Copyright 2011 Society of Photo-Optical Instrumentation Engineers.
This paper was published in Proceedings of SPIE (Proc. SPIE Vol. 8008, 80080F, DOI: http://dx.doi.org/10.1117/12.905427) and is made available as an electronic reprint (preprint) with permission of SPIE. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper are prohibited.

Optimization of FPGA processing of GEM detector signal

Wojciech M. Zabołotny[a] and Tomasz Czarski[b] and Maryna Chernyshova[b] and Henryk Czyrkowski[c] and Ryszard Dąbrowski[c] and Wojciech Dominik[c] and Katarzyna Jakubowska[b] and Lesław Karpiński[b] and Grzegorz Kasprowicz[a] and Krzysztof Kierzkowski[c] and Ignacy M. Kudła[c] and Krzysztof Poźniak[a] and Jacek Rzadkiewicz[b] and Zbigniew Sałapa[c] and Marek Scholz[b]

[a]Institute of Electronic Systems, Warsaw University of Technology, ul. Nowowiejska 15/19, 00-665 Warszawa, Poland ;

[b]Institute of Plasma Physics and Laser Microfusion, ul. Hery 23, 01-497 Warszawa, Poland ;

[c]Institute of Experimental Physics, Faculty of Physics, Warsaw University, ul. Hoża 69, 00-681 Warszawa, Poland

ABSTRACT

This paper presents analysis of processing method of the signal from Gas Electron Multiplier (GEM) detector acquired in our Field-Programmable Gate Array (FPGA) based readout system. We have found that simple processing of GEM signal received from the charge amplifier, sampled at 100MHz with 10-bit resolution, after low-pass filtering with 15 MHz cut-off frequency, provides accuracy similar to obtained by processing of the raw GEM signal sampled at 2.5 GHz frequency with 8-bit resolution. Even when 3 bits are lost due to long term instability of the detector and analog part of the system - resulting in 7-bit effective resolution, the reasonable accuracy is still preserved. Additionally we have analyzed computational power required to perform the real-time analysis of the GEM signal, taking into consideration resources offered by the FPGA chip used in the prototype platform.

Keywords: GEM detector, hit energy estimation, hit position estimation, FPGA, ADC, DSP

1. INTRODUCTION

The FPGA based readout system for the GEM[1] detector was proposed and described in [2]. In this system (see Fig.1) the GEM signal amplified in the charge amplifiers and low-pass filtered is fed into analog-to-digital converters, and further processing is done digitally in the FPGA chips. However some design decisions depend on required sampling frequency and resolution of ADC. As the required number of analog channels in the final system is quite high (256 or 512), the price of analog to digital converters significantly affects cost of the whole system. The affordable ADCs offer 10-bit resolution with maximum sampling frequency of 100 MHz. Therefore our first goal was to verify, whether processing of GEM signal sampled with 100 MHz sampling frequency digitized with 10-bit resolution allows us to estimate the energy and position of the hit with sufficient accuracy. Another factor affecting the cost of the whole detection system is the price of FPGA chips. Required complexity of those chips depends on algorithms needed to estimate energy and position of the hit. Therefore we wanted also to verify, that even the simplest algorithms are able to provide reasonable accuracy.

2. THE MEASUREMENT SYSTEM

The measurement system used to collect data used for our analysis is described in [3]. On the output we have received signals from 16 neighbouring GEM stripes amplified in the charge amplifier with bandwidth 150 MHz. The signal was recorded by the digital oscilloscopes (4 4-channel Tektronix MSO4104 oscilloscopes) triggered by the signal from the 8^{th} strip. The signal bandwidth was limited in the oscilloscopes with 20 MHz internal low-pass filter. Trespass of the selected signal over the set voltage level triggered registration of 1000 samples of the signal (500 samples before the trigger and 500 samples after the trigger) in all 16 channels. In this way we have obtained data sets containing signals similar to shown in the Fig.2 (however to keep the picture clear, only signals from 6 strips are shown in the figure). For our analysis we have used three sets containing c.a. 50000 signals (a few cases with overlapping hits or with interferences have been manually deleted).

