Design of the PIP-II Tunnel Geodetic Control Network

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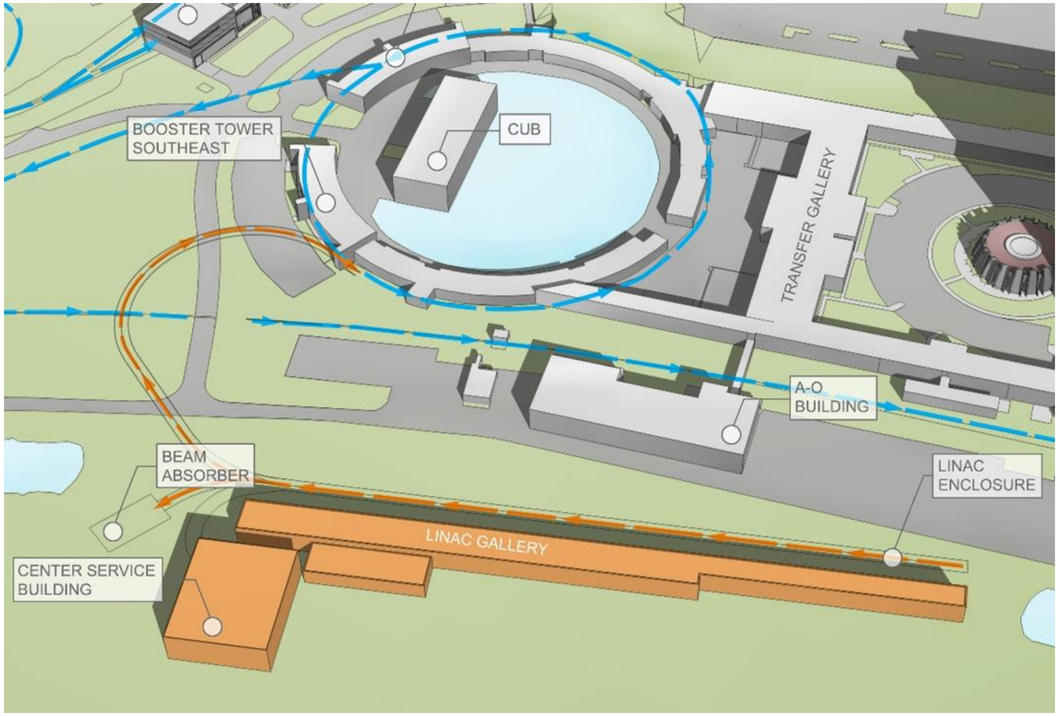
Overview

- **Introduction**
- Technical Requirements
- Network Design
- Network Results
- Network Verification
- Conclusion

Introduction

- Proton Improvement Plan II
- 215-meter long Linac will accelerate protons up to 800 MeV
- Beam will then transported through Beam Transfer Line (BTL)
- Beam will finally inject into Booster
- Main sections
  - Warm front-end (HBB)
  - SRF Linac
  - Beam Transfer Line (BTL)
  - Total length ~ 550 m



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General Tolerance Requirements

- **<u>All values in this presentation are shown to 1σ confidence level</u>**

- The Alignment Network shall provide a single-point absolute measurement accuracy of 0.50mm RMS relative to the FSCS-Z absolute frame
- The Alignment Network shall provide a relative measurement accuracy of 0.25mm RMS between points separated by <100m, relative to a local frame
- The Alignment Network shall support the combined alignment tolerances specified in the misalignment tolerances document

Component Tolerance Requirements

- The total RMS value of all the error components added quadratically shall not exceed the placement requirements
- Placement requirements were based on multiparticle simulations
- Based on the requirement that the beam can propagate through the **whole SRF Linac (~ 175 m)** with a high probability with specified errors **without orbit correction**
- For network verification, this requirement was extended for the entire beamline (~ 550 m) for thoroughness

Cold Component Tolerance Requirements

Beam Line Element	Trans. X-Offset (mm)	Vert. Y-Offset (mm)	Long. Z-Offset (mm)	Pitch (mrad)	Yaw (mrad)	Roll (mrad)
Cavities						
HWR Cavity	0.5	0.5	1	3	3	*NR*
SSR1 Cavity	0.5	0.5	1	3	3	*NR*
SSR2 Cavity	0.5	0.5	1	3	3	*NR*
LB650 Cavity	0.5	0.5	1	2	2	*NR*
HB650 Cavity	0.5	0.5	1	1	1	*NR*
Solenoids						
Solenoid HWR*	0.5	0.5	1	1	1	5
Solenoid SSR1*	0.5	0.5	1	1	1	5
Solenoid SSR2*	0.5	0.5	1	1	1	5

Cold Instrumentation	X-Offset (mm)	Y-Offset (mm)	Z-Offset (mm)	Pitch (mrad)	Yaw (mrad)	Roll (mrad)
Cold BPMs	0.5	0.5	1	*F*	*F*	5*

Warm Component Tolerance Requirements (1/2)

Beam Line Element	X-Offset (mm)	Y-Offset (mm)	Z-Offset (mm)	Pitch (mrad)	Yaw (mrad)	Roll (mrad)
Front End						
Ion source	0.25	0.25	5	*F*	*F*	*NR*
LEBT Solenoid	0.25	0.25	5	*F*	*F*	40
LEBT Dipole Magnet	0.25	0.25	5	*F*	*F*	*F*
LEBT Chopper	0.25	0.25	5	*F*	*F*	*NR*
RFQ entrance/exit	0.125	0.125	2	*F*	*F*	1
MEBT Quad	0.25	0.25	0.5	*F*	*F*	4
MEBT Corrector	1	1	0.5	*F*	*F*	4
Bunching cavities	0.175	0.175	1	*F*	*F*	*NR*
200 Ohm Kicker	0.25	0.05	0.25	*F*	*F*	*F*
MEBT Absorber	1	0.125	1.5	0.25	2	5
Differential Pumping Insert	0.25	0.25	5	1	1	*NR*
SRF Linac						
RT Linac Quad	0.25	0.25	0.5	*F*	*F*	3
RT Steering Dipole	1	1	1	10*	*F**	5
Straight Ahead Dump	1	1	5	5	5	*NR*

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Warm Component Tolerance Requirements (2/2)

