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Mechanical Vibrations of the ATLAS ITk Structures Under Transportation Loads

G. Vallone, E. Anderssen, D. Boettcher, T. Claybaugh (presenter), M. Janda, K. L. Veale

Forum on Tracker Detector Mechanics 2023

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Outline

- Introduction
- Transportation Loads
- FE Modeling
- Measurements
- Conclusion

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Introduction

- There are many **shipments** planned for the ITk global mechanics:
  - **Outer Cylinder** (OC) from Applied Composites – San Diego (ACSD) to LBNL, LBNL to CERN
  - **Strip Barrels** (Layer 3 and 2) from ACSD to LBNL, LBNL to CERN, CERN to Oxford, back to CERN
  - Strip Barrels (Layer 1 and 0) from LBNL to CERN, CERN to Oxford, back to CERN
- Loads of interest: **truck**, **plane**, and **handling**
- Correct evaluation of **loads** and **box design** crucial to protect our structures

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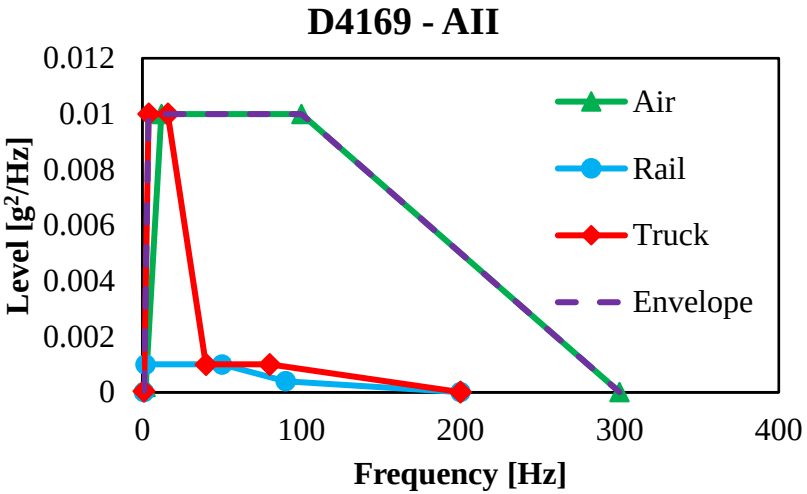
Transportation Loads



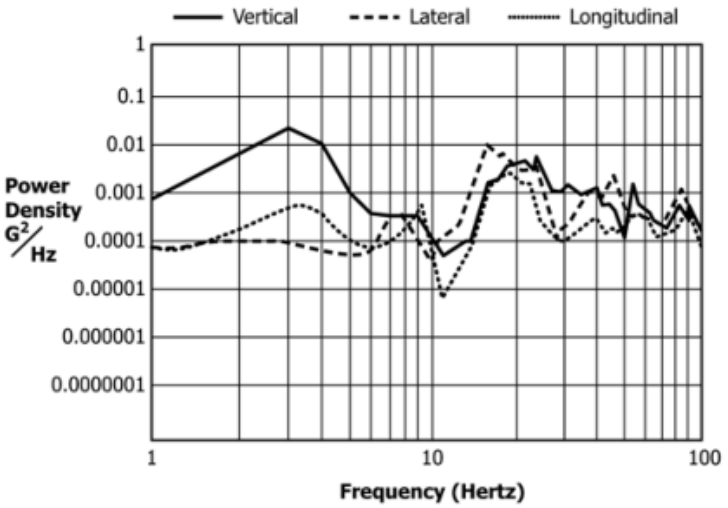
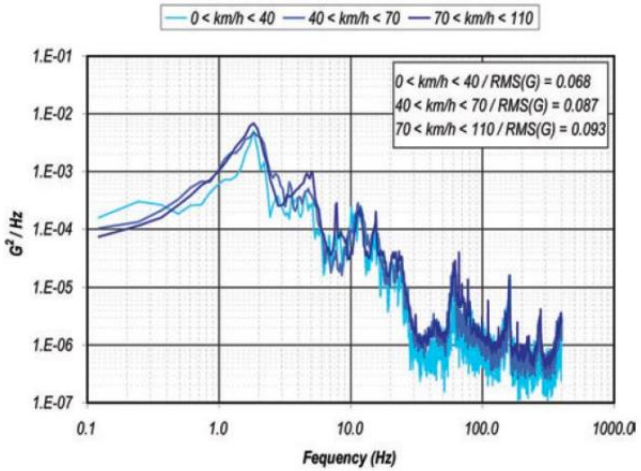
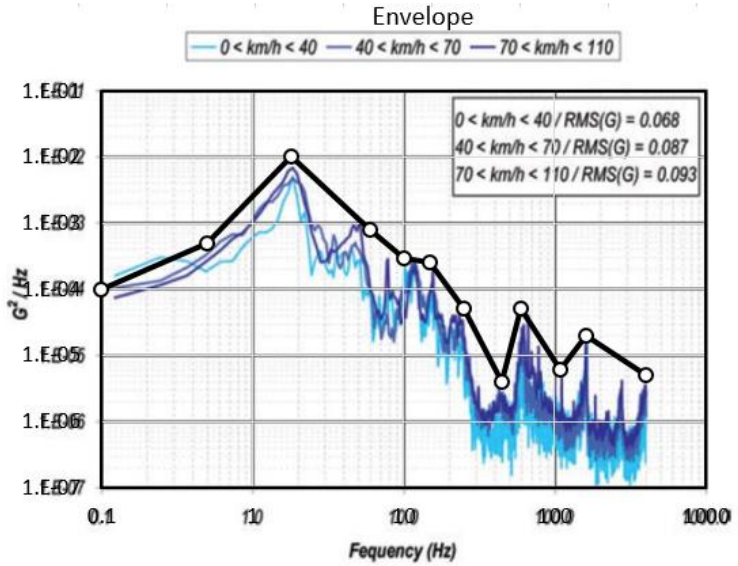


FIG. X2.1 Sample Truck Vibration Data



- **Standard** transport **loads**:
  - *ASTM-D4169-16*
  - *ASTM-D4728* (Sample truck vibration data)
- **Measured** data for air ride truck from: '*Design Report for the DUNE APA shipping frames*'
  - Air truck significantly damped
    - Only vertical loads available, can use lateral loads from ASTM-D4728

Transportation Loads - Fitting



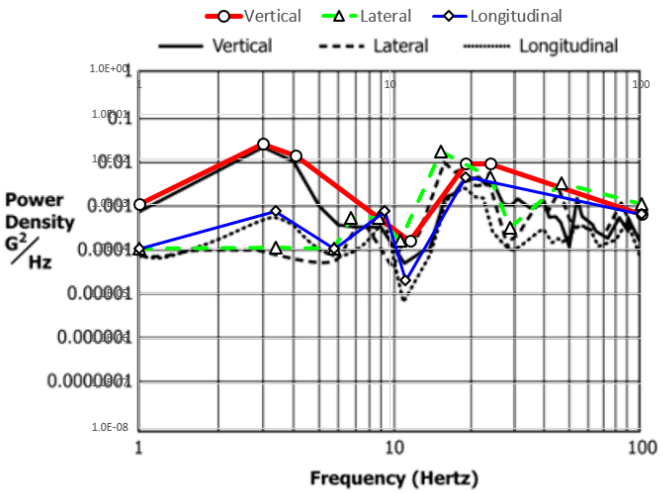
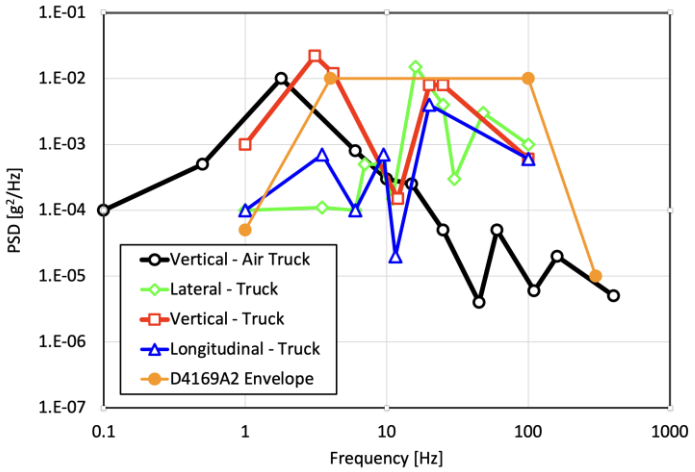


FIG. X2.1 Sample Truck Vibration Data

- **Conservative fitting** of the available data
- Another option could be to agree with the transportation firm for limits
- **Vertical peak** at ~ 2 Hz, **lateral** at 15 Hz, **longitudinal** at 3 Hz and 25 Hz



