An Introduction to the Mechanics of Materials Interacting with Energetic Particle Beams and Their Testing

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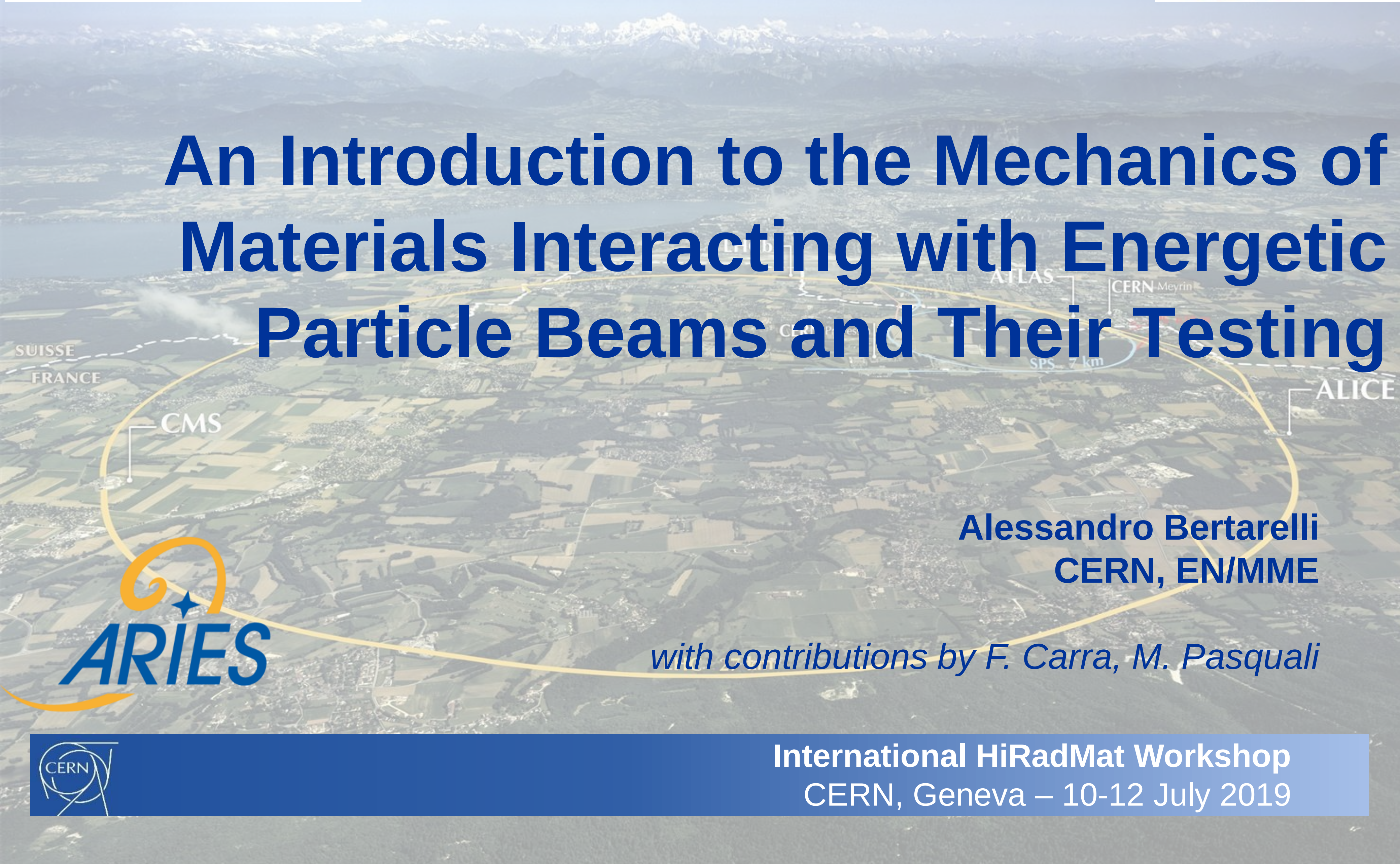
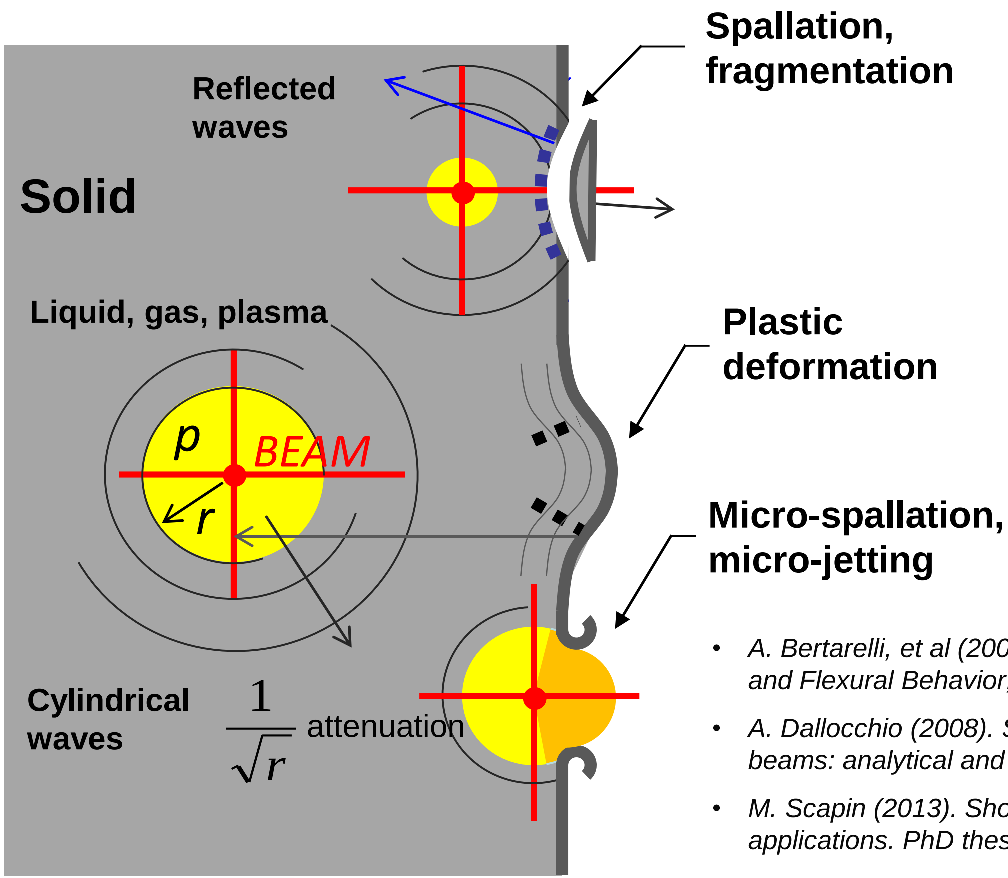
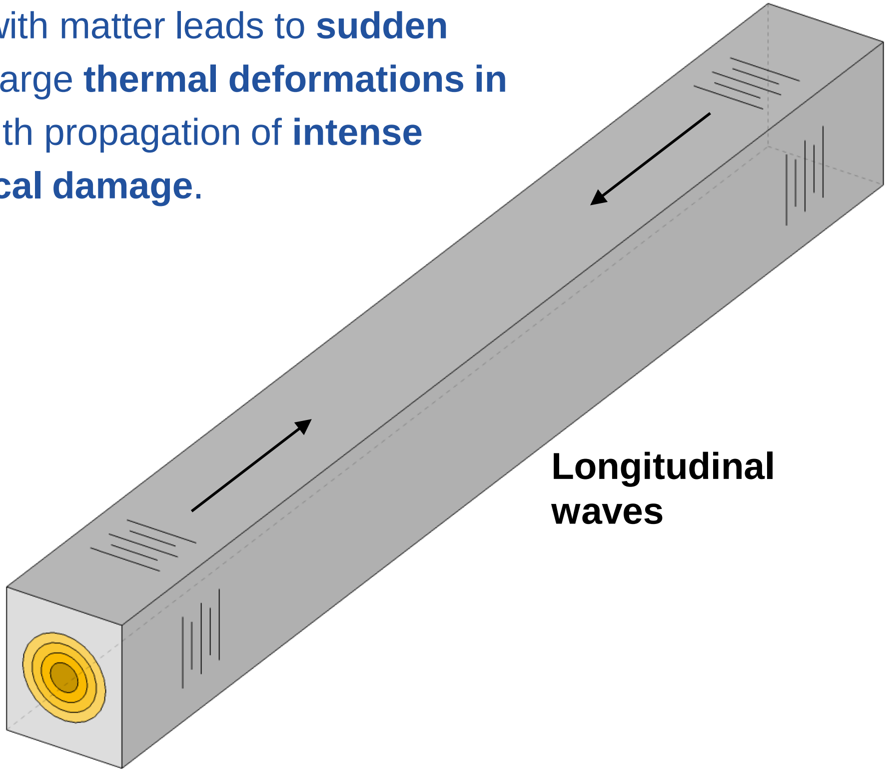


Dynamic Phenomena Induced by Rapid Heating

- **Interaction** of high energy, high intensity particle **pulses** with matter leads to **sudden temperature rises** (with possible changes of phase) and large **thermal deformations in very short times** (initially **prevented by mass inertia**), with propagation of **intense pressure waves,** possibly leading to **extensive mechanical damage**.





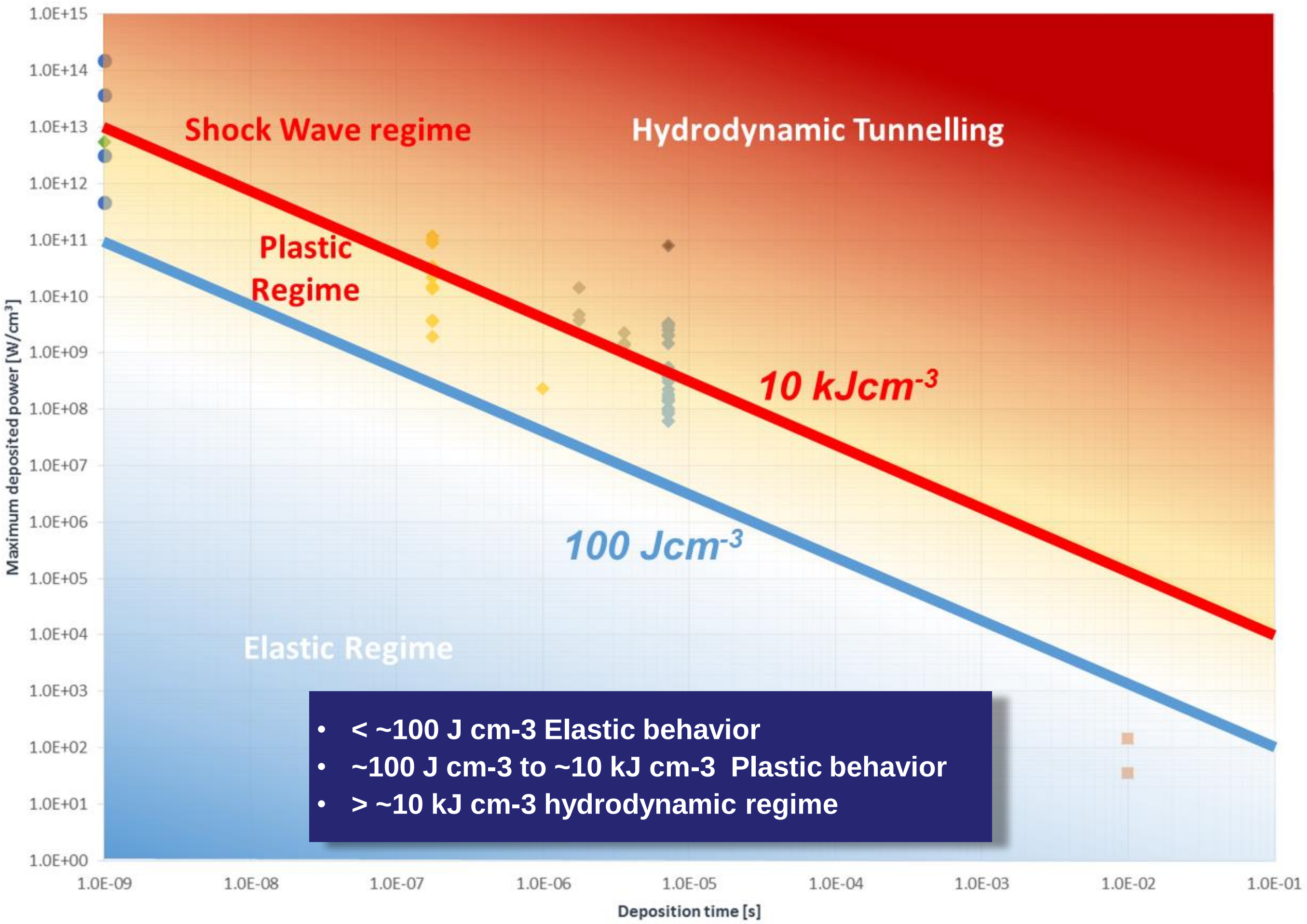
- *A. Bertarelli, et al (2008). Dynamic Response of Rapidly Heated Cylindrical Rods: Longitudinal and Flexural Behavior, J. Appl. Mech., Vol. 75, issue 3, 031010.*
- *A. Dallocchio (2008). Study of thermomechanical effects induced in solids by high-energy particle beams: analytical and numerical methods. CERN-THESIS-2008-140.*
- *M. Scapin (2013). Shock-wave and high strain-rate phenomena in matter: modeling and applications. PhD thesis, 10.6092/polito/porto/2507944.*
- *F. Carra (2017). Thermomechanical Response of Advanced Materials under Quasi Instantaneous Heating. PhD thesis, https://zenodo.org/record/1414090.*

L. Peroni *et al*
(Politecnico di Torino)

Dynamic Regimes Induced by Rapid Heating

- Structure responses depend on the intensity and duration of the energy deposition ⇒ **Elastic**, **Plastic**, **Shockwave**, **hydrodynamic tunneling** regimes…
- In spite of variety in conditions and materials, **threshold** for energy density with (some) general validity (at least locally) can be indicatively derived …

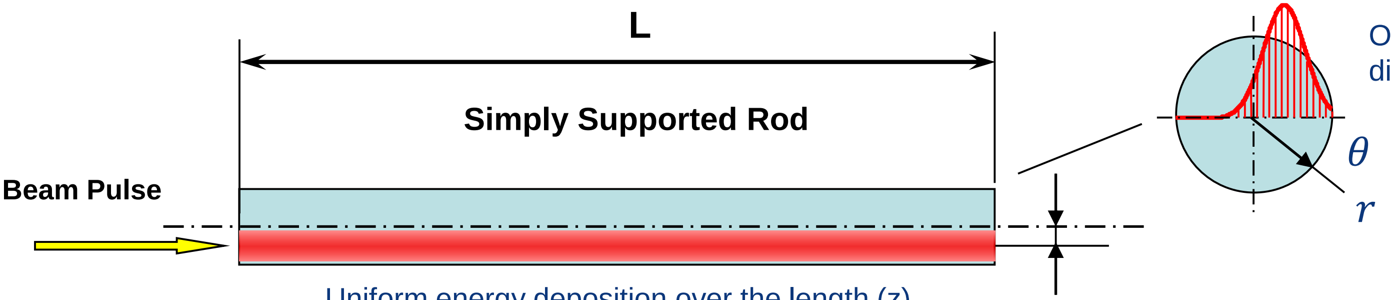
A. Bertarelli (2016). Beam-induced damage mechanisms and their calculation. CERN Yellow Reports, v. 2, p. 159, Jan. 2016. ISSN 00078328.



- **< ~100 J cm-3 Elastic behavior**
- **~100 J cm-3 to ~10 kJ cm-3 Plastic behavior**
- **> ~10 kJ cm-3 hydrodynamic regime**

Thermally-induced Dynamics: Elastic Regime

- The elastic response can in some simple cases (slender rods) be computed analytically …
- Thermal expansion of the impacted material is initially prevented by its mass inertia ⇒ purely compressive state
- Dynamic response induced with stress waves departing from free rod ends



Offset Gaussian energy distribution $U(r,\theta)$

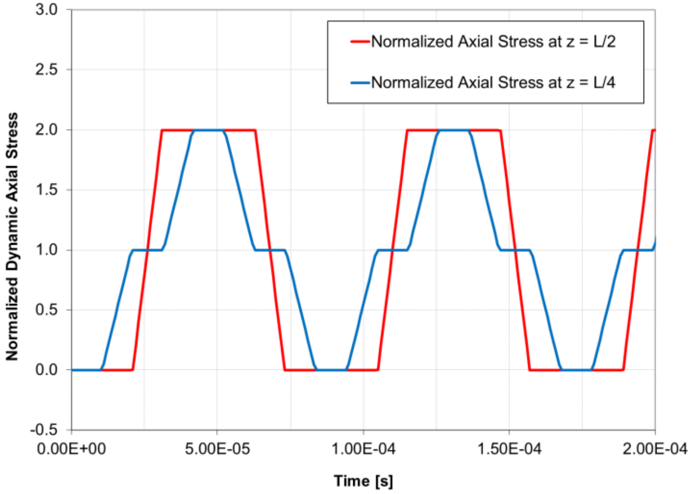
Uniform energy deposition over the length (z)

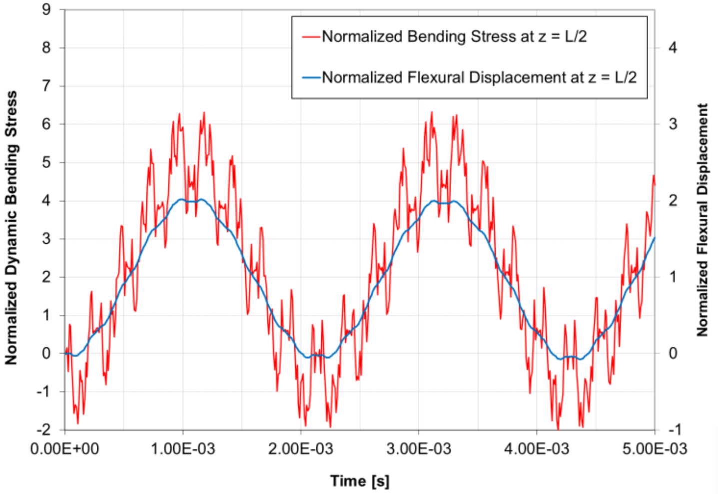
- Global dynamic response of the target is governed by the total energy deposited averaged on its cross-section:
- Even in elastic regime, some properties as internal damping can only be assessed experimentally …

$$\bar{U}_{max} = \frac{1}{\pi R^2}\iint_{0\;0}^{R\;2\pi} U r dr d\theta\Big|_{max}$$

$$\bar{T}_{max} = \bar{U}_{max}/\rho c_p$$ (no diffusion)

$$\sigma_{RefMax} = E\alpha\bar{T}_{max}$$ (axial)



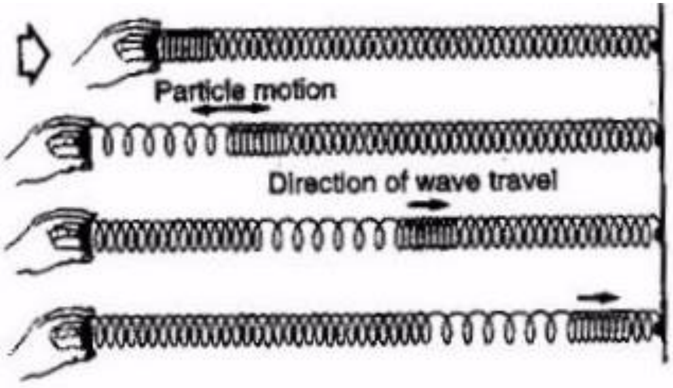


- *A. Bertarelli, et al (2008). Dynamic response of rapidly heated cylindrical rods: longitudinal and flexural behavior. J. Appl. Mech. 75:1-13.*
- *M. Pasquali et al. (2019). Dynamic response of advanced materials impacted by particle beams: the MultiMat experiment. Submitted to the DYMAT2019 Workshop.*

