LHCb **2005-030**
LPHE **2005-013**
8th June 2005

Measurements on the VeLo analog link system

Jeremie Borel[1], Aurelio Bay[2], Raymond Frei[3], Guido Haefeli[4], Laurent Locatelli[5]

Laboratory for High-Energy Physics, Swiss Federal Institute of Technology, Lausanne

Abstract

A 50 m copper link will be used to carry the signal from the VeLo detector to the TELL1 modules in the barracks. The line driver and receiver circuits must compensate the frequency dependent signal attenuation. We present the measurement of the transfer functions for each component, a simulation of the system and a study to improve the quality of the response.

[1]E-mail:`Jeremie.Borel@epfl.ch`
[2]E-mail:`Aurelio.Bay@epfl.ch`
[3]E-mail:`Raymond.Frei@epfl.ch`
[4]E-mail:`Guido.Haefeli@epfl.ch`
[5]E-mail:`Laurent.Locatelli@epfl.ch`

1 Introduction

The first element of the VeLo readout is the Beetle chip. Each Beetle chip reads 128 channels which are multiplexed into 4 lines carrying 32 analog levels plus 4 header pseudo-bits. The header encodes the pipeline position in the Beetle buffer and some other information about the internal settings of the chip.

The data transport from the Beetle to the barracks is done via 50 m long analog copper links. The line induces a loss of the amplitude, modifications in the frequency spectrum and might suffer of electric noise pick-up. Therefore a differential transmission is used and a line-driver is inserted between the Beetle and the line to amplify the signal and to correct the frequency response of the whole system.

In this note we present our studies of the analogue system which was already described in [1]. Since then a tuned version of the system has been used in test beams. Section 5 will discuss the tuning procedure.

In short, the system consists of a "repeater board", the link cable and a "receiver board". The signals are fed into the repeater board which contains the line drivers and a special network designed to preshape them before transmission. At its far end the cable is plugged into the receiver board. The signal is sampled at 40 MHz and readout by a RB3 module (a prototype of the TELL1 [2]).

Section 2 of this note will present the measurements and simulations of the transfer functions of each subsystem. Section 3 will discuss the network tuning procedure. Section 4 presents some measurements with the Beetle chip, and section 5 gives the conclusion.

2 Transfer functions of the analog link system

The transfer functions of each components have been measured by feeding them with sinusoidal signals of known frequency. For comparison, in Figure 1 we show the transfer functions of the driver, of the cable itself, of the receiver, and the three combined. Note that for the receiver the real gain is twice what is shown in Figure 1 because of the 50 Ω input load of the oscilloscope. This does not occur for the other devices, because 50 Ω is exactly what they normally see.

One sees that the global response of the line is almost flat until 40 MHz. However we could notice about −2 dB attenuation around 10 MHz. In order to understand this behaviour, an electric model is needed. In the following sections we present in detail each element together with its associated model.

2.1 The line driver

The main purpose of the line driver is to preshape the signal to compensate the finite bandwidth of the cable. The idea is that the transfer function of the driver exactly compensates the transfer function of the cable at least up to 40 MHz. The electronic layout used is shown in Figure 2. Mathematically it consists of a two pole-zero network, hence the two slopes of 20 dB per decade we see on the Bode diagram of Figure 3.

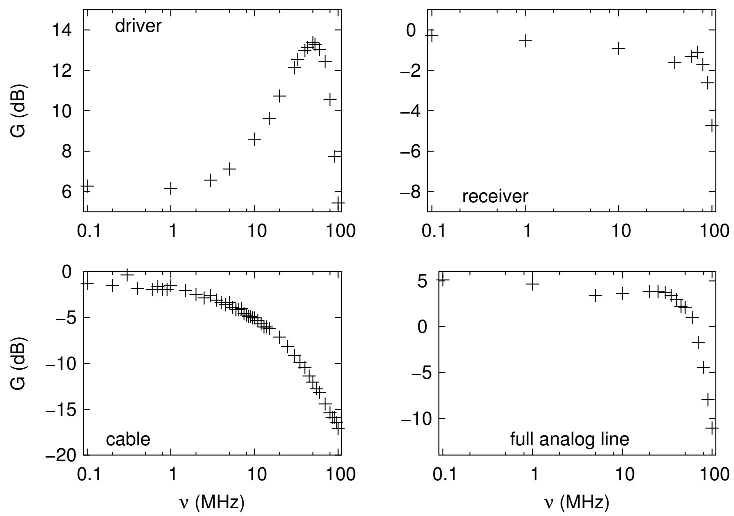

Figure 1: Transfer functions of each element of the VeLo analog link. Upper left the driver, upper right the receiver, bottom left the cable. The bottom right gives the transfer function of the whole system.

