DEVELOPMENT OF FRONT-END ELECTRONICS FOR THE LUMINOSITY DETECTOR AT ILC

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ABSTRACT: The design and measurements of the prototype front–end electronics for the luminosity detector (LumiCal) at International Linear Collider (ILC) are presented. The challenges of the LumiCal front-end are pointed out and the proposed architecture comprising switched–gain preamplifier, pole–zero cancellation circuit (PZC) and switched–gain shaper is described. The preamplifier works for a wide range of input capacitance values reaching more than 100 pF. The input charge dynamic range is 0.4 fC – 10 pC and covers more than 4 orders of magnitude. The circuit has to be fast with a peaking time (T_{peak}) of about 70 ns. The prototype ASIC including 8 channels was designed and produced in 0.35 μm CMOS technology. The results of measurements on gain, noise, input pulse rate and crosstalk are presented.

INTRODUCTION

In the future International Linear Collider (ILC) the luminosity measurement will be done by LumiCal detector which will constitute important part of the Forward Calorimetry region [1]. The project of LumiCal front–end electronics depends on several assumptions concerning detector architecture [2]. At present development stage it is assumed that the LumiCal detector is built of 30 layers of 300 μm thick DC–coupled silicon sensors with unit capacitance ranging from 10 pF – 100 pF. These sensors will be connected to the multichannel front–end ASICs. In total about 200,000 channels will need to be readout. The LumiCal readout should work in two modes: the physics mode and the calibration mode. In the physics mode the front–end should process signals up to 15 pC per channel while in the calibration mode it should be sensitive to signals as small as 2 fC (corresponding to half of the minimum ionizing particle (MIP) energy deposition). Because of very high expected particle occupancy, the front–end electronics should resolve signals separated in time by about 350 ns and so should be very fast. Since in the ILC experiment after each 1 ms of active beam time there will be 200 ms pause [3] the requirements on readout electronics power dissipation may be strongly relaxed if a power switching off is applied in the pause.

The paper is organised in two parts. In the first part the design of the charge preamplifier and shaper is presented. In the second part the measurements performed on the prototype ASICs are discussed together with the results. Then the conclusions follow.

CIRCUIT DESIGN

To fulfill all the requirements the front–end electronics [4] comprising the charge sensitive amplifier, the pole–zero cancellation circuit (PZC) and the shaper was designed, as shown in fig. 1. The "mode" switch changes effective values of R_f, C_f, R_i and C_i components and so changes the front–end gain.

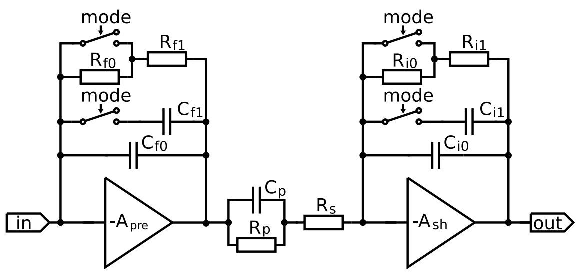

Fig. 1. Block diagram of a single front-end channel

The low gain (large C_f) is used for the physics mode when the front–end processes signals with large charge depositions in a sensor, while the high gain (small C_f) is used in the calibration mode when a MIP sensitivity is needed. Assuming high enough open loop gain of preamplifier (A_{pre}) and shaper amplifier (A_{sh}) the transfer function of this circuit is given as:

$$\frac{U_{out}(s)}{I_{in}(s)} = \frac{1}{C_f C_i R_s} \cdot \frac{s + 1/C_p R_p}{s + 1/C_f R_f} \cdot \\ \cdot \frac{1}{(s + 1/C_i R_i)(s + 1/C_p(R_p||R_s))} \tag{1}$$

