LHC Collimation Project CERN

EuCARD

HiRadMat High-Radiation to Materials

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Engineering Department

Interaction of High Energy Particle Beams with Solids: *Numerical Simulations and Experiments on LHC Collimators*

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Workshop on

Advanced Mechanics in Accelerator Technology (AMAT)

CERN/Polish Academy of Sciences/Cracow University of Technology

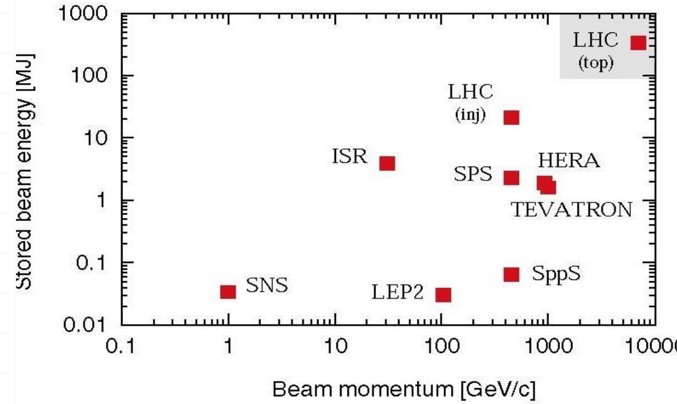
Geneva, 19th April 2014

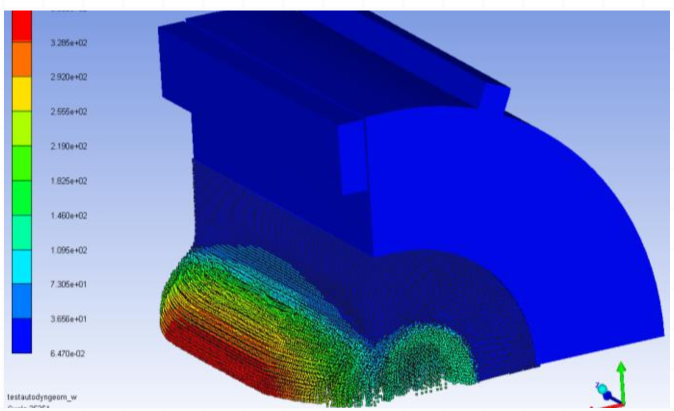
Outlook

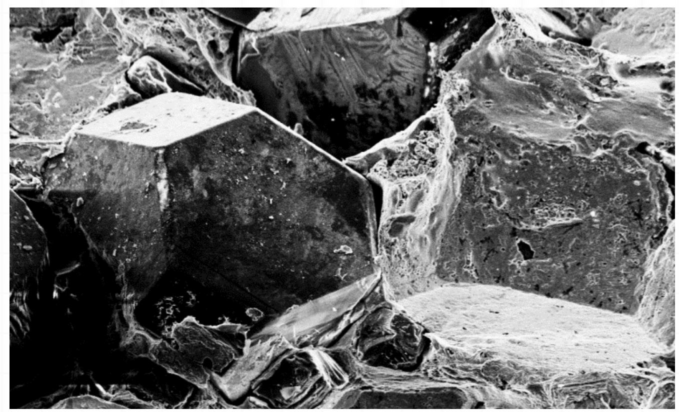
- **Introduction**
- Numerical Simulations
- Experiments at HiRadMat Facility
- Conclusions

Context

- **Beam-induced accidents** represent one of the most dangerous and though less explored events for Accelerators.
- **Beam Intercepting Devices** (**BID**) are inherently exposed to such events
- **LHC beam energy** is **2 orders** of magnitude above previous machines. Stored **energy density** is **3 orders** of magnitude higher.
- **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.







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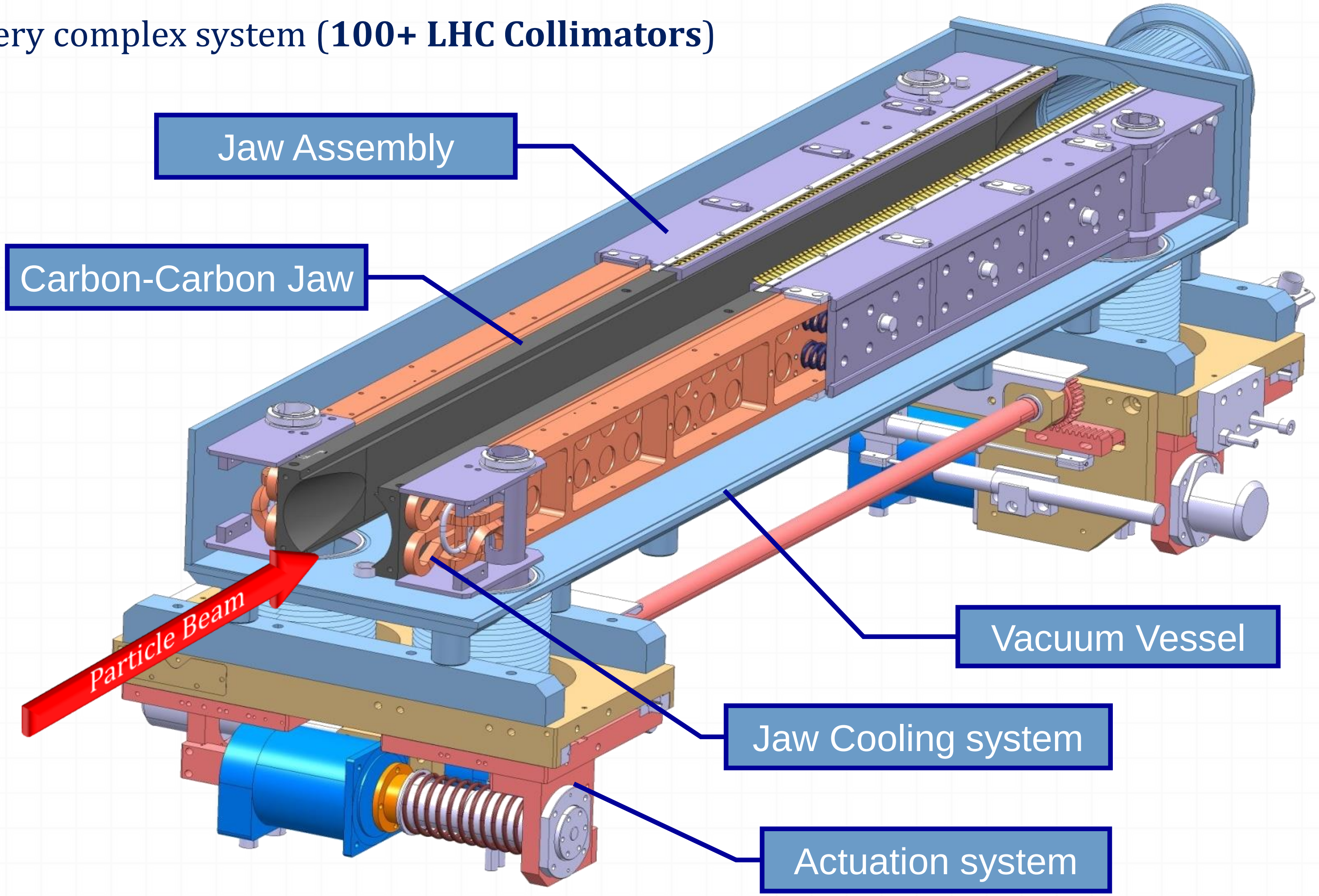
BID example: LHC Collimators

- **Several types of collimators** at multiple locations required.
- Very complex system (**100+ LHC Collimators**)

Secondary Collimator (TCSG) Cutaway



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Novel Materials for Collimators

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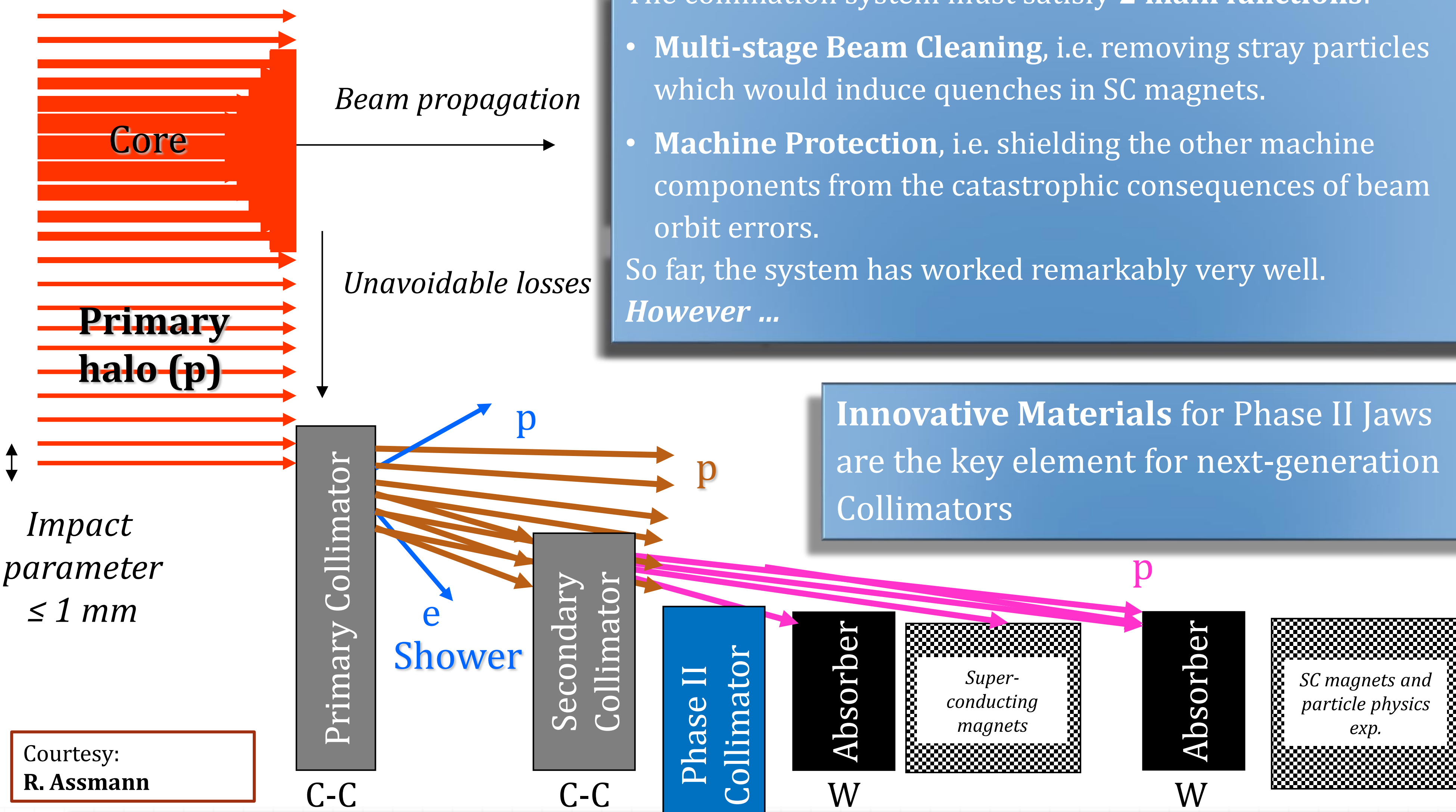
The collimation system must satisfy **2 main functions**:

- **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 …

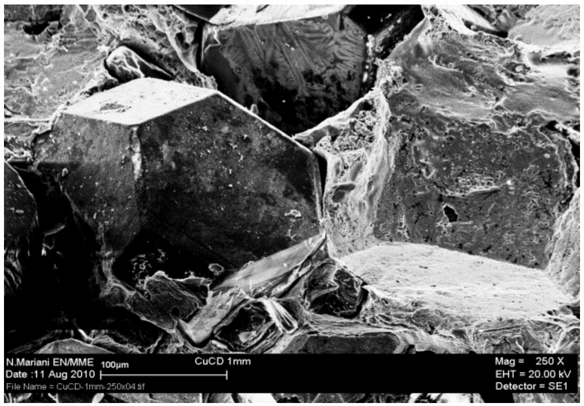


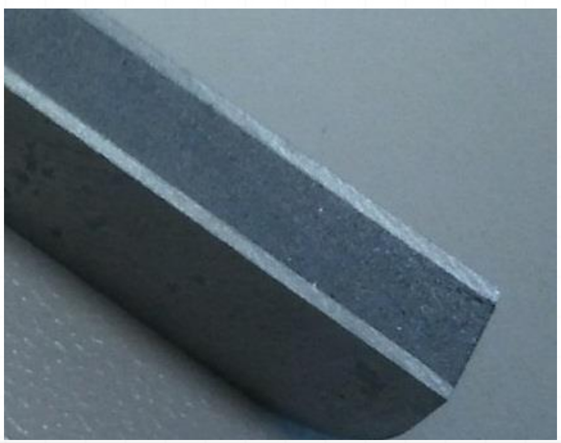
Innovative Materials for Phase II Jaws are the key element for next-generation Collimators

