Tracking decay positrons in a magnetic field for muon microscope applications

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a) Background

The purpose of this paper is to evaluate what kind of spatial resolution could be achieved if the **positron detectors gain position sensitivity**. Recent developments of scintillation fibers [1] and silicon photo multipliers (SiPMs) [2] have made possible position sensitivity and high timing resolutions necessary for µSR.

Ideal virtual detectors with perfect positional identification and no positron scattering are assumed. We assessed the effect of granularity of the detectors and the distances of the detector arrangements from the sample. Then, the effect of materials in the track, such as cryostat walls and scintillation fiber themselves, are evaluated.

b) The beam conditions and detector setup

We used G4Beamline [3] as our simulation tool. A width-less muon beam centered at (x,y) = (0,0) travels in the positive z direction, hitting a 1 mm thick target made of carbon whose center is located at z=0. We applied a uniform magnetic field in the z-direction. The muon decay is the usual Michel decay mode. The definition of the axis and the geometry of the detectors are shown in Fig.1. A muon beam (as indicated by the dark blue line) travels towards the detector (grey). The position sensitive detectors, which are all 1 mm thick, are located at z=100, 150, and 200 mm (labeled F1, F2, and F3 respectively in the image below) and y=-100, -150 and -200 mm (labeled D1, D2, D3), both having dimensions of 100 x 100 mm^2, 150 x 150 mm^2, and 200 x 200 mm^2 , respectively.

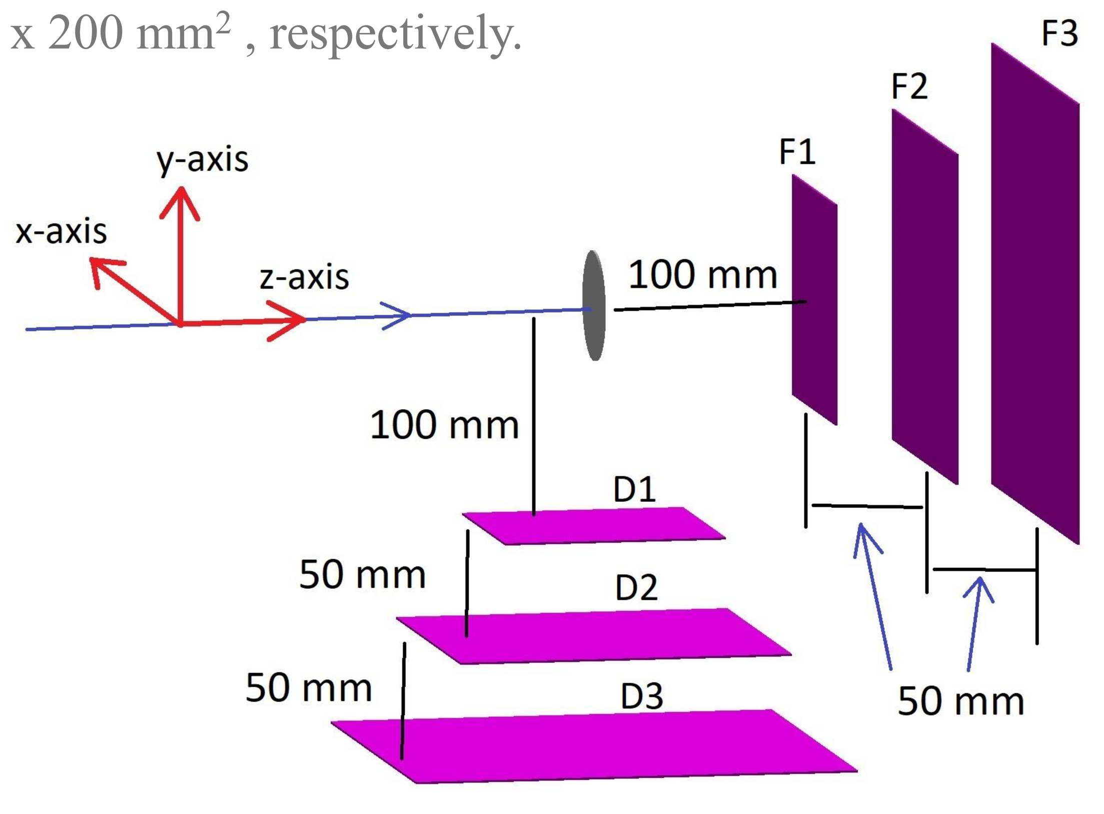

Figure 1: Experimental Setup

c) Theoretical Model

Since the positron is moving at a considerable fraction of the speed of light, we need to take special relativity into account:

$$m = \gamma m_0$$

Because the positron is in a magnetic field, the equation of motion is:

$$m\vec{a} = q(\vec{v} \times \vec{B})$$

Solving the equation of motion, we find that the solution is:

$$x = Rcos(\alpha t - \delta) + K_1$$

$$y = -Rsin(\alpha t - \delta) + K_2$$

$$z = Ct + D$$

d) Accuracy of algorithm

As shown in Fig.2a, we find that our algorithm is more accurate than the quadratic interpolation algorithm.

