Resolving Nuclear Reaction Products at Solenoid Focal Spot

Carlos Granja, *Member, IEEE*, Jan Jakubek, *Member, IEEE*, Pedro N. de Faria, Rubens Lichtenthäler, Alinka Lépine-Szily, Stanislav Pospisil, *Member, IEEE*

Abstract– **For studies of astrophysical interest and nuclear reactions with radioactive nuclei, charged particle products emitted from nuclear reactions such as ^{7}Li + ^{9}Be are routinely produced, separated and focused onto a focal spot by ion focusing separators such as a superconducting solenoid. The separation and focusing of desired ion groups onto the focal plane is however not complete, being also accompanied by unwanted ion groups. The mass- and energy-resolving but also the spatial focusing power of these separators are also limited and often spread out. In order to evaluate and determine and minimize these effects we decided to analyze the spectral and spatial distributions of ion reaction products at a superconducting solenoid. For this purpose we use the position-sensitive quantum-counting pixel detector Timepix which provides energy or time sensitivity per pixel. This device resolves different ion groups and measures the spectral and spatial spread distributions. Single ions are detected and individual ion groups can be identified and distinguished by multi-parameter event-by-event and pattern recognition analysis of the characteristic ion signal response in the pixelated detector. We present the capabilities of the technique on the indicated reaction above which is studied at the radioactive ion beam facility RIBRAS in Brazil. Several ion groups arriving at the focal plane are established such as ^{7,8}Li, ^{4,6}He and ^{3}H together with their spatial and spectral distributions. The energy– and spatial–spread of the solenoid resolving power at the focal plane can be thus evaluated with a resolution of tens of keV and few µm, respectively. The detector serves moreover as an online verification and calibration imager for the ion optics separator and beam focusing monitoring. Results are presented for measurements with a 24 MeV ^{7}Li beam and a thin ^{9}Be target with the solenoid tuned for selection and focusing of produced radioactive ^{8}Li.**

I. Motivation

Experimental studies of nuclear reaction products (e.g. yields and angular cross sections) and secondary product induced reaction (e.g. reactions with radioactive beams for astrophysical studies) demand high fluxes but also enhanced resolving and high focusing power ion optics systems such as superconducting solenoids. The mass- and energy-resolving but also the spatial focusing power of these instruments is limited by several effects and often spreads out resulting even in overlaps. It is thus desirable to have a tool to verify and independently measure these effects which can also serve to test and calibrate the ion optics (selection, separation and focusing) of these ion separators.

Superconducting solenoids are wide range and compact sized instruments used for separating and focusing emitted ions in nuclear reactions at low energies. Such ion separators are used at dedicated facilities for production of radioactive ion beams [1],[2],[3]. Knowledge of the ion yield and beam composition as well as spectral- and spatial-spread distributions at the focal spot is valuable for verification of extracted beam purity and calibration of the instrument resolving and focusing power.

In this work we report the direct measurement of the distribution of ions emitted and focused onto the solenoid focal spot in the reaction ^{9}Be(^{7}Li, ^{8}Li)^{8}Be. We make use of the high granularity of the quantum counting semiconductor hybrid pixel detector Timepix [4] which is equipped with per pixel energy capability. The device provides noiseless detection of single particles such as heavy charged particles including heavy ions in wide dynamic range of energy [5].

II. Pixel Detector Timepix

For the detection of ions we use a Timepix detector [4] with 256×256 square pixels (total 65.536 pixels) with pixel size 55 µm equipped with a 300 µm thick silicon sensor. Using a high frequency clock Timepix provides a Wilkinson-type signal processing ADC per pixel which provides energy or time sensitivity per pixel. Each pixel can be independently configured [1] to operate in one of three supported modes: counting, energy, or time modes.

III. Experimental

Measurements were performed at the radioactive ion beam facility RIBRAS [2] which is equipped with a superconducting 6.5 T solenoid installed at the 8 MeV Pelletron accelerator in São Paulo. The solenoid features a wide-acceptance angle (2º–6º) and wide-range focusing power.