Thermally-induced Dynamics: Plastic Regime

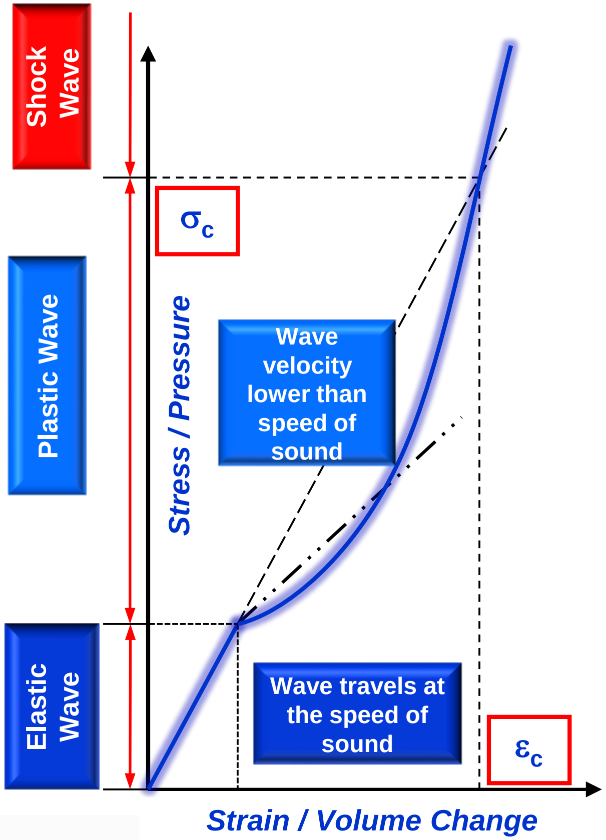
Thermally-Induced Dynamic Effects

- High-energy accelerator components are usually designed to work in the **Elastic Regime** …

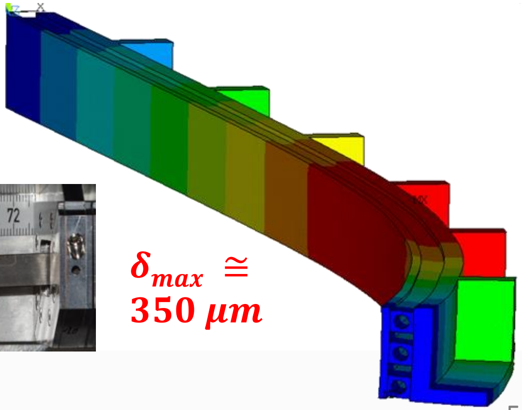


Plane strain approximation for the propagation of stress waves

HOWEVER



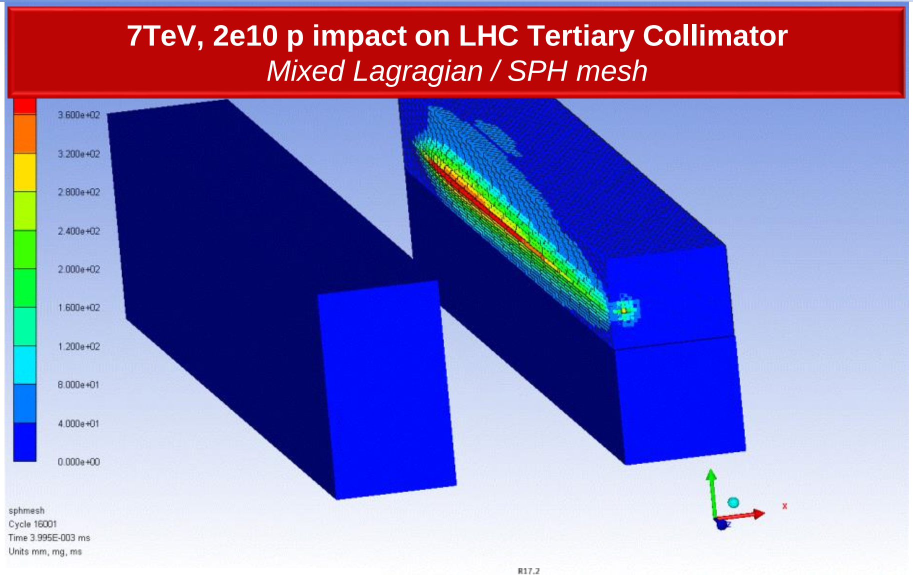
- Beam impact accidents can provoke **permanent deformations** of the component…⇨
- **Plastic Regime**
  - *Small (negligible) changes in material density*
  - *Irreversible plastic deformations*
  - *Stress waves slower than speed of sound*
- In plastic regime, an **implicit FEA code** (e.g. ANSYS) is usually adopted to simulate structure response …



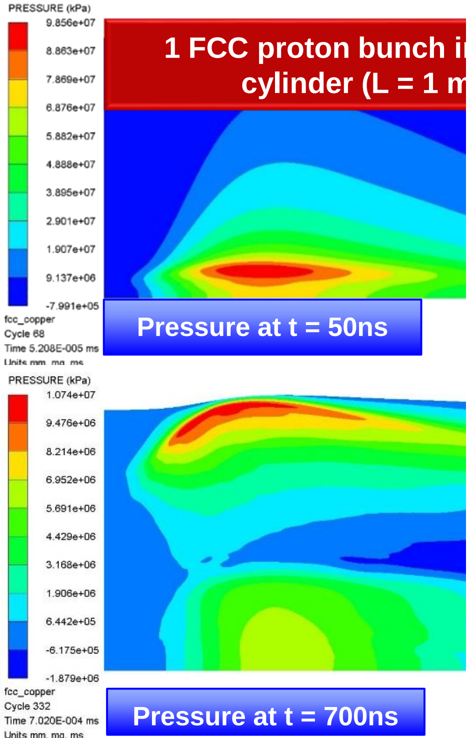
$\delta_{max} \cong 350\ \mu m$

Thermally-induced Dynamics: Shockwave Regime

- When the impact induces **large density and phase changes ($U \gg 100$ kJ cm^{-3})**, classical **Structure Dynamics** approach is **no longer viable**.
- In these regimes, materials tend to behave like fluids ⇨ Hydrodynamic approach ⇨ **Hydrocodes** (e.g. Autodyn, LS-Dyna …), **highly nonlinear wave propagation** tools
- Complex material **Constitutive Models** are required, i.e. **Equations of State, Strength Model** and **Failure Model** which are often unavailable …



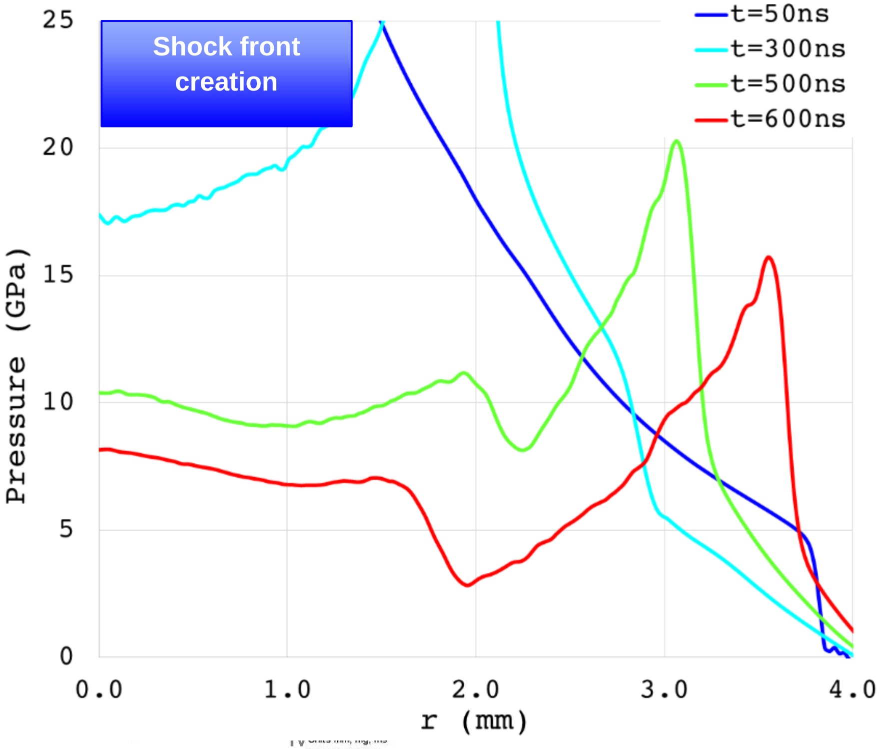
7TeV, 2e10 p impact on LHC Tertiary Collimator
Mixed Lagragian / SPH mesh



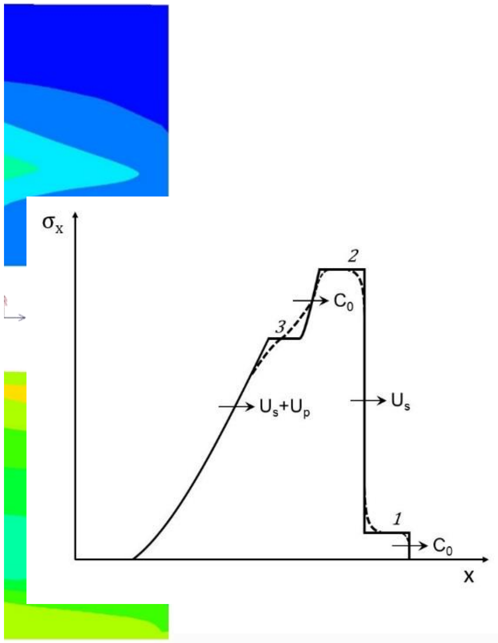
1 FCC proton bunch i
cylinder (L = 1 m

Pressure at t = 50ns

Pressure at t = 700ns



Shock front creation



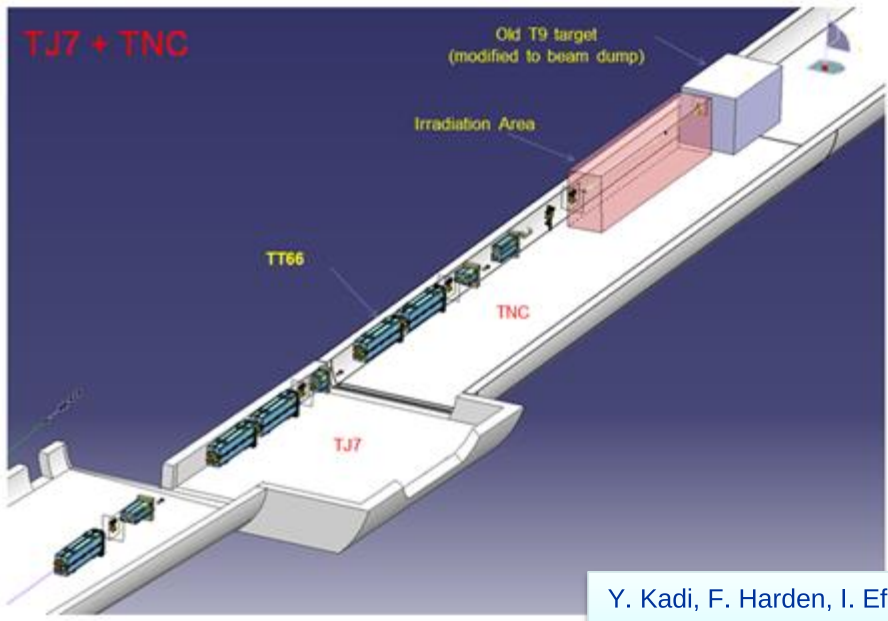
Why Experimental Tests?

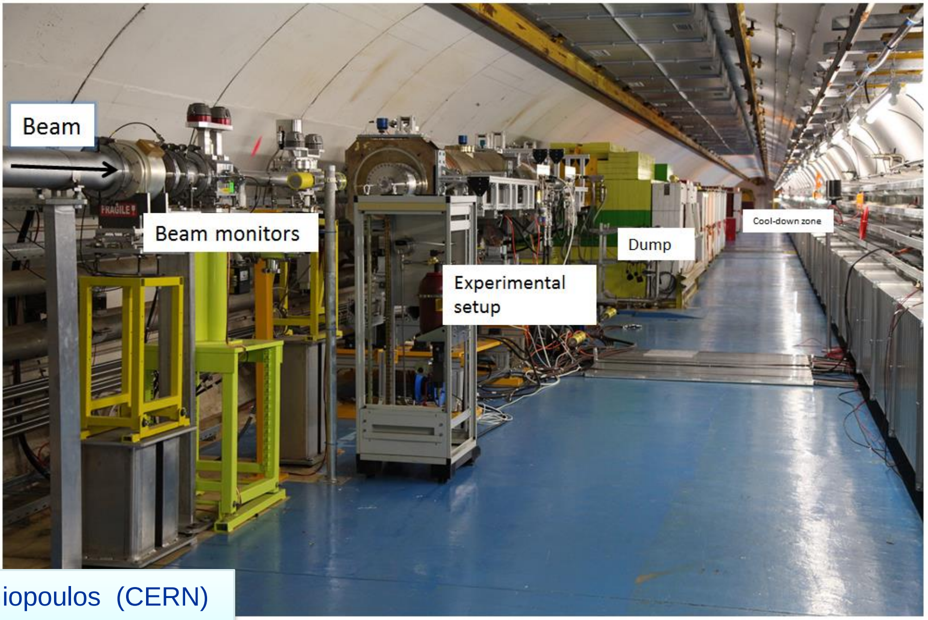
Why is experimental validation important?

- With accidental beam impacts, one enters a relatively unknown territory, that of **high power impacts and ballistics**.
- When **large density changes, phase transitions, fragmentations** are involved, one has to resort to special advanced highly nonlinear tools (**Hydrocodes**).
- These **state-of-the-art wave propagation codes** can be very reliable, provided the **complex material models** required are available and precise.
- Material constitutive models at **extreme conditions** are **scarce** and mostly drawn from military research (**classified**). They are often **unavailable** for specific alloys and composites
- **Advanced** and/or **novel materials** are required in high energy accelerators, for which characterization is incomplete or non-existing.
- Even for less extreme cases, a number of **time-dependent properties** relevant to dynamic structural response are hardly available (e.g. high strain-rate mechanical behaviour, internal damping, viscoelastic properties …)
- Additional consequences on UHV, electronics, bellows cannot be easily anticipated by numerical simulations.
- Only **ad-hoc in-beam material tests** can provide the correct inputs for numerical analyses benchmarking simulation results on **simple specimens** and validate the design of **complex structures**.
- **HiRadMat** (High Radiation to Materials) is the **ideal facility to test materials and systems** under high intensity pulsed particle beams.

HiRadMat (High Radiation to Materials) Facility

- HiRadMat offers in particular **great flexibility** as to pulse **intensity**, **duration** and **brightness** and to the **type of experimental setups** it can host …
- This permits testing both **full, complex structures**, to **qualify designs** and **small, simple specimens** to **benchmark simulations** and **disentangle various phenomena** …
- HiRadMat flexibility can be exploited to reach **conditions exceeding those imposed by the SPS** by:
  - Reducing beam transverse size down to 0.25 mm (σ) to **increase peak energy density** U_{max} which governs **local damage** (spallation, fragmentation, local melting …)
  - Reducing sample cross-section to **increase average energy density** $\bar{U}_{max}$, hence **amplifying global elastic (plastic) stress waves** (which depend upon average temperature)





Y. Kadi, F. Harden, I. Efthymiopoulos (CERN)

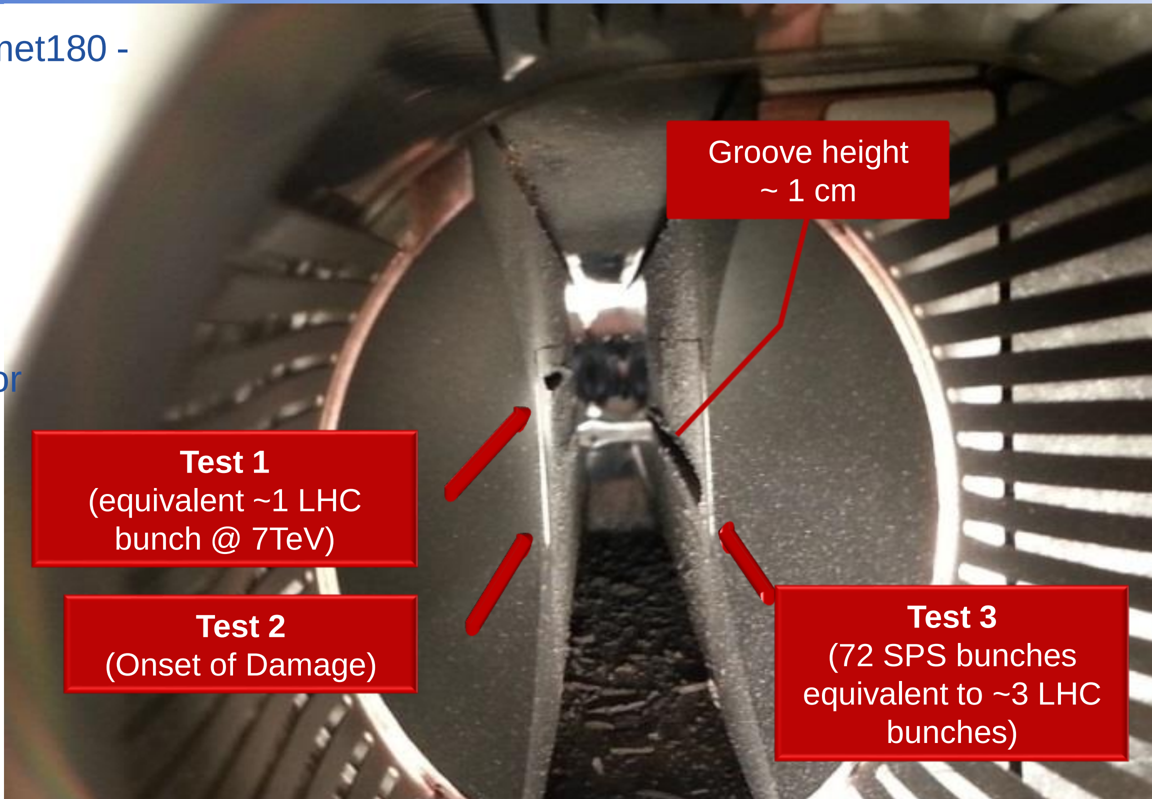
Example of Full Structure Test: HRMT09

Experimental Testing and Validation

2012 test on full LHC Tertiary Collimator (Inermet180 - **Tungsten alloy** as active material)

- Beam size ($\sigma_{x/y}$) 0.53 × 0.36 mm^2
- Impact depth: 2 mm
- 3 impact tests (24, 6, 72 bunches)
- **Goal**: **determine damage limits** for collimator materials

Simulated with **Autodyn SPH** (Smooth Particle Hydrodynamics) for W core; **Lagrangian** for outer parts …

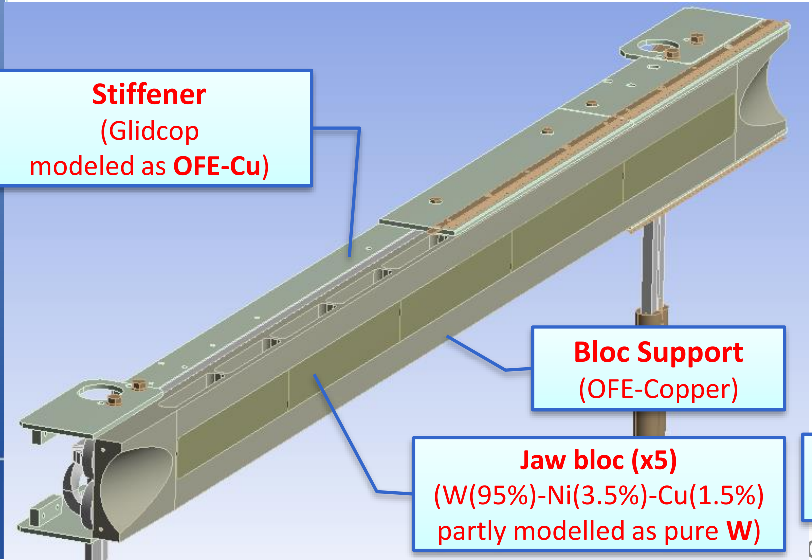


Groove height ~ 1 cm

Test 1
(equivalent ~1 LHC bunch @ 7TeV)

Test 2
(Onset of Damage)

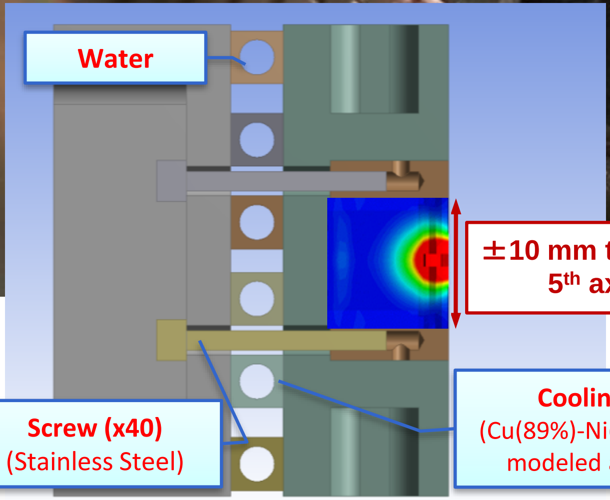
Test 3
(72 SPS bunches equivalent to ~3 LHC bunches)



Stiffener
(Glidcop modeled as **OFE-Cu**)