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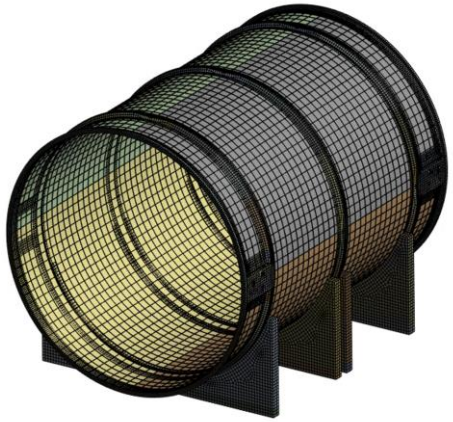
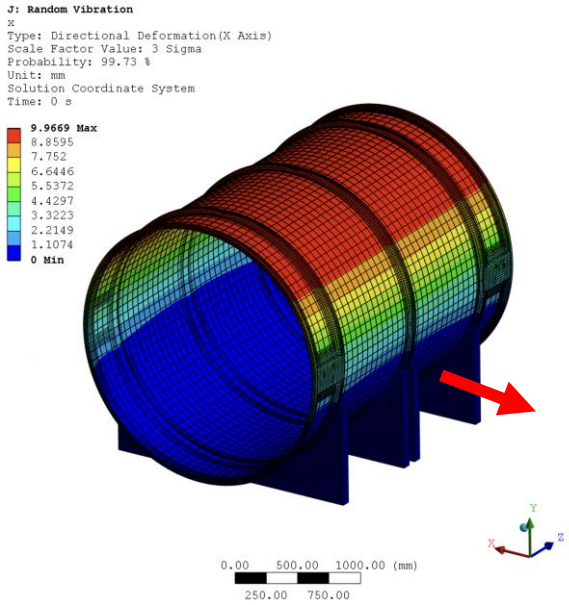
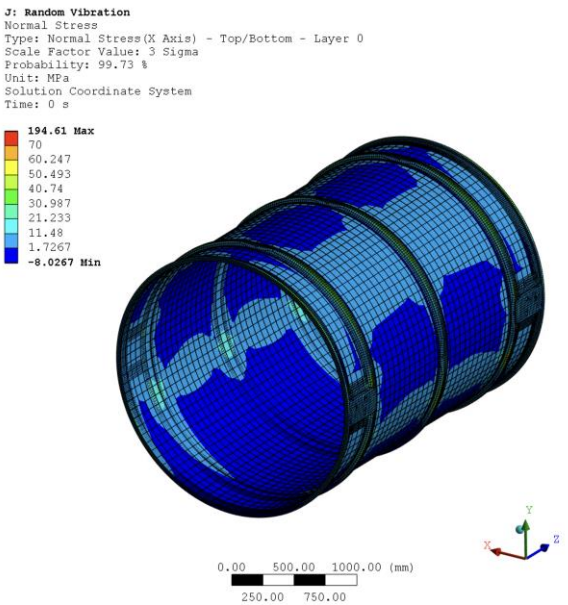
Box Design - Preliminary

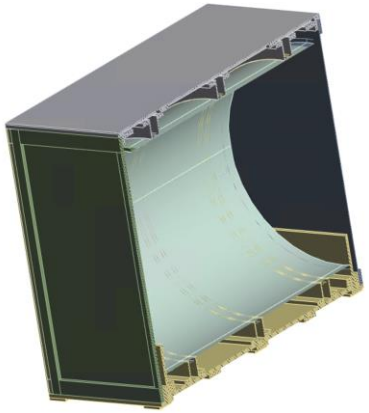


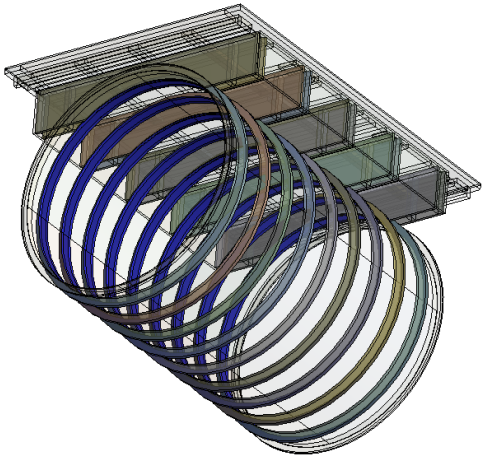


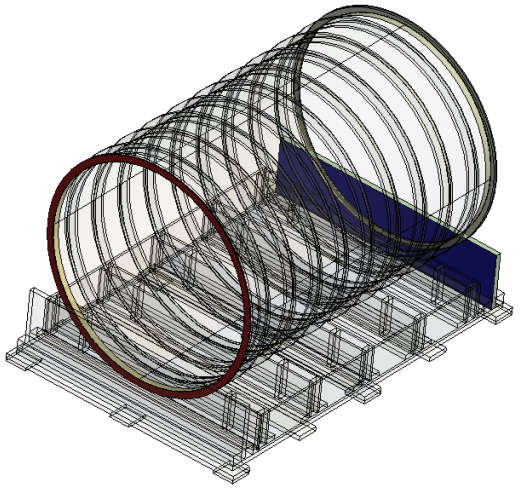


- Preliminary analysis performed with the OC supported only on the bottom
  - **High** (but **not dangerous**) **stresses** (~ 200 MPa)
  - Significant **displacements** (~ 9 mm in the horizontal plane), which could lead to 'impacts' against the box sides
  - Reinforcing the OC ends with stiffening crosses does not solve the problem

Final Box Design - Model Description

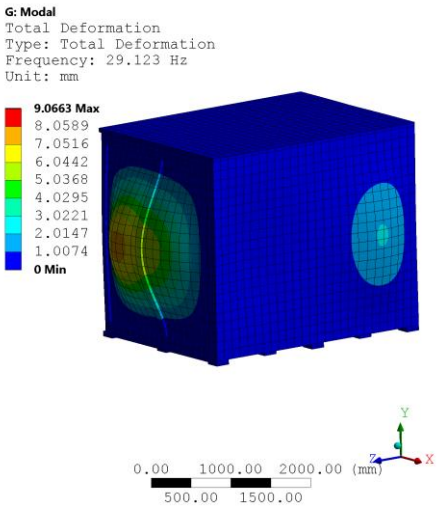


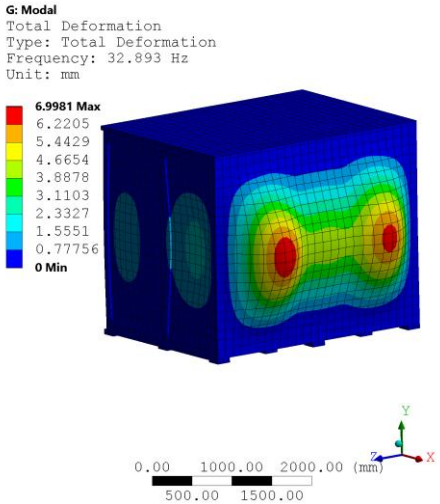


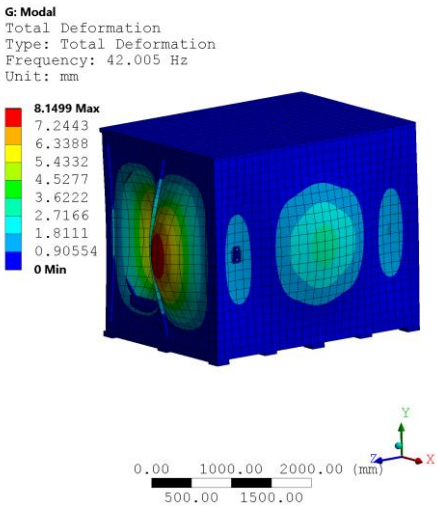


- **New design** with 'tight' fit between box and shell
- Connections:
  - Top, bottom against the hat stiffener flat
  - Flange against longitudinal plates
  - All simulated as **bonded**, which should be realistic for prestressed contacts and **small vibrations**
- Model results presented only for the OC, same considerations apply to SB

