High resolution position measurements using a micro-channels plate with a delay line readout

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Introduction

We discussed, in a previous use-case datasheet, the use of resistive anode readout for localization purposes. This kind of device is simple to develop and easy to use but suffers some basic defects that can complicate their use:

- The dynamics needed on localization channels is the product of the input particles dynamics and of the localization dynamics. In order to fulfill localization uncertainty, you must guaranty low noise operations (low noise preamplifiers and perfect EMC).
- The detector "dead time" (due to the resistors and parasitic capacitances) is about some tens of nanoseconds (say 60ns for instance) and if two particles hit the detector in this time interval, it's impossible, neither to localize the particles, nor to say that there was two particles.

In order to cope with these problems, delay lines anodes readout has been developed. The main ideas are:

- If you can measure a pulse arrival time with, say 200ps uncertainty, travelling thru a delay line of, say 100ns for instance (corresponding to the length of your detector), you naturally have a localization uncertainty of 1/500 of your detector length (whatever the incident particle dynamics).
- The detector dead time is now purely defined by the rise-time and fall-time of the different signals (say a few ns) and it's generally possible to know that the several particles hit the detector at the same time, and sometimes, to reconstruct, in this particular case, the most probable impinging positions.

In fact, the main drawback of delay-lines readout is that it relies on time measurement, which is generally difficult to perform correctly (at least time calibration on each individual channel). Numerical data acquisition systems, like FASTER, are based on quartz clocking synchronization and this way, largely simplify timing calibration procedures.

What will you find in this educational document?

- An example of delay line readout anode coupled to a micro-channels plate detector
- How to perform detector calibration and data analysis
- How to make high performances localizations using this detector with FASTER

1. The device and its electronic

The MCP that illustrates this use-case is a two stages 80mm diameter Hamamatsu stack whose localization delay-line (DL) readout comes from RoentDek (see www.roentdek.com for more details on signal extraction). The complete device is represented on Fig. 1. All data were recorded using a 1keV Na+ ion beam.

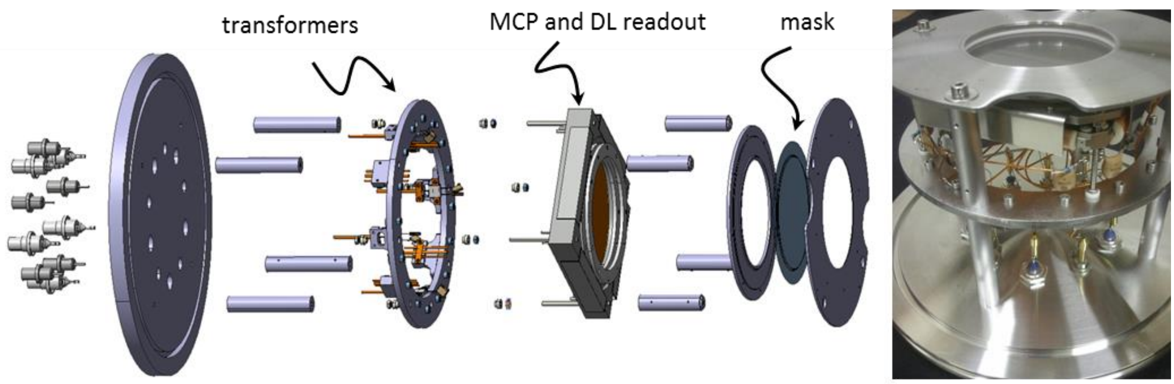

Fig. 1: sketch of the MCP and its RoentDek delay-line readout (left) and mounting (right)

The delay-line pulse time propagation (*Tp*) on both axes is 80ns for a localization length *L* of 80mm. Four signals are produced for localization purpose (*top*, *bottom*, *left* and *right*) whose arrival time should be measured referred to a start time coming from the rear side of the MCP, *Tmcp*. Typical MCP signals have a rise time of about 2ns and a fall time of about 3ns.

The principle of the delay line readout is quite simple (see Fig. 3 for axis references), at least at first order.

Suppose a particle hits the detector at x=20mm. The *Tmcp* signal starts the FASTER event building. At about the same time, a pulse is produced on the delay line (about a half of the *Tmpc* signal charge). About a half of the signal flies left and the other half flies right. The left part takes 20ns to go out the delay-line as the right part takes 60ns, as drawn on Fig. 2.

