6.1 Position-sensitive electron detection system

The position-sensitive electron detection system that was developed in this work is composed by a module consisting of an electronic circuit, hybrid, that gives support to a 1 mm thick silicon pad sensor and hosts the front-end electronics, realized as an application specific integrated circuit (ASIC). The ASICs are embedded on four micro-chips, connected to the pad detector, besides the signal lines and bias voltage for the detector. The sensor is read out by the four self-triggering ASICs of 128 channels each, which are wire bonded to the pad side of the silicon detector. The task of the ASICs front-end electronics (also denoted by VATAGP3 chips) is first, to provide an analog signal proportional to the energy of the incoming electron and second, to generate a timing trigger. Therefore the circuit organization is divided in two parts. The signal part (or VA part) that generates the analog signal and the trigger part (or TA part) that generates the trigger. The properties of each of the parts will be thoroughly discussed in the following subsections.

Further stages of electronics follow the ASICs front-end circuit and are often named by the data acquisition (DAQ) system. The DAQ system provides signals controlling chip operation and managing data flow, and its block diagram for the present module is sketched in fig. 6.1. It consists of three blocks, the intermediate board (IB), the VME board and a personal computer (PC). In between the VME board and the PC there is the PCI/CPI-VME link interface card-SIS/100/3100 used for subsequent data transfer from the VME buffers to the PC through an optical fibre that is linked to a National Instruments PC card. The importance of each block on the data collection will be briefly described in the next sections. The concept of interconnecting the VME buffers to the PC, via an opto-link is the answer to the fact that the user needs to be in a radiation free zone to control the detector. The opto-link connection guarantees that function without electronic pickup noise many meters apart.
6.1.1 ASICs front-end electronics

The 128 channel low noise self-triggering VATAGP3 ASIC is produced by IDEAS [1] and is derived from the usual VIKING VA1 ASIC arrangement, previously applied to EC detectors as described in ref [2]. Each one of the 128 channels of the VA1 ASIC includes a low noise charge sensitive preamplifier, a slow semigaussian shaper (nominally a 3 µs shaping time that can be adjusted), a sample/hold circuit and an analog multiplexer. Besides this analog VA part, the VATAGP3 ASIC has in addition the denoted digital TA part connected to each ASIC channel, consisting of a fast shaper (of ∼150 ns shaping time) followed by a level discriminator and a monostable that produces a trigger signal if the shaped signal exceeds the discriminator reference level set by the user. This allows the use of the ASIC in a self-triggering configuration, essential for fast triggering as is required in order to realize high count rates. Besides, such configuration opens the possibility of operating in three readout modes: serial, sparse and sparse with adjacent channels.

Figure 6.2(a) shows a block diagram of one of the 128 VATAGP3 ASIC channels and illustrates its working principle in figure 6.2(b) by means of the trigger (line1), hold (line4) and analog output (line2) signals, recorded by the oscilloscope during a $^{241}$Am ($\gamma$-detection) run, taken in serial readout mode.
In the slow VA chain, a Sample and Hold signal (S&H) is applied at the peaking of the slow shaper signal in order to store the value to be later read out. In the fast TA chain, the signal from the fast shaper is applied to a discriminator, and the outputs of all of the 128 discriminators are OR’ed together providing the trigger for the data acquisition (named FOR). Each discriminator output is also stored in a register. If the sparse readout is used, only the analog values of the channels for which the discriminators were above the threshold will be read, together with the channel (pad) addresses. The probability of having more than one trigger when applying the common S&H signal in sparse readout mode can be reduced if the OR’s generation is blocked by enabling the disable-late-trigger (DLT) signal. This is an important feature of the VATAGP3 ASIC available for all readout modes, since if desired, the first discriminator output can block the generation of furthers OR’s until receipt of a reset.

The chip performance optimizing requires applying appropriate control currents and voltages to the input pads of the chip. The most important are marked in figure 6.2(a) and next listed: bias $v_{fp}$ determines the feed-back resistor value of the preamplifier, $v_{sfs}$ the shaping time of the fast shaper ($\sim 150$ ns) and $v_{ss}$ the shaping time of the slow shaper (0.5-5 $\mu$s), both over a limited range. There is also a master bias $mbias$ which sets all biases to an optimal value.
according to a preset map, optimized in the chip simulation and the rest can be left unconnected. The chip is configured by a control register. The most relevant features are summarized as follows:

- Gain stage with three different values of the gain. The gain of the fast shaper may be increased in four steps (2 bits).
- Chip address for identification if more than one are used. In the present case four are used.
- Mask individual channels, to prevent noisy channels from triggering (trigger mask).
- Test mode to enable charge injection directly into the readout channel, determined by the test mask. This feature is very useful to test the electronics in the absence of the detector.
- Each discriminator output can be masked. There is a common threshold for all the 128 discriminators, but a DAC mask (3 bits) for fine threshold alignment of single discriminators can be used.
- Leakage current compensation is automatically adjusted in each preamplifier channel.
- Three readout modes: serial, sparse, and sparse with adjacent channels are available.

6.1.2 Module assembly

Figure 6.3 shows a photo of the EC module, consisting of a silicon detector and four of VATAGP3 chips sitting at the hybrid that was projected, produced and tested at CERN within the scope of this work. The hybrid is a printed circuit board (PCB), which routes and fans out the chip signals and provides mechanical support for the chips and the detector. The detector-chip inter-connections consist of aluminium wire-bonds, 22 \( \mu \)m thick, bonded with ultra-sound technique to the respective metal contacts of the detector. The same technology is used to connect the chip contacts to the line traces on the PCB.
Mechanically, the hybrid is a 94 mm wide and 115 mm long board. The detector measures 32 mm by 32 mm and the ASIC is a 0.6 mm thick, 7 mm wide and 10 mm long silicon chip. The detector is hold at the hybrid by four ceramic alumina plates (8×10×0.5 mm$^3$) with thermal glue. The detector top electrodes (pad side) are connected to the inputs of each chip at ground potential. The detector is biased using a positive voltage applied to the detector back-side (backplane), usually denoted by the depletion voltage.

The electron detector was produced at SINTEF by the planar technology [3], which is capable of producing detectors with very low leakage currents and optimum operational characteristics. This detector presents the same layout described for the off-line EC electron detectors [2]. The only remarkable difference is the detector thickness; presently 1mm, which influences its static properties, i. e, its leakage current vs applied voltage (I-V) and capacitance vs. applied voltage (C-V) characteristics [3]. 1 mm thick detectors were found to fully deplete at $\sim$160 V and to have very low leakage currents $\sim$15-50 pA. Besides, coupling these detectors to a self-triggering readout technology reduces the trigger overall noise since the backplane signal is skipped [4].
6.1.3 VME DAQ: Serial, Sparse and Sparse with adjacent pads

The VME DAQ readout system may be divided in three main blocks: (1) the intermediate board (IB), (2) the VME board and (3) the PC. The IB represents an intermediate phase of electronics processing since it supplies the biases and the threshold level analog values to the VATA module, the necessary level conversion from TTL to VATA standards and also serves as relay for logic signals passing between the VATA chips and the VME board, which provides signals controlling the chips operation and managing the data flow. This includes the analog to digital conversion, the packing of data of an event and the data transfer to the storage and control device, i.e. the PC.

Before a data acquisition run the VME board generates the sequence that loads the mask, i.e. a string of bits consisting of two main informative parts: the chip specific settings and the channels set out of triggering, either because they are too noisy or for testing purposes. The mask is supplied by the DAQ software to the chip register, with the IB serving as relay. The trigger signal that is generated if the amplitude of the shaped pulse exceeds the threshold voltage of a level discriminator (one value set per pad) is driven through the IB to the VME board. This starts the readout sequence by generating and sending the hold signal to the chip, after a delay corresponding to the picking time of the VA part (\(\sim 4 \mu s\)) of the chip. The externally applied hold signal, which triggers the S&H circuit, fixes the value of the analog output. The peak of the analog pulse is sampled by a proper adjustment of the delay between the trigger and the hold signal. Immediately after the trigger signal the DLT signal may be generated at the IB to discard all triggers until the readout is finished, the moment in which the IB sends the reset signal to the chip.

The sampled values of the analog outputs of all channels are stored in a pair of multiplexers (readout UP and DOWN) existing inside the VATAGP3 ASIC. Each multiplexer is shifted and clocked by the VME electronics, making the sampled analog value available on the output buffer. With the first clock pulse sent to the first chip the VME sends the shift_in_DOWN (UP)
bit to enable the analog value of each channel at the output\_DOWN (UP) to be read out. The
multiplexer readout DOWN is shifted in descending order and the multiplexer readout UP in
ascending order with respect to the readout channel number. Using the pair of multiplexers,
there are three ways of reading the analog values from the buffer:

- **Serial readout** – The DOWN (UP) output produces all channel samples from the first
  (last) to the last (first) channel, independently of the one that triggered. The readout time
  for 512 channels in one module (four chips) is about 480 \( \mu \text{s} \). Thus, the maximum
  counting rate would be 2 KHz.

- **Sparse readout** – The channel that triggered is stored in a buffer and only the hit
  channel signal is available on both multiplexer outputs, which significantly increases the
  readout speed. Ideally it would be \( 480 \mu \text{s} / 512 = 0.94 \mu \text{s} \), that is, the maximum expected
  count rate is 1 MHz.

- **Sparse with adjacent channels readout** – After the channel that triggered (i), on
  output DOWN (UP) the samples of channels i+1 (i-1), i+2 (i-2), etc. are available. Note
  that “channels adjacent” on the readout chip are not necessarily geometrically adjacent
  in the pad space of the sensor (see fig. 6.4). This number of adjacent channels is defined
  by the user and limits the readout speed.

