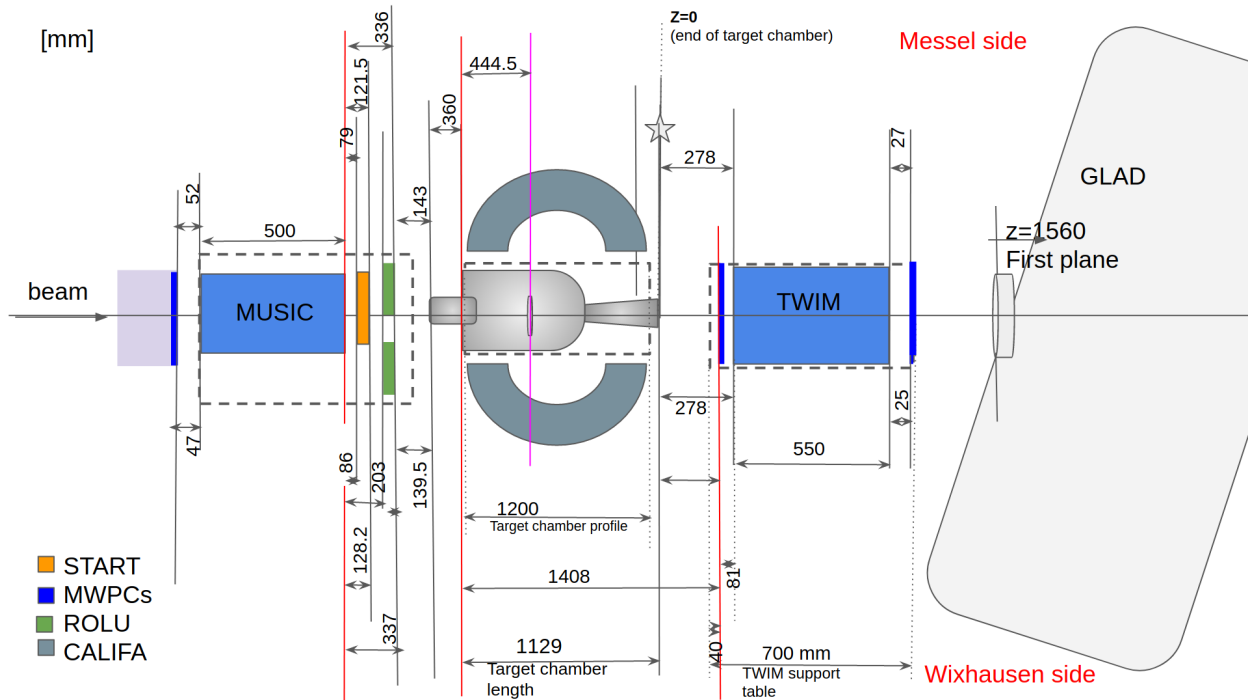
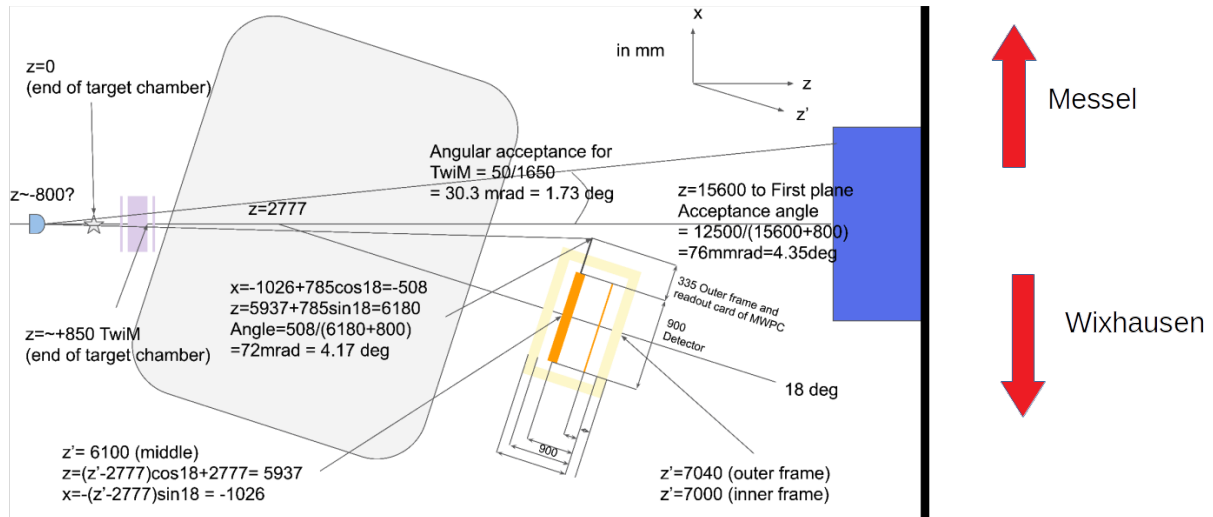


Radius/Momentum Calculation for S444 Experiment

February 2020 - Overview

Tobias Jenegger

0.1 The Setup



1 Geometry and relative position of the detectors in the beam direction

Here, the positions are given for the s444 and s467 experiments

z position of the MWPC0: $z_{MW0} = -2520$ mm
z position of the target: $z_T = -684.5$ mm
z position of the MWPC1 in front of the Twin-MUSIC: $z_{M1} = 279$ mm
z position of the middle of the Twin-MUSIC: $z_{Twin} = 553$ mm
z position of the MWPC2 after the Twin-MUSIC: $z_{M2} = 854$ mm
 α tilted angle of GLAD (14 degrees): $= 0.244$ rad
effective length of GLAD: $L_{eff} = 2067$ mm
z middle of GLAD $z_{Gm} = 2577$ mm
horizontal of the central path (18 degree) $\theta_{out0} = \pi/10$ rad
z position of the MWPC3 after GLAD $z_{M3} = 5937$ mm
z position of the ToFwall $z_{ToFW} = 6660.2$ mm

Correspondence between the GLAD current and the magnetic field: $I = 3584$ A, $B = 2.2$ T

Positions of the TOFWPads:

1 \Rightarrow Messel

27 \Rightarrow Wixhausen

2 RUNS used for calibration = SWEEP RUNS without target

RUN	Beam ion	Beam Energy [AmeV]	GLAD current [A]	Comments
36	12C primary	400	1444	before broken motor, here we see that tof is about 5ns faster. So they probably changed the position of the TOFW afterwards
37	12C primary	400	1444	it has be seen that motor drive not working
38	12C primary	400	1444	tof is back with new gates *magnet sweep 1444A
39	12C primary	400	1498	
40	12C primary	400	1501	
41	12C primary	400	1501	stopped with 1558 A
42	12C primary	400	1558	
43	12C primary	400	1558	stopped with 1653 A
44	12C primary	400	1653	
45	12C primary	400	1653	stopped with 1748 A
46	12C primary	400	1748	
47	12C primary	400	1748	stopped with 1843 A
48	12C primary	400	1843	
49	12C primary	400	1843	stopped with 1938 A
51	12C primary	400	1938	
52	12C primary	400	1938	stopped with 1444 A
53	12C primary	400	1444	
54	12C primary	400	1444	stopped with 1349 A
55	12C primary	400	1349	
56	12C primary	400	1349	stopped with 1254 A
57	12C primary	400	1254	
58	12C primary	400	1254	stopped with 1159
59	12C primary	400	1159	
60	12C primary	400	1159	stopped with 1064
61	12C primary	400	1064	
62	12C primary	400	1064	stopped with 1444 A
123	12C primary	650	1748	stopped with 1957
124	12C primary	650	1957	
	=	sweeping		
	=	stable GLAD current		