We operated the Timepix detector at low bias (e.g., 15 V) and long pixel signal shaping time in order to maximize the energy dynamic range [5]. The per–pixel threshold level was about 4 keV and the internal reference clock frequency 10 MHz. Power, control and data acquisition to the detector chipboard were provided by integrated USB-based readout interface [6]. Operation and online visualization were managed by the modular software package Pixelman [7]. The detector was calibrated [8] with characteristic X–rays from radioactive sources (^{241}Am, ^{55}Fe) and verified with α particles

Manuscript received November 22, 2011. This work was supported by the Research Program 6840770029 of the Ministry of Education, Youth and Sports of the Czech Republic. Work carried out in frame of the Medipix Collaboration.

C. G., J. J., and S. P. are with the Institute of Experimental and Applied Physics (IEAP) of the Czech Technical University (CTU) in Prague, Czech Republic (telephone: +420-224259394, e-mail: carlos.granja@utef.cvut.cz).

P. F., R. L., and A. L. S. are with the Instituto de Física da Universidade de São Paulo, Brazil.

978-1-4673-0120-6/11/$26.00 ©2011 IEEE

(from ^{241}Am, ^{244}Cm and ^{252}Cf). All pixels were operated in energy (so-called Time-over-threshold – TOT) mode [4],[8] with the exception of few noisy and/or radiation damaged pixels which were individually switched off.

Measurements were performed in vacuum with the detector placed at the solenoid focal spot position as illustrated in Fig. 1. Emitted ions are taken into the solenoid path and are separated and focused according to field lines given by an applied high current field. Collimators and a Faraday cup catcher remove undesired ion products. In this work a 24 MeV ^{7}Li beam was sent onto a 12 µm thick ^{9}Be target. The solenoid was set to select and focus product ^{8}Li.

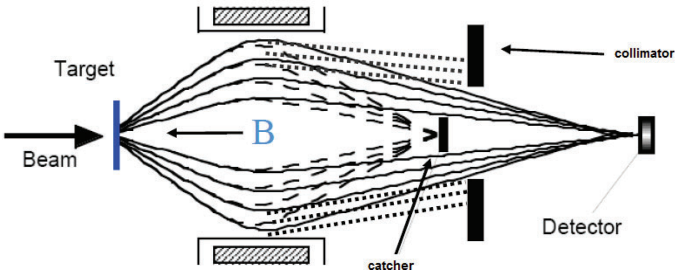

Fig. 1. Layout of the experimental setup: the Pelletron ^{7}Li beam was sent onto a thin ^{9}Be target foil. Reaction products are taken into the large-angle aperture RIBRAS solenoid which was tuned to select and focus ^{8}Li onto the focal spot at which place the pixel detector was mounted.

IV. Detection of Ions at Focal Spot

The detection and visualization of ions arriving to the focal spot by Timepix is shown in Fig. 2. Short exposition times were set (e.g., 1 ms) to avoid pile-ups and record individual events.

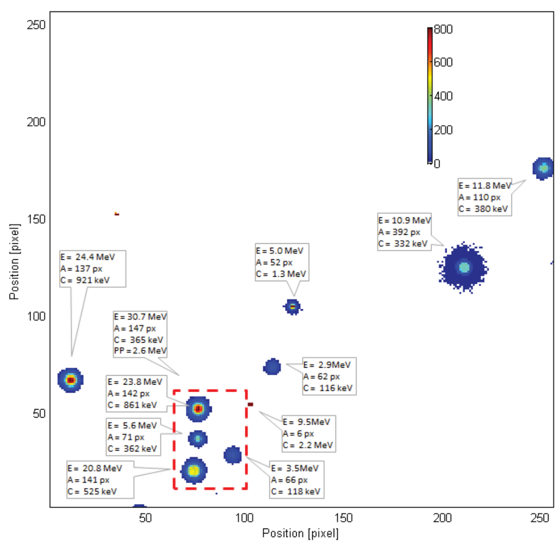

Fig. 2. Detection and spatial visualization of ion products at the focal plane by Timepix. A 1 ms exposure frame is shown of the full sensor area (256 × 256 square pixels). The detector was operated in energy (TOT) mode and bias 15 V. The energy measured by each pixel is shown by the color bar in keV. The highlighted region is shown expanded in Fig. 3. Each cluster of pixels corresponds to a single event. Values for the given cluster area (A), height (C) and energy (E) are indicated (see text).

