HL-LHC-BGI: Assessing Potential Magnets

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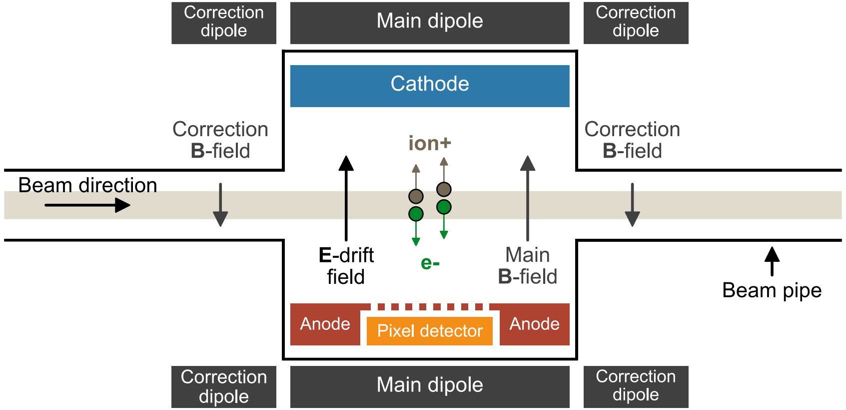
HL-LHC BGI Meeting – 4th March 2024

Introduction to BGI Electric and Magnetic Fields

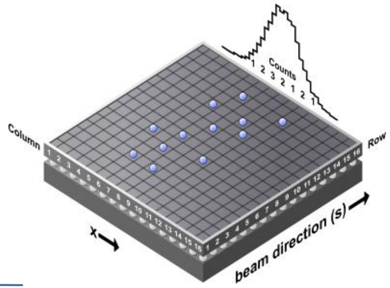
Ideal Electric and Magnetic Fields

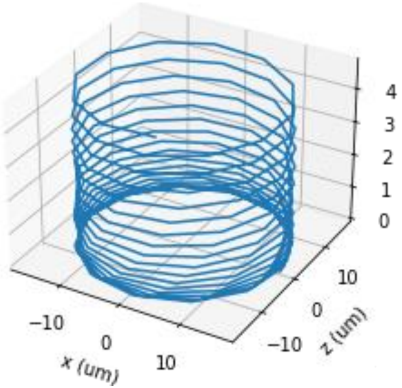


$$\dot{\vec{r}}(t) = \overrightarrow{\Omega_c} \times \overrightarrow{\mathrm{r}_c} + \frac{q}{m}\begin{pmatrix}0\\E_y\\0\end{pmatrix} t$$

$$f_{gyro} = \frac{|q|B_y}{2\pi m} \sim 20\ \mathrm{GHz}\ (\mathrm{T} = 60\ \mathrm{ns})$$

$$r_{gyro} = \frac{v_\perp m}{|q|B_y} \sim (670\ \pm 10)\ \mu m$$





BGI Requirements

Requirements

$$\boxed{\frac{\boldsymbol{\Delta_{\epsilon_n}}}{\boldsymbol{\epsilon_n}} < \mathbf{5\%} \qquad \Rightarrow \qquad \frac{\boldsymbol{\Delta_\sigma}}{\boldsymbol{\sigma}} < \mathbf{2.5\%}}$$

Beam size uncertainty comes from:

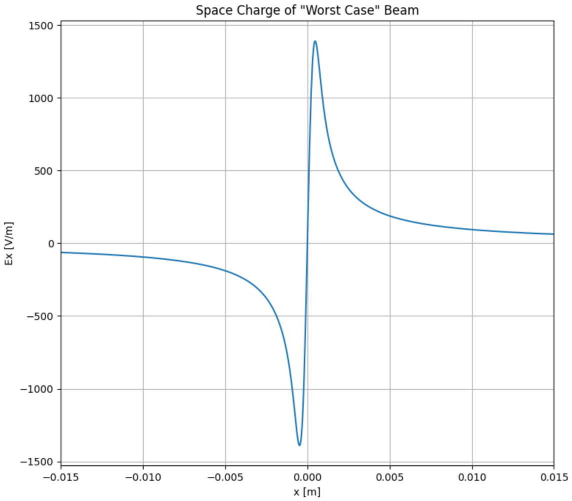
$$\Delta_{\epsilon_n}^2 = \left(\frac{\partial \epsilon_n}{\partial \sigma}\Delta\sigma\right)^2 + \cancel{\left(\frac{\partial \epsilon_n}{\partial \beta}\Delta\beta\right)^2} + \cancel{\left(\frac{\partial \epsilon_n}{\partial \gamma_r}\Delta\gamma_r\right)^2} + \cancel{\left(\frac{\partial \epsilon_n}{\partial \beta_r}\Delta\beta_r\right)^2} \quad \Rightarrow \quad \frac{\Delta_{\epsilon_n}}{\epsilon_n} = 2\frac{\Delta_\sigma}{\sigma}$$

Beam size systematic uncertainties are dependent on:

1. Space charge
2. Electric field uniformity and strength
3. Magnetic field uniformity and strength

Beam Type Used

- 2.2e11 protons/bunch
- Simulated 60,000 ionization electrons
  - ~ 15 ms integration time
  - ~ 0.29 % statistical uncertainty



protons

BGI	Beam	at	σ_x [mm]	σ_y [mm]
BGIH.5L4.B1	Standard	Injection	1.171	1.081
		Collision	0.319	0.302
	BCMS	Injection	1.054	0.977
		Collision	0.319	0.302
BGIV.5L4.B1	Standard	Injection	1.166	1.087
		Collision	0.318	0.302
	BCMS	Injection	1.049	0.978
		Collision	0.318	0.302
BGIH.5R4.B2	Standard	Injection	1.171	1.068
		Collision	0.322	0.296
	BCMS	Injection	1.171	1.068
		Collision	0.322	0.296
BGIV.5R4.B2	Standard	Injection	1.166	1.071
		Collision	0.321	0.296
	BCMS	Injection	1.049	0.963
		Collision	0.321	0.296

ions

BGI	Beam	at	σ_x [mm]	σ_y [mm]
BGIH.5L4.B1	baseline	Injection	2.505	2.323
		Collision	0.416	0.390
	75 ns option	Injection	3.102	2.877
		Collision	0.492	0.461
BGIV.5L4.B1	baseline	Injection	2.494	2.326
		Collision	0.414	0.391
	75 ns option	Injection	3.089	2.880
		Collision	0.490	0.461
BGIH.5R4.B2	baseline	Injection	2.505	2.285
		Collision	0.418	0.383
	75 ns option	Injection	3.101	2.830
		Collision	0.494	0.452
BGIV.5R4.B2	baseline	Injection	2.494	2.291
		Collision	0.416	0.383
	75 ns option	Injection	3.088	2.836
		Collision	0.492	0.453