BTL						
RT BTL Quad	0.25	0.25	0.5	*F*	*F*	3
RT BTL Dipole	0.25	0.25	0.5	*F*	*F*	2
RT Steering Dipole	1	1	1	10*	*F**	5
BTL Septum	0.25	0.25	0.5	*F*	*F*	3
BTL Switch Dipole	0.25	0.25	0.5	*F*	*F*	3
BTL Beam Absorber	1	1	5	5	5	*NR*
Beam Line Element	**X-Offset (mm)**	**Y-Offset (mm)**	**Z-Offset (mm)**	**Pitch (mrad)**	**Yaw (mrad)**	**Roll (mrad)**
Faraday Cup	0.5	0.5	0.5	*NR*	*NR*	*NR*
Fast Faraday Cup	0.5	0.5	0.5	3	3	*NR*
LEBT Allison Scanner	1	1	1	5*	5*	5
MEBT Allison Scanner	1	1	1	1*	3*	5
RT BPM	0.25	0.25	0.5	*F*	*F*	5
Laser Wire	0.25	0.25	0.25	*F*	*F*	5
Wire scanner	0.5	0.5	0.5	*F*	*F*	5
Scraper	0.25	0.25	0.25	3	3	3
ACCT	0.5	0.5	0.5	*NR*	*NR*	*NR*
DCCT	0.5	0.5	0.5	*NR*	*NR*	*NR*
RWCM	0.5	0.5	0.5	*NR*	*NR*	*NR*
Longitudinal pickup	0.5	0. 5	0.5	*NR*	*NR*	*NR*

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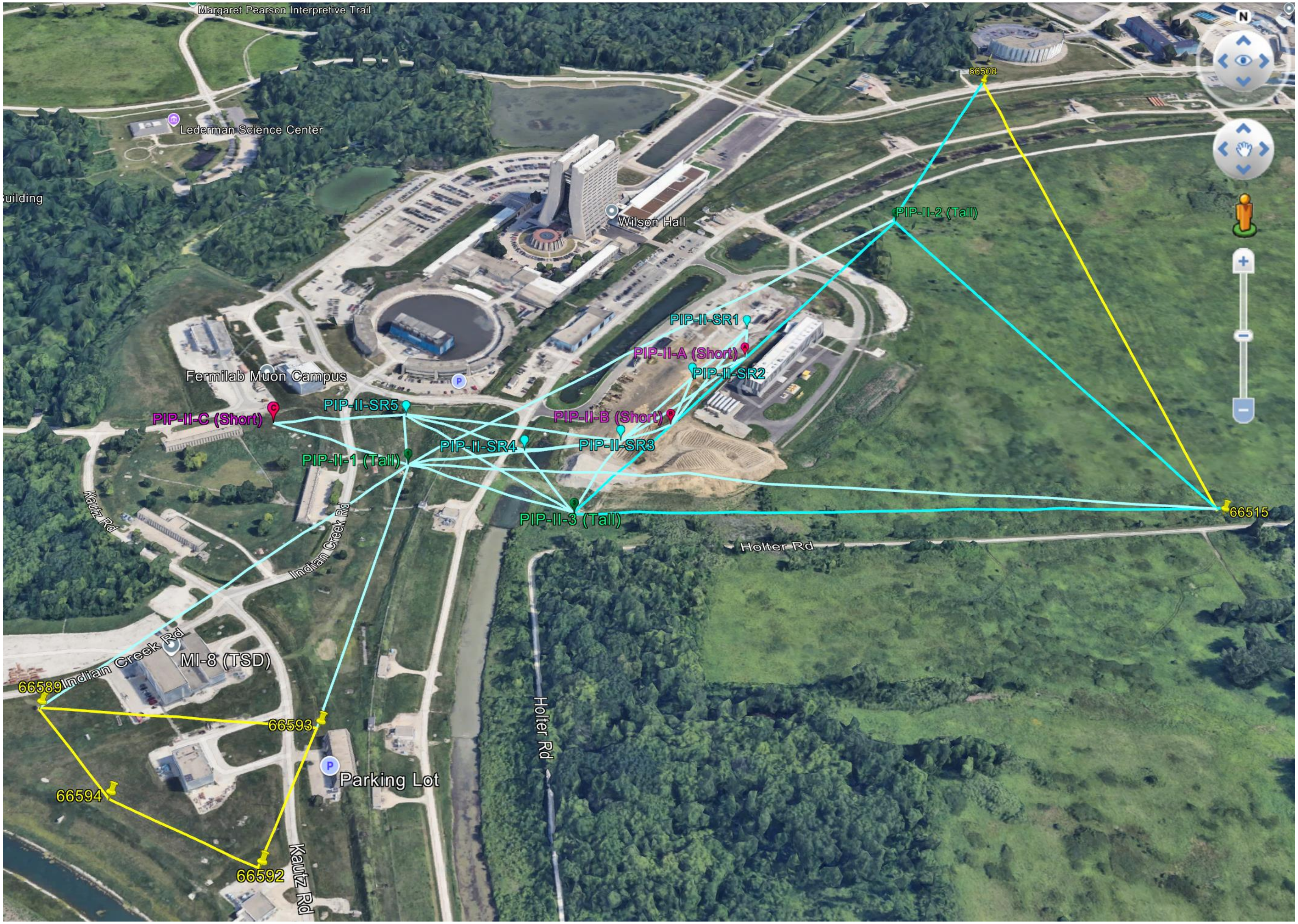
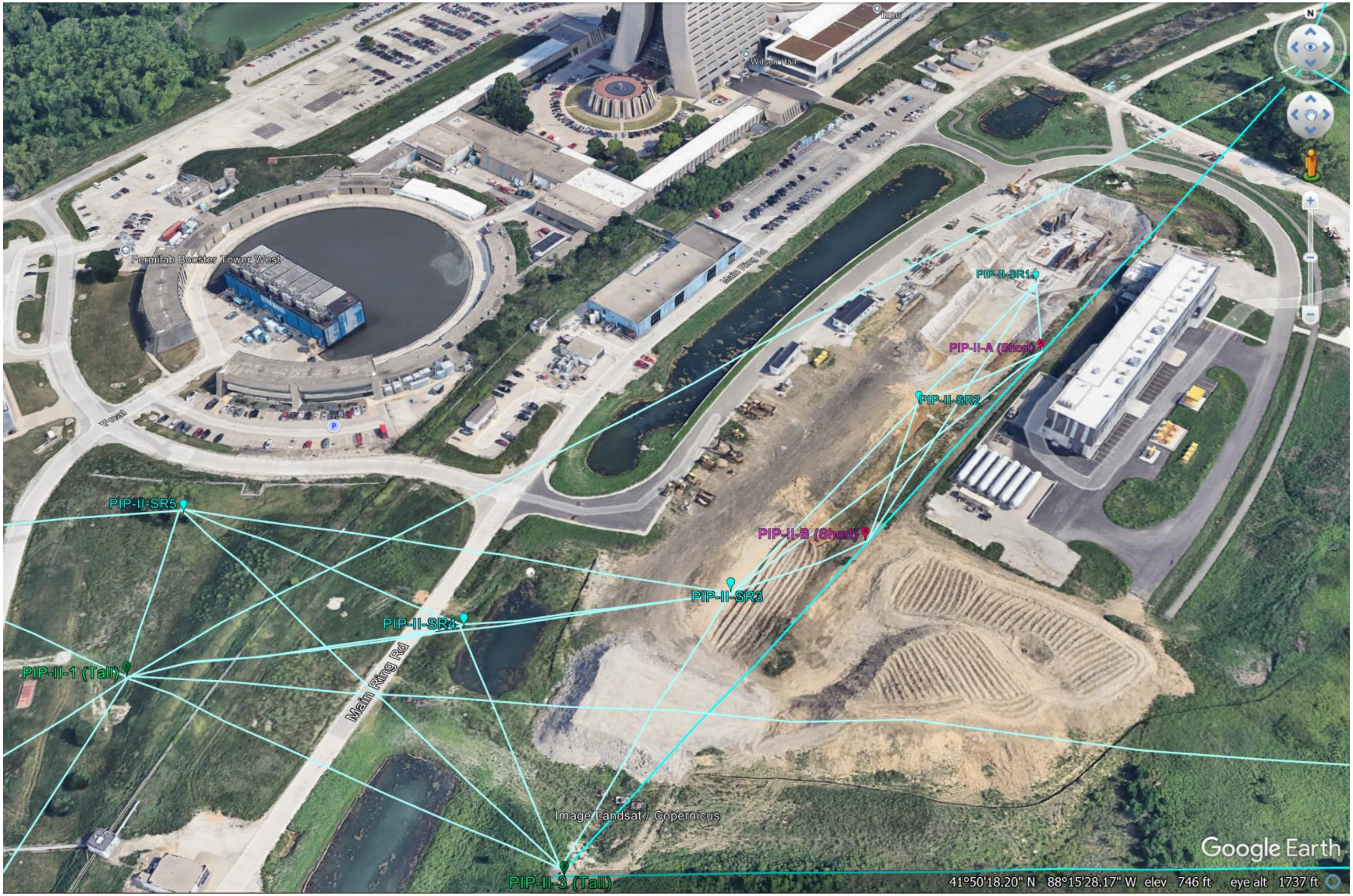
Surface Network - Overall



