Reconstruction of particles’ trajectories for hadrontherapy using the FOOT experiment data

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Summary.

- Introduction.
- Foot experiment.
  - FOOT experiment Set Up.
  - FOOT experiment reconstruction.
- Propagator.
  - Physical and Numerical fundamentals.
  - Propagator.
- Results.
- Conclusion.
- Bibliography.

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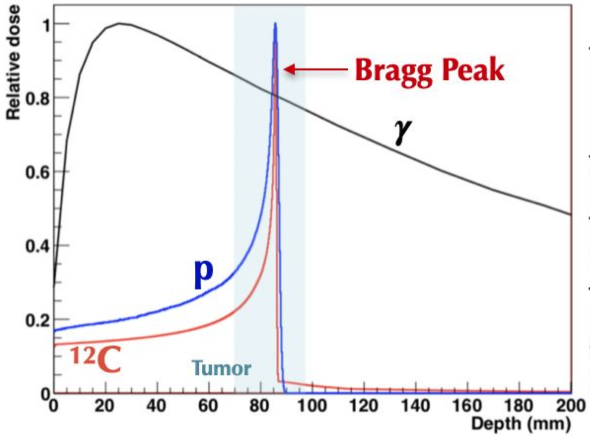
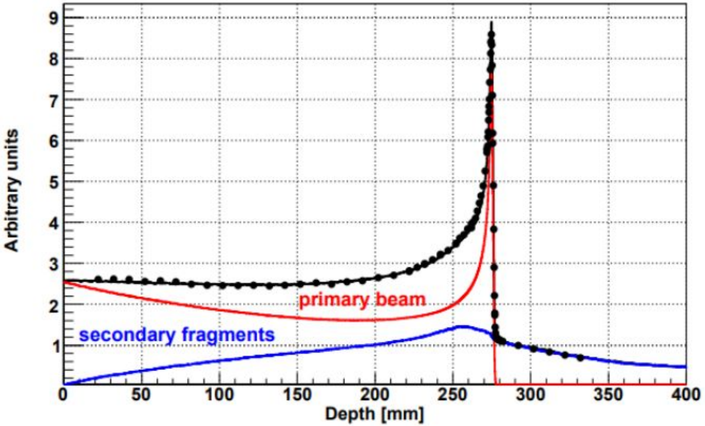
Introduction.

Introduction.

- Motivation.
  - Cancer in France.
    - Leading death cause: accounting 30%
  - Treatments.
    - Surgery.
    - Chemotherapy.
    - New therapies.
      - Brachytherapy.
      - Immunotherapy.
      - Etc…
    - Radiotherapy.
      - X-ray.
      - Hadrontherapy.
        - Ballistic advantages.
        - Fragment’s dose deposit.



D. Cussol, Nuclear Physics and Hadrontherapy (2000)



A. Mairani, PhD Thesis 2008

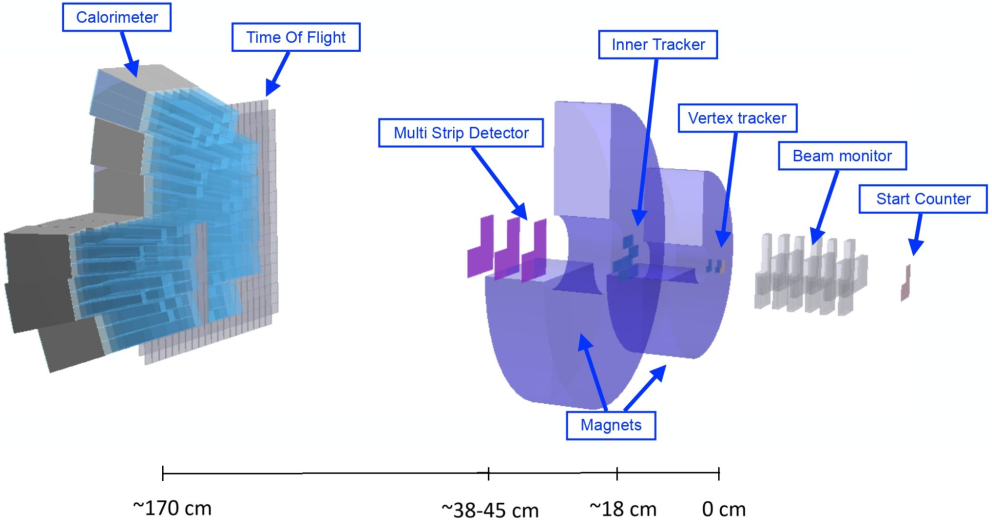
FOOT experiment.

