Optimization of CVD Diamond Detector for ALPHA Experiment at CERN

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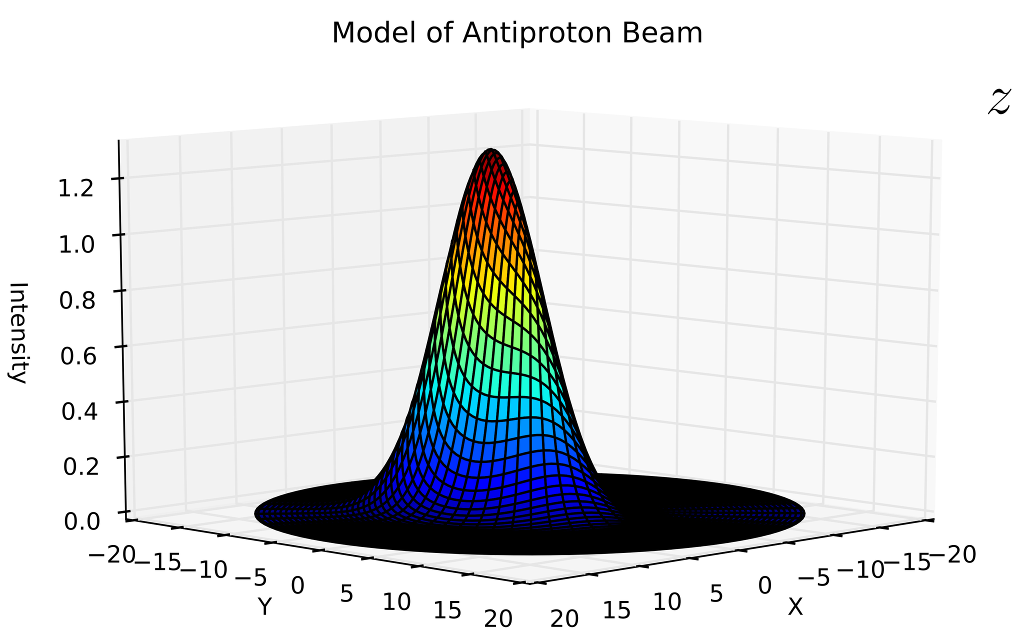
Antiproton Beam

Antiproton ($\bar{p}$) beams at CERN have a roughly Gaussian distribution with elliptical symmetry. These beams are pulsed and produced every 100 seconds. There are approximately 3×10^7 antiprotons in each pulse and its relative intensity was simulated as the z-component in cylindrical coordinates. When antiprotons hit a CVD diamond detector, an $\bar{p}$ may ionize a carbon atom, ultimately resulting in the emission of an electron. In the presence of an external electric field, freed electrons move away from the diamond lattice (Tapper 2000 *Rep. Prog. Phys.* **63**: 1286) and are detected through the metal plates on the diamond's surface. These signals proportional to $\bar{p}$ flux were simulated and further investigated to identify the antiproton beam's physical characteristics (namely centroid position, σ_x, and σ_y).



$$z = \frac{100}{2\pi\sigma_x\sigma_y} e^{-\left[\frac{(r\cos\theta - r_o\cos\theta_o)^2}{2\sigma_x{}^2} + \frac{(r\sin\theta - r_o\sin\theta_o)^2}{2\sigma_y{}^2}\right]}$$

