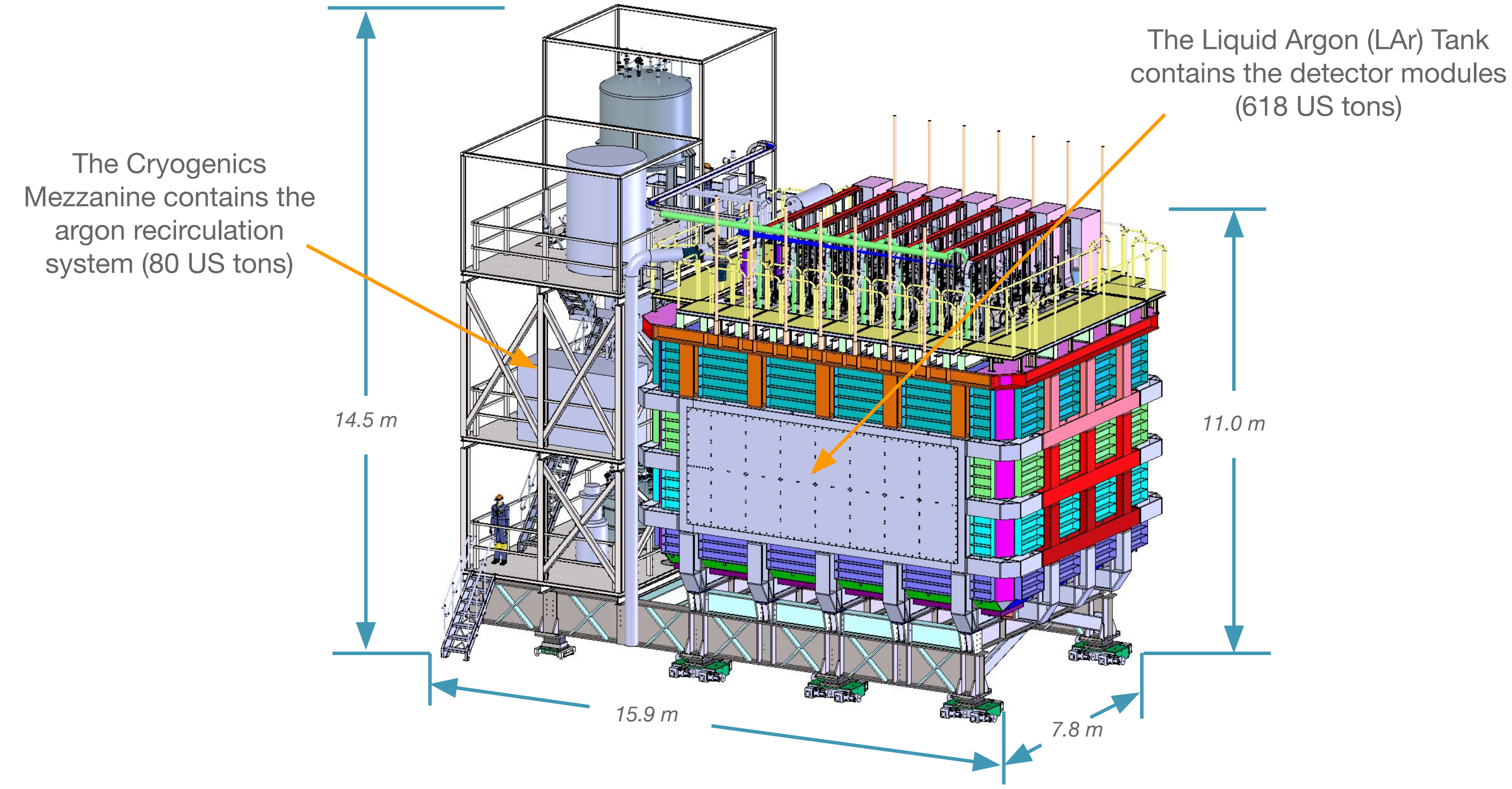
DUNE-ND PRISM Movement System Integrated Design and Interfaces

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

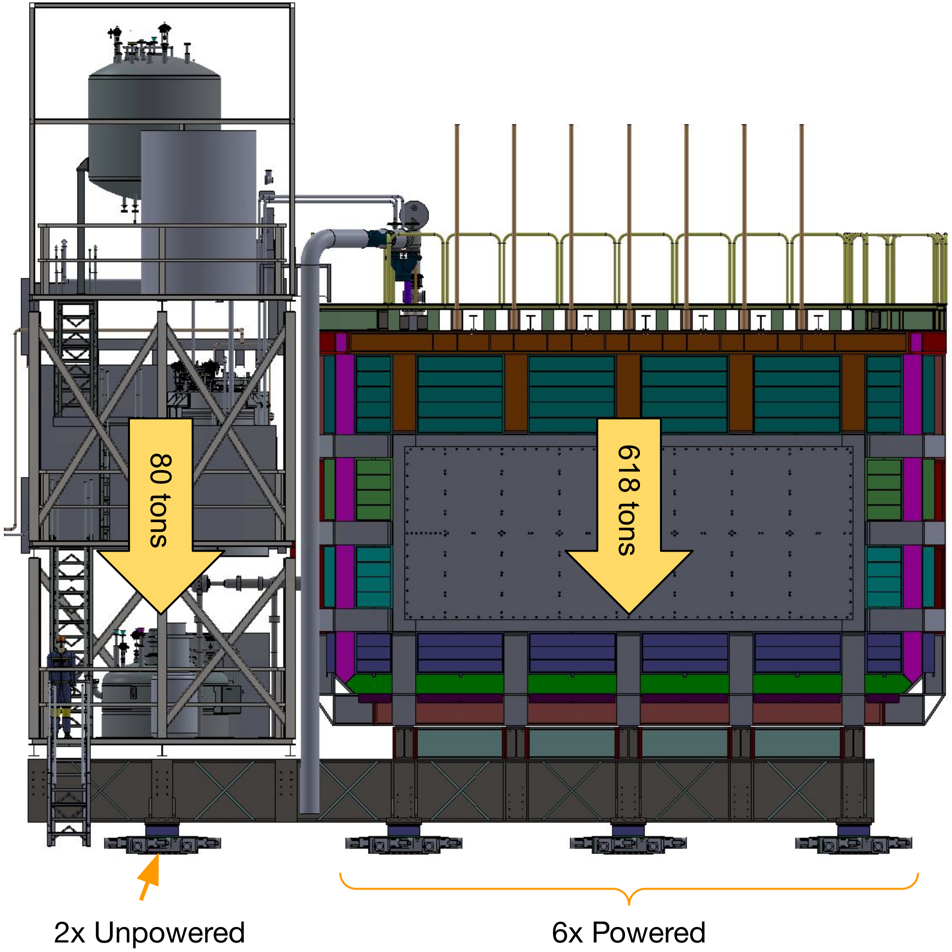
The PRISM System supports the movement of the 700 ton ND-LAr Detector



ND-LAr uses eight 200 ton capacity rollers, six of which are powered

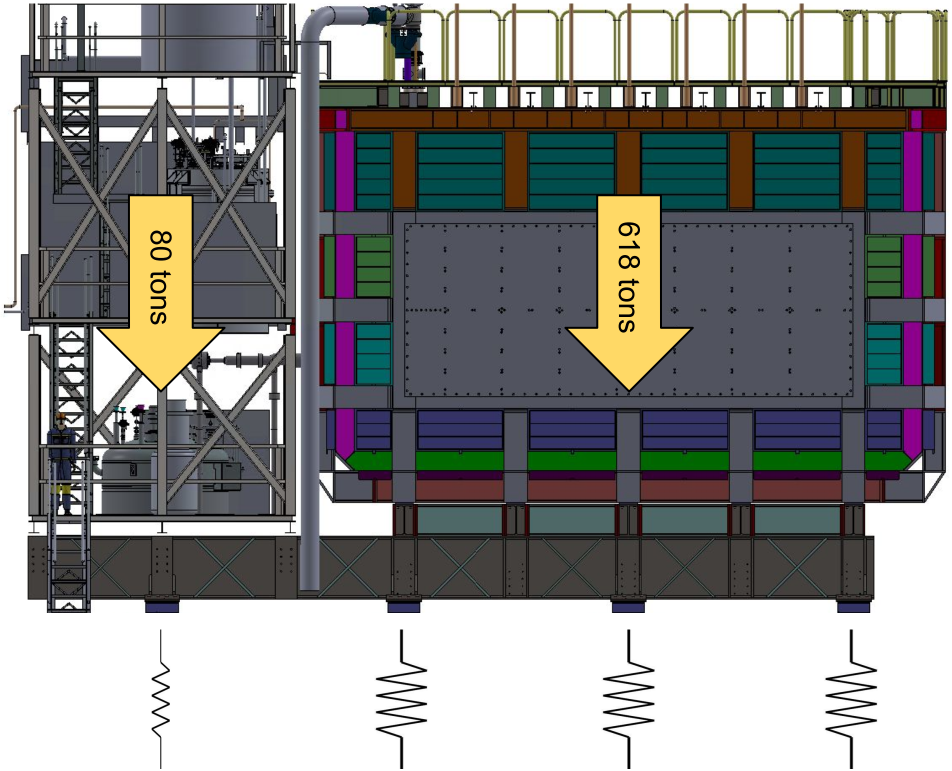
	Cryo Mezzanine	LAr Tank
Weight (US tons)	80	618
Roller Count	2	6
Roller Type	Unpowered	Powered
Nominal Roller Load (US tons)	40	103
Min Roller Load (US tons)	none	34
Max Roller Load (US tons)	200	200

- Maximum roller load set by roller capacity
- Minimum roller load set by traction requirements
  - 34 ton limit is conservative as it assumes it takes all 6 powered rollers to move the detector
  - More on this later

