DUNE-ND PRISM Movement System Requirements and Specifications

DUNE ND PRISM Team
PRISM Design Assessment
November 19th, 2024

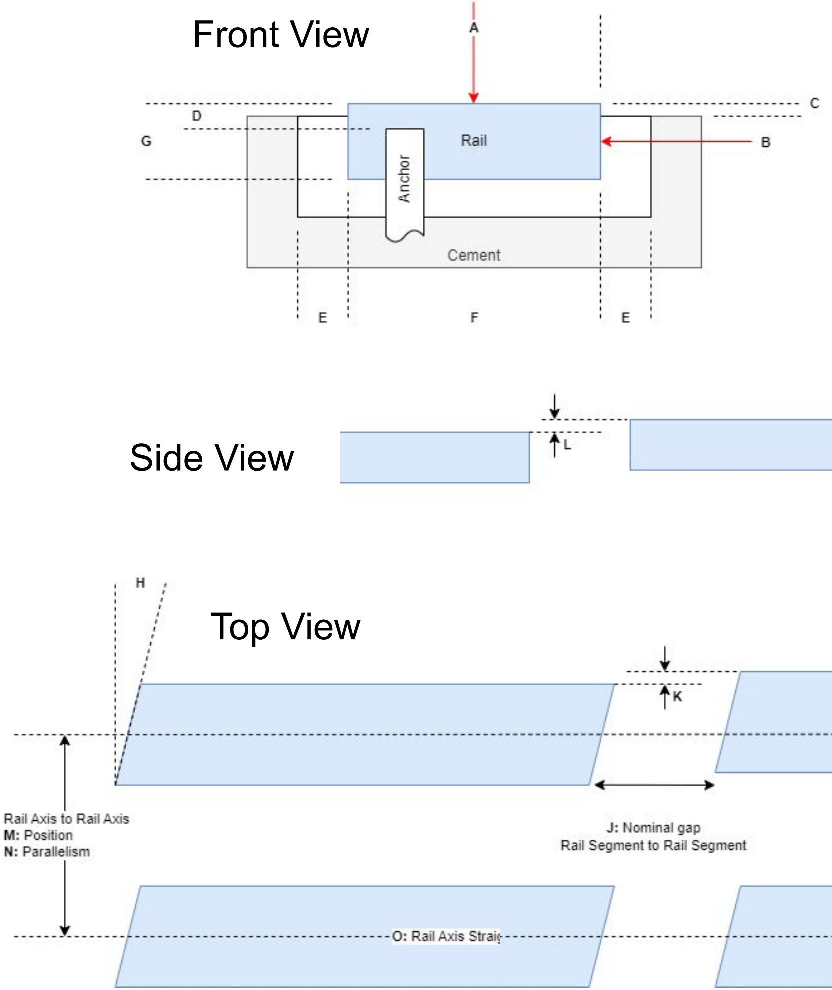
Flowdown Requirements

ID	Requirement Text	Value	Units	Rationale
ND-M4	ND shall make measurements in different neutrino fluxes, covering energies from 0.5-3.0 GeV	-	-	To probe the energy dependence of neutrino interactions, and predict oscillated FD spectra, ND must move off-axis
ND-C2.1	PRISM shall move ND-LAr+TMS to at least 28 meters off-axis	28	m	PRISM must allow off-axis data taking to at least 30.5 me off- axis to cover the energy range of the second oscillation peak. The fiducial volume of ND-LAr is 3 m wide so its midpoint must be able to move up to 28 m.
ND-C2.3	PRISM shall place ND- LAr+TMS within 10 cm of its desired position.	10	cm	PRISM must place the detector elements accurately enough such that the neutrino spectrum matches the targeted spectrum at the desired off-axis position.
ND-C2.4	PRISM shall measure the ND- LAr+TMS off-axis position to within 1 cm	1	cm	The placement of ND-LAr+TMS must be accurately known to predict the neutrino flux at a given off-axis position
ND-C2.5	The detector downtime between PRISM movements period shall be < 8 hours (including ramp down/up)	8	hours	A complete movement cycle should be completed within a standard work shift to minimize complexity and downtime.
ND-C2.6	The PRISM system shall allow at least 10 movements each operational year	10	cycles	A complete set of off-axis measurements, requiring $\gtrsim$ 10 movements given the 3 m width of ND-LAr fiducial volume, is needed to avoid combining data across years, which may have considerable variations in the operating conditions.
ND-C4.2.1	ND-LAr+TMS shall be capable of performing on-axis neutrino beam monitoring at least once a month	1	/month	Monthly checks of the on-axis beam conditions mitigate the risk of unusable FD data due to unexpected beam variations

