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Considerations on the ICARUS read-out and on data compression

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Abstract

In this memo we propose some possible upgrades of the ICARUS DAQ system. The items concerned are:

- Modification of the response function of the preamplifiers mounted on the V791Q analogue board to eliminate unwanted undershoots;
- Increase of the gain of the front-end read-out to reduce the contribution of digitization to electronic noise;
- Lossless data compression algorithm suited for on-line application (at crate or board level) as well as for existing data.

1 The ICARUS front-end amplifier

The schematics of the ICARUS front-end preamplifier mounted on the CAEN - V791 analogue boards (32 channels per board) is shown in Figure 1. The circuit is an integrator characterized by a feedback time constant $\tau_f = R_f C_f$ followed by a "base-line restorer". The latter is introduced to attenuate the low frequency fluctuations of the signal baseline and is characterized by a time constant $\tau_r = (R_1||R_2)C_z$; while the low frequency components ($\omega << 1/\tau_r$) are suppressed, the high frequency ones ($\omega >> 1/\tau_r$) are amplified by a factor R_3/R_4.

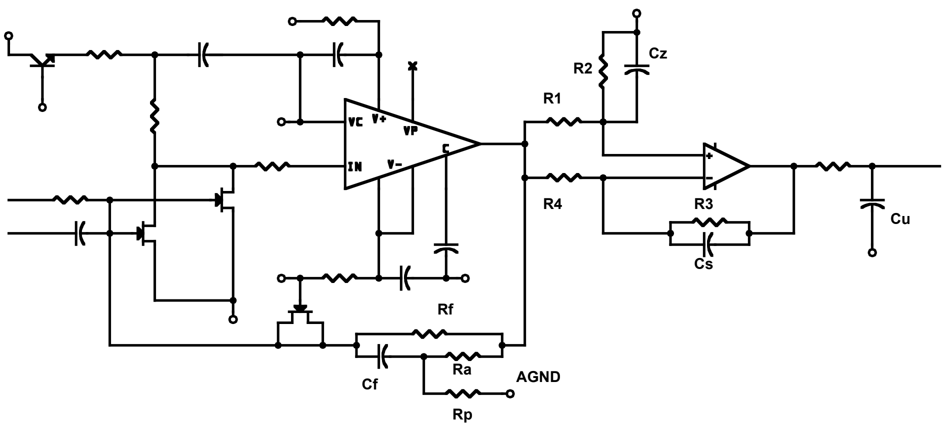

Figure 1: *Schematic layout of the front-end ICARUS amplifier mounted of the CAEN - V791 analogue boards.*

In the ICARUS DAQ chain, two versions of the V791 analog boards are used. To avoid pile-up and maximize the dynamic range, on the collection plane and the first induction plane, where the induced current yields an approximately unipolar signal (Figure 2), it was decided to adopt a "quasi-current" configuration (V791C). This means that the feedback amplifier time-constant is small with respect to the typical signal width ($3\mu s$).

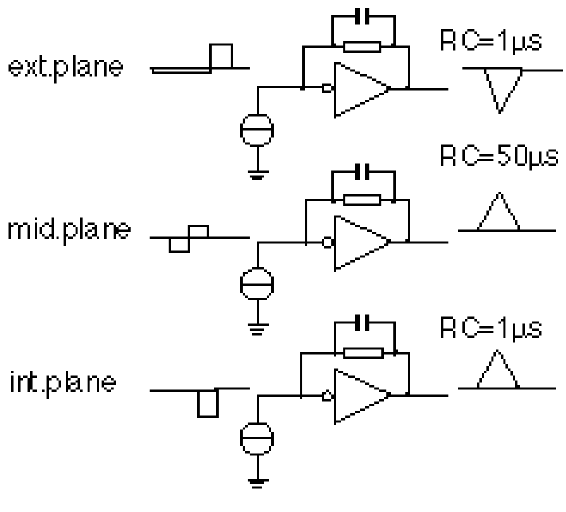

Figure 2: *Sketch of the signal shapes from the three ICARUS read-out planes.*

On the second induction plane (middle plane in Figure 2), where the induced current is bipolar, a "quasi-charge" configuration (V791Q: approximate integrator with long τ_f with respect to signal width) was preferred because it allows conditioning the signal in such a way that the shape is similar to that of the other two planes.

