Preliminary results on a modified Thomson Parabola Spectrometer design for laser-driven ion accelerators

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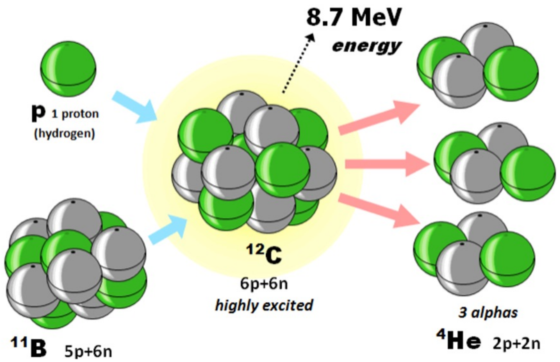
Motivation

Investigation and detection of ionic products of 11B(p,α)2α initiated by the interaction of laser with matter



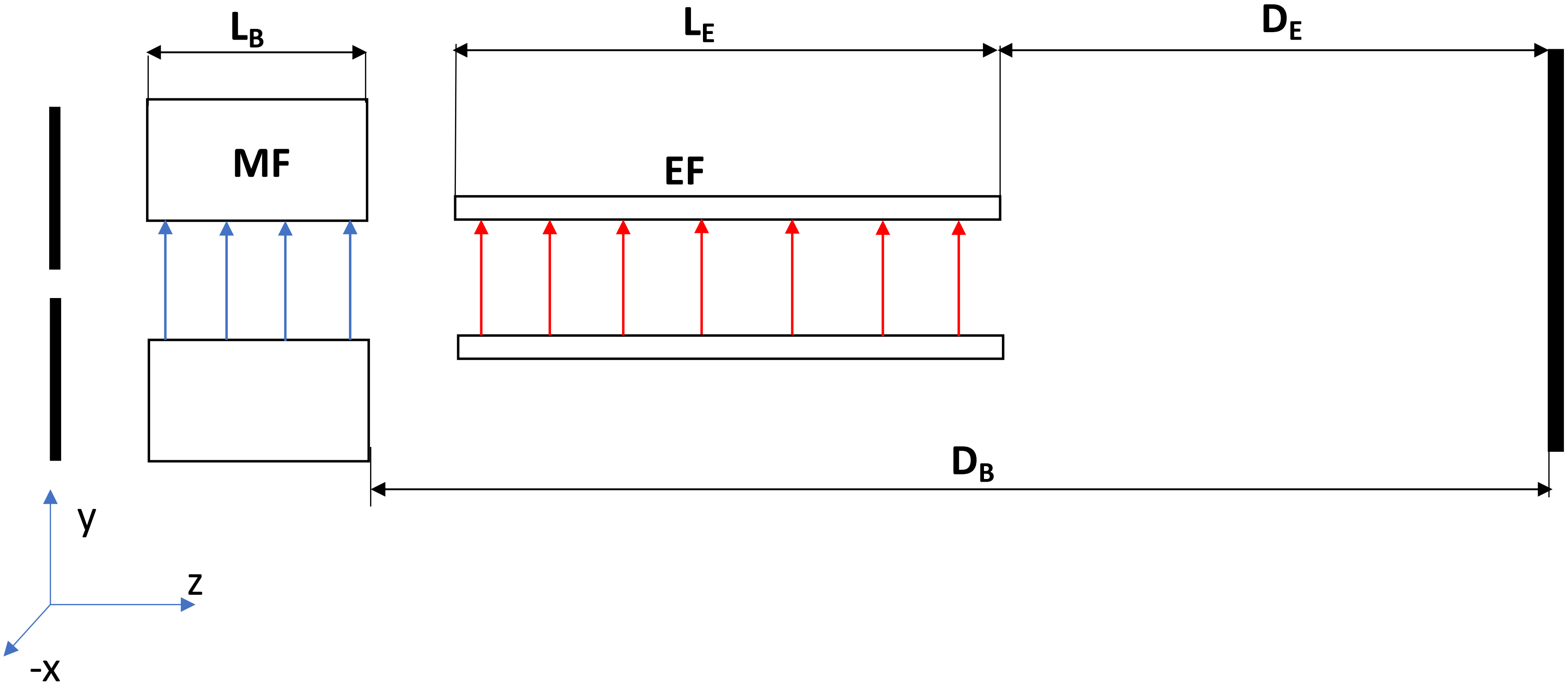
The proton boron-11 reaction – first an intermediate unstable carbon nucleus is formed, which rapidly splits into three alpha particles.

https://fusionandthings.eu/2019/06/05/new-calculations-show-proton-boron-fusion-is-still-difficult/

Aim

Development of a modified Thomson Parabola Spectrometer (TPS) dedicated to differentiate proton and alpha particles traces with energy ranges of 5-50 MeV and 2-10 MeV, respectively.

