A Radially and Rotationally Adjustable Magnetic Mangle for Particle Beams

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Myriad Magnets

Phillips Exeter Academy, Exeter, NH, USA

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Experiment Motivation

Testing the viability of an adjustable magnetic mangle Halbach array as a proof of concept for electromagnet alternatives in accelerators

Goals:

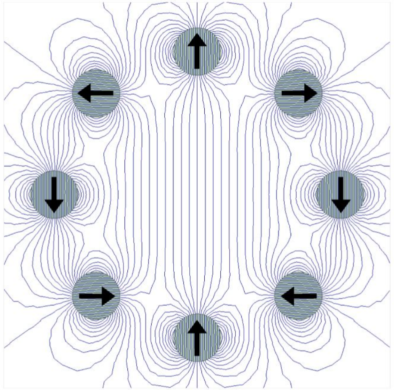
- Replace electromagnets, whose **energy usage is a contributor to climate change**
- **Safer** to use near other electronics, like pacemakers, due to small external field
- Modular design: **cost effective** (compared to electromagnets), reduces waste, convenient

Magnet design: introduction

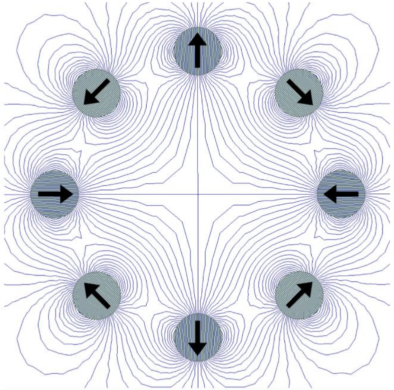
A mangle of 8 permanently diametrically-magnetized cylinders arranged in a circle to produce either a dipole or quadrupole field

Modularity:

- By rotating the magnets, the mangle can be switched: dipole ↔ quadrupole configurations
- By moving the magnets radially inward or outward, the field strength can be adjusted



(a) Dipole arrangement



(b) Quadrupole arrangement

Magnet design: determining optimal cylinder number

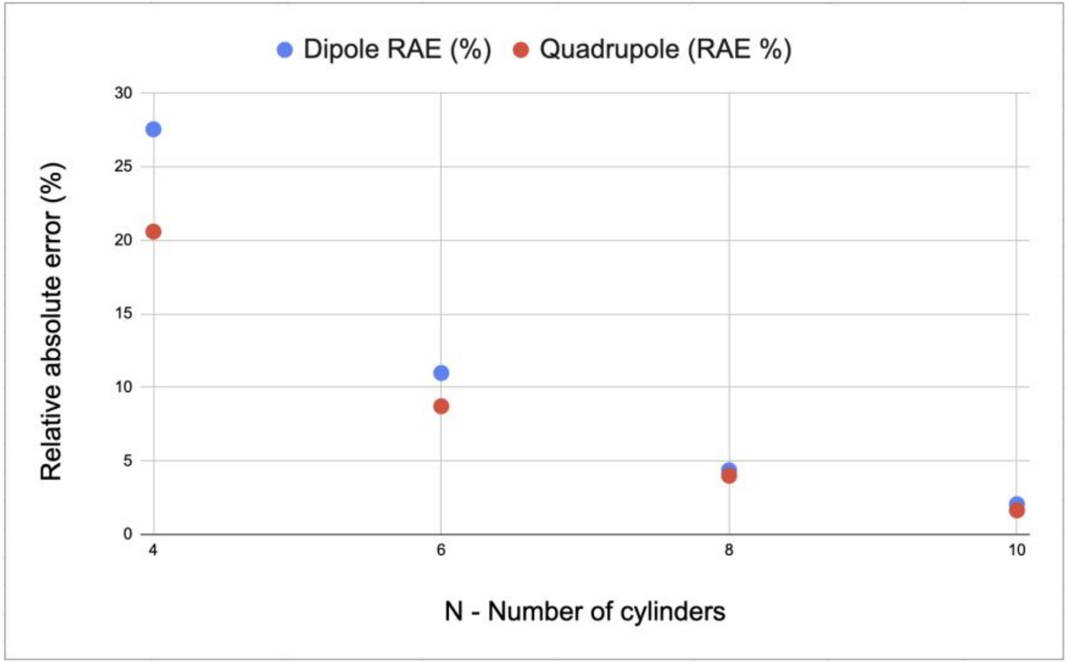
- As *N*, the number of magnets, increases, deviation from ideal magnetic field decreases, but for very large *N* rotating each magnet becomes impractical
- Performed simulations in ANSYS Maxwell and quantified the deviation of the mangle's field from the corresponding ideal field using RAE

$$\text{RAE} = \frac{\sqrt{\sum_{i=1}^{n} |\vec{B}_{mangle_i} - \vec{B}_{ideal_i}|^2}}{\sqrt{\sum_{i=1}^{n} |\vec{B}_{ideal_i}|^2}}$$

$\vec{B}_{mangle_i}$ and $\vec{B}_{ideal_i}$ are the mangle field and corresponding ideal field vectors at a given sample point *i* out of *n* total sample points.

Magnet design: determining optimal cylinder number

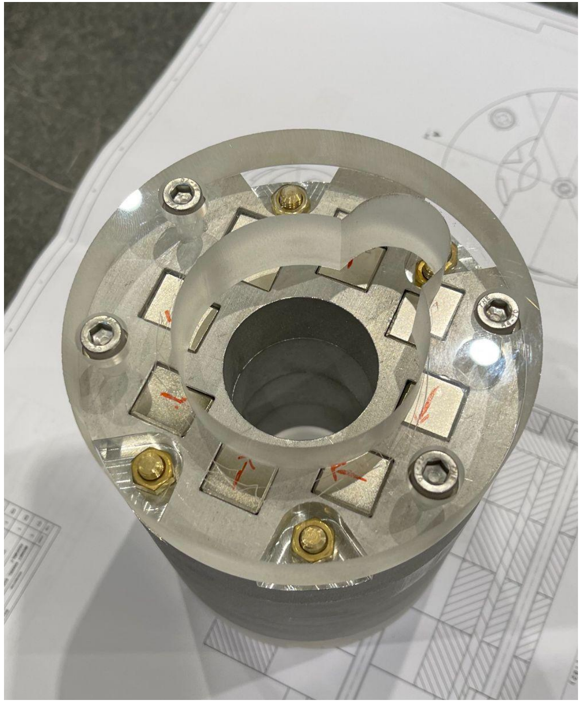
- Performed simulations in ANSYS Maxwell and quantified the deviation of the mangle's field from the corresponding ideal field using Relative Absolute Error (RAE)

