



Updates on the thermo-mechanical studies of the TDE dump block assembly

- Follow-up of Presentation of the 7th HL-LHC Collaboration Meeting -

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EN-STI-TCD



8th HL-LHC Collaboration Meeting – 18th of October 2018

Agenda

- Introduction
- Thermal and structural simulations
 - Load Application
 - Stress Evaluation
- Real Data Acquisition
 - Vibrometer Data
 - Performed Interventions

More details:

EDMS 1890875 [Presentation of 7th collaboration meeting],

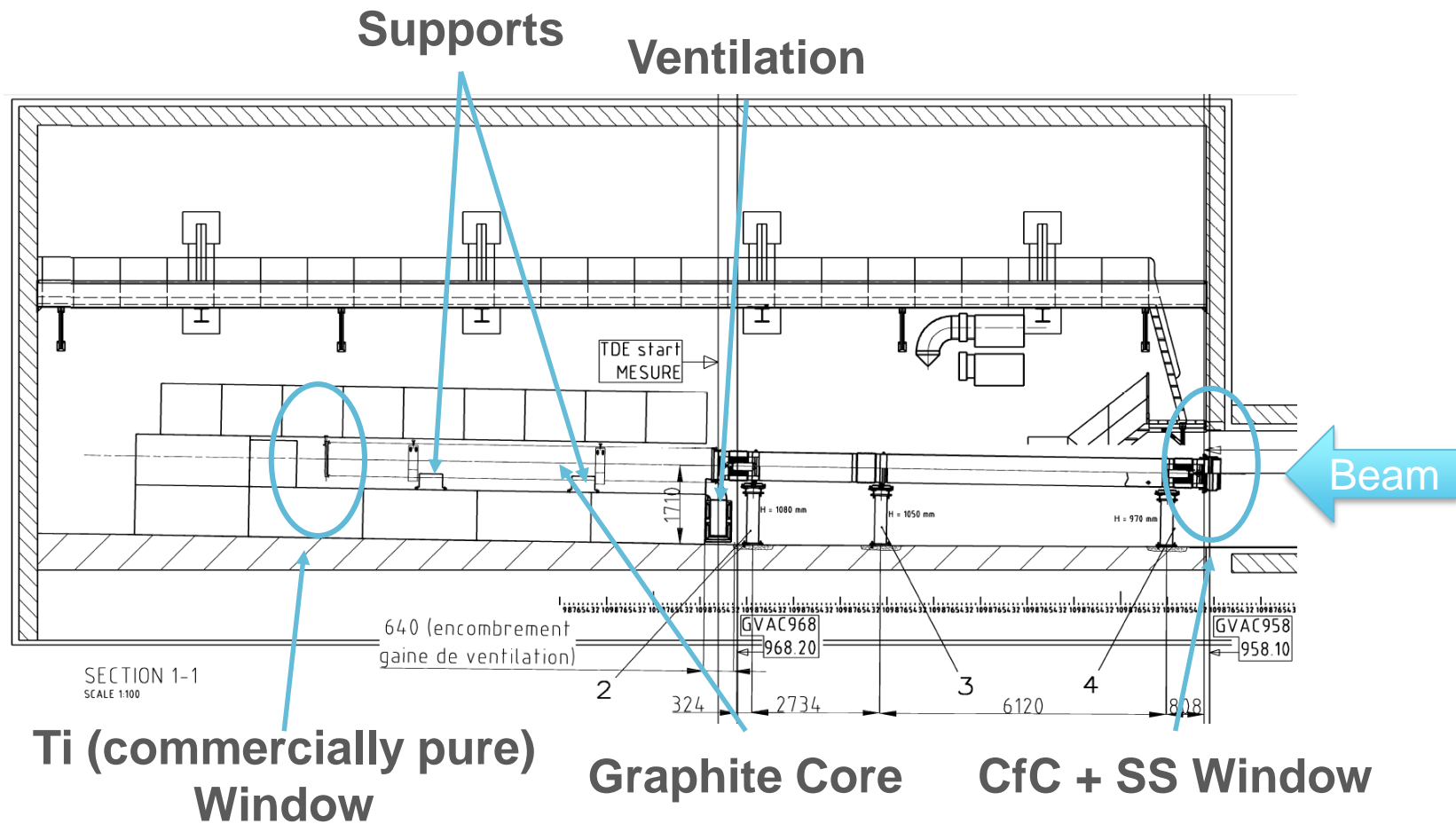
EDMS 2029814 [documentation for HW-baseline, still under Approval]

Photo of Dump and of Support Structure from Downstream



B
e
a
m





Overview of the Dump Cavern in UD62

- The two dumps are placed each in a cavern: UD62 and UD68
- The dumps consist of a stainless-steel housing and a core made of graphite.
- The whole sector of the beam pipe is filled with N₂-Gas at an overpressure of 200mBar.
- A window separates the dump (N₂) from the machine vacuum (upstream) and another window enclosing the N₂ volume in the core.

Relevant documents

- Dump High Density Segment
 - Assembly: https://edms.cern.ch/ui/file/575402/AA/lhctde_0021-vAA_plt_cp.pdf
- Dump Low Density Segment
 - Assembly: https://edms.cern.ch/ui/file/428955/AB/lhctde_0006-vAB_plt_cp.pdf
 - Details about Graphite: https://edms.cern.ch/ui/file/425522/1/conception_tde4.pdf
- Upstream Window
 - <https://edms.cern.ch/document/1080998/1>
 - https://edms.cern.ch/ui/file/682805/0/lhcvdwb_0001-v0_plt_cp.pdf
- Downstream Window
 - <https://edms.cern.ch/document/756992/1>

Load Application

	Run2 Beam Parameters		HL Beam Parameters		
	LHC BCMS	LHC Standard 25ns	LHC BCMS	LHC Standard 25ns	LHC BCMS Retrigger Scenario
Energy	7 TeV	7 TeV	7 TeV	7 TeV	7 TeV
Bunch intensity	1.3E11	1.3E11	2.0E11	2.3E11	2.3E11
Emittance	1.37 $\mu\text{m rad}$	2.6 $\mu\text{m rad}$	1.37 $\mu\text{m rad}$	2.08 $\mu\text{m rad}$	1.7 $\mu\text{m rad}$
Sweep pattern	HL	Run2	HL	HL	HL
Number of Bunches	2604	2748	2604	2748	2604

The following beam parameters were used. They were determined with the FLUKA simulations which were the starting point of the presented simulations.

Load Application

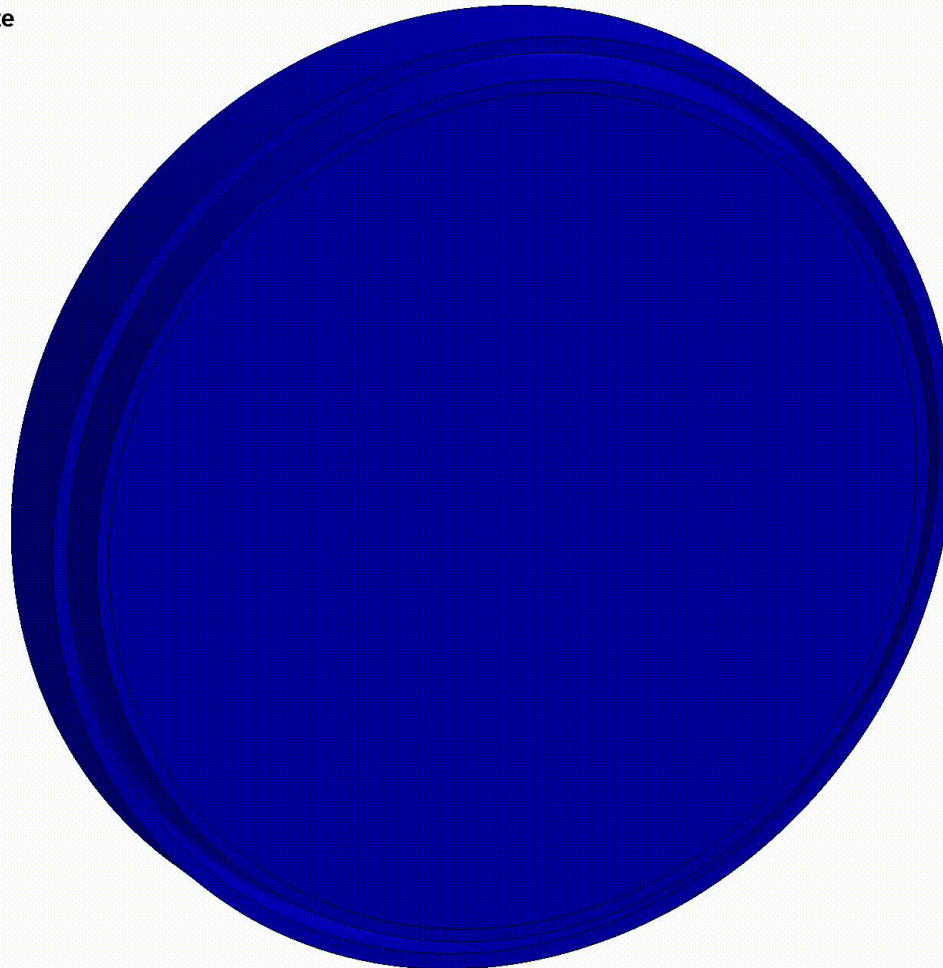
TDE - Front Window HL 6V2H - Graphite

Time = 0

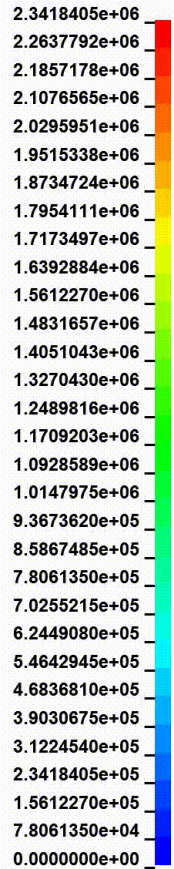
Contours of Effective Stress (v-m)

max IP. value

max=0, at elem# 1

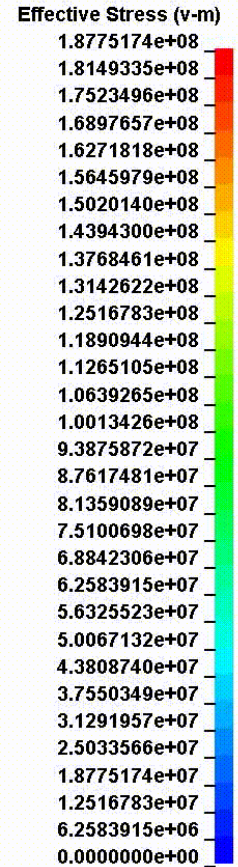
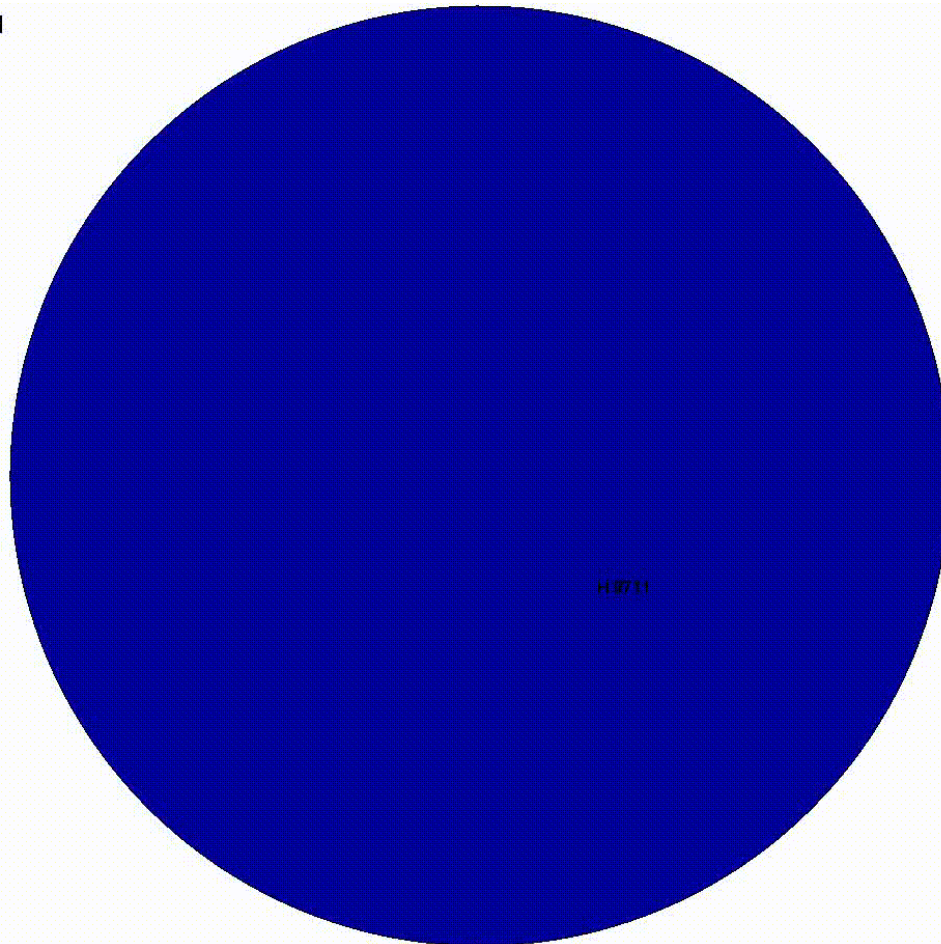


Effective Stress (v-m)



Upstream Window – Carbon Fibre Disc

TDE - Down-Stream Window - HL6V2H
 Time = 0
 Contours of Effective Stress (v-m)
 max=0, at elem# 1

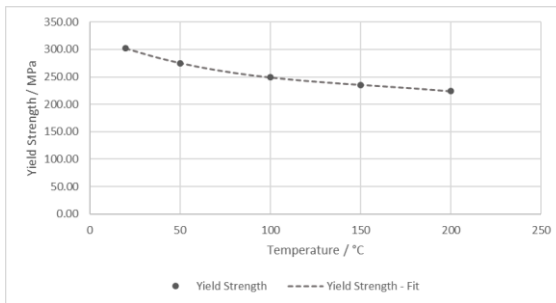


Downstream Window – Titanium Disc

Stress Evaluation

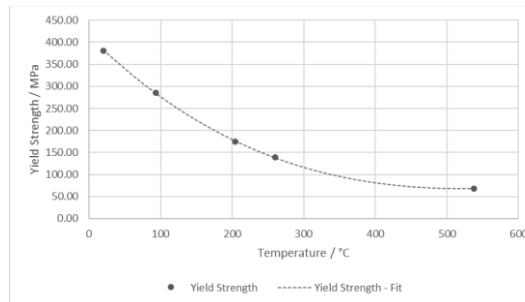
- A Python script evaluates for each material point at each time point the temperature dependent safety factor against permanent deformation
- It uses, an interpolation function for the temperature dependent yield strength and compares the result with the local eq. v. Mises Stress

SS316LN



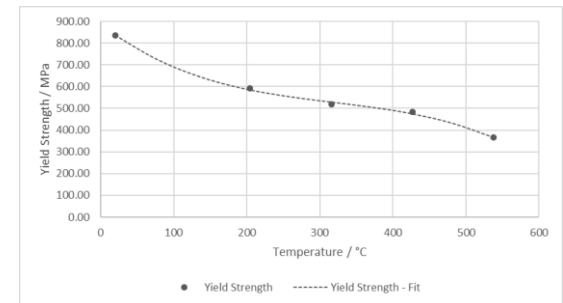
Designer Handbook, Specialty Steel Industry of North America, Washington DC (1998) - extracted from MPDB v7.71, Copyright 2014 by JAHM Software, Inc.

