Data Acquisition System for the PICASSO Experiment

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1. Introduction

Several key astronomical observations indicate that the Universe contains a special type of matter - Dark Matter (DM). Physics research groups look for the experimental evidence of DM in the form of elementary particles. One such project - the PICASSO experiment (Project In CAnada to Search for Supersymmetric Objects) - is taking place in the deep underground facilities of SNOLAB at Sudbury, Ontario in Canada (at ~2km depth) (Fig. 1) [Leroy & Rancoita (2009)].

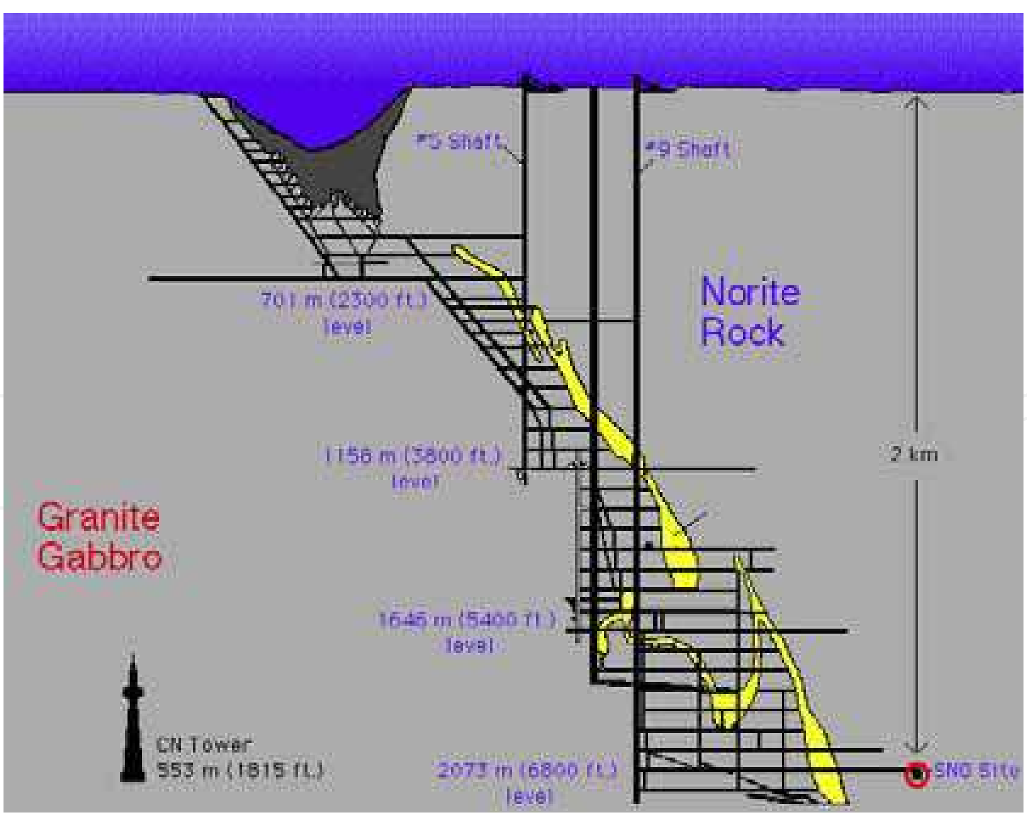
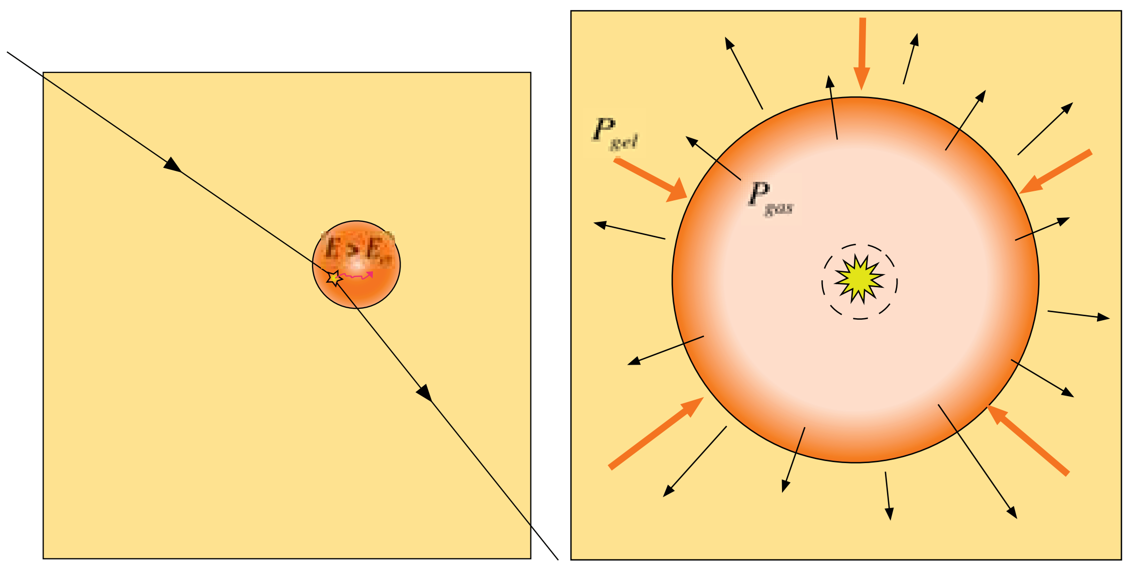


Fig. 1. Location of the PICASSO experiment at the SNOLAB cavity at the VALE-INCO coppernickel mine in Lively, Ontario, Canada.

It employs a phenomenon long used in bubble chamber detectors, where a superheated liquid starts to boil precisely along the tracks of charged particles. Although, all candidates for DM particles are considered to be electrically neutral, they nevertheless could react weakly with detector material creating detectable recoil nuclei. Historically bubble chambers were made of relatively large homogeneous volumes of superheated liquid. All such detectors were required to be re-pressurized immediately after each detected event in order to avoid dangerous and rapid pressure build-up. PICASSO detectors exploit this technique in a modified manner by using small droplets of superheated liquid dispersed and suspended in an elastic gel. Each superheated droplet acts as a small independent bubble chamber and will be contained in the gel. In order to trigger a phase transition possible, at least a minimum critical energy must be deposited by interacting particles within a critical volume along its track (Fig. 2).



(a) Reaction inside the droplet can cause nuclear recoil;

(b) Liquid-to-gas phase transition;

Fig. 2. Illustration of a neutral particle reaction within the superheated droplet (a) followed by the transition into the gas bubble (b).

However, all detectors based on the principle of superheated liquid droplets must be repressurized eventually in order to keep the detector active. This brings expanded gas bubbles back into their droplet state and thus reverses the detector back to its original active state. If detectors are placed in a low radiation background environment, sufficiently long time may pass before the re-pressurising procedure will be needed. This specific detector type has the ability to effectively enhance the nuclear recoil signal over background radiation interactions (such as β and γ). Therefore, this type of detector could reveal the existence of dark matter by observing nuclear recoil interactions of DM particles in the superheated liquid droplets. Exploding gas bubbles create sound which is detected by a number of piezoelectric sensors located on the exterior surface of the detector. The PICASSO detectors need a special electronic platform that has been developed at the University of Montreal. This chapter describes only the general structure of the data acquisition system (DAQ) without dealing with details of the investigation of the signals and the sensors used in the PICASSO detector [Gornea et al. (2000), Gornea et al. (2001)].

2. History of the PICASSO experiment.

It is only natural to expect that larger physics experiments arrive from smaller scale trials. At the time of this publication the PICASSO experiment has already passed through several stages of its development with different detector technologies, a variety of sensory hardware and several data acquisition systems. The first detectors were relatively small. They were equipped only with one or two piezoelectric sensors. Each transducer channel had its own individual preamplifier box (Fig. 3).

(a) One of the earlier types of detectors;

(b) One of the earlier preamplifier boxes;

Fig. 3. A small size 1L PICASSO detector with only two sensors (a) and single channel preamplifier (b).