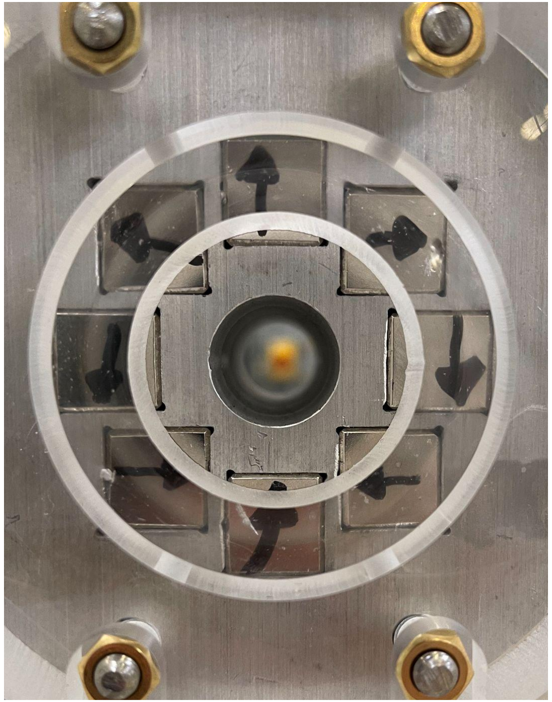


Final Stationary Array

- **Goal**: test the **utility of Halbach** arrays as alternatives to electromagnets, and study the effect of a **changing radius**

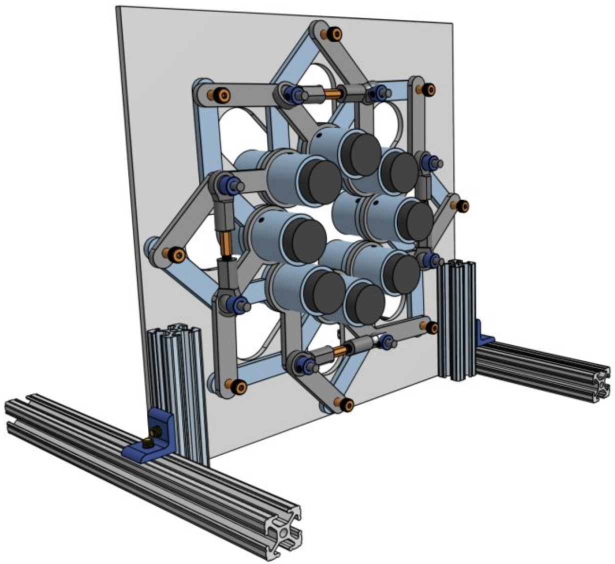
- Two Halbach **dipole arrangements,** stronger magnets → larger magnetic field

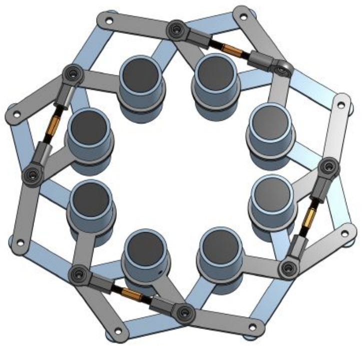


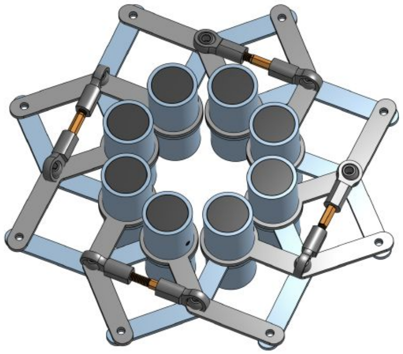


Successfully Used in Beam Area

Original Mangle Design







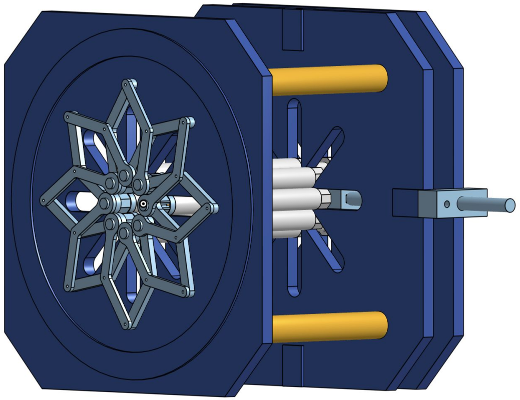
- **Goal**: create on-the-fly radial and rotational adjustment of our magnet
- **Updates**: experiment handling safety, structural safety

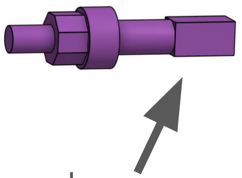
Final Experiments at CERN:

- Explore stationary Halbach arrays
- Update mangle with improved lock mechanism

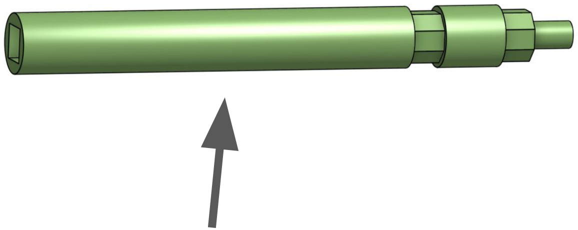
Final Adjustable Array (Design)

- **Goal**: provide a **proof of concept** of a fully adjustable magnetic mangle
- **Magnets within casings**, prevent involuntary translational/rotational movement
- Rotation → **casings slide radially**, octagonal pins

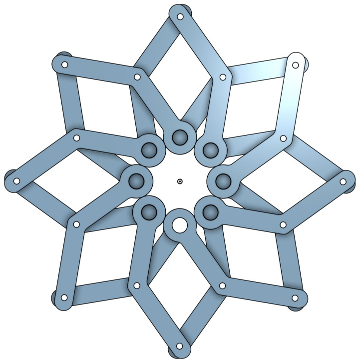




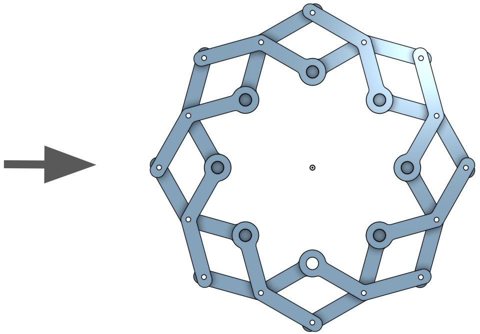
Key can be inserted and rotated to lock in place



