DUNE-ND PRISM Movement System Risks and Prototype Testing

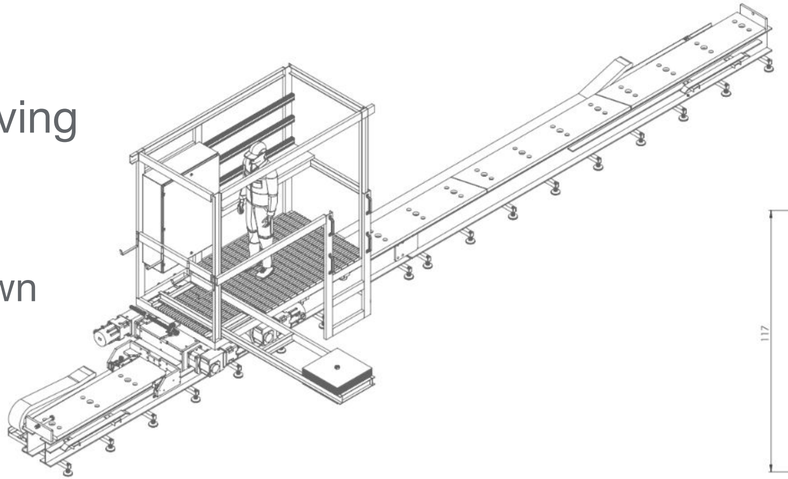
DUNE ND PRISM Team
PRISM Design Assessment
November 20th, 2024

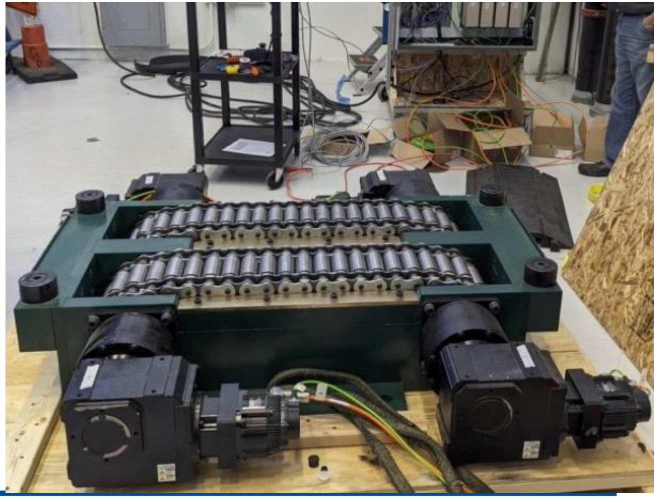
Overview

- Baseline prototyping plans (UMN Single-Roller Prototype)
- Primary risks in the baseline plan (i.e. post-prototyping)
- Additional potential tests to further mitigate risks:
  - UMN full-load testing
    - Compression tests with hydraulic cylinders
  - Integrated System Test
    - Above-ground assembly of the entire ND-LAr detector + PRISM roller system
    - Fill with water to test motion system at ~full loading (w/ liquid)

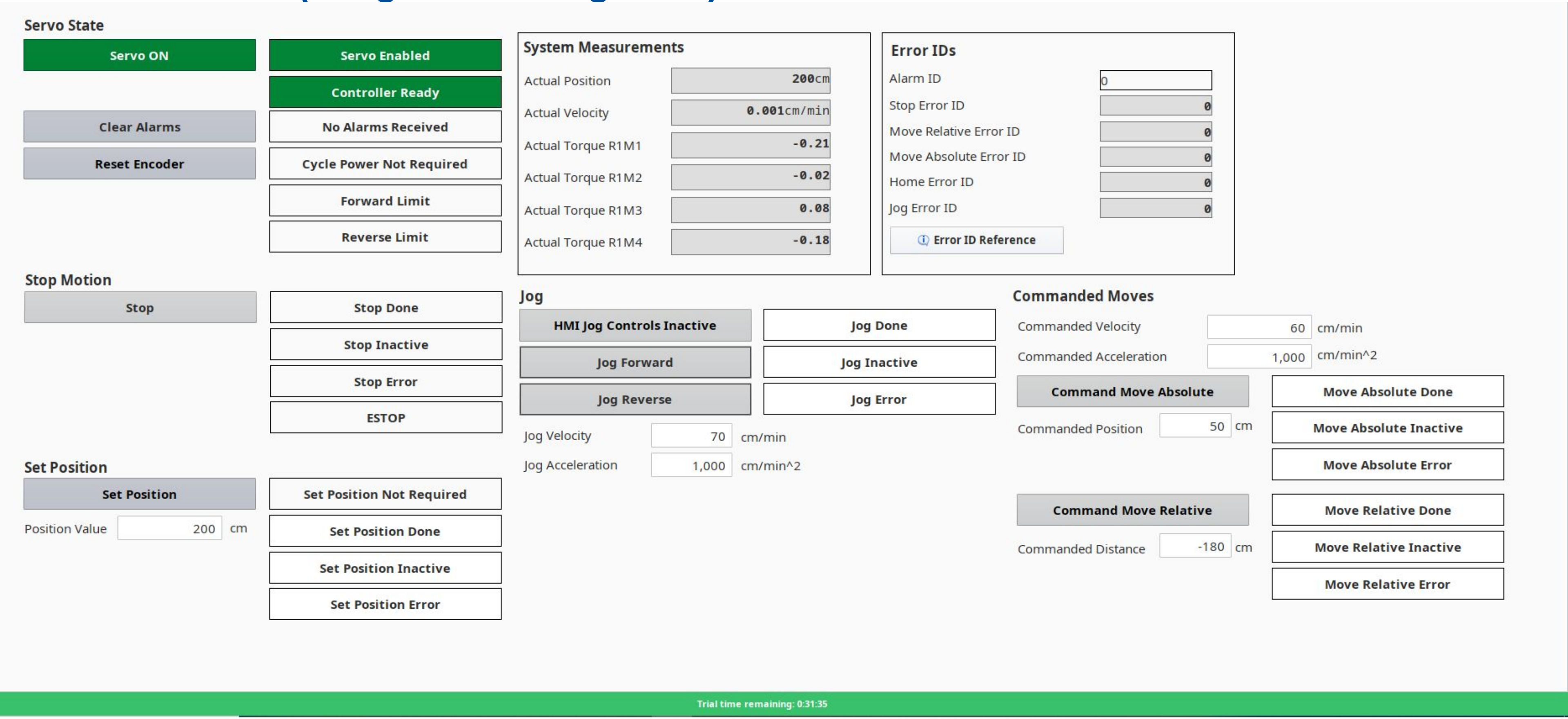
UMN Single-Roller Prototype (Funded)

