Project for physics teaching, making elementary particles visible and studying their properties with Medipix detectors

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Abstract. This project aims to make elementary particles visible for students to study their properties within the classroom, using a unique microelectronics device, the size of a USB stick, called Minipix-edu. Over the last 15 years, efforts have been made to use the Minipix detectors for educational purposes. The device makes it possible to view and easily distinguish several types of these elementary radiation quanta on the screen of a laptop. It is a good time now for the proposal of a European-wide education initiative based on the Minipix-Edu, since XXXXXXXXXXXXXX could provide a considerable number of Minipix educational kits on loan to interested entities.

1. Introduction

Besides the air we breathe, the photons from the sun and photons from our electronic screens that we see, we are also surrounded by many other invisible elementary quantum particles. These range from trillions of tiny neutrinos, many free electrons, to a few muons and very rare radioactive atoms, such as radon. Most of the adult population has only a very vague knowledge of the existence of such particles. Using the integrated silicon device Minipix, USB-size [1] with a 2 cm^2 sensitive area and tens of thousands of active cells, it has become possible to visualise and easily distinguish in real time different types of elementary radiation quanta using the screen of a laptop [2].

The Minipix detectors, which are based on the Timepix chips developed from the Medipix detectors at CERN [3], have proven to be a powerful tool to teach radioactivity and particle physics, among many other topics, to pre-university students. The potential of microelectronics for use in understanding the radiation environment becomes clear to them, and a better understanding of the electromagnetic spectrum and its many orders of magnitude can be acquired. Several educational initiatives have arisen across Europe over the last 15 years, using the Timepix camera at high school level and changing the way radioactivity and particle physics are thought of. Moreover, the diversity of approaches and characteristics of these projects has been a source of feedback and synergies with many goals being achieved.

CERN@School was the first project developed around the idea of bringing experimental particle physics to secondary schools and some of their aims and achievements are reviewed below. Together with its successor, the Institute for Research in Schools (IRIS), they have led the way and, undoubtedly, have inspired those who have followed in their footsteps [4].

Shortly after, the XXXXXXXXXXXXXXXXXXX at the XXXXXXXXXXX started to develop an educational project with the new, at that time, MX-10 detector, which has become an extremely successful initiative across the Czech Republic, their SESTRA kits [5] and, especially, their manual "Experiments Using Pixel Detector in Teaching Nuclear and Particle Physics"[6], have proven to be really useful in high school classroom and in universities.

Another recent effort is the ADMIRA initiative [7] which was born from the collaboration among XXXXXXXXX, the XXXXXXXXXXXXXXXXXXXXX of the University of Barcelona (UB) and the XXXXXXXXXX in Gavà (XXXXXX) to motivate students in the STEM subjects by using Minipix detectors. Despite the practical challenges imposed by the pandemic the initiative became, in a couple of years, a growing project that now involves tens of schools sharing detectors, resources and knowledge. To highlight the sensor's many amazing possibilities, some evidence of the work done by students from the ADMIRA network is presented below.

This success stimulated the XXXXXXXXXXXXX to boost these initiatives, promoting a network of members of the Medipix Collaboration supporting and organising detector loan systems among schools, so the use of Timepix detectors in secondary schools may become common in high schools across Europe. The first steps of this XXXXXXXXX project are presented at the end of the article.

2. The Minipix detector

Most of the initiatives currently deployed across the EU use a readout system of the Timepix detector called Minipix and Minipix EDU developed by ADVACAM, a company based in Czechia [8].

This instrument is based on developments by the Medipix Collaborations and R&D work for the large LHC experiments at CERN [9]. Minipix is a readout system for the Timepix detector which has a sensitive area of $2cm^2$. It is USB compatible and has the size of a typical memory stick. It has 65536 active cells arranged in a square matrix of 256x256 pixels (figure 1).

