Long-Baseline Neutrino Experiment

LBNE Lattice & Line Design

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Outline

- Design Overview
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  - Magnets
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    - Lattice Functions
    - Beam Envelope & Magnet Apertures
    - Final Focus & Spot Size Tuning
    - MI-10 Extraction
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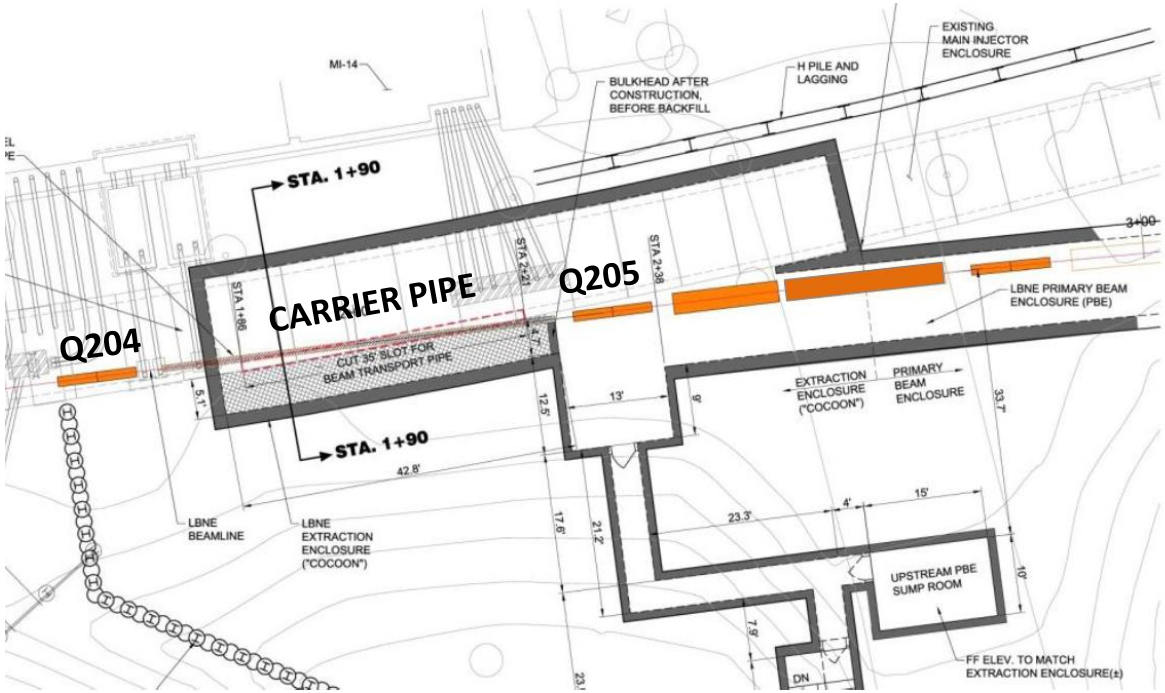
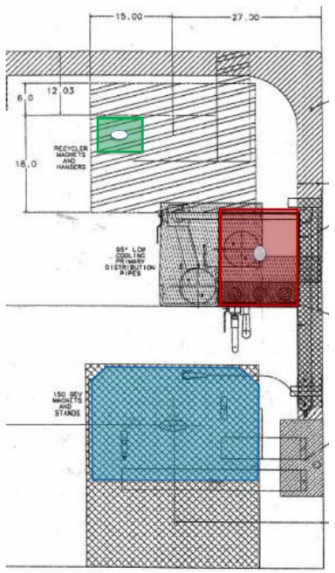
- Other Stuff
  - Sensitivity to Gradient Errors
  - Trajectory Control
  - Power Supply Ripple Effects
  - Known Interferences
  - Magnet Parameters