Acoustical signals were acquired independently from each sensor. Five channel analog-to-digital converter (ADC) VME boards were designed using ALTERA's FLEX10K family (Fig. 4). Besides difficulties of the firmware debugging, this FPGA platform had limitations concerning the recorded waveform length and scalability. Matching timing information obtained by different boards was difficult. At the end of the first phase of the experiment, it was clear that in order to accommodate many more of detector channels and longer waveforms, the experiment would need a new data acquisition hardware. The newer version of the DAQ system is detailed in this report while the description of the older system can be found in [Gornea et al. (2000), Gornea et al. (2001)].

Fig. 4. Previously used VME module for PICASSO data acquisition.

3. Detector and DAQ architecture.

The electronic system of the PICASSO detector includes several functionally independent subsystems. Each one is dedicated to control specific detector parameters (e.g. temperature and pressure regulation, on-line detector calibration, etc.) or to collect and process acoustical signals. Experimental data consist of waveforms from acoustical piezoelectric sensors simultaneously acquired from the entire detector. In its current stage, the detector layout consists of a set of 8 clusters, each containing 4 detector modules adding to a total of 32 detectors (Fig. 6 and 5). A group of 4 detectors is placed in an insulated metal box (Fig. 7) - Temperature-Pressure Control Sysytem (TPCS), where the temperature can be set to a pre-determined value with a precision of about ±0.5 °C. While the temperature can be set individually to each TPCS, the pressure can be set for all detectors simultaneously only.

Each detector has 9 piezoelectric sensors working as a group. There are three layers of sensors on the external surface of the acrylic container. Each layer contains three sensors distributed evenly along the detector's perimeter covering 120° sectors. Layers of sensors are rotated by 60° relative to each other. This is done for complete coverage of the active volume and acoustical triangulation of the event position. Sensors are made with cylindrical shape piezoelectric transducers mounted inside brass containers designed as Faraday cages in order to reduce electrical noise (Fig. 8). Electrical signals from piezoelectric sensors are sent over coaxial cables to be amplified and digitized. Each detector module is equipped with its own subset of electronics (preamplifiers and ADCs) in order to operate independently from the other units. These electronic boards are located in a metal enclosure placed outside and above the cluster of 4 detectors. The location of these board enclosures is chosen so as to keep the length of the coaxial cables to the practical minimum in order to minimize any induced electrical noise. Special care is taken to reduce the microphonic effect of the cable as

Fig. 5. View of the PICASSO set-up at the SNOLAB underground facility.

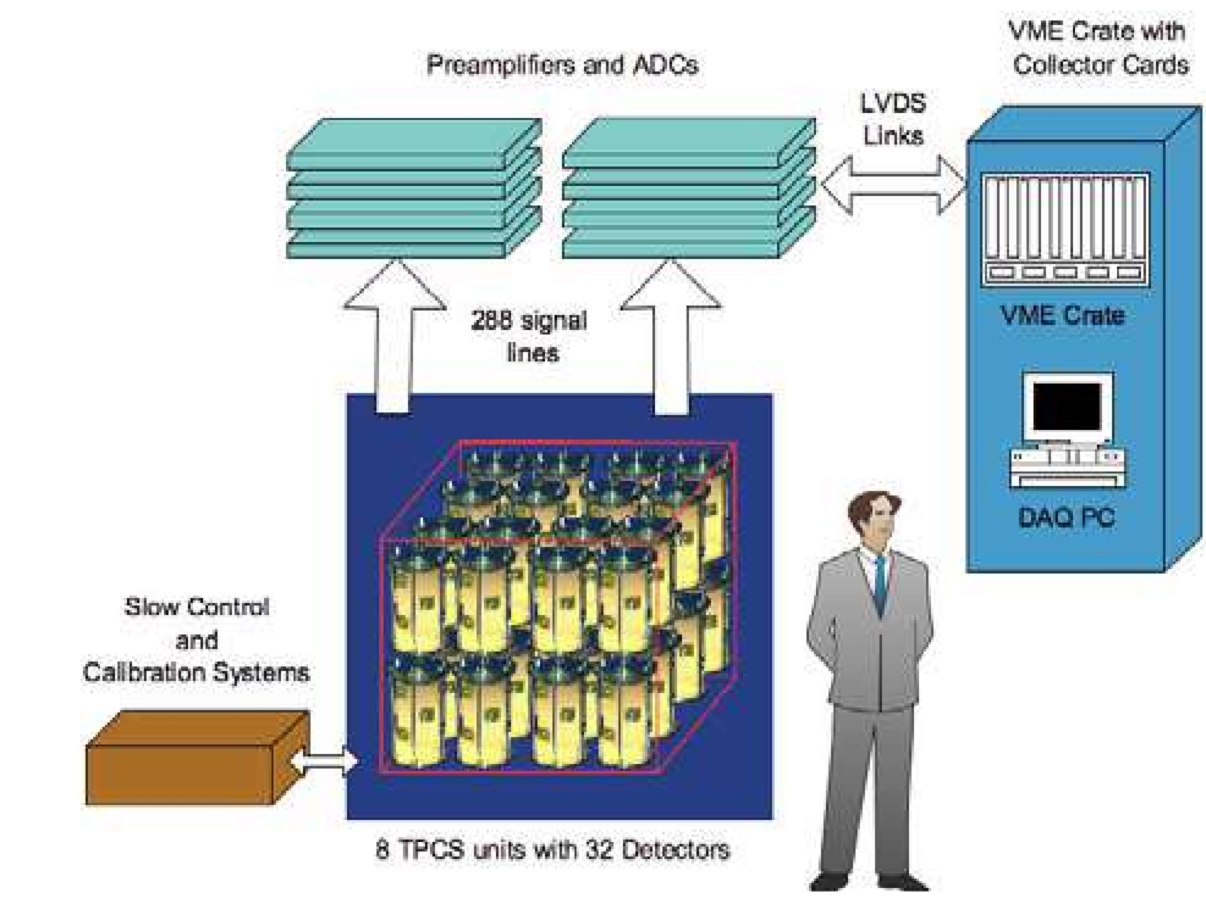


Fig. 6. PICASSO experiment from the DAQ perspective.

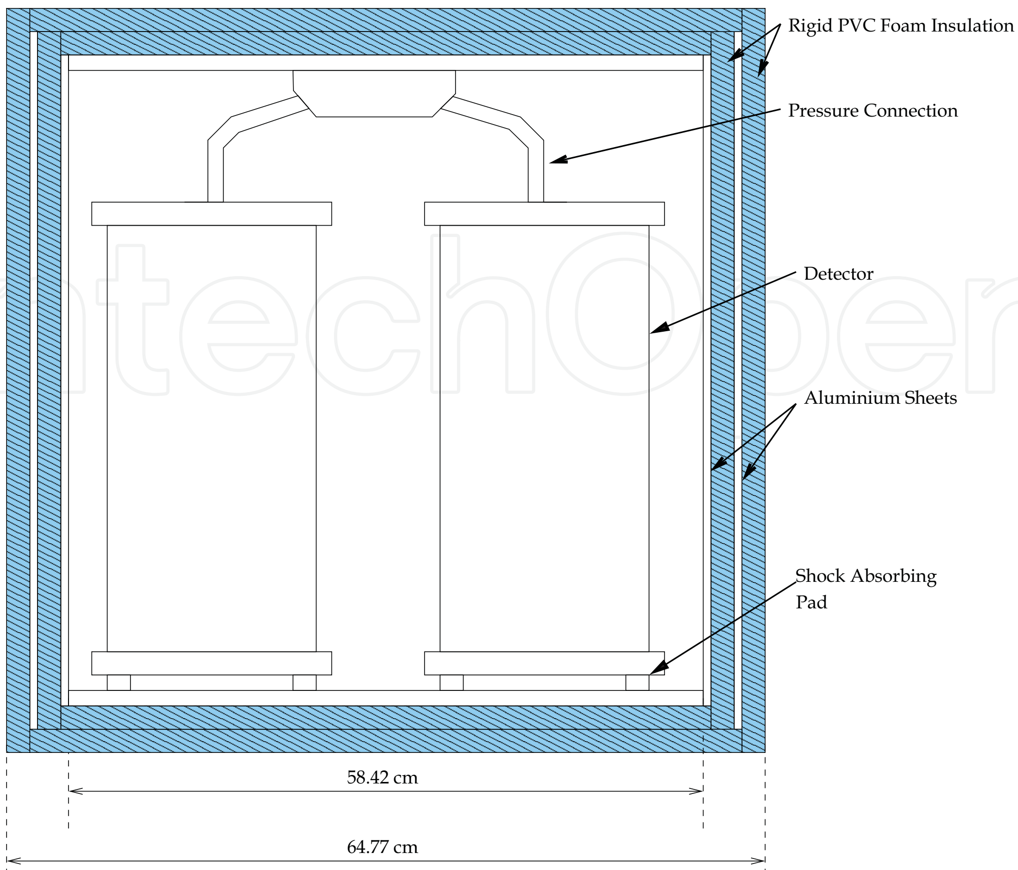


Fig. 7. The Temperature and Pressure Control System box (TPCS) (from [Clark (2008)].