Surface Network - Detail



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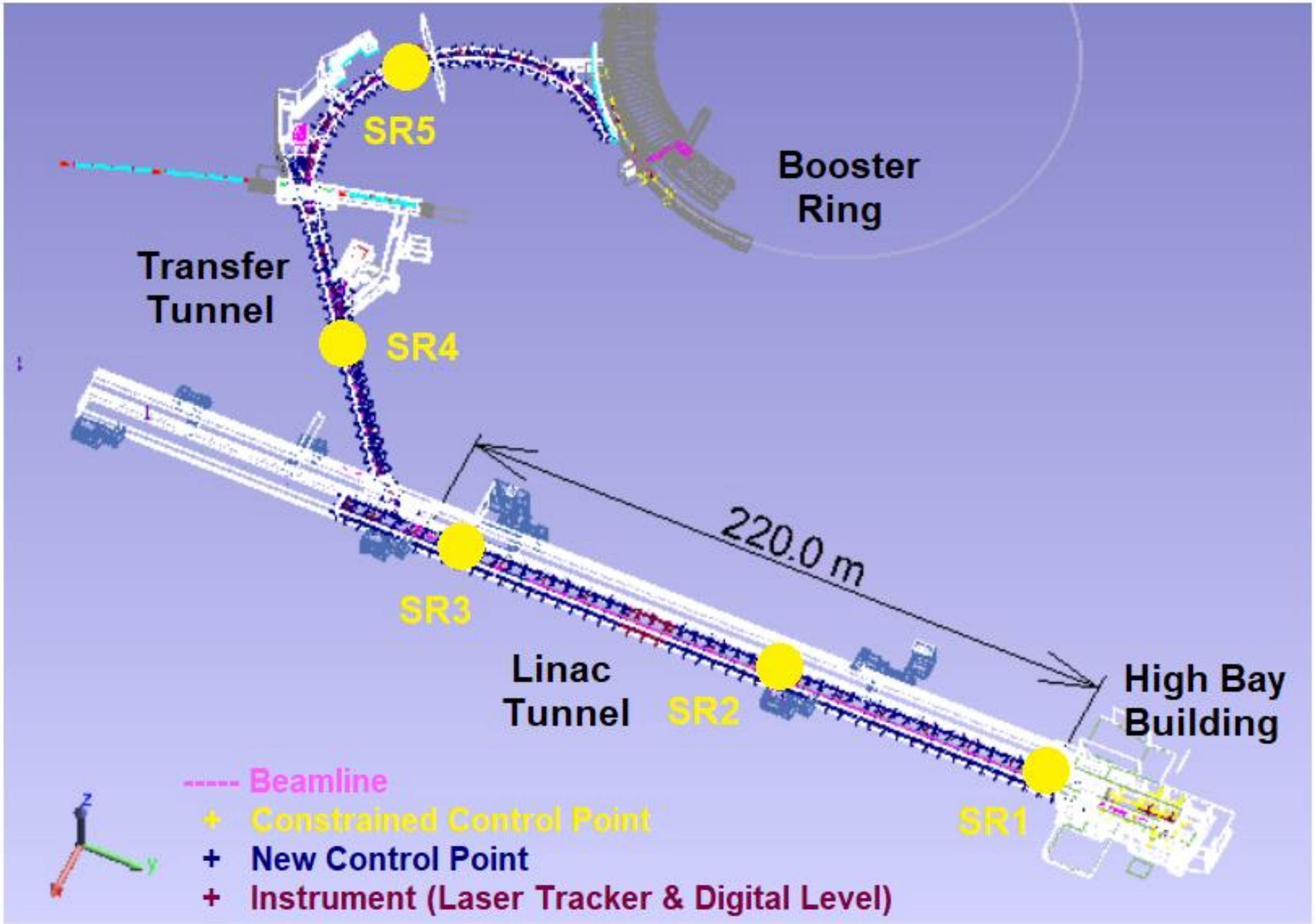
Tunnel Network - Overall