In practice the real readout output will depend also by how fast is the computer. With the
present setup it is expected that that the counting rate could almost double (e.g. 3 KHz to 6
KHz) if data monitoring during acquisition is stopped.
Fig. 6.4 Mapping of the detector indicating the channel indexation number. It is clearly seen that the “adjacent” numbered channels, for the readout, are not necessarily physically adjacent. The lines indicate the edge of each (1 to 4) chip channels. Note that despite of the readout logic being binary, only 484 channels are connected into detector. Each chip has 7 channels not bonded.

The same shifting clock (set to 1.2 MHz) is used by the pair of flash 12-bit ADCs (up to 10 MHz) which digitize both (UP and DOWN) outputs, amplified by the IB. The digitized signals are packed into an event and stored in the output buffer of the VME controller. The VME board is inserted into a VME crate which provides the necessary power. The VME standard (IEEE-1014-1987) is used for communication between the PC and the VME board. The software which controls the board function is partially executed by the Field Programmable Gate Array (FPGA) of the board (readout sequence generation, event packing) but mostly done by the PC.

The PC closes the DAQ loop and serves as a master control device and storage media. The specially designed DAQ and display software collects and stores events prepared by the VME board and allows the user to change the mask of the chips and determine the readout mode. The complete EC data analysis is performed off-line on the stored data sets as previously described in chapter 3. Details about data processing will be given in the following sections.
6.1.4 Software for data taking and processing

The software used in the new EC experimental setup may be classified in three groups: (1) the data acquisition software, (2) the post-processing and (3) the analysis software. The first one is called VMEDAQ. It is the control and readout software running under Linux. This collects and stores the events prepared by the VME board and allow the user to set the readout mode, to change the mask and other configuration parameters of the chip. Among other important features, available during data acquisition, the VMEDAQ software has a set of displays for monitoring pedestals, energy spectrum, EC 2D-anisotropy patterns and other plots in real measurement time. Nevertheless, the data on screen refers always to raw data, that is, without pedestal subtraction. Pedestals and noise are determined by the program, monitored and saved together with the raw data. Still, the VMEDAQ calculated pedestals are not used in post-processing data. Instead a post-processing software named VREDX was developed to provide full control of the data, that is, it extracts the raw data, performs pedestal calculation from scratch and subtract them from the raw data. By definition of pedestals, i.e., the mean charge of a channel without a hit event, it can only be determined in serial readout mode and in sparse with adjacent channels readout modes. However, it is possible to estimate the equivalent pedestals offset in “pure” sparse readout mode by a calibration software method included in VREDX software.

In serial readout mode, both VMEDAQ and VREDX calculate equivalent pedestals, but in sparse with adjacent channels readout mode, the pedestals are only correctly determined by VREDX that uses non hit events of the adjacent channels to estimate pedestal values.

6.1.4.1 VMEDAQ data acquisition software

VMEDAQ is a graphical user interface (GUI) front end for DAQ++ that has been developed by Lacasta et al [5]. It uses the GIMP toolkit (Gtk) library to build the graphical users interface [6]. VMEDAQ has been initially developed for the data acquisition within the frame
of the CIMA collaboration [7] and recently modified and updated to fit the EC technique requirements during on-line electron detection. This task has been easily made thanks to this application, being generally enough to load of dynamically linked libraries that contain the implementations of different Modules and RunManagers (i.e. data receivers that allow to define different data acquisition modules). The application is driven by an XML configuration file where the locations of the libraries, as well as the running parameters are indicated. VMEDAQ also provides a graphical interface to edit the configuration parameters of the chip. Examples are: the discriminator threshold level, the current control enable (enables leakage current compensation), the polarity of the current control enable (it is -/+ depending on the p/n electrode detector being used for radiation detection), the test_on, e.g., if test_on = 1 enables the use of a calibration pulse at cale/cali inputs for individual channel testing, and others. These parameters are loaded on the 651-bit long control register (set by regin and clkin signals) each time that pedestals are acquired or the serial readout mode is enabled.

The VMEDAQ program also implements the Monitor and DataLogger objects so that data can be monitored and stored. The monitor object provides the means to graphically display data, which is of crucial importance for the on-line EC experiments dealing with short-lived isotopes. The data logger object reads the electrical signals (e.g. trigger) and log the data in internal memory to later export it to a file or other applications. In fact the referred EC experiments obliged to the development and implementation of some extra graphical monitoring features like the selection of the electron energy window to observe each chip and/or of the integral four chips energy spectrum display. An auto scale updating emission channeling pattern display was also added for crystal axis monitoring during acquisition. This is crucial to align a specific sample crystalline direction relatively to the detector in a short time.

Figure 6.5 shows the main window of VMEDAQ. On the left, just below the menu, there is a large button that shows the state of the acquisition and allows setup the acquisition control. That gives access to a pop-up menu accessing different DAQ commands. Below are the widgets
that are used to select the behaviour with respect to the triggering (either internal – by software – or external) and of the interrupt system. This refers to the way in which the application realizes that there is data available. There are 2 possibilities:

- **Poll**: VMEDAQ uses the default DAQTrigger object and the module has to poll or block until there is data.
- **Interrupt**: VMEDAQ sleeps until some mechanism awakes it and then it reads the data.

At the bottom left there are a number of small widgets showing the module identifier and providing a number of buttons to open the configuration dialog and monitoring window for that module.

![VMEDAQ main window screenshot.](image)

Figure 6.5: VMEDAQ main window screenshot.

Figure 6.6 shows a monitor window screenshot taken during a $^{111}$In sparse mode run. It is shown the chip3 energy spectrum composed by the four major conversion electron lines of $^{111}$In at 145, 168, 219 and 242 keV and the corresponding raw channeling pattern around the SrTiO$_3$ <100> axis. Note that the trigger level was set around 35 keV (70 DAQ units) in order to exclude the Cd X-rays from the data acquisition process. Besides, the 2D pattern display can be exchanged with the channel hit map histogram display instead. By clicking on pedestal section, one can roughly monitor pedestals and noise during the acquisition in serial and sparse with adjacent channels readout modes.
Fig. 6.6 VMEDAQ monitor screenshot of the LINUX based readout software for on-line EC experiments with the new fast Si pad detector system in sparse mode. The data visible in the centre of the screen was obtained from a SrTiO$_3$ single crystal implanted at ISOLDE with $^{111}$In for test purposes. It shows the energy spectrum of the conversion electrons from $^{111}$In and the corresponding EC pattern of the SrTiO$_3$ <100> direction, as displayed during the measurement.

VMEDAQ defines a data format scheme for storage based on different blocks of information. There are two groups of data blocks: (1) informative, containing information like begin or end of file, pedestals and, (2) data container blocks where the actual data is stored. The later blocks are those to be extracted, processed and converted to an ASCII file by the VREDX data processing software, next described.
6.1.4.2 VREDX data processing software

VREDX is a Fortran program that was developed to extract raw data from the VMEDAQ output file, determine pedestals, and subtract them from data in serial and sparse with adjacent channels readout modes. Pedestals are determined to each group of events, $N_e$, up to 99999, in any of those modes that might be of particular importance during long runs (e.g. several days and weeks). In this case, it cannot be guaranteed that noise and pedestals remain stable without significant fluctuations.

The data extraction is performed according to different analysis and debugging criteria. In the program, noise is referred to as the variance of the pedestal distribution ($rms$). After subtracting the pedestal from the measured ADC (1024 channels) signal in each event, the result is stored in an ASCII file of two columns (channel, $ADC$-$PEDESTAL$). This ASCII file is then read by the old standard EC analysis program $RED$ to generate single channel and/or integral energy spectra and EC patterns. The RED program was written in FORTRAN by U. Wahl in 1996 to reduce 2D EC patterns according to a selected energy window and has been used ever since in $DOS$-$Windows$ operative systems.

**Serial readout mode**

The relevant parameters in each valid event are the energy and position of the electron hitting the detector that triggered the readout by generating a charge above a certain value. This value is channel characteristic and is determined by the selected threshold and by the so called base line or pedestal, $p_i$, of a channel $i$. According to the processing algorithm implemented in the VREDX software, the pedestal, $p_i$, of a channel $i$ is obtained by averaging for each channel $i$ the raw ADC digitized values, $s'_i$, when free of electron hits. The mean and $rms$ values of the
$s_i^e$ histogram are assigned to the pedestal, $p_i$, and noise, $\sigma_i$, of a channel $i$. The algorithm goes as follows: first pedestals are calculated using all events of the first bunch, $N_e$.

$$p_i = \frac{1}{N_e} \sum_{e=1}^{N_e} s_i^e$$  \hspace{1cm} (6.1)

$$\sigma_i^2 = \frac{1}{N_e} \sum_{e=1}^{N_e} (s_i^e)^2 - p_i^2$$  \hspace{1cm} (6.2)

Some values $s_i^e$ may contain hits, which makes it mandatory to take a bunch of events, $N_e$, large enough so that pedestals can be taken as approximately correct. With these first $p_i$ and $\sigma_i$ values, the second run is made on the second sequential bunch of events where only ADC values $s_i^e$ verifying $s_i^{e+1} < p_i^e + k \times \sigma_i^e$ are accepted for the pedestal subtraction. Generally, $3 \leq k \leq 5$. Once the pedestals and noise values are calculated for each bunch of $N_e$ events, sequentially for all bunches, these are then used to identify the hit channels at the respective bunch by accepting those events that verify now $s_i^e > p_i^e + k \times \sigma_i^e$. Then subtracting for all readout channels the pedestal, $p_i^e$, from the raw ADC digitized value, $s_i^e$, the signal spectrum is obtained, whose values reveal the spectrum of detected electrons.