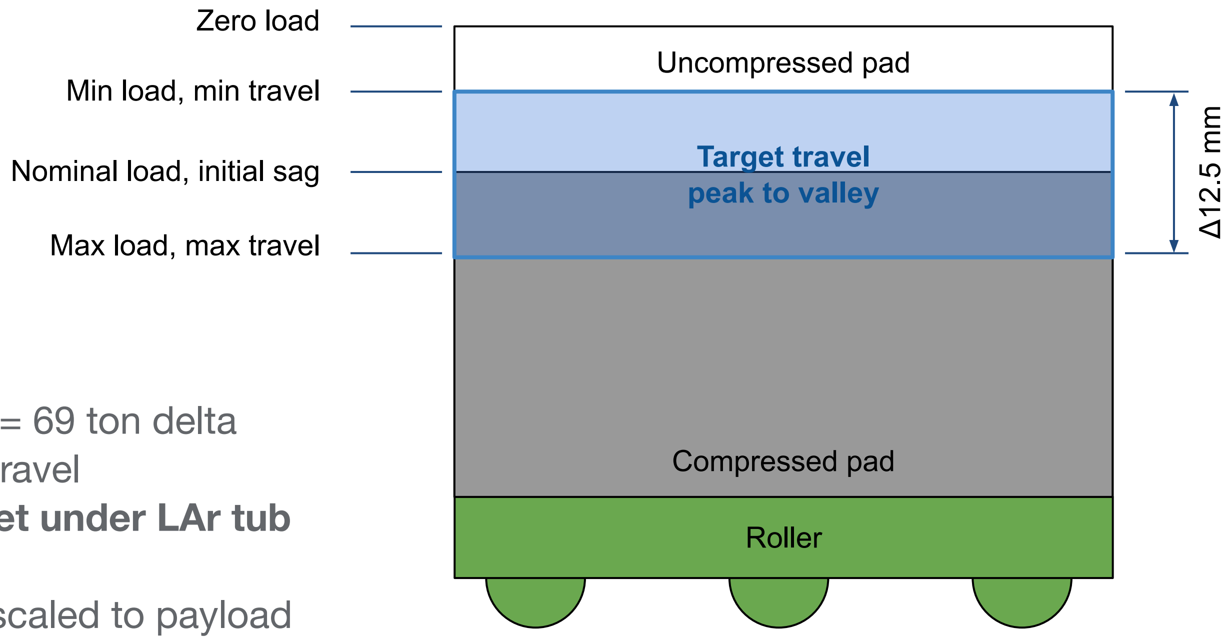


Detector on rollers is modeled as a mass suspended on springs

- Analytical models used for basic sizing assume stiff subframe and point masses
- FEA model incorporates realistic detector frame stiffness and detailed load distribution



Heavier LAr tank case sets spring stiffness target, lighter cryo mezzanine follows



- 103 US ton nominal - 34 ton min = 69 ton delta
- 12.5 mm flatness / 2 = 6.25 mm travel
- 69 / 6.25 = **11 US tons/mm target under LAr tub**

- Cryo mezzanine spring stiffness scaled to payload
  - Ensures initial sag matches LAr tank rollers
- 40 US ton nominal
- (40 / 103 tons) * 11 = **4.3 US tons/mm under cryo mezzanine**

Hilman recommends a Fabreeka Fabric Pad (or "F-Pad") for vertical compliance

- Available up to 1" thick
- σ_y = 69 MPa [10 ksi] compressive strength
- 13.8 MPa [2 ksi] recommended working stress
- Equivalent compressive modulus $E=\sigma/\varepsilon$
  - From Figure 1 at working stress
    - σ = 2 ksi = 13.79 MPa
    - ε = 0.14
    - E = 98.5 MPa
- Fabreeka Fabric Pad datasheet

Determine the area and thickness of the F-Pad cushion to satisfy the established conditions. The F-Pad has a safe working stress of up to 2000 psi (13.8 MPa) if impacts are infrequent. If impacts occur frequently (one per second) stress is limited to 500 psi (3.5 MPa). However, there is a safety factor of about 5 to 1 because the F-Pad's compressive strength is in excess of 10,000 psi (69 MPa). This example will assume impacts are relatively frequent and will limit the working stress to 1000 psi (6.9 MPa).The minimum area (A_f) therefore is:

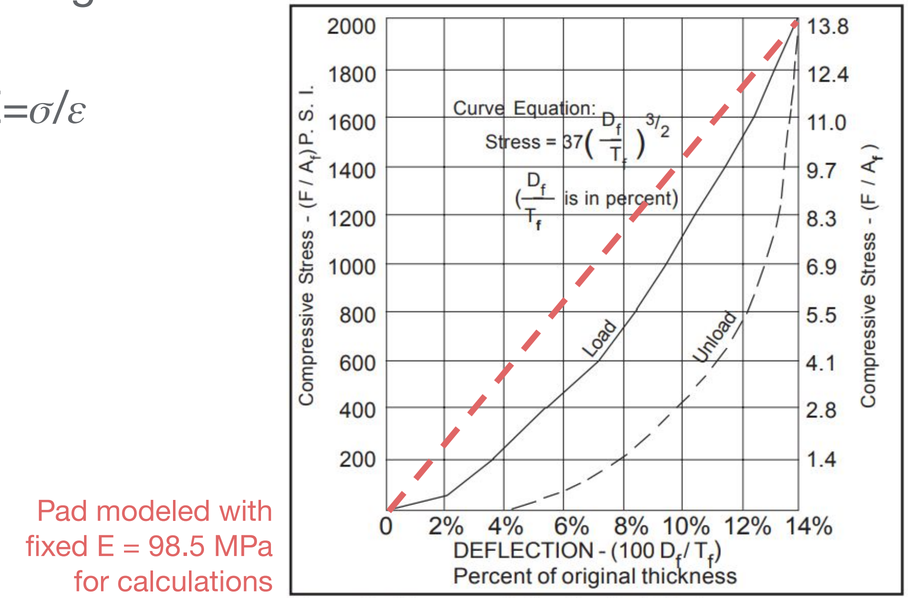
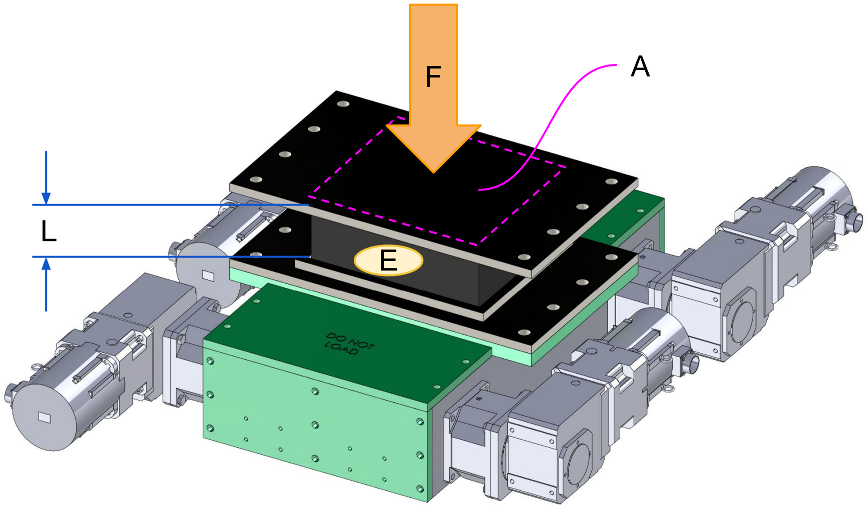


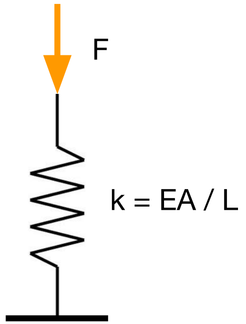
Figure 1 - Stress vs. Deflection for F-Pad

Pad compression modeled as linear spring

- $\Delta L = FL / EA = F (L/EA) = F / k$
  - $k = EA / L$
  - Assume E = 98.5 MPa
  - $F = k\Delta L$ equivalent to Hooke's law $F=kx$

	Cryo Mezzanine	LAr Tank
Modulus (MPa)	98.5	98.5
Pad footprint (in)	12 x 18	16 x 20
Pad A (in^2 [m^2])	216 [0.139]	320 [0.206]
Pad L (in [mm])	14 [356]	8 [203]
Stiffness k (US tons/mm)	**4.3**	**11.1**
Deflection at min load (mm, %)	0, 0%	3.1, 1.5%
Deflection at nominal load (mm, %)	9.4, 2.6%	9.3, 4.6%
Deflection at max load (mm, %)	46.9, 13.2%	18.1, 8.9%





We are also working with Hilman to evaluate Fabreeka's softer SA-47 material

- SA-47 has also been used for long term structural applications like bridges and concrete structures
- Roughly half the stiffness of the fabric pad material, allowing for smaller pad thickness and/or larger pad area
- Allowable working stress and unload curve are still unknown, so design assumes fabric pad for now
- Fabreeka SA-47 datasheet

FABREEKA SA-47® PADS

COST-EFFECTIVE AND ENVIRONMENTALLY FRIENDLY

- Withstands compressive load up to 8,000 psi
- Evenly distributes load between two structural elements
- Accommodates non-parallel, load bearing surfaces
- Allows for small rotations
- Meets most DOT and federal specifications for reinforced elastomeric pads and masonry pads
- Effective temperature range is 0°F to 180°F

SA-47 bearing pads are made from masticated rubber using a blend of recycled rubber compounds and synthetic fiber reinforcement. The random oriented fibers, provide enhanced compressive strength, stiffness, and tensile strength when compared to unreinforced or virgin bearing pad materials.

Since 1947, SA-47 random oriented fiber bearing pads have been widely used in construction applications such as structural bearings, precast/prestressed concrete structures, bridges, masonry pads, and railway tie pads. SA-47 material is also utilized for vibration isolation and shock reduction applications.

PHYSICAL PROPERTIES

PROPERTY	TEST	SPECIFICATION
*Hardness - Shore "A":	ASTM D2240	80 ± 5
*Tensile Strength:	ASTM D412	741 psi (min) ± 25%
*Elongation:	ASTM D412	15% (min) ± 25%
Compressive Strength:	ASTM D575	8,000 psi
Tear Strength:	ASTM D624	150 psi
Low-Temp Brittleness:	ASTM D2137	PASS

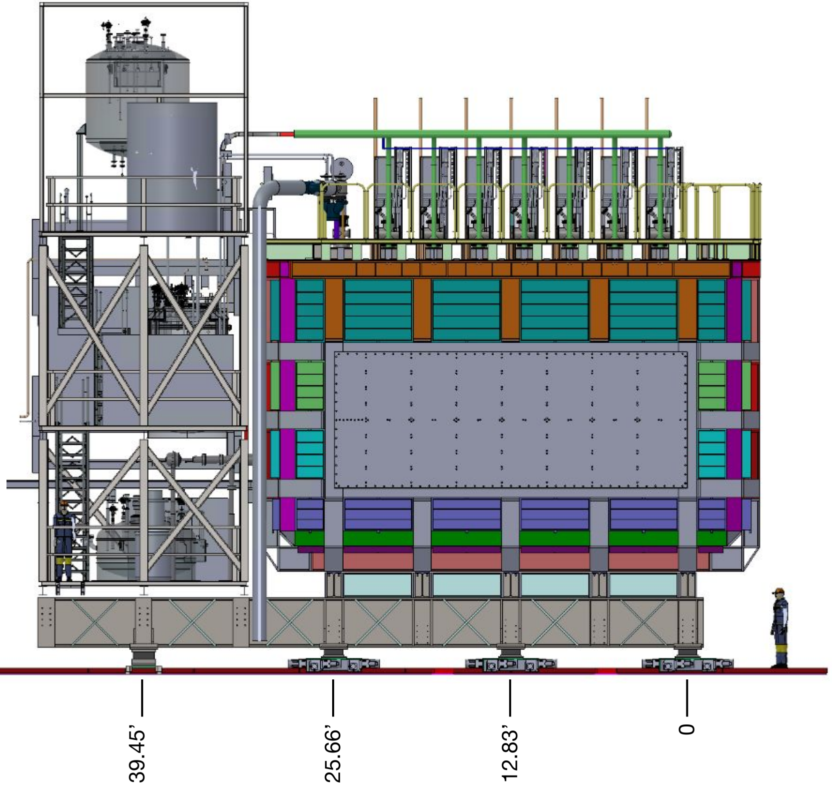
*Initial Heat Aged - Per ASTM D573, Method C, 70H@70°F