Bloc Support
(OFE-Copper)

Jaw bloc (x5)
(W(95%)-Ni(3.5%)-Cu(1.5%) partly modelled as pure **W**)



Water

±10 mm through 5th axis

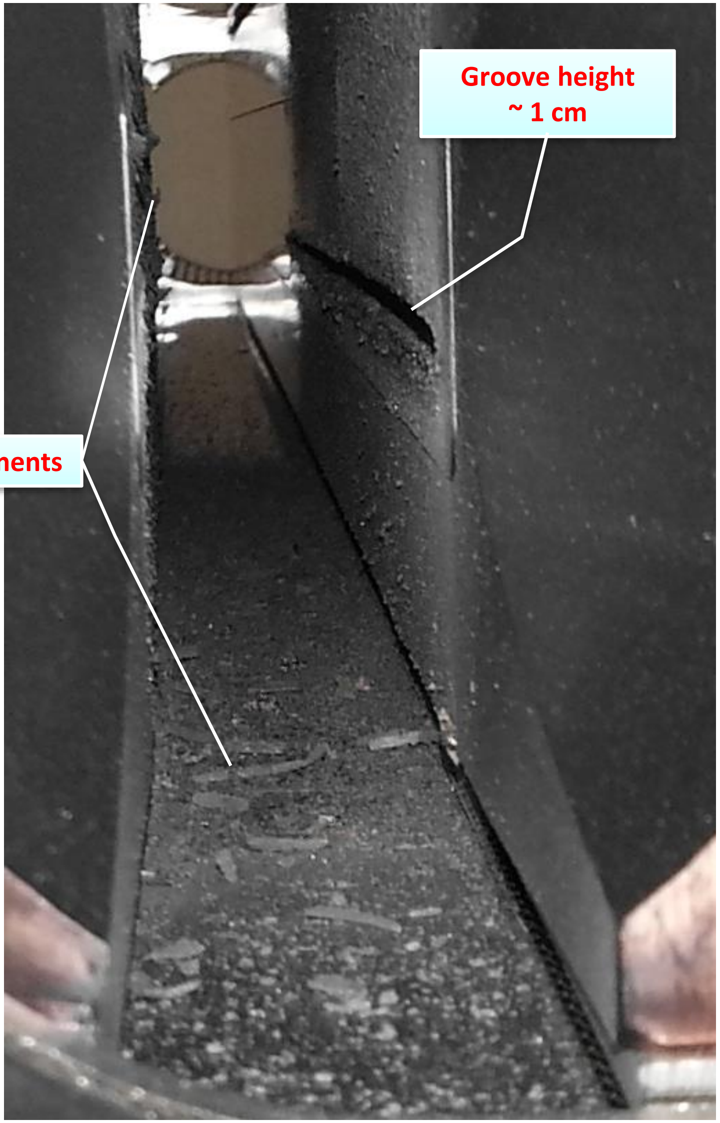
Screw (x40)
(Stainless Steel)

Cooling Pipes
(Cu(89%)-Ni(10%)-Fe(1%) modeled as **OFE-Cu**)

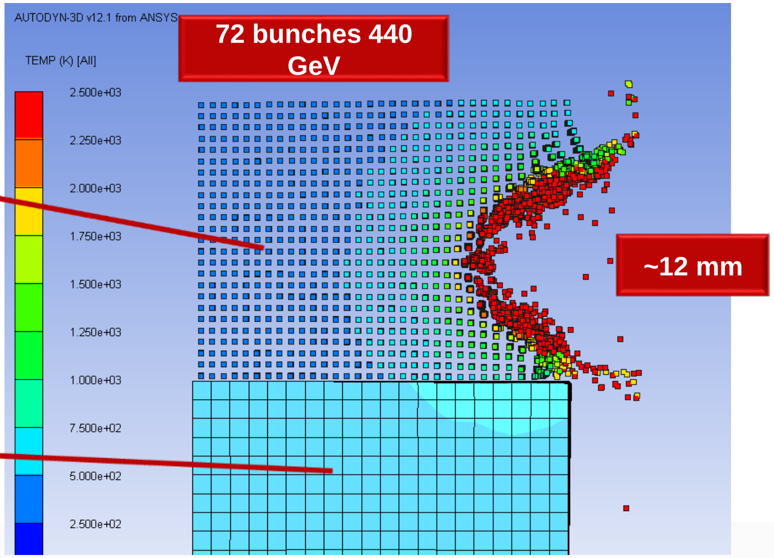
Example of Full Structure Test: HRMT09

Analysis of Test 3

- Impressive quantity of tungsten alloy ejected (partly bonded to the opposite jaw, partly fallen on tank bottom or towards entrance and exit flanges)
- Vacuum degraded. Tank contaminated
- Groove height ~ 1 cm (consistent with numerical simulations)


Groove height ~ 1 cm

Ejected W fragments



72 bunches 440 GeV

~12 mm

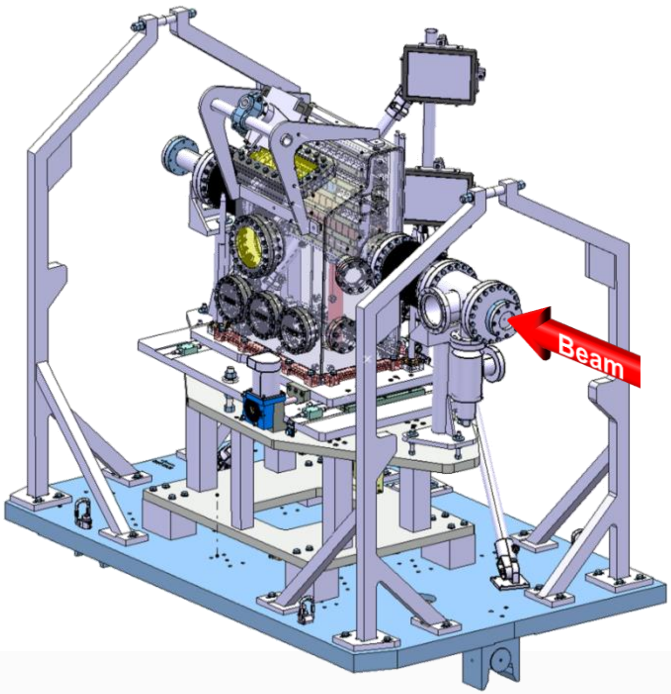
SPH scheme allowing to simulate fragmentation and droplet motion

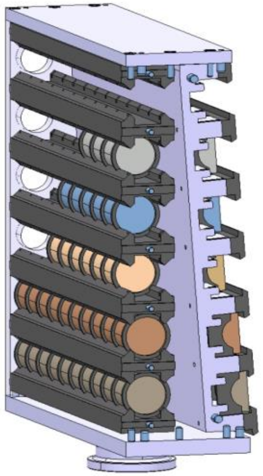
Lagrangian mesh

Example of test on simple specimens: HRMT14

2014 experiment featuring a **movable sample holder** equipped with **6 + 6 stations** each hosting **up to 10 specimens** of two different shape for **medium intensity** and high **intensity pulses**. Main goals

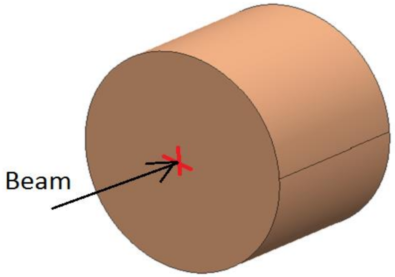
- **Benchmark** advanced **numerical simulations** and material **constitutive models** through extensive acquisition system
- Characterize **six existing** and **novel materials** under development for HL-LHC Collimators: **Inermet180**, **Molybdenum**, **Glidcop**, **MoCuCD**, **CuCD**, **MoGr**
- Collect, mostly in **real time**, experimental data from different acquisition systems (**Strain Gauges**, **Laser Doppler Vibrometer**, **High Speed video Camera**, **Temperature and Vacuum probes**)



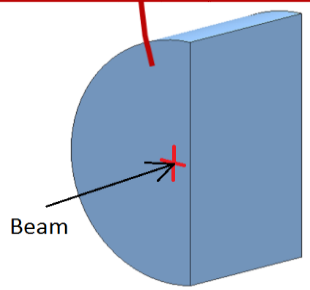


Beam Parameters	
Beam energy	440 GeV
Number of protons per bunch	1.1e11
Bunch Spacing	25 ns

Medium Intensity Tests:
Sample: Ø 40 mm , L30 mm



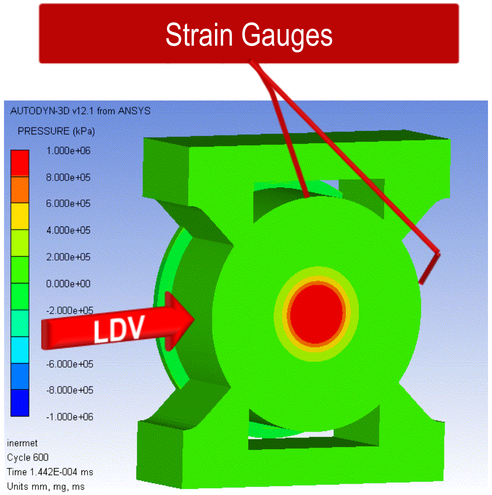
High Intensity Tests:
Sample: half-moon;
Beam Offset 2 mm

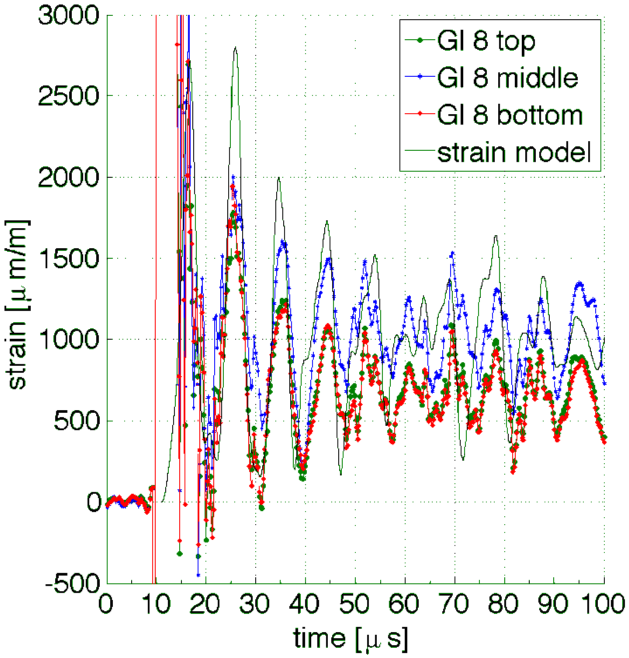


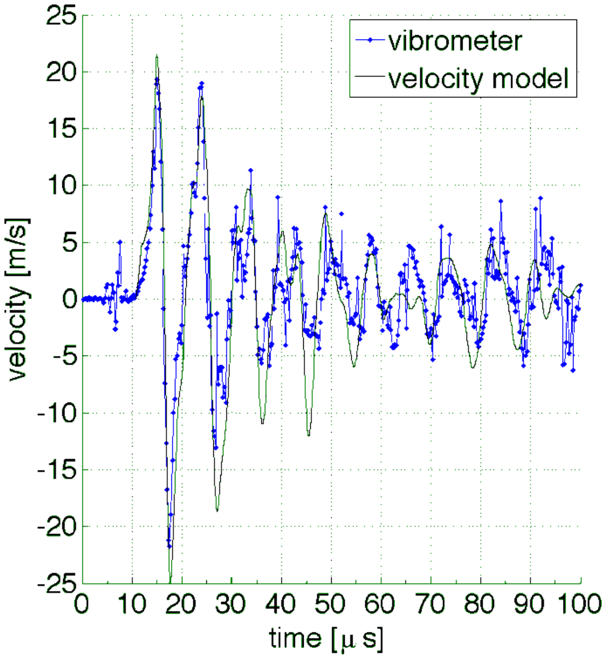
Example of test on simple specimens: HRMT14

Medium Intensity Tests

- Extensive hydrocode numerical analysis (Autodyn).
- Comparison of simulated **circumferential strains** and **radial velocity** with measured values on sample outer surface.







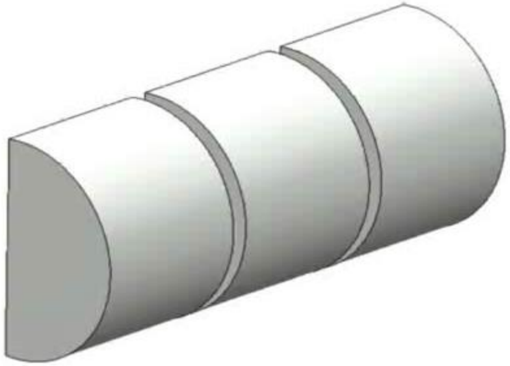
Inermet180
24 b (scraped)

Total intensity:
2.7e12 p
σ ≅ 1.4 mm

Example of test on simple specimens: HRMT14

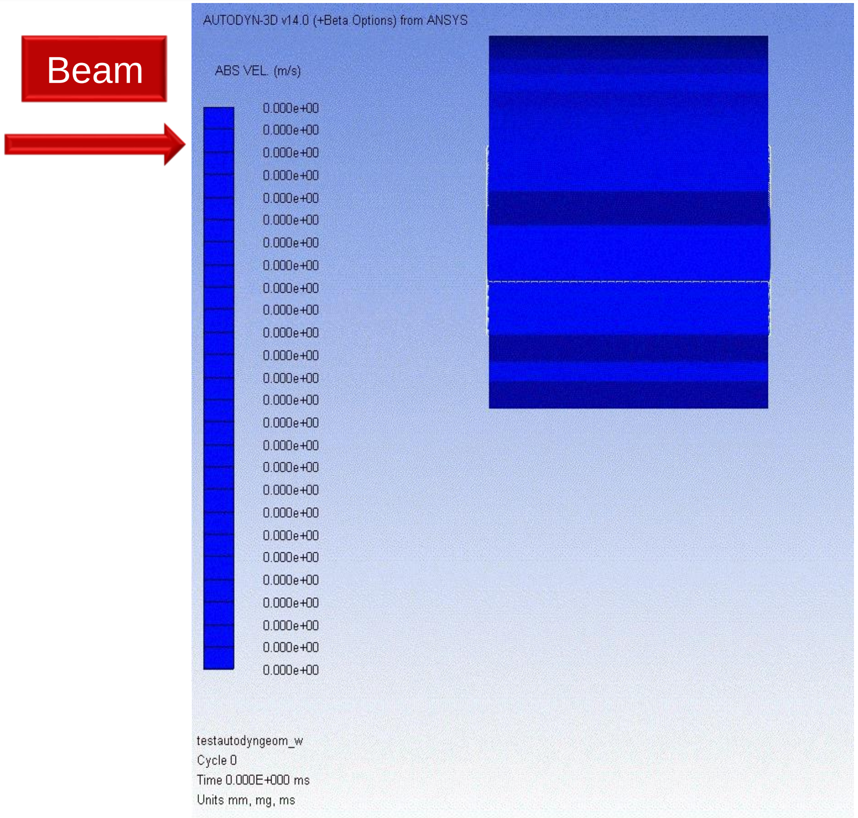
High Intensity Tests

Tungsten alloy samples as seen from test-bench viewport and remote fast-speed camera

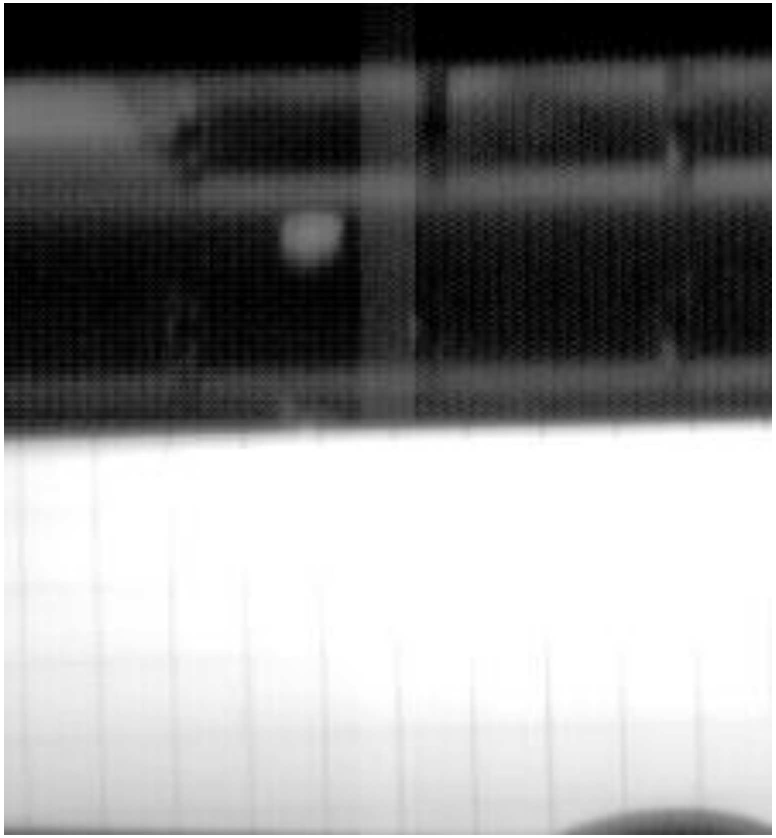


Example of test on simple specimens: HRMT14

High Intensity Tests: Comparison between numerical simulation (SPH) and experiment



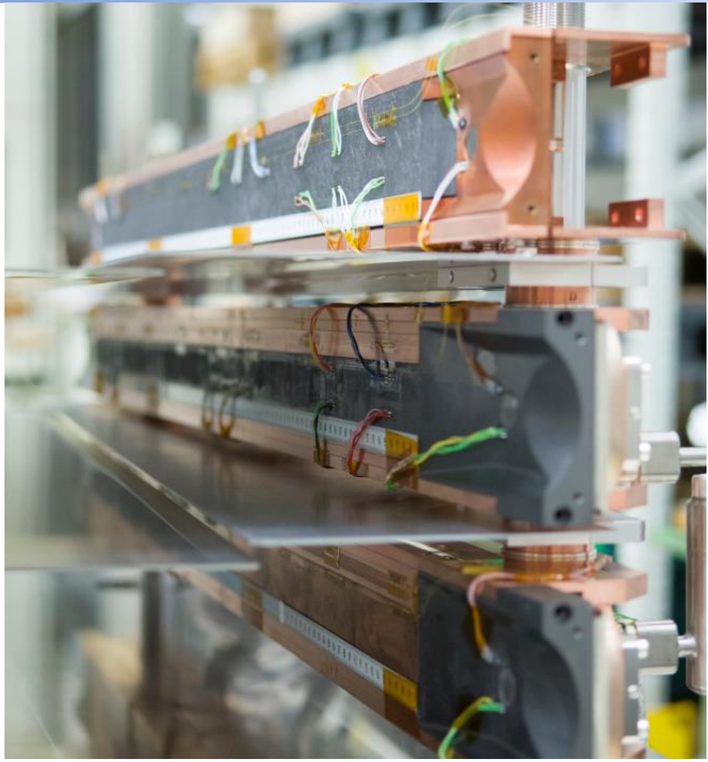
testautodyngeom_w
Cycle 0
Time 0.000E+000 ms
Units mm, mg, ms

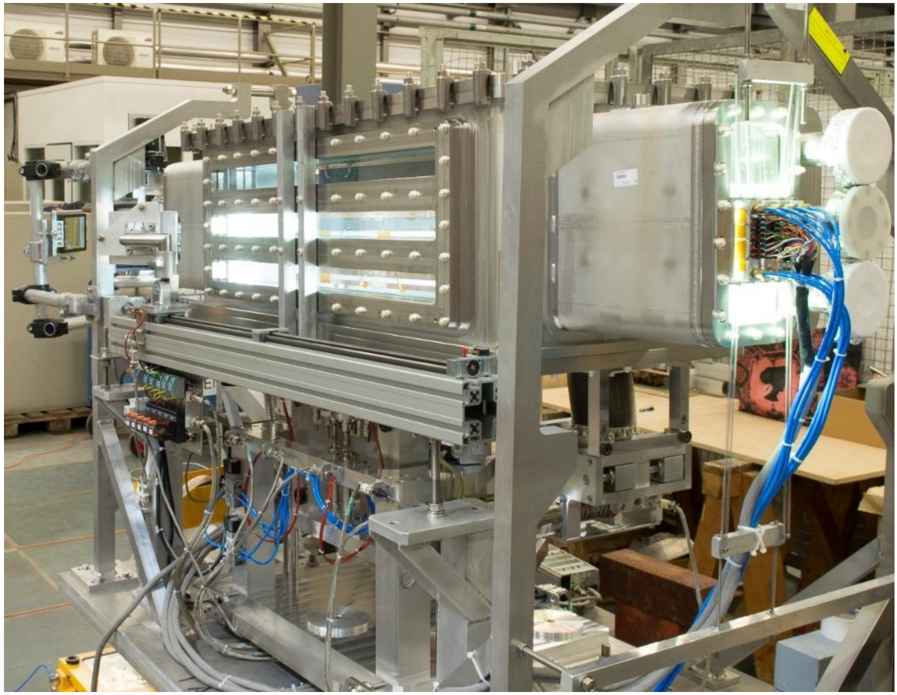


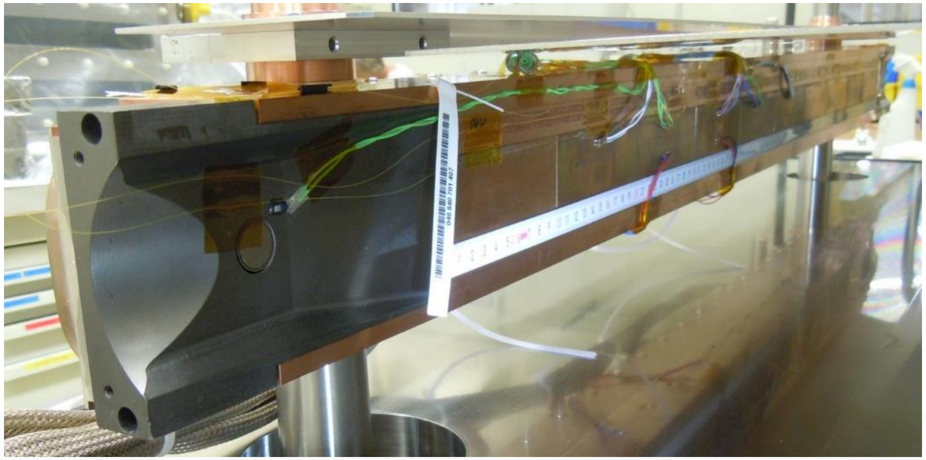
Case	Bunches	p/bunch	Total Intensity	Beam Sigma	Specimen Slot	Velocity
Simulation	60	1.5e11	9.0e12 p	2.5 mm	9	316 m/s
Experiment	72	1.26e11	9.0e12 p	1.9 mm	8 (partly 9)	~275 m/s

Example of Full Structure Test: HRMT23

- **Experiment** performed in 2015 to simultaneously test **3 complete jaws** (in **CFC**, **MoGr**, **CuCD**) of **2 different designs** (LHC and HL-LHC); system equipped with **comprehensive** set of **online sensors**, viewports for **optical acquisition** and fast dismounting system, permitting reuse.
- Allowed validation of **absorber jaw materials, as well as integral HL design** (taperings, BPM, housing, cooling circuit, brazing)
- **Achieved** $\boldsymbol{U_{max}}$of **HL-LHC** accidental cases, by squeezing the beam
- For CuCD, **exceeded** $\boldsymbol{\bar{U}_{max}}$ of the HL-LHC accidental case; for MoGr and CFC LIU beam is needed!





