Inaccuracy of coordinate determined by several detectors' signals

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Abstract.

In order to locate particle position, it is necessary to have several signals of spaced detectors, since the amplitudes of these signals depend on the particle interaction point. For all position sensitive detectors the crucial characteristic for using as tracking or imaging detector is the accuracy of coordinate determination. The position resolution is closely connected not only with the energy resolutions of detectors but also with the correlations between the signals' fluctuations. In this paper, general relation between position and energy resolutions that accounts for the correlation between the signals' fluctuations of detectors was derived. This general relation was used for the special cases of two and three detectors' outputs. Using these formulae and experimental calibration data allows, without any technical improvements of detectors, significantly improve position resolution by rather simple procedure of experimental data handling.

1. Introduction

The fundamental problem for all position sensitive detectors is to not only determine the incident particle coordinate, but also determine its inaccuracy. As the position and energy resolution are closely connected, then for any position sensitive detector the most important question is how the inaccuracy of the reconstructed position connects with the signal fluctuations at the detectors' outputs.

The task of determining and improving spatial resolution of a position sensitive detector is of great importance, because the particle coordinate inaccuracy determines the uncertainties of all reconstructing quantities in particle physics. As the inverse variance of each reconstructed quantity is determined by the combination of inverse variances of the measured observables, then, any reduction in uncertainties of particles coordinates results in increasing of accuracy of reconstructing quantities.

2. Relationship between position and energy resolution

Let us consider any position sensitive detector with I outputs. Signals from outputs $\{Q_i\}$, $(i=\overline{1,I})$ must depend on the position vector of a particle interaction point $\vec{r}$. The sum signal

$$Q=\sum_{i=1}^{I} Q_i \qquad (1)$$

gives the information on the particle energy E.

For determination of the particle interaction point, it is necessary to choose a theoretical model that gives the relationship between the position vector of a particle interaction point $\vec{r}$ and the signals at the outputs $\{Q_i\}$, $(i=\overline{1,I})$. Let such a relationship between the position vector $\vec{r}$ and signals at the outputs $\{Q_i\}$ has the form

$$\vec{r}=\vec{f}(\{Q_i\})=\sum_{\alpha=1}^{3} f_\alpha(\{Q_i\})\cdot\vec{e}_\alpha\,, \quad (2)$$

where functions $f_\alpha(\{Q_i\})$ $(\alpha=\overline{1,3})$ relate the coordinates of position vector and signals at the outputs $\{Q_i\}$

$$x_\alpha=f_\alpha(\{Q_i\})\,. \quad (3)$$

The deviation of the reconstructed coordinate x_α from its mean value

$$\langle x_\alpha\rangle=f_\alpha(\{\langle Q_i\rangle\})\,. \qquad (4)$$

can be reasonably approximated by the linear terms of the Taylor expansion

$$x_\alpha-\langle x_\alpha\rangle=\sum_{i=1}^{I}\partial_i f_\alpha\cdot\left(Q_i-\langle Q_i\rangle\right), \qquad (5)$$

where the partial derivatives

$$\partial_i f_\alpha = \frac{\partial}{\partial Q_i} f_\alpha(\{Q_i\})\Big|_{\{\langle Q_i \rangle\}}, \qquad (6)$$

are evaluated at the point $\{\langle Q_i \rangle\}$.

After squaring and taking the expectation value of both sides, we find that the variance of the particle coordinate deviation has the form:

$$\sigma_\alpha^2 = \sum_{i=1}^{I}\sum_{j=1}^{I} \partial_i f_\alpha \cdot \partial_j f_\alpha \cdot \rho_{i,j}\sigma_i\sigma_j\,, \qquad (7)$$

In the formula (7) by definition

$$\sigma_\alpha^2 = \left\langle (\Delta x_\alpha)^2 \right\rangle = \left\langle \left(x_\alpha - \langle x_\alpha \rangle\right)^2 \right\rangle, \, (8)$$

$$\rho_{i,j}\sigma_i\sigma_j = \left\langle \Delta Q_i \cdot \Delta Q_j \right\rangle = \left\langle \left(Q_i - \langle Q_i \rangle\right)\cdot\left(Q_j - \langle Q_j \rangle\right) \right\rangle, \qquad (9)$$

where $\rho_{i,j}$ is the correlation coefficient between ith and jth signals' fluctuations. For coinciding indices the correlation matrix element $\rho_{i,i} = 1$, and

$$\rho_{i,i}\sigma_i\sigma_i = \left\langle \Delta Q_i \cdot \Delta Q_i \right\rangle = \left\langle (\Delta Q_i)^2 \right\rangle = \left\langle \left(Q_i - \langle Q_i \rangle\right)^2 \right\rangle = \sigma_i^2\,, \qquad (10)$$

represents the variance of the signal at the ith output.