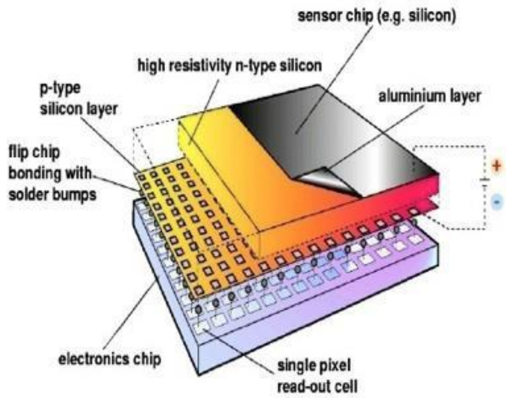

Figure 1. Schematic view of the assembly of a silicon sensor (top) and a readout chip with the matrix of processing circuits. The sensor cells are connected to the signal processing cells by microscopic solder bumps, which take less than 15µm on the 55µm pixel dimension.

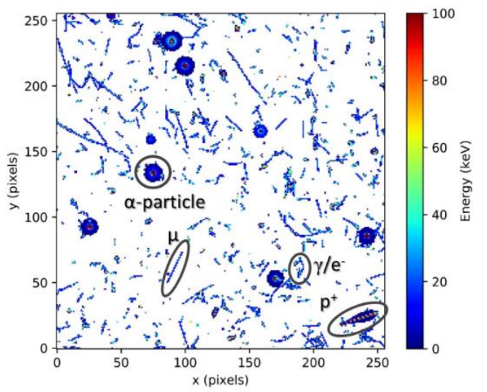

Figure 2. Radiation at Zugspitze (altitude 2700 m) as seen with Timepix3 (60 minutes frame). The recording shows a few different particles, with their typical clusters of deposited energy, in keV, per pixel, on a colour scale.

Each sensor pixel is connected by a solder ball to its own signal processing circuit. The Timepix chip can be used like a camera. When the electronic shutter is open, each pixel circuit can be used to determine the energy released by a particle interacting in the sensor [10]. When the shutter is closed, the data on all pixels is read out, producing an image of the charge deposited in the sensor. Thus, particle traces are visualised on a microscopic level (each cell is 55x55 μm^2), which allows one to easily distinguish several types of elementary radiation quanta using the screen of a laptop, as shown in figure 2.

An ionising particle generates thousands of free electrons (figure 3, left) as it interacts with the semiconductor silicon sensor. These charges move in the applied electric field inducing a current at the input of the corresponding amplifier connection (figure 4). The electronics in each pixel can measure the amplitude of this signal. When properly calibrated, the detector permits the measurement of the particle's energy deposition in the pixel. In the case of the Timepix3 ASIC (a successor to the Timepix ASIC used in Minipix-edu) a very precise timestamp (~ns) can be recorded on each pixel, allowing the 3D reconstructions of the particle's track [11].

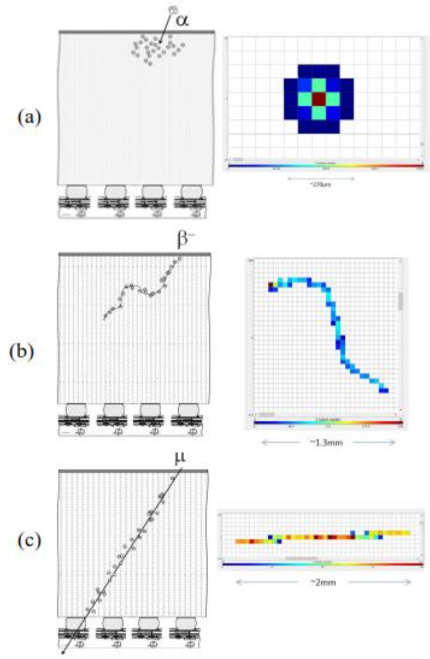

Figure 3. Representation of the hybrid pixel detector ionisation (left) for alpha (a), beta (b) and muon (c) and their tracks visualized with the Timepix software (right). The sensor material (not to scale) is on the top and it is connected through flip chip to the readout electronics at the bottom.