- 1 motorized roller + 1 non-motorized roller on a moving platform at U. of Minnesota
  - Currently under construction
  - Motion control testing has begun with roller upside down
- Goal is to integrate the vendor-provided motion control system with the DUNE control system
  - Program standard acceleration/velocity movement profiles, emergency stop profiles, etc.
  - Integrate monitoring systems
    - Determine positioning precision and position knowledge
  - Verification of safety system performance
    - Integration with motion control system
  - Tests of side-loading from roller and rail misalignments at 1% total load
- This test is currently in our baseline plan





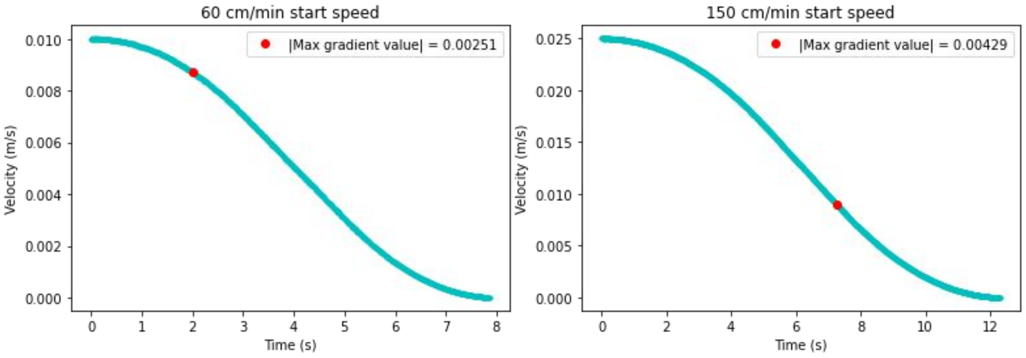
Controls GUI (Integrated into Ignition)



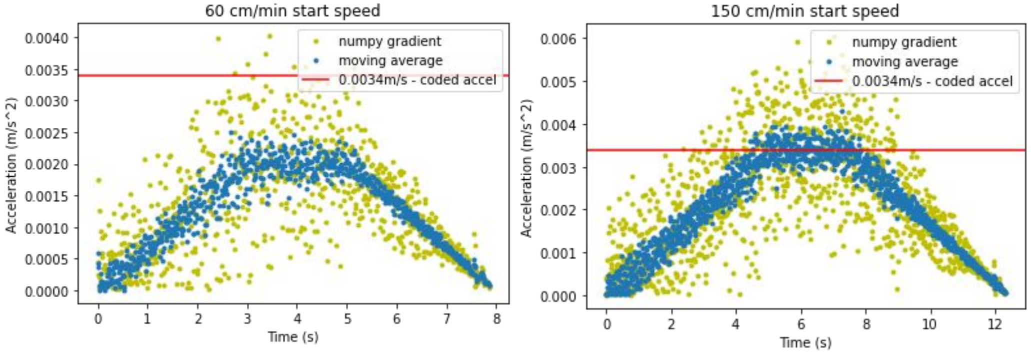
Movement System Controls

- Hilman provides a fully integrated system, including movement controls
- Acceleration is linearly ramped up/down to start/stop motion (constant jerk)
  - Very smooth motion
- At U of Minnesota, a motion system GUI has been built in Ignition
  - Ignition is the slow control system used by the DUNE FDs, the ND cryogenic systems, and ND “2x2” prototype detector, and other detectors