System Lifetime: 25 years

DUNE ND Rail System Tolerances

- The Rail System is provided by DUNE Near Site Conventional Facilities (NSCF)
- The PRISM team provided detailed requirements for rail segment installation tolerances
  - These tolerances were included in the bid package NSCF sent to construction firms
- However, NSCF could not guarantee that the specified tolerances would be able to be met
  - Instead, they guaranteed that a set of looser tolerances achieved by a previous Fermilab Project (Mu2e) could be met

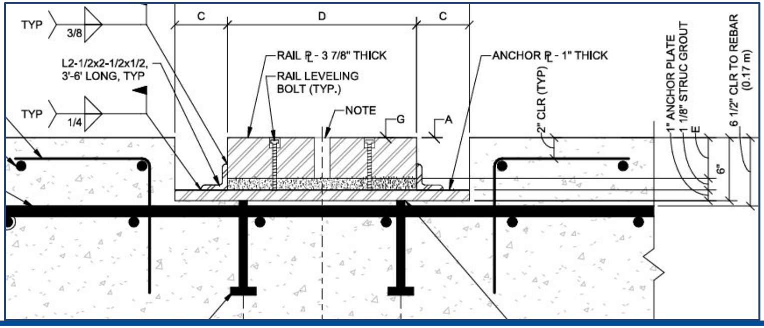


LBNF/DUNE

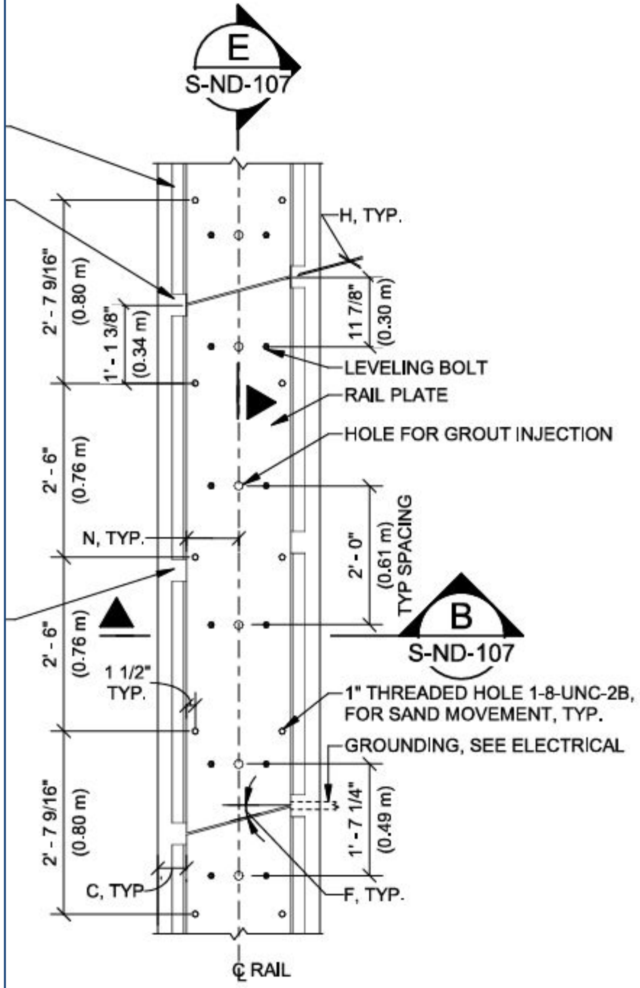
DUNE ND Rail System

- Rail system consists of ~8'-long, 4"-thick steel plates that are cut at a 15° angle on the ends
- The rails are mounted on steel plates with jack screws to allow for precise leveling
  - The lower plates are mounted to concrete which sits on top of bedrock
- Angle bars are then welded to connect the top and bottom plates (to help resist side loads)
- Grout then fills the gap to support the detector load

View along a rail:



View above a rail:



Mu2e Rail Tolerances

- The Mu2e project specified looser tolerances on their rail system than we specified for our rail system
  - The construction company hired for Mu2e was able to meet Mu2e's specified tolerances
- Since NSCF has a working example of the Mu2e tolerances, they are confident the rail system can be constructed to at least this level of precision
- We have adjusted our PRISM design requirements to match the Mu2e rail tolerances

Tolerances specified by PRISM to NSCF:

NOTATED DIMENSION VALUES, TOLERANCES, AND DESCRIPTIONS				
NOTATION	DESCRIPTION	DIMENSION (IN, U.N.O.)	TOLERANCE (IN, U.N.O.)	NOTES