The $rms$ $\sigma$, obtained from a single channel histogram is over-sized by a part of base-line fluctuations caused by fortuity power-supply variations on each chip. The result of such variation is a common shift of the analog values for all channels of the same chip in an event, which can be effectively removed in a second step of the algorithm by a common mode $c^e$ calculation:

$$c^e = \frac{1}{N_e} \sum_{i=1, \text{not hit}}^{N_e} (s_i^e - p_i)$$  \hspace{1cm} (6.3)

where the sum runs over all output channels on each chip that are below a noise cut, $i.e.$ generally defined by $s_i^e < p_i^e + k \times \sigma_i^e$. The noise cut can more or less sensitively separate the
signal from the noise, and for a common cut of $s_i^e - p_i^e \rangle 4\sigma_i$. For hit channels the difference should be above $k\sigma_i$, with $k = 3-5$, optimum value to be determined for a specific problem.

The common mode can only be calculated for serial readout mode, where all channels are available, making $N_c$ large enough so that the error on $e^e$ per chip is small. In serial readout mode the common mode calculation improves the energy resolution of the signal, which in the algorithm is obtained by subtracting for each electron ADC signal event the $p_i^e$ and $c_i^e$.

**Sparse with adjacent channels readout mode**

The formalism used in *sparse with adjacent channels* readout mode to determine pedestals and to perform their subtraction from the data is similar to the one developed for *serial* readout mode. In this mode, the algorithm takes pedestals from a certain amount of non-hit adjacent channels (specified by the user). Those channels are consecutive in indexation number but are not always physically adjacent due to the bond mapping of the detector (see fig. 6.4). Physically neighbouring channels are also further excluded by default in order to avoid charge sharing effects to influence the pedestal calculation and thus, to improve energy resolution.

The optimum number of adjacent channels that may be taken in each run depends on the desired readout speed and disk space availability for data storing. With the present PC speed—single processor – about 10% readout speed is lost per each 10 adjacent channels added for count rates above 1000Hz.

**Sparse readout mode**

In “pure” sparse readout mode the pedestal offset for each channel can only be estimated after performing the spectrum gain calibration with several energy sources, as will be explained. Since gain variations from channel to channel were found to be considerably bigger in this readout mode, a dedicated calibration routine was developed and included in VREDX, whose
algorithm is explained in table 6.1. The gain variations from pad to pad are significant and may reach up to 25 ADC units. In the absence of pedestal calculation, the standard calibration method assuming zero value of the ADC as the zero energy (only valid after pedestal subtraction) by only using one energy value to obtain each channel gain, cannot be used. In spectrum is taken as an example in page 218 after offset and gain correction.

After estimating the pedestal (or offset) value for each channel, the VREDX program will subtract it from the measured ADC signal during data extraction.

Table 6.1: Energy calibration procedure for sparse readout mode.

<table>
<thead>
<tr>
<th>PROBLEM</th>
<th>SOLUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Diagram of problem" /></td>
<td><img src="image" alt="Diagram of solution" /></td>
</tr>
</tbody>
</table>

**Problem:** Gain and offset shifts are big — how to generate a histogram of ADC values that can be properly used for offset and gain calibration purposes for all channels.

**Gain Calibration Procedure**

1. Find ADC bin with maximum counts on each valid channel \( b(i) \), \( i = 1...512 \)
2. Going downwards, \( b(i), b(i)−1, b(i−2) \)... find the first ADC bin with zero counts on each valid channel \( b_0(i) \), \( i = 1,...,512 \)
3. Certify that ADC bins from \( b_0(i)−5 \) up to \( b_0(i)−1 \) are still zero. Only then validate \( b_0(i) \) for each channel. If not continue looking for it at step 2.
4. Find mean value of \( b_0(i) \) for all \( i \) valid channels, \( b_0\text{ mean} \)
5. Shift each channel ADC spectra histograms by \( −b_0(i)+b_0\text{ mean} \) mean. This will create a histogram with enough statistics that will allow the user to:
6. Define search intervals for finding 2 or 3 calibration peaks, in ADC units.
7. Run again VREDX and find the peaks on each pad. For this the window range set by the user are shifted by \( b_0(i)−b_0\text{ mean} \) on each pad \( i \).
8. VREDX uses now the found peaks and the correspondent energies to perform the linear energy calibration.
6.2 Prototype testing

Optimizing the performance of the Si module requires a good understanding of the readout electronics response, both of the analog \((VA)\) and of the trigger \((TA)\) parts. Numerous tests have been carried out to understand and optimize the performance of the Si modules. Tests can be performed both by using calibration sources of known energy, when a detector is already bonded, or with a calibration pulse, setting the chip to TEST mode. The advantages of using radioactive sources are that the chips can be tested in normal operating mode, when the noise is lower. This because in TEST mode tests must be carried out at a threshold higher than the lowest possible that will be set for data taking. In the case of the \(VA\) part, the aim is to optimize parameters such as noise that will determine the energy resolution, crucial for the performance of the prototype when detecting low energy electrons. In addition, it is necessary to establish a relationship between the energy deposited in the silicon sensor and the output value of the readout system. This has been done separately for gamma rays and electrons. Table 6.2 lists the isotopes used for testing, classified as gamma and electron emitters.

<table>
<thead>
<tr>
<th>Radioisotope</th>
<th>(E_{\gamma}) (keV)</th>
<th>(E_{X-ray}) (keV)</th>
<th>(E_{e-}) (keV)</th>
<th>Run mode</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gamma emitters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{241})Am</td>
<td>59.9</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>(^{57})Co</td>
<td>122</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>X-ray emitters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tb</td>
<td>44.4 - 50.6</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Ba</td>
<td>32.6 - 36.5</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Ag</td>
<td>22.1 - 25</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Mo</td>
<td>17.4 - 19.7</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Rb</td>
<td>13.4 - 16.7</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>Electron emitters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{181})Hf</td>
<td>133.0</td>
<td>57.1 - 65.5</td>
<td>65.6-130.8</td>
<td>✓</td>
</tr>
<tr>
<td>(^{141})Ce</td>
<td>145.4</td>
<td>35.9 - 40.9</td>
<td>105-144.7</td>
<td>✓</td>
</tr>
<tr>
<td>(^{111})In</td>
<td>171.3 - 245.4</td>
<td>23.1 - 26.2</td>
<td>143.3-244.8</td>
<td>✓</td>
</tr>
<tr>
<td>(^{169})Yb</td>
<td>93.6 - 307.77</td>
<td>49.7 - 50.1</td>
<td>50.4-248.3</td>
<td>✓</td>
</tr>
</tbody>
</table>
6.2.1 Noise performance

Figure 6.7 shows from top to bottom plots of pedestals, pedestals $\sigma_{\text{rms}}$ values (noise) for all channels and the rms histogram acquired in serial readout mode without source. The first plot shows the average pedestal values for the channels from the first to the fourth chip. Per chip, the measured averaged values are 180, 190, 200 and 170 respectively, in ADC units. The second plot shows the pedestal rms values for each channel, which looks quite chip independent, with mean value determined to be $\sim 1.9$ rms. This value corresponds to the width of a Gaussian curve fitted to the noise distribution, all channels included, displayed on the third plot of figure 6.7. The overall noise of the system during a serial mode run was further calculated using a $^{241}$Am source, which has a characteristic gamma line at 59.5 keV.

![Figure 6.7 Pedestals and noise distribution measured for all 512 channels in serial readout mode without source.]

Figure 6.8 shows from top to bottom: the acquired hit map, the $^{241}$Am histogram of hits in pad #100 and the Gaussian fit performed to the $\gamma$-peak obtained in this channel number 100. The pedestal spread, i.e. the channels ADC offsets spread, is taken with the detector not
revealing real \( \gamma \) or events in order to characterize the “overall noise” of the system, upon illumination with normal \( \gamma \) or electron events. The fit has been done on the 59.5 keV gamma line. Taking the average of pedestals sigma (\( \sim 1.916 \) ADC bin; see fig. 6.7 bottom plot), the noise was calculated as follows:

\[
\text{Noise} \ (e^-) = 1.916 \ ADC \ bin \times \left( \frac{1}{175.8} \times \frac{59.9 \times 10^3}{3.6} \right) e^-/ADC \ bin = 180 \ e^- \quad (6.4)
\]

The position of the photopeak was 175.8 to which corresponds the photopeak of 59.9 keV. The charge necessary to create an electron hole pair in silicon is 3.6 eV.

The main contributions to the calculated readout electronics noise come from the noise at the input load capacitance, \( i.e., \) detector capacitance plus FET gate capacitor of the charge sensitive preamplifier and of the detector leakage current [4].
The preamplifier noise can be parameterized as $ENC_{pr} = a + b \times C_{load}[pF]$, where $C_{load}$ is the total parallel capacitance at the input [3]. The $a$ and $b$ parameters depend on the electronics employed, and can be evaluated by measuring the noise performance of the chip using passive components for a given shaping time ($T_p$), i.e. components such as resistors and capacitors. These parameters were determined by A. C. Marques [3] for the previous version of the chip, which has the same VA readout structure, for four different values of shaping time by means of PSPICE simulations. The results are shown in table 6.3.

