Magnetic field direction measurements for d_2^n experiment

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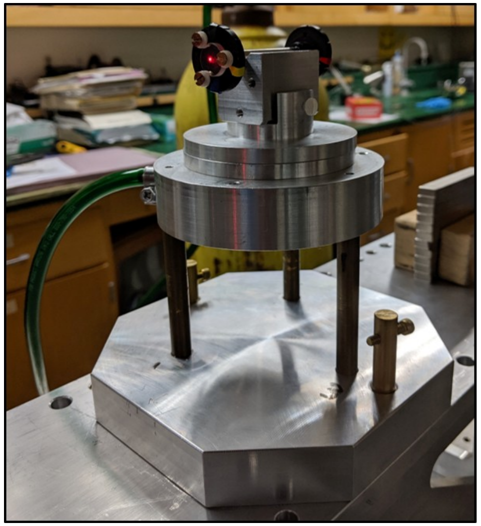
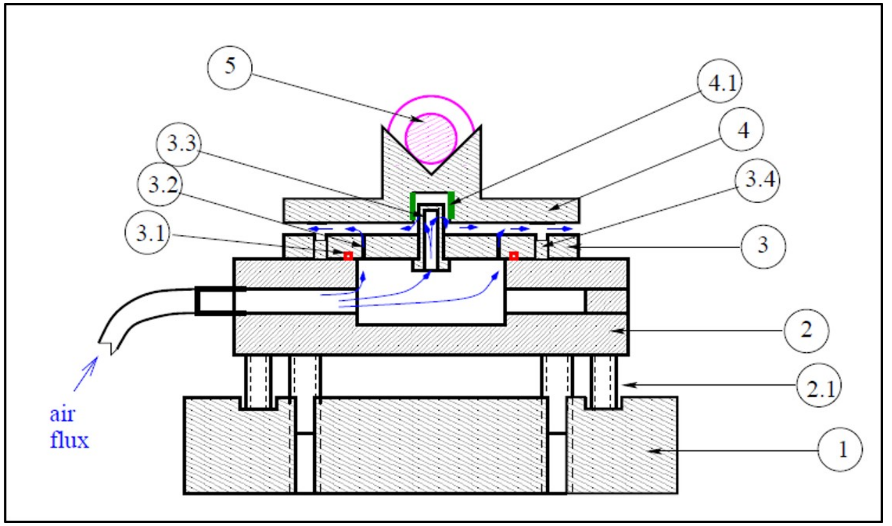
Outline

- The horizontal compass and compass mirror alignment
- Compass measurements setup in Hall C
- Helmholtz and correction coil settings
- Determining magnetic field direction
- Survey data analysis and results
- Error analysis
- Summary

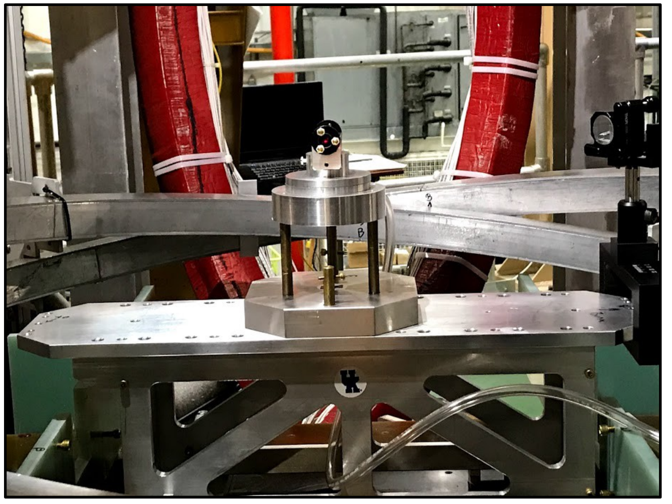
The horizontal compass and compass mirror alignment

The horizontal compass





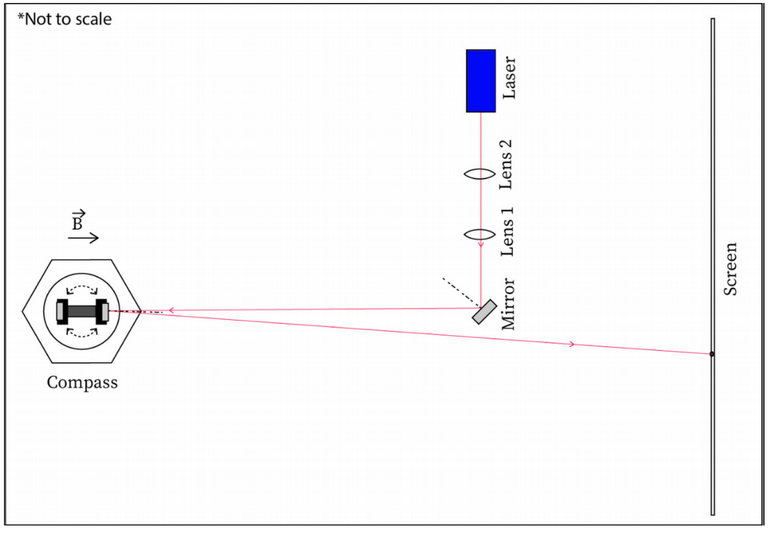
- An air-floated compass was built at the University of Kentucky.
- Goal was to measure absolute direction of the target magnetic field in the Hall C coordinate system precisely to about ±0.1°.
- Field direction was measured by reflecting a laser beam off the compass mirrors, aligned exactly perpendicular to the magnetic axis of the magnet.

