Studies for transport of crab cavities equipment

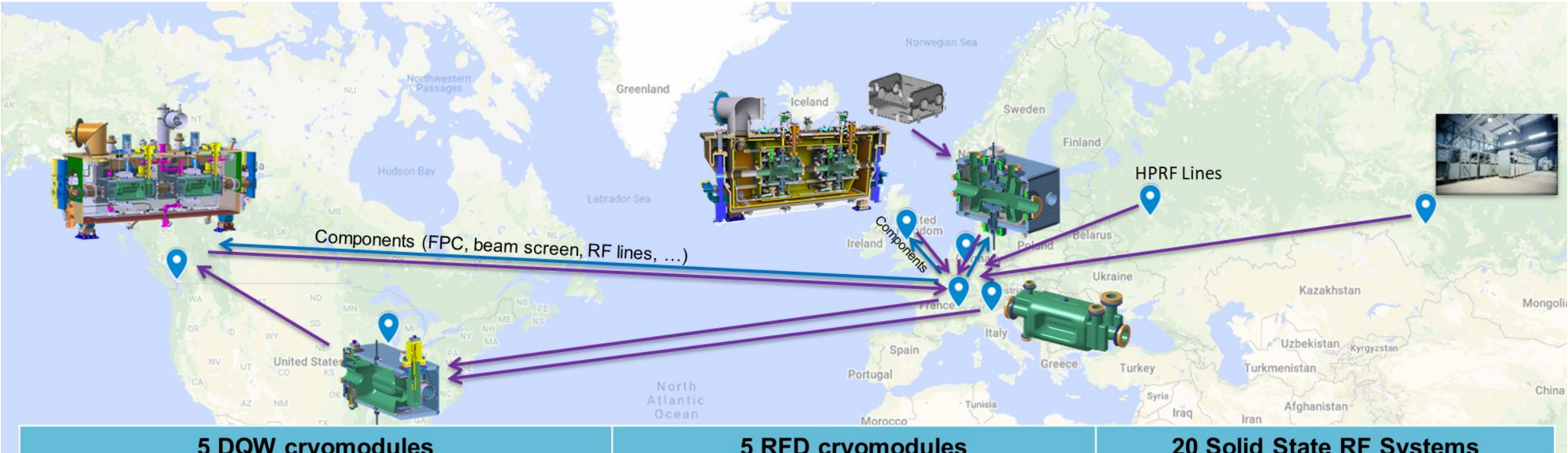
Teresa Guillén Hernández on behalf of WP4

14th HL-LHC Collaboration Meeting, Genoa (Italy), 7-10 October 2024

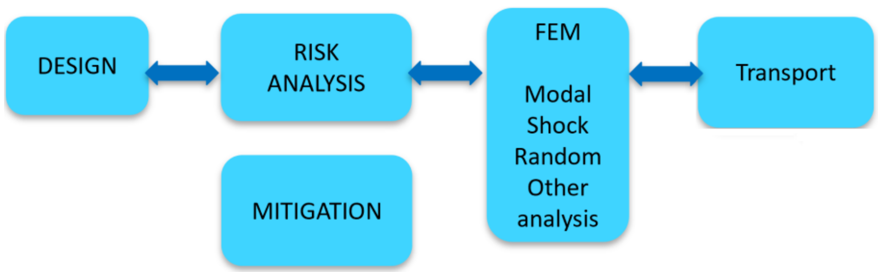
Outline

- Introduction
- Risk analysis
- Risk mitigation
- HOMs transport calculations
- Conclusions

Introduction



5 DQW cryomodules	5 RFD cryomodules	20 Solid State RF Systems
• Cavities + processing + helium vessels by Research Instruments (**DE**) & **CERN** • Cold magnetic shields by **UK** • HOM couplers + antennas by **CERN** • 4 CM by **UK** (STFC) & 1 CM at **CERN** with some components from **CERN** • All cavities & CM cold validation tests at **CERN** (and a few at Uppsala-Sweden)	• Bare cavities by Zanon (**IT**) under **US-AUP** • Processing + cold magnetic shield + helium vessel + HOM couplers + antennas + cold tests by **US-AUP** • 5 CM by **TRIUMF-Canada** with some components by **CERN** • CM cold validation tests at **CERN**	• High power solid state amplifiers by **BINP-Russia** • High power RF lines, circulators, loads by **MEPHI-Russia**



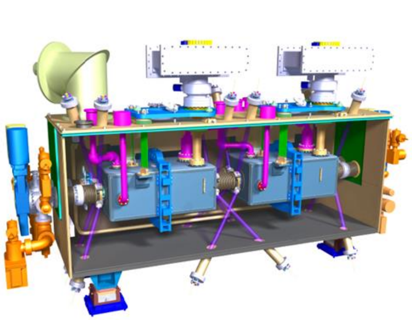
- M. Garlasche ¨Transport of RFD Equipment to UK¨ 11th HL-LHC Collaboration Meeting. 2021

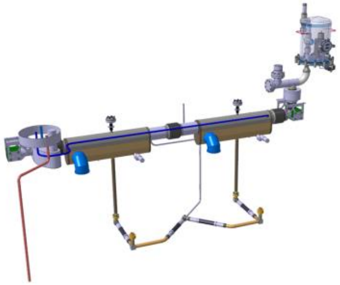
Risk analysis

- What issues can arise during transport
  - Shock
  - Vibration
  - Contamination/humidity
  - Untightening screws
  - Misalignment

- What equipment is critical
  - Manufacturing Cost/ delay
  - Material properties
  - Difficulty of risk detection

- Risk analysis on
  - Components
  - Assemblies
- Deep analyses of risks
  - FEM