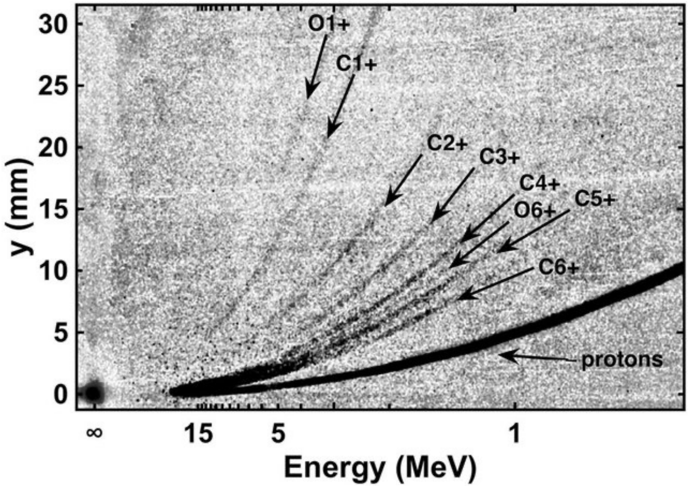
Standard TPS



Possible solutions for sufficient q/m resolution

Species separation can be increased by

- Electric field strength
- Longitudinal extension
- Drift range extension



Soloviev, A., et al. "Experimental evidence for short-pulse laser heating of solid-density target to high bulk temperatures." *Scientific Reports* 7.1 (2017): 1-10.

Possible limitation

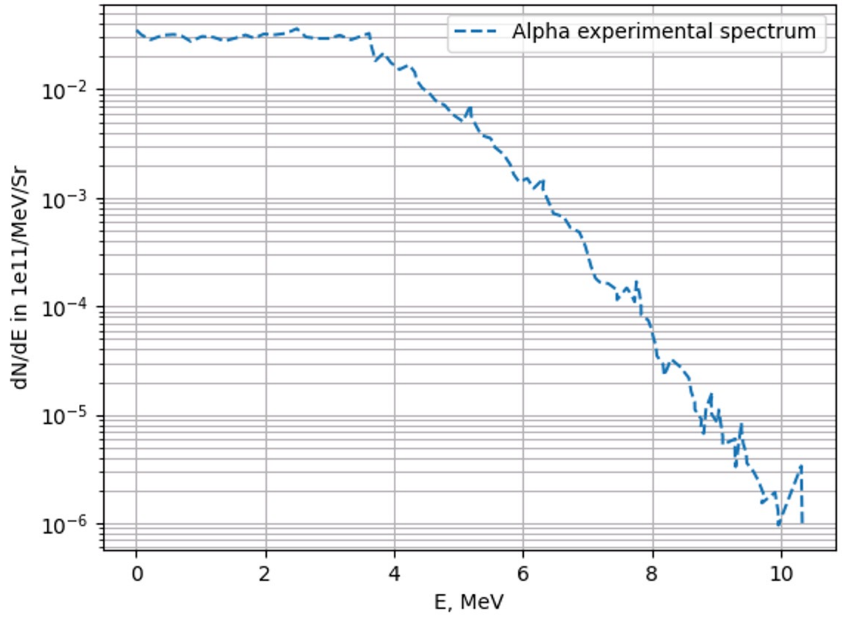
Electric field

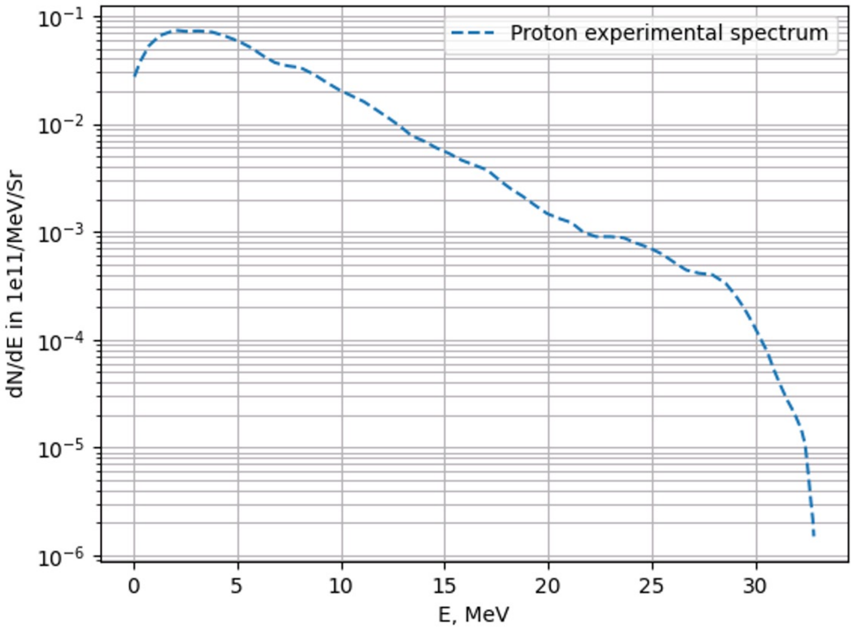
- Dielectric breakdown of vacuum
- Fringe effect