Titanium (commercially Pure)



Titanium CP2, Annealed
AMS 4900 and AMS-T-9046 for plates, documented in MMPDS-01

Titanium (Ti6Al4V)



Ti Grade 5, Annealed AMS4911 for 10mm thickness, Basis A documented in MMPDS-01

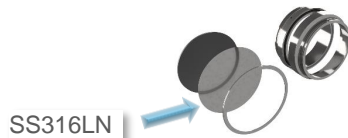
Used interpolations:

$$R_y = -1.47 \cdot 10^{-5} T^3 + 6.97 \cdot 10^{-3} T^2 - 1.312 \cdot T + 325.28 \quad R_y = -9.57 \cdot 10^{-7} T^3 + 2.26 \cdot 10^{-3} T^2 - 1.577 \cdot T + 412.24 \quad R_y = -6.88 \cdot 10^{-6} T^3 + 6.61 \cdot 10^{-3} T^2 - 2.520 \cdot T + 883.5$$

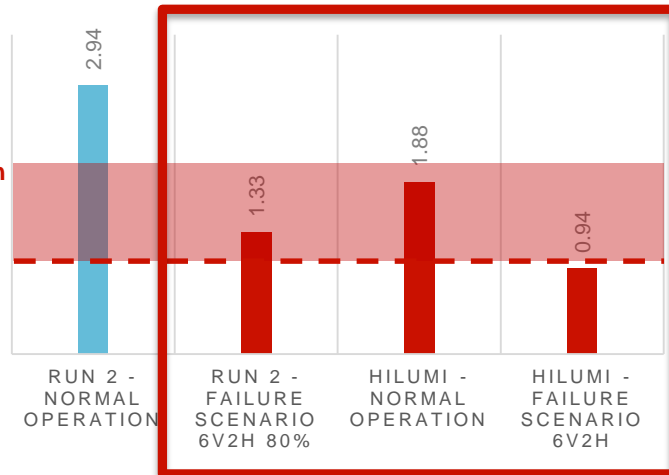
For each evaluated peak temperature the yield strength is then evaluated at a 5°C higher temperature

Stress Evaluation

Upstream Window



SAFETY FACTOR AGAINST YIELDING



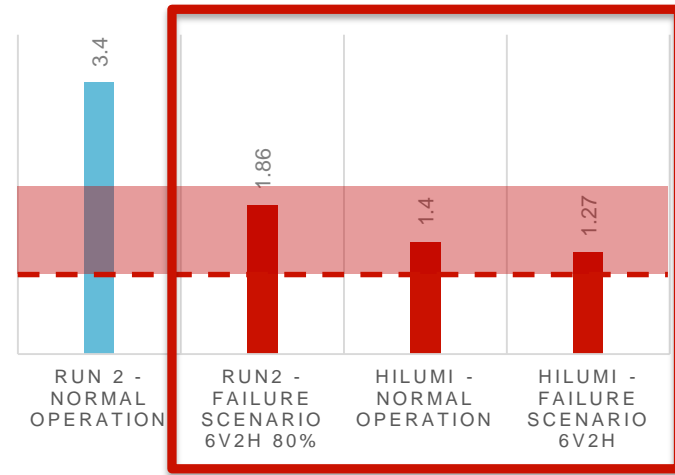
Necessary Margin
Underneath, safe operation is not guaranteed

$$S_y = \frac{R_y}{\sigma_{eq}}$$

Downstream Window



SAFETY FACTOR AGAINST YIELDING



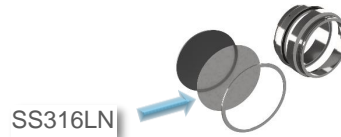
Lower limit
Underneath, the material deforms permanently

S_y = safety factor against yielding (permanent deformation) around reached temperature; always conservative
 R_y = yield strength of the material
 σ_{eq} = equivalent v. Mises stress

The expected stress levels in the windows are too high for a long-term and reliable operation

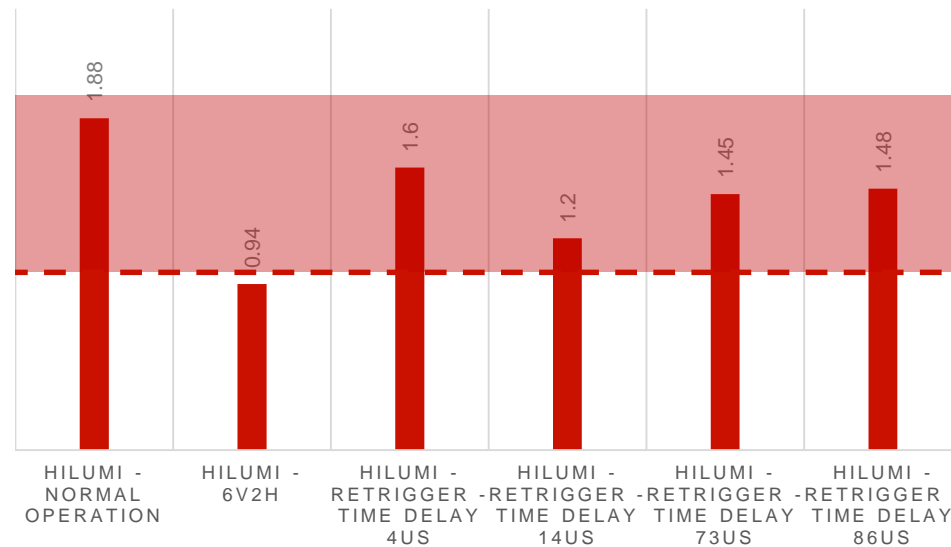
Stress Evaluation

Upstream Window



SAFETY FACTOR AGAINST YIELDING

Necessary Margin
Underneath, safe
operation is not
guaranteed



Lower limit
Underneath,
the material
deforms
permanently

The expected stress levels in the window are too high for a long-term and reliable operation

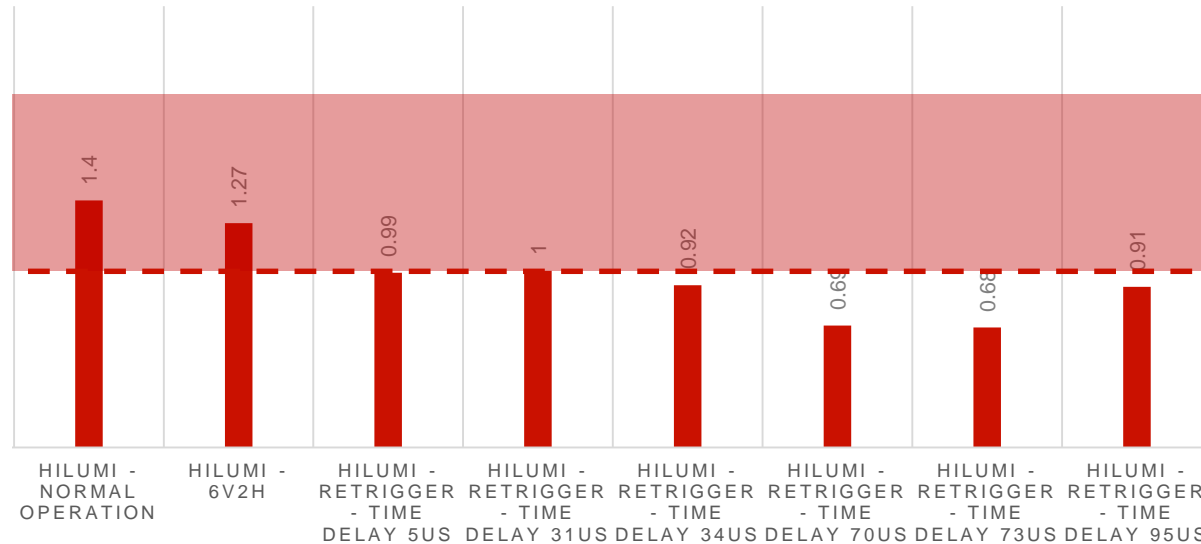
Stress Evaluation

Downstream Window



SAFETY FACTOR AGAINST YIELDING

Necessary Margin
Underneath, safe
operation is not
guaranteed

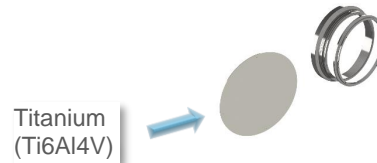


Lower limit
Underneath,
the material
deforms
permanently

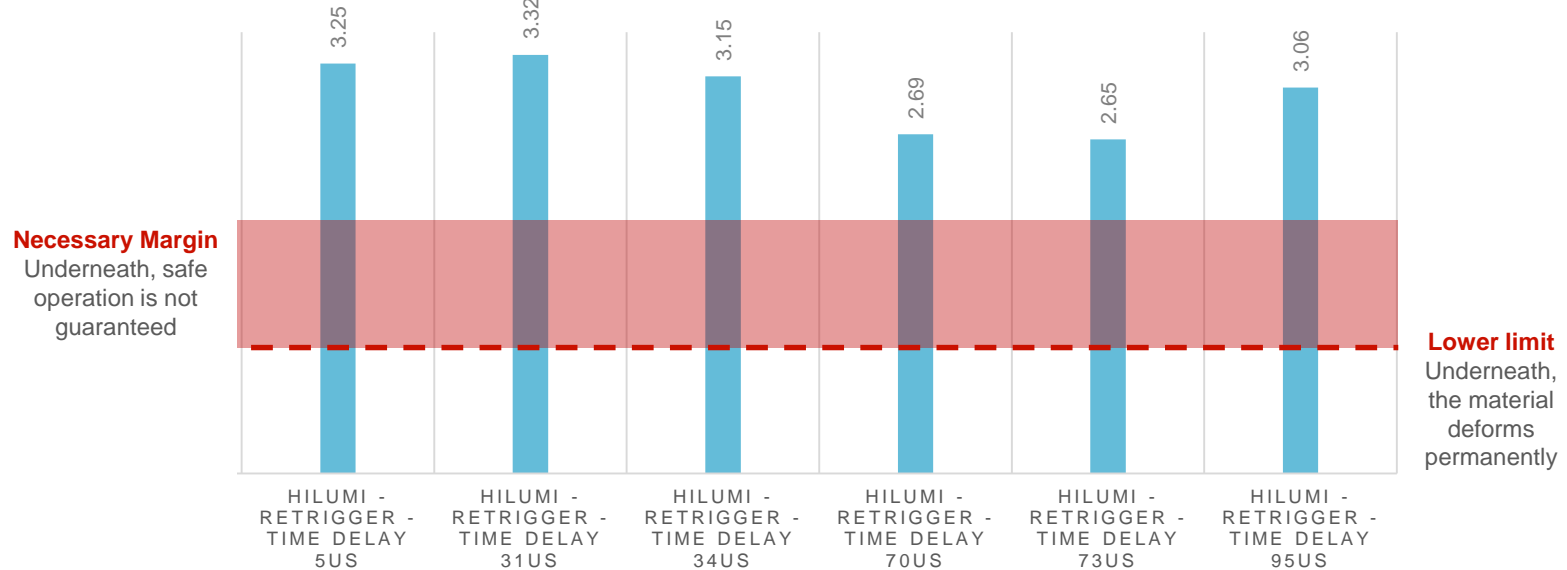
The expected stress levels in the window are too high for a long-term and reliable operation

Stress Evaluation

Downstream Window



SAFETY FACTOR AGAINST YIELDING



The expected stress levels for an upgraded window made of Ti6Al4V is acceptable for the considered load cases

Summary

- Both windows not suited in their current state for HiLumi or end of Run3
 - Core is not studied because of lack of data
 - Complete loss of deflection possible case with unknown effects
- Upgrade with Titanium Ti6Al4V will ensure survival for considered load cases
 - Future collaboration with NTNU promising → **After the start of tests > 8 months necessary before reliable data is available**
 - **Influence of material density change on FLUKA result**
 - **Until now not possible to simulate the risk of radioactive contamination**

Further open points:

Leaks, Vibration, Monitoring of the Device, ...?

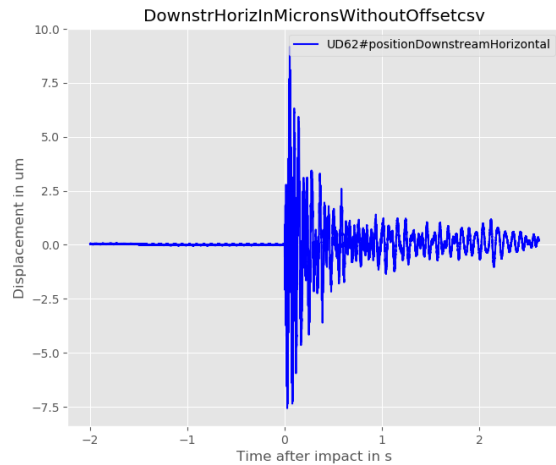
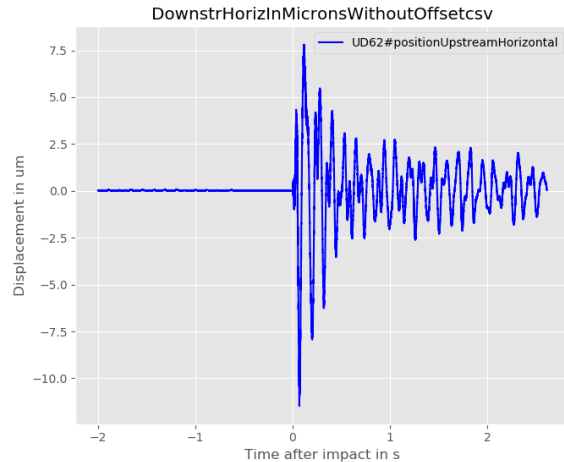
Clear Functional Specification for the dump assembly necessary

Real Data Acquisition

- During technical stop increase of acquiring rate for the N2-gas pressure to 1kHz with same trigger as for vibrometers
- Data analysis ongoing if there are pressure spikes causing additional loosening of collars and consequently leading to leaks
- Modal analysis ongoing to identify Eigen-frequencies and –modes of the dump structure
- Intervention made aware of severity of impacts on the structure during normal operation
- Again, vibrations were not considered to occur during the design of the device