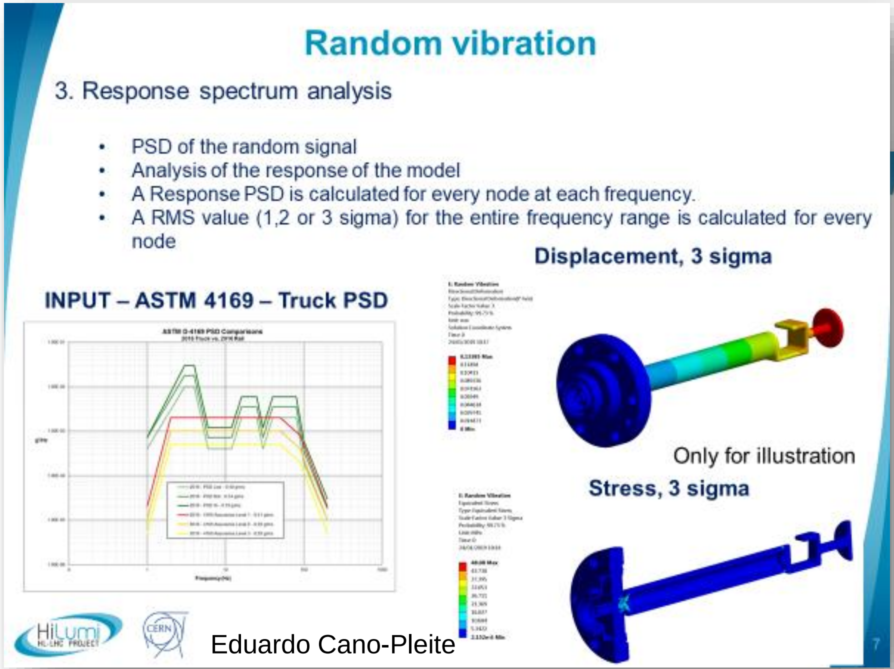


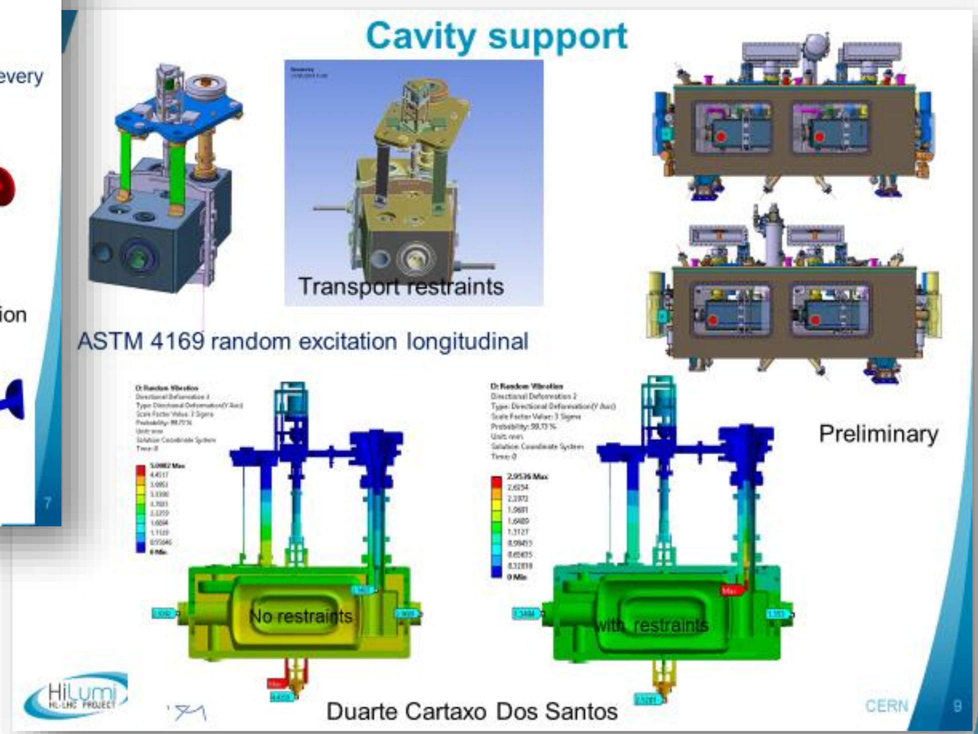


- K. Artoos ¨Transport aspects¨ International review of the CRAB cavity system design and production plan for the HL-LHC. 2019
- M. Garlasche ¨Transport of RFD Equipment to UK¨ 11th HL-LHC Collaboration Meeting. 2021

Risk mitigation

- Some mitigations are applied **on the design** of the equipment





- K. Artoos ¨Transport aspects¨ International review of the CRAB cavity system design and production plan for the HL-LHC. 2019
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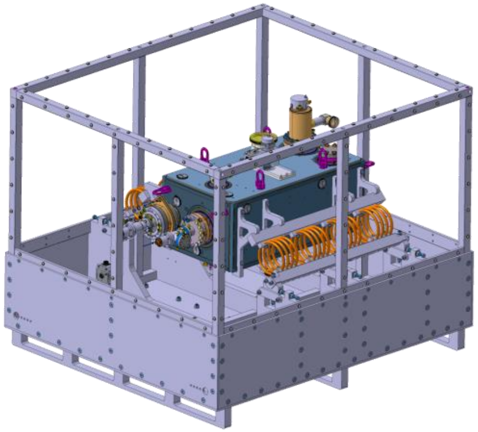
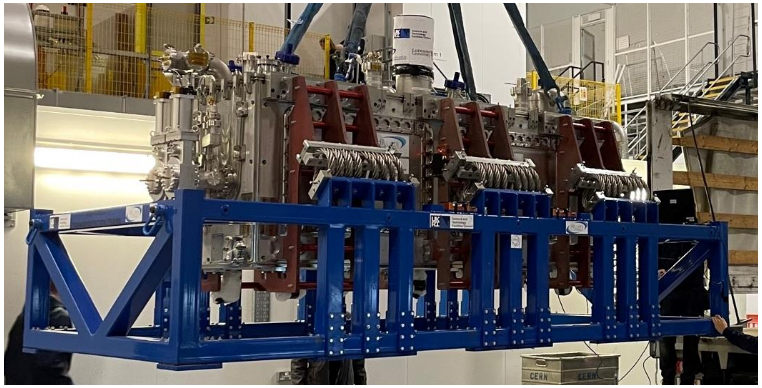
Risk mitigation

- Other risks are mitigated **designing transport equipment**

Transport frame for the Dressed Cavity



Transport frame for STFC RFD cryomodule. Courtesy of T. Capelli



Rigid boxes with foam for transport of HOMs antennas and HOMS assembled. Courtesy of S. Barriere.

- M. Garlasche ¨Transport of RFD Equipment to UK¨ 11th HL-LHC Collaboration Meeting. 2021

HOMs transport calculations

- Verify the integrity of the HOMs during transport
- RFD AUP H-HOM
- FEM analyses for transport
  - Modal
  - Shock
  - Random vibration
  - Fatigue

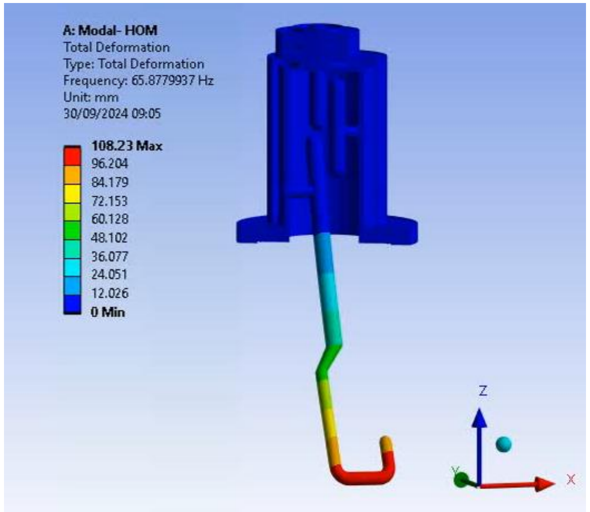
Calculations done on the components **without mitigation methods**