***Tables from BGV/BGI Review on 19th October 2022

Complications from Non-Uniform Fields

(neglecting space charge)

$$\dot{\vec{r}}'(t) = \overrightarrow{\Omega'_c} \times \overrightarrow{\mathrm{r}'_c} + \frac{B_y}{|B|^2}\begin{pmatrix} -E'_z \\ 0 \\ E'_x \end{pmatrix} + \frac{q}{m}\begin{pmatrix} 0 \\ E'_y \\ 0 \end{pmatrix} t + \begin{pmatrix} 0 \\ \dot{y}'(0) \\ 0 \end{pmatrix}$$

ExB Drift

Solution to Lorentz equation for non-uniform electric field in “prime” frame of reference, where $\vec{B} = B'_y \hat{y}'$, from Bittencourt et al.

Rotate to BGI’s frame of reference to consider non-uniform magnetic field

$$\dot{\vec{r}}(t) = \boldsymbol{R}_{\boldsymbol{r}'\to\boldsymbol{r}}(\boldsymbol{\alpha},\boldsymbol{\gamma})\dot{\vec{r}}'(t)$$

$\boldsymbol{\alpha} \rightarrow \angle$ of rotation about $\hat{\boldsymbol{z}}$’

$\boldsymbol{\gamma} \rightarrow \angle$ of rotation about $\hat{\boldsymbol{x}}^*$

$$\boldsymbol{R}_{\boldsymbol{r}'\to\boldsymbol{r}}(\boldsymbol{\alpha},\boldsymbol{\gamma}) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & -\sin\gamma \\ 0 & \sin\gamma & \cos\gamma \end{pmatrix}_{\boldsymbol{r}^*\to\boldsymbol{r}} \begin{pmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}_{\boldsymbol{r}'\to\boldsymbol{r}^*}$$

Understanding Profile Shift

(neglecting space charge, omitting cyclotron motion)

$$\dot{x}_s(t) = \frac{E_x \sin\alpha \cos\alpha \sin\gamma + E_y \sin\gamma \cos^2\alpha - E_z \cos\gamma \cos\alpha}{|B|} + \frac{q}{m}\left(E_x \sin\alpha \cos\gamma + E_y \cos\alpha \cos\gamma + E_z \sin\gamma\right) \sin\alpha \, t$$

$$B_z \to 0 \Leftrightarrow \gamma \to 0$$

$$\dot{x}_s(t) = -\frac{E_z B_y}{|B|} \cos\alpha + \frac{q}{m}(E_x \sin^2\alpha + E_y \sin\alpha \cos\alpha)t$$

$$\sin\alpha = \frac{B_x}{|B|}; \ \cos\alpha = \frac{B_y}{|B|};$$

$$\dot{x}_s(t) = \frac{B_y}{|B|^2}\left(\frac{q}{m}(E_x B_y + E_y B_x)t - E_z B_y\right)$$