Magnetic field

- High magnetic field causes gyration – particles cannot reach the detector
- Fringe effect
- Long drift electric length makes magnetic field drift range longer

Experimental spectrum





Bonvalet, J., et al. "Energetic α-particle sources produced through proton-boron reactions by high-energy high-intensity laser beams." *Physical Review E* 103.5 (2021): 053202.

Analytical formulation

Equation of ion motion in the TPS is

$$\frac{d\vec{p}}{dt} = q\left(\vec{E} + \frac{\vec{p}}{m\gamma}\times\vec{B}\right)$$

where $m, q, p, \gamma, E\ and\ B$, are the ion mass, charge, momentum, Lorentz factor, electric and magnetic field, respectively.

Analytical formulation (cont.)

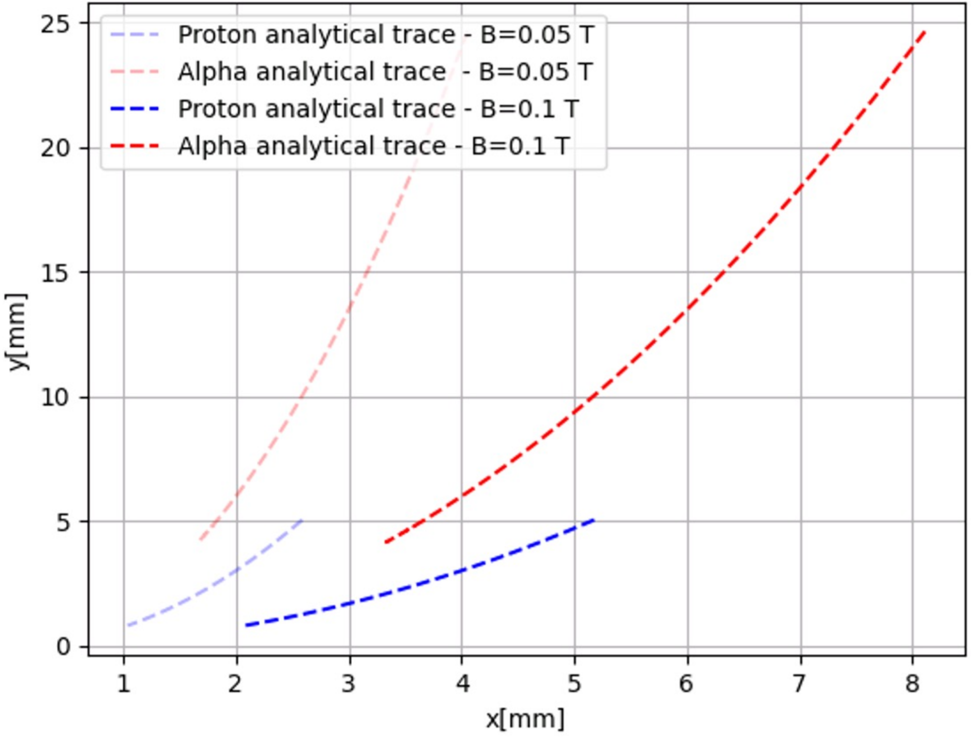
Displacement of ions on the detector plane along x and y directions as

$$x = \frac{1}{\sqrt{\gamma^2 - 1}} \frac{qB}{mc} L_B \left(D_B + \frac{L_B}{2} \right)$$
$$y = \frac{1}{\gamma^2 - 1} \frac{qE}{mc^2} L_E \left(D_E + \frac{L_E}{2} \right)$$