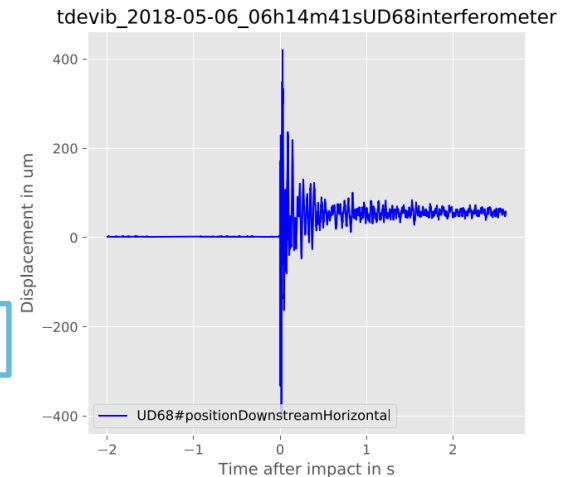
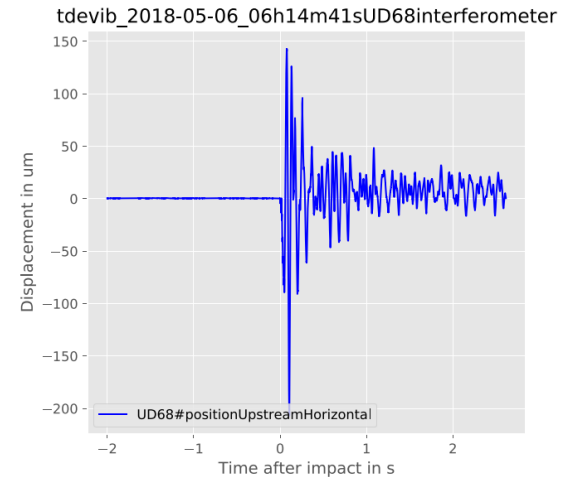
Horizontal Displacement

Modal Hammer



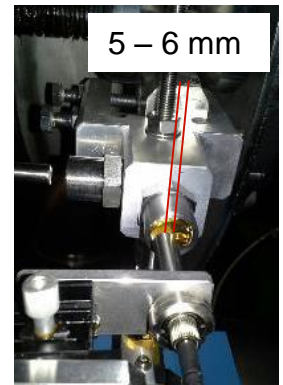
30/11/2016, B1 (UD68), 6.5 TeV,
915 bunches

270MJ beam



Summary Vibrometers

- Easy accessible signals in TIMBER
(TDE.UD68.B1.VIB:POSITIONUPSTREAMALIGNED, ...)
- The actual data files are stored in dfs with a sample rate of 200kHz
- **Signal lost during high-energy dump**
→ not clear what the permanent displacement is
- Loss of signal could be due more severe “vibrations” than expected
→ loss of reflected light beam



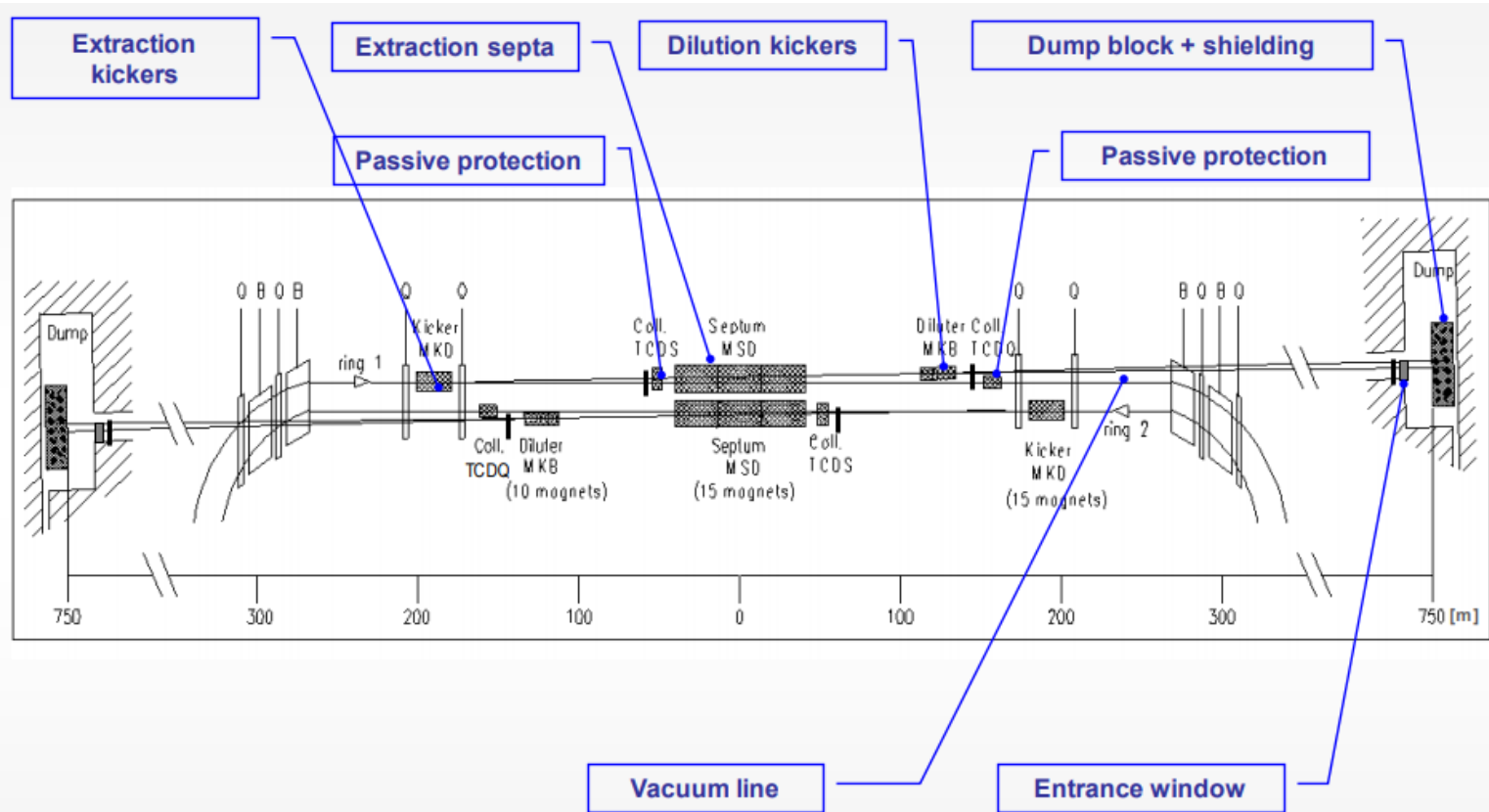


Thanks for your Attention

Thanks to everybody contributing to the retrieved simulation results and the preparation of the technical stop. Especially Matthias Frankl and Christoph Wiesner for numerous explanations and the provided input data for the simulations.



- Backup

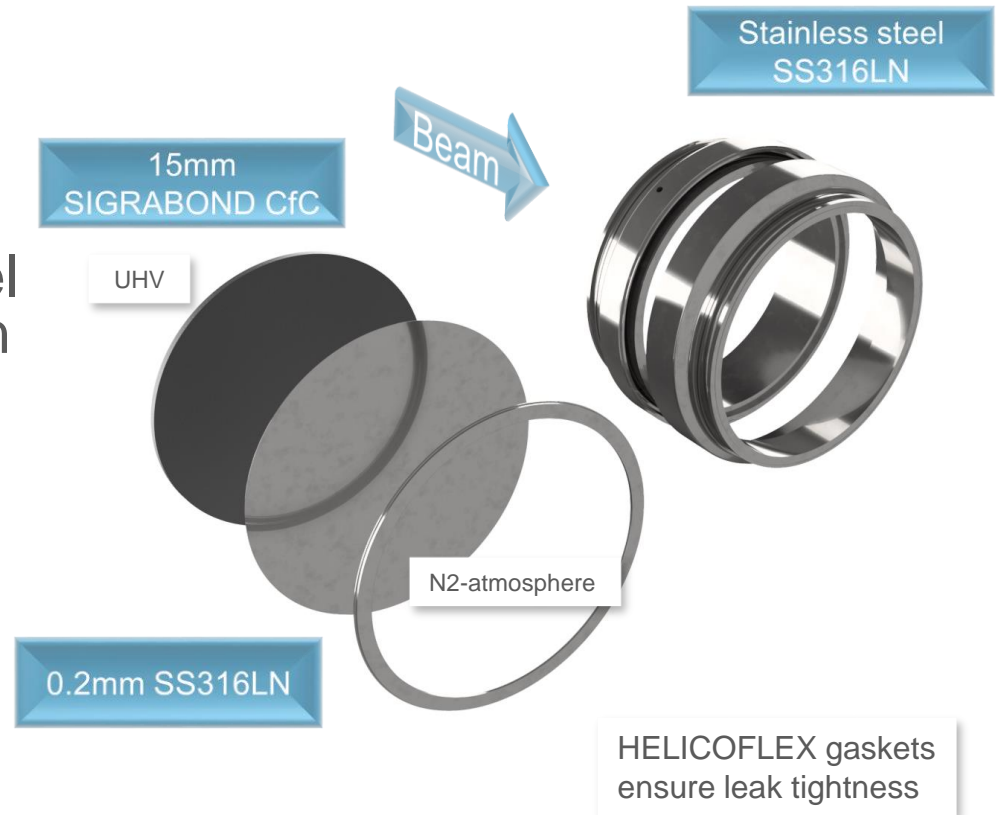


Schematic overview of beam dumping system without Q4 (LBDS)

The only devices covered by the presented work are the entrance window and the Dump.

Upstream Window

- 15mm CfC plate placed in the stainless-steel flange with transversal isotropic material characteristics
- 200um thick stainless-steel foil welded to the flange on top of the CfC plate to separate machine vacuum from Nitrogen-gas atmosphere
- **Beam spot size** dominates stress generation

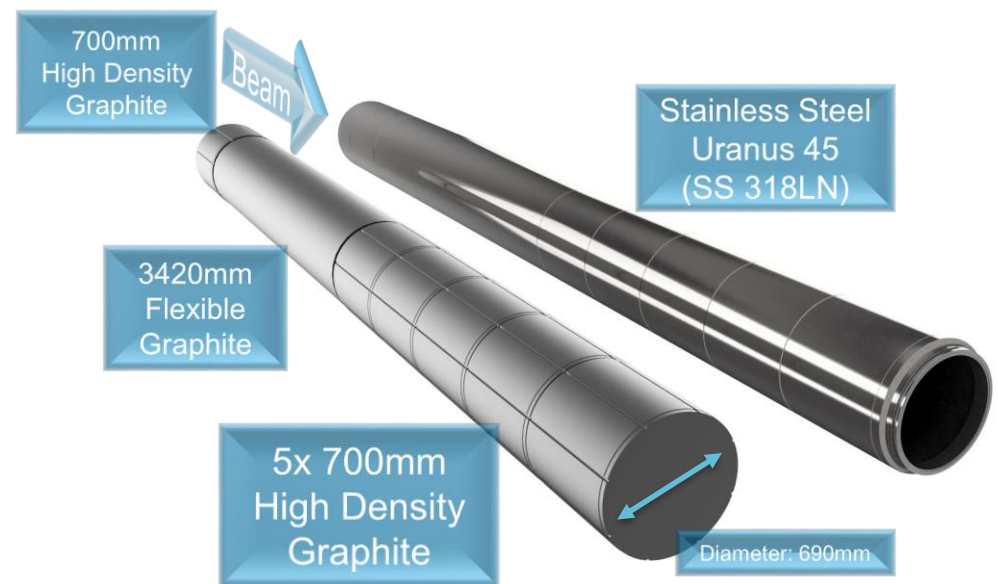


Source:

<https://edms.cern.ch/document/1867550/1>

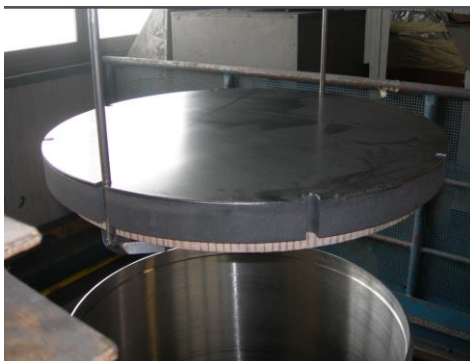
Dump

- Approx. 8.4m long graphite core with a diameter of 700mm and a graded density of 1.2g/cm^3 and 1.7g/cm^3
- 12mm thick, duplex stainless-steel welded pressure vessel
- Surrounded by approx. 1000t of concrete/steel radiation shielding



Flexible Graphite:
SIGRAFLEX L20012-C
High Density Graphite:
SIGRAFINE R7300 P500, shrink fitted
Source:
<https://edms.cern.ch/document/1867550/1>

Low Density Graphite Sector



Downstream Window

- Window keeps Nitrogen inside
- It separates the dump core from the **external** environment (if it breaks, the cavern gets contaminated)
- **Beam total intensity** dominates stress generation, due to showers caused by the dump core



Source:

<https://edms.cern.ch/document/1867550/1>

- Material Tests

Oxidation Studies (performed by SGL)

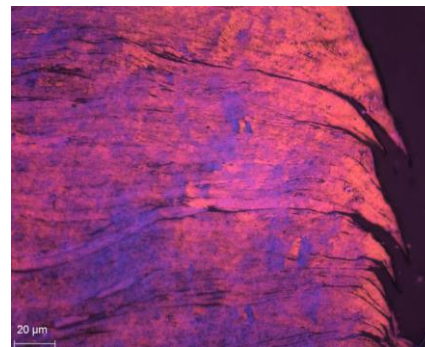
<https://edms.cern.ch/document/1848986/1>

- Oxidation Tests of graphite (Sigrafine R7300 and Sigraflex) finalized

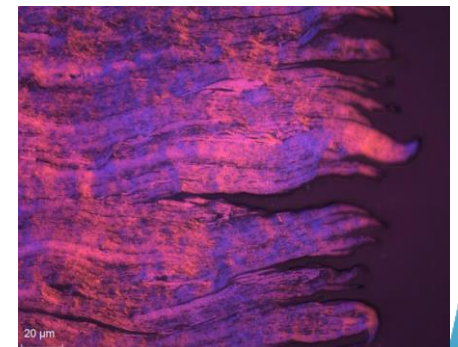
Temperature	Time	Atmosphere	Mass Loss		Comment
			Sigrafine	Sigraflex	
2500°C	1s	15ml Air	0.03%	0.11%	Mean of 3 samples in 5 experiments
2500°C	10s	150ml Air	0.66%	0.99%	Mean of 3 samples in 5 experiments
2500°C	100s	1200ml Air	5.80%	16%	Mean of 3 samples in 2/3 experiments; Standard deviation: 7.4%/16.5%
1200°C	1000s	Air	3.96%	25.50%	Mean of 6 samples in 1 experiment
1200°C	100s	Air	0.49%	2.50%	Mean of 5 samples in 1 experiment
1500°C; cool down in air to 150°C	10s – 20s	Air	1.6%	2.5%	Mean of 2 experiments with 1 sample each

- Mass loss for all tests at the surface (max depth at 1200°C of 1mm) due to high temperature
- No permanent change of material properties found (density, Young's modulus)
- Violent exothermic reaction excluded
- **Nitrogen gas is not inert at $T > 1500^\circ\text{C}$**

