Referencing and Stability Studies of the Fermilab 3.9 Ghz (3rd harmonic) Cryomodule for DESY TTF/Flash

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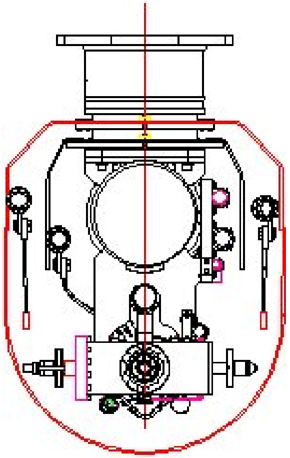
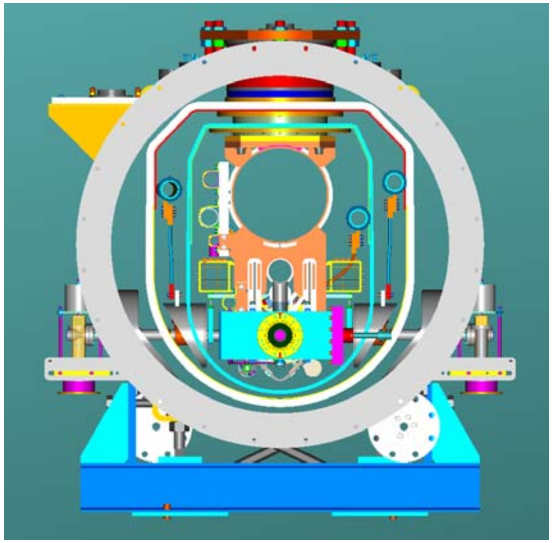
Introduction

- Part of TESLA Technology Collaboration activities and Fermilab/DESY technology transfer agreement between the laboratories
- Scope: Provide a 3.9 GHz cryomodule to DESY Laboratory, Germany for the Tesla Test Facility (TTF)/FLASH
- Two configurations of 3.9 GHz cryomodule shipment to DESY considered:
  - as *individual components*
  - as a *fully assembled* module
- Advantage of fully assembled cryomodule (from assembly perspective)
- Requirements:
  - module must arrive without damage
  - must maintain pre-transport alignment

3.9 GHz Cryomodule

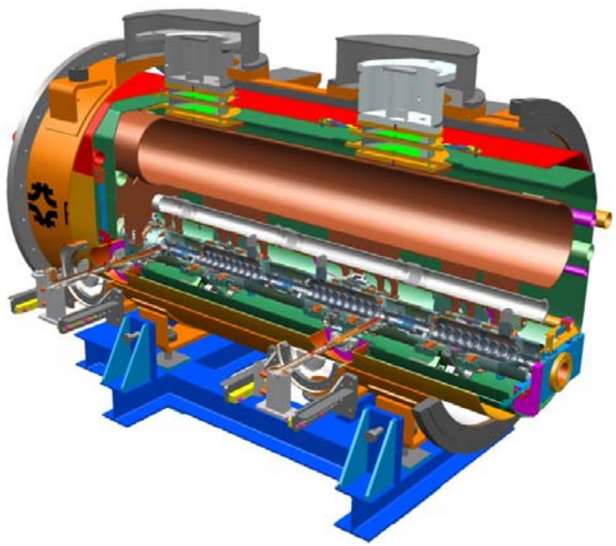
- Four dressed 9-cell niobium superconducting RF cavities.
- A stainless steel 300 mm diameter Helium Gas Return Pipe (HeGRP) supports cavities - acting as a spine
- Each cavity directly attached via four vertical plates to GRP:
  - plates are welded to the GRP,
  - c-shaped housings with spring loading firmly capture the cavity support lugs (ensure vertical and lateral rigidity).
- Two posts support the entire cold mass structure inside the vessel:
  - rest on mount flanges located axially atop 1 m diameter vacuum vessel
- Two aluminum heat shields hang from the same two column supports.





Transport Testing Strategy

- Given:
  - Shipment method: transatlantic travel by aircraft and truck transport
  - Relative alignment requirements of cavities:
    - within the cavity string
    - with respect to the vacuum vessel.
  - Preliminary shock limit criteria :
    - Vertical - 4g
    - Transverse - 5g
    - Longitudinal - 1.5g



- Studies focused on
  - shock load
  - vibration (in terms of displacement and frequency)
- Two types of testing implemented;
  - subjecting base frame to peak shock by using a pendulum hammer apparatus
  - accumulative effects via over-the-road loading.

Cold mass and Cryomodule Mockup

- Developed a cold mass mockup:
  - Essential - testing actual components was not possible.
  - A combination of plastic and stainless steel used to simulate the cold mass
- Cold mass inserted into a vacuum vessel
- During transport -> support columns are locked against the vacuum vessel flanges

Transport Assembly Design

- System is relatively stiff
- Isolation designed to reduce shock by a factor of 2.
- Distance from center of gravity (CG) to the centerline of the isolators optimized to reduce cryomodule motion

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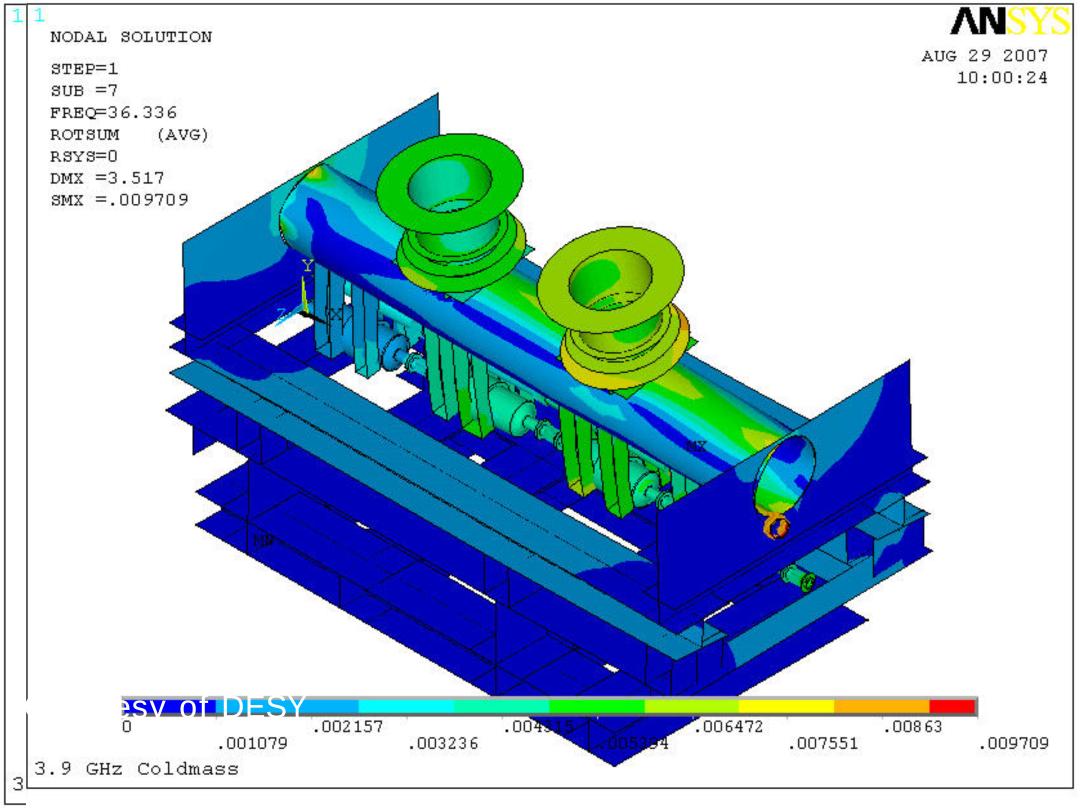
3.9 GHz Coldmass Mockup Analysis