Further author information: (Send correspondence to W.M.Z.)
W.M.Z.: E-mail: wzab@ise.pw.edu.pl, Telephone: +48 22 234 7717

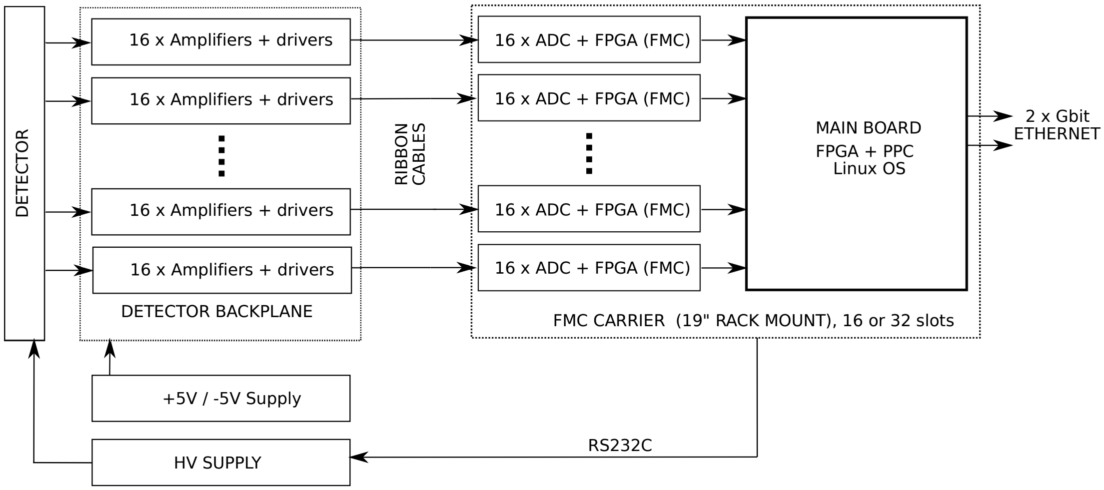

Figure 1. Acquisition and processing system block diagram

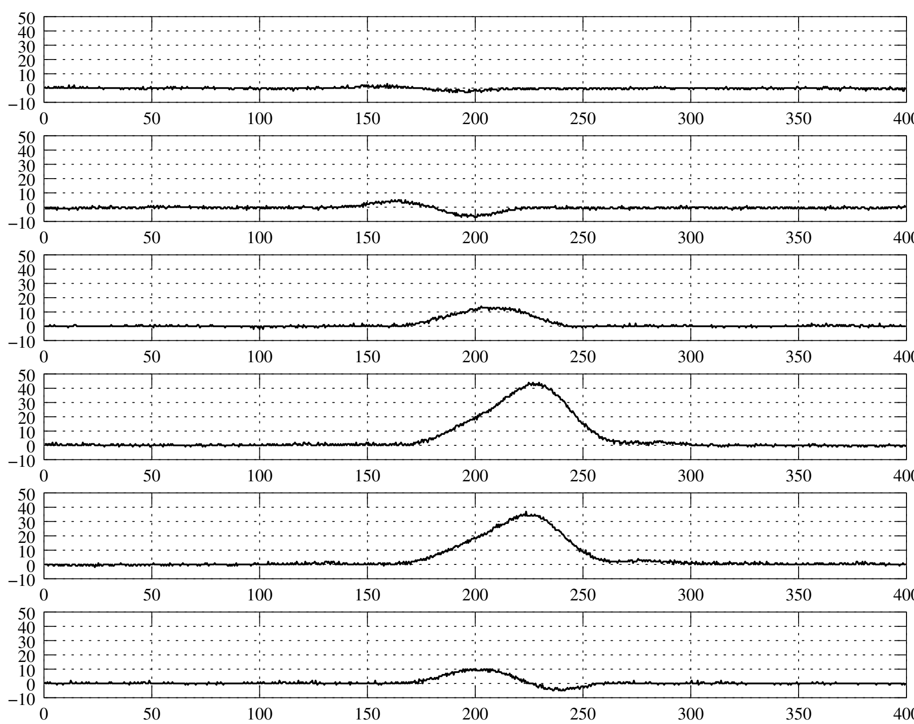

Figure 2. The GEM signal acquired by the digital oscilloscopes with 2.5 GHz sampling frequency and 8-bit resolution. Signals from 6 neighbouring strips shown. X-axis: time in ns, Y-axis: voltage in arbitrary units.

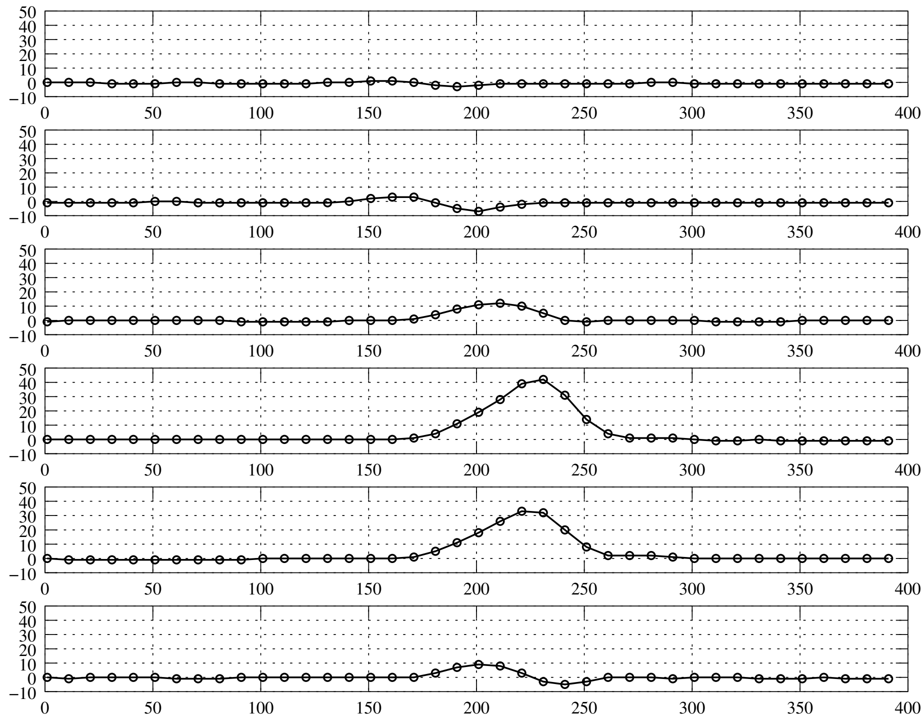

Figure 3. The GEM signal, filtered with 40MHz antialiasing filter and decimated to 100 MHz. Signals from 6 neighbouring strips shown. X-axis: time in ns, Y-axis: binary values of the sample.

3. THE REFERENCE SIGNAL PROCESSING ALGORITHM

Let's denote sample recorded in channel i ($i \in \mathbb{Z}$ and $1 \leq i \leq 16$), at position j ($j \in \mathbb{Z}$ and $1 \leq j \leq 1000$) as $S_{i,j}$. In the reference signal processing algorithm we first removed the offset from signal recorded in each channel. The offset value was estimated from the first 200 samples of the signal (before beginning of the pulse). The offset estimated in each channel was then subtracted from the signal in this channel. Signal without offset will be denoted as $\widetilde{S}$.

$$C_{\mathrm{offs},i} = \frac{1}{200}\sum_{j=1}^{200} S_{i,j} \tag{1}$$

$$\text{for } j \in \mathbb{Z} \text{ and } 1 \leq j \leq 1000\text{: } \widetilde{S}_{i,j} = S_{i,j} - C_{\mathrm{offs},i} \tag{2}$$