RFD AUP H-HOM transport calculations

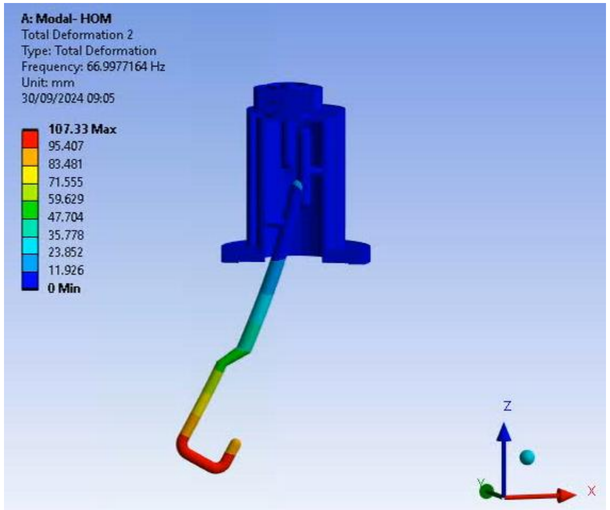
1. Modal analysis

- It is a preliminary analysis needed before
  - Response spectrum analysis
  - Random vibration analysis
- Natural frequencies and modes

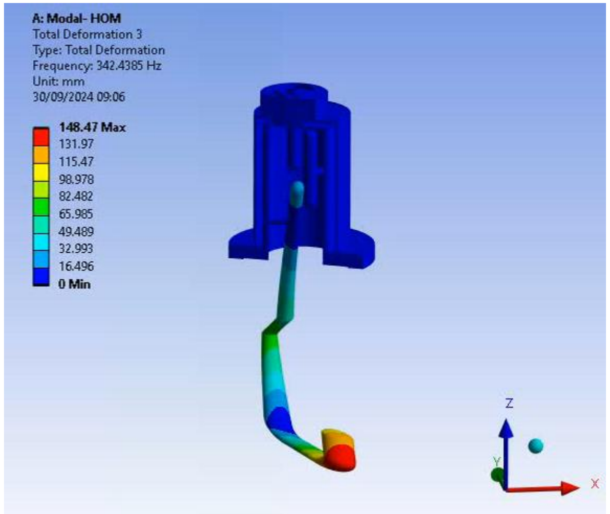
Mode 1



Mode 2



Mode 3



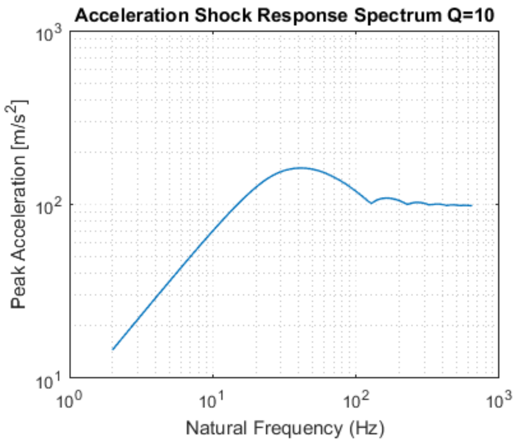
Mode	Frequency [Hz]
1	65.9
2	67.0
3	342.4
4	349.0
5	445.5

RFD AUP H-HOM transport calculations

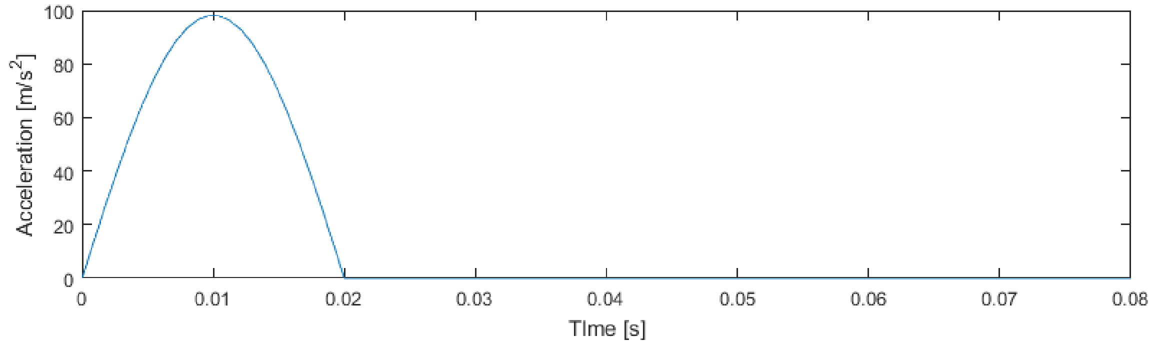
2. Shock analysis

- Dynamic and non-deterministic load in a very short time
- 2 approaches
  - **Response spectrum analysis** - 10 g and 20 ms in the **frequency domain**

Experimental value
More critical than MIL-STD-810H



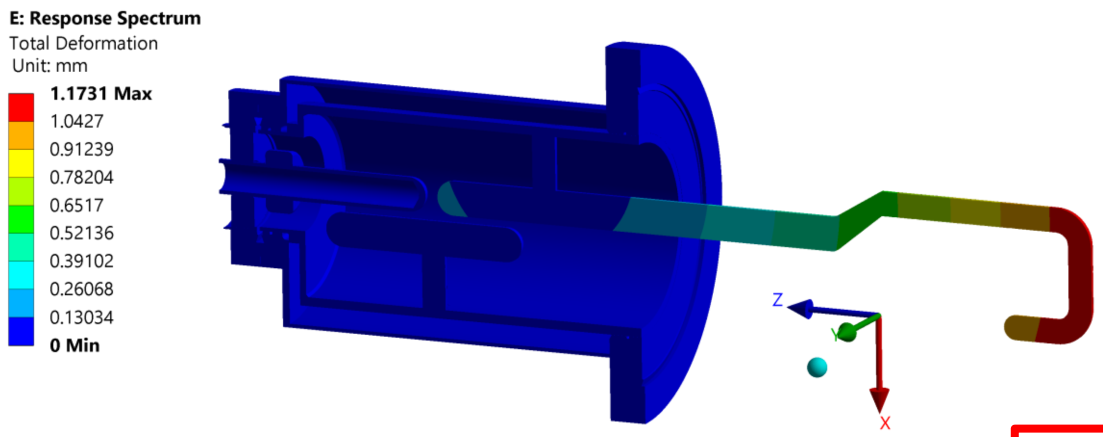
  - **Transient analysis** - 10 g and 20 ms in **time domain**

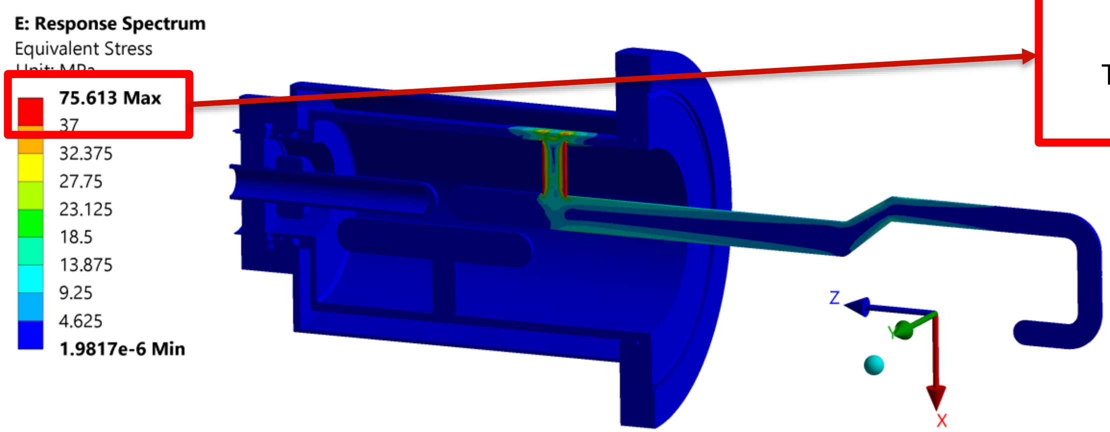


RFD AUP H-HOM transport calculations

2. Shock analysis – Response spectrum

- Results – X direction (most critical)
  - **Response spectrum** – Max stress = **75 MPa > 37 MPa** = $R_{P0.2}$