Heavy charged particles produce a large signal in the pixelated sensor which spreads onto several adjacent pixels forming a *cluster* of pixels (see Fig. 3). The event energy is given by the sum of the energies of all pixels in the cluster. The area is the number of pixels in the cluster. The height is the energy registered by the central pixel. The values for these quantities are included in Fig. 2.

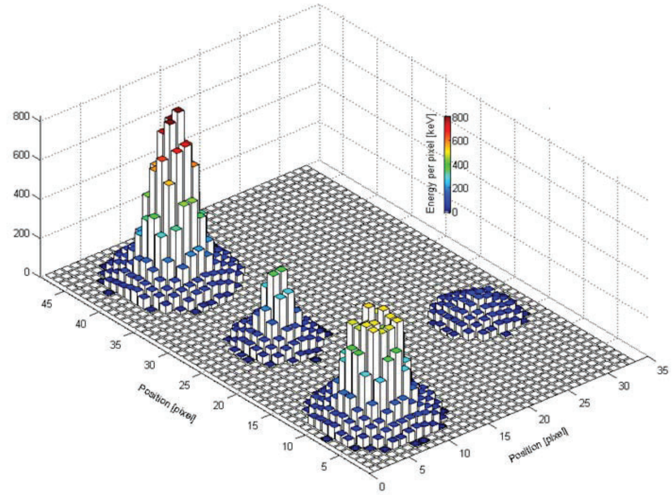

Fig. 3. Detailed sensor region of 48 × 34 pixels (highlighted region from Fig. 2) showing the detection of four ions. The energy per pixel registered, shown by the color bar, can be also displayed in the vertical axis.

A. *Timepix Ion Resolving Power*

The signals produced by ions in the Timepix detector are determined namely by their deposited energy – i.e., the ion kinetic energy [5]. The resulting pixel clusters thus exhibit for ions a characteristic round shape, the area of which is proportional namely to the deposited energy but also to the applied bias. Similarly, also the charge collected by the central pixel (called cluster height), depends on these conditions too.

However, the detailed profile or shape of ion clusters, expressed by these spectroscopic quantities in terms of energy (E), area (A) and cluster height (H), could be sensitive also on other effects such as different linear energy transfer, local charge density, eventual plasma effect and localized/temporal Coulomb repulsion in the generated charge cloud. Particularly sensitive can be the correlations between these quantities as well as their ratios – e.g., A/E and H/E.

B. *Energy, Area and Height Spectra*

Spectra for the spectrometric quantities of cluster area (A), height (H) and energy (E) are shown in Fig. 4 for few thousand frames collected. Data correspond to solenoid and detector settings of Fig. 2.

C. *Multi-parameter Correlated Spectra*

These spectroscopic quantities can be correlated and analyzed with each other as shown in Fig. 5. These two-dimensional distributions of cluster area and energy or cluster height and energy separate and reveal groups of events.

