An Overview of HiRadMat Experiment on Collimator Materials

A&T Sector Seminar
14^{th} March 2013

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on behalf of the LCMAT Design Team
with contributions from many people from BE, DG, EN, TE, PH Departments and Politecnico di Torino

EN Engineering Department

Outlook

- **Context**
- Introduction to HRMT14-LCMAT Experiment
- Numerical Simulations
- Instrumentation and Validation Tests
- Results and Analysis
- Conclusions

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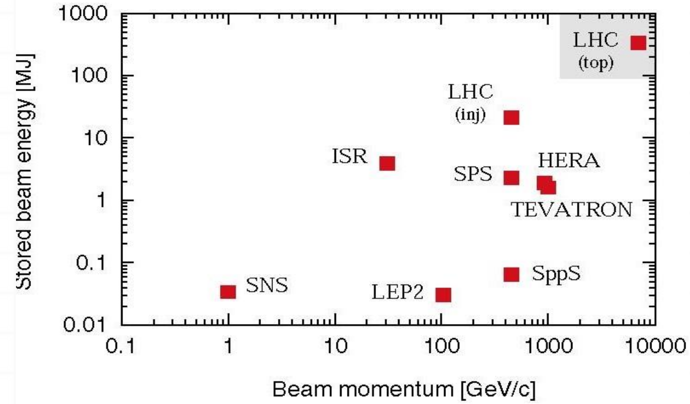
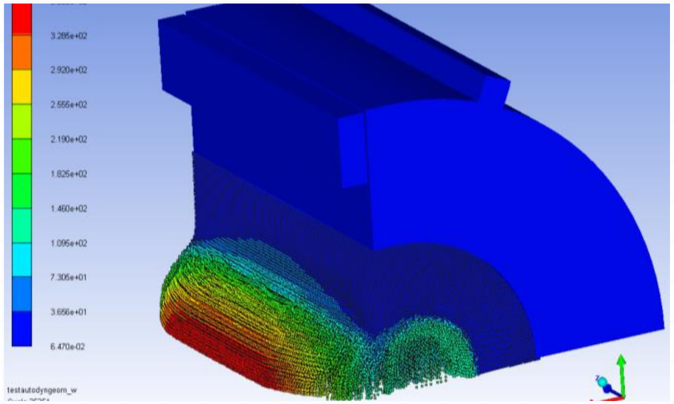
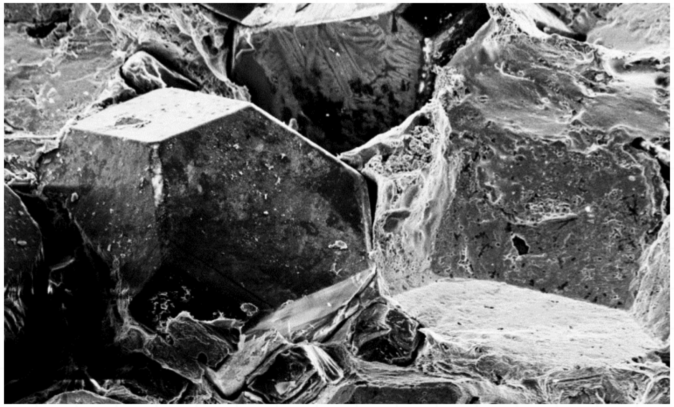
Context

- **LHC beam energy** is **2 orders** of magnitude above previous machines. Stored **energy density** is **3 orders** of magnitude higher.
- **Beam-induced accidents** represent one of the most dangerous and though less explored events for the LHC.
- **Novel, yet-to-characterize, composite materials** are under development to meet these challenges.
- New sophisticated and powerful **numerical tools** (**Hydrocodes**) are used to simulate accidental events. Limitations exist as to material constitutive models.



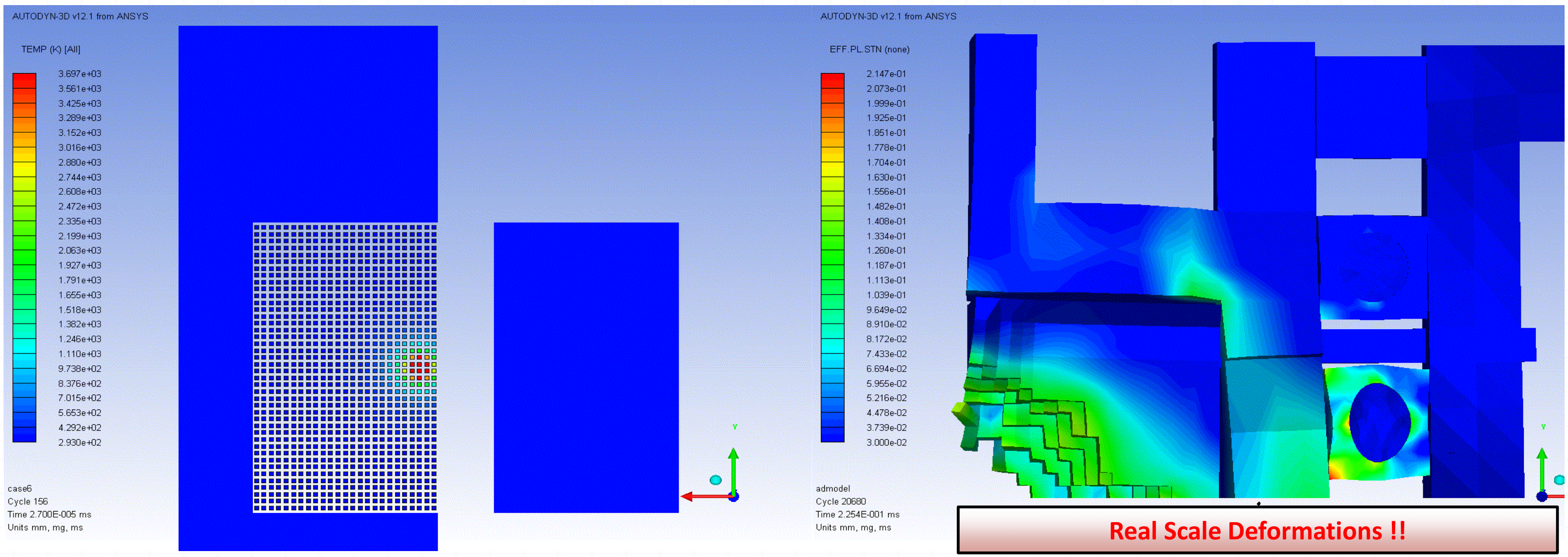




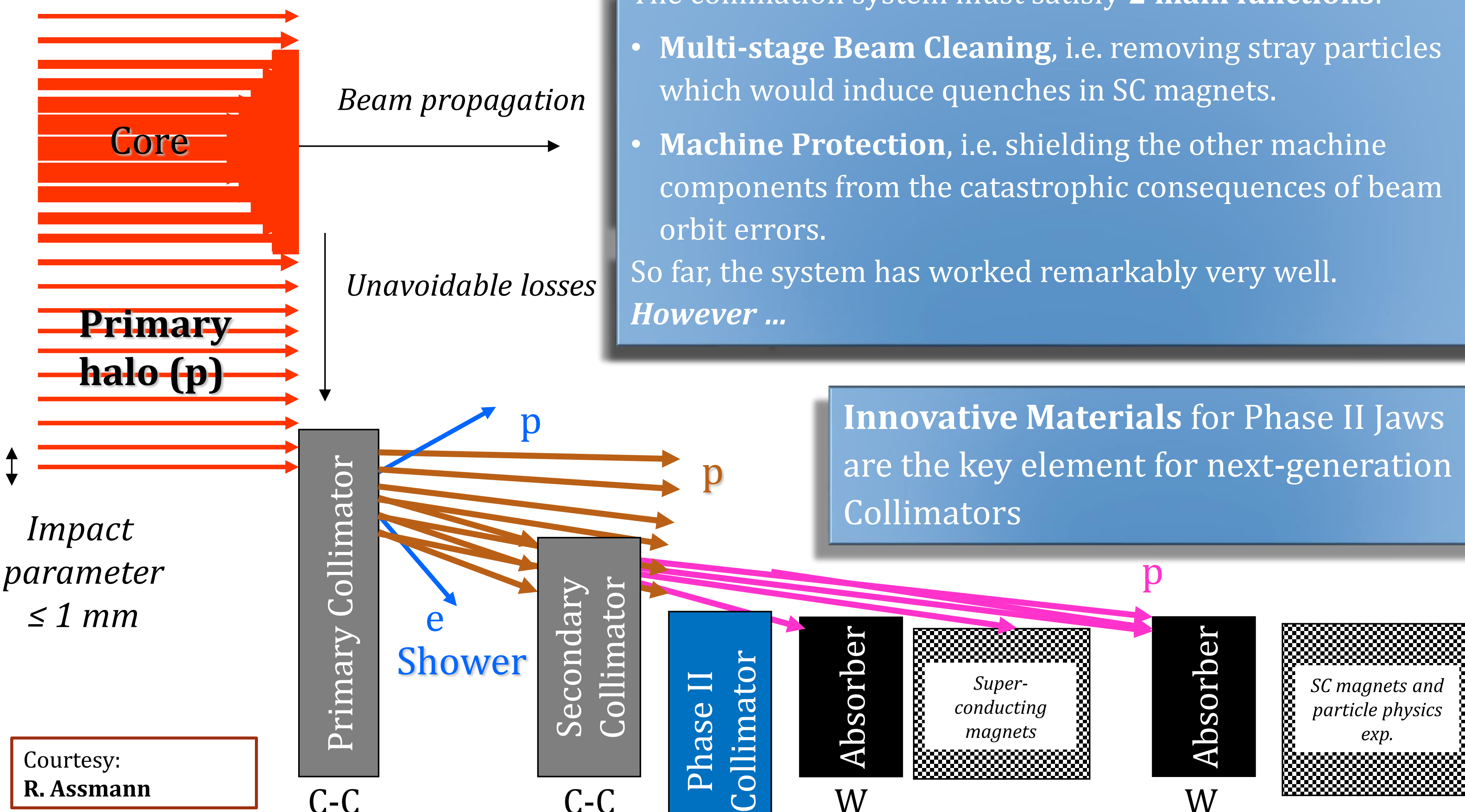
Example: Accident on TCTA

Simulation of 8 LHC bunches at 5 TeV impacting a Tungsten Jaw

- Probability of **water leakage** due to very severe plastic deformations on pipes.
- Impressive **jaw damage**:
  - Extended eroded and deformed zones.
  - **Projections** of hot and fast solid tungsten bullets (**T≈2000K**, V_{max} **≈ 1 km/s**) towards opposite jaw. Slower particles hit tank covers (at velocities just below ballistic limit).
  - Risk of "bonding" the two jaws due to the projected re-solidified material.



Novel Materials for Collimators



The collimation system must satisfy **2 main functions**:

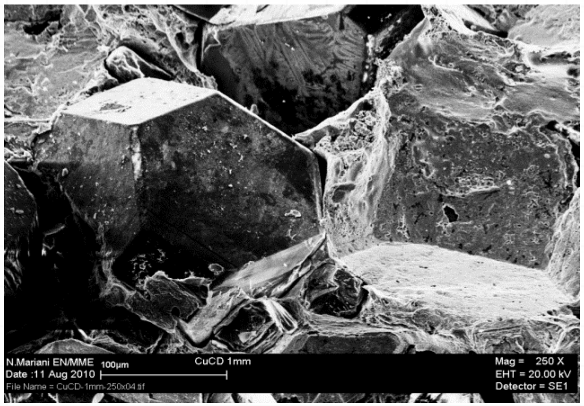
- **Multi-stage Beam Cleaning**, i.e. removing stray particles which would induce quenches in SC magnets.
- **Machine Protection**, i.e. shielding the other machine components from the catastrophic consequences of beam orbit errors.

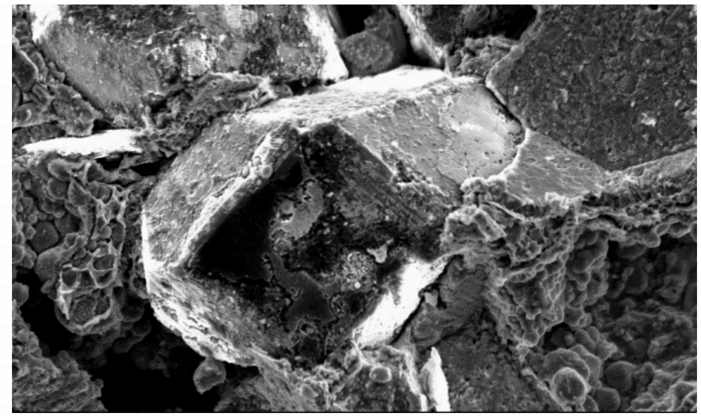
So far, the system has worked remarkably very well.
However …

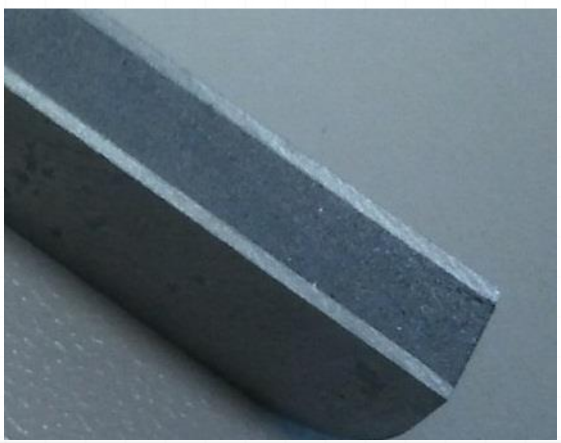
Innovative Materials for Phase II Jaws are the key element for next-generation Collimators

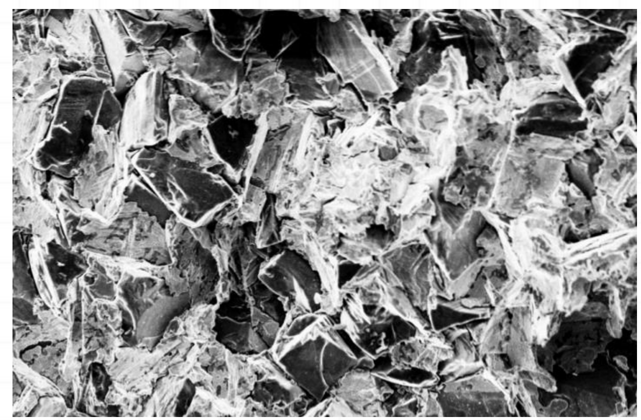
Novel Materials for Collimators

- **Metal Matrix Composites (MMC)** for advanced thermal management materials combine properties of Diamond or Graphite (high ***k*,** low ρ and low ***CTE***) with those of Metals (**strength**, γ, etc.)
- Candidate materials include **Copper-Diamond** (**CuCD**), **Molybdenum-Copper-Diamond** (**MoCuCD**), **Silver-Diamond** (**AgCD**), **Molybdenum-Graphite (MoGr)**

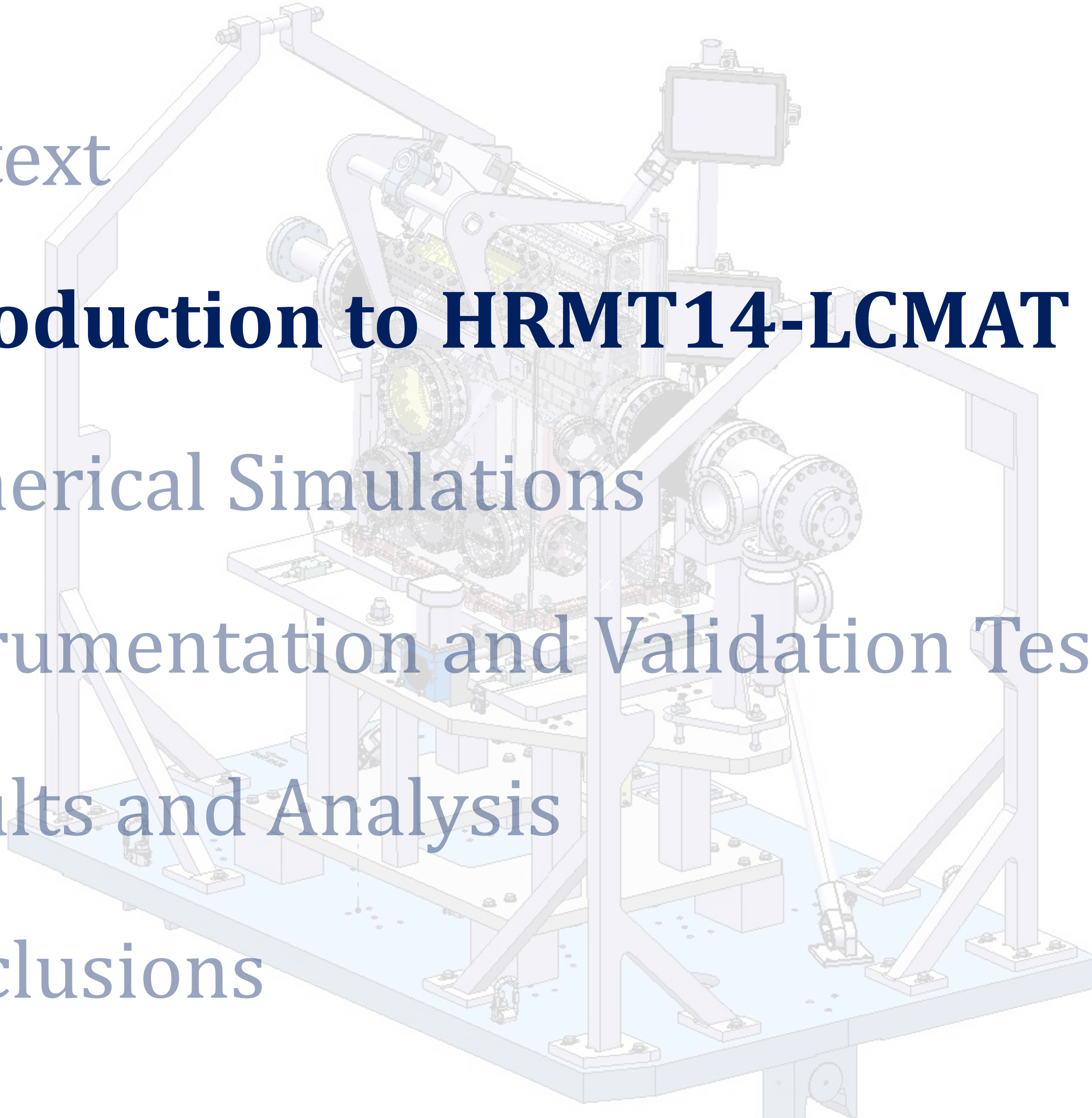








Outlook



- Context
- **Introduction to HRMT14-LCMAT Experiment**
- Numerical Simulations
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What is HiRadMat?

HiRadMat
High-Radiation to Materials

- HiRadMat is a facility designed to study the impact of intense pulsed beam on materials
  - Thermal management;
  - Radiation Damage to materials;
  - Thermal shock – beam induces pressure waves.

Courtesy: I. Efthymiopoulos

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Why HRMT14 Experiment?

- To **test** materials for *Beam Intercepting Devices* (**BID**) under the **extreme conditions** they may encounter in case of beam impacts.
- To **qualify** collimators for series production and **installation in the LHC**, specifically high-Z Tertiary Collimators (TCTA and TCTP) (also through complementary **HRMT9 experiment** – ref. A. Rossi, S. Redeaelli et al.).
- To quantify **collimator damage** for LHC Operating Scenarios.
- To characterize **novel materials** currently under development for Phase II Collimators.
- To **benchmark** advanced numerical simulations, powerful but based on limited and scarce literature data on **material constitutive models**.
- To **collect**, mostly in real time, **experimental data** on **Constitutive Models** of BID Materials (Equations Of State, Strength Models, Failure Models …).

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HRMT14 Contributors

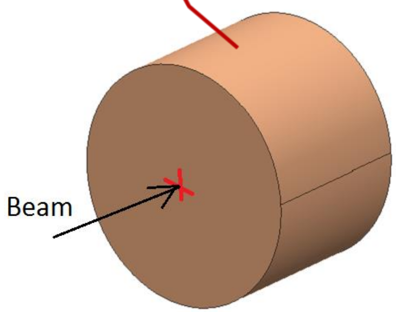
- **BE-ABP**: experiment advising, approval and financing. Microphones. Survey and alignment.
- **BE-OP**: HiRadMat beam operation
- **DG-RP:** Radioprotection support and validation.
- **EN-HE**: test bench transport and installation.
- **EN-ICE**: acquisition software, hardware support.
- **EN-MEF**: HiRadMat facility management, fast camera lease and support. Experiment and facility activation simulation.
- **EN-MME**: coordination, engineering, general design, DAQ design and instrumentation, manufacturing, metrology and assembly.
- **EN-STI**: motorization and controls, remote control interface, FLUKA simulations, Be window design.
- **PH**: cable characterization and mirrors coating.
- **TE**: PCB manufacturing. Support in flash circuit design. Support to vacuum design.
- **Politecnico di Torino**: support in engineering, simulations and testing.

With financial support from EC through EuCARD Collaboration

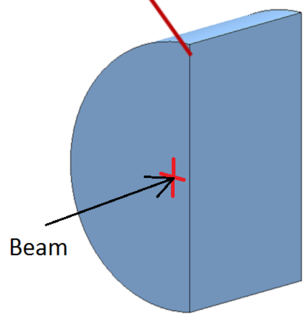
Experiment Specification

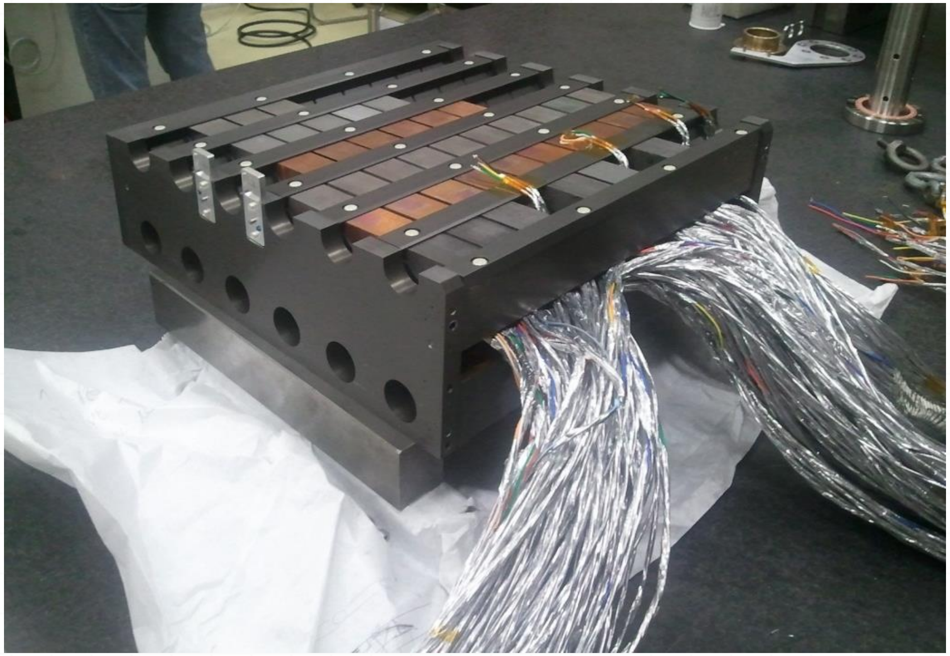
- **6 different materials:** *Inermet 180 (95%W, 3.5%Ni, 1.5%Cu), Glidcop (Cu+0.15%Al_2O_3), Molybdenum, Molybdenum-Copper-Diamond, Copper-Diamond, Molybdenum-Graphite*
- **6+6 Target Stations** with **2 specimen types** for each material for **Medium intensity** and **High intensity** tests
- **10 slots** per target station with up to **10 specimens** (according to material density)
- Extensive **Data Acquisition System**
- **Post-irradiation** analysis

Medium Intensity Tests:
Type 1 Sample
(Ø 40 mm L30 mm)



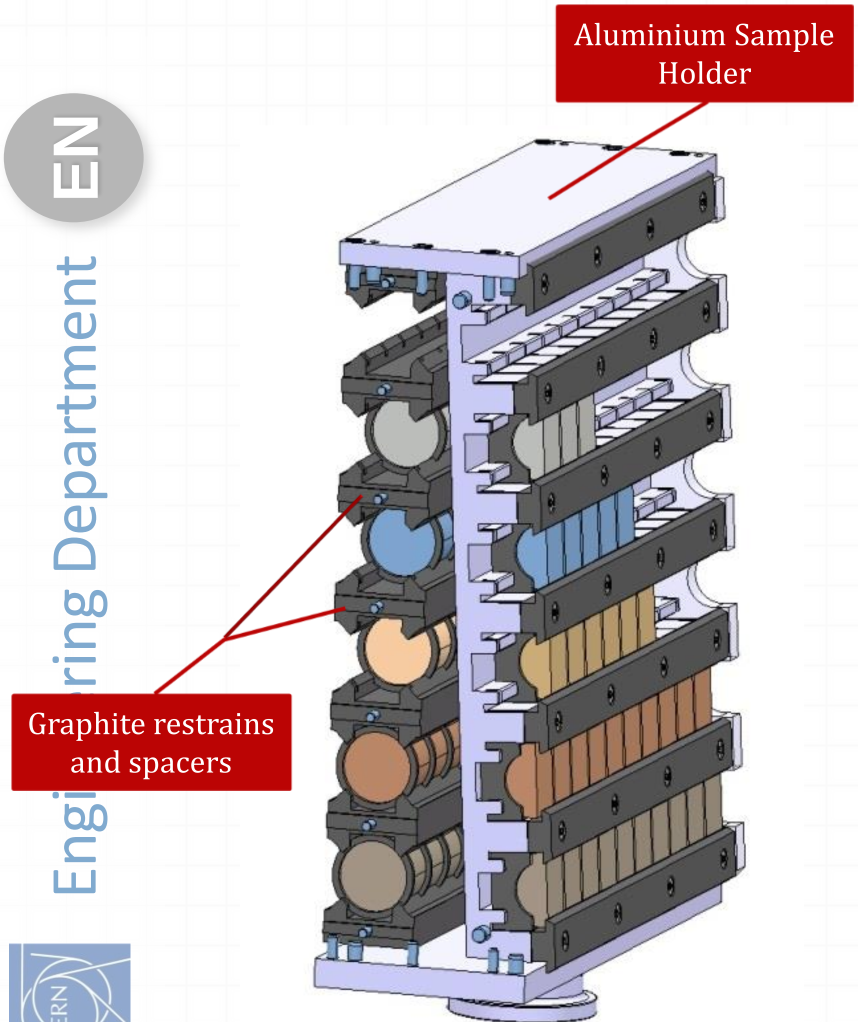
High Intensity Tests:
Type 2 Sample
(half-moon, Offset 2 mm)

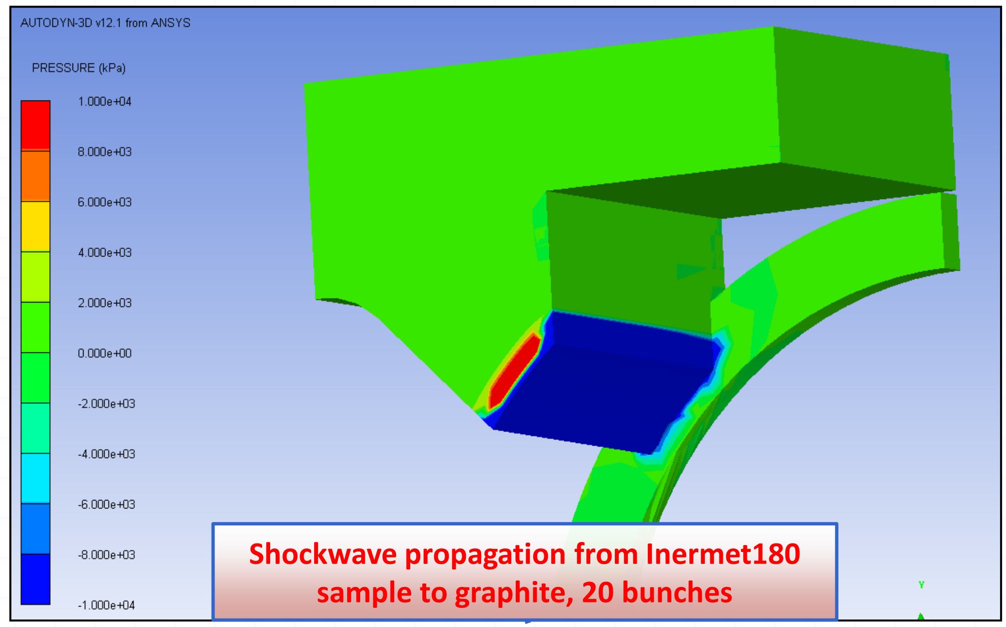




Design Overview

- **Sample holder** in Al 6082 T6: good elastic limit, low density
- **Restraints and spacers** in graphite, as a barrier to transmission of shockwaves (low shock impedance). Equivalent to **free-free boundary condition**
- **Thermo-structural calculation** performed on supports: acceptable deformations and stress transmitted

