SPICE Simulation Of The Pad Sensor Readout Chain.

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The readout chain for pad sensors was simulated using LTspice[1] program and it is illustrated on fig1. In this simulation the pad sensors are represented as 50 pF capacitors, seven pads are AC decoupled by capacitors Cd1-Cd7 and connected to the summation point via lossy transmission lines Tc1-Tc7, each with different length. The bias is applied on each pad individually over Rb1-Rb7 resistors. From the summation point the signal goes through a short transmission line Tpa to a preamp E1. The preamp is connected to a differential driver E3, which drives 10 m of differential cable represented by a transmission lines Tpa1 and Tpa2. Other side of the cable is connected to a an integral shaper LT6600-2.5 (low noise differential amplifier and 4th order 2.5 MHz low-pass filter), which acts as an antialiasing filter. From here the differential signal will go directly to an ADC.

The current pulse in pad detector is a result of charge induction due to the drift of electrons and holes originated along the track. The pulse has very sharp front, and a tail which is a sum of two components of equal area: fast component ~10 ns due to drift of electrons and slow component ~30ns due to drift of holes[2] . The input signal is simulated as 2mA double-exponential current pulse with rising time constant 2 ns, flat top of 1 ns and falling time constant of 20 ns, the injected charge is 4000 fC which correspond to 1000 MIPs, a half of the maximum signal, expected from the single pad.

The preamp is modeled as an ideal trans-conductance amplifier with gain of 10 KOhm and with input impedance of 50 Ohm, this impedance is divided in two parts: noisy Rin_hot=8 Ohm and noiseless Rin_cold=42 Ohm.

The differential driver (AD8132 or AD8137) is modeled as an ideal voltage regulator.

1 Available free from http://www.linear.com/company/software.jsp
2 Helmuth Spieler, '**Semiconductor Detector Systems** ' Oxford University Press, USA (September 27, 2005) also page 85 of http://www-physics.lbl.gov/~spieler/Heidelberg_Notes_2005/index.html