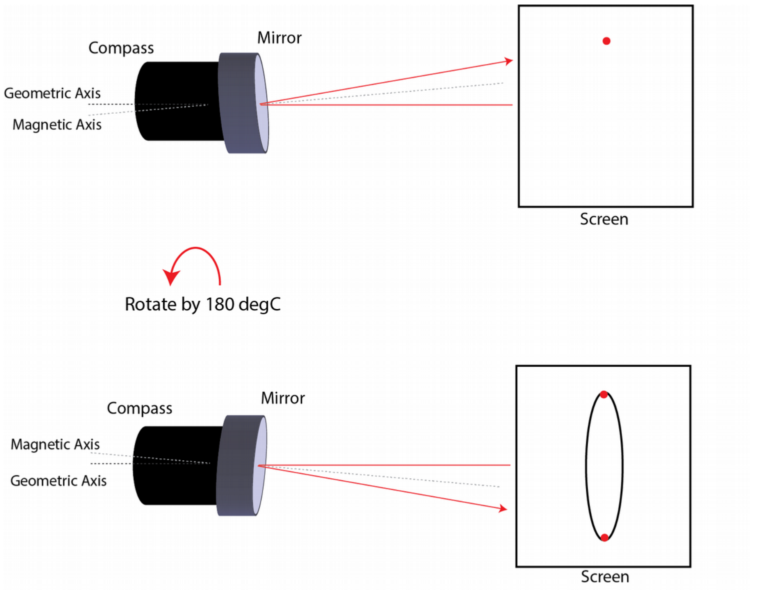


Compass installed in Hall C

Compass mirror alignment

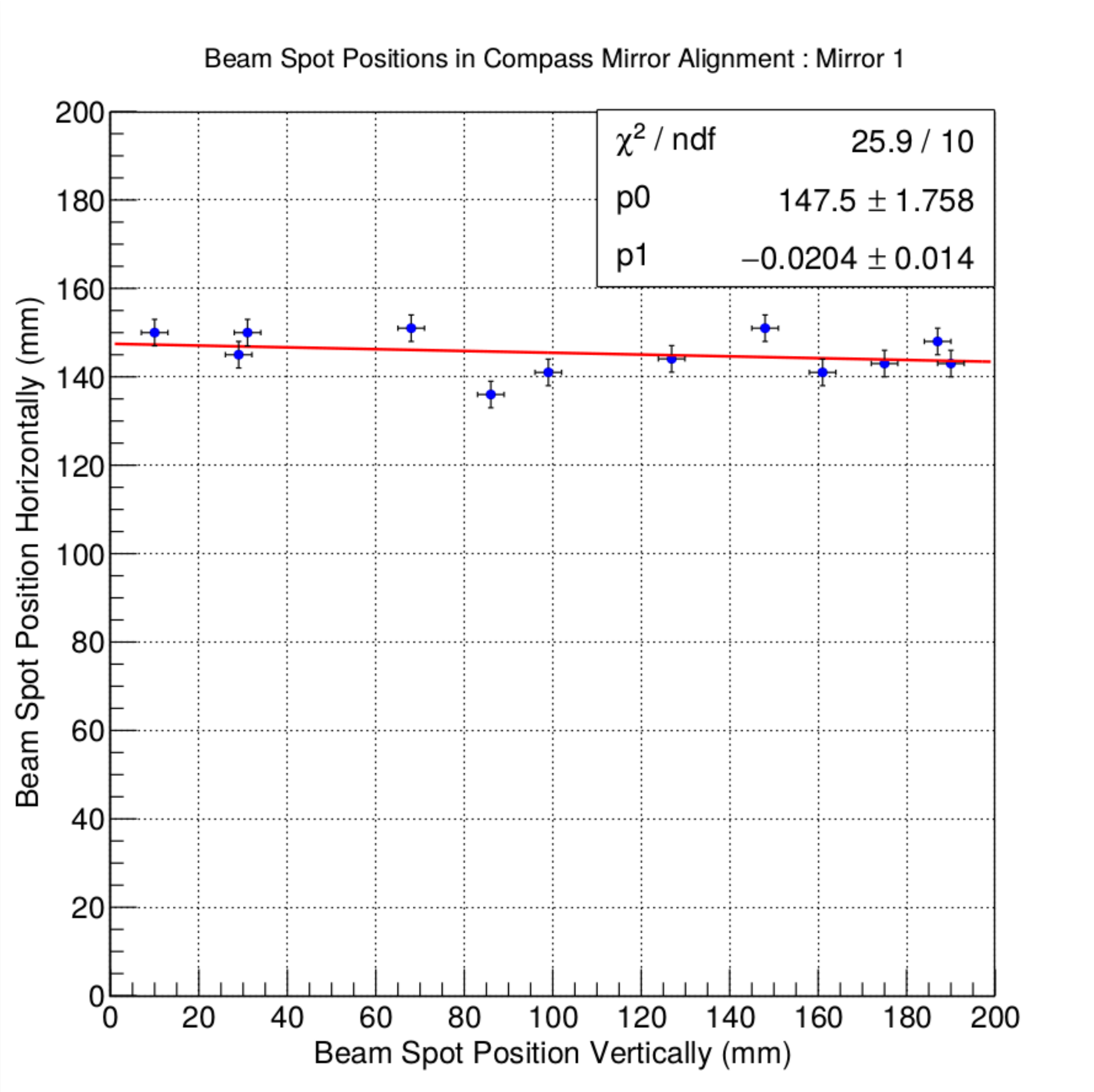
- Cylindrical compass magnet had mirrors (0.5 inch diameter, 0.3 mm thick) and circular scales (marked every 30°) attached to both ends of it.
- Three brass screws and and springs were used to align the mirrors on the compass magnet.
- Magnetic field direction was given by the surface normal of the compass mirror.





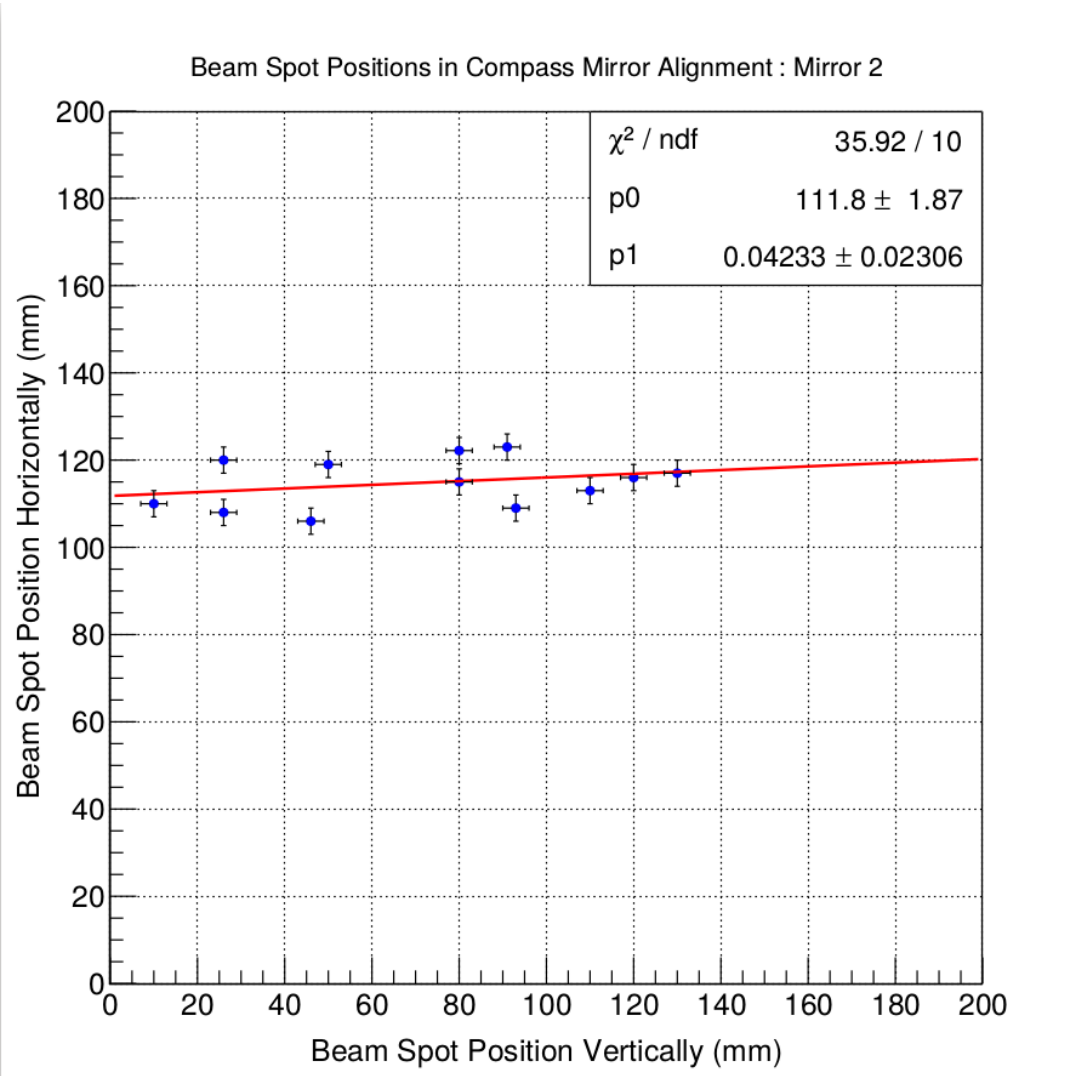
- The geometric and magnetic axes of the cylindrical magnet do not coincide.
- Reflected laser beam from the compass mirror inscribed an ellipse on a screen as a result of 360° scan of the magnet.
- The compass mirrors were aligned parallel to the magnetic axis of the compass magnet to minimize the horizontal error by reducing the ellipse to a line.