Both boards were optimized in terms of gain and signal-to-noise ratio in a test campaign performed with the 50 liter LAr-TPC in the first months of the year 2000. The final values chosen for components of the V791 boards are presented in Table 1.

V791	R_f	C_f	R_p	R_a	R_1	R_2	R_3	R_4	C_s	C_u	C_z
C	$10M\Omega$	$3.3pF$	$1.2k\Omega$	$22k\Omega$	$100k\Omega$	$270k\Omega$	$27k\Omega$	$10k\Omega$	$39pF$	$2.2nF$	$1\mu F$
Q	$100M\Omega$	$1pF$	–	0	$33k\Omega$	$270k\Omega$	$270k\Omega$	$33k\Omega$	$3.9pF$	$22nF$	$1nF$

Table 1: *List of components values for the two versions of the V791 boards (C&Q). The values of C_f is known with 10% accuracy.*

On the V791C board the feedback constant is $\tau_f \simeq 1.6\mu s$ and the gain is $5.5\pm0.5 ADCcounts/fC$. The electronic noise calculated on a time window of $50100\mu s$ (comparable with a typical width over which a signal is searched for) is about 1.2 ADC counts, for an input capacitance of 400 pF. Given the short value of τ_f the "base-line restorer" does not play an important role, hence its time-constant is set to a very high value ($\tau_r \simeq 100ms$).

On the V791Q board the feedback time-constant was chosen to be very large with respect to the typical signal width ($\tau_f \simeq 100\mu s$). It follows that the bandwidth of the preamplifier extends toward lower frequencies, which are responsible for unwanted fluctuations of the base-line level. To attenuate this effect a short time- constant of the "base-line restored" was chosen ($\tau_f = 33\mu s$). In this configuration the gain is $6.5 \pm 0.5 ADCcounts/fC$ and the overall decay time constant is about $30\mu s$. The electronic noise is less than 1.2 ADC counts. Low frequency fluctuations are present but do not affect signal reconstruction; their effect is mainly a reduction of the dynamic range of the whole read-out chain.

2 Front-end performance on the T600 semi-module

After the technical run held in Pavia during the summer 2001, the performance of the V791C boards mounted on the first T600 semi-module are found to be very close to the design values; only slightly higher value of the electronic noise is measured (1.7 ADC counts) probably due to the difficult environmental conditions in the mounting hall in Pavia.

On the other hand the V791Q version presents an unwanted under-shoot in the signal shape, that partially affects the event reconstruction capability from the middle plane. The amplitude of the undershoot is at least 15% of the signal pulse height (depending on signal duration) and extends for several tens of microsecond (Figure 3).

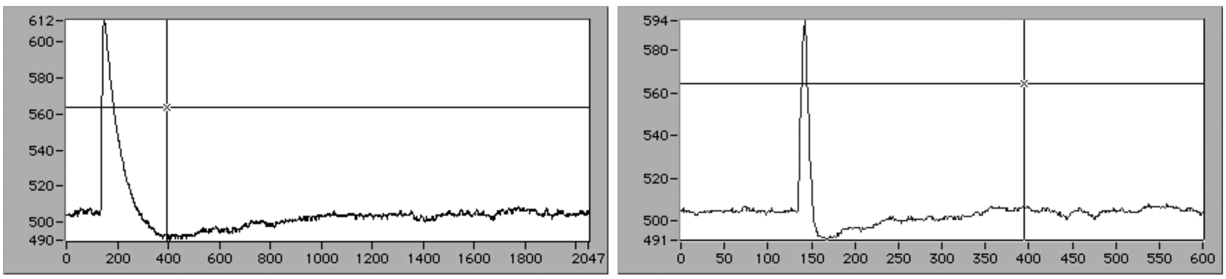

Figure 3: *Signal shapes from the present version of the V791Q analogue board: response to step test pulse (left), square test pulse (width = $3\mu s$, right).*

The effect of the undershoot on signal reconstruction is negligible for isolated tracks because its amplitude is comparable with the electronics noise fluctuations; however (Figure 4) it does affect events with large energy depositions (e.g.: electromagnetic showers) where the baseline cannot be determined very well track by track because the tracks are very close to each other.