Simulation Model of the Pad Sensors Readout Chain

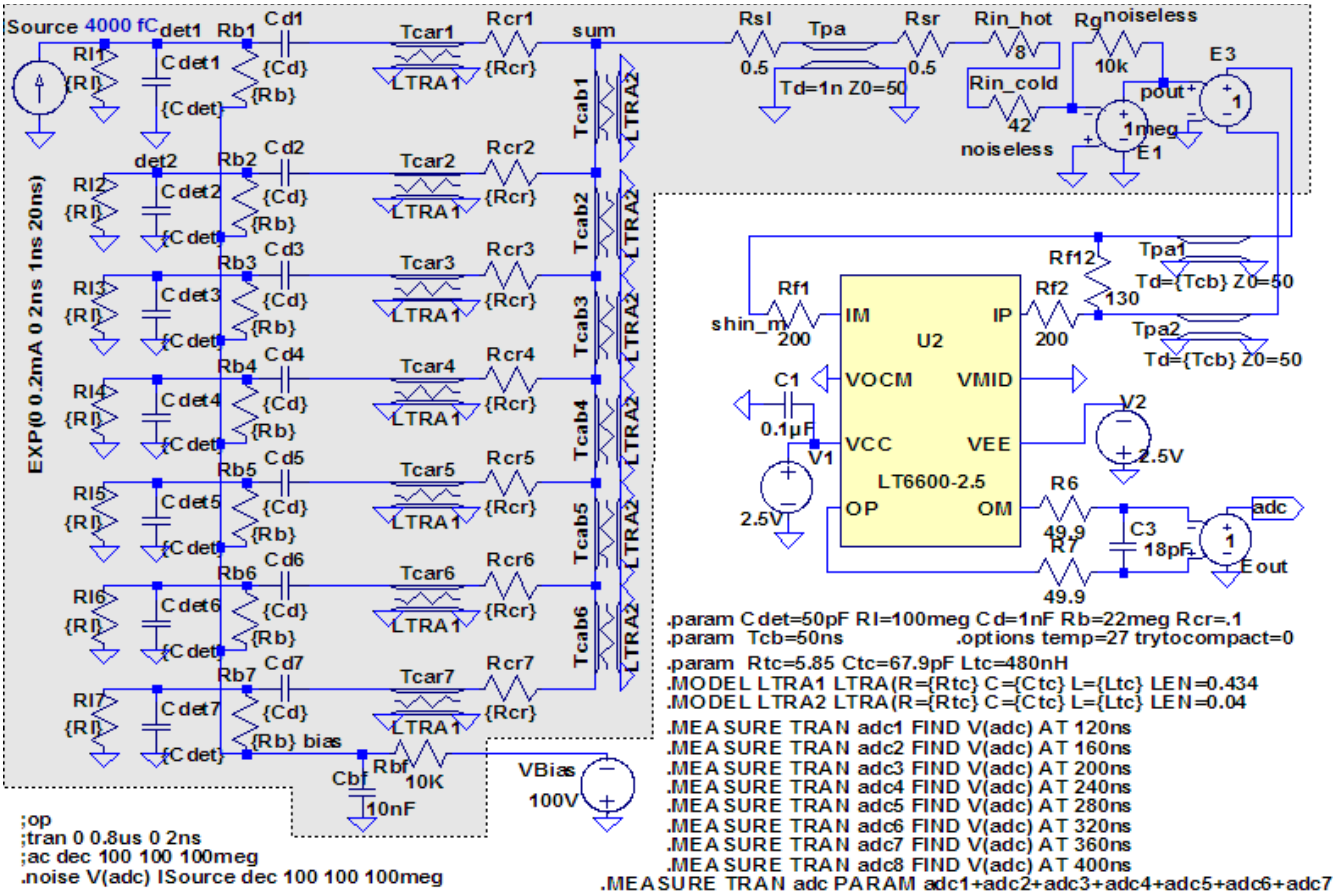

Fig. 1: Simulation model of the pad sensor readout chain. The elements in shaded area are near the detector.

The lossy transmission line parameters are represented in .MODEL and . PARAM statements on fig.1 and they are explained in the next section. For this simulation the following parameters were used:

1. Unit resistivity Rtc = 5.85 Ohm/m
2. Unit capacitance Ctc = 67.9 pF/m
3. Unit inductance Ltc = 480 nH/m
4. The line lengths of Tc1-Tc7 varies from 62mm to 434mm

The line impedance of each line is Z=sqrt(Ltc/Ctc) = 84 Ohm.

Transmission Line Analysis

Source: "High-Speed Digital Design A Handbook of Black Magic". Howard W. Johnson and Martin GrahamPrentice Hall, 1993; ISBN 0-13-395724-1

Mathcad source: http://www.sigcon.com/lib/htm/MSTRIP.htm

local source: http://www.phenix.bnl.gov/~suhanov/ncc/electronics/signal_processing/mstrip.mcd

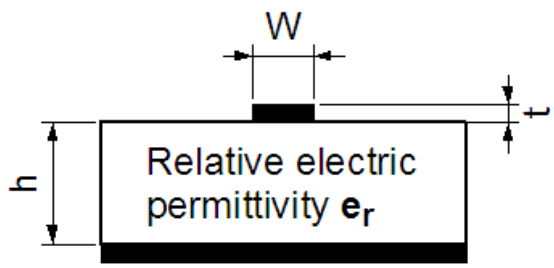

Fig. 1a: Microstrip line.