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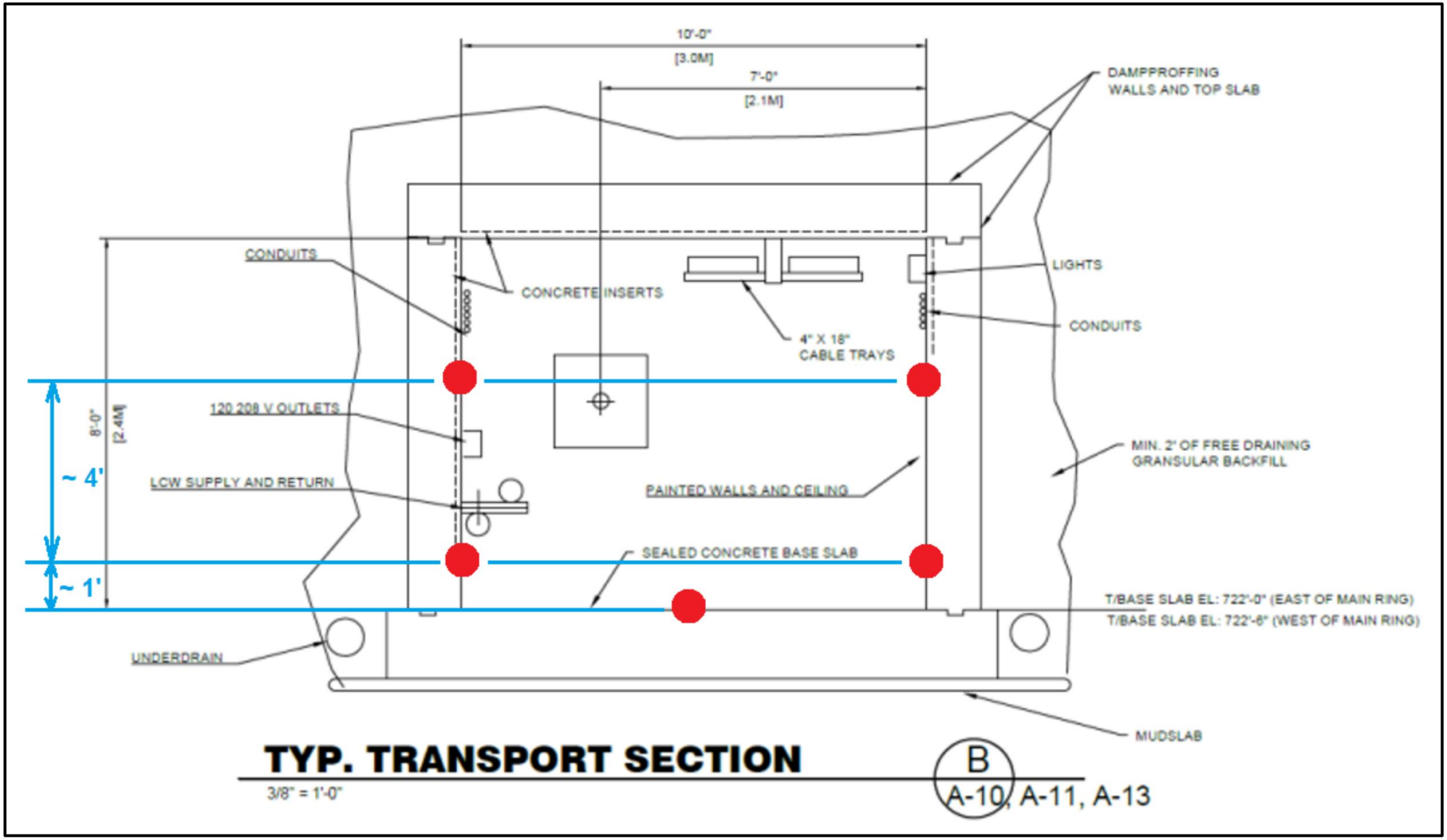
Tunnel Network – Control Point Placement



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Control Points and Instrument Specifications

- Kyjak Bolt

- Instrument Uncertainties

Instrument Type	Instrument Model	Uncertainties
Laser Tracker	Leica AT401/AT403	$\sigma_{Hz,V} = 1'', \sigma_a = 0.008\ mm, \sigma_b = 2.5\ ppm$
Digital Level	Leica DNA03	$\sigma_a = 0.050\ mm, \sigma_b = 2\ ppm$
Total Station	Leica TS60	$\sigma_{Hz,V} = 0.5'', \sigma_a = 0.600\ mm, \sigma_b = 1\ ppm$

Pre-Analysis Details (1/2)

- 621 control points
- 52 laser tracker/Digital Level Setups
  - Trackers and levels collocated for convenience
  - Should approximate elevation measurements to a reasonable level
- 8 total station setups
- 1257 laser tracker/digital level observations
  - Slope Distance
  - Horizontal Direction
  - Vertical Angle
  - Rod Reading
- 56 total station observations
  - Slope Distance
  - Horizontal Direction
  - Vertical Angle

Pre-Analysis Details (2/2)

- Weighted Constraints
  - 5 sight-riser points
  - 31 points in the High Bay Building (HBB)
  - 24 Booster points
- Constrained Point Uncertainties
  - HBB and Booster uncertainties unavailable
  - Method 1: Surface Network Uncertainty + Transfer Uncertainty (2D)
    - Sight-Riser Surface Network Points (Single Component): 0.218 mm
    - Transfer Uncertainty (Wild NL, Single Component): 0.250 mm for 10-meter drop
    - Quadrature (Single Component): 0.332 mm
  - Method 2: 2006 Tevatron Network Adjustment Results (3D)
    - $\sigma_X = 0.325$ mm, $\sigma_Y = 0.315$ mm, $\sigma_Z = 0.315$ mm
  - **Decision: $\sigma_X = \sigma_Y = \sigma_Z = 0.325$ mm**

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Pre-Analysis Results (1/2)

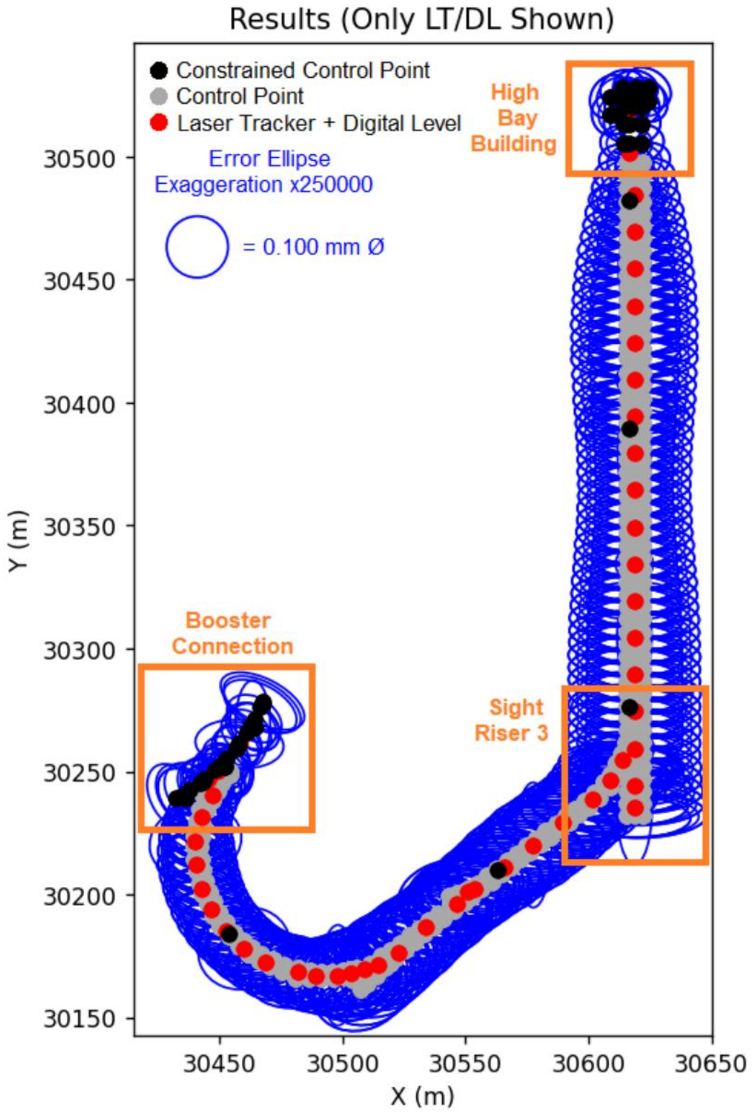
- 3D uncertainties calculated using error propagation
- Custom Python program