FABREEKA®
A STABILUS COMPANY

1023 TURNPIKE ST // STOUGHTON, MA 02072 // 1-800-322-7352
info@fabreeka.com // WWW.FABREEKA.COM

Rail flatness tolerances are split into global and local requirements

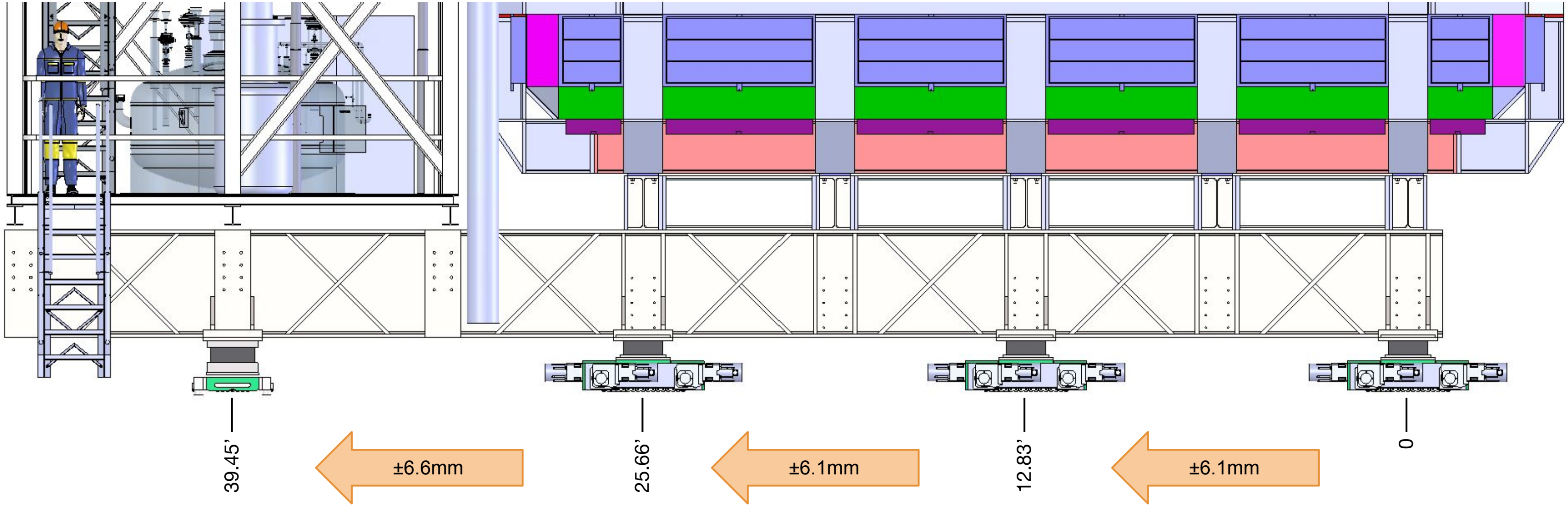
- 12.5mm flatness applies over entire rail
  - ±5mm at installation, up to 2.5mm settling
- 5.7mm flatness applies over any given 12’ [3.66m] span
  - ±1.6mm at installation, up to 2.5mm settling
  - Note that rollers are spaced just over 12’ apart

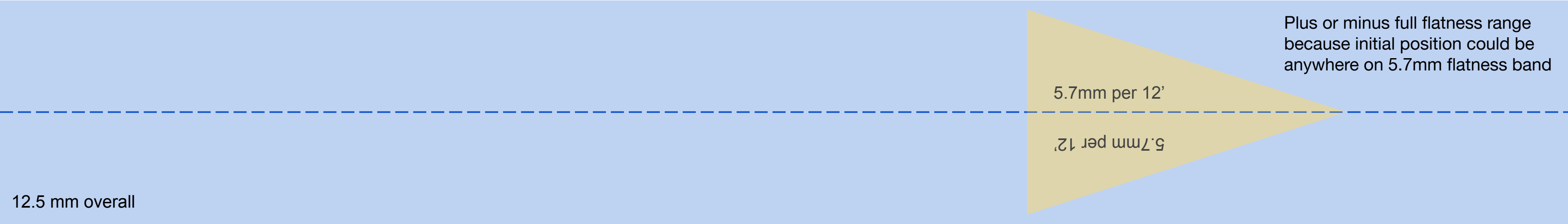


▱ | 5.7mm Over any 12’ span

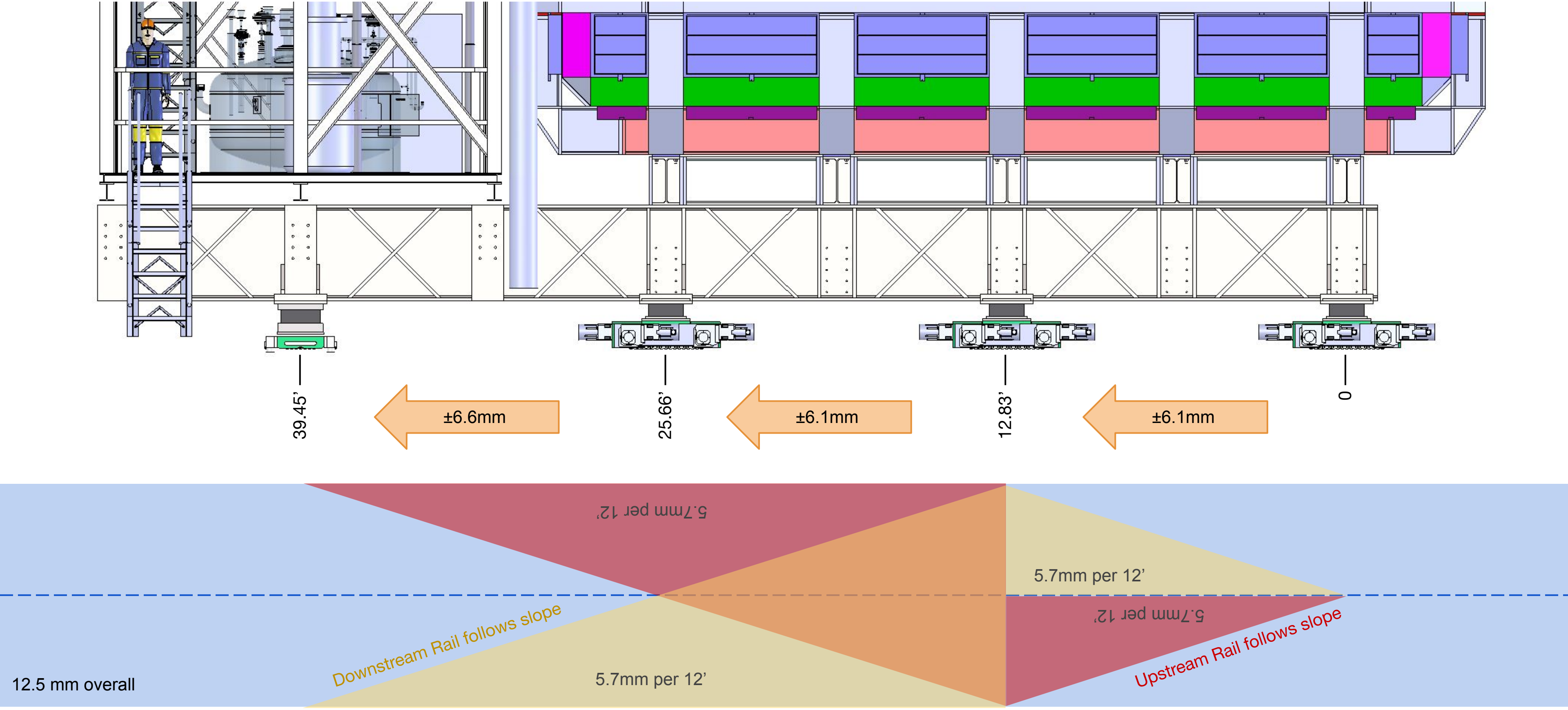
▱ | 12.5mm Over entire rail

Max displacement roller to roller governed by local slope limit



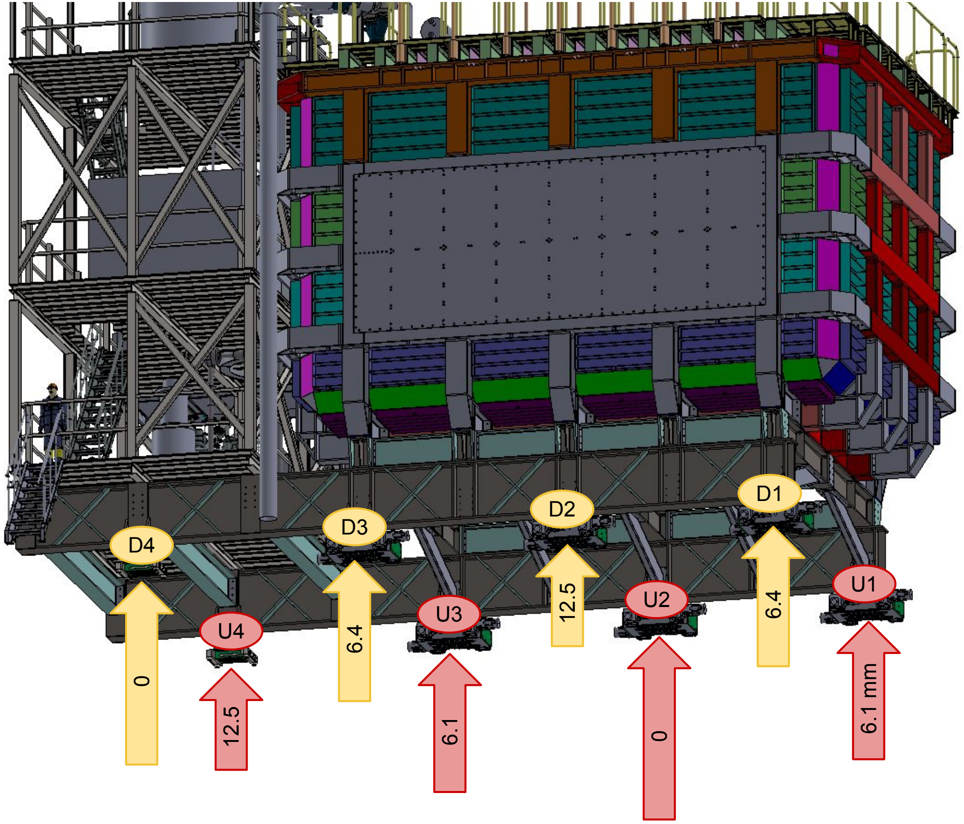


Worst case displacement occurs when rollers under LAr tank CG span the full 12.5 mm range and neighboring rollers slope up and down from there