FOOT experimental setup.

- Detectors involved.
  - Pre-target region.
    - Start Counter (SC).
    - Beam-Monitor (BM).
  - Interacting and tracking region.
    - Permanent Magnets.
    - Vertex (VTX).
    - Inner Tracker (IT).
    - Microstrip SIlicon Detector (MSD).
  - Downstream region.
    - Time-of-Flight Wall (TW).
    - Calorimeter (Cal).

- Graphite Target.
- Beam Characteristics.
  - 12C at $E_{beam} = 0.2$ GeV/u

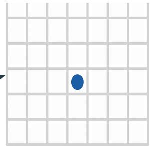
CNAO24 experiment.

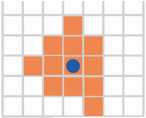


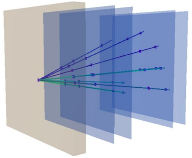
CNAO24 configuration.
Image taken from:
https://indico.in2p3.fr/event/23982/contributions/94968/attachments/65042/90558/GDRdet_interdisciplinar_22062021.pdf

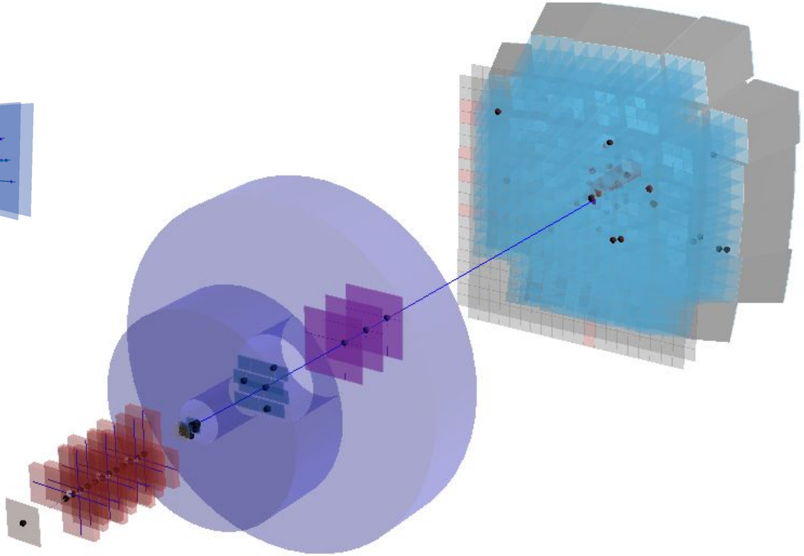
FOOT Reconstruction.

- Terms:
  - Hit.
  - Cluster.
  - Track.
  - Vertex.
- FOOT uses a Kalman Filter.
  - Lorentz force.
  - Loss energy.
  - Scattering.
- Mass assumption coming from TW.
  - If Z=1 $\longrightarrow$ A = 1.
  - If Z $\neq$ 1 $\longrightarrow$ A = 2*Z.
- Refit for differents isotopes.









Global reconstruction. Image taken from Ch. FINCK propagator presentation.

Propagator.

Propagator: Physical and Numerical fundamentals.

- Bethe-Bloch implementation.
  - Crossing through various materials.

$$\left\langle -\frac{dE}{dx}\right\rangle = K\frac{z^2}{\beta^2}\frac{Z\rho}{A}\left[\ln\left(\frac{2m_ec^2\beta^2\gamma}{I}\right)-\beta^2\right]$$

$$\Delta E = \left|\frac{dE}{dx}\right|\Delta x$$

- Lorentz Force.
  - Relativistic Lorentz force.
    - Curvature depend on charge-momentum ratio q/p.

$$\vec{F} = q\vec{v}\wedge\vec{B}$$

$$\frac{d\vec{\beta}}{dt} = \frac{q|\vec{\beta}|}{p}\vec{\beta}\wedge\vec{B} \qquad (1)$$

Propagator: Physical and Numerical fundamentals.

Runge-Kutta Methods.