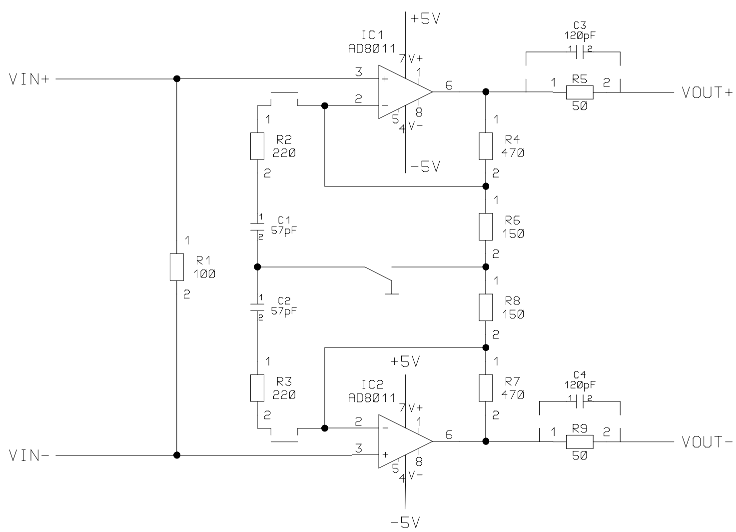

Figure 2: Electronic layout of the Driver (version 4 in [1]).

Explicitly the transfer function of this driver is:

$$G(s) = G_0 \frac{(1+s\tau_{za})(1+s\tau_{zb})}{(1+s\tau_{pa})(1+s\tau_{pb})}$$

where

$$\begin{aligned}
s &= \jmath\omega, \ (\jmath^2 = -1) \\
G_0 &= \frac{R_4 + R_6}{R_6} \frac{R_L}{R_5 + R_L} \\
\tau_{za} &= C_3 R_5 \\
\tau_{pa} &= C_3 (R_5 /\!\!/ R_L) \\
\tau_{zb} &= C_1 (R_2 + R_4 /\!\!/ R_6) \\
\tau_{pb} &= C_1 R_2.
\end{aligned}$$

The $/\!\!/$ operator is standard in electronic ($R_1 /\!\!/ R_2 = \frac{1}{1/R_1 + 1/R_2}$) and we assume that the layout of the driver is symmetric i.e. $R_2 = R_3$, $R_5 = R_9$, etc..

Thus we can calculate the associated pole zero values:

	pole (MHz)	zero (MHz)
τ_a :	12.6	8.36
τ_b :	53	26.5

One sees by looking at Figure 3 that the module of the transfer function is accurate before the high-frequency cut-off. This later is due to the operational amplifier characteristics and parasitic effects not taken into account in the calculation.

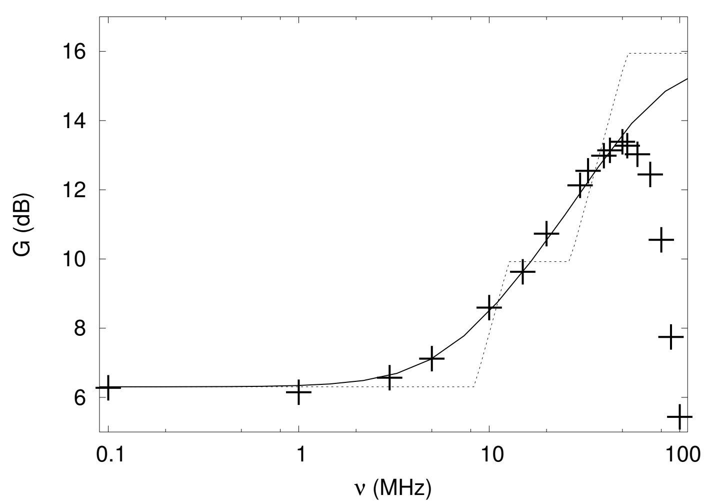

Figure 3: Line driver transfer function. The crosses are the measured points. The continuous line is the calculated module of the transfer function. The dotted line is the asymptotic Bode diagram.