Magnet Inside

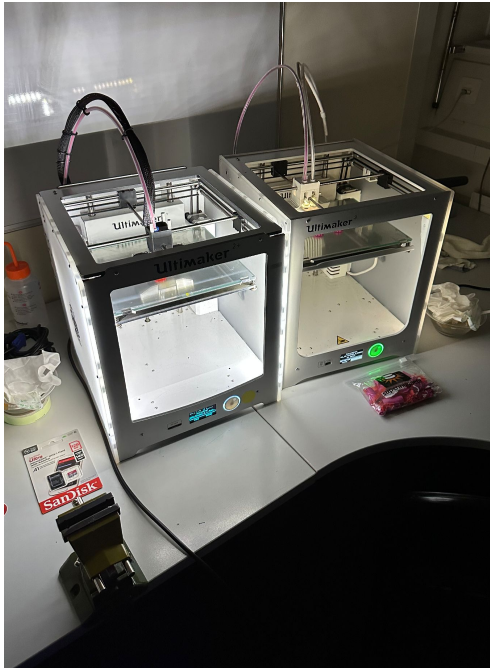


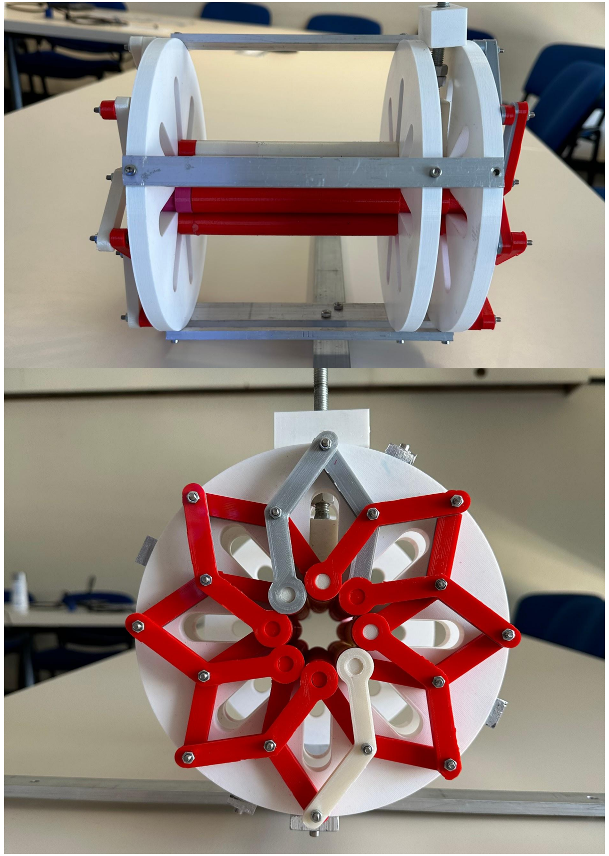
Small Radius



Large Radius

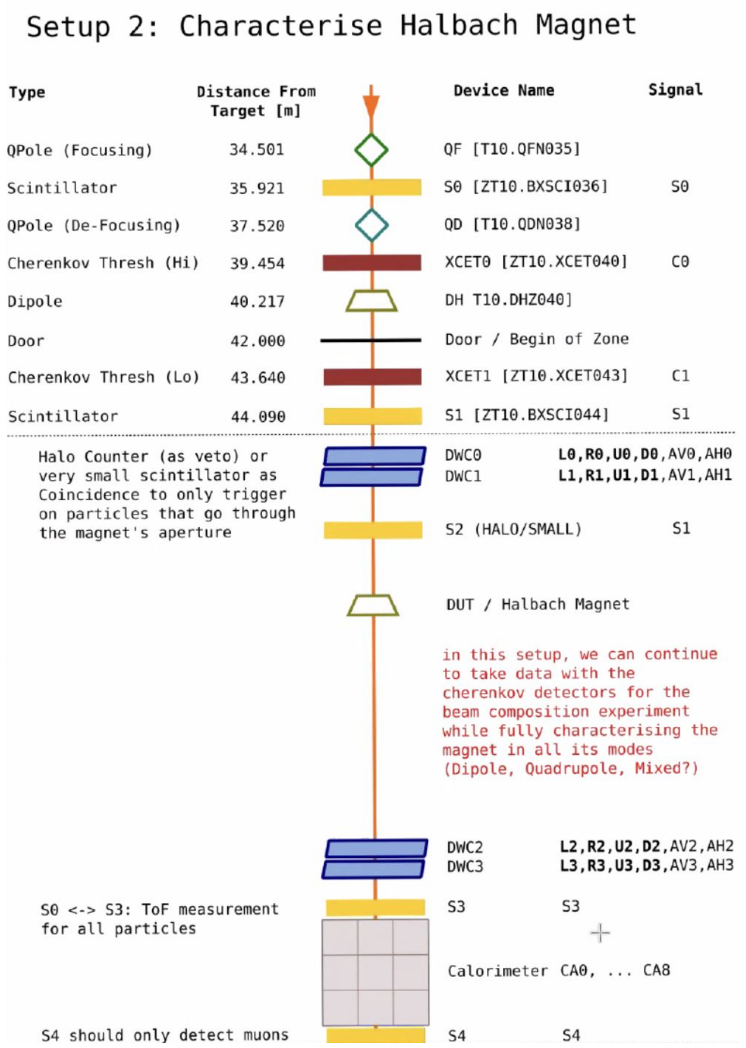
Final Adjustable Array (Fabricated)