A	T/RAIL TO T/CONCRETE	0	+ 0.250 - 0.00	TOP SURFACE OF CONCRETE SLAB OUTSIDE OF TRENCH SHALL NOT BE HIGHER THAN THE TOP SURFACE OF THE RAIL.
B	T/RAIL SEGMENT TO T/LEVELING BOLT (HIGHEST POINT ON BOLT)	0.375	+/- 0.125	THE HIGHEST POINT ON THE LEVELING BOLTS SHALL BE LOWER THAN THE TOP SURFACE OF THE RAIL SEGMENT.
C	RAIL EDGE TO TRENCH WALL	5	+ 0.50 - 0.00	GAP BETWEEN LATERAL SURFACE OF THE RAIL AND THE LATERAL SURFACE OF THE TRENCH SHALL BE 5" MINIMUM.
D	RAIL SEGMENT WIDTH	18	+/- 0.005	APPLIES TO EACH INDIVIDUAL SEGMENT.
E	RAIL SEGMENT THICKNESS	3.875	+/- 0.125	APPLIES TO EACH INDIVIDUAL SEGMENT.
F	RAIL SEGMENT END ANGLE	15°	+/- 0.2°	APPLIES TO EACH INDIVIDUAL SEGMENT.
G	RAIL SEGMENT FLATNESS		+/- 0.005	APPLIES TO EACH INDIVIDUAL SEGMENT, TOP SURFACE BLANCHARD GROUND. DIMENSION FROM END-TO-END OF RAIL SEGMENT, EACH DIRECTION, ALONG THE TOP SURFACE OF RAIL SEGMENT.
H	RAIL SEGMENT-TO-SEGMENT AXIAL SPACING	0.375	+/- 0.125	GAP DISTANCE BETWEEN RAIL SEGMENTS ALONG THEIR LENGTHS.
J	RAIL SEGMENT-TO-SEGMENT LATERAL ALIGNMENT	0	+/- 0.010	LATERAL DIFFERENCE BETWEEN ADJACENT RAIL SEGMENTS.
K	RAIL SEGMENT-TO-SEGMENT VERTICAL ALIGNMENT	0	+/- 0.010	VERTICAL DIFFERENCE BETWEEN ADJACENT RAIL SEGMENTS.
L	RAIL-TO-RAIL SPACING	SEE PLAN	+/- 0.125	DIMENSION FROM RAIL AXIS TO RAIL AXIS.
M	RAIL-TO-RAIL PARALLELISM	SEE PLAN	+/- 0.125	RAIL AXIS TO RAIL AXIS DEVIATION FROM PARALLEL, MEASURED AT THE END OF EACH RAIL.
N	RAIL STRAIGHTNESS	SEE PLAN	+/- 0.0625	INDIVIDUAL RAIL SEGMENT AXIS DEVIATION FROM RAIL AXIS.
O	RAIL TOP SURFACE FLATNESS		+/- 0.040	FLATNESS OF AN ENTIRE RAIL, ACROSS ALL SEGMENTS.
P	RAIL SEGMENT GAPS BETWEEN AXIAL AND TRANSVERSE RAILS	5	+ 0.50 - 0.00	GAPS BETWEEN ENDS OF TRANSVERSE RAILS AND SIDES OF MAIN AXIAL RAILS. EQUAL IN VALUE TO NOTATION C.