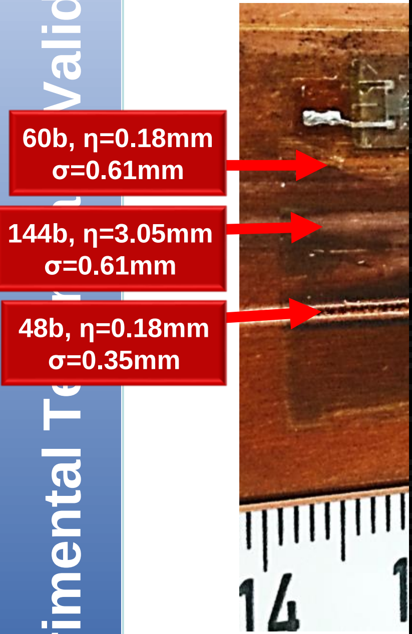


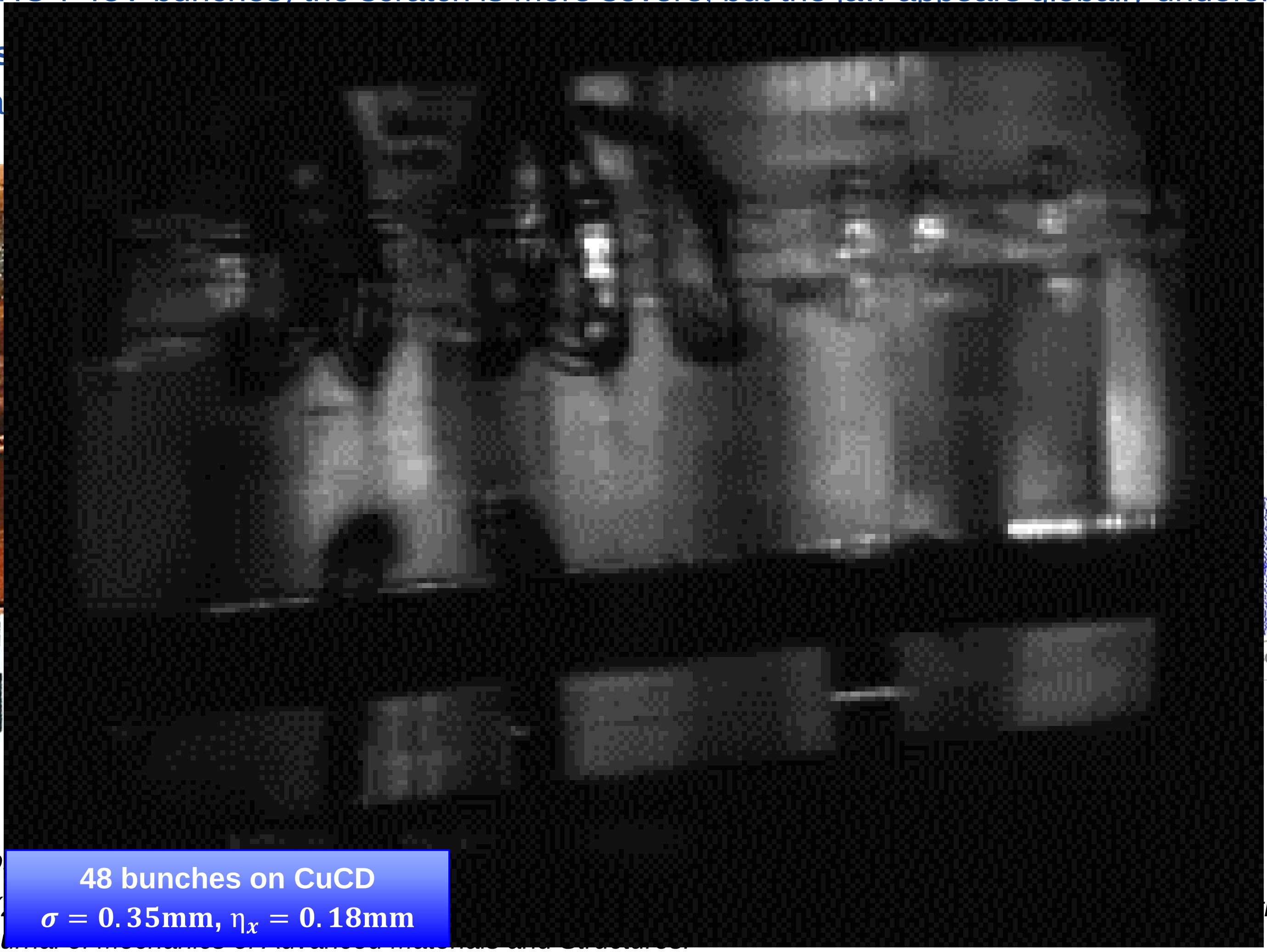
Example of Full Structure Test: HRMT23

Experimental Te

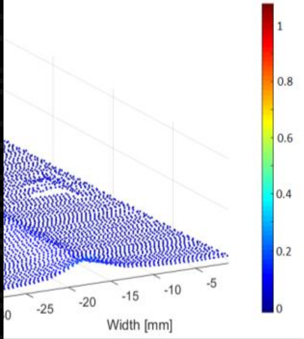
Validation

- **CuCD** on HL-LHC jaw survived (with a limited surface scratch on the Cu coating) the impact of **24 b, σ 0.35 mm** at 440 GeV, with peak energy density (U_{max}) **equivalent to 1 LHC bunch** at 7 TeV
- At **48 b** (~2 LHC 7 TeV bunches) the scratch is more severe, but the jaw appears globally undeformed
- This **qualifies** damage could be compensa





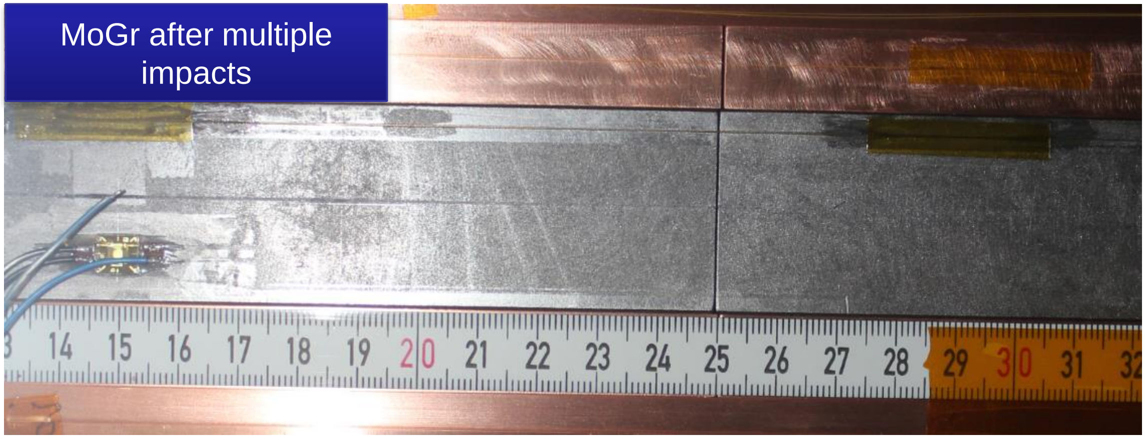
48 bunches on CuCD
$\sigma = 0.35\text{mm}, \eta_x = 0.18\text{mm}$

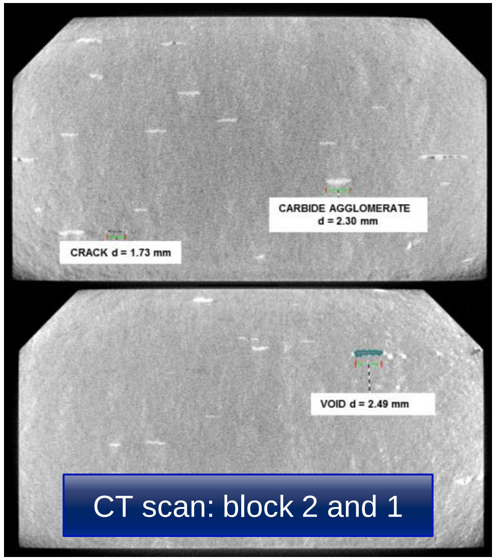


- *F. Carra (2017). https://zenodo.o*
- *G. Gobbi et al. (radiation examination. Journal of Mechanics of Advanced Materials and Structures.*
- *F. Carra et al. (2019). Mechanical robustness of HL-LHC collimator designs. Accepted in IPAC19, Melbourne, Australia.*

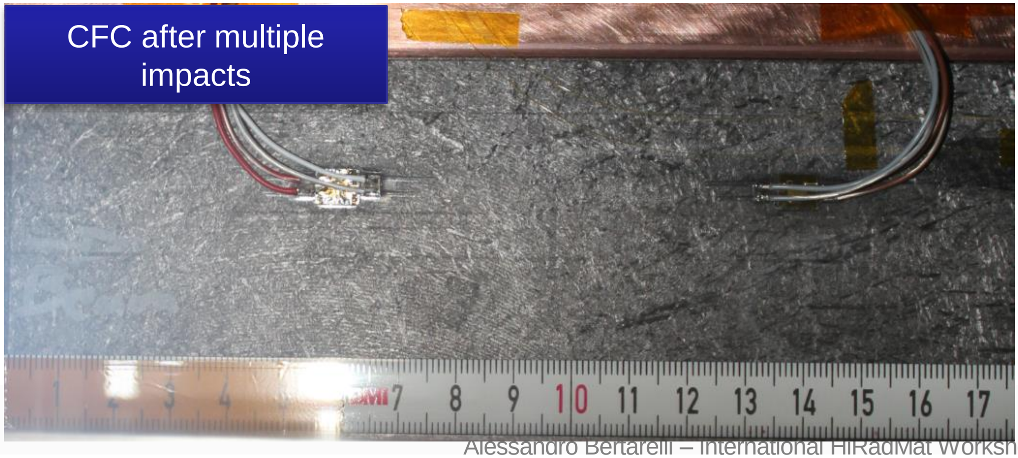
Example of Full Structure Test: HRMT23

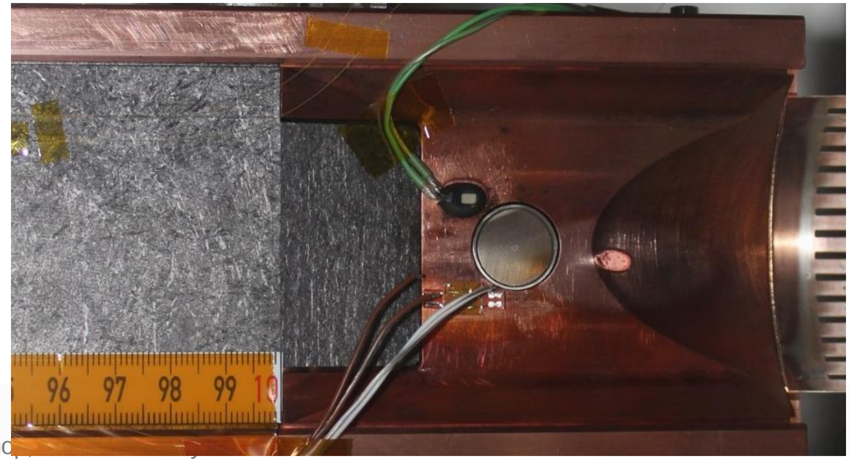
- In the case of **CFC** and **MoGr**, minor traces visible after the grazing impacts at 144 b and 288 b
- Deeper impacts (even at 288b) → no damage (smaller tensile wave at surface)
- No $\overline{U}_{max}$- induced damage on downstream blocks
- Downstream Glidcop tapering locally melted, BPM button lost functionality → For HL-LHC, change to **MoGr tapering** and to **Ti BPM**


MoGr after multiple impacts



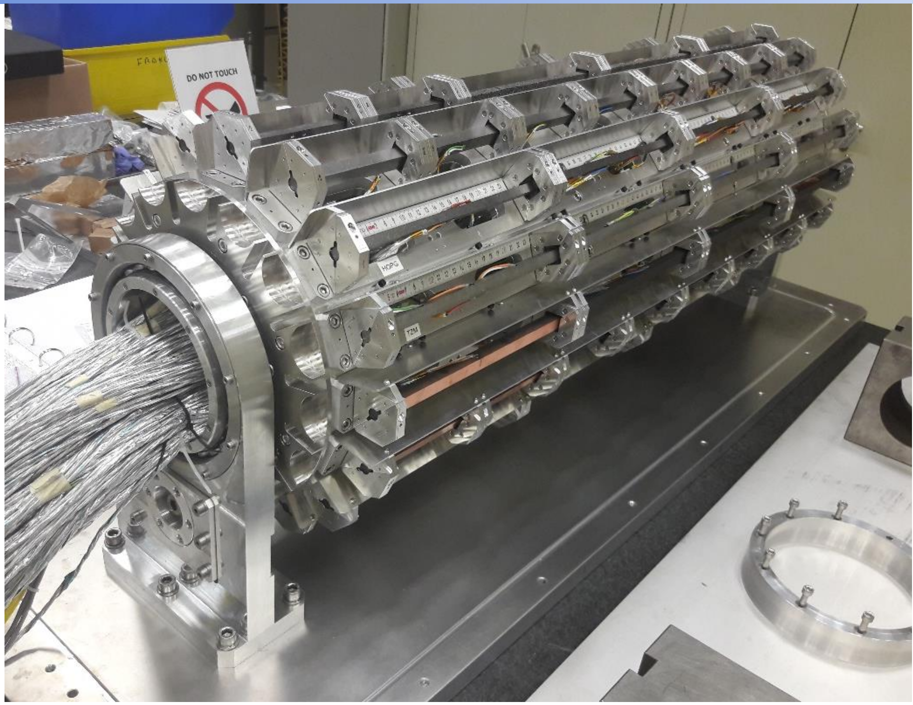
CT scan: block 2 and 1


CFC after multiple impacts



Example of test on simple specimens: HRMT36

- Experiment performed in **October 2017**
- Al vessel hosting under inert gas a rotatable barrel equipped with **16 target stations**, each one embarking **up to 8 slender specimens**, with **rectangular cross-section**
- **18 different materials** tested, ranging from ultra light C foams to W heavy alloys
- MoGr, CFC and graphite **coated** with **Mo**, **Cu**, **TiN**
- **Platform reusable** in future HRMT tests



- **Main objectives**:
- **Test materials** and **coatings** with $\boldsymbol{U_{max}}$ equivalent or exceeding that of **HL-LHC Beam Injection Error**
- Reach and exceed $\bar{U}_{max}$ of HL-LHC (**factor 2-3 higher**!) thanks to **sample section ~1/10th** of collimator jaw section
- Acquire material **dynamic responses** deriving / extending **constitutive models** and **material properties** required in numerical simulations

Example of test on simple specimens: HRMT36

- Specimen geometry chosen to **generate easily detectable, separable signals** which can be associated to quasi-independent phenomena with different timescales:
    - **Pulse duration (τ) < 1 ÷ 10 μs**. Associated to signal rise time. Highest strain rate effects ($\dot{\varepsilon} \cong 10^1 \div 10^4 s^{-1}$). Comparable to transverse period (**T_t**). Transverse mechanical strength.
    - **Longitudinal Period (T_L) ~100 μs**. Frequency of longitudinal waves (adiabatic). Dynamic elastic constants and damping ratio. Axial strength.
    - **Flexural Period (T_F) ~1 ms**. Frequency of lateral oscillations. Plasticity. Flexural strength. Permanent deformations.
    - **Thermal diffusion time (t_d) 0.1 ÷ 1 s**. Temperature measurement. Drift in lateral oscillations.
- Beam impacting targets with **variable offsets** at various intensities and brightnesses:
    - **Zero offset**. Excites longitudinal vibration. High frequency (5÷50 kHz). **Intensity**: **1 to 288 b** at 440 GeV. **Beam size**: **0.25, 0.5, 2 mm**
    - **Intermediate offset**. Additionally excites lateral oscillations. Lower frequencies (100÷2000 Hz). **Intensity**: **1 to 288 b** at 440 GeV. **Beam size**: **0.25, 0.5, 2 mm**
    - **Grazing impact**. Probe coating strength. Surface damage. **Intensity**: **144 and 288 b** at 440 GeV. **Beam size**: **0.25 mm**

HiRadMat
High-Radiation to Materials

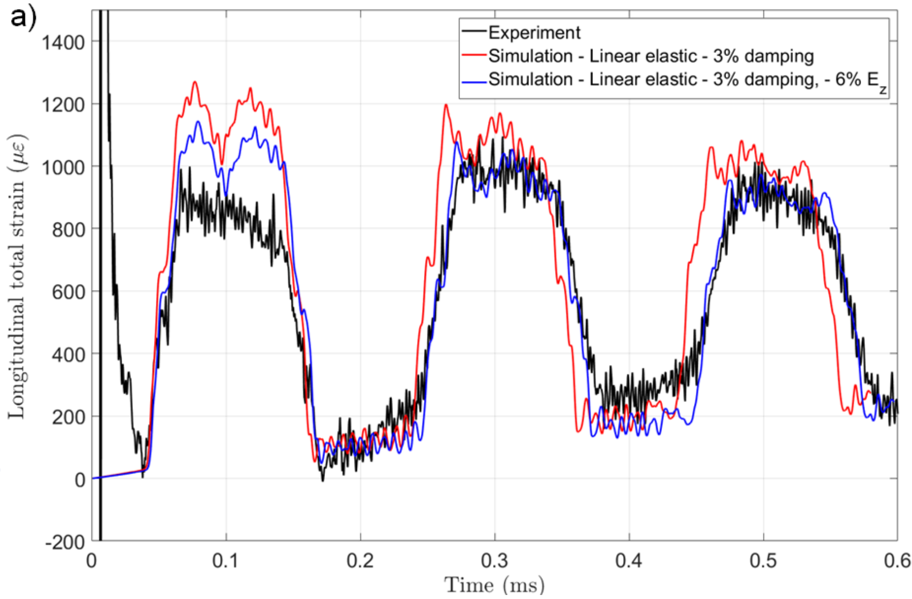
Example of test on simple specimens: HRMT36