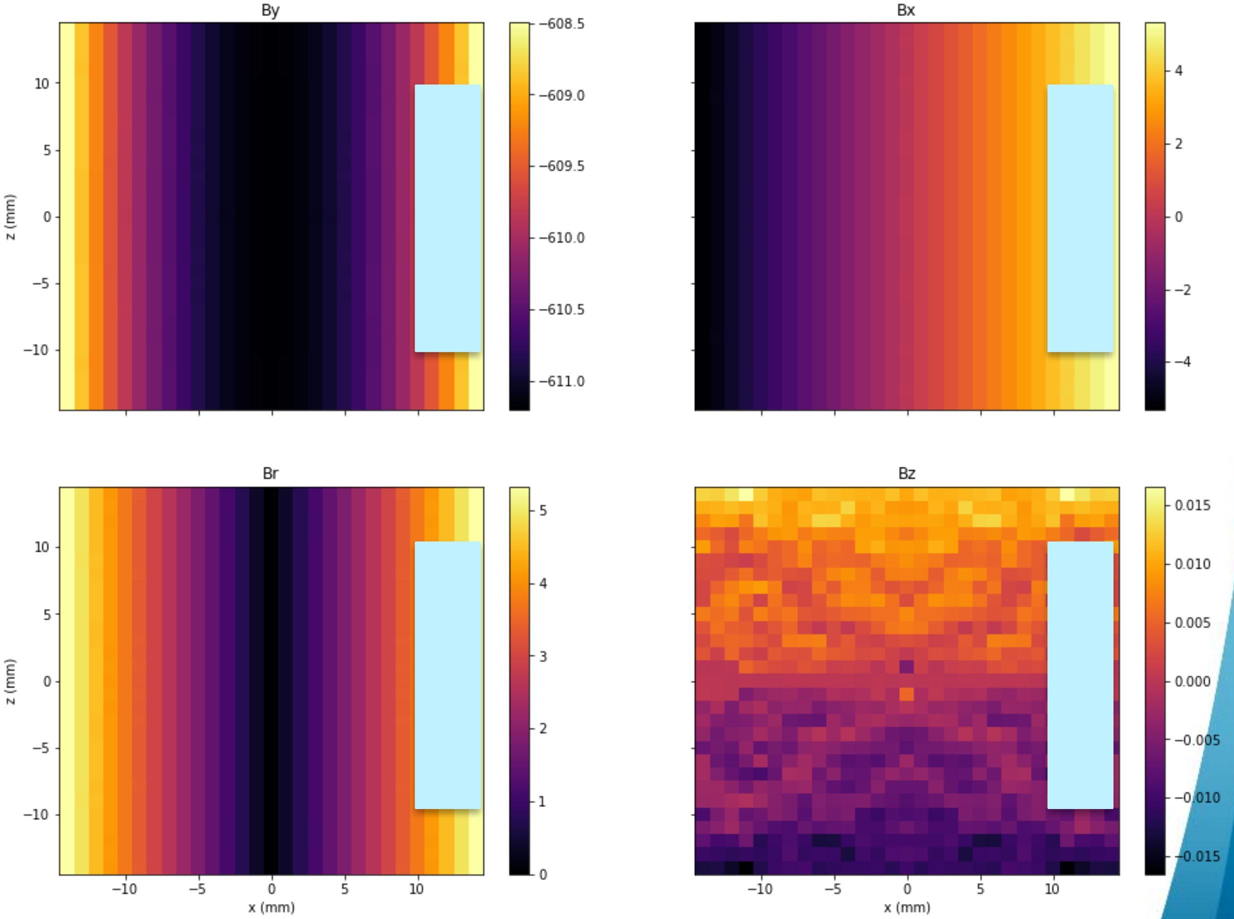
Accelerating drift

ExB Drift

Magnetic Fields

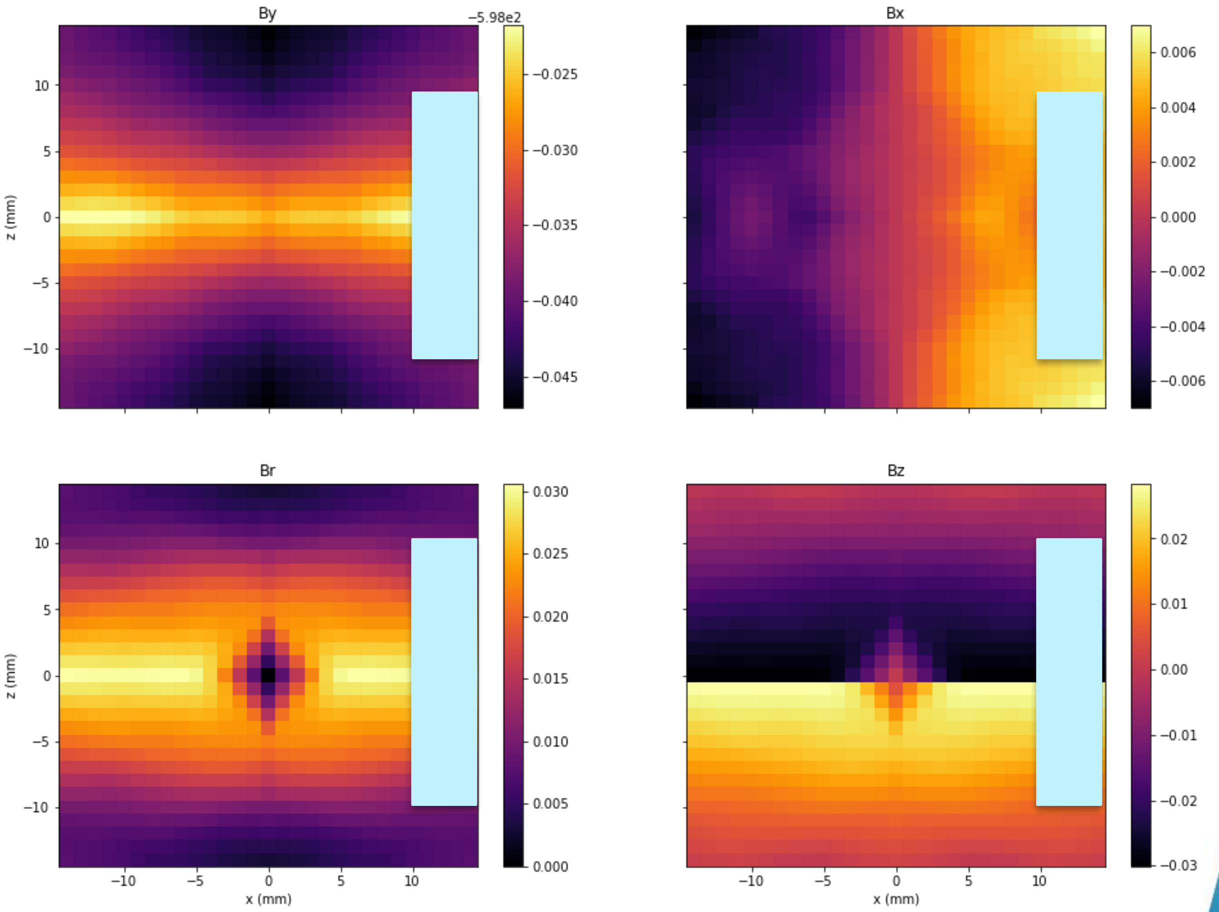
MDXL Magnet

- **150 mm** space in y
- Modification of original MDX magnet to enlarge space for instrument
- "Affordable option"
- $B_y = 610\ \pm$ $1\ \mathrm{mT}\ \ (0.1\%\ \mathrm{error})$
- $B_r = 3\ \pm 2\ \mathrm{mT}\ \left(\frac{B_r}{B_y}\times 100\% = 0.44\%\right)$



Rolls Royce Magnet

- Expensive low distortion option
- $B_y = 598.04 \pm 0.01\ \mathrm{mT}\ \ (0\%\ \mathrm{error})$
- $B_r = 0.02 \pm 0.01\ \mathrm{mT}\ \left(\frac{B_r}{B_y} \times 100\% = 0.003\%\right)$