Horizontal error from mirror alignment
Mirror 1



Error in determining the horizontal angle, generated from compass mirror alignment : **±0.06°**

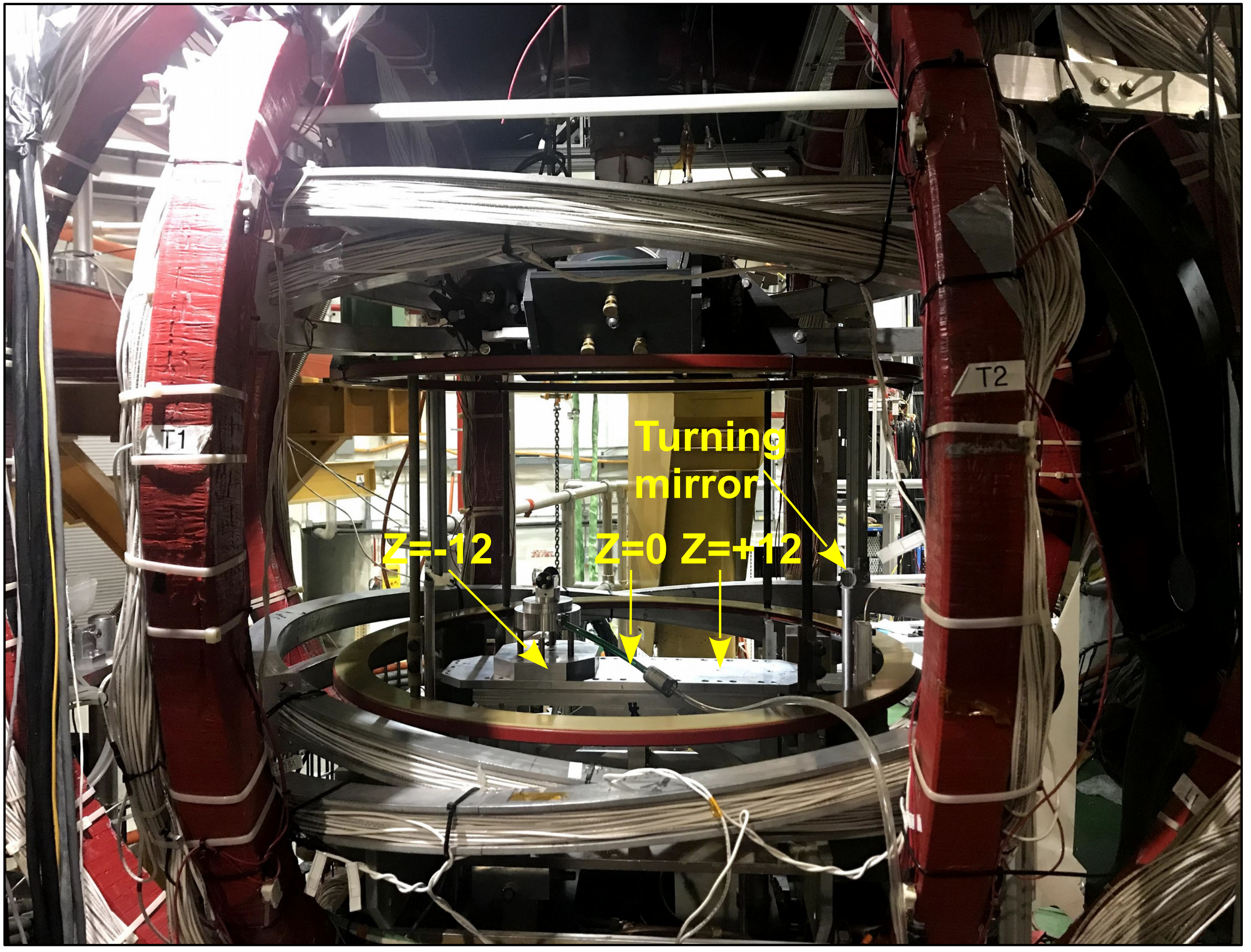
Horizontal error from mirror alignment Mirror 2



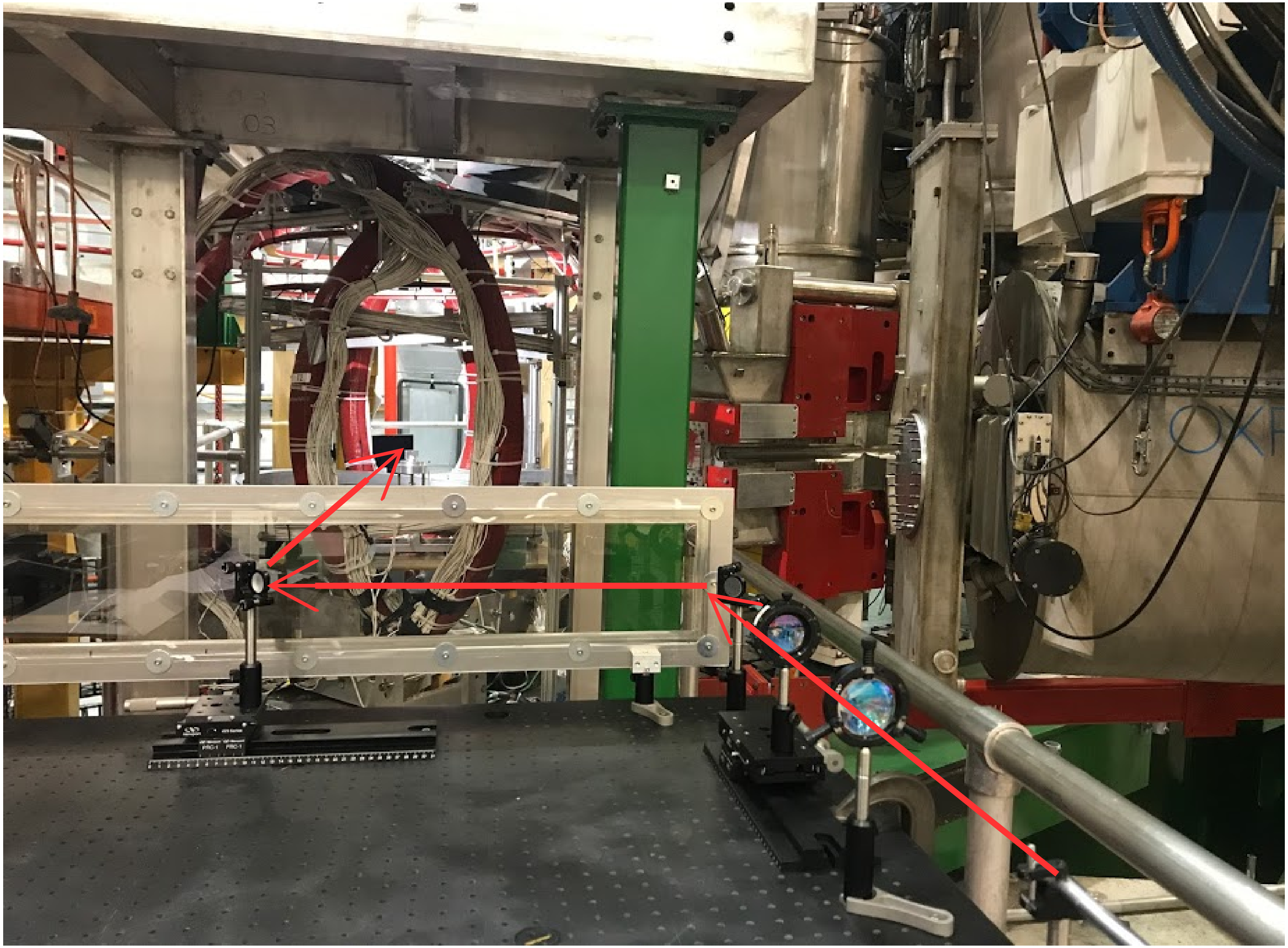
Error in determining the horizontal angle, generated from compass mirror alignment : **±0.08°**