- f is the Lorentz force described in Eq. 1

- Runge-Kutta-Nyström.

$$\vec{K}_1 = \vec{f}(\vec{\beta}, \vec{x})$$
$$\vec{K}_2 = \vec{f}\left(\vec{\beta} + \tfrac{1}{2}\vec{K}_1, \vec{x} + \tfrac{1}{2}\vec{\beta}h + \tfrac{1}{2}\vec{K}_1 h^2\right)$$
$$\vec{K}_3 = \vec{f}\left(\vec{\beta} + \tfrac{3}{4}\vec{K}_2, \vec{x} + \tfrac{3}{4}\vec{\beta}h + \tfrac{3}{4}\vec{K}_2 h^2\right)$$
$$\vec{K}_4 = \vec{f}\left(\vec{\beta} + \tfrac{2}{9}\vec{K}_1 + \tfrac{1}{3}\vec{K}_2 + \tfrac{4}{9}\vec{K}_3,\ \vec{x} + \vec{\beta}h + \left(\tfrac{2}{9}\vec{K}_1 + \tfrac{1}{3}\vec{K}_2 + \tfrac{4}{9}\vec{K}_3\right)h^2\right)$$

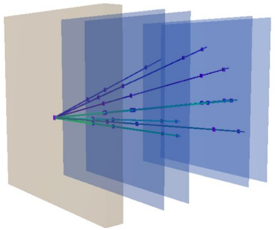
$$\vec{\beta}_{\text{new}} = \vec{\beta} + h\left(\tfrac{2}{9}\vec{K}_1 + \tfrac{1}{3}\vec{K}_2 + \tfrac{4}{9}\vec{K}_3\right)$$
$$\vec{x}_{\text{new}} = \vec{x} + \vec{\beta}h + \left(\tfrac{7}{24}\vec{K}_1 + \tfrac{1}{4}\vec{K}_2 + \tfrac{1}{3}\vec{K}_3 + \tfrac{1}{8}\vec{K}_4\right)h^2$$
$$\vec{\beta}' = \vec{\beta}h + \left(\tfrac{7}{24}\vec{K}_1 + \tfrac{1}{4}\vec{K}_2 + \tfrac{1}{3}\vec{K}_3 + \tfrac{1}{8}\vec{K}_4\right)h^2$$
$$\epsilon = \left\|\vec{\beta}' - \vec{\beta}_{\text{new}}\right\|$$

- Runge-Kutta 4(5)

$$\vec{K}_1 = \vec{f}(\vec{\beta}, \vec{x})$$
$$\vec{K}_2 = \vec{f}\left(\vec{\beta} + \tfrac{1}{5}h\vec{K}_1, \vec{x} + \tfrac{1}{5}h\vec{\beta}\right)$$
$$\vec{K}_3 = \vec{f}\left(\vec{\beta} + h\left(\tfrac{3}{40}\vec{K}_1 + \tfrac{9}{40}\vec{K}_2\right), \vec{x} + h\tfrac{3}{10}\vec{\beta}\right)$$
$$\vec{K}_4 = \vec{f}\left(\vec{\beta} + h\left(\tfrac{3}{10}\vec{K}_1 - \tfrac{9}{10}\vec{K}_2 + \tfrac{6}{5}\vec{K}_3\right), \vec{x} + h\tfrac{3}{5}\vec{\beta}\right)$$
$$\vec{K}_5 = \vec{f}\left(\vec{\beta} + h\left(-\tfrac{11}{54}\vec{K}_1 + \tfrac{5}{2}\vec{K}_2 - \tfrac{70}{27}\vec{K}_3 + \tfrac{35}{27}\right), \vec{x} + h\vec{\beta}\right)$$
$$\vec{K}_6 = \vec{f}\left(\vec{\beta} + h\left(\tfrac{1631}{55296}\vec{K}_1 + \tfrac{175}{512}\vec{K}_2 + \tfrac{575}{13824}\vec{K}_3 + \tfrac{44275}{110592}\vec{K}_4 + \tfrac{253}{4096}\vec{K}_5\right), \vec{x} + h\tfrac{7}{8}\vec{\beta}\right)$$

$$\vec{\beta}_4 = \vec{\beta} + h\left(\tfrac{25}{216}\vec{K}_1 + \tfrac{1408}{2565}\vec{K}_3 + \tfrac{2197}{4104}\vec{K}_4 - \tfrac{1}{5}\vec{K}_5\right)$$
$$\vec{\beta}_5 = be\vec{t}a + h\left(\tfrac{16}{135}\vec{K}_1 + \tfrac{6656}{12825}\vec{K}_3 + \tfrac{28561}{56420}\vec{K}_4 - \tfrac{9}{50}\vec{K}_5 + \tfrac{2}{55}\vec{K}_6\right)$$
$$\epsilon = \left\|\vec{\beta}_4 - \vec{\beta}_5\right\|$$
$$\vec{x_{\text{new}}} = \vec{x} + h\vec{\beta}$$

Propagator.