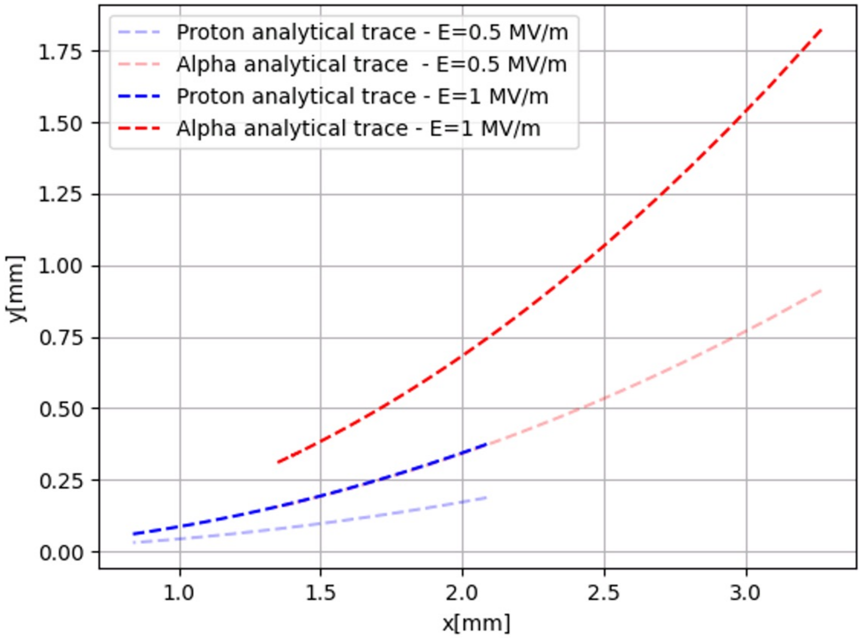
Track of particles of a given q/m ratio on the detector place

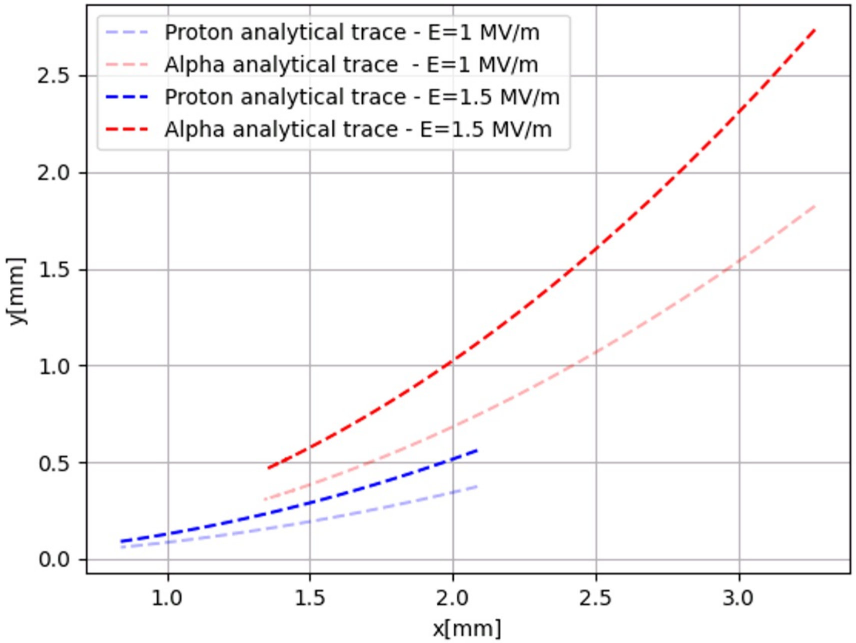
$$y = \frac{m\, E\, L_E}{q\, B^2\, {L_B}^2} \frac{(\frac{L_E}{2} + D_E)}{(\frac{L_B}{2} + D_B)^2} x^2$$

Analytical prediction - magnetic field strength



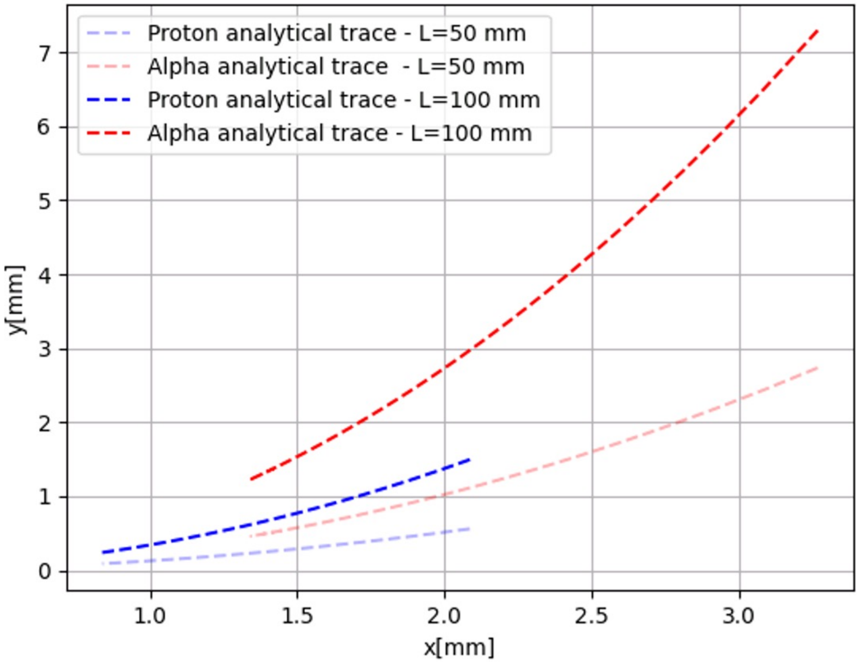
Analytical prediction - electric field strength