MI-10 Tunnel → LBNE Enclosure Transfer





RECYCLER

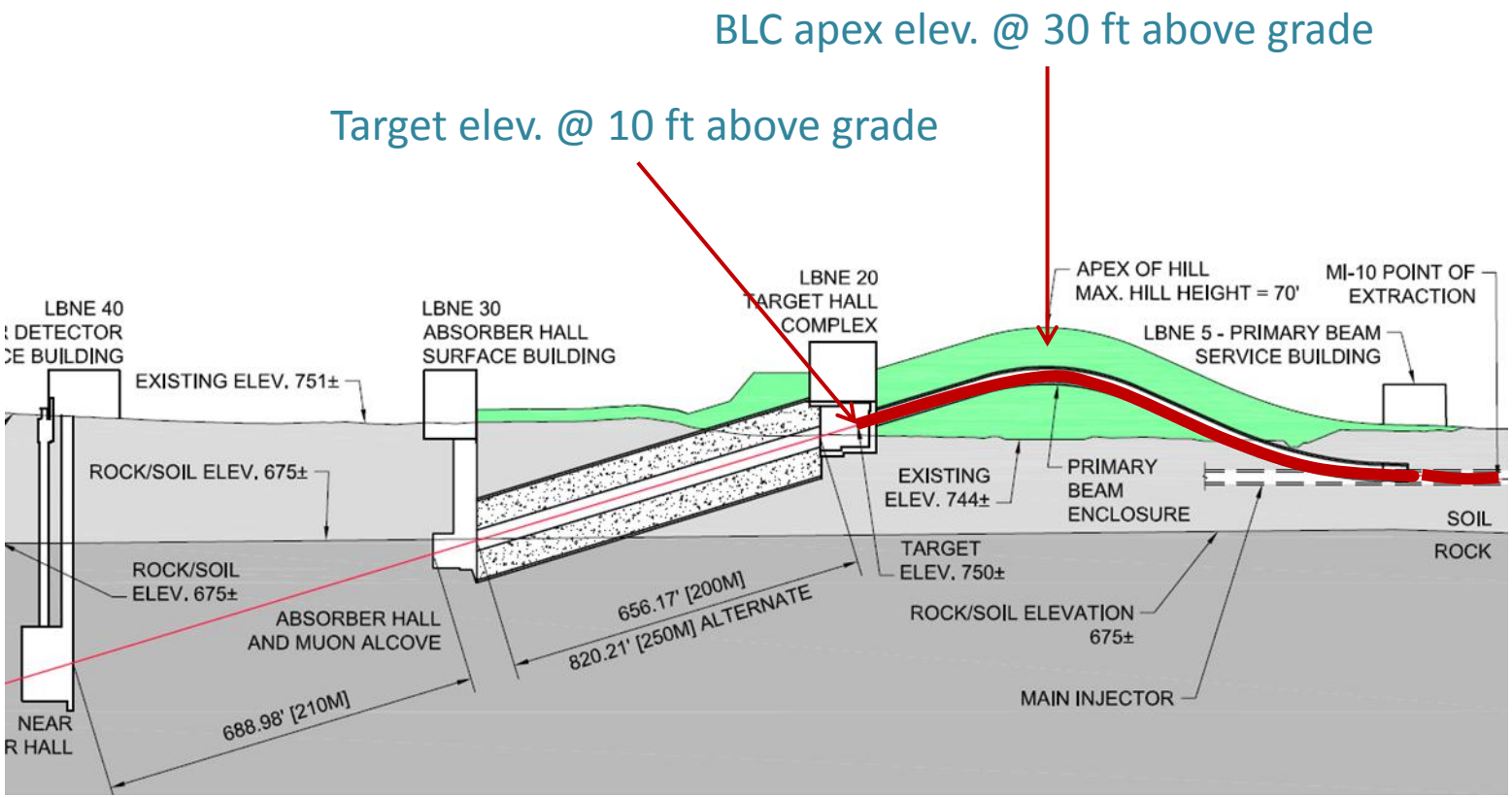
LBNE Q204

INJECTOR

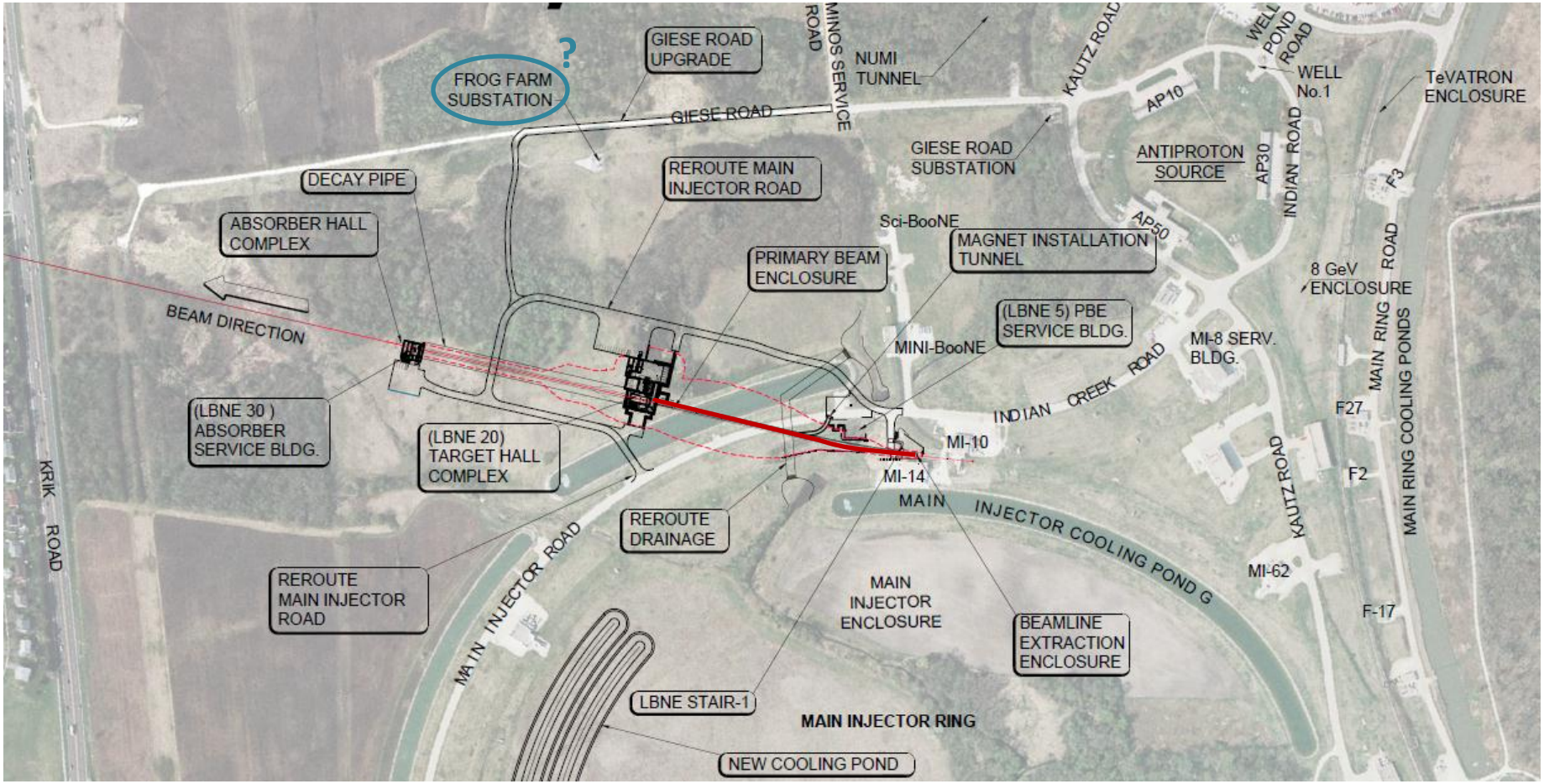
Transport from the existing MI tunnel enclosure into the new LBNE enclosure showing the carrier pipe connecting the MI-10 & LBNE enclosures (left), and separation of Q204 at the u/s end from the Main Injector & Recycler Rings (right).

Primary Beam & Hill Cross-section

THE PRIMARY BEAMLINE EXTRACTS PROTONS FROM MI-10 & TRANSPORTS TO THE TARGET ABOVE GRADE



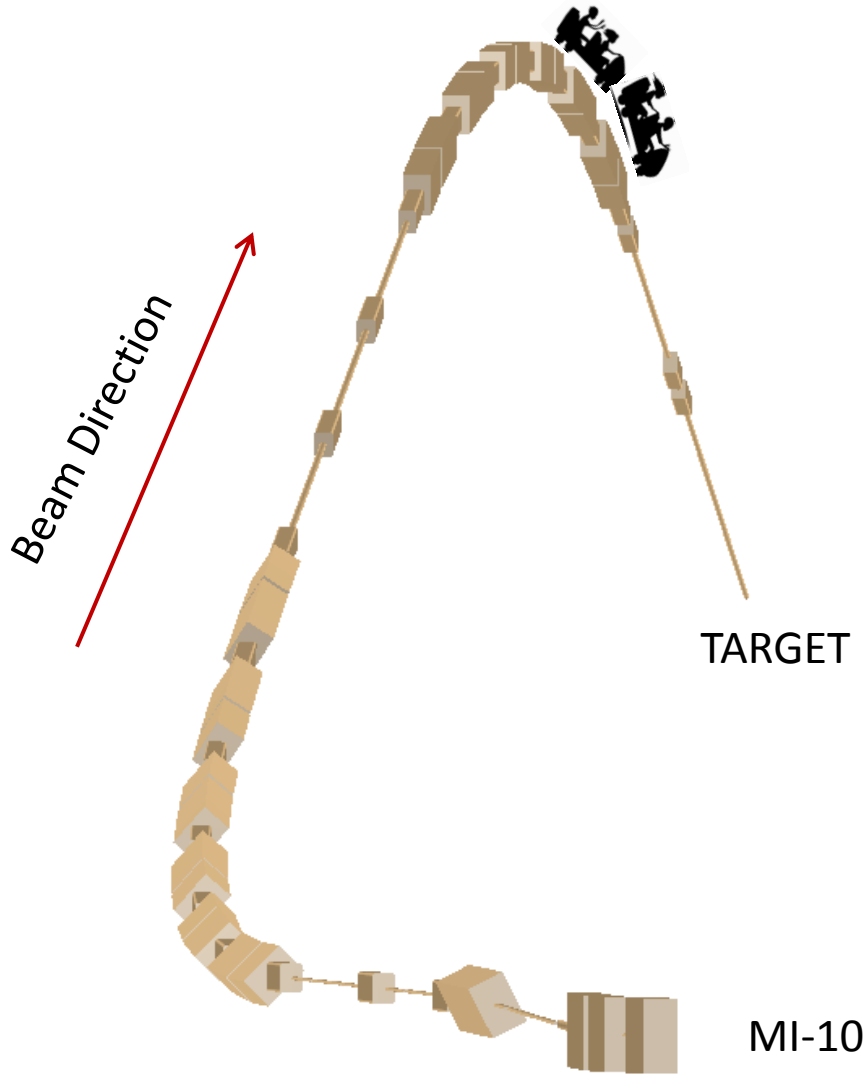
Aerial View of LBNE Trajectory



Trajectory

- Beam is extracted vertically from MI-10 *via* 5 horizontal kicker modules d/s of MI quad Q100, and 3 Lambertsons plus a C-magnet straddling MI Q102.
- A rolled dipole steers the beam through the enclosure wall, while bisecting the MI & Recycler magnet elevations.
- In the LBNE tunnel the beam is bent 7.2^{o} horizontally to align with SURF in South Dakota, and upwards by 143 mr. A second series of vertical dipoles bend the beam down through 244 mr to complete vertical alignment to SURF, with ϕ = -101 mr.
- Target elevation is fixed at 750 ft (~10 ft above grade) & maximum BLC elevation is 770 ft (~3 stories above grade).
- Distance from MCZERO to center of LAr FD = 1286873.765 m ±

LBNE – the Ride



Magnet Complement

- All major magnets are well-understood, proven designs
  - In the main body of the line all dipoles are Main Injector-style IDA/IDB (6m) & IDC/IDD (4m) magnets
  - Quadrupoles are all of the MI-style 3Q120 (3.048 m) or the shorter 3Q60 version (1.524m)
  - **New IDS trims have 3” pole tip gap & design spec of 250 μr (RMS).**

Magnet	Common Name	Steel Length	Strength at 120 GeV	Count
Kickers	NOvA extraction type	1.295 m	0.0589 T	5
ILA	MI Lambertson	2.800 m	0.532 / 1.000 T	3
ICA	MI C Magnet	3.353 m	1.003 T	1
IDA/IDB	MI Dipole 6 m	6.100 m	1.003 – 1.604 T	13
IDC/IDD	MI Dipole 4 m	4.067 m	1.003 – 1.604 T	12
QQB	MI 3Q120 quadrupole	3.048 m	9.189 – 16.546 T/m	17
QQC	LBNE 3Q60 quadrupole	1.524 m	11.135 – 17.082 T/m	4
IDS	LBNE trim dipoles	0.305 m	Up to 0.365 T	23

  - IDA/IDB sagitta = 11.7 → 18.6 mm *c.f.* 16 mm design nominal
  - IDC/IDD sagitta = 5.2 → 8.3 mm *c.f.* 7 mm design nominal