A more accurate prediction of the high frequency behavior can be achieved through numerical simulations by the Spice program. We have used the Spice model of the operational amplifier provided by the manufacturer [3]. Figure 4 show the results with and without taking into account the effect of stray capacitances. A better result is obtained when parasitic effects are included by the insertion of a ~1 pF capacitor in parallel to R4 and R7.

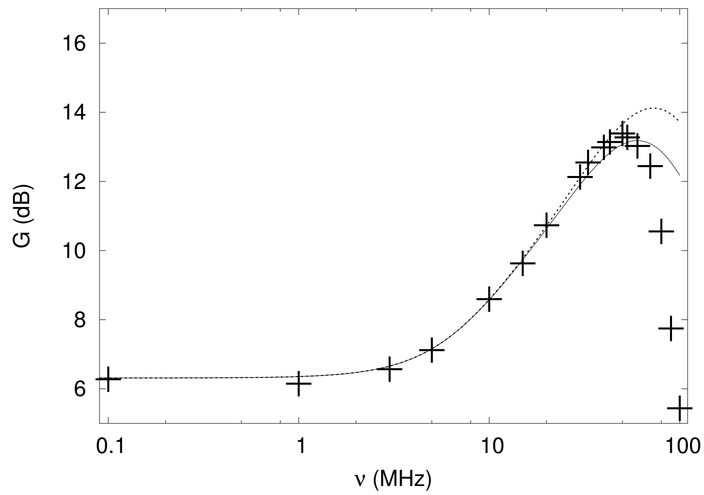

Figure 4: Line driver transfer function. The crosses are the measured points. The dotted and continuous lines are the Spice results without and with stray capacitances included.

2.2 The receiver

The receiver prototype we have studied is shown in Figure 5. It is designed to process the symmetric signal from the twisted pair cable and to amplify it by a factor two before digitization. The receiver is built with a differential amplifier [3] with a flat response until about 100 MHz, according to manufacturer. The results of our measurements are given in Figure 6 showing an amplification constant within 2 dB up to about 90 MHz, followed by a fast drop. Results from a Spice model of the circuit are also shown.

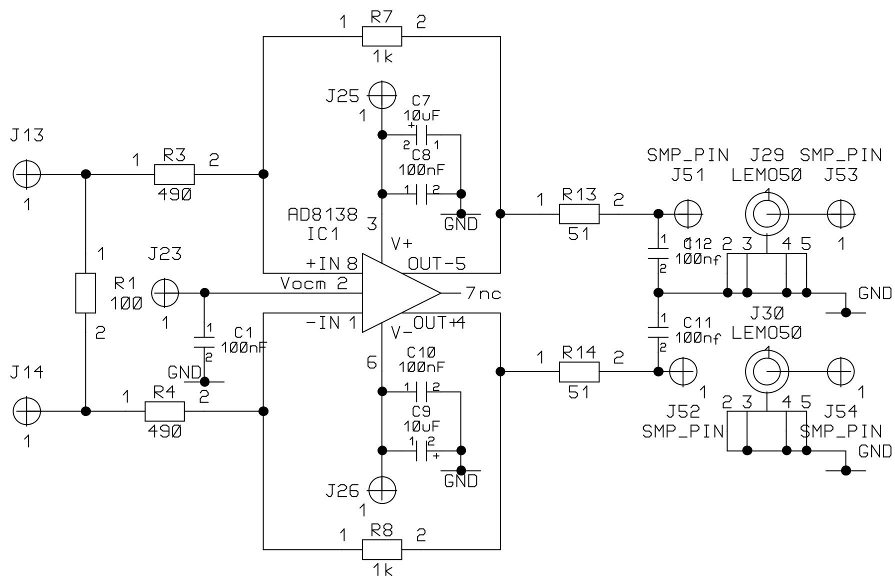

Figure 5: Electronic layout of the receiver.