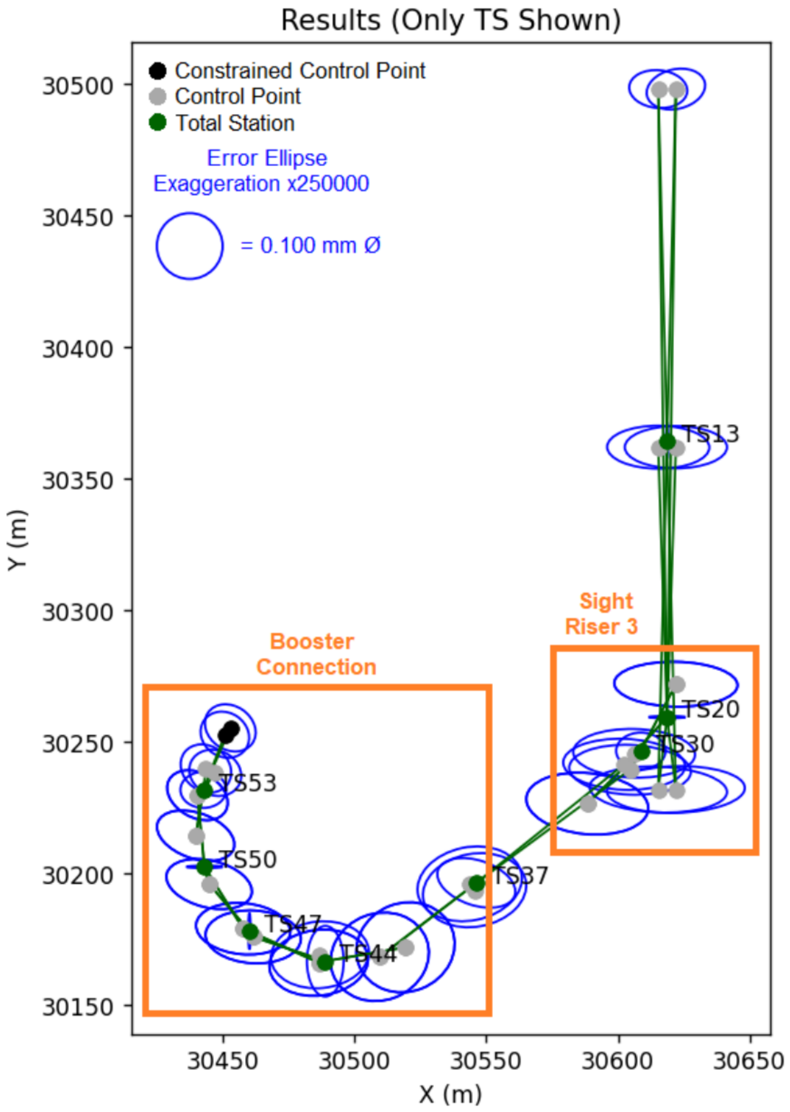
- Results

Station Uncertainties	Hz (2D) / V (1D), mm
Mean Absolute	0.152 / 0.055
Max Absolute	0.210 / 0.069
Mean Relative (< 100 m)	0.105 / 0.030
Max Relative (< 100 m)	0.212 / 0.067

- Meets absolute accuracy requirements of 0.500 mm
- Meets relative accuracy requirements of 0.250 mm

Pre-Analysis Results (2/2)





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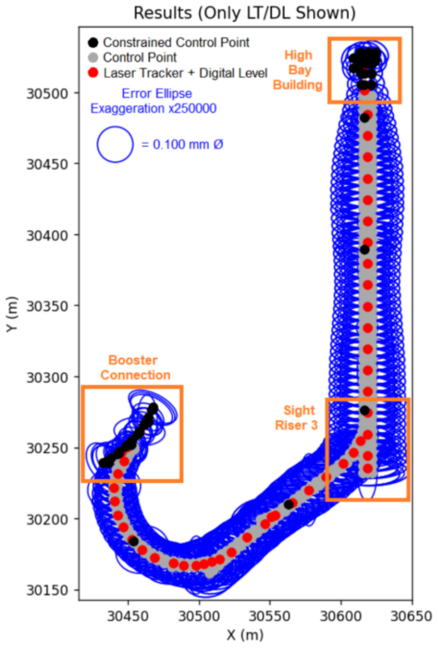
Network Verification

- Need to verify that the quadrature of **global** and **local** errors can meet alignment tolerance requirements
- Global errors
  - Network uncertainty
- Local errors (metrology)
  - Noise in metrology measurements
  - Stand adjustment errors

Global Errors – Network Uncertainty (1/2)

- Coordinate uncertainties needed to be turned into alignment uncertainties
  - Transverse, elevation, and longitudinal position
  - Pitch, roll, yaw orientation
- Calculated by dividing tunnel network into sections and using best-fit transformations
- 52 existing laser tracker setups were used to define tunnel sections
  - Used for convenience



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Global Errors – Network Uncertainty (2/2)

- Used the following algorithm on all 52 laser tracker positions
  1. Identify all control points measured from instrument
  2. Create VCV submatrix of only the measured control points from full network VCV matrix
  3. Propagate measured control point errors through best-fit transformation
  4. Compute uncertainties in transformation parameters

- Results

Cold & Warm					
X (trans., mm)	Y (vert., mm)	Z (long., mm)	Pitch (mrad)	Yaw (mrad)	Roll (mrad)
0.201	0.057	0.168	0.008	0.009	0.004

Warm – Front End					
X (trans., mm)	Y (vert., mm)	Z (long., mm)	Pitch (mrad)	Yaw (mrad)	Roll (mrad)
0.078	0.048	0.056	0.001	0.004	0.001