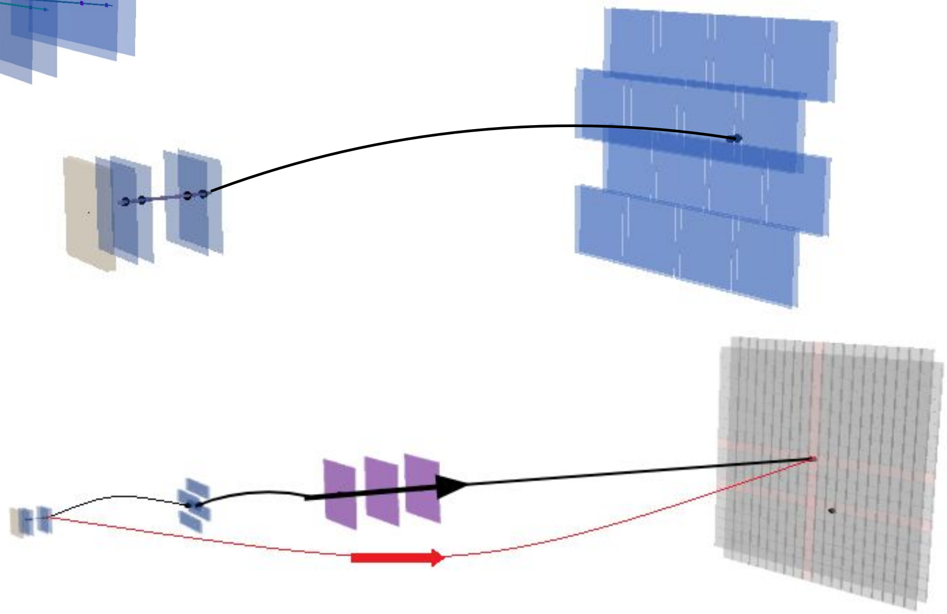


- Based on RK and Energy loss.
- MC-based observable.
  - All information is known (A, Z, p).
- Reconstructed deducted observable.
  - Deduce A-Z (cf Slide 7.)
  - Momentum.

$$p = \sqrt{E^2 + 2mAE}$$

- Propagator.
  - 3rd pixel sensor in VTX detector.
  - Clusters association.
- Residuals.