Height above ground **H := 0.2 mm**
Width of trace **W := 0.1 mm**
Thickness of trace **t := 0.035 mm** (1-oz copper plating weight)
Length of wire **X: = 434 mm**
Relative electric permittivity **e_r := 4.5**
Resistivity of copper at 20C **p20 := 2.5E-8** Ohm*m

Selection of Cut-Off Frequency of the Low-Pass Filter

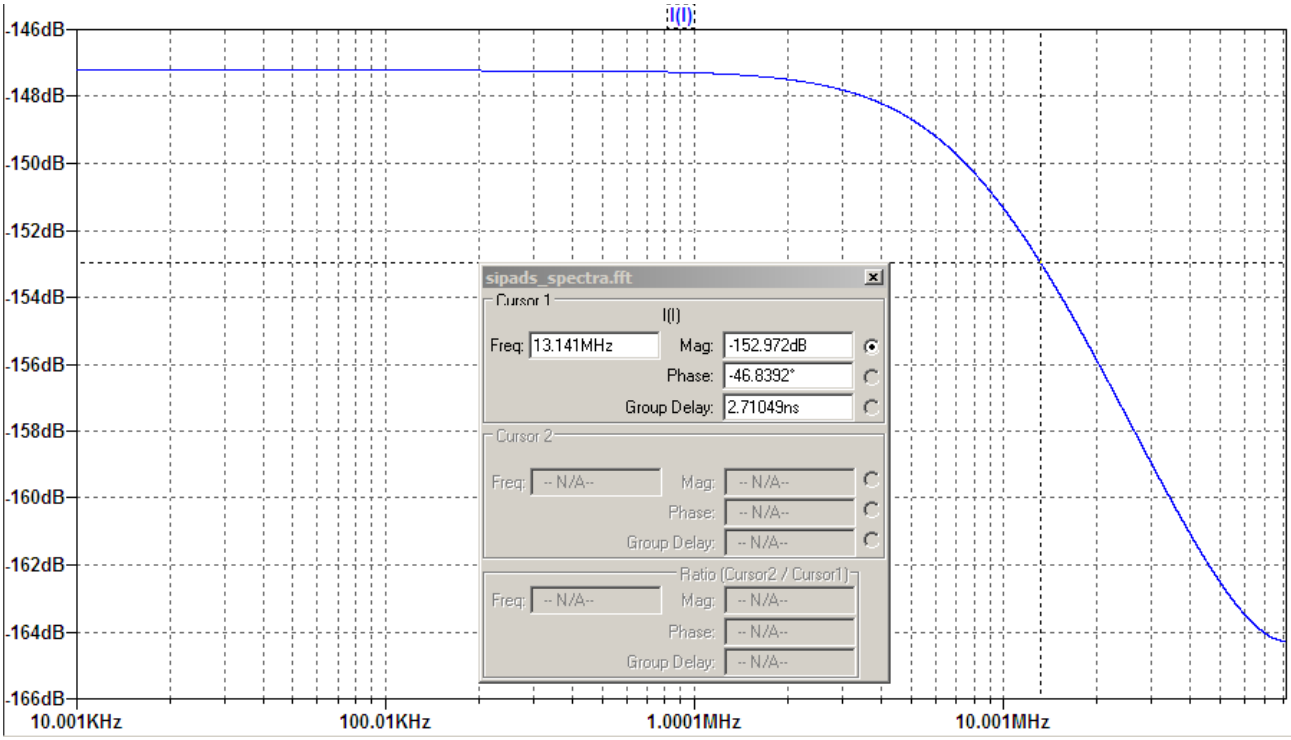

Fig. 2: Spectrum of the source signal. The bandwidth (where amplitude drops by 6 bB) is 13 MHz