Compass measurements setup in Hall C

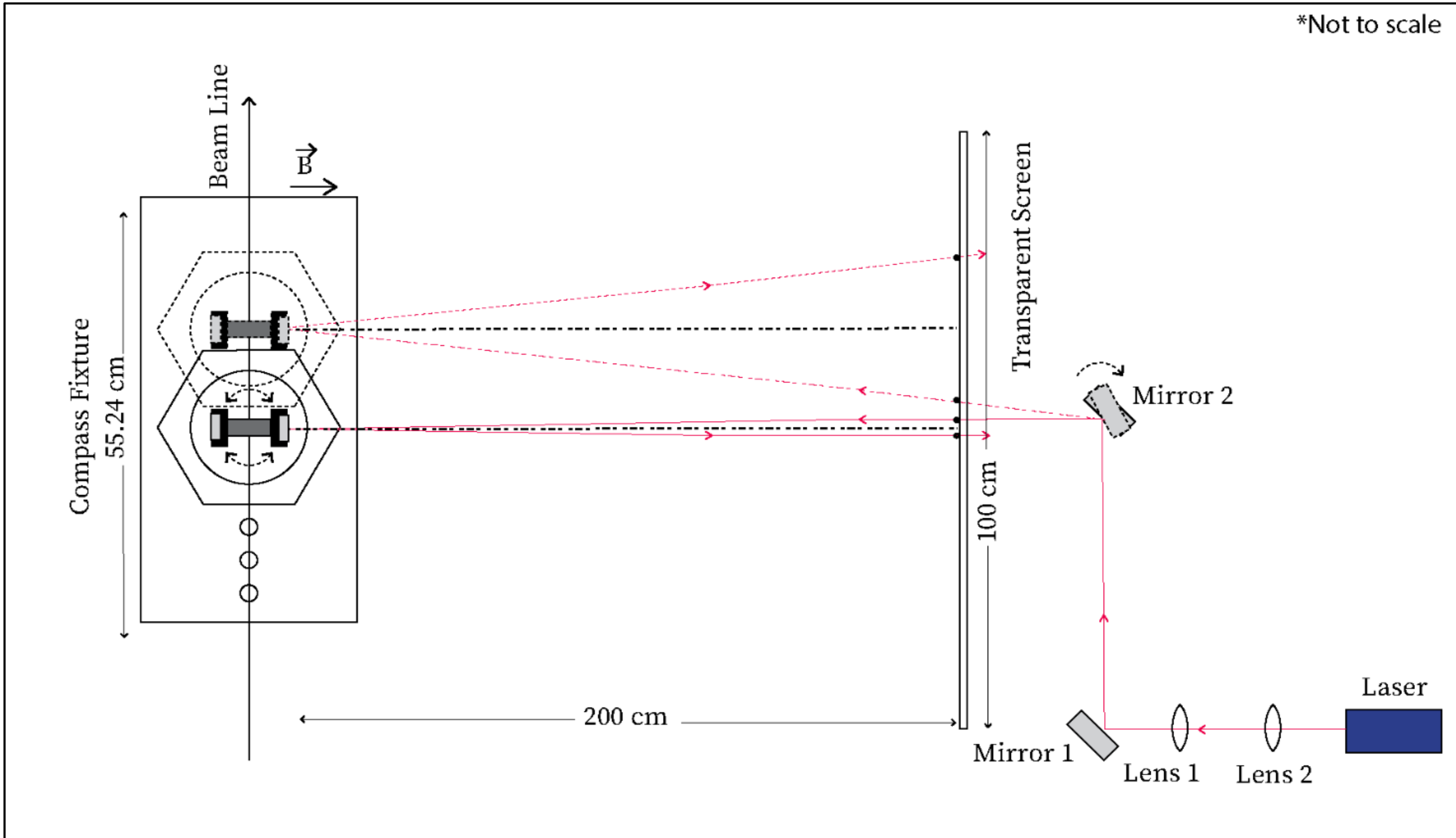
Compass setup in Hall C



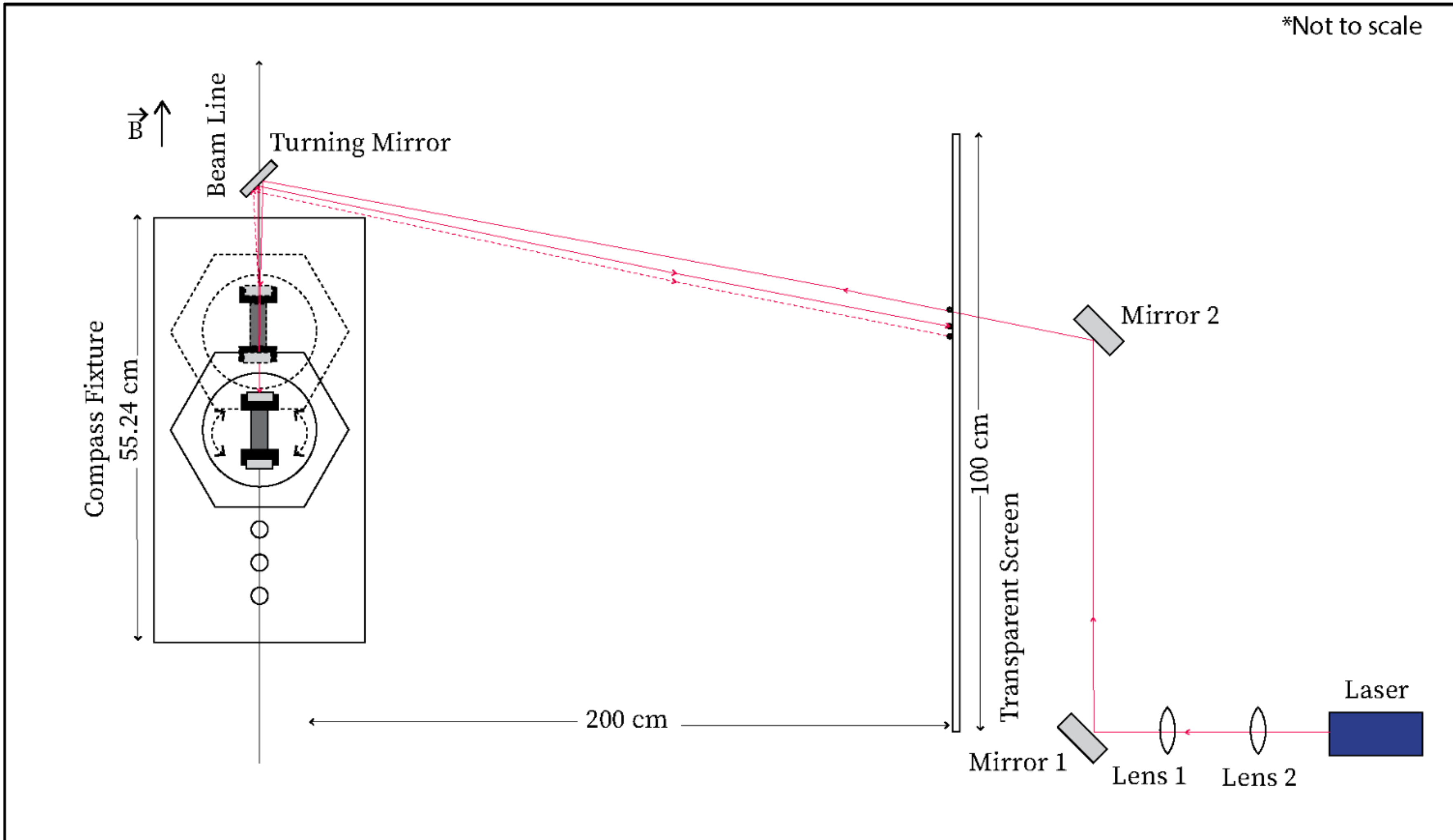
Compass setup in Hall C



Scanning the transverse field direction along the target length



Scanning the longitudinal field direction along the target length



Helmholtz and correction coil settings

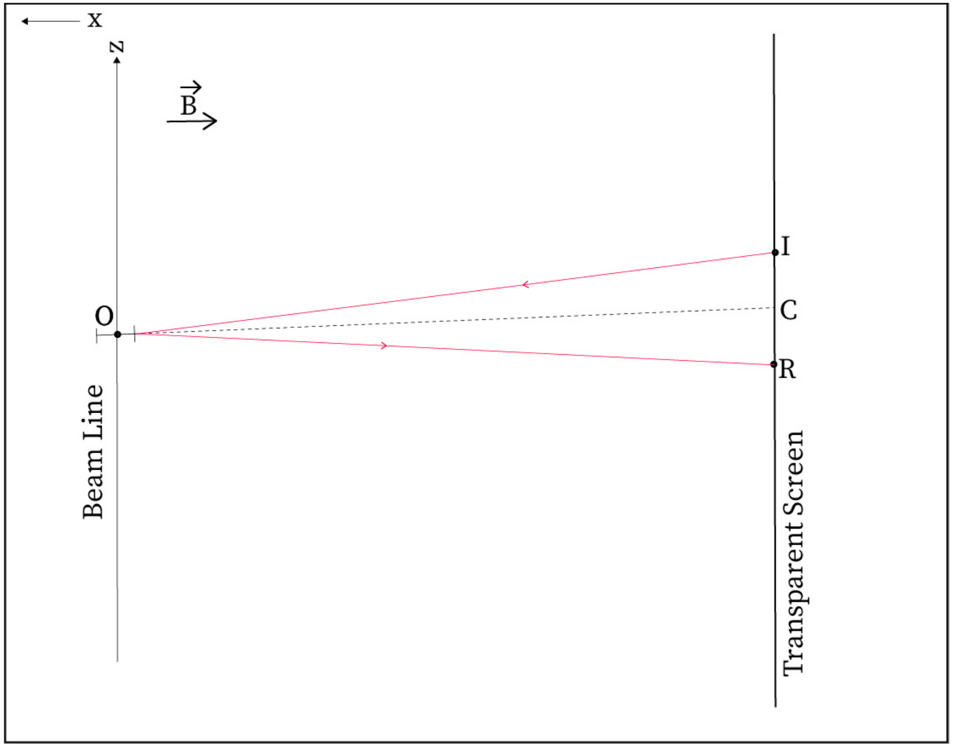
Helmholtz coil and correction coil settings

Kin Set	Pol Dir	MainL (A)	MainS (A)	VL (A)	VS (A)		Field direction from strip chart
11 deg, 7.5 GeV/c	+x	7.407	0.137	4	6	Production	88.936 deg
		7.418	0.136	4.03	6.04	Compass measurement	
	-x	-7.364	-0.237	4.1	6	Production	268.109 deg
		-7.366	-0.24	4.1	6.04	Compass measurement	
	+z	0	7.225	4.5	6.5	Production	0 deg
		0	7.227	4.49	6.55	Compass measurement	
	-z	0	-7.305	4.7	6.9	Production	180 deg
		0	-7.308	4.72	6.95	Compass measurement	
14.5 deg, 6.4 GeV/c	+x	7.406	0.139	4.3	6.1	Production	88.936 deg
		7.418	0.138	4.31	6.15	Compass measurement	
	-x	-7.385	-0.239	4.2	6.1	Production	268.109 deg
		-7.386	-0.238	4.2	6.15	Compass measurement	
	+z	0	7.298	4.6	6.3	Production	0 deg
		0	7.294	4.6	6.32	Compass measurement	
	-z	0	-7.398	4.9	7	Production	180 deg