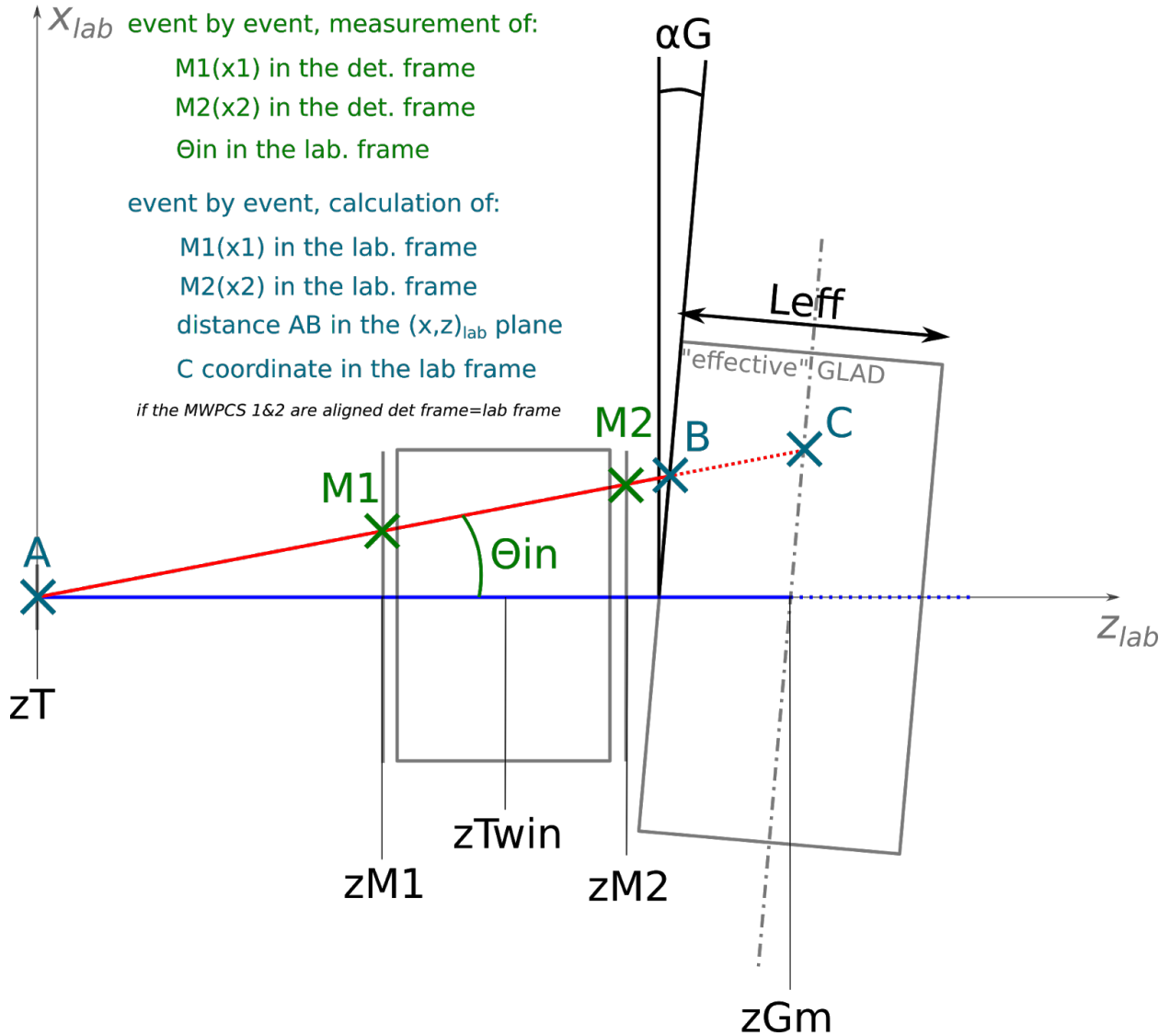
2.0.1 Other RUNS used for various checks:

RUN 70: 2 cm C target
 RUN 80: 10.86 mm C target
 RUN 81: 24.53 mm CH2 target
 RUN 67: 24 mm CH2 target
 RUN 68: 1 cm C target
 RUN 79: 12.29 mm CH2 target
 RUN 75: 21.98mm C target

3 Methods for flightpath reconstruction in the (x,z) plane

3.1 The "Kickplane" method

3.1.1 From MW0 to the entrance of GLAD, the ion is following a straight line



The straight line trajectory from MW0 to entrance before glad is defined by:

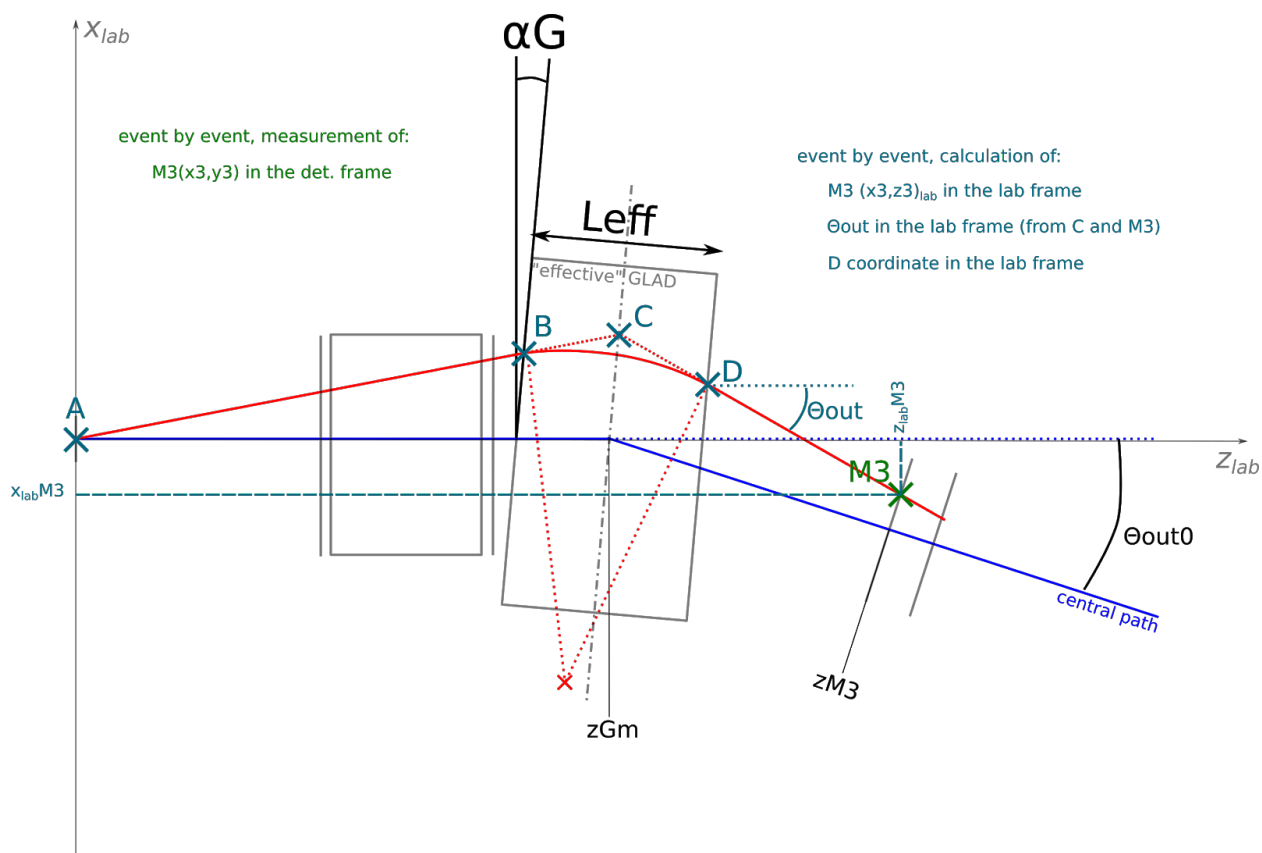
⇒ one absolute value before GLAD

absolute = calibrated position in mm in the laboratory frame

To get the position, use the position given by one MWPCs (1 or 2)

⇒ the theta angle (theta_in) before GLAD

3.1.2 From entrance to the exit of GLAD, the effective trajectory is circular



⇒ one absolute position at MWPC3

1. Extend the line of flight of the ion before the GLAD.
2. The point of intersection with the "kickplane" (symmetry axis line of GLAD magnet) is the kickpoint C.
3. Draw a straight line between C and the absolute position at MWPC3 = M3.
4. theta_out is the positive angle between the z-beam direction and the line between C and M3.

The curvature radius ρ is given by¹:

$$\rho = \frac{L_{\text{eff}}}{2 \cdot \sin\left(\frac{\theta_{\text{in}}}{2} + \frac{\theta_{\text{out}}}{2}\right) \cdot \cos(\delta)}$$

With δ :

$$\delta = \arctan\left(\left|\frac{\frac{\cos(\theta_{\text{out}}) - \cos(\theta_{\text{in}})}{\sin(\theta_{\text{out}}) + \sin(\theta_{\text{in}})} + \tan(\alpha)}{1 - \frac{\cos(\theta_{\text{out}}) - \cos(\theta_{\text{in}})}{\sin(\theta_{\text{out}}) + \sin(\theta_{\text{in}})} \cdot \tan(\alpha)}\right|\right)$$