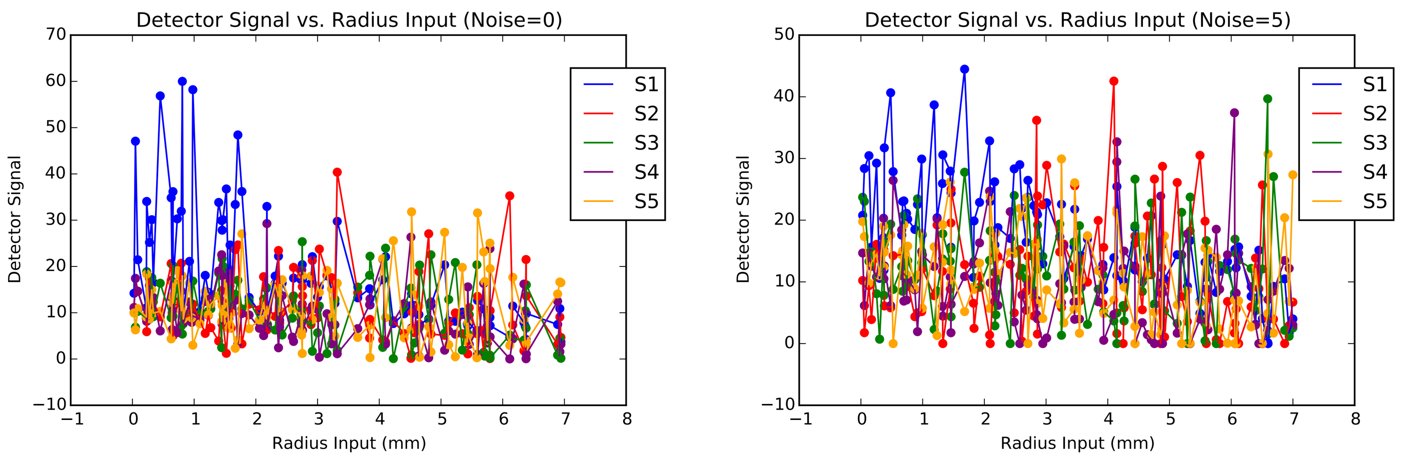
$$S3 = \int_{\frac{3\pi}{4}}^{\frac{5\pi}{4}}\int_{R1}^{R2} z \times r\,dr\,d\theta$$

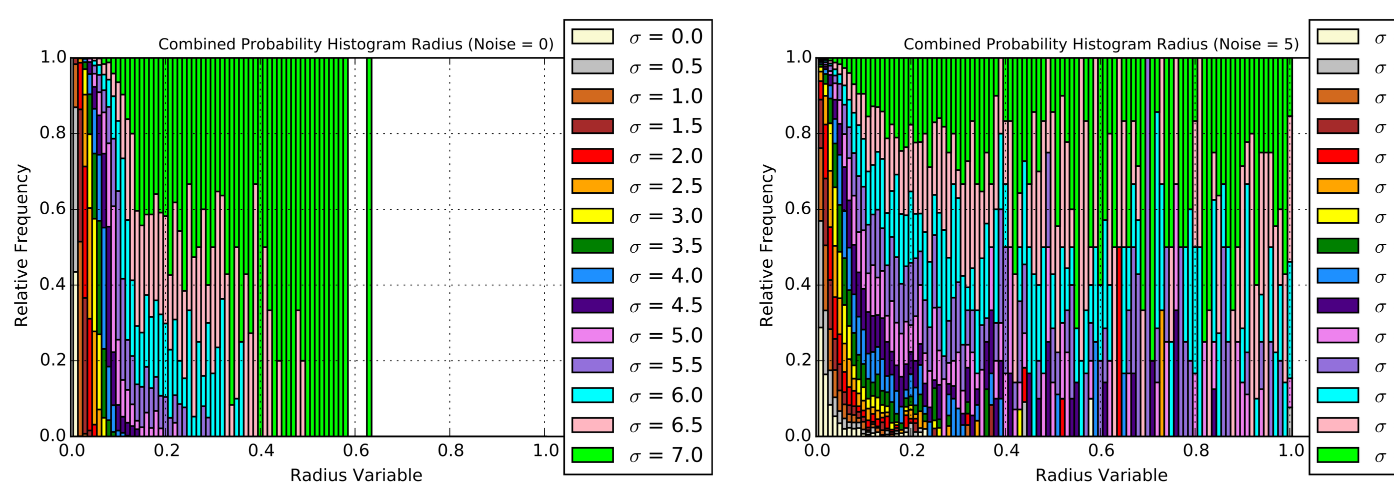
(An example computation of the signal [in mV] in Region 3)