SEM picture of cross section of a Sigraflex sheet
1000s at 1200°C



Argon



Air



PRE-STUDY ON SIGRAFLEX TENSILE PROPERTIES

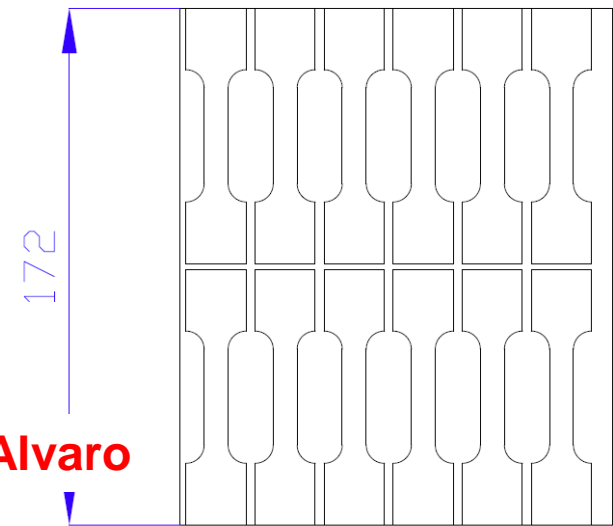
Filippo Berto, Antonio Alvaro

Pre-study on SIGRAFLEX tensile properties

As delivered sigraflex sheet

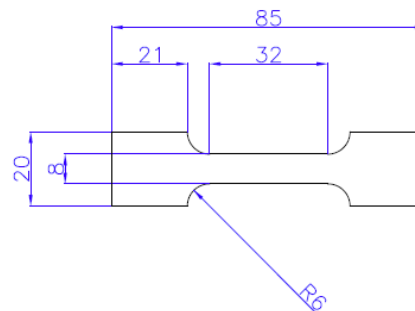


Specimen positioning
with respect to the
sigraflex sheet



Work and Material of **Filippo Berto and Antonio Alvaro**

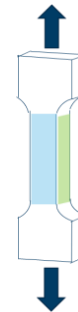
Specimen design



Experimental Methodology

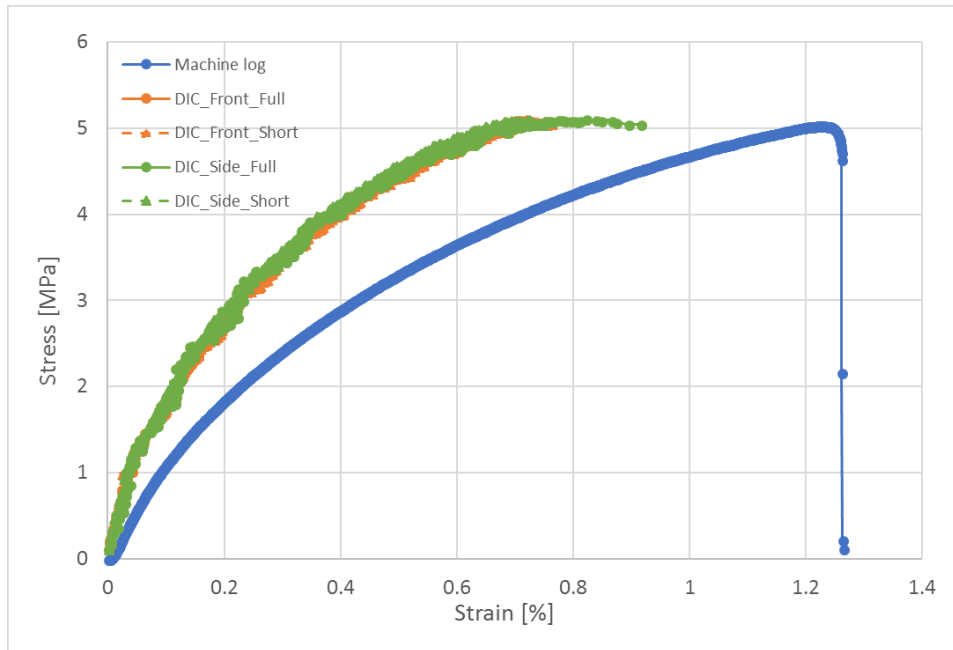
Work and Material of **Filippo Berto** and **Antonio Alvaro**

- MTS equipped with 1 and 5 KN load cell (NTNU lab with DIC provided by SINTEF);
- Four strain rates (ranging from $3.13\text{E-}4$ to $3.13\text{E-}1$ 1/sec);
- Two parallels for each strain rate;
- Two cameras Digital Image Correlation (DIC) for strain analysis of both front (blue surface) and side (green surface) of the specimen;



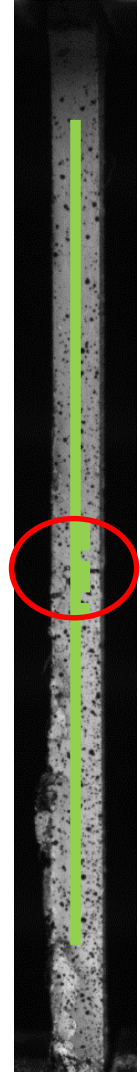
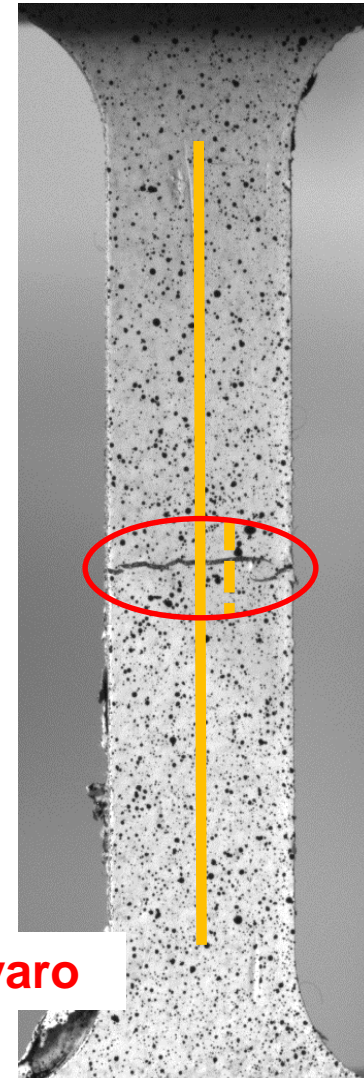
Example Result

Results: specimen 0.01B



Front

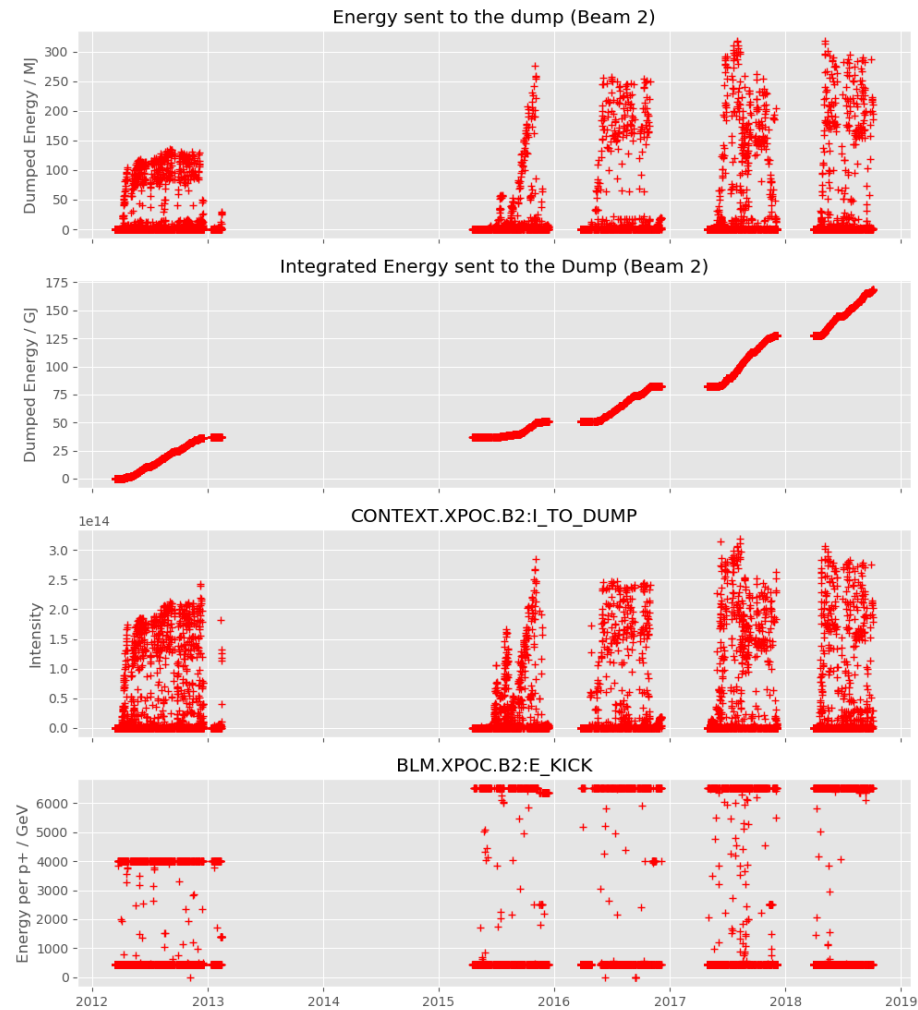
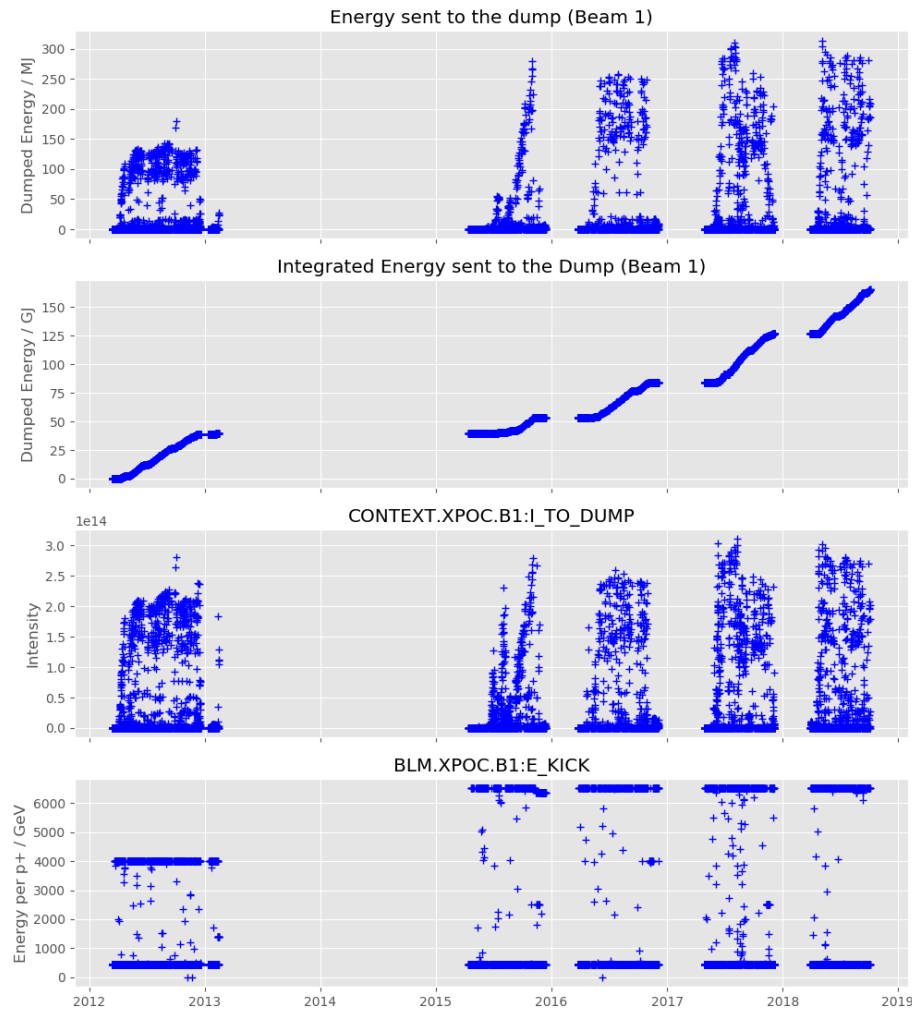
Side



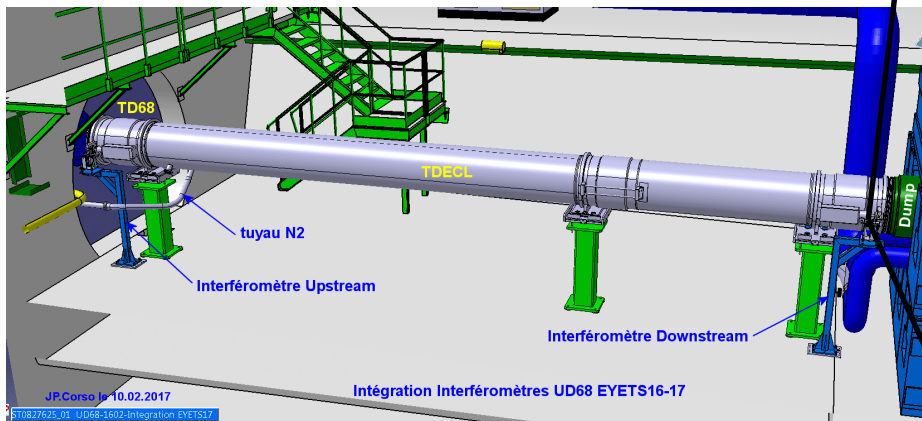
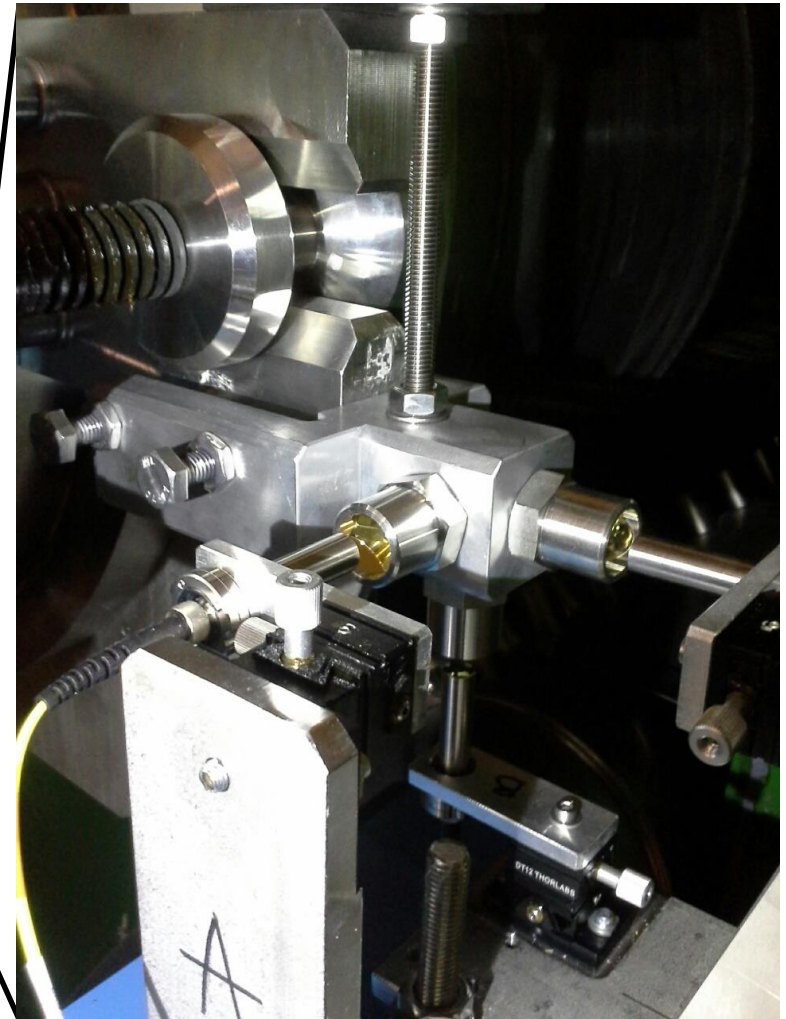
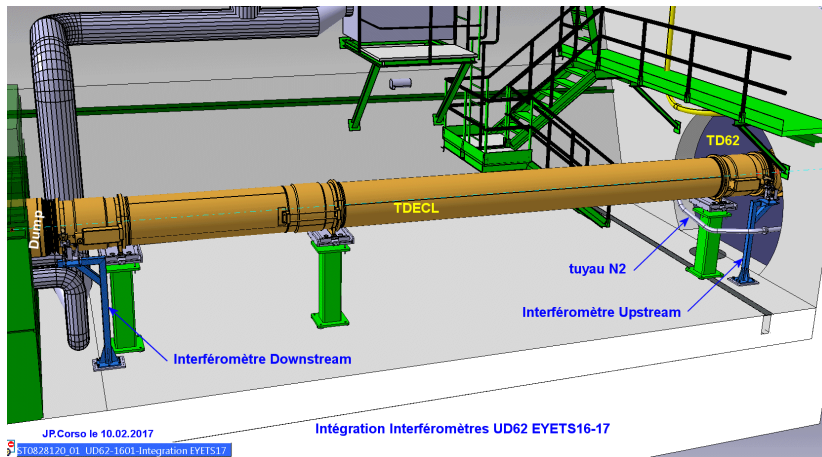
Work and Material of **Filippo Berto** and **Antonio Alvaro**