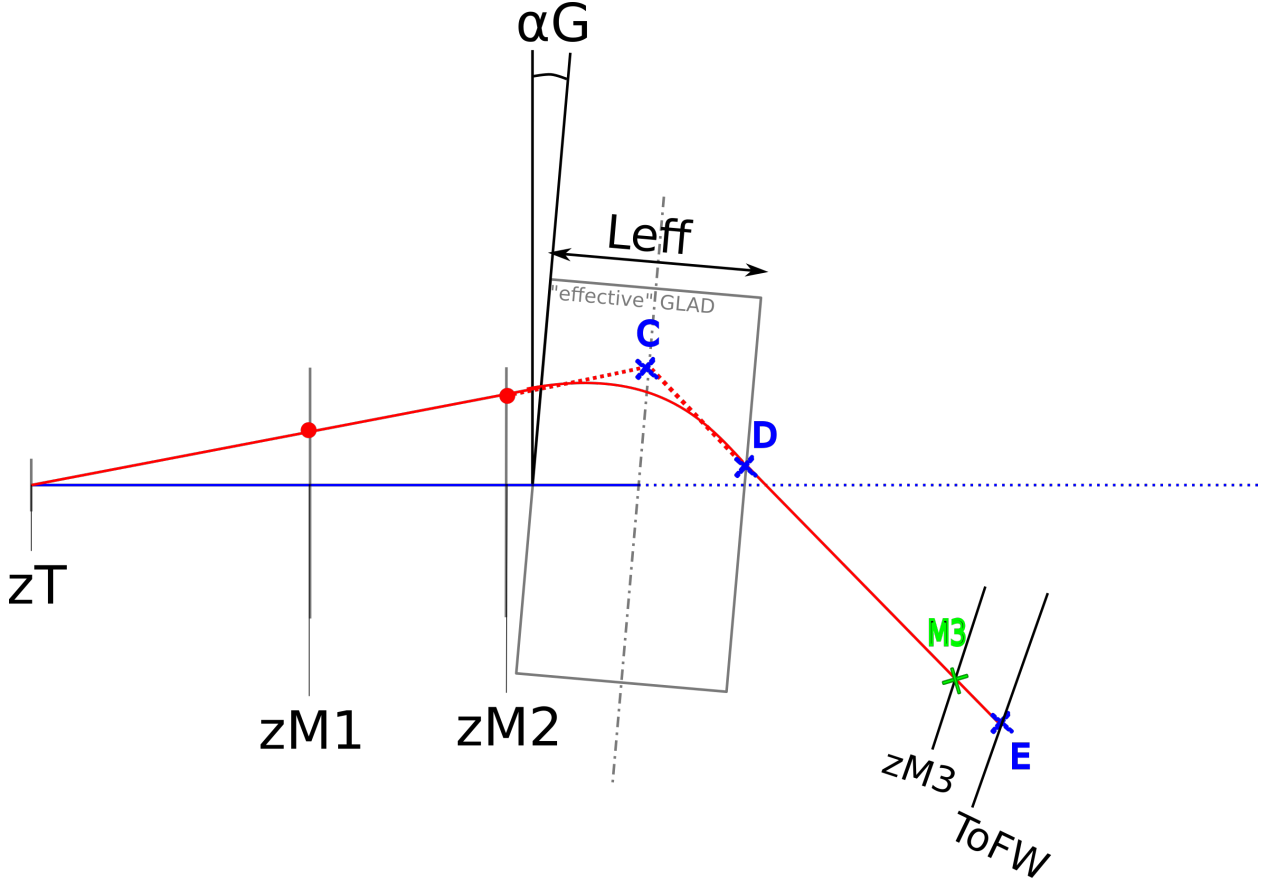
The full derivation can be found in the appendix.

The circular trajectory is then given by:

$$\omega = 2 * \left| \arcsin\left[\frac{BD}{2 \cdot \rho}\right] \right|$$

with BD = length of the BD segment

3.1.3 After GLAD up to the TOFW, the trajectory is a straight line



The straight line trajectory from D to E is defined by:

¹for consistency checks the $\cos(\delta)$ term can be omitted, as it plays a minor role

- ⇒ the output angle from GLAD θ_{out}
- ⇒ one absolute position after GLAD in the laboratory frame M3

With this information the straight line trajectory length after GLAD can be measured. It starts at the exit point of GLAD D and follows the straight line (characterized by the angle θ_{out} and the absolute position at MWPC3) until the intersection with the ToFW (middle position of the ToFWall $z_{ToFW} = 6660.2mm$, tilted angle = 18°).

Finally the pathlength in the (x,z) plane from the target position to the ToFW is given by:

$$P = AB + \rho \cdot \omega + DE$$

where:

A = (x,z) position at the target point

B = (x,z) position at the GLAD entry point

D = (x,z) position at the GLAD exit point

E = (x,z) position where the constructed trajectory line hits the ToFW

The assumption for the "Kickplane" method is that the kickpoint for each event lies on the predefined Kickplane, the symmetry axis line of the GLAD magnet.

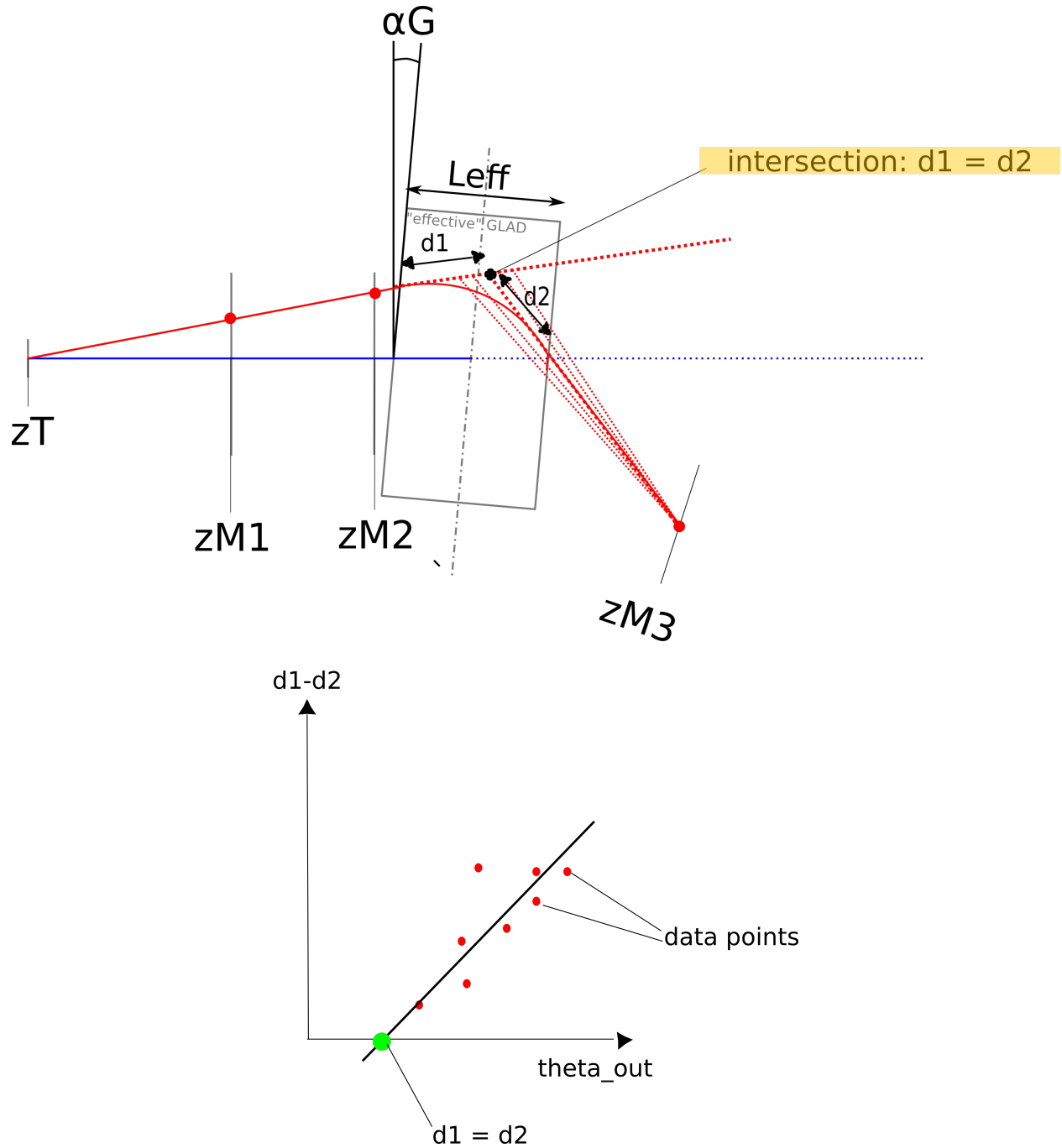
3.2 The "Fit-Track" method

For the "Fit-Track" method the assumption that the kickpoint C lies on the symmetry axis line of the GLAD magnet is rejected. Instead following algorithm is applied: ²

1. Extend the line of flight of the ion before the GLAD.
2. Draw a line from the point MW3 to C (as constructed with the "Kickplane" method).
3. Now sweep the straight line after the kickpoint, leaving the position MW3 unchanged but sweeping the intersection point along the inline beam.
4. For each sweeping step plot θ_{out} versus (d1-d2) where d1 is the distance between B and the point of intersection and d2 the distance between D and the intersection point accordingly.
5. 50 sweeping steps are performed.
6. Fit the final θ_{out} versus (d1-d2) plot with linear least square fit.

²This algorithm is motivated from https://www.blogs.uni-mainz.de/fb08-kernphysik/files/2018/09/PHDThesis_OlgaBertini.pdf, section 3.4

7. Find the intersection of the abscissa. The corresponding θ_{out} value is now the corrected one which should be used for the calculation of the radius.