From the equation (1) it follows that

$$\sigma_Q^2 = \sum_{i=1}^{I}\sum_{j=1}^{I} \rho_{i,j}\sigma_i\sigma_j\,, \qquad (11)$$

where σ_Q is the mean square deviation of the sum signal. In a similar manner, from the equation for the sum of ith and jth detectors' signals

$$Q_{i,j} = Q_i + Q_j\,, \quad (12)$$

it follows that

$$\sigma_{i,j}^2 = \sigma_i^2 + \sigma_j^2 + 2\rho_{i,j}\sigma_i\sigma_j = \sigma_{j,i}^2\,, \qquad (13)$$

where $\sigma_{i,j}^2$ is the variance of the sum of ith and jth detectors' signals. Thus, the correlation coefficient between ith and jth signals has the form

$$\rho_{i,j} = \frac{1}{2}\frac{\sigma_{i,j}^2 - \sigma_i^2 - \sigma_j^2}{\sigma_i\sigma_j}\,. \; (14)$$

As the correlation coefficients between the signals' fluctuations have always negative sign, then from (7) it follows that the correlation between the signals' fluctuations must reduce the mean square deviation of the incident particle coordinate.

With accounting for the correlation between the fluctuations of the signals, the mean square deviation of the incident particle coordinate reduces to

$$\sigma_\alpha^2 = \sum_{i=1}^{I} \partial_i f_\alpha \cdot \sigma_i^2 \sum_{j=1}^{I} \left(2\delta_{i,j} - 1\right)\partial_j f_\alpha + \frac{1}{2}\sum_{i=1}^{I}\sum_{j=1}^{I}\left(1 - \delta_{i,j}\right)\partial_i f_\alpha \cdot \partial_j f_\alpha \sigma_{i,j}^2\,, \; (15)$$

General formula (15) is applicable to any relationship between the incident particle coordinates and signals at the position sensitive detector outputs $\{Q_i\}$, and provided a theoretical basis for position resolution estimation from experimental data.

3. Position resolution of a strip detector with two outputs

Let us consider any strip detector with two outputs. Let x-axis goes from the left to the right detector with the origin in the middle of the strip. Let $Q_1 = Q_L$ and $Q_2 = Q_R$ are the signals of the left and the right detectors. From (15) the variance of the incident particle coordinate reduces to

$$\begin{aligned}&\sigma_x^2 = \sum_{i=1}^{2} \partial_i f_x \cdot \sigma_i^2 \sum_{j=1}^{2} \left(2\delta_{i,j} - 1\right)\partial_j f_x + \frac{1}{2}\sum_{i=1}^{2}\sum_{j=1}^{2}\left(1-\delta_{i,j}\right)\partial_i f_x \cdot \partial_j f_x \sigma_{i,j}^2 = \\ &\partial_1 f_x \sigma_1^2 (\partial_1 f_x - \partial_2 f_x) + \partial_2 f_x \sigma_2^2 (\partial_2 f_x - \partial_2 f_x) + \partial_1 f_x \cdot \partial_2 f_x \sigma_{1,2}^2 = \\ &\partial_L f_x \cdot \partial_R f_x \cdot \sigma_Q^2 + \left(\partial_L f_x - \partial_R f_x\right)(\partial_L f_x \cdot \sigma_L^2 - \partial_R f_x \cdot \sigma_R^2)\end{aligned} \quad ,(16)$$

where $Q = Q_L + Q_R$ is the sum signal, and σ_Q^2 is its variance.

This formula is symmetric with respect to the left and the right detectors.

3.1 Position resolution of a strip detector for "centroid" formula

Now, "centroid" formula

$$x = f_x^c (Q_L, Q_R) = L \frac{1}{2} \frac{Q_R - Q_L}{Q_R + Q_L} \,. (17)$$

is in common use for estimation of an incident particle coordinate in strip detectors.