$$\mathrm{Res} = \vec{Pos}_{Out} - \vec{Pos}_{Extrpl}$$

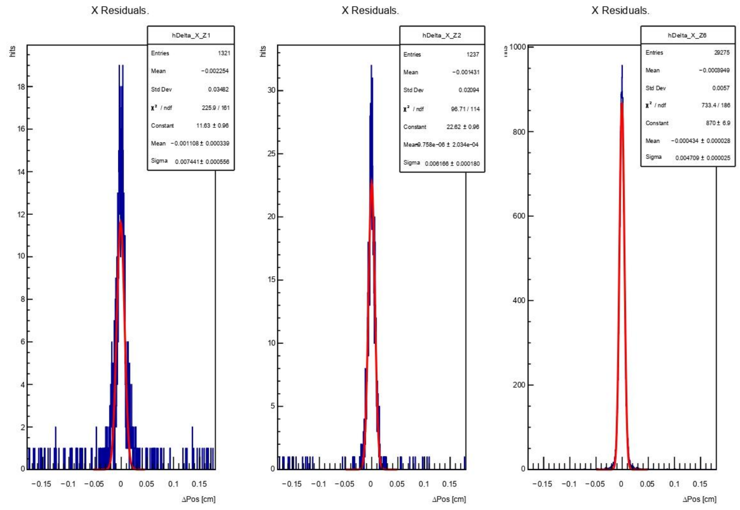


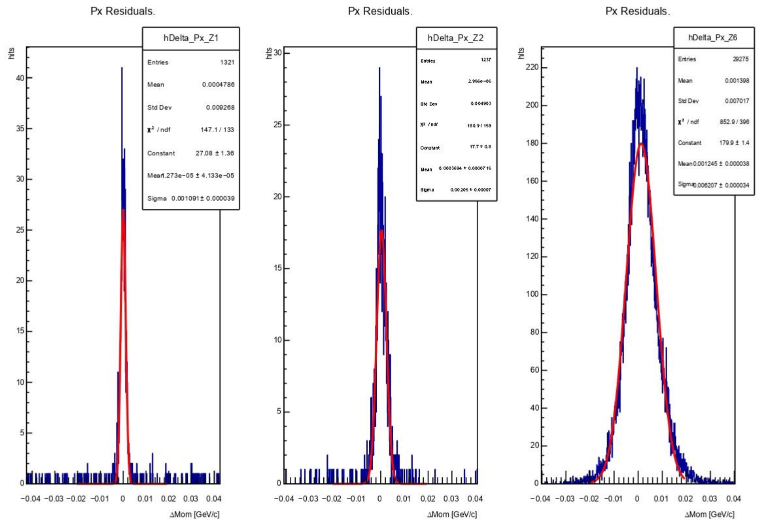
Global reconstruction by detector planes. Image taken from Ch. FINCK propagator presentation.

Results.

Results: VTX-IT propagator.

MC-based hits.





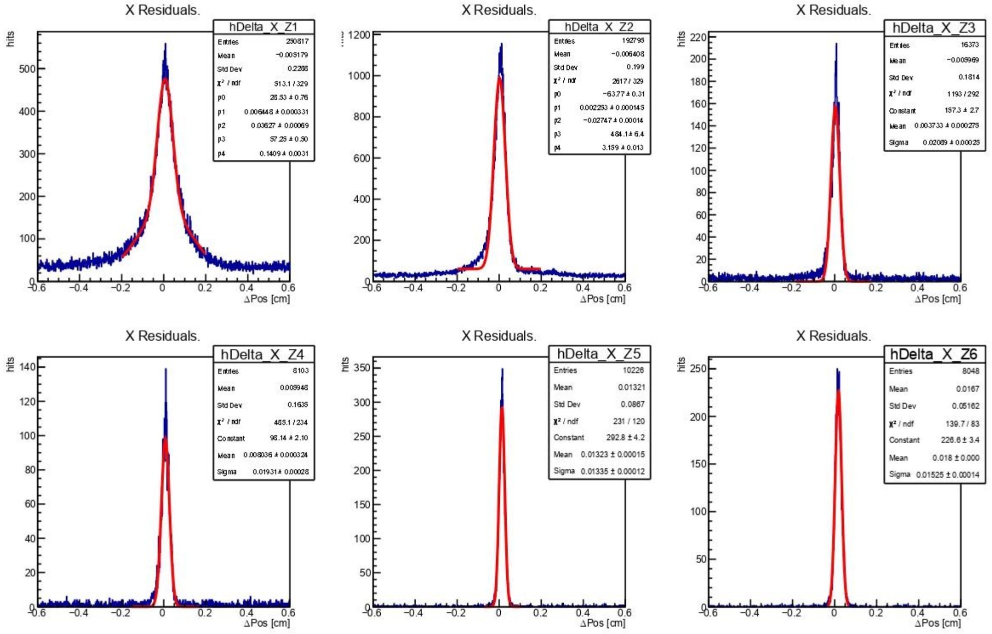
- X-coordinate positional residuals.
- Protons, Alpha particles and Carbon ions.
- Residuals are centered on 0.
    - Residuals mean μ ≃ -11 , 0.1 and -4.3 μm.
- → Model seems to work.

- X-coordinate momentum residuals.
- Protons, Alpha Particles and Carbon ions.
- Residuals are centered on 0.
    - Residuals mean is about few MeV/c μ ≃ 0.013, 0.37 and 1.245 MeV/c.

Results: VTX-IT propagator.

Data-Like mass assumption.