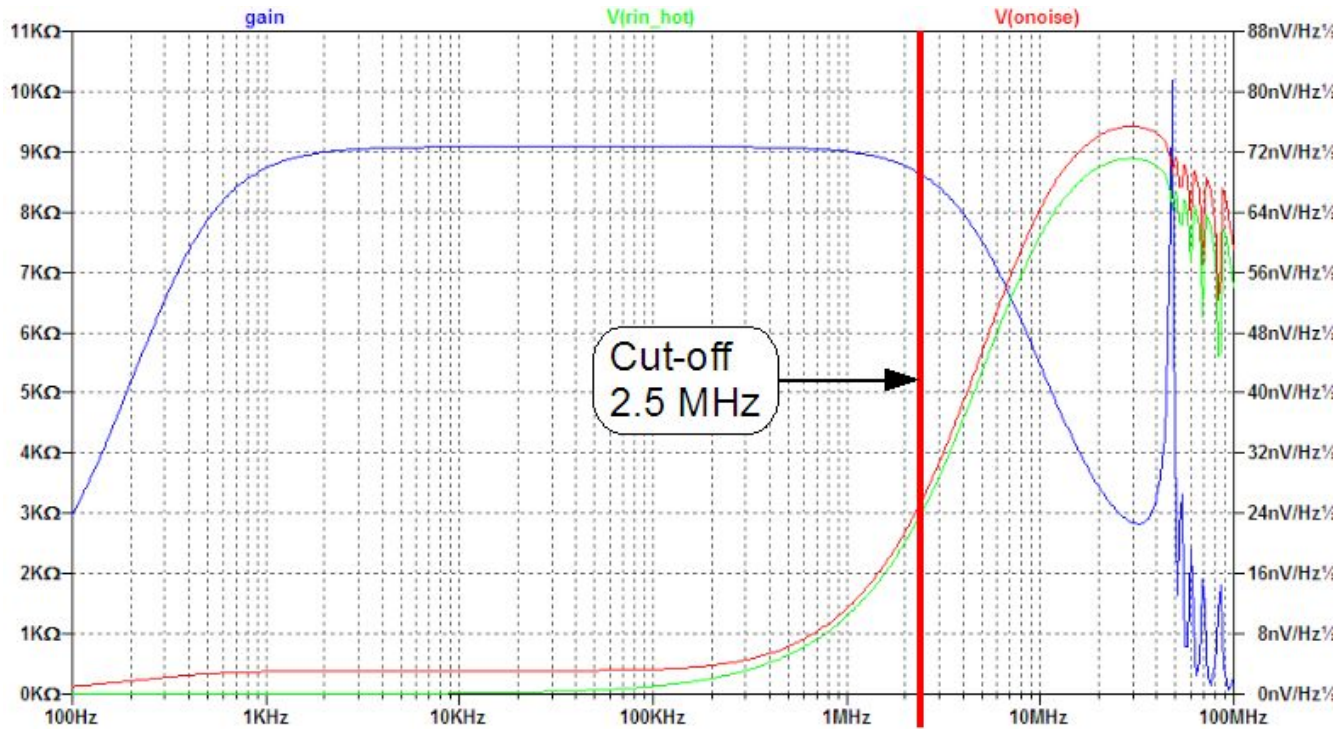

Fig. 3: Gain (blue) and noise (red) at preamp output.

The bandwidth of the source signal is 13 MHz (fig. 2), the gain of the system from the source to the preamp output is shown on fig.3; it is determined by combination of detector capacitance, transmission lines, and input impedance of the preamp. On the same figure is shown the noise at the preamp output (red) and the contribution to the noise from noisy part of the impedance Rin_hot (green). We select the cut-off frequency for the low-pass filter based on this figure. At frequencies around 2.5 MHz the gain starts to decline and at the same time the noise is rising.

The cut-off frequency = 2.5 MHz.