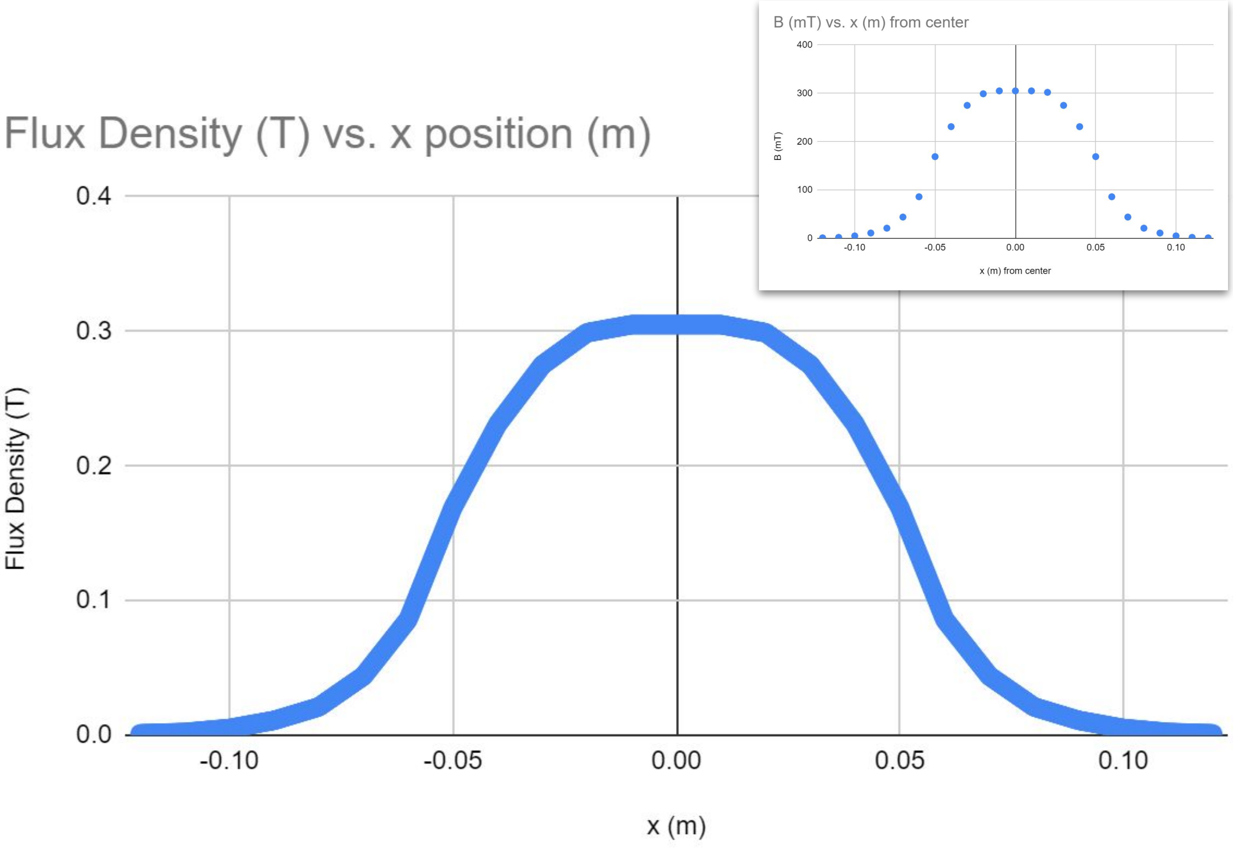
Successfully Used in Beam Area

Experiment design: Detector Setup

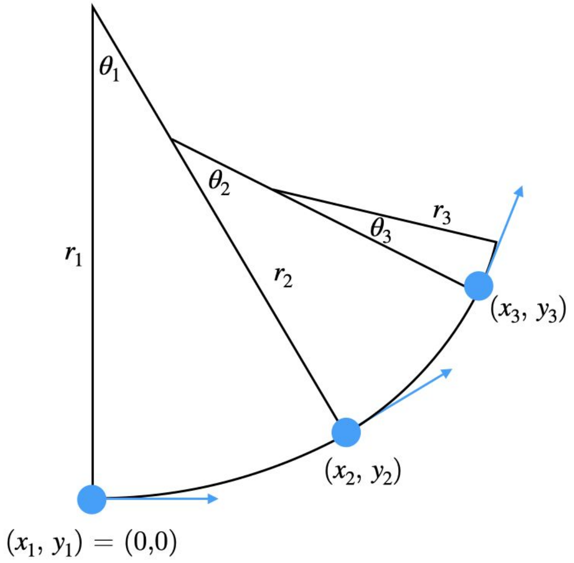


Stationary Mangle Longitudinal Flux Density Profile

- Plateau in middle of mangle cavity
- Flux density drops off rapidly outside of mangle
- Linear interpolation



Predicted Magnet Deflection



$$r(x) = \frac{p}{qB(x)}$$

$$\theta_n = \arcsin\left(\frac{x_{n+1} - x_n + r_n \cos\left(\frac{\pi}{2} - (\theta_{n-1} + \theta_{n-2} + \theta_{n-3} + \dots \theta_1)\right)}{r_n}\right) - (\theta_{n-1} + \theta_{n-2} + \theta_{n-3} + \dots \theta_1)$$

$$y_{n+1} - y_n = r_n\left(\cos(\theta_{n-1} + \theta_{n-2} + \theta_{n-3} + \dots \theta_1) - \cos(\theta_n + \theta_{n-1} + \theta_{n-2} + \theta_{n-3} + \dots \theta_1)\right)$$

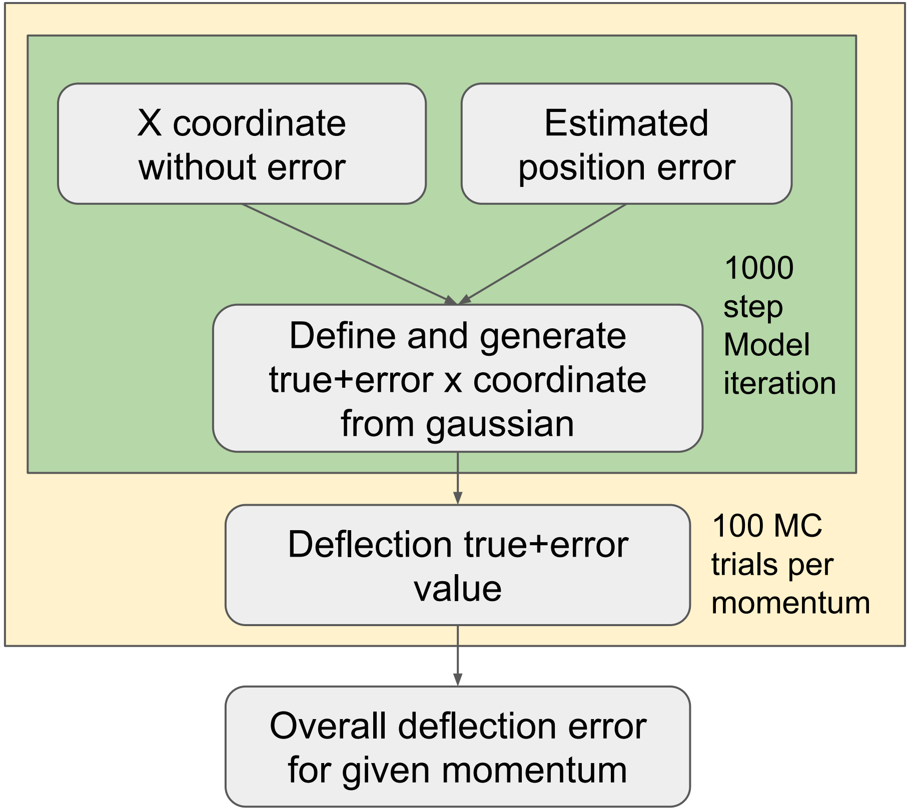
- Given flux density B(x), radius of curvature r(x) is obtained
- Iterate over circular arcs (1000 steps)
- Propagate to DWC2 position after exiting magnet field

Predicted Magnet Deflection - MC Error Propagation

- Gaussian distributions were generated for each source of error (e.g. x-coordinate measurement, teslameter flux density measurement, linear interpolation error).