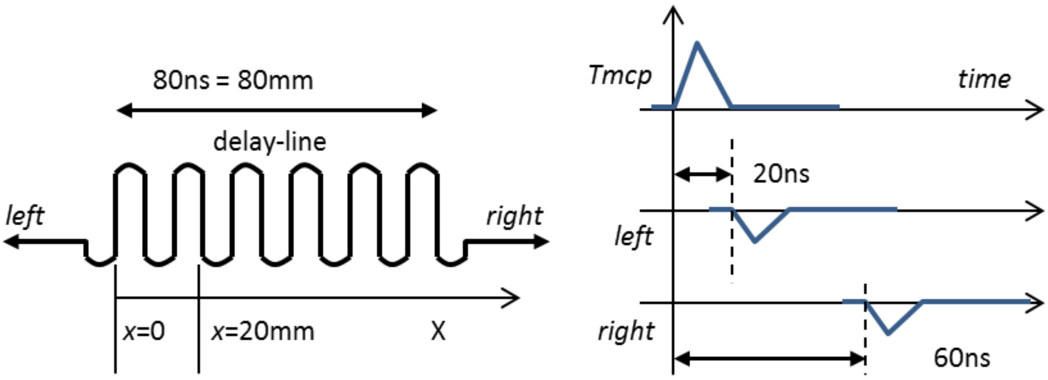

Fig. 2: MCP & delay-line signals vs particle position

So, if *Tmpc* is the arrival time of the incident particle at *x* position (combining all delays, as cables or time propagation in preamplifiers, …), *Left* and *right* pulse times write:

$$left = Tp \cdot \frac{x}{L} + Tmcp$$

$$right = Tp \cdot \frac{L - x}{L} + Tmcp$$

Without any calibration, one can note that the *left–right* variable is directly related to *x* and extends form –*Tp* to +*Tp* (here -80ns to +80ns).

The incident particle position estimator is obvious:

$$\tilde{x} = \frac{L}{Tp} \cdot (Tp + left - right)$$

And one also sees that:

$$left + right - 2 \cdot Tmcp = Tp$$

As the delay-line time propagation is a constant, this relation is a very convenient way to check data consistency as we will see later (in order to detect pile-up events for instance).

2. Data acquisition:

All five signals feed 50Ω matched wideband voltage preamplifiers of gain 50 before entering FASTER inputs. As MCP signals is fast, you must use CARAS daughter boards (500MHz, 12bits) to process them, as show on Fig. 3.