Fig. 8. Single detector unit.

well. In case of the piezoelectric sensors, this microphonic effect of the cable can be quite problematic due to the very high impedance of both - the sensors and the preamplifiers. Although, just one sensor is required per detector to provide a minimum of meaningful information for the data analysis, generally all 9 channels per detector module are required to make detectors most efficient and to perform off-line analysis of event localization [Aubin (2007)] within the detector volume. The most important step taken during the development of the second stage of the experiment was the design of a scalable data concentration scheme. In order to collect data from different modules and to be able to relate them in time, a special VME data collector card was designed. This card is a multi-purpose system able to concentrate data from 12 independent data sources (in the case of PICASSO, one source is one detector with 9 sensor waveforms). It has already been successfully used for the TIGRESS experiment [Martin (2007)]. For the purpose of the PICASSO application, special firmware logic has been developed and custom tailored to acquire and record a large number of acoustical signals from a multitude of detectors. Detailed description of the collector card operation is given later in this chapter. Fig. 9 demonstrates the relationship between different parts of the data acquisition and Fig. 10 presents the block-diagram for one detector channel.

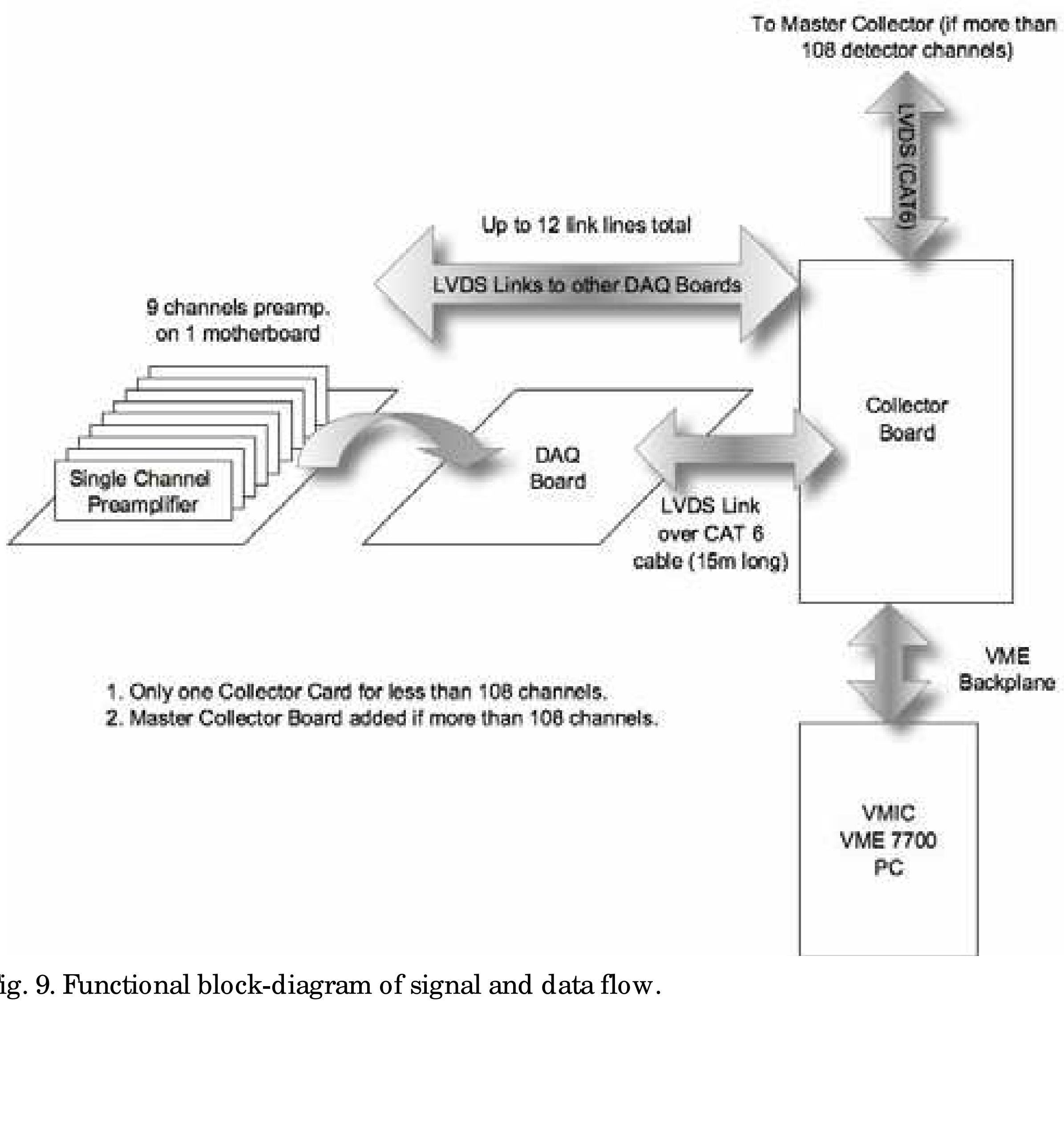


Fig. 9. Functional block-diagram of signal and data flow.

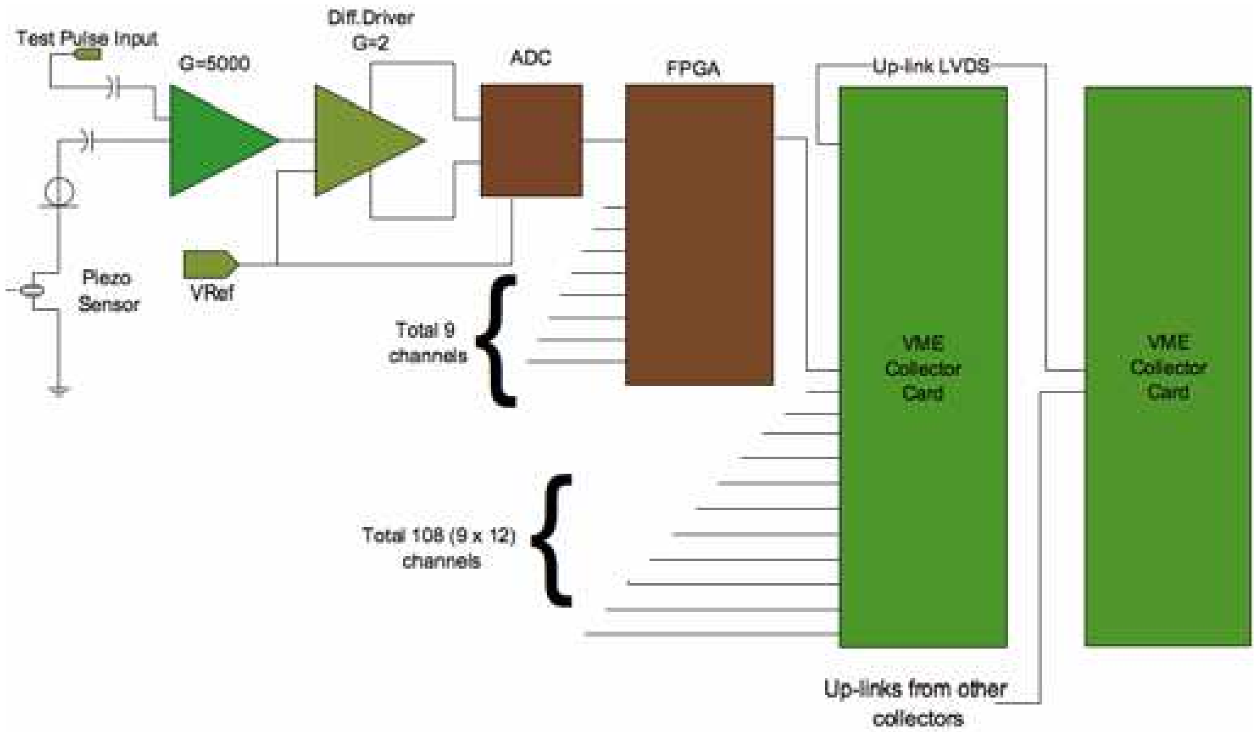


Fig. 10. Block-diagram for one detector channel.