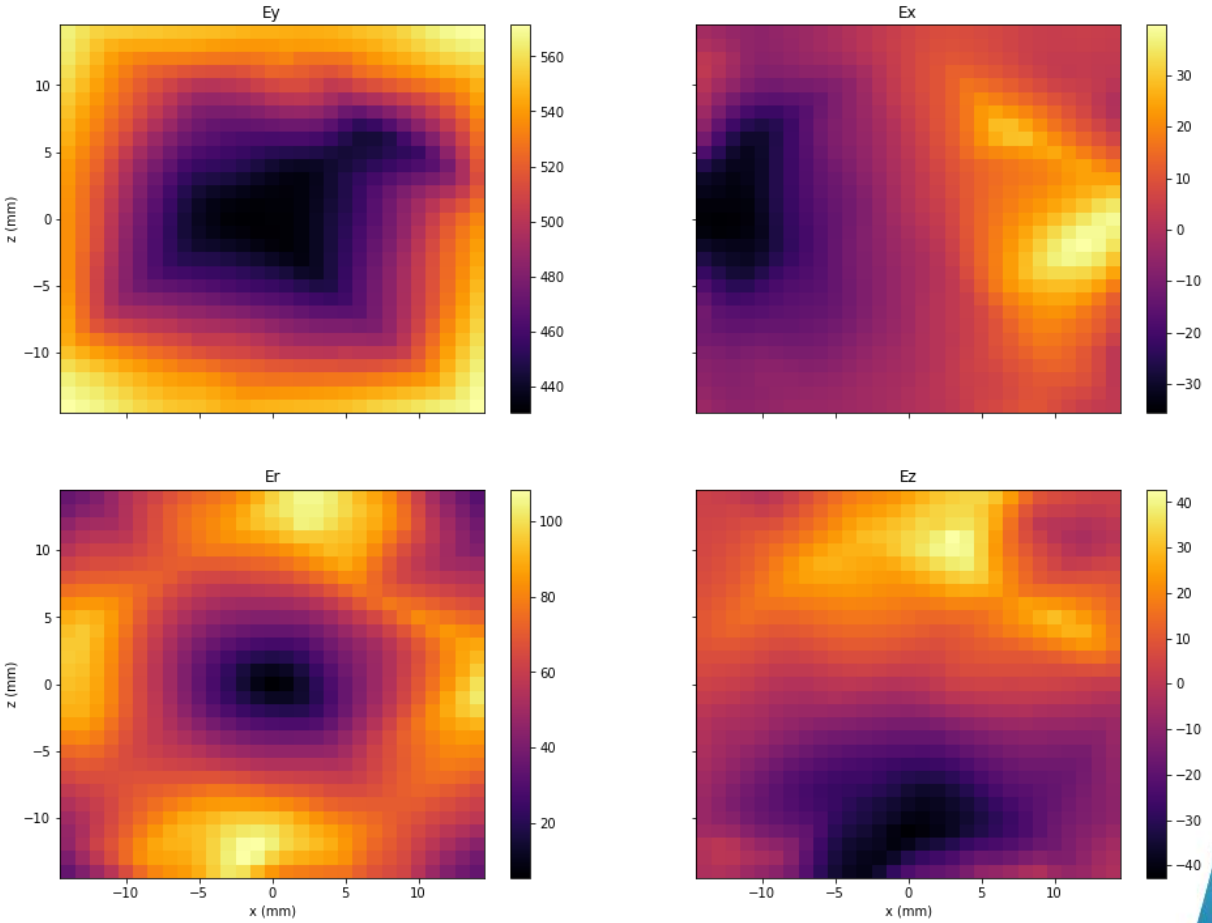


Electric Fields

CF250 Design Electric Field

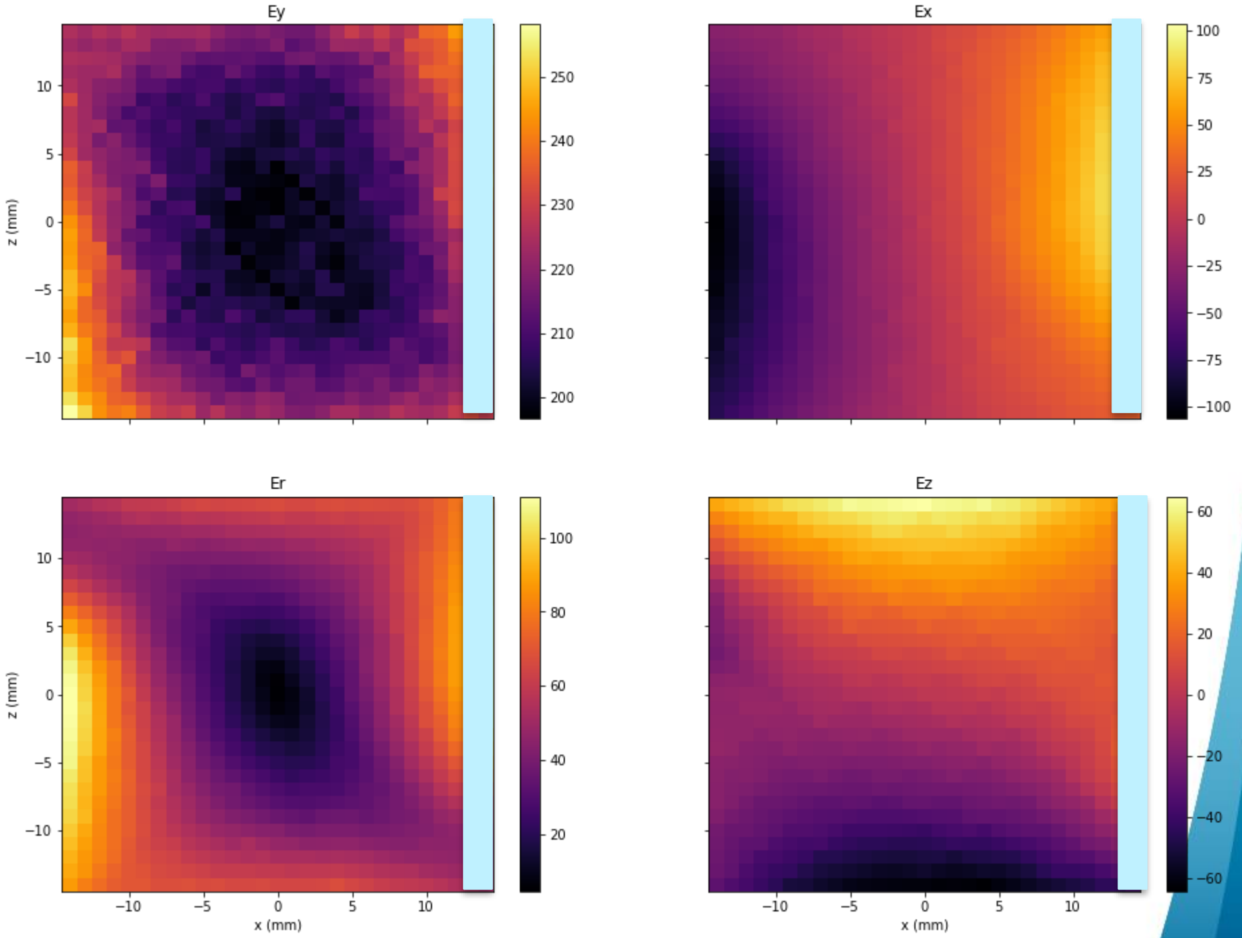
- $E_y = 500 \pm 40 \, \frac{\text{kV}}{\text{m}}$
  (7.7% error)