For relationship (17) we have

$$\partial_L f_x^c = -L \frac{\langle Q_R \rangle}{\left(\langle Q_R \rangle + \langle Q_L \rangle\right)^2} = -L \frac{\langle Q_R \rangle}{\langle Q \rangle^2}, \quad (18)$$

$$\partial_R f_x^c = L \frac{\langle Q_L \rangle}{\left(\langle Q_R \rangle + \langle Q_L \rangle\right)^2} = L \frac{\langle Q_L \rangle}{\langle Q \rangle^2}. \quad (19)$$

Then, the variance of an incident particle coordinate (16) reduces to

$$\sigma_x = \frac{L^2}{\langle Q \rangle^2} \left(\frac{\langle Q_R \rangle}{\langle Q \rangle} \sigma_L^2 + \frac{\langle Q_L \rangle}{\langle Q \rangle} \sigma_R^2 - \frac{\langle Q_L \rangle}{\langle Q \rangle} \frac{\langle Q_R \rangle}{\langle Q \rangle} \sigma_Q^2 \right). \quad (20)$$

Let $p_L = Q_L / Q$ and $p_R = Q_R / Q$ be relative shares of the sum signal, $p_L + p_R = 1$. Then, the mean square deviation of the incident particle coordinate has the form

$$\sigma_x = \frac{L}{\langle Q \rangle} \left(\langle p_R \rangle \sigma_L^2 + \langle p_L \rangle \sigma_R^2 - \langle p_L \rangle \langle p_R \rangle \sigma_Q^2 \right)^{1/2} \quad (21)$$

3.2 Position resolution of a strip detector with finite transparency of the strip and sensors' interfaces

In strip detectors with one type of information particles, that determine the signals at the sensors' outputs, i.e. photons as information particles in scintillation strip detector, and Cooper pairs as information particles in superconducting strip detectors, more realistic with respect to the "centroid" formula is the relationship derived in [1]

$$x = \frac{L}{2\alpha}\ln\frac{Q_L\exp(-\alpha/2)+Q_R\exp(\alpha/2)}{Q_L\exp(\alpha/2)+Q_R\exp(-\alpha/2)}, \qquad (22)$$

where the dimensionless parameter $\alpha = L/\Lambda$ is the ratio of the strip length to the absorption length of information particles. The formula (22) accounts for the information particles losses during propagation through the absorber to the ends of the strip.

In [2, 3], it was shown that for the relationship (22) the mean square deviation of the incident particle coordinate has the form:

$$\sigma_x = L\frac{\sinh\alpha}{\alpha}\frac{1}{<Q>}\frac{\left(\langle p\rangle\sigma_L^2+\langle q\rangle\sigma_R^2-\langle p\rangle\langle q\rangle\sigma_Q^2\right)^{1/2}}{\left(\langle p\rangle^2+\langle q\rangle^2+2\langle p\rangle\langle q\rangle\cosh\alpha\right)}, \quad (23)$$

However, in deriving formula (19) in [1] it was assumed absolutely transparent interface between the strip absorber material and detectors. That is, all information particles that reach the interface are absorbed by the sensor.

The relationship that accounts for the finite transparency of the interface in a symmetric strip detector, which follows from the formulae derived in [4], has the form

$$x = \frac{L}{2\alpha}\ln\frac{Q_L(1-\beta)\exp(-\alpha/2)+Q_R(1+\beta)\exp(\alpha/2)}{Q_L(1+\beta)\exp(\alpha/2)+Q_R(1-\beta)\exp(-\alpha/2)}, \qquad (24)$$

where the parameter α accounts for the information particles losses and β accounts for the finite transparency of the interface. For the absolute transparent interface $\beta = 0$.

For the relationship (21) the mean square deviation of the incident particle coordinate has the form [5]

$$\sigma_x = \frac{L}{\alpha<Q>}\frac{\left[(1+\beta^2)\sinh\alpha+2\beta\cosh\alpha\right]\left(\langle p\rangle\sigma_L^2+\langle q\rangle\sigma_R^2-\langle p\rangle\langle q\rangle\sigma_Q^2\right)^{1/2}}{\left\{(1-\beta^2)\left(\langle p\rangle^2+\langle q\rangle^2\right)+2\langle p\rangle\langle q\rangle\left[(1+\beta^2)\cosh\alpha+2\beta\sinh\alpha\right]\right\}}. \quad (25)$$

The formula (22) gives the most general relationship between the mean square deviation of the incident particle coordinate and the variances of the strip detector's signals. For the absolute transparent interface, i.e. $\beta = 0$, the formula (25) reduces to the formula (23). For the absence of the information particles losses, i.e. $\alpha = 0$, and the absolutely transparent interface, i.e. $\beta = 0$, the formula (25) reduces to the formula (21).