Although it is small, there is an increase of σ (standard deviation of the estimated position) as the magnetic field increases (Fig.2b).

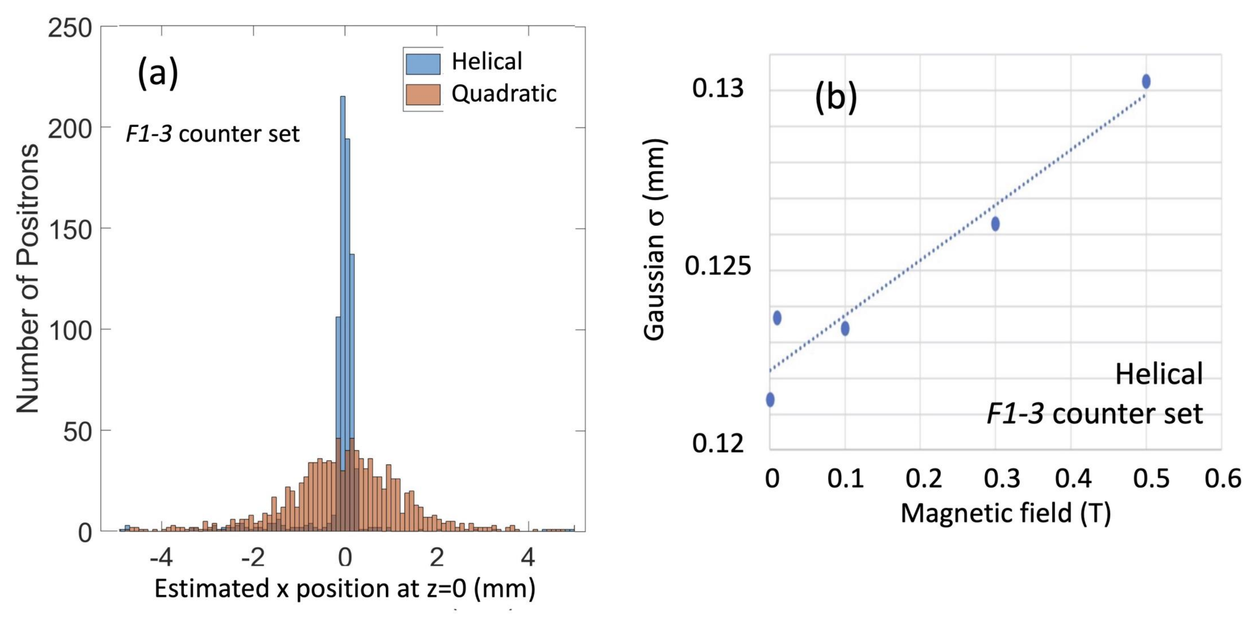

Figure 2: **a:** Helical vs Quadratic extrapolation for B = 0.3 T. **b:** Magnetic field dependence for the Helical Approximation standard deviations.

e) Detector granularity dependence

In Fig.3 (a), we compare the estimated source position for the Forward detectors and Down detectors in B=0.3 T. The Down detectors estimates the beam position at (0.0,0.0) ± 0.401 mm, which is over three times worse than the Forward detector. (Fig.3a and b), which is (0.0,0.0) ± 0.126 mm

Scintillation fibers have a finite width which would limit the spatial resolution possible for the hit positions. Because of the optical detectors (SiPM) size [2] and the scintillator thickness necessary to gain enough photons, the width of ~1 mm is the practical lower limit for the positron detection. We rounded the positional coordinates of the simulations to the detector granularity and plotted the positional estimate Gaussian σ as the function of the detector pixel size in Fig.3b.