In the resulting signal $\widetilde{S}$ we searched for the maximum value in the whole data set. Let's assume, that the maximum was found in data from strip N as sample at position M (sample $S_{N,M}$ according to the previous definition). Then we discarded cases, where $N < 4$ or $N > 13$ (because in this cases we had no recordings from 3 stripes before and next to the N^{th} strip). Similarly we discarded cases, where $M < 301$ or $M > 700$. Then we calculated the charge estimate in each channel as the sum of the samples surrounding the global maximum:

$$\text{for } i \in \mathbb{Z} \cap [N-3, N+3] : C_i = \sum_{j=M-300}^{M+300} \widetilde{S}_{i,j} \tag{3}$$

The charge associated with the pulse (proportional to the hit energy) was then estimated as:

$$C_{hit} = \sum_{i=N-3}^{N+3} C_i \tag{4}$$

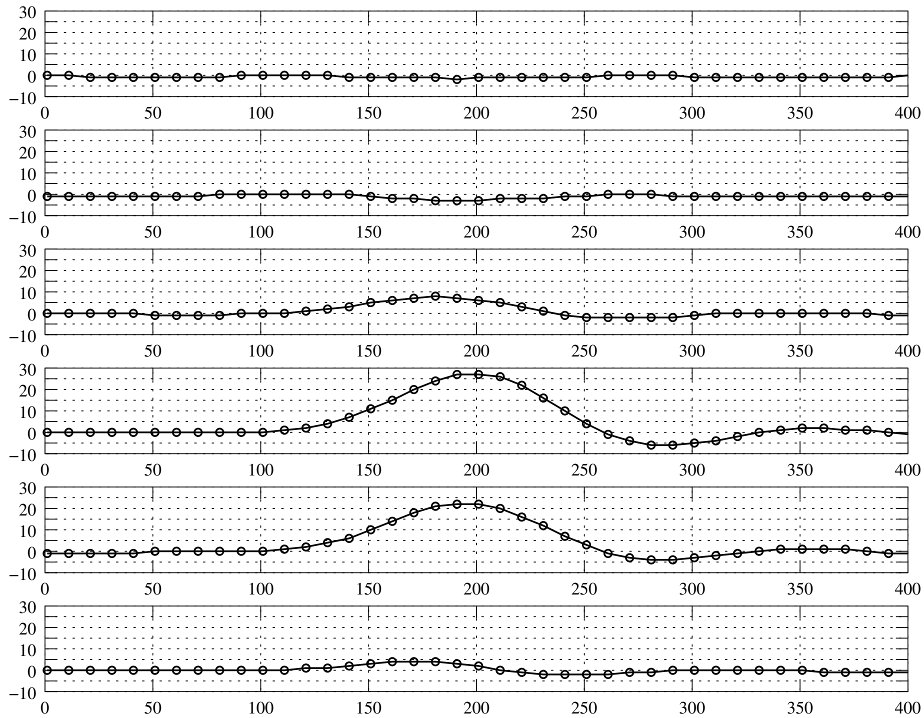

Figure 4. The GEM signal, filtered with 15 MHz antialiasing filter and decimated to 100 MHz. Signals from 6 neighbouring strips shown. X-axis: time in ns, Y-axis: binary values of the sample.

The position of the hit was then calculated as the "center of weight" of the charge collected in stripes from $N-3$ to $N+3$.

$$X_{hit} = \frac{\sum_{i=N-3}^{N+3} iC_i}{\sum_{i=N-3}^{N+3} C_i} \tag{5}$$

3.1 Modelling of the processing of the signal in the final system

Simulations of processing of the signal in the final system were performed in the Octave[4] environment. We tested two approaches. In the first one the signal was downsampled to 100 MHz using the standard “decimate” function, which used the low-pass filter with 40 MHz cut-off frequency, and additionally performed the forward and reverse filtering of the signal - to minimize the phase shift. However such downsampling, in presence of the additive noise in the signal, increases the resolution due to the dithering effect. Therefore we have finally quantized the resulting signal with 7-bit resolution. Sample signal after such downsampling and quantization is shown in the Fig.3.