Stopping Velocity vs Time



Stopping Acceleration vs Time



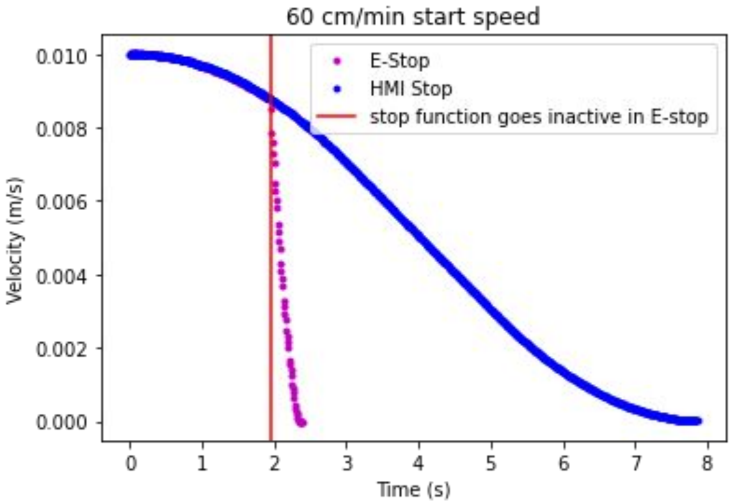
LBNF/DUNE

Roller Control System: Initial Lessons Learned

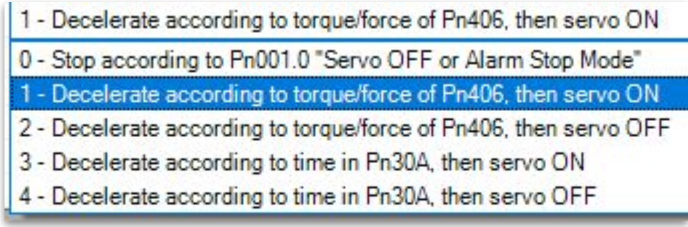
- While the system has been working well for the past several months, some issues had to be addressed in the initial set up:
  - The servo motor controls had several errors that had to be cleared before the system could initiate motion
  - Initially, the system could only move a few centimeters before faulting
    - After several iterations with Hilman/Faber, the source code on the hardware PLC was modified to address the issue:
    - "The latest version of the code added a 50ms input debounce filter on the STOP0 input. The STOP0 input was randomly turning on/off, likely due to noise."
  - The control system GUI was built into a touchscreen demo module (timeouts every 2 hours)
- Hilman was very responsive to all of these issues, and worked with us to get them solved (this required several iterations)
- We also sent a graduate student to the Yaskawa home office in Waukegan, IL to be trained in PLC programming
  - We can now modify the source code to add additional controls not included in the original GUI

Roller Controls: Next Steps

- The Yaskawa control hardware used in the movement control system has a variety of (sometimes inter-connected) options for stopping the detector
- Normal (HMI) stop is handled by firmware based on user inputs of velocity, acceleration, and jerk
- Limit switches immediately initiate an immediate coast-to-stop, but other options are available
- Emergency stop buttons begin a normal stop before switching to an HMI stop 2 seconds later
- We are exploring all of the possible options, and will iterate with Hilman as we progress
  - Eventually these options will be ported to Ignition (slow control)



Limit switch stopping options:

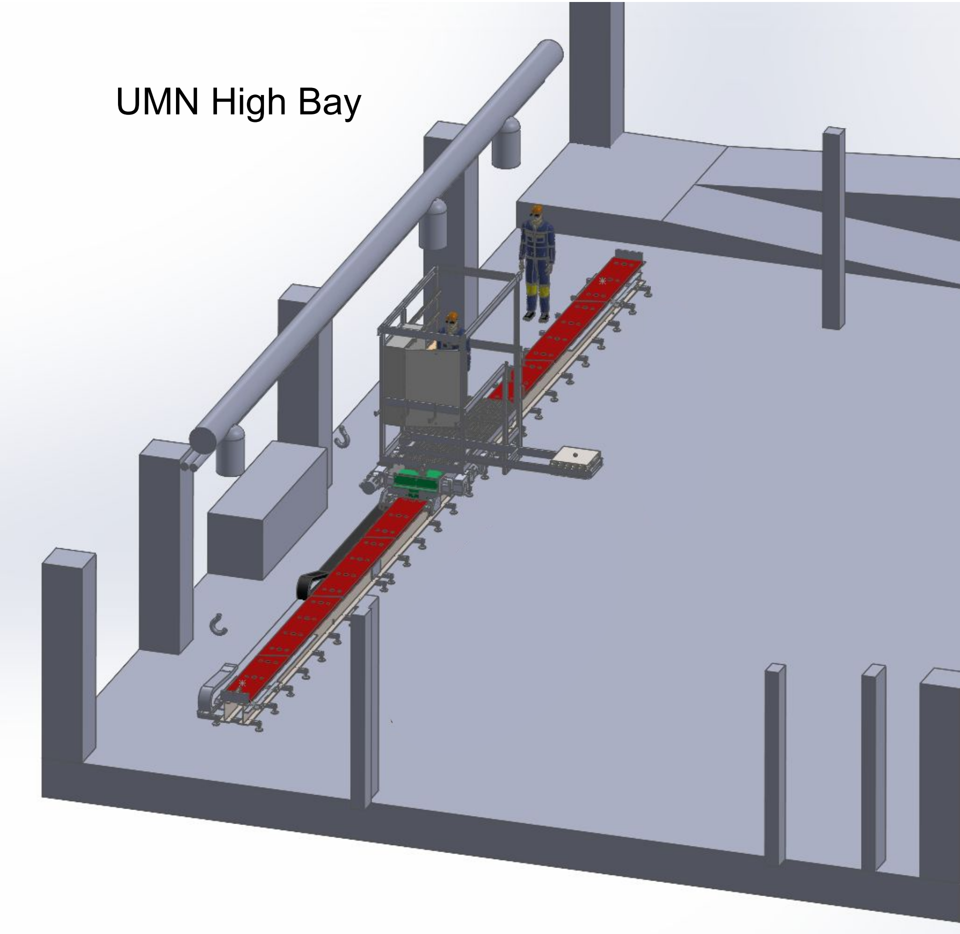


There are the following four stopping methods.