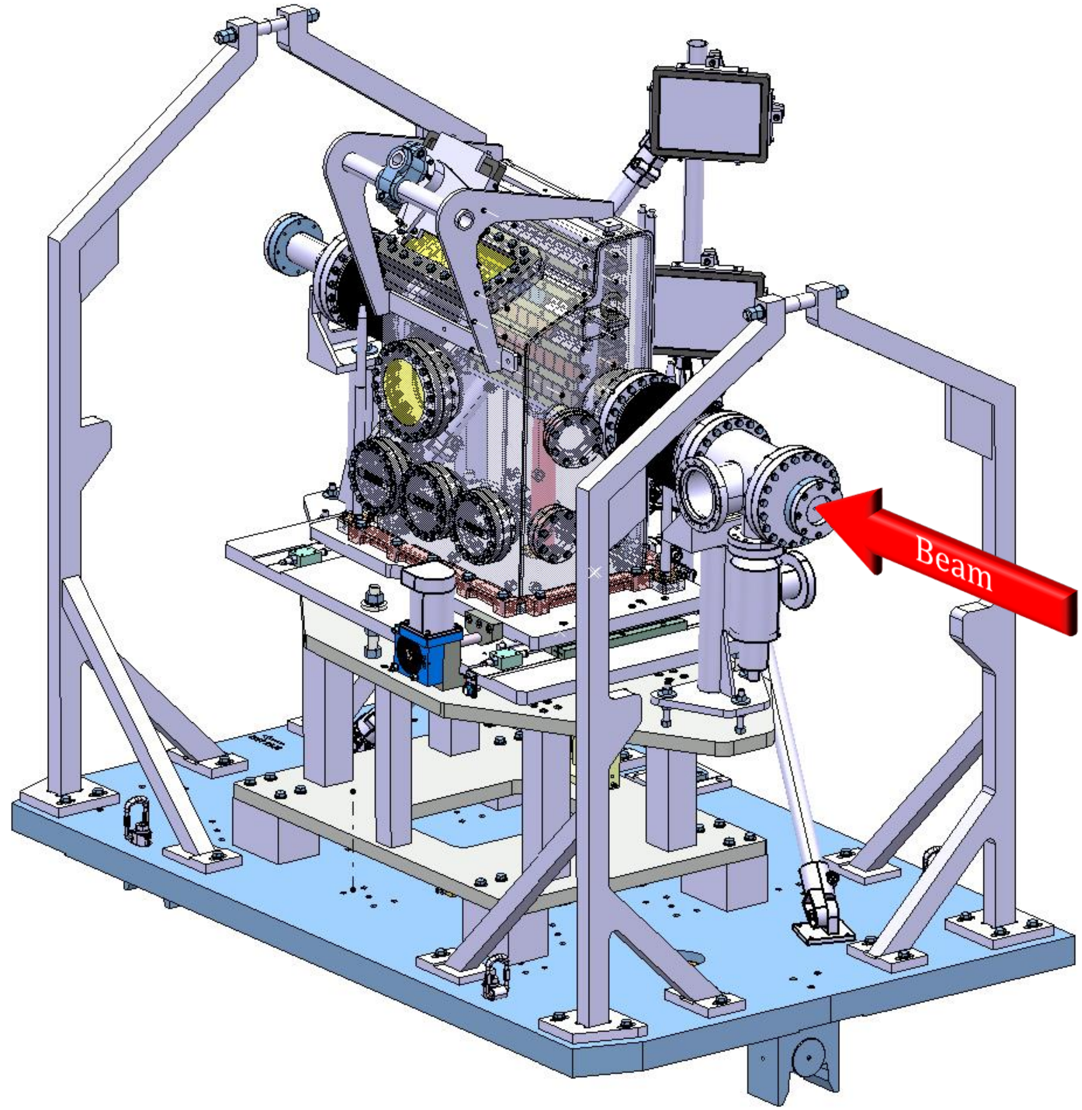




Design Overview

Test-bench main features

- Mobile Sample Housing:
  2 d.o.f.: vertical and lateral
- Vacuum Vessel
- Beryllium windows for stand-alone layout
- 3 optical viewports
- Quick-dismounting system
- Pumping port
- Embarked mirror set



LHC Collimation Project CERN

Beam and Irradiation Parameters

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- Beam energy: **440 GeV**
- Bunch spacing: **25 ns**
- Protons/bunch: ~**1.1e11** (lower when scraped)
- **1** to **144 bunches per pulse**
- Total Pulses: **52** (excluding alignment)
- Total Bunches: **1558** (excluding alignment)
- Total Protons: **~ 1.7e14**
- Test Runs: **27-28 Sept**, **2-4 Oct 2012**

Irradiation Summary

Type 1 Targets	Total n. of protons	Total n. of bunches	Beam size (σ_x x σ_y) [mm x mm]	Number of pulses
Inermet 180	4.3e12	51	~1.5 x ~1.5	6
Molybdenum	8.0e12	112	~1.5 x ~1.5	7
Glidcop	7.8e12	111	~1.5 x ~1.5	6
MoCD	1.4e13	135	~1.5 x ~1.5	7
CuCD	1.4e13	136	~1.5 x ~1.5	8
MoGr	1.5e13	149	~1.5 x ~1.5	10

Type 2 Targets	Total n. of protons	Total n. of bunches	Beam size (σ_x x σ_y) [mm x mm]	Number of pulses
Inermet 180	9.1e12	72	1.9 x 1.9	1
Molybdenum	2.85e13	216	2 x 2	2
Glidcop	1.77e13	144	2 x 2	2
MoCD	1.96e13	144	2 x 2	1
CuCD	1.95e13	144	2 x 2	1
MoGr	1.95e13	144	2 x 2	1

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Simulations of Shock-waves

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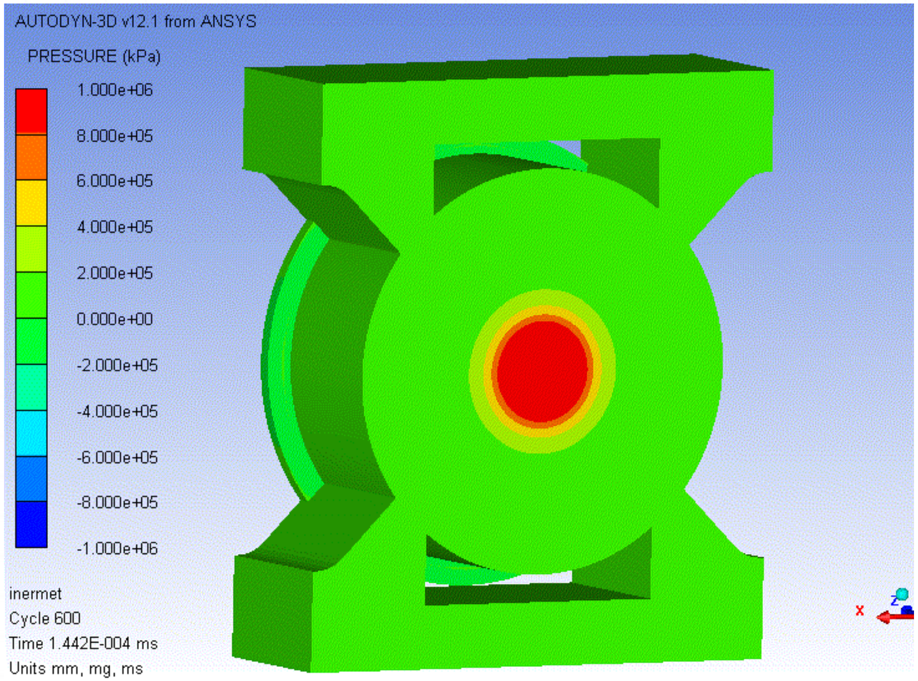
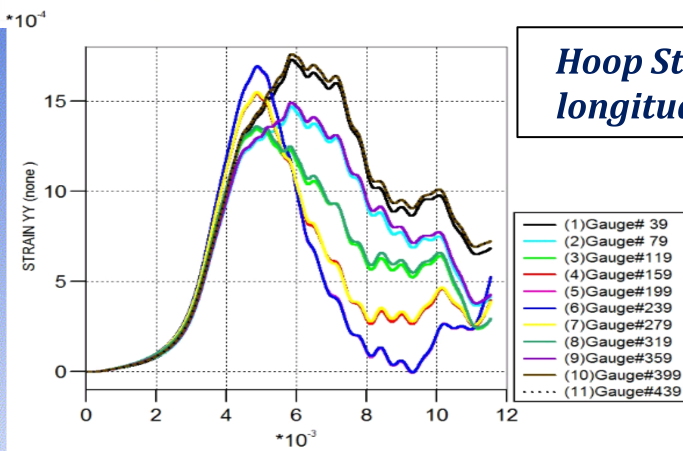
- Extensive simulations (Autodyn Hydrocode), based on FLUKA input (EN-STI), allowed to define pulse parameters (number of bunches, bunch spacing and sigma).
- Focus on **Hoop** and **Longitudinal Strains** and **Radial velocity** measured on sample outer surface

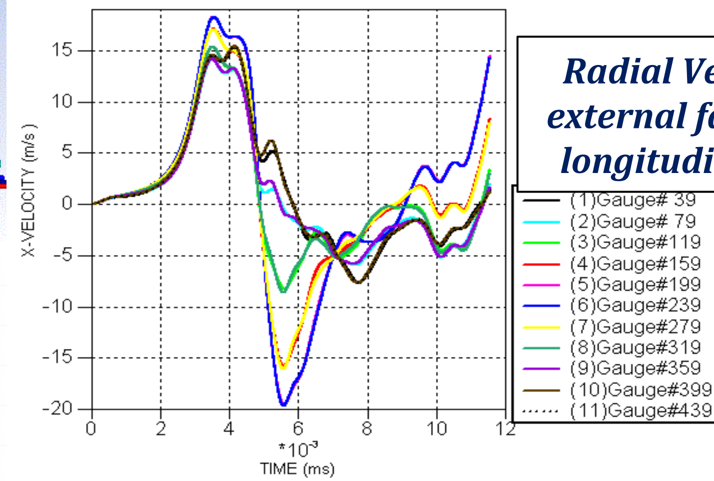


Pressure wave propagation pattern

Example: Simulations on Inermet 180
(σ = 2.5 mm, 20 b, intensity 1.5e11 particles)



Hoop Strain at various longitudinal positions



Radial Velocity on the external face at various longitudinal positions

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Simulations of Target Explosion

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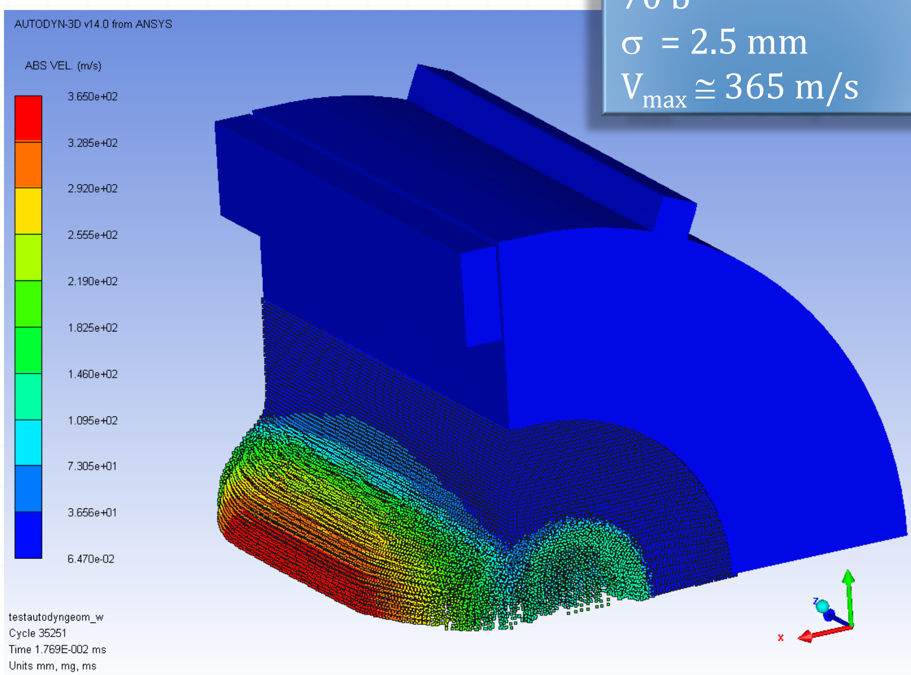
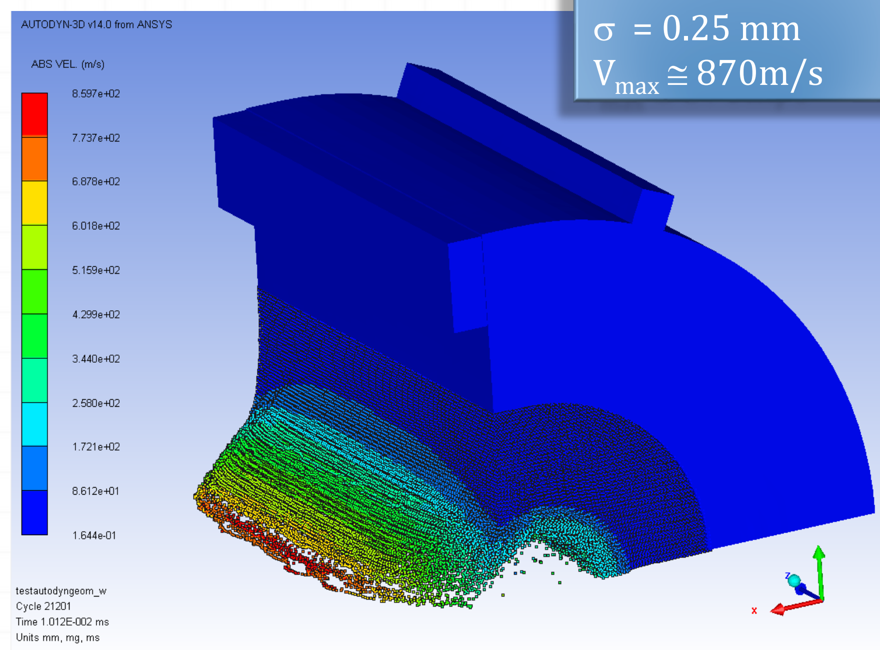
Additional *Smooth-Particle-Hydrodynamics* (**SPH**) calculations allowed determining damage extension, particle fragment velocity and trajectories to optimize pulse parameters and assess:

- **Potential damages** to tank, windows and viewports
- **Material density** changes
- Feasibility of **Optical Acquisition** (exposure time and number of frames per second).



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



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

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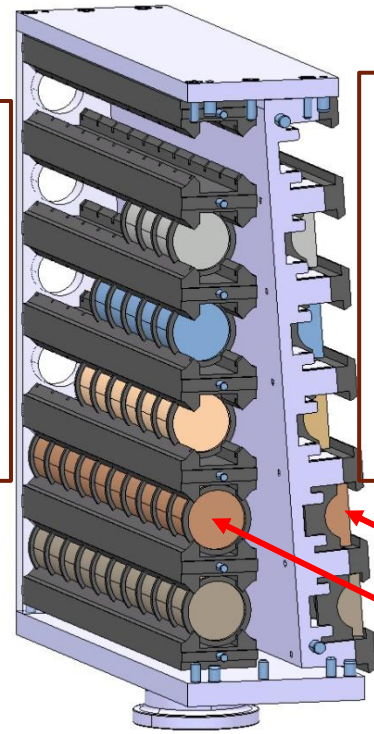
Instrumentation Design

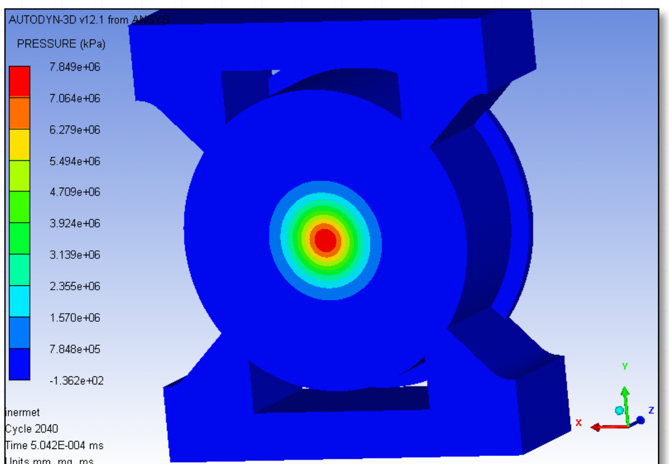


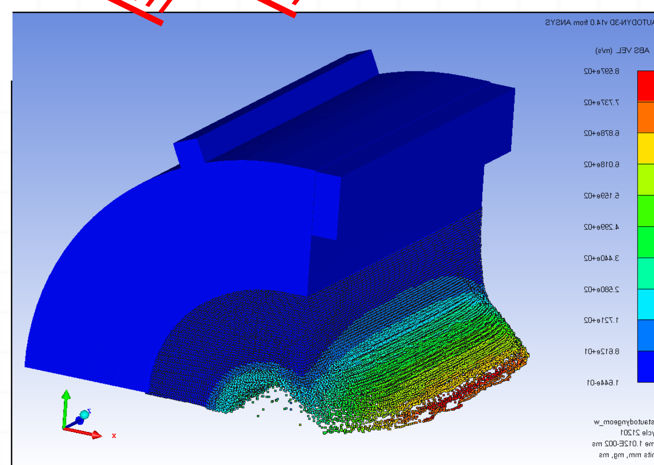
Medium Intensity Beam Impacts :

- Azimuthal strain measurements on the surface of the sample;
- Radial vibration measurements;
- Temperature measurements;
- Sound measurements.

High Intensity Beam Impacts :

- Azimuthal strain measurements on the surface of the sample;
- Fast speed camera to follow the fragment front formation and propagation;
- Temperature measurements;
- Sound measurements.





Instrumentation Design

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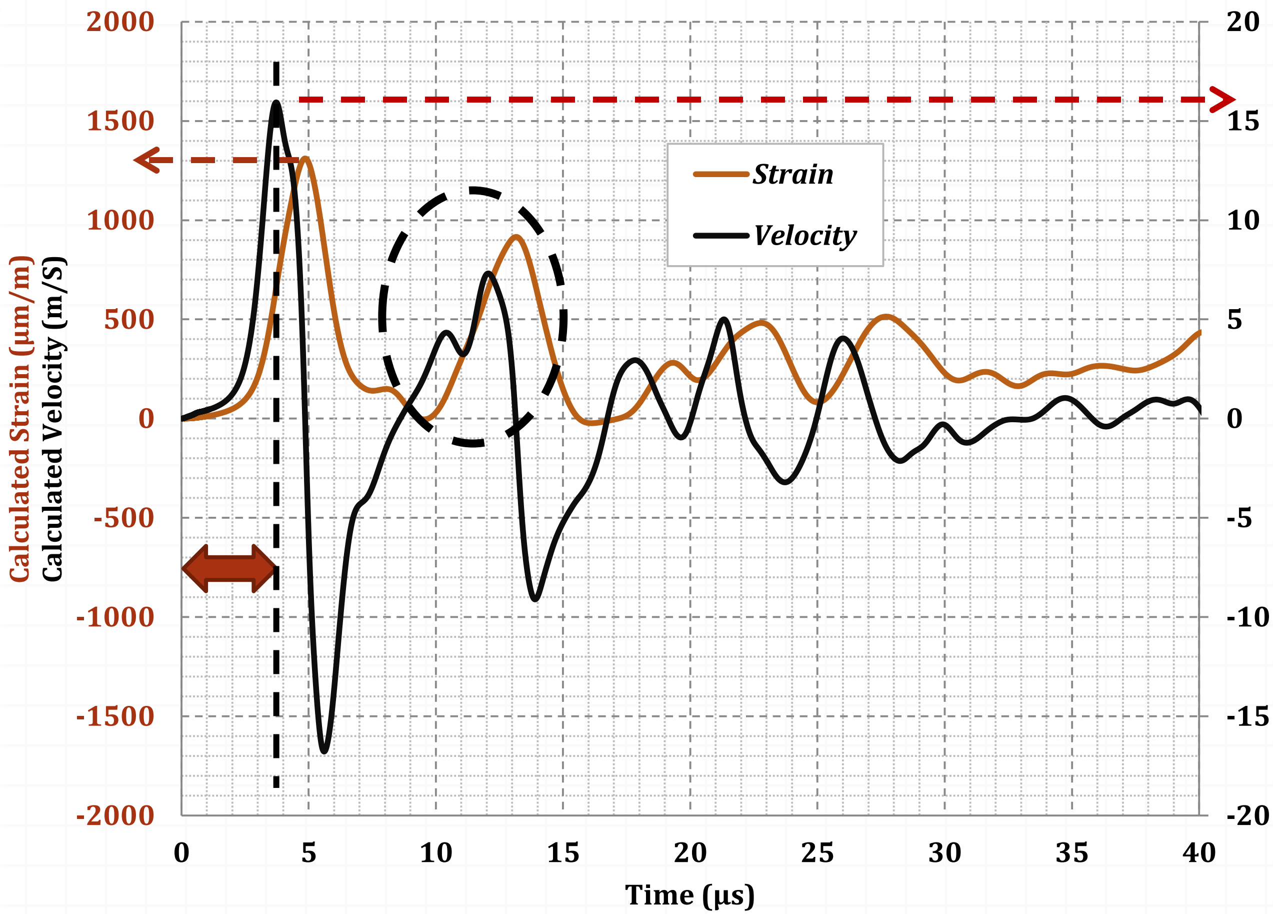
Simulation for Inermet Sample # 24 bunches

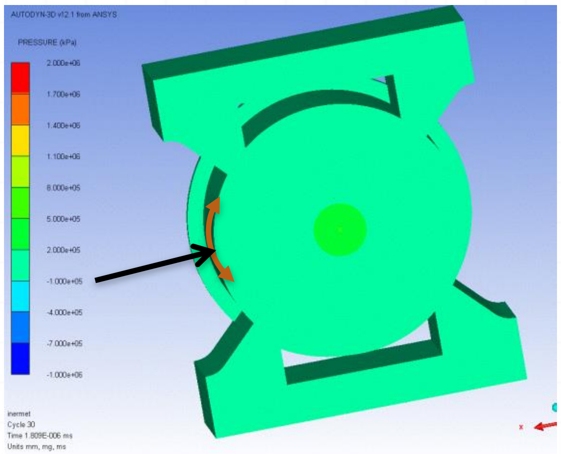


High Amplitude :

- Up to 3000 μm/m
- Up to 25 m/s (depending of materials)

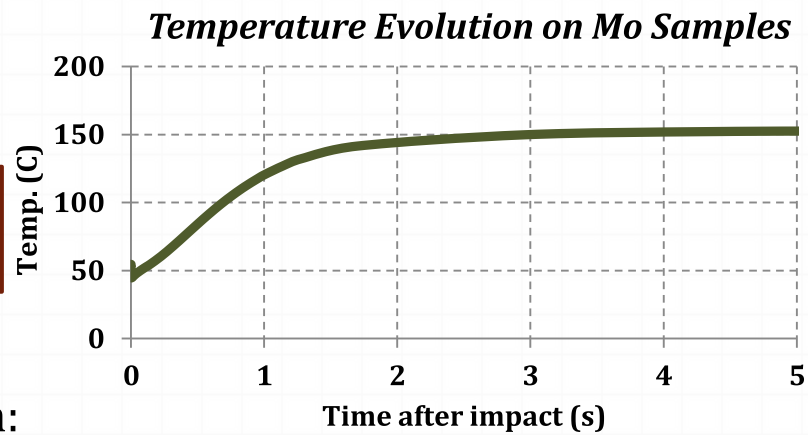
Fast speed effects :

- 4 μs for the 1st wave
- Periodic effects of 1.5 μs



Instrumentation Design

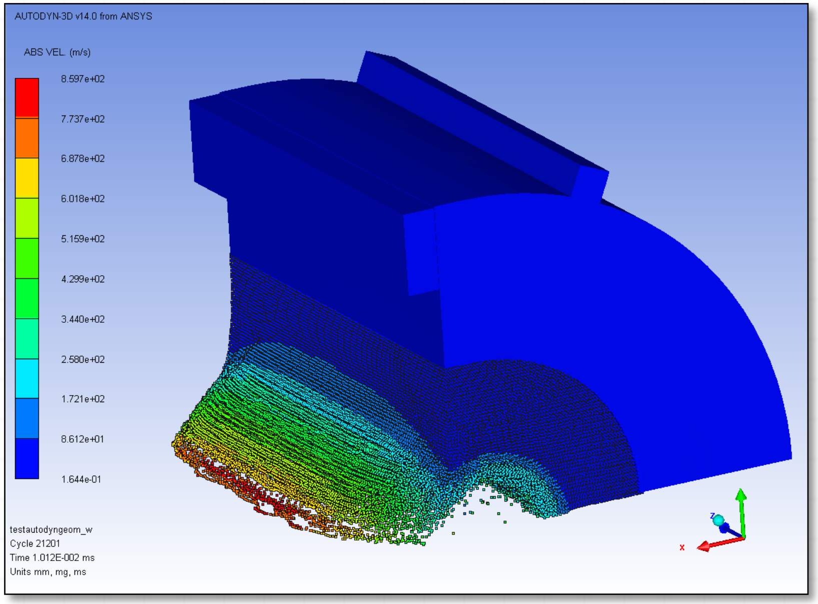
- Temperature :



Worst case : ΔT of 100K in few seconds
Cooling down : Few minutes

- Movie of the Fragment cloud propagation:

Simulation for 72 b, σ 2.5 mm, 1.08e13 p
Cloud Advancing speed ~ 316 m/s



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Instrumentation Design

	Physical effects	Max Amplitude	Time response	Quantity	Sensors	Sampling Frequency
Electrical Systems	Azimuthal Strain	3000 µm/m	1.5 µs	122	Strain Gauges	4 MHz
	Longitudinal Strain	3000 µm/m	1.5 µs	122	Strain Gauges	4 MHz
	Temperature	150 °C	1 s	36	Pt100	100 Hz
	Vacuum Level	10-6 mbar	1 s	1	Pirani Gauge	100 Hz
Optical Systems	Radial Velocity	24 m/s	1.5 µs	1	Laser Doppler Vibrometer	4 MHz
	Particle Front propagation	316 m/s	5µs	1	Fast Speed Camera + Flash System	20000 fps

- A real challenge due to the quantity of channels and the bandwidth !!!
- Synchronisation of the measurements
- And the environmental conditions….