Certainly such processing of the signal is not possible in the final system, but it allowed us to check if the downsampling itself preserves sufficient amount of information to estimate the pulse charge and position.

In the second approach the signal was filtered with the 6^{th} order Butterworth low-pass filter with 15 MHz cut-off frequency, and decimated to 100 MHz. Finally the signal was also quantized with 7-bit resolution to eliminate increase of resolution due to dithering effect. Results of processing of the same sample signal with this method is shown in the Fig.4.

Use of signal sampled with 100 MHz frequency required modification of the algorithm. Instead of 1000 samples per channel in each dataset we had only 40 samples. The offset was calculated from the first 10 samples of the signal.

$$C_{\text{offs},i} = \frac{1}{10}\sum_{j=1}^{10} S_{i,j} \tag{6}$$

Table 1. Correlation coefficients between parameters estimated from the original, full quality signal and parameters estimated from the downsampled and quantized signal.

	Cut-off frequency of the low-pass filter: 40 MHz Forward and reverse filtering Final quantization: 7-bits			Cut-off frequency of the low-pass filter: 15 MHz Final quantization: 7-bits		
Data set / Parameter	acq4	acq5	acq6	acq4	acq5	acq6
Pulse energy	0.99595	0.99654	0.99868	0.99465	0.99434	0.99500
Hit position	0.99933	0.99903	0.99986	0.99962	0.99894	0.99952

$$\text{for } j \in \mathbb{Z} \text{ and } 1 \leq j \leq 40\text{: } \widetilde{S}_{i,j} = S_{i,j} - C_{\text{offs},i} \tag{7}$$

The position of the maximum $\widetilde{S}_{N,M}$ was found as previously. The total charge in each channel was calculated from 21 samples surrounding the global maximum.

$$\text{for } i \in \mathbb{Z} \cap [N-3, N+3] : C_i = \sum_{j=M-10}^{M+10} \widetilde{S}_{i,j} \tag{8}$$

The charge associated with the pulse (proportional to the hit energy) was then estimated as previously:

$$C_{hit} = \sum_{i=N-3}^{N+3} C_i \tag{9}$$

The position of the hit was as previously calculated as the "center of weight" of the charge collected in stripes from $N-3$ to $N+3$.

$$X_{hit} = \frac{\sum_{i=N-3}^{N+3} iC_i}{\sum_{i=N-3}^{N+3} C_i} \tag{10}$$

4. COMPARISON OF PARAMETERS ESTIMATED FOR ORIGINAL AND DOWNSAMPLED SIGNALS

To check if the required preprocessing (filtering and downsampling) of the signal impairs possibility to estimate hit energy and position, we have performed following checks:

- We have verified, that the histogram of the estimated pulse charge (energy) correctly reflects the dual peak spectrum typical for ^{55}Fe radiation source used in the test (5.9 keV peak for ^{55}Fe and argon escape peak at 2.9 keV). Sample results are shown in the Fig. 5 and Fig. 6.
- We have verified that histograms of estimated hit position have similar shapes for the raw and downsampled and quantized signals. Sample results are shown in the Fig. 7 and Fig. 8.
- To have a more objective comparison of parameters estimated from the original signal with parameters estimated from the downsampled and quantized signal, we have calculated the correlation coefficients. Sample scatterplots are shown in the Fig.9,10, 11 and 12. The numerical results obtained for three analyzed data sets are summarized in the Table 1.