4. Signal amplifier.

The amplifier design for piezoelectric sensors present several challenges. First of all, the bandwidth and the gain have to be chosen in order to preserve the information about the time evolution of the pressure build-up from the evaporation of the superheated droplet. Unfortunately, a piezoelectric material might have a very irregular non-linear response to the applied force. To better understand the difficulties arising here, the reader can be referred to the recent second edition of [Arnau (2008)]. For the purpose of the current work it is necessary to mention the lack of sufficient understanding of all details in the process of bubble creation and evolution triggered by nuclear reactions in superheated liquids. Different Dark Matter nuclear recoil experiments use slightly different methods of acoustical detection. The PICASSO group's study of acoustic signals shows that signals generated by rapid phase transition in the superheated liquid can be detected in the wide frequency region between ~1 KHz and ~200 KHz by different types of sensors. There is an indication that significant acoustic power is emitted in the low range of the frequency spectrum (Fig. 11). At the same time one can expect an external acoustical noise in the audio range at the low frequency end of the spectrum be quite significant and special care must be taken to reduce it.

The second challenge is a very high impedance of piezoelectric material. It gets even more complicated if the behaviour of the piezoceramic at different temperatures is taken into account.

Instead of individual preamplifier boxes used by PICASSO previously for each sensor, the new units combine 9 single channel boards carried on one motherboard. Each motherboard is assigned to one detector equipped with a full set of 9 sensors. This arrangement allows a considerable saving per channel on extra cables, connectors and enclosures. Overall view is presented in Fig. 12.

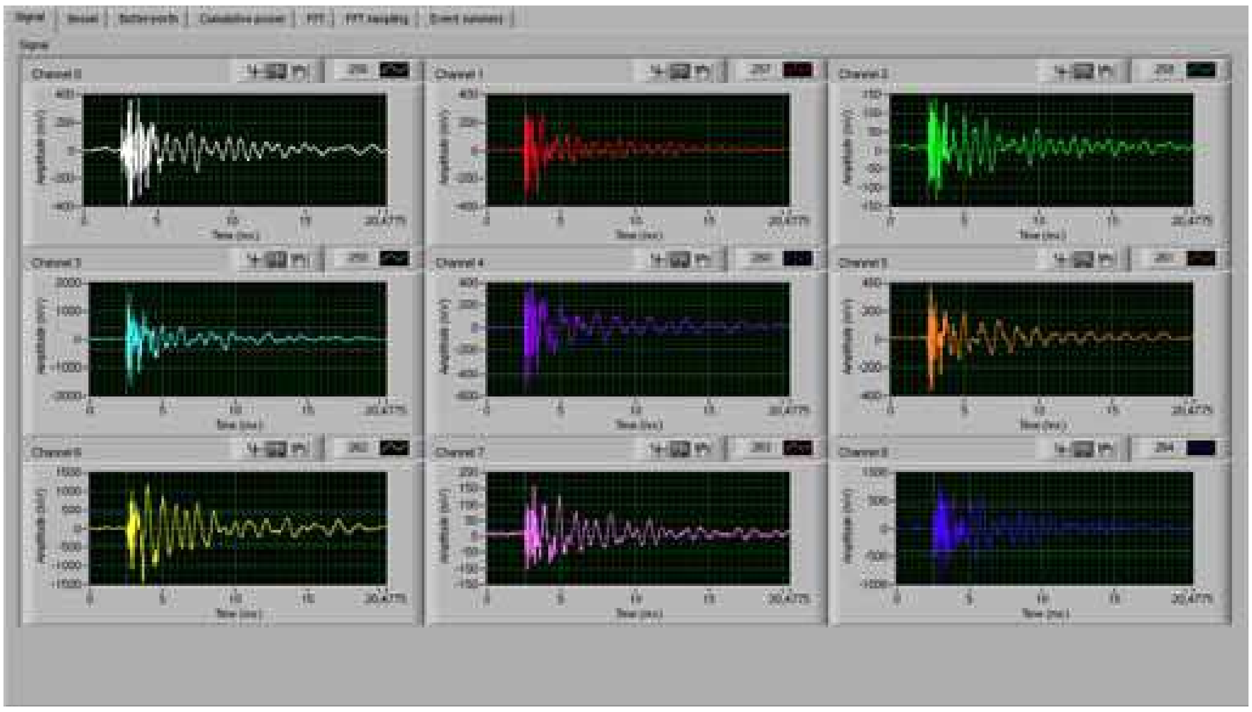


Fig. 11. Signal waveforms for one event obtained from a single detector.

Fig. 12. Electronics for one detector module (Front: Single channel boards on the carrier board; Back: Digitizing board; Small circuit left of digitizing board: 1-wire temperature sensor).

4.1 Single channel.

The single channel board carries a two-stage preamplifier with a DC coupled input and a band-pass filter. This board has a single ended output with a total gain of both stages between 1000 and 4000 depending on the requirements of the experiment. Due to the very high impedance of the piezoceramic, the first stage of the preamplifier is designed using n-JFET transistors. There were several versions of this board, each used at different periods of time of the experiment. The first version of the preamplifier had a pair of low noise n-JFET transistors connected in parallel, in order to cope with the large capacitance piezoelectric sensors (Fig. 13).

Later, when larger gain rather than ability to work with large capacitance of the signal source was requested, a second version of the preamplifier was built using an improved version of the microphone amplifier presented by A. Shichanov in 2002. Unfortunately, the original Internet link to his schematic is not active anymore. Therefore, we would like to present it here (Fig. 14) only with a minor modification. At the time of this writing, PICASSO is using this front stage in the single channel preamplifier boards. Each pair of JFET transistors has to be selected after closely matching by the value of saturated drain-to-source current and the pinch-off voltage.

Such a selection was performed with the help of specially built hardware controlled by USB-1408FS (Measurement Computing Corporation) - USB bus-powered DAQ module with 8 analog inputs, up to 14-bit resolution, 48 kS/s, 2 analog outputs, and 16 digital I/O lines. Software control was designed based on the National Instruments LabVIEW program. Nearly a thousand MMBFJ309LT1 n-channel JFET transistors were measured, sorted and grouped into closely matching pairs.