- Operational Feedback

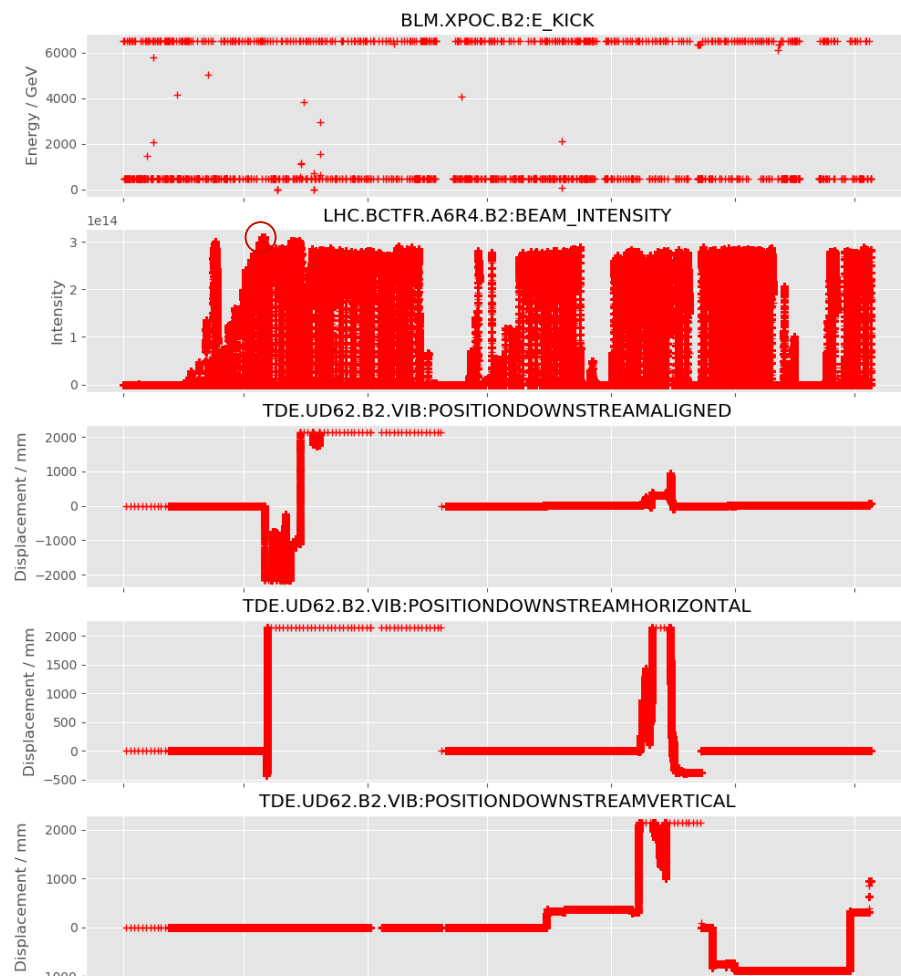
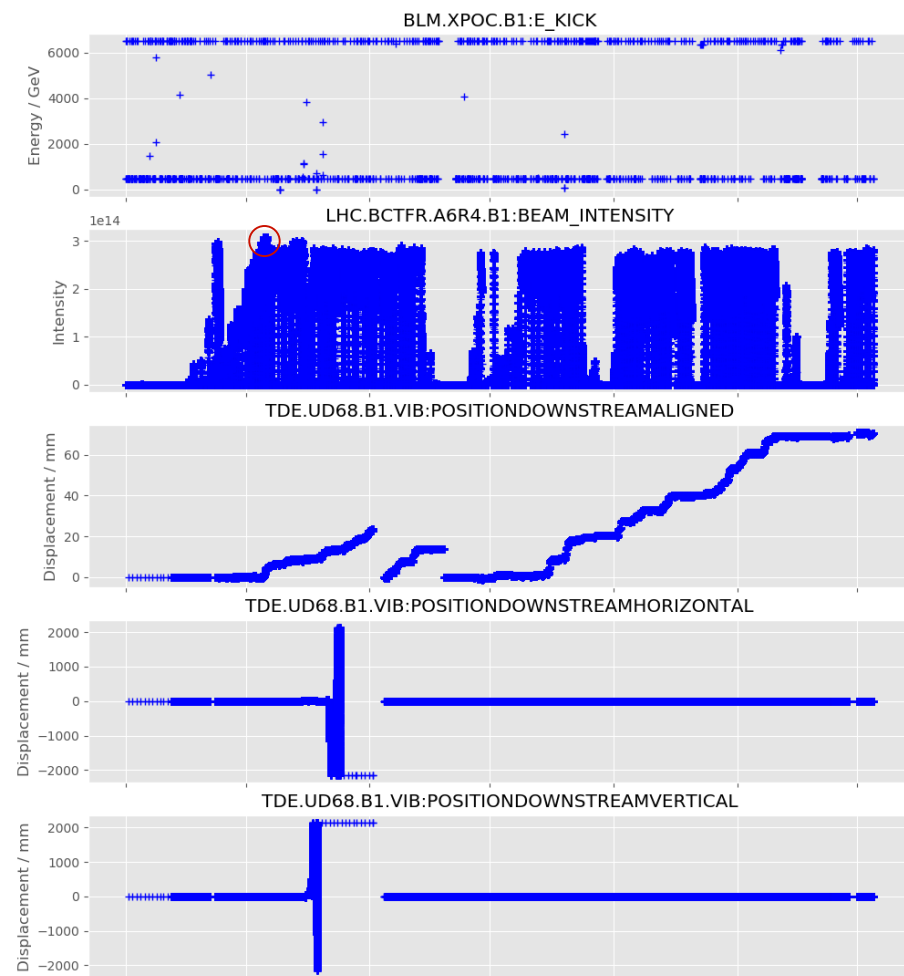
All Dumps from 2012 on until 04.10.18



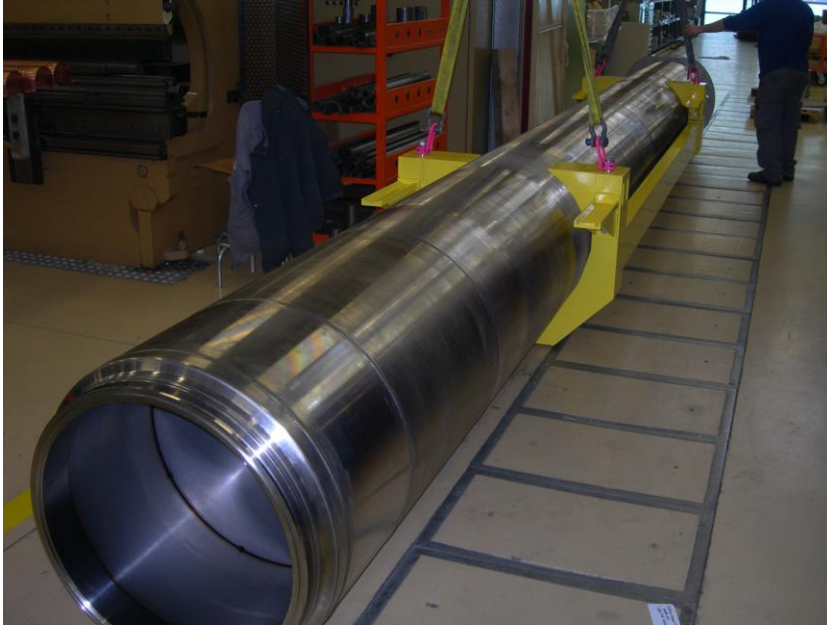
Vibrometers



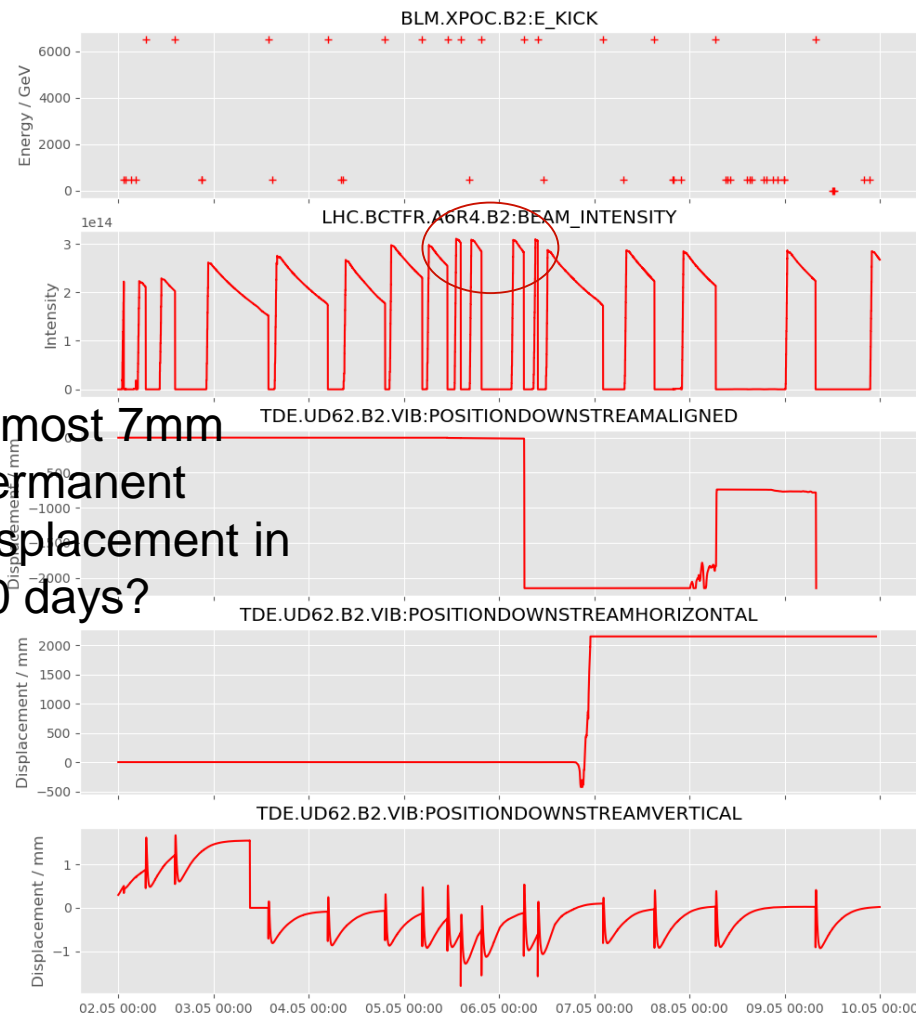
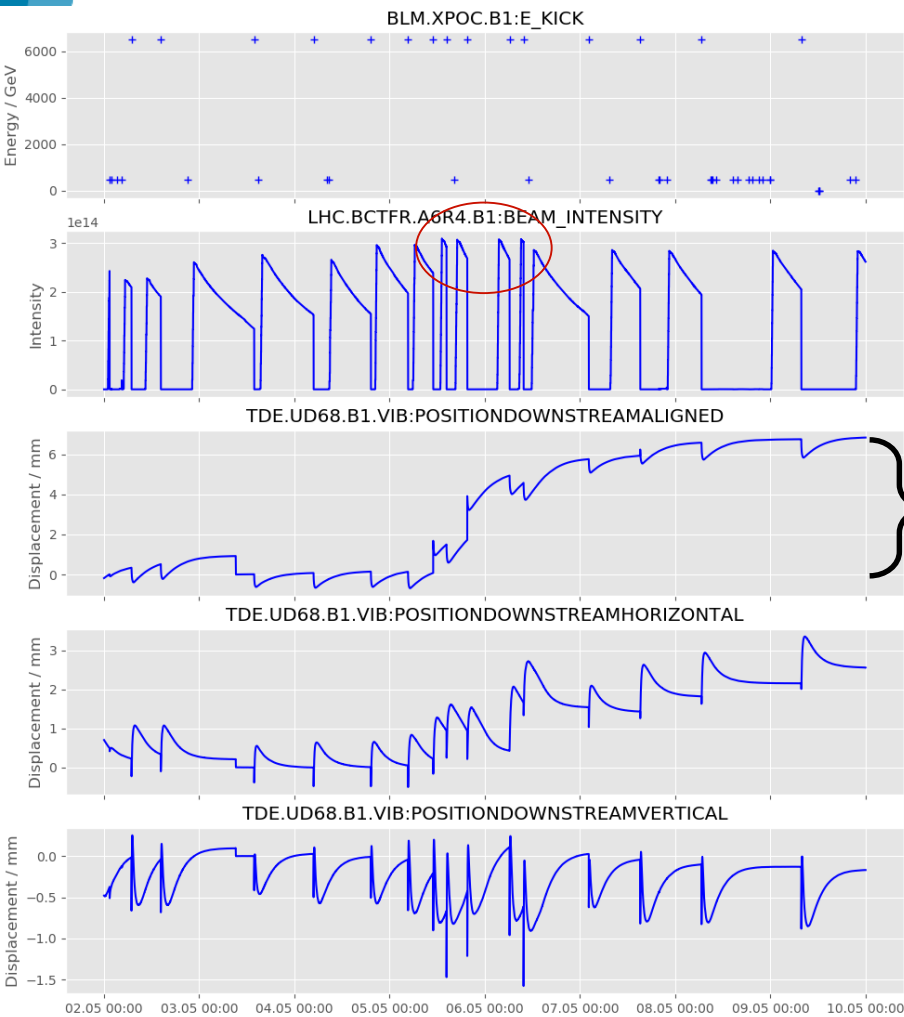
All Dumps from 2018 until 04.10.18



All signals lost at some point
Around 70mm displacement in UD68?