Motor Stopping Method	Meaning
Stopping by Applying the Dynamic Brake	The electric circuits are internally connected to stop the Servomotor quickly.
Coasting to a Stop	The motor stops naturally due to friction during operation.
Zero Clamping	The speed reference is set to 0 to stop the Servomotor quickly.
Decelerating to a Stop	Emergency stop torque is used to decelerate the motor to a stop.

UMN Test Facility Status

- The construction of the track began last week
  - "Cart" construction for the top of the rollers will begin in December
- Testing for early 2025:
  - Friction testing of roller cylinders on the rail for various rail finishes and lubrication
  - Side load testing (using load cells) to determine ratio to normal load
  - Rail misalignment tests (segment-to-segment transitions)
- More extensive testing of roller motion scenarios to take place in 2025
  - Including monitoring system and safety system testing



Primary PRISM Risks

Risk Rank	Title	Prob	Cost Impact	Schedule Impact	P * Impact (k$)	P * Impact (months)
3 (High)	Motion System Failures	40 %	500 -- 1500 -- 3000 k$	3 -- 6 -- 12 months	667	2.8
2 (Medium)	Friction-Induced Side Loads	25 %	50 -- 600 -- 1000 k$	2 -- 4 -- 6 months	138	1
2 (Medium)	B Fields May Impact Rollers & Control Cabinet	25 %	100 -- 200 -- 300 k$	1 -- 2 -- 3 months	50	0.5
1 (Low)	TMS detector weight or CG changes	25 %	50 -- 300 -- 500 k$	1 -- 1 -- 2 months	71	0.3
1 (Low)	NDLAr detector weight or CG changes	15 %	50 -- 300 -- 500 k$	1 -- 1 -- 2 months	43	0.2
1 (Low)	Utility design changes	35 %	50 -- 100 -- 250 k$	0 months	47	0

- Most impactful risks are listed here
  - Some additional smaller cost/schedule risks have also been defined

Risk #1: Motion System Failures

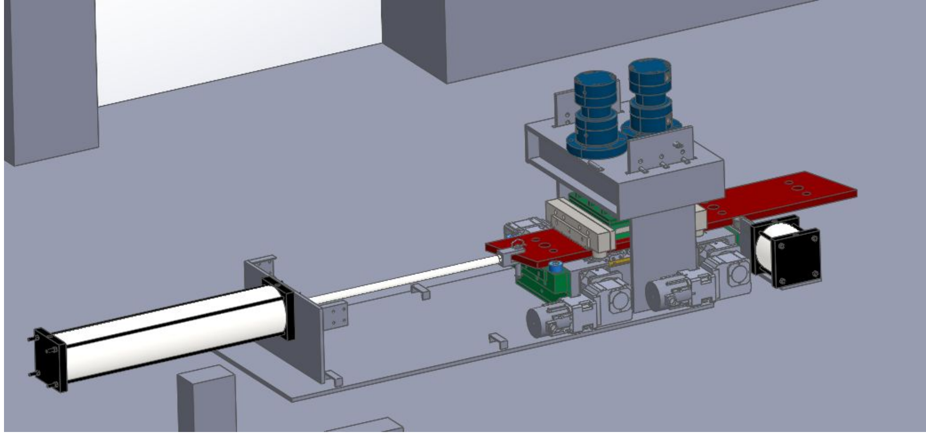
- In the baseline plan, the movement system is received from the vendor and installed for the first time underground in the Near Detector Hall at Fermilab
- If the motion system fails to operate properly after installation, the ND installation scheduled will incur delays, as the installation plan requires several movements of both detectors (e.g. taking turns under the 60 ton cavern crane)
- Motion system failures may be caused by, e.g.: roller misalignments, rail misalignments, load distribution, servo motor synchronization, electronics noise, frame construction tolerances, …
- Debugging motion system issues may require iteration with Hilman (and its control system vendor, Faber, Inc.), and could require replacement of portions of the system
  - Total system cost is several $M
  - Standing army costs for a several month installation delay is $1M-$2M