Mu2e Tolerances:

B. Tolerances: the track plates and pull plates shall be furnished with a flatness tolerance of .125" over a 12' length. If necessary, a press shall be used to achieve this flatness. Matching ends of plates are to be parallel and perpendicular to the length of the plate. If required, mill the ends of the plates to achieve this squareness. If the plates are bowed, fabricate with the bow up.

C. Fill all of the holes, except the grout holes, with cosmoline grease and cover with a 1/8" cap plate before shipping.

Requirement #1: Vertical Tolerances and Compliance

ID	Requirement Text	Value	Units	Rationale
ND-PRISM 1	The PRISM design and mounting of the rollers shall accommodate for a 12.5 mm flatness of the rail over the entire rail length.	12.5	mm	This requirement is based on standard construction tolerances of the rails (+/-5mm), and 2.5 mm settling under load and over time. The combination of these two numbers results in a 12.5 mm overall flatness. NSCF is confident that this requirement will be met by the construction firm. Note: the flatness required in the drawings that have been sent out for bid are more stringent (+/- 0.040 in or +/- 1 mm). Our requirement provides us a factor of margin of ~6x in case the construction firm that will deliver the cavern is only able to achieve standard construction tolerances.
ND-PRISM 1a	The PRISM design and mounting of the rollers shall accommodate a flatness of 5.7 mm over a 12' (3.7 m) span.	5.7	mm	Over a 12' (3.7 m) span, standard construction tolerances for the rail flatness are tighter (+/- 1/16" (1.6 mm)). This design requirement also takes into account up to 2.5 mm of potential settling over time. The combination of these two numbers results in a 5.7 mm flatness over a 12' (3.7 m) span.

- "Standard construction tolerances" refer to what was specified for (and achieved by) the Mu2e rail system
- NSCF provided a conservative estimate of 2.5 mm of settling over the life of the experiment
- The PRISM system is designed to accommodate "standard construction tolerances" + settling (caveat in 1b rationale)

Requirement #1 (continued): Vertical Tolerances and Compliance

ID	Requirement Text	Value	Units	Rationale
ND-PRISM 1b	The PRISM rollers shall accommodate a vertical step of 1.6 mm where 2 adjacent rail segments meet	1.6	mm	Standard construction tolerances for the vertical alignment of the ends of 2 adjacent rail segments is (+/- 1/16” (1.6 mm)). If settling over time moves the rail segments outside of this tolerance, then the rails will need to be adjusted.

- “Standard construction tolerance” for the vertical alignment of adjacent rail segments in compatible with the requirement for the powered Hilman rollers
- Any “settling” that takes place over the life of the experiment cannot produce a rail-to-rail vertical step larger than 1.6 mm
  - Settling is expected to happen over O(m) distance scales, and is not expected to induce a larger vertical step
  - However, PRISM will specify a maintenance procedure and interval to check the vertical step and correct it if it exceeds the 1.6 mm specification over time.