$$x = r\cos\theta$$
$$y = r\sin\theta$$

Noise Simulation

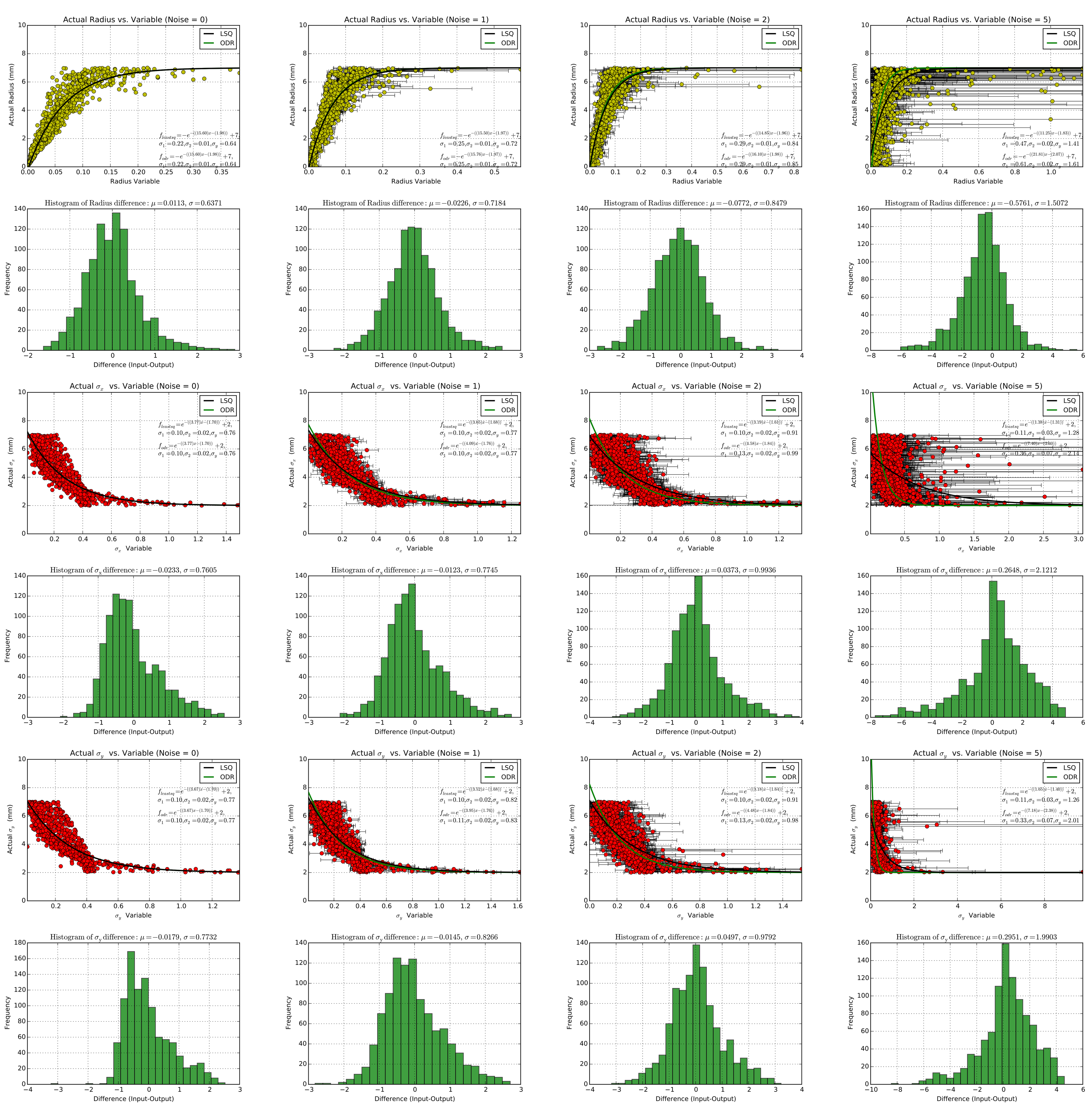
- Instrumental uncertainty and cosmic noise disrupts readings and introduces errors of Gaussian nature.
- The various levels of error (i.e. σ_{Noise}) tested in the detector signals were: 0, 1, 2, and 5 mV. (Note: the maximal total signal is 100 mV due to normalization of the beam.)
- Total noise from all sources was accounted by using Monte Carlo methods.
- Signals with noise were within a range of $\pm 2\sigma_{Noise}$ from its corresponding error-free signal.