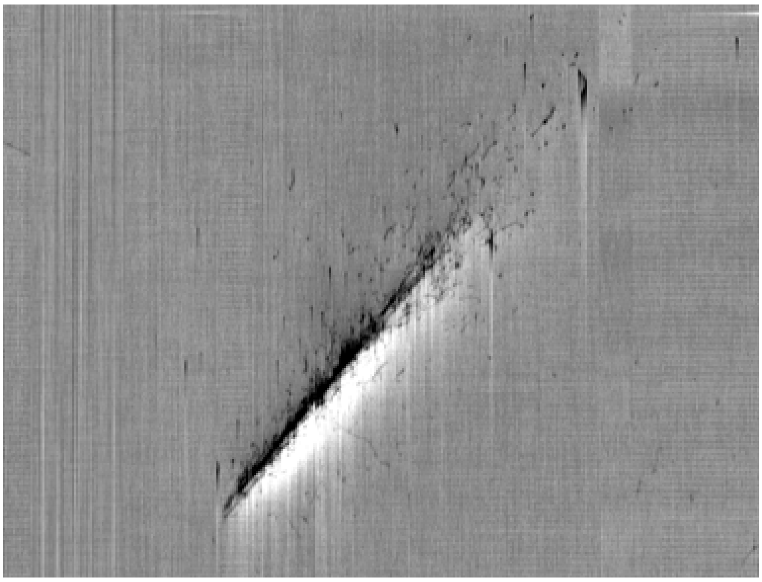

Figure 4: *Induction view of an electromagnetic event in the T600 semi-module. The wire numbering is on the horizontal axes, drift time on the vertical one. The white region is the undershoot due to the present layout of the V791Q analogue board.*

The origin of the undershoot sits in the "interference" between the feedback time-constant of the integrator and that of the "base-line restorer", that are too similar to each other ($100\mu s$ and $33\mu s$ respectively). In fact in order to minimize any undershoot after the "base-line restorer", its input signal should vary slowly in a time interval comparable to τ_r. This condition is clearly not satisfied in the V791Q configuration. Figure 5 shows a simulation performed with MICROCAP 7 that should help clarifying the problem. The bottom line shows the response function ($\tau_f = 100\mu s$) of the integrator to a step function; this is used as input to the "base-line restorer". The top line in the output of the restorer; the undershoot in clearly visible.

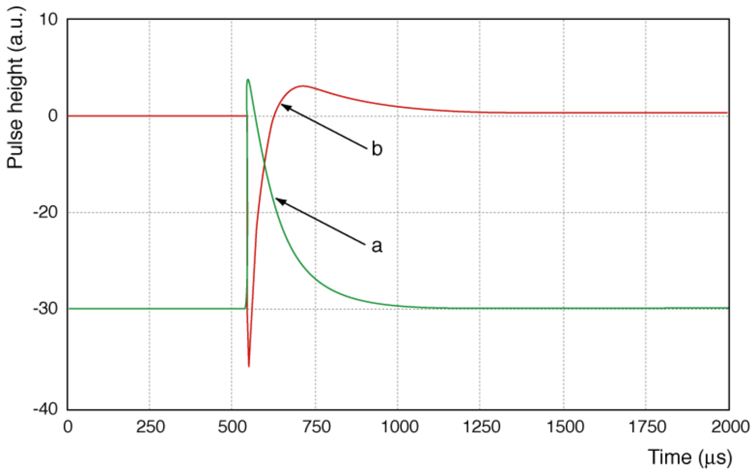

Figure 5: *Signal shapes from the present version of the V791Q analogue board: response to step test pulse at the output of the integrator (a), at the output of the base-line restorer (b).*

3 Possible solution to the undershoot problem

An improvement of the shape response of the V791Q preamplifier could be reached (without modifying the design and layout of the board) by simply changing the components that determine the time-constants of the preamplifier chain. A scheme close to that adopted on the V791C could be followed, namely a feedback time- constant close to the required design value ($\tau_f \simeq 30\mu s$) and a base-line restorer time-constant at least an order of magnitude higher ($\tau_r >> 300\mu s$). Clearly the drawback is a wider bandwidth of the front-end read-out chain towards low frequency, hence a higher sensitivity to base-line fluctuations.

The best compromise between undershoot minimization and low-frequency noise fluctuations has been investigated both with simulations and experimentally modifying the time-constants (τ_f and τ_r) of some channels on the V791Q boards mounted on the 50 liter LAr-TPC (equipped with 4 m long cables like in the T600). In order to leave the gain and possibly the signal-to-noise ratio unchanged, the new value of τ_f has been obtained only reducing R_f from $100M\Omega$ to $30M\Omega$; for the same reasons higher values of τ_r have been obtained increasing C_z.