Environmental Conditions

HiRadMat High-Radiation to Materials

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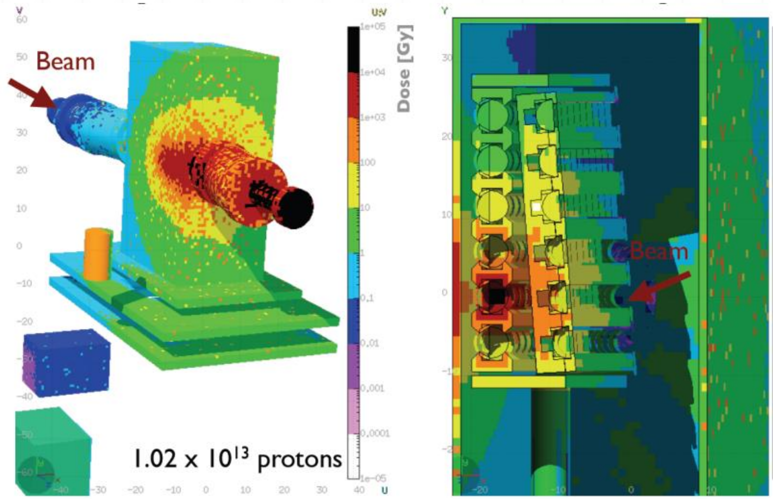
- **High radiation Level on the Tank:**

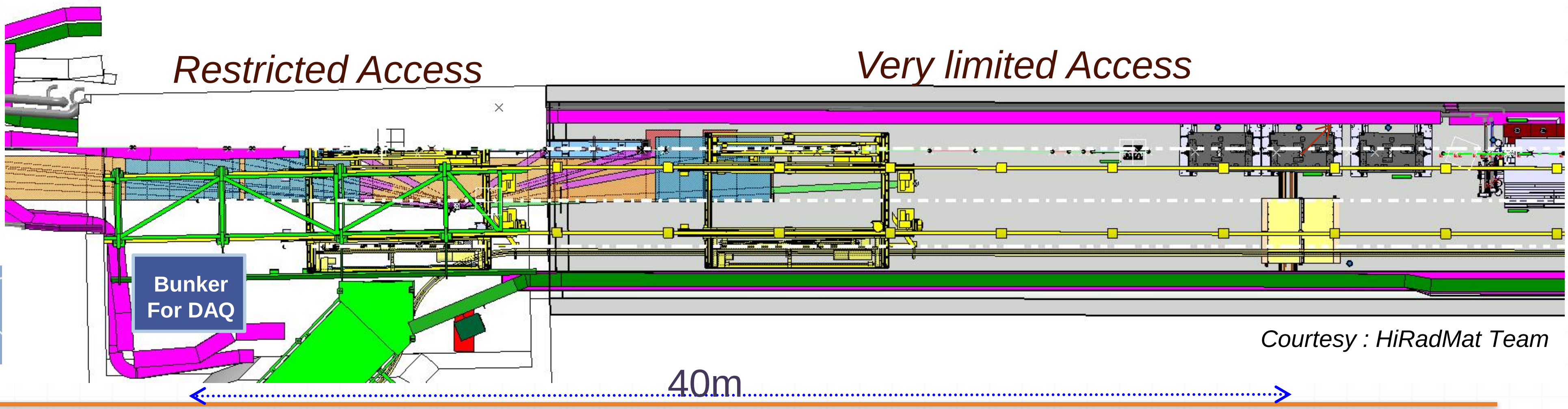
  Fluka simulations foresee as conservative assumption ~250 kGy integrated. **No modern electronic device can resist!**



Courtesy : V. Boccone (EN-STI)

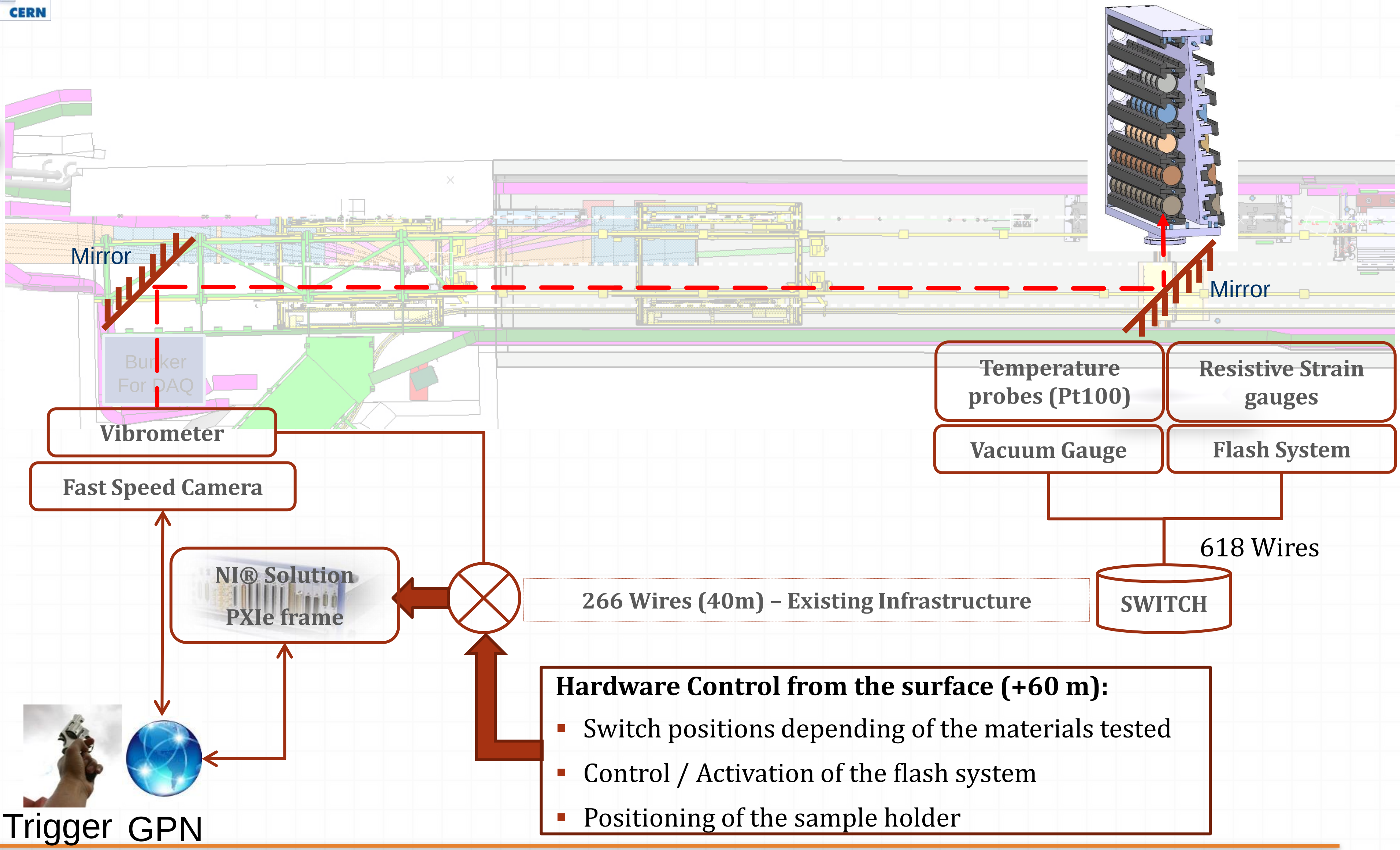
- **HiRadMat Configuration:**

  Limited number of connectors available on the table + distance between the bunker and the tank



Courtesy : HiRadMat Team

Implementation



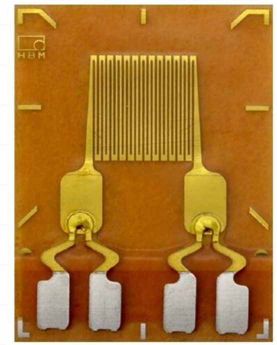
Strain Measurements

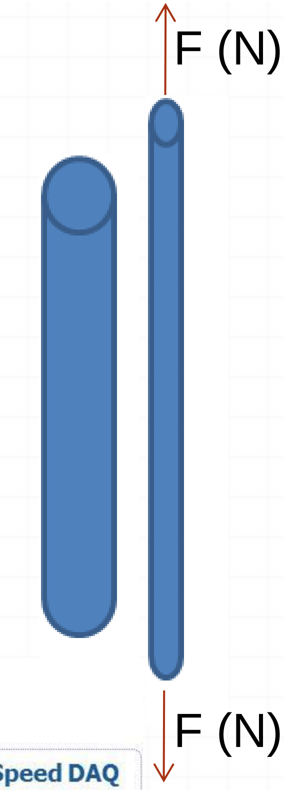
- The resistance of a wire (R) is a function of three parameters :

$$R = \rho \frac{L}{S}$$ with R (Ω), Length (m), Section (m^2) and ρ (Ω /m)

When gauge is deformed, electrical resistance changes.

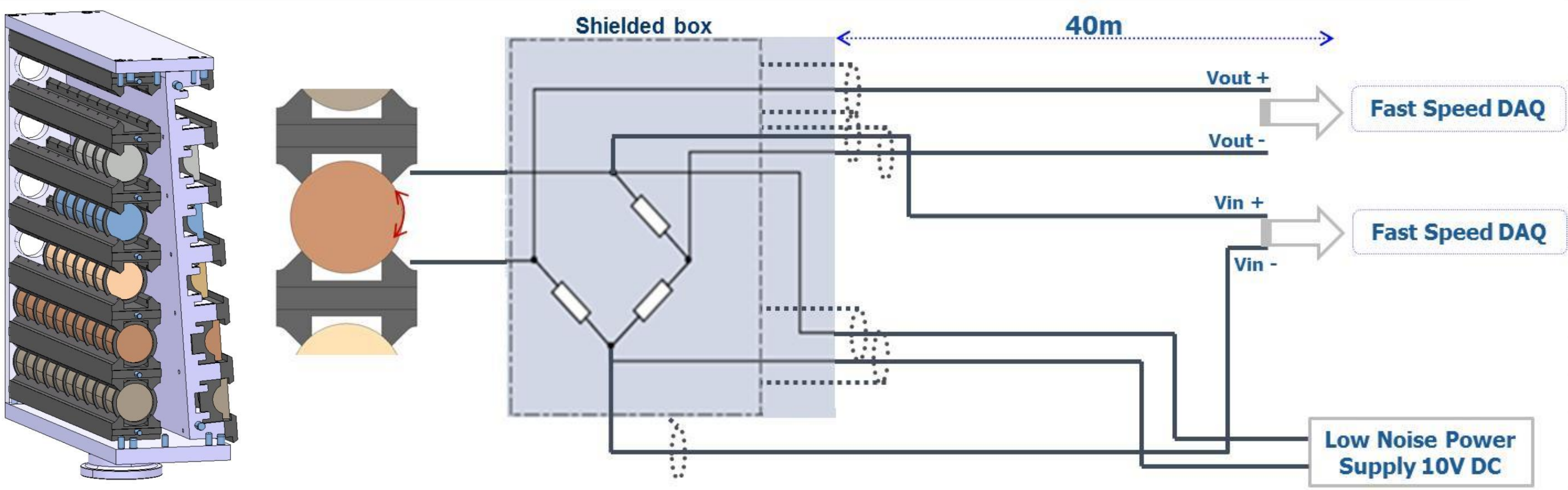
$$\frac{\Delta R}{R} = k \frac{\Delta L}{L}$$ with k : Gauge factor





→ For 2000 µm/m, ΔR is equal to 11 µΩ !

→ Measurements inside a Wheatstone Bridge :



Strain Measurements

- Dynamic response of the strain gauges (Typically around 50 kHz) ?

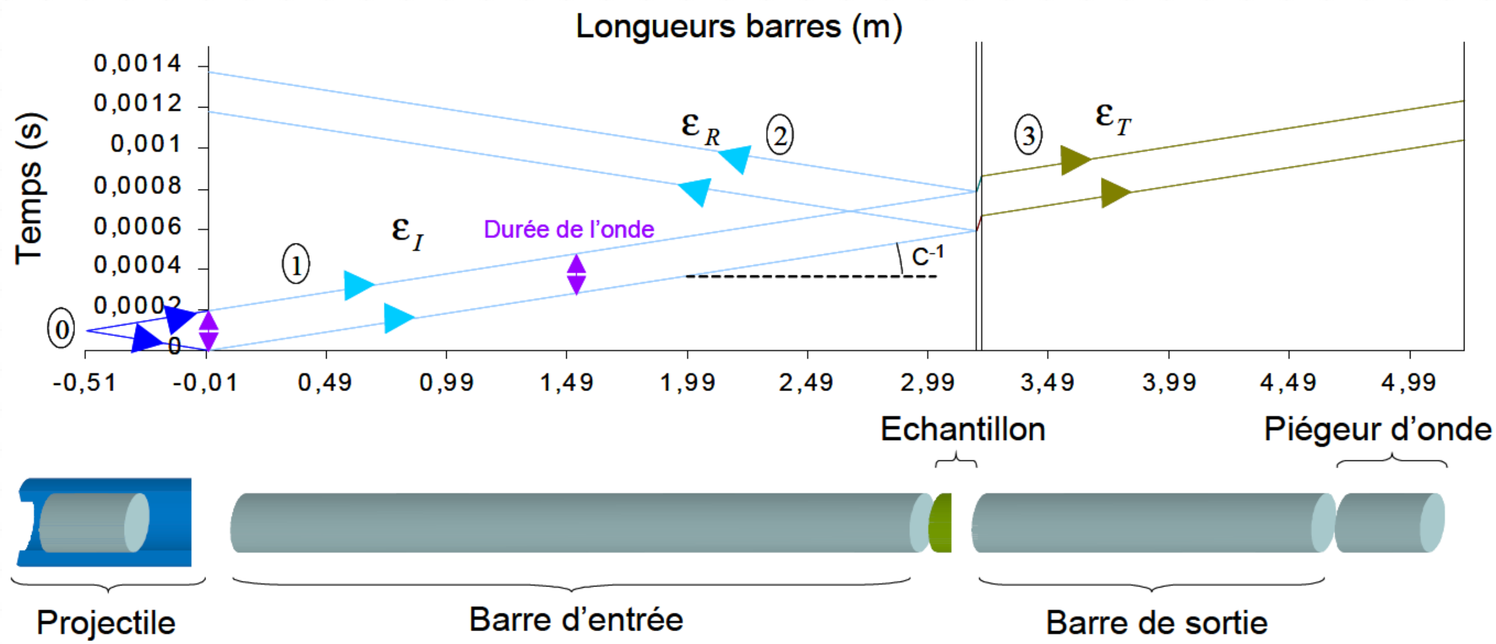
Very critical strain measurement requests validation tests !

→ Increase our knowledge for this bandwidth (higher than 50 kHz) ;

→ Check the dynamic response of the gauges and the glue ;

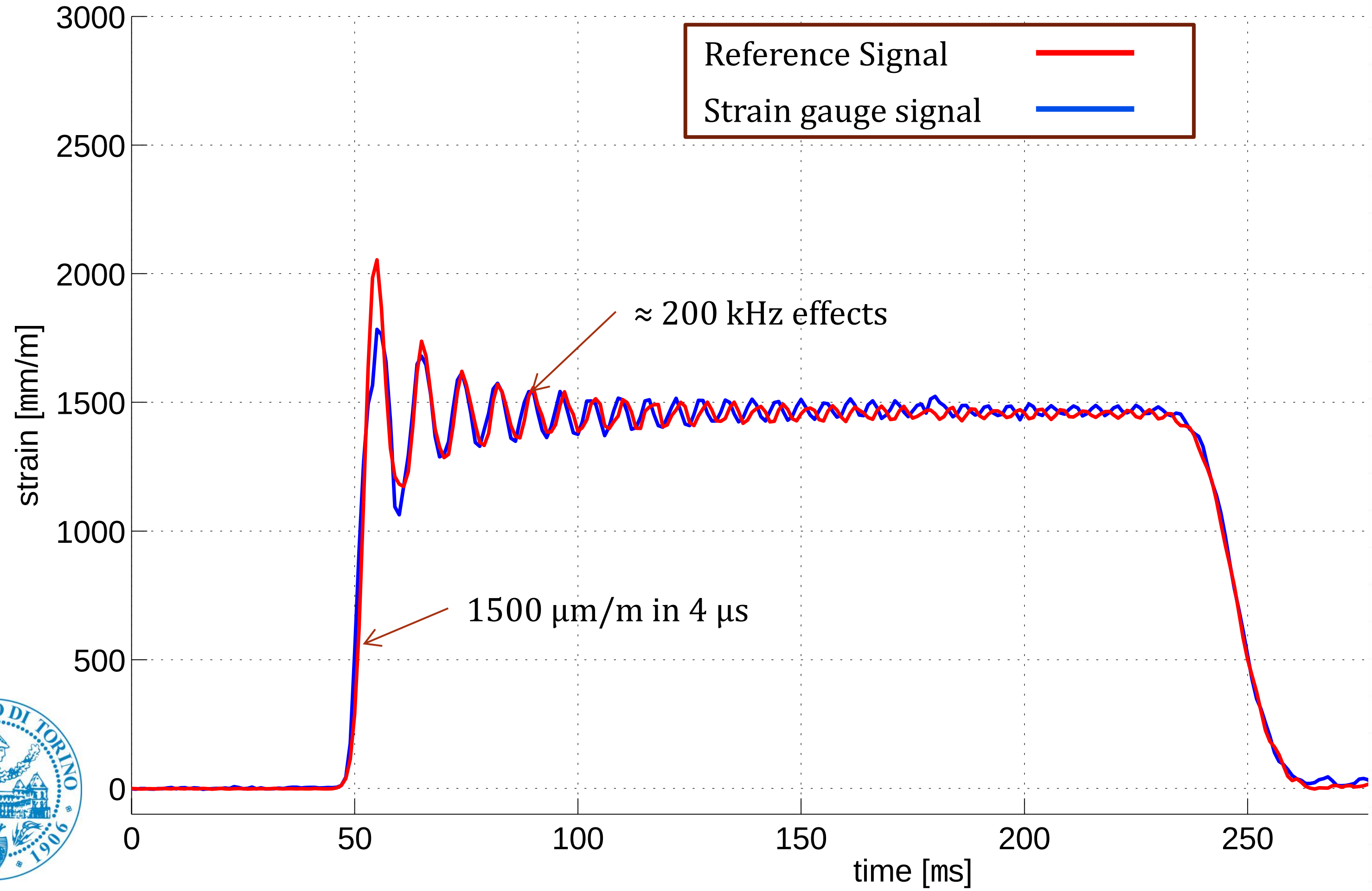
→ Evaluate the signal to noise ratio and the accuracy of the measurements ;

→ Hopkinson bars test bench



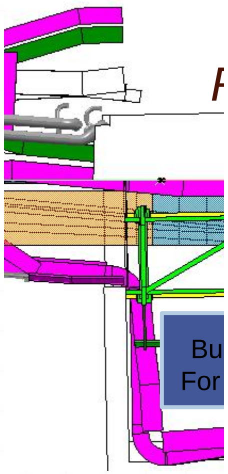
Strain Measurements

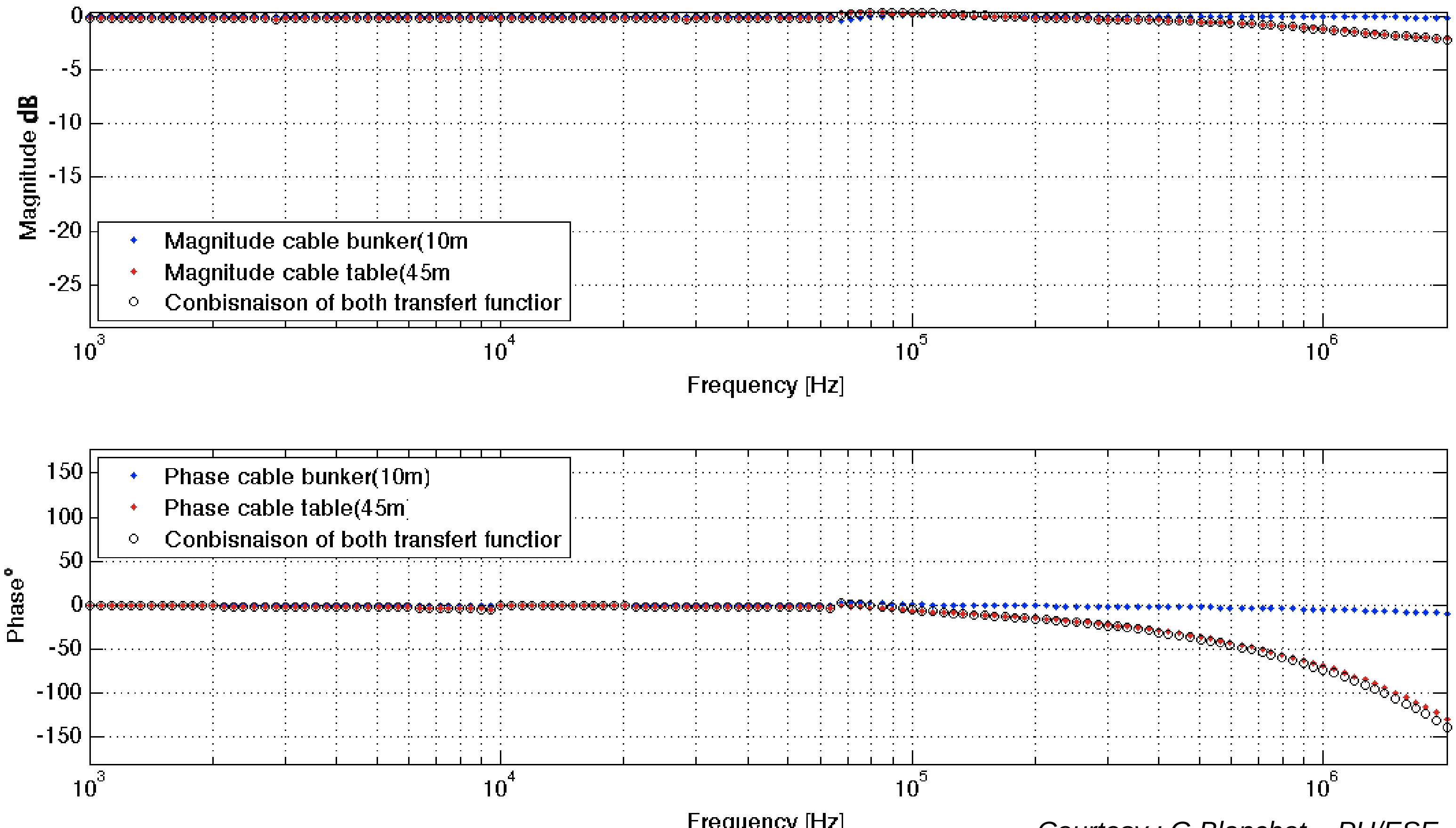
- Validation results



Cable effects

- Characterization of the cable effects
  - ➔ Typical signal from the strain gauges : 25 mV (Full Scale) up to 1 MHz
  - ➔ 42 m of cables - Mixed of cables



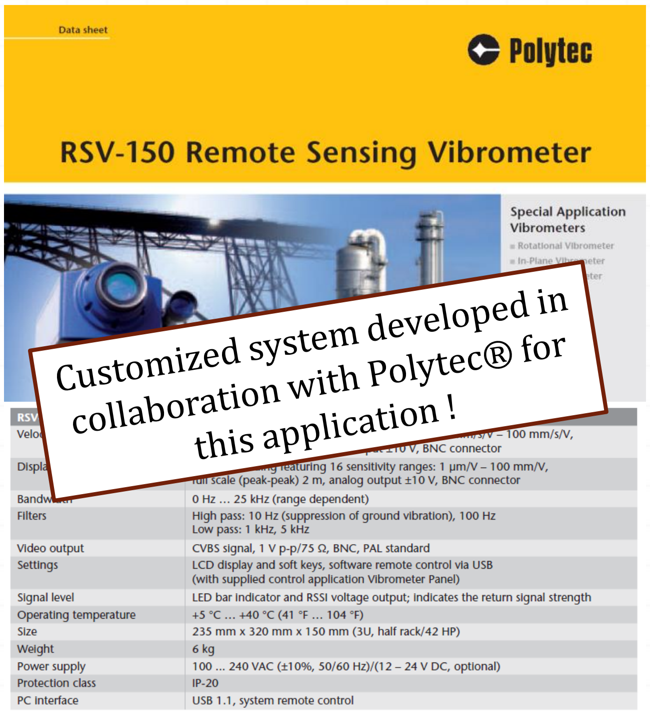


at Team

Courtesy : G Blanchot – PH/ESE

Radial Velocity Measurements

- Radial measurements performed with a Laser Doppler Vibrometer equipped with :
  - ➔ Targeting laser (green)
  - ➔ Infrared laser for measurements
  - ➔ Long range lens
  - ➔ In line video camera with reticle overlay



Data sheet

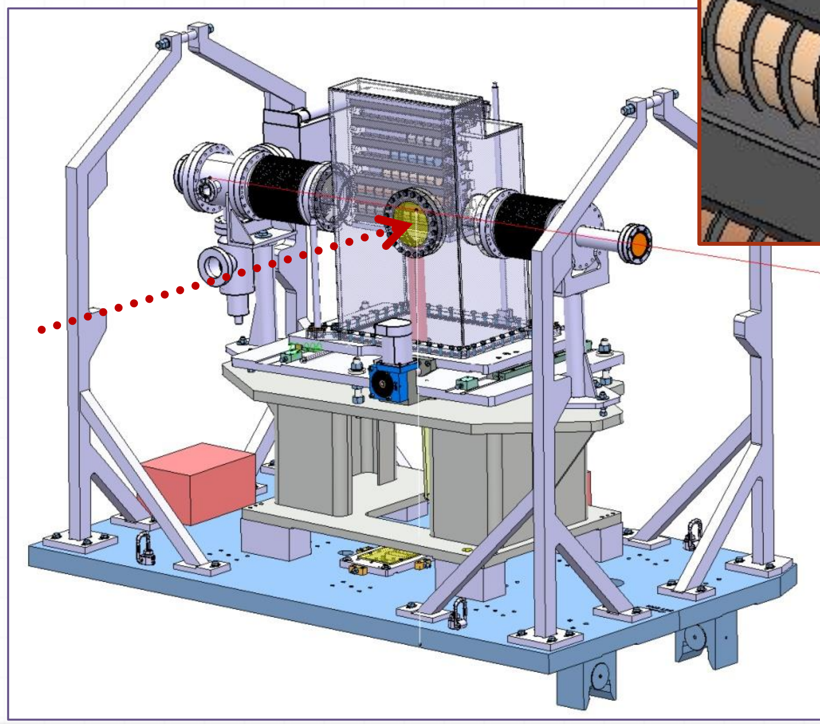
Polytec

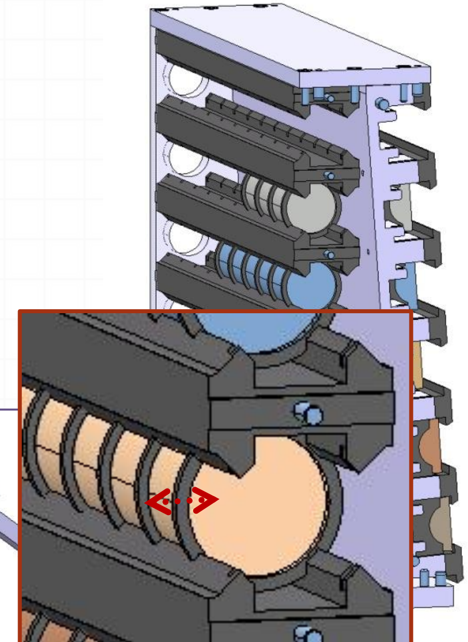
RSV-150 Remote Sensing Vibrometer

Special Application Vibrometers

RSV[illegible]	
Velo[illegible]	[illegible] mm/s/V – 100 mm/s/V, [illegible] ±10 V, BNC connector
Displa[illegible]	[illegible] featuring 16 sensitivity ranges: 1 µm/V – 100 mm/V, full scale (peak-peak) 2 m, analog output ±10 V, BNC connector
Bandw[illegible]	0 Hz … 25 kHz (range dependent)
Filters	High pass: 10 Hz (suppression of ground vibration), 100 Hz Low pass: 1 kHz, 5 kHz
Video output	CVBS signal, 1 V p-p/75 Ω, BNC, PAL standard
Settings	LCD display and soft keys, software remote control via USB (with supplied control application Vibrometer Panel)
Signal level	LED bar indicator and RSSI voltage output; indicates the return signal strength
Operating temperature	+5 °C … +40 °C (41 °F … 104 °F)
Size	235 mm x 320 mm x 150 mm (3U, half rack/42 HP)
Weight	6 kg
Power supply	100 … 240 VAC (±10%, 50/60 Hz)/(12 – 24 V DC, optional)
Protection class	IP-20
PC interface	USB 1.1, system remote control

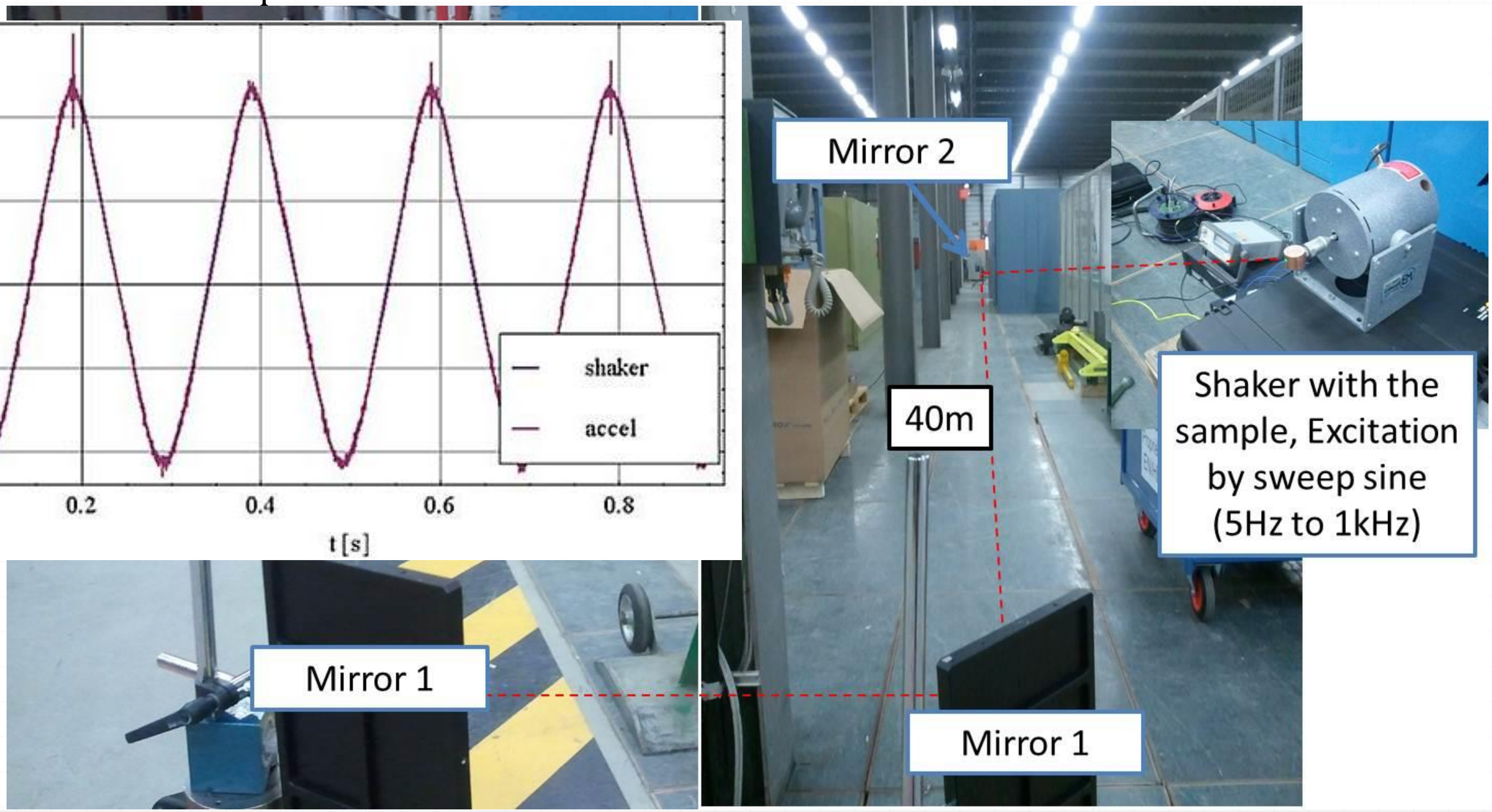
Customized system developed in collaboration with Polytec® for this application !