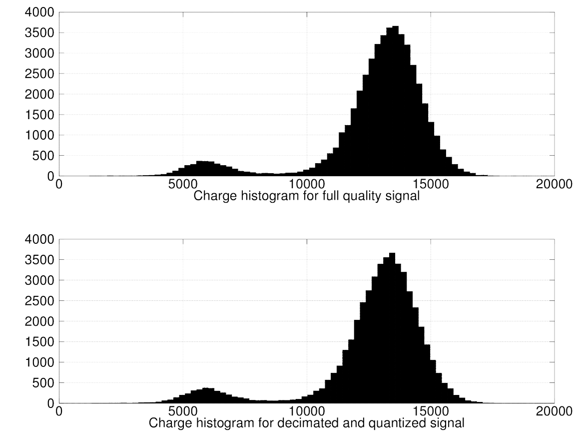

Figure 5. Comparison of histograms of charge estimates for the full quality signal and for the downsampled and decimated signal. Antialiasing filter cut-off frequency: 40 MHz. X-axis scaled in arbitrary units. Y-axis scaled in number of hits.

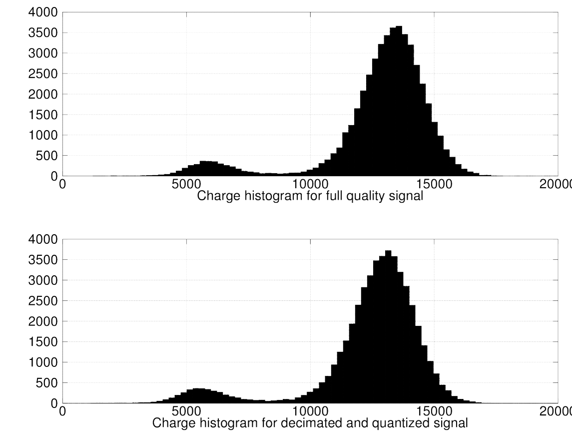

Figure 6. Comparison of histograms of charge estimates for the full quality signal and for the downsampled and decimated signal. Antialiasing filter cut-off frequency: 15 MHz. X-axis scaled in arbitrary units. Y-axis scaled in number of hits.

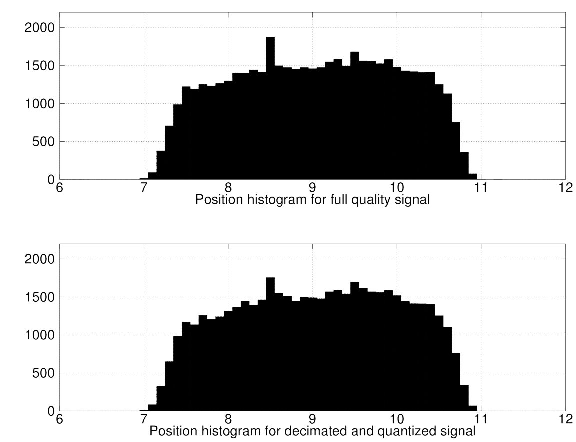

Figure 7. Comparison of histograms of position estimates for the full quality signal and for the downsampled and decimated signal. Antialiasing filter cut-off frequency: 40 MHz. X-axis scaled in strip numbers. Y-axis scaled in number of hits.

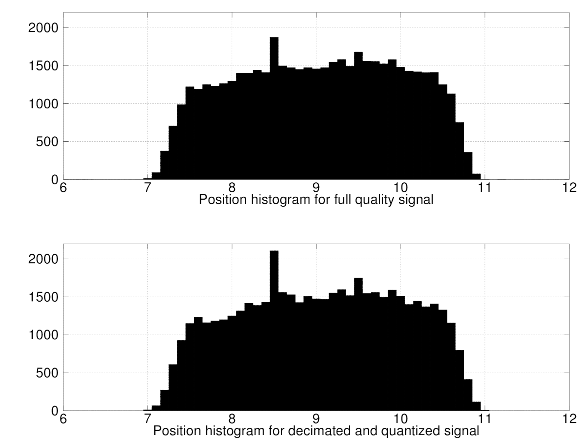

Figure 8. Comparison of histograms of position estimates for the full quality signal and for the downsampled and decimated signal. Antialiasing filter cut-off frequency: 15 MHz. X-axis scaled in strip numbers. Y-axis scaled in number of hits.