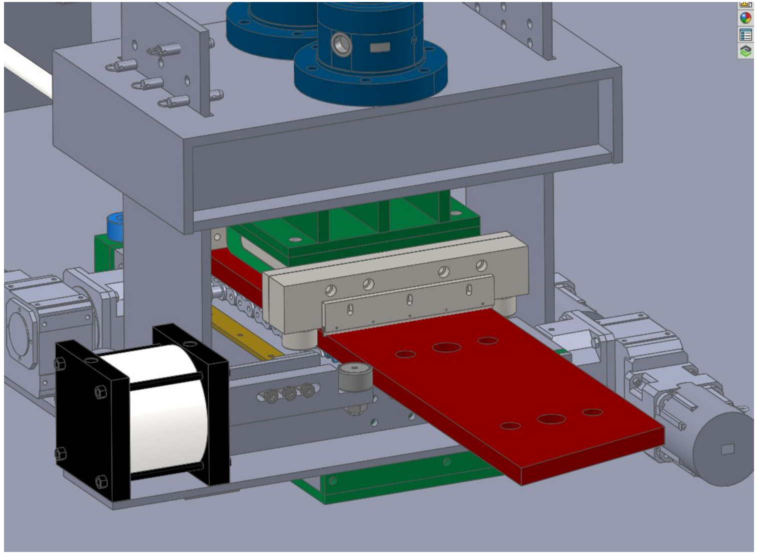
Risk #2: Friction-Induced Side Loads

- If the force of static friction between the rollers and the rails is too high, slight roller misalignments may induce a side load that exceeds the capacity of the rails (34 tons)
  - The behavior of the rollers when friction-induced side loads are applied may depend on the total load on the roller
  - Conditions of the ND cavern can affect the coefficient of friction between the roller and the rails
  - The ability of the cam followers to resist side loads depends on loading
    - Side-loading on the cam followers depends on the rail straightness and roller alignment
  - Cam followers can induce side loads on rails segments that are not yet loaded
- Risk Responses
  - Simplest case: slight adjustment to existing system (e.g. alignment and/or lubrication)
  - Moderate case: Movement guidance system modifications (reconfiguration of "cam follower" design and deployment)
  - Severe case: Rail system and/or detector frames require major strength enhancement to withstand observed side loads

Single Roller Full Load Test

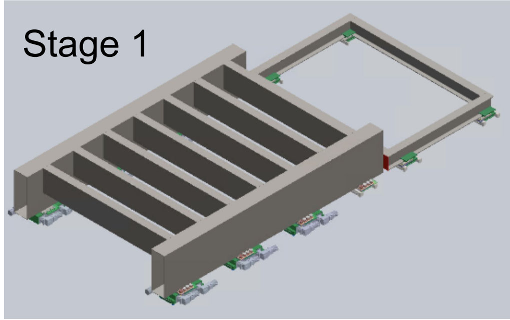
- A proposed, currently unfunded, enhancement to the UMN testing program is a full-load movement test
- Hydraulic cylinders compress the powered and non-powered rollers onto a free rail segment, which allow for several tests up to 300 tons of loading:
  - Drive system force capabilities
  - Compliant pad testing/verification
  - Rolling resistance
  - Rail side-load / slipping determination
- Fairly inexpensive test
- Some additional risk mitigation, but substantial integrated-system risks remain

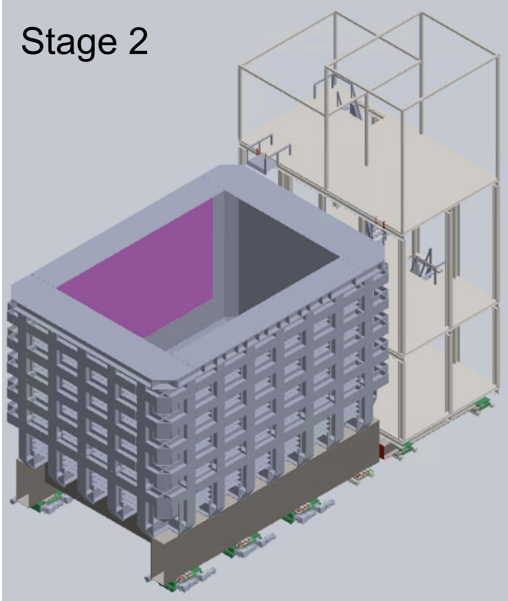




Integrated System Test

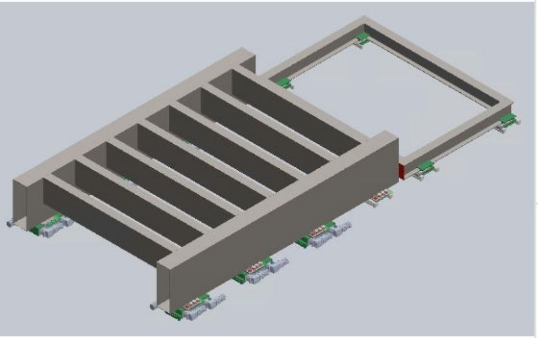
- A more substantial test designed to mitigate most of the risk associated with Risks #1 & #2 is the integrated system test
  - Before installation begins at Fermilab, the cryostat warm structure and the ND-LAr PRISM system would be constructed at the NOvA Far Detector site (Ash River, MN)
    - NOvA was installed using rollers and rails similar to PRISM
    - This is one of the only facilities with large-area, high-capacity floors for testing the PRISM system near full loading
  - The costs of this test are in technician time, rails, and shipping
    - The test primarily uses actual ND components (PRISM & cryostat)
- The goal is to commission the PRISM system prior to going underground at Fermilab, and test the system response to misalignments
  - PRISM is used to install ND-LAr and TMS, as both detectors take turns under the 60 ton cavern crane throughout installation
  - Any issues with PRISM during installation can result in large schedule delays and standing army costs