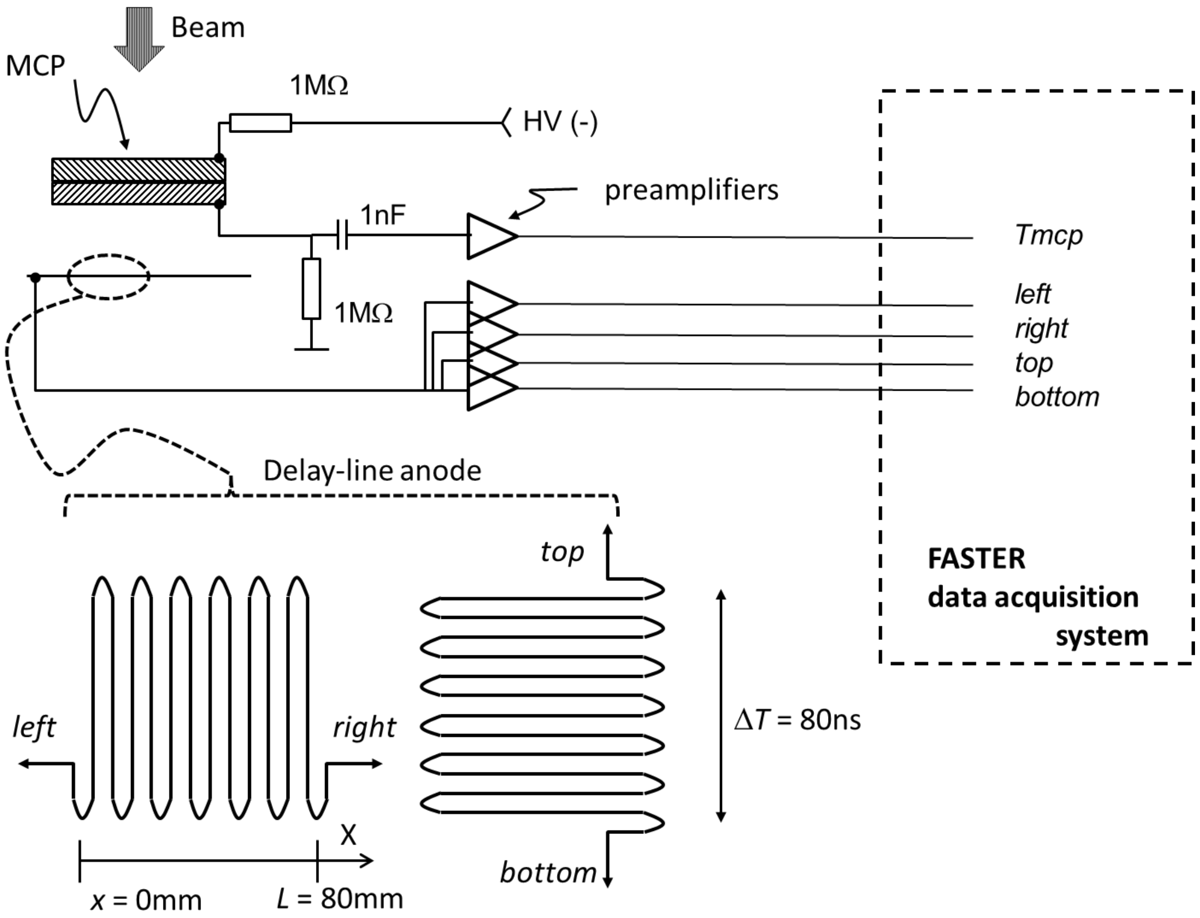

Fig. 3: Connecting of the MCP + delay-line readout to a FASTER data processing and acquisition system

For every signal, you must use the FASTER internal Constant Fraction Discriminator (CFD) for timing measurements. You can also take benefit of charge measurements on each channel in order to help reconstruction of piled-up signals for instance (using up to 4 integration windows per channel). Doing so, Faster will timestamp every signal with a 2ns resolution (for event grouping purpose) but will also give you a CFD timing quantification of ≈7,8ps (1ns/128 exactly). Beware this figure is the FASTER timing measurements quantification bit. It doesn't represent the uncertainty of the results which is generally far worse (depending on the physics, detector and electronics).

3. Localization example

3.1. Raw image plotting

An immediate way to check if the detector is properly running is to plot *bottom-top* vs *left-right* on a bidim plot. The plotting scale should extend form –*Tp* to +*Tp* on both axes and, provided the cable length and the same, the MCP image should be centered as represented on Fig. 4.