Radial Velocity Measurements

- Validation results
  - ➔Test performed in BA7, same configuration as HiRadMat facility
  - ➔Same components as for the final measurement



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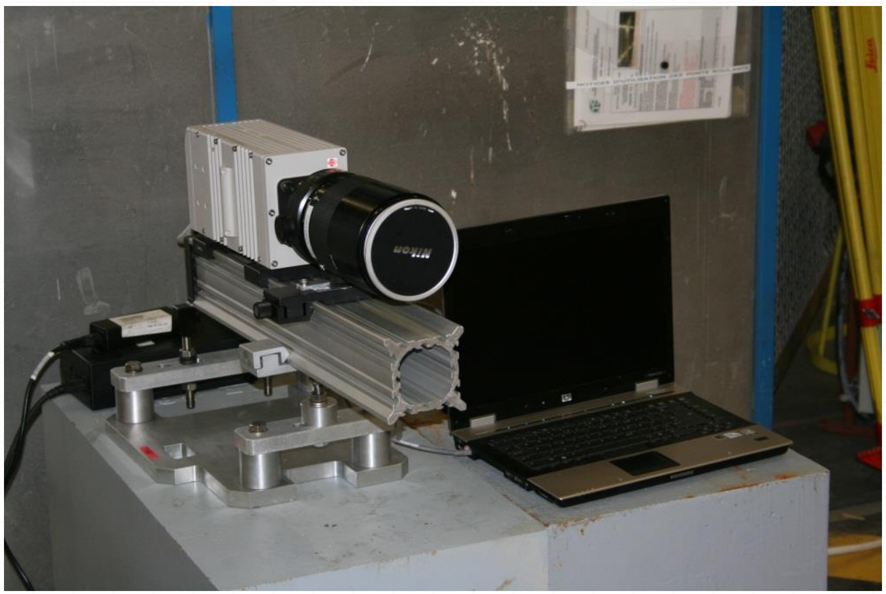
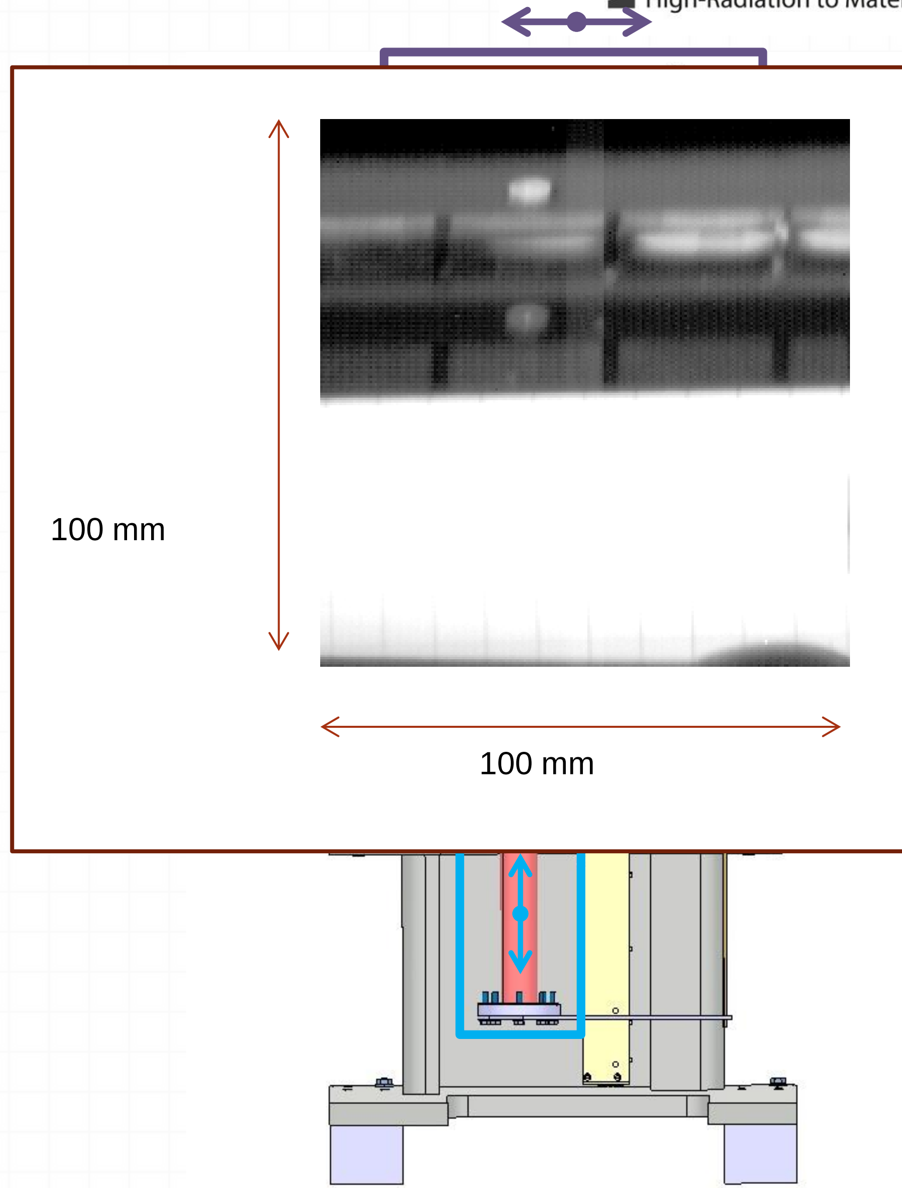
High Speed Camera

High Speed Camera Specifications:

- Distance: ~42 m,
- Optical Circuit: 3 mirrors + 1 window,
- Lens: Nikkor 1000 mm,
- Observable area at 42 m: ~100x100 mm,
- Frame rate: 20000 fps,
- Shutter time: 5 µs.





Courtesy : HiRadMat Team

High Speed Camera

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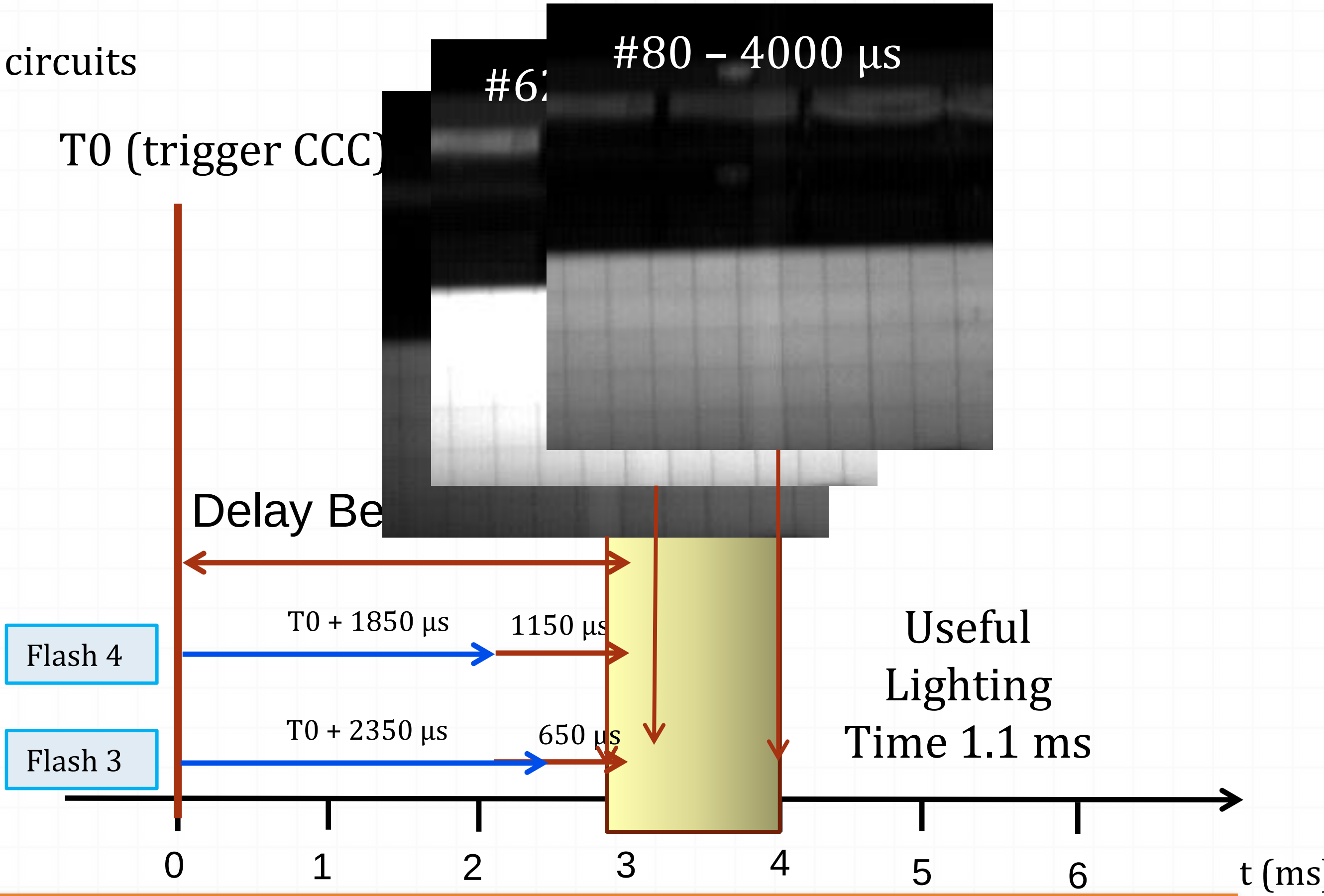
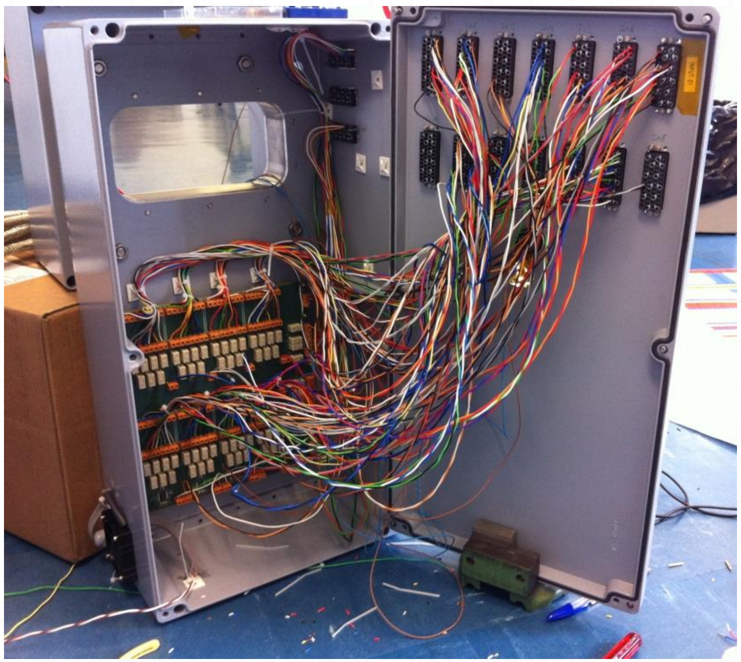
Engineering Department

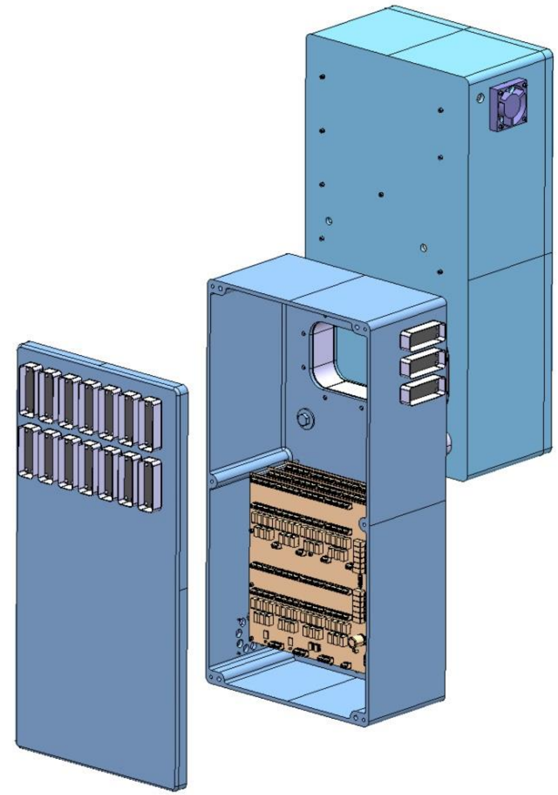
- Vintage Xenon Flash Light
- Robust 1970’s electronic components
- Very high luminosity
- Customized electronic circuits



RadHard Switch

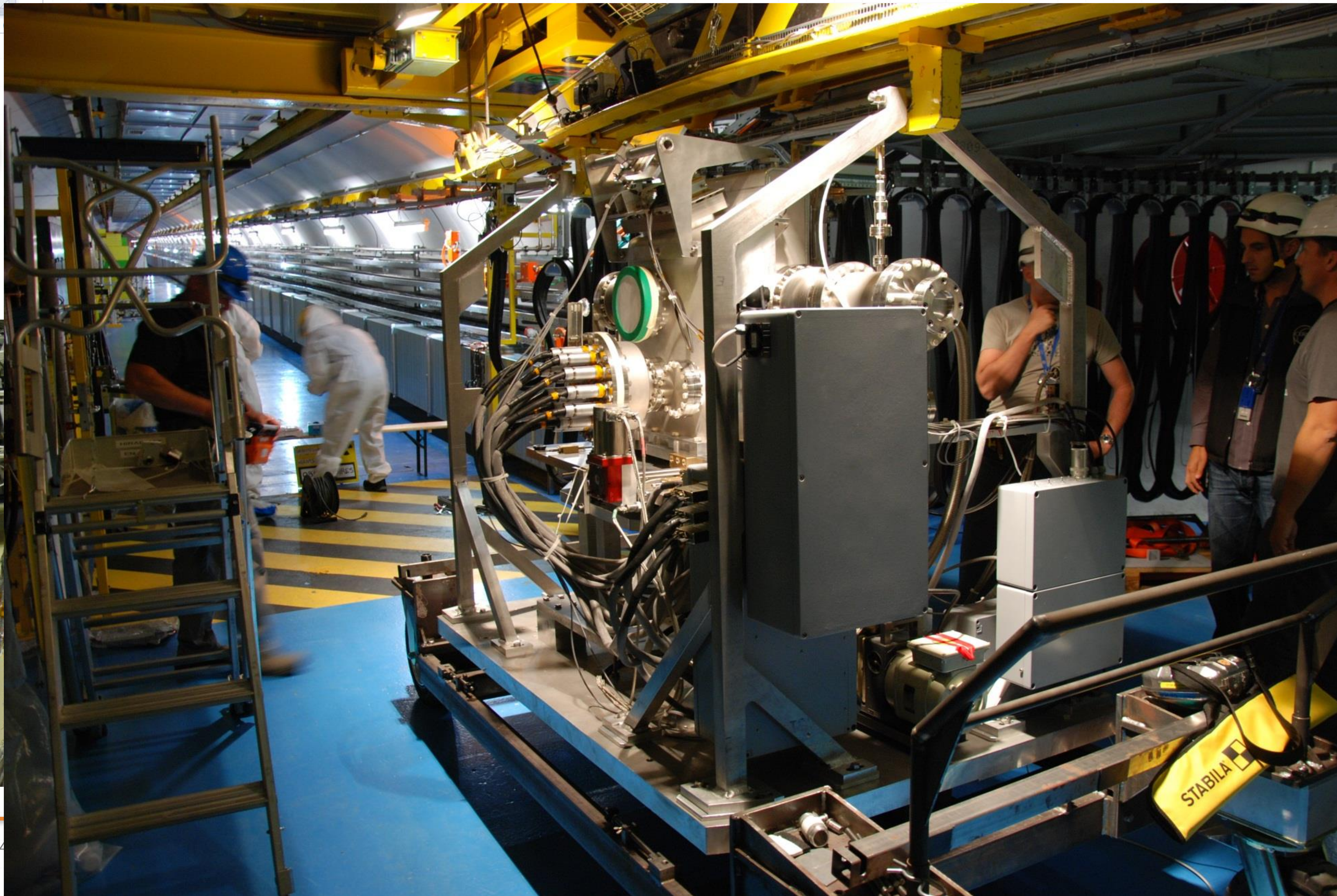
- Switch multiplexing (1:8)
- Radiation Hard Components
- Electrical Consumption : 90 Watts (Air cooling)
- Special design for low noise level signals
- Wheatstone bridge integrated on the board



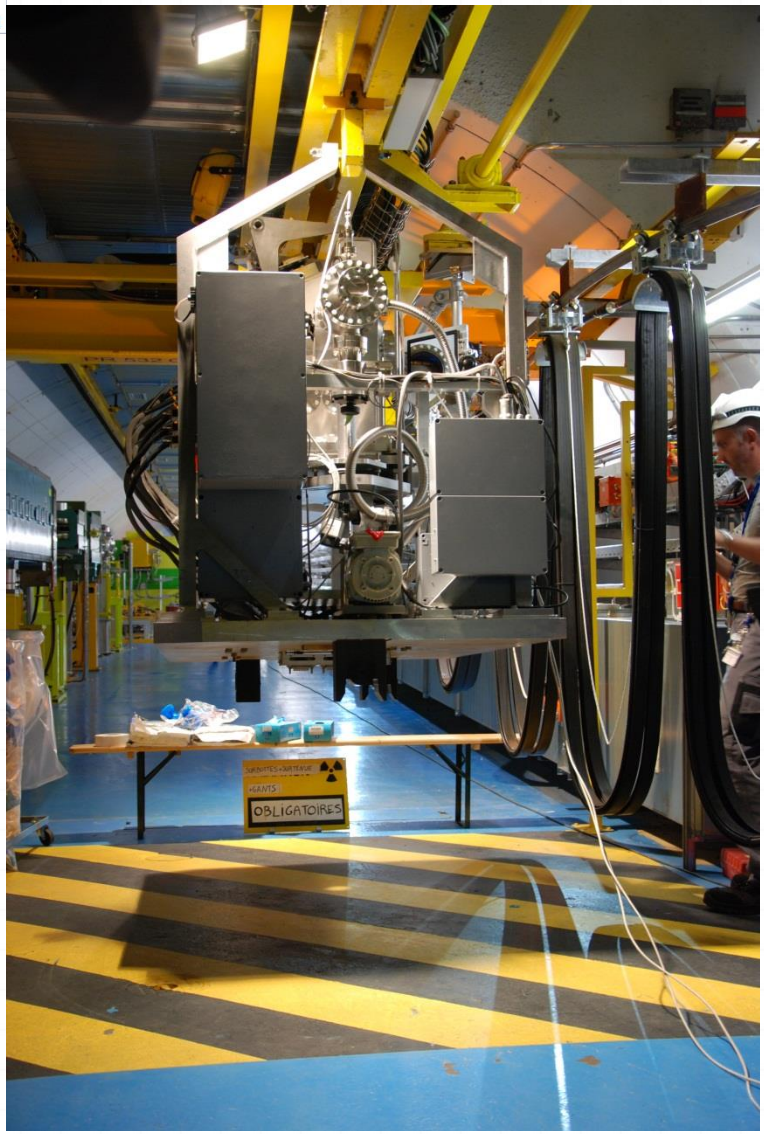


Courtesy : B. Magnin TE-MPE and Pablo Fernandez Carmona EN-MME

Mounting Operations



Installation



Timing for acquisition

HiRadMat High-Radiation to Materials

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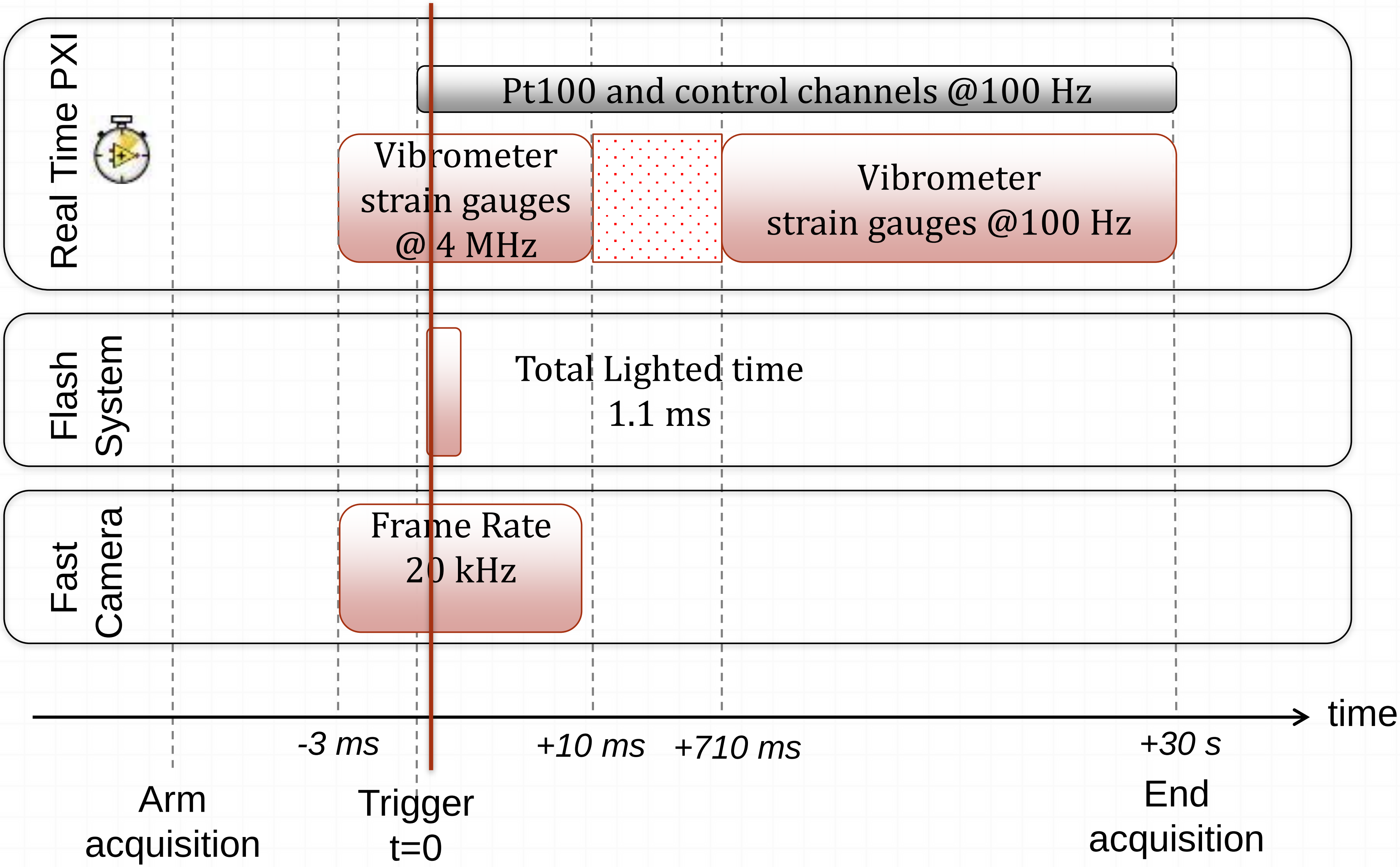
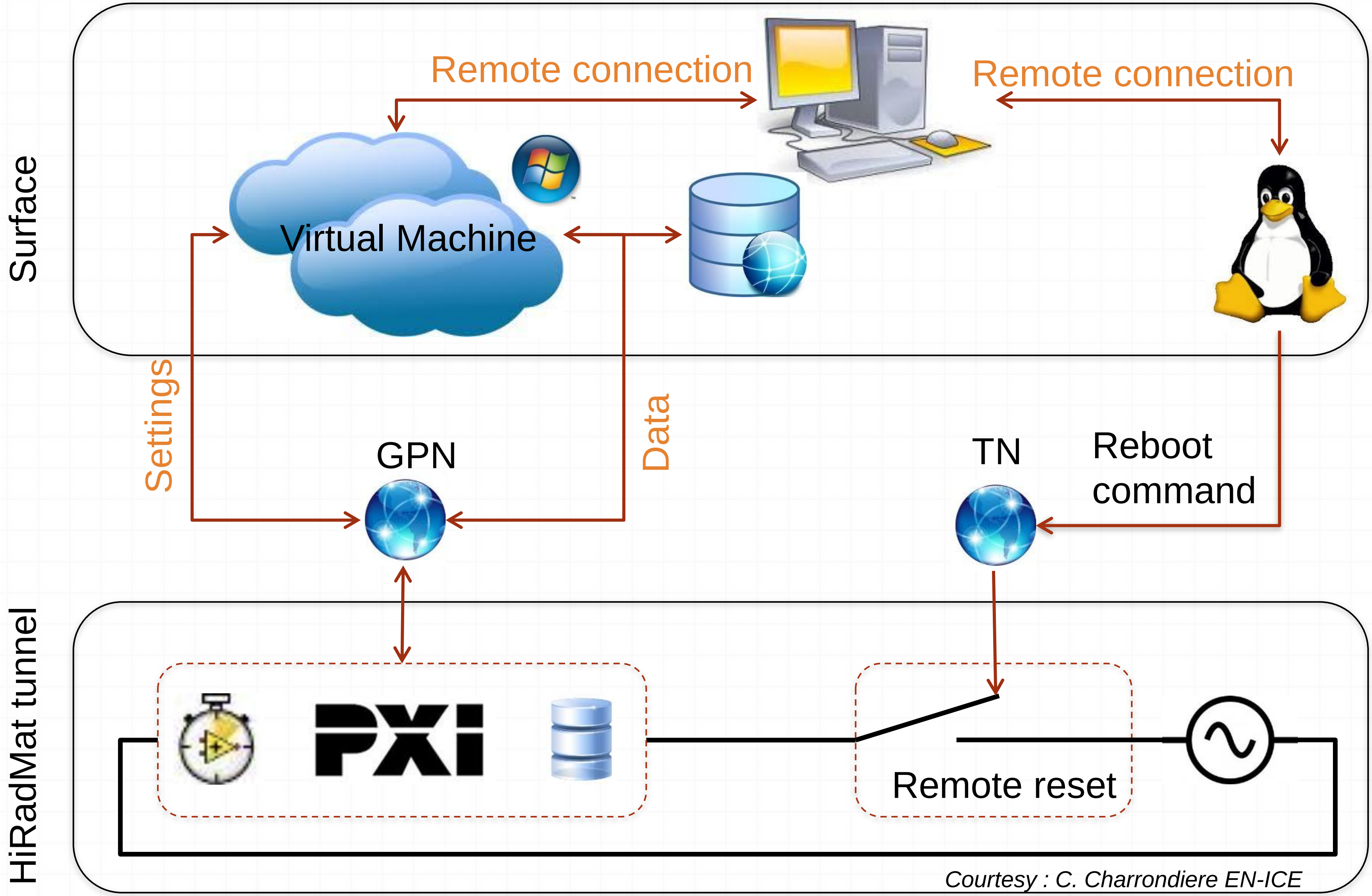


Courtesy : C. Charrondiere EN-ICE

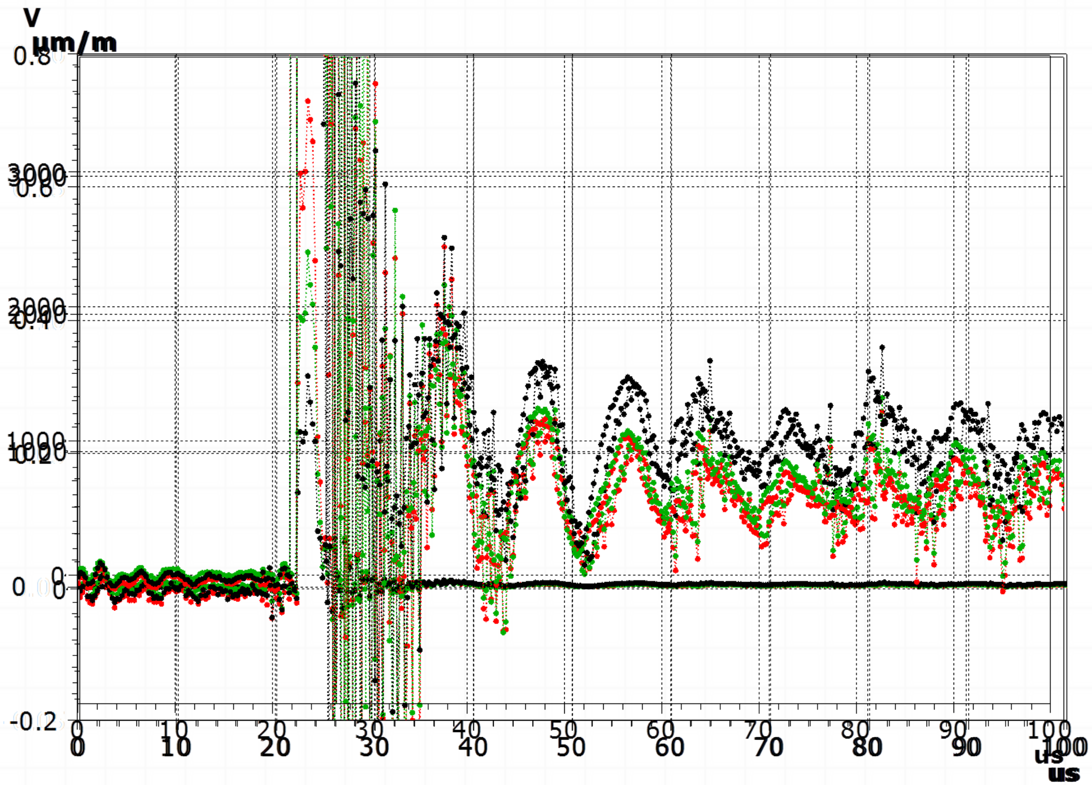
Software Implementation

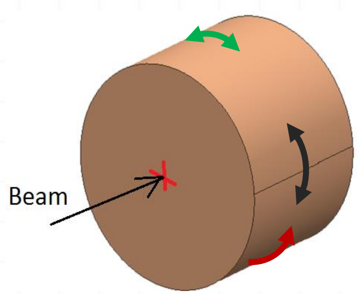


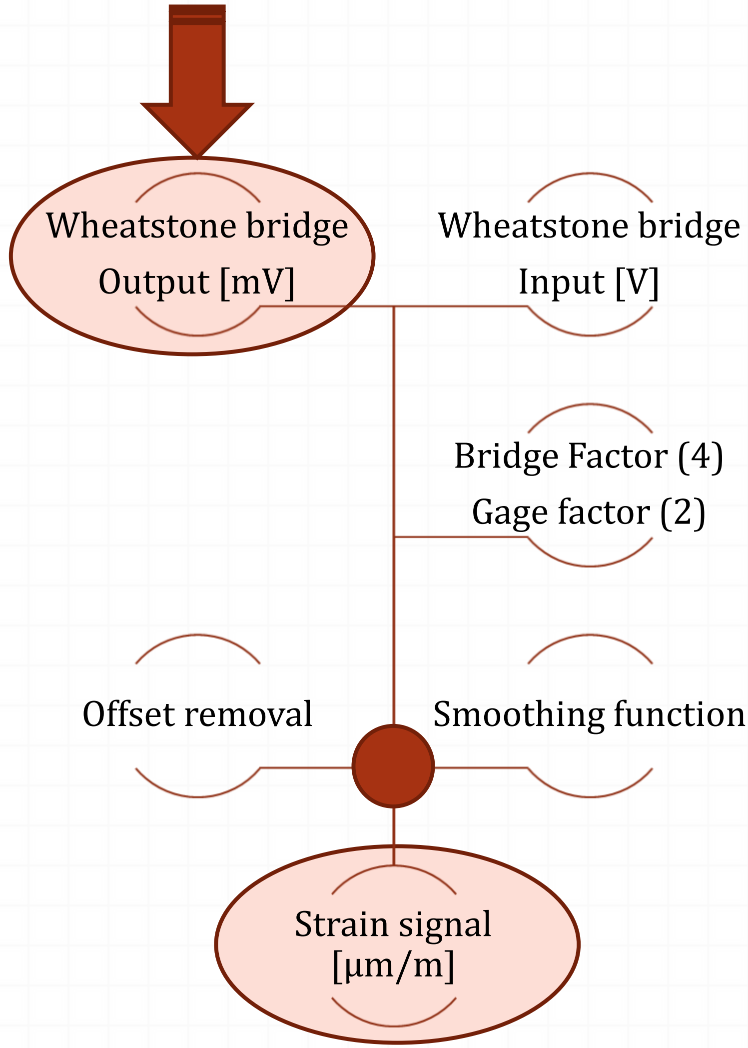
Measurements and Analysis

- 52 impacts generated on the 12 target stations
- 40 GB of raw data
- Typical results for the Glidcop materials at 72 bunches