Plasticization

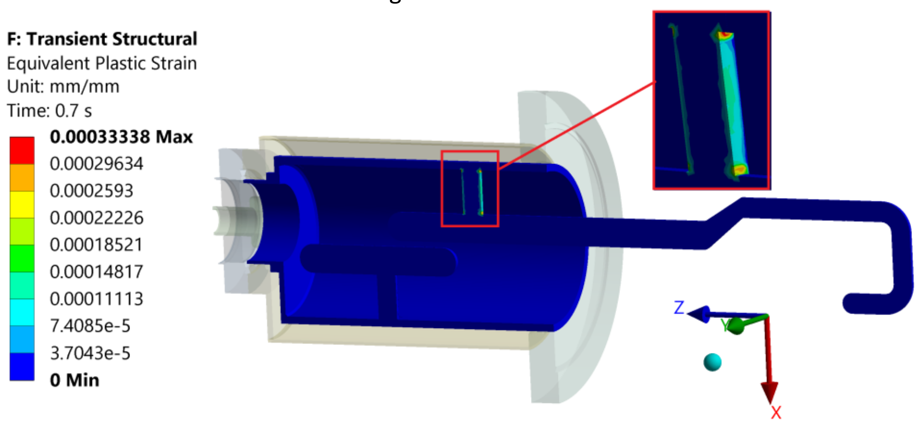
Transient analysis needed

RFD AUP H-HOM transport calculations

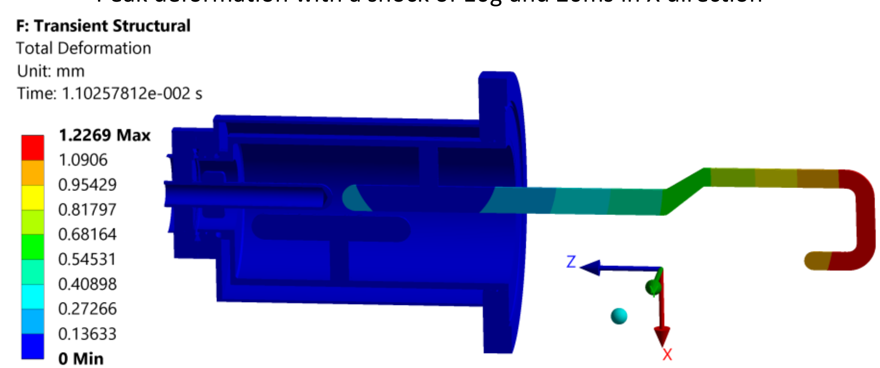
2. Shock analysis - Transient

- Results -X direction (most critical)
  - Time-dependant simulation needed to analyse the effect of the high stresses on the permanent deformation
  - Important simulations parameters:
    - Total time = 0.7 s – it is enough to damp most of the oscillations
    - Damping ratio = 2% (standard value)

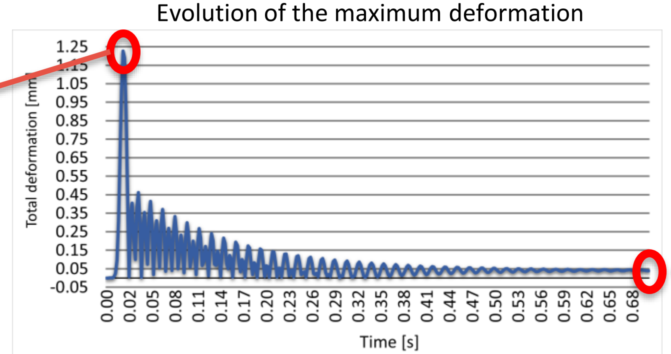
Plastic strain with a shock of 10g and 20ms in X direction



Peak deformation with a shock of 10g and 20ms in X direction



Evolution of the maximum deformation



Peak instantaneous deformation = 1.23 mm
<
Space hook-cavity = 9mm

Permanent deformation
⩽
0.04mm

RFD AUP H-HOM transport calculations

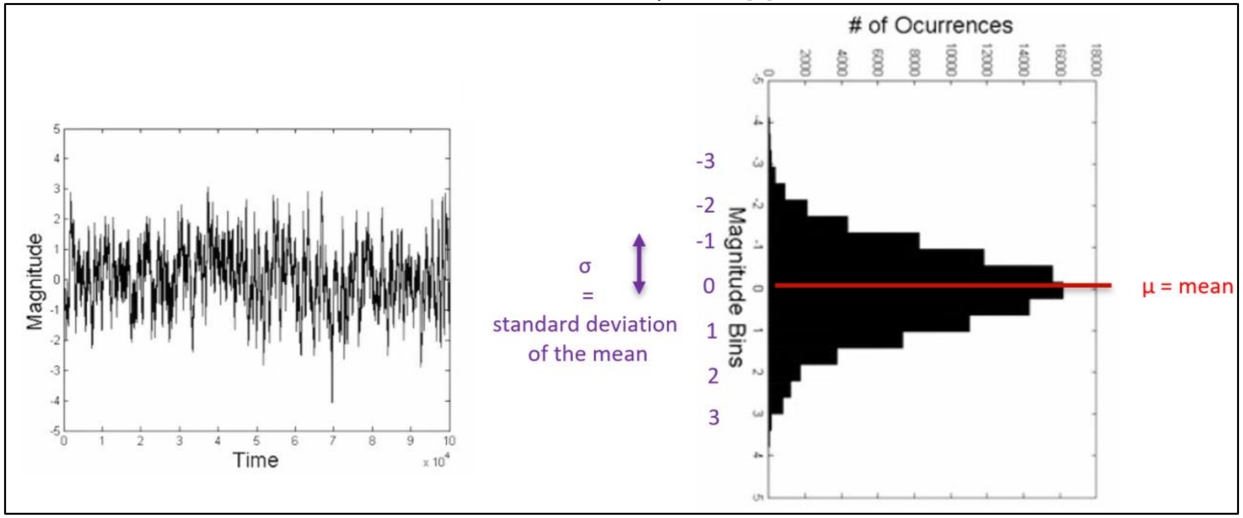
3. Random vibration analysis

- Dynamic, non-deterministic loads in a long time
- RV = Gaussian process: stationary and zero mean

Also the stresses

Amplitud-time history [1]

Gaussian random process [1]