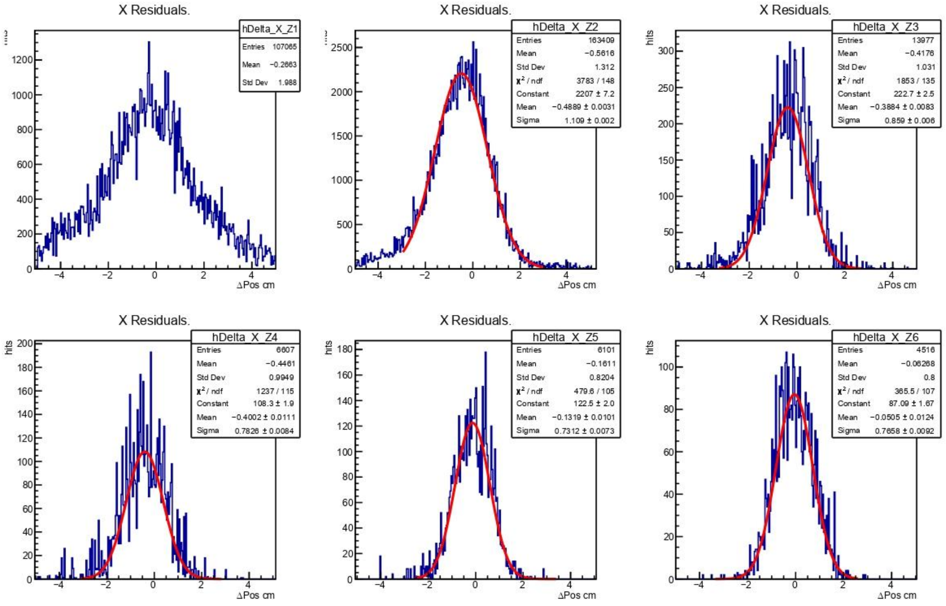
- X-coordinate positional residuals.
- All the species.
- Residuals centered around 0.
  - Scattering processes in protons.
  - Less scattering for heavier q/p ratio.
- Few dozen µm deviation.
  - Good initial propagation model.



Results: VTX-IT-MSD-TW.

MC-based hits.

- Residual mean value deviation under cm magnitude order. (For Z=6: μ = -0.51 cm)
- Scattering.
  - Lighter species, mean value is closer to 0, but having a larger distribution.
- Time-of-Flight Resolution. $\sigma_{TW} = \frac{2}{\sqrt{12}} \approx 0.56\,\mathrm{cm}$



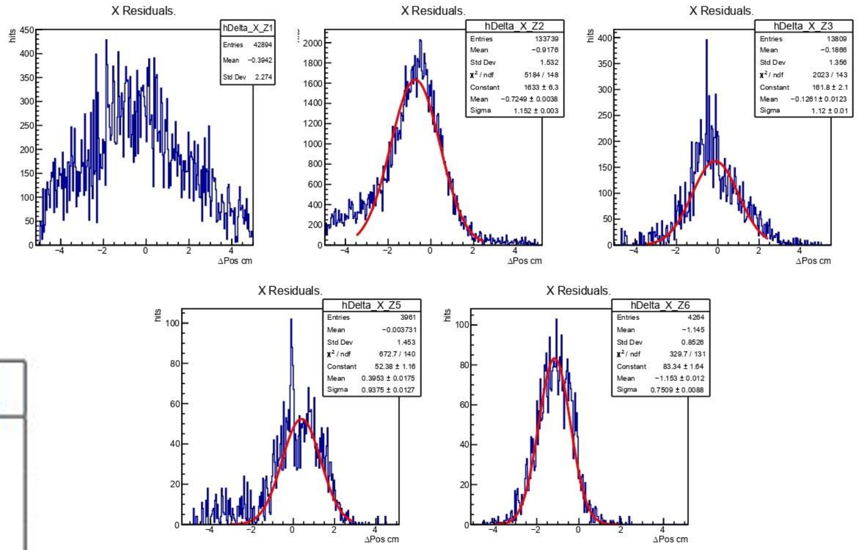
Z	Mean (μ) [cm]	Std. Dev. (σ) [cm]
1	-0.266	1.988
2	-0.489 ± 0.003	1.109 ± 0.002
3	-0.388 ± 0.008	0.859 ± 0.006
4	-0.40 ± 0.01	0.783 ± 0.008
5	-0.13 ± 0.01	0.731 ± 0.007
6	-0.51 ± 0.01	0.766 ± 0.009

Results: VTX-IT-MSD-TW.

Data-Like mass assumption.

- TW reconstruction is just few deviated than MC-based. (For Z=6: μ=-1.15 cm)
- Not enough data to conclude satisfactory for Z=3, Z=4 and Z=5.
- Mass and momentum estimation → Remains a good estimation.
- Biased ?

Z	Mean (μ) [cm]	Std. Dev. (σ) [cm]
1	-0.291	1.707
2	-0.699 ± 0.005	1.082 ± 0.004
3	-0.24 ± 0.02	1.09 ± 0.01
4	-1.87 ± 0.03	0.90 ± 0.03
5	-0.39 ± 0.03	0.98 ± 0.02
6	-1.15 ± 0.02	0.76 ± 0.01



Conclusion.

Conclusion.

- Simple propagator model works correctly (Assess with MC data).
- Model has a good performance to propagate to the TW detector, magnitude order of centimeters (With real-like data) → Propagation along ~170cm.
- Fast propagator to check displacement of detectors.
- Implementation to go further.
  - Diffusion consideration on cluster's association.
  - Taking into account residuals alignment.