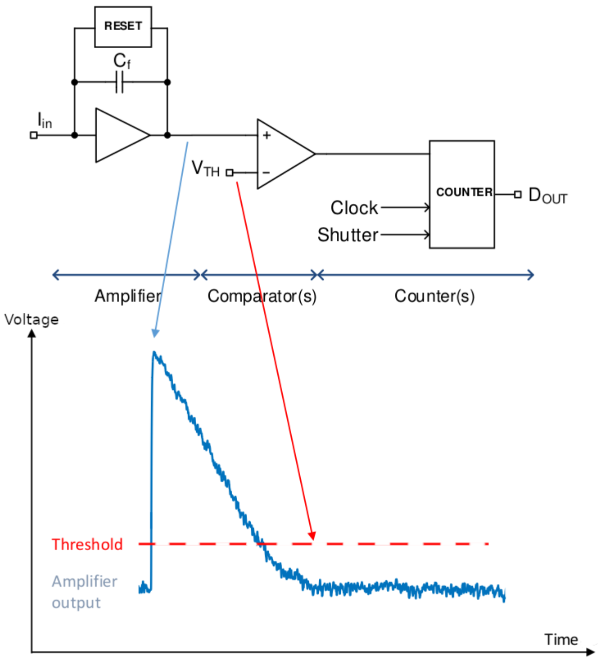

Figure 4. (top) Timepix cell schematics. The pixel is divided into three blocks: the amplifier, the comparator and the counter [12]. The plot of the voltage versus time is shown (bottom). The amplified signal (continuous line) and the threshold (dashed line) are shown. The Time over Threshold (ToT) of the amplified signal is measured by the counter and provides information on the energy of the particle.

According to the particle's properties (its electrical charge, mass, energy…), the students can recognise different elementary particles from the shape of their pixel clusters (figure 3, right). For example, X- and soft γ-rays interacting with the sensor typically create clusters of 1 or 2 pixel widths [13]. β particles and the Compton electrons produced by the interaction of higher energy photons in the sensor can cover fairly long distances in the silicon. Due to their low mass they are deflected and scattered, so that they appear as shorter or longer "worms". Instead, α particles are identified as large “round” shapes as they generate a high density of charge near the entrance of the detector, which leads to great transient currents in pixels neighbouring the initial impact point.

3. Origins of the initiative and current projects

During the last 15 years, several projects have begun in order to bring experimental particle physics to secondary schools using different Medipix detector readouts. Their main characteristics, goals and achievements are presented in this section. Some of the initiatives currently being deployed are covered in section *5. Actions taken and future proposal* at the end of this paper.

3.1. Institute for Research in Schools

The connection between the Medipix detector and education grew out of a school visit to CERN in 2007, 15 years ago [14]. From that visit, thanks to the collaboration among different entities, the plans to use Timepix detectors in schools arose in parallel with the development of LUCID [15] (figure 5a) and the programme known as CERN@school, which was a key impetus to create the Institute for Research in Schools in the UK. During this period, many resources and different experiences have been developed.

3.2. XXXXXXXXXXXXXXXXXXXX

XXXXXXXXXX is the leading institution in the Czech Republic, aiming to promote the application of Timepix-based particle cameras in education and physics teaching.

There are many education-kits at XXXXX, high schools and institutions like science centres, museums or the planetarium. These kits, first MX-10 from Jablotron (Timepix), now SESTRA (figure 5b) based on Minipix Edu from ADVACAM [16] serve to organise training sessions for teachers, workshops, occasional demonstrations and other similar educational activities like lending to students for the carrying out of their projects. Some examples of research tasks performed by students of the high school XXXXXX, XXXXXXX, XXXXXX at the Czech national competition “Students’ Professional Activities” in the section of physics are the projects “Radiation background measured with pixel detector in the atmosphere and above the atmosphere”, “Robot with pixel detector for radiation measuring”, “Dosimetric applications of the semiconductor detector Medipix” and “Influence of Earth’s magnetic field on charged particles moving in its range” [17]. The last two projects have received awards for their excellence. Furthermore, most users of particle cameras in the Czech Republic have passed XXXXXXX training courses.