The result seems quite encouraging. With a feedback time-constant of $30\mu s$, the "base-line restorer" time-constant can be pushed as high as 1 ms ($C_z = 30nF$) without increasing significantly the base-line fluctuations. Figure 6 (curves a, b) presents the comparison between the present signal response to a step test pulse (simulating long lasting signals due the showers or inclined tracks) of the standard V791Q and the modified one; the undershoot in the modified configuration does not exceed 3% of the pulse height.

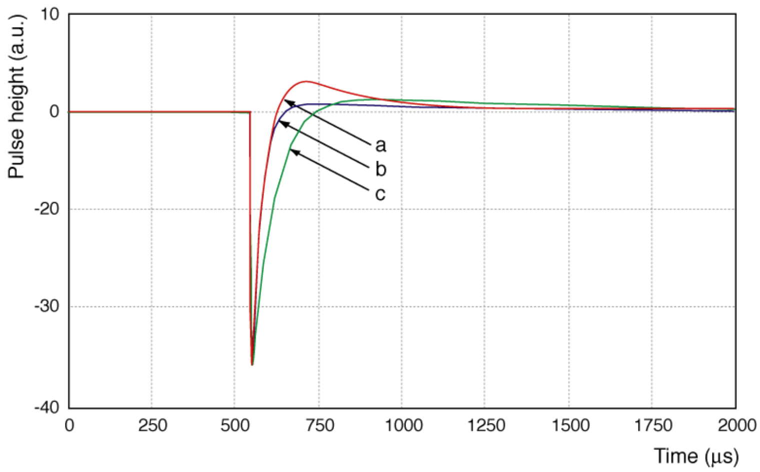

Figure 6: *Signal shapes from three versions of the V791Q board; response to a step test pulse: (a) $\tau_f = 100\mu s$, $\tau_r = 33\mu s$ (standard); (b) $\tau_f = 30\mu s$, $\tau_r = 1ms$; (c) $\tau_f = 60\mu s$, $\tau_r = 1ms$.*

The same comparison is shown in Figure 7 (curves a, b) but for a $3\mu s$ wide square pulse (simulating isolated tracks); in this case the undershoot of the new configuration is slightly more pronounced (about 6%) and it not due to the "base-line restorer" but to the preamplifier itself (τ_f is "only" 10 times larger that the signal width). Nevertheless it has to be recalled that in case of signals due to isolated tracks, (with pulse height ranging from 10 to 20 ADC counts), a 6% undershoot is not visible because it is well under 1 ADC count.

The sensitivity to low frequency fluctuations can be appreciated from the comparison of the frequency response of the present configuration to that proposed here (Figure 8, curves a,b). The frequency response differs only below 10 kHz (at most 14 db); recalling that the frequency spectrum characterizing the typical ICARUS signals is largely above 10 kHz, it can be anticipated that the reconstruction quality would not be affected by the proposed modifications of theV791Q boards.

For completeness and the overcome the problem of the undershoot in short signals, a further configuration with $\tau_f = 60\mu s$ ($R_f = 60M\Omega$) and $\tau_r = 1ms$ has been simulated and tested

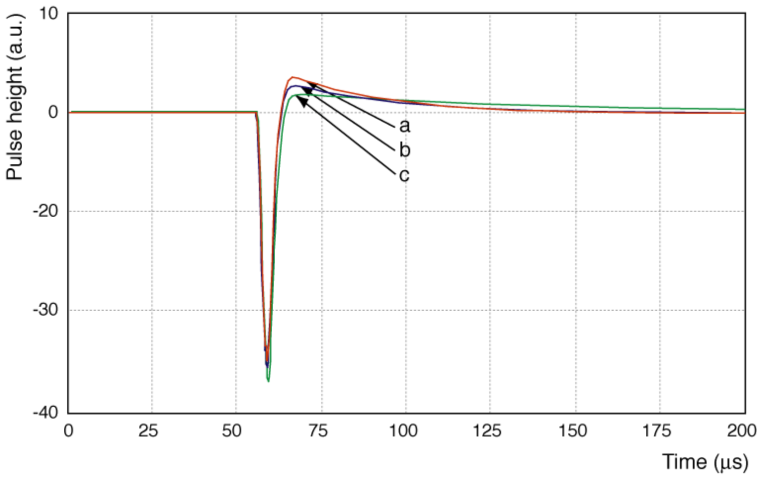

Figure 7: *Signal shapes from three versions of the V791Q board; response to a 3μs wide test pulse: (a) $\tau_f = 100\mu s$, $\tau_r = 33\mu s$ (standard); (b) $\tau_f = 30\mu s$, $\tau_r = 1ms$; (c) $\tau_f = 60\mu s$, $\tau_r = 1ms$.*