- FEA Modal study initially defined instrumentation locations on coldmass



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Cryomodule On Site Road Test

- Transport test completed on Fermilab site
- Help to confirm FEA and refined model
- Coldmass Mockup transport
  - Dry run results (excitation frequencies)
  - Ringing of coldmass mockup (resonant frequencies)

Cryomodule Mockup On Site Road Test

- Assembled cryomodule mockup transport:
  - Evaluate maximum shock , acceleration in x, y & z
  - Evaluate maximum displacement

- Extra measures were taken to ensure that the support system is secure during transport mockup assembly

Cold mass Mockup Modal Results

Mode	Direction	FEA (Hz)	Ringing (Hz)	Dry Run (Hz)	Comment(s)
	x & y			5	
	z		7		
	x & y			9	
	x, y & z			10.8	
1	z	**14.3**	**14**		Movement at support brackets
	x, y & z			16	
2	y	16.8			Frame movement
3	z	**22.4**	**24**		Movement at support brackets
4	y	22.9			Coldmass movement
	z			27	
5	z	**30.7**	**31**		Frame movement

Cold mass Mockup Modal Results

Mode	Direction	FEA (Hz)	Ringing (Hz)	Dry Run (Hz)	Comment(s)
6	y	**31.4**	**31**		HeGRP movement
7	x	**36.3**	**35**		Coldmass twist
	x, y & z			37	
8	y	37.9			Local GRP movement
	x, y & z			41	
9	z	**42.2**	**42**		Mid support bracket movement
	x, y & z			45	
10	x & y	51.5			Coldmass twist
	x, y & z			55	

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Instrumentation Configuration

- 18 Geophones
  - 3 geophones per cavity (x, y and z) evenly spaced in z (longitudinally)
  - 3 geophones on support isolation fixture (in x, y and z)
  - 3 geophones on base frame (in x, y and z)
- Addition:
  - 2 Shocklog devices (to correlate with geophones data)
  - 2 Accelerometers on bellows
  - Geophones on adjacent flanges
- A GPS unit - provide absolute acceleration and deceleration of the truck

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Transport Studies

- First phase: 3 over-the-road transport studies => one on site, two off-site on interstate
- Second phase: three peak shock studies by using a pendulum hammer apparatus
- Third phase: 1 over-the-road transport study to O’Hare Airport and back

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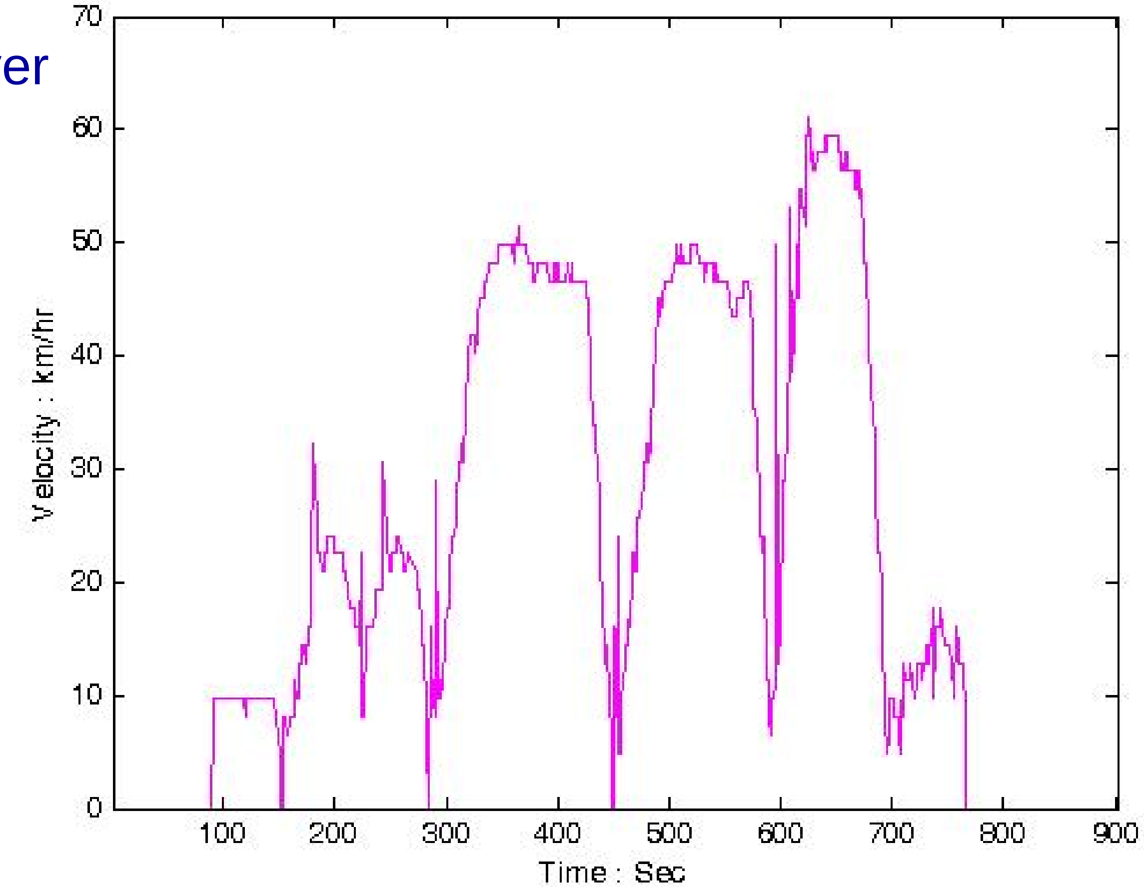
Transport Results

Preliminary

- Peak vertical shock:
  - 2 g on the base frame
  - 0.6 g on the isolation fixture and cavities.
- Peak transverse shock:
  - 2.5 g on the base frame.
  - 1.5 g on the fixture and cavities
- Highest peak shock - measured along the truck on the base frame > 3g
- Absolute longitudinal acceleration and deceleration measured - little correlation was found between these loads with the peak values reported.
- Maximum peak shock of 2 g were found only on the base frame.
- Transverse motion:
  - 1.6 mm on the isolation fixture
  - 1.4 mm longitudinal displacement