Testing and Validation

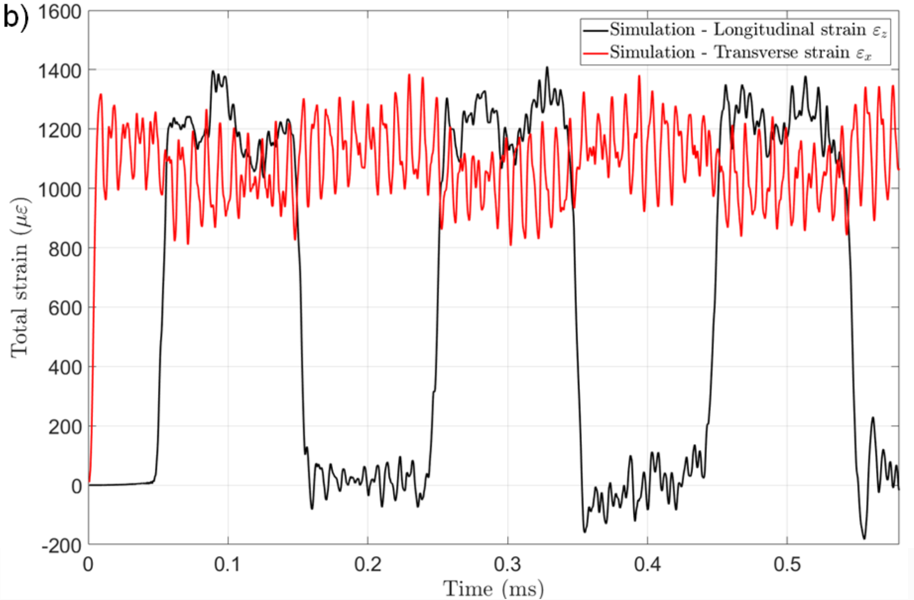
Analysis of results:

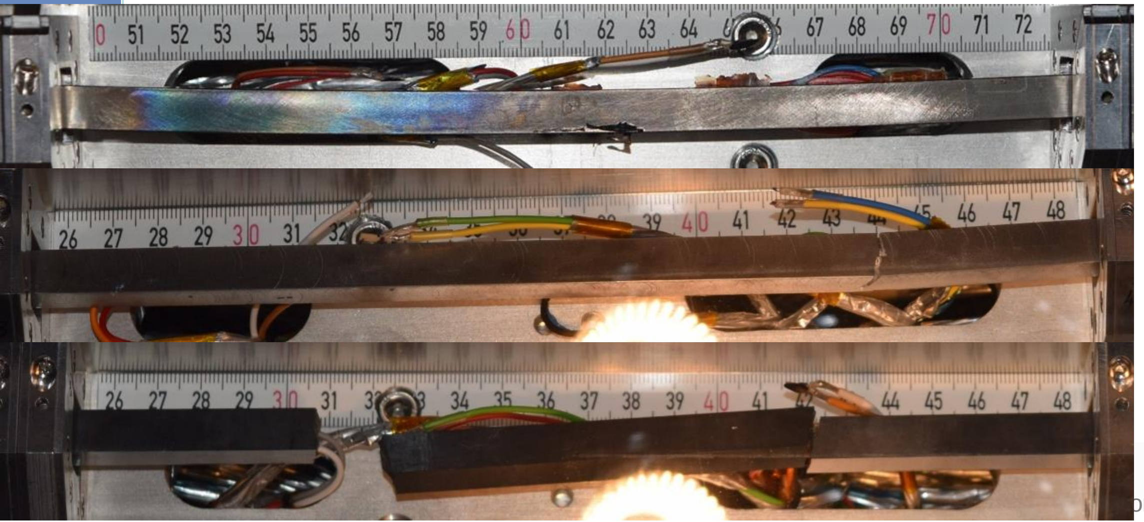
- Good agreement with simulations
- Elastic constants of several materials updated
- Role and extent of internal damping assessed
- All carbon-based materials survived impacts at **HL-LHC** $\bar{U}_{max}$
- Surface damage induced on coatings at U_{max} exceeding HL-LHC: larger in Cu coatings (lower melting point), smaller in Mo and TiN. Damaged stripes ~ 1÷3 mm wide
- Plastic permanent deflections induced in some high-Z materials
- Some unexpected failures (SiC and TZM) recorded

a)



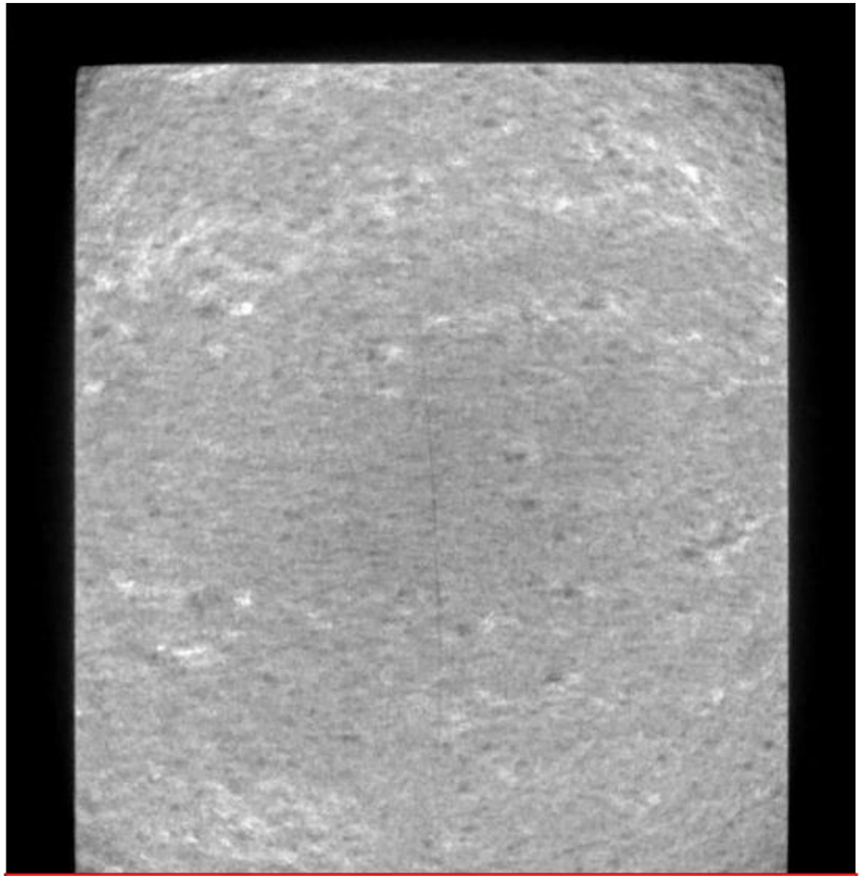
b)





Example of test on simple specimens: HRMT36

- On top of observing the onset of damage related to $\boldsymbol{U_{max}}$ **(upstream samples)**, onset of damage related to $\boldsymbol{\overline{U}_{max}}$ **(downstream)** was also determined
- Sample section ~1/10 of collimator block section → increased $\overline{U}_{max}$



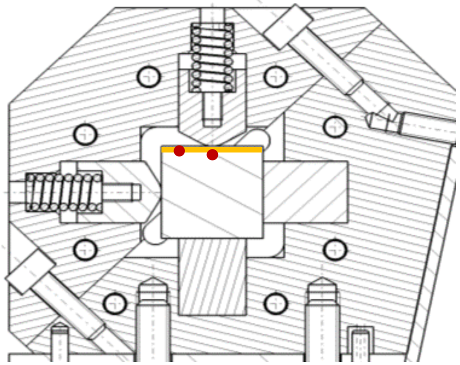
MoGr sample n. 8
(highest average energy density per section)

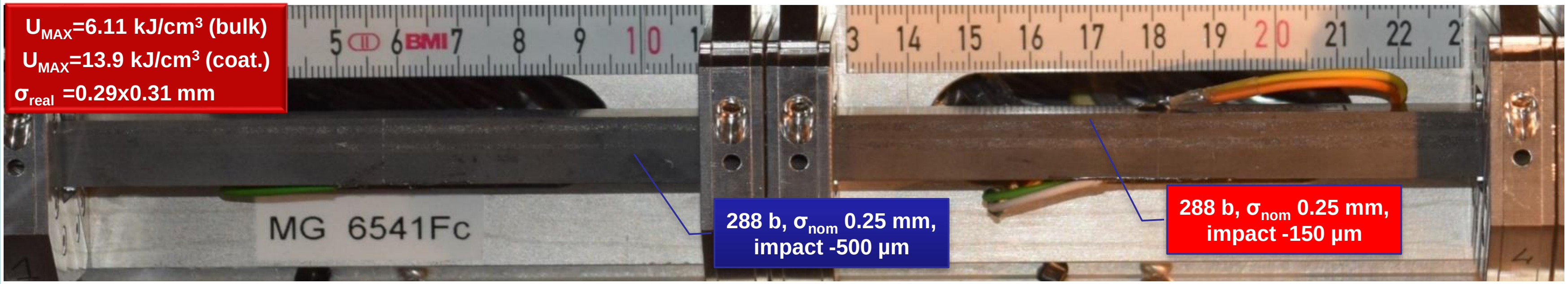
- Appearing on samples with $\overline{U}_{max}$ **2.5 higher** than HL-LHC accidents
- Samples with $\overline{U}_{max}$ equal to HL-LHC → below onset of damage

- *F. Carra et al. (2017). The "Multimat" experiment at CERN HiRadMat facility: advanced testing of novel materials and instrumentation for HL LHC collimators. J. Phys.: Conf. Ser., Vol 874, Issue 1.*
- *A. Bertarelli et al. (2018). Dynamic testing and characterization of advanced materials in a new experiment at CERN HiRadMat facility. J. Phys.: Conf. Ser.1067 082021.*
- *M. Pasquali et al. (2019). Dynamic response of advanced materials impacted by particle beams: the MultiMat experiment. Submitted to the DYMAT2019 Workshop.*
- *F. Carra et al. (2019). Mechanical robustness of HL-LHC collimator designs. Accepted in IPAC19, Melbourne, Australia.*

Example of test on simple specimens: HRMT36

- **Grazing impact**. Probe coating strength (Cu, Mo, TiN) and surface damage.
- Smallest available beam size (**0.25×0.25 mm²**) at max bunch intensity (**1.4e11 p/b**)
  Impacts at **144** (on Cu) and **288 b** (all) at different depth (**150 μm** and **500 μm)**

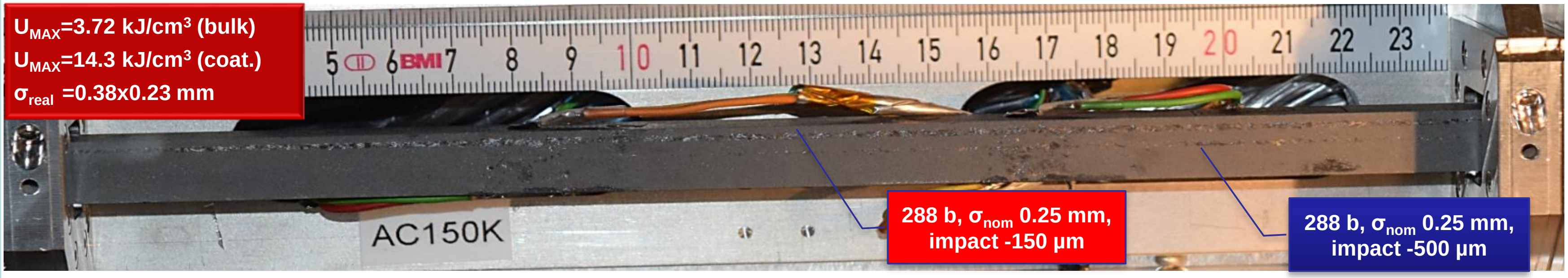




U_{MAX}=6.11 kJ/cm³ (bulk)
U_{MAX}=13.9 kJ/cm³ (coat.)
σ_{real} =0.29x0.31 mm

288 b, σ_{nom} 0.25 mm, impact -500 μm

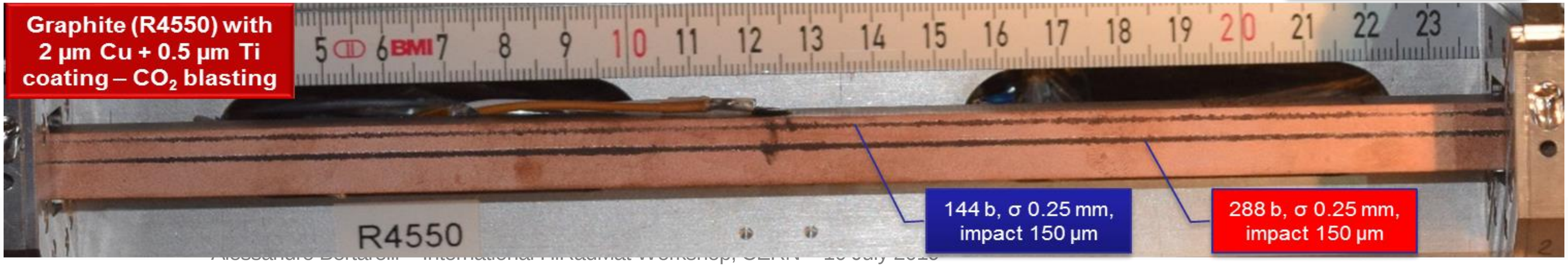
288 b, σ_{nom} 0.25 mm, impact -150 μm



U_{MAX}=3.72 kJ/cm³ (bulk)
U_{MAX}=14.3 kJ/cm³ (coat.)
σ_{real} =0.38x0.23 mm

288 b, σ_{nom} 0.25 mm, impact -150 μm

288 b, σ_{nom} 0.25 mm, impact -500 μm



Graphite (R4550) with 2 μm Cu + 0.5 μm Ti coating – CO_2 blasting

144 b, σ 0.25 mm, impact 150 μm

288 b, σ 0.25 mm, impact 150 μm

Summary

- High energy particle accelerators handle beams with **extremely high destructive potential** in case of interaction with matter
- The analysis of beam-matter interaction involves several disciplines and requires a **multiphysics approach**
- When interaction phenomena do **not** lead to extensive **changes of density** or **phase transitions**, material response can be analysed with a good degree of approximation by classical **thermoelasticity principles**
- **Otherwise**, advanced nonlinear tools (**hydrocodes**) must be invoked: these numerical codes rely on complex **material constitutive models** encompassing the full range of states of matter
- Only **dedicated**, **carefully designed experiments** in **ad-hoc facilities** such as HiRadMat can benchmark advanced numerical simulations and provide the **final validation** for systems potentially exposed to interaction with highly energetic beams
- The **flexibility of HiRadMat** allows to perform **tests** on **full, large structures** as well as on **small, simple specimens**, providing **results of interest well beyond the High Energy Physics community**
- It is possible, playing with beam brightness and sample cross sections, to **reach peak energy densities** and **average energy densities exceeding** those expected in **HL_LHC** …
- … however, only an upgrade of **the facility operating with full LIU beams** can allow **to test full equipment** to be operated in **HL-LHC,** further enhancing this **key asset** for the Particle Accelerator community and beyond …

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High Energy Particle Accelerators Challenges

- Particle beams have reached **unprecedented energy** and **energy density (363 MJ** for the LHC, **690 MJ** for its **High Luminosity upgrade** (**HL-LHC**)).
- **Beam-induced accidents** and **beam losses** among the **most relevant issues** in the design and operation of high power particle accelerators!
- This is particularly relevant for components intrinsically exposed to such events (**Beam Intercepting Devices) …**

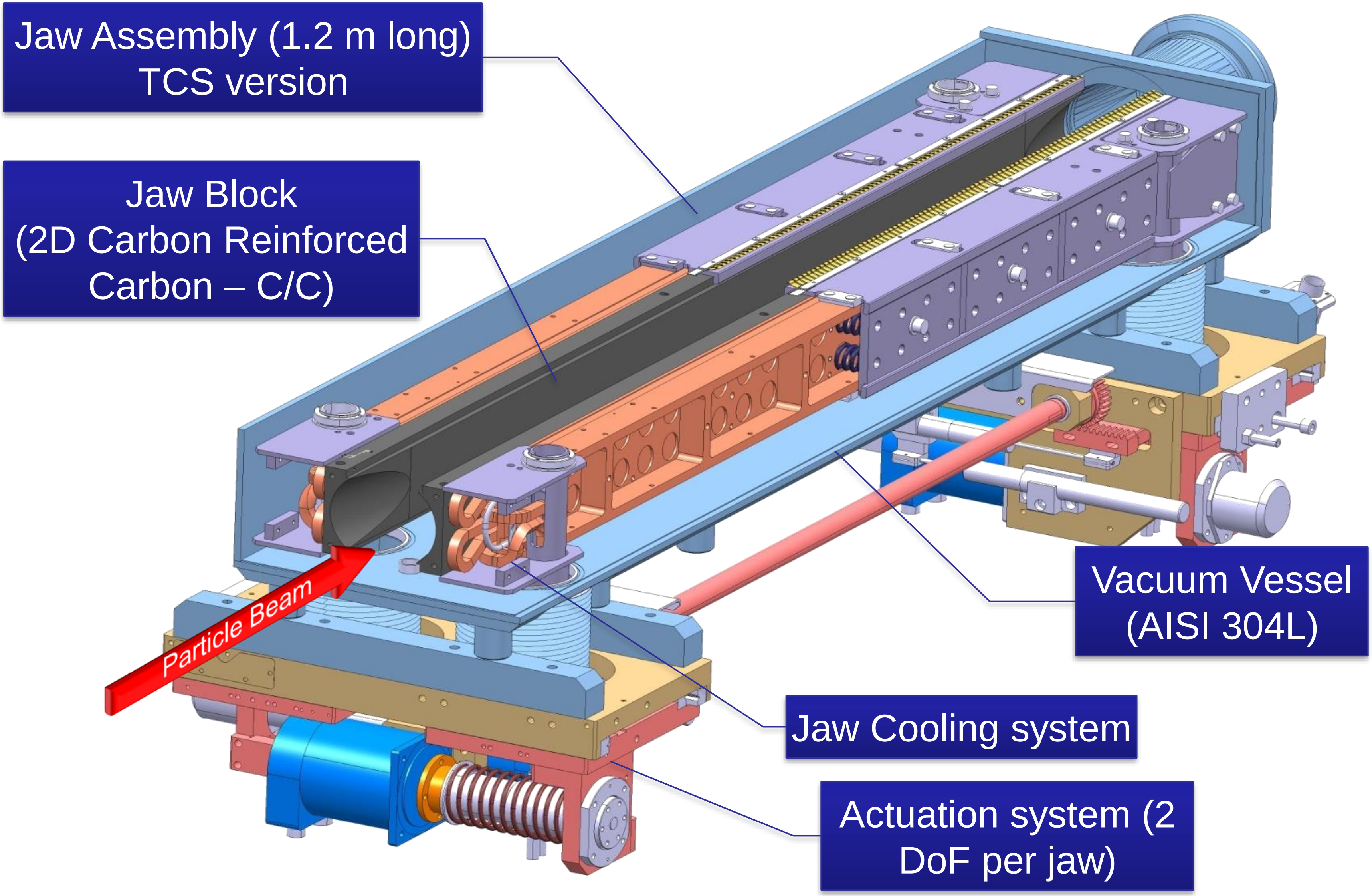
This trend is set to become even more compelling for future super-accelerators, e.g. **8500 MJ** for future **100 km FCC-hh** proposal

What is HL-LHC Energy equivalent to?