Strain analysis







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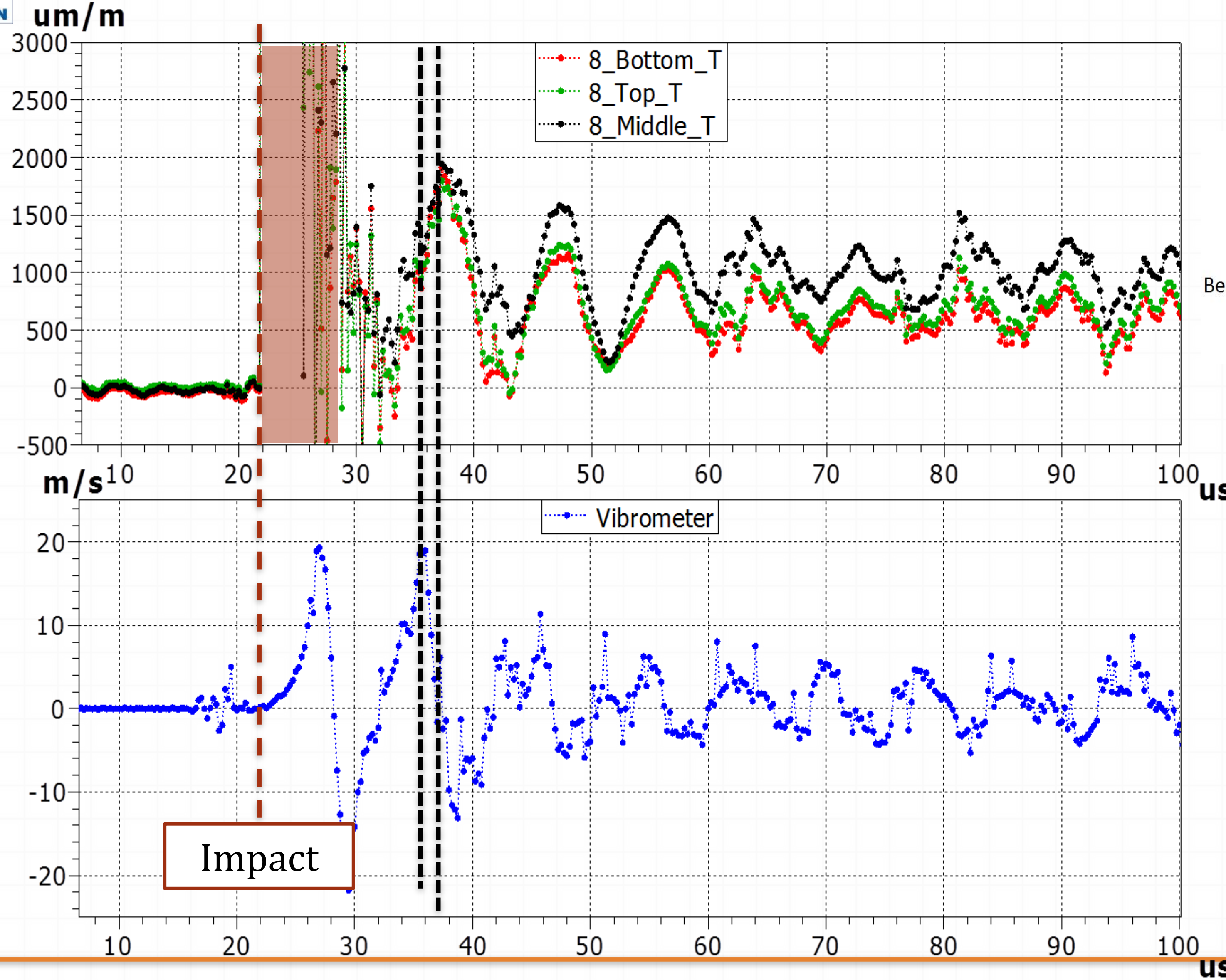
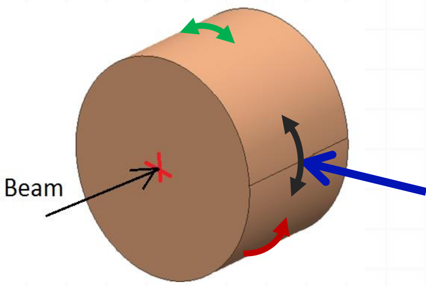
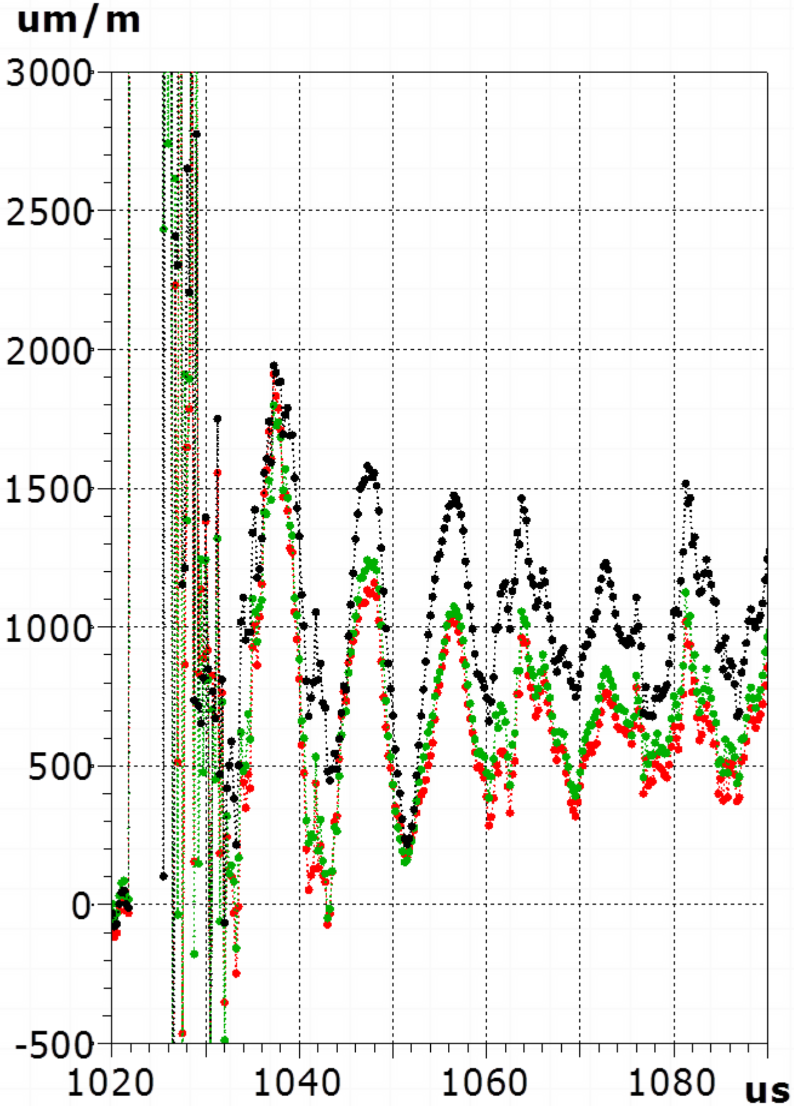
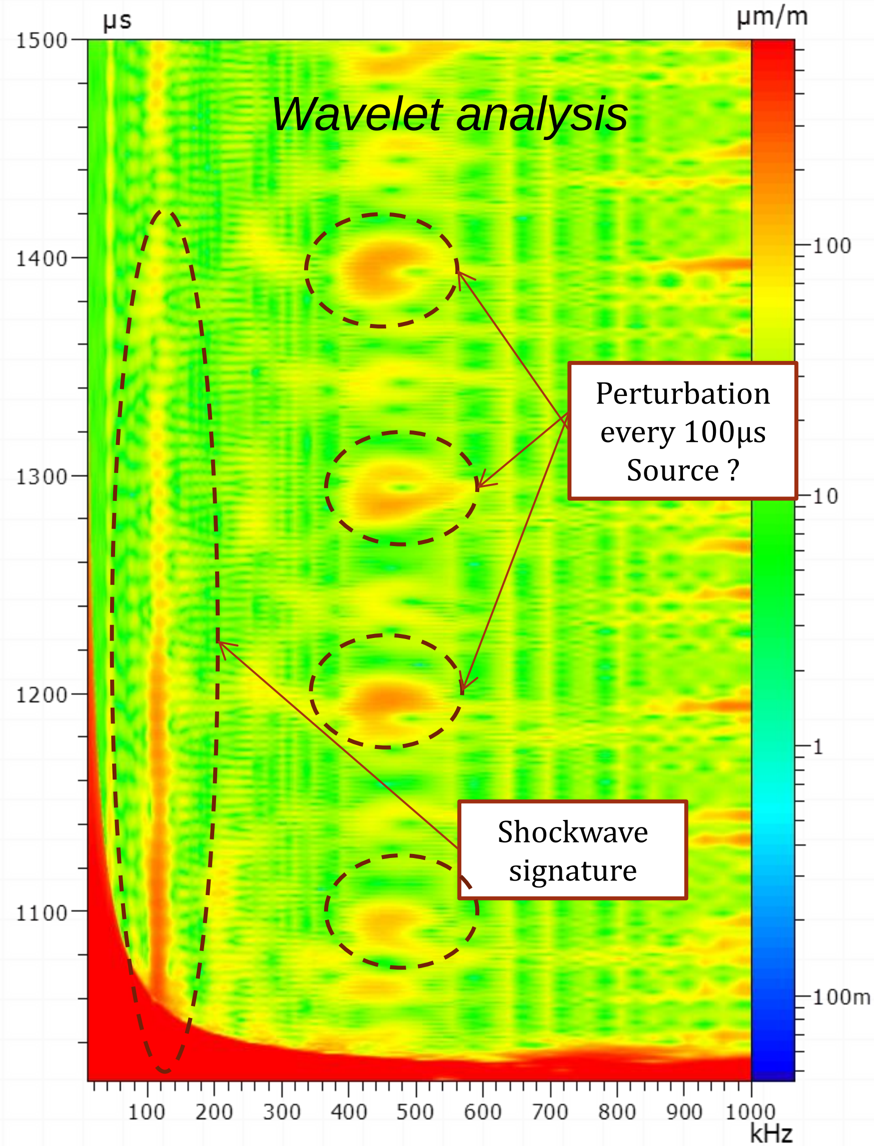
Velocity / Strain Comparison



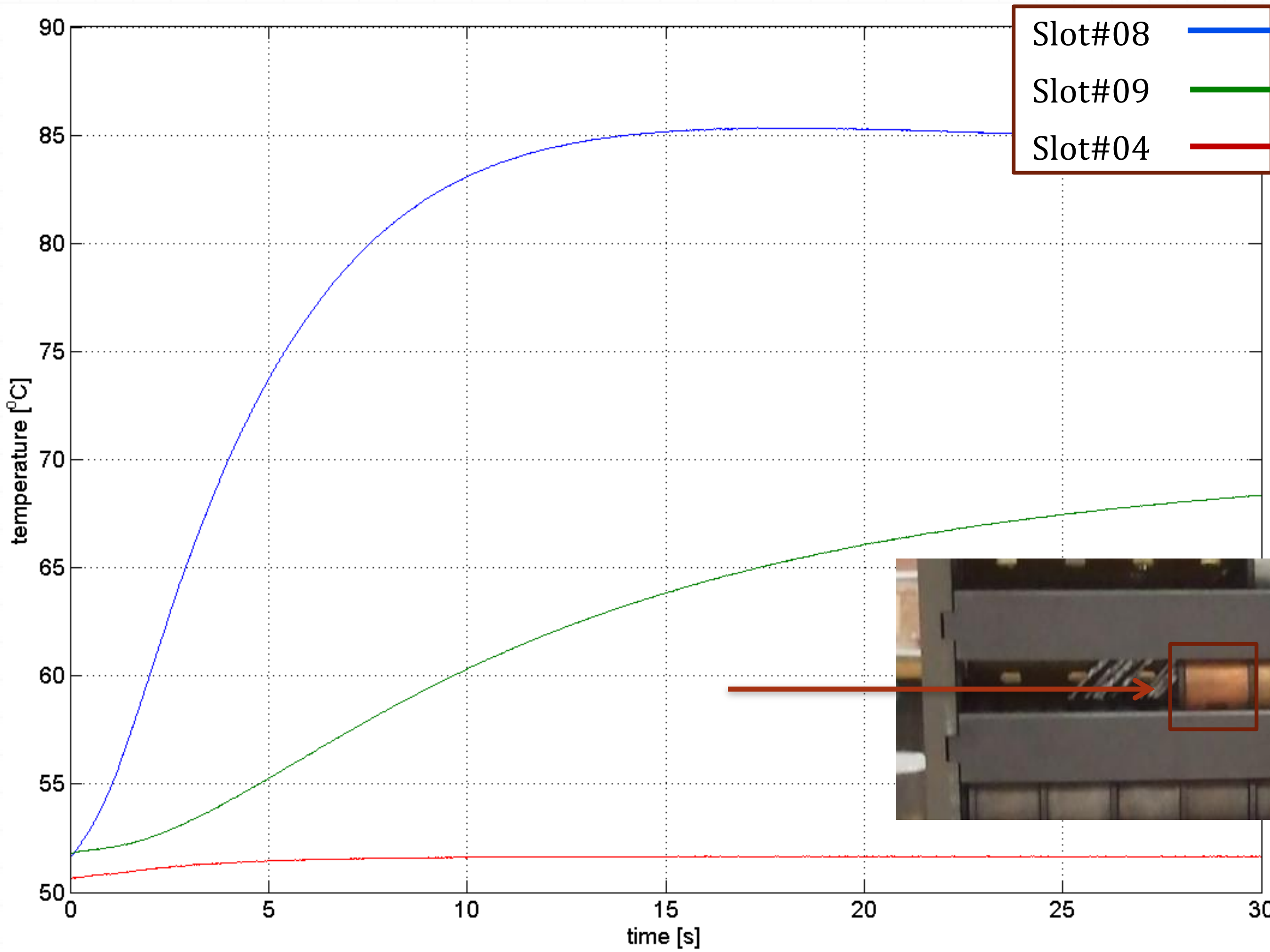


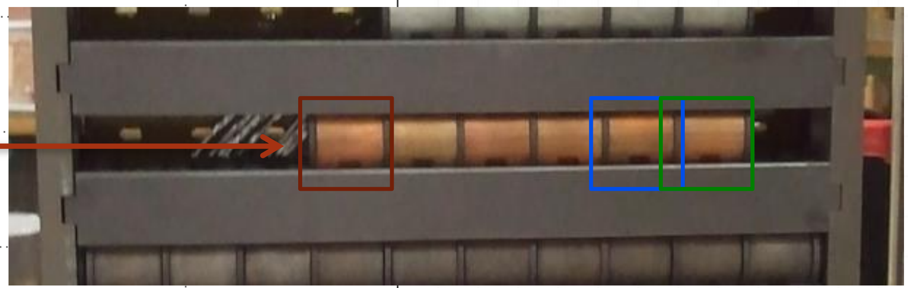
Frequency Strain Analysis





Temperature results



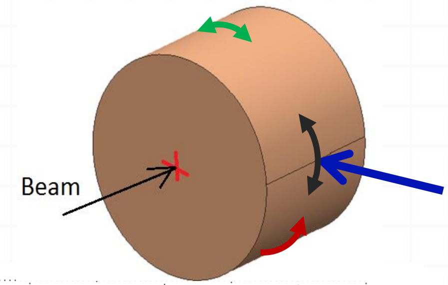


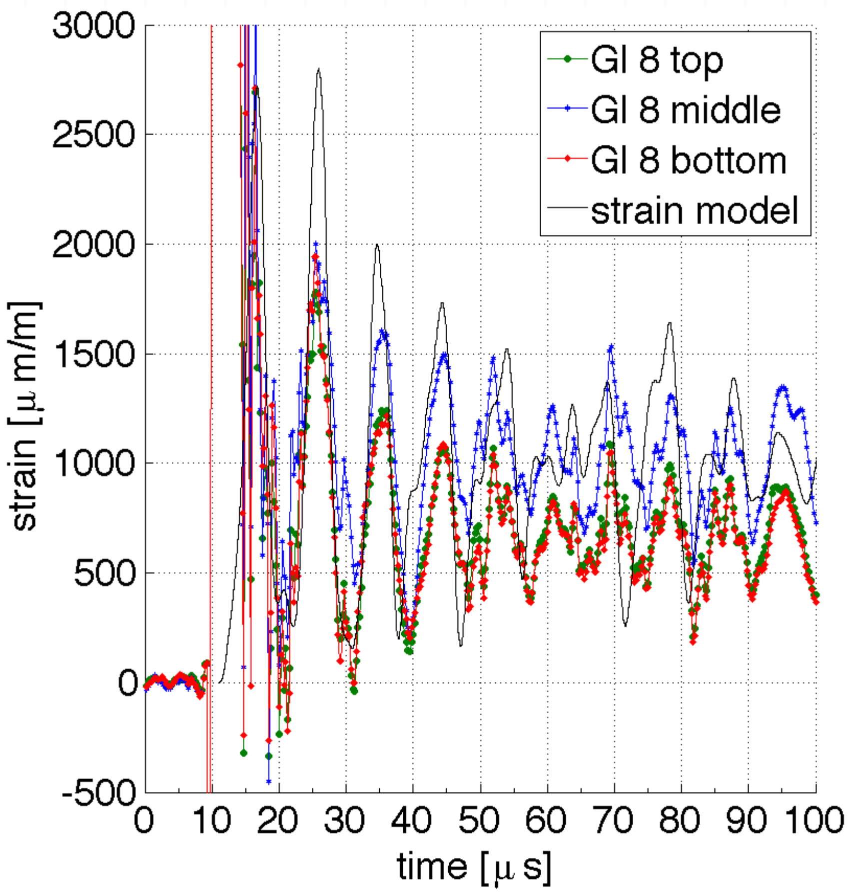
Outlook

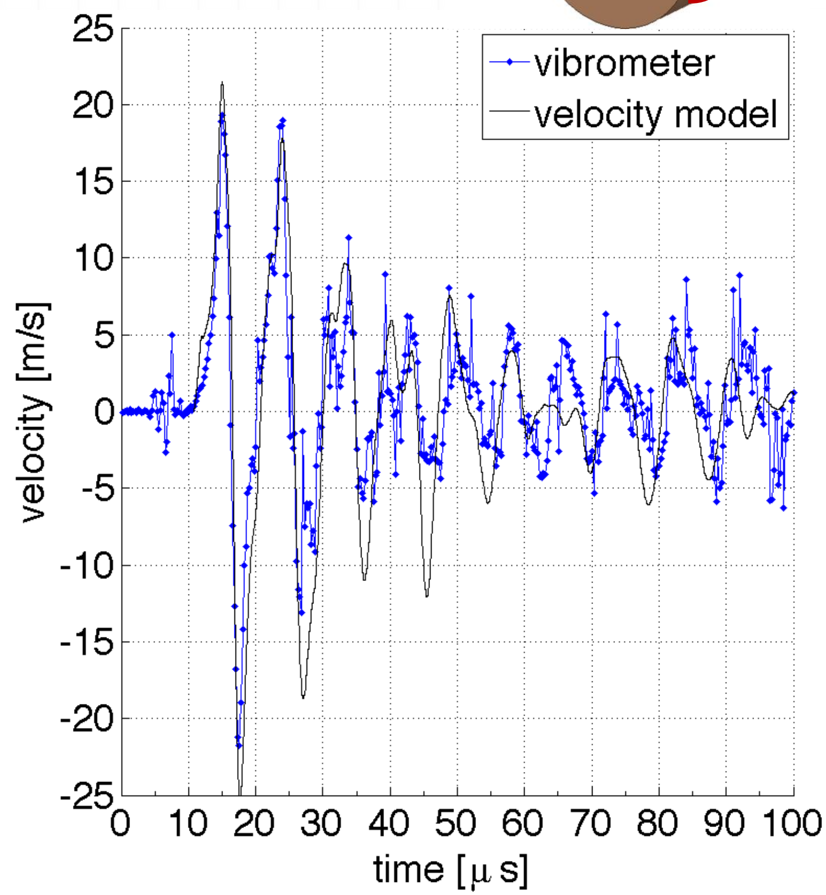
- Context
- Introduction to HRMT14-LCMAT Experiment
- Numerical Simulations
- Instrumentation and Validation Tests
- **Results and Analysis**
- Conclusions

Medium intensity tests

Glidcop Sample – Slot#08
72 b (scraped), Total intensity: 4.66e12 p, σ ≅ 1.3 mm

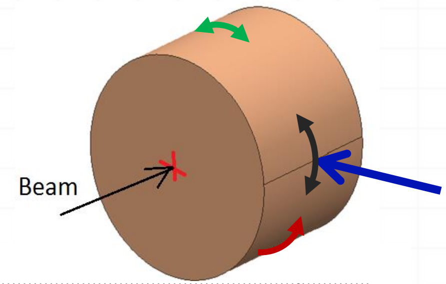


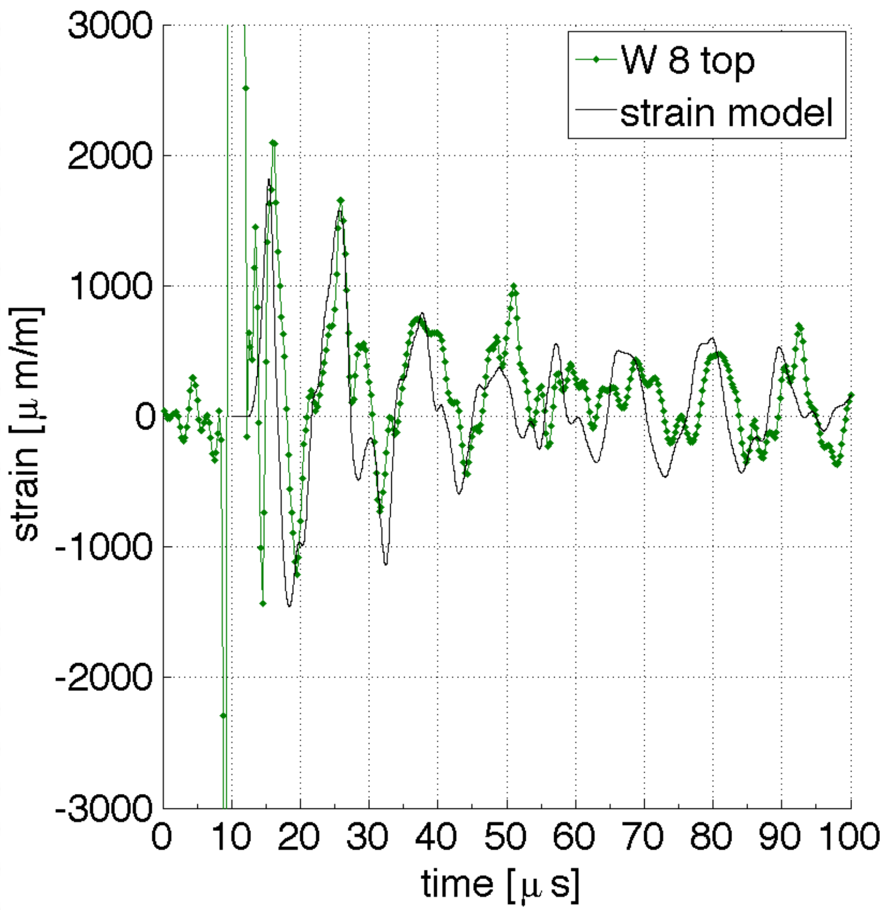


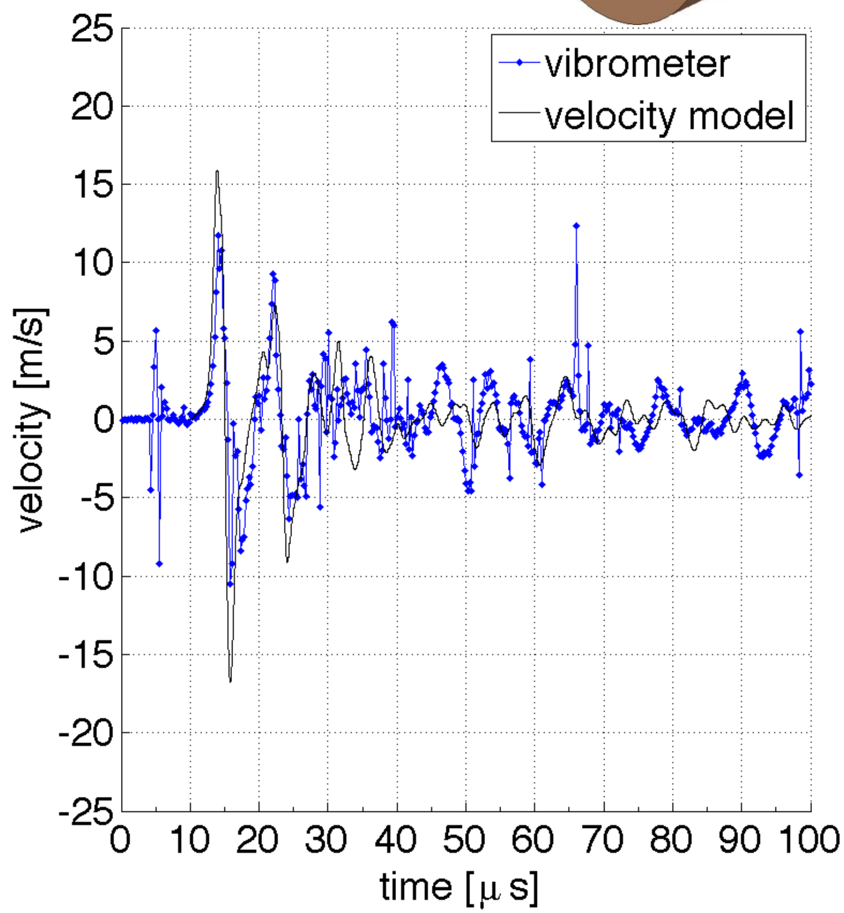


Medium intensity tests

Inermet Sample Slot#08
24 b (scraped), Total intensity: 2.7e12 p, σ ≅ 1.4 mm

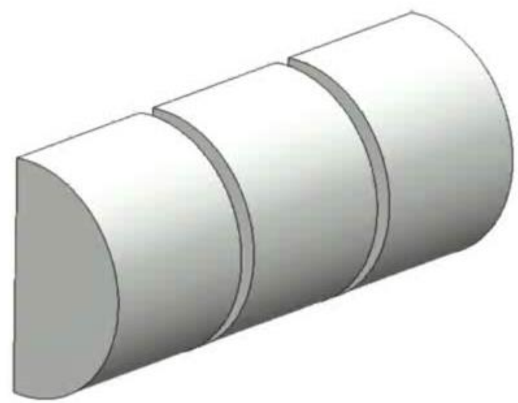






High Intensity Tests (Type 2)

Inermet samples as seen from viewport and camera



High Intensity Tests (Type 2)