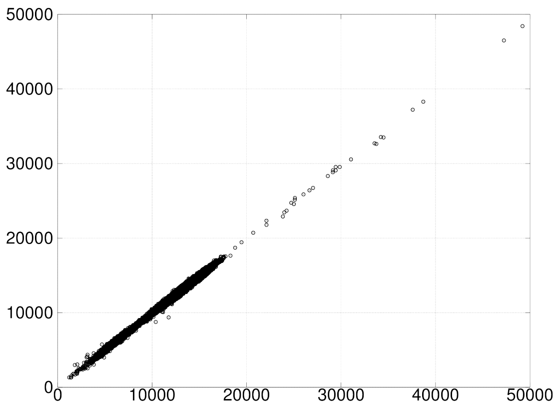

Figure 9. Correlation between the charge estimates for the full quality signal (X-axis) and for the downsampled and decimated signal (Y-axis). Antialiasing filter cut-off frequency: 40 MHz. Axes scaled in arbitrary units.

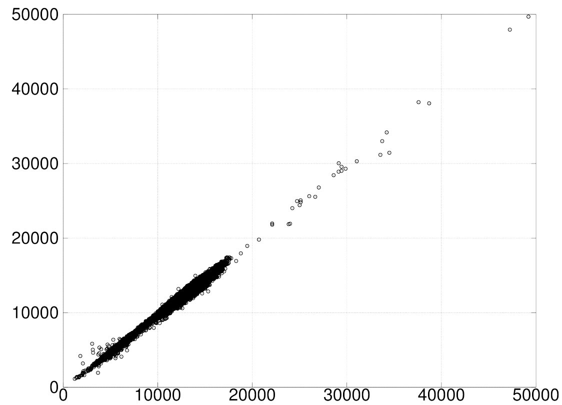

Figure 10. Correlation between the charge estimates for the full quality signal (X-axis) and for the downsampled and decimated signal (Y-axis). Antialiasing filter cut-off frequency: 15 MHz. Axes scaled in arbitrary units.

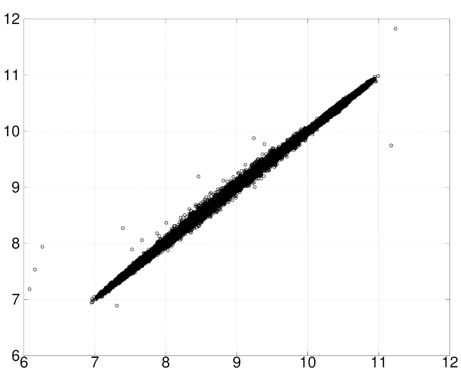

Figure 11. Correlation between the position estimates for the full quality signal (X-axis) and for the downsampled and decimated signal (Y-axis). Antialiasing filter cut-off frequency: 40 MHz. Axes scaled in strip numbers.

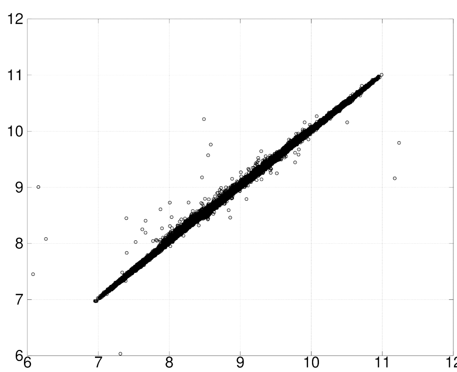

Figure 12. Correlation between the position estimates for the full quality signal (X-axis) and for the downsampled and decimated signal (Y-axis). Antialiasing filter cut-off frequency: 15 MHz. Axes scaled in strip numbers.

5. DISCUSSION

Obtained results show, that even signal downsampled to 100 MHz after low-pass filtering with cut-off frequency of 15 MHz and quantized with 7-bit resolution may be efficiently used to estimate energy and position of the hit, even when using the simplest algorithm. It is also visible, that for higher cut-off frequency and lower phase shift of the antialiasing filter, the results are slightly better.