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Appendices.

Appendix: Energy Loss.

- Energy Loss Calculated theoretically passing through the Graphite Layer with I=78 eV and ρ ≈ 1.99 g/cm^3.

Thickness	Species	$\langle \Delta E \rangle$ in MeV
x=0.25cm	$Z = 1$	2.003
	$Z = 2$	8.012
	$Z = 3$	18.028
	$Z = 4$	32.049
	$Z = 5$	50.077
x=0.5cm	$Z = 6$	144.222

$E_c = E_{beam} \times A - \Delta E$ with $E_{beam} = 0.2 GeV/u$

Appendix: Results VTX-IT.

MC-based hits.

Z	Mean (μ) [μm]	Std. Dev. (σ) [μm]
1	-11 ± 3	74 ± 6
2	0.1 ± 2	62 ± 2
6	-4.3 ± 0.3	47.0 ± 0.3

- X-coordinate table positional residual from MC-based hit. For species Z=1, Z=2 and Z=6.

Z	Mean (μ) [MeV/c]	Std. Dev. (σ) [MeV/c]
1	0.013 ± 0.04	1.09 ± 0.04
2	0.37 ± 0.07	2.05 ± 0.07
6	1.245 ± 3.8	6.21 ± 0.03

- X-coordinate table momentum residuals from MC-based hit. For species Z=1, Z=2 and Z=6.

Appendix: Results VTX-IT.

TW-reconstructed hits.

Z	Mean (μ) [μm]	Std. Dev. (σ) [μm]
1	64 ± 3	362 ± 7
2	23 ± 1	275 ± 1
3	37 ± 3	209 ± 3
4	80 ± 3	193 ± 3
5	132 ± 2	135 ± 1
6	180 ± 2	156 ± 2

- X-coordinate table positional residual from TW-reconstructed hit. For species all the species.

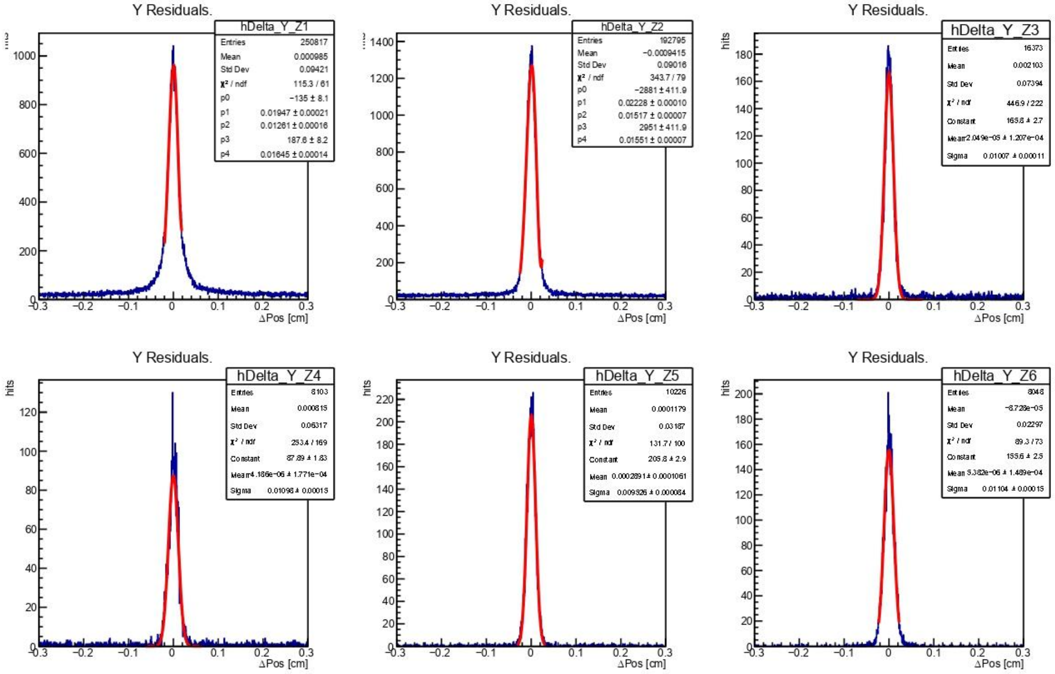
Z	Mean (μ) [μm]	Std. Dev. (σ) [μm]
1	194 ± 2	126 ± 2
2	223 ± 1	151 ± 1
3	0.04 ± 1.8	110 ± 2
4	0.21 ± 1.2	101 ± 1
5	3 ± 1	96 ± 1
6	0.65 ± 1.3	111 ± 1

- Y-coordinate table positional residuals from TW-reconstructed hit. For species all the species.

