## mPIXdaq: Data acquisition for *miniPIX EDU* pixel detector

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The miniPIX EDU is a camera for radiation based on the Timepix pixel read-out chip with 256x256 radiation-sensitive pixels of 5x55µm² area and 300µm depth each. The chip is covered by a very thin foil to permit α and β radiation to reach the pixels. The device is enclosed in a sturdy aluminum housing with a USB 2.0 interface.

Other than single semi-conductor chips or simple Geiger counters, this device provides two-dimensional images of particle traces in the sensitive detector material. The high spatial resolution compared to the typical range of particles in silicon is useful to distinguish the different types of radiation and measure their deposited energies. α-particles are completely absorbed and deposit all of their energy in the sensitive area, allowing usage of the device as an energy spectrometer.

The vendor provides a ready-to-use program for different computer platforms as well as a software-development kit for own applications.

The code provided here is a minimalist example to read out single frames, i.e. a full set of 256x256 measurements accumulated over a given, fixed time interval. Each frame is displayed as an image with a logarithmic color scale representing the deposited energy. The analysis of the recorded signals, i.e. clustering of pixels, energy determination and visualization, is achieved with standard open-source tools for data analysis. It is therefore well-suited to give high-school or university students detailed insights and to enable them to carry out their own studies.

Getting ready for data taking

This code has been tested on *Ubuntu*, *openSuse* and on *Raspberry Pi* for the 32bit 64bit versions of *OS12*. Other Linux distributions, however, should not pose any problem.

To get started, follow the steps below:

- Get the code from gitlab @ KIT
  `git clone https://gitlab.kit.edu/Guenter.Quast/mPIXdaq`.

  This repository includes the python code and a minimalistic set of libraries provided by ADVACAM. `cd` to the `mPIXdaq` directory you just downloaded.
- Set up the USB interface of your computer to recognize the miniPIX EDU:
  `sudo install_driver_rules.sh` (to be done only once), then connect the *miniPIX EDU* device to your computer.

The package may also be installed in your virtual python environment:

- `python -m pip install .`

Now everything is set up to enjoy your miniPIX EDU. Just run the *Python* program from any working directory by typing

`run_mPIXdaq.py`.

If you plan to record data, note that the path to the output file is relative to the current working directory.

Note that the *pypixet* initialization is set up to write log-files and configuration data to the directory */tmp/mPIX/*.

It is also worth mentioning that on some systems the current directory, “.”, needs to be contained in the `LD_LIBRARY_PATH` so that the *Python* interface *pypixet* finds all its *C* libraries. This is also done in the *Python* script `run_mPIXdaq.py` by temporarily modifying the environment variable `LD_LIBRARY_PATH` if necessary and then restarting to execute the *Python* code. Starting the *Python* code by a different mechanism may not work without adjusting the environment variable `LD_LIBRARY_PATH`. In the *bash* shell, this is achieved by `export LD_LIBRARY_PATH='.'` on the command line. Note, however, that such a permanent change could open up a security gap!

Running the example script

Available options of the *Python* example to steer data taking and data archival to disk are shown by typing

`run_mPIXdaq.py --help`, resulting in the following output:

```
usage: run_mPIXdaq.py [-h] [-v VERBOSITY] [-o OVERLAY] [-a ACQ_TIME]
         [-c ACQ_COUNT] [-f FILE] [-t TIME]
         [--circularity_cut CIRCULARITY_CUT] [-r READFILE]

read, analyze and display data from miniPIX EDU device

options:
  -h, --help            show this help message and exit
  -v VERBOSITY, --verbosity VERBOSITY
                        verbosity level (1)
  -o OVERLAY, --overlay OVERLAY
                        number of frames to overlay in graph (25)
  -a ACQ_TIME, --acq_time ACQ_TIME
                        acquisition time/frame (0.2)
  -c ACQ_COUNT, --acq_count ACQ_COUNT
                        number of frames to add (1)
  -f FILE, --file FILE  file to store frame data
  -t TIME, --time TIME  run time in seconds
  --circularity_cut CIRCULARITY_CUT
                        cicrularity cut
  -r READFILE, --readfile READFILE
                        file to read frame data
```

The default values are adjusted to situations with low rates, where frames from the *miniPIX* with an integration time of `acq_time = 0.2` are read. For the graphics display, `number_of_buffers=25` recent frames are overlaid, leading to an integration time of 5 s. These images represent a two-dimensional pixel map with a color code indicating the energy measured in each pixel.