- Truth+errors were generated according to the gaussian distribution for each line of iteration.

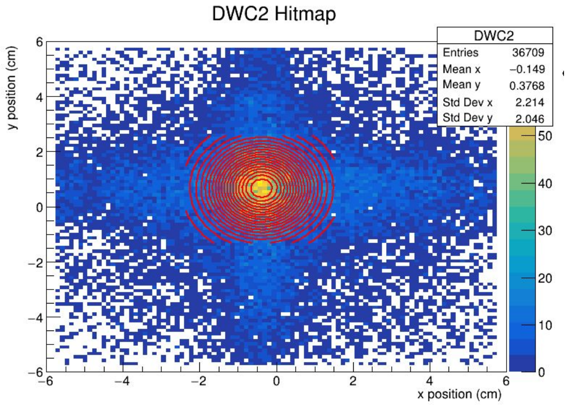
- 100 trials for each momentum value, true+error values were inputted to the model, and stdevs were calculated for the output deflection distributions.

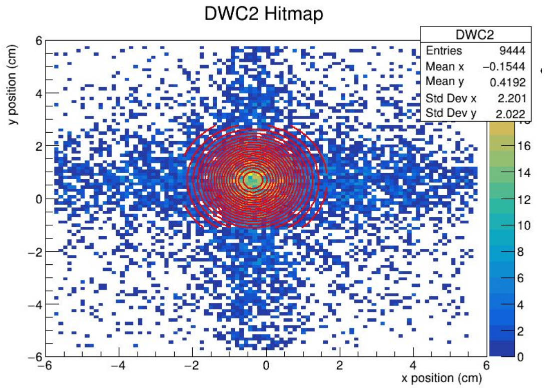


Results

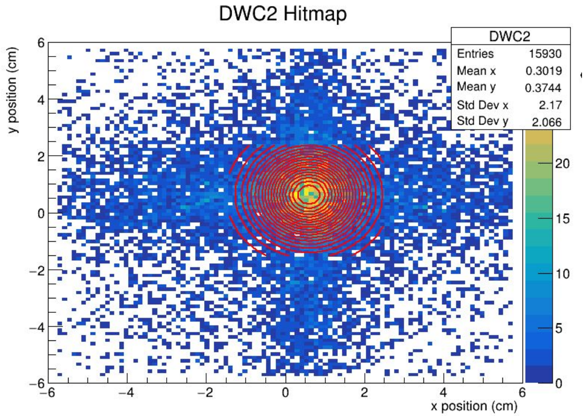
± 8 GeV DWC Magnet Effects (r_{mag}= 2.5 cm)

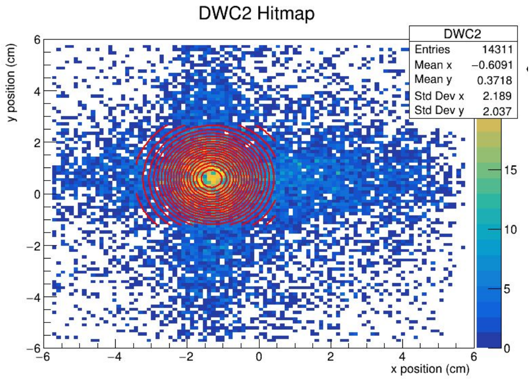
No magnet





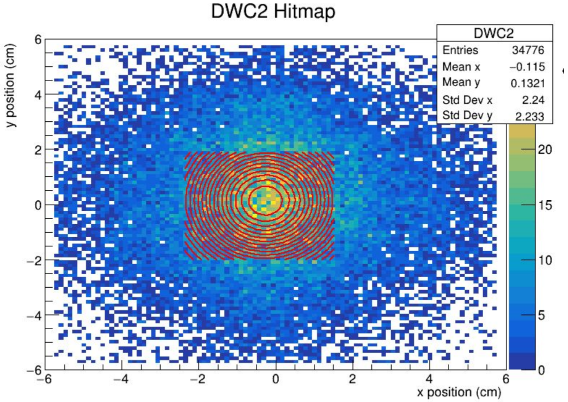
Magnet

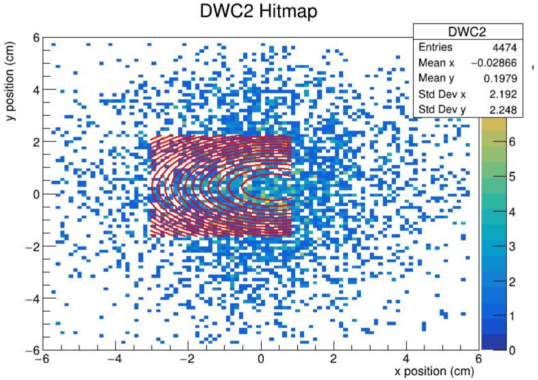




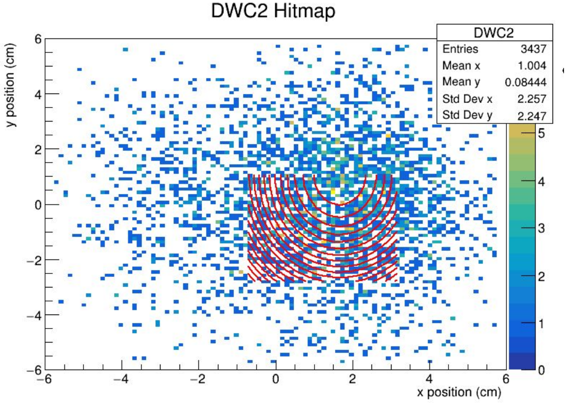
± 2 GeV DWC Magnet Effects (r_{mag}= 3.5 cm)