Optics

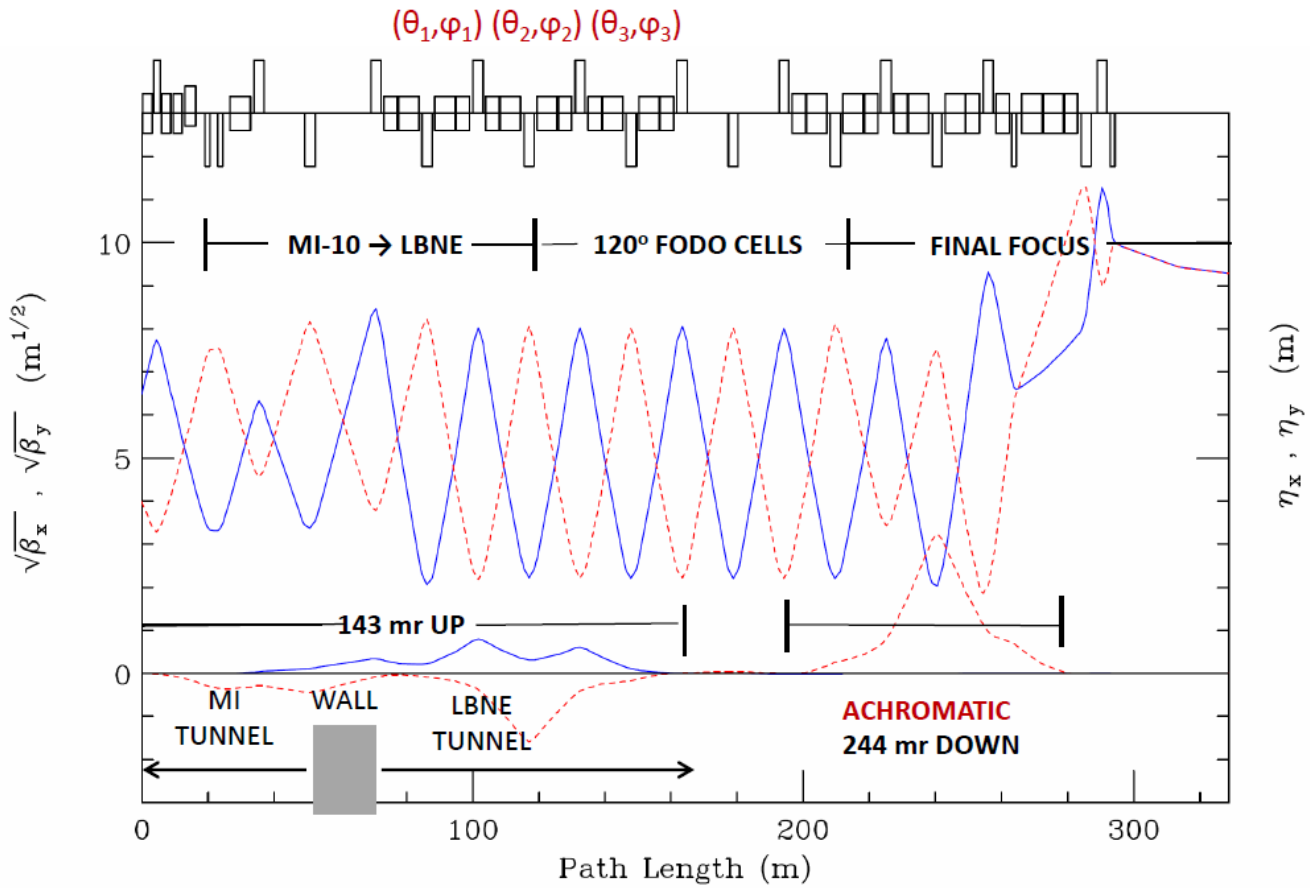
- To avoid losses the beam size in the LBNE transfer line can not exceed that of the Main Injector circulating beam.
- The ultra-clean transport requirements virtually compel the lattice to be configured from distinct optical modules.
  - Every focusing center has a dual-plane BPM & dipole corrector
  - Every half-cell has *space* reserved for a multi-wire or other diagnostics.

- Spot-size on target must be tunable over a wide range: from $\sigma \sim 1.0 \rightarrow \sim 4.0$ mm to accommodate a beam power upgrade to 2.4 MW.
- Physics dictates it must *also* be continuously tunable over the range 60 → 120 GeV/c for optimizing the neutrino oscillation spectrum.

Satisfying the above conditions requires that the final focus β^* be tunable over a range x32 (!).

- *Subsequent discussions , unless stated otherwise, assume nominal MI beam parameters of $\varepsilon_{99} = 30\pi\ \mu m$ (normalized) & $\Delta p_{99}/p = 11.e\text{-}4$, with $\sigma^* = 1.50$ mm.*

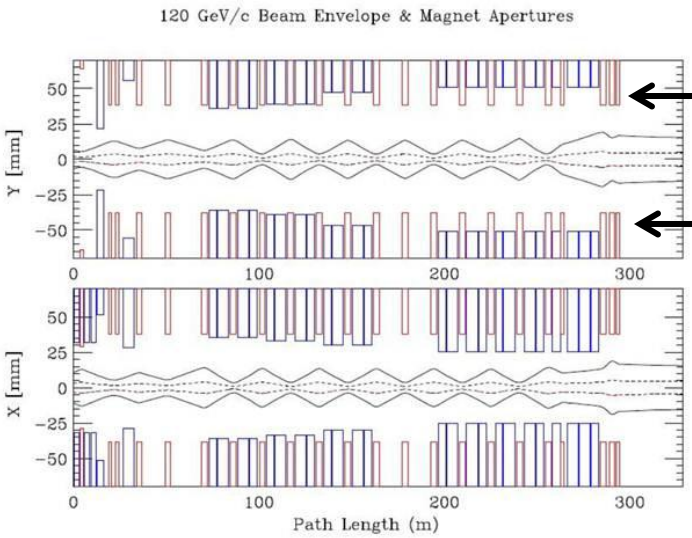
Lattice Functions

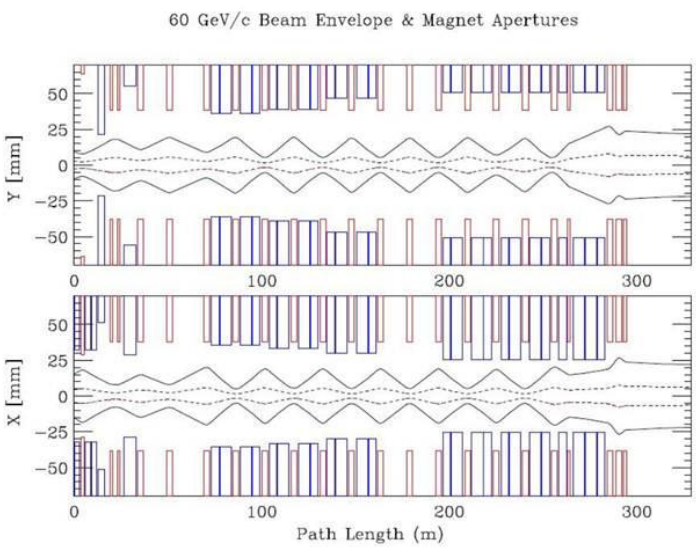


Horizontal (solid) and vertical (dashed) lattice functions of the LBNE transfer line

The final focus is tuned for $\sigma_x = \sigma_y = 1.50$ mm at 120 GeV/c with $\beta^* = 86.33$ m and nominal MI beam parameters $\varepsilon_{99} = 30\pi$ μm & $\Delta p_{99}/p = 11\times10^{-4}$

Beam Envelopes & Magnet Apertures





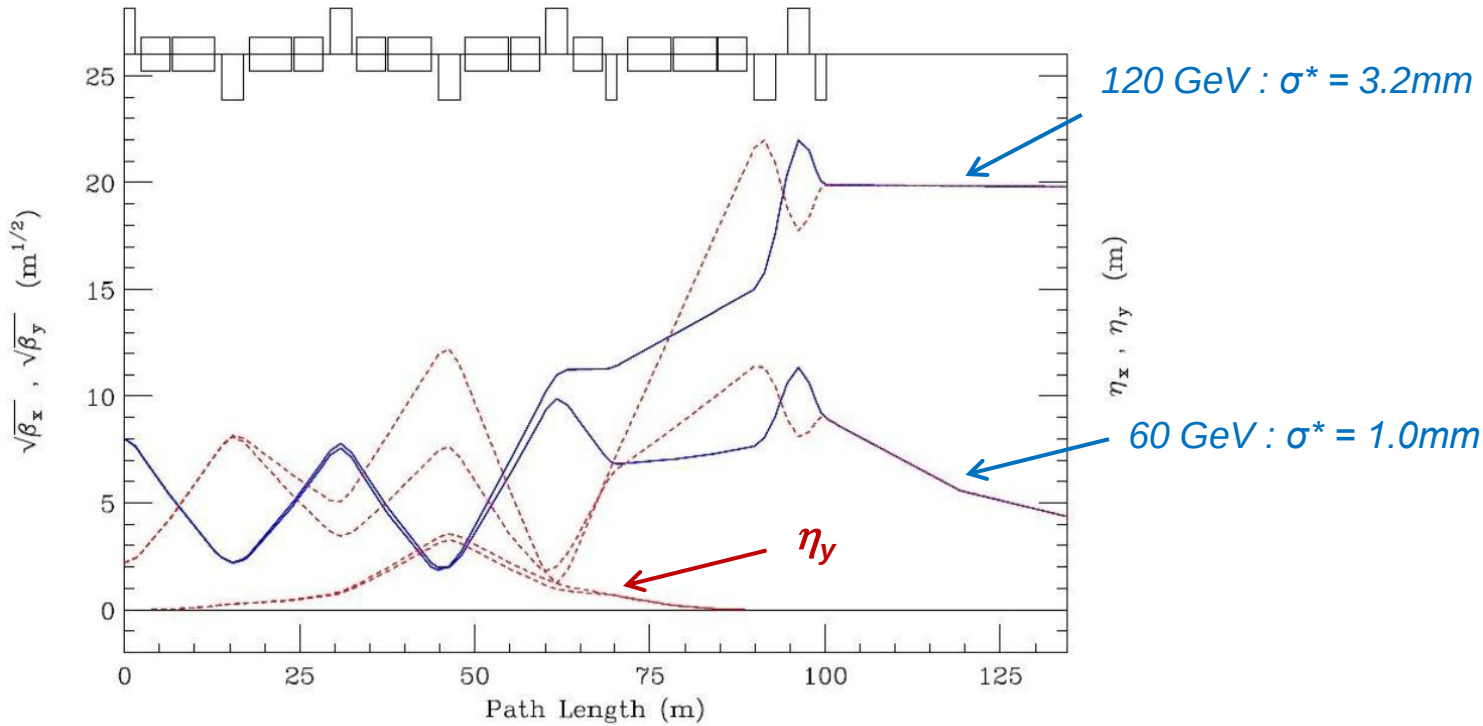
*Dipole apertures, shown in **blue**, include the effects of sagitta & rolls.*