Transient Analysis

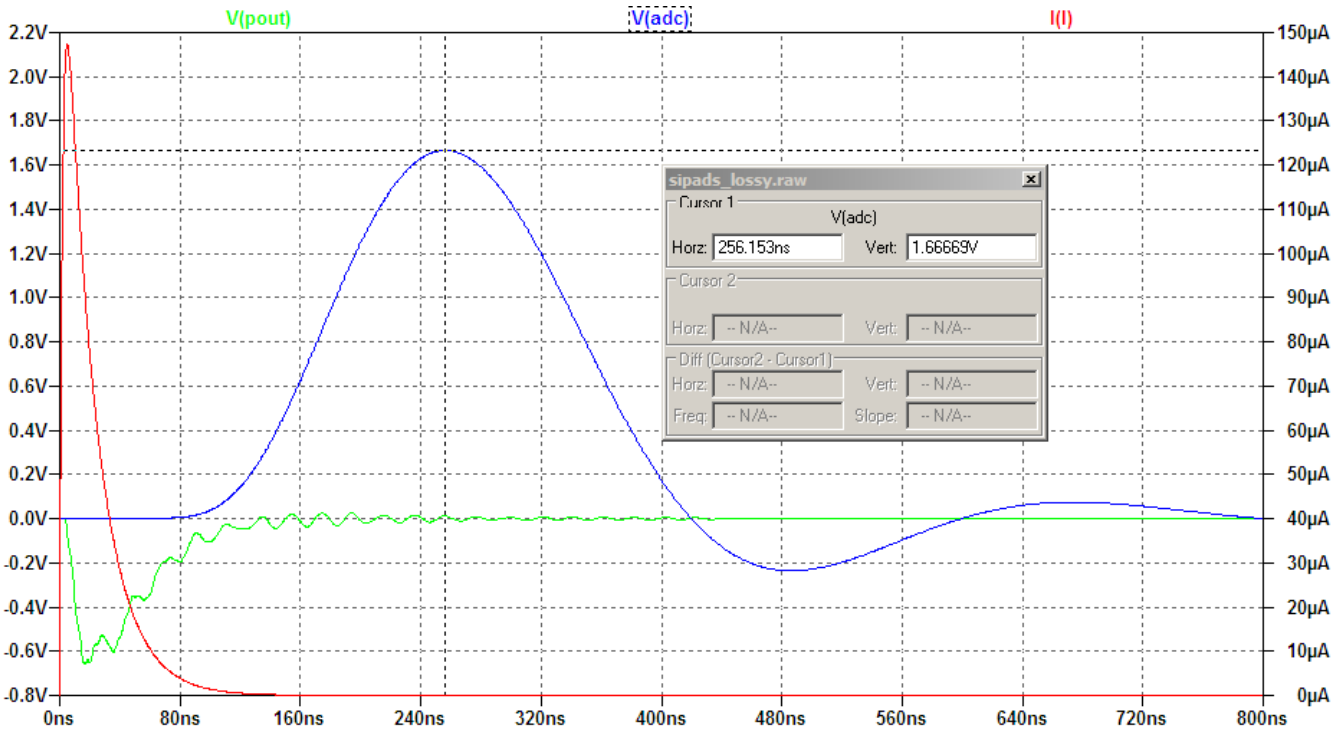

Fig. 4: Transient analysis of the pad readout chain.

The transient analysis of the readout chain is shown on fig.2. The blue line shows the output of the shaper, the green curve is an amplitude at the preamp output, one can see that there are significant reflections caused by mismatched impedances of lines TC1-TC7 and Tpa. These reflections are fully integrated and do not appear on the output signal.

Nonlinearity. Simulation for small signals shows exactly the same shape, no deviation from linearity has been detected.