- $E_r = 65 \pm 20 \, \frac{\text{kV}}{\text{m}}$
  $\left(\frac{E_r}{E_y} \times 100\% = 13\%\right)$



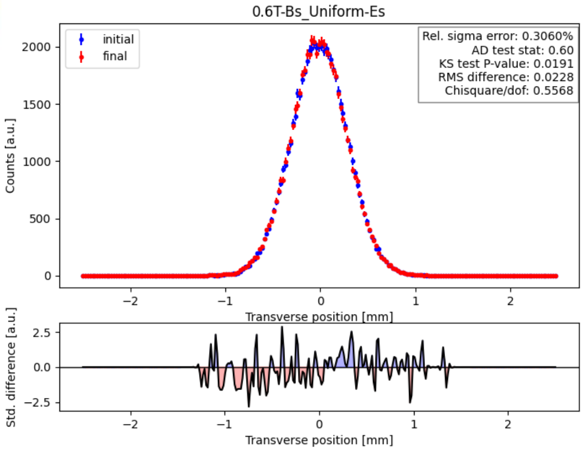
SPS Design's Electric Field

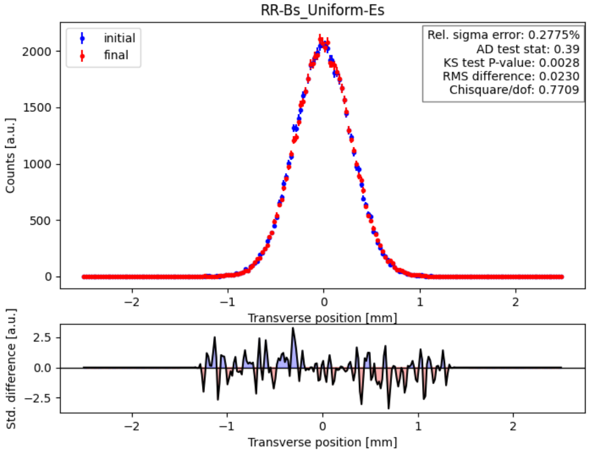
- $E_y = 220 \pm 10 \frac{\text{kV}}{\text{m}}$ (5.9% error)
- $E_r = 54 \pm 23 \frac{\text{kV}}{\text{m}}$ $\left(\frac{E_r}{E_y} \times 100\% = 25\%\right)$

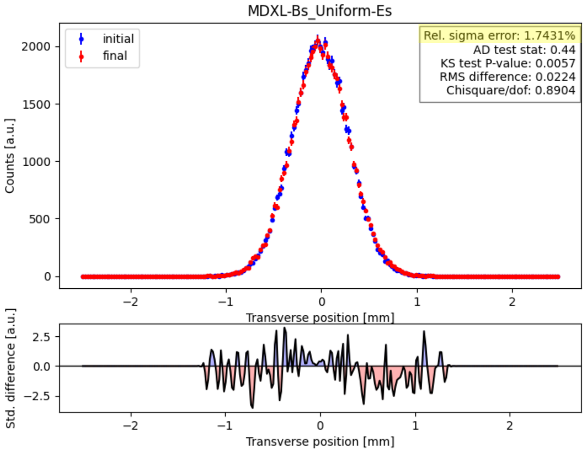


Results

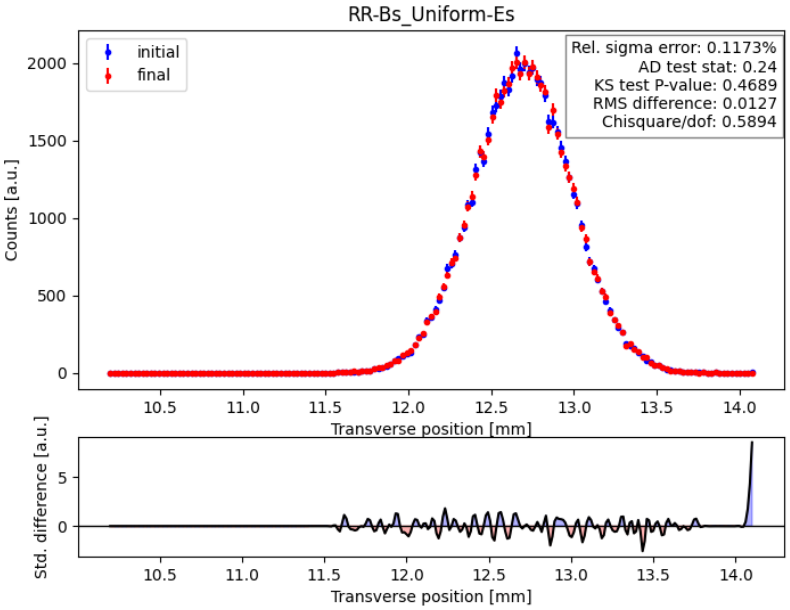
Uniform Electric Field (Centered)