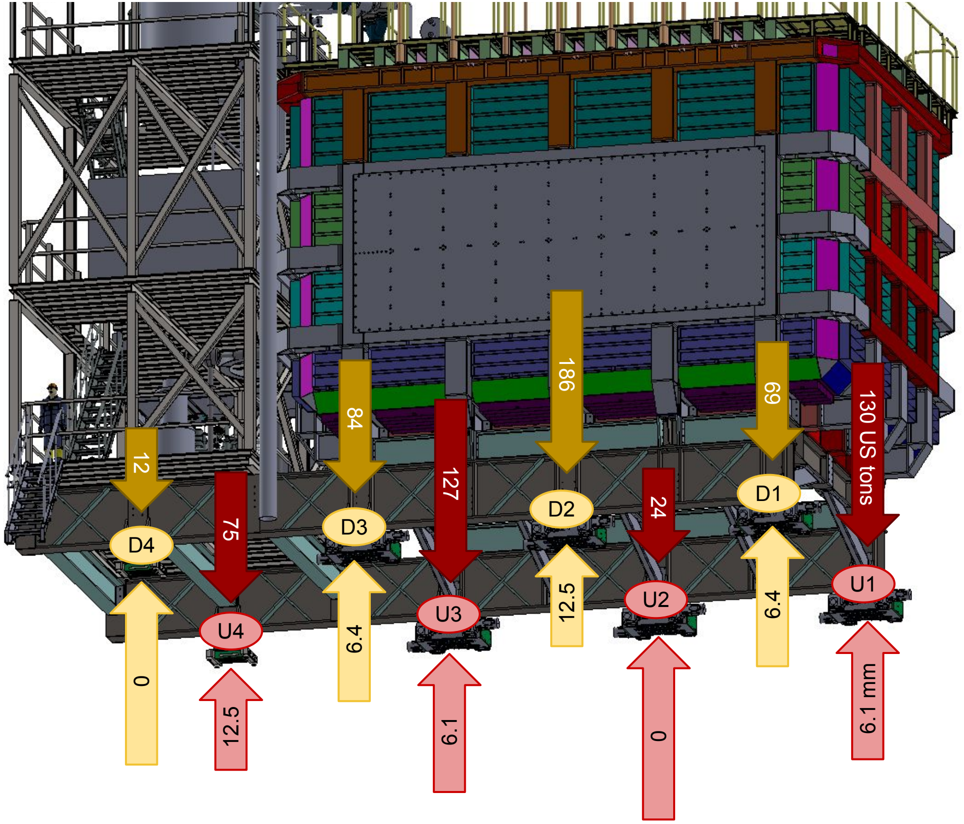
Worst case displacement occurs when rollers under LAr tank CG span the full 12.5 mm range and neighboring rollers slope up and down from there

- Upstream rollers (U1…U4) lowest at U2
- Downstream rollers (D1…D4) highest at D2
- Vertical delta roller to roller is driven by 5.7 mm per 12’ slope
- Maximum cumulative delta limited by 12.5 mm overall flatness



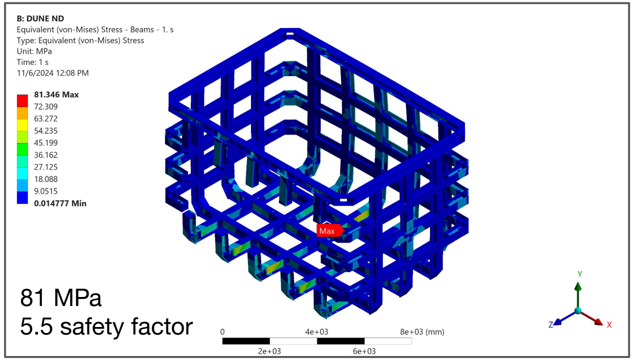
FEA results from worst case sloped rail displacement, loads in US tons

- Highest 186 ton load (D2) remains below 200 ton limit
- Lowest 24 ton load (U2) is below 34 ton limit
  - Neighboring rollers compensate
  - To overcome static friction we need 205 tons across all powered rollers
    - •3 rollers at min 68 tons
    - •4 rollers at min 51 tons
    - •5 rollers at min 41 tons
    - •6 rollers at min 34 tons
  - In this case, 5 remaining powered rollers at ≥69 tons

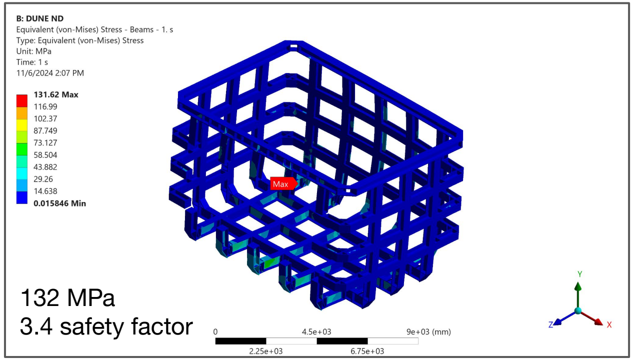


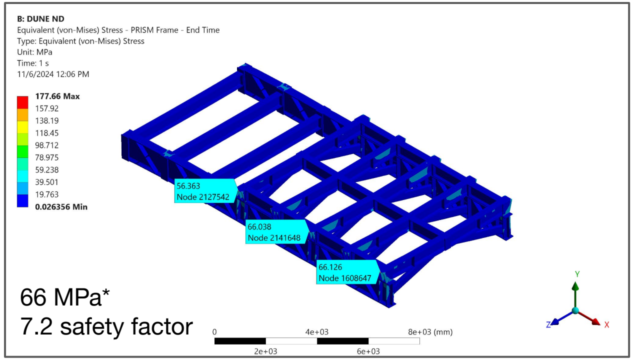
ND-LAr Cryostat frame stress increases under sloped condition but safety factor remains above 2.0 target (evaluated against yield strength)

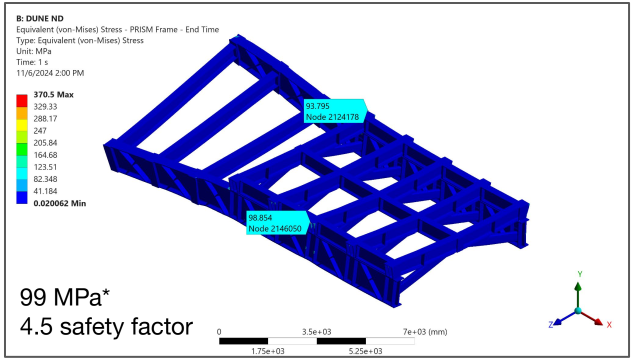
Nominal



Slope



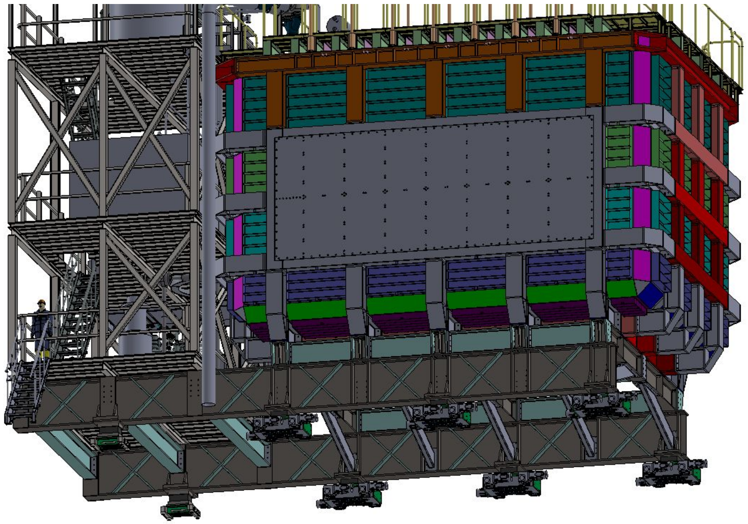




**Apparent PRISM frame stress peaks under cryo mezzanine are a non-physical result of FEA contact conditions and are currently being addressed*

ND-LAr Vertical Compliance Summary

- Eight 200 ton rollers readily support the 700 ton ND-LAr detector
- Hilman's standard fabric pad solution accommodates rail flatness tolerances
  - Rollers do not exceed rated capacity
  - Rollers maintain drive traction
  - ND-LAr Cryostat frame remains within stress limits



Friction Study: Steel wheel on Steel rail

- Similar application : Railroad trains
- Railroad trains are widely studied and predictable in performance
- Train Wheel = Hilman double strand chain rollers and railroad tracks = Hilman 18" steel tracks
- Traction is generated by the engine. In this case 200T X .25 = 50 Tons
- Max Traction is greater or equal to rolling resistance, 6000T x .008 = 50 tons

Freight=6000 Tons / engine *Engine=200T*

6000 x .008 = 200 x .25

Load x $COF_{rolling}$ = Engine x $COF_{traction}$

Friction Study: Steel wheel on Steel rail

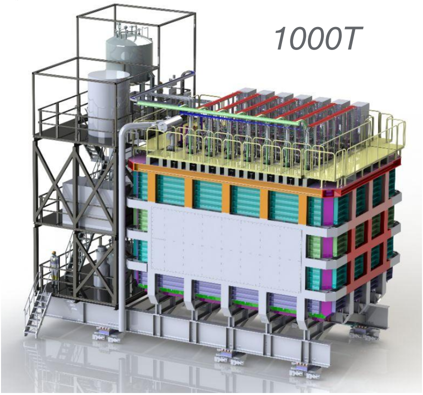
- Hilman rollers have system–wide rolling resistance coefficient of 0.03 (as per Hilman)
  - Individual rollers have much smaller rolling resistance
- Since “engine weight” = “load”
- Then, traction just has to be greater than .03

Targeting $COF_{traction}$

Minimum = .05 (to overcome rolling resistance)

Maximum = .15 (to avoid overloading rail and cam follower)

More…



Rolling Resistance = 1000T x .03= 30 Tons

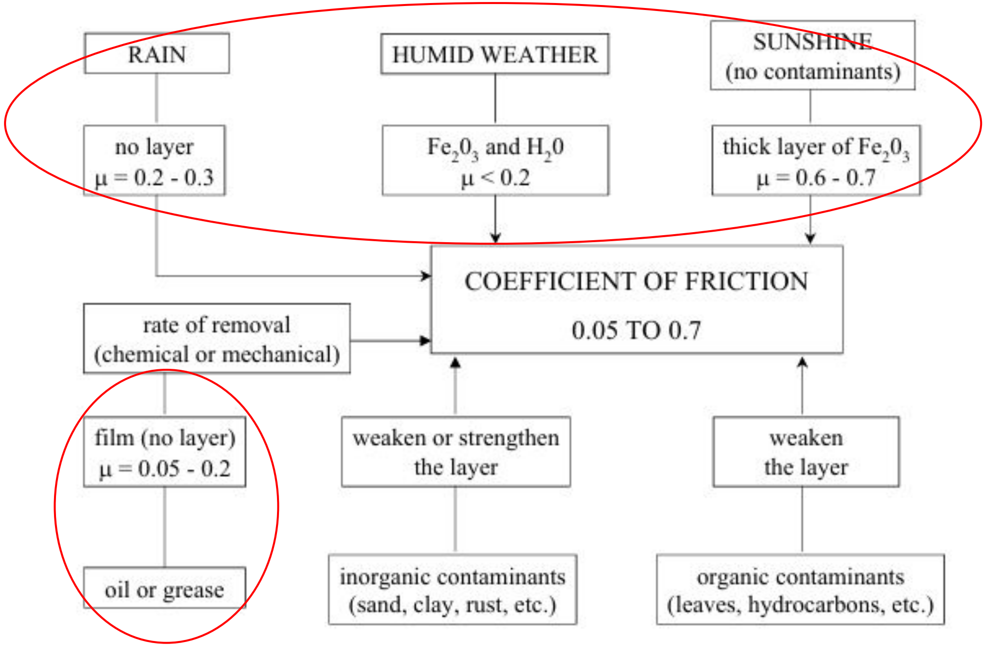
$COF_{rolling}$ = .03

$COF_{traction}$ = .05-.20 target

A survey of Wheel/ Rail Friction

From Office of Research Development and Technology, Federal Railroad Administration:

- Leaving the rails exposed will result in highly variable friction (0.05-0.70)
- Dry steel on steel has .60-.70 is too high and can result in steering issues. Cam follower side guides can overload and bend.
- Too low we can have traction issues
- Controlled oil/grease application will give us better control (0.05-0.20)



Source:
A survey of Wheel/Rail Friction, Federal Railroad Administration
Office of Research Development and Technology, U.S. Department of Transportation

Hilman Rails and Oil spray

- <u>$COF_{traction}$ control example:</u>
- Using some light oil spray can result in predictable performance
- Sample $COF_{traction}$ of WD40 is 0.11-0.14
- Added benefit: Protecting rails and the rollers from corrosion

Properties

Corrosion Protection (on freshly sanded mild steel panels)

Exposure*	Results
Humidity (JAN-H-792)	No rust after 1000 hours
Salt Spray (FED STD 151)	No rust after 50 hours
Salt Spray (FED STD 151)	Rust beginning after 100 hours

*USA standards

Lubrication: Dynamic coefficient of friction

BEARING PRESSURE	COEFFICIENT	TEST
100psi	0.112	Heat treated 4340 steel
1000psi	0.114	with normal blue oxide
2000psi	0.129	film against itself
3000psi	0.138	lubricated with
4000psi	0.145	WD-40.

Friction Study - Summary

System Constraints:

System Rolling Resistance = 0.03 *(from Hilman)*

- In order to overcome system resistance, we'll need μ>0.03

Lateral Load Spec to NSCF = 0.17 *(200 US ton roller, 34 US tons lateral load [Force limit specified to NSCF])*

- To guarantee that we won't overload the rails laterally, we are targeting μ<0.17

Material Characteristics:

Roller/Rail Coef. of Friction = 0.05 - 0.20 *(DOT Report, oiled or greased)*

- A feasible range of friction based on DOT analysis of lubricated rails is $0.05 < \mu < 0.2$

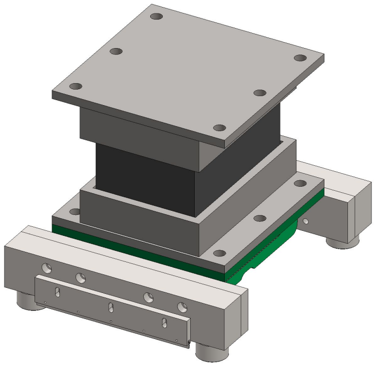
DUNE Initial Target:

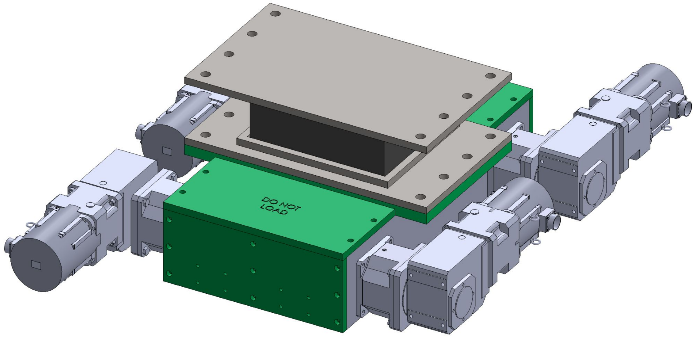
Roller/Rail Coef. of Friction = 0.05 - 0.15

- Can be achieved with standard lubricants

Backup

8 Roller Design – Area and Height Tune

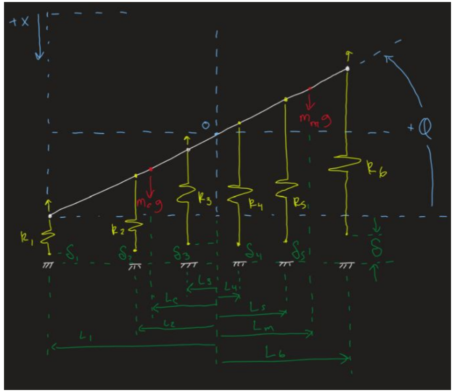


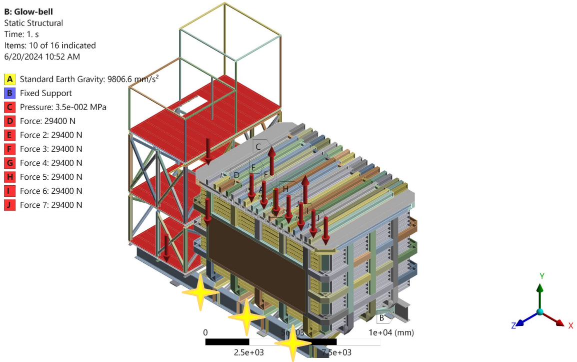


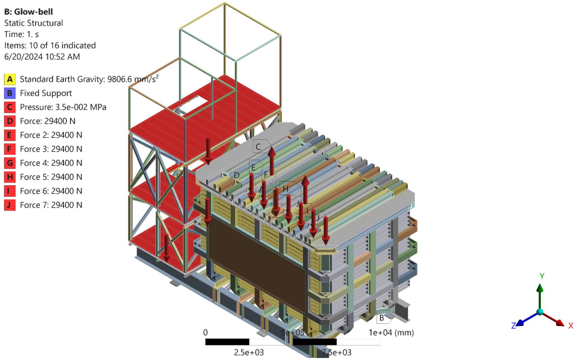
	Unpowered Rollers under Cryo Mezz	Powered Rollers under LAr Tub
Cross sectional area relative to roller mounting plate	49%	40%
Footprint (in)	12 x 18	20 x 16
Thickness (in, mm)	14 in [355.6 mm]	8 in [203.2 mm]
Initial sag (mm, % total thickness)	9.4 mm, 2.6%	9.3 mm, 4.6%
Peak compressive stress / working stress limit	2.2	1.6

- Peak compressive stress based on 100 US ton limit on unpowered rollers and 200 US ton limit on powered rollers
- Compressive stress safety factor based on 2000 psi [13.8 MPa] working stress from Hilman
  - Material compressive yield strength is 5x higher at 10 ksi

Three step approach to isolate pad performance from frame compliance







Analytical Model

- Point masses at centers of LAr tank and cryo mezzanine
- Infinite beam (frame) stiffness

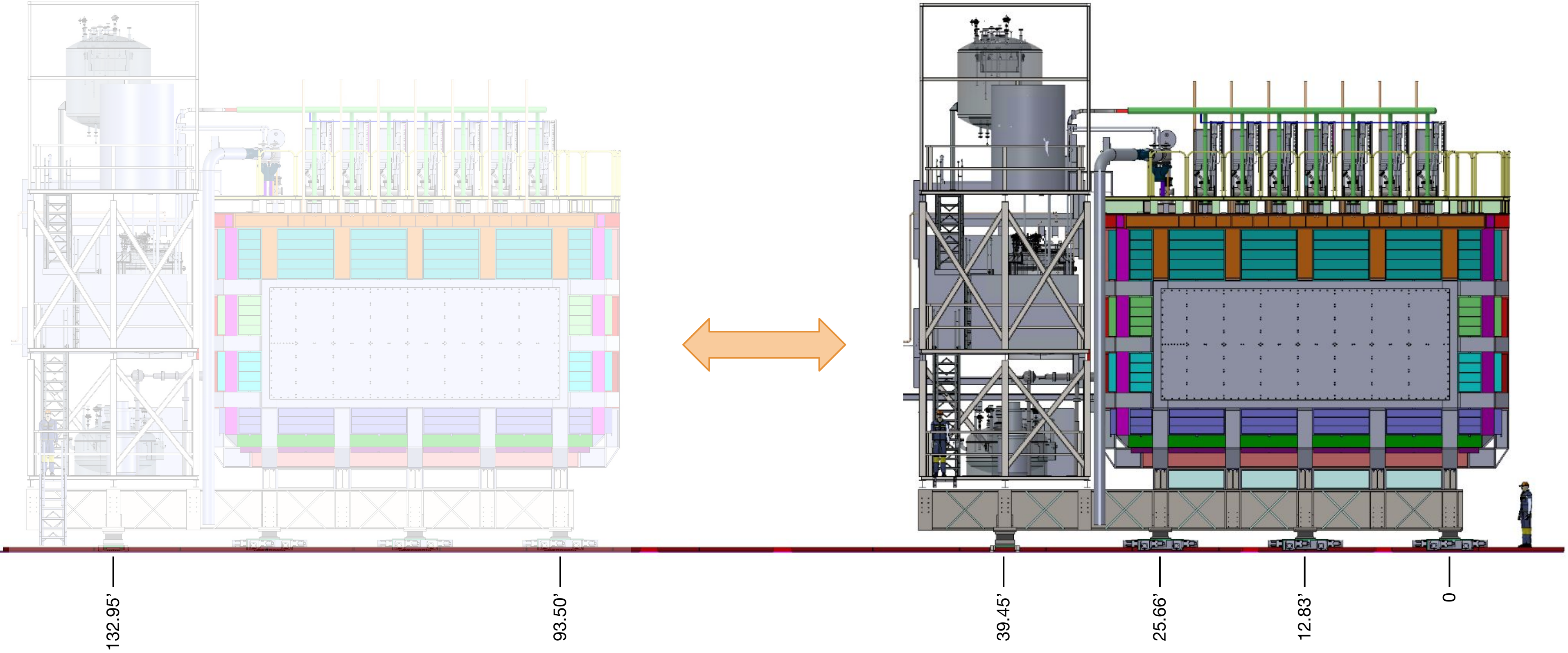
FEA with stiff frame

- Representative weight distribution and operational loads
- Representative warm structure and cryo mezzanine
- PRISM frame with accurate geometry but 100x steel modulus