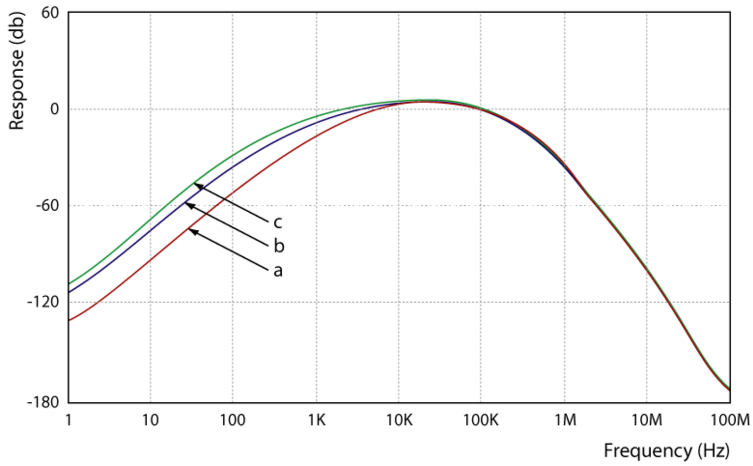

Figure 8: *Frequency response of three versions of the V791Q board: (a) $\tau_f = 100\mu s$, $\tau_r = 33\mu s$ (standard); (b) $\tau_f = 30\mu s$, $\tau_r = 1ms$; (c) $\tau_f = 60\mu s$, $\tau_r = 1ms$.*

(Figure 6, 7 and 8 curve c). The undershoot ranges from 3 to 4% but the low frequency components is increased by another 6 db. An interesting advantage of this configuration would be that it introduces less distortion in long- lasting signals like very inclined tracks or electromagnetic showers (cfr. decay time in Figure 6 curve c).

Both modified configurations require the replacements of only two surface mounted components (R_f and C_z) per channel (64 per board). A summary of the modifications of the V791Q boards and the related changes in performance is presented in Table 2.

4 Increasing the gain of the ICARUS front-end analogue chain

As mentioned above, during the optimization studies the gain of the ICARUS DAQ chain was set to 5.5 count / fC for the V791C (those used to read the collection wires) and 6.5 count / fC for the V791Q (those used to read the second induction wires). This corresponds to about 12 ADC counts

R_f	τ_f	C_z	τ_r	Undershoot level	Max. increase in low frequency response ($< 10kHz$)
$100M\Omega$	$100\mu s$	$1nF$	$33\mu s$	$> 15\%$	-
$30M\Omega$	$30\mu s$	$30nF$	$1ms$	$3 - 6\%$	$+14db$
$60M\Omega$	$60\mu s$	$30nF$	$1ms$	$3 - 4\%$	$+22db$

Table 2: *List of the modified components values for the two versions of the V791Q and related performance.*

for the charge released by a minimum ionizing particle over 3 mm (wire pitch) in extremely pure liquid argon. The choice was motivated by the requirement of maximizing the dynamic range while keeping the electronic noise above the level of 1 ADC counts (below this value the contribution of the "digitization noise" would be relevant).

Exploiting the data collected with the T600 semi-module, the electronic noise was measured to have an r.m.s. of 1.7 ADC count (S/N 7), slightly higher that expected. Under these conditions, the ionization signals can still be extracted quite efficiently. Unfortunately there are factors that can affect the extraction and reconstruction efficiency: a finite value of the electron lifetime reduces the pulse height; the electron diffusion broadens the pulse width and reduces the height. In principle a higher gain could help improving the signal extraction even at constant signal-to noise ratio, because high frequency noise can be smoothen with specific filters (e.g: median filter) and the signal rising edge would be more "sharp". Furthermore the "digitization noise" would be less relevant.