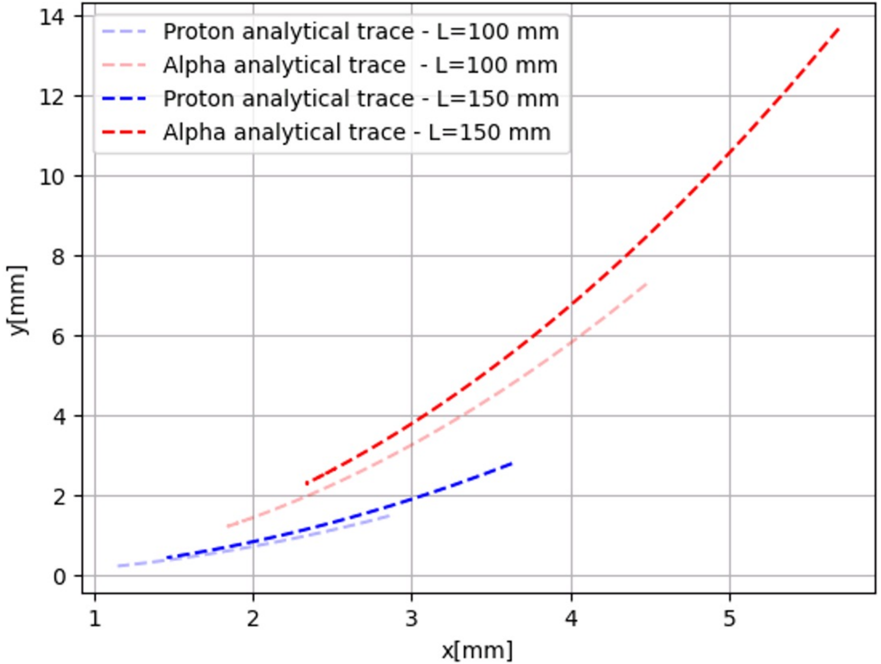




E=0.5 MV/m	E=1 MV/m	E=1.5 MV/m
0.076561 mm	0.153122 mm	0.229684 mm

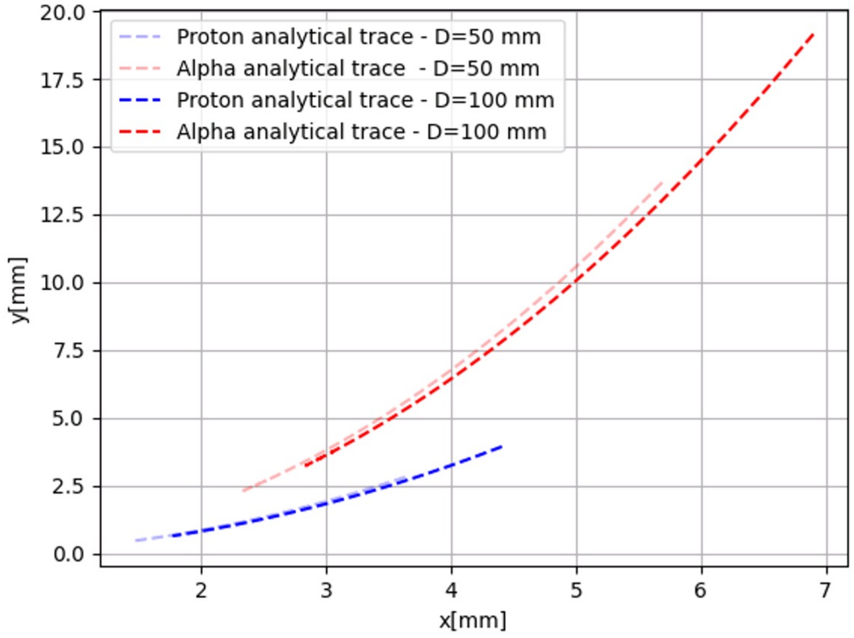
Analytical prediction - electric field length