USS Harry S. Truman

160 kg TNT

LHC (Secondary) Collimator Main subsystems



Jaw Assembly (1.2 m long)
TCS version

Jaw Block
(2D Carbon Reinforced Carbon – C/C)

Vacuum Vessel
(AISI 304L)

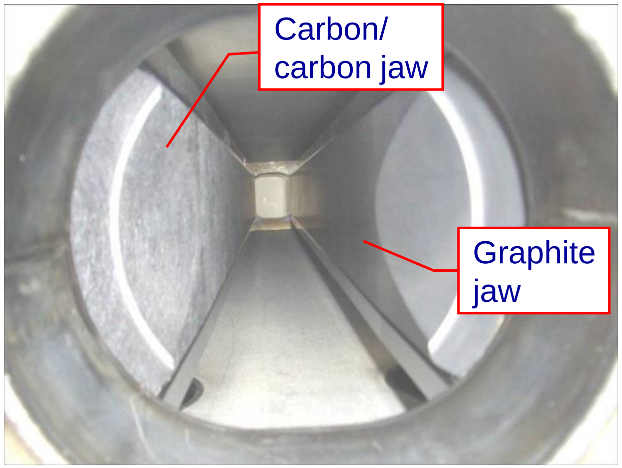
Jaw Cooling system

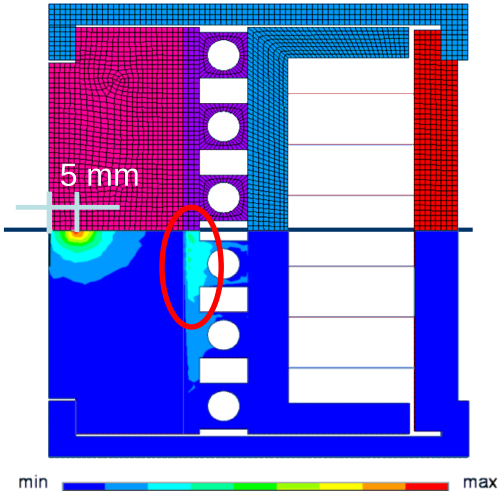
Actuation system (2 DoF per jaw)

Dynamic Plastic Regime: Example

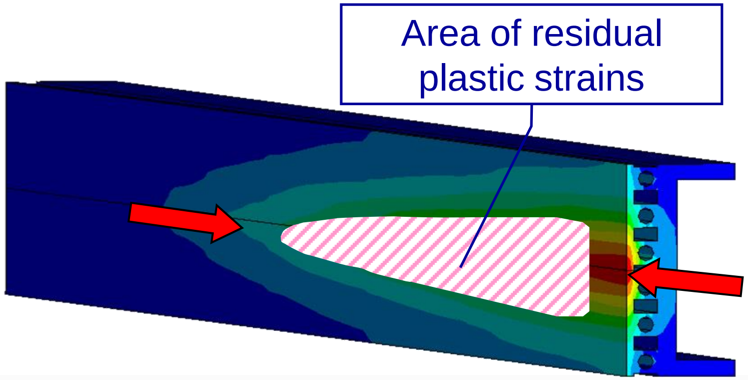
- In plastic regime, an implicit FEA code (e.g. ANSYS) is usually adopted to simulate structure response.

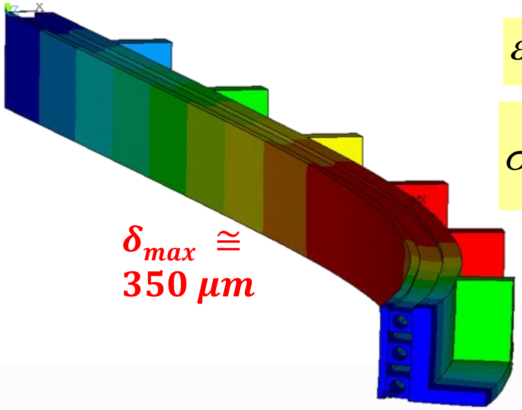
Example: LHC Secondary Collimator submitted to robustness test in 2004 (288 x 1.15x10^{11} p, 450 GeV)





- *3D coupled analysis to assess* ***temperature, stresses and strains***
- *Priority given to critical carbon-based jaw blocks ⇨* ***post-mortem analysis confirmed survival of both blocks.***
- *A moderate* ***T increase*** *(~70°C) on OFE-Cu back-plate was* ***initially ignored …***
- *A simple analytical check anticipated what numerical simulation then confirmed…*





$\delta_{max} \cong 350\ \mu m$

$$\varepsilon_{z_{\max}} = -\alpha \Delta T_{\max} \cong -0.0012$$

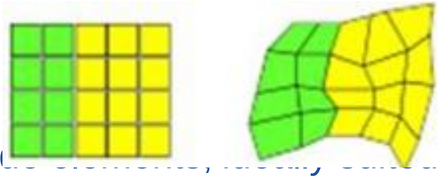
$$\sigma_{z_{\max}}^{lin} = -\frac{E \alpha \Delta T_{\max}}{1-\nu} \cong -210 MPa$$

Numerical Codes: Hybrid mesh (Hydrocodes)

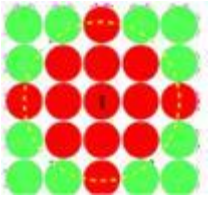
Hydrocodes are **highly nonlinear wave propagation tools**, initially developed for high speed mechanical impacts, where solids can be approximated as **fluids (deviatoric stresses neglected)**.

Simulations can be performed using two different meshing schemes, **Lagrangian** and **SPH**:

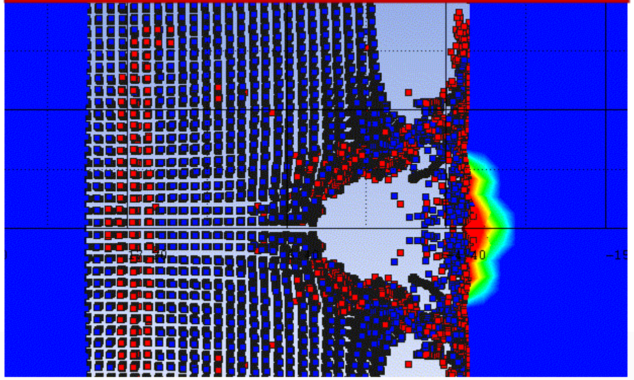
- **Lagrangian mesh** moves and distorts with the material it models as a result of forces from neighboring elements.
  - Most efficient solution for structures.
  - Very slow when element incur in large deformations.



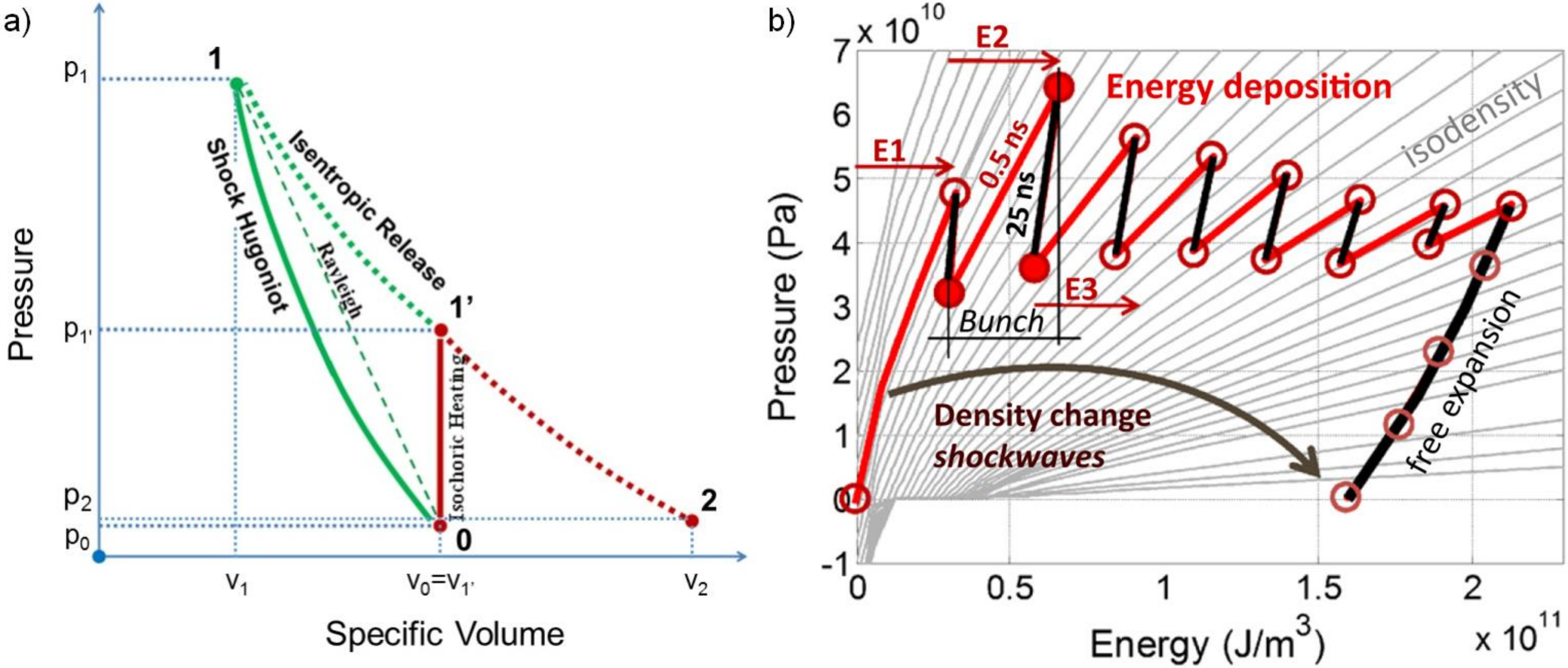
- **SPH** (**Smooth Particle Hydrodynamic**): mesh-free method, with single node elements, ideally suited for problems with extensive material damage and separation.
  - Possibility to study crack propagation inside a body and motion of ejected fragments/liquid droplets.
  - SPH elements must be generally very small to accurately model the material. Compromise to be found between accuracy and computation time.



7TeV, 1.3E11 protons impact on LHC Tertiary Collimator



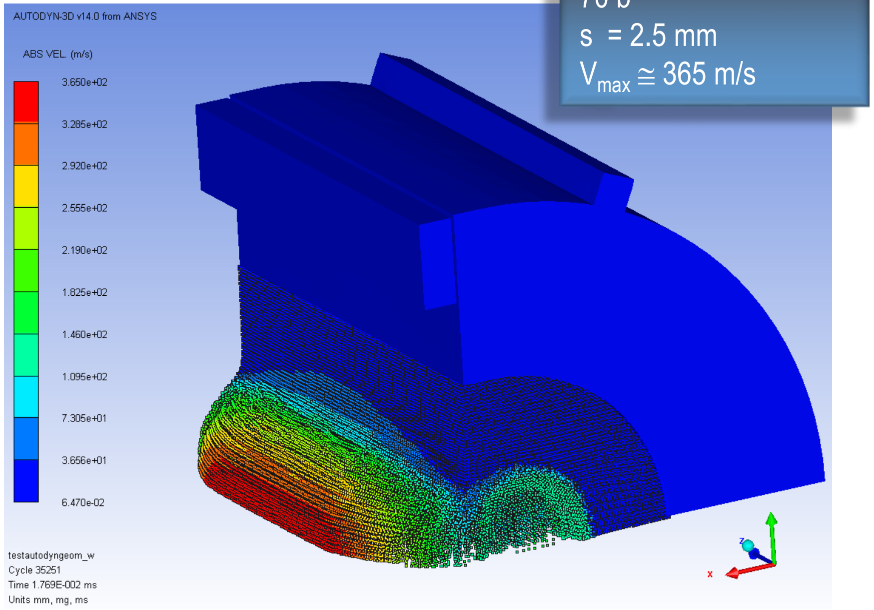
Interaction SPH - Lagrangian mesh:
When an SPH particle approaches a Lagrangian part the interaction matrix must take into account the non penetration of solids and turn kinetic energy into deformation.


a)
Pressure
p1
p1'
p2
p0
1
1'
0
2
Shock Hugoniot
Rayleigh
Isentropic Release
Isochoric Heating
v1
v0=v1'
v2
Specific Volume
b)
x 10^10
Pressure (Pa)
7
6
5
4
3
2
1
0
-1
E1
E2
E3
0.5 ns
25 ns
Bunch
Energy deposition
isodensity
Density change
shockwaves
free expansion
0
0.5
1
1.5
2
x 10^11
Energy (J/m^3)

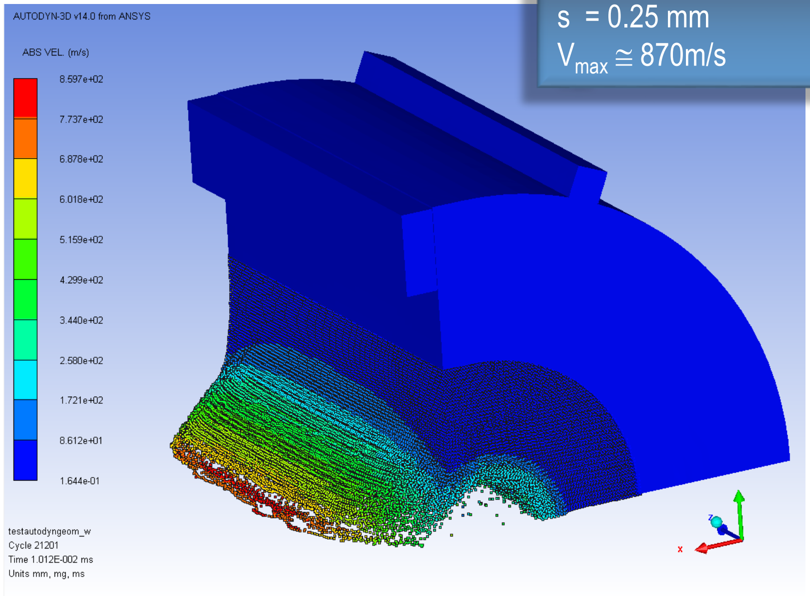
Example of test on simple specimens: HRMT14

High Intensity Tests

- Smooth-Particle-Hydrodynamics (SPH) calculations allowed determining damage extension, particle fragment velocity and trajectories.
- Assessment of potential damages to tank, windows and viewports.
- Material density changes.

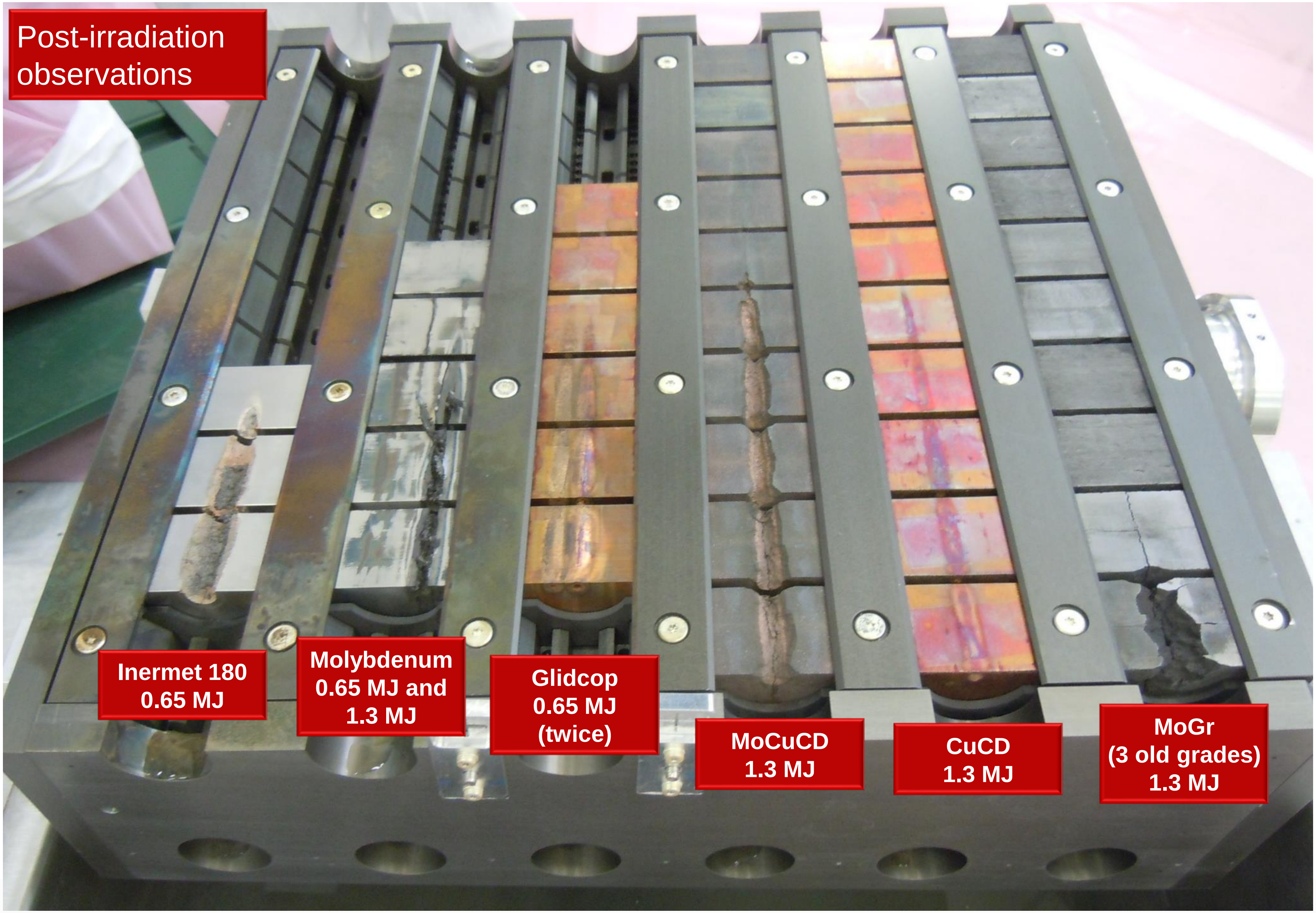


Inermet180
70 b
s = 2.5 mm
$V_{max} \cong$ 365 m/s



Inermet180
60 b
s = 0.25 mm
$V_{max} \cong$ 870m/s

Example of test on simple specimens: HRMT14



#	Material	Density [g/cm³]	Coated	Coating Material
1	IT180	18.0	✗	
2	Ta10W	16.9	✗	
3	Ta2.5W	16.7	✗	
4	TZM	10.0	✗	
5	CuCD IFAM	5.40	✗	
6	CuCD RHP	5.40	✗	
7	SiC	3.21	✗	
8	MG-6403Fc	2.54	✓	TiN
9	ND-7401-Sr	2.52	✗	
10	MG-6530Aa	2.50	✓	Cu
11	MG-6541Fc	2.49	✓	Mo
12	HOPG	2.26	✗	
13	TG-1100	2.19	✗	
14	R4550	1.90	✓	Cu
15	CFC AC150K	1.88	✓	Mo
16	Ti6Al4V (AM)	1.62	✗	
17	CFOAM	0.40	✗	
18	Al 6082-T651 (UoHud)	2.70	✗	

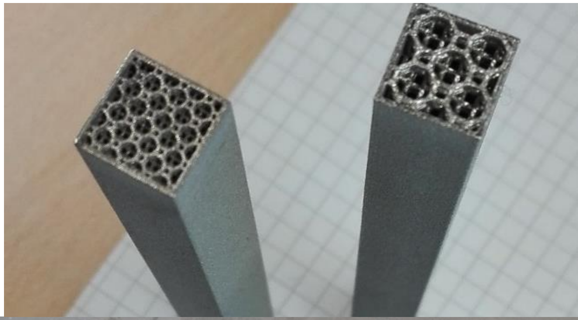
high density

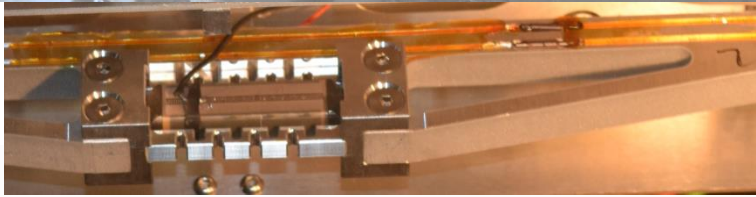
medium density

low density

Dedicated setup

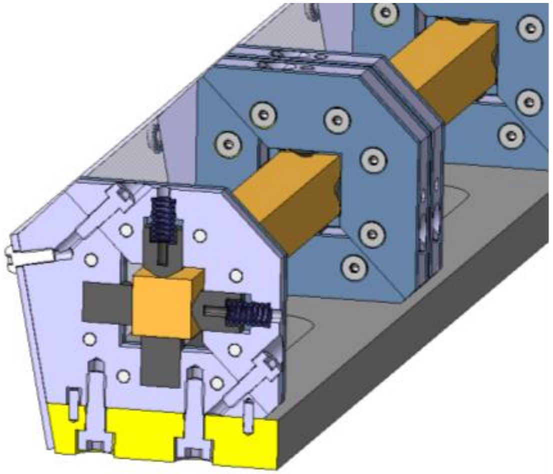
- **18 materials/grades** to be tested.
- **4 grades** of **MoGr** from 2 manufacturers (BB and Nanoker)
- **3 coatings**, **Cu**, **Mo** (CERN) and **TiN** (DTI)
- Different combination of surface and thermal treatments (48h firing, CO2 blasting, US cleaning);
- **2 grades** of **CuCD** from 2 suppliers (RHP and IFAM)
- Novel **carbon-based materials** as **HOPG** (Highly-Ordered Pyrolitic Graphite) and **Titanium-Graphite (TG-1100)**
- Additively Manufactured Titanium samples (**Ti6Al4V**);
- Actively controlled (via piezoelectric transducers) **Al** samples (UoH)