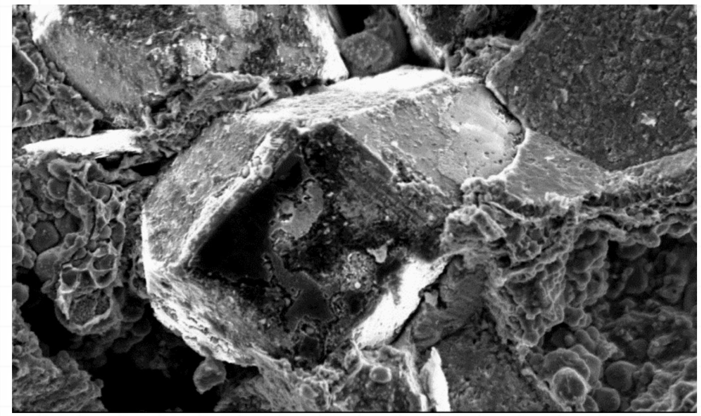
Courtesy:
R. Assmann

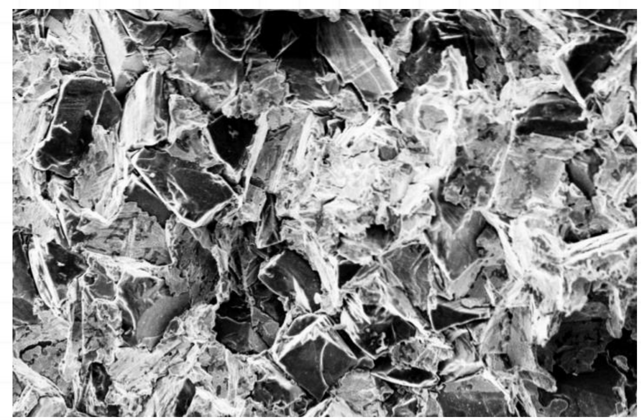
Novel Materials for Collimators

- **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)**









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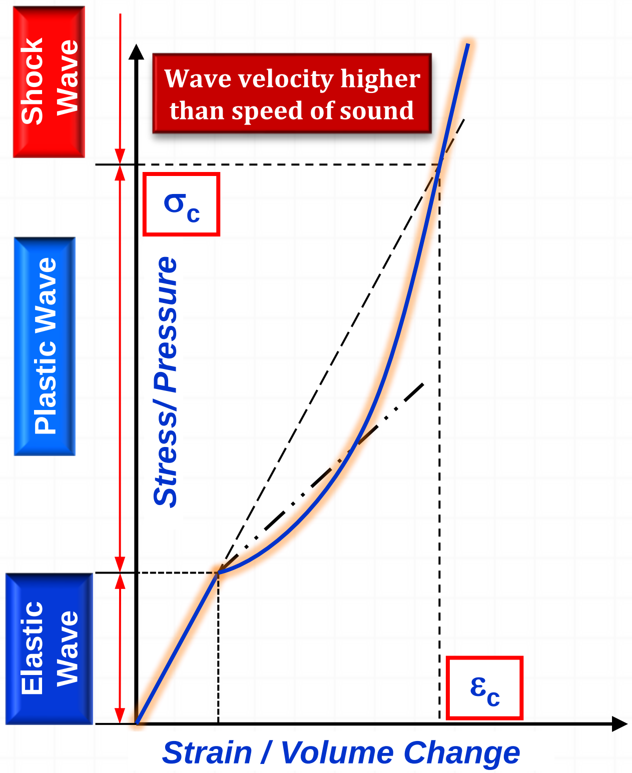
Beam Induced Dynamics

- Rapid interactions of particle beams with solids induce **Dynamic Responses** in matter.
- **Three** main Dynamic Response **Regimes** exist, depending on several parameters **(**deposited **energy** and **energy density, interaction duration, material strength** and **thermal properties):**

- **Regime 1: Stress Waves and Vibrations in the Elastic Domain**
  - Low deposited energy density.
  - Negligible changes in density.
  - Stress wave at elastic Speed of Sound (C_0).
  - Treated with standard FEM codes (e.g. Ansys).

- **Regime 2: Stress Waves and Vibrations in the Plastic Domain**
  - Medium deposited energy density.
  - Permanent deformations.
  - Stress wave slower than C_0.
  - Can still be treated with standard FEM codes.

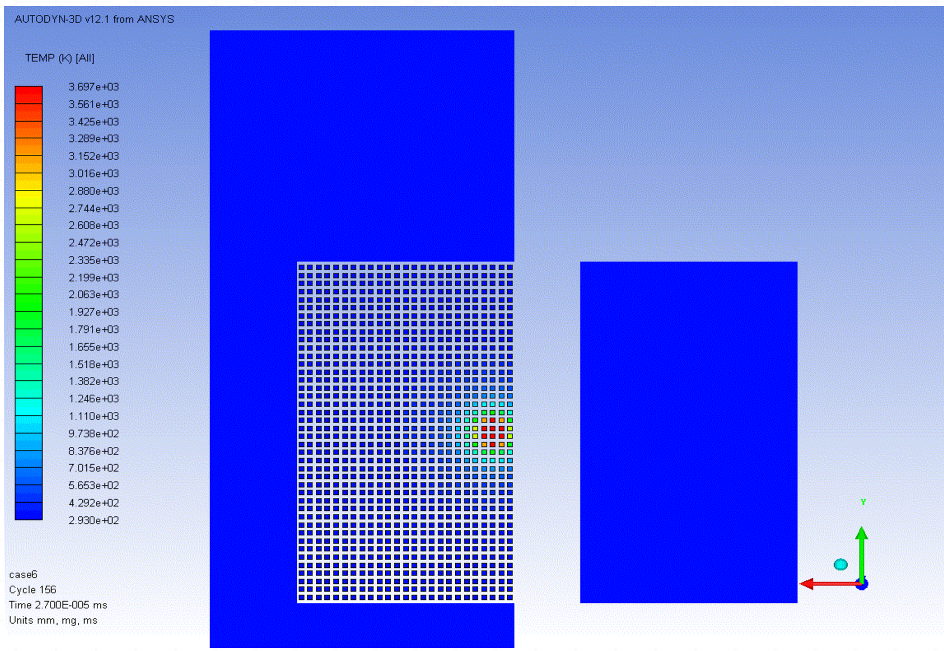
- **Regime 3: Shockwaves**
  - High deposited energy density.
  - Strains and pressure exceed a critical value.
  - Wave faster than elastic sound speed. Change of density.
  - Require **special numerical tools (Hydrocodes)**.

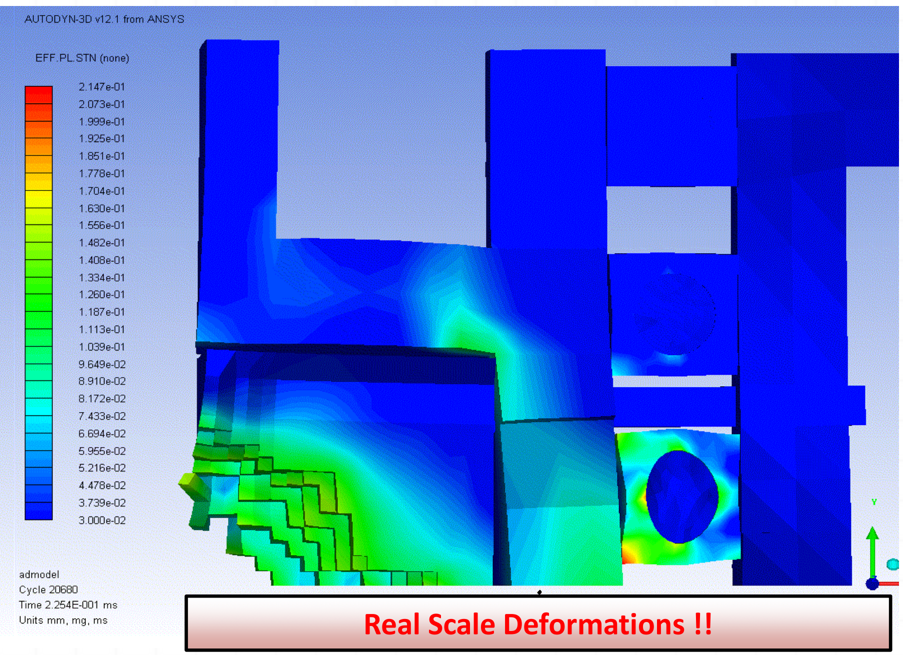


Accident Simulation on Collimator

8 LHC bunches at 5 TeV impacting a Collimator 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**, $\mathbf{V_{max} \approx 1\ km/s}$) 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.





Flies in the Ointment

- Hydrodynamic codes are powerful tools, however one should be cautious since enters a relatively unknown territory, that of high power explosions and ballistics.
- Existing material **Constitutive Models** at extreme conditions are hardly available as mostly drawn from military research and classified.
- Constitutive Models for specific mixtures and alloys are often totally unavailable.
- Simulations are unavoidably affected by (unknown) uncertainties and approximations.
- Consequences on UHV, electronics, bellows cannot be readily simulated.
- **Only dedicated material tests can provide the correct inputs for numerical analyses and validate/benchmark simulation results**.
- Based on this, **two complementary experiments** at **HiRadMat** facility were approved:
  - Destructive Test of a **complete tertiary collimator** for a thorough, integral assessment of beam accident consequences (**HRMT09**).
  - Controlled test on a **multi-material test bench** hosting a variety of specimens conveniently instrumented for online and offline measurements (**HRMT14**).

Outlook

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- Introduction
- Numerical Simulations
- **Experiments at HiRadMat Facility**
- Conclusions

What is HiRadMat?

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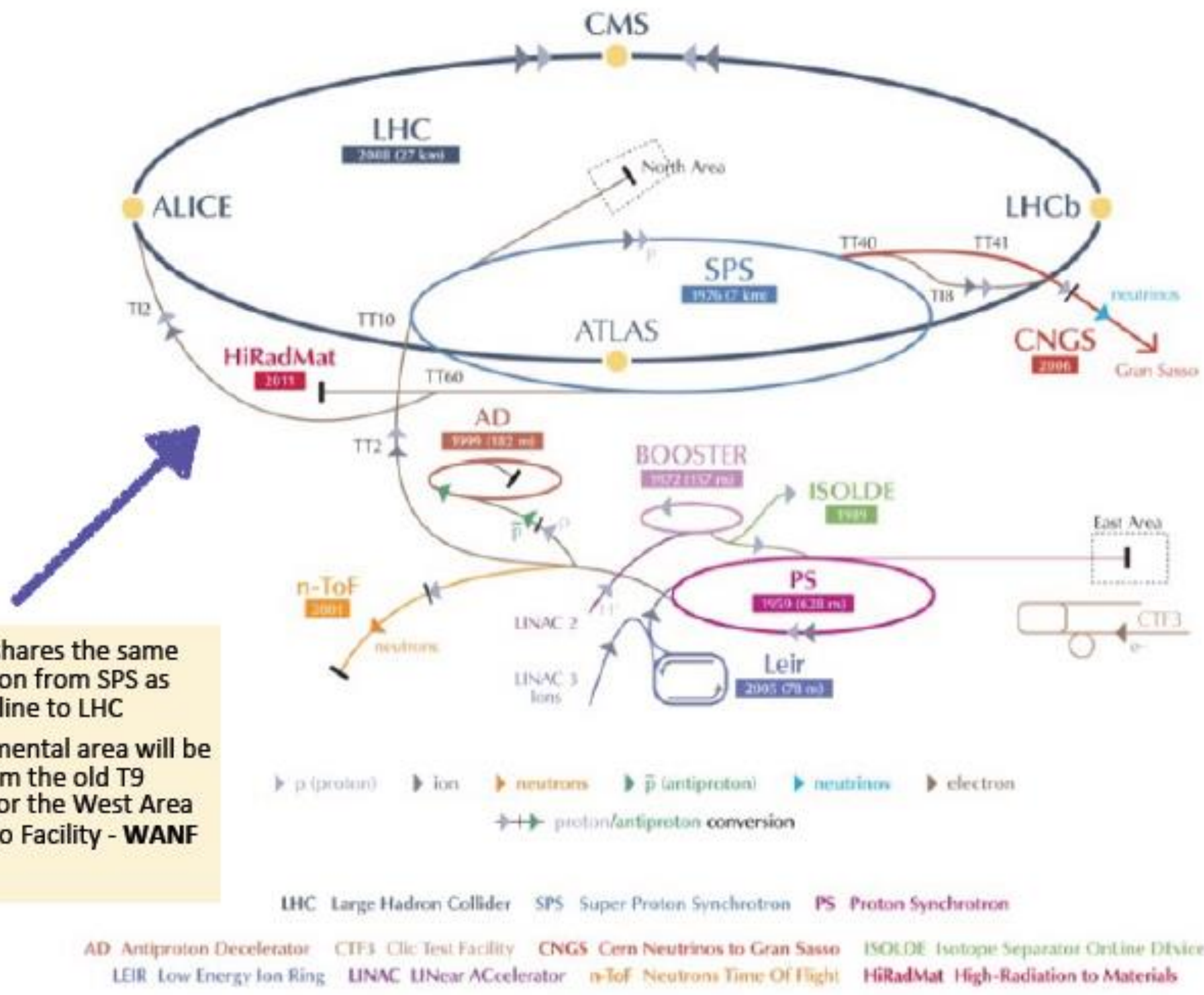