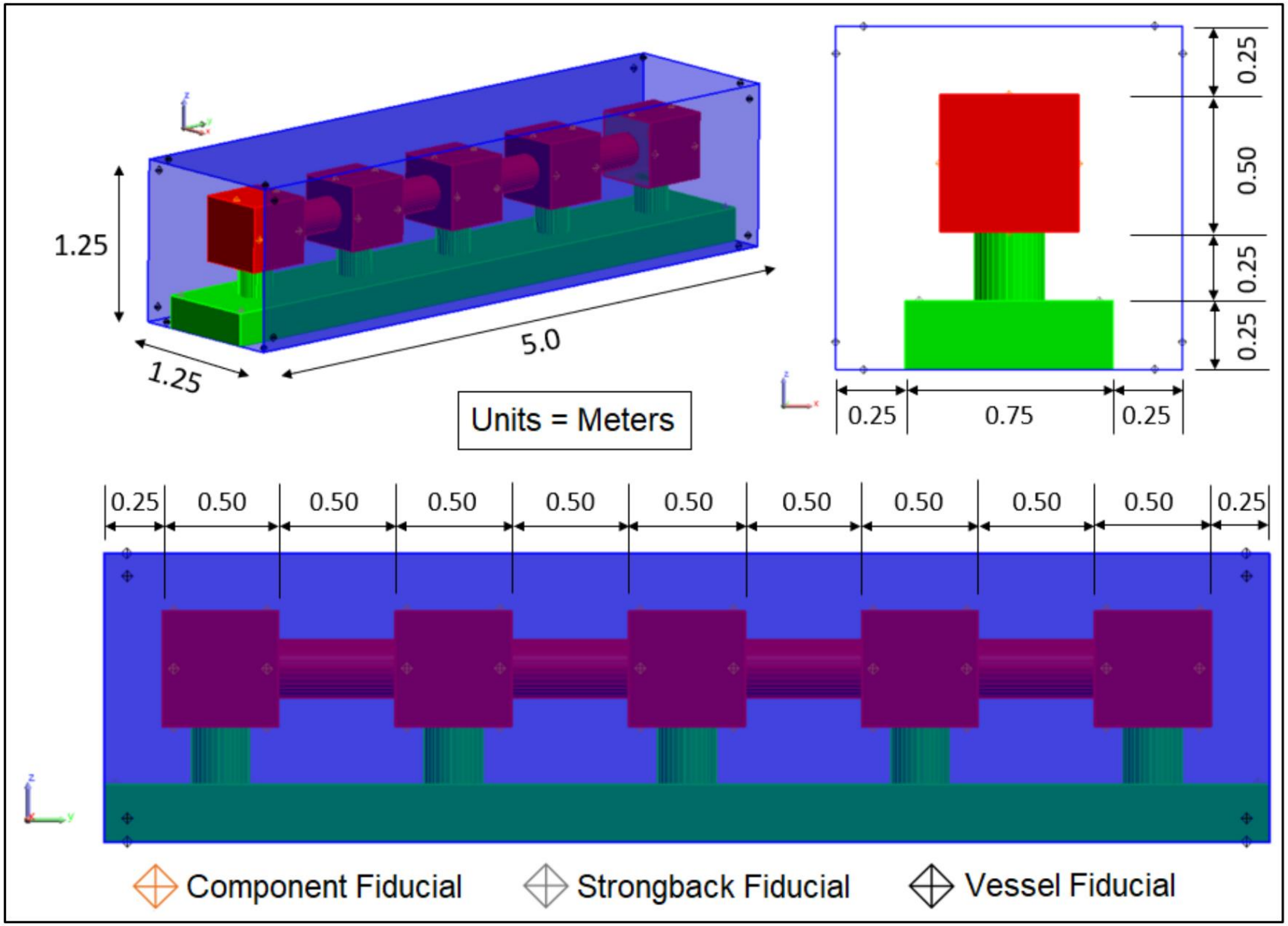
Local Errors

- Local error sources
  - Fiducial positions
  - Component electrical center positions
  - Mechanical feature positions (ex: flange centers, stud positions, etc.)
- Focused on fiducial positions only due to time constraints
- Should still provide a reasonable estimate for verification purposes

Local Errors

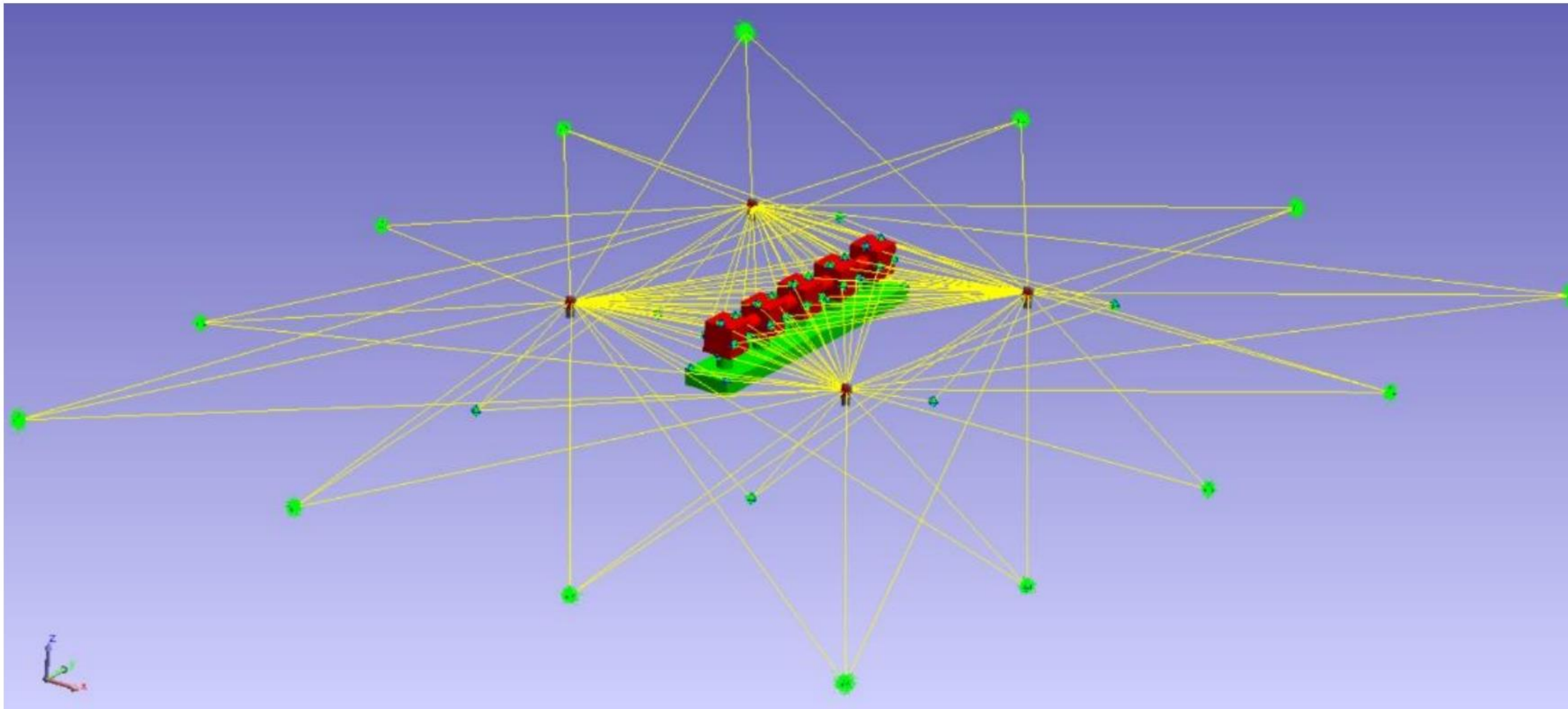
- Cold Component Analysis
  1. Individual component alignment on strongback
  2. Component string & strongback insertion into vacuum vessel
  3. Vacuum vessel placement inside tunnel
- Warm Component Analysis
  - Direct placement of component in tunnel only
- Picked a basic model due to time constraints
  - Dimensions chosen to best represent all components