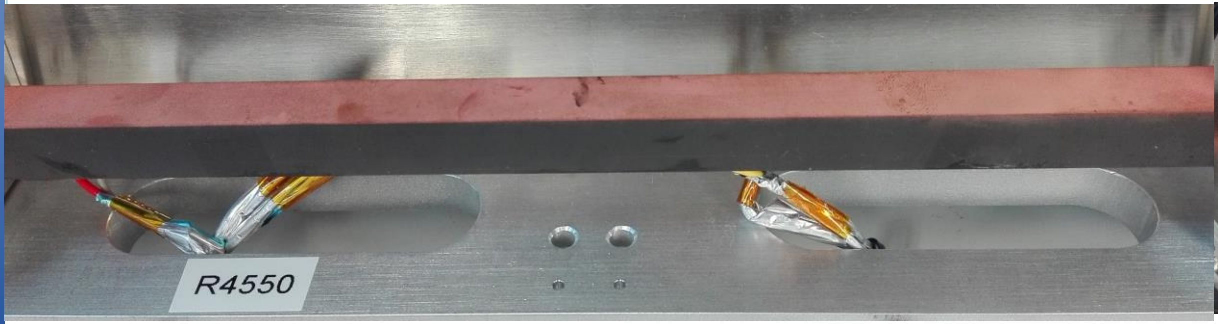




MultiMat Design Overview

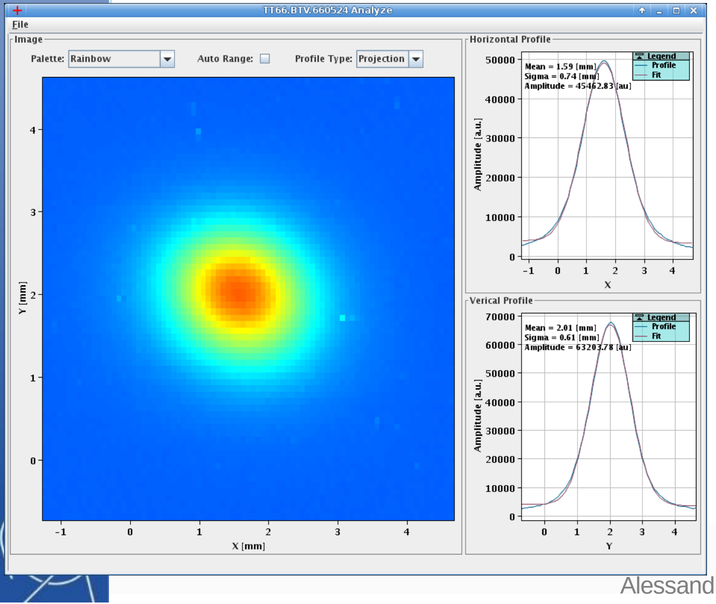
- Specimens of simple geometry (**slender bars,** length **120** or **248 mm**) to generate simple wave signals, relatively easy to acquire and benchmark. **Some low-Z samples coated** (Mo, Cu, TiN)
- **Simply supported** bars, axially **free** to expand.
- Mainly **square cross section** (8×8 to 12×11.5 mm^2) to disentangle anisotropy and simplify PIE





Experiment Runs

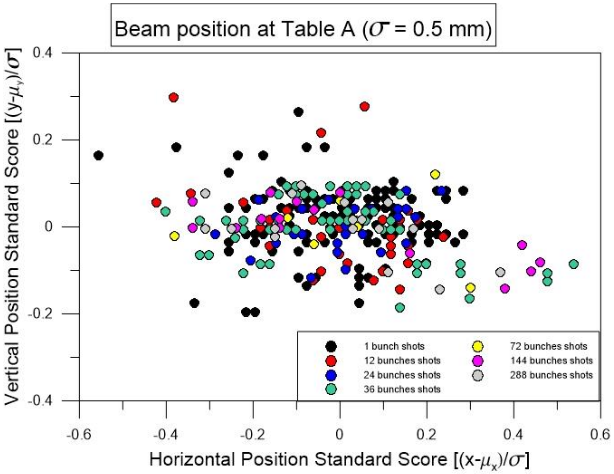
- Installed **2 October**
- Experimental runs from **3 October** to **17 October**
- 478 pulses (including BBA and parking position). **2.25x10^{15}** POT (in line with initial request)
- Intensity ranging from **1 b** to **288** b, typically **1.3x10^{11} p/b**
- Beam rms size (nominal): **0.25×0.25**, **0.5×0.5**, **2×2 mm^2**
- Good beam stability and repeatability, particularly important for grazing impacts (all data available on logbook)

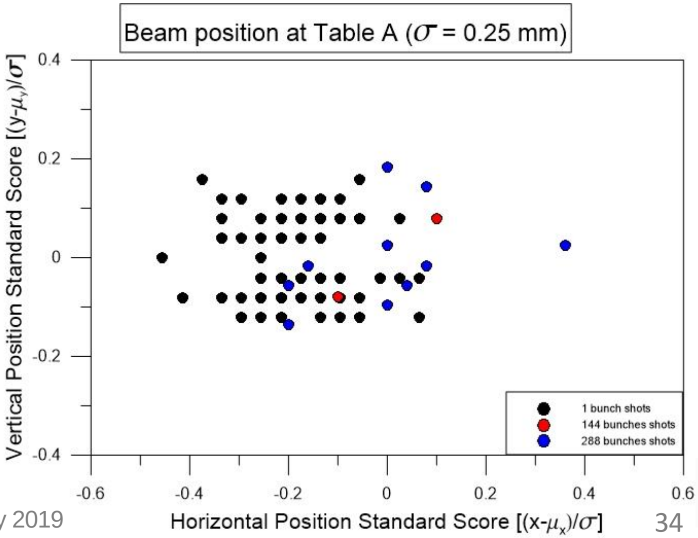


Palette: Rainbow
Auto Range: ☐
Profile Type: Projection

Mean = 1.59 [mm]
Sigma = 0.74 [mm]
Amplitude = 45462.83 [au]

Mean = 2.01 [mm]
Sigma = 0.61 [mm]
Amplitude = 63203.78 [au]

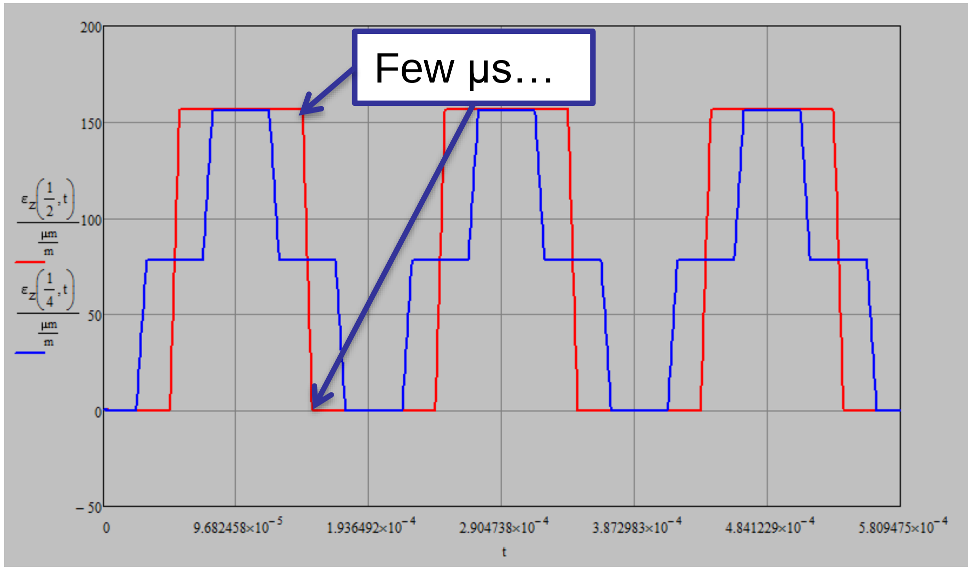

Beam position at Table A (σ = 0.5 mm)

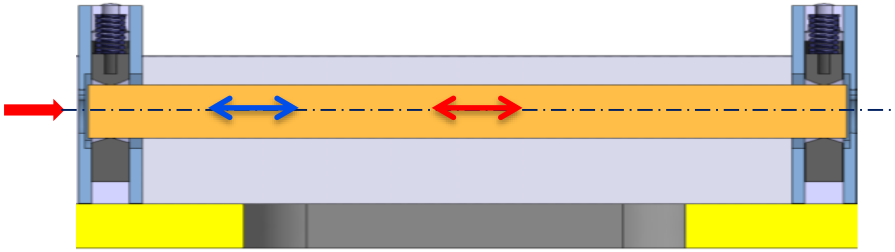

Beam position at Table A (σ = 0.25 mm)

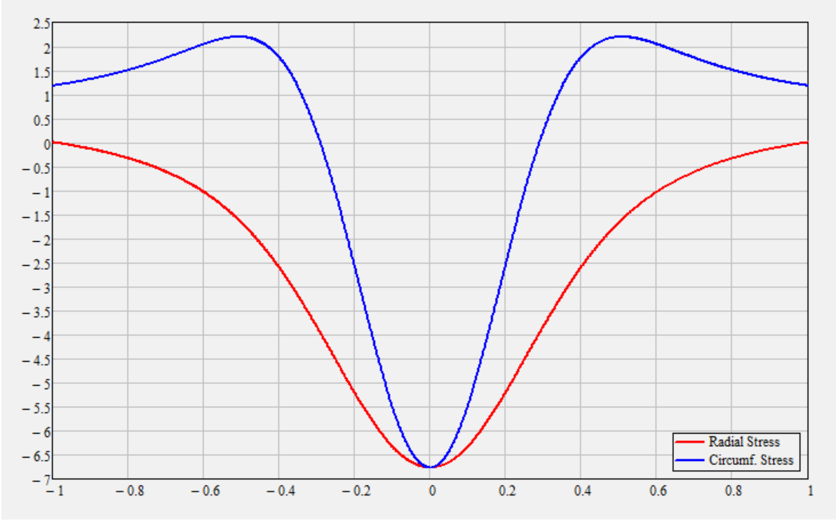
No Offset Impact

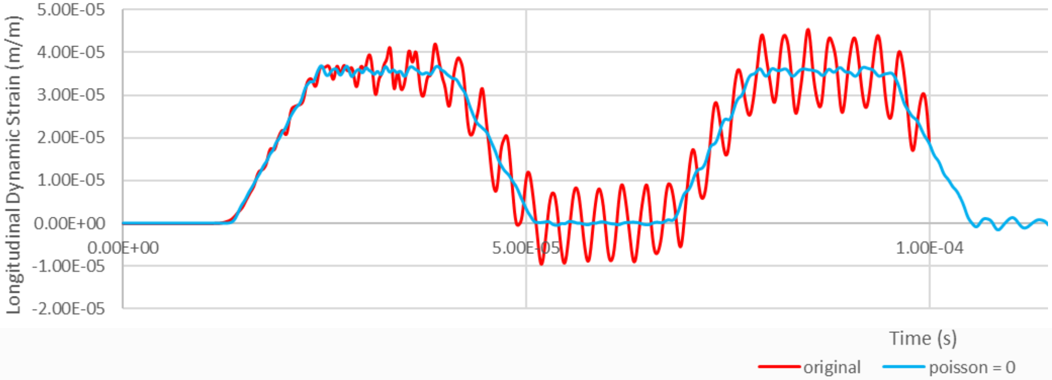
Preliminary Results

- Excites longitudinal vibration.
- High frequency (5÷50 kHz).
- Shock. Strain rate effects. Internal damping.
- Weaker signals for low-Z materials → Small cross-section
- Larger beam size (2 mm) to prevent excessive radial and azimuthal stresses in high-Z materials
- Radial waves (ignored in analytical approximation) depending on Poisson’s ratio and target geometry



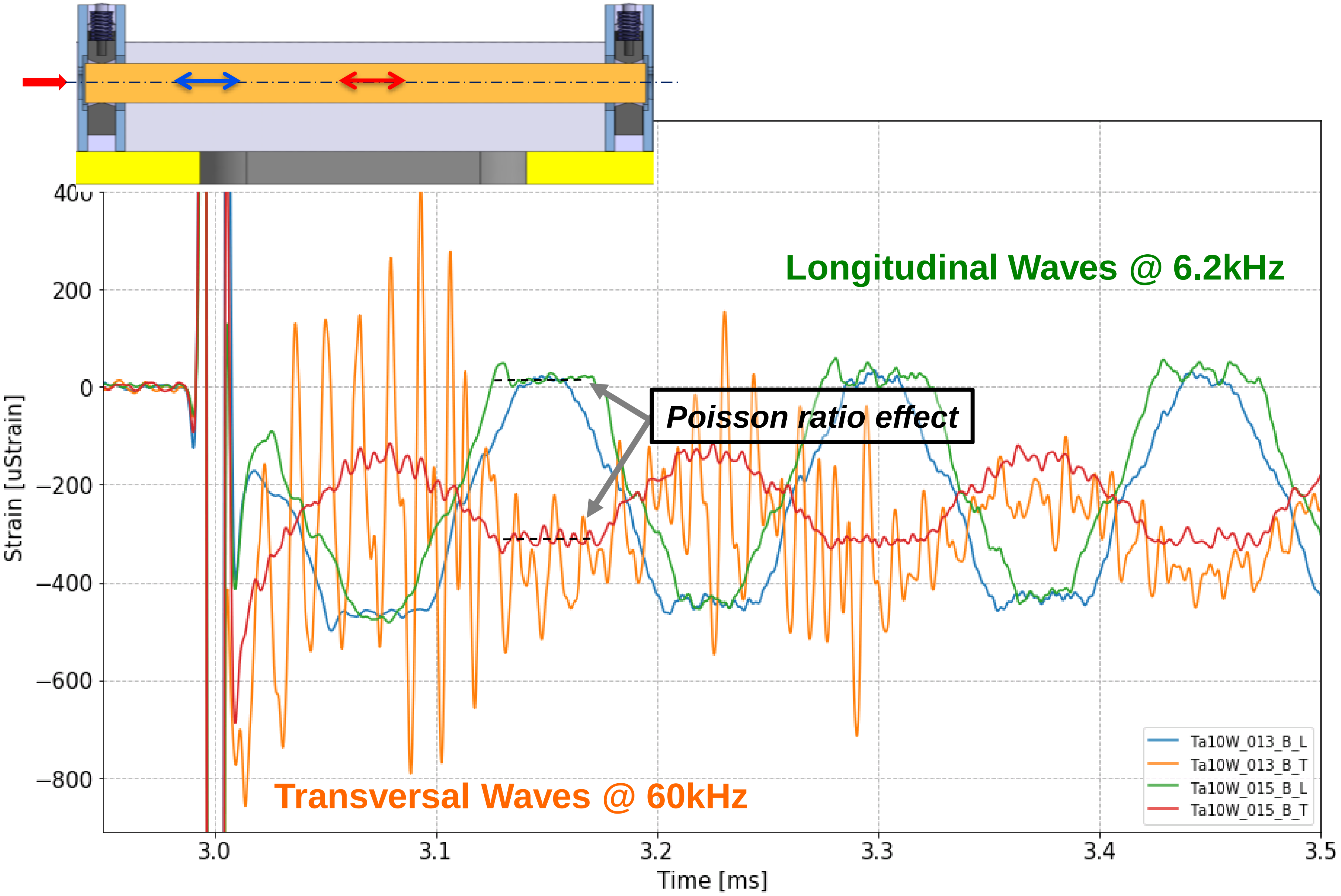






No Offset Impact: Ta10W (1b 1.49e11)

Preliminary Results



Longitudinal Waves @ 6.2kHz

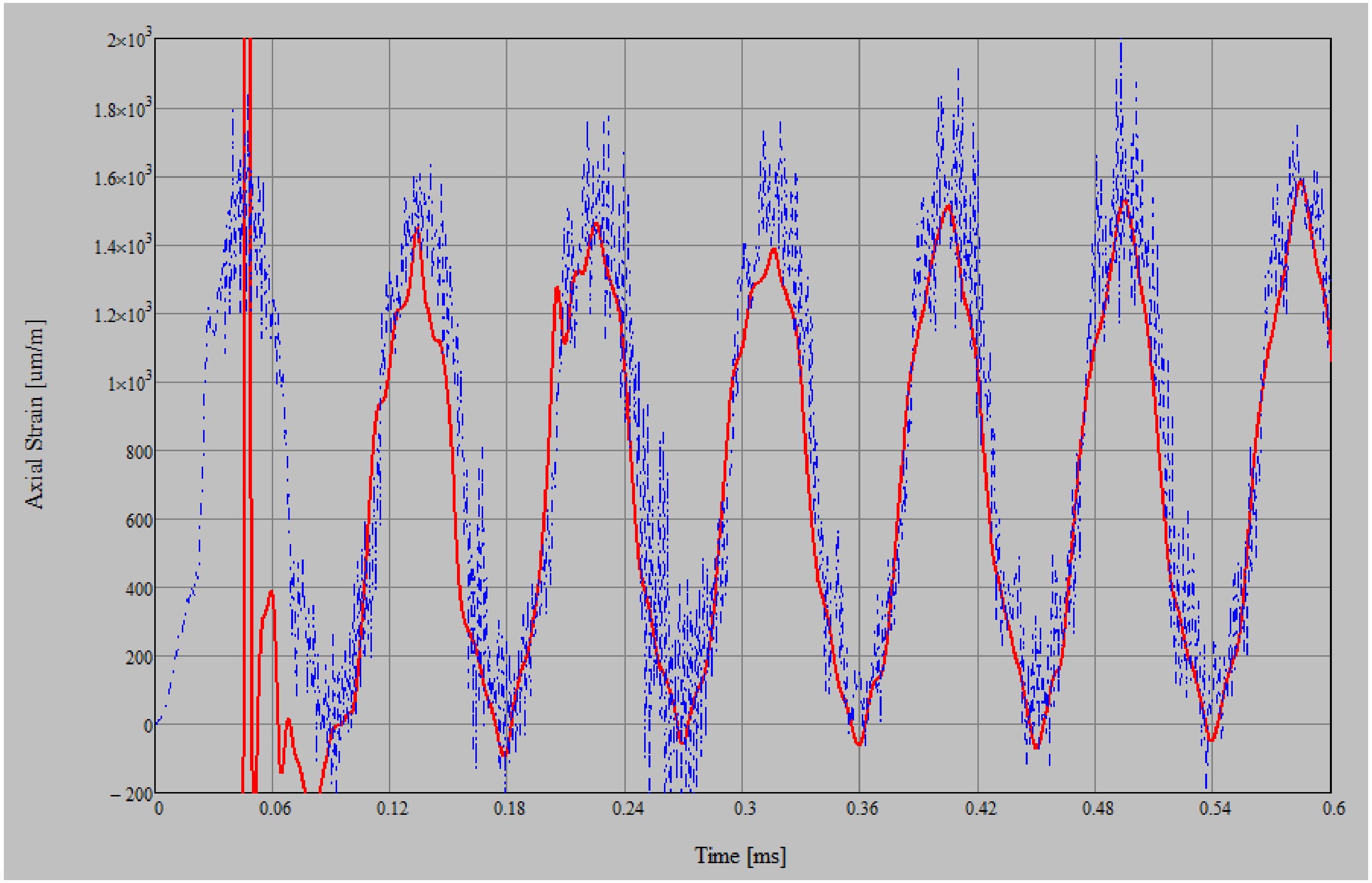
Poisson ratio effect

Transversal Waves @ 60kHz

No Offset Impact: TZM (Strain Gauge vs Simulation)

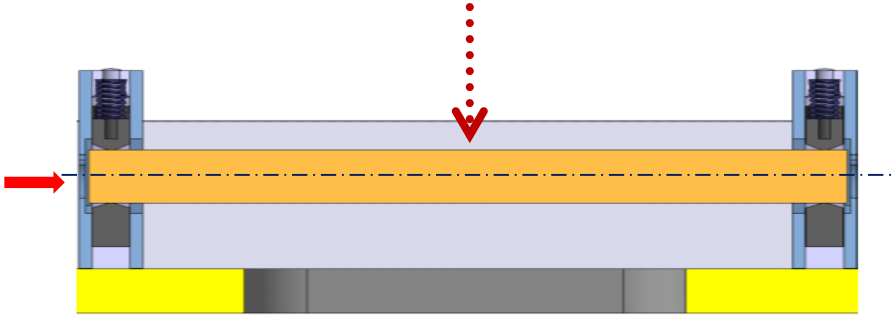
- Experimental data: Pulse 348. Axial impact 12 b, rms beam size 2 mm, 1.12e11 p/b
- Axial strain gauge at specimen centre
- FLUKA data: 12 b, rms beam size 0.5 mm, 1.3e11 p/b, circular cross section R 7.5 mm
- FLUKA scaling factor 1/1.8