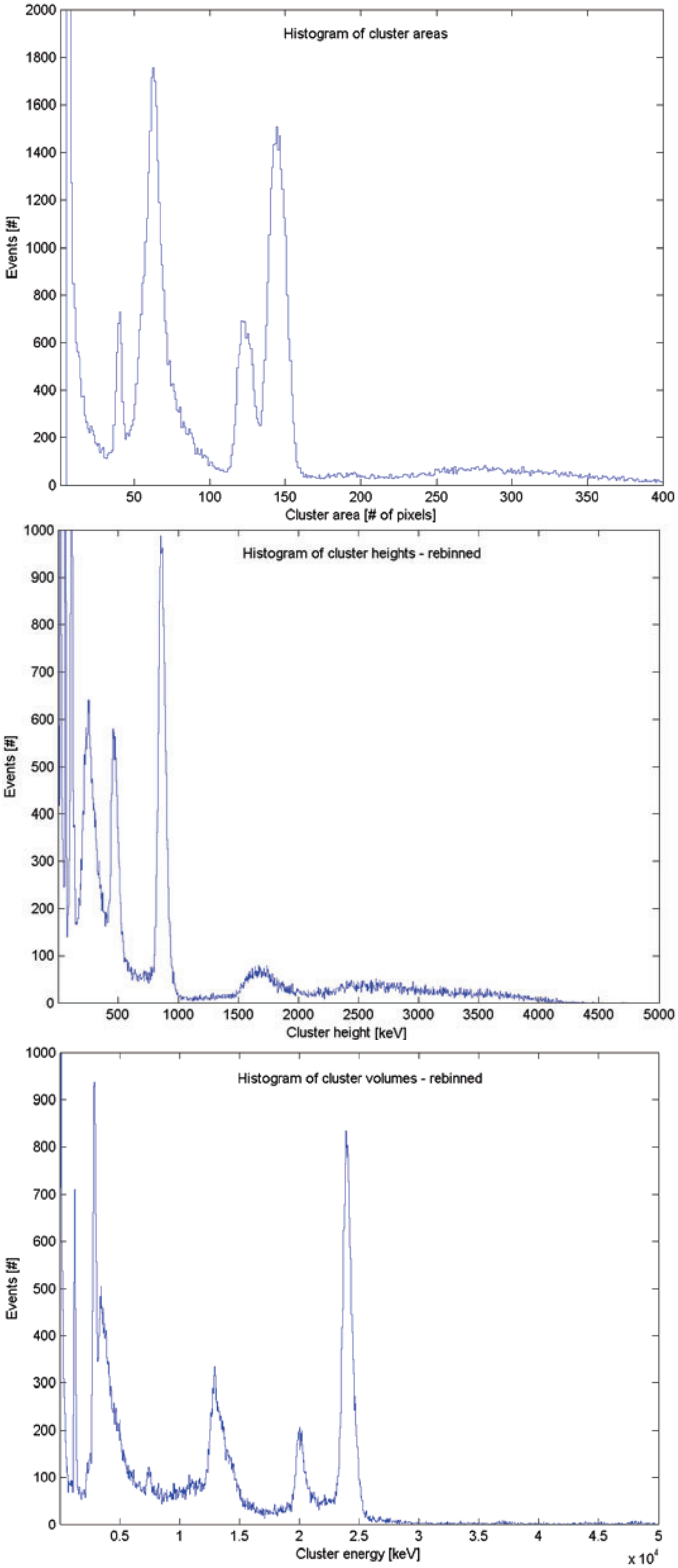

Fig. 4. Spectra of ion cluster area (top), height (middle) and energy (bottom) obtained by Timepix at the solenoid focal spot. The detector was operated in TOT mode and bias 15 V. The area, height, and energy channel bins are 1 pixel, 4 keV and 40 keV, respectively.

The data shown were produced with low cutoff imposed on corresponding cluster shape limits such as the removal of events with areas smaller than e.g., 4 pixels (which correspond to unwanted electrons and energetic X-rays).

Single events are analyzed by pattern recognition algorithms [9] and can be then identified, selected or rejected based on these multi-parameter correlations. Applying a first level filtering criteria, where unwanted events such as X rays or pile-ups are removed, the figures display a total of 96.754 events.