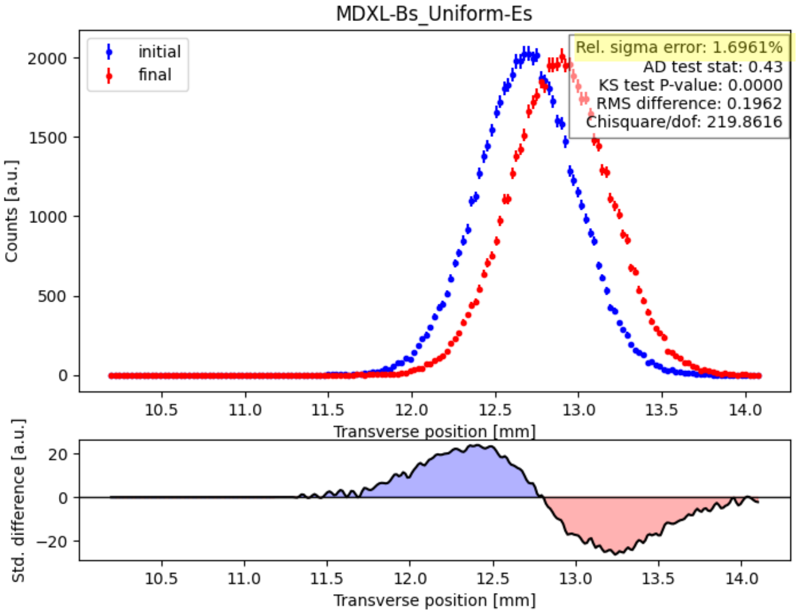




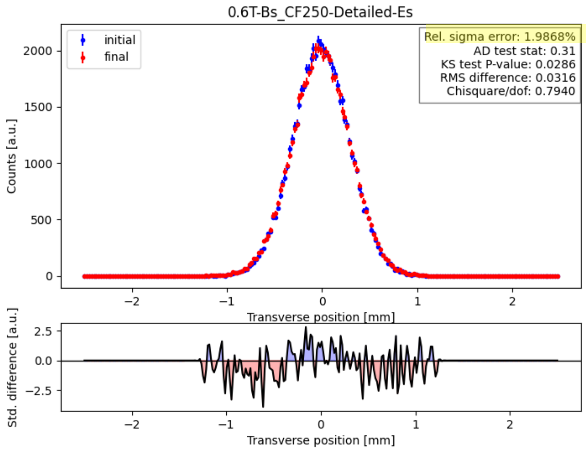


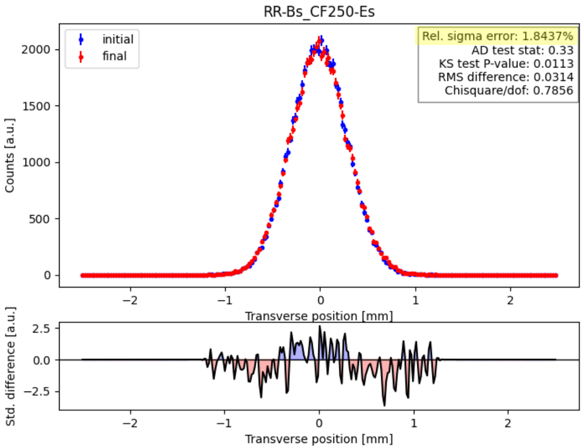
Uniform Electric Field (Worst Case)

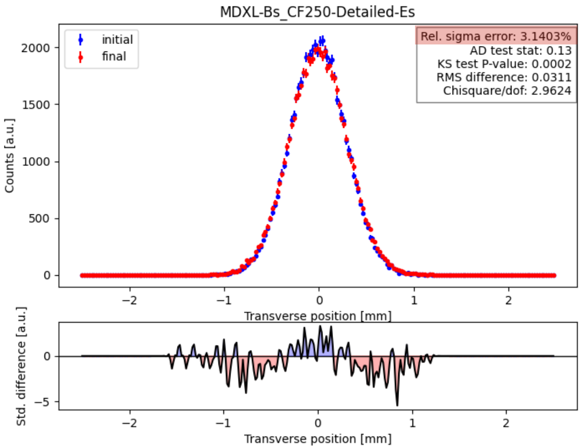




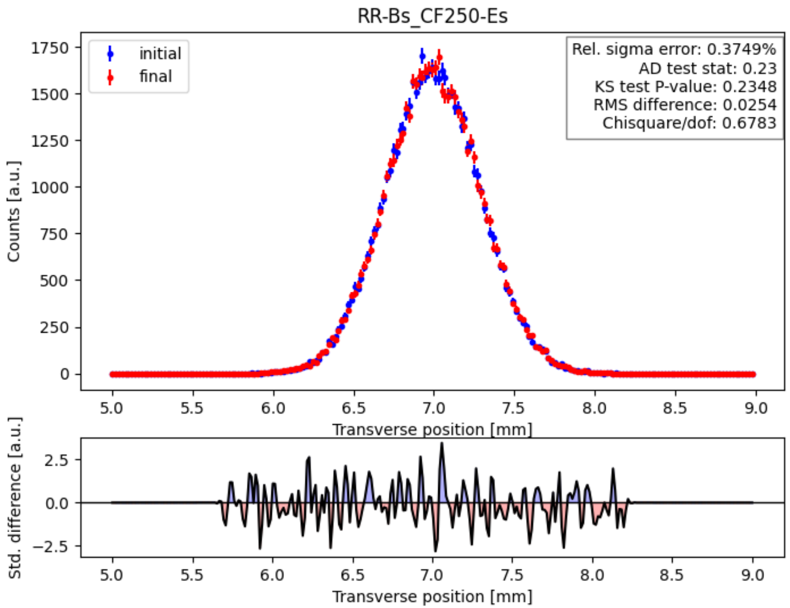
CF250 Design Electric Field (Centered)