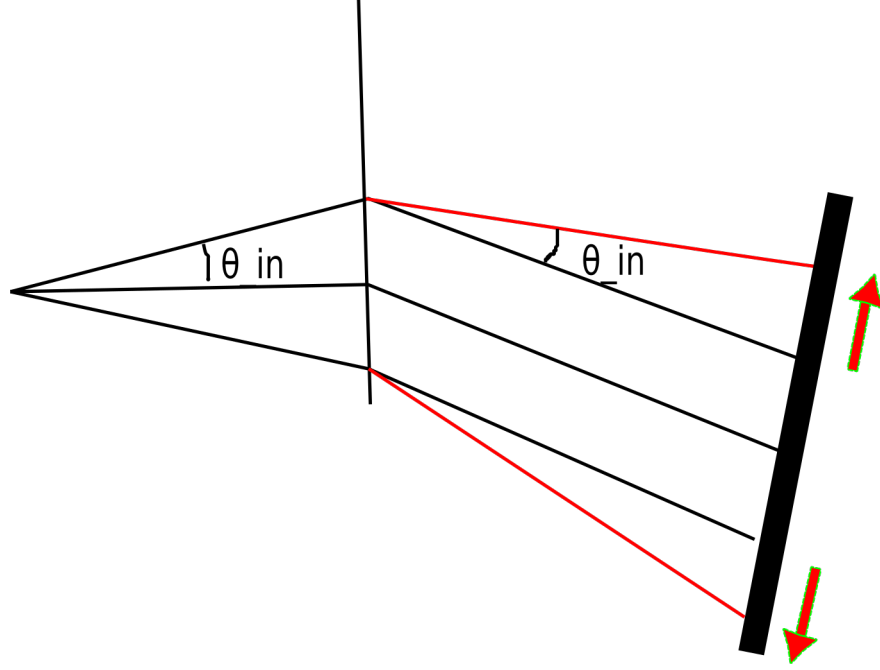
3.3 The "Theta_in correction" method

Here the "Kickplane" method is used and subsequently the θ_{out} is corrected by θ_{in} . That means:

$\theta_{out_corr} = \theta_{out} - \theta_{in}$.

Consequently the θ_{in} dependence of ρ vanishes(neglecting the $\cos(\delta)$ term):

$$\rho = \frac{L_{eff}}{2 \cdot \sin\left(\frac{\theta_{in}}{2} + \frac{\theta_{out_corr}}{2}\right)} = \frac{L_{eff}}{2 \cdot \sin\left(\frac{\theta_{out}}{2}\right)}$$



3.4 Final method: "Advanced Fit-Track" method

The same track finding algorithm as for the "Fit-Track" method is used with the only difference that the value for θ_{in} is calculated from the fit of θ_{out} vs. x_{MW3} :

The parameters of the linear fit are used for the calculation of θ_{in} :

$$\theta_{in} = \alpha - a \cdot x_{MW3} - b$$

With **a** being the slope and **b** the offset of the fit. This method prevents from adding up the errors from θ_{in} measurement.

α corresponds to the mean value of the θ_{out} from the fit of θ_{out} vs. x_{MW3} .

4 Plots

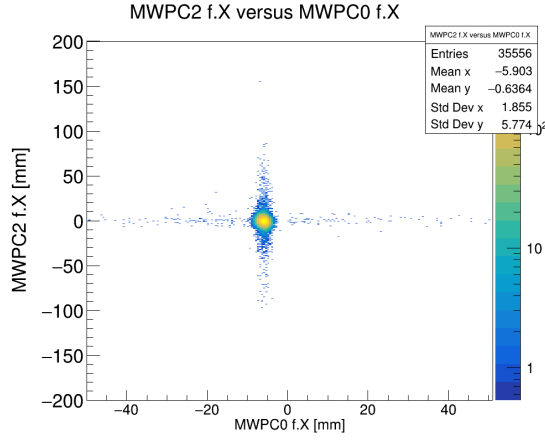
In this section all the plots for the various track finding algorithms are presented. For the calculation of the θ_{in} angle MWPC1 and MWPC2 are used. Alternatively MWPC0 and MWPC2 could be used, to get a longer lever arm (work in progress ...).

4.1 MWPC1 vs MWPC2 - x position

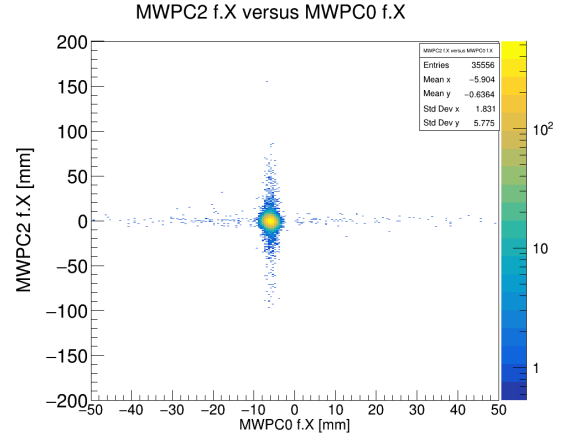


Figure 1: MWPC1 vs MPWPC2 - x position for sweep runs 39-61.

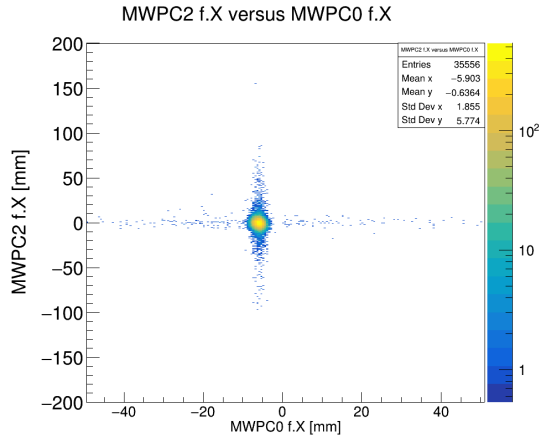
4.2 MW0 vs MW2- x position



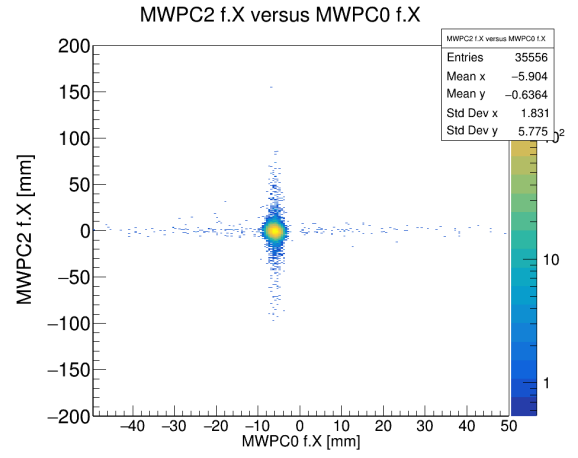
(a) "Kickplane-Method"



(b) "Theta_in correction-Method"



(c) "Fit-Track-Method"



(d) "Advanced Fit-Track-Method"

Figure 2: MWPC2 vs MWPC0 - x position for sweep runs 39-61.

4.3 MW1 vs MW3 - x position

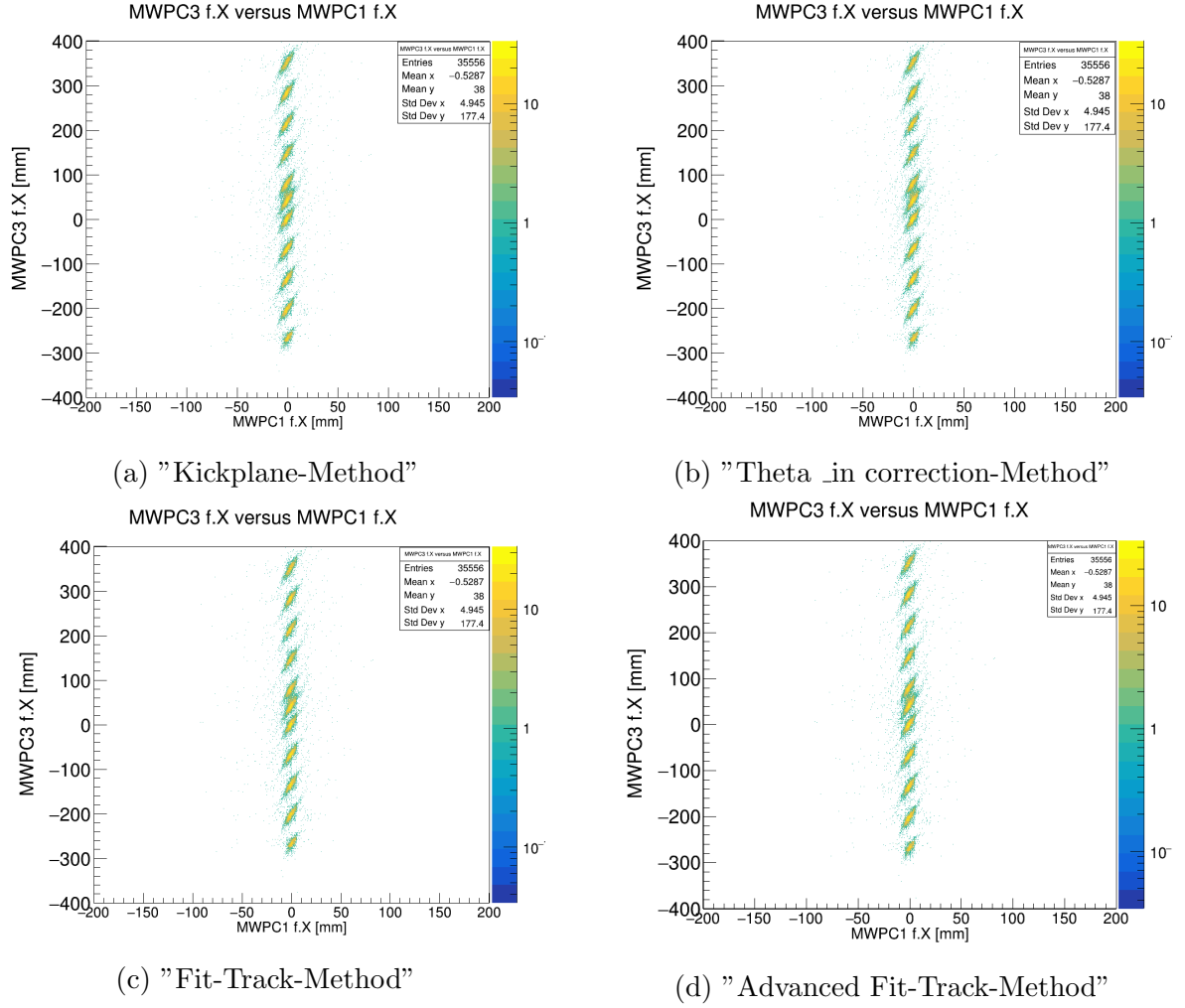
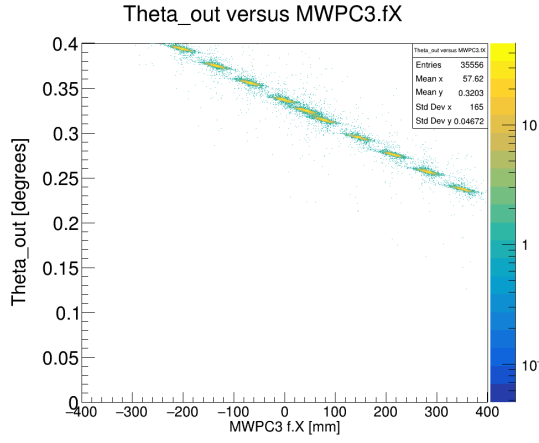
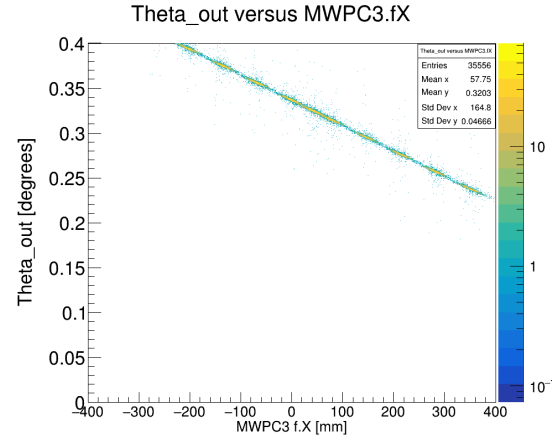


