONSIDERATIONS ON THE DESIGN OF FRONT-END ELECTRONICS FOR SILICON CALORIMETRY FOR THE SSC*

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Abstract

Some considerations are described for the design of a silicon-based sampling calorimetry detector for the Superconducting Super Collider (SSC). The use of silicon as the detection medium allows fast, accurate, and fine-grained energy measurements— but for optimal performance, the front-end electronics must be matched to the detector characteristics and have the speed required by the high SSC interaction rates. The relation between the signal-to-noise ratio of the calorimeter electronics and the charge collection time, the preamplifier power dissipation, detector capacitance and leakage, charge gain, and signal shaping and sampling was studied. The electrostatic transformer connection was analyzed and found to be unusable for a tightly arranged calorimeter because of stray capacitance effects. The method of deconvolutional sampling was developed as a means for pileup correction following synchronous sampling and analog storage.

Introduction

This paper presents a graphical analysis of the noise inherent in a silicon detector and the associated preamplifier and shaper in relation to the detector leakage current, capacitance and charge collection time, and preamplifier power consumption and dynamic range. It includes an examination of the effects of stray capacitances on the electrostatic transformer connection of detector elements and presents a method to correct for pulse pileup in a synchronous detector system.

System Noise Issues

In a well designed system, the noise level is mainly determined by the detector, preamplifier, and pulse-shaping function. Achieving a low noise level depends upon adjusting several parameters, but the values of those parameters needed may conflict with other requirements such as dynamic range or power dissipation. To better understand the interaction of various system parameters on the noise generated, we studied the simple model of a silicon detector and a bipolar preamplifier (shown in Fig. 1). The detector is represented by the current source i_{DET} and capacitance C_{DET}. The shot noise due to the silicon leakage is lumped together with that due to the preamp input transistor base current and is labelled i_n. The source e_n represents the equivalent noise voltage of the preamp. This model is a simplified version of one analyzed by Blalock[1].

A graphical study was made of the noise contours for bipolar preamplifiers at very short shaping time constants (10–100 ns). The nominal system for these studies was a detector with 35-pF capacitance and 10-μA leakage current, and a preamplifier with 5-pF feedback capacitance, 30-kΩ feedback resistance, and 100-Ω equivalent noise resistance. The noise current (i_n) was assumed to be predominantly due to detector leakage. Families of curves of equivalent noise charge vs shaping time were generated for various detector leakage currents (Fig. 2), detector capacitances (Fig. 3) and amplifier input noise as related to preamplifier first-stage emitter currents (Fig. 4). The equivalent noise charge is given in terms of rms electrons (rms e).

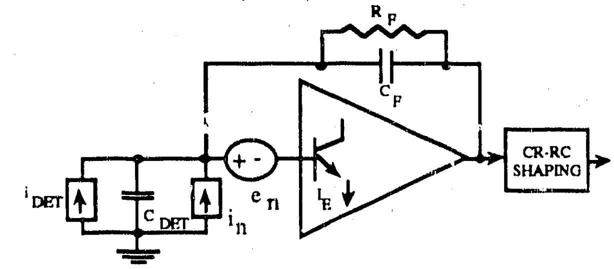

Figure 1. Silicon detector and preamplifier noise model.

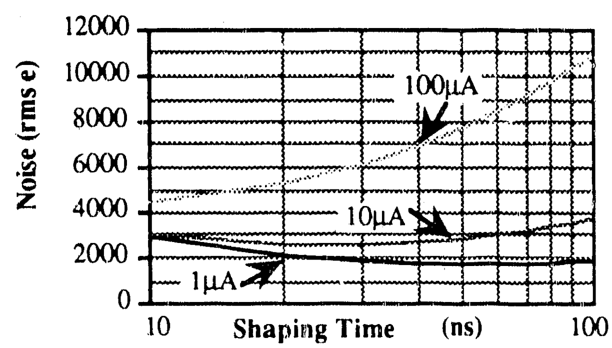

Figure 2. Amplifier noise as a function of shaping time and detector leakage current for bipolar preamplifier.

A point extremely important to SSC operation is that detector leakage is not a major noise source in the likely operating region (i.e., shaping times of 15 to 30 ns). The equivalent noise voltage due to the preamplifier is the dominant source for detector leakage currents under ~100 μA

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(Fig. 2). The contribution due to the feedback resistor (30 kΩ) was negligible even though it is much smaller than the usual 100 MΩ or more. These results are consequences of the short shaping times.