HiRadMat High-Radiation to Materials

Inermet : comparison between simulation and experiment

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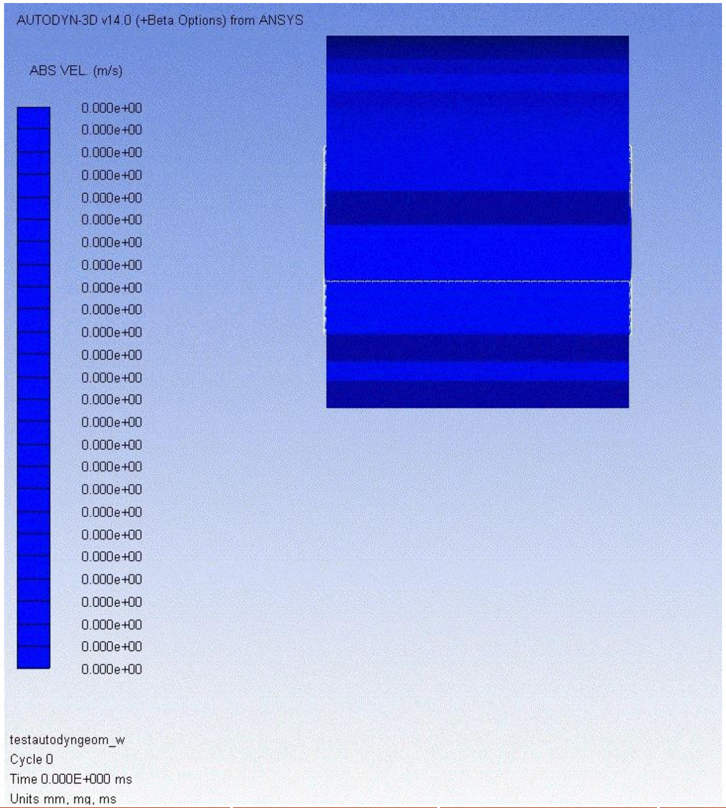
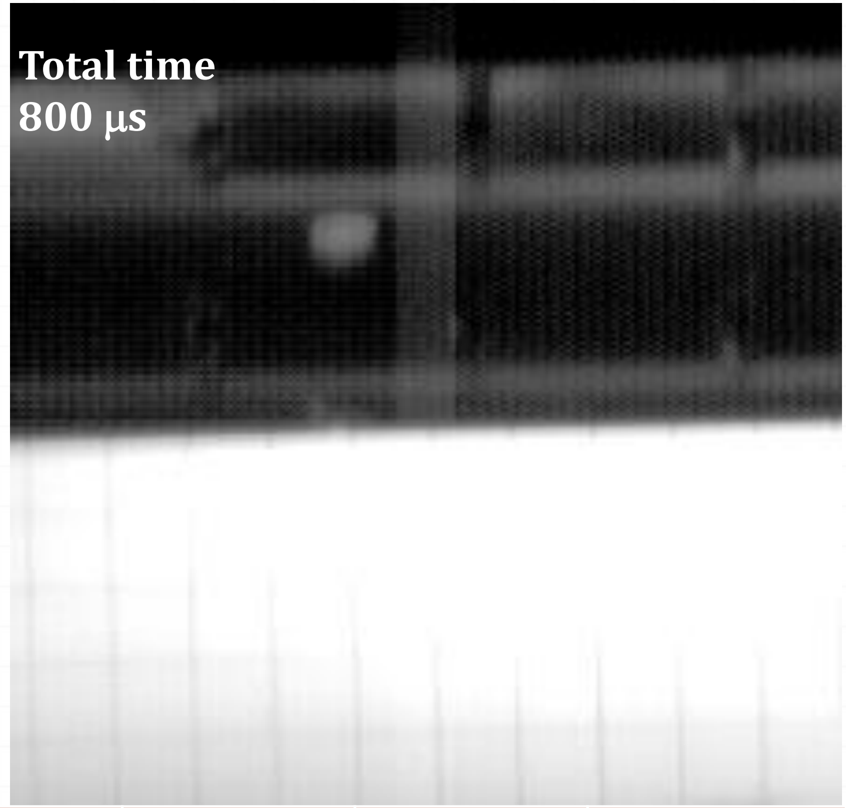
Beam



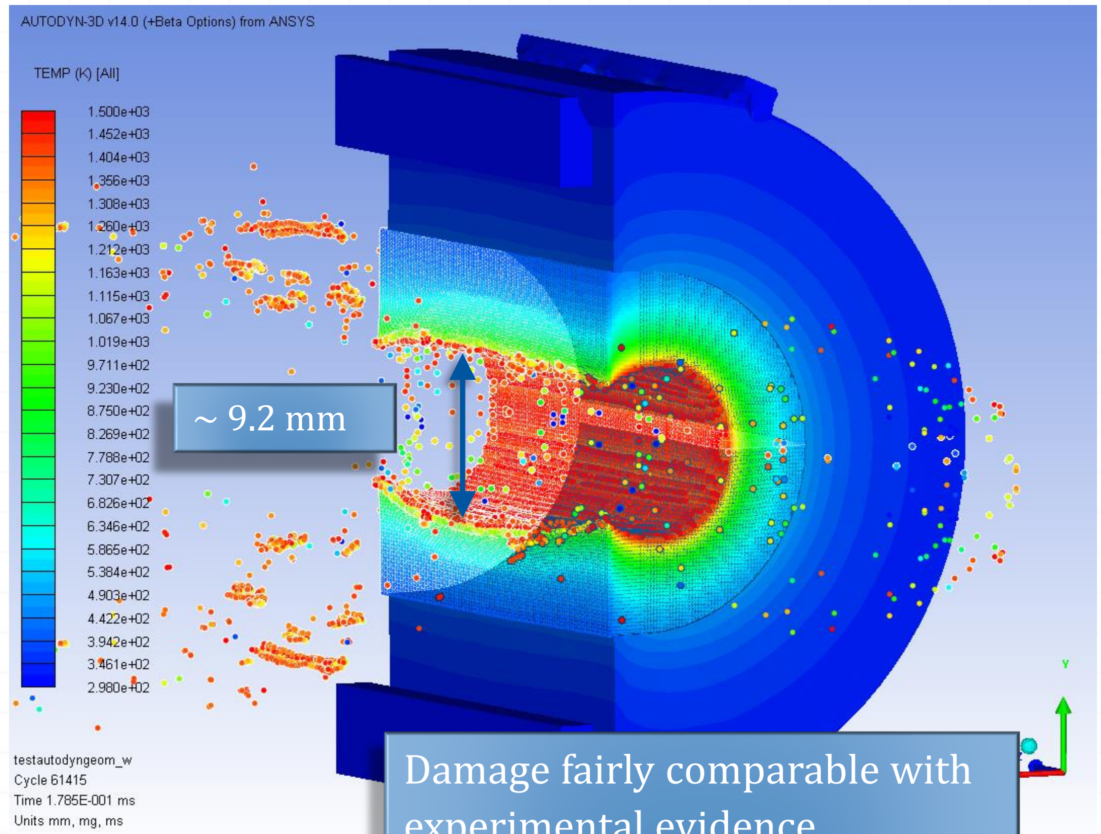


Case	Bunches	p/bunch	Total Intensity	Beam Sigma	Specimen Slot	Velocity
Simulation	60	1.5e11	9.0e12 p	2.5 mm	9	**316 m/s**
Experiment	72	1.26e11	9.05e12 p	1.9 mm	8 (partly 9)	**~275 m/s**

Post-irradiation Analysis

Inermet Type 2 specimens hit on their centre (2mm from free surface)
Simulation: 72 b, Total intensity: 1.08e13 p, σ ≅ 2.5 mm
Experiment: 72 b, Total intensity: 9.03e12 p, σ ≅ 1.9 mm

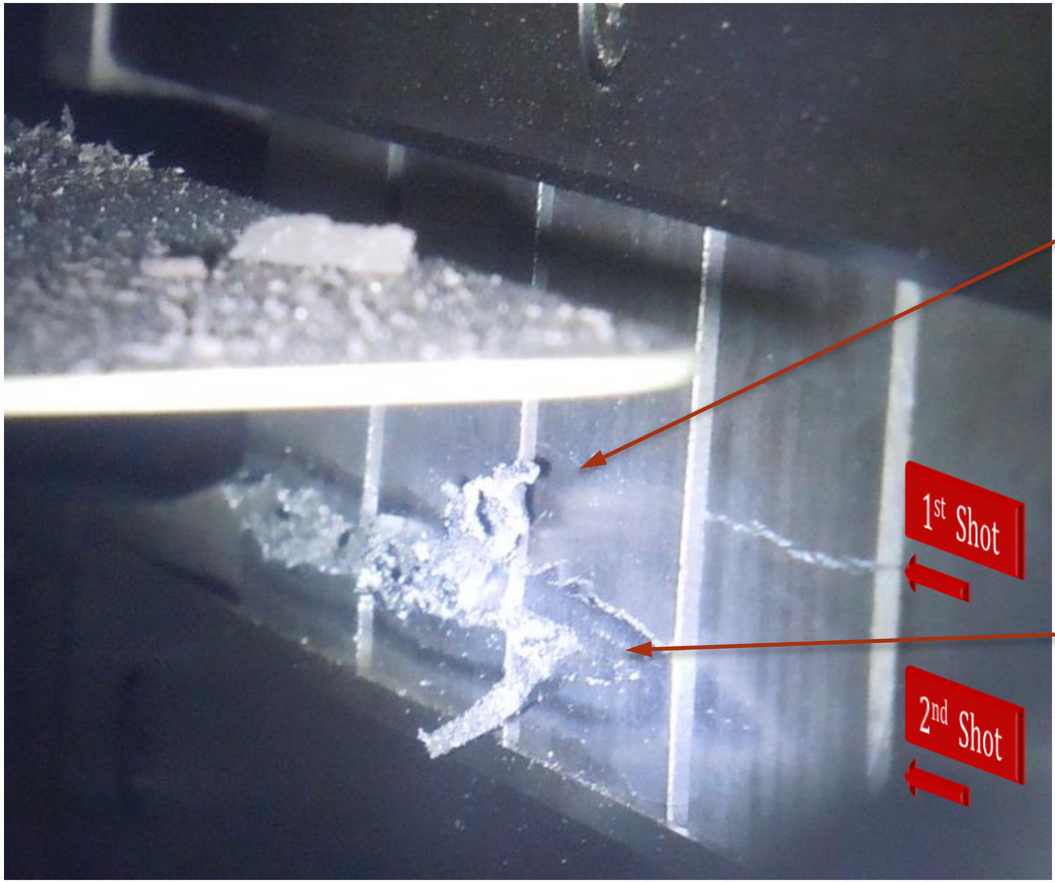
- No observable plastic deformation
- Large fragments chipped off specimen surface
- Granular aspect of damaged microstructure.



Damage fairly comparable with experimental evidence

Post-irradiation Analysis

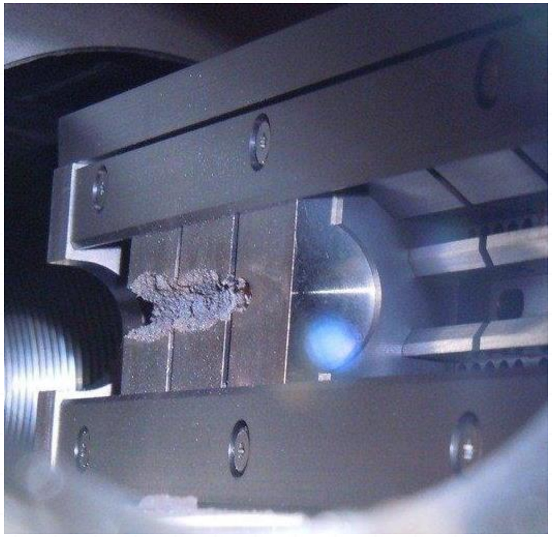
Two shots on Molybdenum Type 2 specimens (2mm from free surface)
Pulse 1: 72 b at centre, Total intensity 9.05e12 p, σ ≅ 1.9 mm
Pulse 2: 144 b 10 mm vertical offset, Total intensity 1.95e13 p, σ ≅ 2.0 mm



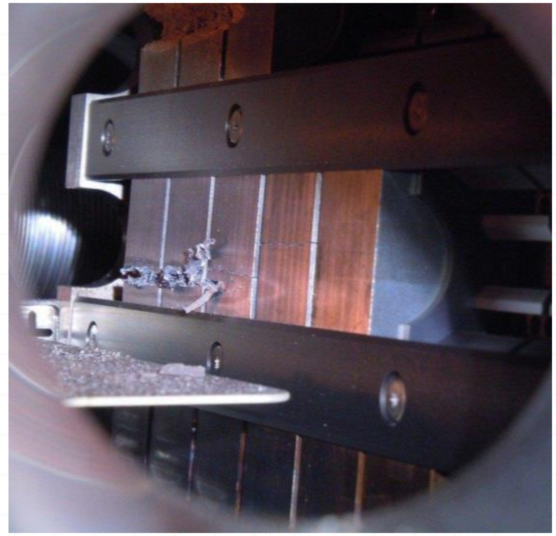
Pulse 1 (72 b as on Inermet)
- No apparent surface deformation
- Crack at Slot 6 to be analysed.

Pulse 2 (144b twice w.r.t. Inermet)
- Damage extension still smaller than on Inermet (~5 mm)
- Evidence of plastic deformation

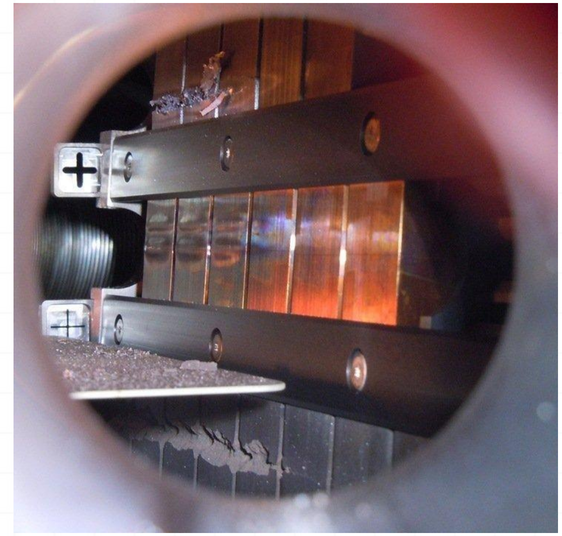
Post-irradiation Analysis



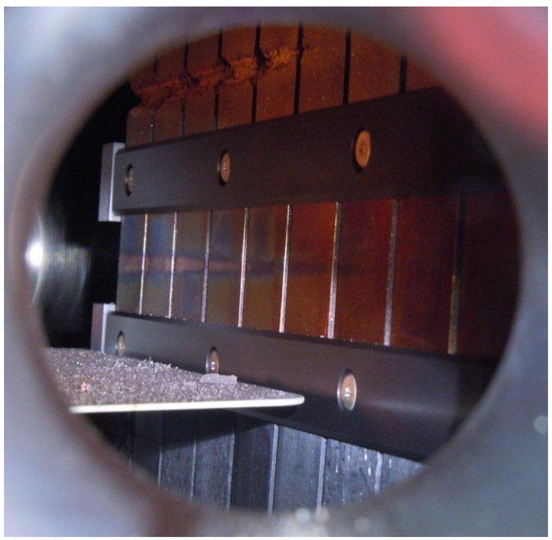
Inermet 180, 72 bunches



Molybdenum, 72 & 144 bunches



Glidcop, 72 bunches (2x)



Copper-Diamond
144 bunches

Molybdenum-Copper-Diamond
144 bunches

Molybdenum-Graphite (3 Grades)
144 bunches

Post-Irradiation Phase

- **Limited observation** of impacted specimens ad-hoc viewport (on upstream side of vacuum vessel) while still on the test-bench. **Done**
- Additional **direct observation** with personnel approaching the vacuum vessel while in the HiRadMat tunnel. **Done**
- Transport to a **class C workshop**. (e.g. PSI hot-cell). **Expected late 2013**
  - Dismounting and specimens NDT (visual observations, measurements)
  - Cutting of relevant samples to observe material damages, degradation, change of physical and metallurgical properties etc.

Due to the significant activation, any handling, inspection and analysis will be discussed and planned with **RP experts**, in line with **ALARA** principles.

Outlook

- Context
- Introduction to HRMT14-LCMAT Experiment
- Numerical Simulations
- Instrumentation and Validation Tests
- Results and Analysis
- **Conclusions**

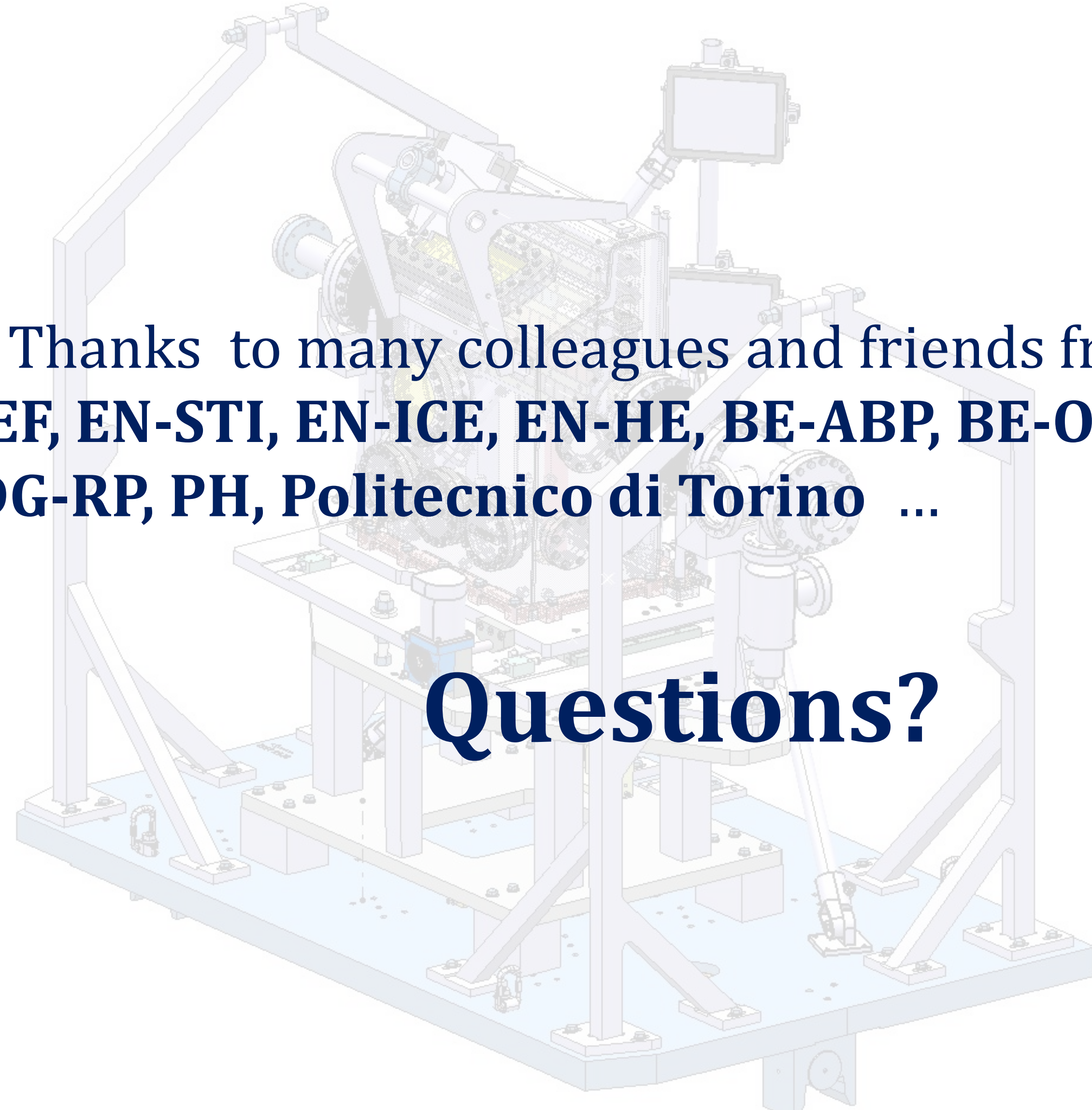
Engineering Department

Conclusive remarks

- The HRTM14 experiment was a success under any point of
- All experiment systems (DAQ, electronics, mec n spite of the very harsh environment an
- Preliminary results on "sta simulations.
- A huge constitutive models for
- ted in order to complete the work and ble information.
- mulations (FLUKA, Autodyn, EOS) to be carried out to further ove simulation/experiment matching and exploit tests potential.

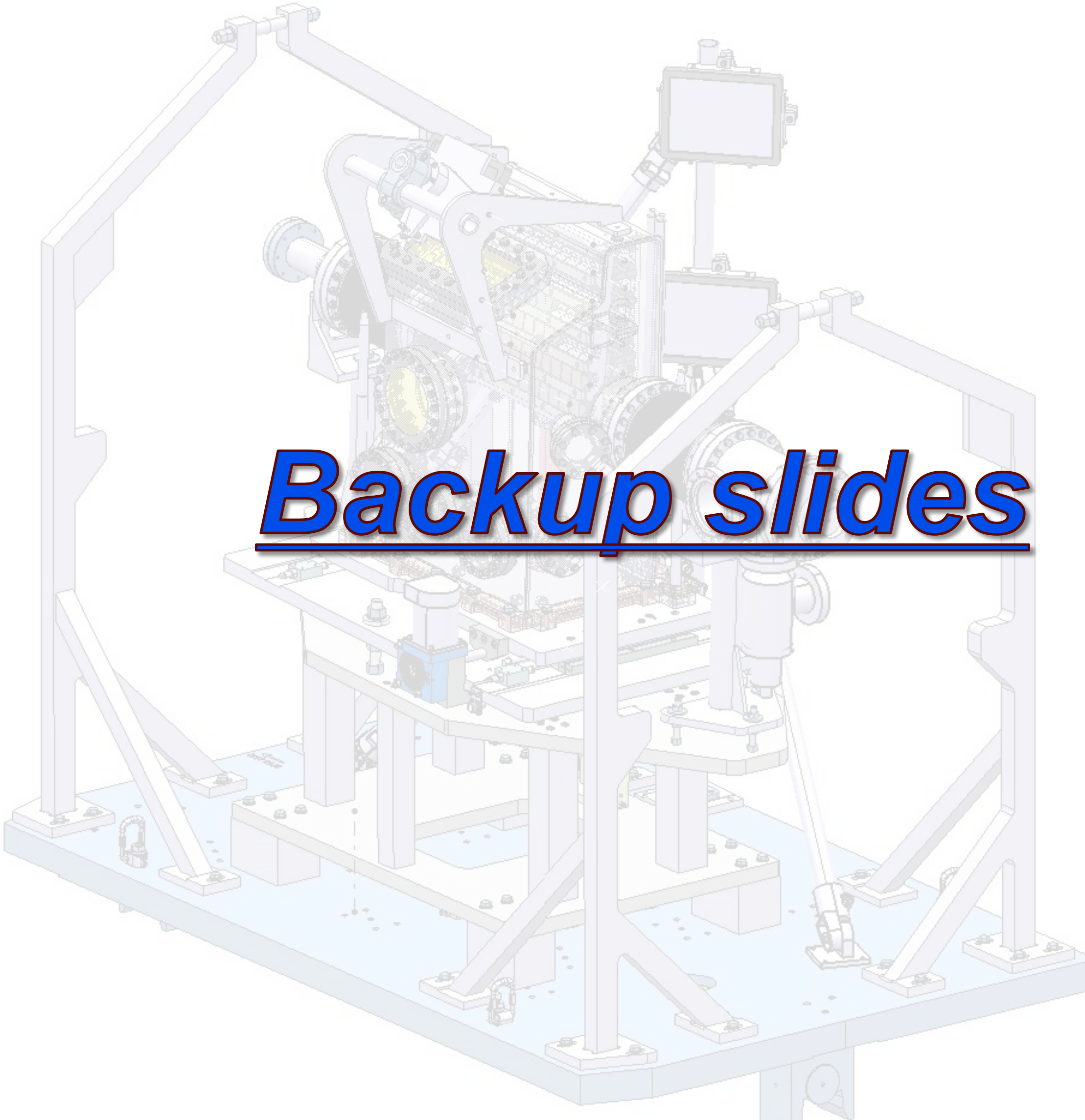
This venture is the result of friendly team work and fruitful collaboration!

It would have been impossible without the invaluable contributions of many people from CERN and outside.



Warm Thanks to many colleagues and friends from **EN-MME, EN-MEF, EN-STI, EN-ICE, EN-HE, BE-ABP, BE-OP, TE-MPE, TE-VSC, DG-RP, PH, Politecnico di Torino** …

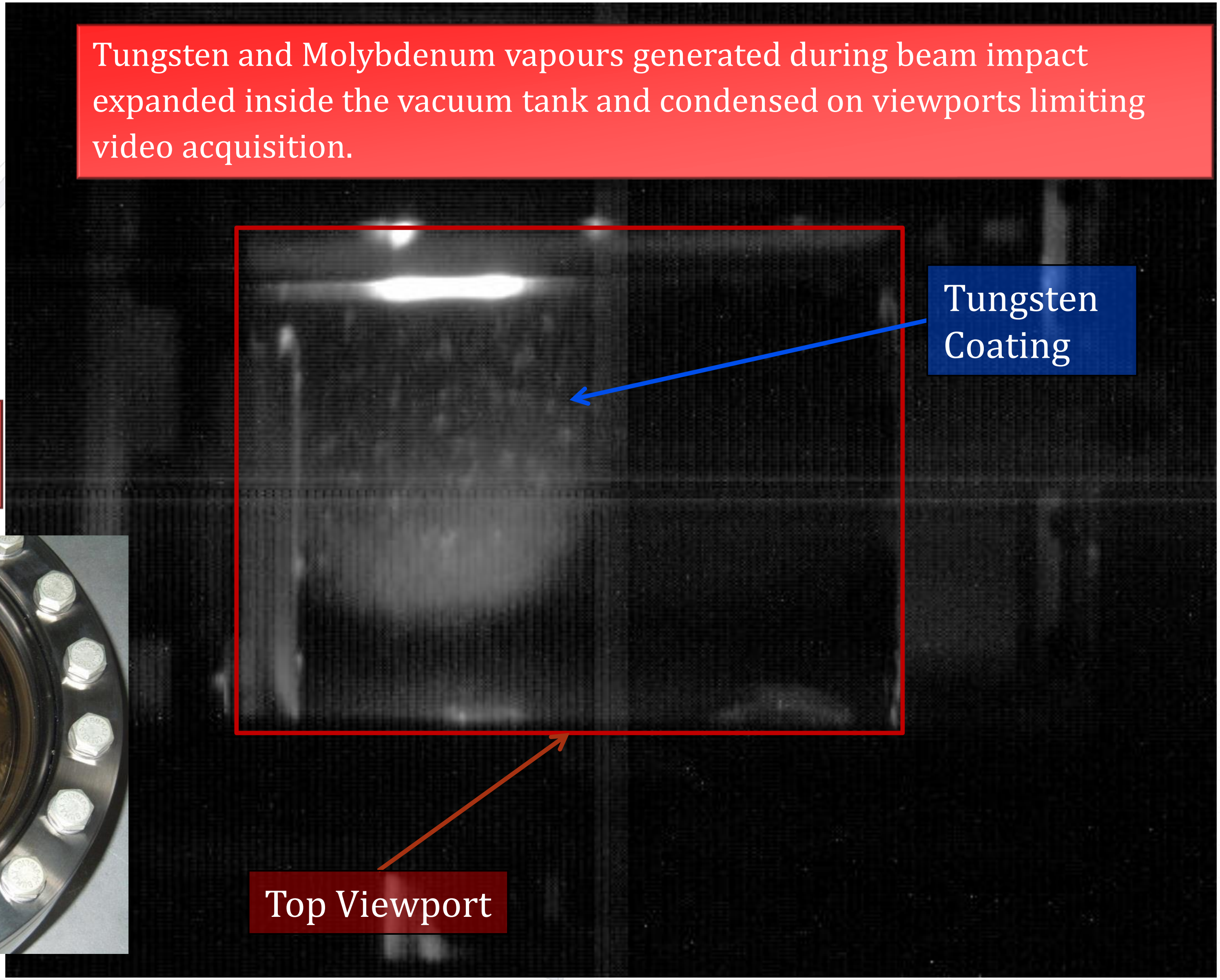
Questions?



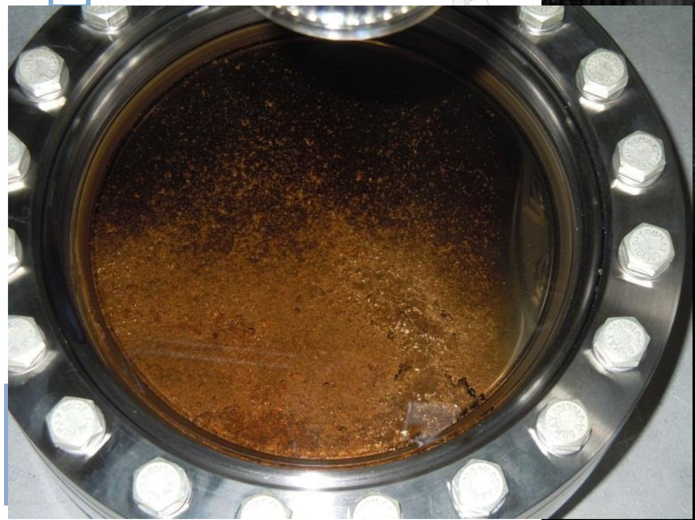
Backup slides

Post-irradiation: Viewports

Tungsten and Molybdenum vapours generated during beam impact expanded inside the vacuum tank and condensed on viewports limiting video acquisition.