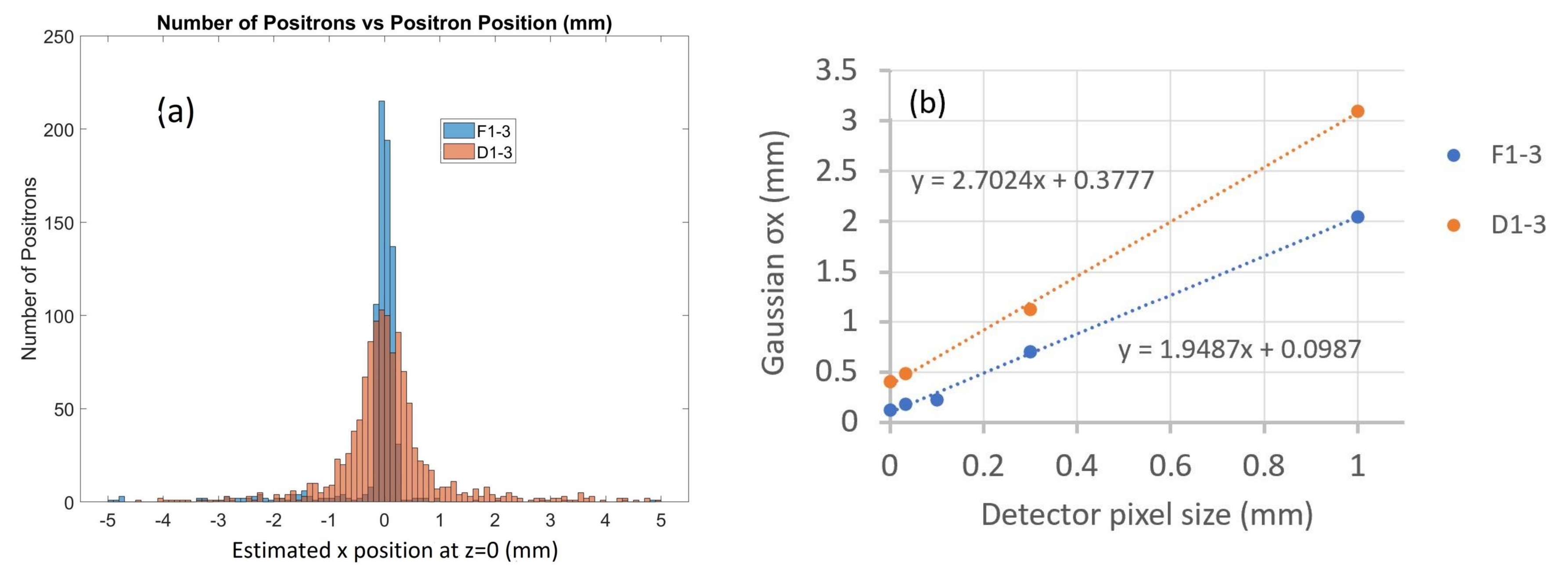

Figure 3: **a:** Positional estimate from the Forward-Backward vs Up-Down detector setup at B = 0.3 T. **b:** Gaussian σ as a function of the detector pixel size.

f) Detector scale dependence and scattering effect

We have checked the D1-3 detector model with 1/2 the scale (distances and sizes) and compared the results from the original size (Fig. 4). The accuracy depends on the scaling and the gaussian σ progressively improves in smaller detector sets.

We found that changing the detector material (or adding a cryostat wall) will affect the accuracy of our position estimate, as having a solid material in the positron's path will cause significant scattering (as shown Fig.3b).

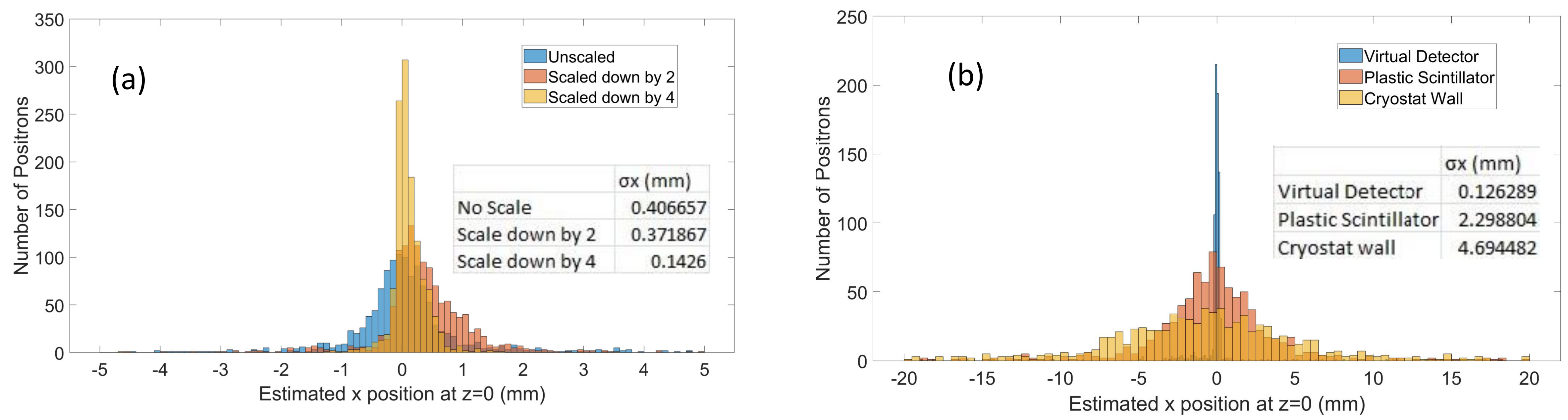

Figure 4: **a:** Up-Down Setup Scaled Down by 4 vs Scaled Down by 2 vs No Scaling **b:** Positron scattering effects

g) Discussion

We have found that the scaled down (smaller and closer) D counters improves the resolution, probably because they detect more positrons with a smaller helical radius which better identify the source position.

The detector granularity (width of the scintillation fibres) will limit the minimum size of the detectors as well as the spatial resolutions.

Positron scatterers (cryostat walls and fibres themselves) make the resolution worse. For the muon microscope application, the detector system must be in the vacuum inside the cryostat chamber.

[1] Ruchti, R. C., Annual Review of Nuclear and Particle Science, **46**, pages 281-319, year 1996,

[2] Claudio Piemonte, Alberto GolNa, Nucl. Inst. Meth. Sec A, **926**, 2019, Pages 2-15, ISSN 0168-9002,

[3] T. J. Roberts and D. M. Kaplan, 2007 IEEE Particle Accelerator Conference (PAC), 2007, pp. 3468-3470,