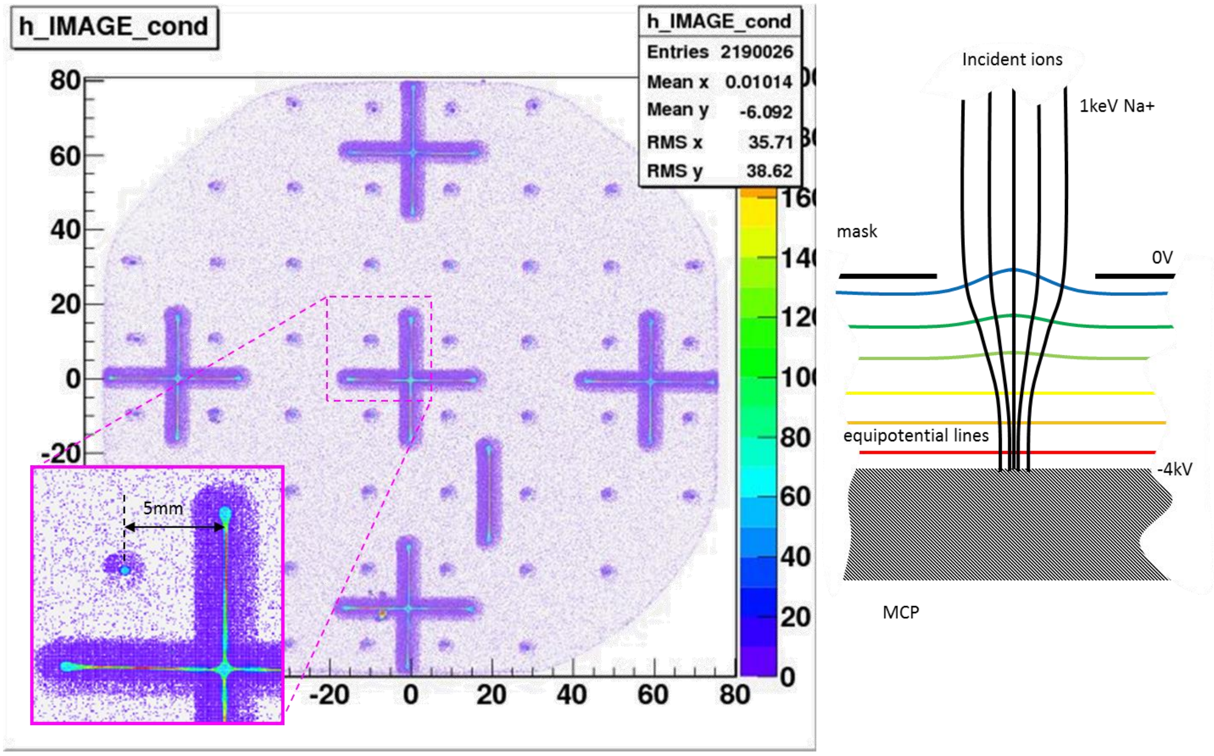

Fig. 4: raw image of *bottom-top* vs *left-right* (pulse times measured by the mean of FASTER CFD)

The MCP was mounted after a mask and the mask to MCP potential was tuned in order to focus incident low energy ions on MCP surface. One immediately sees the sharpness of the focusing, and potentially, the high spatial resolution of the device.

The violet shadow surrounding each spot or cross comes from neutralized ions. They are not affected by the focusing effect of the mask and travel straight to the MCP.

3.2. Check of data consistency

As previously mentioned, data consistency can be checked several way.

First, whatever the position, the *left*+*right*-2x*Tmcp* or *top*+*bottom*-2x*Tmcp* times should be constant and about the delay-line propagation time.

The Fig. 5 shows such tests. On left part is presented *top*+*bottom*-2x*Tmcp* vs *bottom*-*top*$\propto y$ for Y axis and *left*+*right*-2x*Tmcp* vs *left*-right$\propto x$ for X axis for the whole surface.

One clearly sees that the sum time is not constant over the detector surface. This kind of behavior is typical of MCP delay-line readouts. It is perfectly reproducible over time but depends on delay-line mounting.

The two histograms at the center of Fig. 5 represent the sum time of all X hits for a small selection on Y axis (top) and all Y hits for the selection on X axis (bottom). The selection areas are on the right.

The shape of these histograms should be gaussian, which is not the case, suggesting a potential effect between X and Y axis measurements.