<table>
<thead>
<tr>
<th>Shaping time ($\mu s$)</th>
<th>$a$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>73,464</td>
<td>5,3613</td>
</tr>
<tr>
<td>1</td>
<td>71,731</td>
<td>3,9776</td>
</tr>
<tr>
<td>2</td>
<td>87,471</td>
<td>2,8652</td>
</tr>
<tr>
<td>3</td>
<td>107,66</td>
<td>2,3034</td>
</tr>
</tbody>
</table>

The load capacitance, $C_{load}$, of a single pad for the 1mm thick EC detector is $\sim 0.7$ pF. Therefore, for the selected 2 $\mu$s shaping time, the preamplifier contribution to the overall electronics noise can be estimated to be $ENC_{pr} = 89.5 e^-$. The contribution to the noise due to the leakage current ($I_{dl}$) of the detector has the expression: $ENC_{dl} = \frac{e^q}{2} \sqrt{qI_{dl}T_p}$, that is, $ENC_{dl} \propto \sqrt{I_{dl}}$, with $e = 2.718$ and $q = 1.6 \times 10^{-19}$. The leakage current on single pads of several 1mm thick unbonded detectors was measured to be $\sim 15-50$ pA. However, after bonding the detector to the readout chips, the leakage current further increases due to the heat generated by the chips, warming up the detector up to 29ºC during operation on air I vacuum without cooling that value increases up to 40ºC and stabilizes at 23ºC if the chips are water cooled. In fact, the leakage current increases with $e^{-E_g/2KT}$ because its behaviour is dominated by the generation current, being $E_g$ the band gap energy of Si (1.12

eV), \( K \) the Boltzman constant \((8.62 \times 10^{-5} \text{ eV/K})\) and \( T \) the temperature in Kelvin. This means, that when the chip is operating at 29ºC the expected leakage is 455 pA. Substituting this value in the previous equation, the leakage current contribution to the overall electronics noise can be estimated to be \( \text{ENC}_{dl} \approx 123 \, \text{e}^- \), which would be 149 e\(^-\) if the detector would be working in vacuum without cooling. Any of these values is higher than the value estimated for the preamplifier noise contribution meaning that, at high temperatures the noise due to the leakage current completely dominates the overall noise behaviour. Active cooling of the readout chips in vacuum is then imperative in order to detect electrons with optimum energy resolution, as it is fully shown in ref. [4].

Adding in quadrature, \( i.e. \, \text{ENC}_{tot} = \sqrt{\text{ENC}_{pl}^2 + \text{ENC}_{dl}^2} \), the two main noise sources referred above one can estimate the total electronics noise to be \( \sim 136 \, \text{e}^- \), which is compatible with the noise value of 180 e\(^-\) determined experimentally using equation 6.4. The difference of about 25% found between these values can be mainly attributed to: (1) the different number of lines crossing the correspondent pads and (2) the charge sharing effect. The latter also influences the position resolution of the detector since the lateral straggling of the electrons lead to events where the charge is shared among several pads. This has been roughly evaluated for the \(^{241}\text{Am}\) serial run considered above by quantifying the fraction of charge deposited by the 59.5 keV photons on neighbouring pads. For this, the multiplicity, \( i.e. \) the distribution of events over the number of pads collecting the signal of photons from the \(^{241}\text{Am}\) source in the 1mm thick detector was plotted in figure 6.9 a). As can be seen for photons of 59.5 keV, only 5% of the events have signal spread over more than one pad and their contribution to the spatial resolution is negligible. All of these considerations are expected to be valid for electrons but, only for low energies, since, for electron energies ranging from 200-1000 keV, losses of resolution can be expected from electron scattering and charge sharing onto detector. In serial readout mode VREDX can do an analysis of channel position by integrating the charge of physically adjacent
channels to the triggering channel. For all the sparse methods, the spatial resolution will depend on the triggering channel alone.

For demonstration purposes, figure 6.9(b) shows the multiplicity measured in a sparse mode run taken with the $^{241}$Am source in the same experimental conditions as in the serial run described above. The plot reveals, as expected by definition of sparse readout, that 100% of read events have only one channel hit. That is, no additional plateau is visible, since only the pad receiving the electron or gamma hit is read.

![Graphs showing hit multiplicity plots](image)

Fig. 6.9 Hit multiplicity plots taken in serial (a) and sparse (b) readout modes.

6.2.2. Gamma source tests

The calibration of the analog part of the chip includes the calculation of the gain factors that relate for each chip channel the energy transferred to the detector during the particle interaction, to the digitized data at the ADC. The relative differences in the VA gains from one channel to another must be determined and the data corrected with the gain factors in order to obtain the information in terms of energy. Also the energy resolution of the detector must be determined.
6.2.2.1 Serial readout mode

VA calibration: gain factors and energy vs. channel calibration

![Am spectrum of hits in a particular pad. The solid line represents a Gaussian fit to the 59.9 keV line obtained at channel #48.](image)

Gamma sources of known energy were employed for the gain factors calculation. To obtain the ADC value corresponding to the 59.9 keV photopeak, the data are histogrammed after pedestal and common mode correction to be fitted with a Gaussian as shown in figure 6.10. Determining the position of the photopeak for two or more energy values allows a linear fit to obtain the gain as the slope and the channel offsets. A simplification can be made assuming that the zero value of the ADC corresponds to zero energy and no offset exists, once pedestals have been subtracted from the data. The gain factor is then obtained from only one calibrating energy value. According to Losa et al. negligible differences (~ 2%) were found between the gain factors calculated by the two methods [8], which is also supported by the calibration data shown in figure 6.15 of this work. The relative gain of each channel was determined for each pad energy spectrum acquired in serial readout mode with the $^{241}$Am source. The fit was performed identically for each spectrum by always choosing the same number of bins to the left and right of the peak to be included into the fit. Then the relative
gains are calculated by dividing the gains with the average gain for all channels in the four readout chips module. The distribution of relative gains over the 512 channels of the four detector readout chips is shown in figure 6.11.

Fig. 6.11 Gain variations over the 512 channels for the four chips of the detector.

Within a chip the gain varies ~1 % regarding each chip mean value, while larger variations exist between the chips (~2%). This variation is significantly higher than the readout channel noise therefore a gain calibration map has to be used to prevent poor energy resolution during analysis.

Figure 6.12 shows (a) typical values of the pedestal for each channel of the detector, (b) the noise referred as sigma in the plot is determined by VREDX the variance of a Gaussian curve fitted to the raw values of the ADC digitized histogram not resulting from any of the triggers of the 484 channels connected to the detector. The distribution of noise values for all pads of the detector is shown in figure 6.12 (c). Gaussian fit gives a mean of ~1.98 ADC bin corresponding to an average noise per channel of ~196.5 e⁻. This value is comparable to the noise value of 180 e⁻ which was determined using a different algorithm from the spread of the pedestals, c.f. figure 6.7. In the Lego plot of figure 6.12(d) the equivalent noise charge for each channel of the detector is shown.
After subtracting for all readout channels the pedestal from the raw ADC digitized data, the final integral spectrum is obtained by reprocessing of the data using the gain map and by summing all the single channel histograms as shown in figure 6.13. At the considered energy the charge is mainly deposited in one pad. The mean energy resolution of the detector for the 59.9 keV gamma ray of $^{241}$Am was determined to be 2.7 keV FWHM.
Using the $^{241}\text{Am}$ gain calibration corrections$^1$, spectra in serial readout mode were taken with $^{57}\text{Co}$ source and with Tb, Ba, Mo and Rb from a X-ray variable source as shown in figure 6.14$^2$. This source consists of an Am source emitting through different metals and thus generating different element specific X-rays. Gaussian fits to the $K_\alpha$ and $K_\beta$ peaks were performed for each element in order to determine their positions in ADC bins. Table 6.4 shows the results for these fits. For Rb the $K_\alpha$ and $K_\beta$ lines are only separated by 3.3 keV and are barely seen, therefore, only the $K_\alpha$ line was fitted. From this table it is possible to extract the energy calibration (energy vs. ADC bin) and resolution curve (FWHM vs. energy) as shown in figure 6.15 (a) and (b). The detector energy response function was linear in the energy range from 13.1 keV to 122 keV. The energy resolution became constant for energies higher than 122 keV and followed a $1/E$ power law. For a fano limited system the electron hole-pair generation energy, $\varepsilon$, also influences the statistics associated to the generation of charges (i. e. Fano Noise) through $FWHM = 2.355\sqrt{F \times E / \varepsilon}$. For Si, the fano factor, F, and the electron hole-pair generation energy, $\varepsilon$, are also determined for Co ($E_\gamma=122$keV) and Tb ($E_{K_\alpha}=44.4$ keV) and no observable differences from the Am gain map were found.

---

$^1$ Gain maps were also determined for Co ($E_\gamma=122$keV) and Tb ($E_{K_\alpha}=44.4$ keV) and no observable differences from the Am gain map were found.

$^2$ Since the acquisition time of each spectrum presented in figure 6.14 was different, several individual plots were made.
energy, $\epsilon$, are 0.12 and 3.6 eV, respectively. The fano factor contribution in Si varies from 70 eV up to 300 eV FWHM for photon peaks with energies between 1-20 keV. Since, the majority of the used gamma sources emit photons with energies higher than $\sim$20 keV, the fano noise marginally affects the energy resolution. In figure 6.15(b)) it is clearly shown that $1/E$ power law (red curve) fits well the data, contrarily to the $1/E^{0.5}$ law (green curve), typical of a fano limited system.

![Graphs showing energy spectra](image)

**Fig. 6.14** $^{54}$Co, Tb, Ba, Ag, Mo and Rb spectra acquired in serial readout mode.
Table 6.4: Relevant data extracted from the analysis of fig. 6.14.