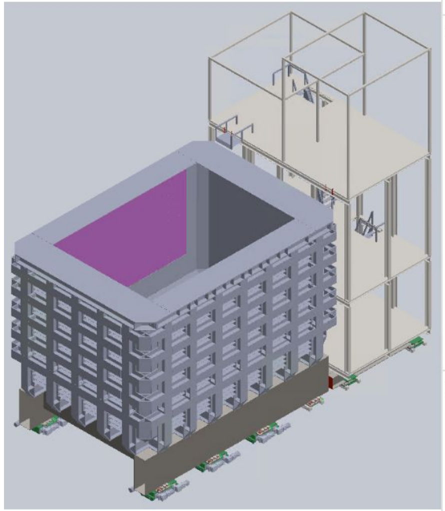


Ash River Block Pivoter

Integrated System Test Stage 1

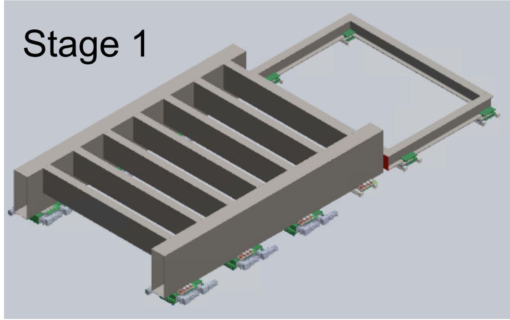
				Integrated Test - Stage 1
8 Roller test with Cryostat frame				
	PRISM	- Test roller synchronization - Roller relative alignment tests - System stability (vibration, acc, etc.) - Test mechanical guidance system - Debug/update 6-roller motion controls	No	**Components:** - 6 Power Rollers - 6 non powered rollers - Control Cabinets - Power and Data Cables - LAr Energy Chain and Hardware **Need Date:** July 1, 2026 **Lead time:** 6 month **Order date:** Jnauary 1st, 2026
	Cryostat	**PRISM Frame only:** - Validates interface with PRISM rollers (not just bolt patterns, but compliance of all components in interface, stresses in frame due to PRISM misalignment, etc etc) - Validates the coupler between the PRISM frames of the warm structure and cryo mezzanine.	No	**Components:** - PRISM Frame **Need Date:** July 1, 2026 **Lead time:** 6 month **Order date:** Jnauary 1st, 2026

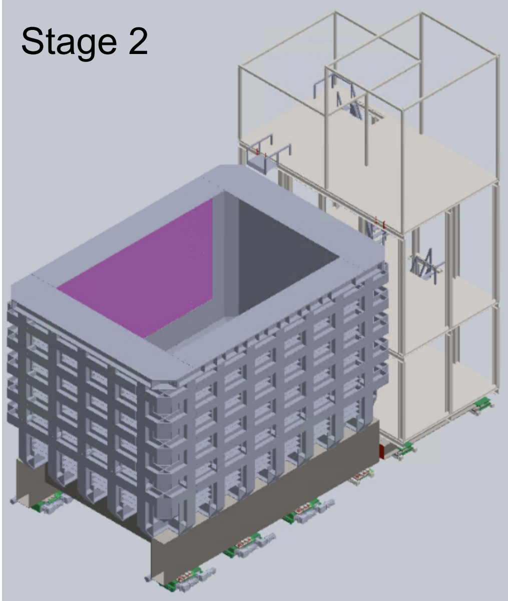
Integrated System Test Stage 2

		Integrated Test - Stage 2		
8 Roller test with Warm structure				
	PRISM	- Perform the above tests at ~full loading - Incorporate energy chain testing - Measure side loads at ~full loading - Test frame stiffness - Test Hilman compliant pads - Test electrical isolation connection design (frame to roller) and its mechanical performance - Fatigue test of roller suspension system - Full installation/commissioning test prior to underground installation	No	**Components: none** **Need Date:** NA **Lead time:** NA **Order date:** NA **Cost:** NA
	Cryostat	**PRISM Frame + Cryogenics Mezzanine + Warm Structure:** - Same benefits as PRISM frame test above, plus additional risk mitigation being able to validate loading of the warm structure. - Same benefits as PRISM + Cryo mezzanine structure testing - Provides training for techs in Warm Structure asm, (though we need to be able to use the same techs in the cavern) - Water fill and increase load on the PRISM system.	No	**Components:** - Warm Structure - Mezzanine and balconies **Need Date:** January 1st, 2027 **Lead time:** 6 month **Order date:** July 1st, 2026
	LAr TPC	- 5 module row assembled in warm structure - instrumented with accelerometers - cable management		

Integrated Test Summary

- The goal of a full integrated test would be to fully commission the motion system prior to beginning the underground Near Detector installation at Fermilab
  - Mechanical, electrical, motion, suspension, controls, misalignments, etc.
  - Performing this integration prior to the underground installation substantially mitigates risks due to motion system failures and unexpectedly large side loading
- Delays during the installation due to issues with the motion system incur a substantial cost
  - Several months of delays -> $1M-$2M in standing army costs
- The test would also provide an opportunity for an installation dry run
  - The ND installation crew could be trained in advance to significantly enhance installation efficiency & reduce risk of delays (ND I&I carries this type of risk)