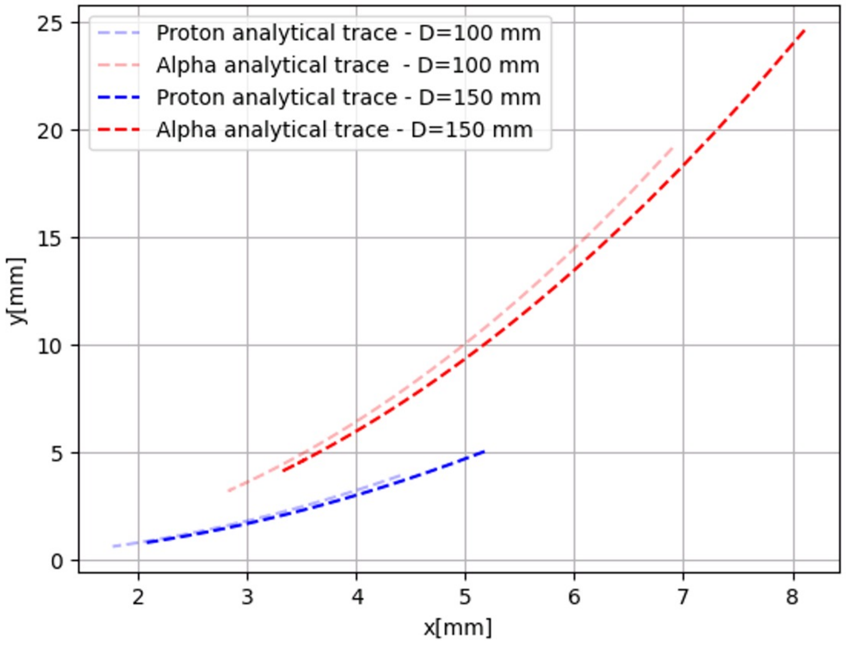




L=50 mm	L=100 mm	L=150 mm
0.229684 mm	0.61249 mm	1.148418 mm

Analytical prediction - electric field drift length



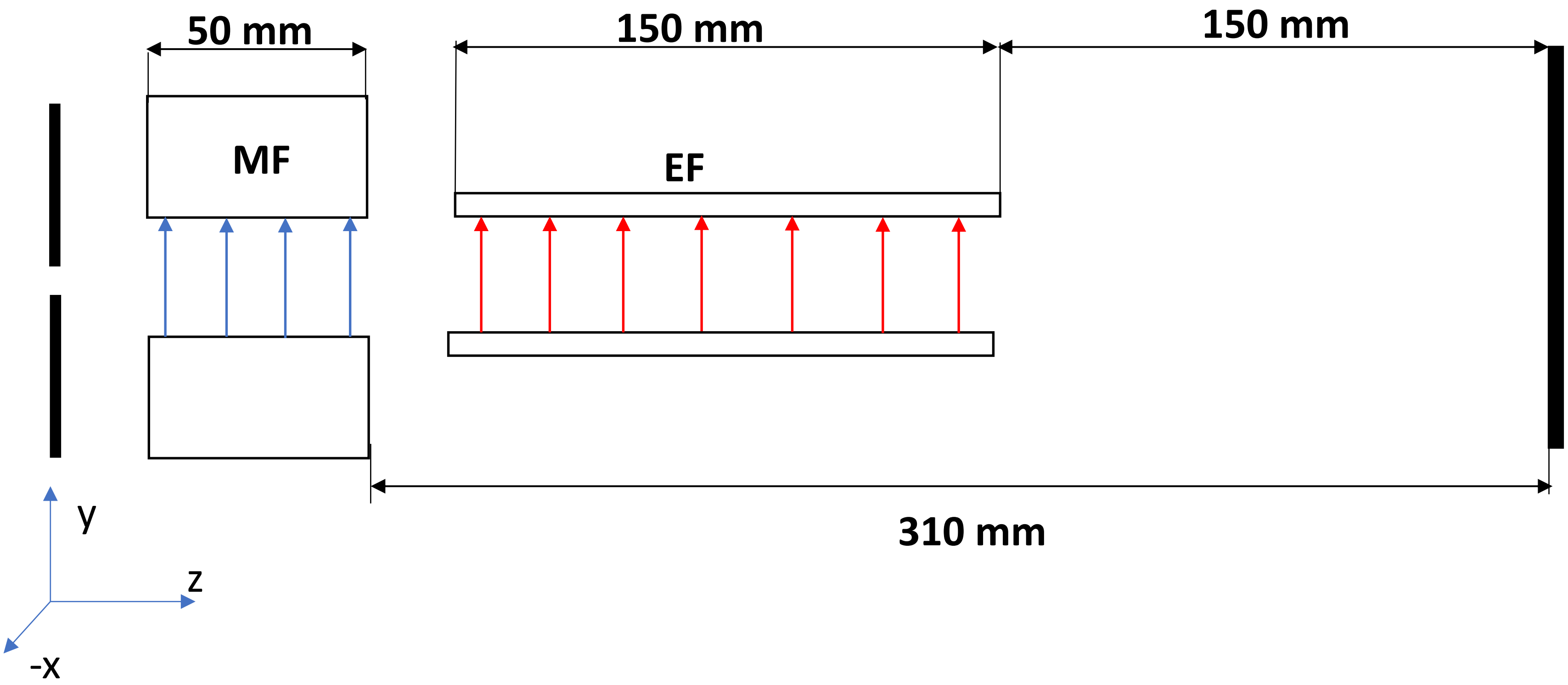


D=50 mm	D=100 mm	D=150 mm
1.148418 mm	1.607786 mm	2.067153 mm

Analytical prediction

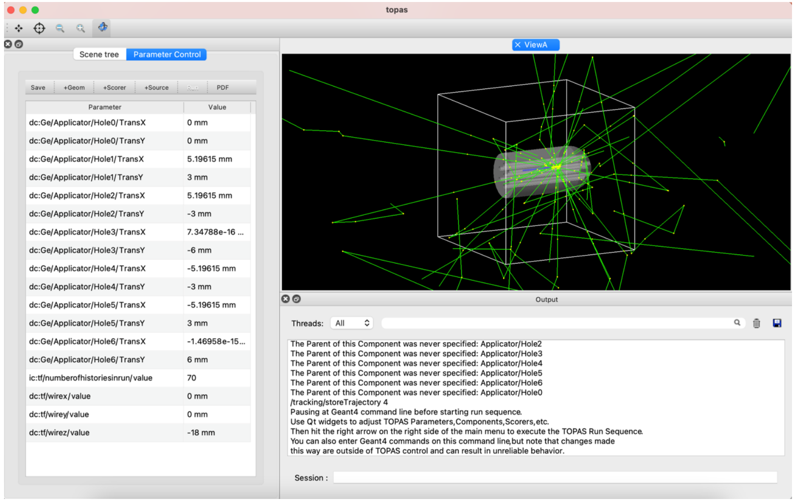
E, MV/m	L, mm	D, mm	Resolution, mm
0.5	50	50	0.076561
1.0			0.153122
1.5			0.229684
1.5	50	50	0.229684
	100		0.61249
	150		1.148418
1.5	150	50	1.148418
		100	1.607786
		150	**2.067153**