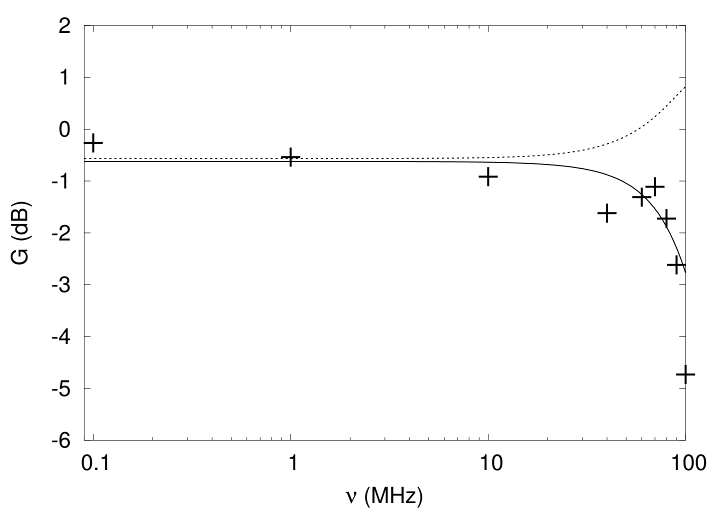

Figure 6: Transfer function of the receiver. The crosses are the measured points. The dotted and continuous lines are the Spice results without and with stray capacitances included.

2.3 The cable

The cable is a CAT6 model with 4 differential pairs individually shielded. Its characteristics can be found in [4]. All the Spice line transmission models we tested failed to reproduce the measured behavior. In order to have a better simulation of the cable (with a 1 dB precision), we implemented a two stages RC network as shown in Figure 7. They reproduce the module of the transfer function, though not the phase. We use voltage controlled sources to decouple each stage. Incidentally this assumption is not far from the real situation. For instance we have measured that the cable attenuation is enough to avoid that signals reflections at the receiver input can reach the driver, at least when the reflected fraction is at the level of few %. The transfer function of such a circuit looks exactly the same as the one from the driver i.e. proportional to $\frac{(\tau_1 s+1)(\tau_2 s+1)}{(\tau_3 s+1)(\tau_4 s+1)}$. The Bode diagram is a "two slopes function" as in Figure 8. The first part under 1 MHz is flat, the 1 to 20 MHz area is the first slope and the second slope falling faster above 20 MHz. The comparison of the simulation with the measured transfer function of the cable is excellent.

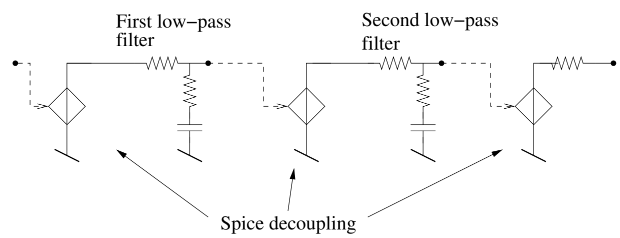

Figure 7: Spice model for the cable.

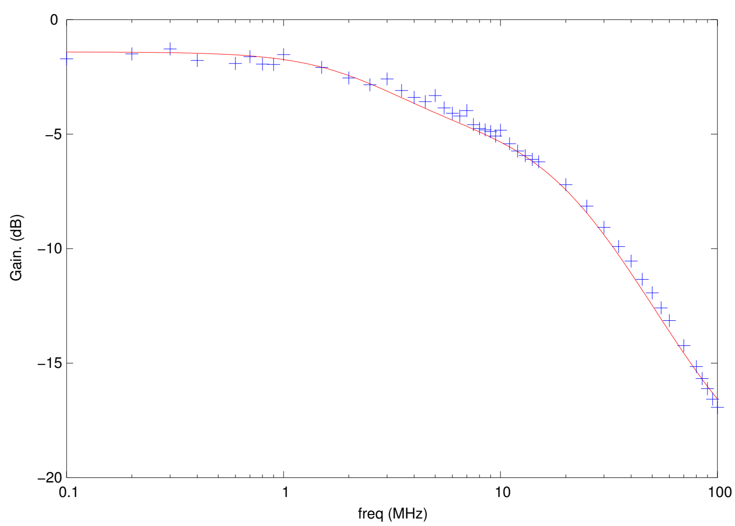

Figure 8: Transfer function of the cable. Crosses are the measured points, the line is the result of the the Spice model of Fig. 7.

2.4 Simulation of the whole system

The global behavior of the system was setup in Spice as in Figure 9, and the corresponding code can be found at URL: `www-lphe.epfl.ch/~jborel/analog`.