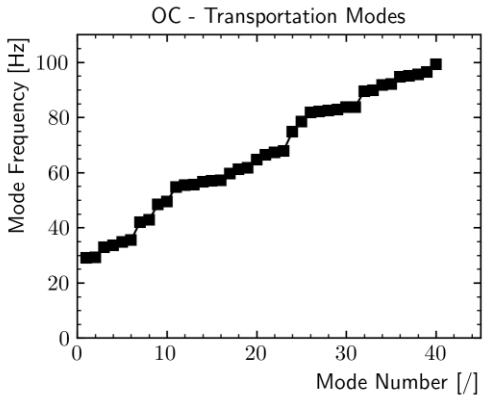
OC – Results – Box Modes



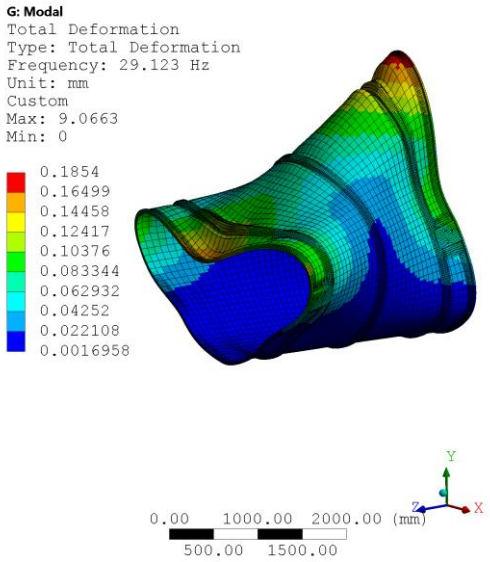


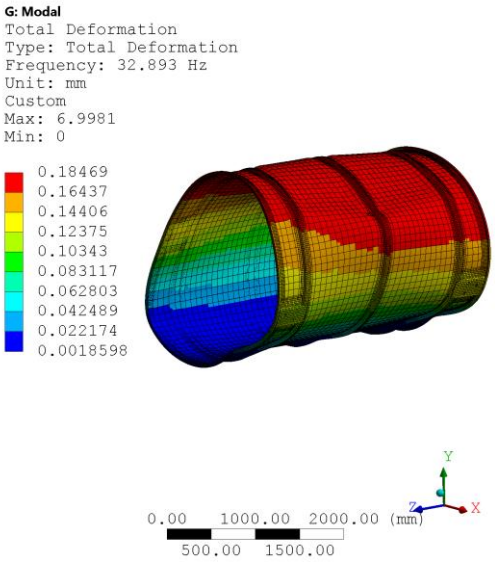


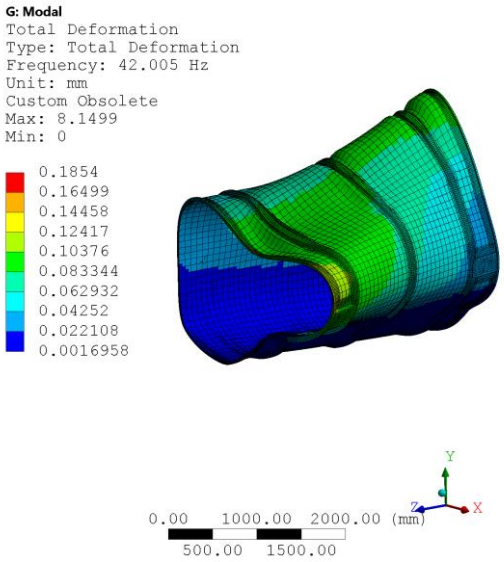
- **First mode** f = 29 Hz
  - This is **above** the **peaks** in the **PSD** data
- All modes mainly move the box
- Mode cut at 100 Hz, 40 modes found



OC – Results – OC Modes

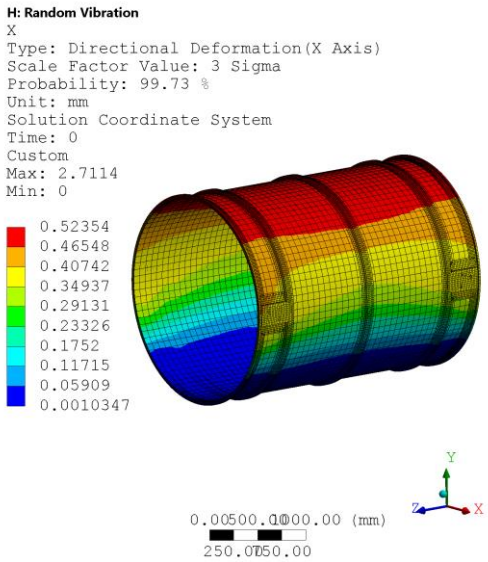


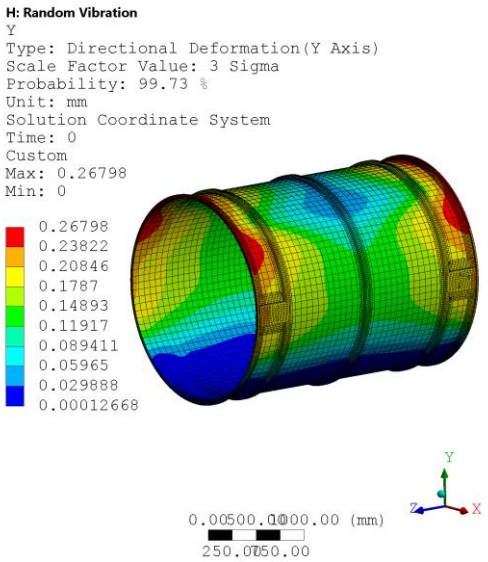


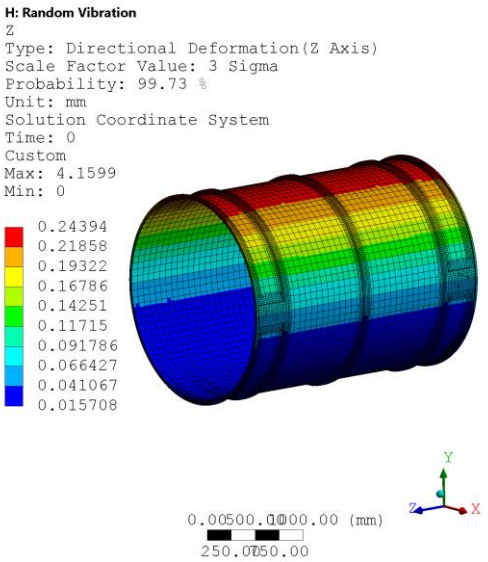


- All modes mainly move the box, but the OC follows
  - Motion ~1 or 2 **orders** of **magnitude smaller** with respect to the box
    - Box hidden, deformations scaled for display purposes

OC – Random Vibration Results







- **Envelope PSD** (shipping loads), 3 sigma **displacements** on the OC:

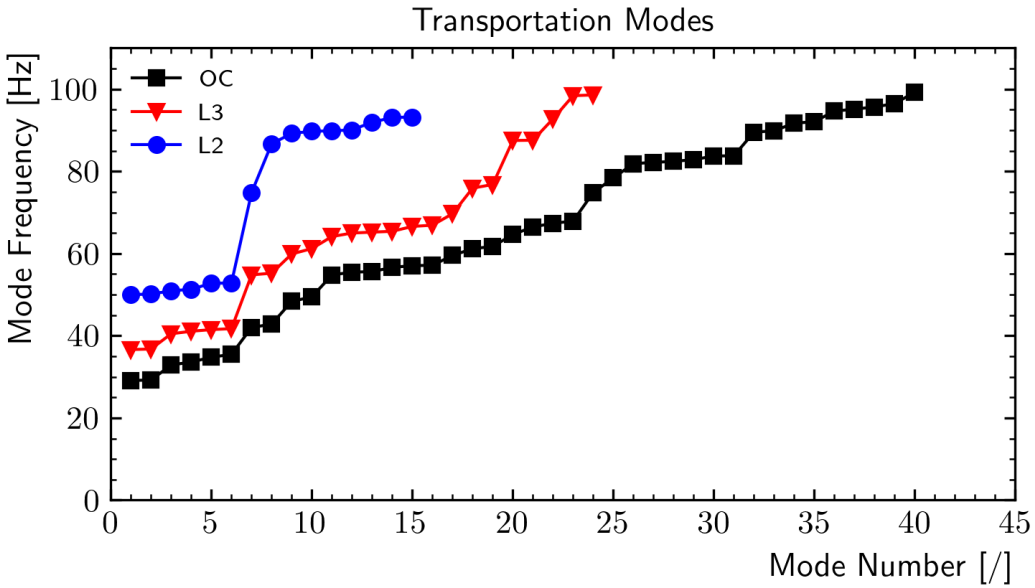
  X: 0.52 mm Y: 0.27 mm Z: 0.24 mm

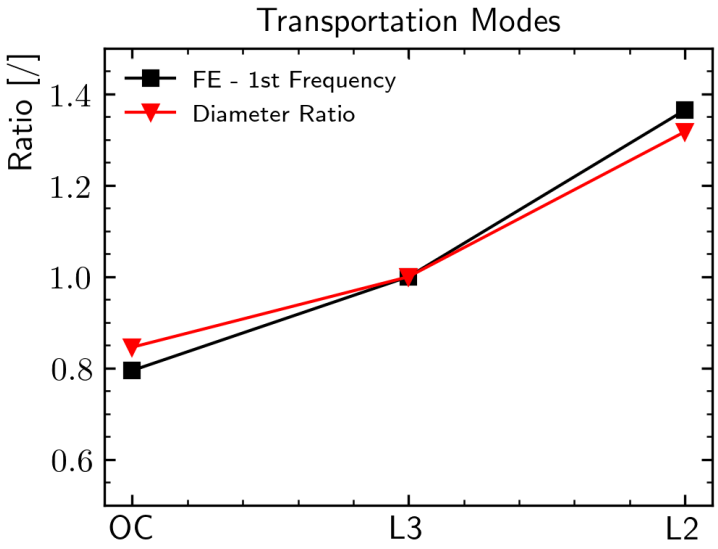
- Vibration on the box significantly larger in the XZ plane (sides and ends):

  X: 2.7 mm Y: 0.27 mm Z: 4.16 mm

- OC is adding a constraint on the vertical displacements (top and bottom)
- OC stresses (not shown) negligible (<10 MPa)

Transportation Modes - Summary





- Same approach for **Layer 2** (L2) and **Layer** 3 (L3) transportation modeling
  - Similar box design for all shells, first mode **frequency scales** with **size**

$$f \sim \sqrt{\frac{\beta / L_0 R}{\rho L_0 R t}} \rightarrow \frac{f_i}{f_j} \sim \frac{R_j}{R_i}$$