<table>
<thead>
<tr>
<th>Elem.</th>
<th>Line</th>
<th>Peak position (ADC bin)</th>
<th>E (keV)</th>
<th>FWHM (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{57}$Co</td>
<td>γ</td>
<td>355</td>
<td>122</td>
<td>3.8</td>
</tr>
<tr>
<td>$^{241}$Am</td>
<td>γ</td>
<td>167.3</td>
<td>59.9</td>
<td>2.7</td>
</tr>
<tr>
<td>Tb</td>
<td>Kα</td>
<td>89</td>
<td>44.4</td>
<td>3.1</td>
</tr>
<tr>
<td> </td>
<td>Kβ</td>
<td>101.4</td>
<td>50.6</td>
<td>2.5</td>
</tr>
<tr>
<td>Ba</td>
<td>Kα</td>
<td>124.9</td>
<td>32.6</td>
<td>2.9</td>
</tr>
<tr>
<td> </td>
<td>Kβ</td>
<td>142.9</td>
<td>36.5</td>
<td>3.4</td>
</tr>
<tr>
<td>Ag</td>
<td>Kα</td>
<td>61.9</td>
<td>22.1</td>
<td>2.3</td>
</tr>
<tr>
<td> </td>
<td>Kβ</td>
<td>70.3</td>
<td>25.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Mo</td>
<td>Kα</td>
<td>48.2</td>
<td>17.4</td>
<td>2.4</td>
</tr>
<tr>
<td> </td>
<td>Kβ</td>
<td>54.3</td>
<td>19.7</td>
<td>2.9</td>
</tr>
<tr>
<td>Rb</td>
<td>Kα</td>
<td>37</td>
<td>13.4</td>
<td>2.7</td>
</tr>
<tr>
<td> </td>
<td>Kβ</td>
<td>—</td>
<td>16.7</td>
<td>—</td>
</tr>
</tbody>
</table>

The data analysis presented above represents a first order assessment of the usefulness of this self-triggering front end ASIC for future EC studies with low energy conversion emitter isotopes. In fact, the data analysis revealed that the data acquisition in serial readout mode is favoured by the new triggering method since the detection efficiency and the energy resolution to low energy γ-rays are enhanced. Tests have shown the capability to detect X-rays of energy as low as 13.4 keV with a FWHM of 2.8 keV. However, for detection of extremely low-energy conversion electrons, the accessible energy range and energy resolution will be limited by the energy loss of the radiation in the undepleted layer of the detector. The operational performance in that respect still remains to be determined and is part of a recent proposal submitted at
ISOLDE under the title “Emission Channeling lattice location experiments with short-lived isotopes”. According theoretical calculations, the electron detection limit is expected to be around 25 keV.

**TA calibration: threshold vs. energy calibration**

The response of the trigger discriminator for a given signal might vary due to noise or common mode. Hence, a method needs to be established to determine a trigger value as a response for a given signal amplitude. This can be done by studying the response of the chips for a given signal while varying the threshold level. If the threshold is lower than the signal amplitude, the signal will be always above the threshold level, and the chip will trigger every time an event occurs. If the threshold is higher than the signal amplitude, the chip will never trigger. But for comparable levels of threshold and signal amplitude, the noise can determine whether a trigger occurs or not. If for each threshold value, the number of triggers in a certain time interval is recorded, a graph with a characteristic shape known as s-curve is obtained (see example in fig. 6.16). Assuming that the noise follows a Gaussian distribution, the shape of the s-curve corresponds to the error function, which is the integral of the gaussian function as shown in the next equation. The error function slope is related to the standard deviation of the gaussian function and thus to the noise.

\[
\text{erfc}(x) = 1 - \text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-z^2} \, dz \quad \text{where} \quad x = \frac{\text{threshold} - 50\% \text{ point}}{\sqrt{2} \text{ noise}}
\]

Fitting the “S-curve” with the error function two important parameters can be determined: the slope and the 50% point, value at which the S-curve reaches half of its high. The first, provides an estimate of the TA noise of the system and the second, being independent of the noise, determines the threshold that should be set for triggering at the peak amplitude of a given energy line.
Figure 6.16 (a)-(b) illustrates the “S-curves” acquired in serial and sparse readout modes with a monochromatic X-ray silver source. Both curves exhibit very well defined plateaus to the left and to the right of the threshold range in which is the 22 keV Ag peak is triggered, which means that a maximum of detection efficiency was achieved in both readout modes. Although, in sparse readout mode the starting plateau of the S-curve begins at 30 DAC units instead of 25 DAC units as in serial readout mode and is 10 DAC units shorter. This means that in sparse readout mode the gamma detection efficiency starts to degrade below 22 keV, as also expected for electrons. Therefore, one may expect to find a lower limit energy detection (LLD) that is higher in sparse readout mode. In line with this, is the ratio of the S-curve slopes, indicating that the TA noise of the spectrum is \( \sim 17-20\% \) higher in sparse than in serial readout mode. The reason for this is not yet completely understood but may be connected with noise equivalent count rate (NECR) differences between those modes. The NECR is inversely proportional to events lost in the detector due to its time uncertainty; thereby NECR is lower in serial readout mode than in sparse readout mode. Complementary, other X-ray sources such as Rb, Mo, Ag, Ba and Tb were used to plot the correspondent S-curves. Associating then each curve 50% point threshold to the energy of each signal peak, one can determine the threshold vs. energy.
calibration line. The calibration lines were determined for serial and sparse readout modes and are shown in figure 6.17.

![Threshold vs. energy calibration lines taken in serial and sparse readout modes with an X-ray variable gamma source.](image)

The intersection of the two calibration lines at 10 keV indicates that this should be the lowest photons detectable energy. Nevertheless, up to \( \sim 15 \) keV the detection efficiency is very low due to noise. Besides, for a given energy the difference between serial and sparse threshold in DAC units approximately follow the linear function:

\[
\Delta v_{\text{thr}} \ (\text{DAC units}) \approx 0.5 \ E \ (\text{keV}) - 7.
\]

Threshold vs. energy calibration tests were not feasible for non-monochromatic electron sources, since these result in a wide spectra of conversion electrons and X-rays hindering S-curves.

### 6.2.3 Test results with electron sources

The whole detection system operating under vacuum has been tested with electron sources since 2007. The main goal of these tests consist in determining, for each readout mode,
the lowest electron energy by the 1mm thick Si pad detector and its correspondent energy resolution when noise is reduced to minimum. For this, several electron calibration sources were used to characterize data acquisition taken in each readout mode of the VATAGP3 chip. The resulting data will be compared and discussed with previous data acquired from gamma sources. Table 6.2 lists the electron sources that were used to characterize a particular readout mode.

### 6.2.3.1 Serial readout mode

The detector performance in serial readout mode was characterized by measuring the pedestals, the noise (i.e. sigma: pedestal r.m.s.), gain and energy resolution using the $^{181}$Hf, $^{141}$Ce, $^{111}$In and $^{169}$Yb electron emitters. As a result, the relationship between the ADC output and the electron energy (in keV) could be determined. Contrarily to the gamma and X-ray tests, which run under air, all electron tests were done with the module under vacuum.

Figure 6.18(a)-(b) show pedestal and noise calculated from VREDX post-processed data. Pedestal distribution measured for all 512 channels clearly show that they may change with time but not so much as they do with applied bias voltage, up to $\sim$7%. Although, channel to channel and chip to chip, pedestal variations are similar to those previously measured with gamma sources. Noise (sigma) values are globally slightly higher when the module is running in vacuum. This may be attributed to an increase of working temperature that is expected to occur when the detector is operating under vacuum. Temperatures of 25-28°C were registered with the detector running in vacuum while being only cooled by water flow. Pedestals from seven channels (e.g. 0, 1, 2, 50, 51, 278 and 279) are considered bad due to their high values of leakage current that increase noise to intolerable levels. Consequently, those pads were masked and their effective pedestal values were set to zero. This masking procedure prevents all pads from having extra noise due to bad pads.
The pad to pad gain variations of the Si detector, when exposed to electrons, were determined from the $^{181}\text{Hf}$, $^{141}\text{Ce}$ and $^{111}\text{In}$ energy spectra after their pedestal and common mode noise correction. The measured pad to pad gain variations from a gaussian fit to the measured peak ADC channel data for each individual pad of the detector are shown in figure 6.18(c). The $^{181}\text{Hf}$, $^{141}\text{Ce}$ and $^{111}\text{In}$ isotopes emit conversion electrons and photons, whose nominal energies are summarized in table 6.4 – column (a) for the most relevant X-rays, conversion electrons and $\gamma$-rays susceptible of being detected with the present detector.

Differently from pure X-ray and $\gamma$ intense sources, conversion electrons sources do not provide a reliable and direct way of performing an absolute energy calibration of the detector. This is due to the reasons that electrons loose energy when travelling through the window and
non-depleted regions of the detector. There are simulation programs of interaction of charged particles with matter that could predict quite well the effective electron energy shifts, however, since this particular detector heterogeneities on doping are not known, such would be quite cumbersome and potentially useless. These facts, however do not avoid a quite good relative calibration of all pads to achieve an integral energy plot from where the majorants for the energy resolution for electrons may be extracted.

For each radioisotope spectrum, from one up to three calibration points were used to convert all ADC channels to a “reference energy”, which was when ever possible X-ray and $\gamma$-lines, or the electron line of highest energy, see table 6.5. Then the resulting relative energy calibrated data was histogrammed to provide a single gain corrected energy spectrum with the data from all pads. Three gain maps were determined since the chips and bias applied voltage were slightly different for each spectrum. With time as passing between measurements it was not possible to maintain all detection system parameters unchanged. Still, only relatively small gain differences within and among the chips from those previously measured for $\gamma$ sources were found. Just in the $^{141}\text{Ce}$ run the third chip registered bigger gain variations but still within tolerable values.

Table 5 reveals that one data point is typically enough to correctly determine the energy vs. ADC calibration.
Table 6.5: Nominal and measured energies of the emitted conversion electrons and photons are listed for $^{181}$Hf, $^{141}$Ce and $^{111}$In isotopes. In addition energy resolution and energy loss are indicated for all energy peaks.