Data analysis consists of clustering of pixels in each frame and determination of cluster parameters, like the number of pixels, energy and circularity. The threshold on circularity is controlled by the parameter `circularity_cut` ranging from 0. for perfectly linear to 1. for perfectly circular clusters. Technically, the covariance matrix of the clusters is calculated, and the circularity is the ratio of the smaller and the larger of the two eigenvalues of the covariance matrix. This simple procedure already provides a good separation of α and β particles and of isolated pixels not assigned to clusters. The latter ones have a high probability of being produced in interactions of photons, while electrons from β radiation or from photon interactions produce long traces, and α particles produce large, circular clusters due to their very high ionization loss in the detector material.

To test the software without access to a miniPIX EDU device or without a radioactive source, a file with recorded data is provided. Use the option `--readfile data/BlackForestStone.npy.gz` to start a demonstration. Note that the analysis of the recorded pixel frames is done in real time and may take some time on slow computers.

Implementation Details

The default data acquisition is based on the function *doSimpleIntegralAcquisition()* from the *ADVACAM Python* API. A fixed number of frames (*acq_counts*) with an adjustable accumulation time (*acq_time*) are read from the miniPIX device and added up.

The chosen readout mode is *PX_TPXMODE_TOT*, where “ToT” means “time over threshold”. This quantity shows good proportionality to the deposited energy ath high signal values, but a strong non-linear behavior for small signals near the detection threshold of the miniPIX. Calibration constants are stored on the miniPIX device for each pixel, which are used to provide deposited energies per pixel in units of keV.

The relevant libraries for device control are provided in directories `advacam_<arch>` for `x86_64` Linux, `arm32` and `arm64` and for Macintosh arm64 architectures. The contents of a typical directory is:

```
  __init__.py   # package initialization
  pypixet.so    # the Pixet Python interface
  minipix.so    # C library for pypixet
  pxcore.so     # C library for pypixet
  pixet.ini     # initialization file, in same directory as pypixet
  factory/      # initialization constants
```

Note that the copyright of these libraries belongs to ADVACAM. The libraries may be downloaded from their web page, ADVACAM DWONLOADS. They are provided here as a *Python* package for convenience.

Data Analysis

The analysis shown in this example is intentionally very simple and based on standard libraries and functions. Pixels are clustered with *scipy.cluster.DBSCAN* (Density-Based Spatial Clustering of Applications with Noise) in a very simple configuration. The shape of the clusters is determined from the ratio of the smaller and the larger one of the two eigenvalues of the covariance matrix calculated from the *x* and *y* coordinates of the pixels in a cluster. For circular clusters, as produced by α radiation, this ratio is close to one, while it is almost zero for the longer traces from β radiation.

The figure below shows the graphical display of the program with a pixel mimage and the typical distributions of the pixel and cluster energies and the number of pixels per cluster. The source used was a weakly radioactive stone from the Black Forest containing a small amount of Uranium and its decay products. The pixel map shown in the figure was sampled over a time of five seconds. The histogram in the lower-right corner shows how well the cluster types discriminate different types of radiation: α rays in the green band with relatively low numbers of pixels pwr cluster, electrons (β) as long tracks with large numbers of pixels per cluster and rather low energies, and □ rays as single pixels not associated to clusters. Some of the electron tracks with typically low energies also stem from photon interactions in the detector material (via the Compton process).