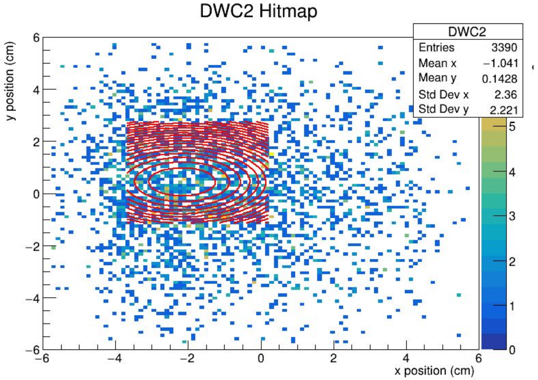
No magnet





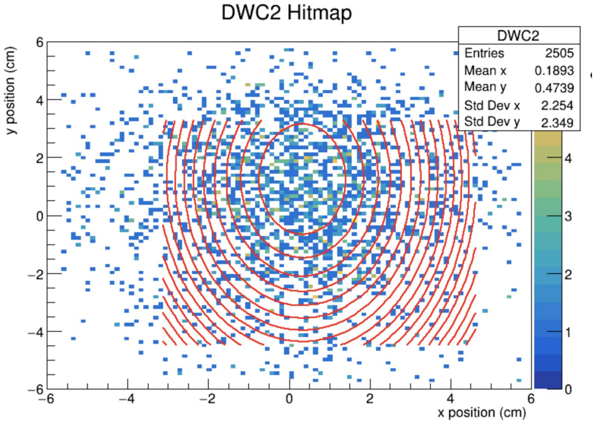
Magnet

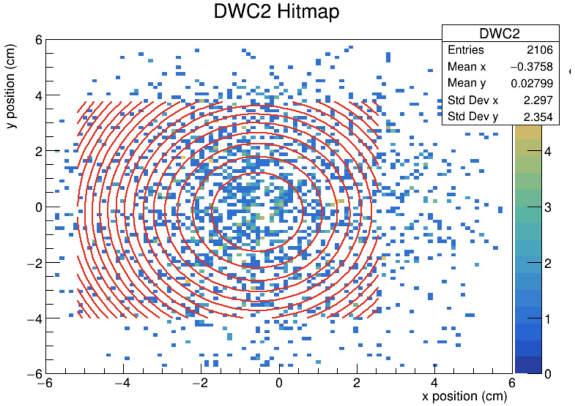




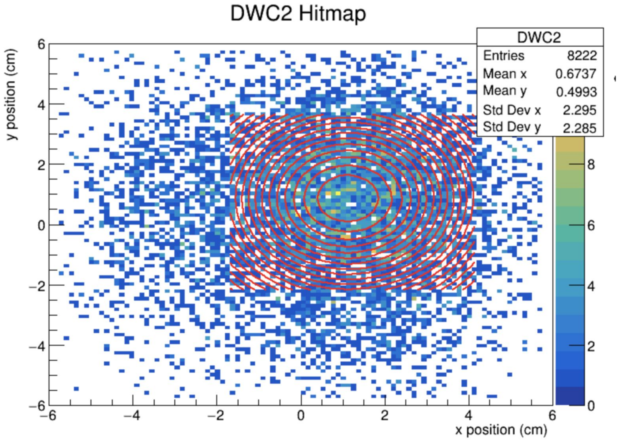
± 1.5 GeV DWC Hitmaps with Adjustable Mangle Array (r_{mag}= 1.5 cm)

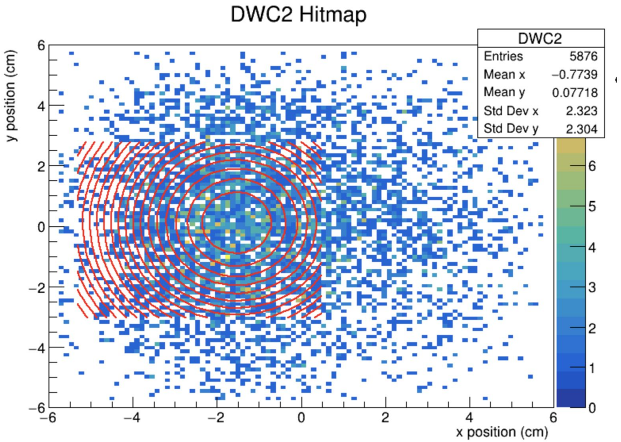
No magnet





Magnet





Experimental vs. Predicted X Deflection (r_{mag} = 2.5 cm)

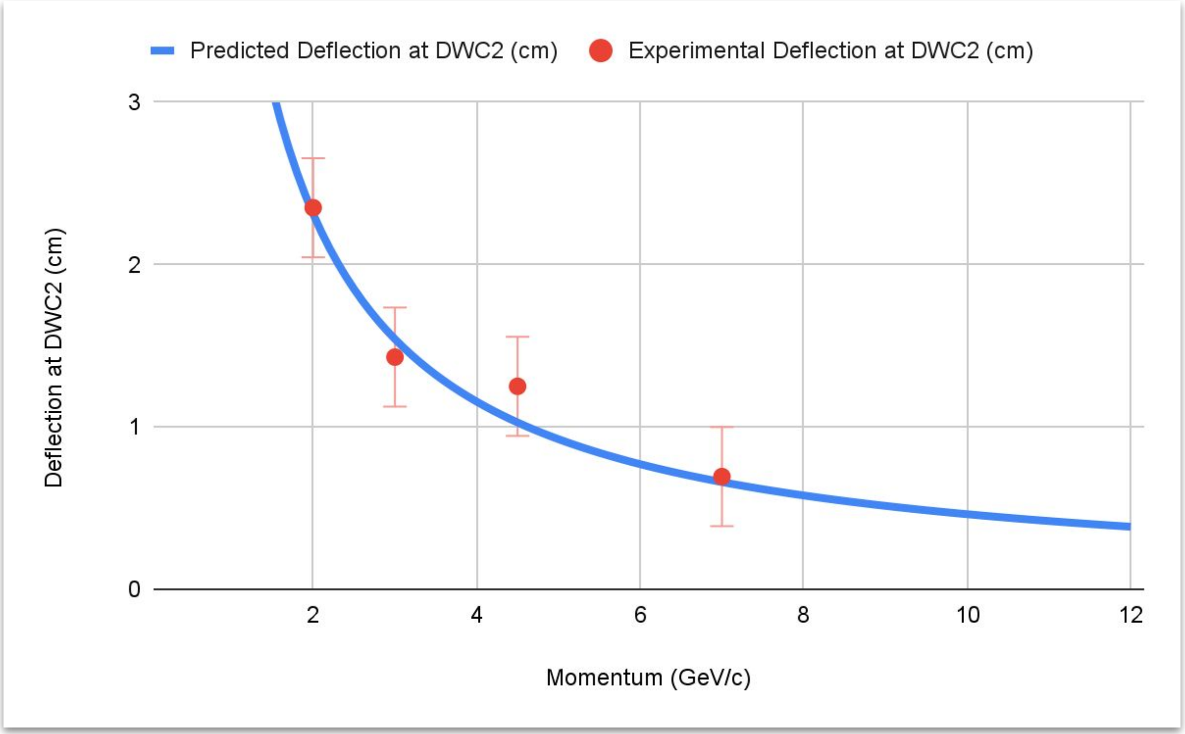
Experimental Error:

Inherent DWC precision	+/- 0.3 mm
Distance from magnet to DWC2	+/- 0.5 mm
2D Gaussian fit	+/- 3 mm

Predicted Error:

Measurement position	+/- 1 mm
Teslameter precision	+/- 1 mT
Linear Interpolation	+/- ~ 5mT

Experimental vs. Predicted X Deflection (r_{mag} = 3.5 cm)



Experimental Error:

Inherent DWC precision	+/- 0.3 mm
Distance from magnet to DWC2	+/- 0.5 mm
2D Gaussian fit	+/- 3 mm

Predicted Error:

Measurement position	+/- 1 mm
Teslameter precision	+/- 1 mT
Linear Interpolation	+/- ~ 5mT

Thank you!