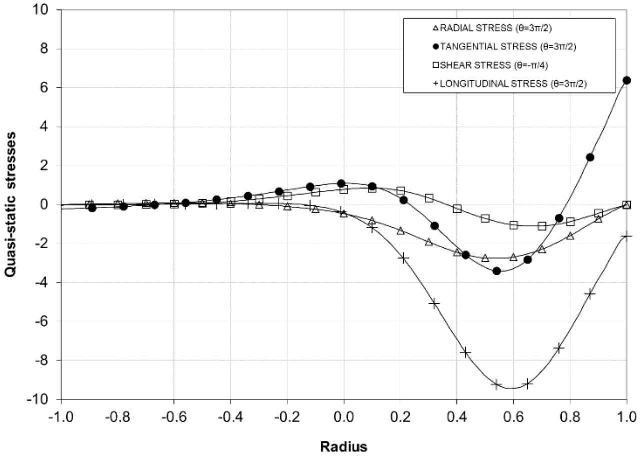
Preliminary Results

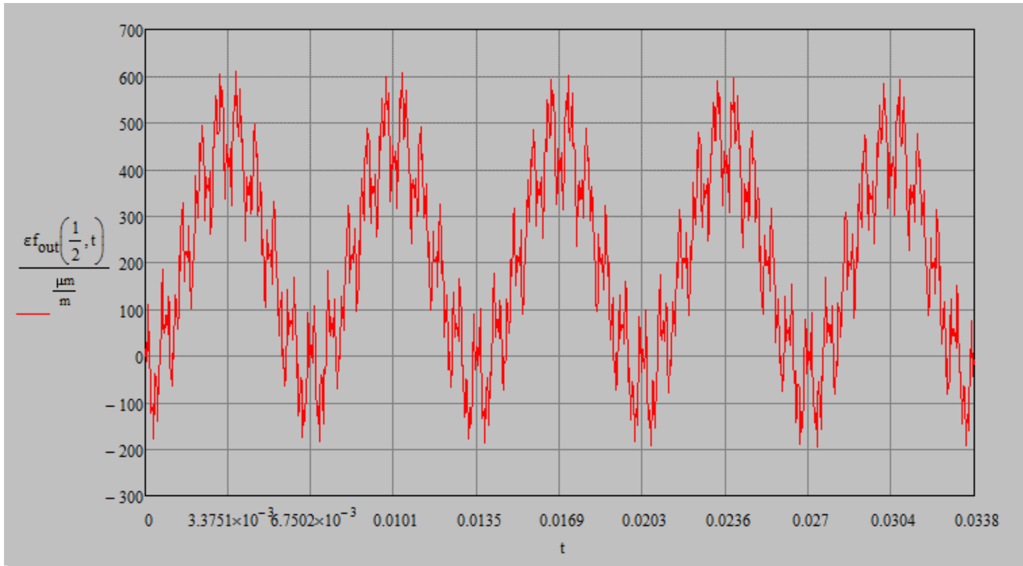


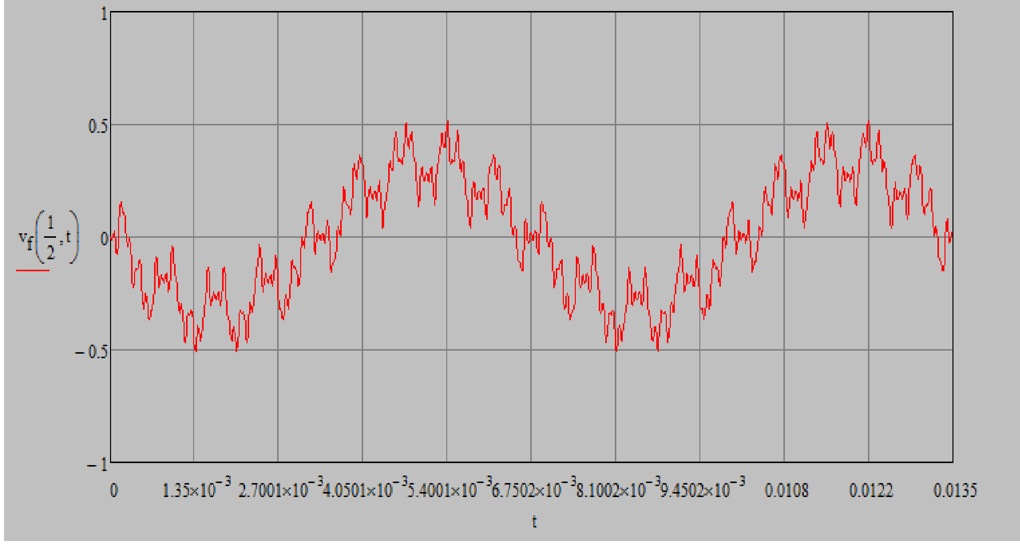
Offset Impact

- **Intermediate offset**. Additionally excites lateral oscillations.
- Lower frequencies (100÷2000 Hz).
- Material strength. Delamination. Internal damping.
- Larger signal intensity

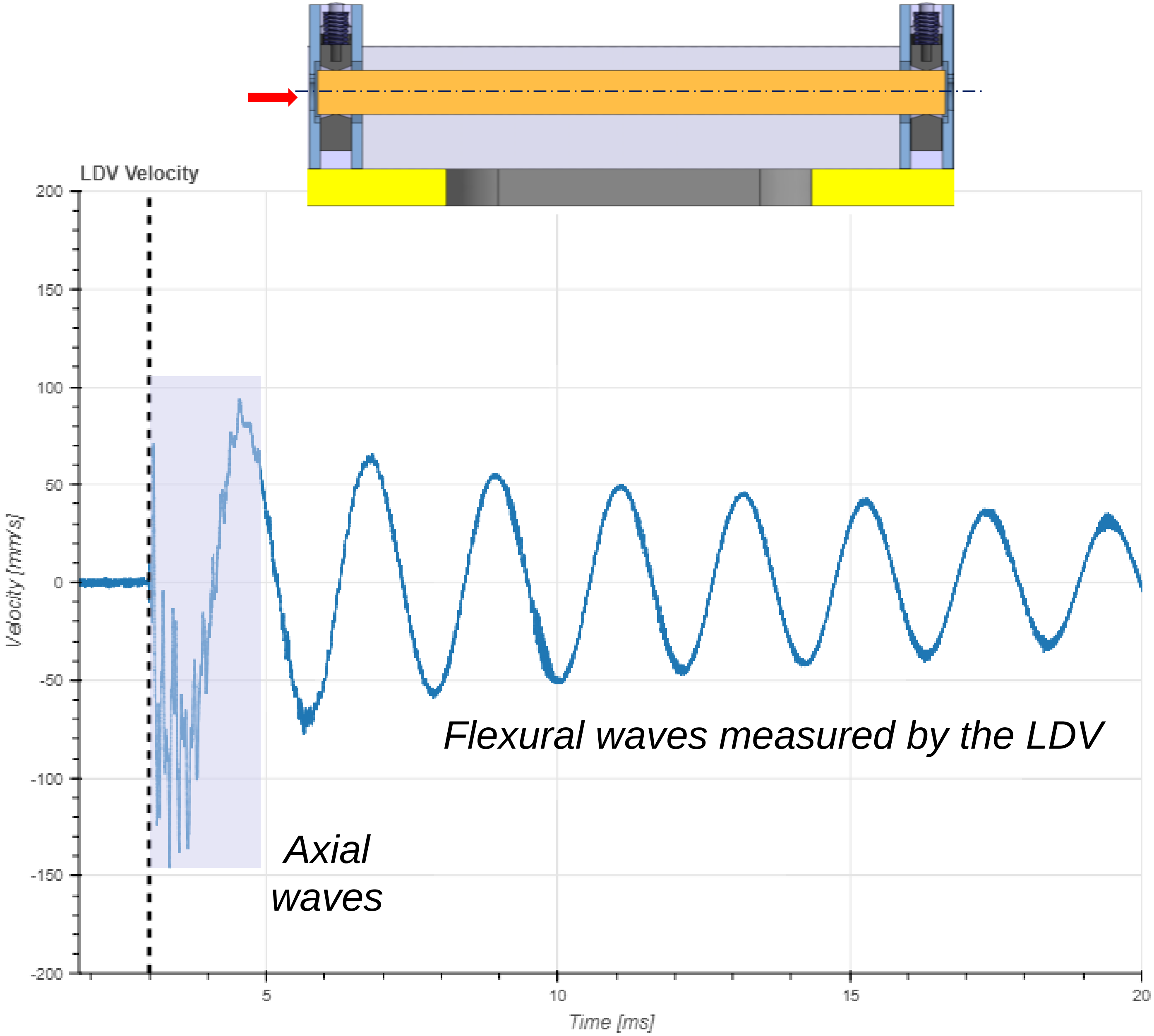








LDV signal from CuCd 1bunch 3mm Offset



Flexural waves measured by the LDV

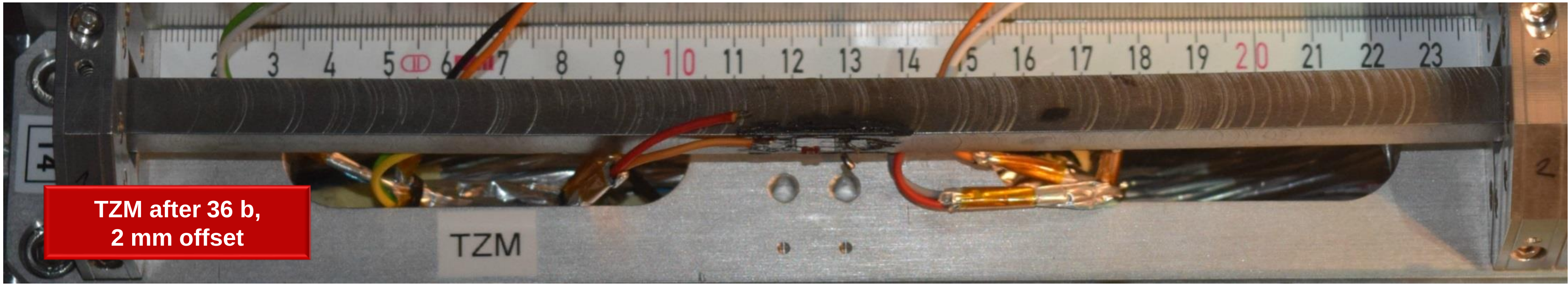
Axial waves

Offset Impact: Permanent Deformation

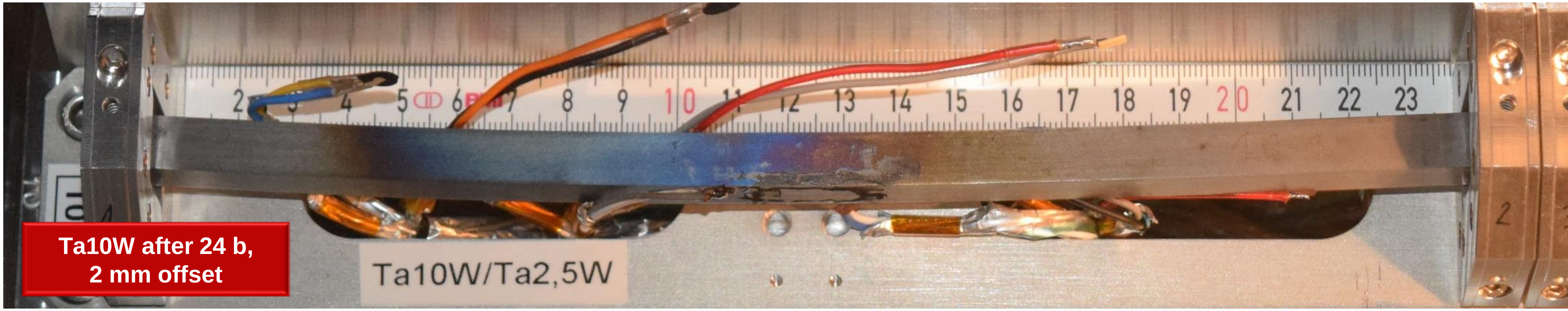
Preliminary Results

- Permanent Deformation induced on high-Z materials

**IT180 after 24 b,
2 mm offset**



**TZM after 36 b,
2 mm offset**



**Ta10W after 24 b,
2 mm offset**

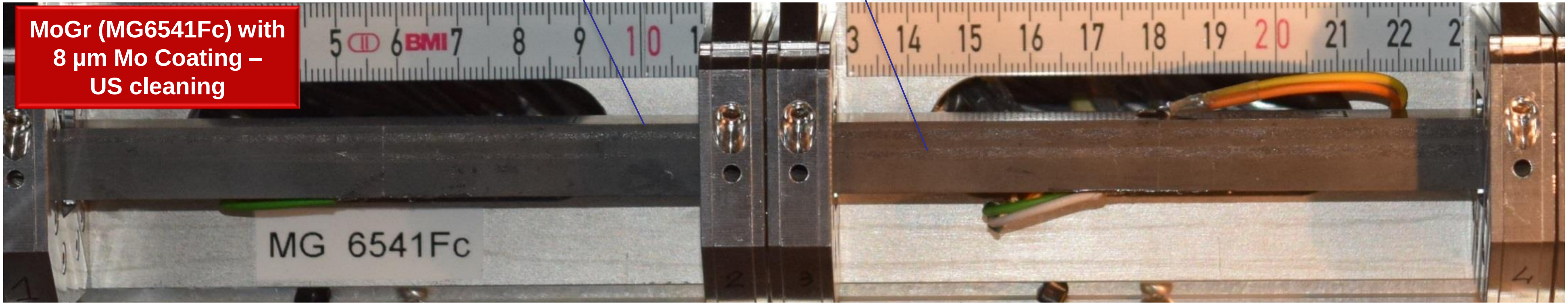
Grazing Impact: effects on Mo Coatings

Preliminary Results

CFC (AC150K) with 8 µm Mo coating – CO_2 blasting

288 b, σ 0.25 mm, impact 150 µm

288 b, σ 0.25 mm, impact 500 µm



MoGr (MG6541Fc) with 8 µm Mo Coating – US cleaning

288 b, σ 0.25 mm, impact 150 µm

288 b, σ 0.25 mm, impact 500 µm

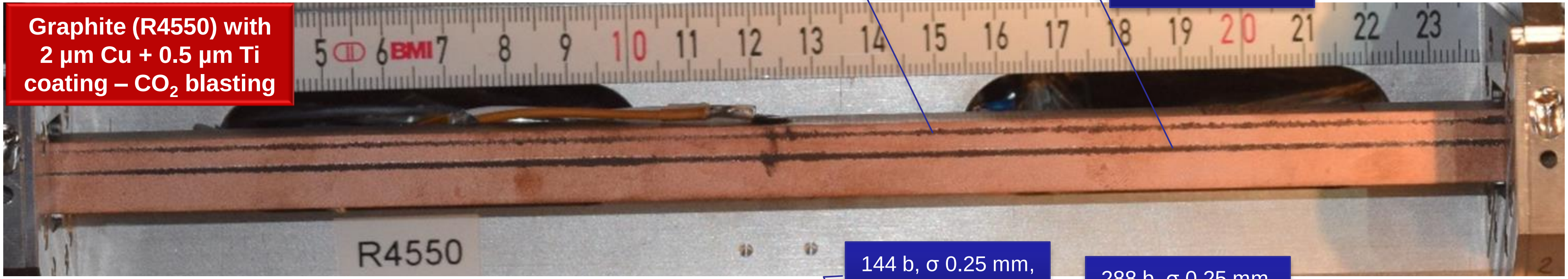
Grazing Impact: effects on Cu Coatings

Preliminary Results

Graphite (R4550) with 2 µm Cu + 0.5 µm Ti coating – CO_2 blasting

144 b, σ 0.25 mm, impact 150 µm

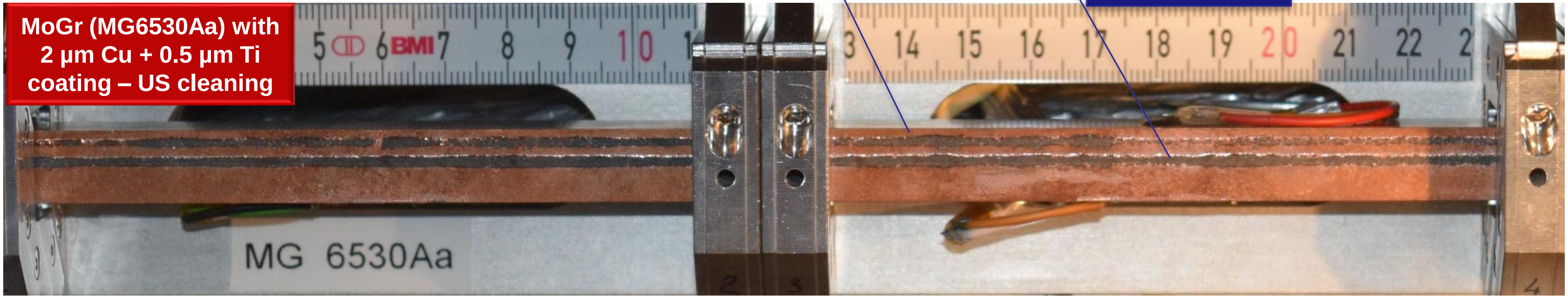
288 b, σ 0.25 mm, impact 150 µm



MoGr (MG6530Aa) with 2 µm Cu + 0.5 µm Ti coating – US cleaning

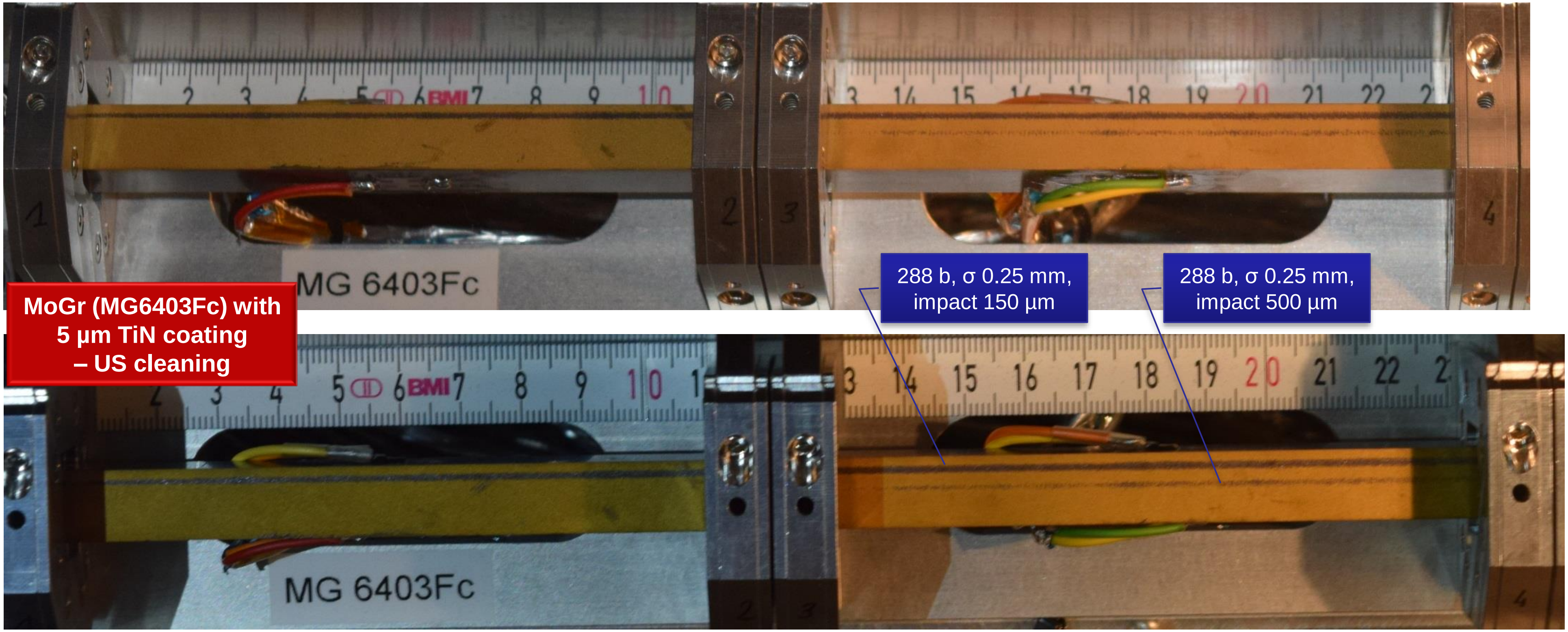
144 b, σ 0.25 mm, impact 150 µm

288 b, σ 0.25 mm, impact 150 µm



Grazing Impact: effects pm TiN coating

Preliminary Results



MoGr (MG6403Fc) with 5 µm TiN coating – US cleaning

288 b, σ 0.25 mm, impact 150 µm

288 b, σ 0.25 mm, impact 500 µm