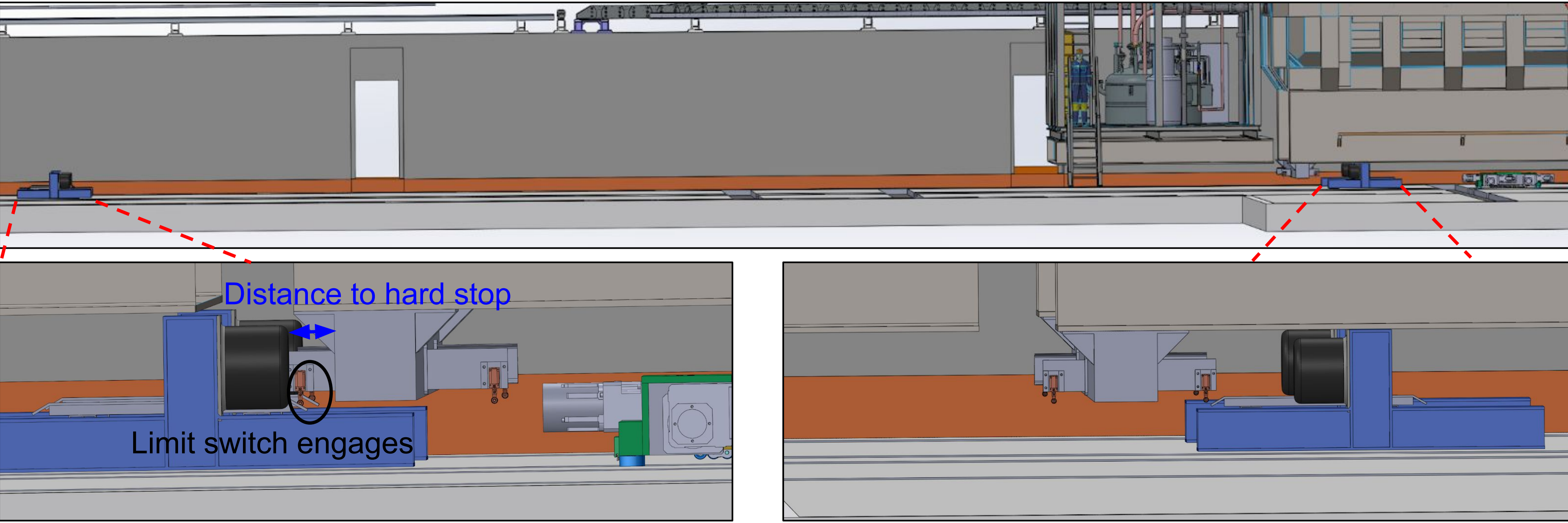
Summary of Risks and Mitigations

- Primary risks:
  - Risk #1: Motion system failures when operated for the first time underground in the near detector hall
  - Risk #2: Friction induced side loads (rollers, rails, cam followers) are larger than expected
- Potential mitigations:
  - Full-load compression / movement tests
    - Less expensive, modest risk reduction
  - Integrated system test
    - More expensive, substantial risk reduction
- We welcome feedback from the committee on the value of performing such tests prior to the ND hall installation

Backup

Detector Stopping Redundancy

- Movement system is programmed with predefined maximum travel distances
  - Additional levels of redundancy are needed in the event of the software malfunctioning
- 3 stages of stopping: (1) software stop, (2) limit switch engages, (3) hard stop
  - Goal is to only every use (1), and (2) ensures that (3) is never used
- Powered Hilmans interface nicely with limit switches (hard stops needed for any technology)



Risk 1: Motion System Failures

- If the Hilman motorized movement system fails, then there are delays in installation and cost increases may be incurred for repairs or replacement.
  - The 1,000 ton motorized movement system is a relatively new product line for Hilman, and unforeseen issues may cause the movement system to malfunction. In particular, synchronizing the 24 servo motors in each movement system may prove difficult.
- Cause or Trigger: After movement system is fully assembled, motion cannot be reliably executed.
- Risk Mitigations:
  - Funded: Single roller prototype at U. Minnesota
  - Unfunded: A full-scale, fully loaded, installation test at Ash River would substantially reduce the potential impact of this risk
- Risk Responses
  - 1. Replace some number of roller components
  - 2. Replace several motorized rollers
  - 3. Replace the entire movement mechanism

Risk 2: Friction-Induced Side Loads

- The steel rollers can induce substantial side loads on either the steel rails or the detector support frames
- Cause or Trigger: Substantial friction-induced side loads observed when movement system is operated
- Risk Mitigations:
  - Funded: Single roller prototype at U. Minnesota
  - Unfunded: A full-scale, fully loaded, installation test at Ash River would substantially reduce the potential impact of this risk
- Risk Responses
  - Simplest case: slight adjustment to existing system (e.g. alignment and/or lubrication)
  - Moderate case: Movement guidance system modifications (reconfiguration of "cam follower" design and deployment)
  - Severe case: Rail system and/or detector frames require major strength enhancement to withstand observed side loads