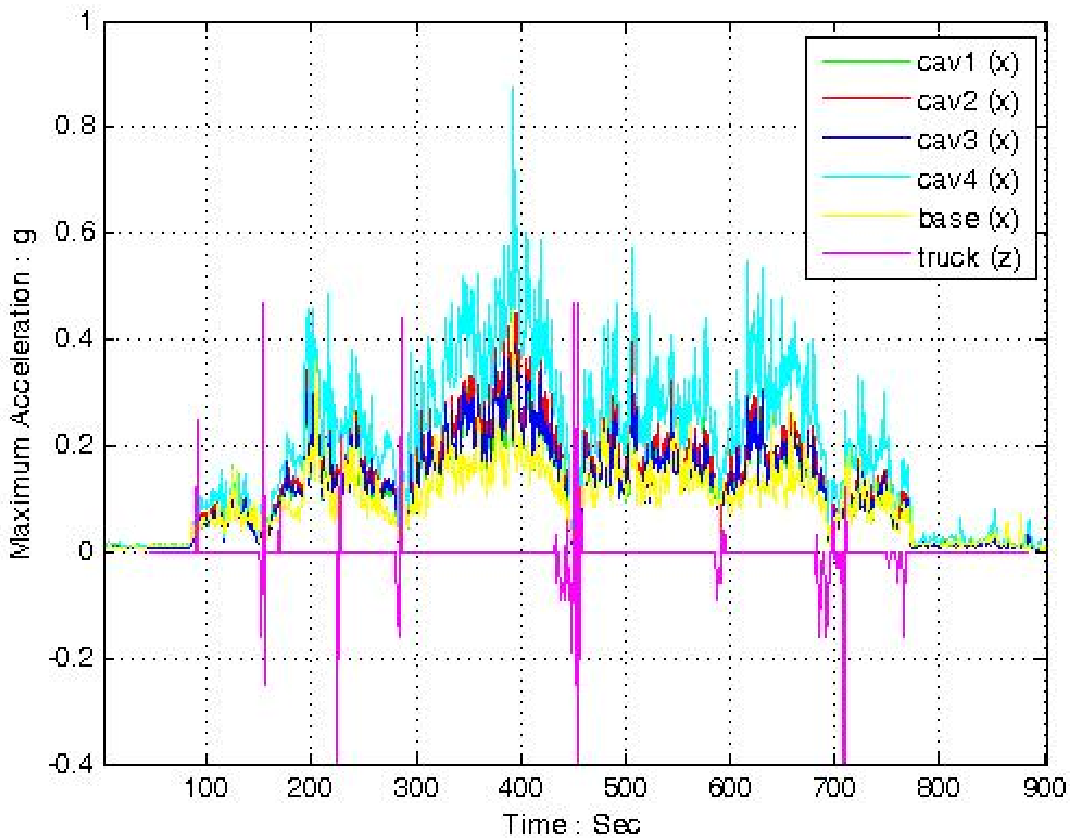
Road Test
Speed Results Example

- Low speed <61 Km/hr over Fermilab site
- GPS used to track speed



Road Test
Maximum accelerations Example

- Transverse shock values of cavities are highest ~ 1g



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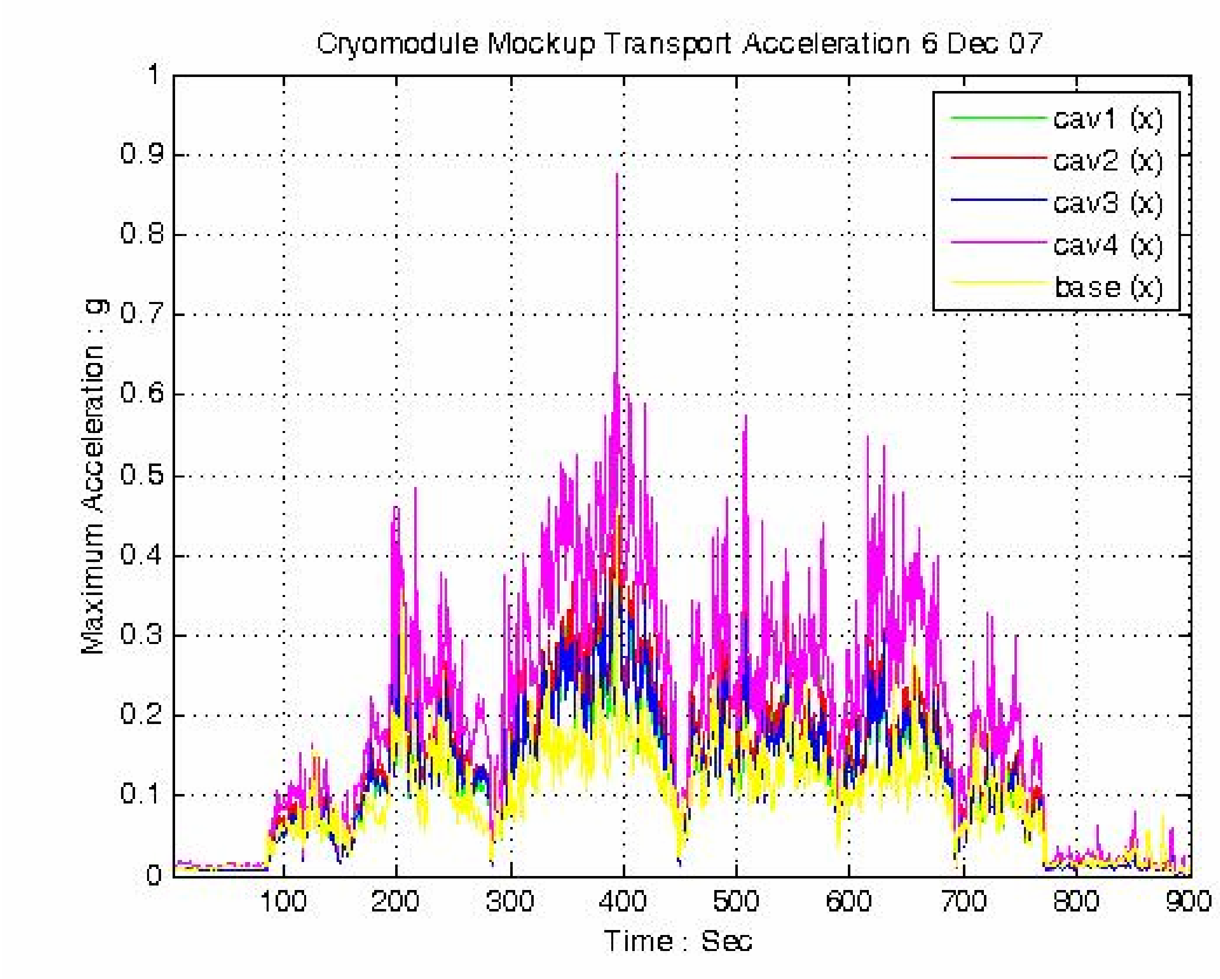
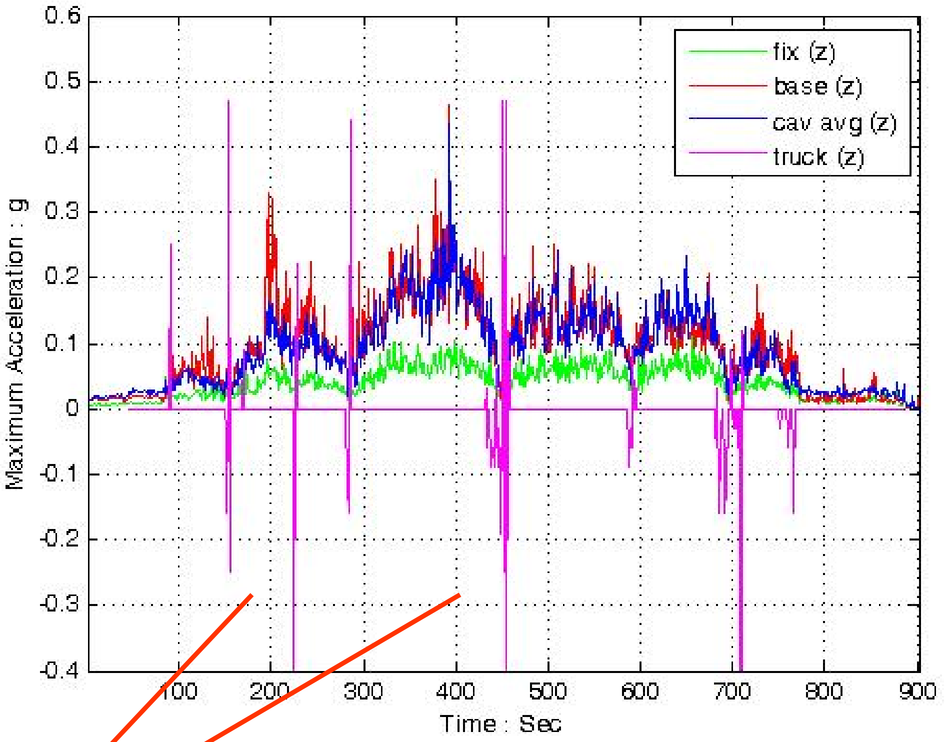
Road Test
Acceleration Results Example