Standard deviation RMS	Probability
1σ	68%
2σ	95%
3σ	99.7%

Limit considered → 3σ | 99.7%

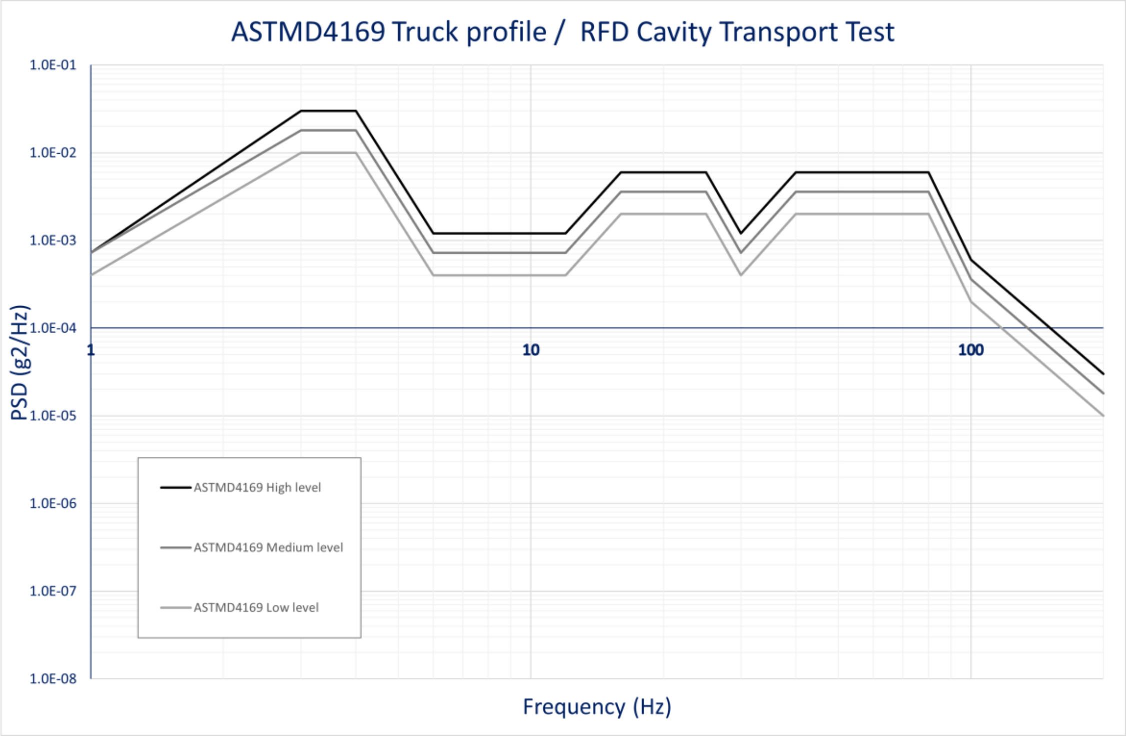
[1] L.E. Ballesteros ¨Failure prediction of structures subjected to random vibrations¨ http://hdl.handle.net/10150/630147

RFD AUP H-HOM transport calculations

3. Random vibration analysis

- Power Spectral Density (PSD) function
  - From time domain – to frequency domain
  - Average Power or energy of the vibration as a function of the frequency

PSD curve of truck transport [2]

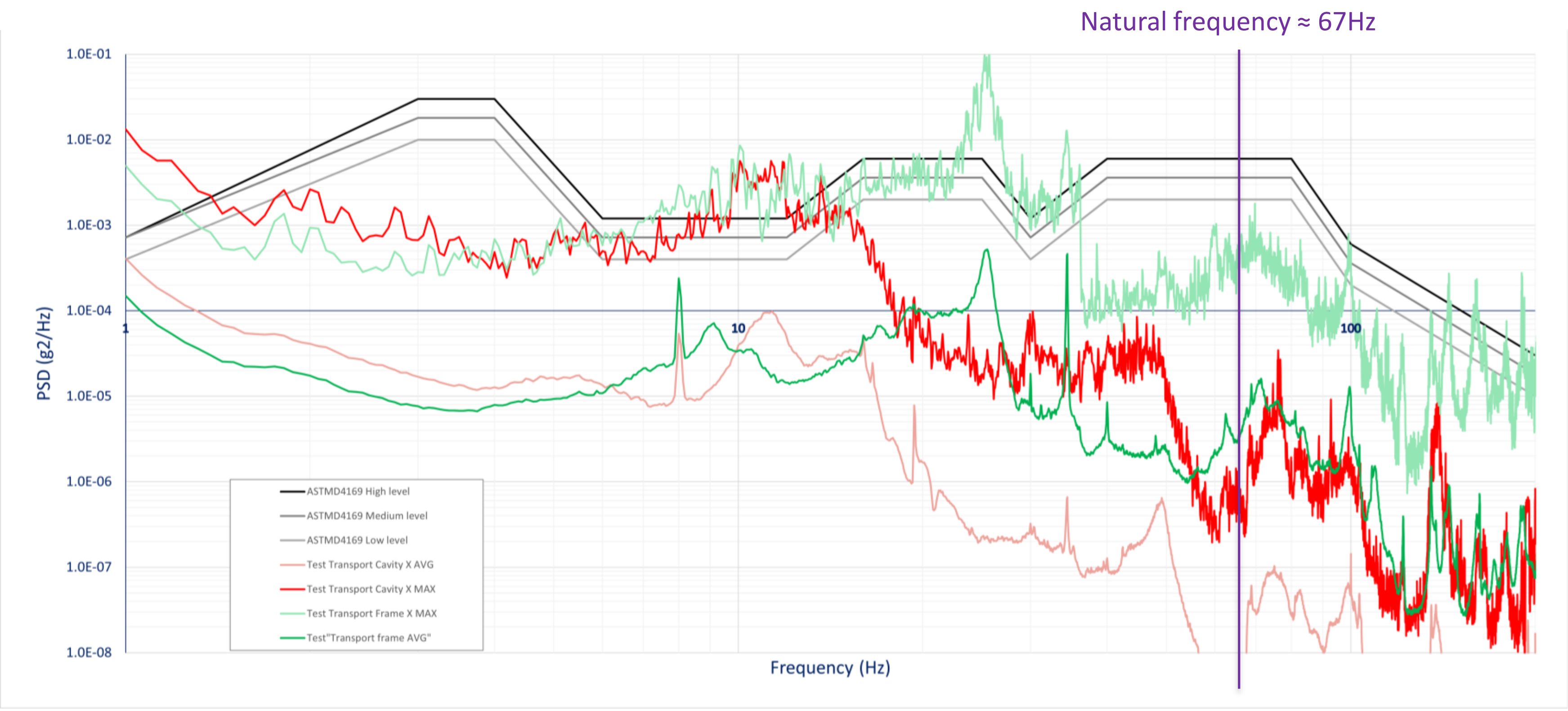


[2] "ASM D4169 -16 - Standard Practice for Performance Testing of Shipping Containers and Systems," ASTM International, West Conshohocken, PA, 2016.