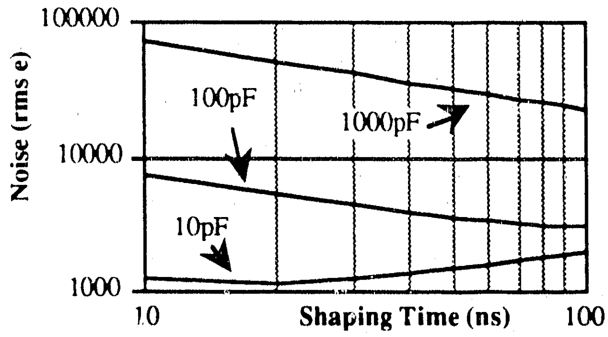

Figure 3. Amplifier noise as a function of shaping time and detector capacitance for bipolar preamplifier.

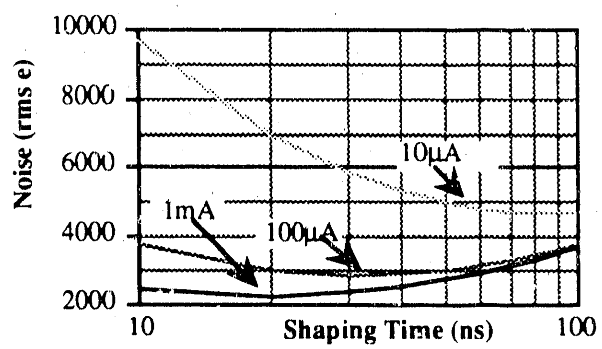

Figure 4. Amplifier noise as a function of shaping time and emitter current in the input device of the preamplifier. An input device with 50-Ω base resistance and 35-pF detector capacitor were assumed.

These studies also highlighted the tradeoffs between detector capacitance and noise. The silicon detector thickness for the electromagnetic calorimeter has largely been set at 400 μm, but the thickness for the hadronic calorimeter has varied between 400 and 500 μm. Several different pad sizes will probably be used. The capacitance is first-order inverse with thickness and the dominant noise mechanism is first-order with capacitance (Fig. 3), while the collected signal is proportional to the thickness for a particle that passes through. Thus, disregarding collection time, the thicker the detector, the better the signal-to-noise ratio is. At room temperature, with 100-V bias, the collection time is 11 ns for electrons and 34 ns for holes with a 400-μm detector. Since the collection time is proportional to the thickness squared, making the detector thinner improves the collection time but degrades the signal-to-noise ratio. Cooling the detector decreases the collection time without signal-to-noise ratio degradation.

Figure 4 illustrates the tradeoff between power consumption and noise. As the current in the input device is increased (and, consequently, power consumption is increased) the equivalent noise charge is decreased. A more subtle interaction occurs with the preamplifier feedback capacitor and the system gain, noise, and power consumption. For a given detector capacitance, the output due to preamp series noise is inversely proportional to the value of the feedback capacitor, as is the output signal (constant signal-to-noise ratio). Because of other noise sources, the total noise contribution increases with increasing capacitor (feedback and detector) values. The feedback capacitor value sets the preamp charge gain, while the feedback resistor and the input count rate affect pileup. The maximum linear signal amplitude output of the preamp is determined by the dc power supply voltage: more dynamic range costs power dissipation (even with devices operating at the same currents). Thus, the selection of the feedback capacitance is a tradeoff between the noise floor and the maximum signal charge for a given supply voltage.

Electrostatic Transformer Connection Analysis

One of the suggested solutions to the problem associated with high detector capacitance has been the use of the electrostatic (series) transformer interconnection of detector elements. Series connections in silicon calorimetry offer advantages of lower detector capacitance (presented to the preamplifier), fewer amplifiers per unit detector area, and fewer interconnect wires when compared with the use of a separate preamplifier for each detector segment and summing the signals from multiple preamplifiers in the same plane and/or tower. For *n* identical detector elements, the series capacitance is reduced by a factor of *n* over the single-element case. Likewise, the portion of charge seen by a low-impedance amplifier connected to the series arrangement is a factor of *n* less than in the single element-case, and this is illustrated in Fig. 5 for a case with five identical elements (C1, C2, C3, C4, and C5).

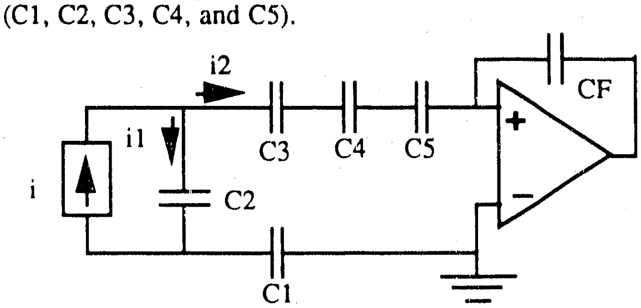

Figure 5. Equivalent circuit of series transformer charge collected from ionization track.