		0	-7.406	4.89	7.05	Compass measurement	
18 deg, 5.6 GeV/c	+x	7.406	0.139	4.4	6	Production	88.936 deg
		7.418	0.145	4.43	6.04	Compass measurement	
	-x	-7.385	-0.239	4.8	6.6	Production	268.109 deg
		-7.387	-0.243	4.82	6.66	Compass measurement	
	+z	0	7.298	2.8	4.1	Production	0 deg
		0	7.293	2.82	4.13	Compass measurement	
	-z	0	-7.398	5.2	7	Production	180 deg
		0	-7.406	5.21	7.05	Compass measurement	
8.5 deg, 2.12 GeV/c	+z	0	7.225	0	0	Production	0 deg
		0	7.227	0.04	0	Compass measurement	
	-z	0	-7.305	3.6	4.5	Production	180 deg
		0	-7.309	3.62	4.52	Compass measurement	

- **+X: Beam right (90 deg)**
- **-X: Beam left (270 deg)**
- **+Z: downstream (0 deg)**
- **-Z: upstream (180 deg)**

Determining magnetic field direction

Determining the transverse field direction



- O (x_O, y_O, z_O) is the compass center (surveyed).
- I (x_I, y_I, z_I) and R (x_R, y_R, z_R) are the incident and reflected beam spots on the screen respectively (surveyed) .
- C (x_c, y_c, z_c) is the midpoint of I and R.
- $\vec{OC}$ gives the magnetic field direction.

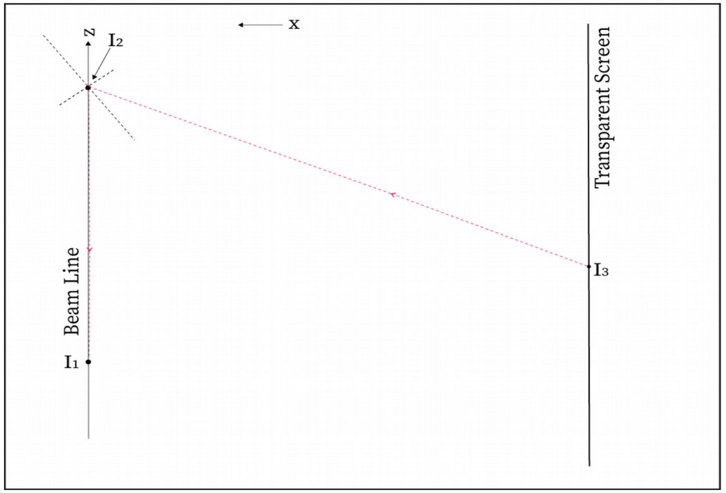
- The angle made by the transverse magnetic field with the beam line (w.r.t. +Z direction) is calculated as,