Appendix: Results VTX-IT. Y-coordinate

TW-reconstructed hits.

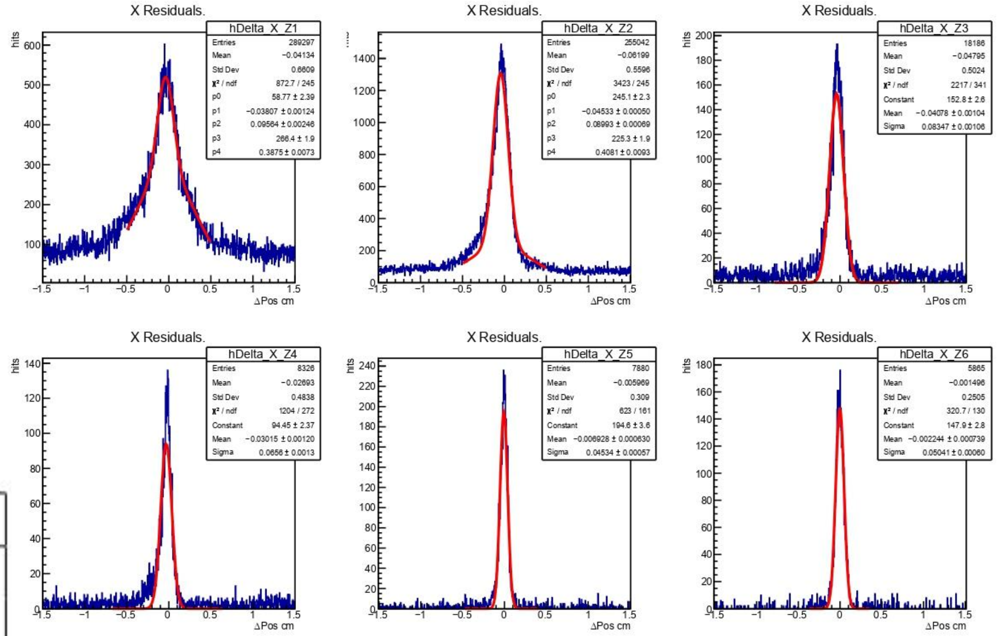
- Fluka simulation.
- Y-coordinate positional residuals.
- All the species.
- Few µm deviation.



Results: IT-MSD propagator.

MC-based hits.

- X-coordinate residuals
- All the species
- Higher deviation than VTX-IT
    - Few hundred deviation for lower species.
- Problematic propagator compared to the VTX-IT?



Z	Mean (μ) [μm]	Std. Dev. (σ) [μm]
1	381 ± 12	956 ± 24
2	-453 ± 5	899 ± 7
3	-407 ± 10	834 ± 12
4	-302 ± 12	656 ± 13
5	-69 ± 6	453 ± 6
6	-22 ± 7	504 ± 6

Appendix: Results IT-MSD.

MC-based hits.

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3	-407 ± 10	834 ± 12
4	-302 ± 12	656 ± 13
5	-69 ± 6	453 ± 6
6	-22 ± 7	504 ± 6

Z	Mean (μ) [μm]	Std. Dev. (σ) [μm]
1	91 ± 4	450 ± 4
2	73 ± 3	350 ± 3
3	70 ± 6	305 ± 5
4	89 ± 9	307 ± 8
5	80 ± 6	278 ± 5
6	65 ± 7	323 ± 6

- X-coordinate table positional residual from MC-based hit. For species all the species.
- Y-coordinate table positional residuals from MC-based hit. For species all the species.

Appendix: Results VTX-IT-MSD-TW

MC-based hits.

Z	Mean (μ) [cm]	Std. Dev. (σ) [cm]
1	-0.266	1.988
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4	-1.87 ± 0.03	0.90 ± 0.03
5	-0.39 ± 0.03	0.98 ± 0.02
6	-1.15 ± 0.02	0.76 ± 0.01

- X-coordinate table positional residuals from TW-reconstructed hit. For species all the species.

Appendix: Results VTX-IT-MSD-TW_Plot

TW-reconstructed hits.

- X-coordinate positional residuals from TW-reconstructed hit. For species all the species.