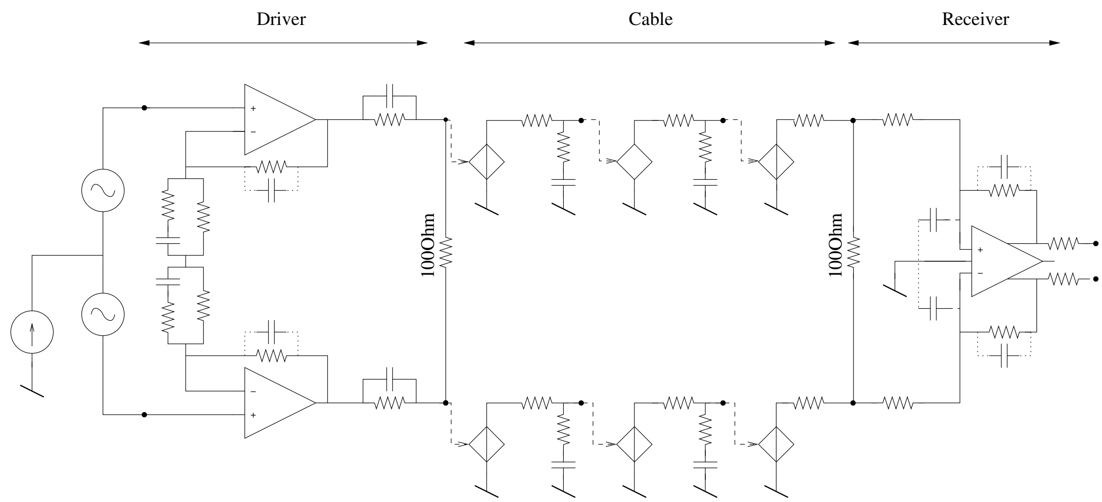

Figure 9: Spice setup of the analog transmission system. The dashed lines indicates the decoupling introduced in the cable model. Parasitic capacitors are shown with dotted wires.

Parasitic capacitors have been included in the simulations to improve the accuracy in the frequency response. Comparison between the measurements and the simulation of the analog link system is shown in Figure 10.

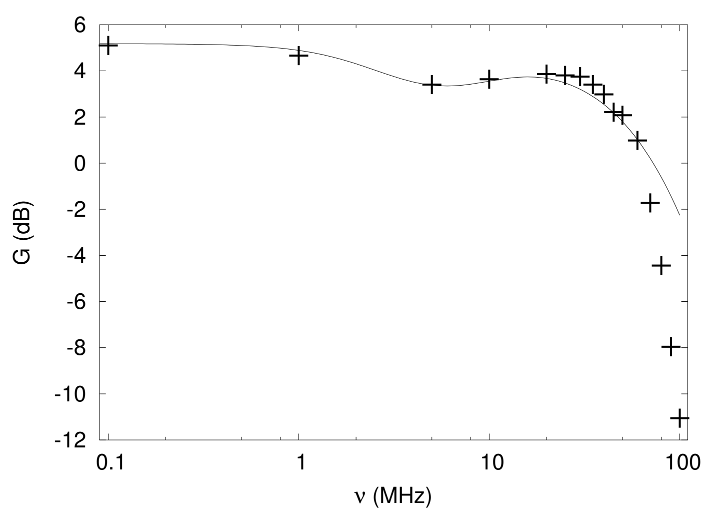

Figure 10: Transfer function of the whole system. The dots are the measurements, and the line is the response given by the Spice model.

Over 60 MHz the gain is somehow too high compared to the measured response

(+2 dB at 70 MHz and +6 dB at 90 MHz). On the other hand the region up to 60 MHz is well reproduced including the -2 dB dip between 3 and 20 MHz, compared to the level at 1 MHz. This last feature is not without consequences as can be seen in Figure 11 showing the responses of the system when square pulses are injected. The amplitude of the square signal used in this test corresponds to about 1 MIP, and the pulse width is of 25, 50 and 75 ns for the 3 series of graphs. The lower 3 graphs are the Spice simulation results while the upper 3 are our measurements. We can observe the signal integration tail extending by ~100 ns. The figures also indicate the amplitudes of the "residuals" (the overshoot measured at 25 ns after the pulse) as a function of the pulse width.

We devote the next section to show the method to correct for this effect, by a re-tuning of the driver compensation network.