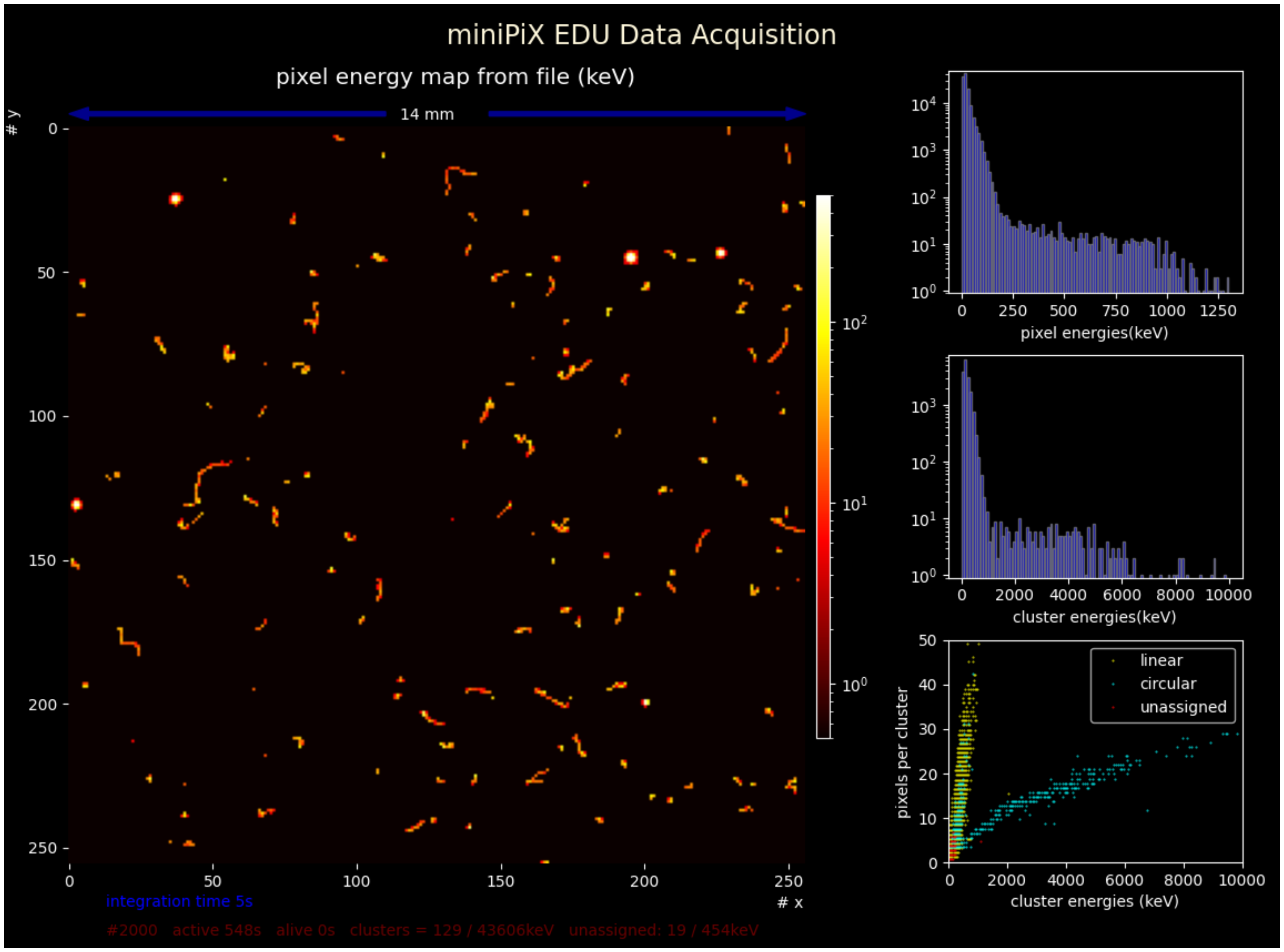

Abbildung 1: The graphical display of miniPIXdaq

Sensor Details

The miniPIX EDU is based on the *Timepix* hybrid silicon pixel device, consisting of a semiconductor detector chip segmented into 256 x 256 square pixels with a pitch of 55 mm that is bump-bonded to the readout chip. Each element of the pixel matrix is connected to its own preamplifier, discriminator and digital counter integrated on the readout chip.

The built-in *Medipix2* variant of the chip is operated in the so-called "frame mode", i.e. all pixels are read out at the same time, providing one frame consisting of the deposited energies per pixel collected during the acquisition time. If operated in time-over-threshold (ToT) mode, returned pixel readings represent the time the signal is over a given threshold in counts of the chip clock (appr. 10 MHz). *ToT* is linearly related to the energy deposition for large deposits exceeding 50 keV. The functional dependence on the deposited energy E, including threshold effects, is approximated by the following function

$$ToT \;=\; a\,E + b - c/(E - t)$$

Approximate values of the calibrations constants are a = 1.6, b=23, c=23 and t=4.3. Each pixel has its individual calibration stored on the chip, which is optionally applied to obtain pixel readings in units of keV. The calibration is reliable up to pixel energies of one MeV. Higher pixel energies may result when frames with short acquisition time are summed up. For details, see the article by J. Jakubek, *Precise energy calibration of pixel detector working in time-over-threshold mode*, NIM A 633 (2011), 5262-5265*.