To test this hypothesis, some V791 boards mounted on the 50 liter LAr-TPC were modified acting on the gain of the linear amplifier placed downstream of the multiplexer and before the ADC. The following amplification factors were applied (one per board): 1.00, 1.35, 1.95, 2.30. Both the V791C and V719Q were modified. Data were taken both with test-pulses of different amplitudes (from 10 ADC counts to 250) and with cosmic rays. Preliminary analysis on the test-pulse data indicates that the detector performance (linearity response and resolutions) is NOT influenced by the gain increase at least in term of reconstruction ability. To conclude the test, we plan to analyze off-line the collected data with an algorithm equivalent to that implemented on the DAEDALUS chip to quantify a possible increase in signal extraction efficiency as a function of the gain. Results should be available soon.

5 A lossless compression algorithm for the T600 data

It is well known that the size of a full event from the T600 semi-module is about 200 Mbytes. The DAEDALUS chip is foreseen to perform zero skipping and hit-finding on-line; however it requires a careful optimization of its parameters to reach finding efficiencies close to 100% while minimizing the false detections. This activity is underway using the T600 data as test ground.

Meanwhile the possibility of lossless compression of the available data would be very useful in term of disk space and data handing (loading from storage devices,). For this purposes a simple method could be implemented based on the following argument; Figure 9 provides a graphical explanation.

At present a single sample (10 bit) is stored in 2 bytes (6 bit are used to record information from DAEDALUS); on the other hand, examining the T600 data one realizes that on every channel, the difference between a sample and the previous exceeds very rarely ± 7 ADC counts. This means that by recording the differences between successive samples one can store four samples in 2 bytes, thus performing a data reduction of a factor 4 without loosing information (the data stream can be exactly recreated except for the DAEDALUS output that are lost).

In case the absolute difference is larger than 7, one can flag the sample (e.g. by the value "-8"

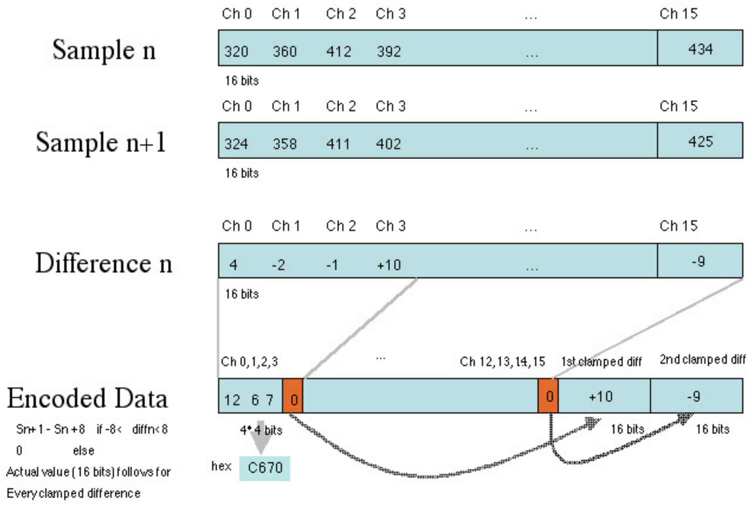

Figure 9: *Schematics of the implementation of the lossless data compression algorithm based on storing the differences between a sample and the preceding one.*

which is otherwise not used) and use the following full 2 byte slot to record the difference value. Depending on the rate of such occurrence, the actual compression factor could be slightly less than 4.

This simple algorithm has been tested on a substantial number of files with data from the T600 semi-module. An overall compression factor of 3.90 was reached. The compression scheme does not involve complex computational method and could be directly implemented as the recording format on the front-end FIFOs. This would reduce the required throughput to collect the data stream. An alternative solution could be to implement the algorithm on the crate CPU, with the drawback that throughput is not reduced at the level of the VME backplane.

Conclusions

Following the studies presented in this memo, a proposal is made to up-grade the V791Q board to a new configuration characterized by $\tau_f = 60\mu s$ and $\tau_r = 1ms$. This would be performed by changing two components per channel (64 per board), namely $R_f = 60M\Omega$ and $C_z = 30nF$.

Concerning a possible modification of the overall gain of the V791, the present results do not provide evidence for an actual benefit from this change; the proposal is to leave the gain untouched.

A lossless data compression of about a factor 3.9 has been demonstrated to be effective on the T600 data. The algorithm could be implemented in pipeline with data collection either on the CPU board in each crate or even in the front-end digital board (further studies are underway).