Physically not possible ...



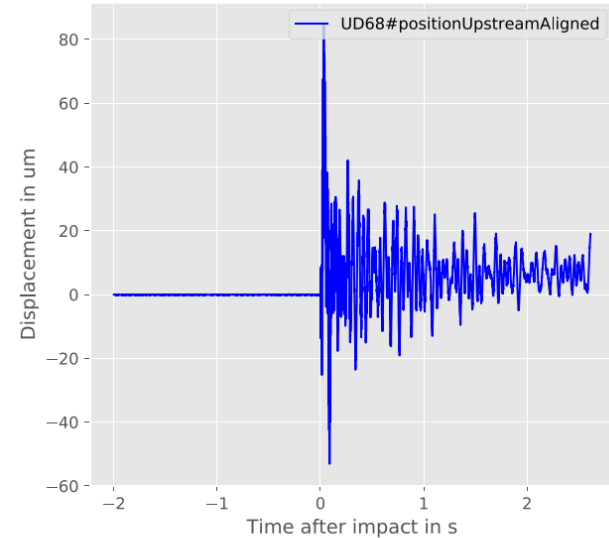
Almost 7mm
permanent
displacement in
10 days?

Marked Dumps:

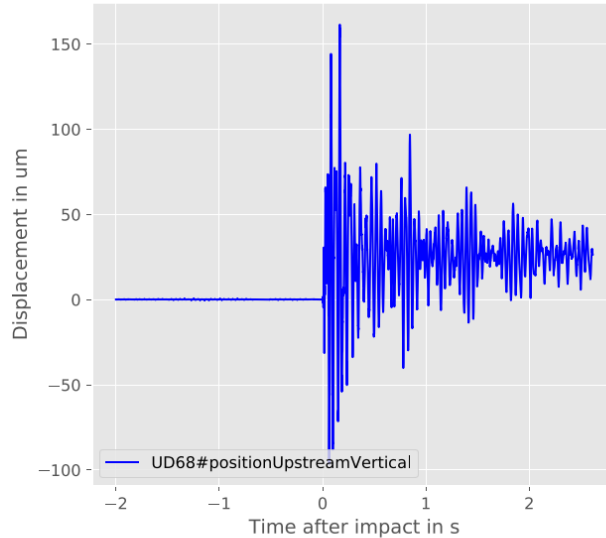
05.05. 14:20 ; 05.05. 19:30 ; 06.05. 06:14 ; 06.05. 09:43

06.05.2018 at 06h14

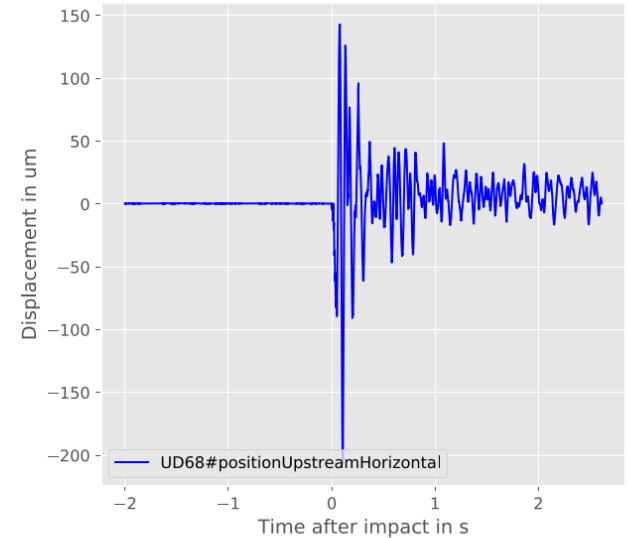
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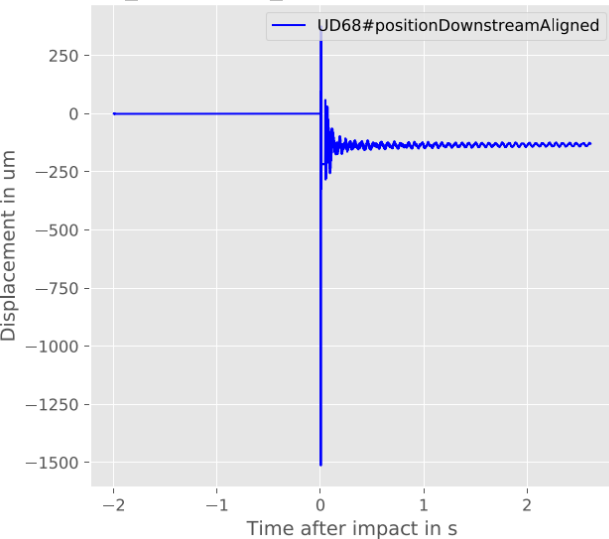
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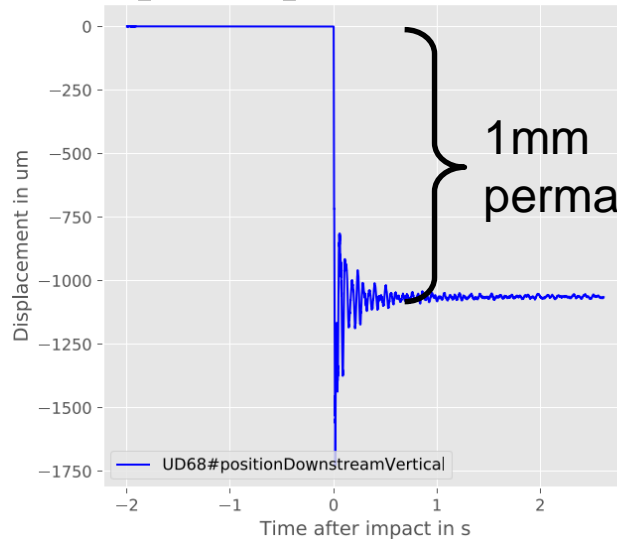
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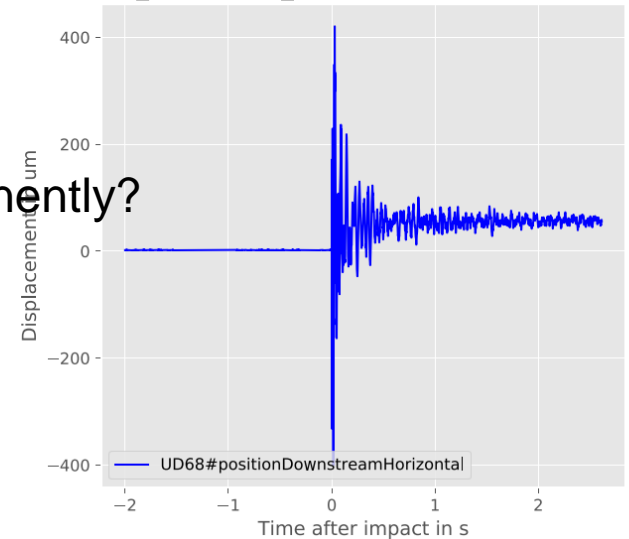
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tdevib_2018-05-06_06h14m41sUD68interferometer



tdevib_2018-05-06_06h14m41sUD68interferometer

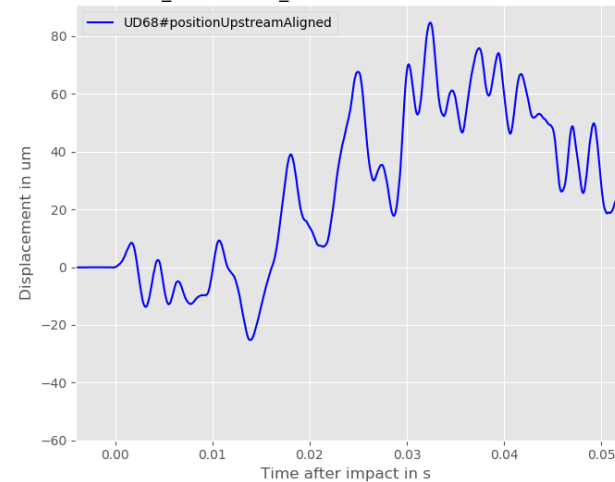


Supports of Connection Line

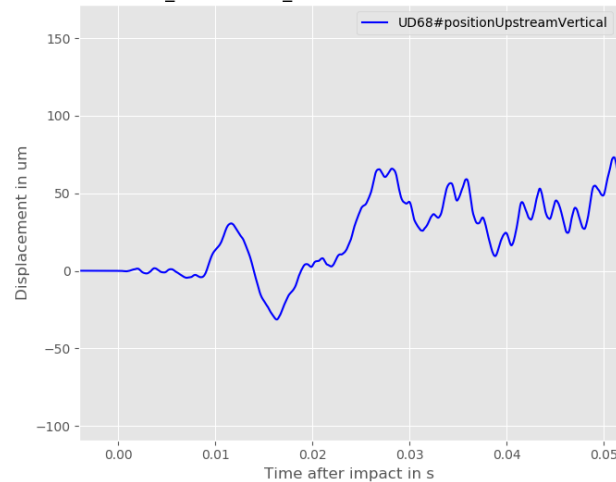


06.05.2018 at 06h14

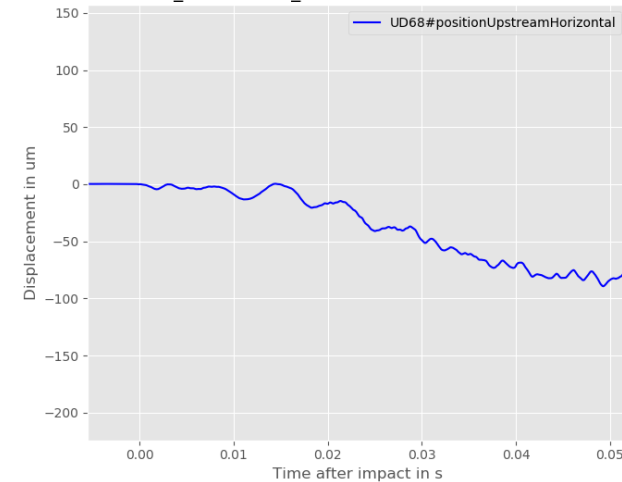
tdevib_2018-05-06_06h14m41sUD68interferometer



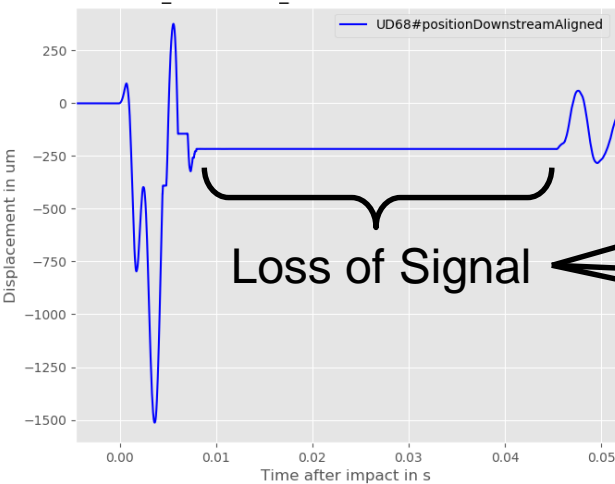
tdevib_2018-05-06_06h14m41sUD68interferometer



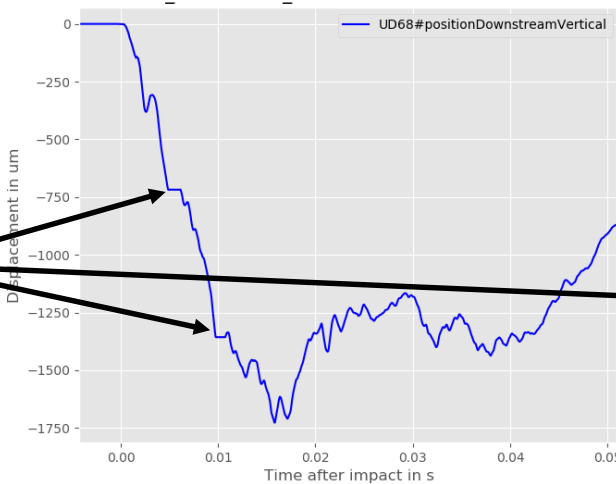
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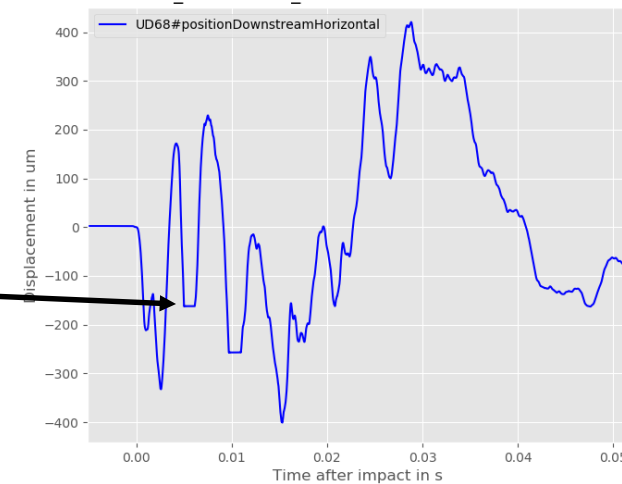
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tdevib_2018-05-06_06h14m41sUD68interferometer