It means that in the final system we may use relatively simple 15 MHz analog antialiasing filter and use 10-bit ADCs with sampling frequency 100 MHz. The 10-bit resolution of the raw acquired signal should allow us to compensate the long-term offset drift and changes of detector gain at the digital part of the system, still maintaining the final effective resolution not worse than 7-bits. The fact that we may avoid implementing drift and gain compensation in the analogue part leads to simplification of the system.

The fact, that the described, simplest algorithms may be used to estimate the hit's charge and position allows us to keep the digital part cheap and simple. In the prototype design, in the FMC boards we have one Spartan 6 XC6SLX16-2CSG324C chip with 32 DSP blocks for 16 analog channels. It means, that we have 2 digital multipliers and 2 fast adders per channel. In theory those multipliers may work with clock frequency of 390 MHz, but due to delays introduced by surrounding logic probably only 200 MHz will be achievable. Therefore we may perform only 4 multiplications and 4 additions per sample in each channel - it means, that even implementation of a simple FIR filter may be difficult.
The tasks which should be performed in each sampling cycle include

- Update of the offset estimator - probably a simple low-pass IIR filter may be used. In case of the first order IIR filter we need 1 multiplication and two additions per sample for this purpose, however for higher strip occupancy more complex offset estimation may be needed. If necessary, we may use the IIR filter with coefficients of form $a_1 = 1 - 2^{-n}$ and $b_1 = 2^{-n}$, which allows to implement the filter without any multiplications, but still two additions per sample will be needed.
- Update of the running sum of 21 consecutive samples (for hit detection). This task may be performed using a FIFO queue in each channel, but again one addition (of the newest sample) and one subtraction (of the sample leaving the FIFO) per sample are needed.

The above analysis shows, that the chip used in the prototype may be used for real-time signal analysis, but its resources will be almost fully used (in fact the situation may be a little improved by the fact, that for 10-bit samples and 100 MHz clock frequency additional adders may be synthesized from look-up tables (LUTs) in the FPGA).

The above analysis does not take into consideration the fact, that FMC FPGAs should be also involved in the task of identification of the hit position. However this task should be performed relatively rarely, and should involve only a few neighbouring channels.

6. CONCLUSIONS

Basing on the results of test measurements acquired with digital oscilloscopes, and simulating operation of the final data acquisition and processing system we have proved that use of relatively cheap 100 MHz/10-bit analog-to-digital converters, connected after the 15 MHz low-pass filter, should provide sufficient accuracy to estimate hit charge and position in the GEM detector. The XC6SLX16-2CSG324C chip used in the prototype FMC boards should be sufficient for real-time analysis of the GEM signals, however implementation of additional functionalities (e.g. related to diagnostics) may require more complex chip.

REFERENCES

[1] Sauli, F., "Gem: A new concept for electron amplification in gas detectors," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **386**(2-3), 531 – 534 (1997).

[2] Kasprowicz, G., Czarski, T., Chernyshova, M., Czyrkowski, H., Dąbrowski, R., Dominik, W., Jakubowska, K., Karpiński, L., Kierzkowski, K., Kudła, I. M., Poźniak, K., Rzadkiewicz, J., Sałapa, Z., Scholz, M., and Zabołotny, W. M., "Readout electronics for the GEM detector," *Proceedings of SPIE* **This Volume**.

[3] Poźniak, K., Czarski, T., Kasprowicz, G., Dominik, W., Lorenc, M., , Chernyshova, M., Czyrkowski, H., Dąbrowski, R., Jakubowska, K., Karpiński, L., Kierzkowski, K., Kudła, I. M., , Rzadkiewicz, J., Sałapa, Z., Scholz, M., and Zabołotny, W. M., "Automatic testbench for GEM detectors," *Proceedings of SPIE* **This Volume**.

[4] "About octave." `http://www.gnu.org/software/octave/about.html`.