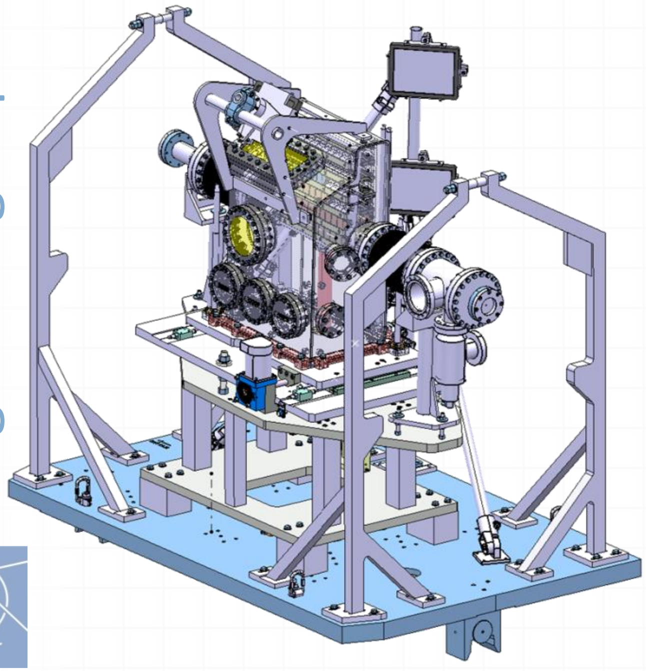
HiRadMat shares the same extraction from SPS as the **TI2** line to LHC

The experimental area will be upstream the old T9 target for the West Area Neutrino Facility - **WANF**

Courtesy:
I. Efthymiopoulos

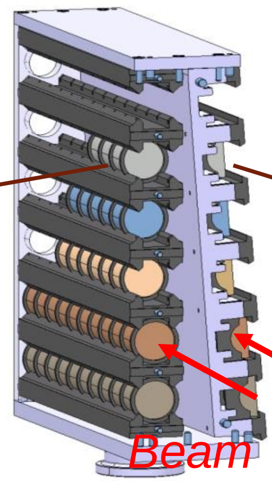
HRMT14 Experiment Setup

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



Medium Intensity (Type 1 samples):

- Strain measurements on sample outer surface;
- Radial velocity measurements (LDV);
- Temperature measurements;
- Sound measurements.



High Intensity (Type 2 samples):

- Strain measurements on sample outer surface;
- Fast speed camera to capture fragment front formation and propagation;
- Temperature measurements;
- Sound measurements.

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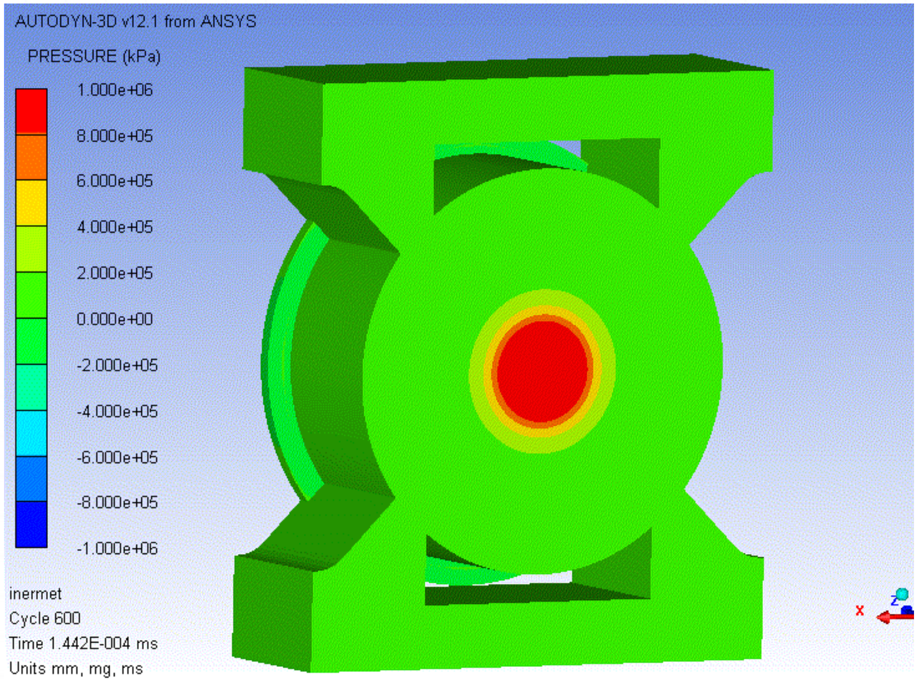
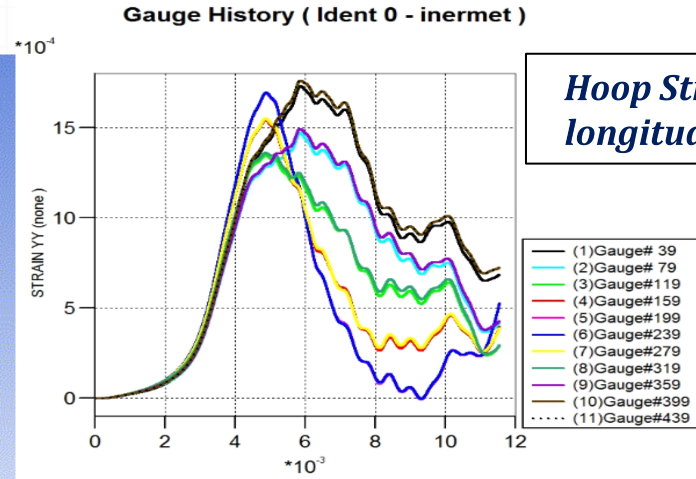
Simulations of Shock-waves

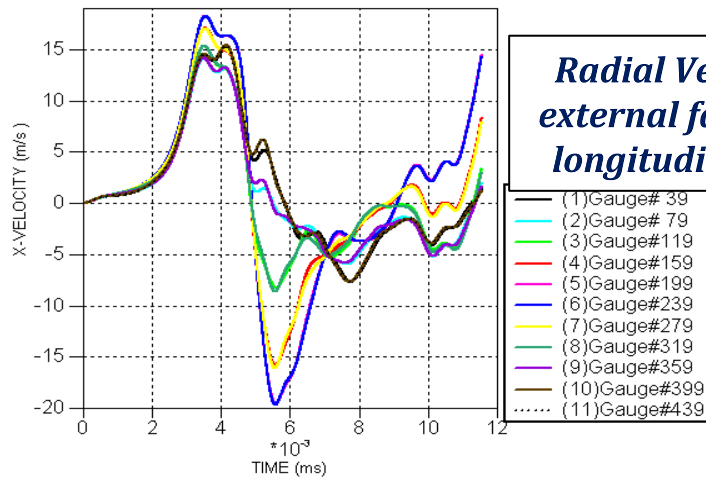
- Extensive simulations (**Autodyn** Hydrocode), based on FLUKA input (EN-STI), allowed to define pulse parameters (number of bunches, bunch spacing and sigma).
- Focus on **Hoop** and **Longitudinal Strains** and **Radial velocity** measured on sample outer surface



Pressure wave propagation pattern



Hoop Strain at various longitudinal positions



Radial Velocity on the external face at various longitudinal positions

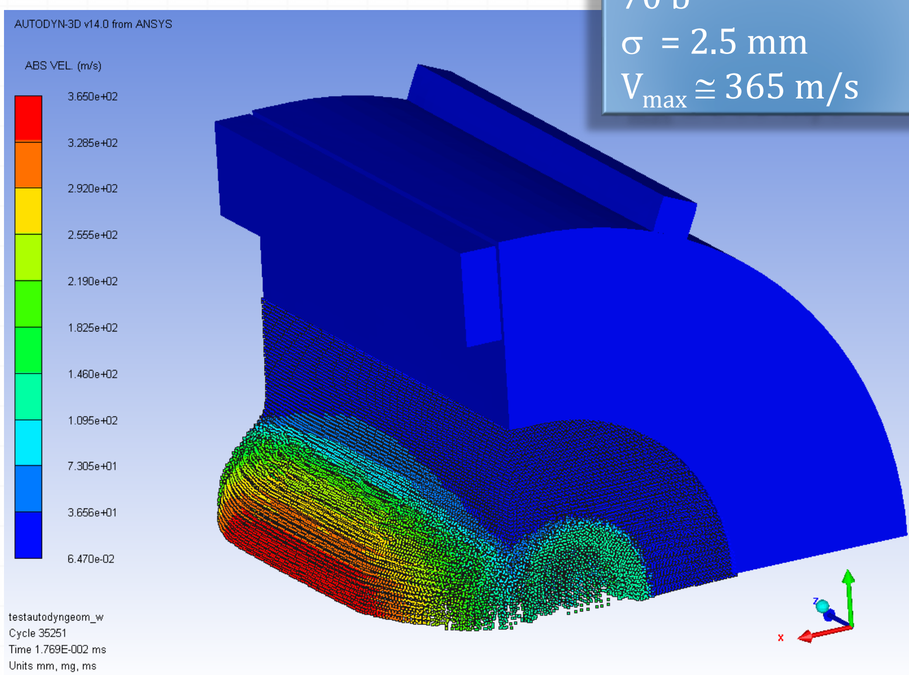
Example: Simulations on Inermet 180
(σ = 2.5 mm, 20 b, intensity 1.5e11 particles)

Simulations of Target Explosion

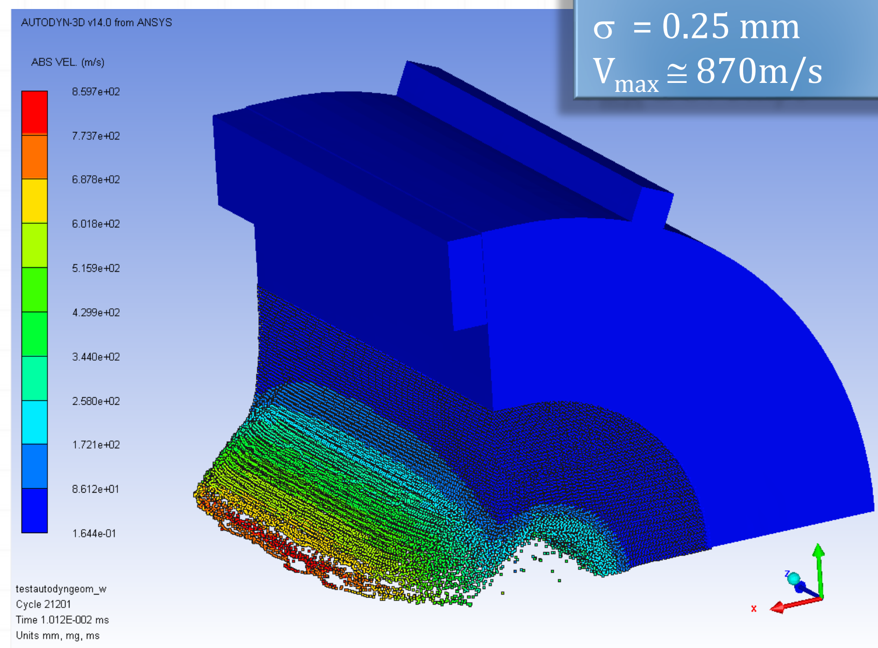
Additional *Smooth-Particle-Hydrodynamics* (**SPH**) calculations allowed determining damage extension, particle fragment velocity and trajectories to optimize pulse parameters and assess:

- **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
σ = 2.5 mm
$V_{max} \cong 365$ m/s