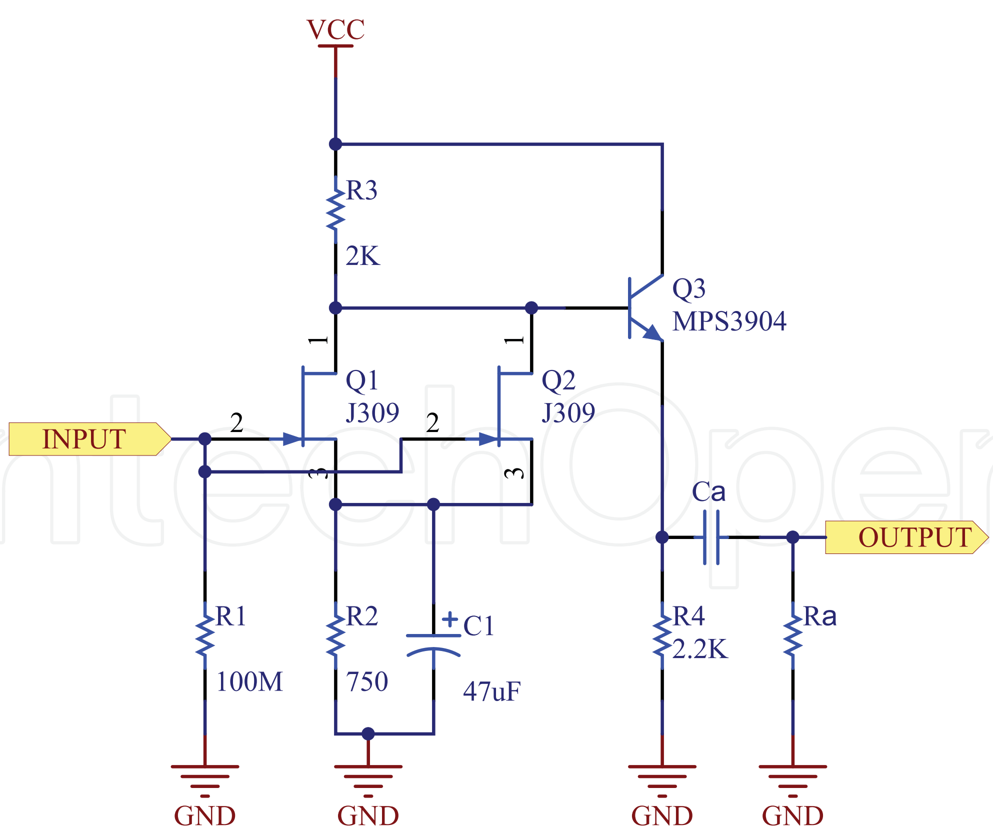


Fig. 13. First stage of the preamplifier in version 1.

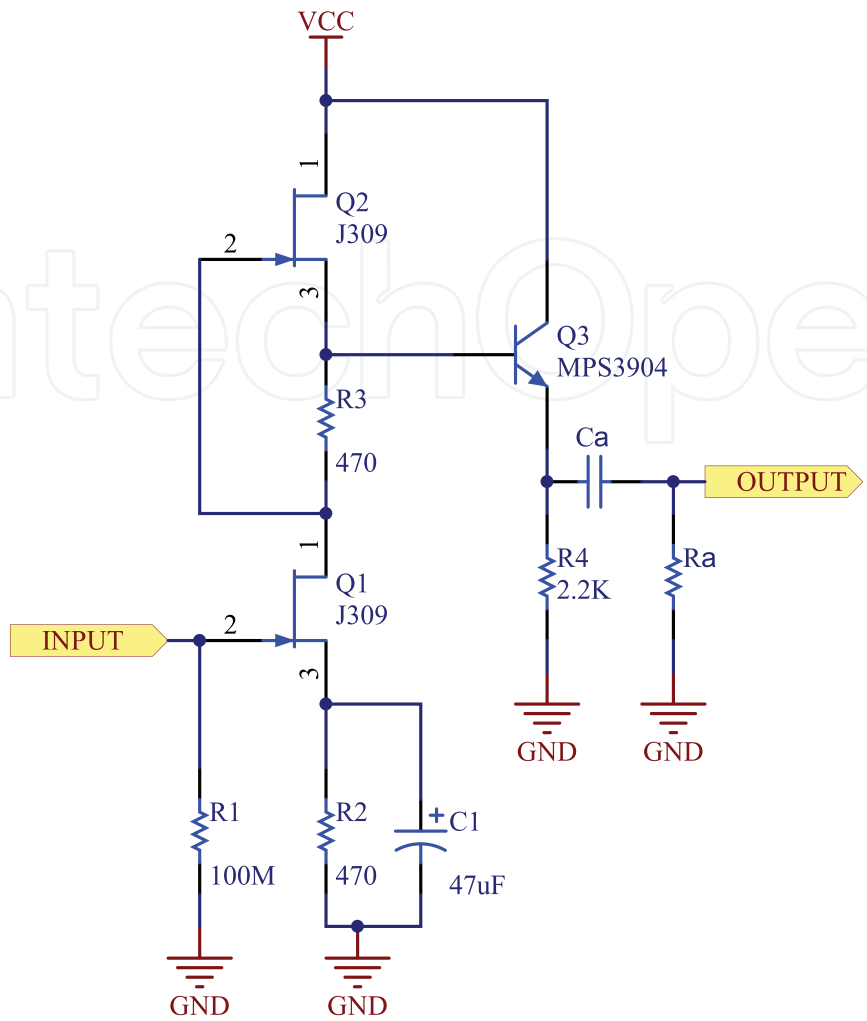


Fig. 14. Part of the microphone amplifier schematics used in the second version of the PICASSO preamplifier.

4.2 Preamplifier carrier board.

The preamplifier carrier board can hold up to 9 single channel boards. It also includes individual differential drivers for the next DAQ stage of digitizing circuitry as well as a reference source used by all of the differential drivers and the ADCs of the next stage. Differential drivers shift the bipolar range of acquired signals to a positive-only range of ADCs. Such a subdivision allows future trials of different amplifiers without changing the layout of the working detector modules. Any upgrade of the system in such a case will require less effort from the detector crew in the difficult underground working environment. The single channel preamplifier board can also be used separately from the current DAQ system with the same type of modules using the single ended data acquisition system which would not require a special data collection schema, i.e. in the stand-alone post-fabrication tests and calibration of the detector. Specifically for that purpose, the frequency range of the single channel amplifier is wider than required by described data acquisition system (Fig. 15). This allows it to be used with sensors which might have different ultrasound frequencies.

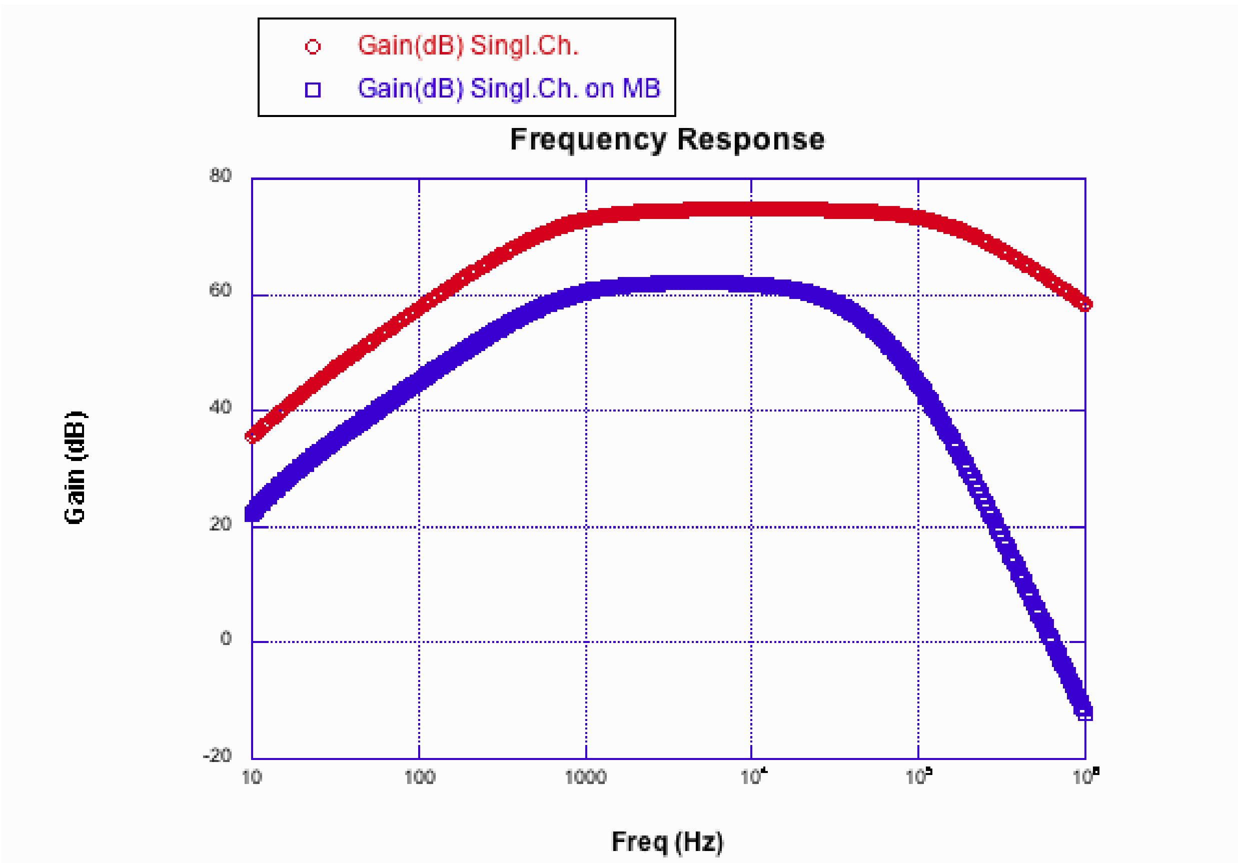


Fig. 15. System signal conditioning.