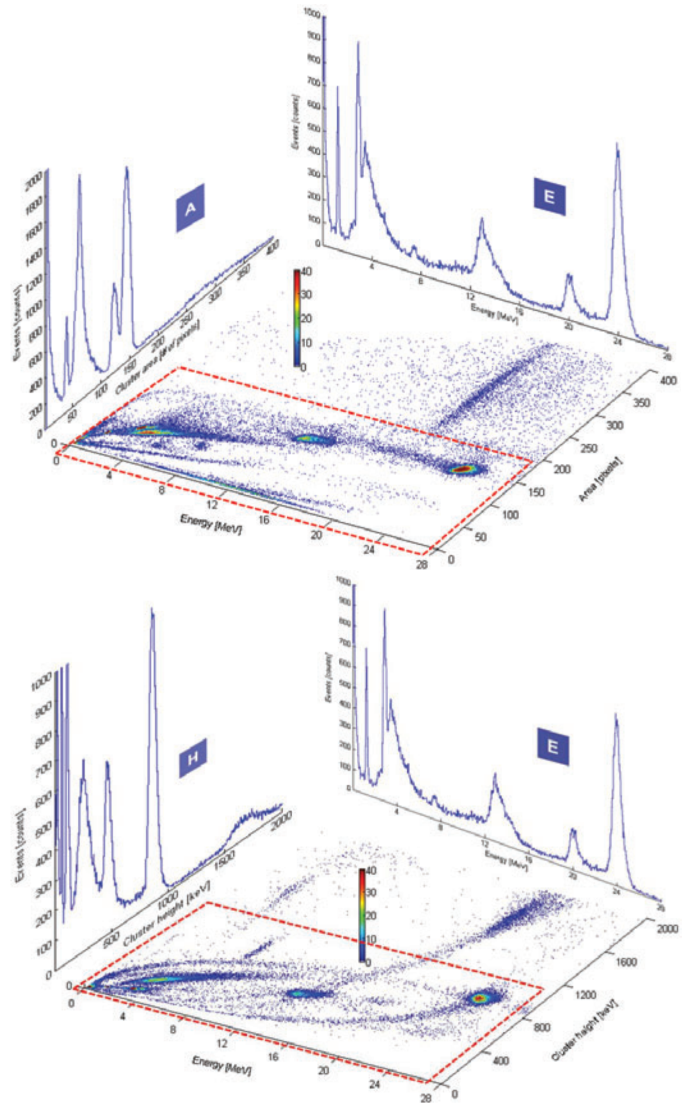

Fig. 5. Distribution of cluster area and energy (top) and cluster height and energy (bottom) obtained by Timepix for 96.754 ions. The number of events per pixel is displayed in color by the vertical bar. The highlighted regions are shown in Fig. 6.

D. *Ion Groups*

The two-parameter distributions reveal a number of ion groups which are not always immediately distinguished in the single-parameter spectra. Expanded regions of Fig. 5 are displayed in Fig. 6 where few selected ion groups are labeled. The positions of several ion groups resolved in the corresponding single-parameter spectra are indicated in Fig. 7. The proportionality of ion energy on these quantities is not conserved – e.g. see the ion groups 1 and 2 for which the monotonic dependence is reversed.

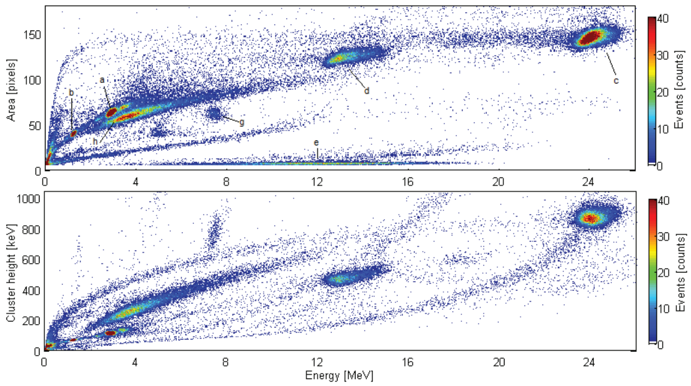

Fig. 6. Expanded regions of Fig. 5. Few ion groups are indicated on the plot on top for illustration.