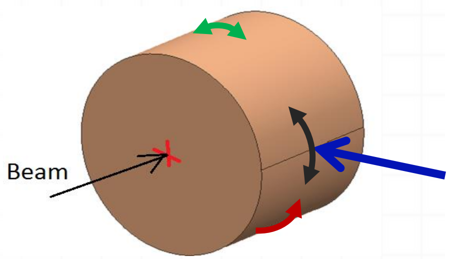


Inermet180
60 b
σ = 0.25 mm
$V_{max} \cong 870$m/s



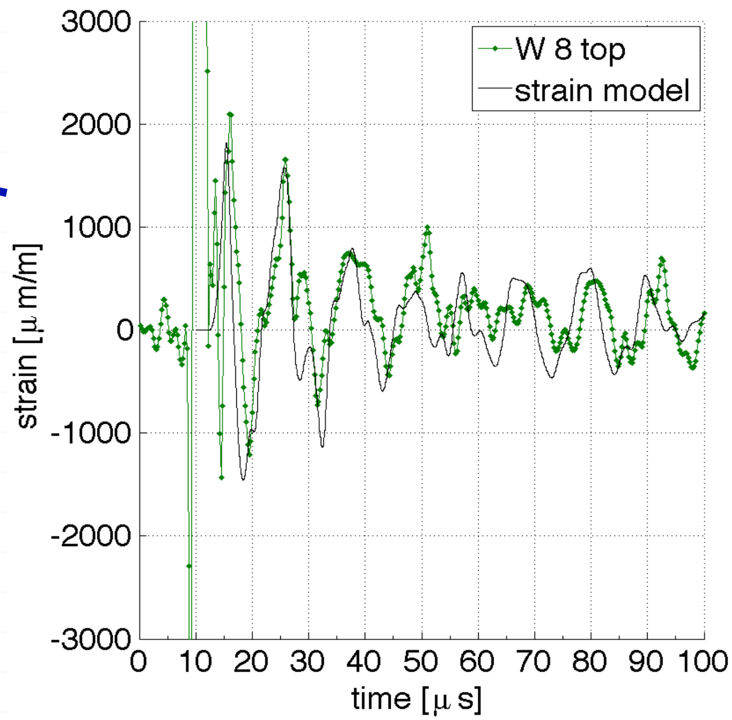
HRMT14: Medium Intensity Tests

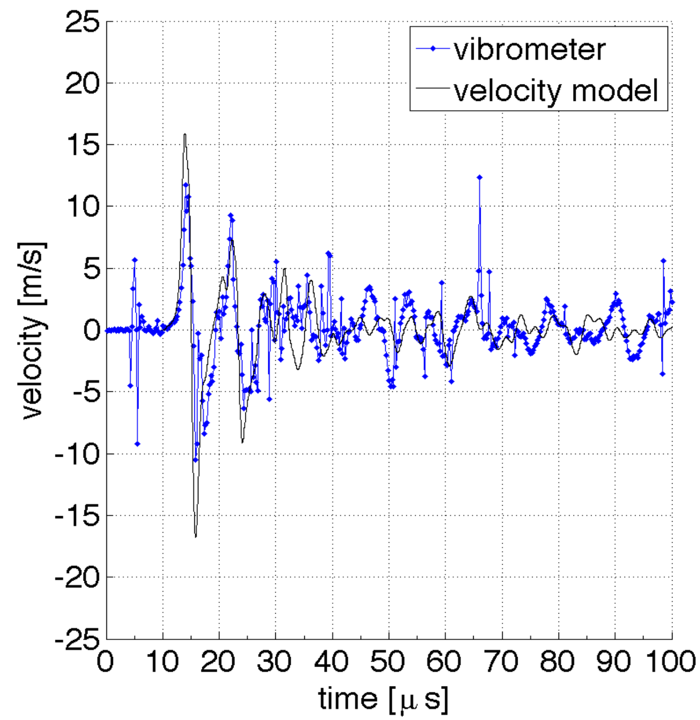
- Extensive numerical analysis (**Autodyn**), based on FLUKA calculations to determine **stress waves**, **strains and displacements**.
- Comparison of simulated **Hoop and Longitudinal Strains and Radial velocity** with measured values on sample outer surface.



Inermet180
24 b (scraped)

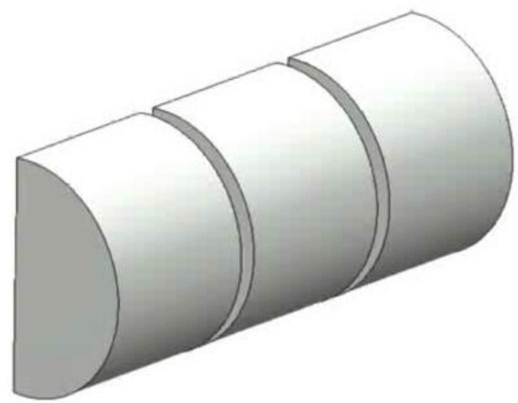
Total intensity:
2.7e12 p
σ ≅ 1.4 mm





HRTM14: High Intensity Tests

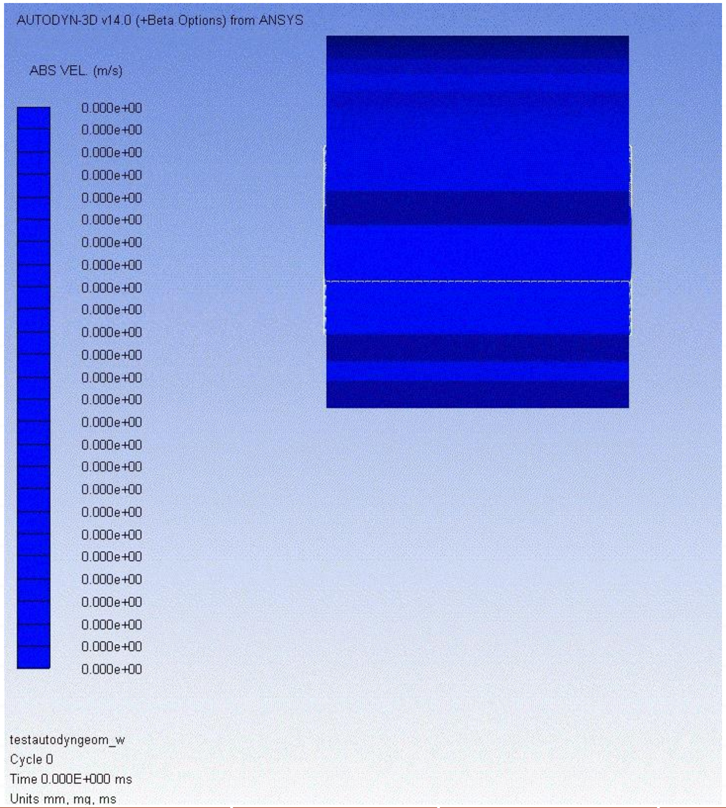
Inermet samples as seen from viewport and camera

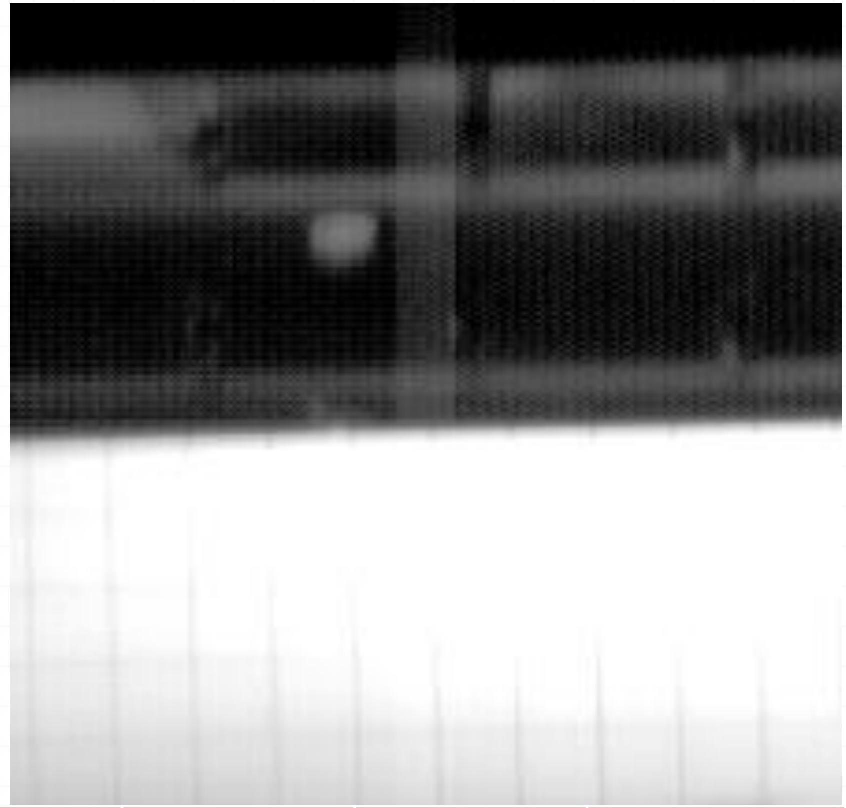


HRMT14: High Intensity Tests

Inermet180 : comparison Autodyn (SPH) between simulation and experiment

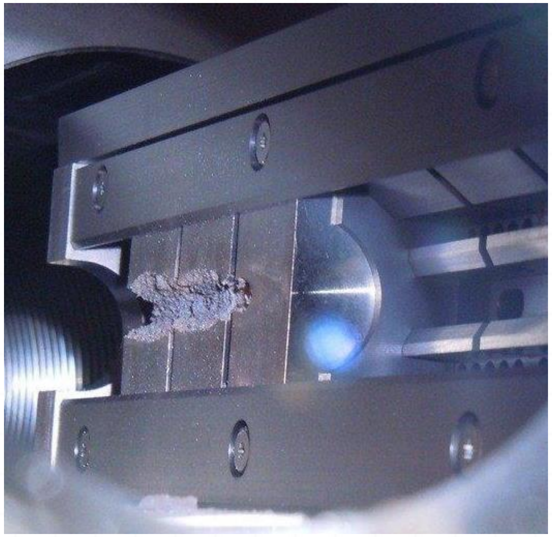
Beam



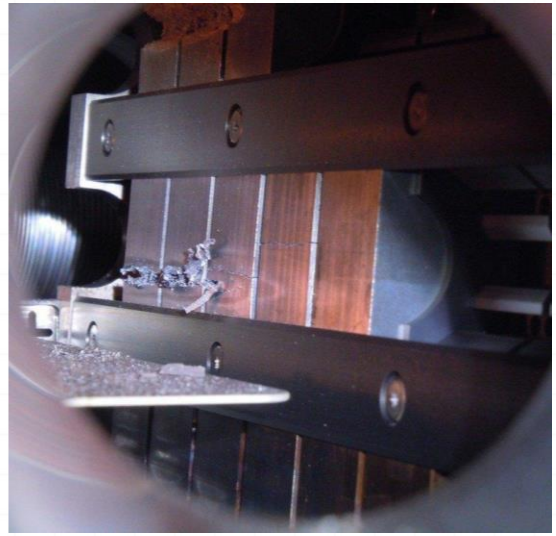


Case	Bunches	p/bunch	Total Intensity	Beam Sigma	Specimen Slot	Velocity
Simulation	60	1.5e11	9.0e12 p	2.5 mm	9	**316 m/s**
Experiment	72	1.26e11	9.0e12 p	1.9 mm	8 (partly 9)	**~275 m/s**

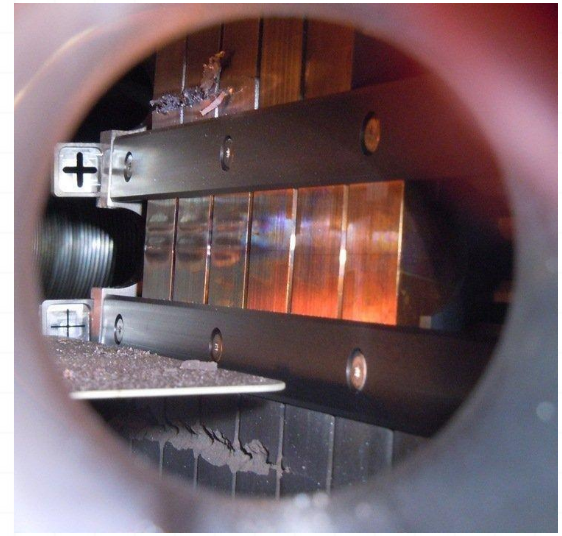
HRMT14: High Intensity Tests



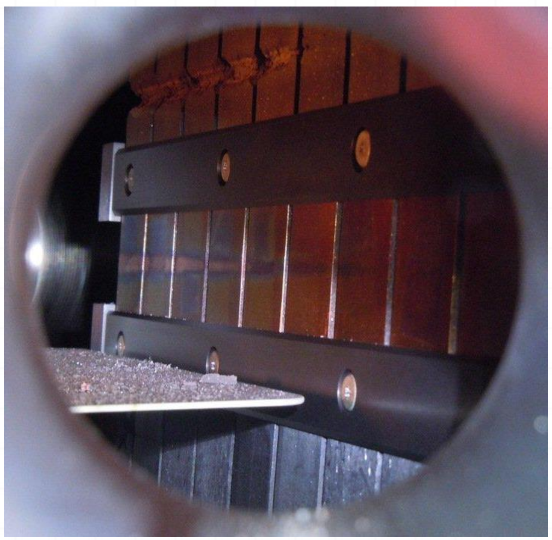
Inermet 180, 72 bunches



Molybdenum, 72 & 144 bunches



Glidcop, 72 bunches (2 x)