Setting properly the PZC parameters ($C_f R_f = C_p R_p$) and equalising shaping time constants ($C_i R_i = C_p(R_p||R_s)$) one obtains standard first order shaping, equivalent to CR–RC filter, with peaking time $T_{peak} = C_i R_i$. A simple first order shaping was chosen as a trade off between the noise and the power dissipation. Regarding the noise a main requirement was to obtain in calibration mode the signal to noise ratio (S/N) of about 10 even for largest sensor capacitances. To this aim a first order shaping was sufficient. Increasing the shaping order would still improve the S/N in calibration mode but it would increase the power dissipation and it would deteriorate the S/N in physics mode configuration (for low gain preamplifier configuration each shaping stage

adds considerably to the total system noise).
Both of the amplifying stages (A_{pre}, A_{sh}) were designed as folded cascodes [5] with active loads and followed by source followers. The input transistor of the preamplifier stage draws a current of about 2.2 mA. Because of a wide input charge dynamic range a large total preamplifier feedback capacitance ($C_{f0} + C_{f1}$) of about 10 pF was chosen. A more detailed scheme of the preamplifier is shown in fig. 2. In order to maximise the gain of preamplifier the active load is implemented as a cascode current source.

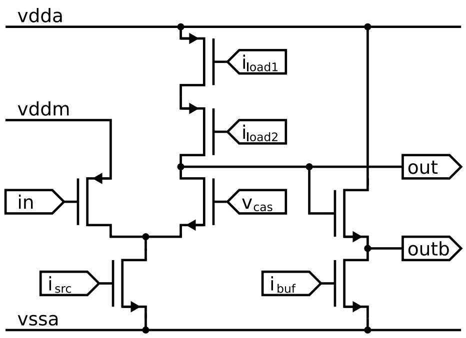

Fig. 2. Block diagram of the preamplifier

In the layout of a prototype ASIC 8 front–end channels were placed. First four channels were implemented with passive feedback and PZC resistances R_f, R_p while the following four channels use MOS transistors in a triode region to this aim. This was done to compare an overall performance of the two feedback schemes. A maximum value of passive resistance ($R_{f0} + R_{f1}$ in the calibration mode) in the first four channels is 1.5 MΩ, while the resistance of MOS transistors in the following four channels is controlled through their gate potential and may reach much higher values. The value of calibration mode feedback capacitance (C_{f0}) of 0.5 pF was chosen for the channels with passive resistors and 0.23 pF for the channels with MOS resistors. The test capacitance (not shown in fig. 1) of 0.5 pF was implemented at the input of each channel and the test inputs were grouped separately for odd and even channels. This was done to allow the ASIC tests without a sensor.

PRELIMINARY MEASUREMENTS

Prototype ASICs were fabricated in 0.35 μm, four–metal, two–poly CMOS technology. The dimensions of each channel in the ASIC layout are $630\mu\text{m} \times 100\mu\text{m}$. Three prototype ASICs were bonded on dedicated PCB boards to test the front–end functionality and to measure their electrical parameters. The photograph of prototype glued and bonded on the PCB is shown fig. 3. One can see the layout of two blocks with four identical front-end channels. The power consumption of about 8.9 mW/channel was measured what confirms well the simulations. After checking the basic functionality (injecting charge and observing the output) the systematic measurements of essential parameters were done. In particular the gain, noise, high pulse rate operation and

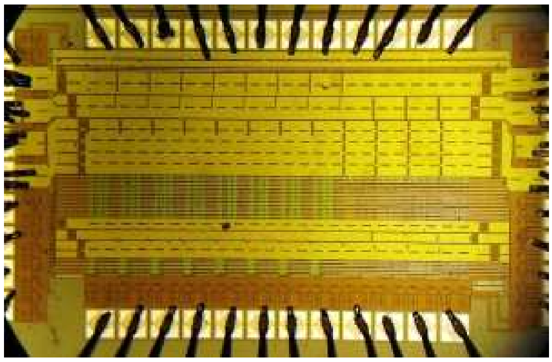

Fig. 3. Photograph of glued and bonded prototype. First 4 channels from the left have passive feedback and next 4 channels have active feedback

crosstalk were studied. Preliminary results of these measurements are discussed in the following.