An example of the series transformer was shown in work published by the SICAPO collaboration[2]. With a 4-mm air gap on each side of the silicon, the parasitics were only 1.7% of the detector capacitance and had relatively little effect. Our current silicon calorimeter design has much smaller distances between the absorber plates, and with printed circuit boards serving as the dielectric, the stray capacitance jumps considerably. We plan to fill a 3-mm gap between absorber planes with 400- to 500-μm silicon, 2-mm thick electronics and 0.5-mm insulation; and the stray capacitance between each detector and the absorbers approaches 50% of the detector capacitance.

A SPICE simulation showed very nonuniform response due to differing charge collection as a function of the position of the detector in the series chain when stray capacitances were included. The model was run for a five-plane tower with stray capacitance equal to 5% of the segment capacitance, a value only 10% of what we expect. Even with this optimistic model, the detector farthest from the preamplifier had half the charge sensitivity of the closest. One might argue that nonuniformity along the position of the tower is inconsequential and can be compensated with a correction factor if the particle traverses all elements in the tower. However, for energy depositions of up to 80 to 90 MeV in a single detector element, the charge gain will depend on its location within the tower. Series transformer connections of silicon detector elements would also add series inductance, which would result in very long preamplifier settling times. Our analysis of signal degradation due to stray capacitances has shown the series transformer option to be untenable.

Shaping and Sampling Considerations

The high clock frequency of the SSC means that shaping times considerably less than 16 ns would be required to prevent pileup. This short shaping time is somewhat of a problem with silicon because the charge collection time is greater than a bunch crossing time. We decided to investigate this problem and see if a method to correct for pileup in a synchronous detector could be developed.

It is generally assumed that sampling followed by analog storage will be needed to save data for analog-to-digital conversion after a first-level trigger. Since earlier samples are available, they can be used in a pileup-correction scheme. For example, if the pulse shape presented to the sampler is a decaying exponential with time constant τ, the correction for the immediately preceding pulse tail is the preceding pulse height times $\exp(-T/\tau)$, where T is the bunch crossing time. This correction is made by subtracting a fraction of the previous sample from the sample that is to be converted, and this can be implemented very simply with a divider and a difference amplifier. This special case has been implemented before for a high-rate liquid argon calorimeter[3].

A more general approach is possible if the system of detector, preamplifier, shaper, sampler, and analog memory is viewed as a sampled data system. That view makes it simple to realize that the pileup due to all previous events can be corrected for if the response of the detector, preamplifier, and shaper is known at the sample times. If the deposition of energy in the detector is considered to be impulse-like and is denoted by $p(t)$ with $p(t) = p(nT)$ at bunch crossing n and zero otherwise, and the impulse response of the system is $h(t)$, then the output of the preamplifier is the convolution of $h(t)$ and $p(t)$ or

$$y(t) = h(t) * p(t) = \sum_{m=-\infty}^{\infty} h(t-mT)\, p(mT). \quad (1)$$

If $y(t)$ is sampled at ΔT after each bunch crossing, then the stored values are

$$y(nT+\Delta T) = \sum_{m=-\infty}^{n} h(nT+\Delta T-mT)\, p(mT). \quad (2)$$

This equation can be solved for $p(nT)$ in terms of $y(mT+\Delta T)$ and earlier samples of the output. The solution is in the form of a finite impulse response (FIR) digital filter, and for the case where $h(t)$ is a decaying function (the low feedback resistor guarantees this), only a small number of terms are needed to provide sufficient accuracy for even extreme pileup. This method can be implemented with dividers and a difference amplifier as illustrated in Fig. 6. We call this method of pileup correction "deconvolutional sampling." This method has some advantages over double correlated sampling. It requires only half the sample rate and can use longer shaping times that are more optimal for noise performance with the preamplifiers likely to be used. Further investigation of this method is planned.

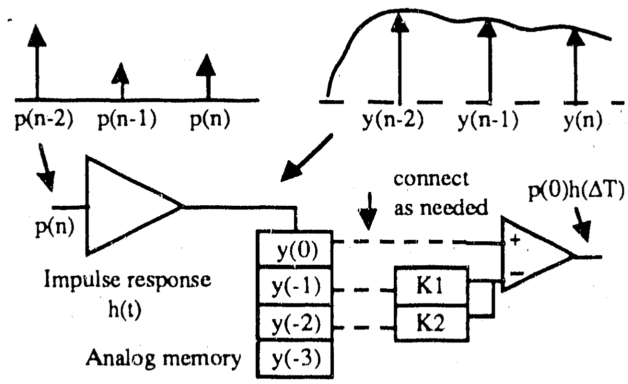

Figure 6. Deconvolutional sampling.

Conclusions

Noise issues specific to silicon calorimetry were explored, and it was found that for likely detector geometries, preamplifiers, and operating region, the noise would be dominated by the equivalent noise voltage of the preamplifier and not by the noise current due to detector leakage. We determined that the series transformer connection of detector elements was not a viable option for closely packed elements with electronics and insulation in between. The deconvolutional sampling method for pileup correction following synchronous sampling and analog storage was developed.

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