Copper-Diamond 144 bunches

Molybdenum-Copper-Diamond 144 bunches

Molybdenum-Graphite (3 grades) 144 bunches

HRMT09 Experiment Parameters

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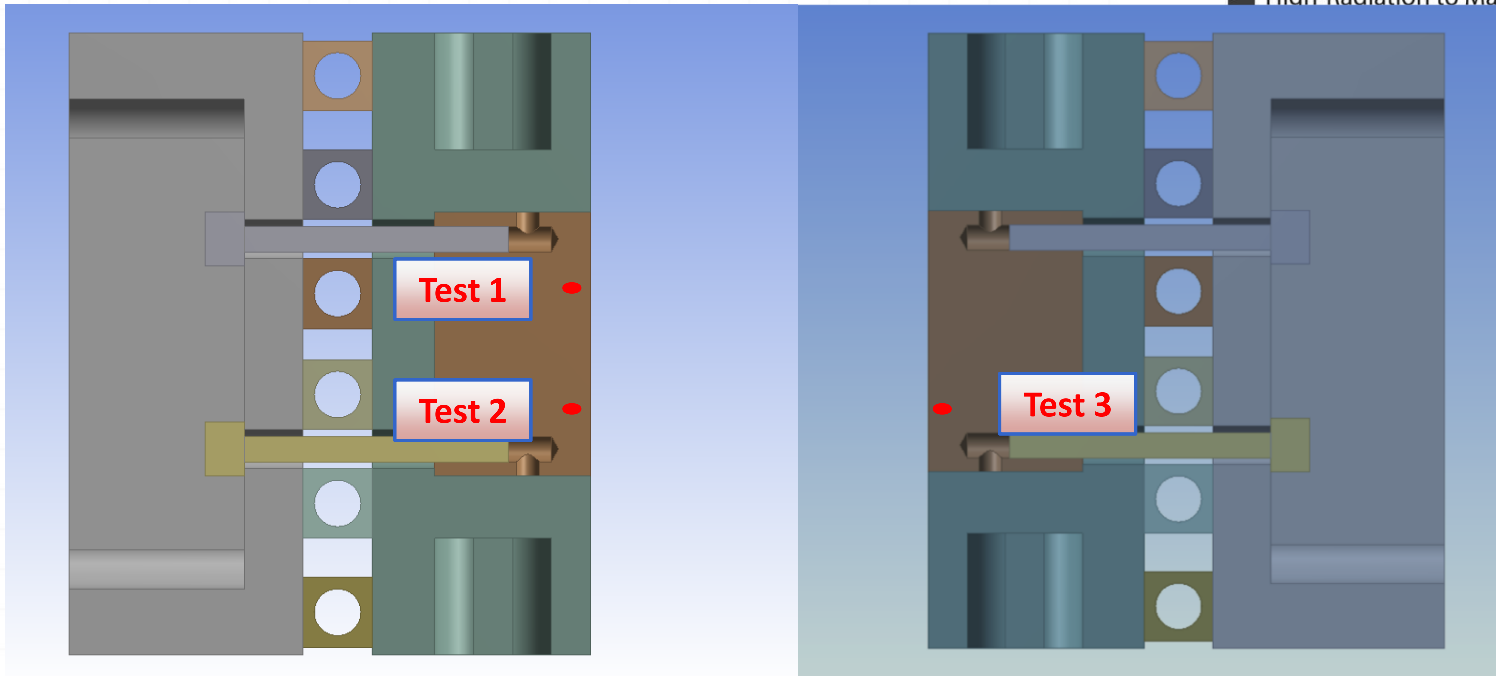
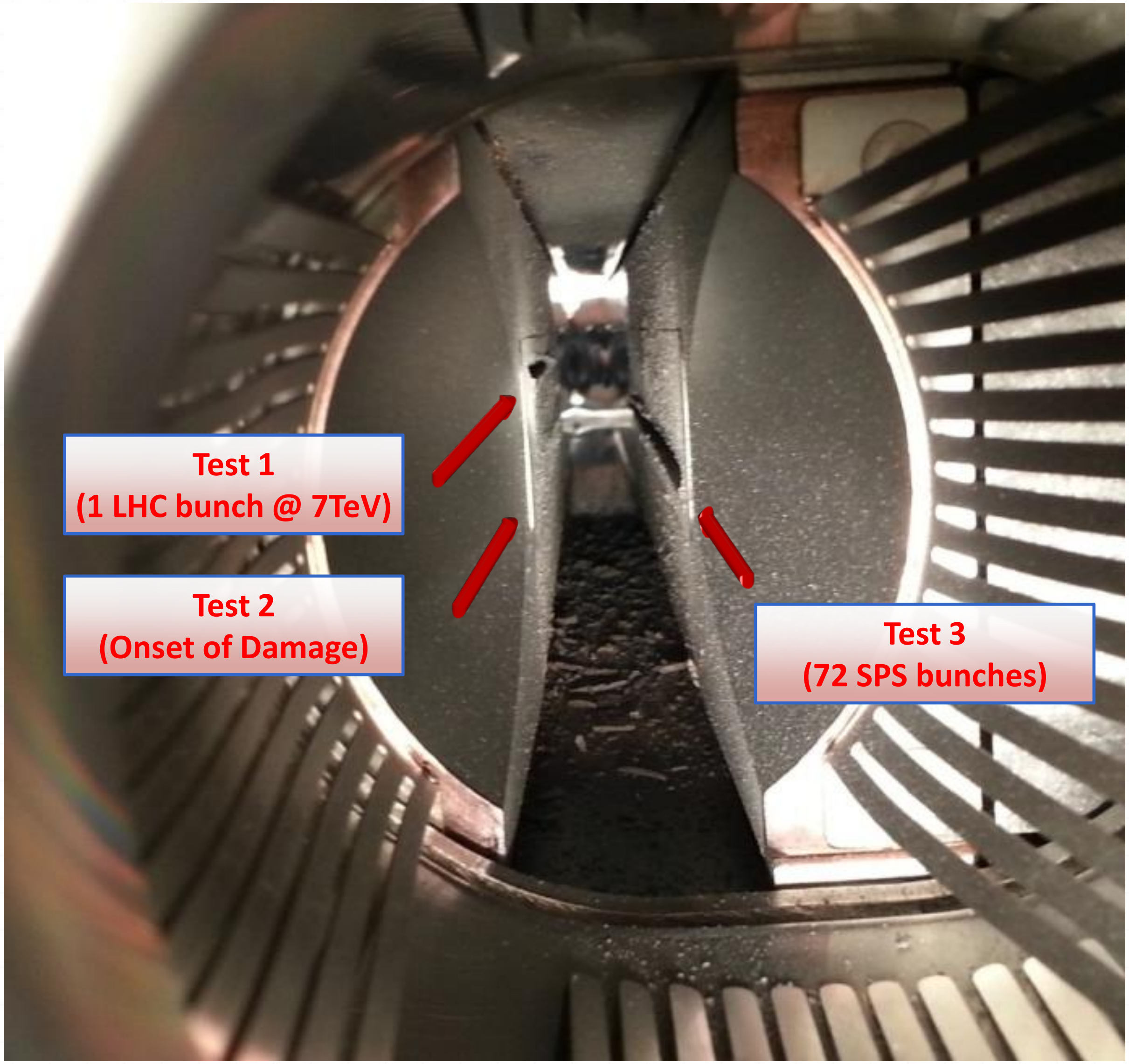
- Beam energy: **440 GeV**
- Impact depth: **2mm**
- Jaws half-gap: **14 mm**



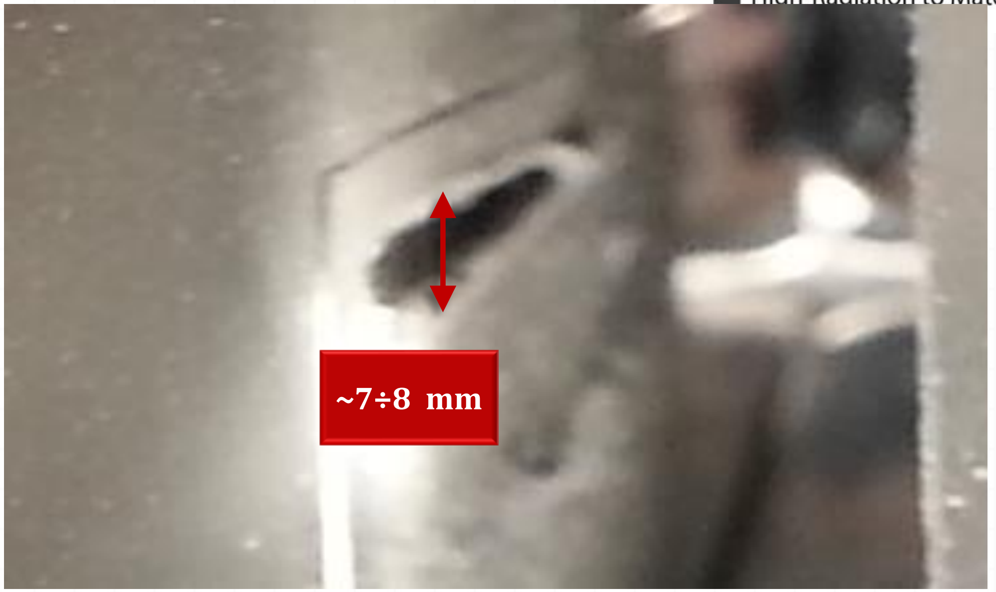
	Test 1	Test 2	Test 3
Goal	**Beam impact equivalent to 1 LHC bunch @ 7TeV**	**Identify onset of plastic damage**	**Induce severe damage on the collimator jaw**
Impact location	Left jaw, up (+10 mm)	Left jaw, down (-8.3 mm)	Right jaw, down (-8.3 mm)
Pulse intensity [p]	3.36×10^{12}	1.04×10^{12}	9.34×10^{12}
Number of bunches	24	6	72
Bunch spacing [ns]	50	50	50
Beam size [σ_x - σ_y mm]	0.53 x 0.36	0.53 x 0.36	0.53 x 0.36

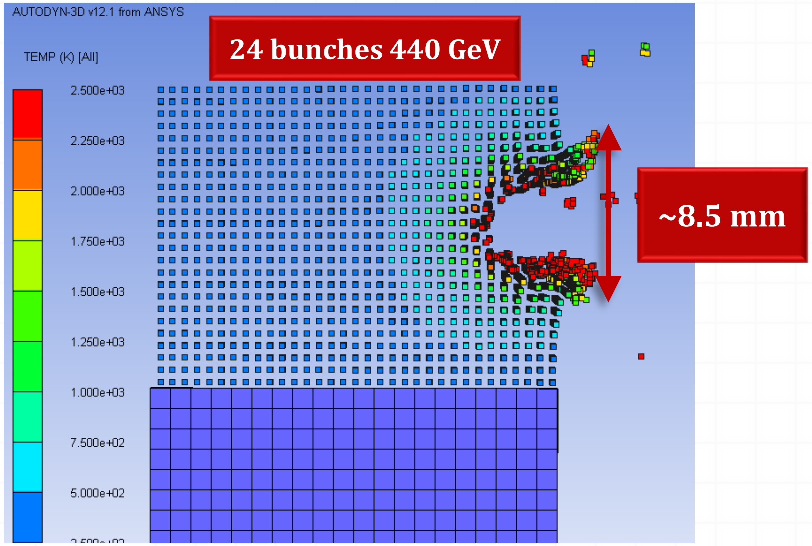
HRMT09: Observation after tests

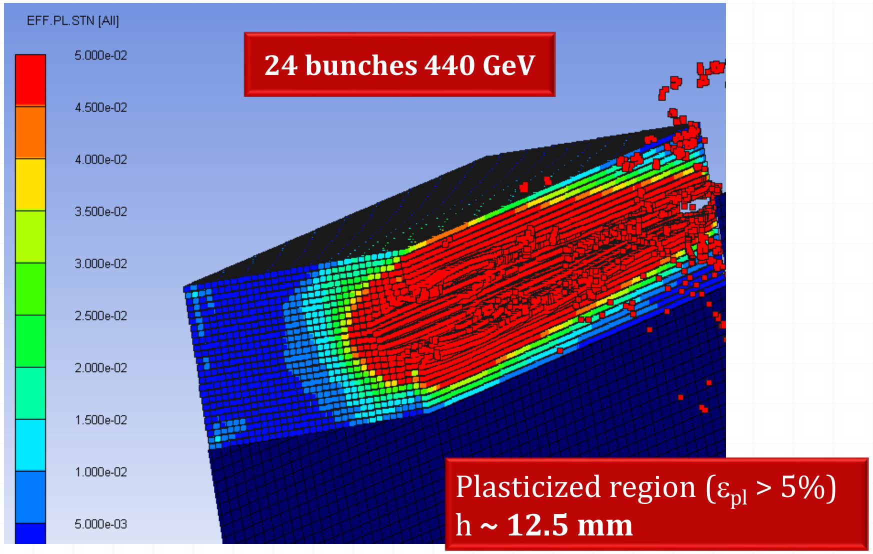


HRMT09: Analysis of Test 1

- **Goal**: beam impact equivalent to **1 LHC bunch @ 7TeV**; intensity **1.5 x 10^{11}p**
- **Qualitative damage evaluation** (to be further analysed …)
- Groove height ~ **7 mm, in good agreement with simulations …**