We see that the expression of the form, where the relative share of the sum signal at the one end is multiplied by the variance of the signal at the other end, and the variance of the total signal is multiplied by the product of the shares, is the peculiarity of all formulae for position resolution of strip detectors.

3.3 Comparison with commonly used formula for position resolution

Now, for estimation of the position resolution of a strip detector commonly used the formula [6]

$$\sigma_x = \frac{pitch}{signal / noise} . \qquad (26)$$

To ensure that (26) overestimates the position resolution of a strip detector, let us represent the amplitude at the output of each sensor as the sum of the signal and the noise

$$Q_i = Q_{i,s} + Q_{i,n} , \quad (27)$$

where $i = L, R$.

As the signal and the noise are uncorrelated, and by definition $\langle \Delta Q_{i,n} \rangle = 0$, then

$$\langle \Delta Q_{i,s} \cdot \Delta Q_{i,n} \rangle = \langle \Delta Q_{i,s} \rangle \cdot \langle \Delta Q_{i,n} \rangle = 0 . \quad (28)$$

Consequently, the variance of the detector's amplitude and the variance of the sum signal can be represented as

$$\sigma_i^2 = \langle (\Delta Q_i)^2 \rangle = \langle (\Delta Q_{i,s})^2 \rangle + 2\langle \Delta Q_{i,s} \cdot \Delta Q_{i,n} \rangle + \langle (\Delta Q_{i,n})^2 \rangle = \sigma_{i,s}^2 + \sigma_{i,n}^2 . \ (29)$$

$$\sigma_Q^2 = \langle (\Delta Q_{Q,s} + \Delta Q_{Q,n})^2 \rangle = \langle (\Delta Q_{Q,s} + \Delta Q_{L,s} + \Delta Q_{R,n})^2 \rangle = \sigma_{Q,s}^2 + \sigma_{L,n}^2 + \sigma_{R,n}^2 . \qquad (30)$$

With accepted definitions, for the position resolution of a strip detector from the formula (26) we have

$$\frac{\sigma_x}{L} = \frac{\sigma_Q}{\langle Q \rangle} = \frac{(\sigma_{Q,s}^2 + \sigma_{L,n}^2 + \sigma_{R,n}^2)^{1/2}}{\langle Q \rangle} . \qquad (31)$$

The factor, which determines the position resolution in equations (21), (23) and (25)

$$(\langle p_R \rangle \sigma_L^2 + \langle p_L \rangle \sigma_R^2 - \langle p_L \rangle \langle p_R \rangle \sigma_Q^2)^{1/2} , \quad (32)$$

after substitution (29) and (30) has the form

$$(\langle p_R \rangle^2 \sigma_{L,n}^2 + \langle p_L \rangle^2 \sigma_{R,n}^2 + \langle p_R \rangle \sigma_{L,s}^2 + \langle p_L \rangle \sigma_{R,s}^2 - \langle p_L \rangle \langle p_R \rangle \sigma_{Q,s}^2)^{1/2} . \qquad (33)$$

It is obvious that the factor (33) is much less than the factor which determines the position resolution in equation (31). Indeed, as always $\sigma_{Ls}^2 < \sigma_{Qs}^2$ and $\sigma_{Rs}^2 < \sigma_{Qs}^2$, then we have the strong inequality

$$\langle p_R \rangle^2 \sigma_{L,n}^2 + \langle p_L \rangle^2 \sigma_{R,n}^2 + (1 - \langle p_L \rangle \langle p_R \rangle) \sigma_{Q,s}^2 < \sigma_{L,n}^2 + \sigma_{R,n}^2 + \sigma_{Q,s}^2 . \qquad (34)$$

When an incident particle hit into the midst of the strip, i.e. $\langle p_L \rangle = \langle p_R \rangle = 1/2$, then the inequality (34) has the form

$$(\sigma_{L,n}^2 + \sigma_{R,n}^2)/4 + 3\sigma_{Q,s}^2/4 < \sigma_{L,n}^2 + \sigma_{R,n}^2 + \sigma_{Q,s}^2 . \quad (35)$$

In this case, if the fluctuation of the amplitude at the output of sensor is determined for the most part by noise, then formula (26) two times overestimates the position resolution of the strip detector.