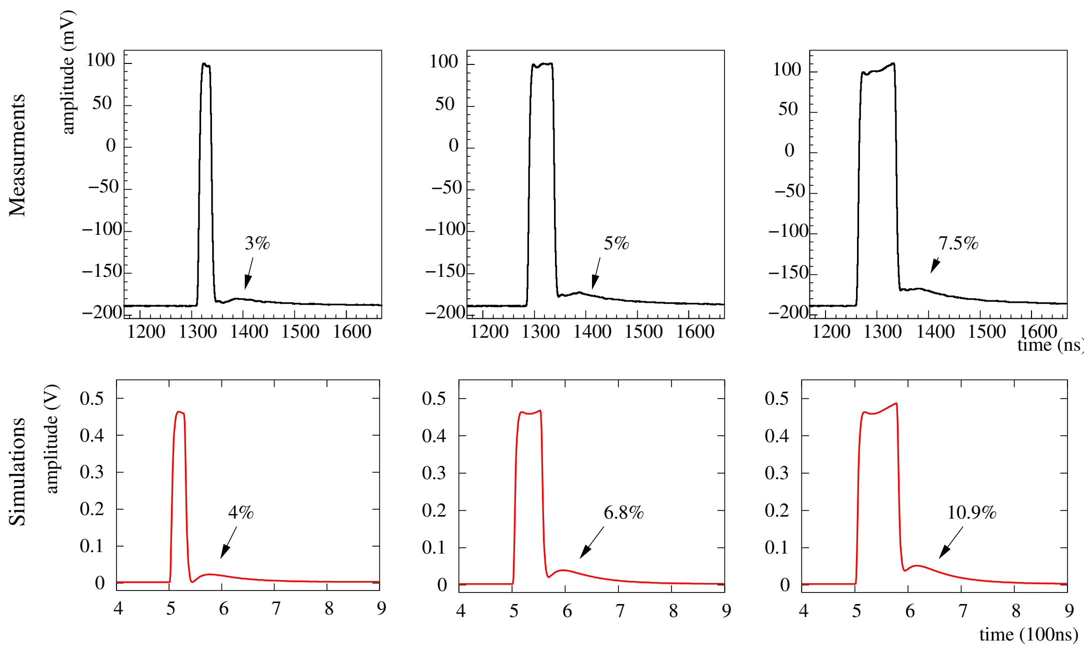

Figure 11: Response of the analogue link to rectangular pulses of 25, 50 and 75 ns width. The results of measurements are the 3 upper plots. The Spice predictions are given in the 3 bottom plots. We have indicated the fraction of the "residual" (the height of the pulse after a delay of 25 ns).

3 Tuning of the feedback network

Because the cable transfer function is so well reproduced by a double RC filter circuit and considering that the driver has exactly the same kind of behavior (two poles, two zeros) one could in principle just reverse the cable function and put resistors and capacitors into the feedback network such that they cancel each other. Unfortunately the optimal values are incompatible with the operational amplifier requirements. The RC resistor needs to be around 500 Ω following [3] to set the bandwidth. The two other resistors are then determined to set the low and high frequencies gain in order not to saturate the amplifier while keeping enough amplification. Thus the only free parameters of the network are the two capacitors.

Values giving good results are $C_1 = 220$ pF and $C_3 = 180$ pF. Figure 12 shows the Spice responses of the tuned configuration. For all the pulses width the residual has now disappeared.

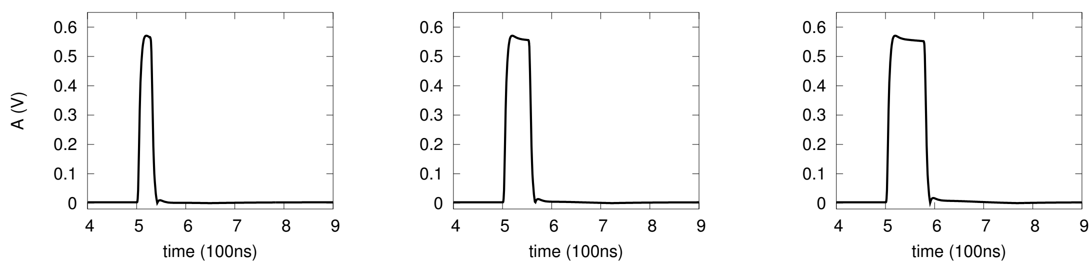

Figure 12: Pulses of 25, 50 and 75 ns from Spice simulation with the capacitor values $C_1 = 220$ pF and $C_3 = 180$ pF.

Figure 13 shows the simulated transfer function of the whole system. We see that the 10 MHz area is now very slightly over-amplified by ∼1 dB with respect to the low frequencies.