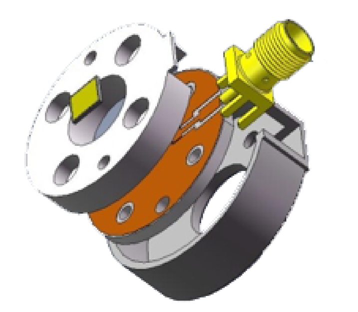


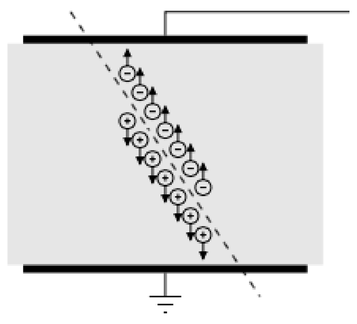
Testing the Optimal Detector

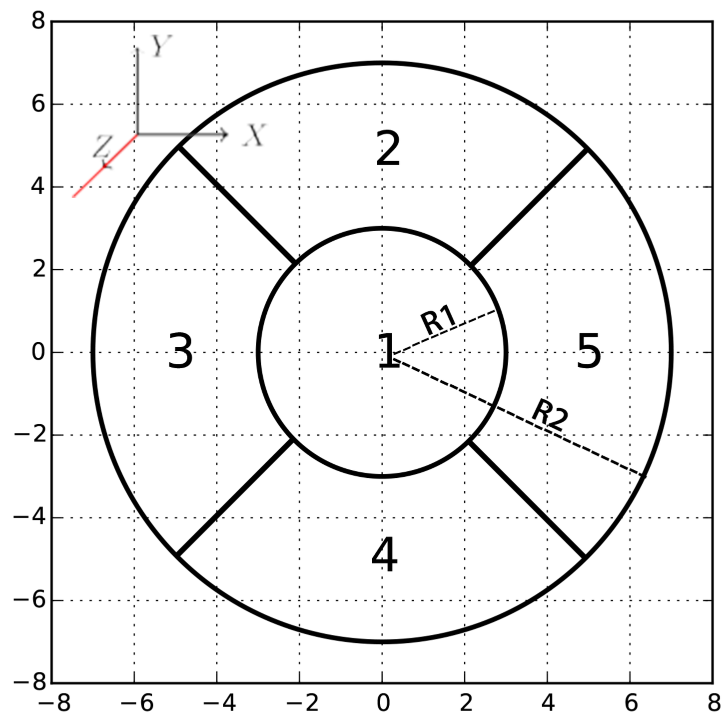
- Orthogonal Distance Regression (ODR) was used to account for errors in the independent variable on the data points—this method reduces to a Least Squares (LSQ) fitting when noise approaches 0.
- $f_1 = e^{-(ax-b)} + 2$ (exponential decay) modelled beam width while $f_2 = -e^{-(ax-b)} + 7$ (reflected exponential decay) modelled the beam's centroid radius (this time using $R_{X2_{output}}$).
- The histograms below are based on ODR results, but LSQ fitting resulted in models with lower overall standard deviation (and $\mu \approx 0$) between the computed and actual radius and/or beam width.
- Errors on the parameters a and b also helped assess the modelling function's capacity to fit the data.