Road Test
Maximum accelerations Example

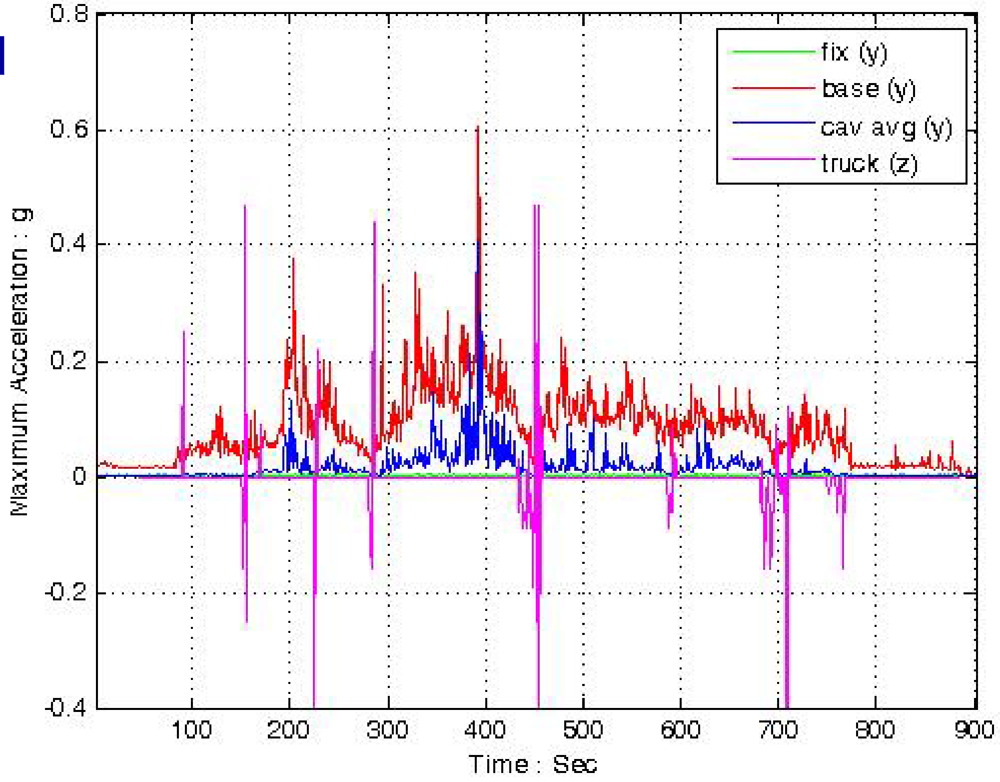
- Longitudinal shock values are mild
- No coupling with truck acceleration/deceleration



GPS data used to estimate acceleration/de-acceleration of truck

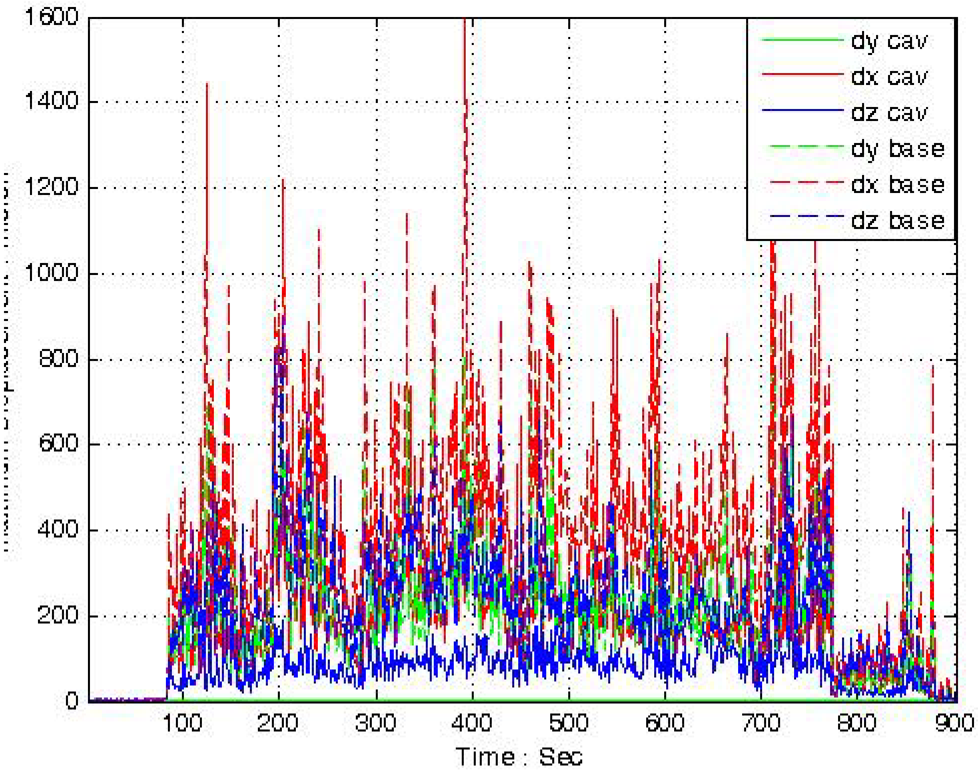
Road Test
Maximum accelerations Example

- Vertical shock values are also mild



Road Test
Maximum displacement of components Example

- Vertical peak base displacement of > 1.6 mm
- Transverse and longitudinal Cavity peak displacements of 1 mm