  - Error within ±5%, approach might be good for scaling to different shell sizes

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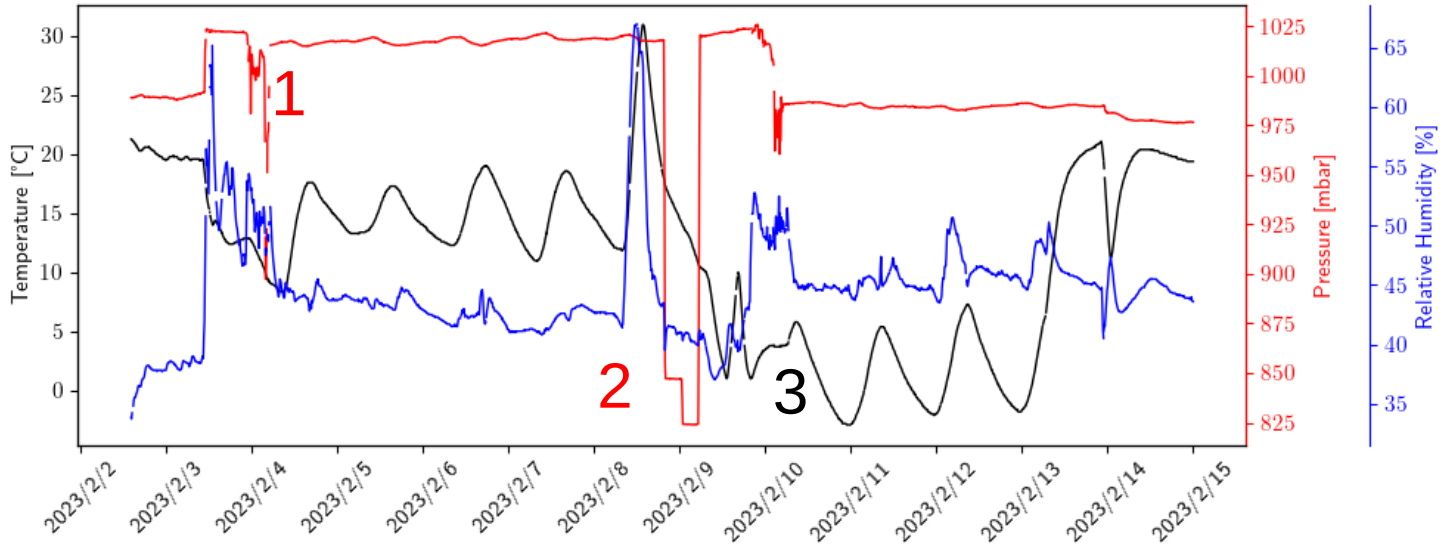
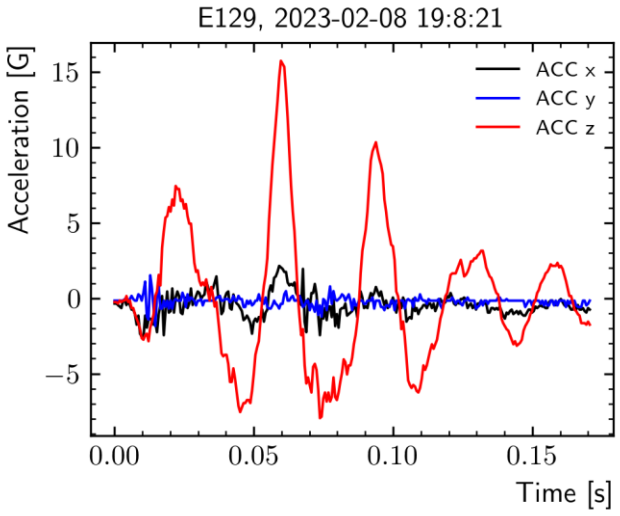
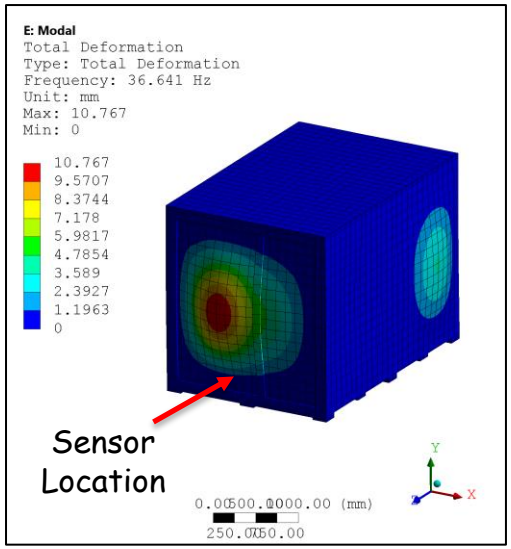
SB L3 – LBNL to CERN

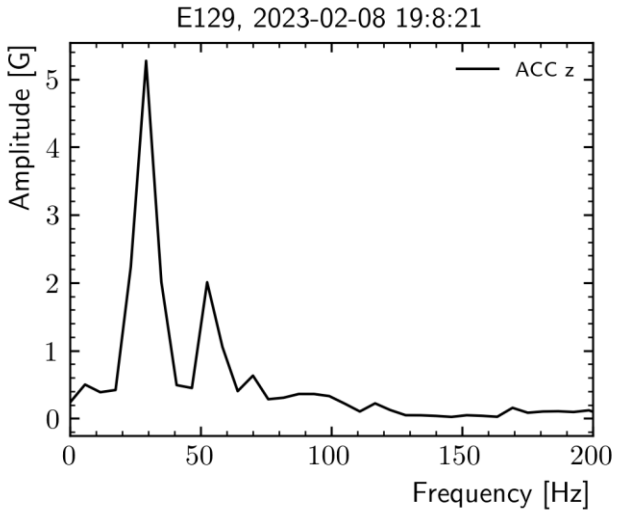


- Accelerometers record **environment** data at fixed time intervals, and **acceleration** '**events**' if triggered (acceleration>threshold)
- Environment data example:
  1. Mountain outside of Los Angeles
  2. Drop in pressure: plane to FRA
  3. Pretty cold in Germany

SB L3 – LBLN to CERN – Longitudinal

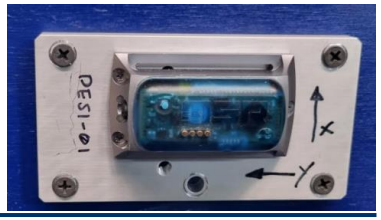


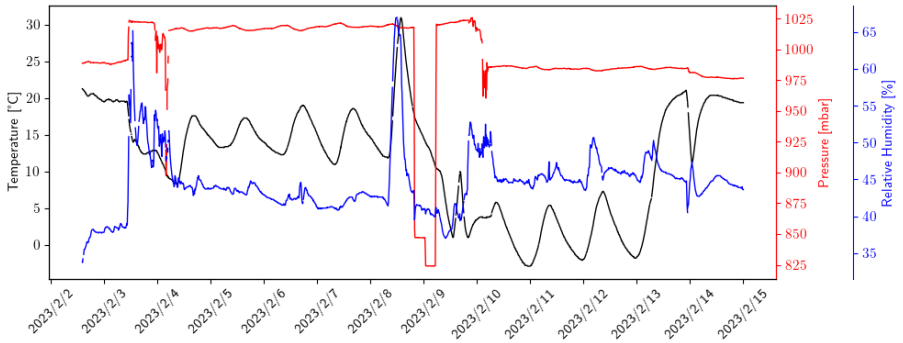


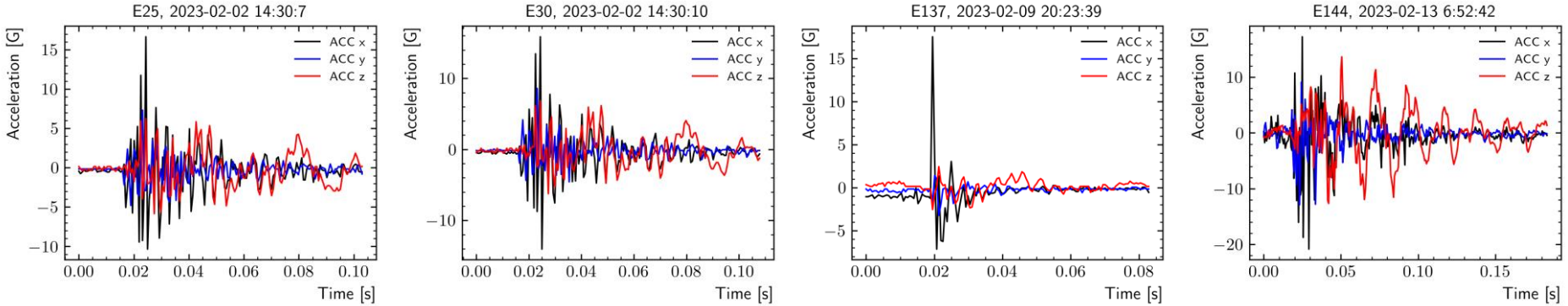


- Scripts automatically isolate and plot events
  - Events with **acceleration** above **10 g** are **flagged**
- Many events with **large vibrations** in z (**longitudinal**)
  - Sensor close to an antinode of the first vibration mode
  - **Model** predicted 36 Hz, reality is 29.2 Hz
    - Not too bad considering that box model was '**bonded**', reality is **bolted** (less stiff)