<table>
<thead>
<tr>
<th></th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
<th>(e)</th>
<th>(f)</th>
<th>(g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energy (keV)</td>
<td>Energy (keV)</td>
<td>Energy (keV)</td>
<td>Energy (keV)</td>
<td>E shift (keV)</td>
<td>FWHM=ΔE (keV)</td>
<td>ΔE(%)</td>
</tr>
<tr>
<td></td>
<td>Nominal</td>
<td>Measured</td>
<td>Measured</td>
<td>Measured</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{181}$Hf</td>
<td>Calib. Meth. X$<em>{K</em>{\alpha}}$ + X$<em>{K</em>{\beta}}$</td>
<td>Calib. Meth. X$<em>{K</em>{\alpha}}$ + X$<em>{K</em>{\beta}}$</td>
<td>Calib. Meth. c.e. M</td>
<td>E = 0.3185 bin + 2.974</td>
<td>E = 0.3211 bin + 1.8445</td>
<td>(e) = (a) - (d)</td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>Ta K$_{\alpha}$</td>
<td>57.08</td>
<td>57.76</td>
<td>57.1</td>
<td>57.26</td>
<td>-0.18</td>
<td>-</td>
</tr>
<tr>
<td>Ta K$_{\beta}$</td>
<td>65.52</td>
<td>64.7</td>
<td>64.2</td>
<td>64.6</td>
<td>0.92</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>Y</td>
<td>133.02</td>
<td>133</td>
<td>133.2</td>
<td>135.9</td>
<td>2.88</td>
<td>-</td>
</tr>
<tr>
<td>K</td>
<td>c.e.</td>
<td>122.12</td>
<td>119.23</td>
<td>119.05</td>
<td>121.5</td>
<td>0.62</td>
<td>3.7</td>
</tr>
<tr>
<td>c.e.</td>
<td>$&lt;$L$&gt;$</td>
<td>130.84</td>
<td>128.15</td>
<td>128</td>
<td>130.8</td>
<td>0.04</td>
<td>3</td>
</tr>
</tbody>
</table>

|       | Calib. Meth. X K$_{\beta}$ | Calib. Meth. X K$_{\beta}$ | Calib. Meth. c.e. M | E = 0.3984 bin + 0.7518 | E = 0.3911 bin + 0 | (e) = (a) - (d) |
|       |       |       |       |       |       |       |     |
| X | Pr K$_{\alpha}$ | 35.86 | - | - | - | - | - |
| Pr K$_{\beta}$ | 40.95 | 40.9 | 40.6 | 40.2 | 0.75 | - |
| Y | c.e. | 145.44 | - | - | - | - |
| K | c.e. | 105.00 | 108.47739 | 101.5 | 101.2 | 3.8 | 3.5 | 3.458 |
| c.e. | $<$L$>$ | 139.30 | 148.8 | 139.2 | 139 | 0.3 | 3.9 | 2.806 |
| c.e. | $<$M$>$ | 144.66 | 154.5 | 144.6 | 144.6 | 0.06 | 3.5 | 2.420 |

|       | Calib. Meth. $\gamma_1$ | Calib. Meth. c.e.M | Calib. Meth. c.e.2 L | E = 0.3154 bin + 0 | E = 0.3102 bin + 0 | (e) = (a) - (d) |
|       |       |       |       |       |       |       |     |
| X | Cd K$_{\alpha}$ | 23.11 | - | - | - | - |
| Cd K$_{\beta}$ | 26.18 | - | - | - | - |
| $^{111}$In | K | 143.34 | 140.68 | 138.4 | 138.4 | 4.94 | 2.6 | 1.879 |
| c.e. | $<$L$>$ | 167.31 | 164.65 | 162 | 162 | 5.31 | 2.3 | 1.420 |
| c.e. | $<$M$>$ | 170.66 | 168.4 | 165 | 165 | 5.66 | - | - |
| Y | c.e. | 245.40 | - | - | - | - |
| c.e. | K | 217.46 | 220.17 | 216 | 216 | 1.46 | 3 | 1.389 |
| c.e. | $<$L$>$ | 241.43 | 241 | 241 | 241 | 0.43 | 3.1 | 1.286 |
| c.e. | $<$M$>$ | 244.78 | 245.4 | 244 | 244 | 0.78 | - | - |

Figure 6.19 shows relative calibrated spectra of $^{81}$Hf, $^{141}$Ce and $^{111}$In according to column (d) of table 6.5.
Fig. 6.19 Energy spectra of $^{181}$Hf (a), $^{141}$Ce (b) and $^{111}$In (c) recorded with the 1 mm thick detector, showing conversion electron lines with energies ranging from 65 keV to 242 keV. The square evidences peaks and energies used for calibration.

In figure 6.19(a), the lowest energy peak of the $\sim$57 keV and $\sim$65 keV $K_\alpha$ and $K_\beta$ X-rays emitted from Ta are visible but mixed with 65 keV, $K$ conversion electrons (detected with
61 keV) from the 133 keV transition. The $\langle L \rangle$ (122 keV) and $\langle M \rangle$ (131 keV) conversion electrons of that transition are well separated, their detected energies being 121 keV and 131 keV (the one used for calibration). The energy resolution of the K, L and M conversion electron peaks are $\sim 4.3$, $\sim 3.7$ and $\sim 3.0$ keV FWHM, respectively, which is worse than for photons of comparable energy, particularly at low energies, due to losses in the detector entrance window.

The $^{141}$Ce radioactive isotope decays to an excited state of $^{141*}$Pr by means of $\beta$ decay. During the subsequent decay of this daughter nucleus to the ground state ($145 \rightarrow 0$ keV transition) conversion electron are emitted. Both the $\beta$- and the conversion electrons signatures (continuum spectrum with discrete peaks emerging) are visible in the recorded spectrum of figure 6.19(b). The energy resolution of the corresponding electron K, $\langle L \rangle$, $\langle M \rangle$ peaks is $\sim 3.5$, $\sim 3.9$ and $\sim 3.5$ keV FWHM, respectively. Better values are expected to be obtained for conversion electron peaks of higher energies. This is the case in fig. 6.19(c) of $^{111}$In ($t_{1/2} = 2.8 d$) decaying to the 416.7 keV excited state of $^{111}$Cd, that fully decays through a radioactive cascade with two transitions, 171 keV plus 245 keV. In the decay, K-shell conversion electrons with energies of 143.3 keV and 217.5 keV are emitted with relative intensities per decay of 9% and 5%, respectively. And from their respective $\langle L \rangle$-shell 167.3 keV and 241.4 keV conversion electrons are emitted. Since the initial decay ($^{111}$In $\rightarrow ^{111}$Cd) is fully electron capture, characteristic Cd K- and L-X-rays are also generated. Note that the trigger level was set around 35 keV in order to exclude the Cd X-rays from the data acquisition process.

The left tail of the electron peaks in the spectra of figure 6.19 is caused by: (1) electrons that have lost part of their energy before entering the sensitive volume of the detector (i.e. in the sample and/or in the detector entrance window), (2) electrons that are backscattered from the detector and do not deposit their full energy and (3) charge sharing events between pads,
i.e. events where one pad does not collect all of the created charge since it is shared with neighbouring pads.

The energy calibration (energy vs. ADC bin) extracted from table 6.4 is shown in figure 6.20. The detector energy response function to electron exposure revealed to be linear in the range of 65.6 to 240 keV but, it is very sensitive to bias voltage variations. Note that the higher the applied voltage the higher the slope of the energy calibration line.

![Energy calibration lines determined from $^{141}$Ce, $^{181}$Hf and $^{111}$In electron spectra acquired in serial readout mode.](image)

Figure 6.21 shows the electron energy resolution curve, which was found to be essentially constant for energies greater or higher than 150 keV and follows a $1/E^{1.3}$ law, c.f. next page. At 122 keV the energy resolution measured with gamma and electron sources is ~3%. At 65 keV the estimated energy resolution for the electron peak of $^{181}$Hf spectrum is ~7%, against the ~4.5% that was measured from the $^{241}$Am energy resolution photopeak. The measured energy resolution curves reveal that in self-triggering serial readout mode the best resolving power is ~1% and is achieved for energies greater than ~150 keV. In fact, this result demonstrates that silicon pad detectors are excellent imaging spectroscopic detectors for energetic electrons up to
~250-280 keV (the preamplifier saturation peak is well visible in figure 6.19 (a) and (b), and barely visible in (c)).

![Figure 6.21 Measured electron energy resolution as function of energy from the $^{181}$Hf, $^{141}$Ce and $^{111}$In collected data in serial readout mode.](image)

Still a more intense study of electron detection efficiency at low energies was not feasible due to the lack of low energy electron emitter sources during the prototype testing phase reserved to this work.

In summary the detection efficiency for electrons and gammas is similar at energies higher than 60 keV. Note that the measured and nominal energies of electrons and some X-rays are small.

**STUDY CASE: $^{169}$Yb spectra X-ray and conversion electron spectra**

Figure 6.22 (a) shows the spectrum from $^{169}$Yb/$^{169}$Tm decay acquired in serial readout mode with the threshold set to ~12 keV. This includes not only the 100, 109, 118, 121, 139, 188, and 248 conversion electrons from the $^{169}$Tm$^*(t_{1/2}=0.66 \mu s)$ state but also the lower energy electrons (34.2-95 keV) from short-lived states which are populated within a few ns following the $^{169}$Yb decay. From the energy spectrum of the $^{169}$Yb decay the energy resolution of the
detector is found to be $\sim$3 keV FWHM for X-rays, and $\sim$2.4-5 keV for electrons. By comparing the spectrum of figure 6.22(a), taken with the present detector, with the spectrum of figure 6.22(b), taken with an old backplane trigger 1mm thick detector [10], the improvement of energy resolution is evident. The energy resolution of the old detector for X-rays and electrons was $\sim$5-6 and $\sim$8 keV FWHM, respectively.