Schematic design



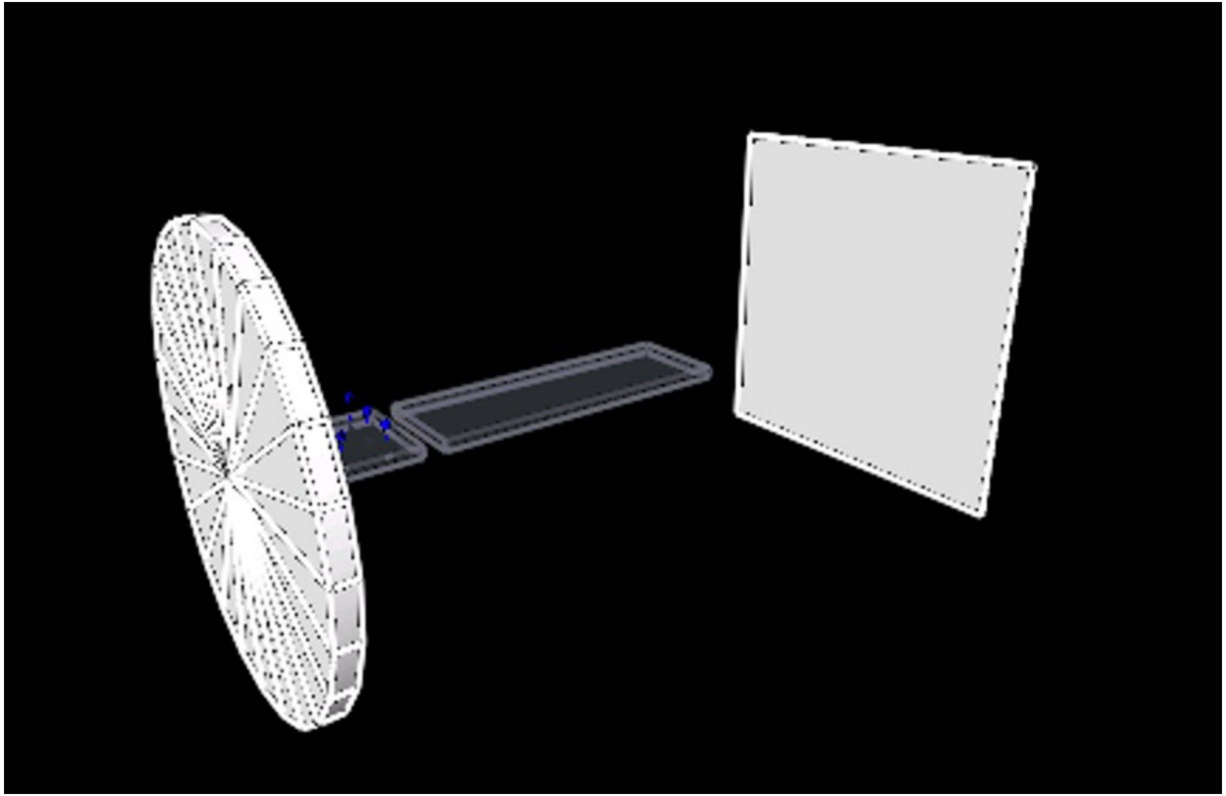
Simulation tool

TOPAS wraps and extends the Geant4 Simulation Toolkit to make advanced Monte Carlo simulation.

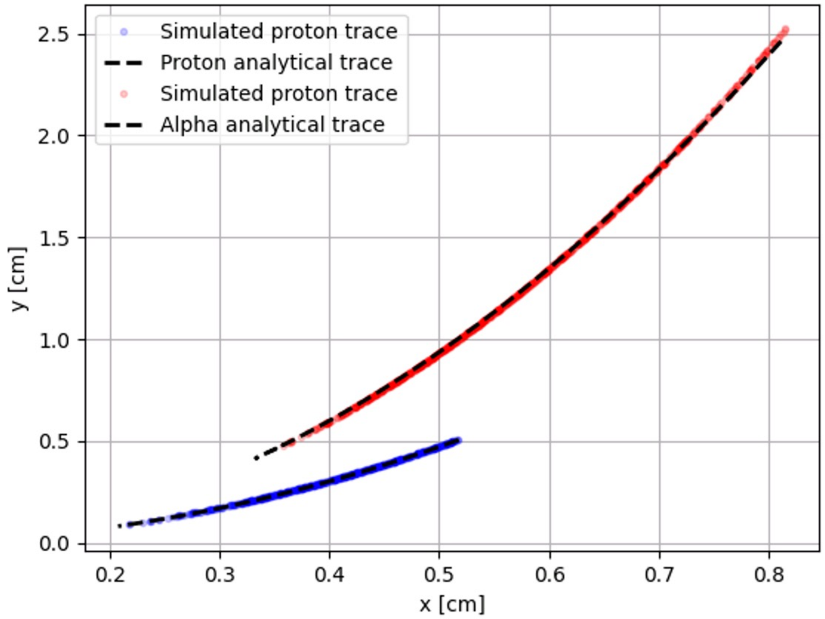


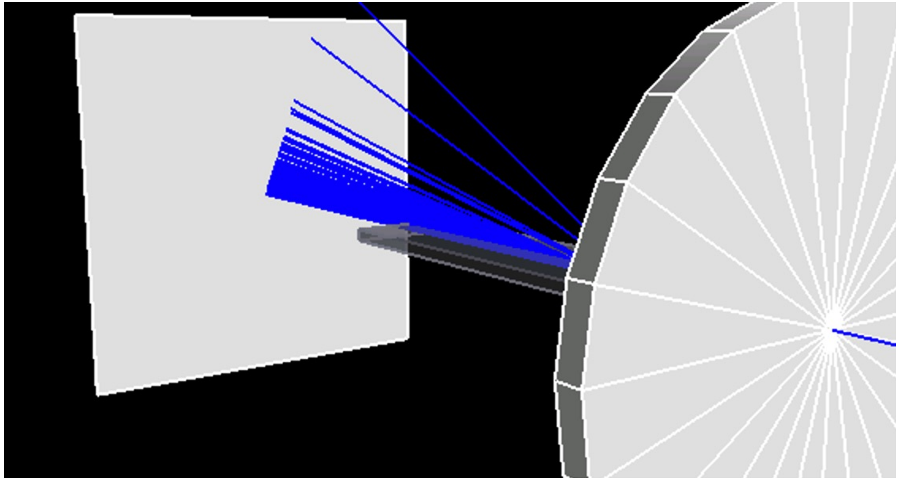
J Perl, J Shin, J Schumann, B Faddegon, H Paganetti. TOPAS: an innovative proton Monte Carlo platform for research and clinical applications https://pubmed.ncbi.nlm.nih.gov/23127075/

Simulated design



Simulation results





Conclusion

1. A preliminary design has been agreed upon - increased electric field, electrode length, and drift length
2. Design benchmarked with simulation using realistic energy spectrum – confirms a good resolution at high energy

Future tasks

1. To implement the detector’s sensitivity
2. To implement a modified shape of the electrode for low energy range
3. To consider beam emittance and realistic source parameters
4. To consider fringe effect for electric and magnetic fields
5. To investigate filtering technique to differentiate ions with the same q/m ratio