The Czech team at XXXXXXX has also produced some educational videos and a manual (figure 5c) for using the Timepix chip called Experiments Using Pixel Detector in Teaching Nuclear and Particle Physics [18]. This manual describes several physics experiments that can be conducted with the device. It will be updated soon and possibly translated to other languages. Some of these experiments are fairly simple and teach basic ideas, while others are of university level and may even lead to results that could be published in scientific literature.

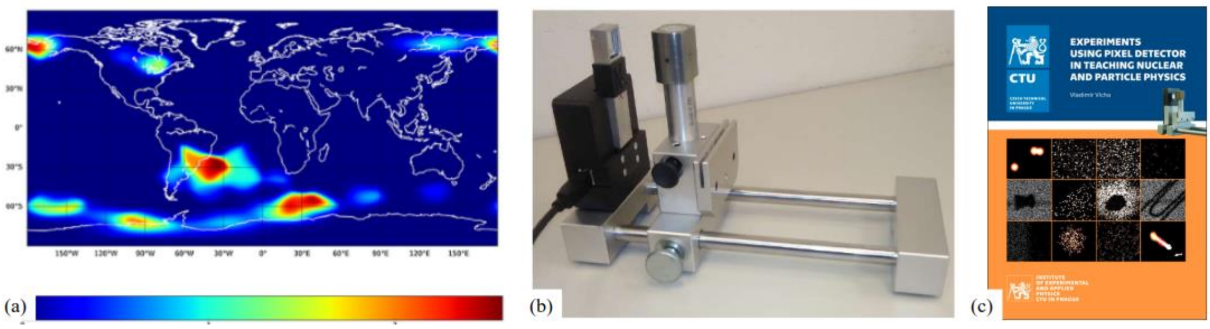

Figure 5. (a) Radiation maps from LUCID for alpha particles, (b) SESTRA School Education Set with Timepix for Radiation Analysis, (c) XXXX experiments manual, by XXXXXX

3.3. ADMIRA Project

The ADMIRA initiative originated in late 2017 from the collaboration of several individuals from different institutions [19]. ADMIRA, which in Spanish means “admire”, is an acronym that in English stands for “Activities with Medipix Detectors to Investigate Radiation in the Classroom”. This initiative aims to stimulate students to look at physics for pleasure -i.e., to admire physics and technology- by using Timepix cameras to introduce experimental particle physics into the classroom.

Thus, through the collaboration of the XXXXXXXXXX XXXXXX at XXXX, the XXXXX at the UB and the XXXXX School, the project started with just one detector used in a single school. To increase the number of schools involved, the ADMIRA team has established, since September 2019, a loan system for the detector for a period of a few weeks for the different schools participating in the initiative. It also provides training for teachers to use the detector optimally on topics related to particle detection and has developed a webpage to share materials and students’ work.

In just a few years, the initiative has involved more than fifteen schools in the project, working together and setting up a collaboration network among the teachers. The fact that it is local in nature - all the schools and institutions belong to the Catalonian region in Spain- has facilitated the deployment of the initiative.

4. Didactic evidence

Throughout the next section, some of the works and activities carried out by students of the ADMIRA initiative are shown to highlight the didactical capabilities of the Minipix camera. Although the detector is mainly used with 16 to 18-year-old students, some teachers of the network have used it successfully with younger students, from 13 and up. In that sense, one of the most exciting aspects of using Minipix detectors is the astonishment felt by the students when they approach some material emitting radiation to the sensor and visualise the distribution in the space of the different particles emitted by the source. An audible ‘Wow!’ can often be heard when the tracks appear on the screen, and this wonderment is even higher with the younger ones.