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Conclusions

- Beam-induced phenomena in matter can be reasonably well treated with Standard FEM Codes up to the onset of Shock Waves.
- **State-of-the art complex numerical methods,** based on advanced wave propagation codes (**Hydrocodes**), must be used to study beam-induced extreme phenomena including **Phase Transitions, Spallation, Explosions**
- Constitutive models required by Hydrocodes (**EOS, Strength Model, Failure Model**) are hardly available, potentially limiting the validity of numerical simulations.
- New and difficult numerical approach required dedicated experimental validation in **HiRadMat** (**HRMT09** and **HRMT 14**). **Both were wholly successful.**
- In particular, all HRMT14 active systems (DAQ, electronics, mechanics) worked properly in spite of the very harsh environment and the technological challenges, allowing to collect a wealth of data.
- The experiments confirmed the **effectiveness of numerical methods and material models to reliably predict beam-induced damages**…

Acknowledgements

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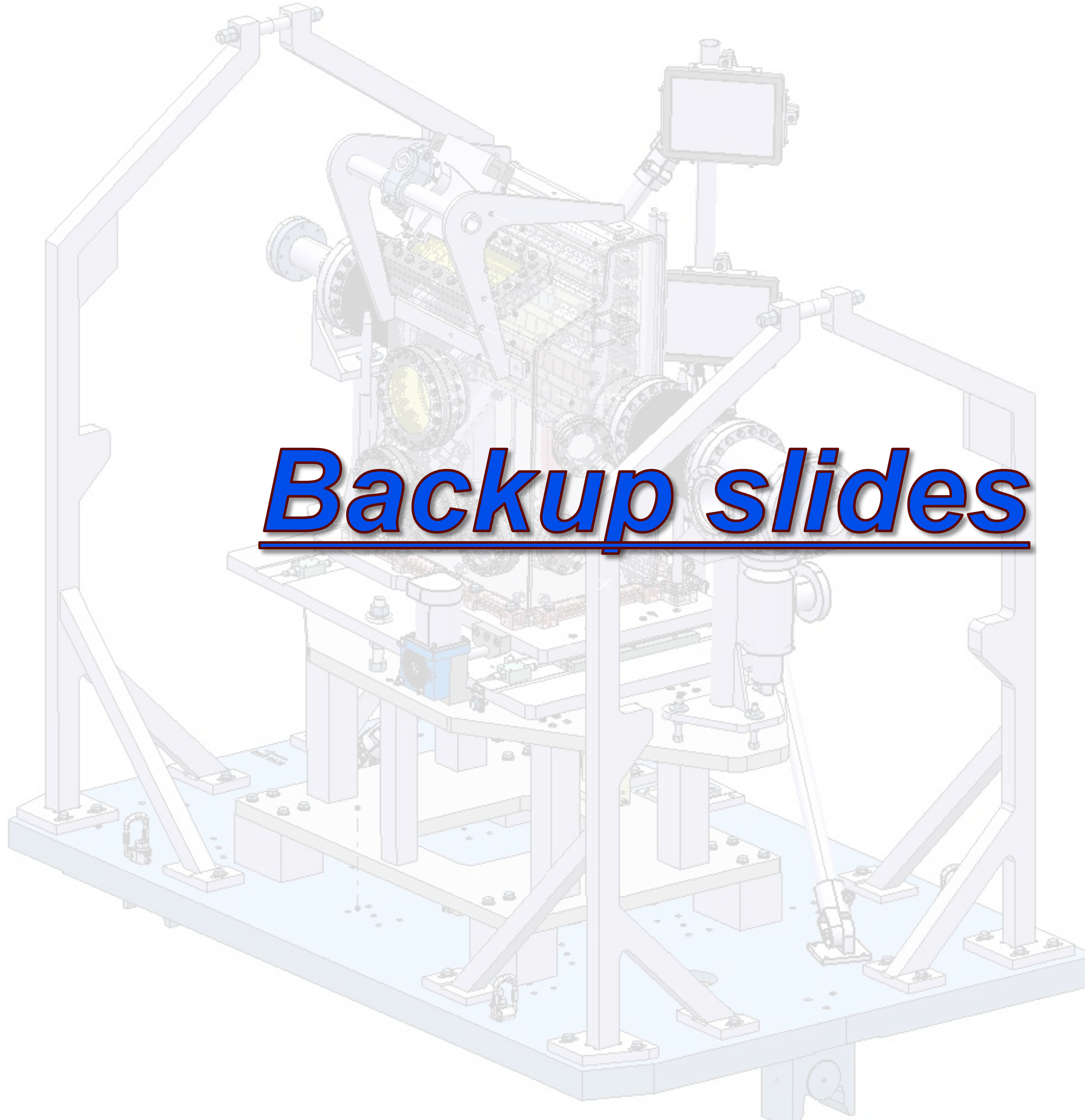
Questions?

Backup slides



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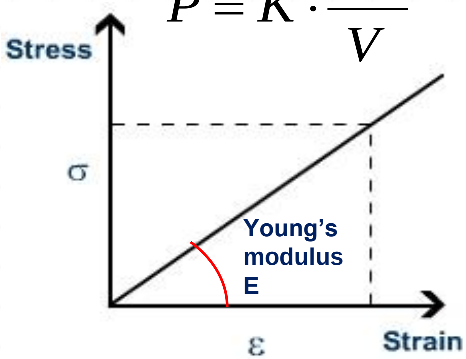
FEM Codes vs. Hydrocodes

Standard FEM Codes

Linear Elastic Behaviour

$$P = K \cdot \frac{\Delta V}{V}$$

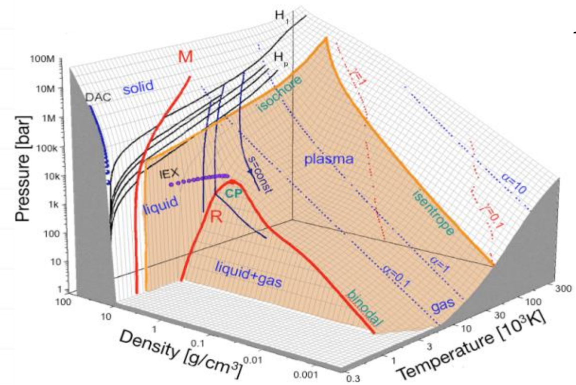


Replaced by

Hydrocodes

Complex Equations of State (EOS)

$$P = f(\rho, E(T))$$



- ✓ Mie-Gruneisen
- ✓ Tabular EOS (SESAME)
- ✓ Tillotson
- ✓ ….

Static Yield Strength

$$\sigma_y = R_{p0.2}$$

Replaced by

Multi-parameter Yield Models

$$\sigma_y = f(\varepsilon, \dot{\varepsilon}, T, \ldots)$$

- ✓ Johnson-Cook
- ✓ Steinberg-Guinan
- ✓ Johnson-Holmquist
- ✓ ….

Static Failure Strength

$$\sigma_{ult} = R_m$$

Replaced by

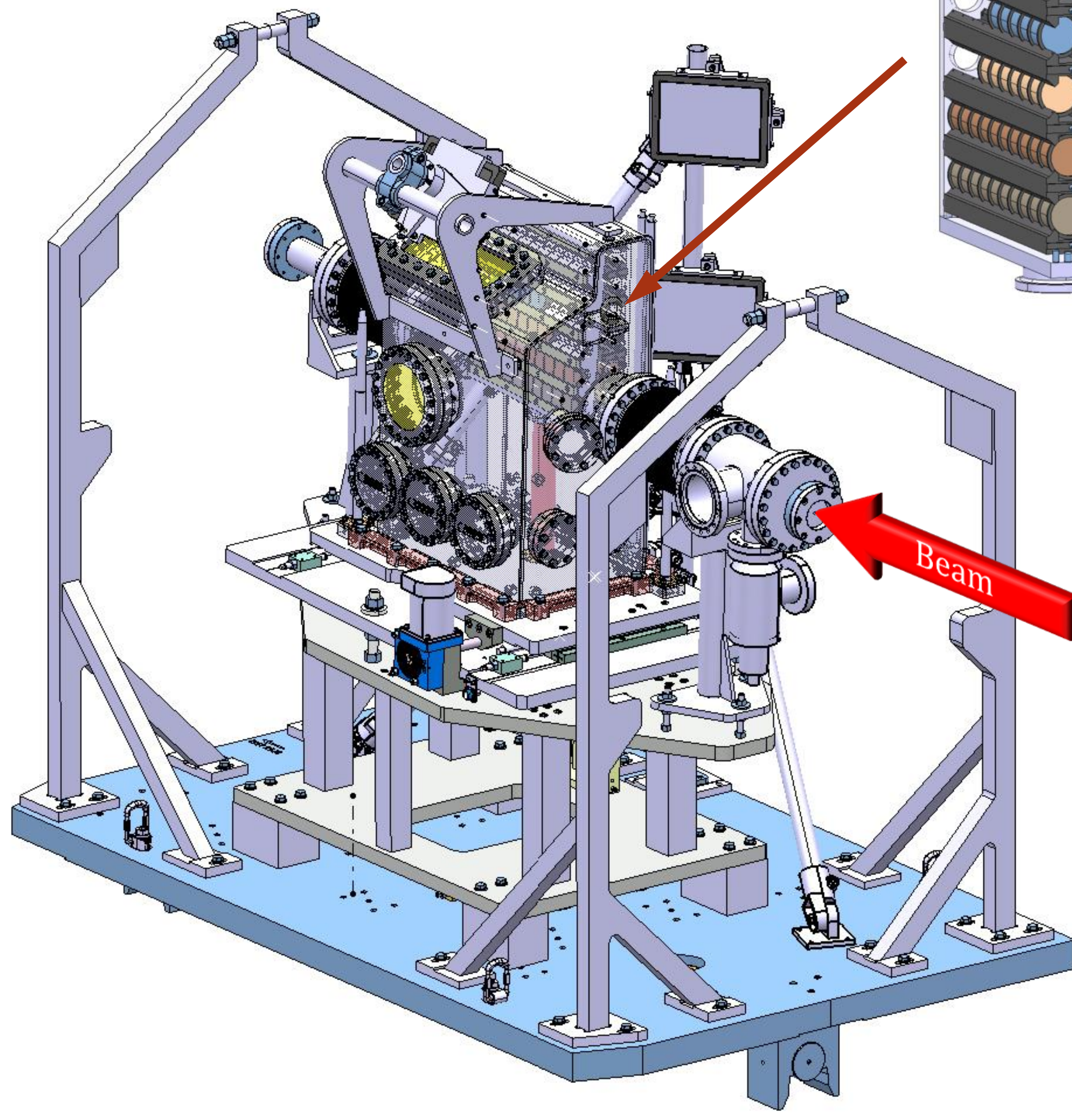
Dynamic Failure Models

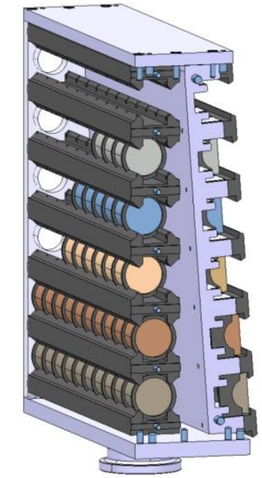
$$Damage = f(\varepsilon, \dot{\varepsilon}, T, P_{\max}, P_{\min}, K_c \ldots)$$

Design Overview

Test-bench main features

- Mobile Sample Holder (2 d.o.f. vertical and lateral)
- Vacuum Tank
- Beryllium windows for stand-alone layout
- 3 optical viewports.
- Quick-dismounting system.
- Pumping port.
- Embarked mirror set.
- Graphite specimen restraints to minimize shock transmission to specimen housing.