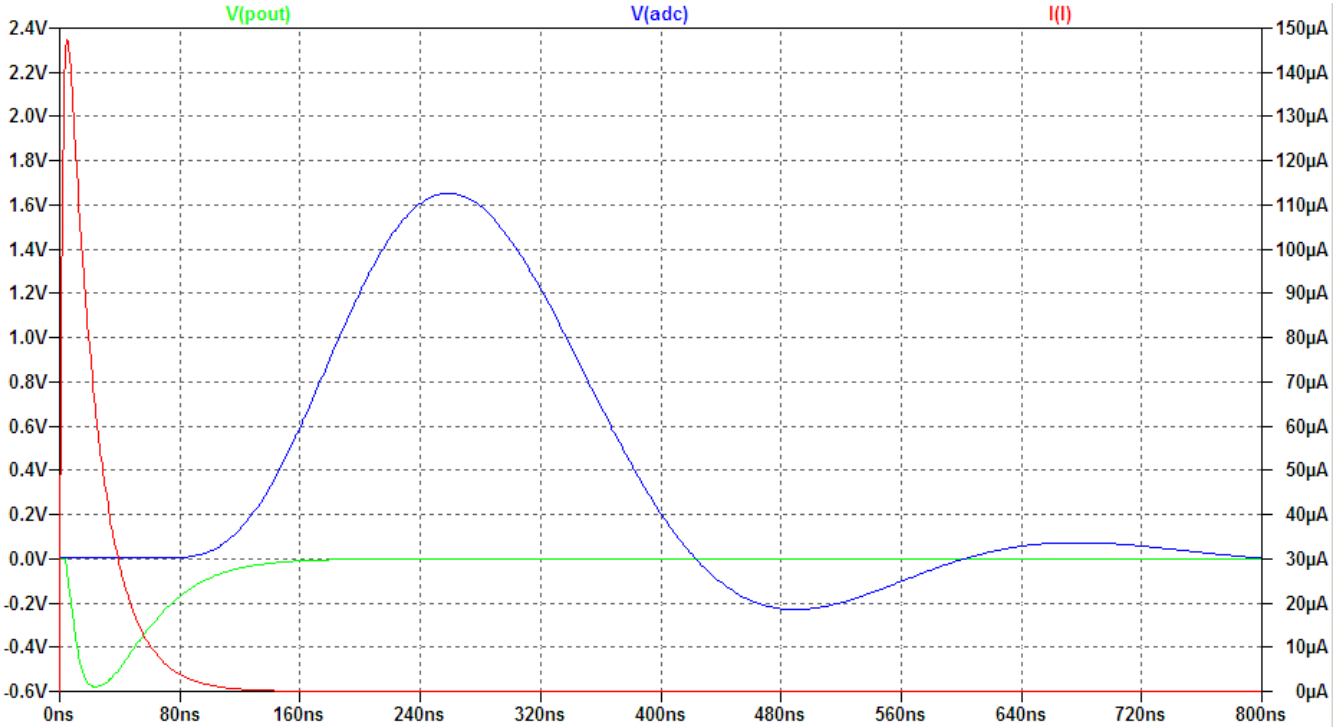

Fig. 5: Transient analysis, Rcr=35 Ohm

The reflections can be eliminated by introducing resistors Rcr1-Rcr7 with values in the range of 35-70 Ohm. As it will be shown later these resistors would significantly contribute to the system noise and therefore are not recommended.

Noise Analysis.