The laboratory exercise proposed for the students and teachers to familiarise themselves with the detector is presented below. By doing so, it is expected that the reader will be able to realise that such advanced concepts in particle physics and science modelling can be experimentally taught in a way pre-university students can understand.

Finally, some examples of students’ research work are presented to show the diversity of topics that can be covered and how adaptable the tool is.

4.1. The laboratory workshop: Introduction to Medipix. Study of radiation and its properties. Comparison of classical and relativistic models in alpha and beta radiation

This activity is based on some of the experiments described in the CTU manual and familiarises students and teachers with the detector’s capabilities. It has been adapted to the knowledge level of a 17-to-18-year-old student in the Catalan educational system and follows the indications of the work of Abrahams and Millar [20]. Therefore, in addition to providing a theoretical framework, in each requirement of the students’ user guide, an icon indicates if the action required belongs to the domain of observables or to the domain of ideas. This classification helps students and teachers to understand what is expected at each step and how both types of actions work together in science to create knowledge.

At the beginning of the workshop guide, a short introduction to radioactivity with some quantum and relativistic concepts is reviewed. They include the dual nature of particles and waves, the energy-mass equivalence principle and the relativistic expression of kinetic energy. The final goal is to present the relationship between the speed and the ratio of the kinetic and rest energy of the particle,

$$v = c\left(1 - \frac{1}{(1+\frac{E_K}{E_0})^2}\right)^{\frac{1}{2}} \qquad (1)$$

where v is the speed of the particle, c is the speed of light in vacuum, E_K is the kinetic energy of the particle and E_0 is the rest energy. Following this theoretical introduction, some information about the Minipix detector and the PixetPro software is provided to allow students to understand how the particles interact with the sensor material and to operate the detector to acquire data.

During the first part of the activity, students are asked to draw (or take a screenshot) and analyse the different trajectories they can observe, as shown in figures 1 and 3. By identifying the different types of radiation by the trace left in the detector, students can relate these tracks to the size, mass, and electric charge characteristics of the different particles that produced them.

In the second part, students measure the kinetic energy of the particles deposited in the detector by selecting one whole path and reading the total energy on PixetPro's Image Info panel, as is shown in figure 5. By carrying out calculations with equation 1, as shown in figure 6, they can obtain the velocity of five alpha and beta particles using the classical and relativistic models. Additionally, they can use this result to calculate the de Broglie wavelength.

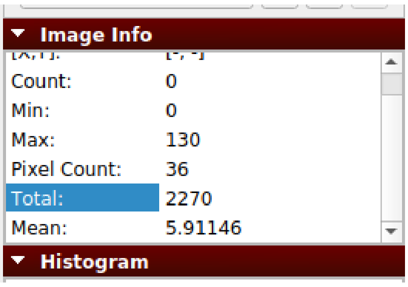

Figure 5. Image Info panel of PixetPRO software, showing the measured data of a single beta track. The Total value is the measured energy (in keV) of the particle.

	Beta 1	Beta 2	Beta 3	Beta 4	Beta 5
E_K[keV]	1953	1878	2504	1282	736
E_K[J]	$3.13\cdot10^{-13}$	$3.01\cdot10^{-13}$	$4.01\cdot10^{-13}$	$2.05\cdot10^{-13}$	$1.18\cdot10^{-13}$
v [ms^{-1}] (r)	$2.93\cdot10^{8}$	$2.93\cdot10^{8}$	$2.95\cdot10^{8}$	$2.87\cdot10^{8}$	$2.73\cdot10^{8}$
v [ms^{-1}] (c)	$8.29\cdot10^{8}$	$8.13\cdot10^{8}$	$9.38\cdot10^{8}$	$6.72\cdot10^{8}$	$5.09\cdot10^{8}$
$v\cdot c^{-1}$ (r)	0.978	0.977	0.986	0.959	0.912
$v\cdot c^{-1}$ (c)	2.76	2.71	1.00	2.24	1.70

Figure 6. Student's beta calculated data from the measured energy E_k for five beta particles, using classical (c) and relativistic (r) models. The same calculations are performed for alpha radiation. As one can see, the classical result is faster than the speed of light.