Table 6.6 summarizes the nominal energy values of Tm X-rays and conversion electron peaks as those measured from each labelled peak of the $^{169}$Yb spectrum shown in figure 6.22(a). Note that to achieve a very good relative gain calibration for all channels and add them for unique histogram the absolute energy vs. ADC bin calibration was performed using the electron peak number 13 as energy reference. At first, its nominal energy value was used but then the resulting energy scale was corrected for the electron energy loss by determining a new energy vs. ADC bin line obtained from considering the Tm Kα-X ray peak and the 63.1 photopeak (peaks number 2 and 4 in fig. 6.22-(a)). In this way, the electron energy loss could be estimated from subtracting the measured ($E_{\text{mes}}$) from the nominal ($E_{\text{teo}}$) energy values subtraction. Extrapolating this result for the 34.2 keV conversion electrons, emitted with the 93.6 keV $\gamma$-ray, such electrons are expected to be detected with $\sim$27.5 keV, which corresponds to one of the small peaks observable in the left shoulder spectrum. This energy value of 27.5 keV as expected detectable energy for the 34.2 keV incident electrons is in agreement with that obtained from the $12/E^{1.3}$ law, used to fit the electron energy resolution curve shown in figure 6.23 (b).
Table 6.6: Theoretical and as measured energy peaks of gamma and conversion electrons emitted from $^{169}$Yb. The measured energy values report to the energy spectrum shown in figure 6.23-(a).

<table>
<thead>
<tr>
<th>E_{\text{theo}} (keV)</th>
<th>E_{\text{mes}} (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50.4</td>
</tr>
<tr>
<td>$e_{K}^{109} + e_{L}^{110}$</td>
<td>50.7</td>
</tr>
<tr>
<td>2</td>
<td>57.8</td>
</tr>
<tr>
<td>$K_{\alpha}\text{Tm X-rays}$</td>
<td>57.1</td>
</tr>
<tr>
<td>3</td>
<td>63.1</td>
</tr>
<tr>
<td>$\gamma\text{ray}$</td>
<td>63.2</td>
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<tr>
<td>4</td>
<td>71.1</td>
</tr>
<tr>
<td>$\gamma_{130.5}$</td>
<td>66.6</td>
</tr>
<tr>
<td>5</td>
<td>83.7</td>
</tr>
<tr>
<td>$e_{L}^{131.6}$</td>
<td>78.9</td>
</tr>
<tr>
<td>6</td>
<td>87.4</td>
</tr>
<tr>
<td>7</td>
<td>99.8</td>
</tr>
<tr>
<td>$e_{L}^{109.8}$</td>
<td>95.2</td>
</tr>
<tr>
<td>8</td>
<td>108.9</td>
</tr>
<tr>
<td>$e_{L}^{118.2}$</td>
<td>103.8</td>
</tr>
<tr>
<td>9</td>
<td>117.8</td>
</tr>
<tr>
<td>$K_{\alpha}$</td>
<td>113.3</td>
</tr>
<tr>
<td>10</td>
<td>121.2</td>
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<tr>
<td>$K_{\alpha}$</td>
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<td>11</td>
<td>124.4</td>
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<tr>
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<td>13</td>
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<td>$K_{\alpha}$</td>
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<tr>
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</tr>
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<td>15</td>
<td>188</td>
</tr>
<tr>
<td>$K_{\alpha}$</td>
<td>184.1</td>
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<tr>
<td>16</td>
<td>192.4</td>
</tr>
<tr>
<td>17</td>
<td>248.3</td>
</tr>
<tr>
<td>18</td>
<td>247</td>
</tr>
</tbody>
</table>

Fig. 6.22 $^{169}$Yb integral gain corrected energy spectra acquired with a 1 mm thick Si pad detector readout by (a) VATAGP3 and (b) VATA readout chips.

The energy vs. ADC calibration and electron energy resolution curve, extracted from table 6.6, are shown in figure 6.23 (a) and (b). Figure 6.23 (b) also shows the gamma energy resolution curve previously obtained in section. It is clear that the detector response is linear over the measured energy range. The relative energy resolution of the energy peaks observed in figure 6.22(a) follow a $12/E^{1.3}$ law, which is comparable to that of figure 6.21, obtained for three electron spectra acquired with different applied voltages. That is, both curves follow a $1/E^{1.3}$ law and only the multiplicative constant is slightly different. Comparing this detector $1/E^{1.3}$ response
for electrons with that of $2.69/E$ for gammas, one may conclude that while the absolute resolution (i.e. in FWHM keV) is approximately constant for gammas, it improves with energy for electrons.

![Energy calibration and energy resolution curves](image)

**Fig. 6.23** Energy calibration (a) and energy resolution (b) curves determined from the electron energy peaks of $^{169}$Yb spectrum acquired in serial readout mode.

Figure 6.24 (a) and (c) show the pedestal and sigma (noise values) over all the detector channels. The mean noise is ≈2 ADC units, which refers to an average equivalent noise charge per channel of 211 e$^-$ (the width of the 138.6 keV electron peak was taken as reference). Figure 6.24(c) shows the distribution of the relative gains over the 512 channels of the four VATAGP3
chips. The resulting map was used to construct the spectrum of the figure 6.22(a), where each channel spectrum is added after calibration.

![Figure 6.24](image)

**Fig. 6.24** (a) Distribution of pedestal, (b) noise (variance values) and (c) gain variations over all the detector channels measured from $^{169}$Yb electron source.

### 6.2.3.2 Sparse with adjacent pads readout mode

Figures 6.25 and 6.26 show electron spectra of $^{181}$Hf and $^{141}$Ce radioactive sources measured in *sparse with 20 and 10 adjacent channels* readout mode, as well as other relevant detector data. The electron spectra have good energy resolution, clearly evidenced by the clean separation of the $E_K$ and $E_L$ lines on both $^{181}$Hf and $^{141}$Ce spectra. The $E_K$ energy peaks of the $^{141}$Ce and $^{181}$Hf spectra have comparable energy resolutions to those measured in serial readout mode. However, in sparse with adjacent pads readout mode all energy lines are less well resolved. This is clearly illustrated in figure 6.28 where the correspondent measured energy resolution curve is shown. It follows a $957/E^{2.2}$ law revealing that for electron energies below $\sim 130$ keV, the energy resolution is worse than in serial and “pure” sparse readout modes. At 65 keV, the measured energy resolution was 10%, corresponding to a FWHM of 6.4 keV, while in serial readout mode it was $\sim 7\%$, *i.e.* 5 FWHM keV.
Fig. 6.25 (a) Distribution of pedestal, (b) noise (variance values), (d) gain variations over all the detector channels and (c) average electron noise measured from $^{181}$Hf electron source. The single pad (e) and integral gain corrected energy spectra (f) were acquired in sparse with 20 channels mode.
Since at lower energies the $^{181}$Hf spectral lines are broader than in serial readout mode, it is difficult separates the $^{181}$Hf 65 keV conversion electron peak from the Ta $K_{\alpha}$ and $K_{\beta}$ X-ray peaks. The causes of this problem might be due to the variation of the preamplifier’s operating point, changing its pulse gain, as it shown in figure 6.25(e) that compares single channels spectra from channels located in central and more peripheral positions. Those corresponding to pads near the detector edge, as channel 306, are significantly contributing to the apparent shift of gain and offset, or “non-linear effect”. Although $^{181}$Hf $E_L$ and $E_M$ energy peaks seem not as
much affected as the lower energy ones, what might hint a non linear response of the detector in this readout mode.

Figure 6.25(d) and 6.26(d) show the gain maps determined for each electron source. Note that both are significantly different from the gain maps obtained in serial readout mode thus making it imperative to use separate gain corrections for each readout mode. The pedestal and noise distributions for the $^{181}$Hf and $^{141}$Ce measurement are shown in figures 6.25 (a)-(f) and figures 6.26 (a)-(c), respectively. The average noise per channel was 1.6 $ADC \text{ bin}$ and 2 $ADC \text{ bin}$ for $^{181}$Hf and $^{141}$Ce sources. The difference in the two values is probably related to the fact that the two measurements were done several months apart with different detector settings and operating temperatures. In contrast, pedestal calculation over the 512 channels looks very similar.

6.2.3.3 Sparse readout mode

An $^{111}$In spectrum was acquired in sparse readout mode as shown in figure 6.27 to allow direct comparison with that of figure 6.19-(c), acquired in serial readout mode. In the absence of pedestal calculation during “pure” sparse data acquisition mode, the pedestals were calculated according the method described in table 6.1 and subsequently subtracted from the data. The energy calibration of the figure 6.27 spectrum was done with both conversion electron K peaks to their expected energies. A first observation is that, apart from a similar gain, of 0.3212 keV/bin, the resolution is noticeable better than that obtained in serial mode, which has to be connected with pedestal calculation methodology. Nevertheless, according to the fit performed to the energy resolution data in the energy range 143-245 keV, it is expected a response proportional to $19.6/E^{1.4}$. According to it, at 65 keV the energy resolution was extrapolated to be $\sim 6\%$, which is not so different from that expected for electrons of the same energy acquired in serial readout mode but still better by $\sim 2\%$. 
Figure 6.28 show the energy resolution curve measured from several electron sources acquired in each one of the three readout modes for data taking that VATAGP3 chip provides. The energy resolution curve acquired from gamma and X-ray sources was added in the plot of figure 6.28 for reference.

![Figure 6.27 Pedestal and gain corrected $^{111}$In spectrum acquired in sparse readout mode. The square evidences peaks and energies used for calibration.](image1)

![Figure 6.28 Electron empirical resolution curves for each VATAGP3 readout mode. The black dashed line corresponds to the measured gamma resolution curve given in figure 6.15.](image2)
6.2.3.4 First $\beta^-$ EC on-line experiments with short-lived isotopes

The technical progress performed in the new EC experimental setup, specially conceived for emission channeling experiments making use of short-lived radioactive probes, will be summarized. On-line high vacuum EC chamber and beam alignment components as well as detector housing consist in the main parts of the setup. It has been fully commissioned as well as the new VME detection system to the first EC experiments performed with $^{56}$Mn(2.6 h) and $^{61}$Co(1.6 h) isotopes in ZnO and GaN.