Pulse shapes

In the first measurements the front–end channel response to charge injected through the input test capacitance was observed. These measurements were performed for different values of input capacitance (C_{det}) within the interesting range. The sensor capacitance was simulated with an external capacitor.

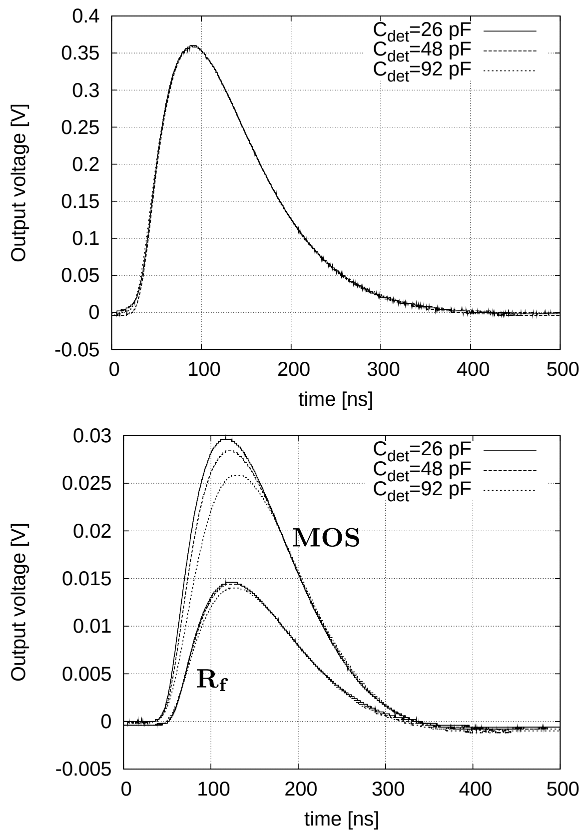

Fig. 4. Output pulses for MOS resistor front–end channels in physics mode (upper) and for MOS and R_f resistor in calibration mode (lower), as a function of input capacitance. In calibration mode $Q_{in} = 10\,fC$, while in physics mode $Q_{in} = 3.3\,pC$

In fig. 4 the pulses observed in physics (upper) and calibration (lower) mode for different input capacitances are presented. For physics mode the results obtained for active (MOS) and passive (R_f) feedback are exactly the same and for this reason only the active feedback curves are shown in the plot. It is seen that both the amplitude and the peaking time ($\sim$70 ns) are not sensitive to the value of input capacitance in this case. On the opposite in the calibration mode the amplitude and peaking time depend slightly on the input capacitance (C_{det}). This dependence is more pronounced for the active feedback case. It may be explained having in mind that in calibration mode the preamplifier's feedback capacitance C_f is small ($\sim$200 fF MOS, $\sim$500 fF $\mathbf{R_f}$) and so the ratio of C_{det} to an effective input capacitance $C_{eff} \simeq A_{pre} \cdot C_{f0}$ is not negligible since the preamplifier gain is below 1000 while the input capacitance goes up to 100 pF. In such a case some part of the input charge is lost on the detector capacitance and the preamplifier can not be considered as purely charge sensitive and C_{det} affects its transfer function. The effect is seen better in active feedback case where the feedback capacitance is smaller. It is not the case in the physics mode, when the feedback capacitance is large ($\sim$10 pF) the aforementioned ratio may be neglected. The described measurements are in good agreement with Hspice simulations performed for both types of resistances and both gain modes.