To help them to understand the meaning of their results, a simple graphical representation of the values obtained is required. Below are some of the results obtained by different high school pupils (17–18-year-olds) in their laboratory experiments which show the velocity computed using the classical (diagonal pattern) and the relativistic (vertical pattern) model for five different alpha (figure 7) and beta (figure 8) particles.

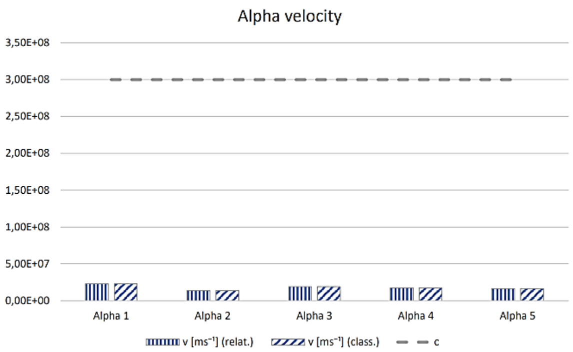

Figure 7. Comparison between alpha particles' velocity computed with the classical (diagonal) and relativistic (vertical) models. The speed of light (dashed line) is also shown as a reference.

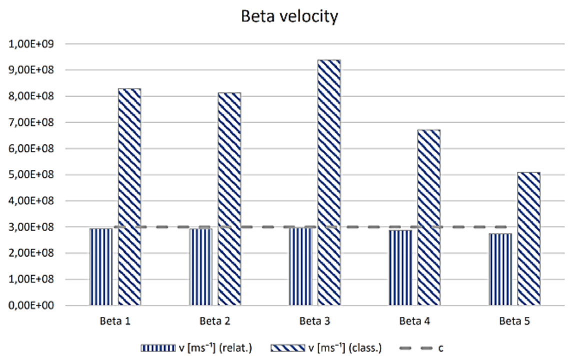

Figure 8. Comparison between beta particles' velocity computed with the classical (diagonal) and relativistic (vertical) models. The speed of light (dashed line) is also shown as a reference.

Those results clearly show the students the difference in the speed between alpha and beta particles. Furthermore, they also emphasise the equivalence of the classical and relativistic model at low speed and the need for the relativistic model to describe beta particles; otherwise, the computed velocity would be faster than the speed of light.

As one can see, these didactic objectives and the results obtained by students using the Minipix represent a substantial qualitative leap compared to those observed in experiments using Geiger meters [21]. This is mainly due to the features of the Minipix detector and its ability to visualise and distinguish different families of particles based on their interaction with the sensor material and measure the energy deposited by particles, which allows the quantitative study of concepts and models that could otherwise only be explained theoretically.

4.2. The Research Task (RT)

The RT is an 18-month project carried out by Catalan baccalaureate students overseen by a tutor in which some kind of experimental investigation is required [22]. The Minipix detector represents a precious tool in those RTs related to modern physics, which would otherwise have severe difficulties fulfilling the practical requirement.

We can identify five main topics baccalaureate students investigated in their RT with the detector. The following is a brief description of the topics studied. Some of this work have been shared through the project's web page [23].

The first field is that of the study of background radiation and dosimetry. Many RTs are related to the study of different radiation sources (minerals, everyday objects and substances), their differences in intensity, type of radiation, collimation of the beam, attenuation by diverse materials, and comparing the mass percentage of a radioactive element in two pure substances. Dosimetry is also a field that benefits from the characteristics of the detector device because, by identifying different types of particles, it allows to apply weights to estimate the damage in biological tissue like plants, algae or bacteria.