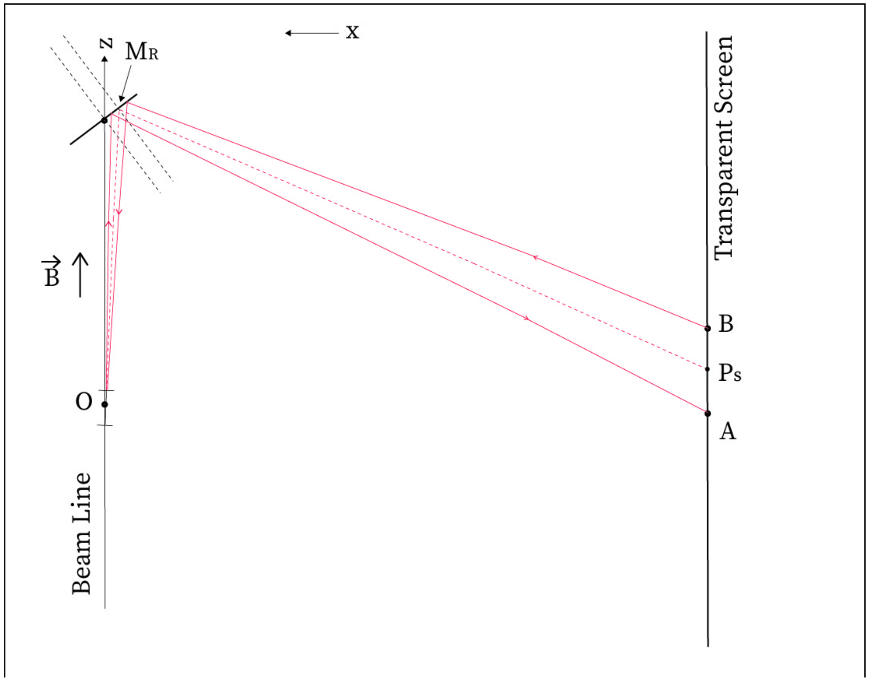
$$\alpha = \arccos\left(\frac{(z_c - z_O)}{\sqrt{(x_c - x_O)^2 + (y_c - y_O)^2 + (z_c - z_O)^2}}\right)$$

Determining the longitudinal field direction

- I_1 and I_2 are the two irises (surveyed) on the beam line and I_3 (surveyed) is the laser beam spot on the screen marked during the turning mirror alignment.

- O is the compass center (surveyed) .





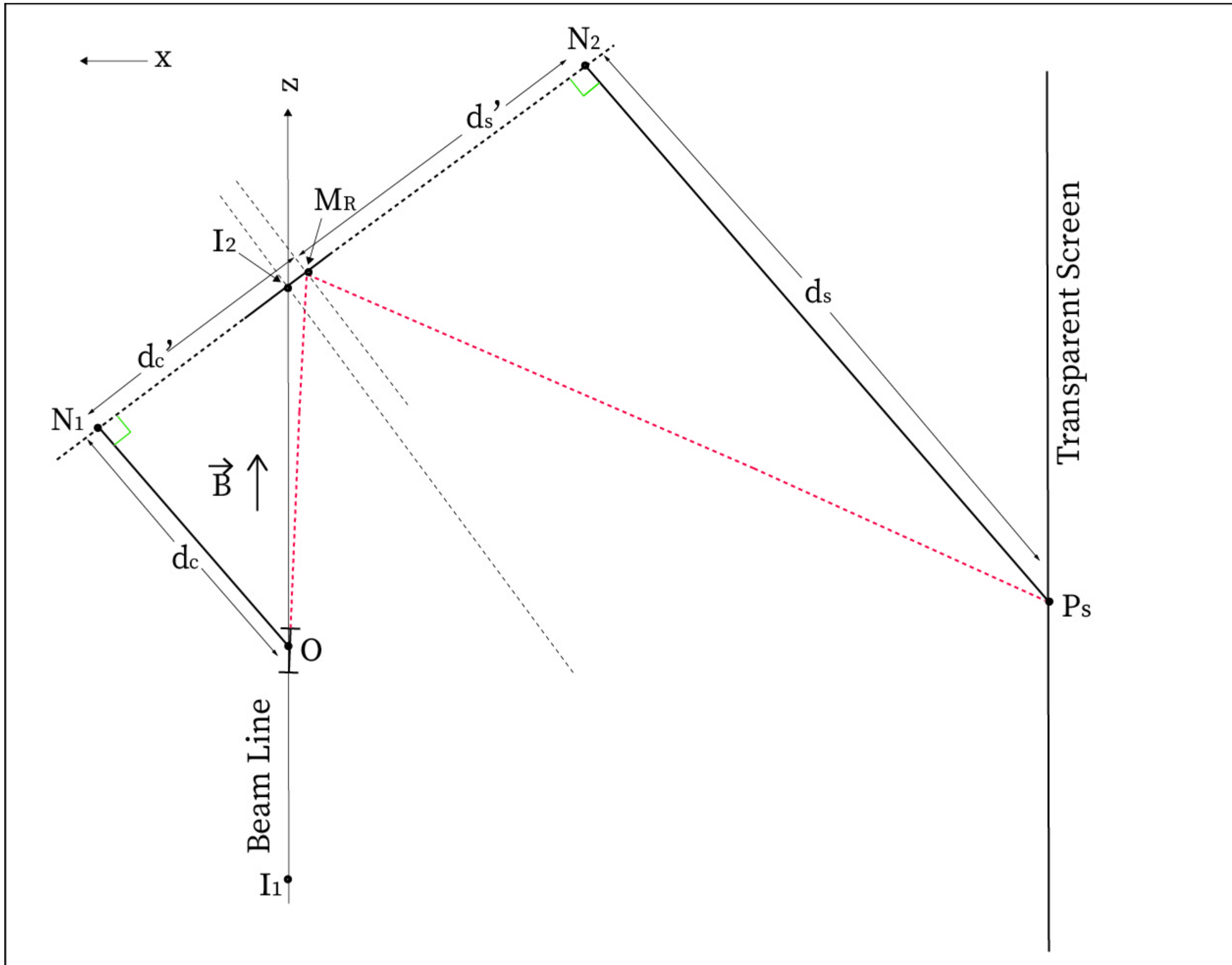
- A and B are the incident and reflected laser beam spots on the transparent screen respectively (surveyed) .

- P_S is the midpoint of A and B.

- M_R is the point on turning mirror that corresponds to P_S on the transparent screen.

- $\overrightarrow{OM_R}$ gives the longitudinal magnetic field direction.

Determining the longitudinal field direction

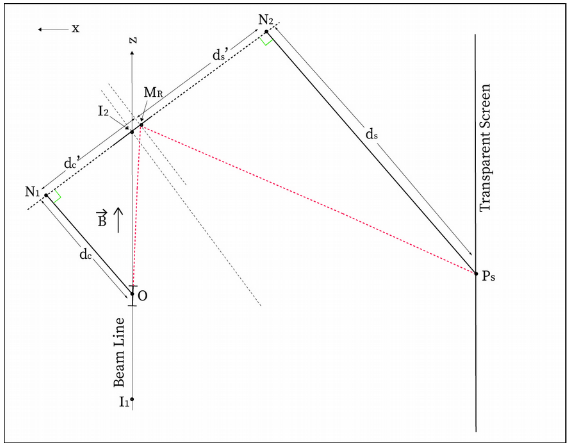


- Solved for M_R from all the information available for each case and determined angle β that $\overrightarrow{OM_R}$ makes with positive Z direction (explained in the next slide).

Determining the longitudinal field direction

- All calculations were done in x-z plane as the compass is only sensitive to horizontal angle.

- Surface normal of the turning mirror is given by the angular bisector of $\overrightarrow{I_1 I_2}$ and $\overrightarrow{I_2 I_3}$.