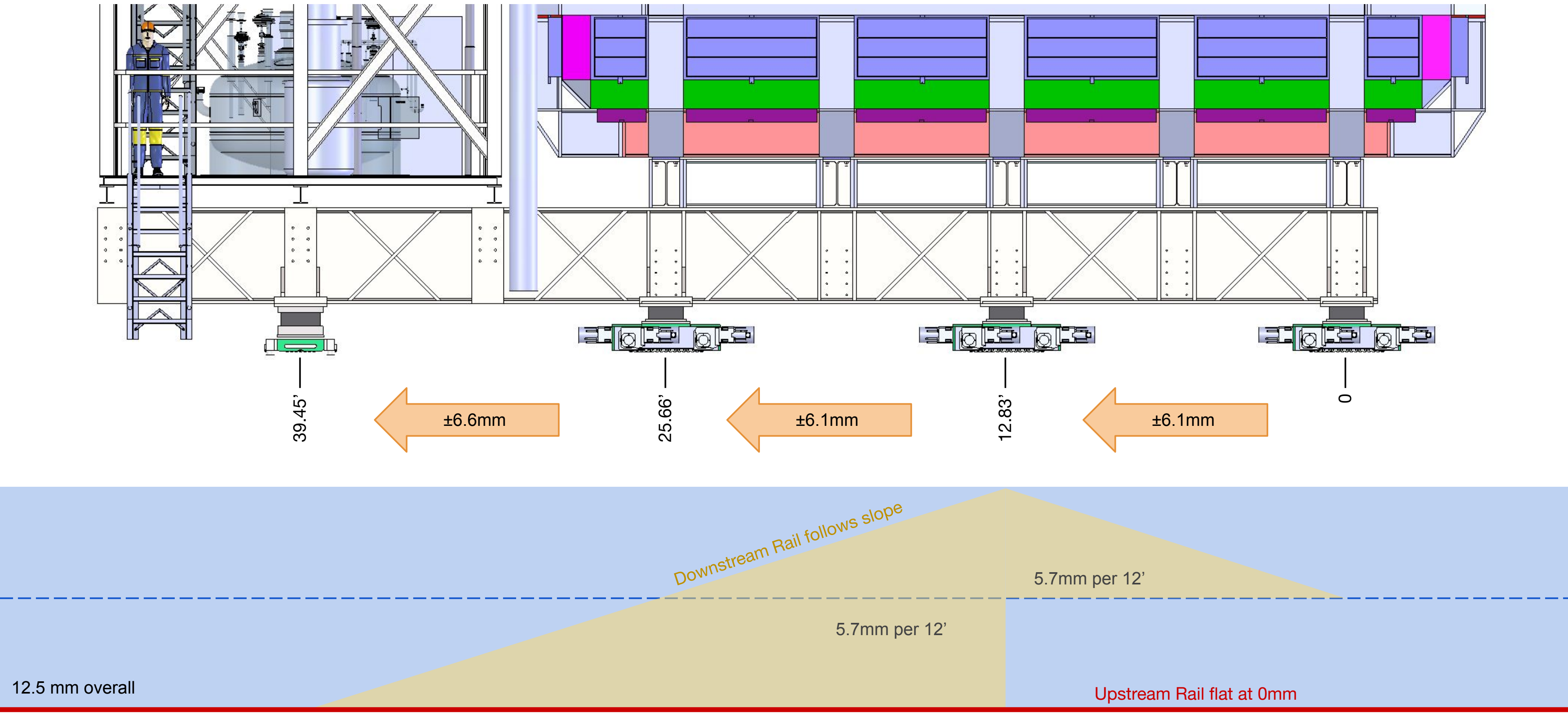
FEA with steel frame

- Representative weight distribution and operational loads
- Representative warm structure and cryo mezzanine
- PRISM frame with accurate geometry and modulus

Full Range of Roller Positions

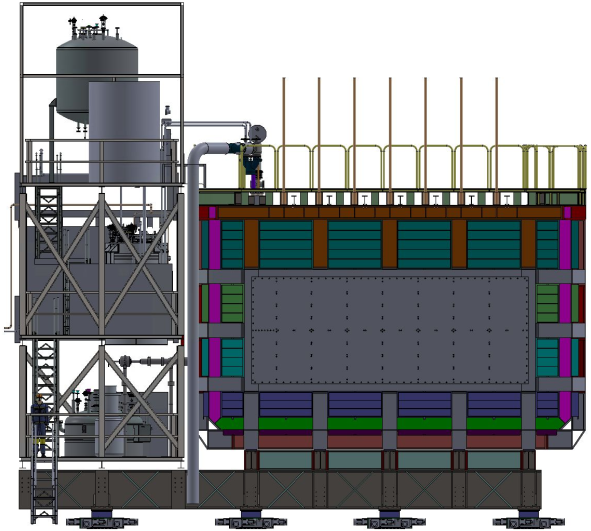


D2 12.5 mm above U2, downstream rollers slope down, upstream rollers flat



Roller Load Distribution from Analytical Model

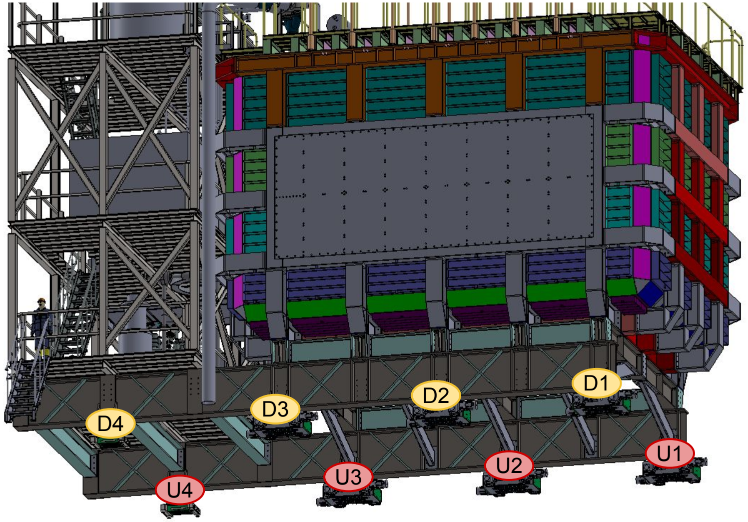
- Analytical model assumes rigid cryostat
  - See 8 roller tab here: Spring Pad EOMs
- Reaction forces in US tons
- Middle rollers (positions 2 and 3) lose traction under -12.5 mm displacement
  - But remaining powered rollers compensate
  - To overcome static friction, need min 205 tons across all powered rollers (see next slide)
    - 3 rollers at min 68 tons
    - 4 rollers at min 51 tons
    - 5 rollers at min 41 tons
    - 6 rollers at min 34 tons



Position	Delta	F_4	F_3	F_2	F_1
N/A	0	40	103	103	103
1	+12.5 mm	59	99	51	140
2	+12.5 mm	31	69	198	51
3	+12.5 mm	3	177	70	100
4	+12.5 mm	67	65	94	122
1	-12.5 mm	21	106	155	67
2	-12.5 mm	49	136	8	155
3	-12.5 mm	77	29	136	106
4	-12.5 mm	13	140	112	84

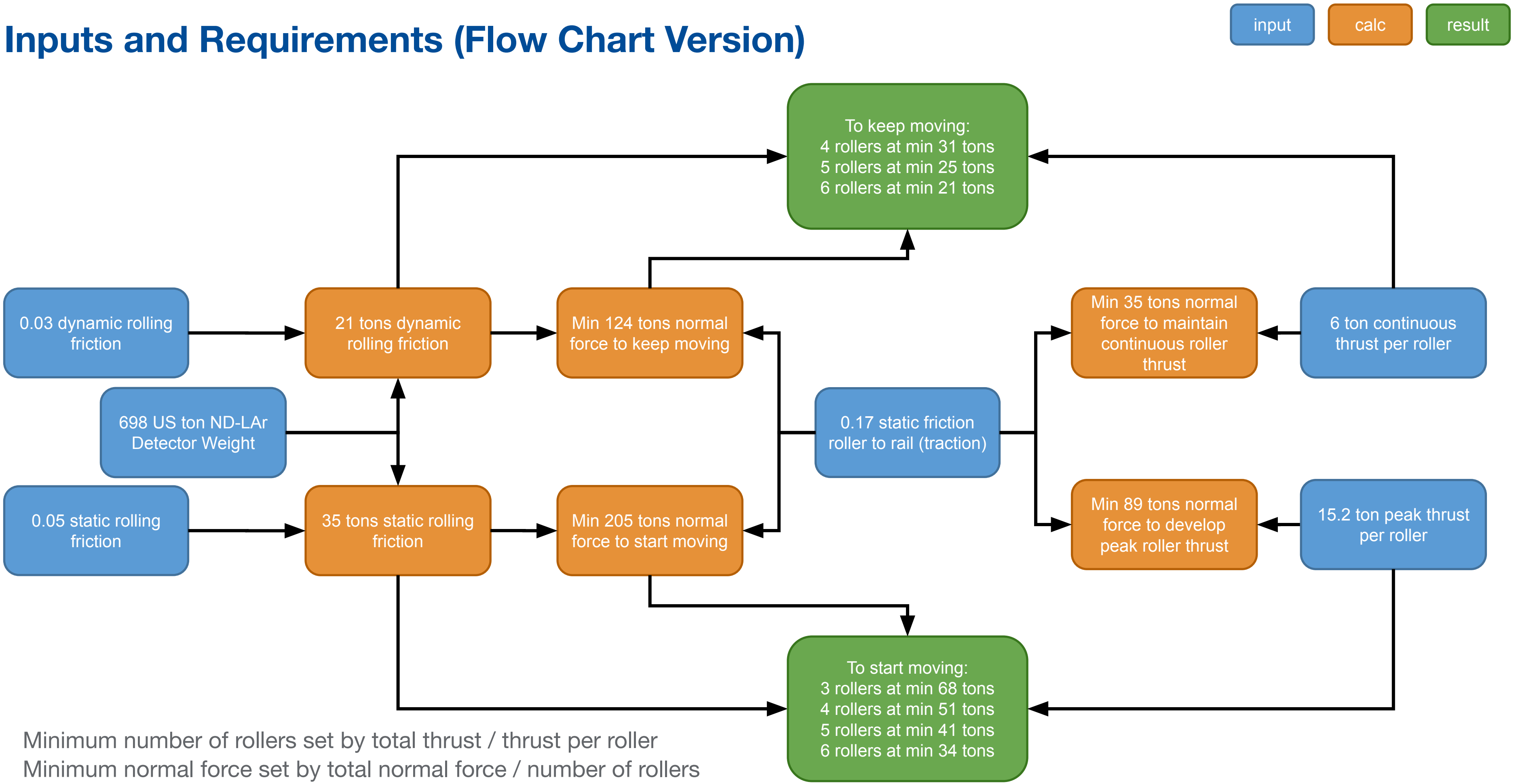
Summary of nominal vs worst case rail flatness

- Nominal case is balanced as intended
- Sloped case redistributes loads but stays within limits



		Roller Position			
		4	3	2	1
Nominal	Downstream	43.21	105.12	104.07	98.90
	Upstream	43.61	106.16	105.54	100.01
Slope	Downstream	12.01	84.16	185.99	69.13
	Upstream	74.72	127.11	23.93	129.57