Risk 3: B Fields May Impact Rollers & Control Cabinet

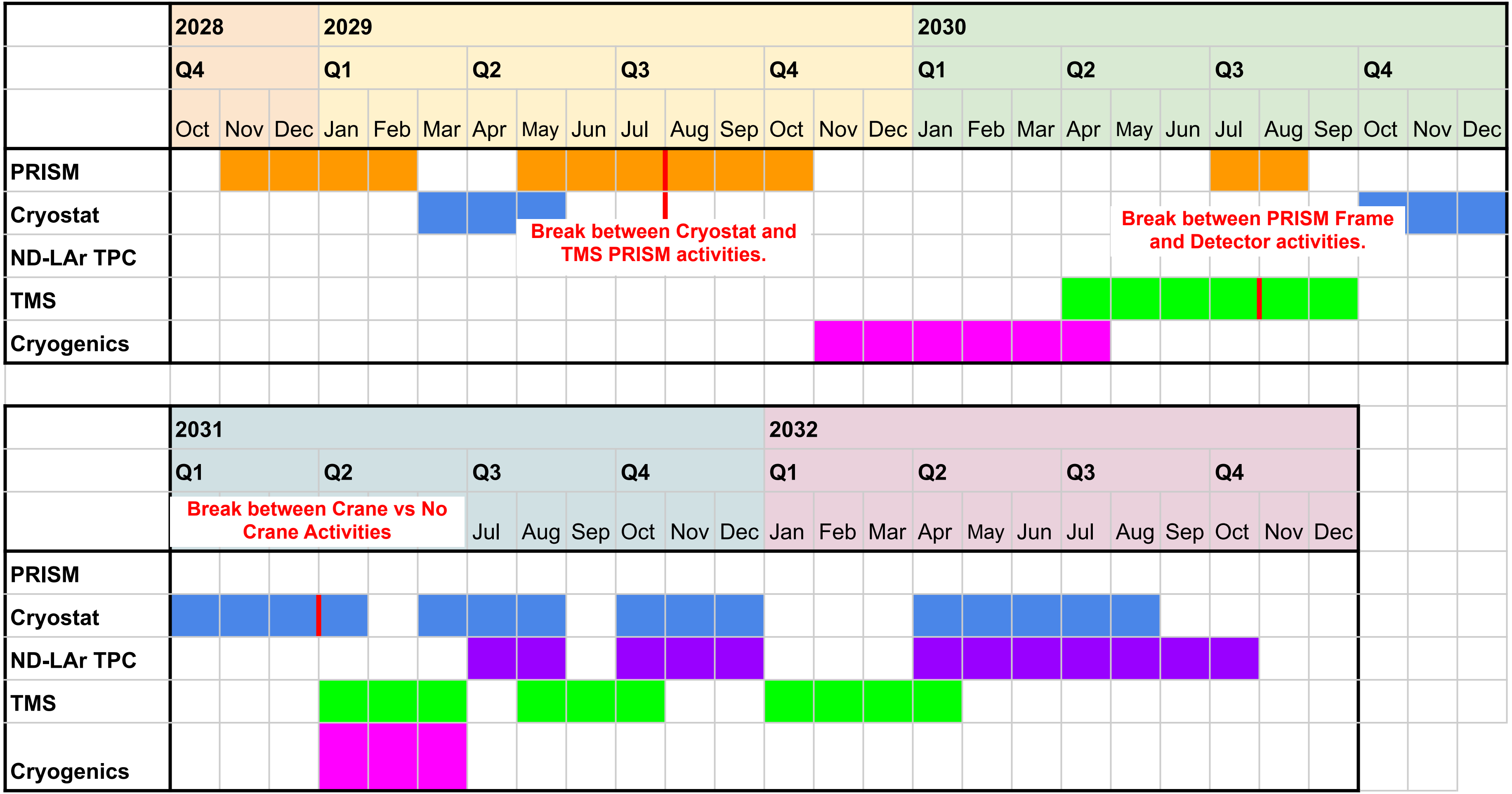
- The magnetic fields from TMS may cause problems for the PRISM control cabinet, the PRISM rollers, or the TMS energy chain.
  - TMS is supposed to have self-canceling field with small fringe fields outside of the detector region, but misalignments can degrade this cancelation
- Cause or Trigger: The as-built TMS magnetic field is found to be larger than 100 gauss at the location of any PRISM system component
- Risk Mitigations:
  - TMS field simulation (including re-evaluation with as-built system)
- Risk Responses
  - Shielding as needed

Risk 4: Detector Weight or CG Changes

- If there are significant changes in the detector weight and CG, then additional engineering and hardware will be required.
- Cause or Trigger: Extra weight added during detector design or detector construction
- Risk Mitigations:
  - Solidify the interface and obtain detailed Mass Budget Allocation from the Detectors. Update on a regular basis
- Risk Responses
  - Modify the system to include additional motorized rollers

Risk 5: Utility Design Changes

- If changes in the utilities that are loaded into the energy chain, then design changes will impact cost and schedule
- Cause or Trigger: Extra utilities added during detector design or detector construction
- Risk Mitigations:
    - Start and manage Power and Data Utility lists
- Risk Responses
    - Modify design and energy chain selection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PRISM
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ND-LAr TPC
TMS
Cryogenics
Break between Cryostat and TMS PRISM activities.
Break between PRISM Frame and Detector activities.
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Q4
Break between Crane vs No Crane Activities
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PRISM
Cryostat
ND-LAr TPC
TMS
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