The second field is the study and detection of muons from cosmic rays, their angle dependence (figure 10) or the interactions with the atmosphere or the detector itself. In some projects, students have also used and compared data provided by external scientific institutions. So, the TimPix Project measurements at ISS (IRIS 2020) or the SATRAM experiment at ESA's Proba-V satellite [24] (both of which use Timepix detectors) have proved to be successful examples of synergy between the three didactical projects presented in this work. In certain cases, students have learnt concepts to explain their observations far beyond those usually reached at the secondary level, like the Bethe-Bloch equation.

There are also applications related to health care that might require some specialised facilities (like x-ray tubes). XXXXX granted access to these devices through the Modern Physics Lab at UB, but the pandemic restrictions stopped these kinds of collaboration. In addition, one student researched the ability of face masks to filter and retain dust particles containing radon in a short experiment.

The fourth topic is related to particle detectors. In some different RTs, students have built cloud chambers and compared their measurements with Timepix measurements. In addition, one student made a radiation detector device [25] and compared the measurements with Timepix data. The student presented his work in an online presentation with people participating from different schools and research centres in Europe.

The last topic some students in the network have studied is computing, Artificial Intelligence and Information Technology. Two students have trained a neural network to identify the radiation type from the trace it deposits in the segmented detector. Another student has designed, built and programmed an ARDUINO device (figure 9), allowing her to automate the orientation of the sensor and relate the number of muons detected with the tilt angle. Another student has trained an artificial intelligence to identify particle type according to the trace it left on the sensor (figure 10). Some of the students have also acquired skills in data processing with Mathlab to process the vast amount of data generated from their experiments.

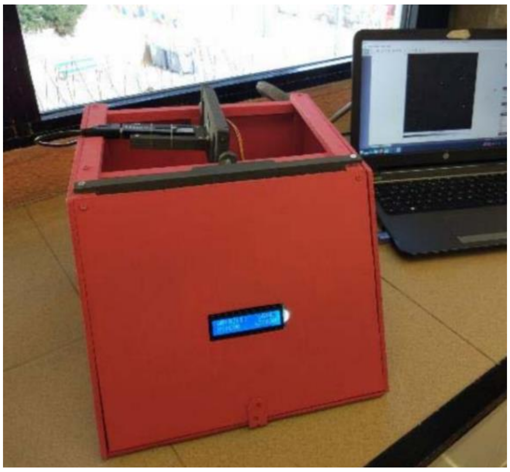

Figure 9. A device designed, built and programmed by one student of the ADMIRA Project, allowing her to tilt the Minipix automatically in order to analyse the dependence between the number of muons detected and the inclination angle of the detector.

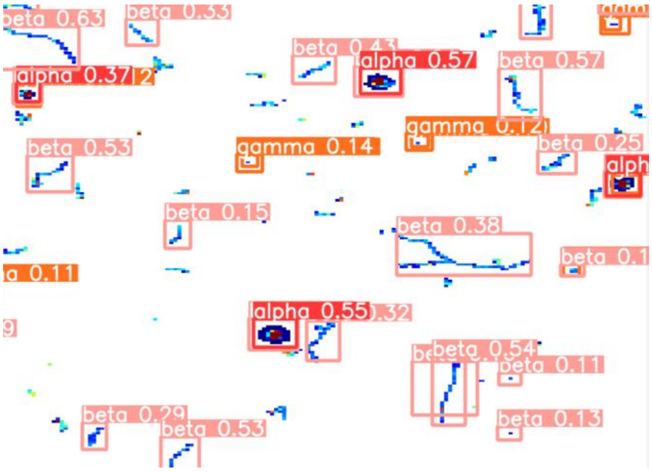

Figure 10. Different types of particles being identified, thanks to the track deposited on the detector, by a convolutional neural network AI trained by an ADMIRA student during his Research Task. These activities highlight the wide range of topics that can be covered with the detector beyond radioactivity and particle physics.

Although some of these tasks do not have the quality level of professional research, some have attained a certain degree of excellence. For instance, two students participating in the programme received awards in 2021 from the University of Girona and the Catalan Chemical Society, recognising their research work [26].