For special case, when an incident particle hit into the end of the strip, for example into the left end of Resistive Charge Division type detector $\langle p_L \rangle = 0$, $\langle p_R \rangle = 1$, $\sigma_{Ls}^2 = 0$, $\sigma_{Rs}^2 = \sigma_{Qs}^2$, and the inequality has the form

$$\sigma_{L,n}^2 < \sigma_{L,n}^2 + \sigma_{R,n}^2 + \sigma_{Q,s}^2 . (36)$$

In this case, if the fluctuation of the amplitude is mainly determined by noise, then overestimation of the position resolution by the formula (26) constitutes 41%.

3.4 Position resolution estimation from experimental data

For estimation of the reconstructed coordinate inaccuracy, from experimental calibration of a specific strip detector one has to determine $< Q_L(x) >$, $< Q_R(x) >$, $< Q(x) >$, $\sigma_L(x)$, $\sigma_R(x)$, and $\sigma_Q(x)$ as a function of x. One can also find parameters α and β by fitting the calibration data to relationship (22) or (24).

For each event of particle registration we have two values of signals Q_L and Q_R. Depending on the chosen model, we can calculate the estimator for the particle coordinate

$$x = L \cdot f_x(p_L), \quad (37)$$

where $p_L = Q_L / Q$, $Q = Q_L + Q_R$ and $f_i(p_L)$ is the appropriate function in the equations (17), (22) or (24).

After determining the coordinate x, the estimators for it's the mean square deviation we can calculate according to the formula

$$\sigma_x(p_L) = L \cdot F_\gamma(p_L) \cdot \delta(p_L), \quad (38)$$

where

$$\delta(p_L) = \frac{1}{Q}\left((1 - p_L)\sigma_L^2(x(p_L)) + p_L \sigma_R^2(x(p_L)) - p_L(1 - p_L)\sigma_Q^2(x(p_L))\right)^{1/2} . \quad (39)$$

In the formula (38)

$$F_c(p_L) \equiv 1, \quad (40)$$

for the "centroid" formula (17);

$$F_1(p_L)=\frac{\sinh\alpha}{\alpha}\frac{1}{\left(p_L^2+(1-p_L)^2+2p_L(1-p_L)\cosh\alpha\right)}, \qquad (41)$$

for the formula (22);

$$F_2(p)=\frac{\left[(1+\beta^2)\sinh\alpha+2\beta\cosh\alpha\right]}{\alpha}\cdot \left\{(1-\beta^2)\left(p_L^2+(1-p_L)^2\right)+2p_L(1-p_L)\left[(1+\beta^2)\cosh\alpha+2\beta\sinh\alpha\right]\right\}^{-1} \qquad (42)$$

for the formula (24).

After calibration of the specific strip detector, all the above formulae can be tabulated as a function of the one parameter p_L.

4. Position resolution of a position sensitive detector with three outputs

Let us consider a detector with three outputs then the variance of the incident particle coordinate (15) has the form

$$\sigma_\alpha^2=\sum_{i=1}^{3}\partial_i f_\alpha\cdot\sigma_i^2\sum_{j=1}^{3}\left(2\delta_{i,j}-1\right)\partial_j f_\alpha+\frac{1}{2}\sum_{i=1}^{3}\sum_{j=1}^{3}\left(1-\delta_{i,j}\right)\partial_i f_\alpha\cdot\partial_j f_\alpha\sigma_{i,j}^2. \quad (43)$$

4.1 Position resolution of a linear detector with three outputs for "centroid" formula

Let us consider a detector with three sensors at the x-axis with the pitch w. After relabeling sensors as follows $Q_1\to Q_{-1}$, $Q_2\to Q_0$ and $Q_3\to Q_{+1}$, we can use for estimation of incident particle coordinate the "centroid" formula

$$x=f_x^c(Q_{-1},Q_0,Q_{+1})=w\frac{Q_{+1}-Q_{-1}}{Q_{+1}+Q_0+Q_{-1}}=w\frac{Q_{+1}-Q_{-1}}{Q}. \quad (44)$$