RFD AUP H-HOM transport calculations

- **Random vibration analysis**

PSD curve of truck transport. From ASTM D-4169 [2] and CERN transport data from STFC to CERN in X direction [3]

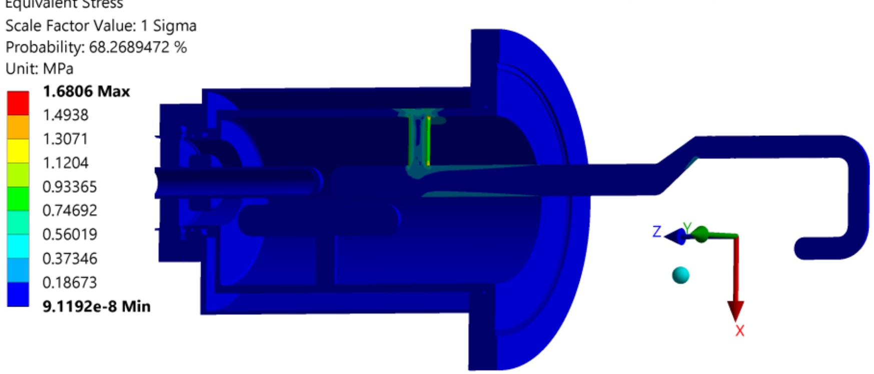


[2] "ASM D4169 -16 - Standard Practice for Performance Testing of Shipping Containers and Systems," ASTM International, West Conshohocken, PA, 2016.
[3] M. Guinchard, "Mechanical vibration and stress measurements on the RFD cryomodule during transport from UK" EDMS 2755675.

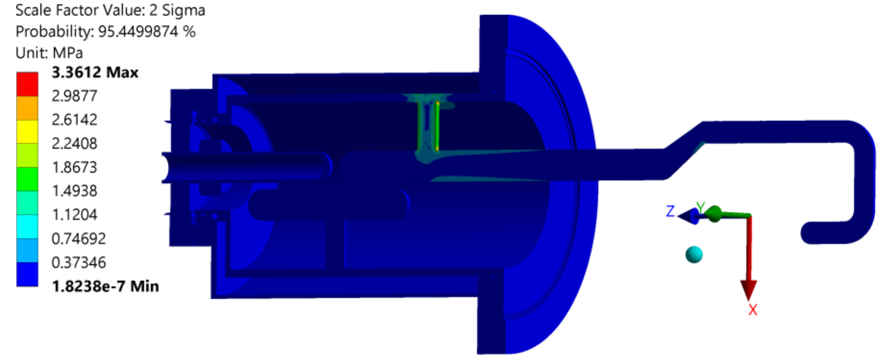
RFD AUP H-HOM transport calculations

- **Random vibration analysis**
  - Results – X direction is the most critical

Probability of occurrence 68.27%
68.25% of probability to not exceed **1.6 MPa**

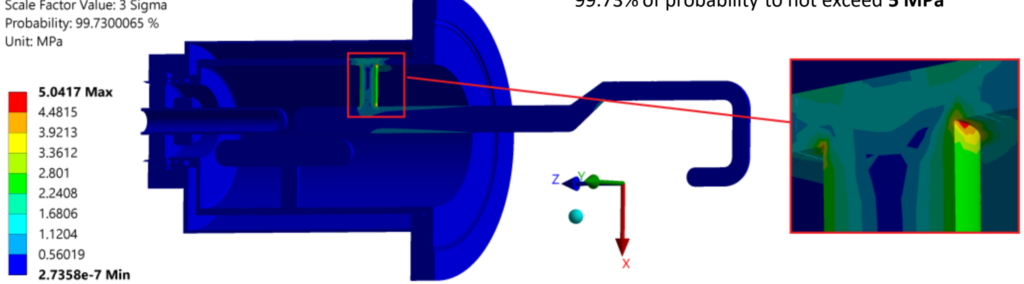


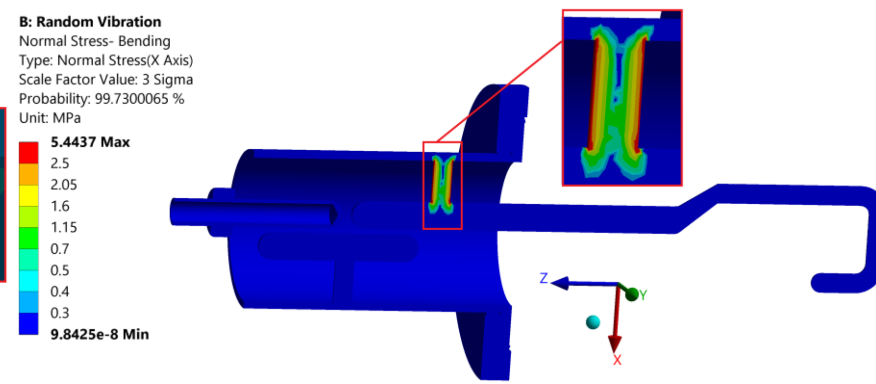
Probability of occurrence 27,18%
95.45% of probability to not exceed **3.4 MPa**



No plasticization but **Cyclic load**.
Therefore, it could failure by:
– **Fatigue** (Assessed by the stress life method)

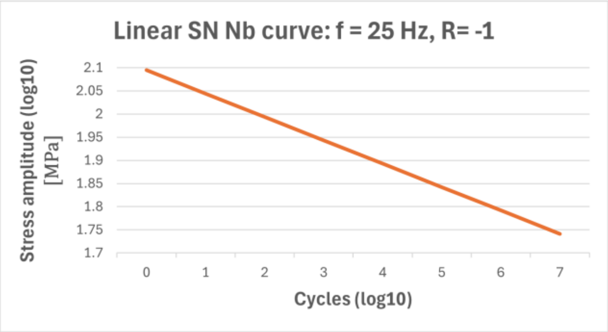
Probability of occurrence 4,28%
99.73% of probability to not exceed **5 MPa**



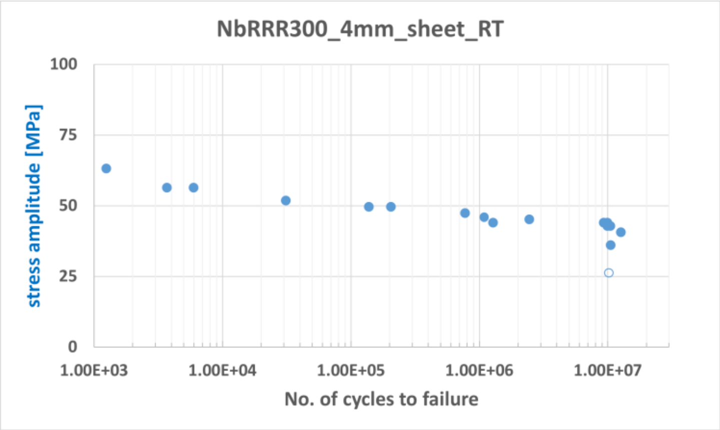


RFD AUP H-HOM transport calculations

- **Fatigue analysis**
  - **Cyclic** random vibration load
  - ANSYS Fatigue tool RV – stress life (Whoeler)
    - S-N curve of Nb
      - Linear or bi-linear
      - R = σ_{min} / σ_{max} = -1 (default)
      - Strain rate (frequency)



SN curve of Nb: f = 25 Hz and R = 0.1 (draft results, pending publication)
Courtesy of A. Galifa



- Three sigma method + Damage (Miner's rule):

RMS stress level	Occurrence Probability P_i	Stress Amplitude [MPa]
1σ	68.27%	1.6
2σ	27.18%	3.4
3σ	4.28%	5