Inputs and Requirements (Flow Chart Version)

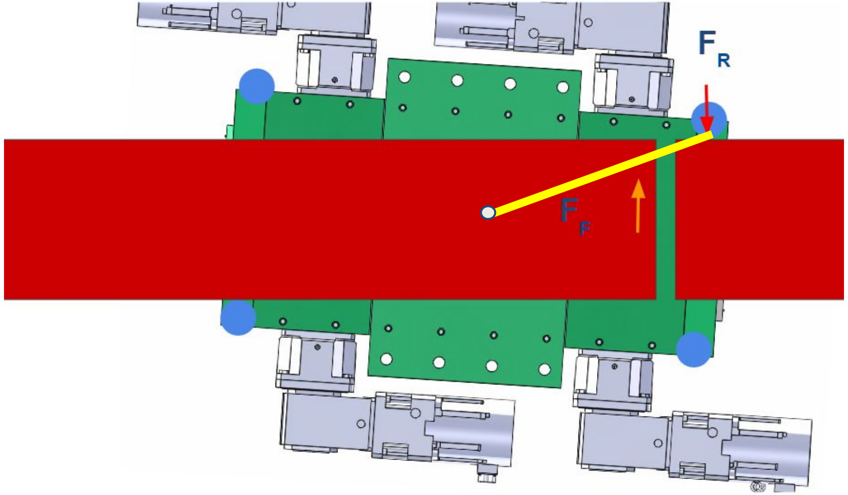


- Minimum number of rollers set by total thrust / thrust per roller
- Minimum normal force set by total normal force / number of rollers

Too high of friction can overload Cam followers

- There are 4 cam followers to keep the Hilman roller on the rail.
- Slight misalignment will happen and will result in roller slowly drifting off axis.

- Each cam follower is rated at 18 Tons
- 2 Cams = 36 Tons
- We have experiments setup to test these numbers.



SMITH Bearing® Number SEALED	D Roller O.D. +.000 -.001	C Roller Width +.000 -.005	d Stud Dia. +.001 -.000	B1 Stud Length	G1 Eff. Thread Min.	G Thread U.N.F. Class 2A	HEX Size	Bearing Dynamic Capacity (lbs)	Bearing Static Capacity (lbs)	Max. Allow Load (lbs)	Track Capacity at 40RC (lbs)
DCR-3	3.000	1.750	1.250	2.500	1.250	1 1/4-12	5/8	29,700	40,200	14,700	13,100
DCR-3 1/4	3.250	1.750	1.250	2.500	1.250	1 1/4-12	5/8	29,700	40,200	17,500	14,100
DCR-3 1/2	3.500	2.000	1.375	2.750	1.375	1 3/8-12	5/8	37,000	49,500	21,000	17,000
DCR-4	4.000	2.250	1.500	3.500	1.500	1 1/2-12	3/4	46,700	58.800	23,400	21,600
DCR-5	5.000	2.750	2.000	5.062	1.563	2-12	1	72,400	98,400	43,300	34,420

Motor and gearbox Calculation

- Yaskawa SGM 7G-09 Servo

Each Roller

- F roller continuous = 5.4 Tons
- F roller peak = 13.8 Tons

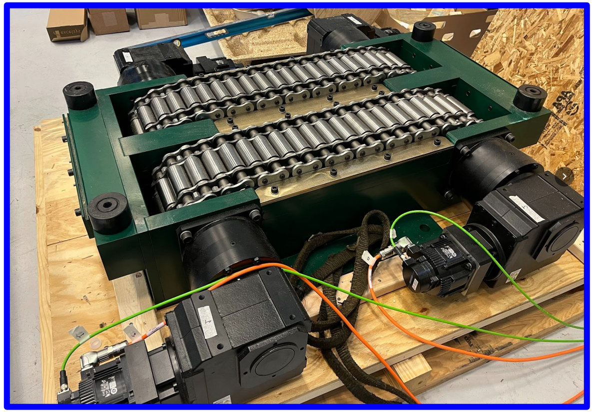
6 Rollers capable of

- $F_{\text{6-roller continuous}}$ = 32.4 Tons
- $F_{\text{6-roller peak}}$ = 82.8 Tons

-vs-

Rolling resistance=

800 Tons x .03 = 24 Tons



SGM7G - 03 A 7 D 6 1

1st+2nd digits | 3rd digit | 4th digit | 5th digit | 6th digit | 7th digit

Σ-7 Series Servo Motors: SGM7G

1st+2nd digits Rated Output

Code	Specification
03	300 W
05	450 W
09	850 W
13	1.3 kW
20	1.8 kW
30	2.9 kW *1
44	4.4 kW
55	5.5 kW
75	7.5 kW
1A	11 kW
1E	15 kW

3rd digit Power Supply Voltage

Code	Specification
A	Three-phase 200 VAC
D	Three-phase 400 VAC

4th digit Serial Encoder

Code	Specification
6	24-bit batteryless absolute
7	24-bit absolute
F	24-bit incremental

5th digit Design Revision Order

Code	Specification
	Global Design Revision for

Servo Motor Specifications: Yaskawa SGM 7G-09D6FK1

$P_{mot} := 0.85\ kW$

$T_{mot} := 5.39\ N \cdot m$

$T_{max} := 13.8\ N \cdot m$

$\omega_{rated} := 1500\ rpm$

$\omega_{max} := 3000\ rpm$

$n_{servos} := 4$

Force Calculations

$v_{NDLAr} := \frac{28\ m}{4\ hr} = 0.117\ \frac{m}{min}$ $\quad v_{NDLAr} = 4.593\ \frac{in}{min}$

$\omega_{sprocket} := v_{NDLAr} \cdot \frac{1}{2\ \pi \cdot r_{sprocket}} = 0.094\ \frac{1}{min}$

$ratio_{gearbox} := \frac{1}{485}$

$\omega_{servo\_calc} := \frac{\omega_{sprocket}}{ratio_{gearbox}} = 45.689\ \frac{1}{min}$

$T_{max\_theoretical} := T_{max} \cdot \left(\frac{1}{ratio_{gearbox}} \right) \cdot n_{servos} = 26.772\ kN \cdot m$

$F_{roller\_max} := \frac{T_{max\_theoretical}}{r_{sprocket}} = 135.827\ kN$

$T_{continuous} := T_{mot} \cdot \left(\frac{1}{ratio_{gearbox}} \right) \cdot n_{servos} = 10.457\ kN \cdot m$

$F_{roller\_cont} := \frac{T_{continuous}}{r_{sprocket}} = 53.051\ kN$

Motor and gearbox Calculation

STOBER P9K Gearbox

Ratio: 1:485

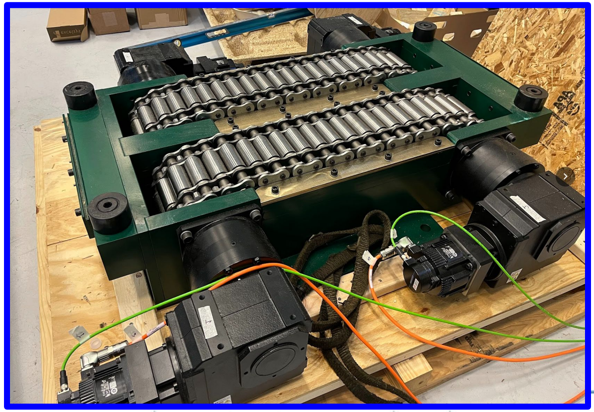
Peak = 5349 Nm

-vs-

Torque from Motor X Ratio

$T_{continuous}$ = 2614 Nm

T_{Peak} = 6693 Nm



Reducer Ratio (i)		Output Torque: Nom. [1] M_{2N}	Accel. M_{2acc}	Accel. Torque for Reduced Backlash M_{2accHT}	Peak [2] M_{2NOT}	Back-lash/ Red $\Delta\phi_2$	Part Number* (Gearhead + Input)	Max. Input Speed RPM (n1): Continuous EL 1,2	Continuous EL 3,4,5,6	Cyclic All	Motor Shaft [3] Max Ø d_{MW}	Input Inertia J_1	Tors. Stiffness C_2
Nom.	Exact	Nm	Nm	Nm	Nm	arcmin					mm	kgcm²	Nm/ arcmin
353.0	38,829/110	1830	2196	-	3890	3.5	P931_0070K402_0500 ME20	3600	3300	5500	≤24	2.7	305
389.9	17157/44	2100	3105	-	6113	3.5	P931_0070K402_0560 ME20	3600	3300	5500	≤24	2.7	305
485.4	38,829/80	2100	3020	-	5349	3.5	P931_0070K402_0690 ME20	3600	3300	5500	≤24	2.7	305

[1] *Based on input speed of 1500 RPM. See page 186 for details on torque calculations.*
[2] *Maximum momentary torque for emergency stops or heavy shock load. (Admissible stops per life of gearhead = 1,000 stops maximum.)*
* *MF = Motor adapter with FlexiAdapt® coupling*

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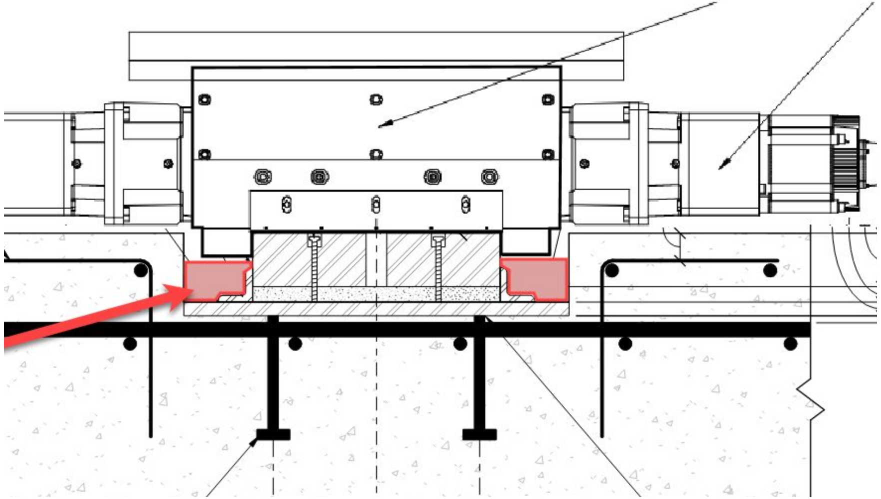
Rail Anchoring

- The NSCF guaranteed side load = 34 Tons
- COF = 34/200T = 0.17

- Rail anchoring system:
- Rails are supported by the epoxy grout, leveling screws and are welded to the subplate.
- The subplate assembly has numerous nelson studs welded to the bottom
- Subplate is embedded into the poured in floor.