Figure 3: MWPC3 vs MWPC1 - x position for sweep runs 39-61.

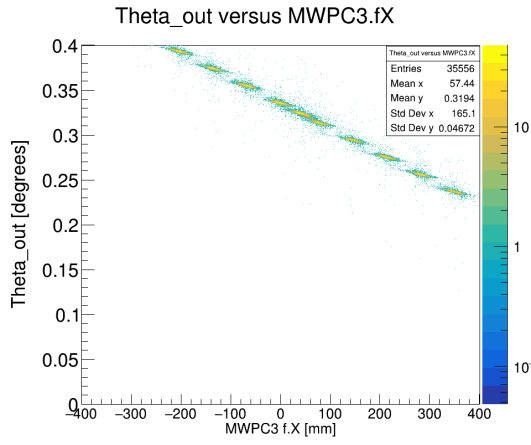
4.4 theta_out vs MW3- x position



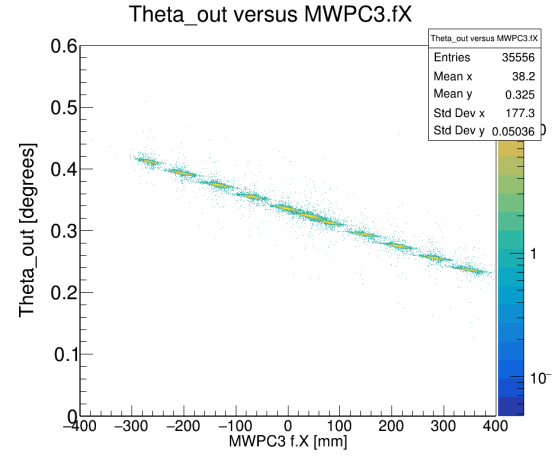
(a) "Kickplane-Method"



(b) "Theta_in correction-Method"



(c) "Fit-Track-Method"



(d) "Advanced Fit-Track-Method"

Figure 4: Theta_out vs MWPC3 x position for sweep runs 39-61.

4.5 theta_in vs MW3 - x position

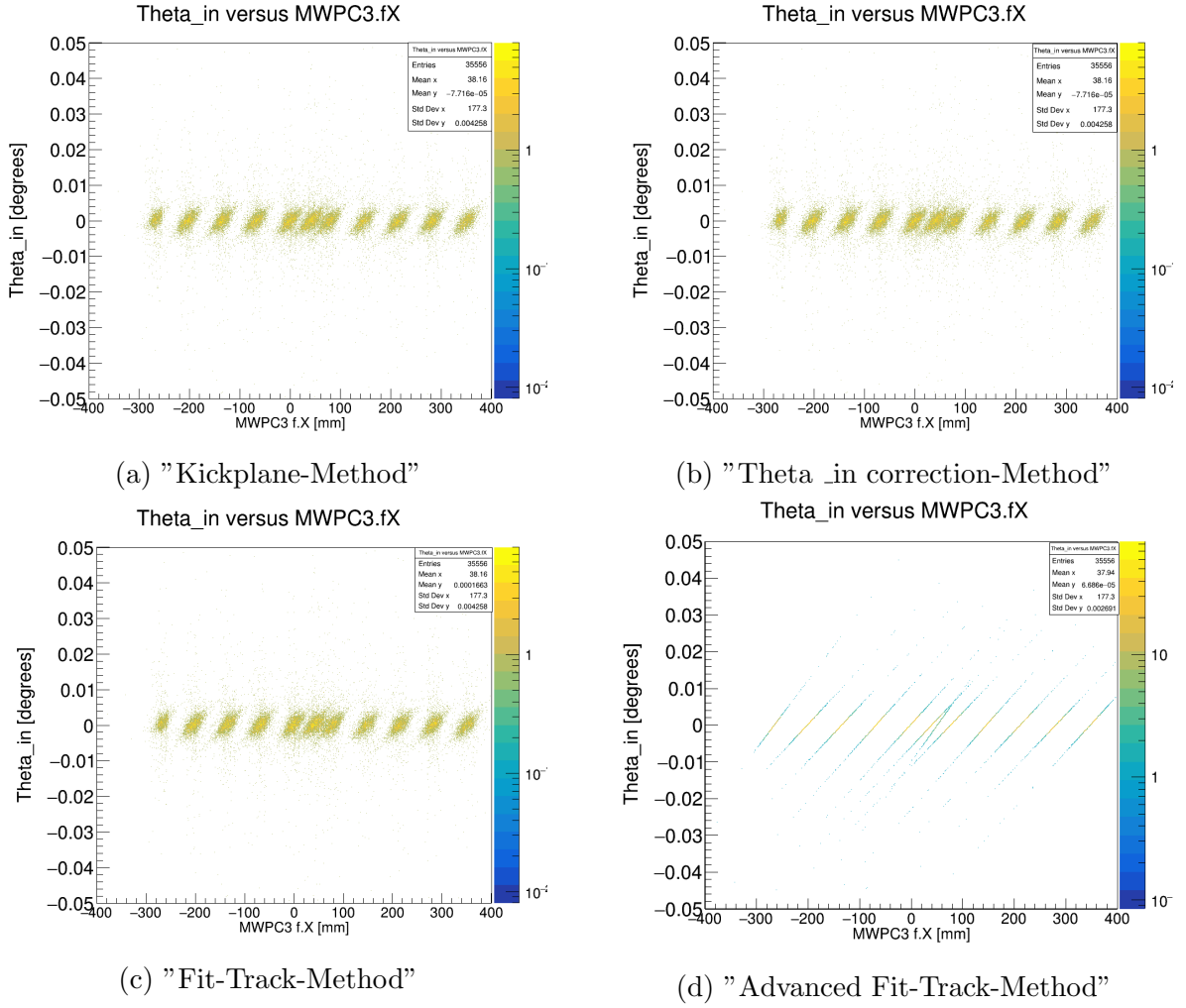


Figure 5: Θ_{in} vs MWPC3 x position for sweep runs 39-61.

4.6 $\theta_{\text{out}} + \theta_{\text{in}}$ vs MW3- x position



Figure 6: $\theta_{\text{out}} + \theta_{\text{in}}$ vs MWPC3 x position for sweep runs 39-61.