Summary Transport Studies

- During road tests: Maximum acceleration less than 1.5 g
- During both road tests, vibration was dominated by low frequency, speed-dependent vibrations from the truck drive train
- Cradle effectively damps high frequency vibrations from the bed
- Cavities vibrate more than the cradle
- Cavities vibrate coherently

- **Further work:**
- Implement a new cradle (isolation fixture and base frame) design with a lower center of gravity
- Continue transport studies, evaluate new cradle and confirm shock values are beneath the design criteria

Alignment Transport Studies

- Scope:
  - monitoring the deformation or displacement of the cryomodule components
  - assess if proper alignment within the cryostat vessel is maintained.
- Greatest concern:
  - cavities alignment within tolerances
  - long-term position stability of the cavities within the cryostat vessel

Alignment Transport Tolerances

- DESY has indicated the overall alignment tolerance requirement of the cold cryomodule for the TTF/FLASH accelerator to be **0.5 mm.**

- Error budget analysis included (among others):
  - referencing of cavities centerline,
  - thermal cycling (warm up cool down),
  - cavity string alignment and
  - referencing to the vessel,
  - string misalignments due to shipping

- Maximum tolerance for alignment and cavities shift during transport < 0.25 mm

Special Alignment Panels

- Special alignment panels (two per each cavity) - used for relative optical measurement to an external reference.

- Two intersecting wires cross along the diagonal, one cross-hair per cavity.

- The alignment panels have a two-fold function;
  - assist in initial assessment of transport stability studies and
  - provide an efficient means for post-transport survey.

- Cryomodule must hold a relative cavity alignment of 0.1 mm in vertical and transverse (to beam) direction.

Special Alignment Panels

Cryomodule Referencing

- High-accuracy Laser Tracker reference control network established in the Industrial Central Building
  - processed as 3-D trilateration (+ precision leveling)
  - relative errors < ±0.1 mm at 95% confidence level
- Cavity supporting structure, must remain in position < 0.1 mm
- More referencing points were installed on the cold mass and the vacuum vessel

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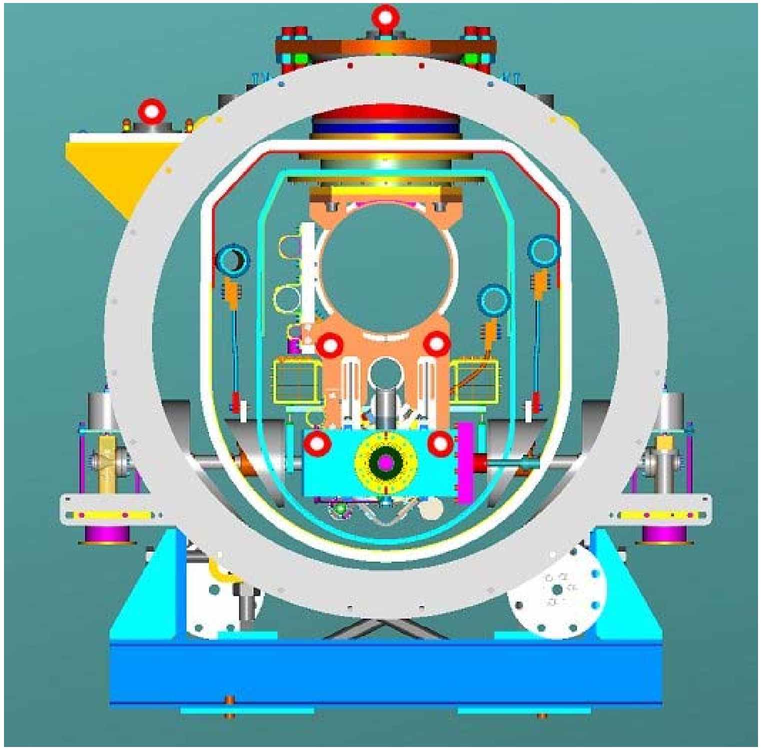
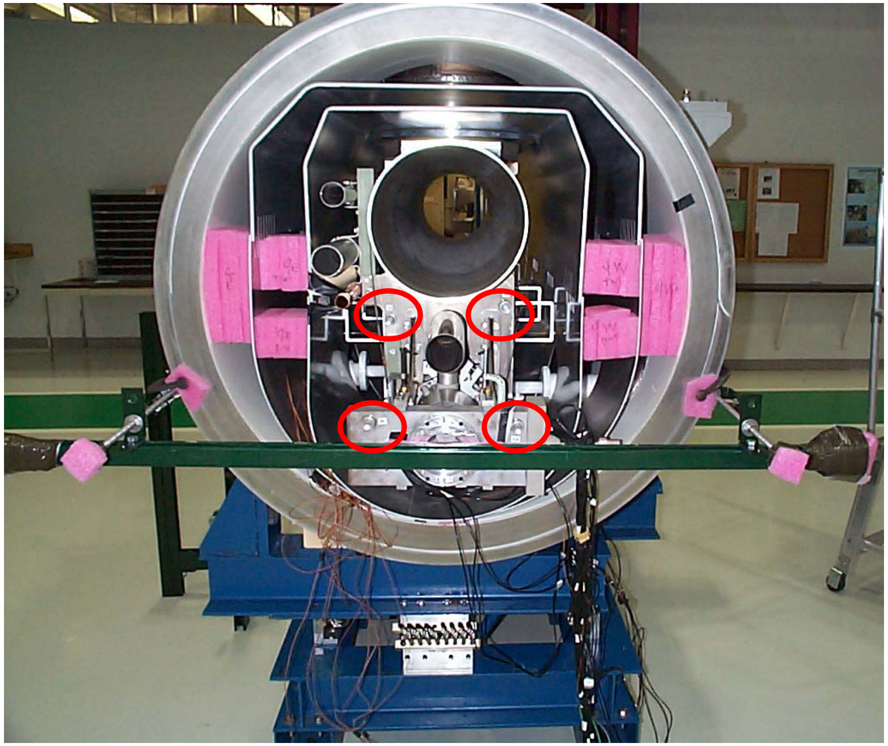
Cryomodule Referencing





Alignment Studies Procedure

- Survey before and after each the transport study
- Instrumentation:
  - API Laser Trackers
  - precision optical levels
  - precision optical alignment telescopes (dual setup)
- Measured:
  - Reference points + alignment panels
  - centerlines of the vacuum vessel and of the GRP
  - planes of the support posts and the vessel's cold mass mount flanges
- Two-step process to integrate the Laser Tracker and optical measurements.
- Calculate coordinates in a invariant local system and their associated variance-covariance matrix for each survey epoch.