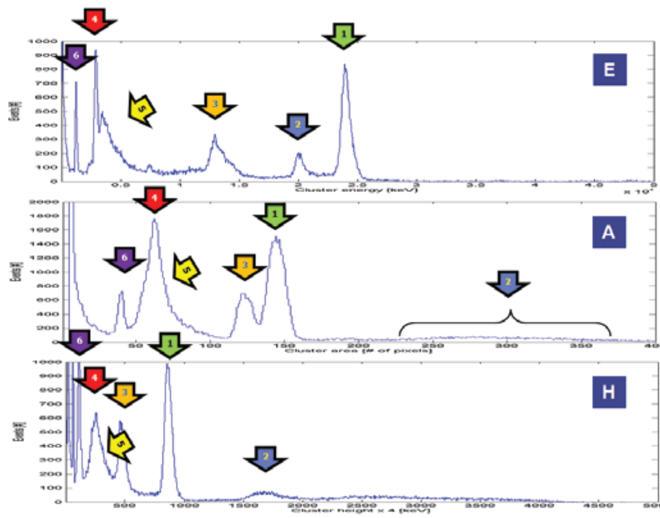

Fig. 7. Few identified ion groups and their corresponding positions in single-parameter spectra (Fig. 4) of energy (top), area (middle) and height (bottom). Groups are labeled by arrows with same number and color.

Single energy spectra corresponding to these ion groups are given in Fig. 8. Gaussian fits are included.

E. Focal Spot Spatial Distributions

The granularity of the pixel detector allows imaging the spatial distribution of ions at the focal spot. The spatial distribution of all ions arriving at the solenoid focal spot is shown in Fig. 9. The position of the shadow by a needle holder is marked (pink lines). Previous radiation damaged regions in the pixelated sensor are indicated too (orange arrows).

The spatial distributions can be produced for individual selected ion groups. The distributions corresponding to the ion groups selected in Fig. 8 are given in Fig. 10.

V. Conclusions

Ion groups at the solenoid focal spot are resolved and can be separated by multi-parameter analysis of the characteristic track patterns in Timepix. The respective spectral and spatial distributions for individual ion groups are measured and visualized, respectively. Ion groups are distinguished by event-by-event and pattern recognition analysis of the characteristic cluster profiles in the pixelated detector in terms of the spectrometric quantities of area, height and energy of cluster traces. The ion resolving power is enhanced by correlations between these quantities. The analysis and effect of their ratios is subject of future work. Assignments to expected reaction product ions such as ^{7,8}Li, ^{8}Li^{2+}, ^{4,6}He and ^{1,2,3}H are underway and demand detailed analysis and comparison with reaction product kinematics and the solenoid resolving power.

Acknowledgments

This research was carried out in frame of the Medipix Collaboration and has been supported by the Research Program MSM 6840770029 of the Ministry of Education, Youth and Sports of the Czech Republic. We are grateful to the staff of the Pelletron accelerator for providing the beam. One of us (R.L.) acknowledges the financial support by FAPESP and CNPq.

References

[1] M.Y. Lee et al., "Study of nuclear reactions with intense, high-purity, low-energy radioactive ion beams using a versatile multi-configuration dual superconducting-solenoid system", *Nucl. Instrum. Meth. A*, vol. 422, pp. 536–540, 1999.

[2] R. Lichtenthäler, et al., "RIBRAS – Radioactive ion beams in Brazil", *Eur. Phys. J. A*, vol. 25, pp. 733–736, 2005.

[3] R. Rafiei, et al., "SOLEROO: A solenoidal exotic rare isotope separator at the Australian National University", *Nucl. Instrum. Meth. A*, vol. 631, pp. 12–21, 2011.

[4] X. Llopart, R. Ballabriga, M. Campbell, et al., "Timepix, a 65 k programmable pixel readout chip for arrival time, energy and/or photon counting measurements", *Nucl. Instrum. Meth. A*, vol. 581, 485–494, *2007*.

[5] C. Granja, J. Jakubek, M. Platkevic, U. Koster, S. Pospisil, "Response of pixel detector Timepix to heavy ions", *Nucl. Instrum. Meth. A* vol. 633, pp. S198 – S202, 2011.