- Perpendicular line to the angular bisector passing through I_2 which is in x-z plane is $\overrightarrow{N_1 N_2}$:

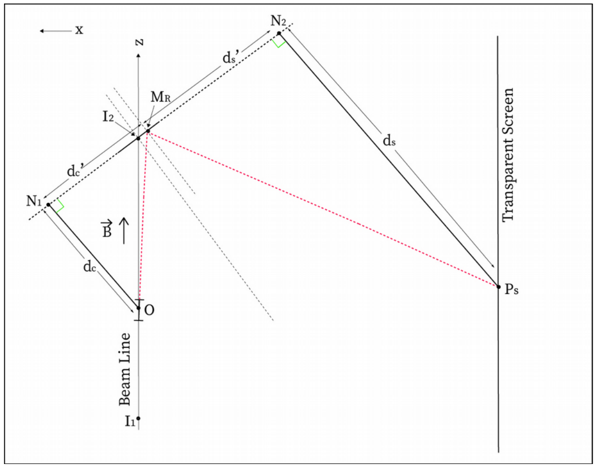
$$\left(z - z_{I_2}\right) = \left(\frac{-1}{m}\right)\left(x - x_{I_2}\right)$$

Where the slope of the angular bisector, $$m = \tan\left(\frac{\arctan\left(\frac{z_{I_2} - z_{I_1}}{x_{I_2} - x_{I_1}}\right) + \arctan\left(\frac{z_{I_2} - z_{I_3}}{x_{I_2} - x_{I_3}}\right)}{2}\right)$$

- Equations of $\overrightarrow{ON_1}$ and $\overrightarrow{P_s N_2}$ (perpendiculars drawn to $\overrightarrow{N_1 N_2}$ from O and P_s respectively) are:

$$z - z_0 = m\left(x - x_0\right) \quad \text{and} \quad z - z_{P_s} = m\left(x - x_{P_s}\right)$$

Determining the longitudinal field direction



- Co-ordinates of N_1 and N_2 were determined by solving ($\overrightarrow{ON_1}$, $\overrightarrow{N_1N_2}$) and ($\overrightarrow{P_sN_2}$, $\overrightarrow{N_1N_2}$) respectively.
- Length of $\overrightarrow{ON_1}$: $d_c = \sqrt{(x_0 - x_{N_1})^2 + (z_0 - z_{N_1})^2}$
- Length of $\overrightarrow{P_sN_2}$: $d_s = \sqrt{(x_{P_s} - x_{N_2})^2 + (z_{P_s} - z_{N_2})^2}$
- Length of $\overrightarrow{N_1N_2}$: $L = \sqrt{(x_{N_1} - x_{N_2})^2 + (z_{N_1} - z_{N_2})^2}$

- M_R was solved from the following equations:

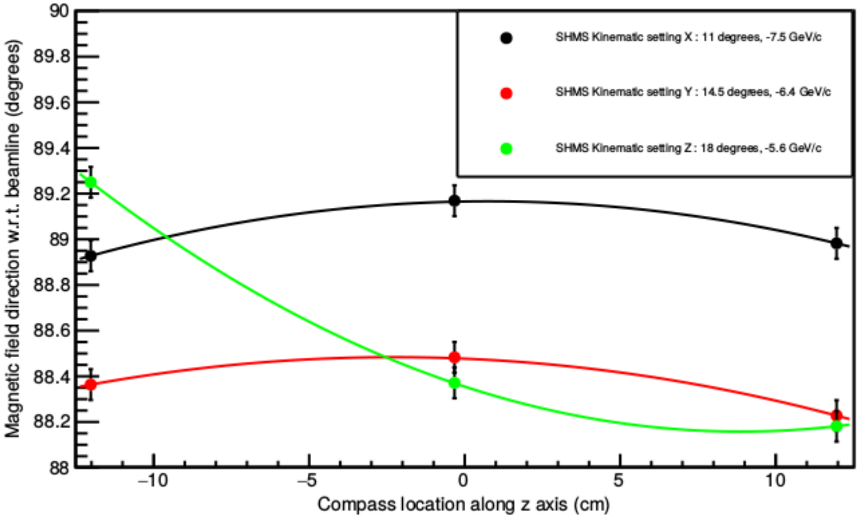
$$d_c' = \sqrt{(x_{N_1} - x_{M_R})^2 + (z_{N_1} - z_{M_R})^2} = L - d_s' \quad \text{and} \quad d_s' = \sqrt{(x_{N_2} - x_{M_R})^2 + (z_{N_2} - z_{M_R})^2} = \frac{L}{\left(1 + \frac{d_c}{d_s}\right)}$$

- The angle made by the longitudinal magnetic field with the beam line (w.r.t. +Z direction) is calculated as,

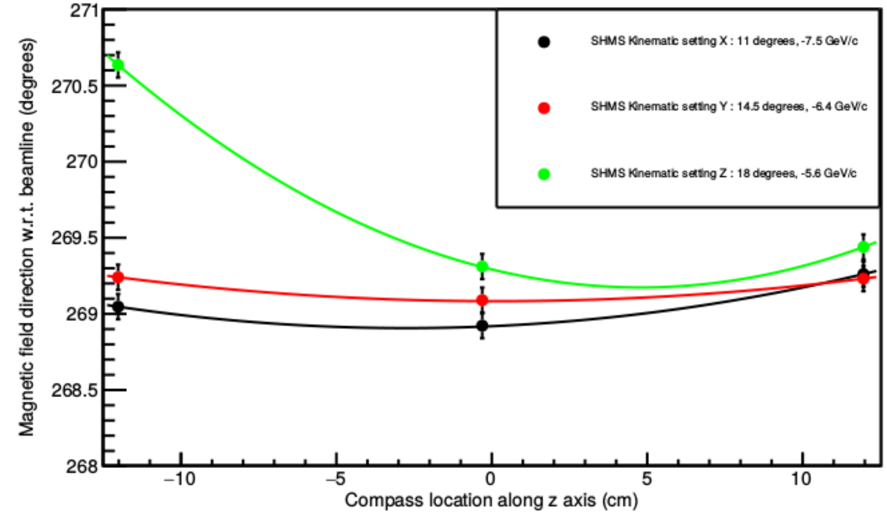
$$\beta = \arccos\left(\frac{(z_{M_R} - z_O)}{\sqrt{(x_{M_R} - x_O)^2 + (z_{M_R} - z_O)^2}}\right)$$

Survey data analysis and results

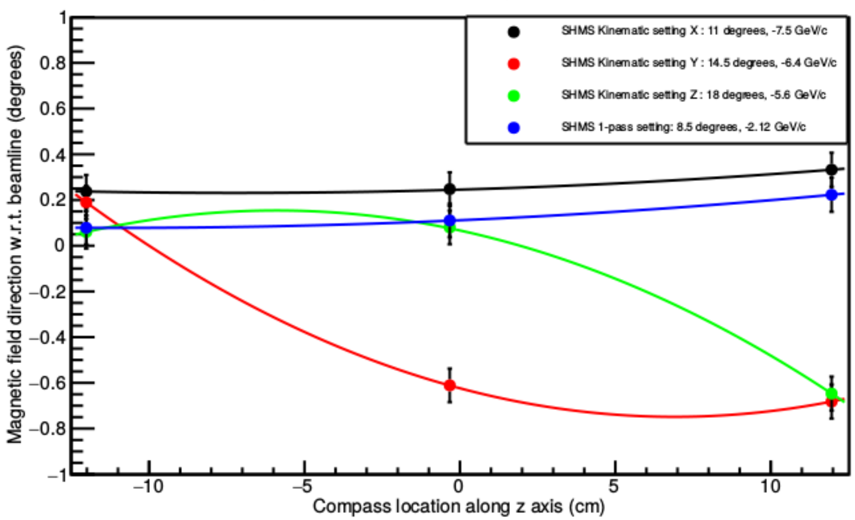
Transverse +X (90 deg, beam right)