*Quadrupole apertures are **red**.*

- The 99% envelopes (dashed) represent nominal MI beam parameters
  [$\varepsilon_{99} = 30\pi$ μm & $\Delta p_{99}/p = 11.e\text{-}4$];
- The 100% envelopes (solid) correspond to the MI admittance at transition .
  [$\varepsilon_{100} = 360\pi$ μm & $\Delta p_{100}/p = 28.e\text{-}4$ ($\gamma_t = 21.600$)]

The beamline can transport, without losses, the worst quality beam that the MI could conceivably transfer.

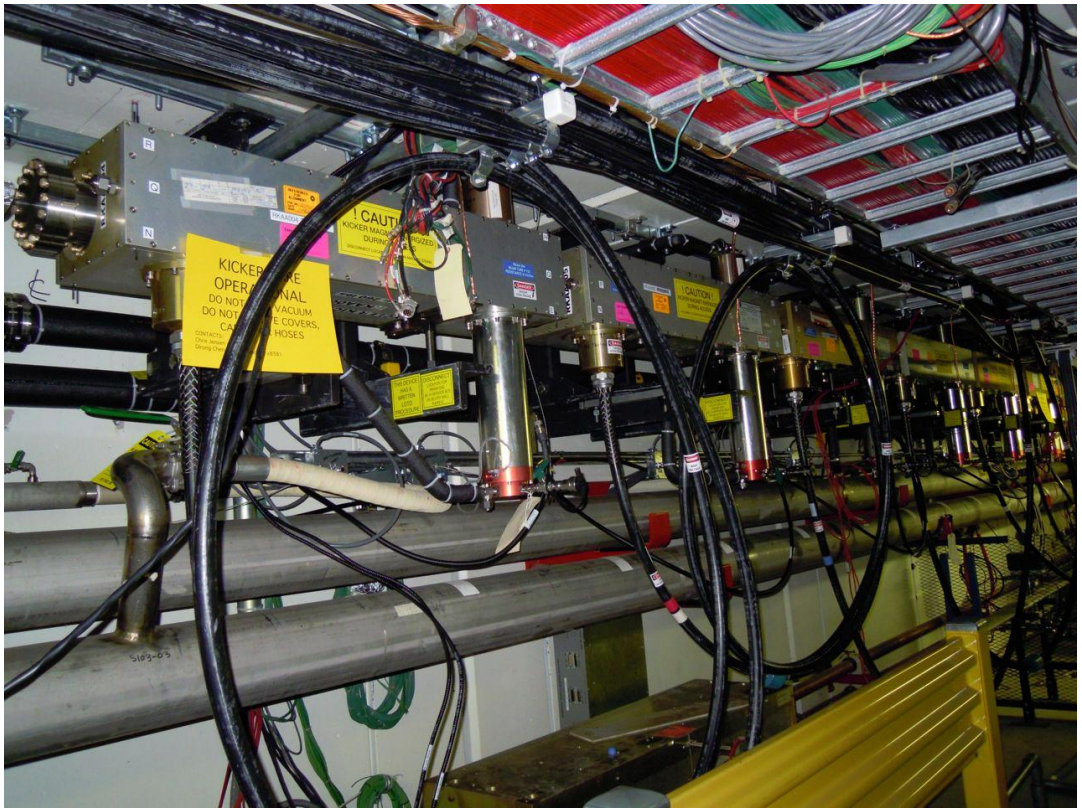
Final Focus & Spot-Size Tuning



The extremes shown correspond to: 60 GeV/c with σ = 1.0mm; β* = 19.184m and βmax = 104m (lower), and; at 120 GeV/c with σ* = 3.20mm; β* = 393 m and βmax = 483 m (upper). Horizontal values are displayed as solid curves & vertical values are dashed.*

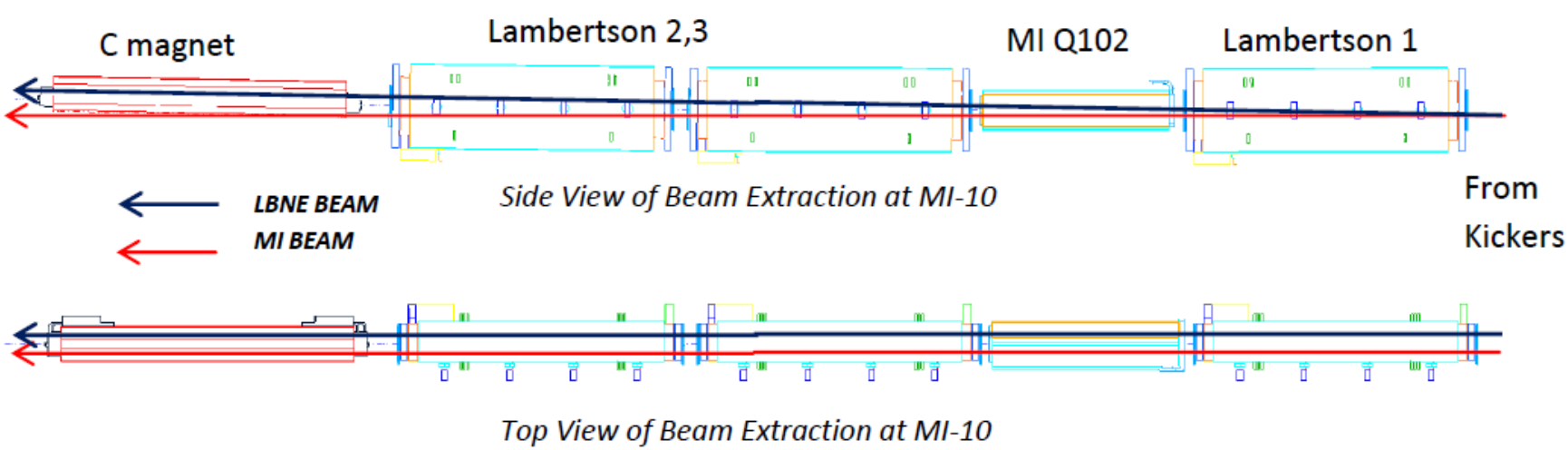
In principle the spot –size can be tuned to σ = 4.00mm, but the 3.20mm limit arises from the 360π mm-mr horizontal acceptance of the final down bend.*

MI-10 Extraction



MI Q104 looking upstream

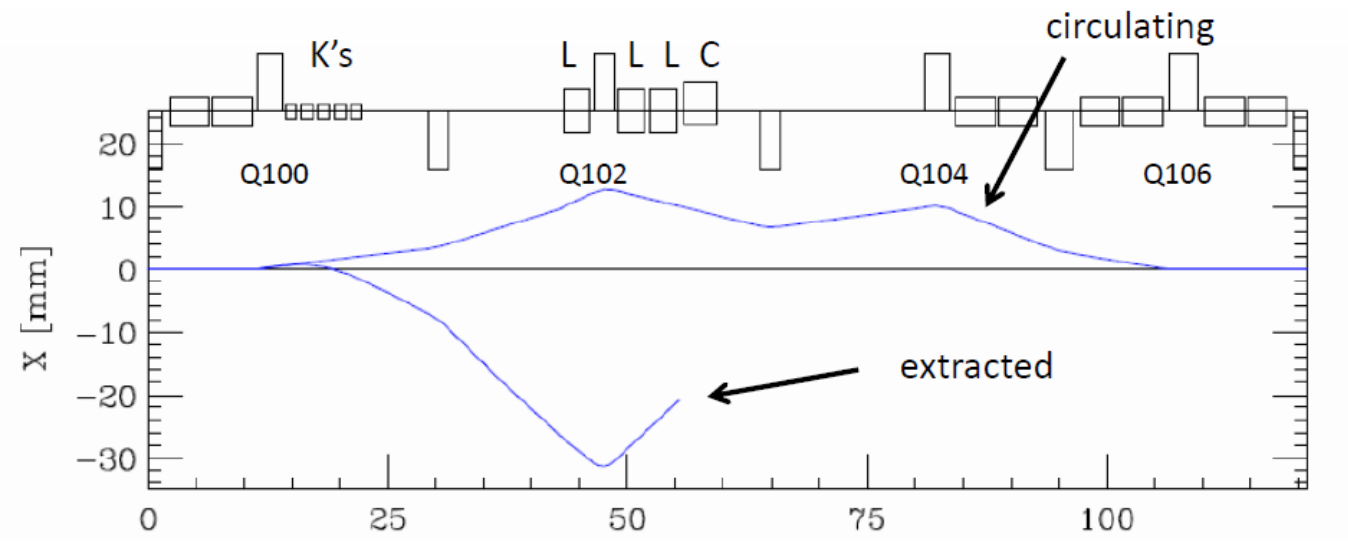
Extraction Element Configuration



LBNE extraction Lambertsons and C-magnet straddling MI quad Q102

- LBNE extraction elements and their configuration are clones of those found at other MI extraction points.