SB L3 – LBLN to CERN – X

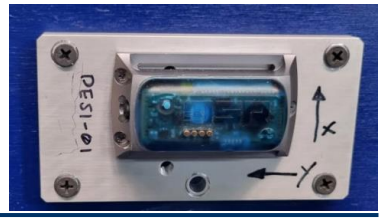


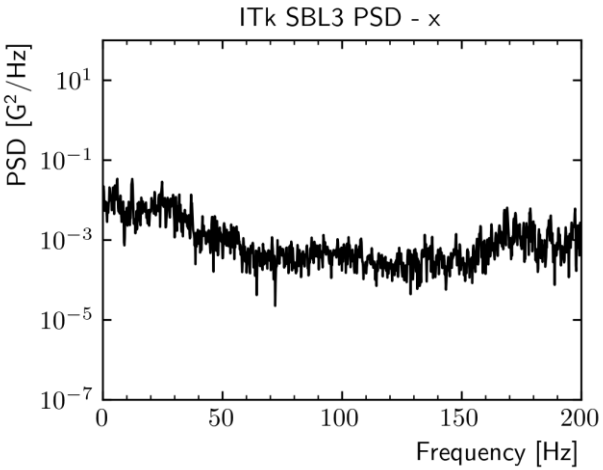


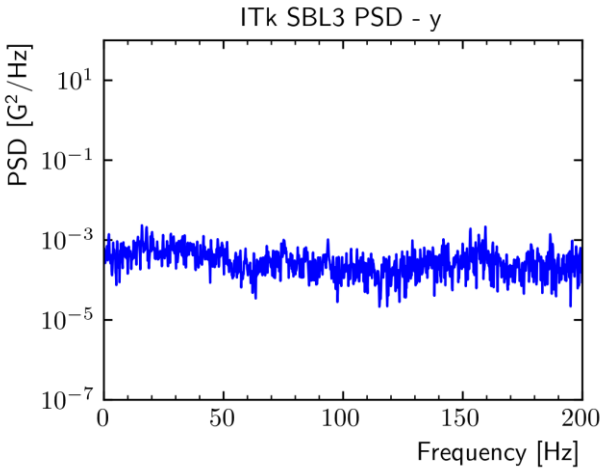


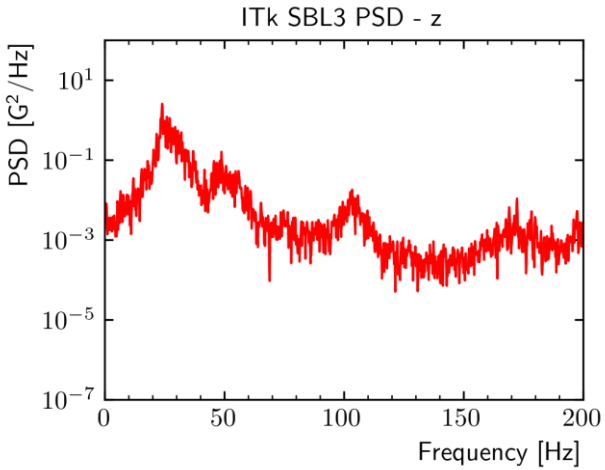
- **Typical** recordings: flagged events (a>10 g) in the vertical direction
  - Accelerations on 02/02: **truck**
  - Acceleration on 02/09: **airplane landing**
  - Acceleration on 02/13: **handling**

SB L3 – LBLN2CERN – PSD



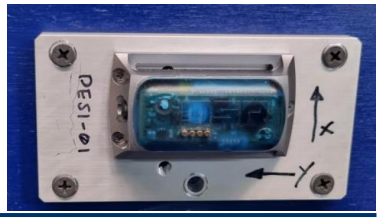


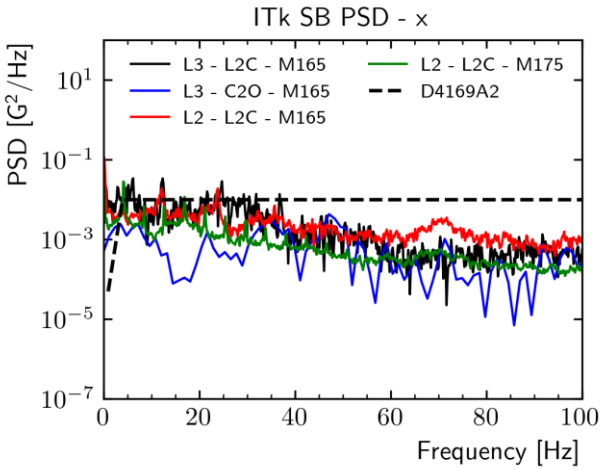


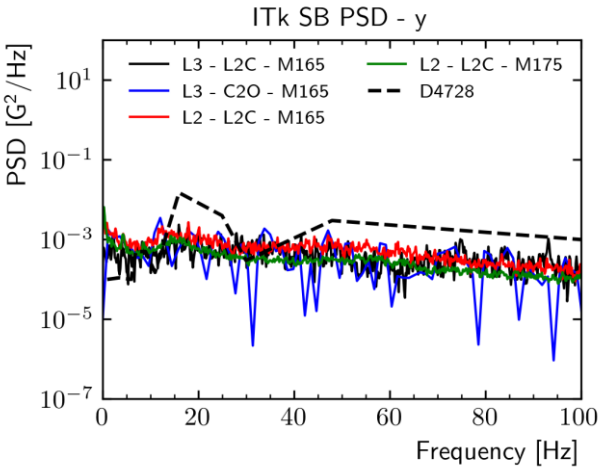


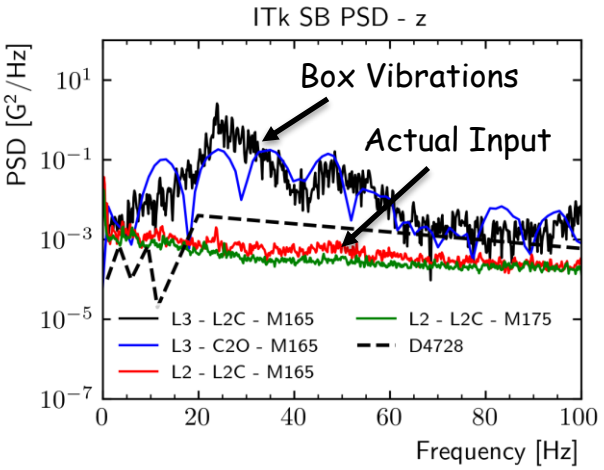
- **PSD** from all recorded events
- Only significant energy is in **longitudinal** (z) **motions**
  - Comparison with FE results suggest that this vibration is **contained within the box**

All Transportation Data









- PSD from all transportation data available
  - Legend: L-LBNL, C-CERN, O-OXFORD
- Sensor moved on the bottom of the crate for **L2**:
  - Measurement ~ input acceleration
  - Bump in **longitudinal** motions **disappeared**
- **Peak** values **similar** to available data from **standards**
  - **Higher** than expected values on the **low end** of the spectrum

L2 Sensor Location

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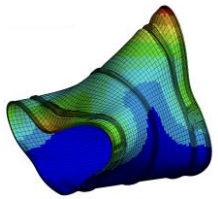
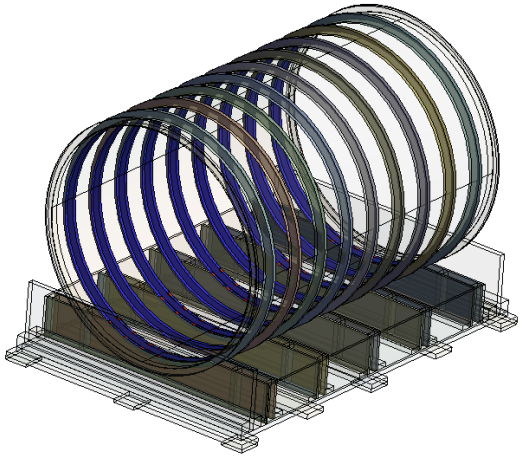
Conclusion

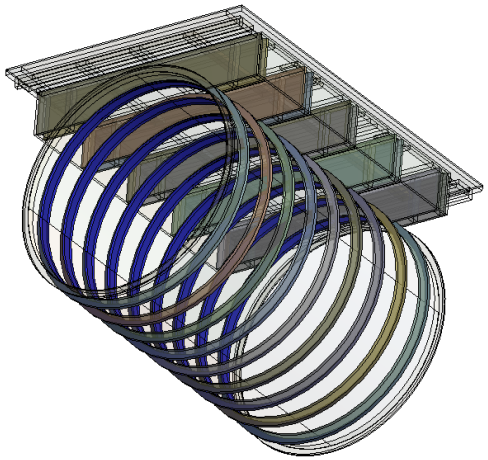


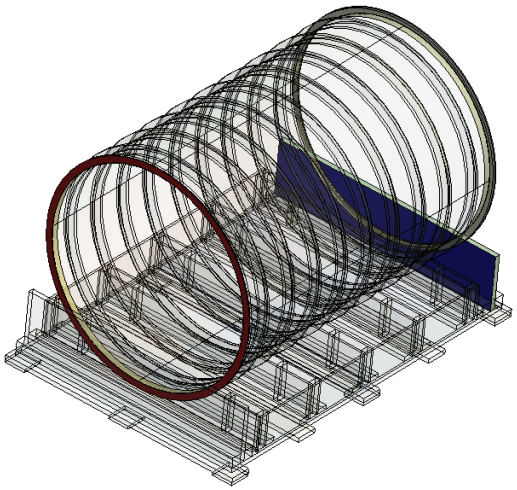
- **Loads** from **literature** review:
  - Conservative approach considering '**envelopes**' of the available data
    - Might not always be feasible for more fragile items
- **Box design**:
  - Supporting only the bottom leads to excessive displacements
  - Optimized box design allows for reduced displacements and stresses
- **Shipping** data **analysis**:
  - Some significant **vibrations** in the **longitudinal** direction (z) for L3
    - FEA suggests that these are only local **vibrations** of the **box**
    - They disappeared when the sensor was moved, as predicted
  - **Sensor placement** can either validate the models or retrieve the input accelerations – both important
  - Measured **PSD seems** larger than expected at lower frequencies
  - Acceleration peaks over 10 g due to airplane landings, handling