For additional signal conditioning flexibility, several layout implementations were introduced both on the single channel board and the carrier board. This allows both printed circuit boards (the single channel and its carrier board) to be assembled for different experimental needs:

- There is a choice between AC or DC coupling of the sensor signals. In the case of AC coupling, the high-pass filter frequency can be adjusted on the carrier board.
- In the first stage of the amplifier it is possible to employ either an active or a passive load. The passive load solution can accept sensors with high capacitance.
- Replacement of the preamplifiers is just a matter of unplugging the old board and inserting the new one and does not require re-soldering of any kind. Preamplifiers can have different gains on the same carrier board to investigate signals in different dynamic regions.

The carrier boards also include a calibration input used with an external pulse generator. It is coupled to each input via a small capacitor. The purpose of the calibration pulse is to monitor the gain of each channel and to investigate a possible degradation or even failing of the sensor itself.

5. Digitizer board.

Differential signals from the preamplifier carrier board are sent to the digitizer board through a short flat cable. Each digitizer board is equipped with 9 serial ADCs with 12-bit dynamic range (ANALOG DEVICES AD7450) controlled by one FPGA circuit (ALTERA Cyclone EPC6T144C8). The reference voltage on the preamplifier carrier board provides

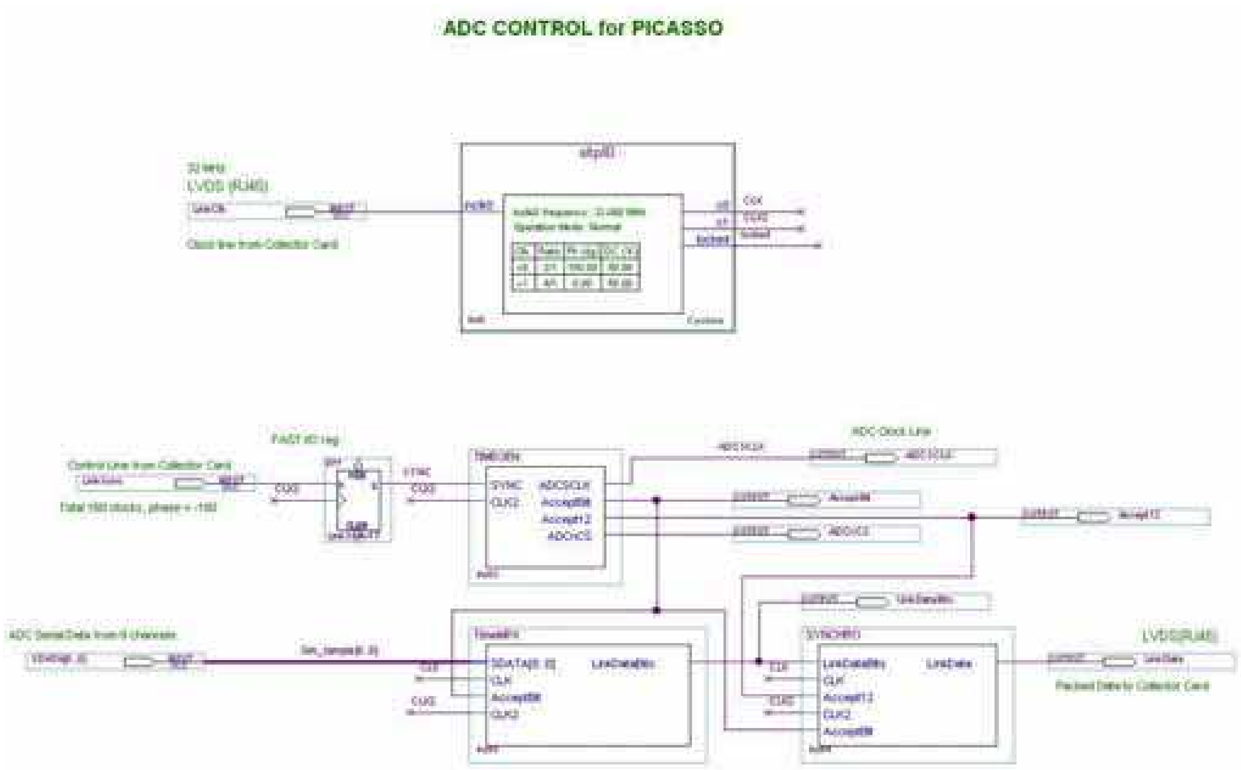


Fig. 16. Top page of the ALTERA Quartus II design software for the ADC controlling FPGA.

reference to all ADCs on the digitizer board as well. Due to the large number of digitizer boards required for PICASSO experiment their design includes only a bare minimum of hardware and firmware. The simplicity of the firmware design can be illustrated by Fig. 16. It shows the top level page of the FPGA design project for the ADC control.

5.1 Interface with the collector.

None of the digitizer boards carries an individual clock source. Instead these boards receive a 32 MHz clock from the collector board over a dedicated LVDS line. In addition to reducing the price of the digitizer board, such a scheme eliminates any run-away de-synchronization problem between different detector modules during long runs. An additional signal that indicates the beginning of the conversion comes from the collector card over a different LVDS line. After receiving the 32 MHz clock the FPGA uses its internal PLL block to create the 400 KHz clock needed by the ADCs as well as all other clocks needed for internal FPGA operation. Upon receiving the start signal for the conversion, the embedded control logic unit starts an acquisition cycle and polls samples from nine channels simultaneously. Each ADC sends one bit every 2.5 μsec to the FPGA until 16 bits are sent (12 bits of data and zero padding). Then the digitizer board transfers them to the collector through a custom made protocol with start and stop bits over CAT6 cables using LVDS levels. The mechanism to build a serial stream of data samples taken simultaneously works as follows: each simultaneously acquired set of 9 bits from each ADC is sorted to form a 9-bit word in serializer logic. Every additional set of 9 bits is attached to the previous word. After all 12 bits are acquired, the entire set is sent to the collector card as a serial stream.
A maximum of 12 DAQ boards can be connected to each collector. When all 108 channels are operational (at 400 Ks/ sec), the collector card handles a data throughput of 518.4 Mbps.

Although the VME system can not process such a continuous data flow, the expected data rate in the normal mode of the detector will be much lower.

6. VME collector card.

The PICASSO DAQ system can have two different architectures. If the total amount of channels needed for the experiment is less than 108, only one collector can be used (Fig. 17). If the experiment requires more than 108 channels, it will need one collector for each group of 108 channels plus one extra collector board as the source of a synchronized clock for each downstream collector.

6.1 Single-collector system.

The structure of a single collector system is presented in the Fig. 18. As it was mentioned above, in the case of 108 channels they produce a data flow with a rate of 1296 bits for every 2.5 μsec (518.4 Mbps). These data are intended to be written in the on-board SDRAM. However, the samples are not recorded there immediately. There is a waiting cycle for 128 sets of such samples. Then every 320 μsec a burst-write process puts data into SDRAM for the entire set of 128 samples for every detector channel. The total amount of data samples recorded is $128 \times 128 = 16384$. In parallel with the continuous recording process, an embedded logic block checks the data flow. When the signal amplitude crosses over the user defined threshold level, then the corresponding channel is marked as active. Threshold comparison is performed on the processed stream of data. At first the raw waveform is digitally rectified. Then the rectified signal goes through the digital amplitude peak detector with constant decay. Such combined process create an envelope around the waveform. Finally only the envelope undergoes a test for threshold crossing. This process is illustrated on the Fig. 19.