Package Structure

This package consists of one *Python* file with several classes providing the base functionality. As mentioned above, it relies on ADVACAM libraries for setting-up and reading the sensor. Other dependencies are well-known libraries from the "Python" eco-system for data analysis:

- `numpy`
- `matplotlib`,
- `scipy.cluster.DBSCAN`
- `numpy.cov`
- `numpy.linalg.eig`

The classes and scripts of the package are

- class `miniPIXdaq`
- class `frameAnalyzer`
- class `runDAQ`
- class `bhist`
- class `scatterplot`
- package script `run_mPIXdaq.py`

Details on the interfaces are given below.

```
class miniPIXdaq:
    """Initialize and readout miniPIX EDU device

    Args:
      - ac_count: number of frames to overlay
      - ac_time: acquisition time
      - dataQ:  Queue to transfer data
      - cmsQ: command Queue
"""

class frameAnalyzer:
    """Analyze frame data
      - find clusters
      - compute cluster energies
      Args: a 2d-frame from the miniPIX
      Returns:
      - n_pixels: number of pixels with energy > 0
      - n_clusters: number of clusters
      - n_cpixels: number of pixels per cluster
      - circularity: circularity per cluster (0. for linear, 1. for circular)
      - cluster_energies: energy per cluster
    """
```

These classes are used by the class `runDAQ`, which initializes all components including the graphical output for monitoring if the on-going data acquisition in real-time. It accepts command-line arguments to set various options, as already described above.

```
  class runDAQ:
    """run miniPIX data acquisition and analysis

    class to handle:

        - command-line arguments
        - initialization of miniPIX device of input file
        - real-time analysis of data frames
        - animated figures to show a live view of incoming data
        - event loop controlling data acquisition, data output to file
          graphical display
    """
```

Tow helper classes implement 1d and 2d histogramming functionality for efficient and fast animation using methods from `matplotlib.pyplot`.

```
class bhist:
    """one-dimensional histogram for animation, based on bar graph
    supports multiple classes as stacked histogram

    Args:
        * data: tuple of arrays to be histogrammed
        * bindeges: array of bin edges
        * xlabel: label for x-axis
        * ylabel: label for y axis
        * yscale: "lin" or "log" scale
        * labels: labels for classes
        * colors: colors corresponding to labels
    """

class scatterplot:
    """two-dimensional scatter plot for animation, based on numpy.histogram2d
    supports multiple classes of data, plots a '.' in the corresponding color
    in every non-zero bin of a 2d-histogram

    Args:
        * data: list of pairs of cordinates [ [[x], [y]], [[], []], ...] per class to be shown
        * binedges: 2 arrays of bin edges [[bex], [bey]]
        * xlabel: label for x-axis
        * ylabel: label for y axix
        * labels: labels for classes
        * colors: colors corresponding to labels
    """
```

A package script `run_mPIXdaq` is provided as an example to tie everything together in a running Program. Because the ADVACAM *Python* interface (`pypixet.so`) expects C-libraries and configuration files in the very same directory as *pypixet.so* itself, some tricky manipulation of the environment variable `LD_LIBRAREY_PATH` is needed to ensure that all libraries are loaded and the *miniPIX* is correctly initialized.

```
#!/usr/bin/env python3
import os, sys
```

```
# pypixet requires '.' in LD_LIBRARY_PATH so that al neccessary C-libratreis are found
#  - add current directory to LD-LIBRARY_PATH
#  - and restart python script for changes to take effect

path_modified = False

if 'LD_LIBRARY_PATH' not in os.environ:
    os.environ['LD_LIBRARY_PATH'] = '.'
    path_modified = True
elif not '.' in os.environ['LD_LIBRARY_PATH']:
    os.environ['LD_LIBRARY_PATH'] += ':.'
    path_modified = True

if path_modified:
    print(" ! added '.' to LD_LIBRARY_PATH")
    try:
        os.execv(sys.argv[0], sys.argv)
    except Exception as e:
        sys.exit('EXCEPTION: Failed to Execute under modified environment, ' + e)
else:  # restart python script for setting to take effect
    # get current working directory before importing minipix libraries
    wd = os.getcwd()
    from mpixdaq import mpixdaq  # this changes the working directory!

    rD = mpixdaq.runDAQ(wd)  # start daq in working directory
    rD()
```