Closed Orbit & Extraction Trajectory through MI-10



Circulating & extracted beam trajectories through MI-10

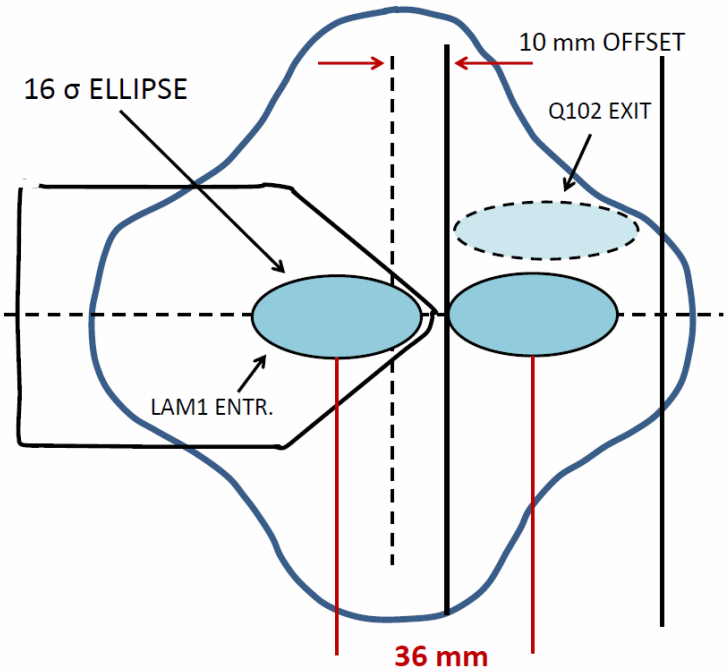
Closed Orbit Bump Quad Offsets (mm)

Q100	2.064
Q102	2.358
Q104	2.171
Q106	2.164

Extracted Beam Elements

Q100	2.064 mm
Kickers	5 x -190.0 μr (0.693 kG/module)
Q102	2.358 mm
LAM1	0.523 T
LAM2&3	0.998 T
C-MAG	0.998 T

Beam-Beam Separation in Quad 102



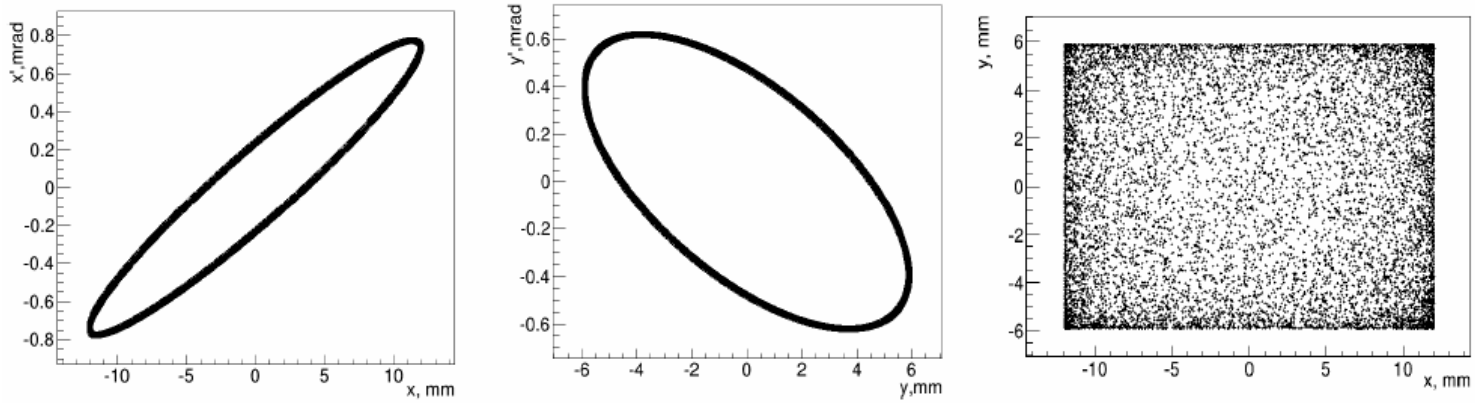
Large Aperture Quad
$5^5/_8$ x $5^5/_8$ Star Chamber

Circulating & extracted beams through Lam1 & Q102

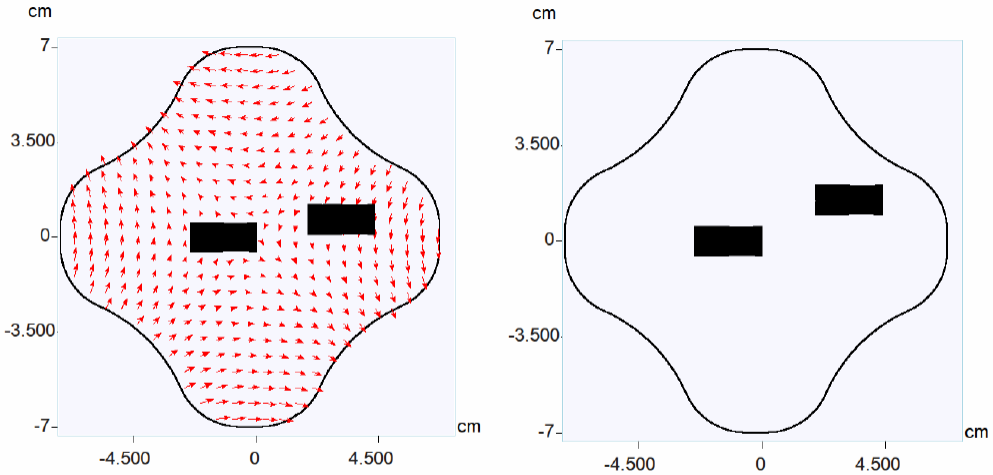
- Closed orbit bump is created by transverse offsets of focusing quads.
- Kickers create 36.2 mm separation at the 1st Lambertson entrance between circulating & extracted beams.

MARS Extraction Tracking

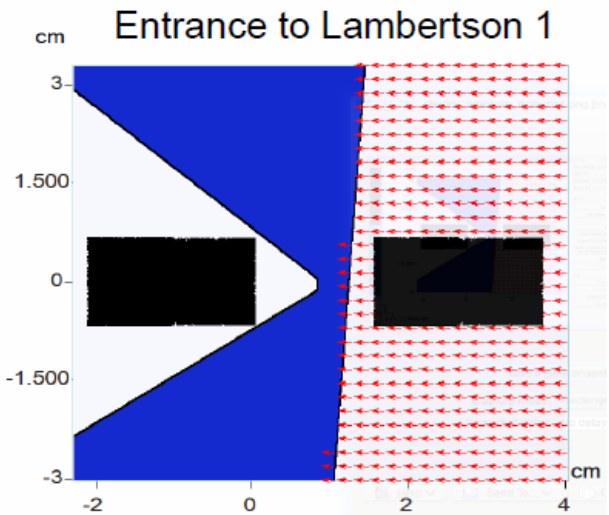
- Normalized 100% beam emittance is $\varepsilon_{100} = 360\pi$ mm-mr
- 10,000 points are selected on a surface in 4-dimensional (x,x';y,y') phase space
- Extraction tracking is from the u/s end of Q100 to the end of the 3rd Lambertson

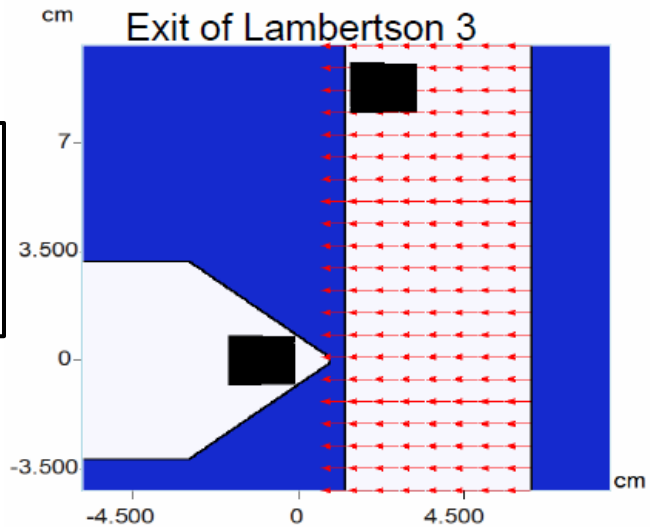


Beam-Beam Separations from MARS



Position of beams at the entrance (left) and exit of qudrupole
Horizontal shifts for all quadrupoles are defined in optics.