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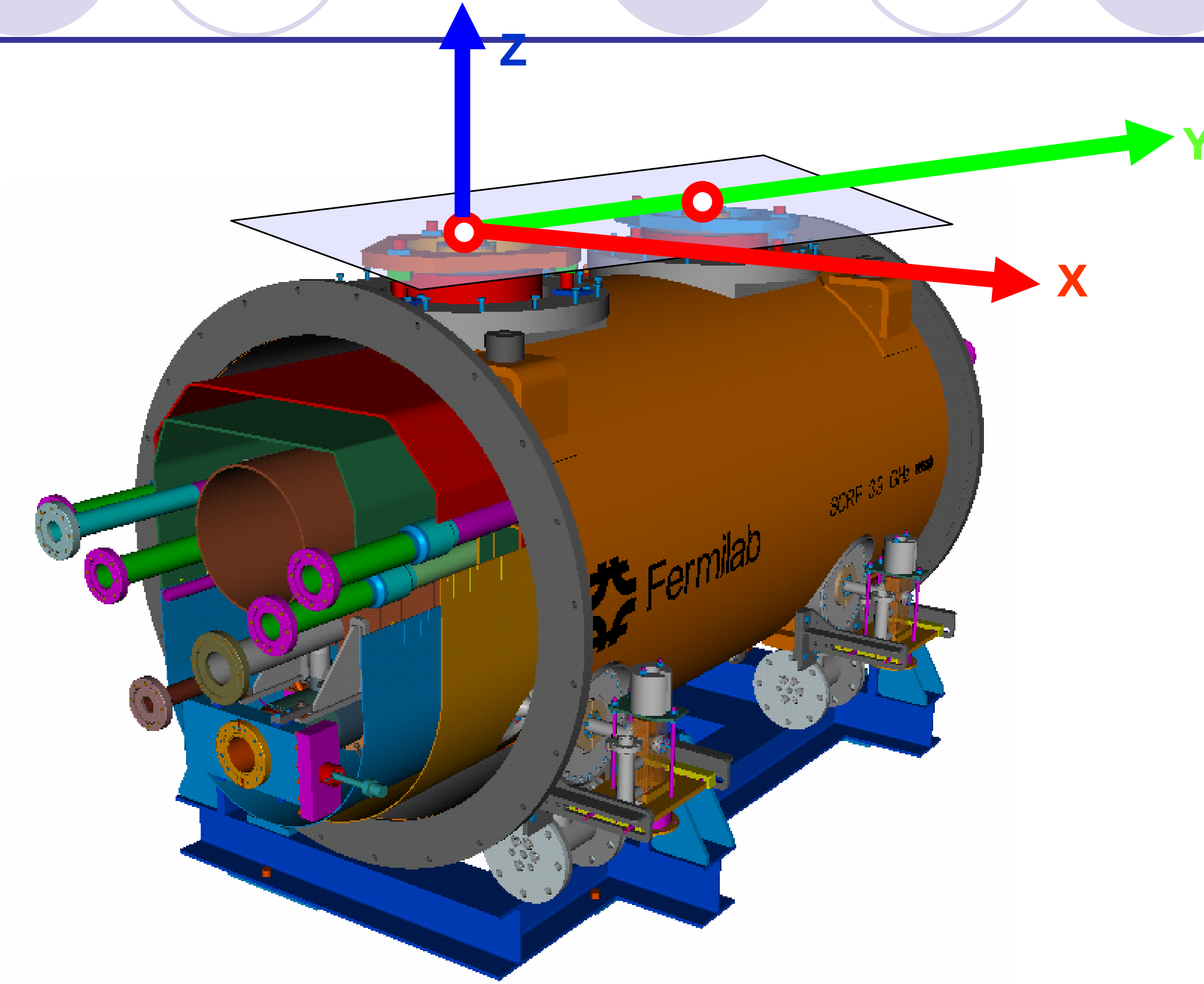
Alignment Dual Telescopes Setup

Local Coordinate System

remains invariable to deformation



Preliminary Analysis

- Analysis performed after each transport test
  - physical misalignments (their amplitude + associated errors)
- Two preliminary deformation studies were analyzed:
  - relative displacements with respect to a local fix coordinate system that remains invariable to deformation,
  - displacements between subsequent tests.
- A threshold based on the rms alignment sensitivities corresponding to 0.150 mm error bar was used to flag misalignments.
- Dynamic response - providing immediate feedback helped correlate the various measurements collected during the tests with the alignment results.

First Study Results

Preliminary

- Lateral movements of the cold mass =>pendulum effect
  - rotation center located at supporting posts sit on the vessel mount flanges.
- All the deformation vectors are within the admissible tolerance
- Cavities maintain relative alignment within the cavity string.

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First Study Results
Preliminary