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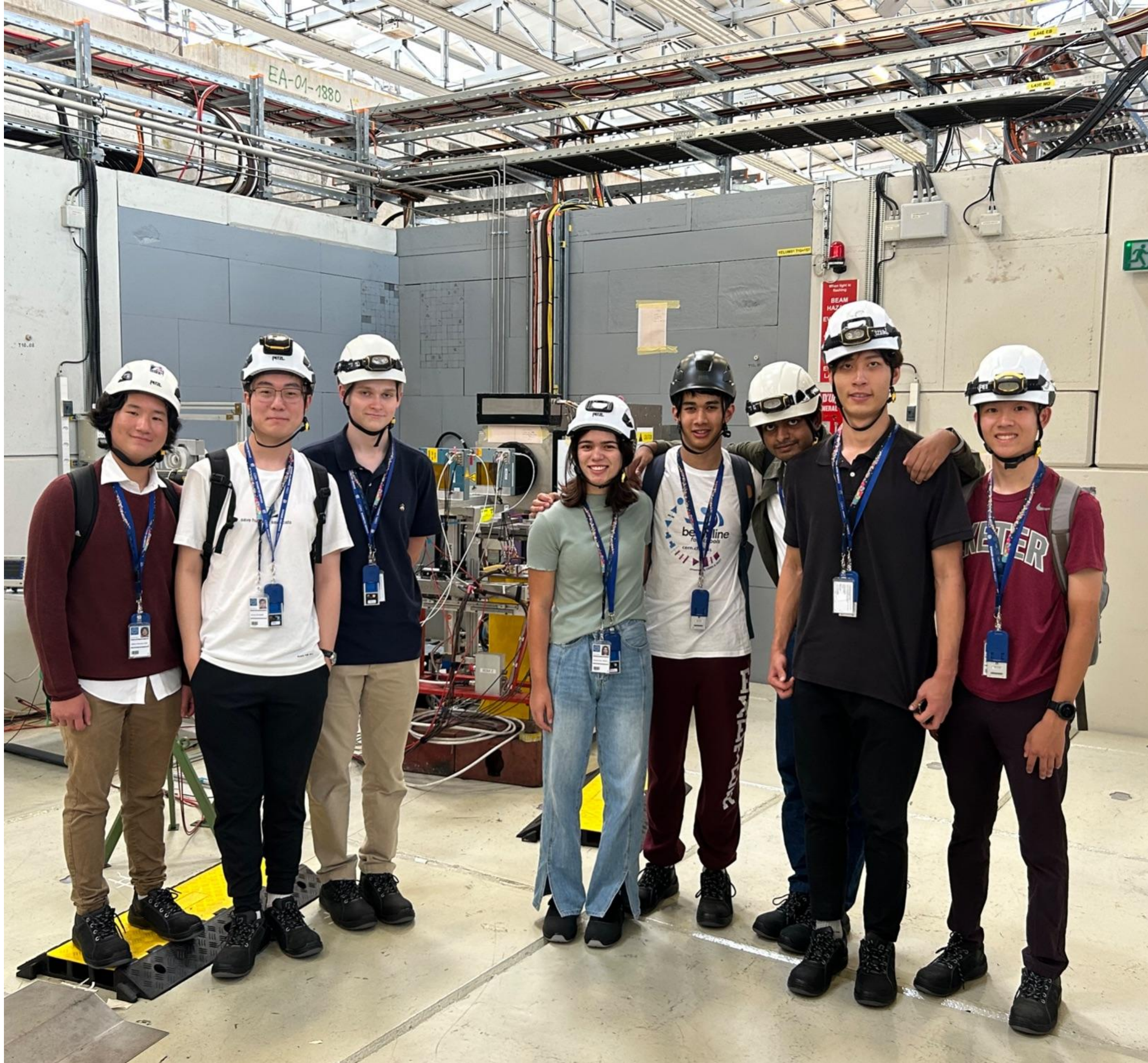
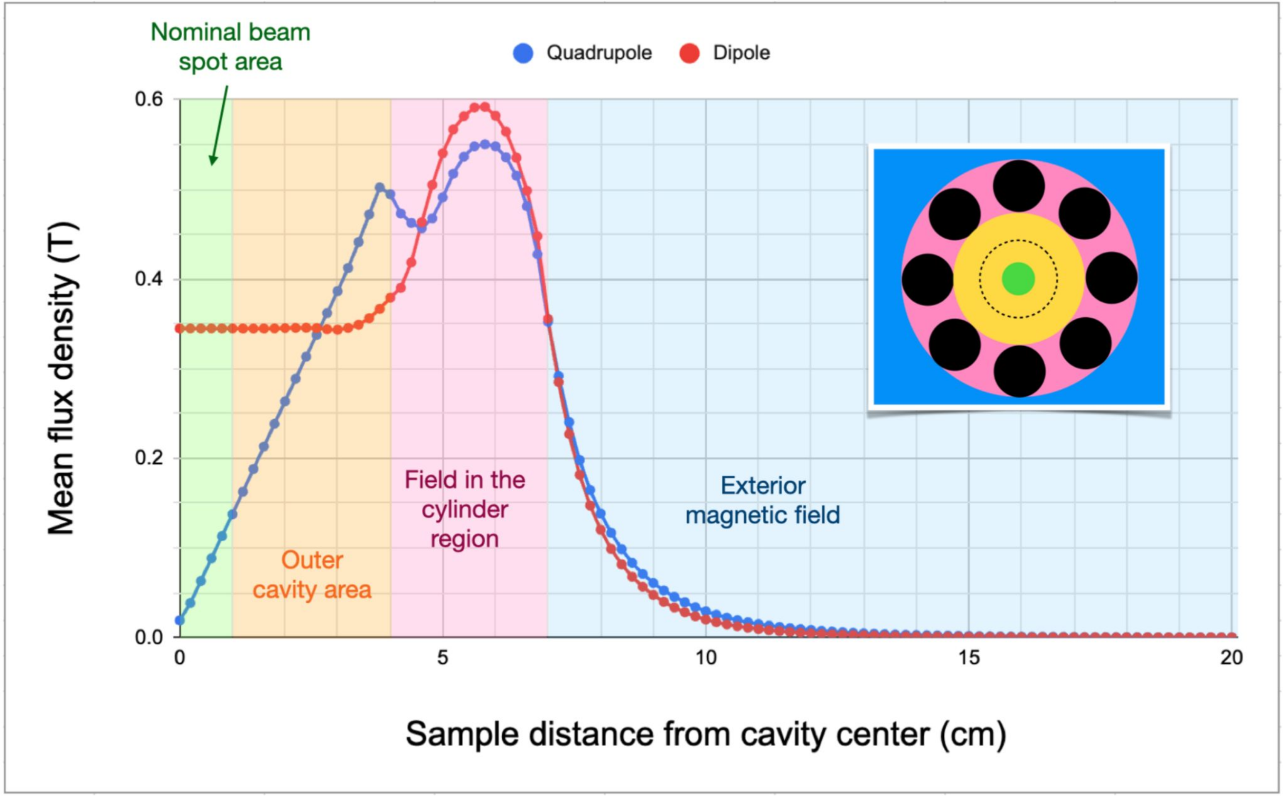
Margherita Boselli

BL4S team and supporters!