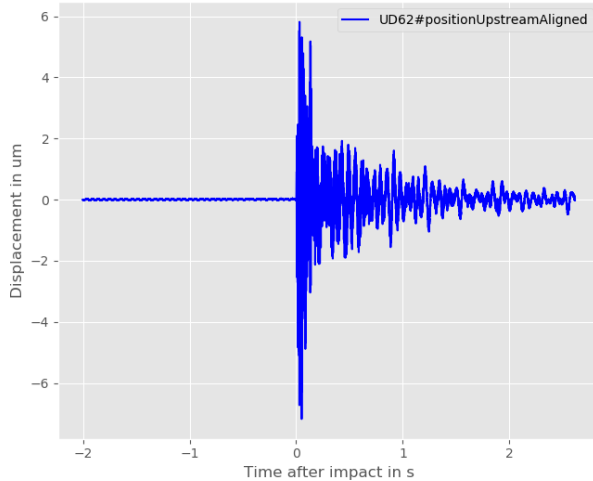


tdevib_2018-05-06_06h14m41sUD68interferometer

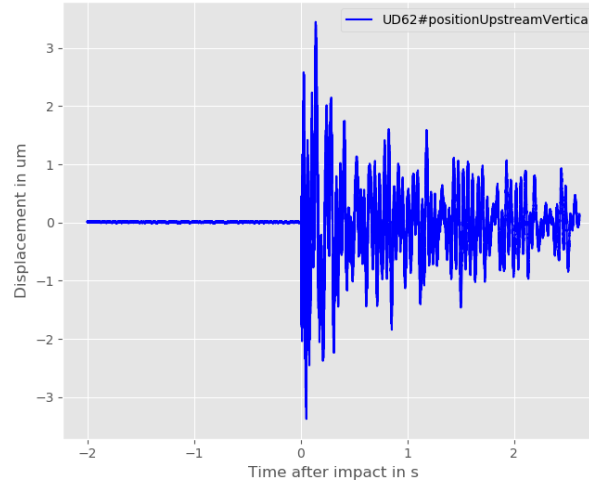


Impact with Modal Hammer UD62 Downstream

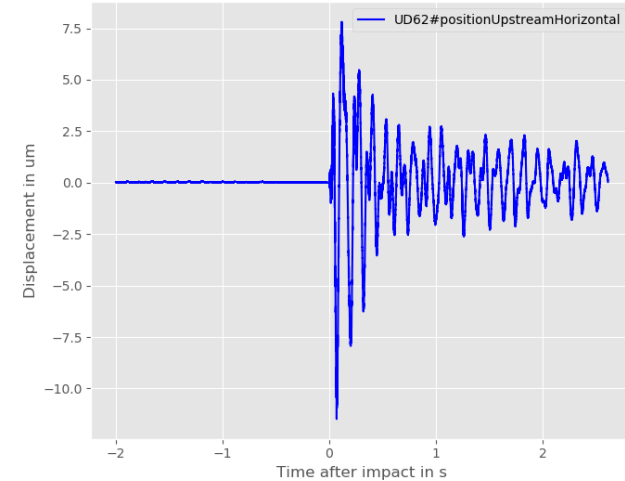
DownstrHorizInMicronsWithoutOffsetcsv



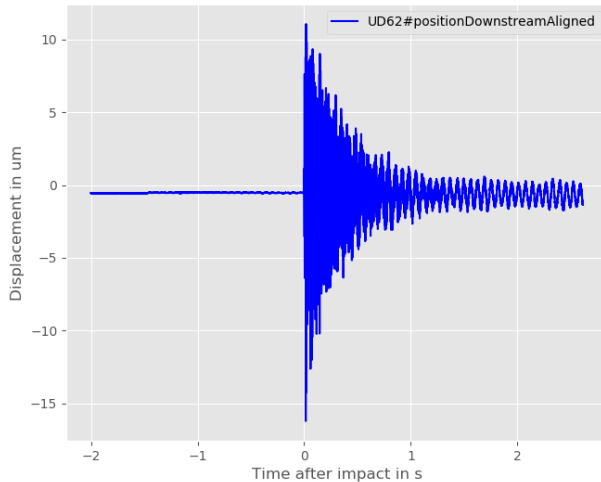
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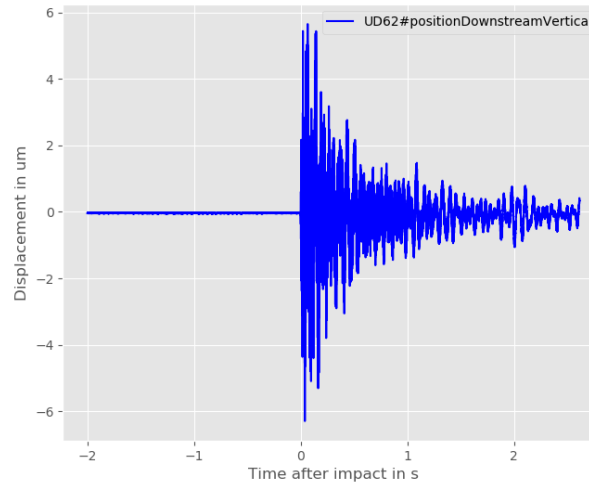
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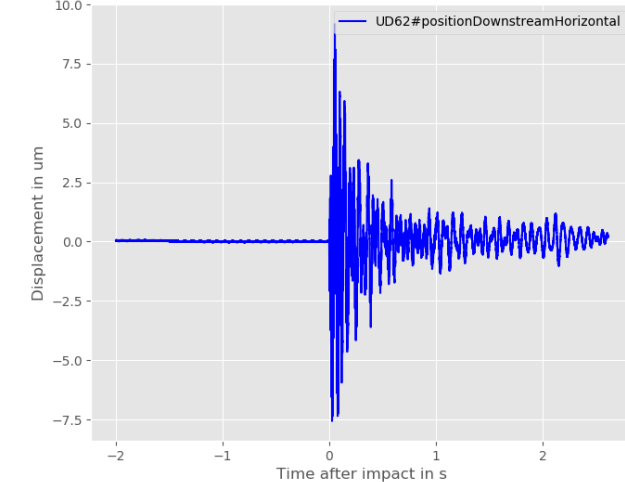
DownstrHorizInMicronsWithoutOffsetcsv



DownstrHorizInMicronsWithoutOffsetcsv



DownstrHorizInMicronsWithoutOffsetcsv



Summary Vibrometers

- TIMBER variable names for vibrometer data:
 - 'TDE.UD68.B1.VIB:POSITIONUPSTREAMALIGNED',
 - 'TDE.UD68.B1.VIB:POSITIONUPSTREAMHORIZONTAL',
 - 'TDE.UD68.B1.VIB:POSITIONUPSTREAMVERTICAL',
 - 'TDE.UD68.B1.VIB:POSITIONDOWNSTREAMALIGNED',
 - 'TDE.UD68.B1.VIB:POSITIONDOWNSTREAMHORIZONTAL',
 - 'TDE.UD68.B1.VIB:POSITIONDOWNSTREAMVERTICAL'

- 'TDE.UD62.B2.VIB:POSITIONUPSTREAMALIGNED',
- 'TDE.UD62.B2.VIB:POSITIONUPSTREAMHORIZONTAL',
- 'TDE.UD62.B2.VIB:POSITIONUPSTREAMVERTICAL',
- 'TDE.UD62.B2.VIB:POSITIONDOWNSTREAMALIGNED',
- 'TDE.UD62.B2.VIB:POSITIONDOWNSTREAMHORIZONTAL',
- 'TDE.UD62.B2.VIB:POSITIONUPSTREAMVERTICAL'

- Simulation Methodology

Used Material Data

Material	Temperature	Material Property					
		Young's Modulus	Poisson's Ratio	Instantaneous CTE	Density	Thermal Conductivity	Specific Heat
	[°C]	[GPa]	[1]	[1/K]	[kg/m ³]	[W/mK]	[J/kgK]
STEEL (SS316L)	20	193.8	0.29	1.70E-05	7970	13.24	485.5
	50	191.3	0.30	1.71E-05	7970	13.71	500.4
	100	187.1	0.30	1.73E-05	7970	14.48	521.2
	150	182.9	0.30	1.74E-05	7970	15.23	538.8
	200	178.7	0.30	1.76E-05	7970	15.96	553.5
SIGRABOND (1501 G)	0	80	0.2	7.0E-06	1500	4.0	625.0
	100	80	0.2	7.0E-06	1500	4.1	-
	200	80	0.2	7.0E-06	1500	4.2	1037.0
Pure Titanium (Grade 2)	20	106.9	0.31	8.28E-06	4430	7.23	523.4
	93	106.9	0.31	8.64E-06	4430	8.68	544.3
	204	106.9	0.31	9.00E-06	4430	10.12	565.2
	260	106.9	0.31	9.18E-06	4430	11.53	575.7
	538	106.9	0.31	9.63E-06	4430	12.93	669.9
Titanium (Ti6Al4V)	20	110	0.31	8.75 E-06	4430	7.23	523.4
	204	97.1	0.31	9.35 E-06	4430	8.68	544.3
	316	90.5	0.31	9.05 E-06	4430	10.12	565.2
	427	81.6	0.31	8.16 E-06	4430	11.53	575.7

SS316L Designer Handbook, Specialty Steel Industry of North America, Washington DC (1998) - extracted from MPDB v7.71, Copyright 2014 by JAHM Software, Inc.

Titanium CP2, Annealed
AMS 4900 and AMS-T-9046 for plates, documented in MMPDS-01

Ti Ti6Al4V, Annealed AMS4911 for 10mm thickness, Basis A documented in MMPDS-01

Material Modelling in LS-Dyna

\$ Steel SS316L: Designer Handbook, Specialty Steel Industry of North America, Washington DC (1998)

\$ extracted from MPDB v7.71, Copyright 2014 by JAHM Software, Inc.

*MAT_ELASTIC_PLASTIC_THERMAL

```
1 0.797E+04
0.0      20.0      50.      100.      150.      200.0
1.938E+11 1.938E+11 1.913E+11 1.871E+11 1.829E+11 1.787E+11
0.29      0.30      0.30      0.30      0.30      0.30
0.170E-04 0.170E-04 0.171E-04 0.173E-04 0.174E-04 0.176E-04
3.018E+08 3.018E+08 2.750E+08 2.493E+08 2.354E+08 2.239E+08
5.600E+06 5.600E+06 5.731E+06 5.816E+06 5.913E+06 6.184E+06
```

*DEFINE_CURVE

```
9999991      0      1.000      1.000      0.000      0.000
-1.000000000000E+02 1.324000000000E+01      0.000000000000E+00 1.324000000000E+01
0.000000000000E+00 1.324000000000E+01
2.000000000000E+01 1.324000000000E+01
5.000000000000E+01 1.371000000000E+01
1.000000000000E+02 1.448000000000E+01
1.500000000000E+02 1.523000000000E+01
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2.000000000000E+03 1.596000000000E+01
```

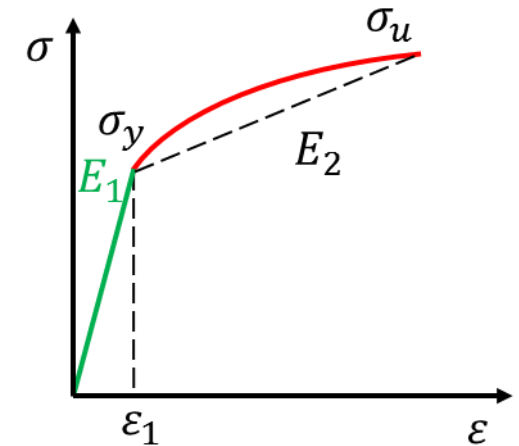
*DEFINE_CURVE

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9999992      0      1.000      1.000      0.000      0.000
-1.000000000000E+02 4.746000000000E+02      0.000000000000E+00 4.746000000000E+02
0.000000000000E+01 4.855000000000E+02
5.000000000000E+01 5.004000000000E+02
1.000000000000E+02 5.212000000000E+02
1.500000000000E+02 5.388000000000E+02
2.000000000000E+02 5.535000000000E+02
2.000000000000E+03 5.535000000000E+02
```

*MAT_THERMAL_ISOTROPIC_TD_LC