Side viewport after impacts



Phase II Materials Overview

LHC Collimation Project

HiRadMat High-Radiation to Materials

Material	C-C	Mo	Glidcop ®	Cu-CD	Mo-CD	Ag-CD	Mo-Gr
Density [kg/m³]	1650	10220	8900	~5400	~6900	~6100	~5600
Atomic Number (Z)	6	42	29	~11.4	~17.3	~13.9	~13.1
T_m [°C]	3650	2623	1083	~1083	~2623	~840	~2520
SSNI [kWm²/kg]	24	2.6	2.5	13.1 ÷ 15.3	6.9 ÷ 10.9	11.4 ÷ 15.4	*7.4 **
TSNI [kJ/kg]	793	55	35	44 ÷ 51	72 ÷ 96	60 ÷ 92	*115 **
Electrical Conductivity [MS/m]	0.14	19.2	53.8	~12.6	~9.9	~11.8	*1 ÷ 18 ***

worse — better

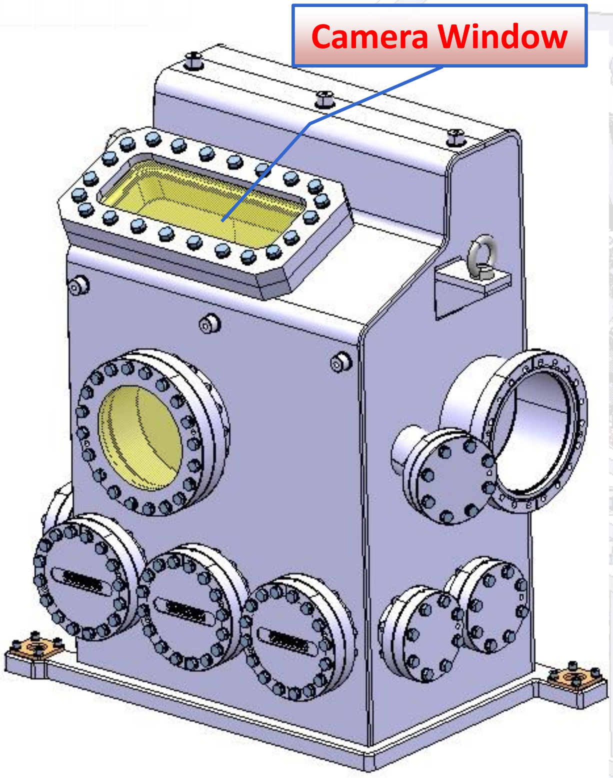
** Estimated values*
*** γ=18 MS/m with Mo surface coating*

- **C-C** stands out as to thermo-mechanical performances. Adversely outweighed by poor electrical conductivity, low Z, expected degradation under irradiation.
- **High-Z metals (Cu, Mo)** possess very good electrical properties. High density adversely affects their thermal stability and accident robustness.
- **Metal-diamond composites** exhibit a balanced compromise between TSNI, SSNI, electrical conductivity , density, atomic number.
- **Molybdenum-graphite,** currently under development and characterization, shows very promising figures of merit.

EN Engineering Department

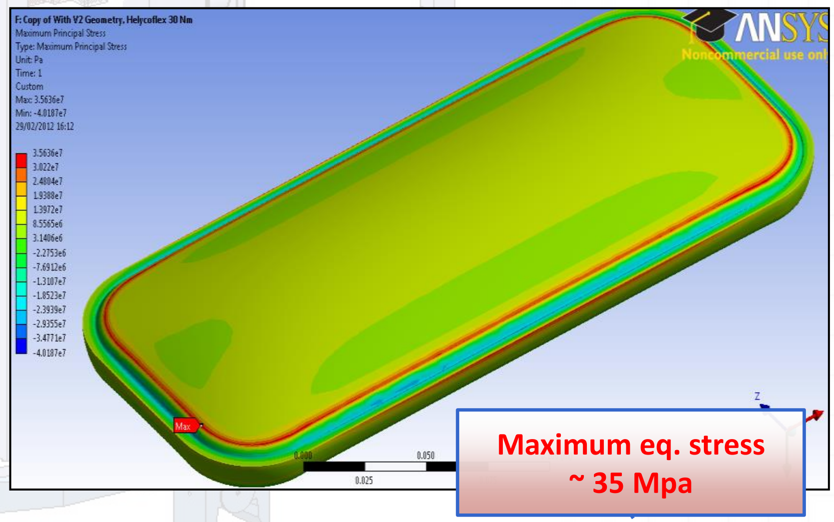
CERN

LCMAT Design Overview

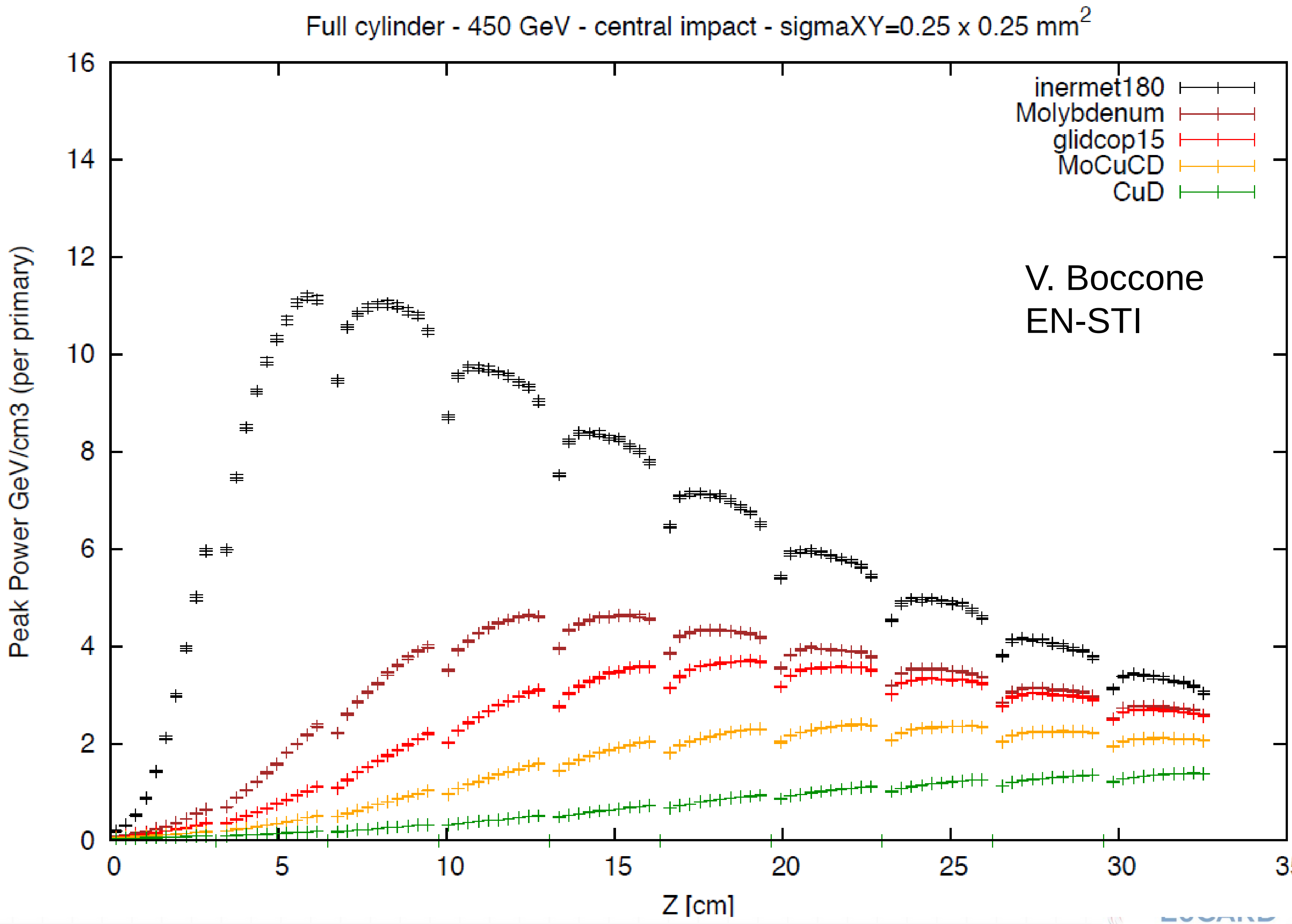


- **Camera window glass** made of Fused silica 7980: radiation resistant, high mechanical properties.
- **Structural calculation**: in the worst case, maximum equivalent stress on the glass after clamping is **35 MPa** (Glass resistance: **52 MPa**)

Material	***Radiation Resistance***	***Young's Modulus***	***Compressive Strength***	***Flexural Strength***	***Hardness***
7980 Fused Silica	No darkening up to 1 MGy	72.7 GPa	1.14 GPa	52.4 MPa	Knoop Hardness (100 g) 522 kg/mm2

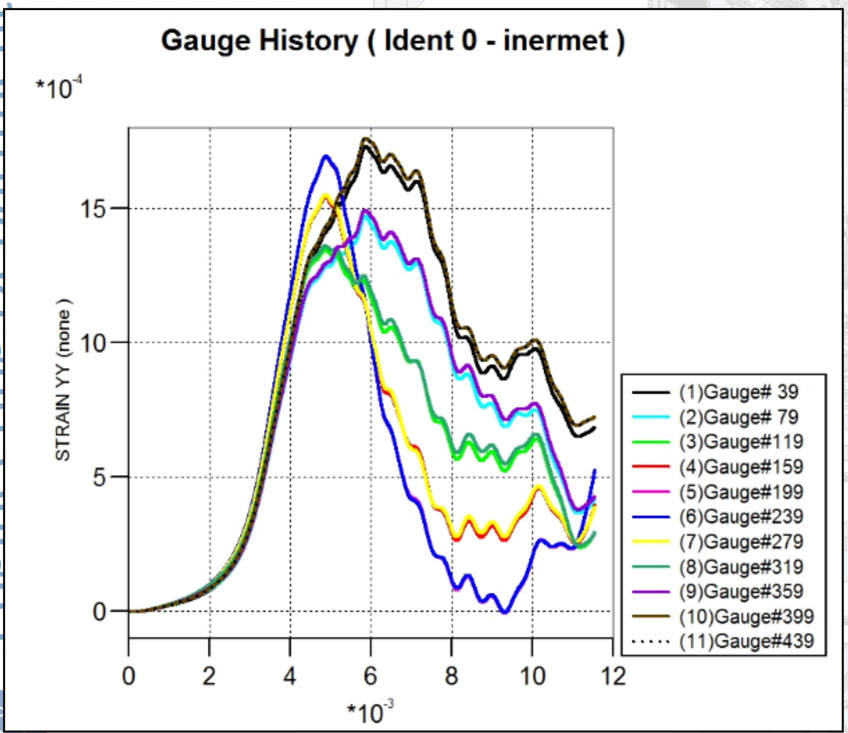


Energy Deposition

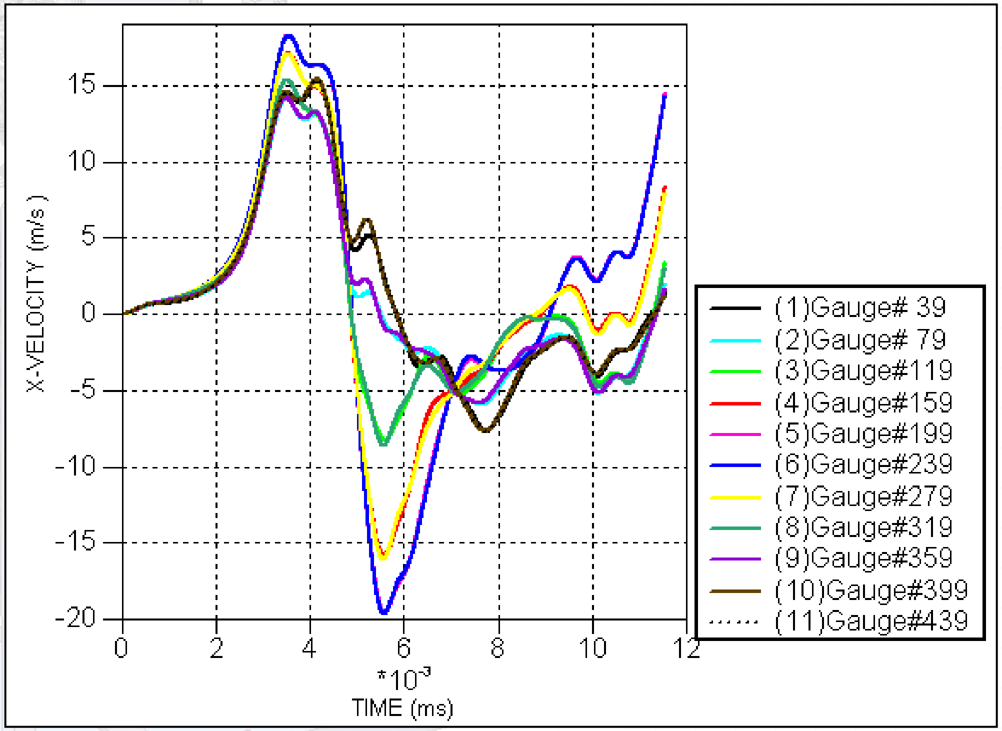


Autodyn: Type 1 Sample

- Maximum number of bunches chosen in order to keep deformations below 0.3%
- Longitudinal and circumferential strain measured by strain gauges on the external face
- Radial velocity measured by LDV on the external face



Circumferential strain in different longitudinal positions, 20 bunches

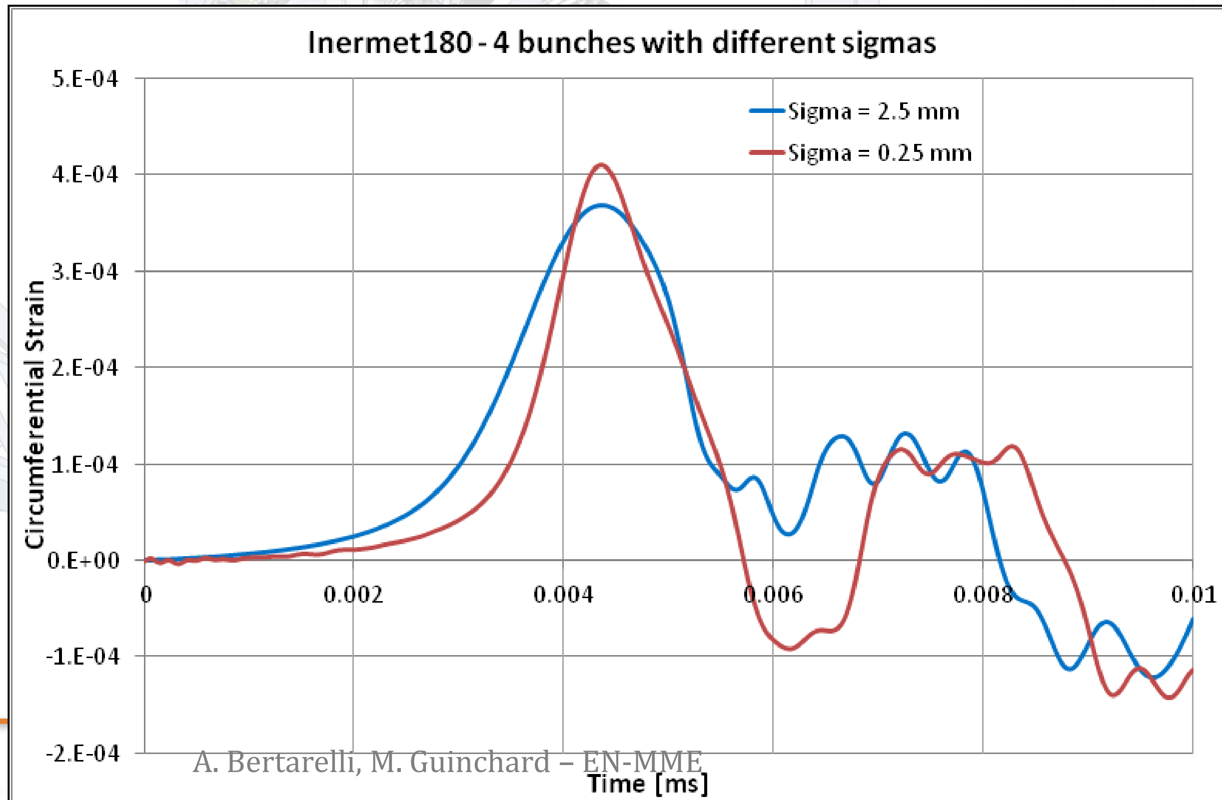


Radial velocity on the external face in different longitudinal positions, 20 bunches

Autodyn: Type 1 Sample

Sigma = 0.25 mm vs Sigma = 2.5 mm

- Similar values measurable on the external face by LDV and strain gauges
- With a larger sigma:
  - Lower damage in the inner volume during first impacts
  - Negligible change of density
  - Beryllium window less charged



Autodyn: Type 2 Sample

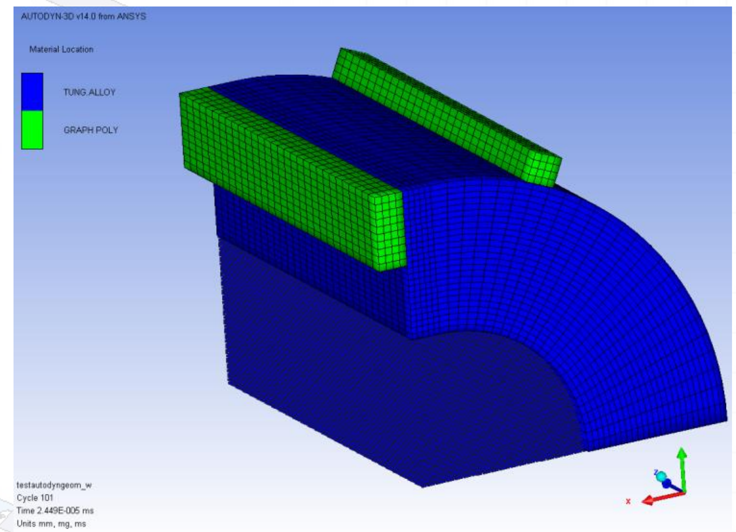
LHC Collimation Project CERN

HiRadMat High-Radiation to Materials

EN

Engineering Department

- Goal of the Experiment:
  - observe the emitted particle spray with High Speed Video Camera
  - Validate proposed Autodyn model used for TCT (Chamonix ‘11)
- Simulations
  - Explicit calculation performed on Inermet180
  - (worst case)
  - Case σ = 0.25 mm and 2.5 mm, bunch intensity
  - 1.5E11 particles/b, 10, 60 and 70 bunches
  - SPH mesh 0.2x0.2x0.2 mm (= FLUKA bins)
  - Simplified Graphite supports for preliminary
  - analysis ➔ Next step: real supports geometry

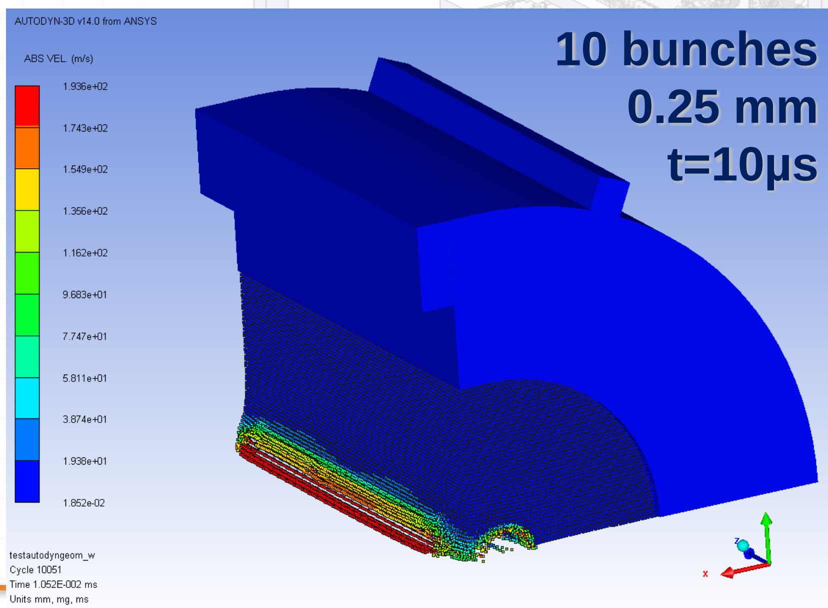


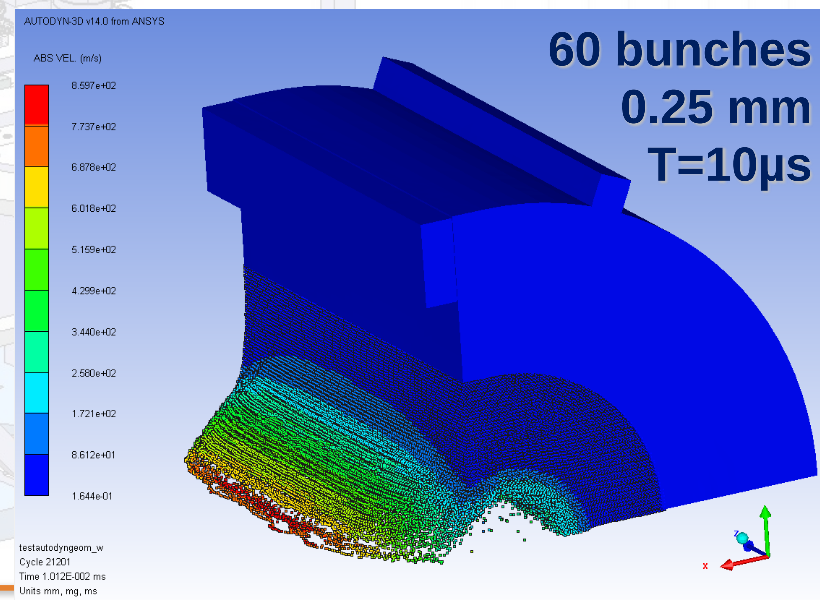
Material	EOS	Strength model	Failure model
Tungsten	Tabular (SESAME)	Johnson-Cook	Hydro (Pmin)
Al-6061	Polynomial	Johnson-Cook	Johnson-Cook
Graphite 4550	Polynomial	Johnson-Holmquist	Hydro (Pmin)
Stainless steel AISI 316	Shock	Johnson-Cook	-

Autodyn: Type 2 Specimens

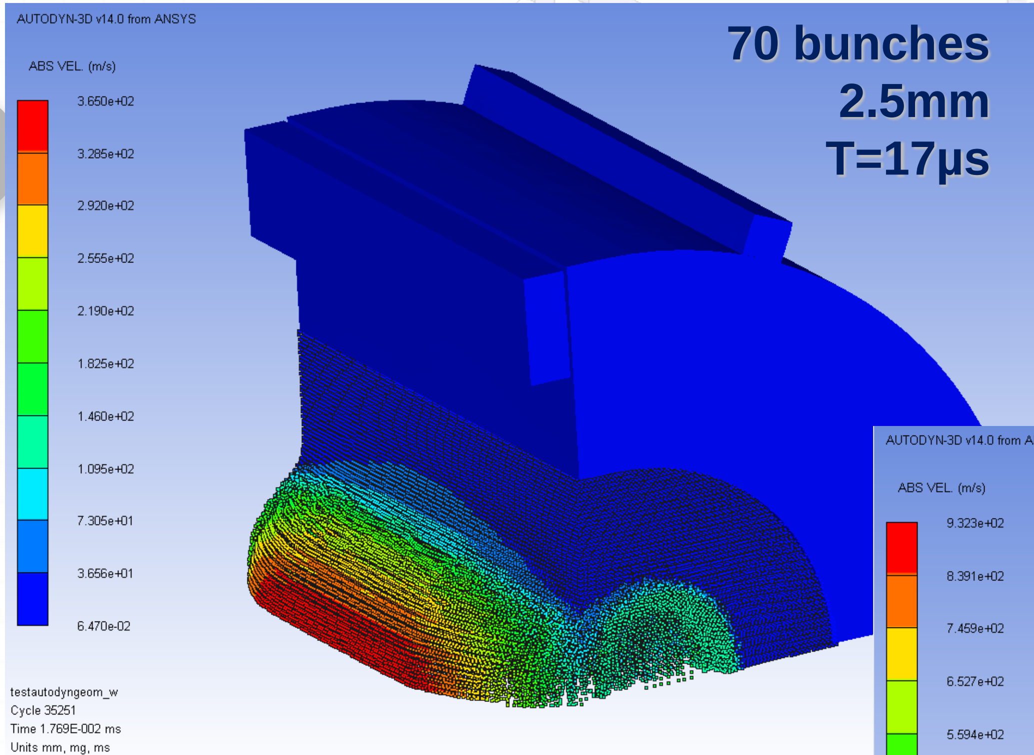
Bunch Number & Sigma	Max T	Max P	Max Internal Energy	Max Particle Speed in X-Dir after 10 µs	Hole Diameter
10 – 0.25x0.25 mm	5’881 K	22.87 GPa	1.289 MJ/Kg	~190 m/s	~2 mm
60 – 0.25x0.25 mm	25’800 K	37.81 GPa	6.741 MJ/Kg	~870 m/s	~7-8 mm
70 – 0.25x0.25 mm	29’190 K	37.81 GPa*	7.795 MJ/Kg	~950 m/s	~8-10 mm
70 – 2.5x2.5 mm	4’606 K	8.572 GPa*	1.075 MJ/Kg	~360 m/s	~10 mm

* Pressure peak is not at the end of the energy deposition,
~60 bunches for 0.25mm, ~65 b for 2.5 mm





Autodyn: Type 2 Sample

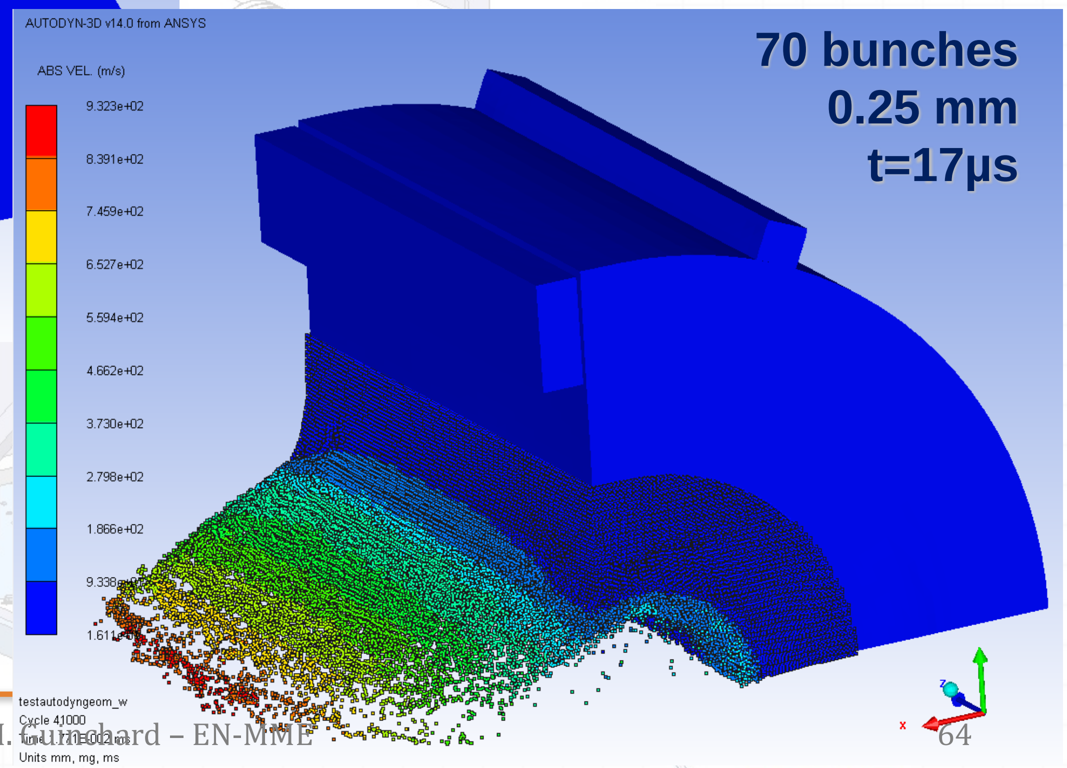


PROS sigma 2.5 mm:

- Less vaporized material (window covering)
- Lower density change
- Lower load on Be window

PROS sigma 0.25 mm:

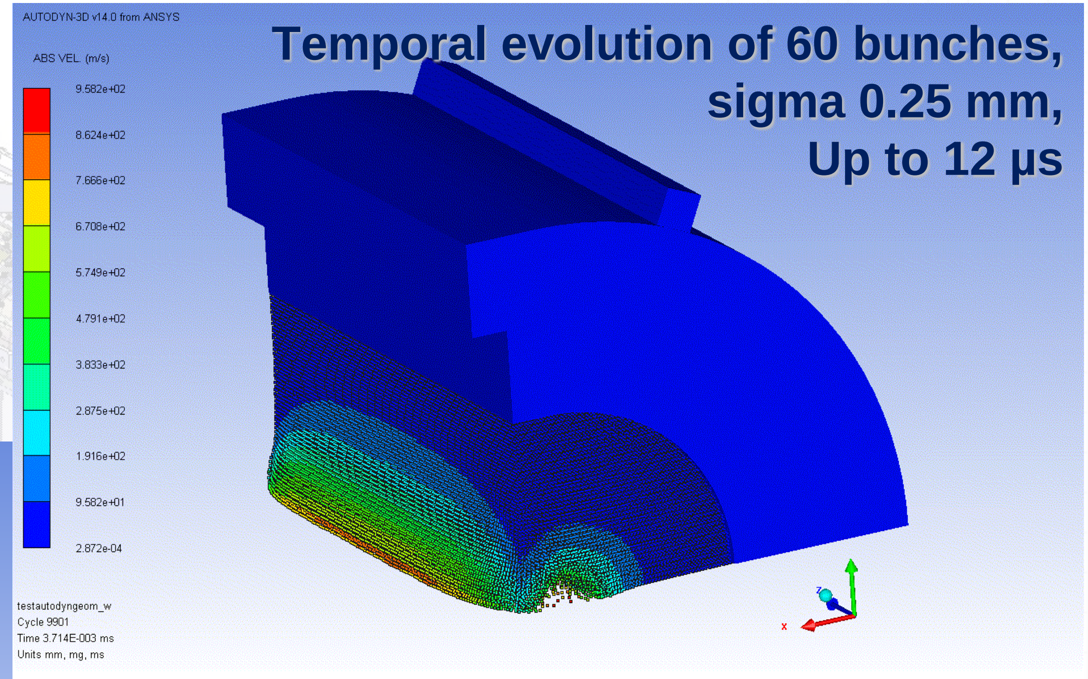
- Representative of high energetic beam impacts
- (~ LHC Scenario)
- Higher particles speeds

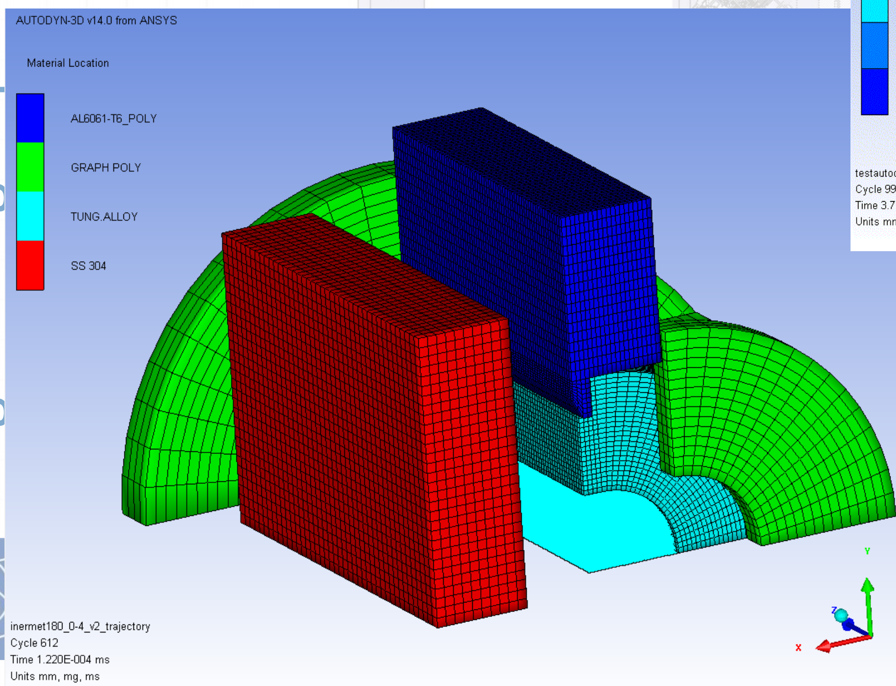


Engineering Department

Autodyn: Type 2 Sample

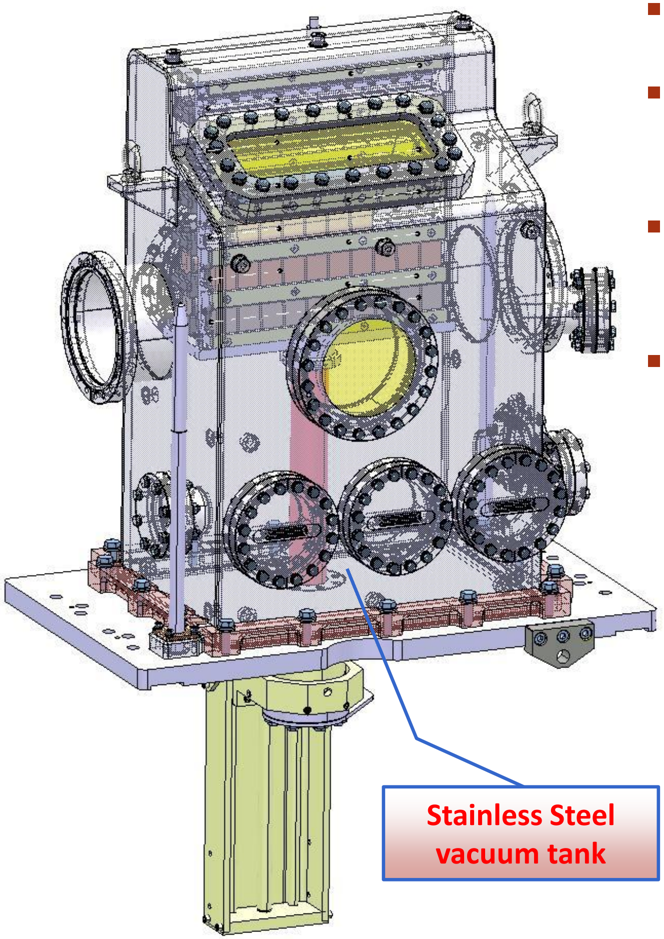
- X-Dir max speed 850 m/s
- Z-Dir max speed ~1500 m/s
- ➔ Graphite downstream and upstream protective discs to be checked!