**On-line EC-setup**

The concept for on-line emission channeling experiments is the same as of off-line experiments, but with the particularity that the crystalline sample is implanted and measured in situ, inside the implantation vacuum chamber. It consists of a new high vacuum chamber matching implantation and measurement. A precision 2-axis goniometer is used to implant and orient the sample towards the new-fast electron Si pad detector for performing the emission yield measurements. In addition, auxiliary components like beam alignment devices, diaphragms and collimators had to be built. All the equipment was projected and made in Portugal at CFNUL-ITN and was assembled at CERN-ISOLDE.

The new on-line EC-setup consists of three main blocks: (1) the first diaphragm-collimator chamber, (2) the implantation chamber and (3) the detector box. In parallel to the dedicated function of each block, many individual features were added turning the whole setup as versatile as possible in order to: optimize the beam alignment, to get collimation down to 1mm beam spot at the sample and finally, to ensure good electron detection geometry. The top view of the new on-line EC setup is illustrated in figure 6.29.
Figure 6.30 in the left side shows a detailed layout of the diaphragm-collimator with its lead shield (this is potentially the most radioactive area of the beam line due to beam losses). In the right side, figure 6.30 shows the implantation chamber with the removable 1 mm collimator, (Note: when this last collimator goes to much radioactive it may be easily replaced by a non-contaminated one) the Faraday cup and the removable rotating shield. (Note: this shield aimed to shadow the detector during in situ annealing has never been used since a valve shuts off the detector during annealing.) In brown is indicated the space occupied by the 2-axis goniometer.

The ion beam coming to the LA2 ISOLDE beam line is first collimated by a variable diameter diaphragm-collimator located on a rotatable disk (fig. 6.30-(a)). Then, beam passes through a second collimator (fig. 6.30-(b)) delivering a beam spot with 1mm diameter on sample. Moving the sample upwards, allows the beam to enter a Faraday located along the sample line for performing stable beam tuning, previous to the use of a radioactive beam. The current may also be measured directly on the sample during implantation at the electrically isolated sample holder. However, the value of this current is typically overestimated by a factor
of 2-3 due to secondary electron emission, which is not suppressed in this case. The beam axis makes a 17° angle with the detector normal.

**Fig. 6.30** Detail side layouts of the diaphragm-collimator_1 chamber (a) and (b) on-line implantation chamber with the second collimator (collimator_2), and the faraday cup.

For global alignment purposes, the full setup (diaphragm-collimator and irradiation chamber) sits in a heavy orientation stand that fully supports the system, see figure 6.31. The table provides several orientation degrees of freedom (e. g. X, Y, Z and tilt) and allows transporting the whole setup from one lab to another.
A gate valve of 80 mm diameter separates the detector box from the irradiation chamber (fig. 6.29). Besides vacuum control, this setup allows to isolate the detector from any damage that might be caused by thermal radiation during sample annealing (valve partially or completely closed during the annealing up to 900ºC). If needed, this protection can also be achieved by rotating the removable thermal shield located around the goniometer sample holder.

The housing box of the 1mm thick position sensitive detector has two movable flanges as shown in figure 6.32. The lateral flange holds the module (i.e. hybrid + detector + chips) and the cooling system of the readout chips. The operating principle of the cooling system is the same of that one used in the off-line setups, described in pages 99 and 100. The lateral flange of the new box is equipped with a vacuum-air feedthrough printed circuit board (PCB) which allows plugging the module of 50 pins directly to a wide cable connected to the VME card. This system was firstly developed at CERN to satisfy EC specific experimental needs for a standard 500 µm EC pad detector in 2001 within the scope of my diploma project [3]. When the detector box is well sealed and attached to the whole system a vacuum down to $5 \times 10^{-7}$ mbar is achieved.
Results

The new on-line EC setup was used for the first time during the June 2007 Mn beam time at ISOLDE to investigate the lattice location of $^{61}$Co (1.6 h) and $^{56}$Mn (2.6 h) transition metals in ZnO and GaN semiconductors, by means of on-line $\beta^-$ emission channeling experiments. While $^{56}$Mn was available directly, $^{61}$Co was obtained through the implantation of its short lived precursor isotope, $^{61}$Mn, and exploiting the $^{61}$Mn (0.7 s)$\rightarrow$$^{61}$Fe (6 min)$\rightarrow$$^{61}$Co (1.6 h) decay chain. The electron spectra acquired during the decay chain represent a first demonstration of the usefulness of the new prototype for EC lattice site location studies with short-lived isotopes. The new detector readout system was found to reach data taking rates up to 3 KHz in sparse with adjacent channels. Higher count rates may be achieved by further hardware and software optimizing.

Figure 6.33 (a) shows from the $^{61}$Mn (0.71 s) $\beta^-$ spectrum acquired during its implantation in ZnO. However, since the activity of $^{61}$Mn saturates very rapidly (typically after 10 half-life), the spectrum of figure 6.33-(a) has evidently additional contributions from the $\beta^-$ spectra of $^{61}$Fe and $^{61}$Co daughter isotopes. Similarly, the acquired $\beta^-$ spectrum
of $^{61}$Fe in figure 6.33 (b), acquired after $^{61}$Mn decay, also has a contribution from the daughter isotope, $^{61}$Co, spectrum. Finally, figure 6.33 (c) shows the $\beta^-$ spectrum of $^{61}$Co decaying to stable $^{61}$Ni isotope. In each figure it is visible the typical continuum $\beta^-$ spectrum shape from which emerge a gamma and two electron lines. From left to right, these are: the 58.8 keV K and 66.5 keV $<L>$ conversion electrons (detected with 53.3 and 61.7 keV) from the 67.4 transition. Besides, the relative intensity increase of those electron peaks as time goes can be also observed in figure 6.33.

The end point energies of the $^{61}$Mn and $^{61}$Fe $\beta^-$ spectra are particularly high; therefore there is a portion of electrons with energy high enough to pass through the depleted layer of the 1mm thick Si detector. This effect causes the right side tail observed in figure 6.33 (a) and (b) for energies above $\sim$200 keV.

Figure 6.34 shows the $\beta^-$ energy spectrum of implanted $^{56}$Mn (2.6 h) in GaN. Notice that the referred energy loss of the very high energy electrons that transverse the detector due to the high end point of $^{56}$Mn isotope is also visible for energies above 200 keV.
The lattice location of Mn in GaN and Co in ZnO was determined in the as implanted state and following annealing up to 900°C. In both cases it was found that the transition metals preferred substitutional cation (i.e. Ga or Zn) sites. This is evident in the experimental β-emission patterns from $^{61}$Co in ZnO and from $^{56}$Mn in GaN in figures 6.35-(a) and 6.35-(b). The patterns for all measured axis are only reported for the last annealing step performed in both set of experiments and have not yet been corrected for the contribution of backscattered electrons. Both Mn- doped GaN and Co-doped ZnO are semiconductor systems for which RT ferromagnetism has been reported and where lattice location experiments of the transition metals are of high interest [11][12].
Fig. 6.35 Experimental EC patterns of (a) $^{61}$Co- and (b) $^{56}$Mn-implanted impurities in ZnO and GaN, after annealing at 800°C and 900°C, respectively.

- $^{61}$Mn implanted
- wait 25 min
- emission channeling patterns measured from $^{61}$Co $\beta^-$ particles
- qualitative result: $^{61}$Co on substitutional Zn sites

- $^{56}$Mn implanted directly
- emission channeling patterns measured from $^{56}$Mn $\beta^-$ particles
- qualitative result: $^{56}$Mn on substitutional Ga sites
6.2.4 Conclusion

A new detection system for EC experiments with a 1mm thick pad detector has been implemented with less noise and better readout speed than previous EC detectors thanks to the new self-triggering readout methodology and availability of sparse readout modes. This was achieved by reading the detector with four VATAGP3 chips and implementing a completely new readout chain relying on the VME methodology for data transfer to the PC and an optolink connection. Such methodology is replacing the older DSP methodology, implemented in previous EC position sensitive detection systems using the backplane signal for triggering. These improvements made possible to detect conversion electrons of 50.38 keV with a very good pad energy resolution of $\sim 5$ keV, which was $\sim 7$ keV for a previous 1mm thick detector readout by VA1 chips. So far, these were the electrons of lowest energy successfully detected by the new module. The absence of low energy conversion electron radioactive source emitters during the testing period of this work made it impossible to accurately determine the lowest detectable energy for electrons. Nevertheless, figure 6.22 evidences the detection of 34.2 keV conversion electrons with a resolution in FWHM keV roughly estimated to be $\sim 9$ keV, being the detected energy being 27.5 keV. Hence, the total electron energy loss in the detector entrance window was 7 keV. The lowest detectable energy for X-ray photons was determined with the detector running in vacuum and water cooled. In this case, the lowest detectable energy, with good efficiency, was 17.4 keV and the corresponding energy resolution was $\sim 2.4$ keV. The detection efficiency and energy resolution of very low energy electrons may improve under readout chips cooling. In fact, the performance of the module cooling below 22°C (down to 1-2°C) wasn’t studied so far. Therefore, this may be an interesting further point to study since such results could be compared to those obtained with VA1 chips, published in ref. [4].

The results obtained with the new prototype show that, the detection at low energies as well as the readout speed are enhanced, thus revealing the possibility of using short lived
isotopes as EC probes at ISOLDE. $^{61}$Co ($t_{1/2} = 1.6h$) and $^{56}$Mn ($t_{1/2} = 2.6h$) implanted in ZnO and GaN were two of the first emission channeling experiments showing the usefulness of the new prototype. In the first case, electron spectra from the $^{61}$Mn ($t_{1/2} = 0.7sec$) and $^{61}$Fe ($t_{1/2} = 5.98min$) precursor isotopes were taken during implantation. Motivated by this work, a research and development project is performing a completely new set of lattice site location studies with short lived probes implanted in semiconductors such as GaN and ZnO.

References