There is sufficient aperture to provide loss-free extraction of a normalized ε_N = 360π μm emittance beam (10.6 σ)

Summary

- Beam is extracted at MI-10 & transported to a target above grade.
- The lattice design is comprised entirely of proven MI-style magnets.
- MI-10 extraction configuration & the beamline provide for loss-free transmission of a 10.6σ beam.
- The final focus is continuously tunable from $\sigma^* = 1.00 \rightarrow 4.00$ mm over the entire momentum range $60 \rightarrow 120$ GeV/c

Ω

Other Stuff

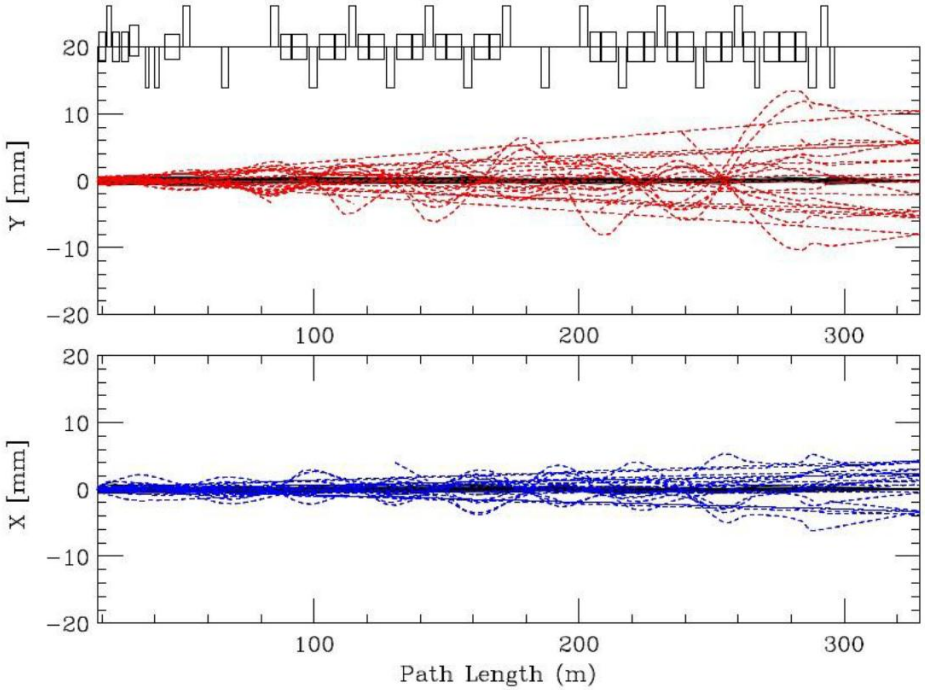
- Sensitivity to Gradient Errors
- Trajectory Control
- Power Supply Ripple Effects
- Known Interferences
- Magnet Parameters

Sensitivity to Gradient Errors

- *Not An Issue!*
- Experience has shown the MI-style 3Q120 quadrupoles to be of very high accelerator quality†
  - $\sigma(\Delta G/G) \sim 0.08\%$ or less, which can be reduced even further for the FODO section with only rudimentary sorting.
  - A simple thin-lens calculation predicts that even the largest error-wave generated in the 99% beam envelope [$\pm$3.74mm at β = 59.6m] would be < 70 microns.

† *Magnet Test Facility measurement data base.*

Trajectory Control



Uncorrected/corrected trajectories with random misalignments and dipole field errors

The plot begins at the u/s end of the 1st Lambertson.

Misalignments (including BPM's)

- $\sigma(\Delta x,\Delta y) = 0.25$ mm
- $\sigma(\psi_{roll}) = 0.50$ mr

Dipole Field Errors

- $\sigma(\Delta B/B) = 10e\text{-}4$

	ORBIT (mm)		CORRECTORS (μr)		ORBIT (mm)		CORRECTORS (μr)	
	X_{max}	X_{RMS}	θ_{max}	θ_{RMS}	Y_{max}	Y_{RMS}	φ_{max}	φ_{RMS}
UNCORRECTED	6.200	1.614	–	–	14.732	3.414	–	–
CORRECTED	0.996	0.285	110.670	26.653	1.101	0.281	114.430	37.901
	BEAM JITTER ON TARGET							
	X (μm)		X' (μr)		Y (μm)		Y' (μr)	
	X_{max}	X_{RMS}	X'_{max}	X'_{RMS}	Y_{max}	Y_{RMS}	Y'_{max}	Y'_{RMS}
CORRECTED	1.079	0.400	0.694	0.230	0.437	0.139	0.330	0.110

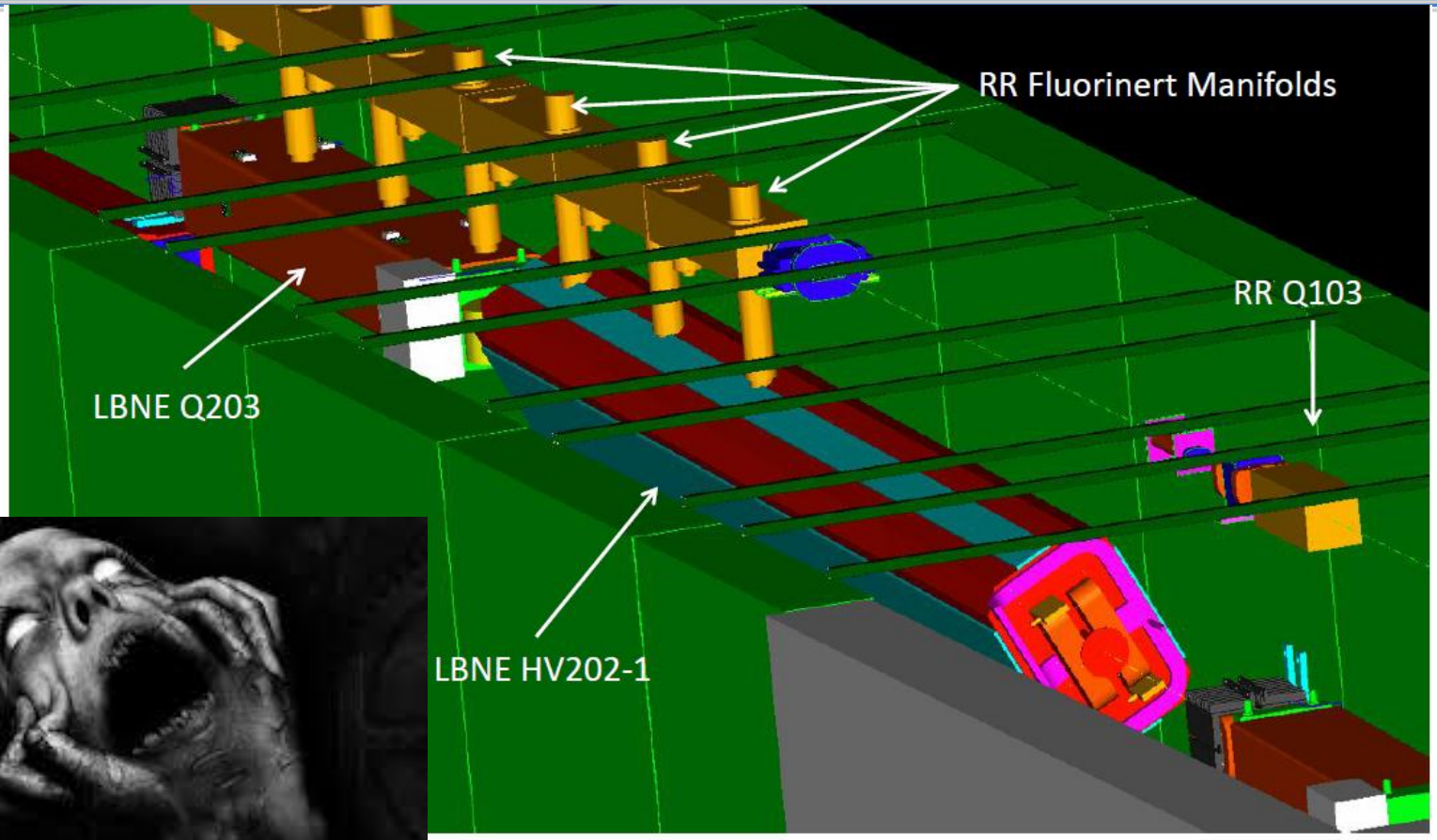
New IDS design spec is 250 μr (RMS).