```
1
9999992      9999991
```

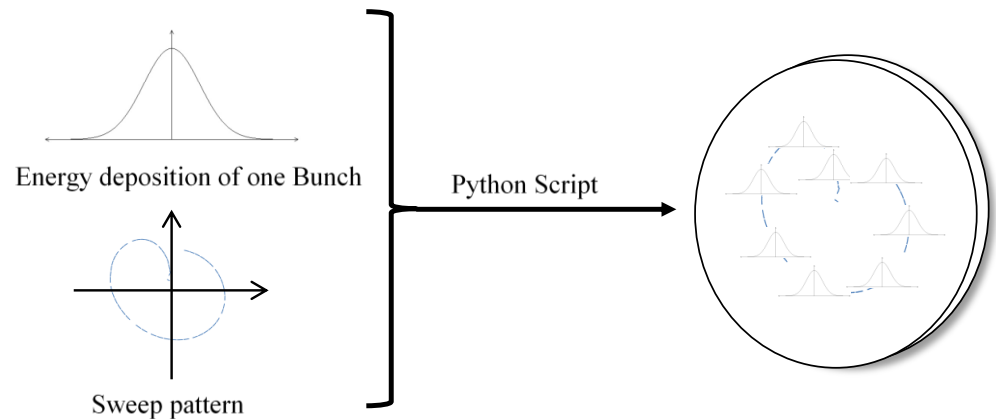
Bilinear model necessary in LS-Dyna to consider temperature dependency



$$\sigma(\varepsilon) = \begin{cases} E_1 \cdot \varepsilon & \varepsilon < \varepsilon_1 \\ E_2 \cdot (\varepsilon - \varepsilon_1) + E_1 \cdot \varepsilon_1 & \varepsilon \geq \varepsilon_1 \end{cases}$$

Load Application

- For the presented work, the energy deposition density of a single bunch is simulated in FLUKA for the different bodies
- The energy deposition density is then interpolated on the finite element mesh in the simulation, based on the changing impact location over time (processing of $1\text{E}9$ - $1\text{E}10$ data points)



Load Application

Longitudinal Profile

- In reality the beam has a bunch spacing of 25ns and a bunch length of a few single ns
- In the simulations a continuous distribution over these 25ns was assumed

For protons at 6.5TeV/7TeV in the LHC it is even shorter

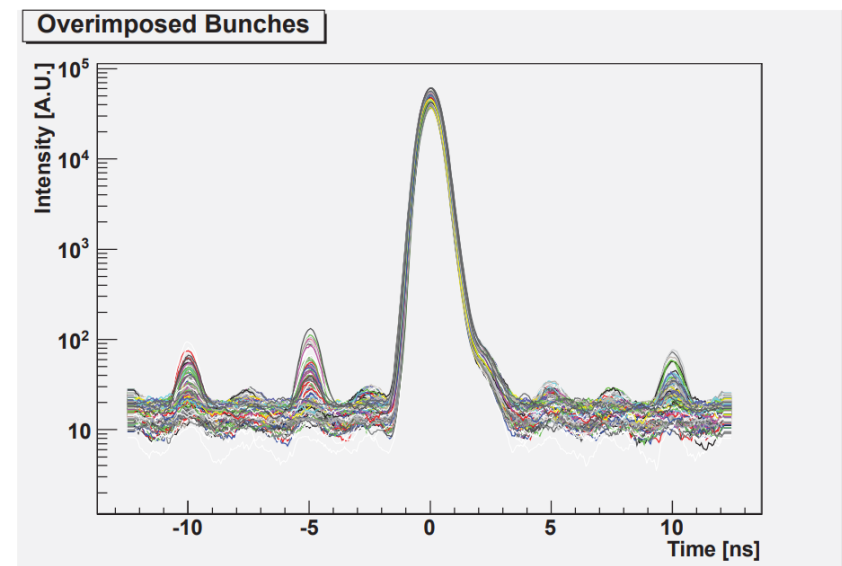
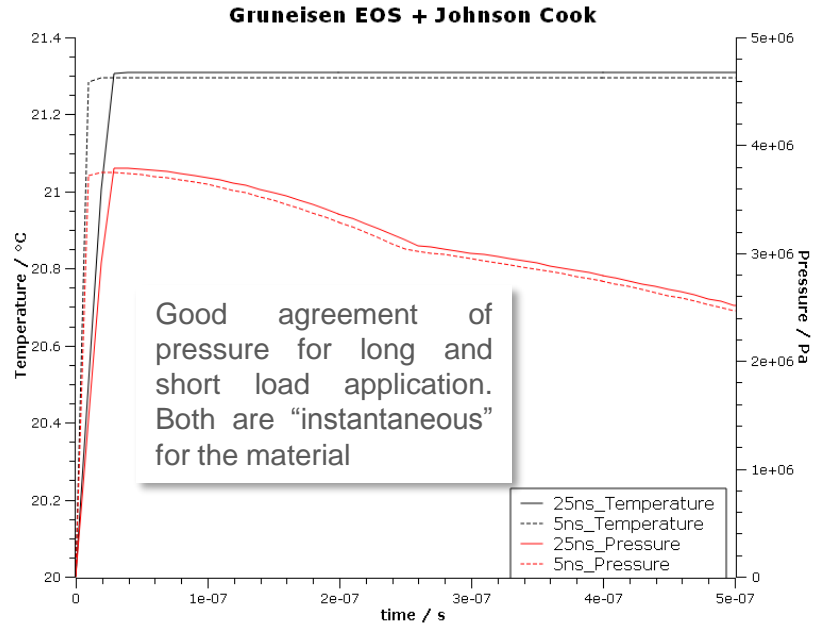
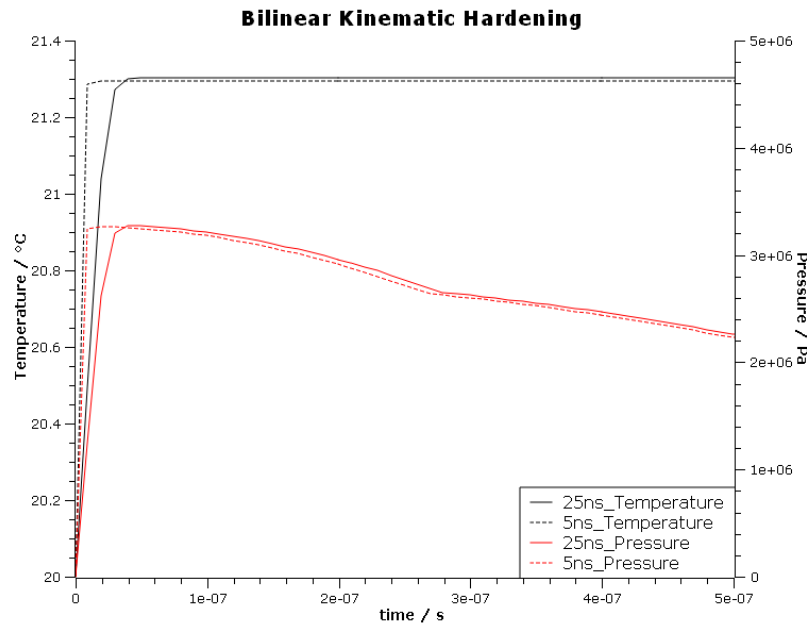


Figure 5: 25 ns slot population as measured by the LDM during a Van Der Meer scan with ions at 1.38 TeV (Fill 3540). Different colors correspond to different (superimposed) slots.

http://cds.cern.ch/record/2302724/files/1639581_53-58.pdf



The following graphs show the difference in the temperature and pressure development for two different material models with one impacting HL standard 25ns bunch in Ti6Al4V. The additional material model is a combination of a Johnson Cook constitutive model and a Gruneisen equation of state to take possible strain-rate dependency into account.

The difference between both material models is based on the different Young’s moduli. For the EOS the treatment of the titanium alloy was not clearly described.

In any case, no difference between the 5ns bunch length and the 25ns bunch length was observable.

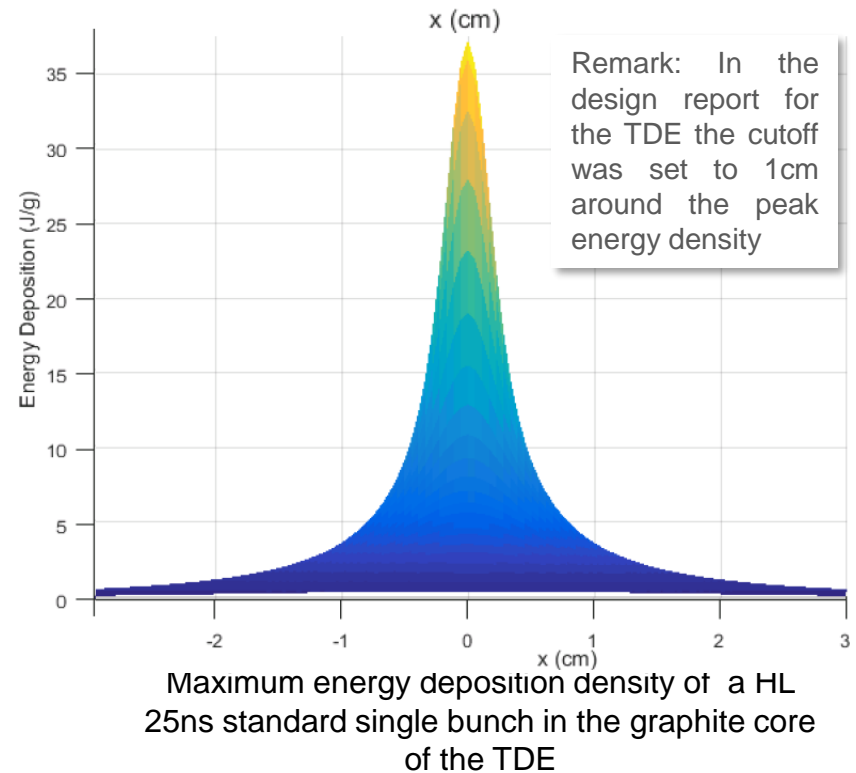
Load Application

Transversal Profile

- To remove numerical noise during the interpolation between the FLUKA binning and the FE-mesh all energy deposition values lower than 0.1% of the peak are set to 0

Source:

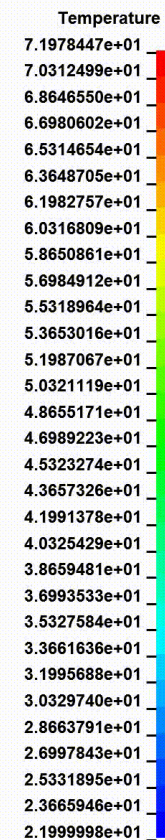
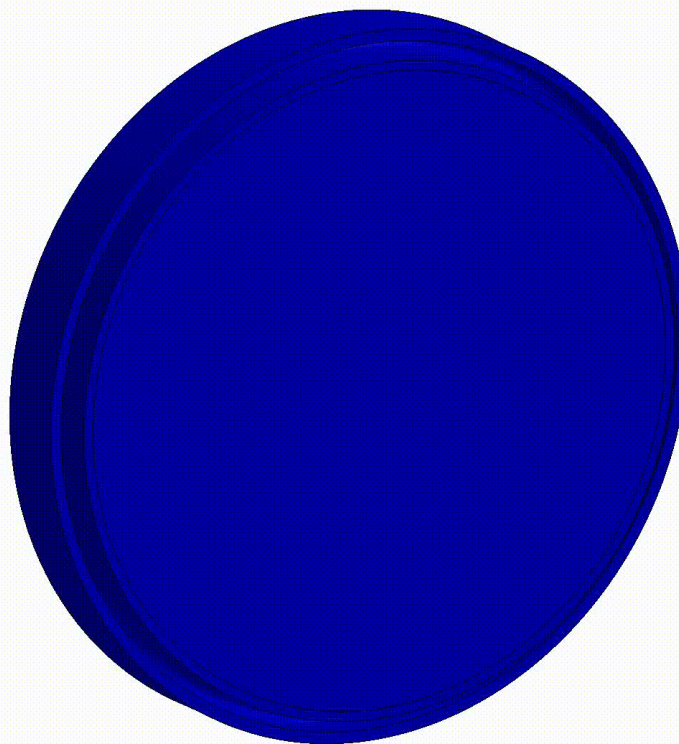
https://indico.cern.ch/event/640562/contributions/2598086/attachments/1479484/2293517/2017_20_06_LIBD_TDE.pdf



Load Application

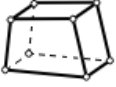






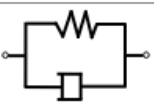

TDE - Front Window HL 6V2H - Graphite

Time = 0
Contours of Temperature
max=22, at node# 1



Mesh Generation

- The mesh is generated in ANSYS Workbench to use the advanced meshing techniques provided by the software package
 - Based on the format of the data exported to LS-Dyna, the maximum allowed number of nodes is 10 per element
- As hexahedral elements, only linear ones are possible

Type	Dimension	Element	Pictorial
Explicit Solid	3-D	SOLID164 8-Node Explicit Structural Solid	
		SOLID168 10-Node Explicit Tetrahedral Structural Solid	
	2-D	PLANE162 4-Node Explicit Solid	
Explicit Shell	3-D	SHELL163 4-Node Explicit Thin Structural Shell	
Explicit Beam	3-D	BEAM161 3-Node Explicit Beam	
Explicit Line	3-D	LINK160 3-Node Explicit Spar (or Truss)	
		LINK167 3-Node Explicit Tension-Only Spar	
		COMBI165 2-Node Explicit Spring-Damper	
Explicit Point	3-D	MASS166 1-Node Explicit Structural Mass	

Source:
ANSYS Manual

Mesh Generation

- Element size is determining the discretization of the geometric domain
- The resulting temperature- and displacement fields get linearized between the nodes
- Determination is optimization between accuracy and computational costs because each DOF increases the size of the system matrices to solve
- Main influence is the beam spot size (discretization of caused heat generation density field and resulting temperature field)
- Maximum temperature or energy deposition density as measure for sufficient element size in the region impacted by the beam

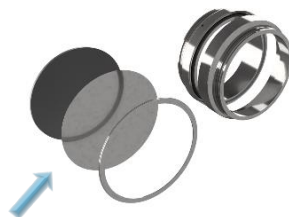
Example of Upstream Window:
1E6 linear shell elements

large element size
(1mm for the upstream window)

Small element size
(200um – 400um for the upstream window)

Stress Evaluation – Retrigger Scenario

Upstream Window



Delay time between MKBs and MKV	Maximum Density of Energy Deposition (LS-DYNA)	Maximum Density of Energy Deposition (FLUKA)	Maximum v. Mises Equivalent Stress	Maximum Temperature	v. Mises Stress for Minimum Safety	Temperature for Minimum Safety	Minimum Safety Factor Against Permanent Deformation
4 us	241.43 J/cm ³ (- 1.0%)	243.9 J/cm ³	160.9 MPa	81.8 °C	160.9 MPa	77.9 °C	1.6
14 us	406.32 J/cm ³ (+ 0.2%)	405.5 J/cm ³	200.1 MPa	126.1 °C	200.1 MPa	126.1 °C	1.2
73 us	207.93 J/cm ³ (- 7.5%*)	224.8 J/cm ³	185.0 MPa	73.2 °C	183.9 MPa	61.3 °C	1.45
86 us	305.57 J/cm ³ (+ 4.3%)	293.0 J/cm ³	179.0 MPa	95.4 °C	168.4 MPa	95.4 °C	1.48

The expected stress levels in the windows are too high for a long-term and reliable operation

Stress Evaluation – Retrigger Scenario

Downstream Window



Melting Temperature
Ti G2: 1670 °C

Delay time between MKBs and MKV	Maximum Density of Energy Deposition (LS-DYNA)	Maximum Density of Energy Deposition (FLUKA)	Maximum v. Mises Equivalent Stress	Maximum Temperature	v. Mises Stress for Minimum Safety (Grade 2)	Temperature for Minimum Safety (Grade 2)	Minimum Safety Factor Against Permanent Deformation Titanium G2
5 us	448.28 J/cm ³ (- 4.1%)	467.9 J/cm ³	184.2 MPa	206.7 °C	179.9 MPa	200.5 °C	0.99
31 us	444.09 J/cm ³ (- 3.4%)	459.53 J/cm ³	180.9 MPa	205.1 °C	176.3 MPa	202.5 °C	1.00
34 us	467.58 J/cm ³ (- 3.2%)	483.24 J/cm ³	185.7 MPa	214.4 °C	184.0 MPa	211.8 °C	0.92
70 us	571.48 J/cm ³ (- 2.8%)	587.74 J/cm ³	209.3 MPa	255.5 °C	203.6 MPa	250.4 °C	0.69
73 us	578.42 J/cm ³ (- 2.9%)	595.75 J/cm ³	211.6 MPa	258.2 °C	210.2 MPa	250.6 °C	0.68
95 us	457.65 J/cm ³ (- 3.4%)	473.88 J/cm ³	192.0 MPa	210.3 °C	191.0 MPa	205.3 °C	0.91

The expected stress levels in the windows are too high for a long-term and reliable operation

Stress Evaluation – Retrigger Scenario

Downstream Window



Delay time between MKBs and MKV	Maximum Density of Energy Deposition (LS-DYNA)	Maximum Density of Energy Deposition (FLUKA)	Maximum v. Mises Equivalent Stress	Maximum Temperature	v. Mises Stress for Minimum Safety (Ti6Al4V)	Temperature for Minimum Safety (Ti6Al4V)	Minimum Safety Factor Against Permanent Deformation Ti6Al4V
5 us	448.28 J/cm ³ (- 4.1%)	467.9 J/cm ³	184.2 MPa	206.7 °C	184.2 MPa	185.5 °C	3.25
31 us	444.09 J/cm ³ (- 3.4%)	459.53 J/cm ³	180.9 MPa	205.1 °C	176.7 MPa	201.8 °C	3.32
34 us	467.58 J/cm ³ (- 3.2%)	483.24 J/cm ³	185.7 MPa	214.4 °C	184.2 MPa	211.5 °C	3.15
70 us	571.48 J/cm ³ (- 2.8%)	587.74 J/cm ³	209.3 MPa	255.5 °C	207.3 MPa	263.7 °C	2.69
73 us	578.42 J/cm ³ (- 2.9%)	595.75 J/cm ³	211.6 MPa	258.2 °C	210.9 MPa	249.4 °C	2.65
95 us	457.65 J/cm ³ (- 3.4%)	473.88 J/cm ³	192.0 MPa	210.3 °C	191.0 MPa	205.3 °C	3.06

Upgrade of downstream window to Ti6Al4V
will ensure survival for considered load cases