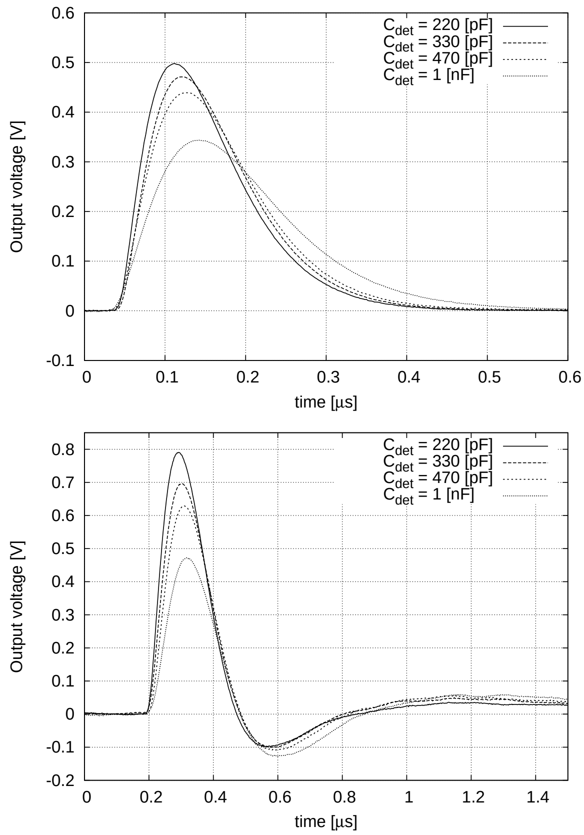

Fig. 5. Output pulses for MOS feedback channels in physics mode (upper) and in calibration mode (lower) for extremely large input capacitances. In calibration mode $Q_{in} = 40$ fC, while in physics mode $Q_{in} = 4.95$ pC

Although the present front–end was designed to work with sensor capacitances up to 100 pF, few qualitative measurements were performed to check its charge sensitivity with much higher input capacitances reaching up to 1 nF. Examples of such measurements are shown in fig. 5 for the front–end with active MOS feedback.

Similar results were obtained for the front–end with passive feedback. One can see that in the high gain configuration (small C_f) apart from significant amplitude drop, a large undershoot appears. On the contrary for low gain configuration the pseudo-gaussian shape is maintained in the whole capacitance range and a significant amplitude drop appears only for the highest input capacitance.

Gain measurements

Systematic measurements of charge gain covering full input signal dynamic range were done for a number of channels.

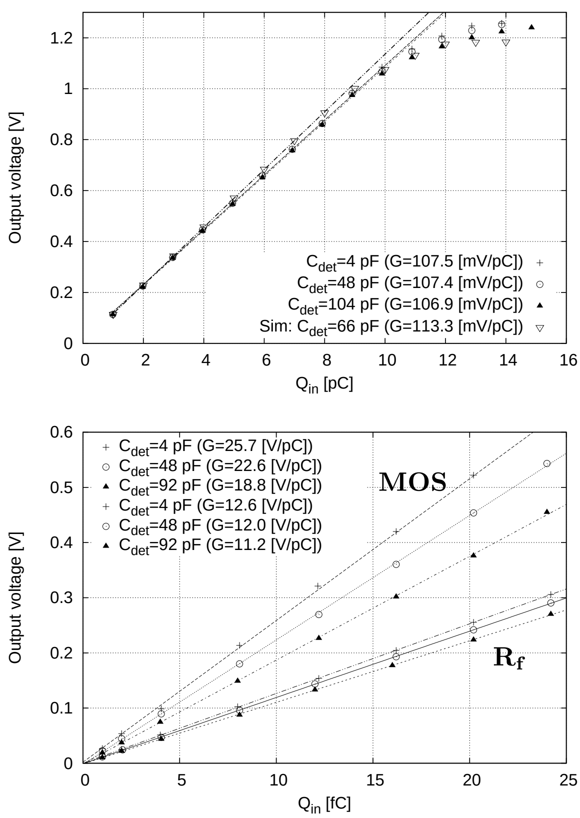

Fig. 6. Gain measured in physics mode for channels with MOS feedback (upper), in calibration mode (lower) for channels with MOS and passive R_f feedback