Extra

SB Design

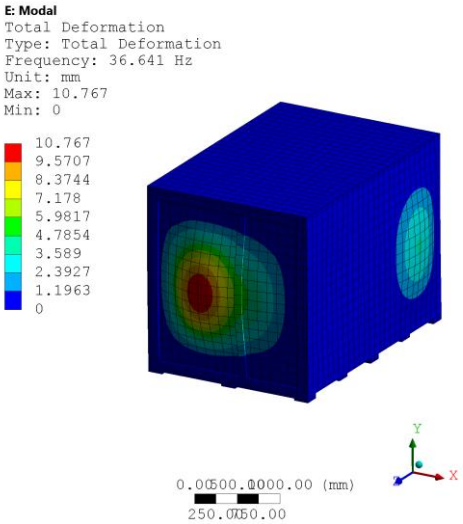


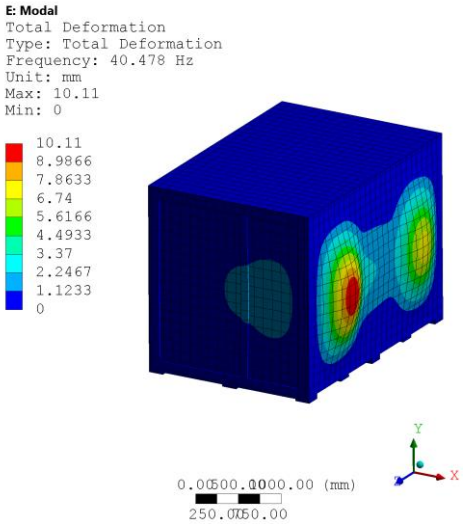


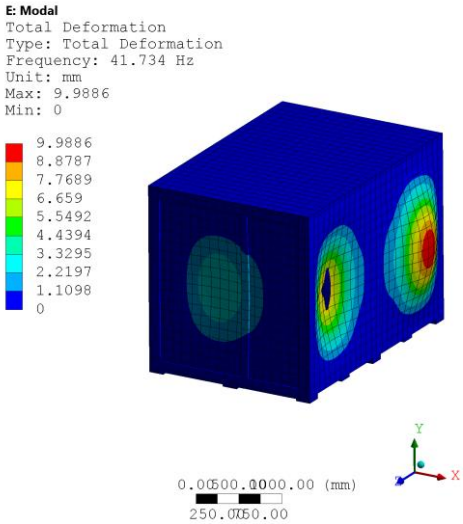


- Box in plywood: 0.5 g/cc^3, 8 GPa modulus
  - Should add steel parts, might improve results
- Connections:
  - Top, bottom against the hat stiffener flat
  - Flange against longitudinal plates
  - All glued, which is true if fit precisely and vibration is small

SB L3 – Results – Box Modes

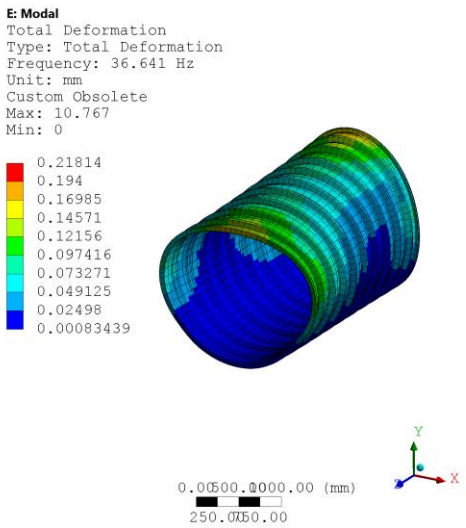


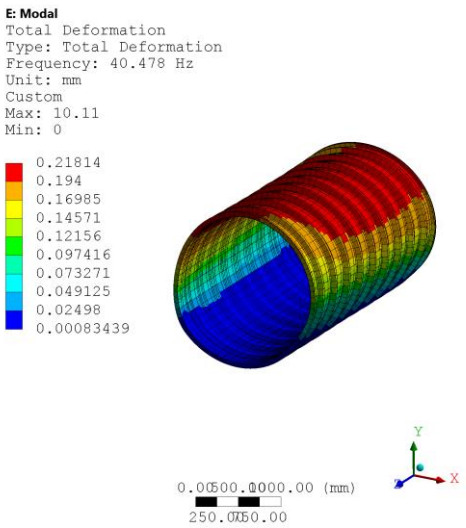


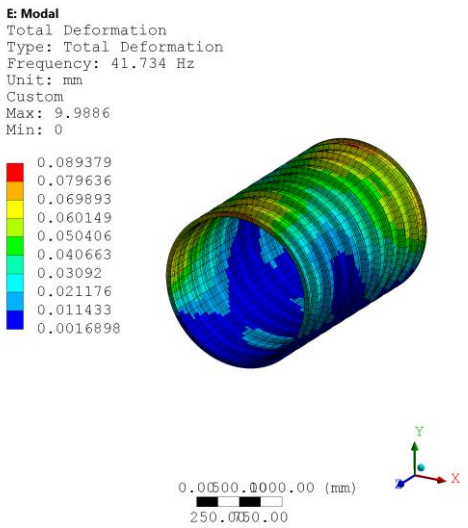


- First mode f = 36 Hz, does not change with finer box mesh
  - This is above the peaks in the PSD data and will probably be better with steel stiffeners
- All modes move mainly the box
- Mode cut at 100 Hz, 24 modes found

SB L3 – Results – SB Modes

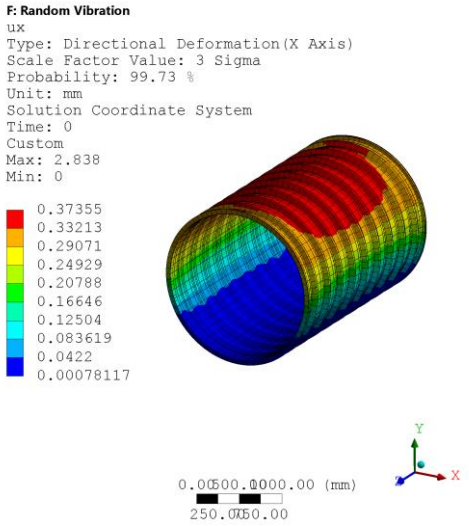


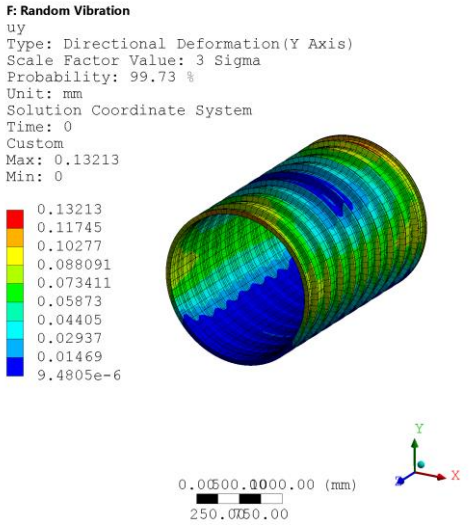


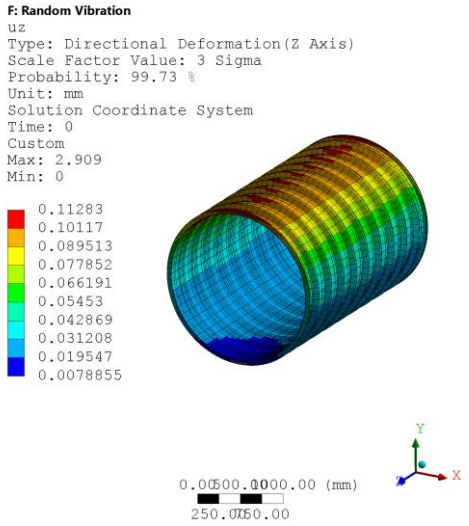


- All modes move mainly the box, but the SB L3 follows
  - Motion ~2 orders of magnitude smaller

SB – L3 - PSD Results







- Results, 3 sigma displacements on the SB L3:

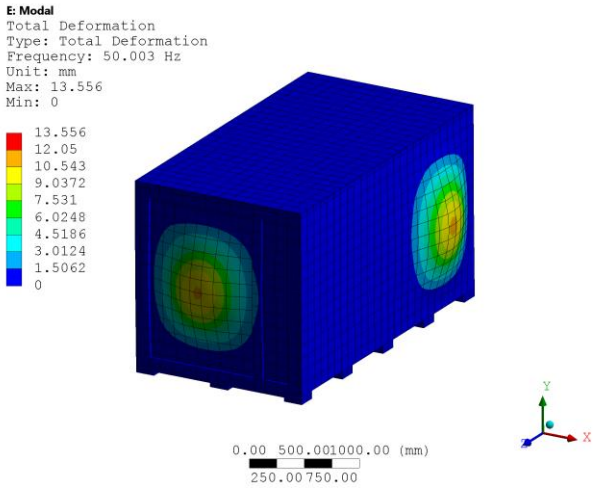
  X: 0.37 mm Y: 0.13 mm Z: 0.11 mm

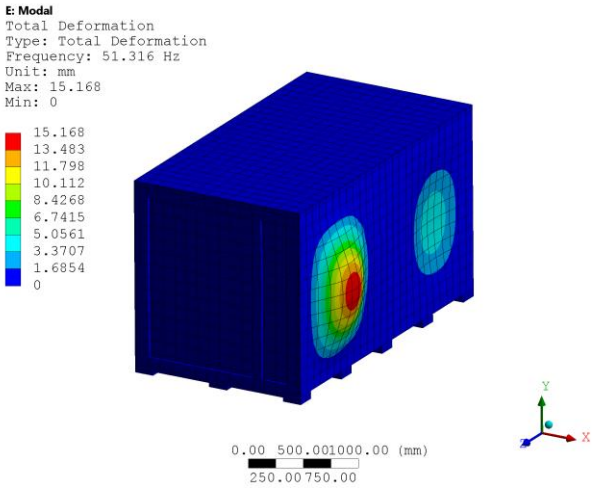
- Vibration on the box significantly larger:

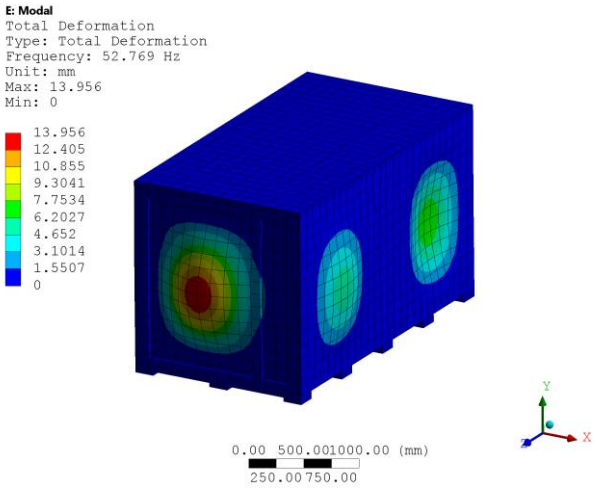
  X: 2.8 mm Y: 0.13 mm Z: 2.91 mm

- L3 is adding a constraint on the vertical displacements

SB L2 – Results - Box Modes

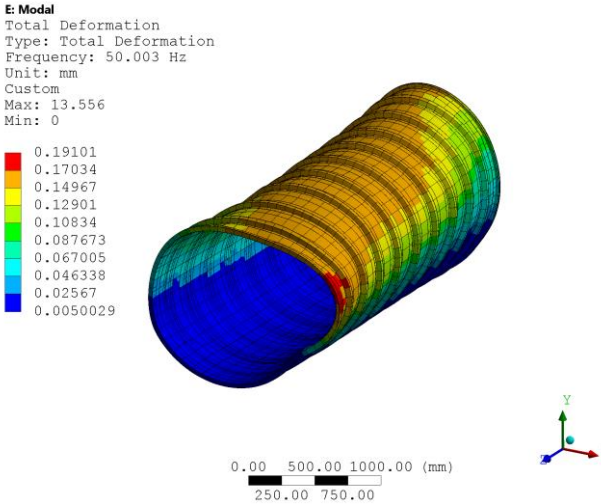


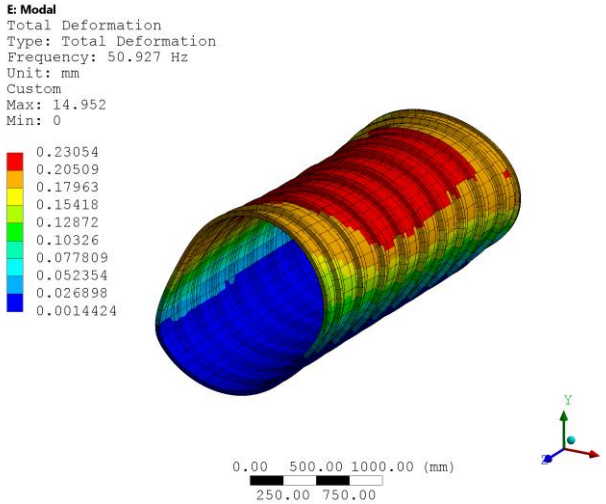


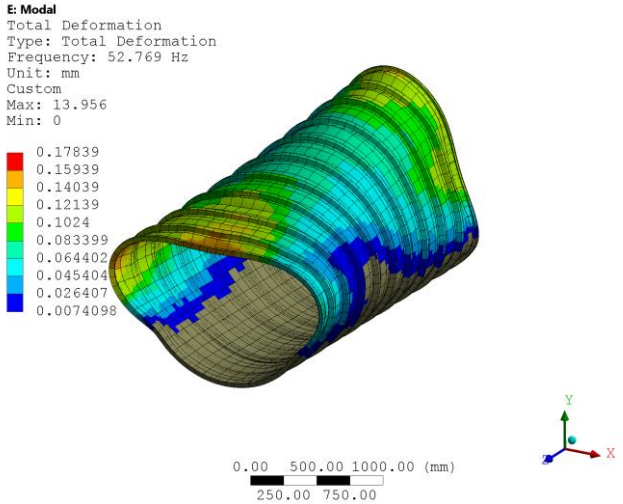


- First mode f = 50 Hz
  - All modes move mainly the box
- Mode cut at 100 Hz, 15 modes found

SB L2 – Results - SB Modes

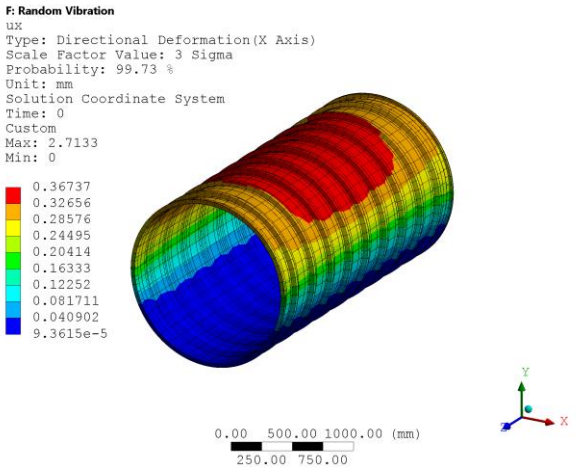


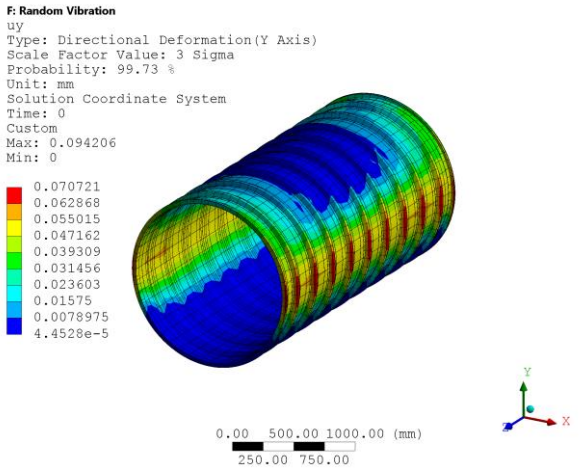


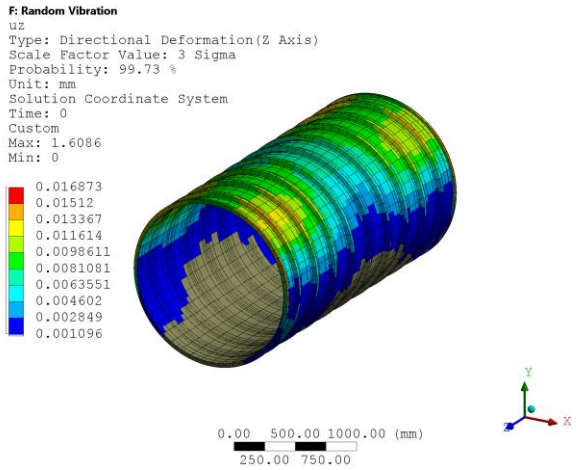


- All modes move mainly the box, but the SB L3 follows
  - Motion ~2 orders of magnitude smaller

SB – L2 - PSD Results







- Results, 3 sigma displacements on the SB L2:

  X: 0.37 mm Y: 0.07 mm Z: 0.017 mm

- Vibration on the box significantly larger:

  X: 2.7 mm Y: 0.09 mm Z: 1.68 mm

- L2 is adding a constraint on the vertical displacements

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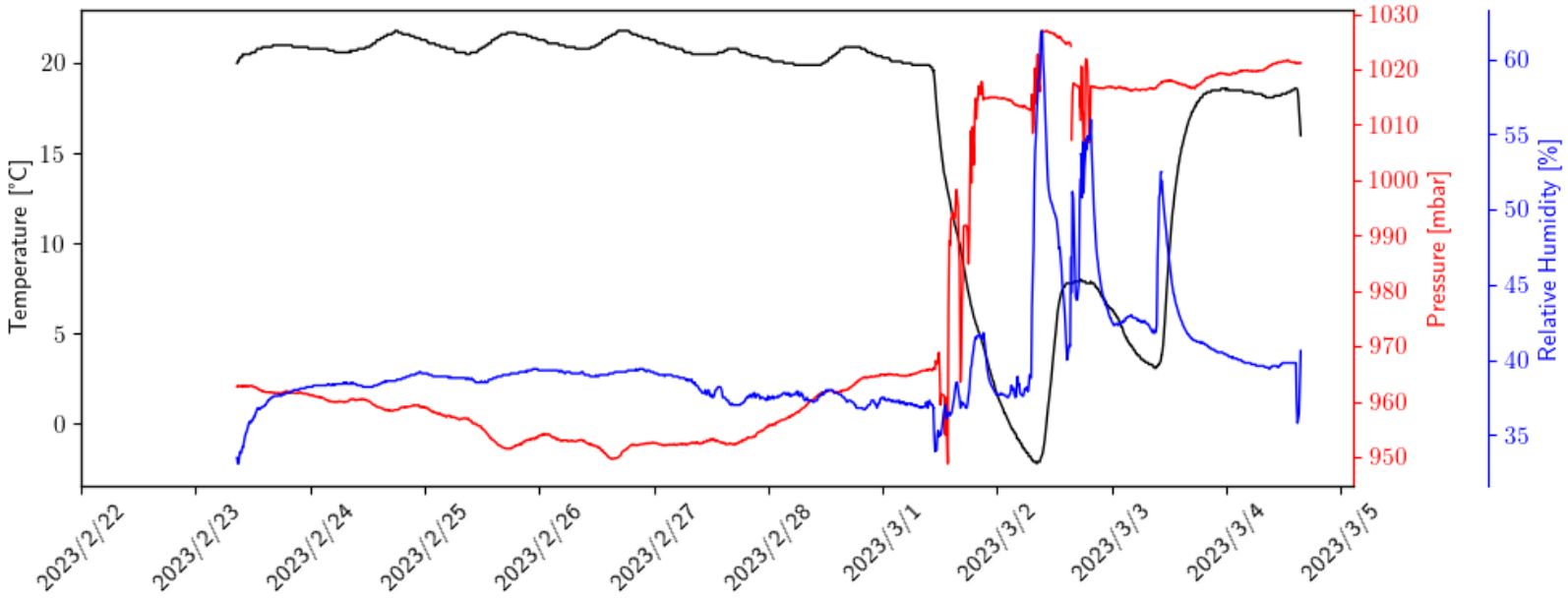
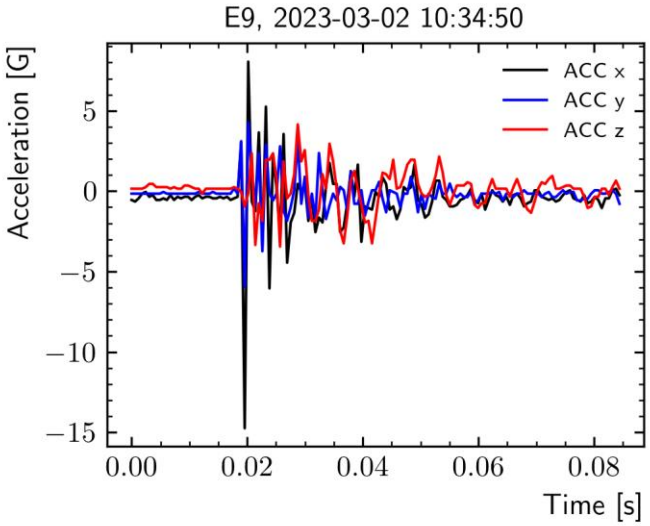
L3 – CERN 2 OXFORD

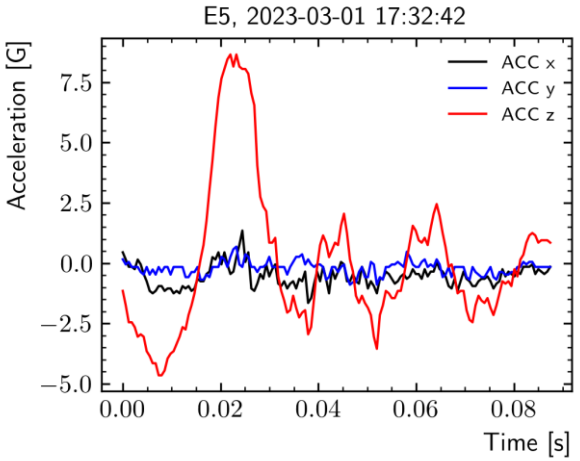
SB L3 – CERN to OXFORD

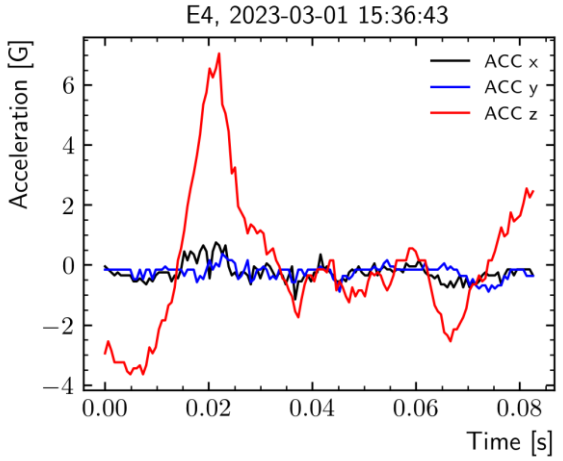


- Sequence:
  1. Accelerometers loaded into crate and sealed 22/02
  2. Crane lift to B180 entrance + Forklift onto truck + drive to UK – 28/02 →02/03
  3. Forklift off truck at oxford + install casters+ move to lab 02/03 10:00am →10:40am
  4. Opening crate and removal of accelerometer 03/03 15:00

Flagged Events







- Only one event (E9) flagged (>10 g)
  - Likely forklift operation
- Couple of loads with some energy content measured on the truck (E4, E5)

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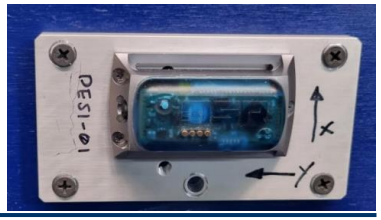
L2 – LBNL 2 CERN

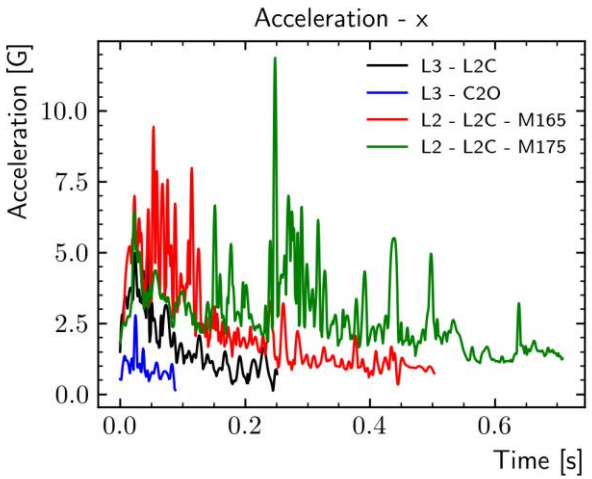
SB L2 – LBLN2CERN

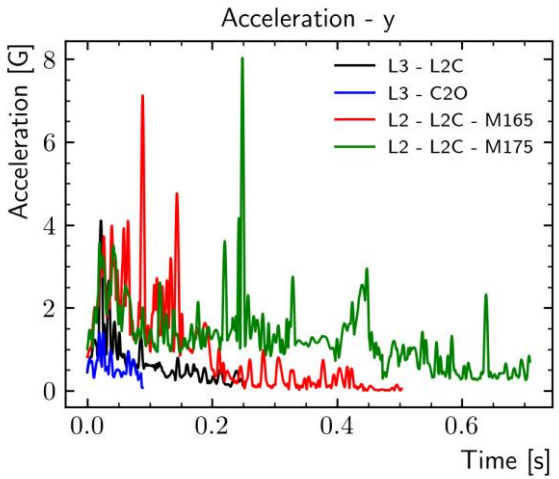
Different sensor installation:

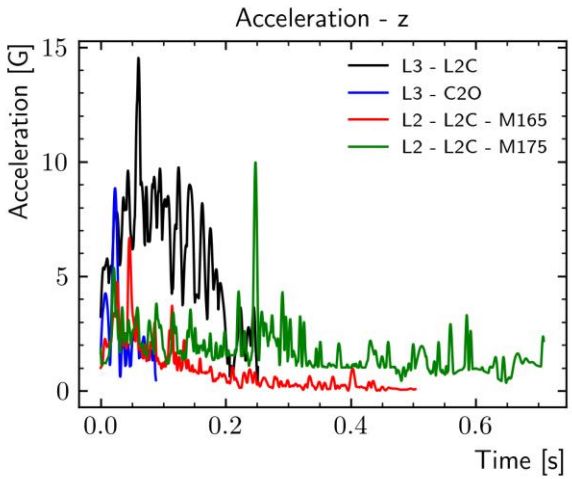
- Additional sensor used (M175, yellow). Should allow better resolution w.r.t. M165 (blue)
- Sensors now moved on the bottom of the crate
- Should allow to monitor more closely the 'input' accelerations

Acceleration Envelope









- Envelope of the worst accelerations as function of time
  - Maximum time window length depends on the actual data as the sensor can get 'retriggered' during an event