CVD Diamond Detector Schematic

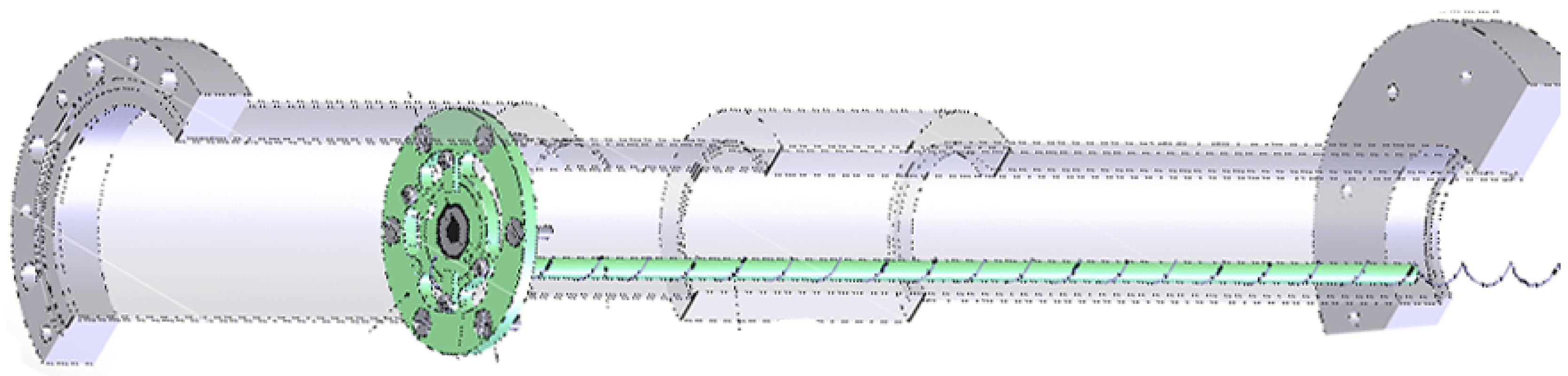






Detector Dimensions Tested (mm)

R1	R2
1	5
1	6
1	7
2	5
2	7
3	6
3	7
4	7
5	7
6	7



Comparison of Detector Designs

- To be as general as possible initially when comparing the 10 different detectors, the same variables were used for each detector when computing the centroid radius, centroid angle, σ_x, and σ_y.
- The beam pipe's radius is 7mm—the necessary outer radius for the design that will be installed—but alternatives were also tested to better understand general trends in optimizing the dimensions.
- A quintic function was used to fit the actual data based on the variables for the centroid radius, σ_x, and σ_y; θ_{output} is the final angular output.
- 1000 random antiproton beams were generated for each test trial when comparing different beam characteristics and detector dimensions.
- Each simulated beam's actual centroid radius, centroid angle, σ_x, and σ_y randomly ranged from $0-7$ mm, $0-2\pi$ radians, $2-7$ mm, and $2-7$ mm, respectively.
- Based on the following results, the R1=3mm/R2=7mm detector appeared to be the optimal detector design, particularly based on its good angular resolution and higher relative resistance to noise.

$$\theta_{output} = \arctan\left(\frac{S2-S4}{S5-S3}\right) \text{ (between } 0-2\pi)$$

$$\sigma_{x_{output}} = \frac{\sqrt{\frac{1}{3}\sum_{n=0}^{2}(S_{2n+1}-\bar{S}_{1,3,5})^2}}{S3+S5+1}$$

$$\sigma_{y_{output}} = \frac{\sqrt{\frac{1}{3}\sum_{n=0}^{2}(S_{2n}-\bar{S}_{1,2,4})^2}}{S2+S4+1}$$

$$R_{X1_{output}} = \frac{\sqrt{(S2-S4)^2+(S5-S3)^2}}{S1+1}$$

$$R_{X2_{output}} = \frac{\sqrt{(S2-S4)^2+(S5-S3)^2}}{(S_{High})(S1+1)}$$

*$R_{X2_{output}}$ was tested only for the optimal detector

$\Delta\theta$ Standard Deviation (mm)

Detector Dimensions (R1/R2)	Noise = 0	Noise = 1	Noise = 2	Noise = 5
1/5	0.241	0.5431	0.7389	1.1295
1/6	0.2044	0.4443	0.6312	0.8967
1/7	0.183	0.3776	0.5614	0.7974
2/5	0.2319	0.5456	0.7705	1.1849
2/7	0.179	0.3871	0.5446	0.8568
3/6	0.1848	0.5034	0.6193	0.9738
3/7	0.1787	0.3803	0.5584	0.8155
4/7	0.1469	0.4453	0.5403	0.9637
5/7	0.1314	0.536	0.7633	1.069
6/7	0.1193	0.7028	0.9561	1.3668