Requirement #2: Roller Loading

ID	Requirement Text	Value	Units	Rationale
ND-PRISM 2	The load at any roller location shall never exceed the rollers load capacity.	200	Metric T	As the PRISM systems roll on the rails the vertical change of elevation (ND-PRISM 1) will cause a change of load distribution. The mounting of the roller system must provide sufficient compliance to not exceed the load capacity at any time. The load capacity is specified by the vendor.,

- The vendor-specified maximum load for the powered Hilman rollers is 200 metric tons.
  - This means that the total load that can be moved with 6 powered rollers is 1200 metric tons
  - This specification is driven by the propulsion capabilities of the rollers, rather than the total weight they can support

Requirement #2 (continued): Roller Loading

ID	Requirement Text	Value	Units	Rationale
ND-PRISM 2a	Sufficient traction between the PRISM rollers and the rail must be maintained at all times to ensure PRISM motion.	-	-	As the PRISM systems roll on the rails the vertical change of elevation (ND-PRISM 1) will cause a change of load distribution. Sufficient vertical load must be maintained on the active rollers to ensure traction. The mounting of the roller system must provide sufficient compliance to ensure traction at any time.

- A system of six 200-ton powered rollers can move 1200 tons
    - The nominal loading of ND-LAr is ~700 tons, so a minimum of 4 rollers must be engaged to move the system
- For a roller to be engaged with the rail, a minimum load on the roller is needed to avoid slipping
    - Hilman uses a system-wide 3% rolling resistance to account for misalignments, cam followers engaging, etc.
        - The rolling resistance for each individual roller is <<1%
- The coefficient of friction between the roller and rail will need to be maintained within an acceptable range to:
    - Prevent roller slipping while trying to drive forward
    - Prevent lateral loads from exceeding the rail anchor capacity
    - (more details in the next talk)

Requirement #3: Lateral Tolerances and Compliance

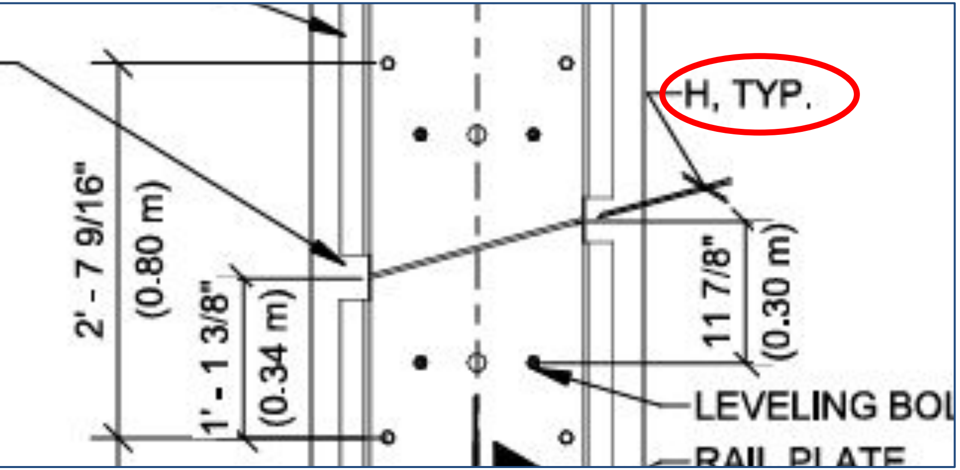
ID	Requirement Text	Value	Units	Rationale
ND-PRISM 3	The integrated PRISM Cryostat/TMS design and mounting of the rollers shall accommodate up to up to +/- 3.175 mm of lateral displacement over the length of the rails, based on NSCF requirements for the rails.	+/- 3.175	mm	Mu2E Tolerances call for +/- 1/8" (+/- 3.175 mm) alignment of the plates centerline to centerline. Note: the straightness required in the architectural drawings are more stringent (+/- 1.6 mm). Our requirement provides us a factor of margin of ~2x in case the construction firm that will deliver the cavern is only able to achieve standard construction tolerances.
ND-PRISM 3a	The PRISM design and mounting of the rollers shall accommodate +/- 1.6 mm of lateral motion imposed by the rail on the cams while transitioning from one rail segment to another.	+/- 1.6	mm	Mu2E Tolerances call for +/- 1/16" (+/- 1.59 mm) alignment of plates at joints. Note: the rail to rail lateral offset required in the existing NSCF drawings are more stringent (+/- 0.010 in). Our requirement provides us a factor of margin of ~6x in case the construction firm that will deliver the cavern is only able to achieve standard construction tolerances.
ND-PRISM 3b	The lateral force imposed by the PRISM system on the NSCF rails shall not exceed 34T.	34	US Tons	This requirement is based on the 34T specification captured in the NSCF drawing package. Per this requirement, NSCF must ensure that the anchoring of the rail can sustain 34T of lateral force, and shall not rely on vertical load from the detector, as a roller cam may produce a lateral force on a rail before the rail be loaded with the vertical load.