The results are shown in fig. 6 for the physics mode (upper) and for the calibration mode (lower). In the physics mode the measurements were performed injecting the charge through an external capacitance. This was done because, with the limited voltage step possible to apply (to not damage the ASIC), it was not possible to cover the whole input dynamic range using internal test capacitance (0.5 pF) only. The measurements were done for charge injections up to 15 pC, as seen in fig. 6 for the front–end with active feedback. Practically the same results were obtained with passive feedback but for the plot clarity they are not shown. It is seen that the circuit is linear up to almost 10 pC and saturates for higher charges injected. As expected the channel response is not sensitive to input capacitance value. The measurements are in good agreement with the simulation results which are shown in the same plot. For the calibration mode the measurements performed for both feedback types are shown in fig. 6 (lower). Only the most interesting input charge range (up to several MIPs) is shown. For all input capacitances both channel types show good linearity. In both channels types the gain depends on the input capacitance value decreasing with increasing C_{det}. Such behaviour was expected from simulations. For the MOS feedback the dependence is more pronounced since in this case the channel feedback capacitance C_f is about half of the value used for the channels with passive feedback.

Noise measurements

Preliminary noise measurements were performed using the HP3400 true RMS meter. The equivalent noise charge (ENC) as a function of input capacitance for both front–end types including physics and calibration mode is shown in fig. 7.

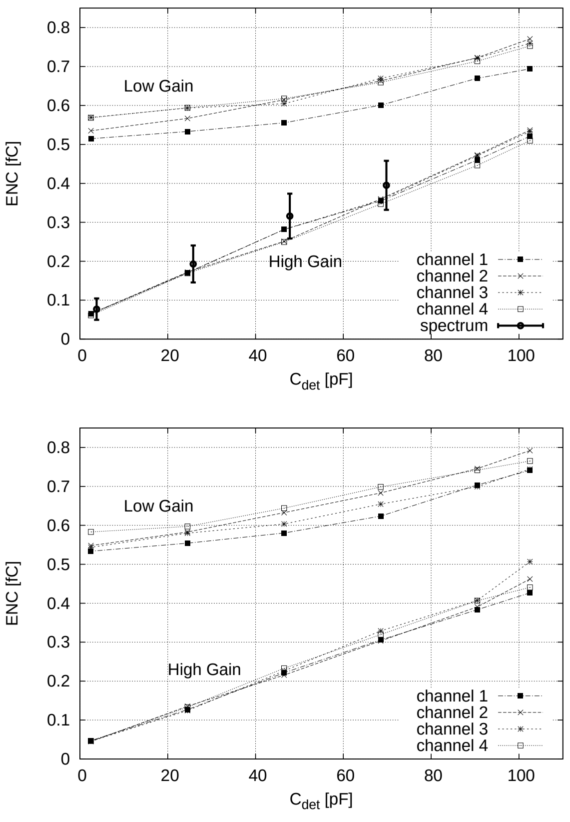

Fig. 7. Noise ENC measurements obtained with true RMS meter for the front–end with passive feedback (upper) and active feedback (lower)

Since the HP3400 bandwidth is only 10 Hz – 10 MHz the numbers may by underestimated by about 20%. The ENC vs C_{det} behaviour and the measured values are generally in agreement with simulations. In particular the signal to noise ratio of 10 is maintained up to almost 100 pF. For few points an additional noise measurement was performed by integrating the noise spectra with HP4195A spectrum analyser. The results of such measurements for passive feedback case are added in fig. 7 (upper). They agree within about 20% with the HP3400 RMS measurements. For a final confirmation of noise performance measurements with particles impinging a sensor are needed and will be performed as soon as a right sensor is available.

Pulse rate measurements

In order to test the PZC circuit operation the front–end response was studied varying the frequency of input pulses. For this study charge injection was realised by sending the staircase waveform from the Tektronix AWG2021 waveform generator. The effect of pulse frequency was estimated comparing the output amplitude obtained for the given input frequency to the amplitude obtained for the reference (low) input frequency. The comparison was done for the stable amplitudes at the ends of pulse trains (usually ∼20 pulses in the train).