[6] Z. Vykydal, J. Jakubek, S. Pospisil, "USB interface for Medipix2 enabling energy and position detection of heavy–charged particles", *Nucl. Instrum. Meth. A*, vol. 563, pp. 112–115*, 2006*.

[7] T. Holy, J. Jakubek, S. Pospisil, J. Uher, D. Vavrik, Z. Vykydal, "Data acquisition and processing software package for Medipix2", *Nucl. Instrum. Meth. A*, vol. 563, pp. 254–258*, 2006*.

[8] J. Jakubek, "Precise Energy Calibration of Pixel Detector Working in Time-Over-Threshold Mode", *Nucl. Instrum. Meth. A*, vol. 633, pp. S262-S266, 2011.

[9] T. Holy, E. Heijne, J. Jakubek, et al., "Pattern recognition of tracks induced by individual quanta of ionizing radiation in Medipix2 silicon detector", *Nucl. Instrum. Meth. A*, vol. 591, pp. 287–290, 2008.

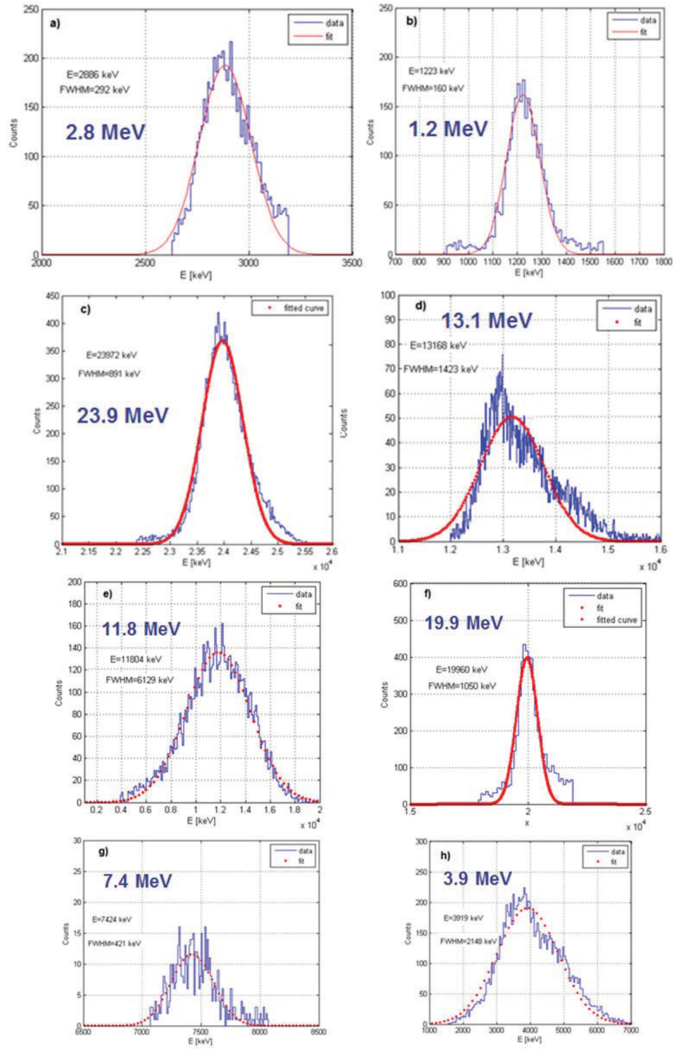

Fig. 8. Energy spectra of several ion groups. Values of energy, FWHM are indicated.