Narrow band process assumption (each zero up crossing = 1 cycle)

$$D = \frac{n_{1\sigma}}{N_{1\sigma}} + \frac{n_{2\sigma}}{N_{2\sigma}} + \frac{n_{3\sigma}}{N_{3\sigma}} < 1$$

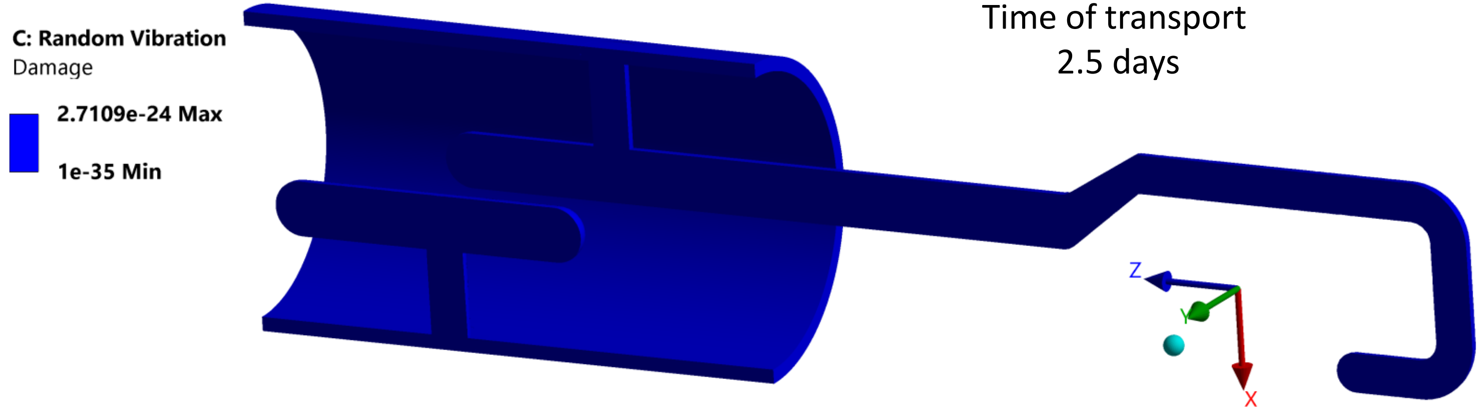
$$n_{i\sigma} = f_o \text{ x T x } P_i\text{; being } f_0 = \frac{1}{2\pi}\frac{\dot{\sigma}0}{\sigma 0}$$

$$N_{i\sigma} = N_2 \text{ x } \left(\frac{S_{i\sigma}}{S_2}\right)^{1/b}$$

Depends on the point considered
$\dot{\sigma}0$ = RMS stress velocity
$\sigma 0$ = RMS stress

RFD AUP H-HOM transport calculations

- **Fatigue analysis**
  - Results



Time of transport
2.5 days

No fatigue fracture

Conclusions

- Transport is a daily and challenging activity of the crab cavity project
- To protect our components and assemblies during transport
  - Risk analysis
  - Risk mitigation
- HOMs calculations: RFD AUP
  - Shock
  - Random vibration
  - Fatigue
- Results show no risk for the component ☺

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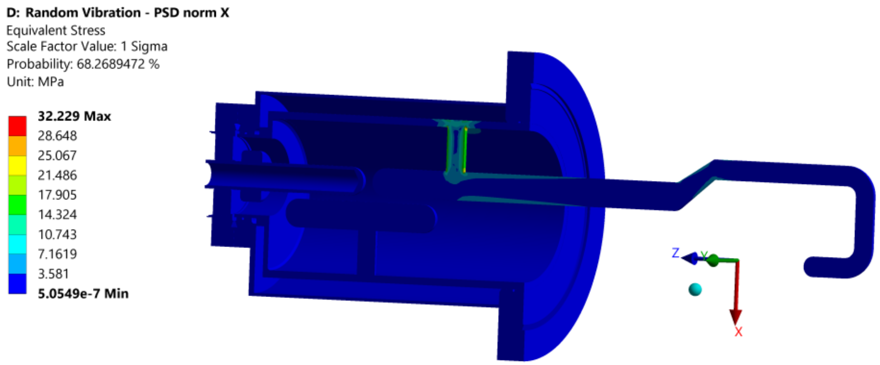
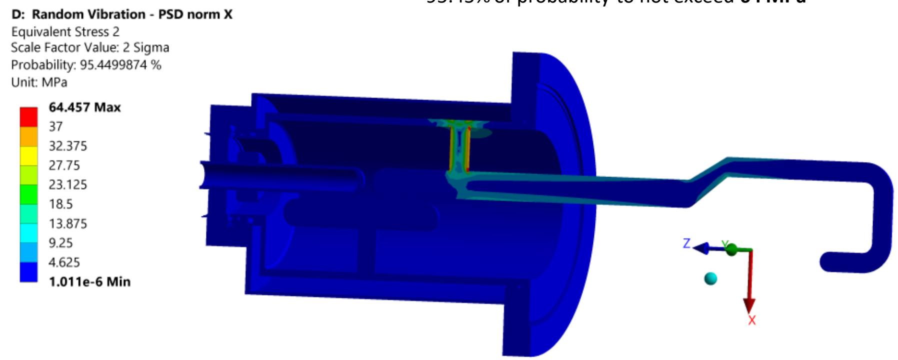
RFD AUP H-HOM transport calculations

- **Random vibration analysis –** max PSD of the norm ASTM D-4169
  - **Results** – X direction is the most critical

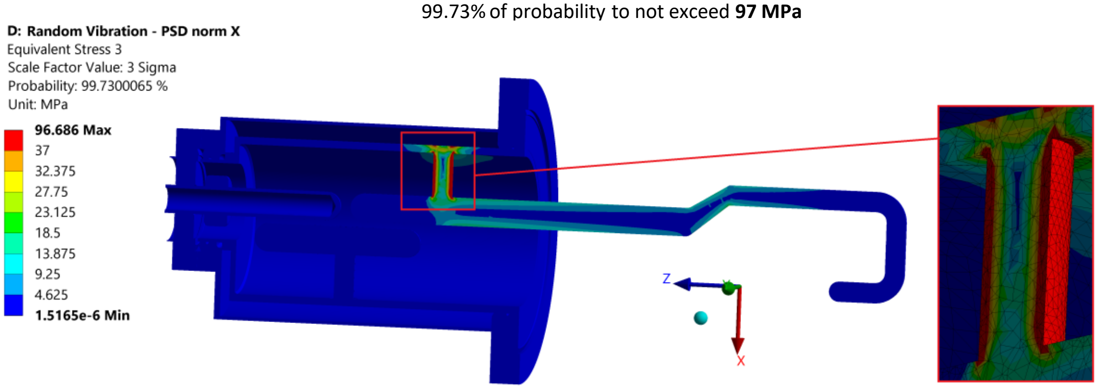
Probability of occurrence 68.27%
68.25% of probability to not exceed **32 MPa**