4.7 θ_{in} vs Radius

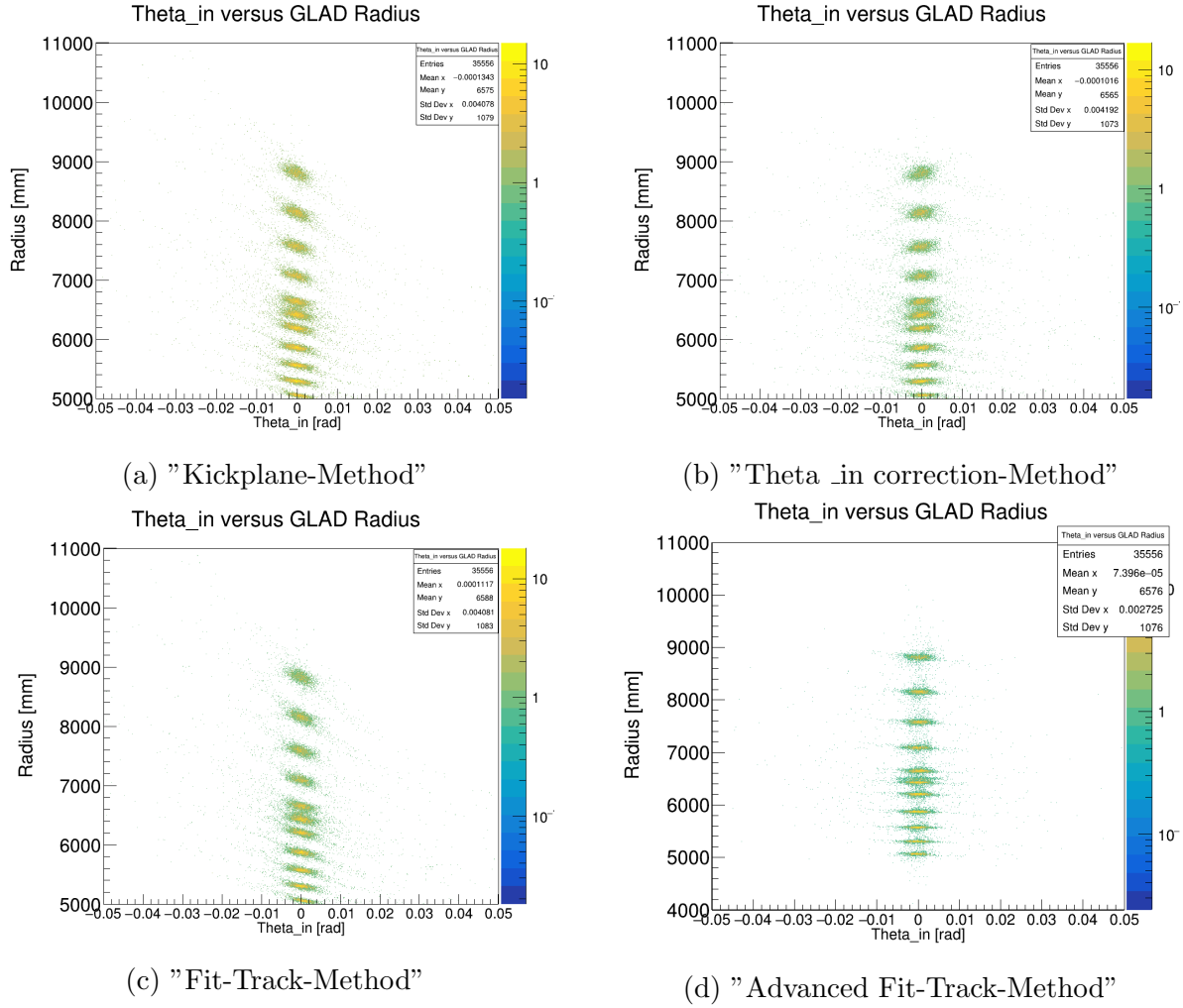


Figure 7: θ_{in} vs GLAD Radius for sweep runs 39-61.

4.8 theta_out vs Radius

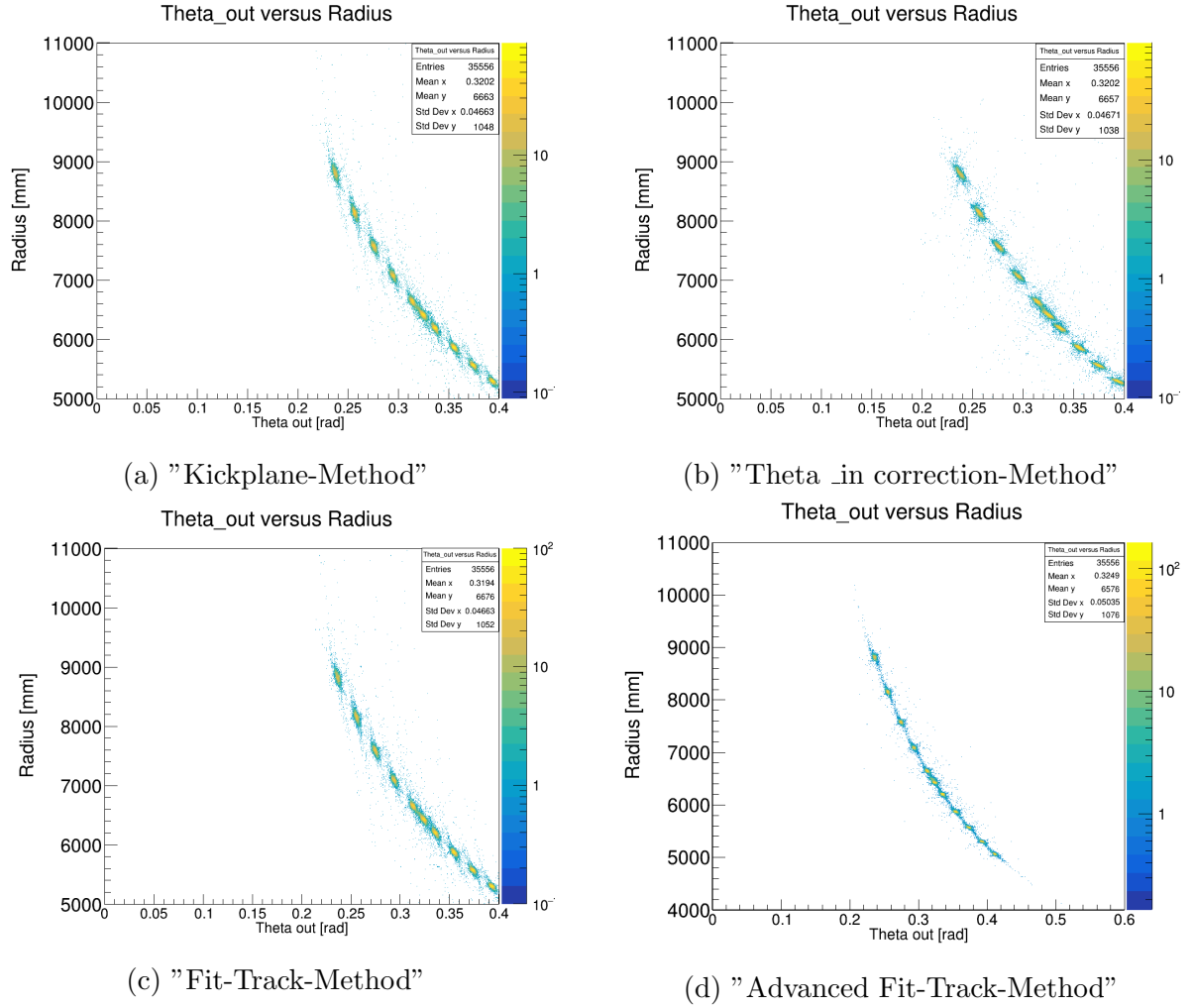
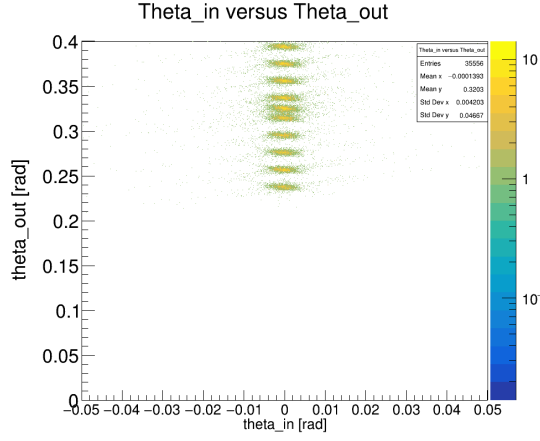


Figure 8: Theta_out vs GLAD Radius for sweep runs 39-61.

4.9 θ_{in} vs θ_{out}



(a) "Kickplane-Method"



(b) "Theta_in correction-Method"



(c) "Fit-Track-Method"



(d) "Advanced Fit-Track-Method"

Figure 9: θ_{in} vs θ_{out} for sweep runs 39-61.

4.10 MW3 vs Radius - x position



Figure 10: MWPC3 x position vs GLAD Radius for sweep runs 39-61.