ΔRadius Standard Deviation (mm)

Detector Dimensions (R1/R2)	Noise = 0	Noise = 1	Noise = 2	Noise = 5
1/5	1.2843	1.5025	1.7583	2.0159
1/6	1.1701	1.2992	1.5868	1.9792
1/7	1.0603	1.2492	1.4784	1.8621
2/5	1.1056	1.2074	1.3989	1.7508
2/7	0.9306	0.9625	1.1177	1.6183
3/6	0.9418	1.0064	1.1648	1.5514
3/7	0.8377	0.8593	1.0149	1.4416
4/7	0.7538	0.8475	0.9147	1.4038
5/7	0.7185	0.7989	1.075	1.5658
6/7	0.6201	0.9857	1.389	1.7478

$\Delta\sigma_x$ Standard Deviation (mm)

Detector Dimensions (R1/R2)	Noise = 0	Noise = 1	Noise = 2	Noise = 5
1/5	1.1726	1.2036	1.2683	1.433
1/6	1.1037	1.174	1.258	1.3679
1/7	1.1383	1.1825	1.2668	1.3807
2/5	1.0922	1.1605	1.3301	1.4231
2/7	1.1732	1.1738	1.2461	1.388
3/6	0.5248	0.724	1.0851	1.3466
3/7	0.6857	0.763	0.8837	1.2631
4/7	0.9131	0.9879	1.163	1.3133
5/7	1.0861	1.134	1.2343	1.413
6/7	1.0644	1.2082	1.3278	1.4243

$\Delta\sigma_y$ Standard Deviation (mm)

Detector Dimensions (R1/R2)	Noise = 0	Noise = 1	Noise = 2	Noise = 5
1/5	1.125	1.2102	1.3061	1.4594
1/6	1.1153	1.1893	1.2587	1.3952
1/7	1.0918	1.1685	1.2555	1.3227
2/5	1.0807	1.1684	1.292	1.4159
2/7	1.2135	1.1965	1.3165	1.3517
3/6	0.5637	0.7386	1.1013	1.3699
3/7	0.7232	0.775	0.9074	1.2735
4/7	0.9036	0.9848	1.0897	1.336
5/7	1.0316	1.1173	1.2656	1.3825
6/7	1.0535	1.1704	1.2863	1.3607

Summary of Results

- The R1=3mm/R2=7mm detector is the best design for antiproton beam detection.
- After numerous variables were tested, θ_{output}, $R_{X2_{output}}$ $\sigma_{x_{output}}$, and $\sigma_{y_{output}}$ were found to be the optimal variables (a [reflected] exponential decay function used the latter 3 variables as input to compute the beam's characteristics).
- Angular resolution is 0.18 (10.3°), 0.38 (21.8°), 0.56 (32.1°), and 0.82 radians (47.0°), for noise levels of 0, 1, 2, and 5 mV, respectively.

ODR Analysis:

- Radial computation precision is 0.64, 0.72, 0.85, and 1.61 mm, for noise levels of 0, 1, 2, and 5 mV, respectively.
- σ_x and σ_y computation precision is 0.76, 0.80, 0.98, and 2.08 mm, for noise levels of 0, 1, 2, and 5 mV, respectively.

LSQ Analysis:

- Radial computation precision is 0.64, 0.72, 0.84, and 1.41 mm, for noise levels of 0, 1, 2, and 5 mV, respectively.
- σ_x and σ_y computation precision is 0.76, 0.80, 0.91, and 1.27 mm, for noise levels of 0, 1, 2, and 5 mV, respectively.

*For beams outside of the tested ranges (i.e. $0 \leq R \leq 7$ [mm], $0 \leq \theta \leq 2\pi$ [rad], $2 \leq \sigma_x, \sigma_y \leq 7$ [mm]), the algorithms are untested and thus not necessarily suitable or as precise as stated.