Probability of occurrence 27,18%
95.45% of probability to not exceed **64 MPa**



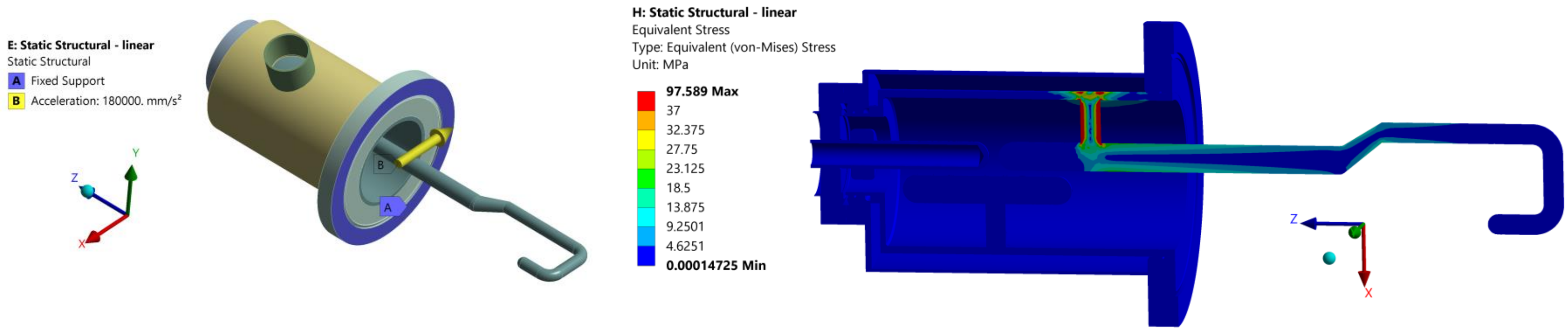
Probability of occurrence 4,28%
99.73% of probability to not exceed **97 MPa**



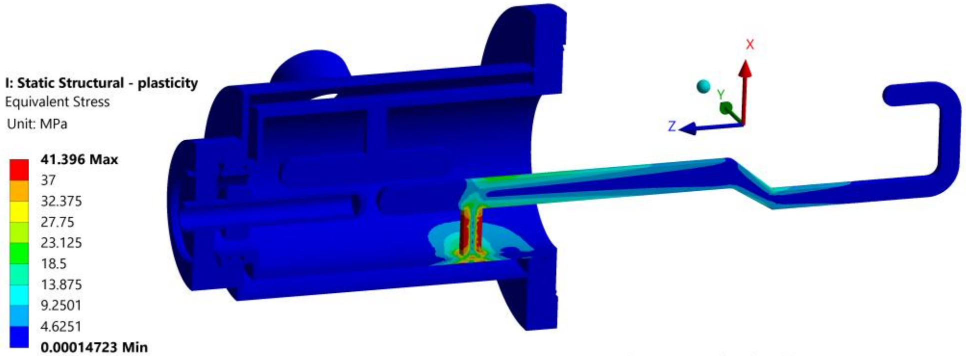
Plasticization

RFD AUP H-HOM transport calculations

- Linear elastic static structural analysis



- Elasto-plastic static structural analysis

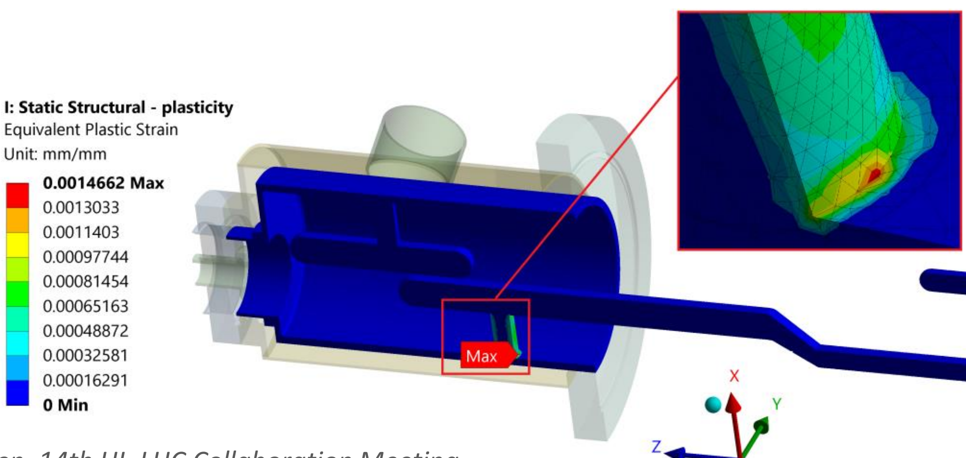


0.1% of **plastic strain** and **cyclic load**.

Therefore, there could be two possible failures:

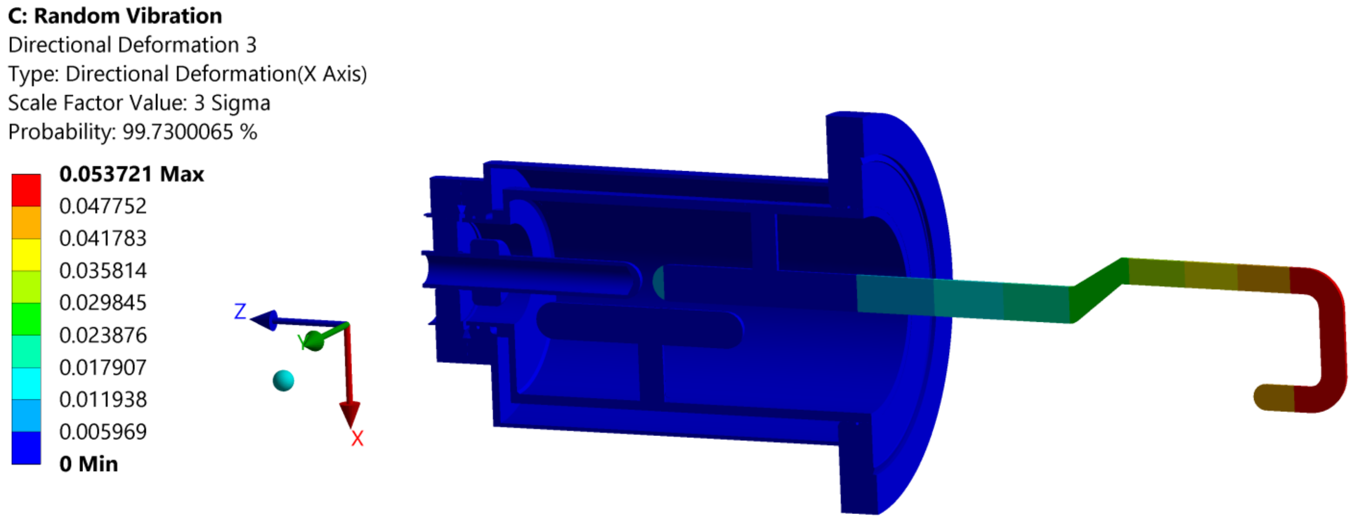
– **Fatigue** (Cannot be assessed for the moment)

– **Ratcheting** (It doesn't happen when we have a Random vibration because the stress cycling is symmetric*)*



RFD AUP H-HOM transport calculations

- **Random vibration analysis**
  - Results – X direction is the most critical



Probability of occurrence 4,28%
99.73% of probability to not exceed **0.05 mm**

0.05 mm << 9 mm (Space hook-cavity)