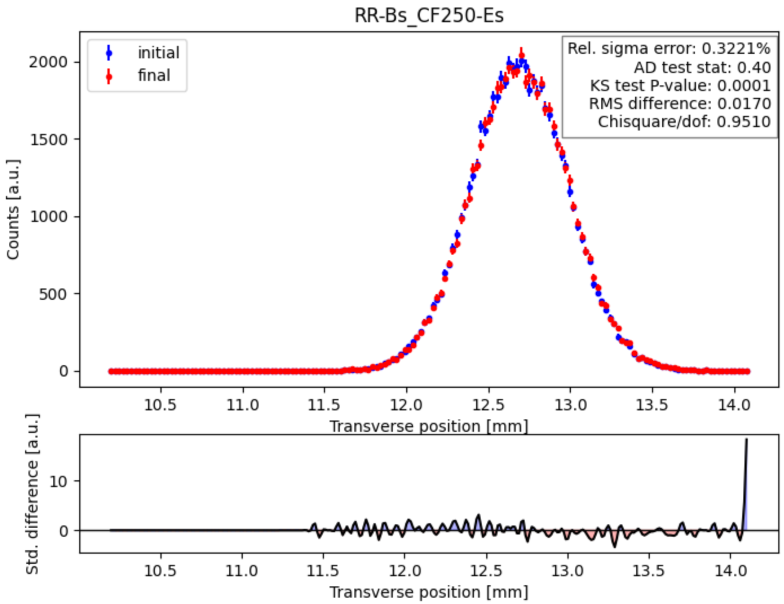




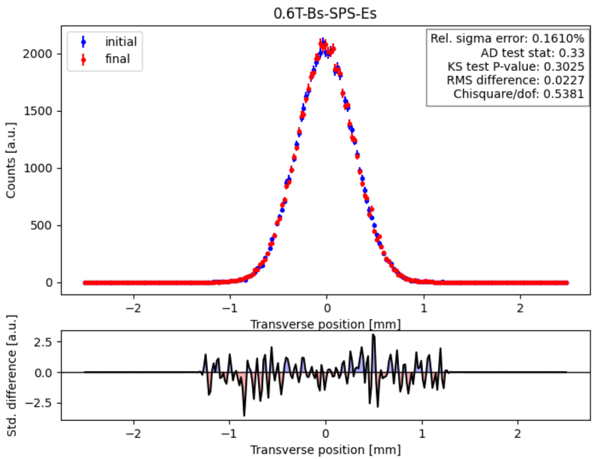


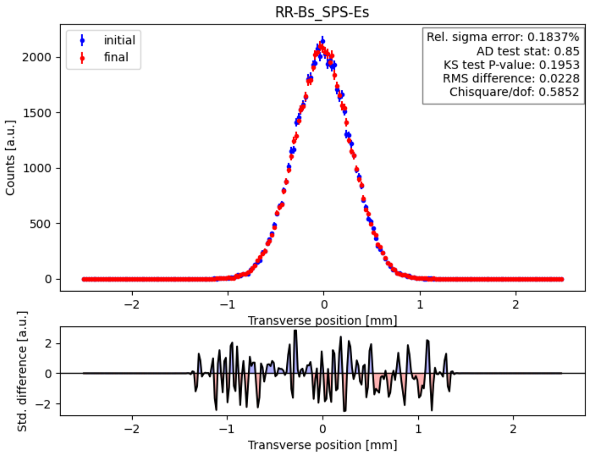
CF250 Design Electric Field (Worst Cases)

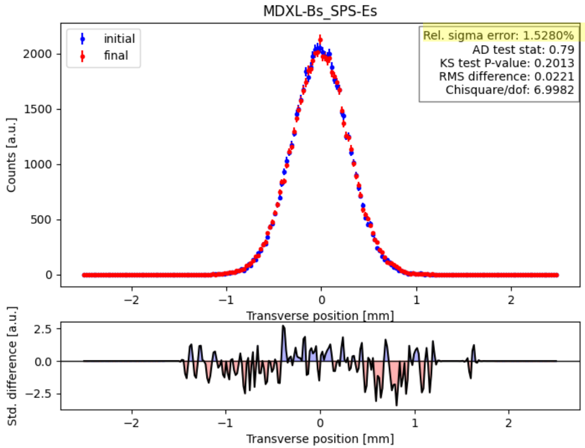




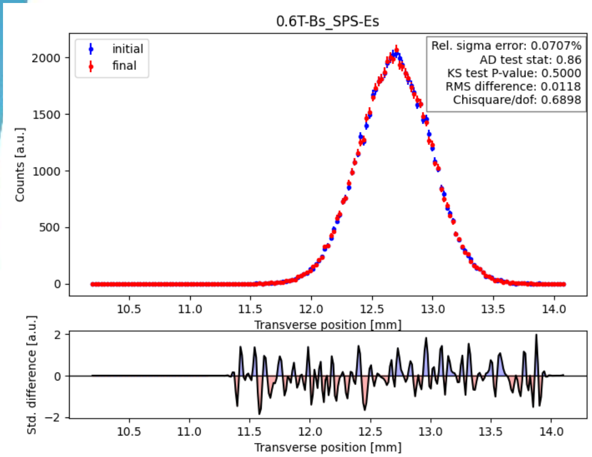
SPS Design Electric Field (Centered)