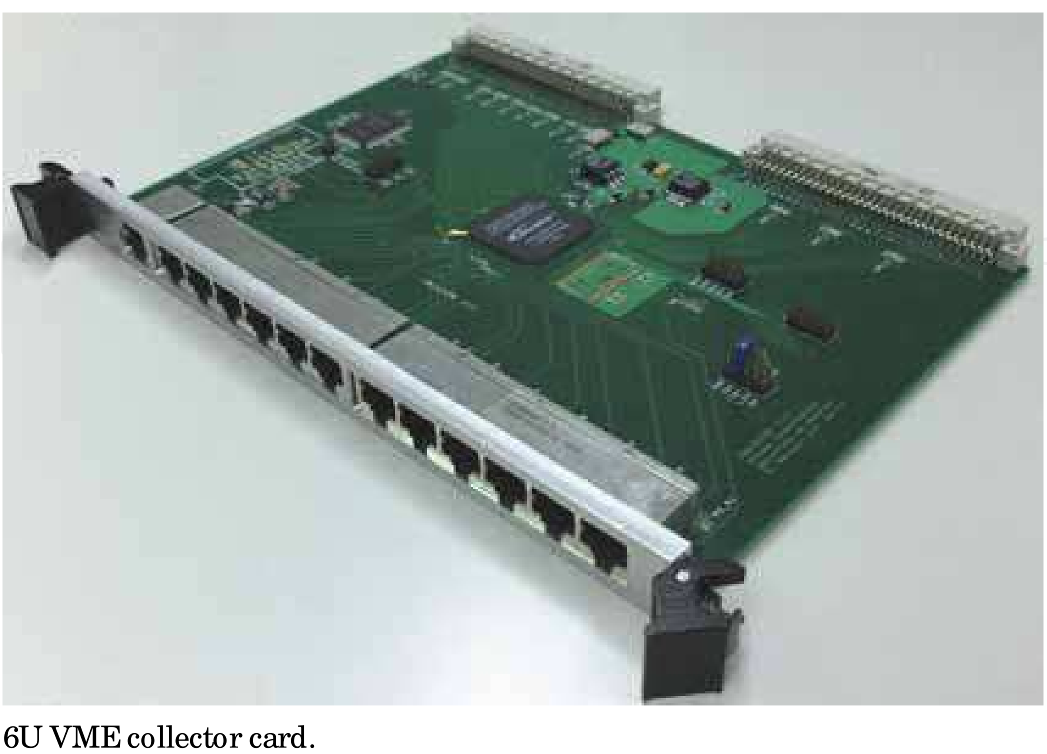


Fig. 17. 6U VME collector card.

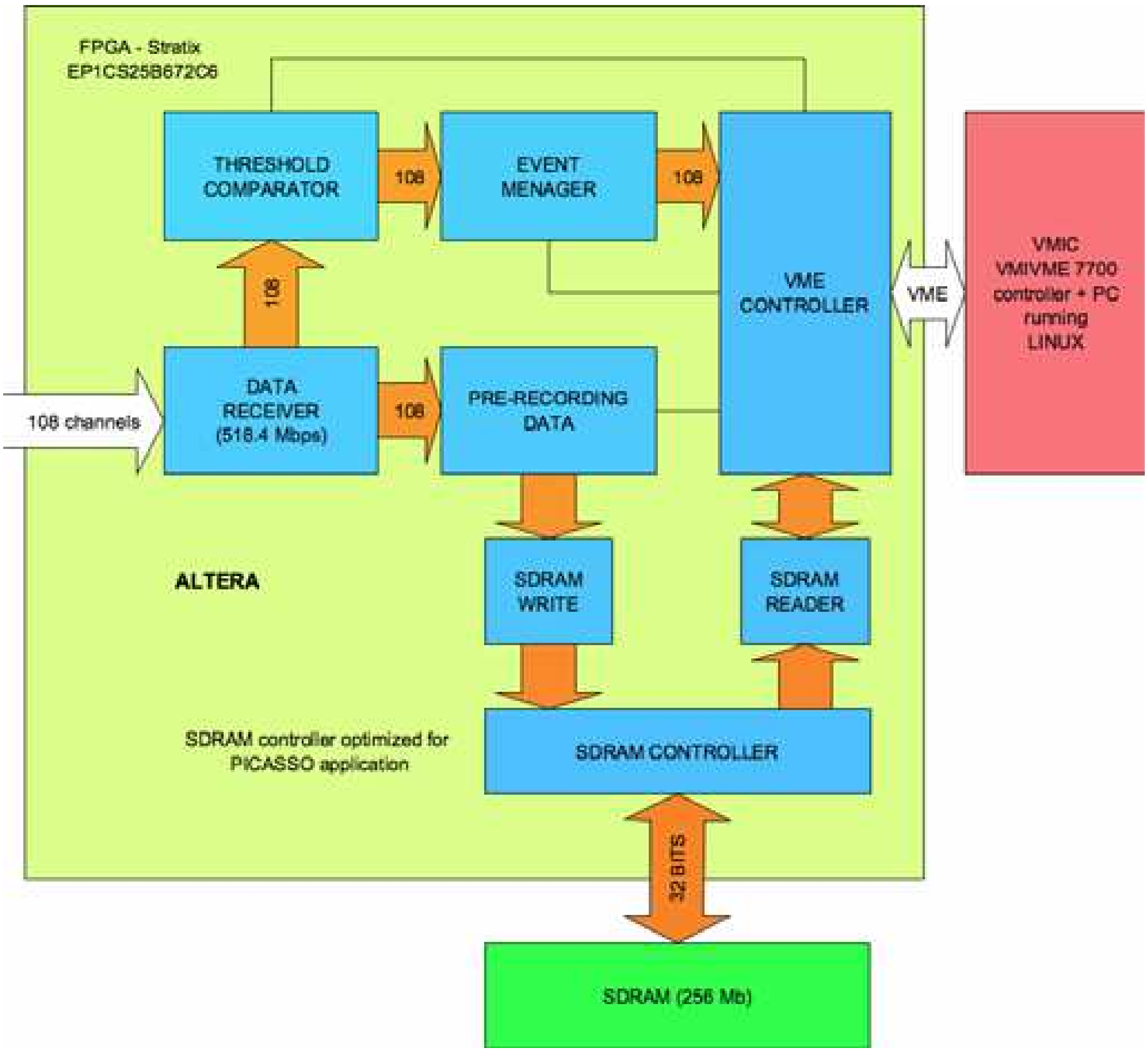
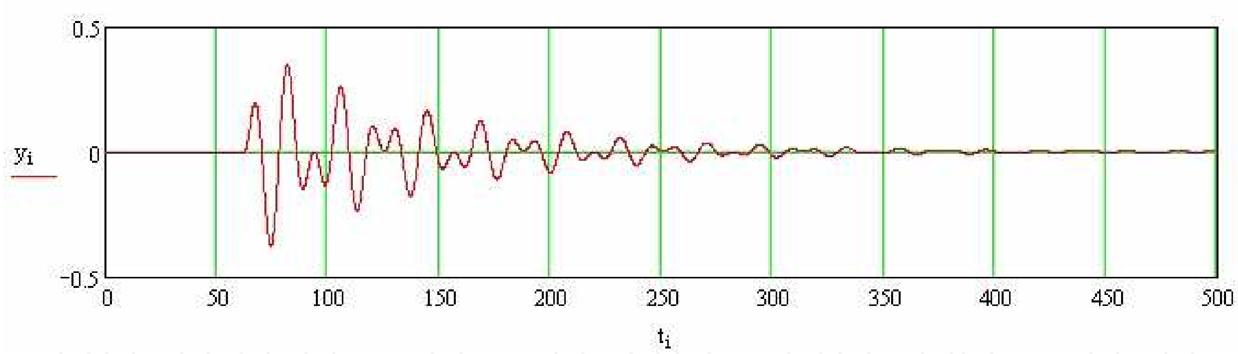
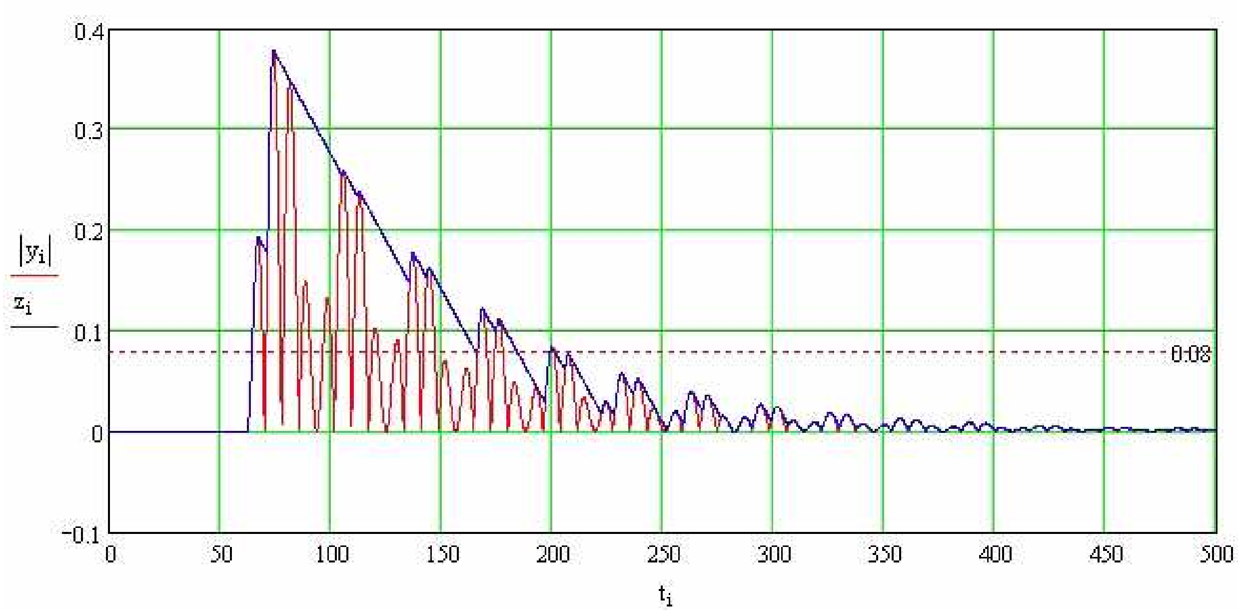