If we introduce relative coordinate

$$\xi=\frac{x}{w}=\frac{Q_{+1}-Q_{-1}}{Q}, \qquad (45)$$

where

$$Q=Q_{+1}+Q_0+Q_{-1} \qquad (46)$$

is the sum signal, then the variance of the incident particle coordinate (43) takes the form

$$\sigma_x^2=\frac{w^2}{\langle Q\rangle^2}\left\{\begin{matrix}\left[2+\langle\xi\rangle\left(1-\langle\xi\rangle\right)\right]\sigma_{-1}^2-\langle\xi\rangle^2\sigma_0^2+\left[2-\langle\xi\rangle\left(1+\langle\xi\rangle\right)\right]\sigma_{+1}^2+\\ \langle\xi\rangle\left(1+\langle\xi\rangle\right)\sigma_{-1,0}^2-\langle\xi\rangle\left(1-\langle\xi\rangle\right)\sigma_{0,+1}^2-\left(1-\langle\xi\rangle^2\right)\sigma_{-1,+1}^2\end{matrix}\right\}, \quad (47)$$

where

$$\langle \xi \rangle = \frac{\langle Q_{+1} \rangle - \langle Q_{-1} \rangle}{\langle Q \rangle}, \qquad (48)$$

This formula is symmetric with respect to the left and the right detectors.

For estimation of the reconstructed coordinate inaccuracy we have to determine from experimental calibration of a specific detector $< Q_{-1}(x) >$, $< Q_0(x) >$, $< Q_{+1}(x) >$, $< Q(x) >$, $\sigma^2_{-1}(x)$, $\sigma^2_0(x)$, $\sigma^2_{+1}(x)$, $\sigma^2_{-1,0}(x)$, $\sigma^2_{0,+1}(x)$ and $\sigma^2_{-1,+1}(x)$ as a function of x.

For each event of particle registration, for three values of signals Q_{-1}, Q_0 and Q_{+1}, we can calculate the estimator for the particle coordinate (44) and the estimator for its mean square deviation according to the formula

$$\sigma_x = \frac{w}{Q}\left\{ \begin{matrix} [2+\xi(1-\xi)]\sigma^2_{-1} - \xi^2\sigma^2_0 + [2-\xi(1+\xi)]\sigma^2_{+1} + \\ \xi(1+\xi)\sigma^2_{-1,0} - \xi(1-\xi)\sigma^2_{0,+1} - (1-\xi^2)\sigma^2_{-1,+1} \end{matrix} \right\}^{1/2}, \qquad (49)$$

If all sensors of position sensitive detector are identical, and the fluctuation of the amplitude at the output of sensors is determined for the most part by noise $\sigma^2_{-1} = \sigma^2_0 = \sigma^2_{+1} = \sigma^2_n$, then formula (49) reduces to

$$\sigma_x = w\frac{\sigma_n}{Q}(2+3\xi^2)^{1/2}. \quad (50)$$

In this special case, if an incident particle hit into the central sensor, $\xi = 0$, then overestimation of the position resolution by formula (26) constitutes 22%.

As in multistrip detector the central sensor is the sensor with maximum signal, so $|\xi| \le 1/2$. For $|\xi| = \pm 1/2$, the maximum of mean square deviation (50) is 4.5% better, than gives the formula (26).

5. Conclusion

Proposed method for estimation of an incident particle coordinate inaccuracy allows, without any technical improvements of an existing position sensitive detector, significantly improve its position resolution by rather simple procedure of experimental data handling.

References

[1] H. Kraus, F. von Feilitzsch, J. Jochum, R.L. Mossbauer, Th. Peterreins and F. Probst, *Quasiparticle trapping in a superconductive detectorlsystem exhibiting high energy and position resolution*, Phys. Lett. B, **231 (**1989**)** 195.

[2] V. Samedov, *Position resolution in DROIDs*, J Low Temp Phys, **151 (**2008**)** 333.

[3] V. Samedov, *Position resolution of a double junction superconductive detector based on a single material*, J of Phys.: Conf. Ser., **97** (2008) n. 012282.

[4] J. Jochum, H. Kraus, M. Gutsche, B. Kemmather, F. v. Feilitzsch, and R.L. Mossbauer, *Dynamics of radiation induced quasiparticles in superconducting tunnel junction detectors*, Ann. Physik, **2** (1993) 611.

[5] V. Samedov, *Once more on the position resolution of DROIDs*, AIP Conf. Proc., **1185** (2009) 397.

[6] F. Hartmann, *Evolution of Silicon Sensor Technology in Particle Physics*, Springer, 2009.