Model

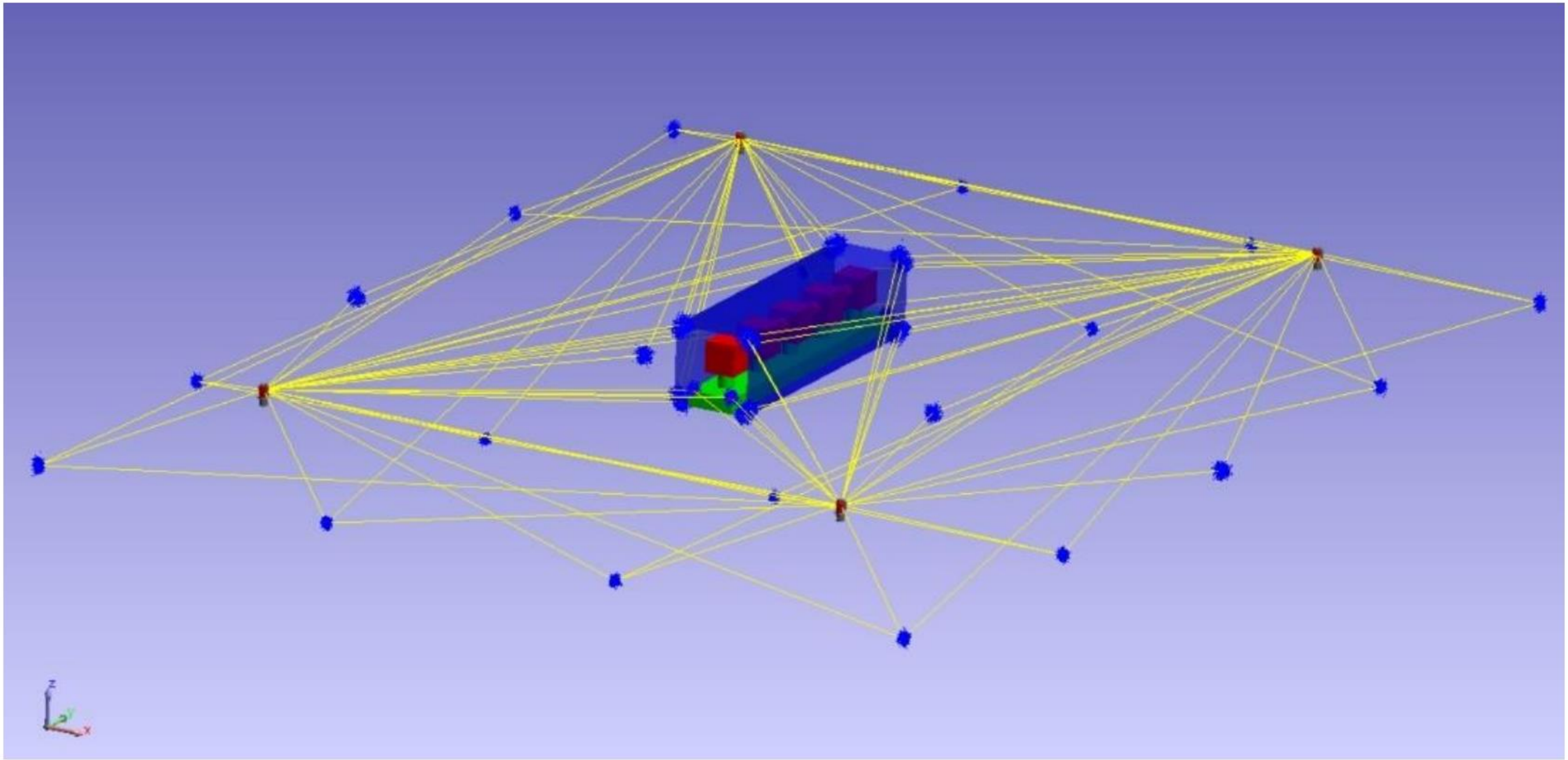


1.25
1.25
5.0
Units = Meters
0.25
0.50
0.25
0.25
0.25
0.75
0.25
0.25 0.50 0.50 0.50 0.50 0.50 0.50 0.50 0.50 0.50 0.25
Component Fiducial
Strongback Fiducial
Vessel Fiducial