Fig. 18. Functional block-diagram of a collector board.

This trigger detection method was taken from the earlier version of the DAQ firmware and ensures consistency in the triggering technique across the different stages of the experiment. When a hit is detected, it is recorded in one of the eight segments contained in SDRAM and information about it is recorded in the event manager. After recording 16384 samples, the current event is locked. The software which runs on the VMIC (VME PC) controller is constantly pooling the event manager to see if there is any event that is locked. When it detects such a locked event, it checks the channel table to see if it corresponds to the user assigned group of channels which allow it to contribute to the event trigger. If it does, it sends a command to download the data desired. If it doesn't, the software unlocks the event to allow recording to continue. This communication of the VMIC controller with the collector card is implemented via the command and status register (CSR) in the collector's FPGA. If the VMIC is too slow, the SDRAM can become full with events locked in it. If this happens, the data would not be recorded anymore and a dead time counter would start to count the number of samples missed. The event manager block controls this logic.



(a) Simulated waveform;



(b) Rectified signal (red graph) from the above plot with the calculated envelope around it (blue graph). Dashed horizontal line represents the threshold level;

Fig. 19. Mathematical illustration of the envelope building process.

6.2 DAQ software and global trigger.

The DAQ software runs on an embedded VME computer and implements various services. The experiment operator can dynamically map hardware resources to logical detection units. The event trigger is defined within each logical group which can be composed of multiple physical modules connected to the same collector board. The DAQ software polls the control and monitoring registers from every installed collector and searches for active acoustic channels. The trigger definition function uses operator defined connection maps and the information acquired from the collectors to compute the event trigger state in real time. The operator can configure the channel trigger thresholds and the multiplicity level. The task list generated by the trigger definition function is processed asynchronously by a transport function which fetches and stores the data on a local hard drive. The collector's firmware supports a parallel operation of trigger monitoring and data transfer services. In the current implementation using an off-the-shelf Linux distribution, the maximum data throughput allowed by the 32-bit block transfer mode has been easily reached. For physics runs, the detector is operated as a collection of logical detection units which are mapped to the 9-channel physical modules. Minimal bias runs using larger logical detection units allow precise determination of the electrical and acoustical correlations between channels. By stacking trigger definition functions, the full detector can be operated as a single logical unit although for physics objectives (e.g. identifying multiple fast neutron scattering) the offline event correlation algorithms are efficient and optimize data storage requirements. Using VME bus extenders, a single node system can acquire data from a 4000 channels detector. Very large scale implementations are possible when employing multiple VME nodes.

6.3 Multi-collector system.

Before the end of year 2007 the PICASSO experiment has crossed the threshold of 108 channels, therefore requiring more than one collector card. The setup has now three collector cards to hold all data samples and one extra card used as a master clock source.

7. Current state of research and future development.

The current phase of the PICASSO experiment has now all 32 detectors and electronics deployed. The data constantly flows to the data storage, and is being analyzed on the regular bases. There are plans at work for the third stage of the experiment where the total number of channels might rise significantly to about 4000 due to corresponding increase of the active mass of the detector. In this case the current scheme where the data stream goes via collector cards most likely will remain as the proven data acquisition technology. However, the analog part of the data acquisition system still has some potentials to be improved.

One of these potentially new tasks is the ability to greatly improve dynamic range of the DAQ by employing additional stage of logarithmic amplification. It is not clear yet if an equal amplitude resolution in the entire dynamic range of the piezoelectric sensor signals has significant implications on the quality of the data analysis. If only the general shape of the waveform spectrum is important, the implementation of a logarithmic amplification stage might still preserve the average threshold level for the detector while folding higher amplitudes back inside the range of the ADC. The latest tests with new preamplifiers indicates that it is possible to adjust the gain of each channel simply by adjusting the power level to the fist stage of the amplifier.

New development in advanced signal processing hardware platforms by the industry constantly offers to physicists ever more compact chips with combined functionalities and improved characteristics. Of special interest for the future of the PICASSO experiment could be multi-channel ADC chips with built-in programmable gain amplifiers. This technology can help to further reduce the per-channel cost of the data acquisition system.

Additional attention will be given to better power distribution system, when preference is given to the delivery of single low voltage AC power to the local units. Using such a solution can eliminate the use of long multi-wire cables with individual DC power lines. It also gives the opportunity to avoid unwanted ground loops in the system.

The future data flux may become to large to be acquired by a flat scheme where a new collector card is simply added to accommodate new channels. In this case the opportunity exists to use an hierarchical structure of collectors with new firmware where a suppression of the empty events is implemented. In such a scheme collectors in higher hierarchical positions can be used to concentrate non-empty waveforms.

Number of channels	288
Frequency range	1..80 KHz
Resolution	12 bit
ADC sampling rate	400 Ks/ s

Table 1. PICASSO DAQ parameters

These plans will be better defined once the data analysis of the current experiment stage will be finished and the behaviour of superheated liquid detectors will be understood with much greater details. Some recent results can be found in [Archambault et al. (2009)].

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Data Acquisition

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The book is intended to be a collection of contributions providing a birdâ€™s eye view of some relevant multidisciplinary applications of data acquisition. While assuming that the reader is familiar with the basics of sampling theory and analog-to-digital conversion, the attention is focused on applied research and industrial applications of data acquisition. Even in the few cases when theoretical issues are investigated, the goal is making the theory comprehensible to a wide, application- oriented, audience.