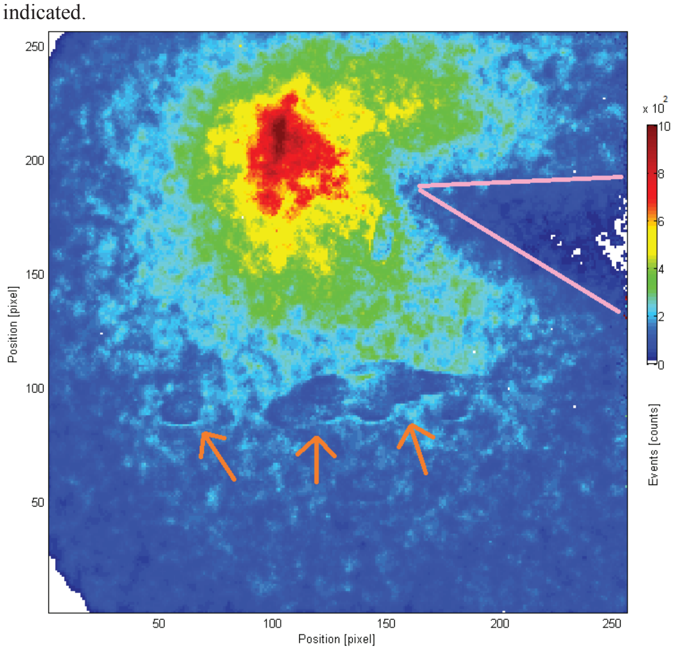

Fig. 9. Spatial distribution of all ions arriving to the focal spot. The spatial density (number of events per pixel) is shown in color by the vertical bar. The full Timepix sensor area is displayed (256×256 pixels = 14 × 14 mm^2). See text.

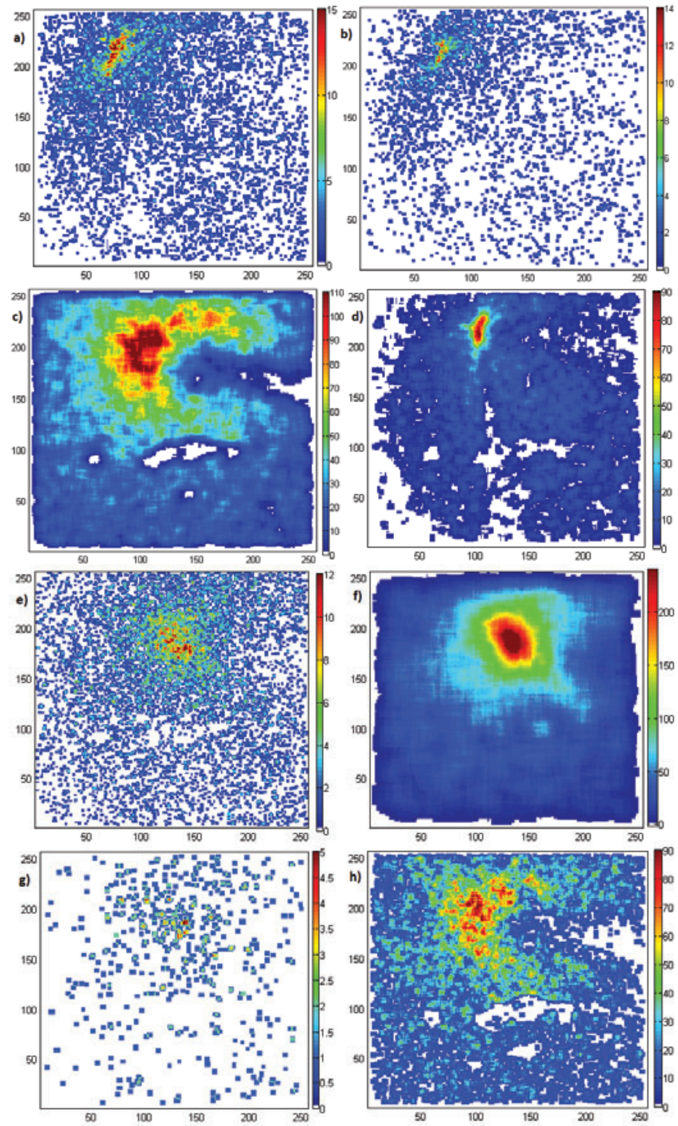

Fig. 10. Spatial distribution of all ions at RIBRAS focal spot. The spatial density (number of events per pixel) is shown in color by the vertical bar. The full Timepix sensor area is displayed (256×256 pixels = 14 × 14 mm^2).