- These requirements are set to accommodate the NSCF rail design

Requirements #4: Rail Segment Gap

ID	Requirement Text	Value	Units	Rationale
ND-PRISM 4	The PRISM system shall be able to accommodate a rail segment-to-segment axial spacing (gap) uncertainty of 3.2 mm	3.2	mm	The gap between adjacent rail segments (⅜" +/- ⅛") was specified by the PRISM team (includes thermal expansion) and should be achievable by NSCF.

- The gap between rail segments is at a 15° angle, which allows the rollers to cross the gap



Requirements #5: Position Tolerance

ID	Requirement Text	Value	Units	Rationale
ND-PRISM 5	The PRISM movement system shall be able to move the detector to a defined location on the rails within +/- 10 cm.	10	cm	Flow down from the high-level physics requirements (ND-C2.3)

- Detector placement precision puts a requirement on the roller control system (note: should be comfortably achievable)
  - More details on the testing of the motion control system will be given in presentation 04

Requirements #6: Travel Time

ID	Requirement Text	Value	Units	Rationale
ND-PRISM 6	The time required to move the detectors across the full 28.5 m range of PRISM travel shall be 4 hours maximum	4	hr	Flow down from the high-level physics requirements (ND-C2.5)

- The longest distance to travel is 28.5 m, so a 4 hour travel time requires a minimum top speed of 2 mm/s
    - This travel time and speed would only require an acceleration of ~0.003g
- The actual operational top speed will be set by the maximum acceleration that can be tolerated by the detector systems
    - This maximum acceleration will only be used during emergency stops
    - This “emergency acceleration” is expected to be ~0.01g

Additional Requirements

- Additional requirements that are less relevant to the design assessment include:
    - Maximum force for hard stops (driven by NSCF anchoring capabilities) -> Determines maximum allowed speed
    - Maximum allowable acceleration
    - Maximum power usage (driven by NSCF transformer size)
    - Must meet safety standards (FESHM)
    - Maximum allowed vibrations
    - Design must include a detailed survey, installation and shimming plan for ensure even load distribution under initial loading
    - Design must include a detailed maintenance and servicing plan

Summary

- The high level requirements flow down to several system capability requirements:
  - Movement frequency (at least 10 movements per yearly run)
    - Must also return to a specified position monthly -> together these imply ~weekly movement frequency
  - Movement distance (28 m) and time (4 hours), which imply a minimum top speed (2 mm/s)
- The precision with which the cavern rails can be installed sets additional technical requirements
  - Our requirements are set to accommodate Mu2e installation tolerances (already built system at Fermilab), rather than the tighter tolerances that have been sent to vendors
  - Must accommodate a 5.7 mm elevation change over a 12’ (3.7 m) span
    - Design solution -> fabric pads (see next talk)
  - Must accommodate ⅛” (3.18 mm) of lateral variation in the rails across the cavern
    - Design solution -> cam follower spacing

Backup