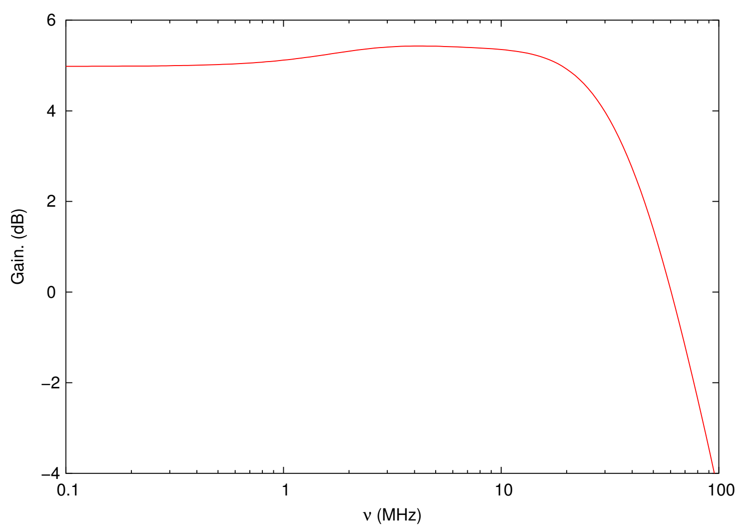

Figure 13: Spice transfer function with a new set of capacitors tuned for better frequency response

The preceding studies have been performed at the signal generator. In real life the pulse is produced by the Beetle chip with its own particular spectral disctribution. In the following section we present some measurements done on the Beetle 1.3 chip.

4 Measurements with the Beetle

It is known that the Beetle is not an ideal source of square signals. In order to quantify this point on our Beetle 1.3, measurements were performed by a gigasample oscilloscope with active probes[6] connected directly at the Beetle output terminated on 100 Ω. All the data were taken with the recommended Beetle settings [5]. The following results involve a pedestal subtraction and in some cases a common mode correction (calculated on non-bonded channels, see [1]).

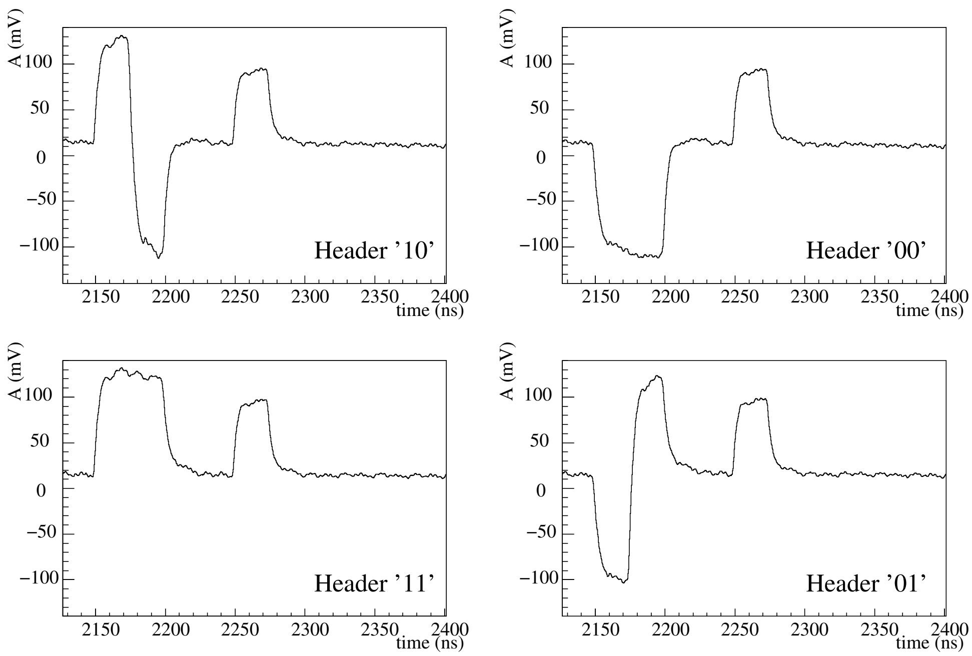

Figure 14: Mean trace for the four header configurations on the first link of the Beetle (link 0). The origin of the abscissa is arbitrary. We notice the $\sim$ 2 MIP equivalent pulse (at $\sim$ 2270 ns) obtained by the injection of charges by a small capacitor bonded to one of the Beetle inputs.