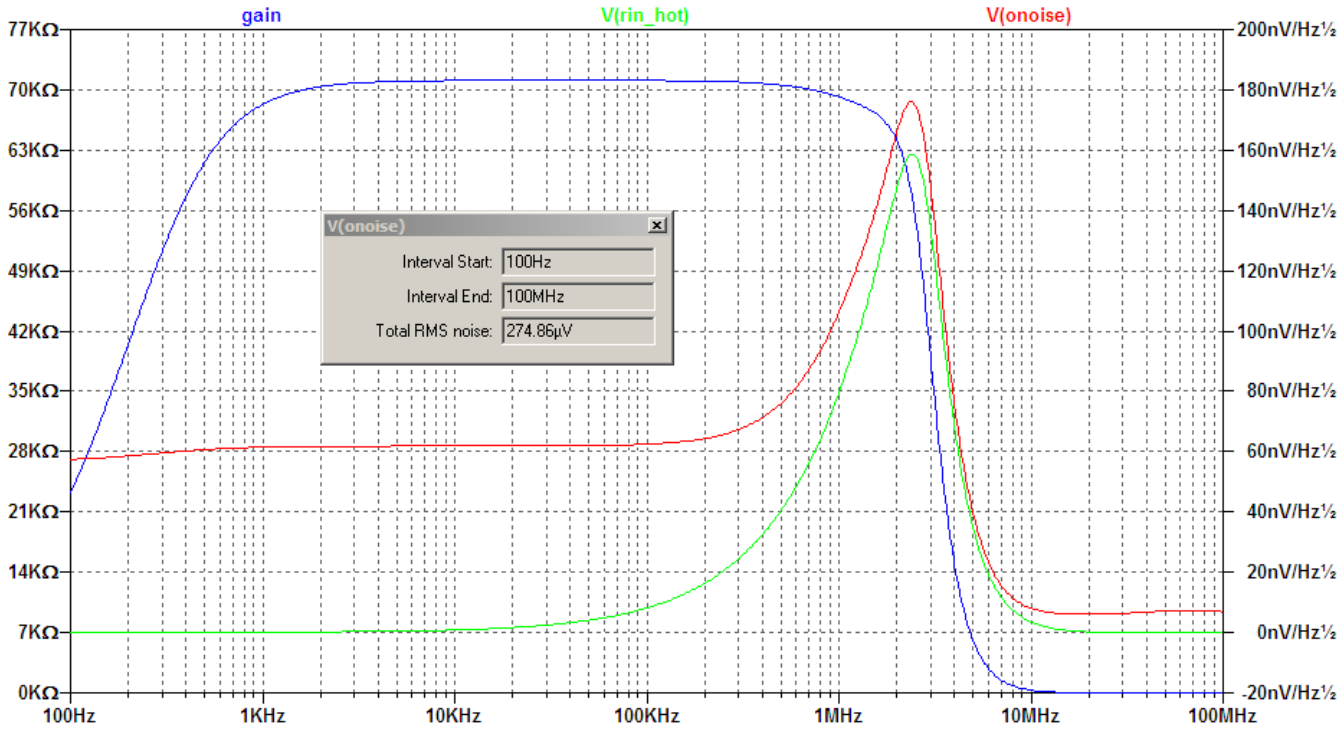

Fig. 6: Gain in KOhm (blue), noise in nV/Hz$^{1/2}$(red) and noise contribution from Rin_hot (green) at the output of the filter.

The main contribution to the noise comes from the serial resistor Rin_hot. Comparing fig.6 with fig.3 one can see that the gain is high in the region where the noise is low and the gain is sharply cut for the region with high noise.

Summary Table

RMS of ADC for diff input 2V p-p = 1.25E-004

	Rcr	SA	PA	PP	ADCsum	RMS1	S/N1	RMS	S/N
	Rcr	Signal Average over 400ns	Peak amplitude	Peak position	ADC sum of 8 samples 50MHz starting at 80ns	RMS Noise 100Hz-100MHz	S/N one sample at a peak	Total RMS noise for 8 samples	S/N including RMS of ADC
	Ohm	V	V	'ns	V	V		V	
1	**Cdet=42pF**, Rin_cold=42, R1=130, R3=R4=200, R2=10K, **LT6600-10** **Cut-off at 10 MHz, 8 samples every 20ns starting at 80 ns**								
1.1	0	0.177	1.240	117.0	3.50	4.37E-004	2.84E+003	1.24E-003	2817
1.2	35	0.177	1.200	118.0	3.50	4.97E-004	2.41E+003	1.41E-003	2480
2	**Cdet=42pF**, Rin_cold=42, R1=130, R3=R4=200, R2=10K, **LT6600-2.5** **Cut-off at 2.5 MHz, 8 samples every 40 ns starting at 120 ns**								
2.1	0	0.347	1.700	251.0	7.39	2.55E-004	6.67E+003	7.32E-004	10096
2.2	35	0.347	1.700	256.0	7.38	2.98E-004	5.70E+003	8.52E-004	8661
	Cdet=50pF, Rin_cold=42								
2.3	0	0.342	1.670	256.0	7.27	2.70E-004	6.19E+003	7.74E-004	**9395**
2.4	35	0.342	1.654	259.0	7.26	3.23E-004	5.13E+003	9.21E-004	7883
	Cdet=60pF, Rin_cold=42								
2.5	0	0.336	1.620	258.0	7.10	2.98E-004	5.44E+003	8.52E-004	8332
2.6	35	0.336	1.605	261.0	7.10	3.51E-004	4.57E+003	1.00E-003	7096