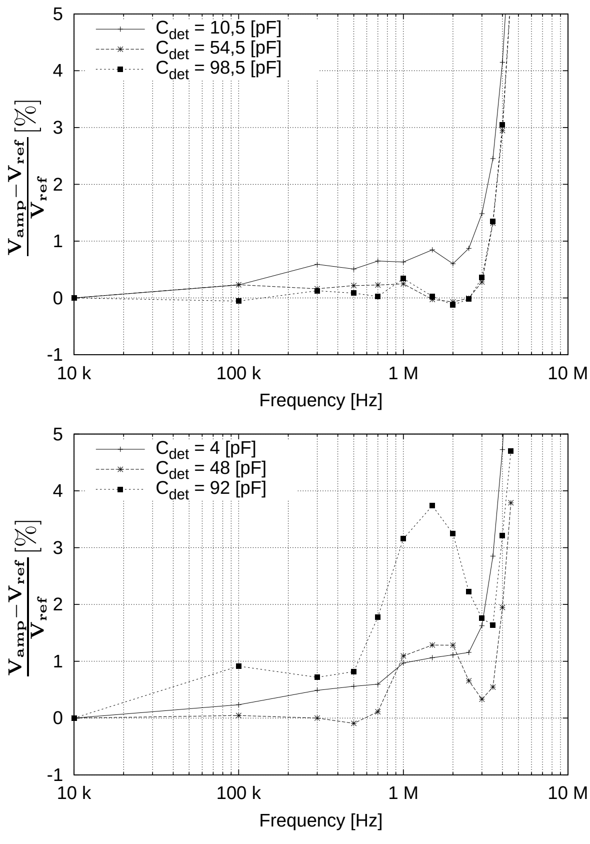

Fig. 8. Amplitude change for R_f resistor front–end channels in physics mode (upper) and in calibration mode (lower)

In fig. 8 the relative differences between measured and reference amplitude are presented respectively only for passive feedback channels. The results are shown for the physics mode (upper) and the calibration mode (lower). It is seen that for physics mode the effect of high rate reaches 2% for input rates of about 3 MHz and is almost not sensitive to input capacitance. Both the absolute numbers and the lack of sensitivity to C_{det} are in good agreement with simulations results. In physics mode (high C_f) the PZC operation should depend only on the

$C_f R_f$ and $C_p R_p$ matching which seems to be very good. On the opposite, in the calibration mode, it was already seen in simulations that C_{det} affects the preamplifier's operation and good PZC cancellation was obtained only for a given input capacitance. This is well seen in fig. 8 where a large spread of curves obtained for different C_{det} is observed. Nevertheless also in calibration mode the PZC works well up to relatively high frequencies since in absolute numbers the degradation with frequency is not much worse than in the physics mode. Similar results were obtained for the front–end with active feedback channels although the absolute effect of high input pulse rate was slightly higher.

Crosstalk

To estimate the crosstalk between the channels a dedicated setup with a simple general purpose PIN diode used as sensor and a laser light impinging this diode was prepared. This was done in order to exclude the possibility of additional crosstalk through parasitic capacitances on the PCB boards which could appear in the standard setup with electrical charge injection through a test capacitance. In the calibration mode relatively low crosstalk was observed which was below 0.1% for the front-end with active feedback and below 0.3% for passive feedback. A slightly higher result in the latter case may be well explained by the fact of large parasitic capacitance of the feedback resistance ($\sim$1 MΩ) which occupied much more area than the MOS transistor in the front-end with active feedback. Significantly higher crosstalk was observed for both front-end in physics mode. In case of active feedback almost 1% crosstalk was measured while for passive feedback it was about 1.5%. The natural candidate to explain such increase is a very large ($\sim$10 pF) feedback capacitance necessary for low gain physics mode which unfortunately adds about 20% of parasitic bulk capacitance. This effect will be addressed in the layout of the next prototypes.

SUMMARY

The first prototypes of the front–end electronics for LumiCal detectors were designed and fabricated. Preliminary tests confirm expected functionality and quantitative measurements regarding gain, noise, peaking time are in agreement with Hspice simulations. All measurements were done for the front–end with active MOS feedback and passive feedback. Generally both types of feedback show similar performance with some small differences. In order to fully verify the performance of the prototypes and to complete the comparison of both feedback types further measurements in realistic conditions, i.e. with sensors and impinging particles, are needed.

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