4.11 MW2 vs Radius - x position

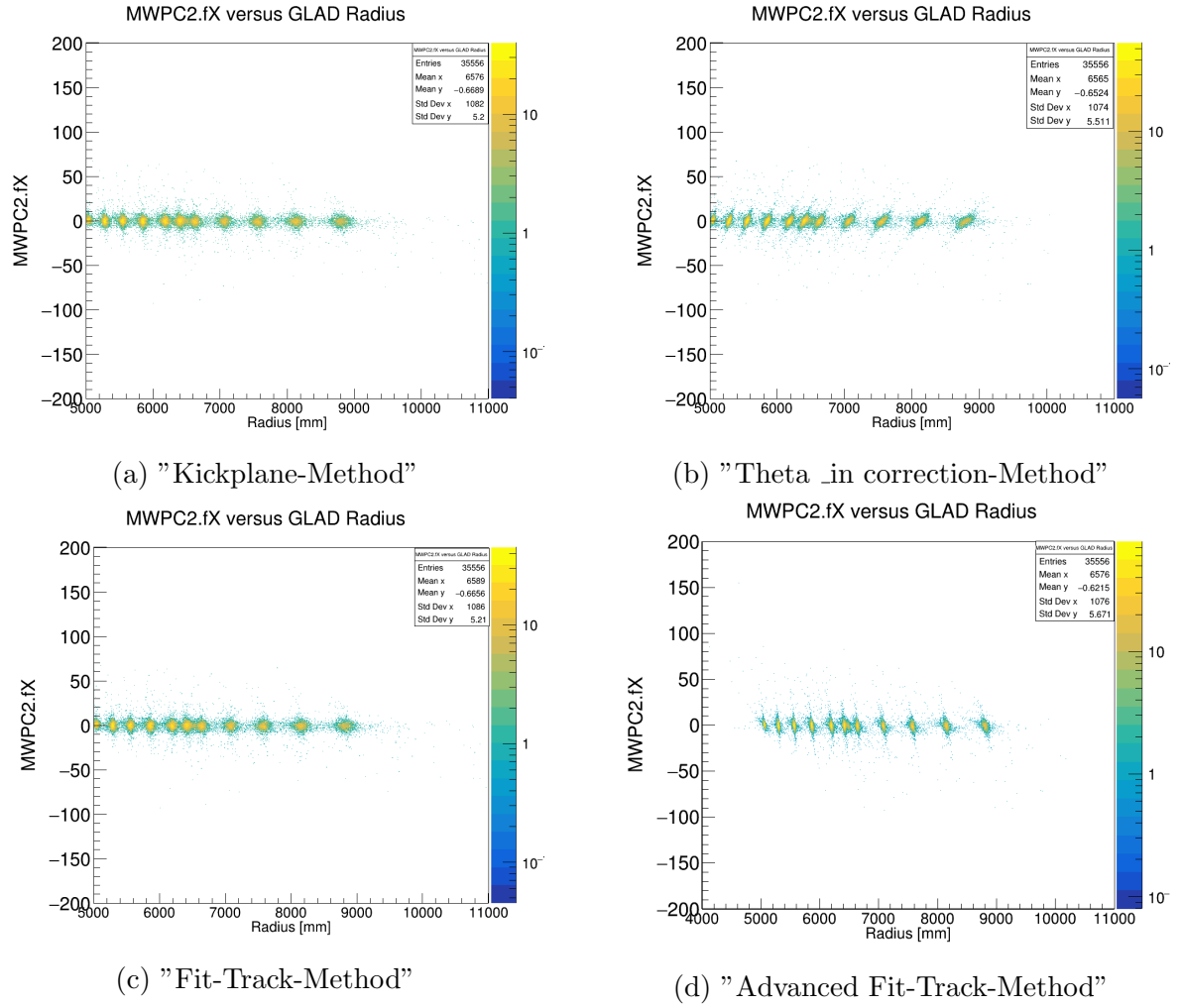


Figure 11: MWPC2 x position vs GLAD Radius for sweep runs 39-61.

5 Relative momentum resolution ”Advanced Fit-Track-Method”

The momentum resolution is calculated from the radius-calculation as $\rho \sim p$. From that follows:

$$\frac{\Delta p}{p} = \frac{\Delta \rho}{\rho}$$

For the evaluation of the resolutions for the various sweep runs the two dimensional plot ”MWPC3.fX versus GLAD Radius” is projected on the abscissa. The resulting 1D plot is fitted with a gaussian. The mean value from the fit corresponds to ρ and the σ to $\Delta\rho$ respectively.

Runnr.	$\bar{\rho}$	σ	rel. resolution
39	6.48911e+03	2.13410e+01	3.289e-03
40	6.42396e+03	1.56313e+01	2.433e-03
42	6.20033e+03	1.42716e+01	2.301e-03
44	5.86854e+03	1.29449e+01	2.206e-03
46	5.57125e+03	1.31369e+01	2.358e-03
48	5.30203e+03	1.07044e+01	2.018e-03
51	5.06232e+03	1.07182e+01	2.117e-03
53	6.64556e+03	1.66141e+01	2.500e-03
55	7.08710e+03	1.91895e+01	2.708e-03
57	7.57474e+03	2.16135e+01	2.853e-03
59	8.15089e+03	2.22151e+01	2.725e-03
61	8.81055e+03	2.72038e+01	3.088e-03

With mean relative resolution $\frac{\Delta\rho}{\rho} = 2.55\text{e-}03$.

6 Limiting Radius/Momentum resolution factors

The radius/momentum resolution is limited by:

- Energy straggling
- Angular straggling
- Angular resolution of MWPC1/2
- position resolution of MWPC3 (higher order??)

6.1 Energy straggling

For the error calculation the mean energy inside the GLAD was used and the corresponding standard deviation. Generally for a charged particle drifting through a magnetic field the radius of the curved path the particle is following is defined as:

$$\rho = \frac{\gamma \cdot \beta \cdot m}{q \cdot B}$$

(considering $c = 1$)

Energy straggling has an effect on β and γ respectively. The measurement uncertainty with respect to β can be calculated as follows:

$$\frac{d\rho}{d\beta} = \frac{1}{(\sqrt{1-\beta^2})^3} \cdot \frac{m}{qB}$$

$$\Delta\rho_\beta = \frac{d\rho}{d\beta} \cdot \Delta\beta = \frac{\Delta\beta}{(\sqrt{1-\beta^2})^3} \cdot \frac{m}{qB}$$

with relative measurement uncertainty $\frac{\Delta\rho_\beta}{\rho} = 5.434e - 04$

6.2 Angular straggling

For the error calculation originating from angular straggling it is considered only angular straggling starting from the backend of the MWPC1. That means for this error calculation it is assumed to have a perfect focussed beam undergoes no broadening until it hits the MWPC1 (always at the same x-y-z position). Angular straggling broadens the beam focus and affects therefore both Θ_{in} and Θ_{out} .

(angular straggling for Θ_{in} can be neglected, higher order...)

For the calculation of measurement uncertainty with respect to Θ_{out} we use the simplified geometrical formula of the radius:

$$\rho = \frac{L_{eff}}{2 \cdot \sin(\frac{\Theta_{in} + \Theta_{out}}{2})}^3$$

From that follows:

$$\Delta\rho_{\Theta_{out}} = -\rho \cdot \frac{1}{2 \cdot \tan(\frac{\Theta_{in} + \Theta_{out}}{2})} \cdot \Delta\Theta_{out}$$

with $\Delta\Theta_{out} = 3.401e - 04$. This is the value calculated with LISE++ from MWPC1 to the very center of GLAD. Hence:

$$\left| \frac{\Delta\rho_{\Theta_{out}}}{\rho} \right| = \frac{1}{2 \cdot \tan(\frac{\Theta_{in} + \Theta_{out}}{2})} \cdot \Delta\Theta_{out} = 1.079e-03$$

6.3 Angular resolution of MWPC1/2

$$\Delta\rho_{\Theta_{in}} = -\rho \cdot \frac{1}{2 \cdot \tan(\frac{\Theta_{in} + \Theta_{out}}{2})} \cdot \Delta\Theta_{in}$$

with $\Delta\Theta_{in} = \frac{2 \cdot \Delta x}{L}$ ⁴ and L the (z-)distance between MWPC1 and MWPC2 (= 575mm).

³on the following pages I set $\Theta_{in} = 0$ and Θ_{out} to the value given by the GLAD field calculator(Mass = 12, Charge = 6, Energy = 400 A/MeV, Current = 1444), see <http://web-docs.gsi.de/~land/glad/>.

⁴ $\Theta_{in} = \frac{x_2 - x_1}{L}$, $\Delta\Theta_{in} = \left| \frac{d\Theta_{in}}{dx_2} \right| \cdot \Delta x_2 + \left| \frac{d\Theta_{in}}{dx_1} \right| \cdot \Delta x_1 = \frac{2 \cdot \Delta x}{L}$

With $\Delta x = 0.1mm$ it follows:

$$\left| \frac{\Delta \rho_{\Theta_{in}}}{\rho} \right| = 1.104e-03.$$

Adding up the above errors quadratically we get:

$$\left| \frac{\Delta \rho}{\rho} \right| = \sqrt{(5.434 \cdot 10^{-4})^2 + (1.079 \cdot 10^{-3})^2 + (1.104 \cdot 10^{-3})^2} = 1.64 \cdot 10^{-3}$$

6.4 Scalability of the field

Using the sweep runs (39-61) with different GLAD currents, the scalability of the B-Field can be analyzed. In figure 12 B_{ρ} from GLAD calculator divided by the mean radius is plotted against the according current values.