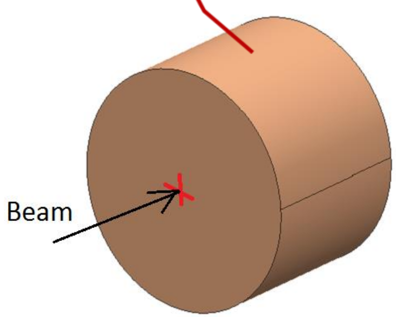




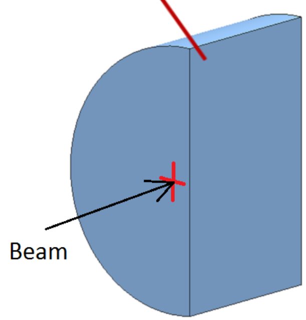
Experiment Specification

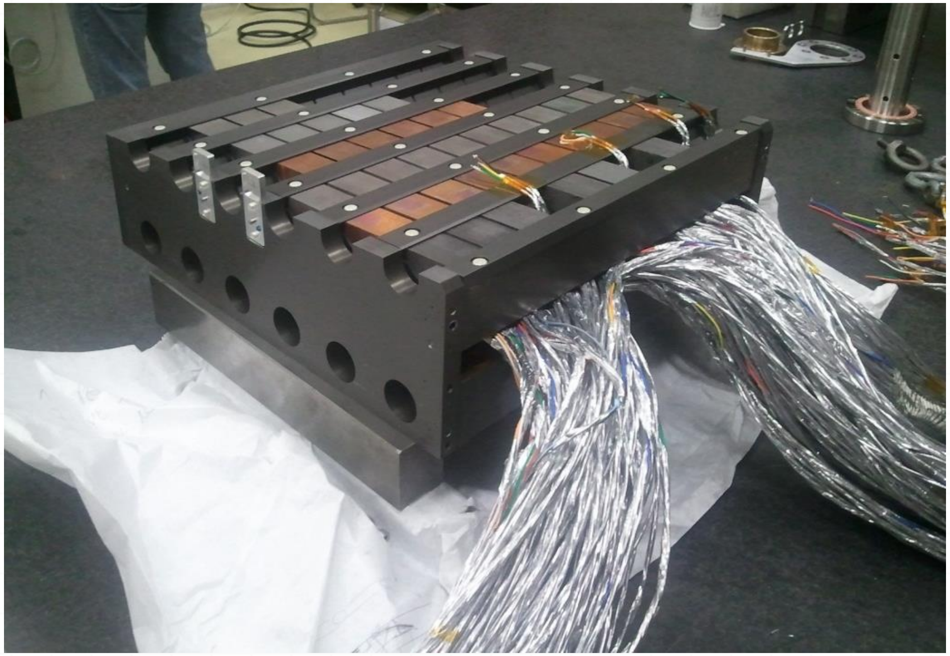
- **6 different materials:** *Inermet 180 (95%W, 3.5%Ni, 1.5%Cu), Glidcop (Cu+0.15%Al_2O_3), Molybdenum, Molybdenum-Diamond, Copper-Diamond, Molybdenum-Graphite*
- **6+6 Target Stations** with **2 specimen types** for each material (Type 1, Type2) for **Medium intensity** and **High intensity** tests
- **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)



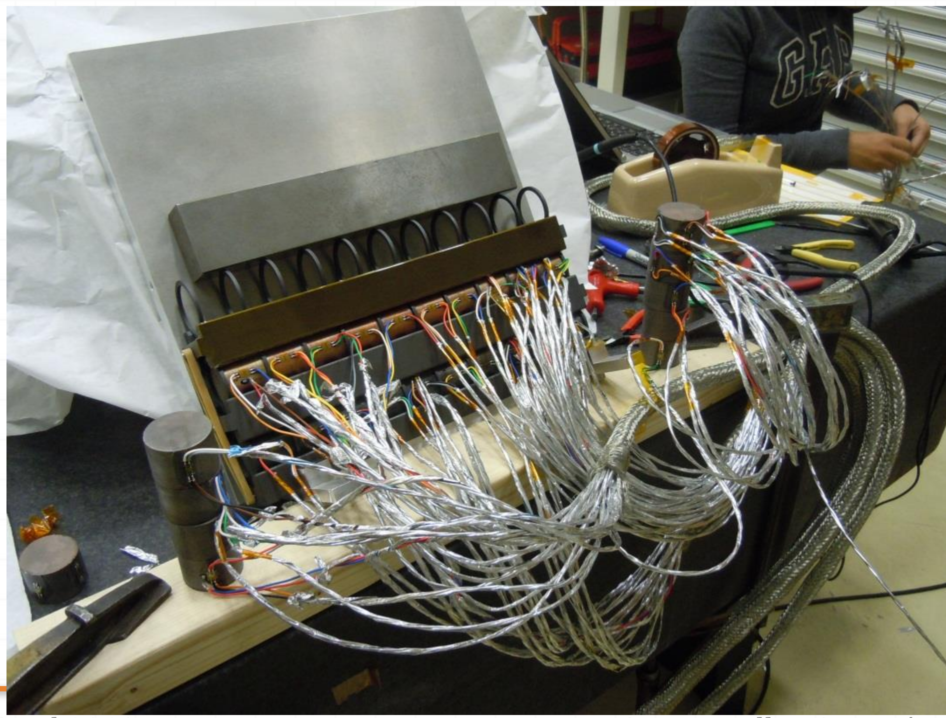
High Intensity Tests:
Type 2 Sample
(half-moon, Offset 2 mm)

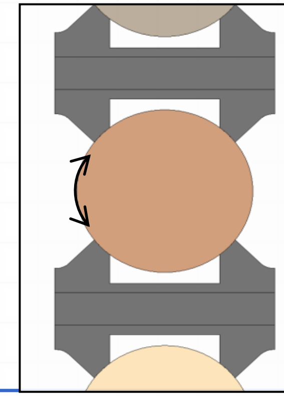




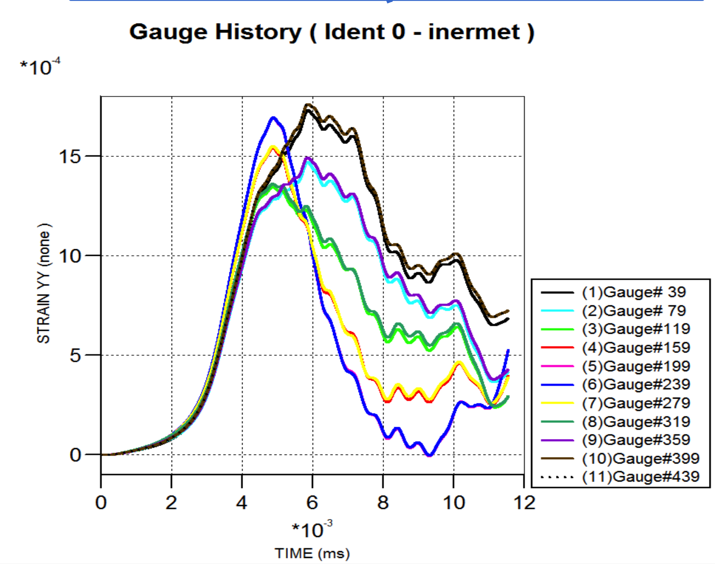
Embarked Instrumentation

- **38 Temperature probes** and 1 **Vacuum** sensor, **Microphones .**
- **244 Resistive Strain Gauges**: measuring circumferential and axial strains generated on outer surface (type 1 and 2).
  - Amplitude : 1500 up to 20'000 µm/m
  - Sampling Frequency: 2 MHz
  - Compliant with high radiation levels
- **4 "Vintage" flashes** (for high speed camera acquisition)



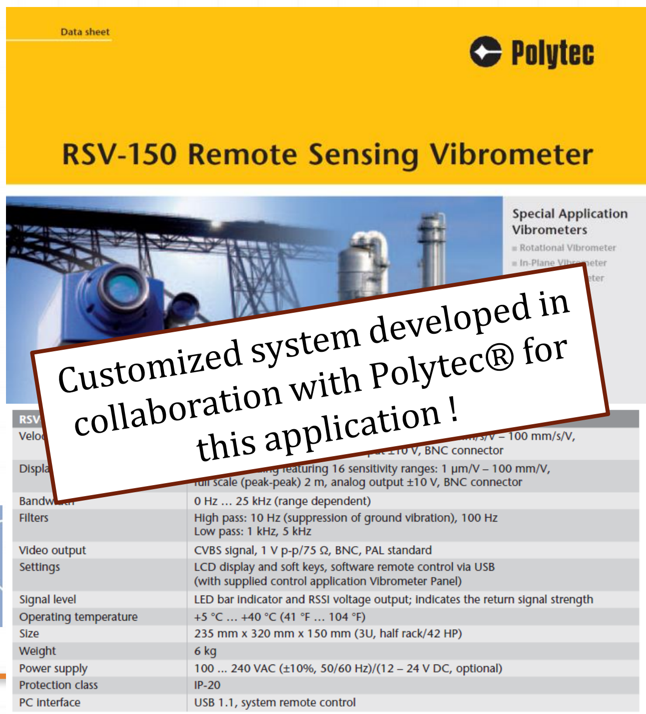


Expected circumferential strain on Inermet180, 20 bunches



Remote Instrumentation

- **LDV**: measuring radial velocity (up to **24 m/s**) of outer cylindrical surface (type 1 samples). Sampling rate: **2.5 MHz**
- **High Speed Camera:** acquiring live images of impacted type 2 samples. Capture rate **20 kfps**. Exposure time **5 µs**.
- Placed in a bunker 42 m upstream of the experiment.


Data sheet

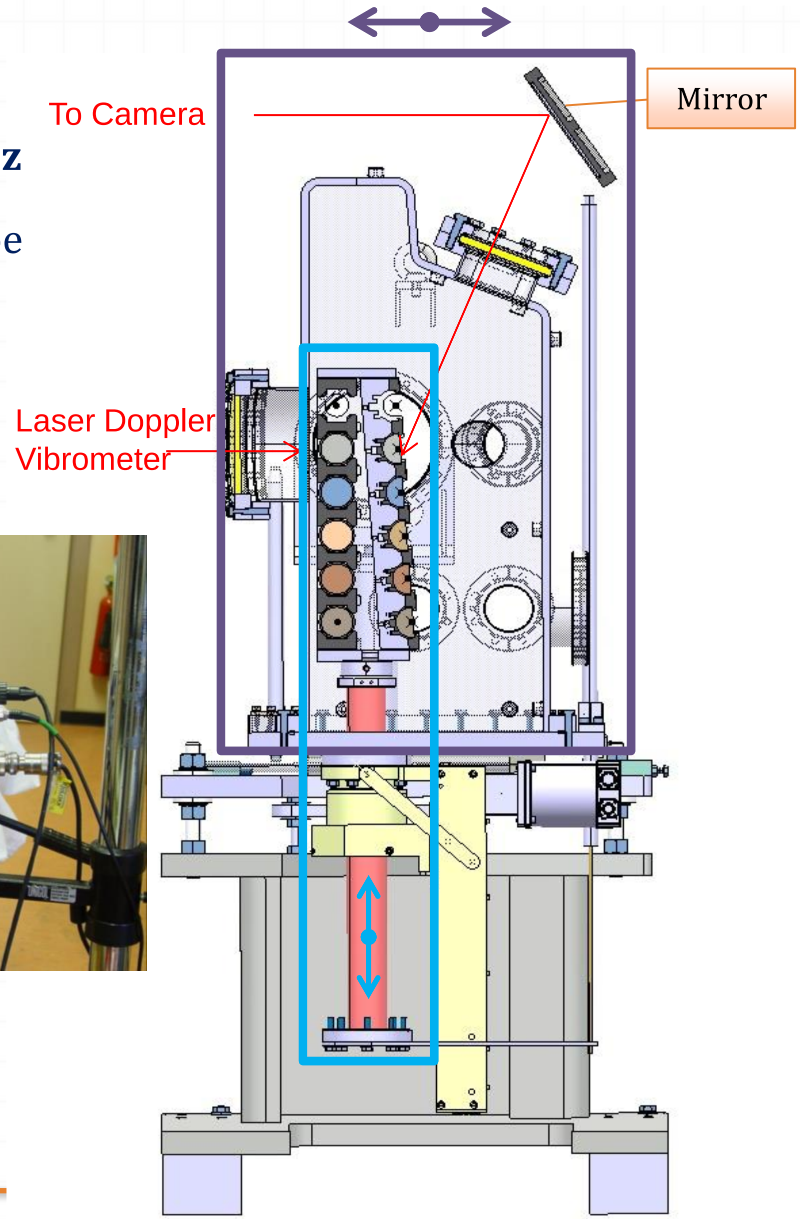
Polytec

RSV-150 Remote Sensing Vibrometer

Special Application Vibrometers
- Rotational Vibrometer
- In-Plane Vibrometer

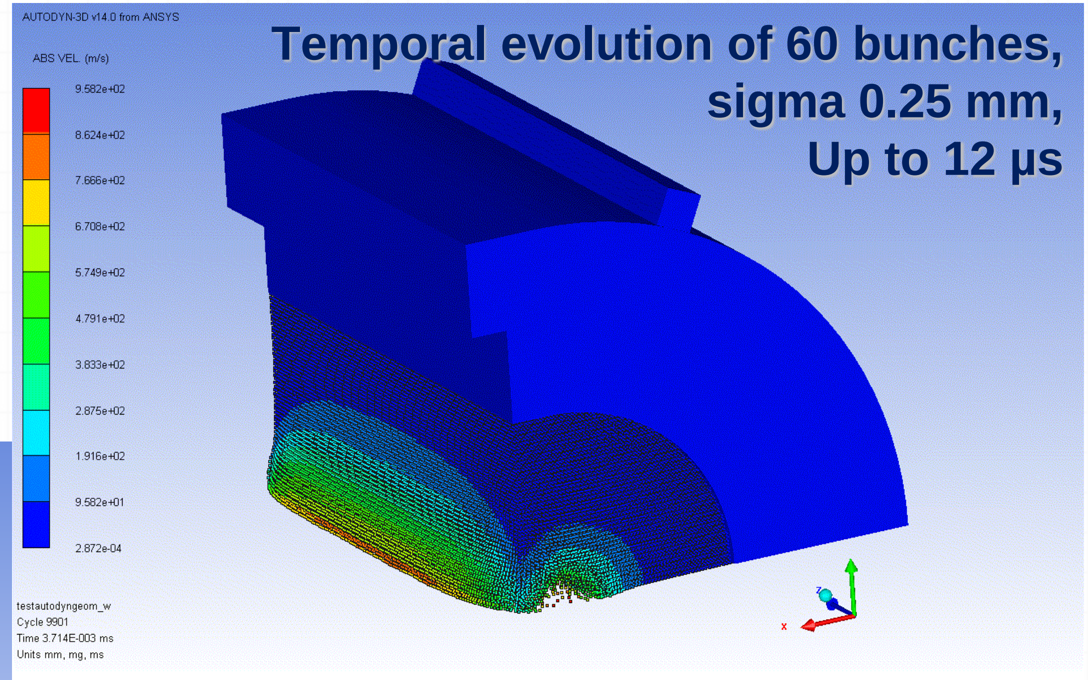
RSV	
Velo…	…m/s/V – 100 mm/s/V, …put ±10 V, BNC connector
Displa…	…featuring 16 sensitivity ranges: 1 µm/V – 100 mm/V, full scale (peak-peak) 2 m, analog output ±10 V, BNC connector
Bandw…	0 Hz … 25 kHz (range dependent)
Filters	High pass: 10 Hz (suppression of ground vibration), 100 Hz Low pass: 1 kHz, 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