Table 1: Noise (RMS1) at the filter output and Signal-to-Noise ratio (S/N), calculated as non-weighted sum of 8 samples.

Table 1 shows the noise at the filter output (RMS1) and the signal-to-noise ratio (S/N), calculated as non-weighted sum of eight ADC samples at different operational parameters. The row 1.1 and 1.2 shows are with 10 MHz cut-off and 50 MHz ADC sampling, the rest is with 2.5 MHz cut-off and 25 MHz sampling. The improvement by using multiple sampling could be derived as ratio of S/N to S/N1 and it is about 50%.

The best signal to noise ratio for detector capacitance of 50 pF is 9395 (row 2.3). In row 2.1 is shown the same ratio for smaller detector capacitance of 42 pF, as expected, it is higher: 10096.

The RMS noise level at the filter output 270 uV (row 2.3, column RMS), to convert it to ENC:

ENC = RMS1/PA*4000fC/e **ENC = 4042 electrons**

In this formula RMS1 is the RMS noise level = 270 uV, PA is peak amplitude = 1.67V, 4000fC is the charge applied to the input, e – electron charge.

The RMS noise after non-weighted sum of 8 samples is 7740 uV (see column RMS in row 2.3) but effective signal increased to 7.27 V (ADCsum) from 1.67 V.

This correspond to ENC of the readout chain = 2665 electrons.

Getting Effective Number Of Bits Greater Than 12.

The problem of achieving the dynamic range of signal measurement better than 12 bits comes from the fact that the effective number of bits (ENOB) of any off-the-shelf fast ADCs is less than 12 bits no matter what resolution they have. In another words if we take for example 16-bit ADC with ENOB=12 and make a single sample then we cannot achieve resolution better than 12 bit.
The obvious solution is to make several samples and sum them up together. In the simplified case when output shape of the filter is flat and we are taking N samples on plateau then the signal-to-noise ratio will improve sqrt(N) times. In the case of arbitrary signal shape the optimal signal-to-noise ratio will be achieved using weighted sum of the samples when the weights follow the shape of the signal.

Further improvement of better than 20% could be achieved using weighted sum of samples.

Rule:
If dynamic range of a system is D (linear scale) and resolution of ADC is A bits (N<2**A) then dynamic range could be improved K*sqrt(N) times using weighted sum of N samples. The coefficient K<=1 depends on the signal shape (for flat shape K=1). The N should be chosen less than (log2(D) – A). The sampling rate of the ADC should be higher than B*N where the B is the bandwidth of the input signal.

Summary

- The readout chain of NCC silicon pad sensor pad is simulated using LTspice program.
- The cut-off frequency of the shaper should be 2.5 MHz, above this frequency the system gain is decreasing and the system noise is rising.
- The ADC sampling rate should be 25 MHz or higher.
- The number of samples should be 8 or larger, this will provide at least 50% improvement of S/N relative to single-sample measurement.
- Using weighted sum provides 20% improvement as compared to non-weighted sum.
- The impedance-matching resistors Rcr1-7 should be avoided. They add to the noise.
- Simulations did not show any nonlinearity.
- For 7*50pF pads the dynamic range above 9350 could be achieved when gain of (preamp + driver) is 10KOhm and its noisy part of input impedance equivalent to 8 Ohm.
- The Equivalent Noise Charge (ENC) at the input is 2700 electrons, or 0.43 fC.