Figure 14 shows the mean trace in the region including the header and a pulsed channel for the four possible header configurations of link 0. The pulsed channel is obtained by the injection of a given charge at the input of the beetle via a small capacitor. The pedestal is computed regardless of the header configuration. One notice that we can only see the two last header pseudo-bits, the other two pseudo-bits being always at "1" they are counted in the pedestal calculation. Hence they disappear in the pedestal subtraction. Figure 15 shows the same traces superimposed.

The important point here is that we can see a $\sim$ 25 ns tail after the header pulses as well as after the injected pulse. These tails depends obviously on the level of the previous channel (header pseudo-bit or real pulse).

From this measurement we conclude that the Beetle 1.3 in our hands has an intrinsic residual value larger than 5%. This result is consistent with [1].

[6]The probes have a 1.5 GHz bandwidth. However, we limited at 200 MHz.

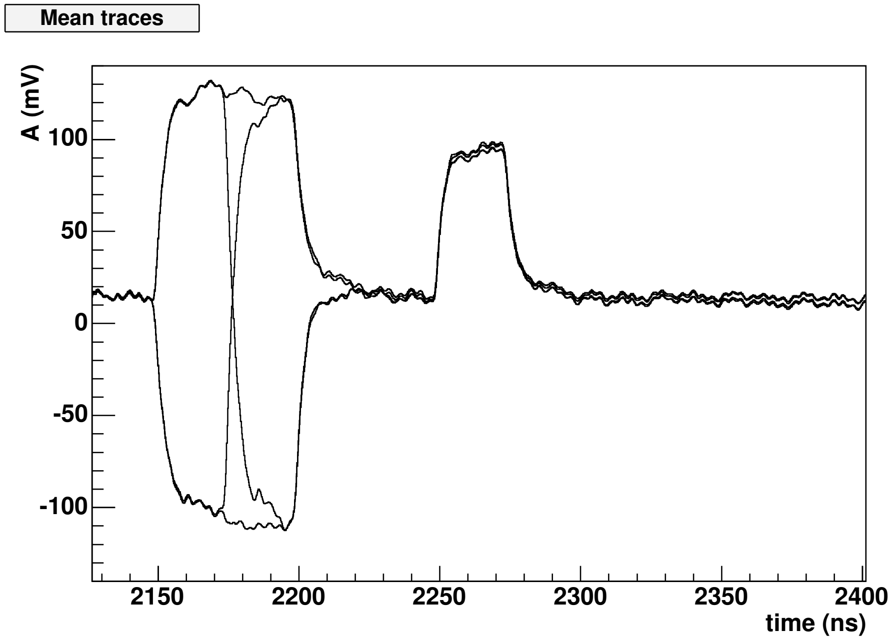

Figure 15: Superimposed mean analog traces at the Beetle output.

5 Conclusion

We have been able to accurately simulate the analog link at the level of 1 dB up to more than 60 MHz. We have shown also that there is at least two kinds of sources of residuals, one coming from the Beetle itself and the second from the link when the system driver–cable is not perfectly compensated in frequency. A very satisfactory compensation can be obtain by tuning the values of two capacitors of the frequency comensation network, reducing to a negligible level the contribution of the analogue link to the residual.

It has been suggested that a correction for the Beetle intrinsic residual could be achieved by introducing an overcompensation in the frequency correction network. This can be done by pushing a little the values of the capacitances in the existing network or, if needed, a third correction pole could be easily implemented on the receiver card.

Nevertheless we now think that a more fexible solution is to introduce a software correction at the level of TELL1 by a FIR filter[7]. The present design of the TELL1 firmware includes this possibility.

References

[1] Laurent Locatelli et al. *Tests on the VeLo analogue transmission line with the TELL1 prototype RB3.* LPHE, October 2004-012.

[7]Finite Impulse Response filter.

[2] Guido Haefeli et al. *TELL1: a common readout board for LHCb*, October 2003. LHCb note 2004-100, IPHE 2004-013.

[3] *Analog Devices*. `www.analog.com`.

[4] F. Zher. *study of the analogue transmission line and its equalizer in the LHCb vertex detextor front-end electronics. Master's thesis, Université de Lausanne, IPHE, March 2003.*

[5] Sven Löchner. Lab measurments with the Beetle 1.3.
http://wwwasic.kip.uni-heidelberg.de/lhcb/Talks.html.