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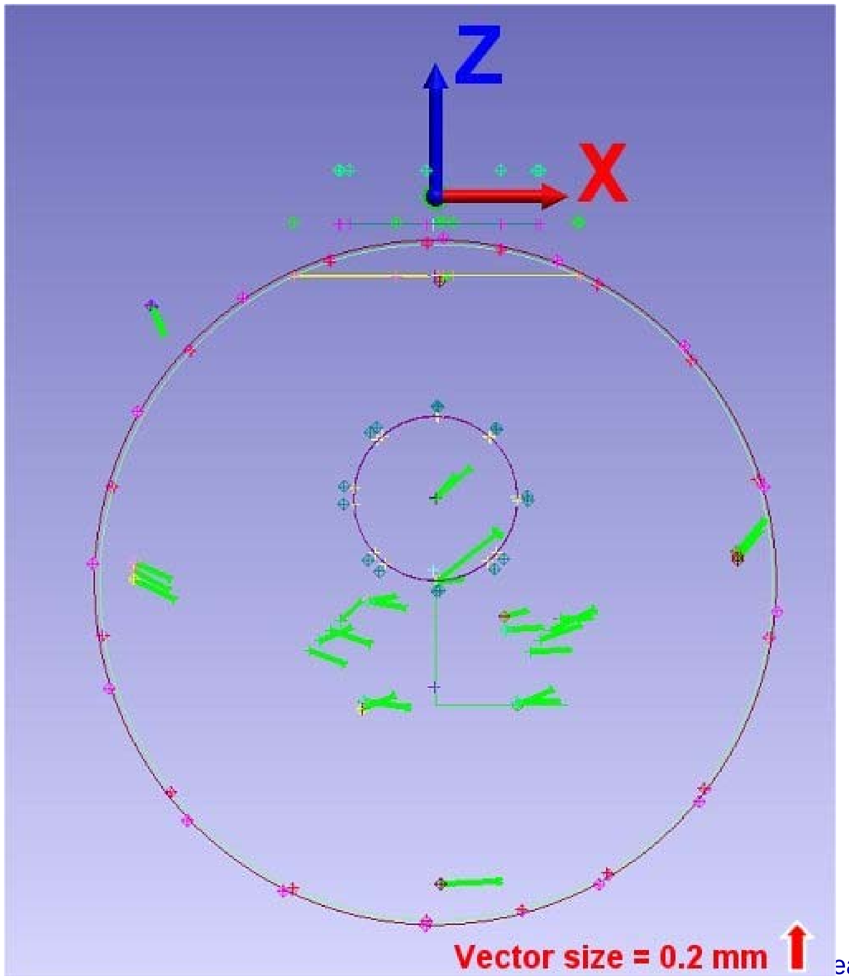
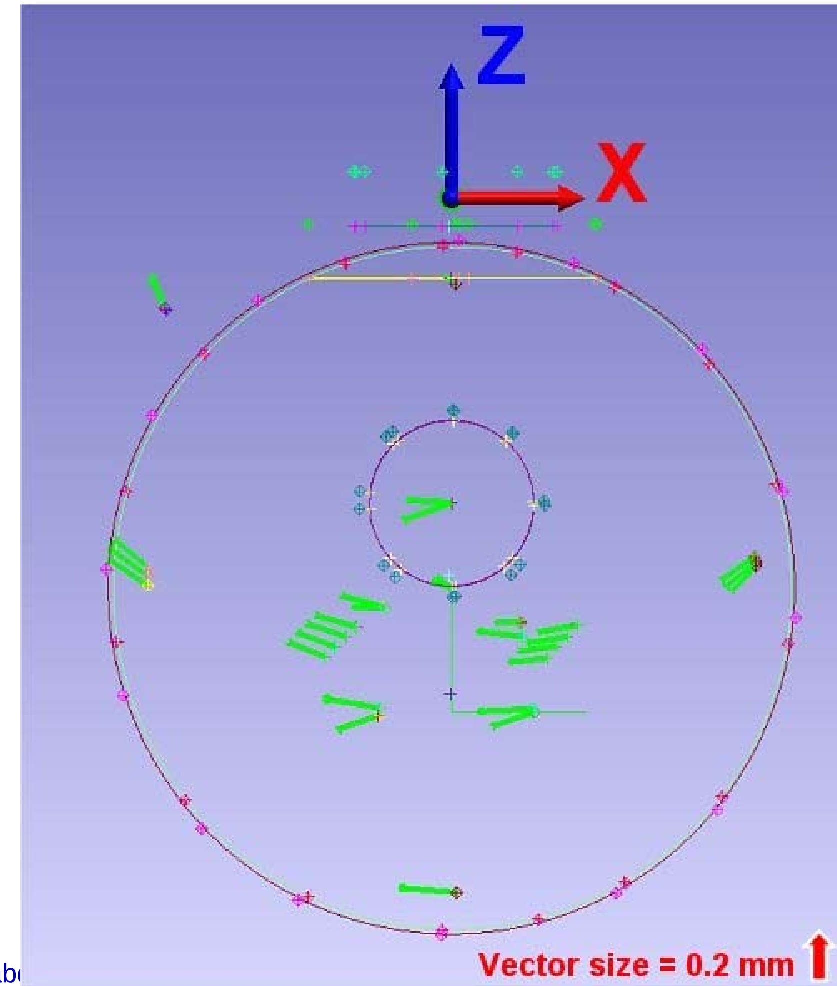
Post peak shock test 1



Post peak shock test 2



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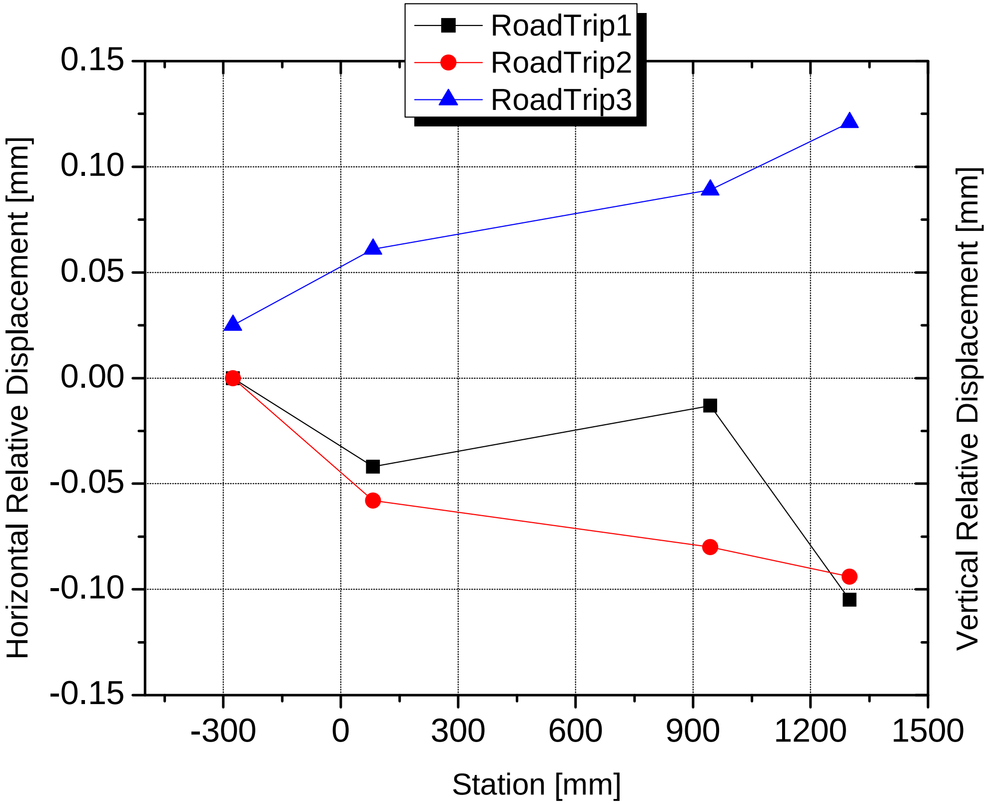
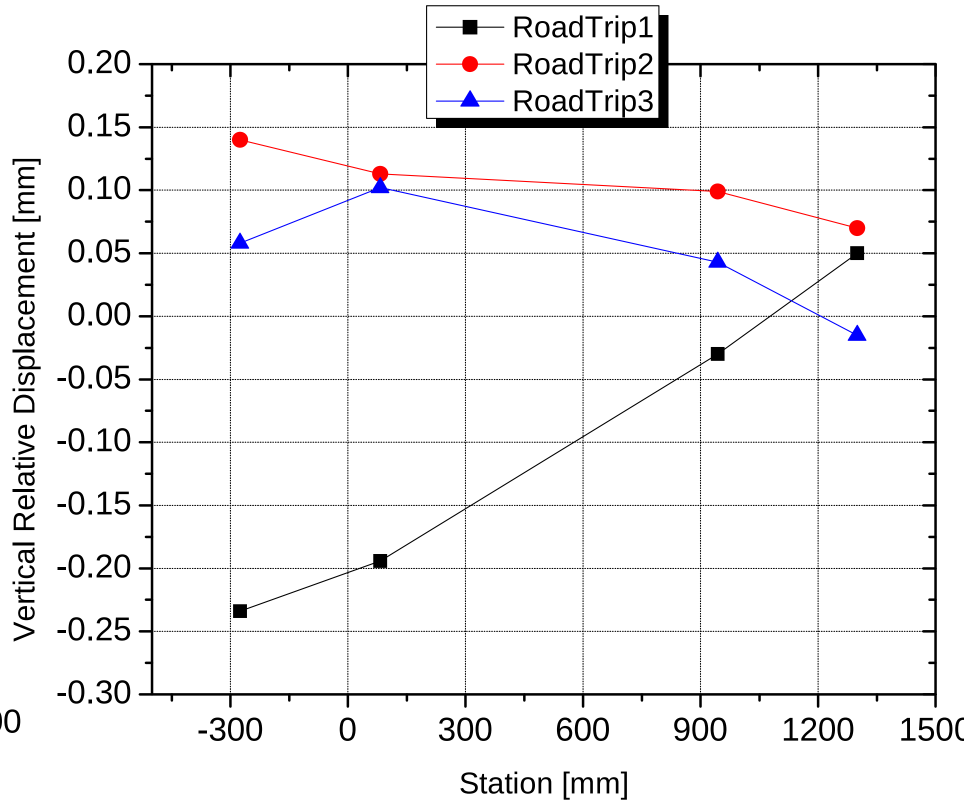
Second study results