Taking the assumption that:

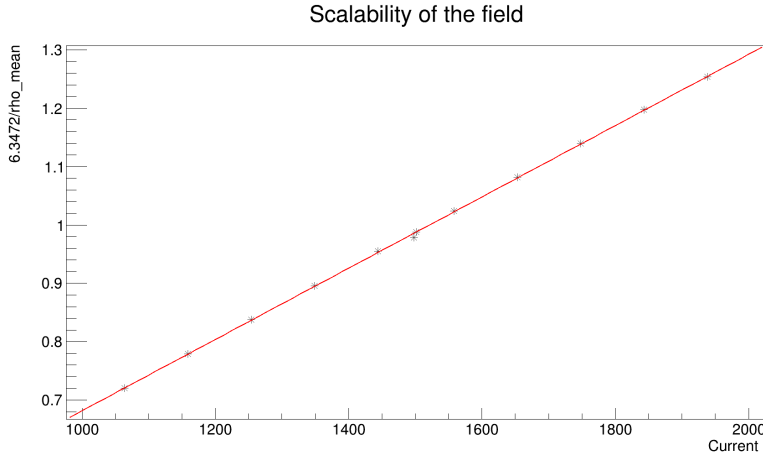


Figure 12

$B = current \cdot k$ (with k being a constant)

we get from the fit in 12:

slope = 0.000610713

offset = 0.0709244

7 Z versus A/q calculations

In this section the target RUNs 82,83,86,88 are analyzed with GLAD current = 1444 A, target = CH2 12.29 mm.

Data is taken for the x-position on MW1,MW2 and MW3, time difference between START and TOFW Detector and charge value from TWIM Music.

The radius of curvature in GLAD is computed using the "Advanced Fit Track" method.

The time of flight is calculated using the time difference between START and TOFW with the respective offsets (for the TOF detector pads) and subtracting from that the time of flight between START detector and target. The latter is calculated using $\beta = 0.714549$ ($\equiv 400A/MeV$) and as distance between START and target 1183.25 mm.

Offsets used for RUNs 82 and 83 (using sweep RUNs 39-61) and for RUNs 86 and 88 (using sweep run 36), respectively:

Detnr. TOFW	Time offset 39-61 [s]	Time offset 36 [s]	Difference [s]
1	1.15079E-07	1.141E-07	-9.789E-10
2	1.13720E-07	1.13329E-07	-3.910E-10
3	1.16304E-07	1.15778E-07	-5.259E-10
4	1.14539E-07	1.13983E-07	-5.560E-10
5	1.15420E-07	1.14922E-07	-4.979E-10
6	1.16052E-07	1.15593E-07	-4.590E-10
7	1.16903E-07	1.16486E-07	-4.169E-10
8	1.16143E-07	1.15781E-07	-3.620E-10
9	1.14394E-07	1.14067E-07	-3.270E-10
10	1.15967E-07	1.15691E-07	-2.759E-10
11	1.12559E-07	1.12337E-07	-2.220E-10
12	1.15962E-07	1.15764E-07	-1.979E-10
13	1.13521E-07	1.13372E-07	-1.489E-10
14	1.15088E-07	1.14989E-07	-9.900E-11
15	1.13676E-07	1.18635E-07	4.958E-09
16	1.12992E-07	1.17986E-07	4.993E-09
17	1.14391E-07	1.19424E-07	5.033E-09
18	1.12076E-07	1.17168E-07	5.091E-09
19	1.13234E-07	1.18360E-07	5.126E-09
20	1.12760E-07	1.17933E-07	5.173E-09
21	1.16445E-07	1.21687E-07	5.242E-09
22	1.16877E-07	1.22138E-07	5.261E-09
23	1.16077E-07	1.21353E-07	5.275E-09
24	1.16127E-07	1.21457E-07	5.329E-09
25	1.14855E-07	1.20219E-07	5.363E-09
26	1.14363E-07	1.19841E-07	5.477E-09
27	1.14435E-07	1.19932E-07	5.496E-09

The proceeding for the Z versus A/q calculations are:

1. Plot without any cuts/restrictions Z versus Radius using the "Fit-Track" method (see [13](#)).
2. From that plot identify the various isotopes and cut on them.
3. Plot for each isotope theta_out vs x_3 and make a linear fit (see [14](#)).

4. Feed the "Advanced Fit-Track" method with the parameters of the fit for the various isotopes (which you can separate using the previously selected cuts).
5. Calculate beta (using the above TOFW offsets) for the various isotopes and plot Z versus A/q.

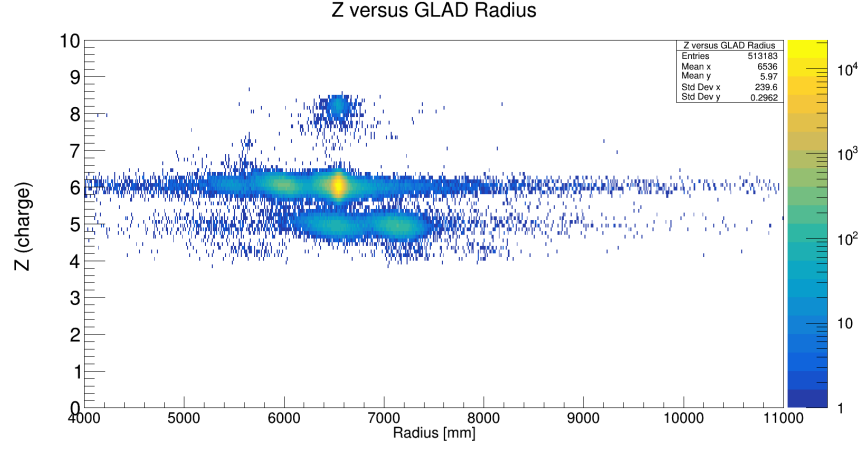
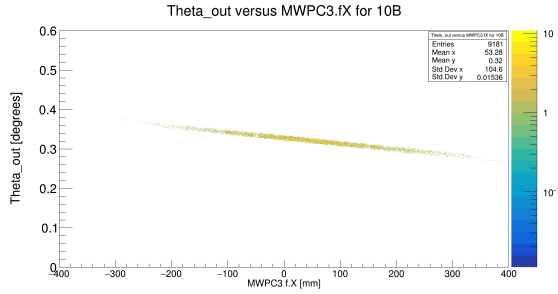
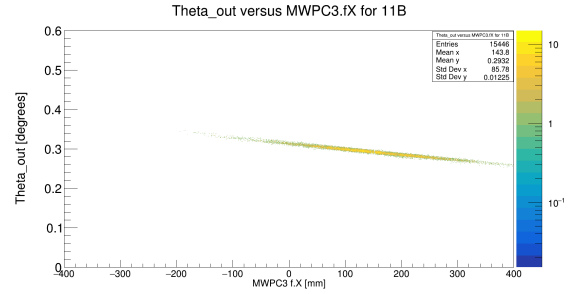


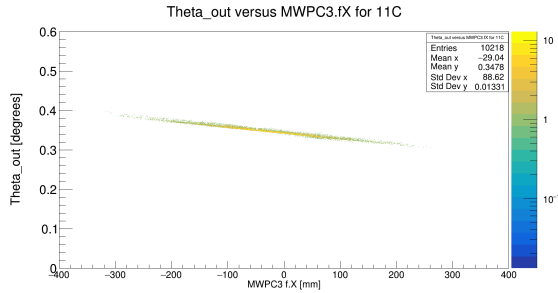
Figure 13: Z versus Radius for RUN 88.



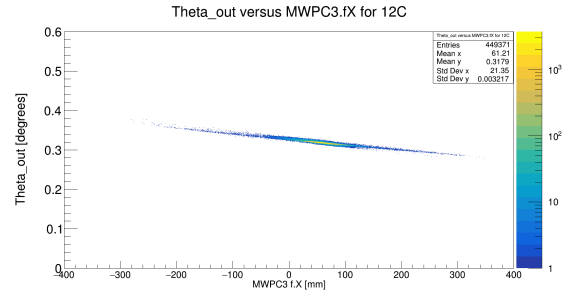
(a) theta_out vs xMW3 for 10B.



(b) theta_out vs xMW3 for 11B.



(c) theta_out vs xMW3 for 11C.



(d) theta_out vs xMW3 for 12C.

Figure 14: theta_out vs xMW3 for isotopes.

The cuts on the various isotopes in 13 are:

10B: $4.6 < Z < 5.26$ and $6232 < R < 6770$

11B: $4.43 < Z < 5.53$ and $6877 < R < 7559$

11C: $5.5 < Z < 6.61$ and $5670 < R < 5980$

12C: $5.45 < Z < 6.7$ and $6285 < R < 6780$

Using this cuts we get following fit parameters for the various isotopes:

Isotope	α	a (= slope)	b (=offset)
10B:	0.32	0.000144005	0.327681
11B:	0.2932	0.000139928	0.313335
11C:	0.348	0.000146679	0.34352
12C:	0.3179	0.00014353	0.326665

Separating the isotopes by the above charge and radius cuts and using the appropriate α , a and b parameters the Radius gets recalculated via the "Advanced Fit-Track" method. The new value for the radius is now used in the A/q calculation:

$$A/q = \frac{B \cdot p \cdot e}{\gamma \cdot \beta \cdot c \cdot u}$$

with:

e : elementary charge = $1.602176634 \cdot 10^{-19} \text{C}$

c : speed of light = 299792458 m/s

u : atomic mass unit = $1.66053906660 \cdot 10^{-27} \text{kg}$

In figure you