Known Interferences

- C-magnet – MI Beamtube ✓
- Q201A/B – MI Q103 ✓
- HT201A – MI Beamtube ✓
- VT203 – MI Tunnel Wall ✓
- Q204 – LBNE Enclosure Wall ✓
- V217A/B Overlap ✓

- LBNE – Recycler Co-existence

LBNE– Recycler Co-existence



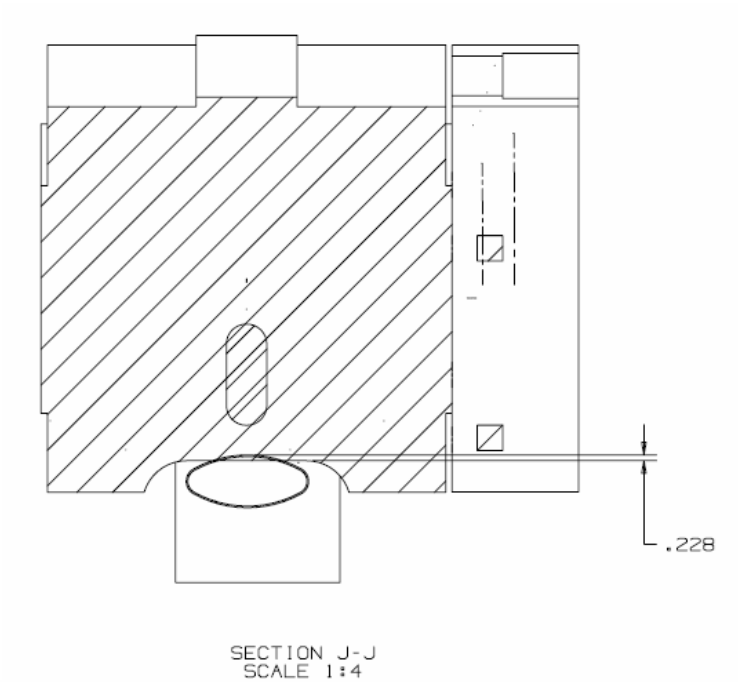
Coraggio ! Avanti !

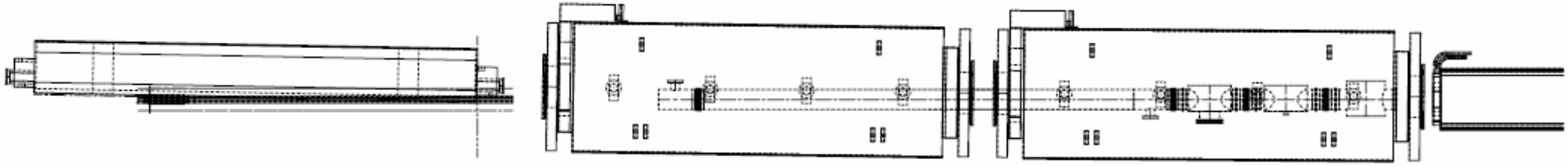
Magnet Parameters

DIPOLE TYPE (#)	L (m)	B (T)	TILT (deg)		QUAD NAME (#)	TYPE	L (m)	G (T/m)
MI-10 EXTRACTION → LBNE								
LAM1	2.8000	0.53242	−90.000					
					Q102	3Q84	2.134	+16.16016
LAM12 (2)	2.8000	1.00000	−90.000					
V100	3.3528	1.00284	−90.000					
MATCH FROM MI → LBNE FODO LATTICE & 143 mr UP BEND								
					Q201→202	3Q60	1.524	−11.13509
IDA/B	6.09981	1.22335	+62.844					
					Q203	3Q120	3.048	+12.48756
					Q204	3Q120	3.048	−9.18907
					Q205	3Q120	3.048	+13.06221
IDC	4.06654	1.38347	−44.126					
IDB	6.09981	1.38347	−44.126					
					Q206	3Q120	3.048	−13.52413
IDA	6.09981	1.38347	−44.126					
IDD	4.06654	1.38347	−44.126					
					Q207	3Q120	3.048	+16.16931
IDC	4.06654	1.10813	−48.179					
IDB	6.09981	1.10813	−48.179					
FODO CELLS								
					Q208	3Q120	3.048	−15.83240
IDA	6.09981	1.10813	−48.179					
IDD	4.06654	1.10813	−48.179					
					Q209	3Q120	3.048	+15.83240
IDC	4.06654	1.00297	−56.109					
IDB	6.09981	1.00297	−56.109					
					Q210	3Q120	3.048	−15.83240
IDA	6.09981	1.00297	−56.109					
IDD	4.06654	1.00297	−56.109					
					Q211→213 (3)	3Q120	3.048	±15.83240
244 mr ACHROMATIC DOWN BEND & FINAL FOCUS ON TARGET								
IDC	4.06654	1.60431	+90.000					
IDB	6.09981	1.60431	+90.000					
					Q214	3Q120	3.048	−13.96520
IDA	6.09981	1.60431	+90.000					
IDD	4.06654	1.60431	+90.000					
					Q215	3Q120	3.048	+16.54570
IDC	4.06654	1.60431	+90.000					
IDB	6.09981	1.60431	+90.000					
					Q216	3Q120	3.048	−15.26976
IDA	6.09981	1.60431	+90.000					
IDD	4.06654	1.60431	+90.000					
					Q217	3Q120	3.048	+13.81046
IDC/D	4.06654	1.60431	+90.000					
					Q218	3Q60	1.524	−17.08214
IDA/B	6.09981	1.60431	+90.000					
IDA/B	6.09981	1.60431	+90.000					
IDC/D	4.06654	1.60431	+90.000					
					Q219	3Q120	3.048	−10.53138
					Q220	3Q120	3.048	+15.80329
					Q221	3Q60	1.524	−13.39482