Lateral Compliance

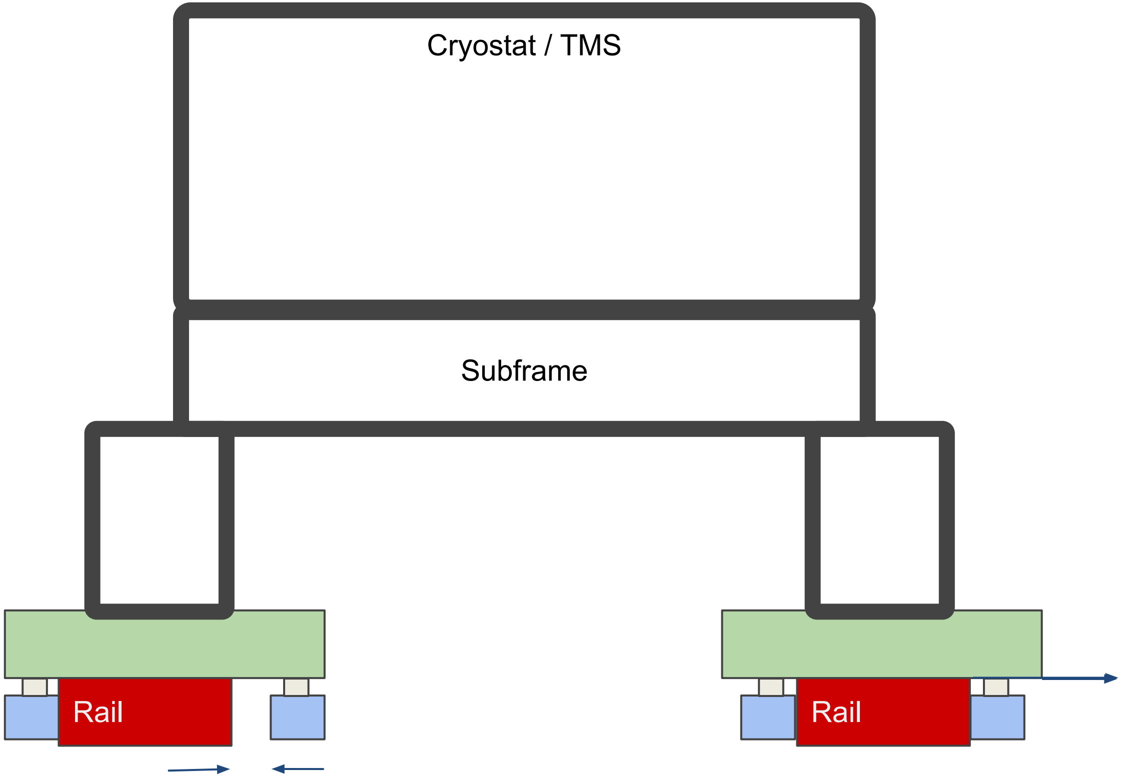
1. Make space between cam followers > than rail tolerance +-⅛”

Options considered

2. Glide plate - back up slide
3. Single side cam follower - back up slide

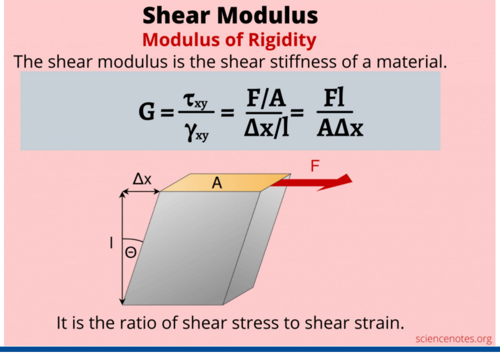
(ii) Steering - PRISM-TMS-Cryostat Integration

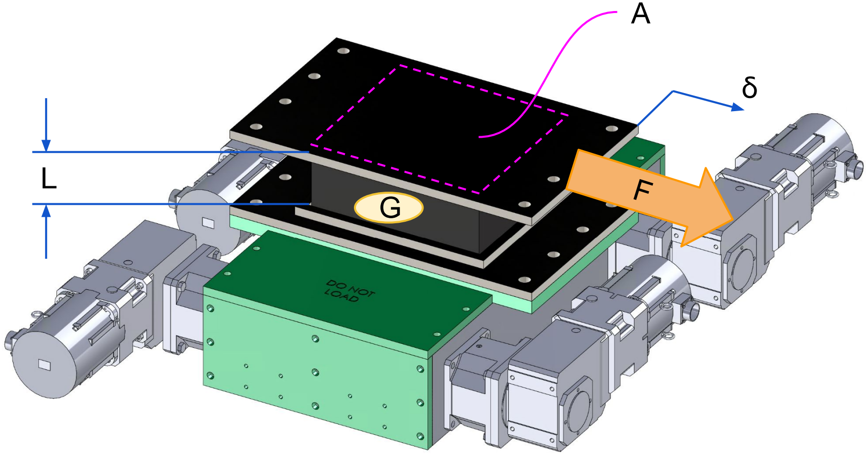
Lateral Compliance



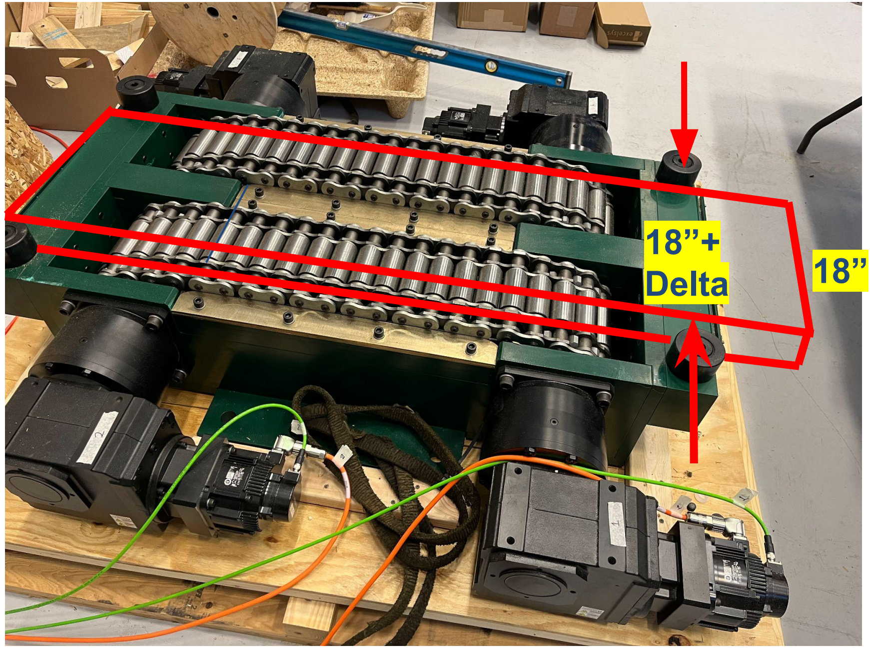
Pad shear modeled as linear spring using classical shear modulus formula

- $\delta = FL / GA = F (L/GA) = F / k_s$
  - $k_s = GA / L$
  - $F = k_s\delta$, see Hooke's law F=kx
- $G = E / (2(1+\nu)) = 32.8$ MPa
  - E = 98.5 MPa
  - Assume $\nu = 0.5$ for rubber
- Resulting k_s= 3.7 US tons/mm for pad under LAr tank
  - A = 16 x 20 in = 320 in^2 = 0.206 m^2
  - L = 8 in = 203.2 mm
  - $k_s = 3.33e^7$ N/m = **3.7 US tons/mm**

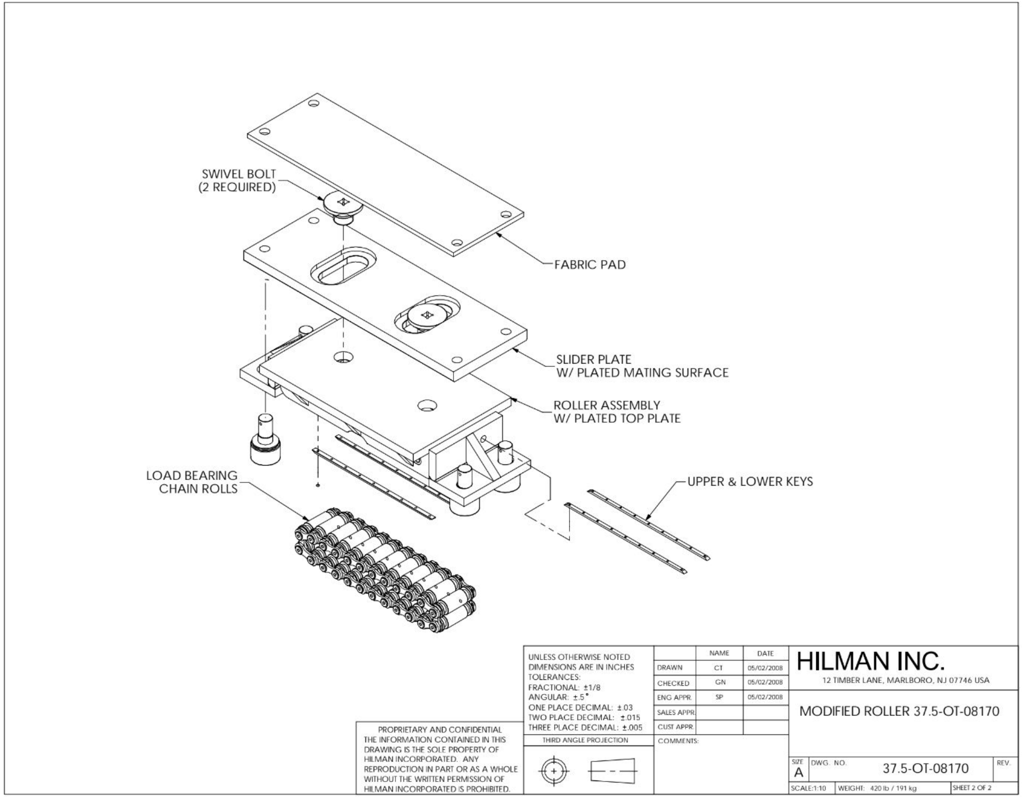




Make space for delta between cam followers



Glide plate


SWIVEL BOLT
(2 REQUIRED)
FABRIC PAD
SLIDER PLATE
W/ PLATED MATING SURFACE
ROLLER ASSEMBLY
W/ PLATED TOP PLATE
UPPER & LOWER KEYS
LOAD BEARING
CHAIN ROLLS
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UNLESS OTHERWISE NOTED
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL: ±1/8
ANGULAR: ±.5°
ONE PLACE DECIMAL: ±.03
TWO PLACE DECIMAL: ±.015
THREE PLACE DECIMAL: ±.005
THIRD ANGLE PROJECTION
NAME
DATE
DRAWN CT 05/02/2008
CHECKED GN 05/02/2008
ENG APPR. SP 05/02/2008
SALES APPR.
CUST APPR.
COMMENTS:
HILMAN INC.
12 TIMBER LANE, MARLBORO, NJ 07746 USA
MODIFIED ROLLER 37.5-OT-08170
SIZE A
DWG. NO. 37.5-OT-08170
REV.
SCALE:1:10
WEIGHT: 420 lb / 191 kg
SHEET 2 OF 2

Cam followers on one side only