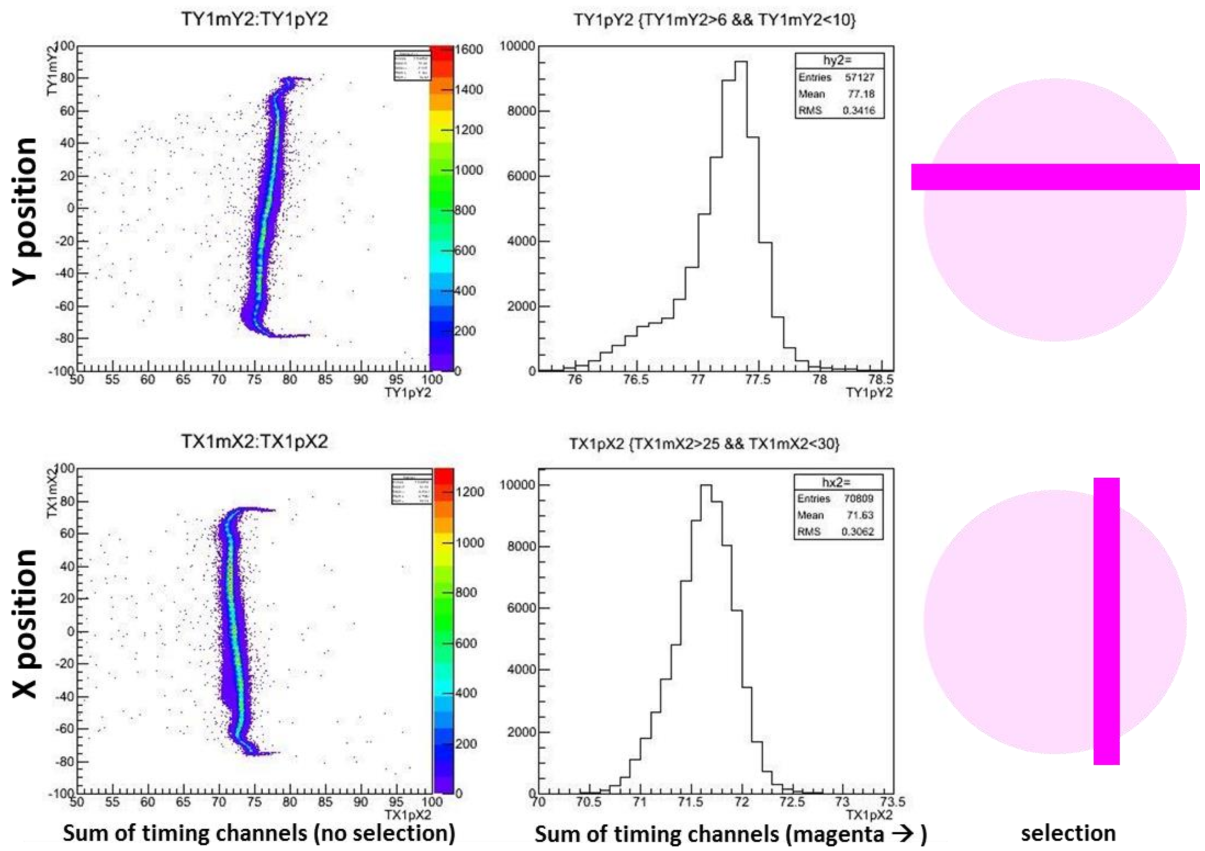

Fig. 5: consistency check for unpiled-up events

All events lying out of the vertical bands on X or Y position are piled-up and should carefully processed.

Sum of timing channels is not the only way to check data consistency. As previously mentioned, the user can measure the charge on each channel. If an event is correct, the sum of adjacent channels (*Qleft+Qright* and *Qtop+Qbottom*) should be proportional to the MCP charge *Qmcp*. The bidim plots of the three possible configurations are presented on Fig. 6.

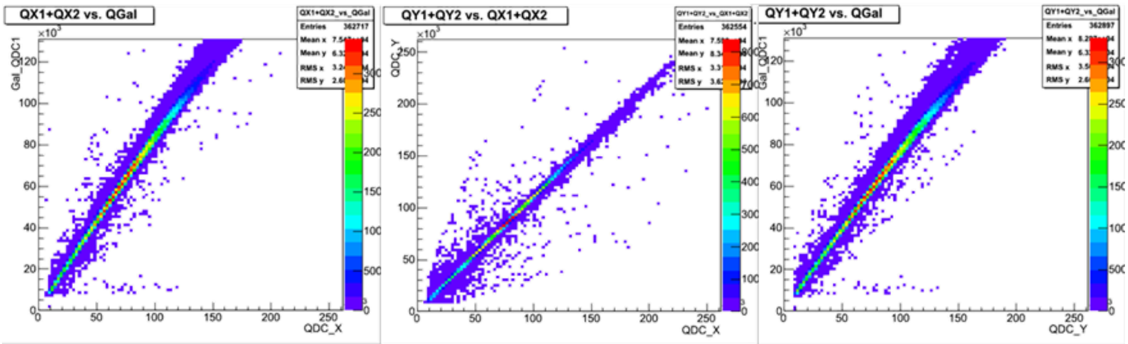

Fig. 6: event consistency check by the mean of charge correlation

This is another sight on data which has nothing to do with timing and which ensure a bit more the event integrity.

3.3. Position measurements uncertainty

There are several ways to estimate delay-line readout position measurement uncertainty.

The best way would be to directly measure point spread function of the imaging system, but in order to do this, one need to use a narrow ion beam (or focus the beam as explained on Fig. 4).

Another simple way consists on measuring timing resolution of the different channels and computing the estimated resolution on position reconstruction. That’s the strategy applied on Fig. 7.