Backup Slides

Magnet design: introduction (cont'd)



Magnet design: defining the corresponding ideal field

For each set of cross-sectional mangle field with a given N, we define the corresponding ideal fields (centered at the origin) to be

$$\vec{B}_{dip}(x, y) = [0, B]$$

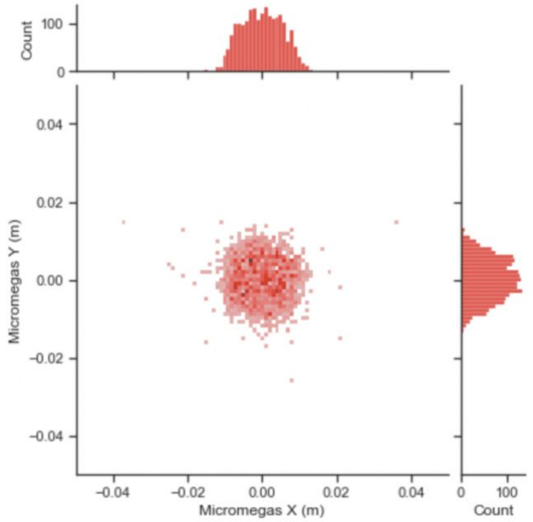
In the dipole case and

$$\vec{B}_{quad}(x, y) = g[-x, y]$$

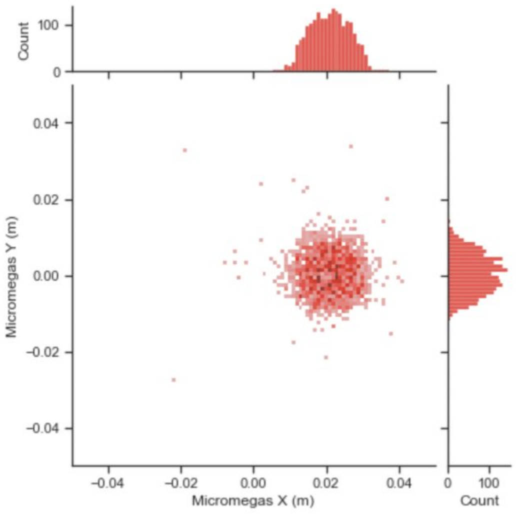
In the quadrupole case.

The magnitude of the ideal dipole's flux density, *B*, is obtained from the flux density at the array center. The ideal quadrupole's magnetic flux gradient, *g*, is obtained through a linear regression.

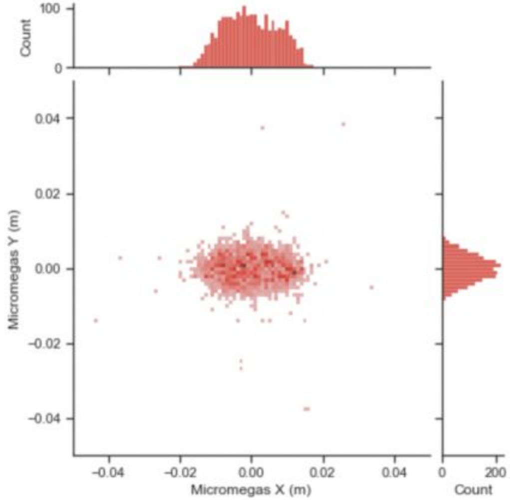
Preliminary simulations - Geant4



(a) No magnetic mangle present in beamline



(b) Dipole configuration with radial arrangement of $d = 6.0$ cm ($B = 0.29$ T)



(c) Quadrupole configuration with radial arrangement of $d = 7.0$ cm ($g = 6.1$ T/m)

Preliminary simulations - Geant4 (cont'd)

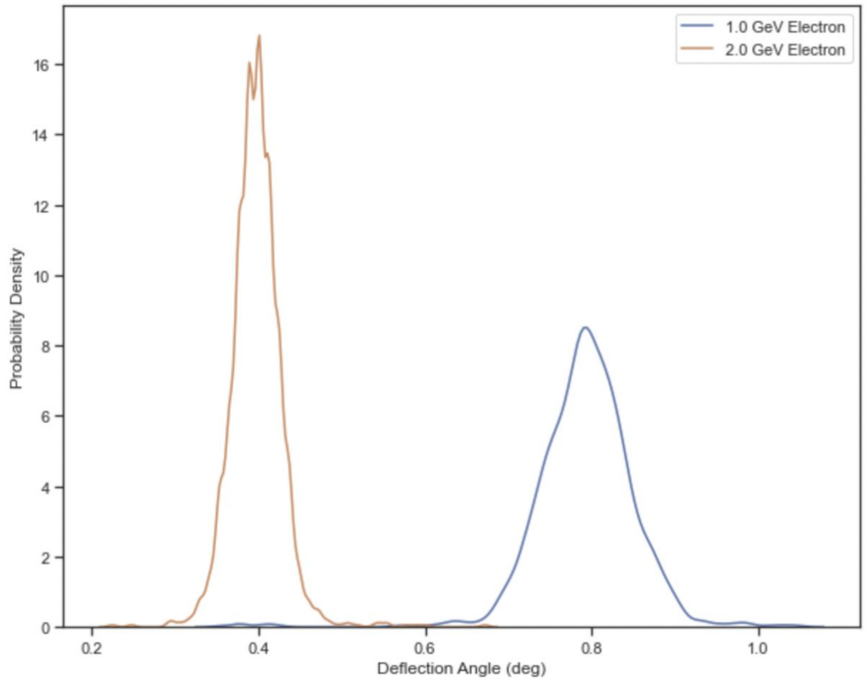


Figure 10: GEANT4 simulation: Normalized deflection angle distributions at 1.0 GeV and 2.0 GeV passing through the mangle dipole configuration.