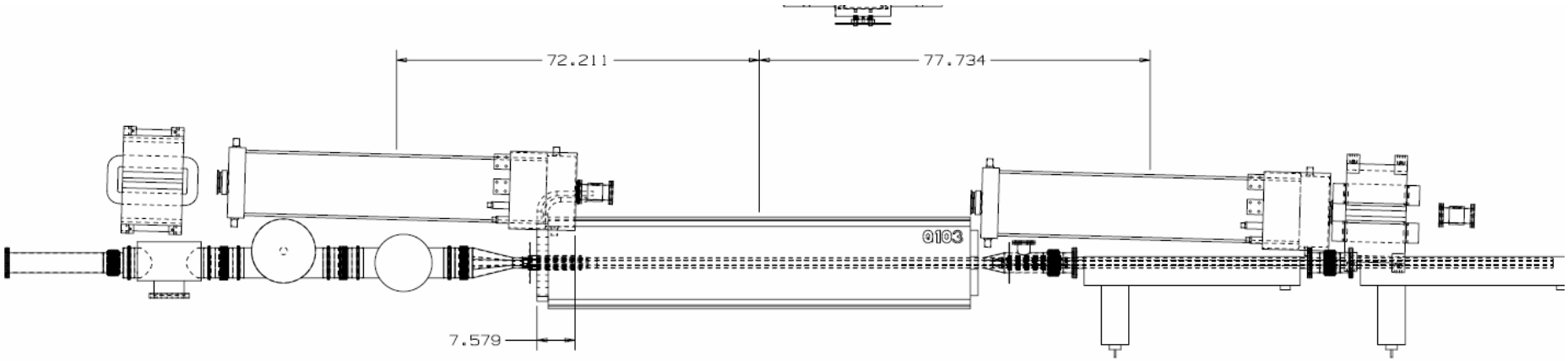
Backoff Interference Pictures

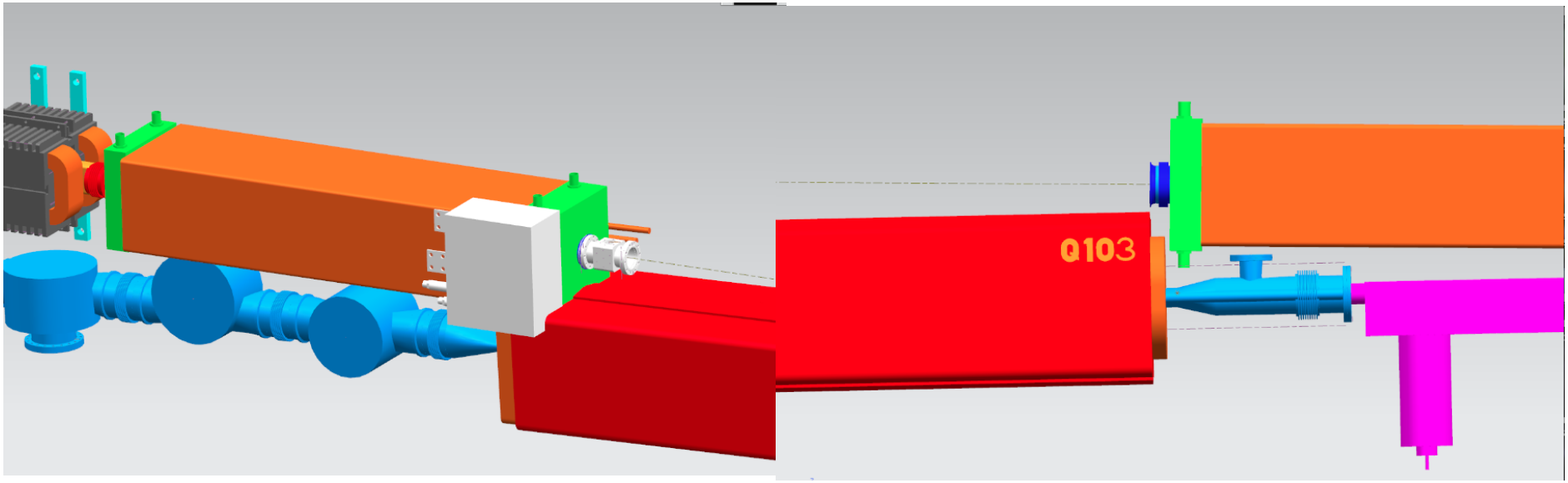
C-magnet – MI Beamtube



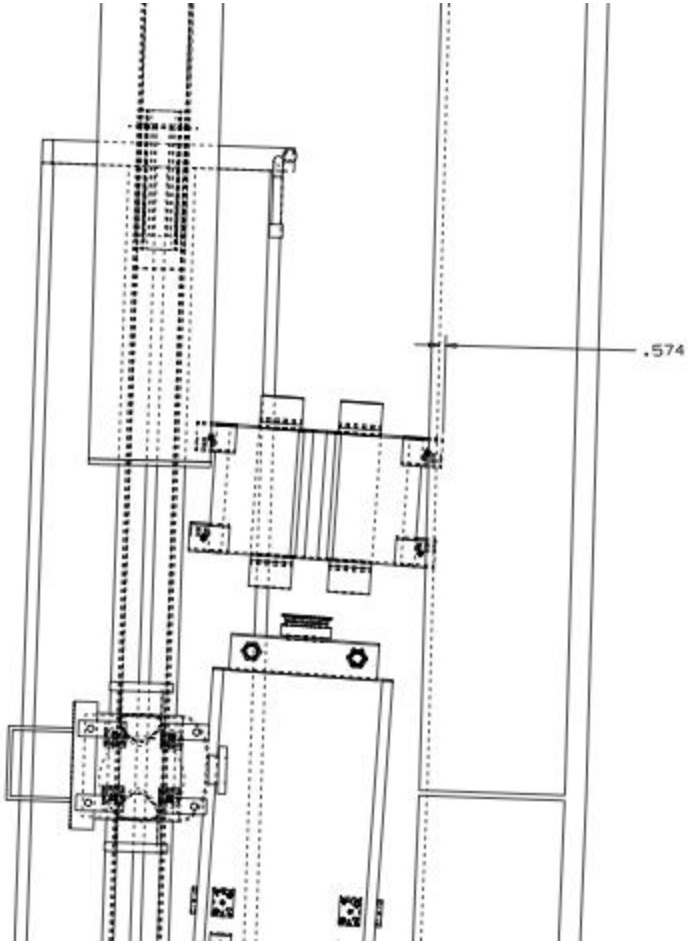


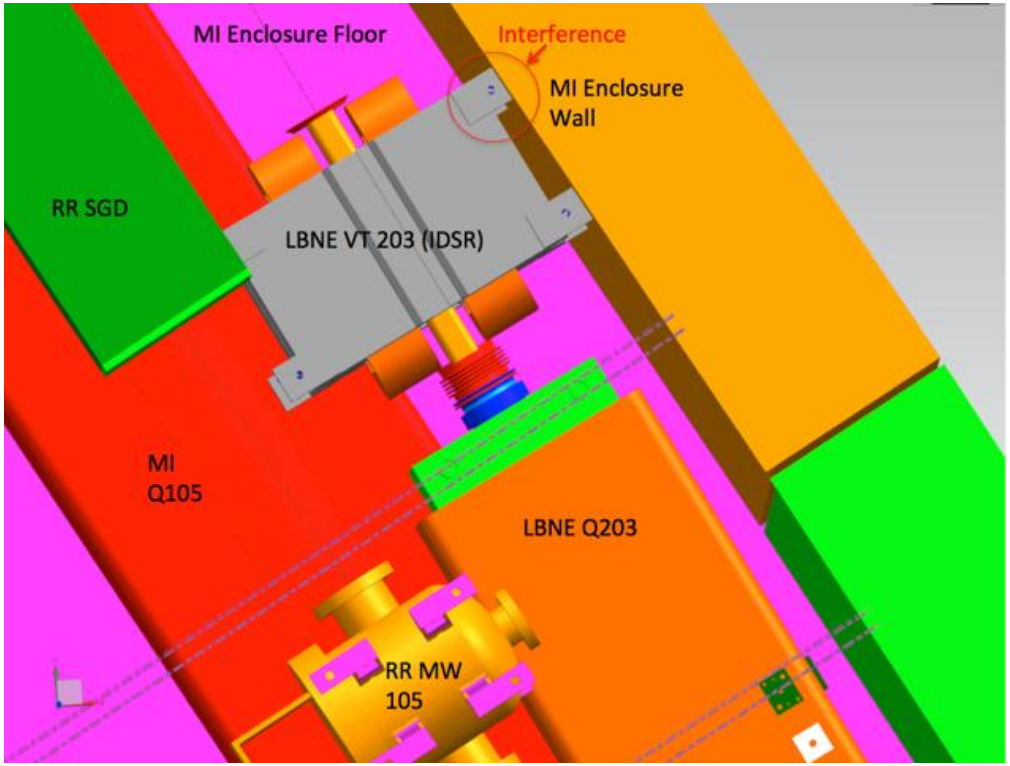
Q201A/B – MI Q103 & HT201A – MI Beamtube



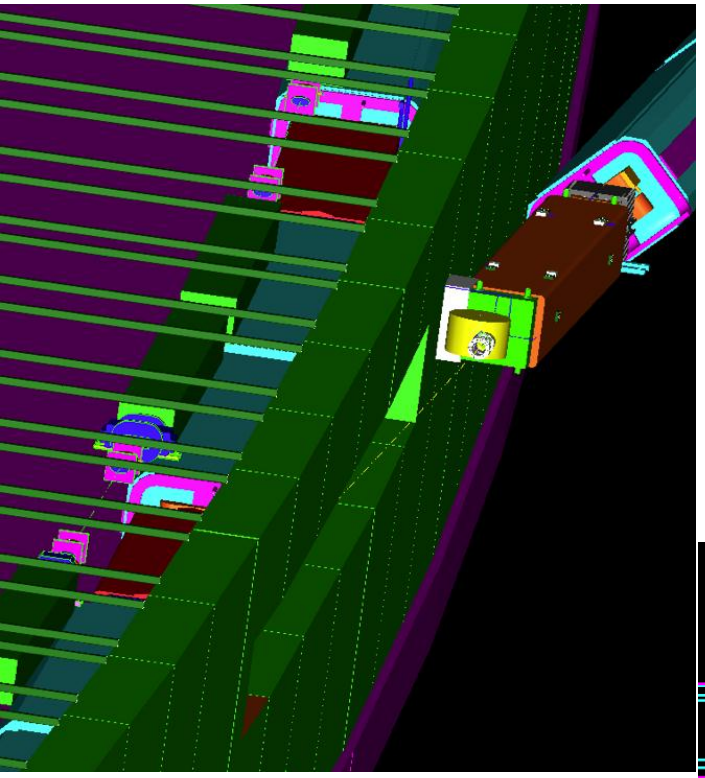


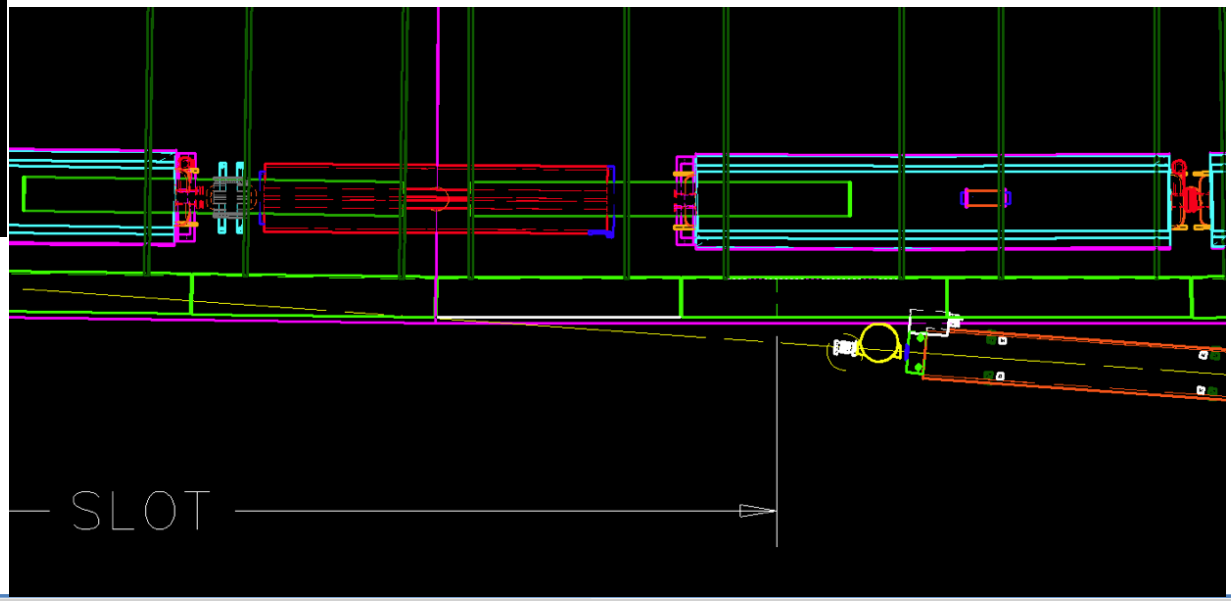
VT203 – MI Tunnel Wall





Q204 – LBNE Enclosure Wall





V217A/B Overlap