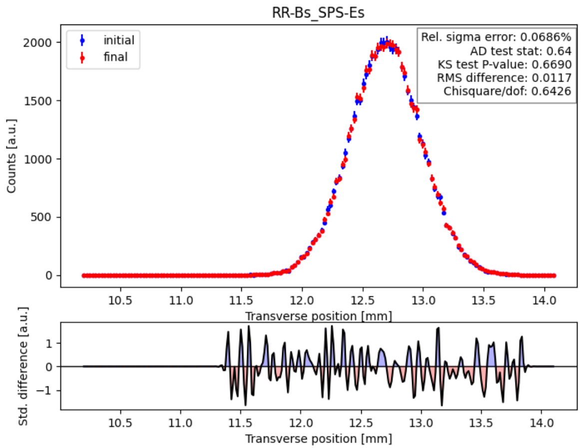


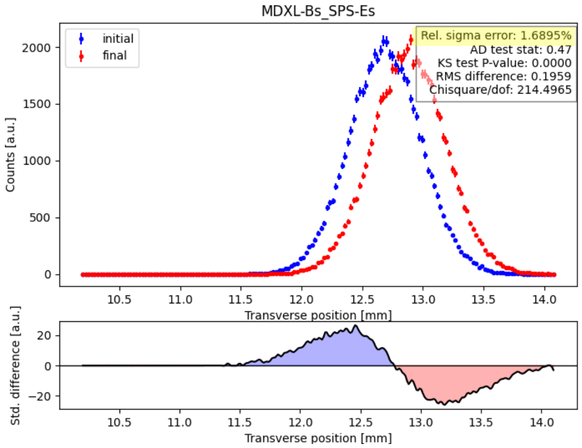




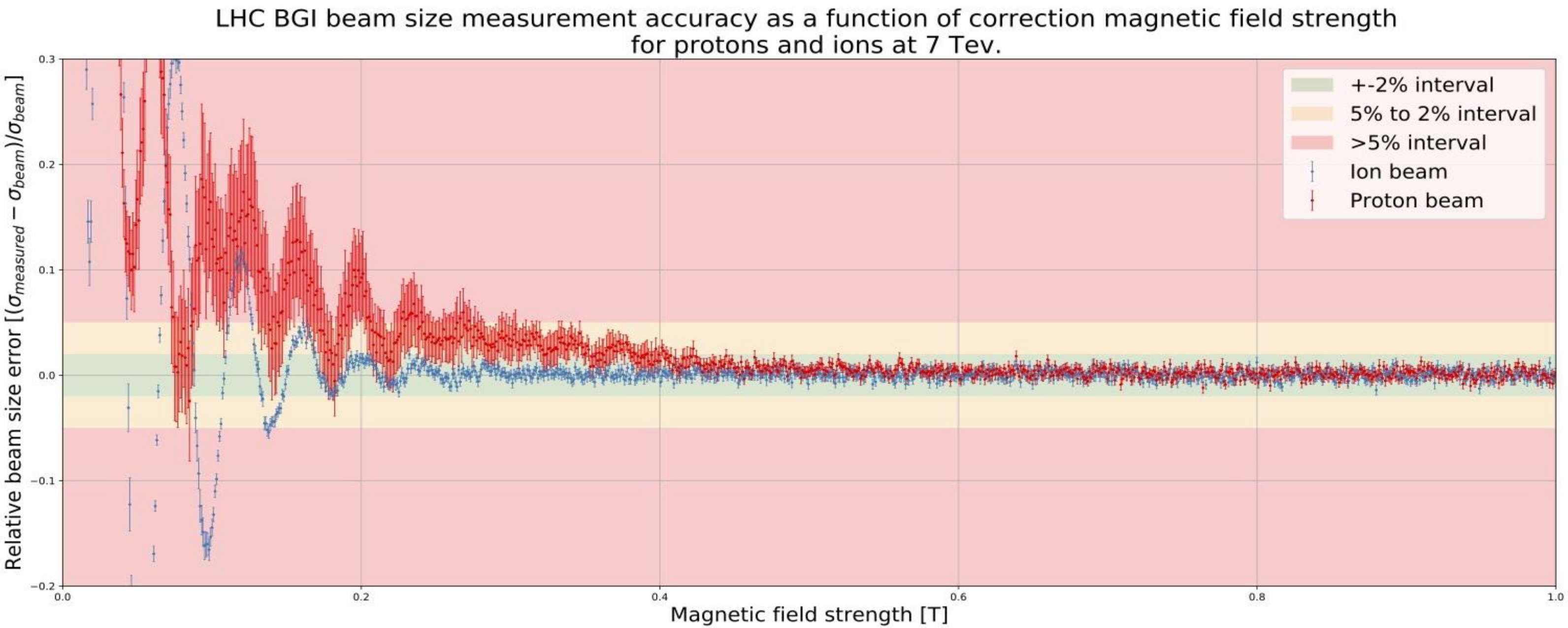
SPS Design Electric Field (Worst Case)



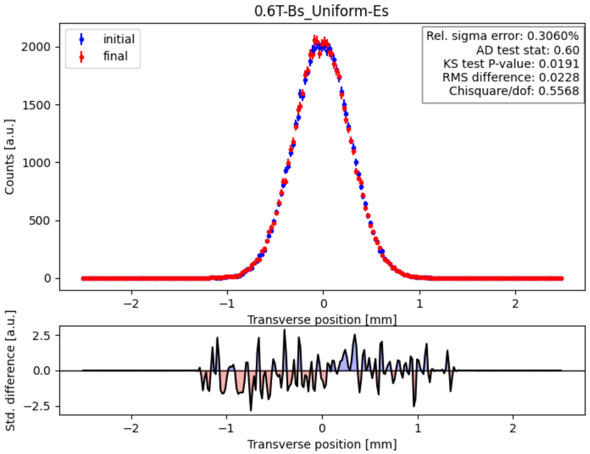


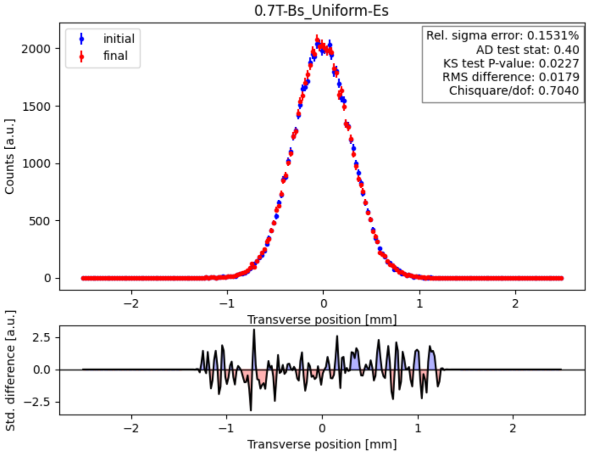


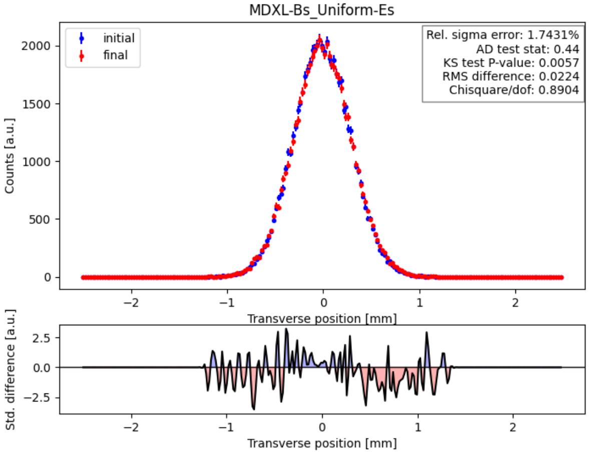
Appendix


LHC BGI beam size measurement accuracy as a function of correction magnetic field strength
for protons and ions at 7 Tev.
Relative beam size error [(σ_measured − σ_beam)/σ_beam]
Magnetic field strength [T]
+-2% interval
5% to 2% interval
>5% interval
Ion beam
Proton beam

Uniform Electric Field







CF250 Design Electric Field