5. Actions taken and future proposal

For all the above reasons, the authors believe now would be a good time to discuss a proposal for the Europe-wide use of the mature Minipix-Edu. The GIREP participation and this report aim to stimulate discussion and input from different sides.

Initially, several kits could be loaned by the XXXX XXXX at XXXXX to interested entities at no charge to the users. After consultation with the European Physical Society EPS, Medipix collaboration members and National Physics Societies and Institutes, the authors intend to initiate the setting up of locally organised volunteer groups in alliance with contributing members in the Medipix Collaborations. The EPS, the National Physics Societies and the Medipix members could define the conditions for obtaining a Minipix instrument by a school or organisation. Still, a requirement would be that at least one of the physics teachers in the school has obtained a "Minipix-Project" licence/certificate after a training course and some examination. This approach has already been successfully used in the Czech Republic, in the UK with CERN@school and in Spain with the ADMIRA project.

Since the end of the GIREP conference in Ljubljana until now, several actions have been taken. Thus, at the international level, 40 students at the International Centre for Interdisciplinary Science and Education (ICISE) School for Medical Physics 2022 used SESTRA kits to carry out several practical exercises in early September, under the support of ICISE/Rencontres du Physics and Vietnam Atomic Energy Institute (VINATOM) in Quy Nhon, Vietnam. Experiments with these kits have become a regular part of the IEEE RT/NPSS schools, including this year's edition of the "IEEE NPSS Workshop on Applications of Radiation Instrumentation", held in Dakar, Senegal in late November.

Besides, in September 2022, the first meeting of the Minipix Users Network was held online with a lecture about Examples of the uses of Minipix in the Classroom and a round table to share ideas, resources and strategies. During the second meeting of the network, held at CERN before the Medipix

Collaboration Meeting in November, the new Proxecto MEDRA initiative was presented. This network node is being deployed by the Galician Institute of High Energy Physics (Instituto Galego de Física de Altas Enerxías, IGFAE) in the north-west region of Spain for this course 2022-2023, using 2 detectors and involving 10 schools. In addition, a new research project was presented to get experimental evidence of the benefits of the use of Minipix detectors as an educational tool. This investigation is expected to be completed in early 2023 and the results should become available during that year. Moreover, some contacts were established to help set up a new node of the network around the Ferrara Division of the National Institute of Nuclear Physics (Istituto Nazionale di Fisica Nucleare, INFN) in Italy. In the Netherlands, the radiation education group at the Freudenthal Institute of the University of Utrecht has also expressed interest in using the Minipix-Edu in their school visits. Finally, some activities were carried out by the Knowledge Transfer Department at CERN to study some of the strengths and weaknesses of the initiative and evaluate the suitability of an Impact Fund application.

On the other hand, the EU and the USA have announced plans to relocate silicon manufacturing to their local regions. Several investment budgets have been planned since the strategic importance of the microelectronics industry forces governments to take decisions to stimulate this field [27]. However, where would all the qualified technical people come from? Many technicians and scientists would have to be educated and finding enough trained people in Europe is somewhat challenging right now. Europe has to educate several tens of thousands of scientists and engineers to staff the planned manufacturing facilities as soon as possible.

In that sense, the Minipix can be presented as an example of an innovative development that has become possible thanks to chip/ASIC progress and the human capability of European engineering in this area. The use of Minipix in education could also increase knowledge and enthusiasm in schools about ICs, semiconductor silicon and clever tools that can be made with CMOS. Thus, more children will choose a technical/science education than they currently do today [28].

6. Conclusion

In order to deal with the geopolitical and environmental challenges of the second half of the 21st century, Europe will need an inspired army of scientists and engineers. Also, greater engagement with the business community across Europe must form an essential element within the overall strategy. Minipix detectors have proven to be a powerful tool to invoke interest in the STEM subjects among students. Clearly, wider access to these devices at secondary-level schools would indeed inspire the up-and-coming generations to sign up to science, technology and engineering.

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