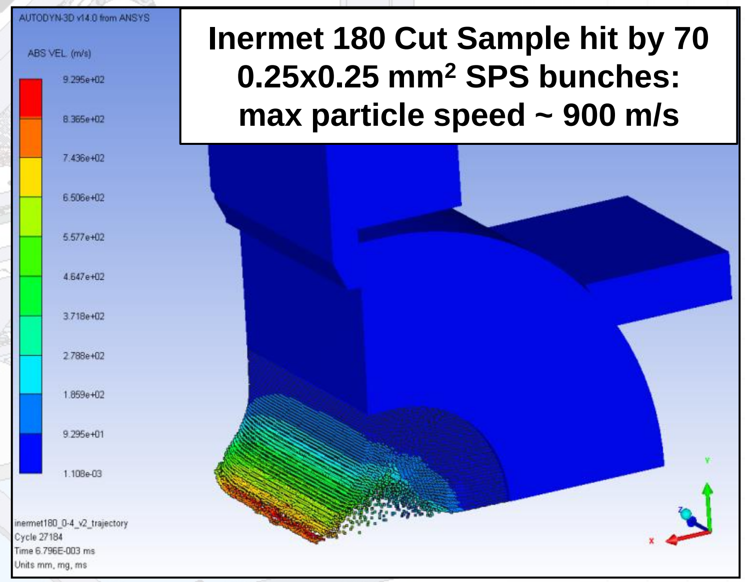


Engineering Department EN

Design Overview

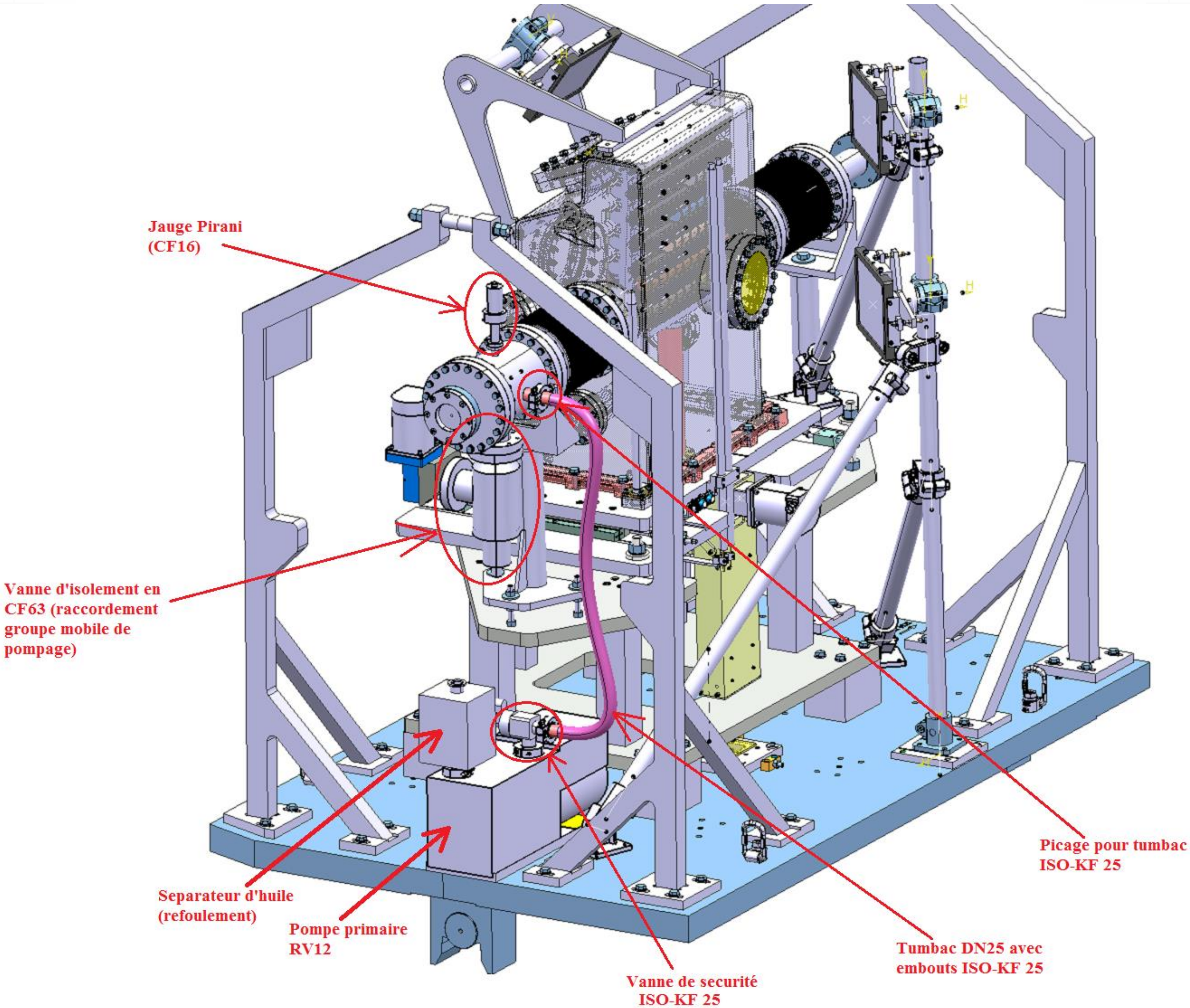


- **Vacuum tank** is made of 304L, 10 mm wall thickness
- **Vacuum:** standard mobile turbo group will allow for pressure below 1mbar
- **Static structural and buckling** analyses performed for tank, glass windows and Be windows. Safety is ok.
- **Debris** generated by beam impacts on samples don't possess enough kinetic energy to plastically deform or drill the tank



- **Fast dismounting system** studied to ease tank opening, decreasing exposure time for operators

Vacuum System



LCMAT Experiment: Specifications

- Beam energy: **440 GeV**
- Bunch spacing: **25 ns** (can be **50 ns**)
- Protons/bunch: **1.5E11**
- Beam size: **0.25x0.25 mm²** (low-density Type 2 samples), **2x2 mm²** elsewhere
- Up to **72 bunches**, mainly limited by Be window.
- Total expected number or protons ~ **1.3E14**
- Total test time: **~ 1 week**

Irradiation Summary

Type 1 Targets	Total n. of protons	Total n. of bunches	Beam size (σ_x x σ_y) [mm x mm]	Number of pulses	Time between each pulse [min]
Tungsten	5e12	35	2 x 2	7	15 ÷ 20
Molybdenum	9.3e12	63	2 x 2	7	15 ÷ 20
Glidcop	9.3e12	63	2 x 2	7	15 ÷ 20
MoCD	1.5e13	101	2 x 2	7	15 ÷ 20
CuCD	1.5e13	101	2 x 2	7	15 ÷ 20
MoC	1.5e13	101	2 x 2	7	15 ÷ 20

Type 2 Targets	Total n. of protons	Total n. of bunches	Beam size (σ_x x σ_y) [mm x mm]	Number of pulses	Time between each pulse [min]
Tungsten	9.1e12	62	2 x 2	3	15 ÷ 20
Molybdenum	1.1e13	74	2 x 2	3	15 ÷ 20
Glidcop	1.1e13	74	2 x 2	3	15 ÷ 20
MoCD	1.1e13	74	0.25 x 0.25	3	15 ÷ 20
CuCD	1.1e13	74	0.25 x 0.25	3	15 ÷ 20
MoC	1.1e13	74	0.25 x 0.25	3	15 ÷ 20

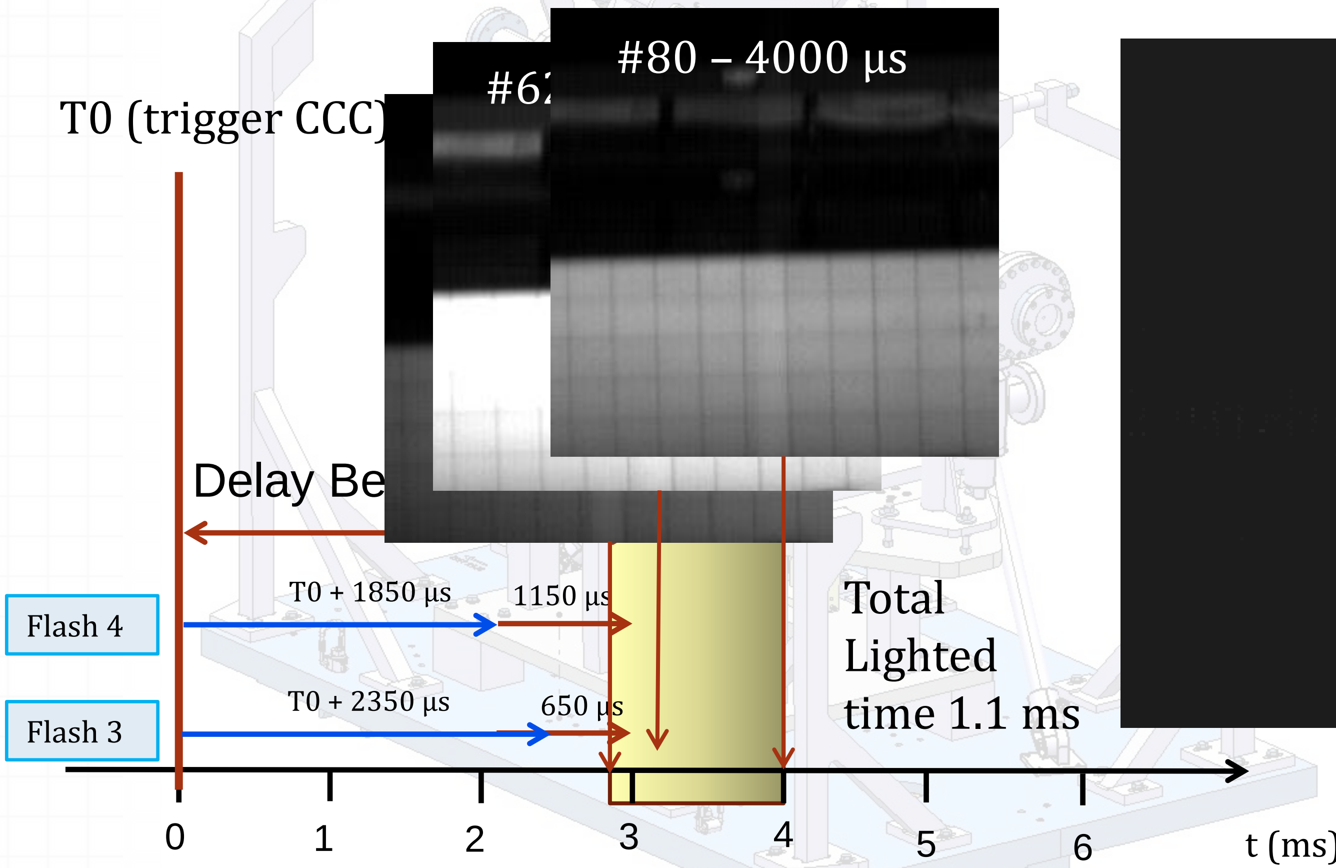
EDMS 1186793, "Specification for tests on collimator material samples in HiRadMat facility", A. Bertarelli

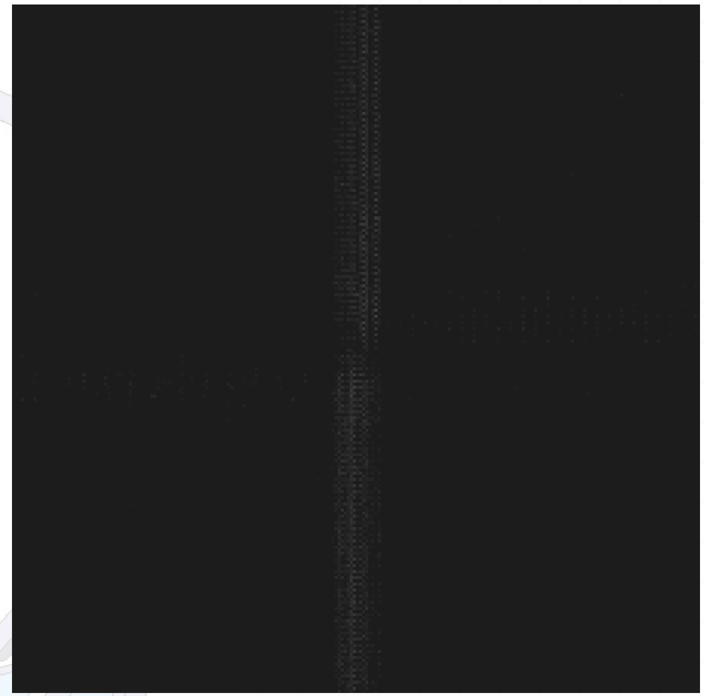
Spec and Calculation Notes

- EDMS 1186793, “Specification for tests on collimator material samples in HiRadMat facility”, A. Bertarelli;
- EDMS 1204238, “Summary of the prompt dose deposited on different components during HiRadMat experiment on material samples for collimators”, F. Carra;
- EDMS 1203115, “HiRadMat collimator material samples: structural analysis of the vacuum tank”, F. Carra;
- EDMS 1199421, “HiRadMat Fused Silica Window: Stress Calculations with Helicoflex Joint Sealing”, N. Mariani;
- EDMS 1198388, “Helicoflex joints for the HiRadMat sample holder”, F. Carra;
- EDMS 1203483, “Graphite supports for material samples test in the HiRadMat facility: structural analysis”, F. Carra;
- EDMS 1208024, “HiRadMat test on collimator material samples: calculation of cooling time for cylindrical samples”, F. Carra;
- EDMS 1223740, “Dimensioning of Copper-beryllium clamps for mirrors used during the HRMT14-LCMAT experiment in the HiRadMat facility”, F. Carra.

High Intensity on Glidcop/1

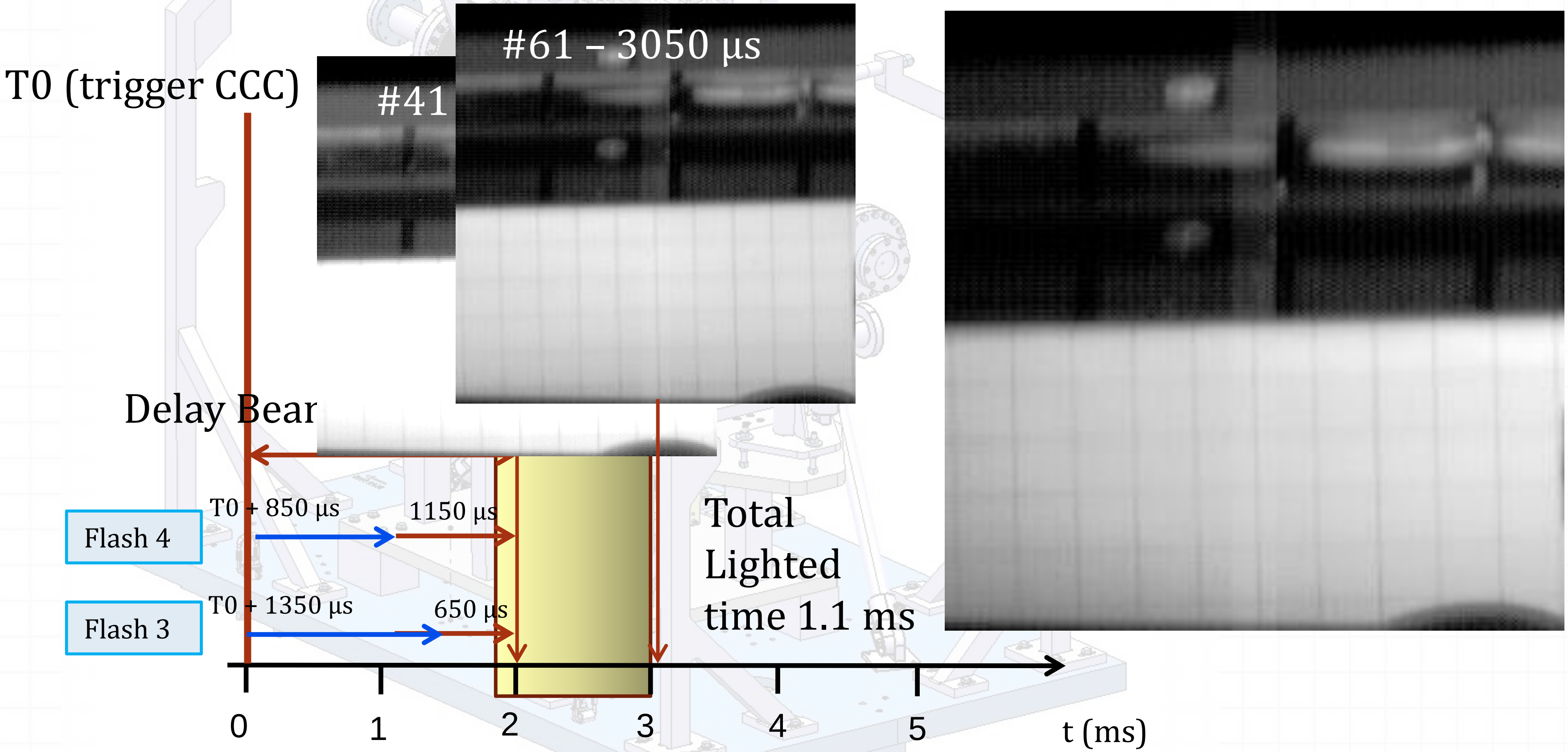
- Delay Beam – T0 = 22 µs (errors in measurements and in CCC pre-trigger settings).
- Configuration: Simultaneous shot of Flash 3 + 4 at t=3 ms.
- ➔ Images acquired between 2.9 and 4 ms after the beam impact!!!!
- Need for higher pre-trigger from CCC!!!





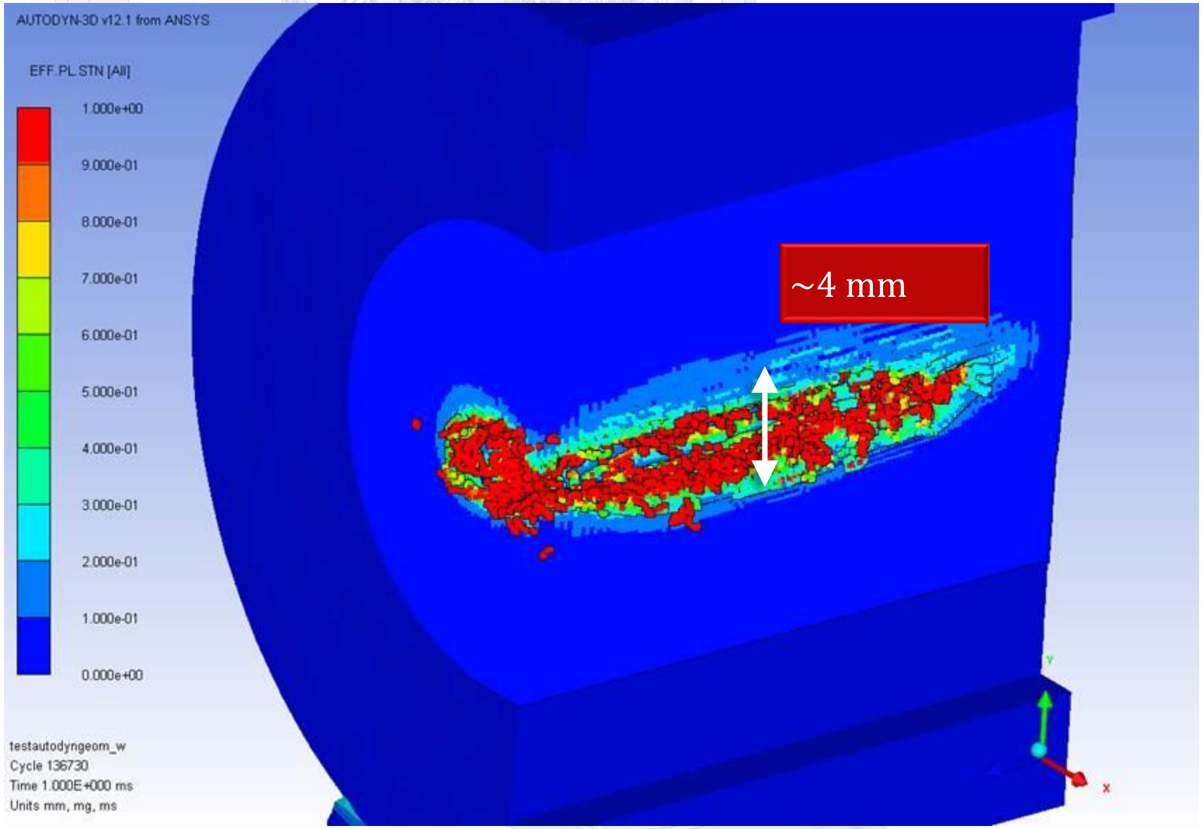
High Intensity on Glidcop/2

- Delay Beam – T0 = 2022 μs (after asking for 4 ms pre-trigger…)
- Configuration: Simultaneous shot of Flash 3 + 4 at t=2 ms.
- ➔ Images acquired between -0.1 ms and 1 ms after the beam impact!!!!
- Successful synchronization between Beam, Video-camera and Flashes!!!

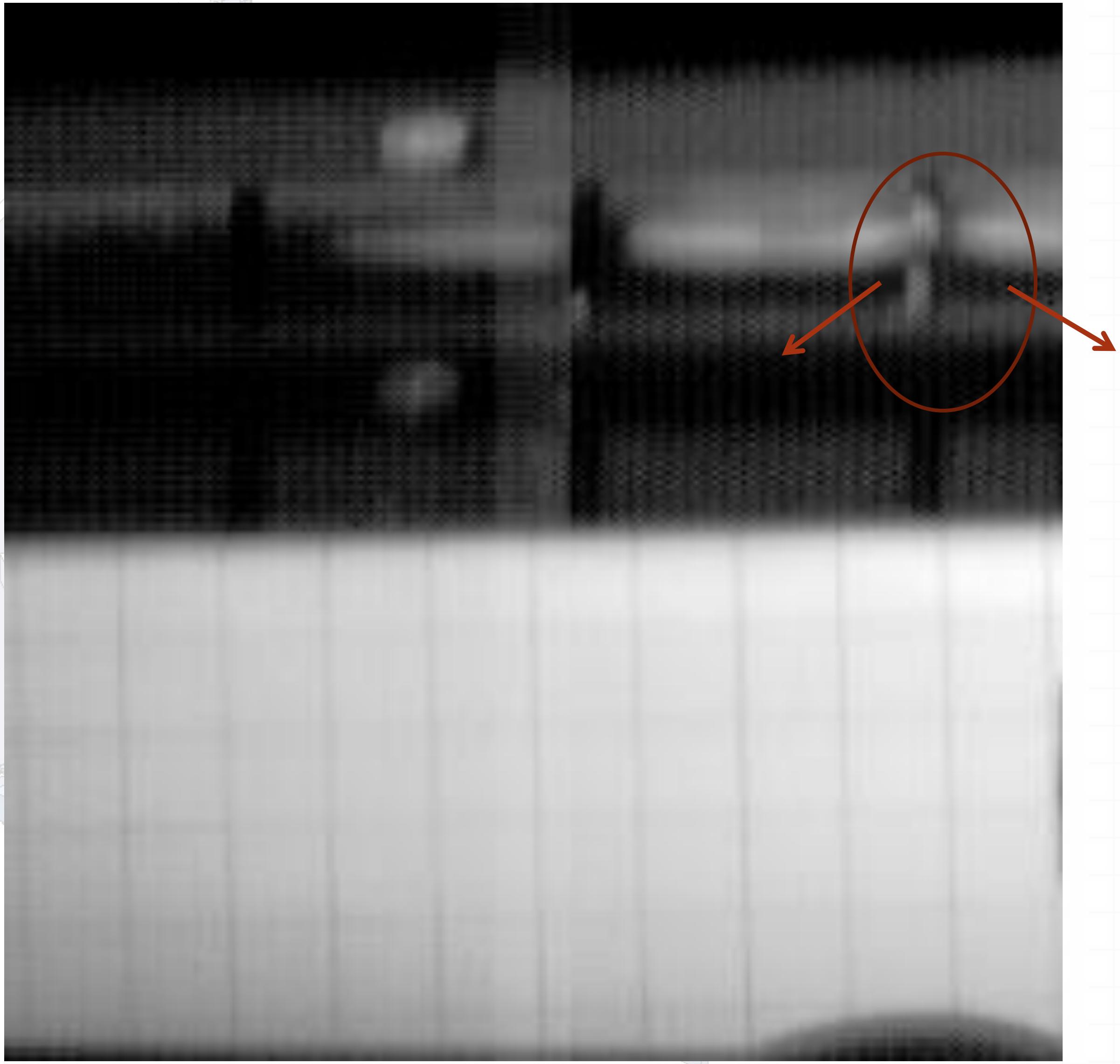


Post-irradiation Analysis

- **Two shots** at 72 b on **Glidcop** Type 2 specimens (2mm from free surface)
- Visual observations after impact seem compatible with simulations (although used failure model used in simulation may be pessimistic and overestimate damage).



Fast video results



Conclusive remarks

Greetings and many thanks from….

… to many colleagues and friends from **EN-MME, EN-MEF, EN-STI, EN-ICE, EN-HE, BE-ABP, BE-OP, TE-MPE, TE-VSC, DG-RP, PH, Politecnico di Torino** …