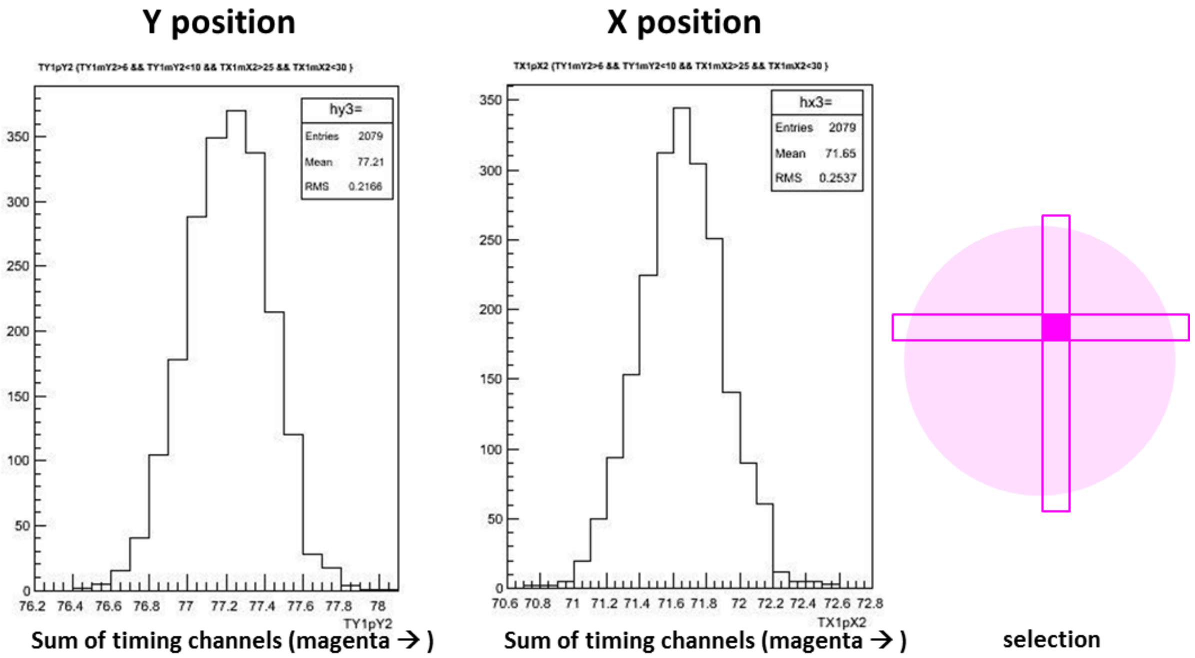

Fig. 7: indirect measurement of localization uncertainty

In order to separate position errors and position measurement uncertainties, one needs to make a small position selection on the image (in magenta on Fig. 6) and plot sum timings on both axes. The histograms show respectively standards deviation of 0.22 and 0.25ns$_{RMS}$ on Y and X axes. As the left graph is the histogram of *left*+*right*-2x*Tmcp*, if one assumes the timing uncertainty σ_t is the same for all channels, the histogram standard deviation writes:

$$\sigma_{sum} = \sigma_{left} \oplus \sigma_{right} \oplus 2 \cdot \sigma_{Tmcp} = \sqrt{6} \cdot \sigma_t$$

The relation suggests a timing uncertainty of about 90 to 110ps$_{RMS}$ per timing channel.

As the localization involves the computation of the difference of two channels, the timing uncertainty is $\sqrt{2} \cdot \sigma_t$ and of the order of 150ps$_{RMS}$ (whatever the deposited charge). The difference in time histogram is 160ns wide (2x*Tp*) representing 80mm. So, one concludes the spatial resolution is about 80µm$_{RMS}$.

This timing resolution is good but one shouldn't overestimate the result. In fact the five signals are correlated, if not in shape, at least in amplitude, making timing measurements easier.

3.4. Piled-up events processing

As previously mentioned the detector dead time of a delay-line readout MCP is far below other kinds of detectors (say 10ns per channel) allowing good reconstruction performances, even for particles hitting the detector in short time windows.

Obviously, grouped events of this kind can't be displayed online (as RHB doesn't incorporate unpiling algorithms) but, data are stored and can be analyzed offline.

The charge measurement performed on each channel when triggered may probably help such reconstruction algorithm.

4. Conclusions

FASTER makes timing measurements easy, largely simplifying the use of delay-lines readouts. The example shown above took benefit of this particularity, having position uncertainties of the order of 100µm$_{RMS}$.

As a consequence, in spite of their relatively high price or building complexity, delay-line anodes show better performances than resistive anodes.

In fact both kinds of readouts have advantages and drawback but both can be implemented in FASTER architecture, allowing the detector designer to concentrate on its instrumentation goals rather than copping with data acquisition system.