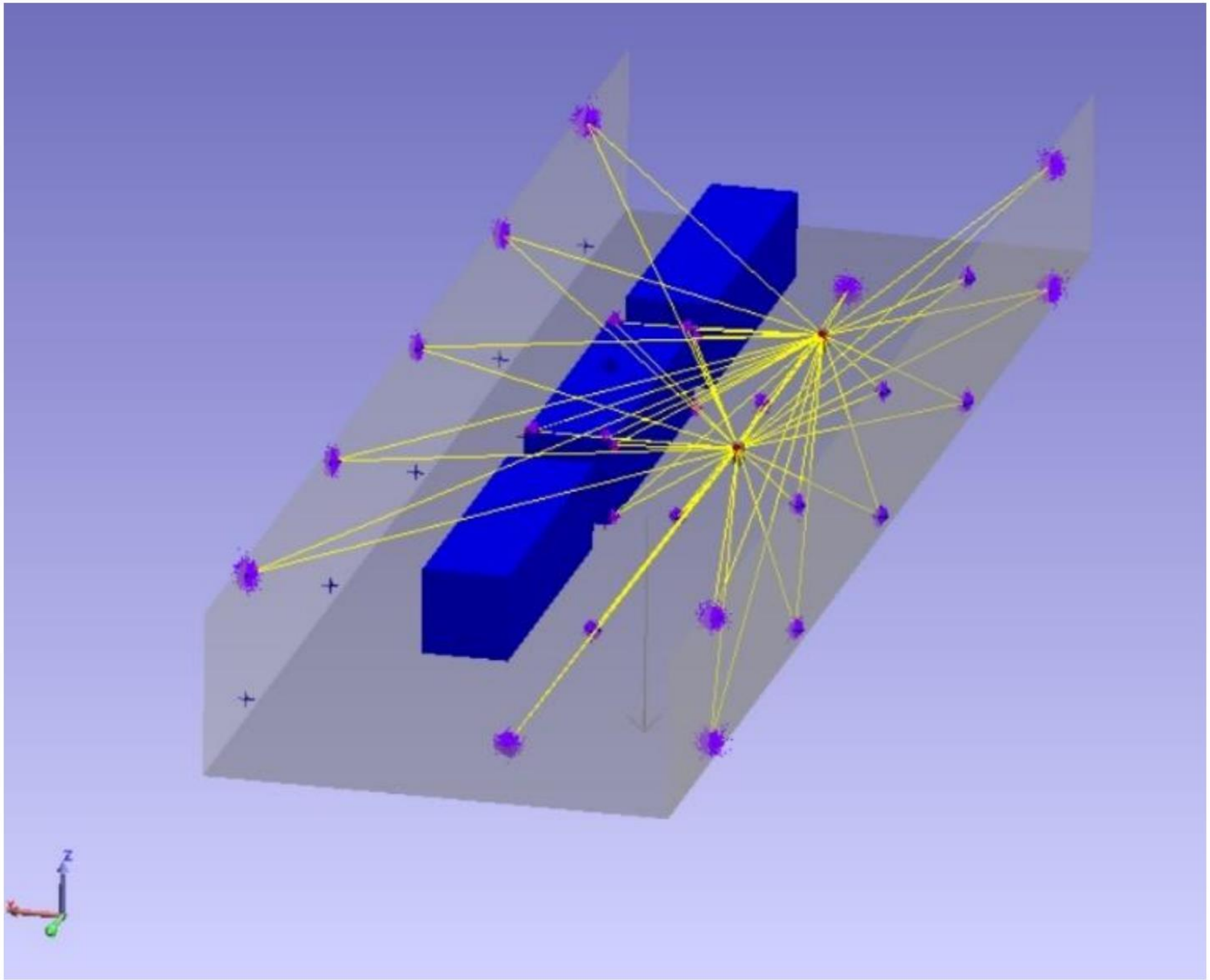
Component Alignment to Strongback



Component String/Strongback Insertion to Vacuum Vessel



Placement of Vacuum Vessel Inside Tunnel



Local Errors – Measurement Noise

- Laser tracker measurement uncertainty
  - Used instrument uncertainty analysis function in SpatialAnalyzer
  - Computed uncertainties on component/strongback/vessel fiducials
- Best-fit transformation uncertainties for cold components
  - Error stack-up from repeated best-fits
    - Component string/strongback insertion to vacuum vessel
    - Placement of vacuum vessel inside tunnel
  - Used custom Python best-fit transformation error propagation program
  - Input: fiducial uncertainties
  - Output: final component alignment uncertainties inside tunnel

Local Errors – Measurement Noise Results

- Cold components

X (trans., mm)	Y (vert., mm)	Z (long., mm)	Pitch (mrad)	Yaw (mrad)	Roll (mrad)
0.006	0.007	0.005	0.009	0.009	0.008

- Warm component uncertainties would be even less significant
  - Assumed to be same as cold components for convenience

Local Errors – Stand Adjustment Error

- Adjustment stands keep components in place
- Component position adjusted by finely threaded bolts or studs on stands
- Mechanical limitations on adjustability
- Practical limit for each fiducial: ± 0.100 mm
  - Based on previous experience
- Estimated alignment uncertainties using Monte Carlo simulations

Local Errors – Stand Adjustment Error – Monte Carlo

- Custom Python program
- Algorithm
    1. Generate shift errors and orientation errors using uniform distribution
    2. Check if all fiducials are < 0.100 mm
    3. If so, move on to next step
        1. Individual component alignment on strongback
        2. Component string & strongback insertion into vacuum vessel
        3. Vacuum vessel placement inside tunnel

Local Errors – Stand Adjustment Error Results

- Cold components

X (trans., mm)	Y (vert., mm)	Z (long., mm)	Pitch (mrad)	Yaw (mrad)	Roll (mrad)
0.103	0.080	0.085	0.138	0.141	0.145

- Warm components

X (trans., mm)	Y (vert., mm)	Z (long., mm)	Pitch (mrad)	Yaw (mrad)	Roll (mrad)
0.050	0.055	0.042	0.133	0.148	0.117

Network Verification Results (Quadrature Calculation)

Cold	X (trans., mm)	Y (vert., mm)	Z (long., mm)	Pitch (mrad)	Yaw (mrad)	Roll (mrad)
Global - Network	0.201	0.057	0.168	0.008	0.009	0.004
Local - Noise	0.006	0.007	0.005	0.009	0.009	0.008
Local - Stand	0.103	0.080	0.085	0.138	0.141	0.145
Total	**0.226**	**0.098**	**0.188**	**0.139**	**0.142**	**0.145**

Warm	X (trans., mm)	Y (vert., mm)	Z (long., mm)	Pitch (mrad)	Yaw (mrad)	Roll (mrad)
Global - Network	0.201	0.057	0.168	0.008	0.009	0.004
Local - Noise	0.006	0.007	0.005	0.009	0.009	0.008
Local - Stand	0.050	0.055	0.042	0.133	0.148	0.117
Total	**0.207**	**0.080**	**0.173**	**0.134**	**0.149**	**0.117**

Warm – Front End	X (trans., mm)	Y (vert., mm)	Z (long., mm)	Pitch (mrad)	Yaw (mrad)	Roll (mrad)
Global - Network	0.078	0.048	0.056	0.001	0.004	0.001
Local - Noise	0.006	0.007	0.005	0.009	0.009	0.008
Local - Stand	0.050	0.055	0.042	0.133	0.148	0.117
Total	**0.093**	**0.073**	**0.070**	**0.133**	**0.148**	**0.117**

Network Verification Results

- All alignment tolerances are expected to be met except for one warm component
  - 0.073 mm > 0.050 mm

	Trans.	Vert.	Long.			
Beam Line Element	**X-Offset (mm)**	**Y-Offset (mm)**	**Z-Offset (mm)**	**Pitch (mrad)**	**Yaw (mrad)**	**Roll (mrad)**
Front End						
200 Ohm Kicker	0.25	0.05 X	0.25	*F*	*F*	*F*

- Can be accounted for by beam-based alignment
- Differential corrections can be applied using precise methods
  - Micrometer < 0.050 mm
  - Interferometer < 0.050 mm

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Conclusion

- Absolute and relative network tolerances are expected to be met
- All alignment tolerances are expected to be met except for one warm component
  - Can be accounted for by beam-based alignment

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- Technical Review
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Thank you!