Preliminary

- Cavities still maintain their relative alignment within 0.1 mm
- The overall maximum transversal shift of the cavity string among all the tests was
  - horizontal = 0.3 mm
  - vertical = 0.4 mm
- Re-referencing of vacuum vessel may be necessary at destination.
- The unsupported ends of the gate valves displaced 0.8 mm in one of the road trips

Second study results
Preliminary





Second study results

Preliminary

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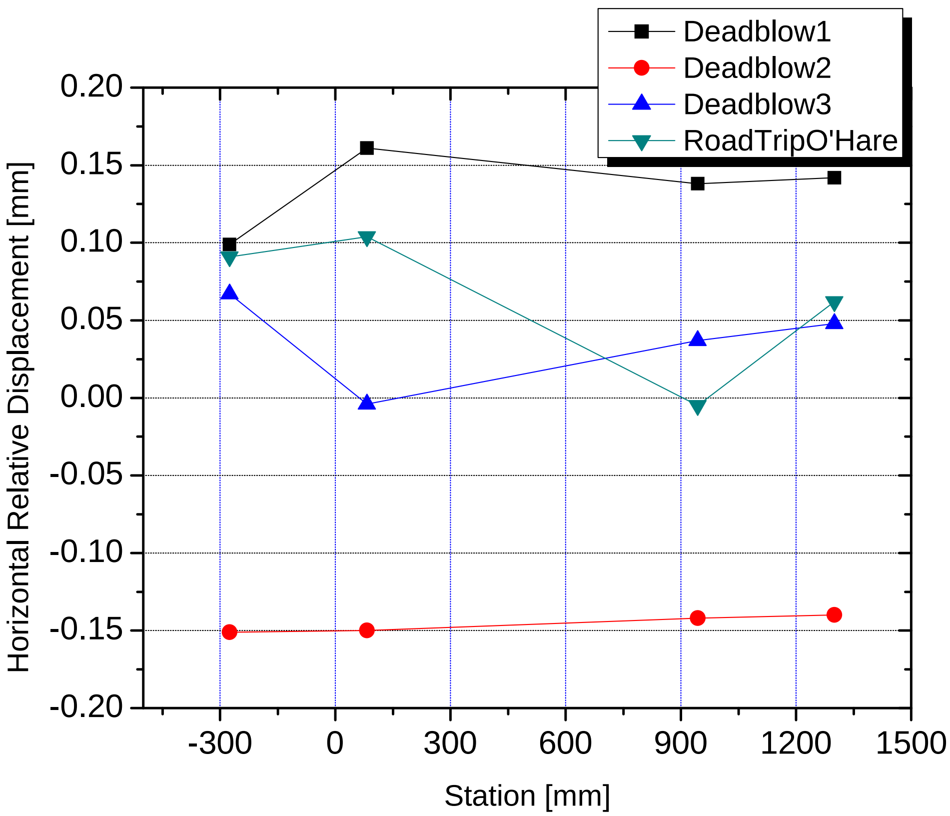

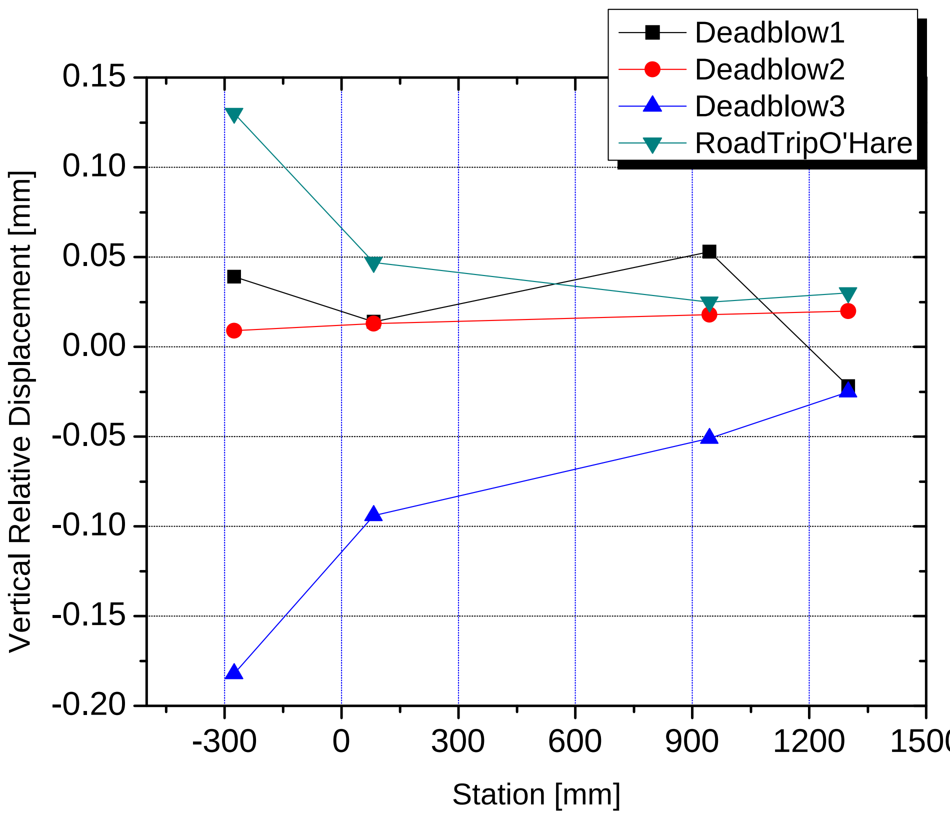

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Summary Alignment Studies

- cavities maintain their relative alignment of 0.1 mm within the cavity string
- alignment with respect to the vacuum vessel is only marginal to the allowable tolerance.
- **Further Work**: perform *Stable Point Analyses* for all the transport tests:
  - a more refined and sensitive for identifying displacement vectors,
  - employs the Iterative Weighted Similarity Transformation (IWST) method