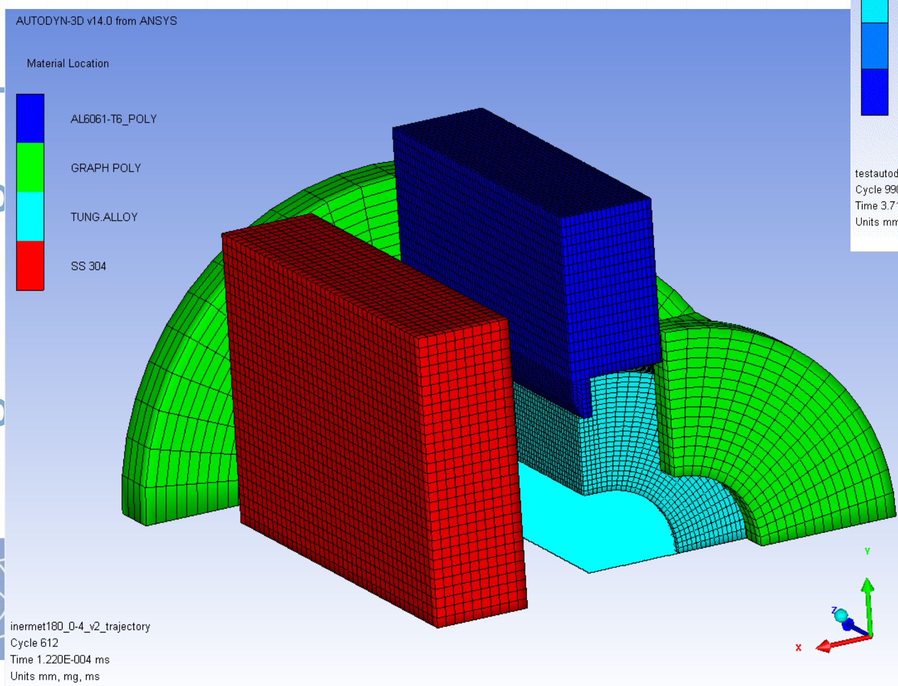
Customized system developed in collaboration with Polytec® for this application !



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!

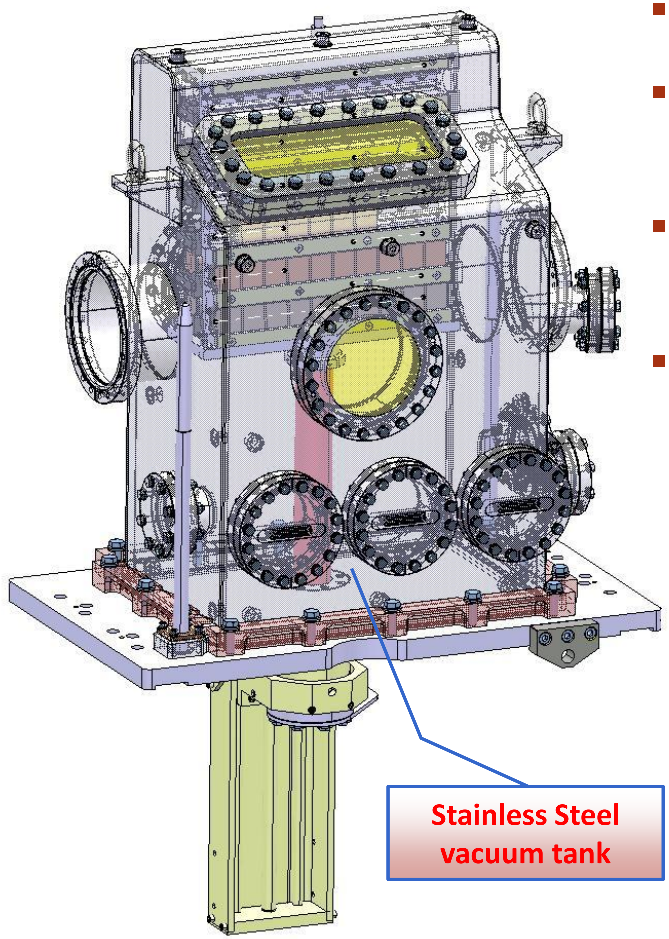


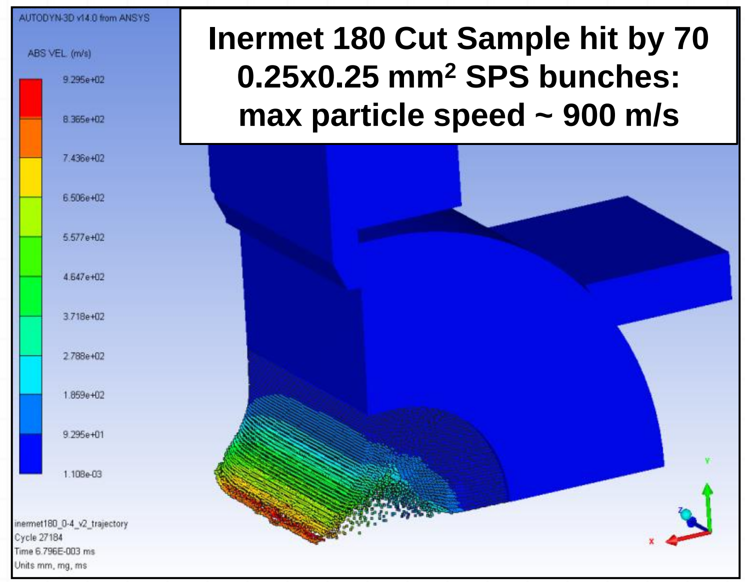


Engineering Department

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

EN
Engineering Department

Post-Irradiation Phase

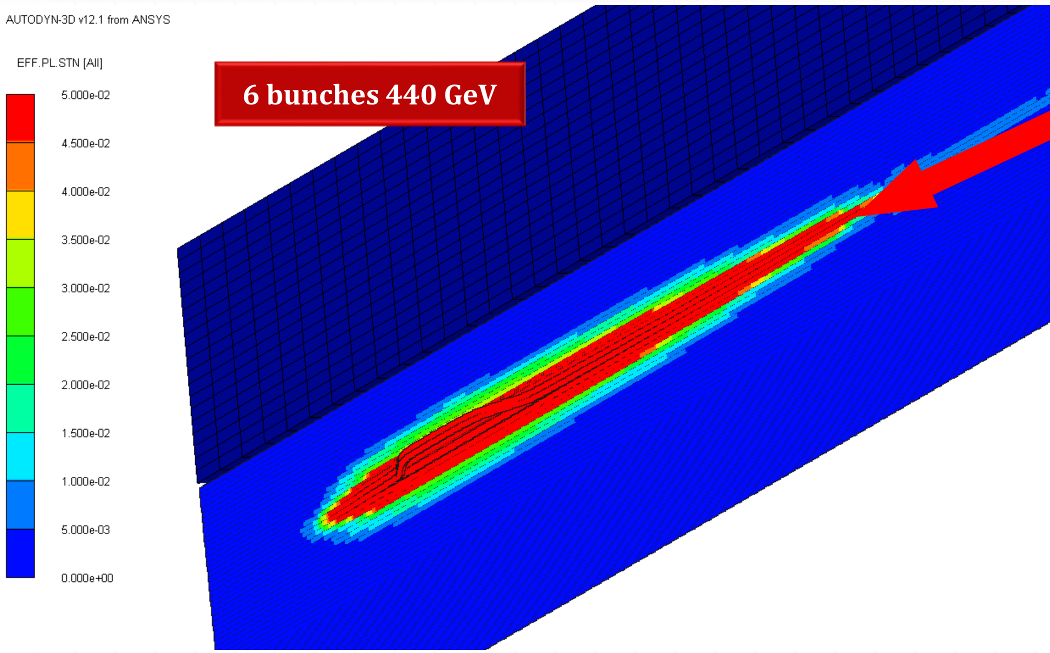
Engineering Department

- **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.

HRMT09: Analysis of Test 2

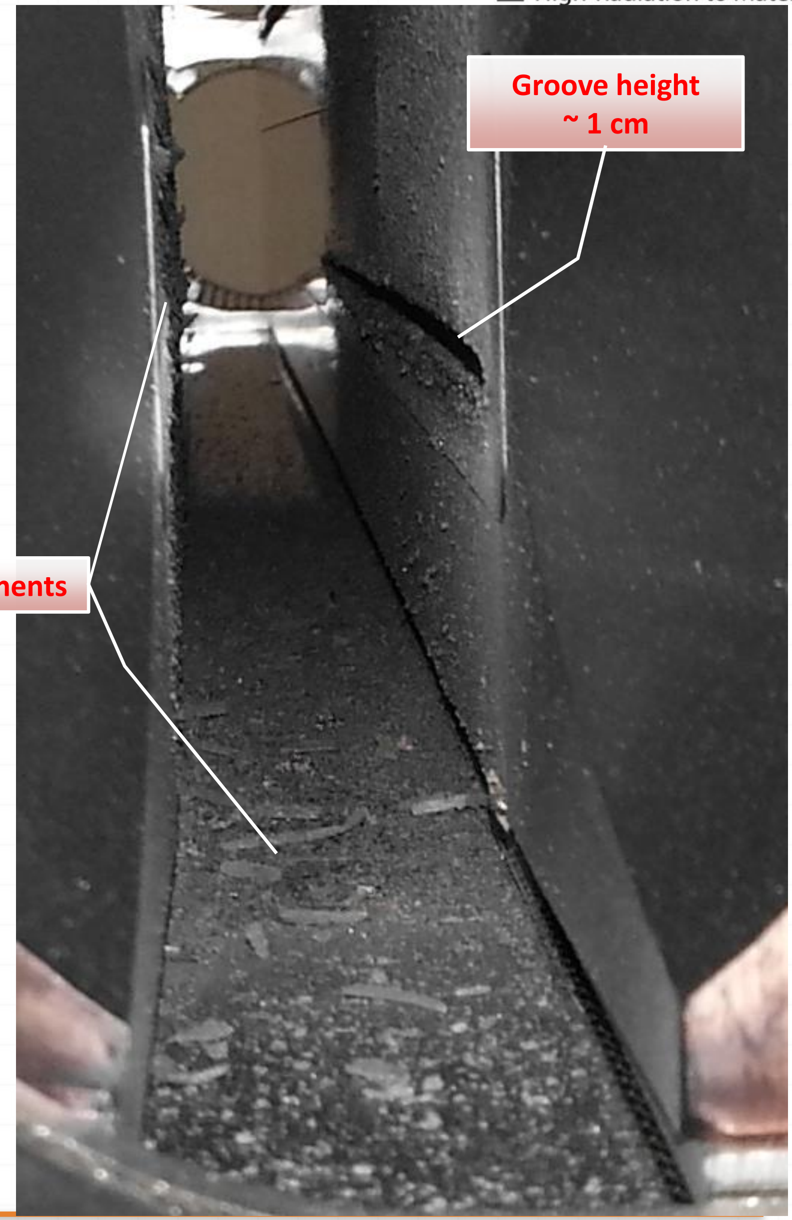
- **Goal**: Identify the **threshold** for **plastic damage**
- Given the projection of particles from the opposite jaw generated during test 3, it's **not possible to detect now a possible plastic deformation**



- Simulations predict plastic deformation with **crack generation without particle detachment**

HRMT09: Analysis of Test 3

- **Goal**: induce **severe damage** on the collimator *(**level 2 damage**: collimator to be replaced)*
- Impressive **quantity of tungsten 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**



HRMT09: Analysis of Test 3

Also in this case results of numerical simulation look consistent with preliminary optical observations …