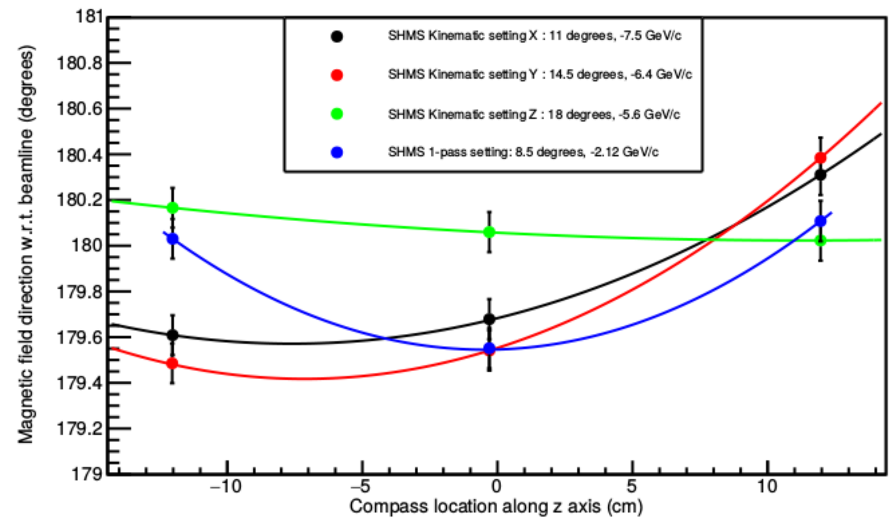
Transverse -X (270 deg, beam left)



Longitudinal +Z (0 deg, downstream)



Longitudinal -Z (180 deg, upstream)



Error analysis

Sources of systematic uncertainties

1. Error in determining the angle (θ) the magnetic field makes with beam line: **~ ±(0.01°-0.03°)**

$$\sigma_\theta = \sqrt{\sum_i \left[\left(\frac{\partial \theta}{\partial x_i} \right)^2 \sigma_{x_i}^2 \right]}$$

Where θ was the function of all the surveyed coordinate variables (x_i) and σ_{x_i} is the error associated with that particular coordinate.

σ_{x_i} for compass and fiducial location = 0.28 mm

σ_{x_i} for points on screen = 0.5 mm

2. Errors from the compass mirror alignment (θ_M): **~ ±(0.06°-0.08°)**

The misalignment between magnetic axis of the cylindrical magnet and compass mirror generated additional errors-

A. Projection of the fitted straight line on the horizontal axis

B. Fit parameter errors

3. Laser beam spot size: **~ ±0.006°**

Lenses were used to make the laser beam spot diameter ~2 millimeters.

4. Position of incident laser beam on the compass mirror: **~ ±0.01°**

The laser beam always reflected off the center of the compass mirror within 0.5 mm uncertainty.

Total uncertainty was within ±0.1° as required!

Uncertainties in compass measurements

Kinematic settings	Polarization direction	Compass locations along z axis (cm)	Magnetic field direction (degrees)	$\pm$ Error$_{Survey}$ (degrees)	$\pm$ Error$_{Mirror}$ (degrees)	$\pm$ Error$_{Spotsize}$ (degrees)	$\pm$ Error$_{Center}$ (degrees)	$\pm$ Error$_{Total}$ (degrees)
SHMS at 11°, -7.5 GeV/c	+X	11.957	88.98	0.018	0.064	0.006	0.01	0.067
		-0.3	89.16	0.018	0.064	0.006	0.01	0.067
		-12.022	88.93	0.018	0.064	0.006	0.01	0.067
	-X	11.957	269.26	0.018	0.08	0.006	0.01	0.083
		-0.3	268.92	0.018	0.08	0.006	0.01	0.083
		-12.022	269.05	0.018	0.08	0.006	0.01	0.083
	+Z	11.957	0.33	0.036	0.064	0.006	0.01	0.074
		-0.3	0.24	0.034	0.064	0.006	0.01	0.073
		-12.022	0.24	0.032	0.064	0.006	0.01	0.072
	-Z	11.957	180.31	0.036	0.08	0.006	0.01	0.088
		-0.3	179.67	0.034	0.08	0.006	0.01	0.088
		-12.022	179.61	0.032	0.08	0.006	0.01	0.087
SHMS at 14.5°, -6.4 GeV/c	+X	11.957	88.23	0.018	0.064	0.006	0.01	0.067
		-0.3	88.48	0.018	0.064	0.006	0.01	0.067
		-12.022	88.36	0.018	0.064	0.006	0.01	0.067
	-X	11.957	269.23	0.018	0.08	0.006	0.01	0.083
		-0.3	269.08	0.018	0.08	0.006	0.01	0.083
		-12.022	269.24	0.018	0.08	0.006	0.01	0.083
	+Z	11.957	-0.68	0.036	0.064	0.006	0.01	0.074
		-0.3	-0.61	0.034	0.064	0.006	0.01	0.073
		-12.022	0.19	0.032	0.064	0.006	0.01	0.072
	-Z	11.957	180.38	0.036	0.08	0.006	0.01	0.088
		-0.3	179.54	0.034	0.08	0.006	0.01	0.088
		-12.022	179.48	0.032	0.08	0.006	0.01	0.087

Kinematic settings	Polarization direction	Compass locations along z axis (cm)	Magnetic field direction (degrees)	$\pm$ Error$_{Survey}$ (degrees)	$\pm$ Error$_{Mirror}$ (degrees)	$\pm$ Error$_{Spotsize}$ (degrees)	$\pm$ Error$_{Center}$ (degrees)	$\pm$ Error$_{Total}$ (degrees)
SHMS at 18°, -5.6 GeV/c	+X	11.957	88.18	0.018	0.064	0.006	0.01	0.067
		-0.3	88.37	0.018	0.064	0.006	0.01	0.067
		-12.022	89.25	0.018	0.064	0.006	0.01	0.067
	-X	11.957	269.44	0.018	0.08	0.006	0.01	0.083
		-0.3	269.31	0.018	0.08	0.006	0.01	0.083
		-12.022	270.64	0.018	0.08	0.006	0.01	0.083
	+Z	11.957	-0.65	0.036	0.064	0.006	0.01	0.074
		-0.3	0.08	0.034	0.064	0.006	0.01	0.073
		-12.022	0.06	0.032	0.064	0.006	0.01	0.072
	-Z	11.957	180.02	0.036	0.08	0.006	0.01	0.088
		-0.3	180.06	0.034	0.08	0.006	0.01	0.088
		-12.022	180.17	0.032	0.08	0.006	0.01	0.087
SHMS at 8.5°, -2.12 GeV/c, one pass	+Z	11.957	0.22	0.036	0.064	0.006	0.01	0.074
		-0.3	0.11	0.034	0.064	0.006	0.01	0.073
		-12.022	0.08	0.032	0.064	0.006	0.01	0.072
	-Z	11.957	180.11	0.036	0.08	0.006	0.01	0.088
		-0.3	179.55	0.034	0.08	0.006	0.01	0.088
		-12.022	180.03	0.032	0.08	0.006	0.01	0.087

Summary

- Finished both the longitudinal and transverse magnetic field direction measurements for all kinematic settings for d_2^n experiment in September, 2020.
  Thanks to Arun, Bill and the Alignment Group for their help!

- The field direction at different locations along target cell deviates from that at the center due to presence of steel structures and effect of HB.

- The uncertainty in the angle measurements was limited to ±0.1° which was the requirement.

Thank you!