EuCARD2 WP11 (Materials for Collimation) kick-off and tasks meeting

Politecnico di Torino: introduction, overview of WP8 work and possible contributions to WP11

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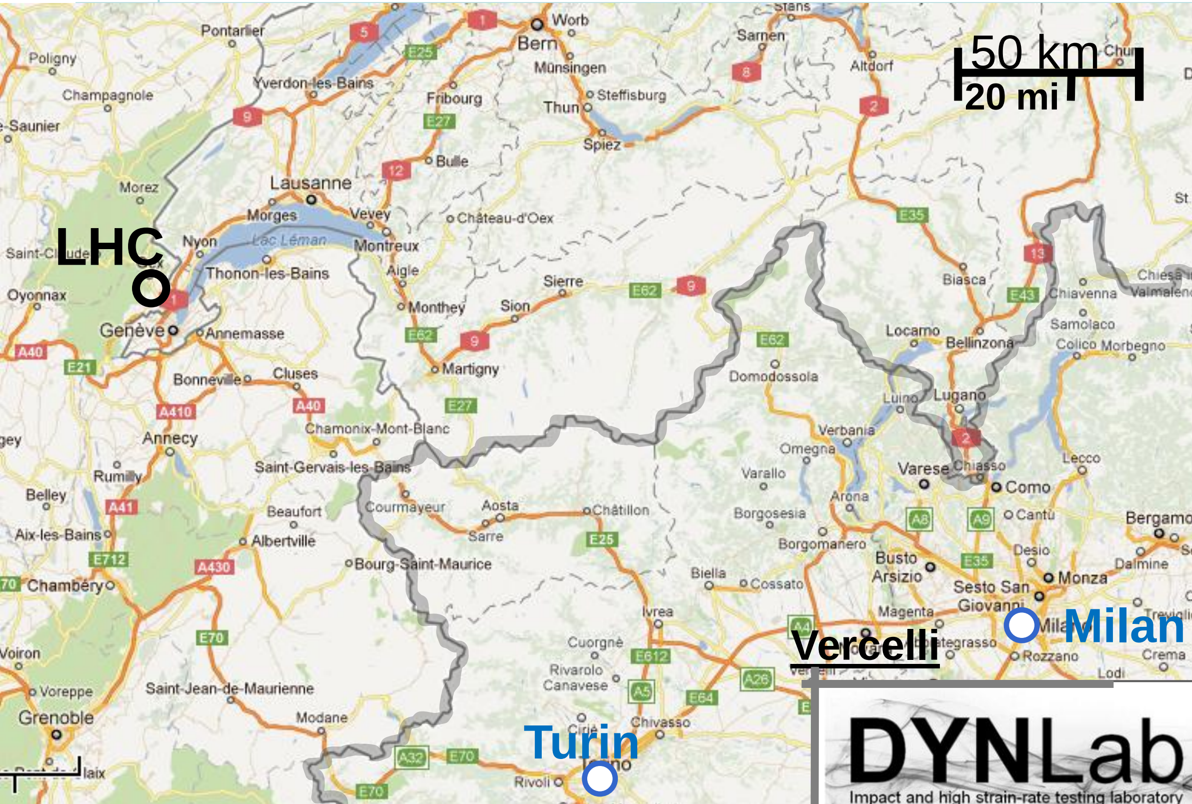
POLITECNICO DI TORINO

Dipartimento di Ingegneria Meccanica e Aerospaziale



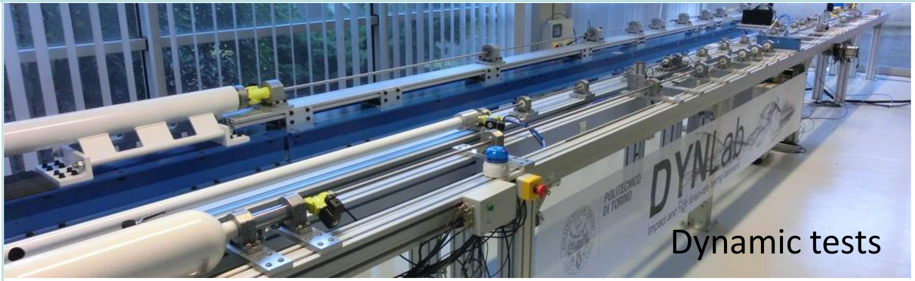
The Politecnico di Torino (POLITO) has **32.000 students** studying on 120 courses (28 Bachelor's degree courses; 32 Master of Science courses; 24 Doctorates and 37 specialization courses). 18 of them are held in English. In the academic year 2012/2013 the Politecnico had around 5.000 students in the first year; in 2012 around 2570 students graduated with a Master of Science or a Bachelor's Degree. Each year, between lectures, laboratories and practical exercises there are **170.000 hours of teaching**.

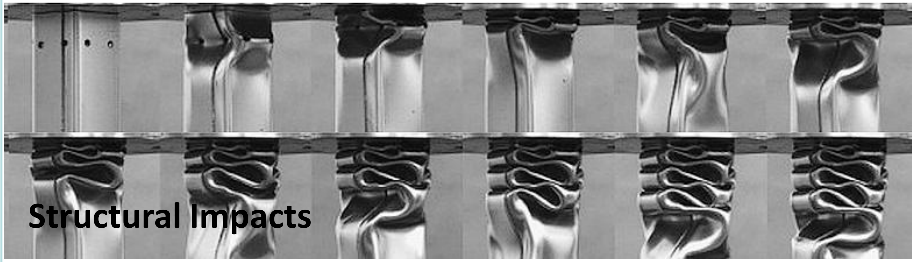
DYNLab
Impact and high strain-rate testing laboratory

DYNLab is an integrated experimental and numerical laboratory operating in the field of materials and structures behaviour under extreme loading conditions. Impact and high strain-rate scenarios are investigated with dedicated experimental facilities and numerically simulated with non-linear finite elements codes.

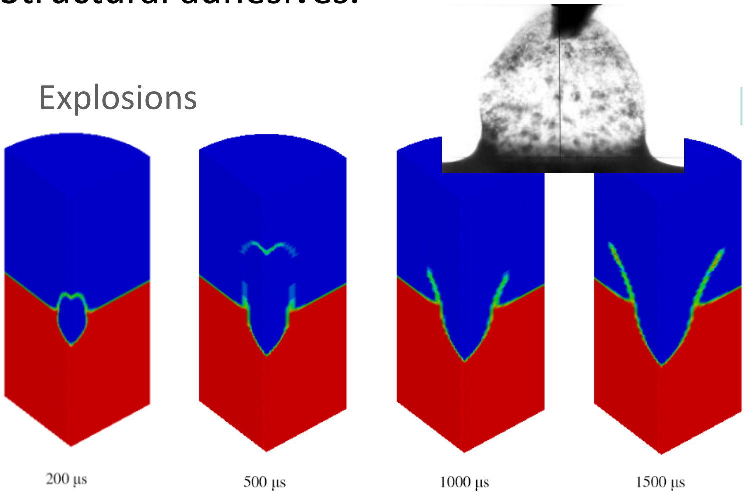
Politecnico di Torino - DYNLab

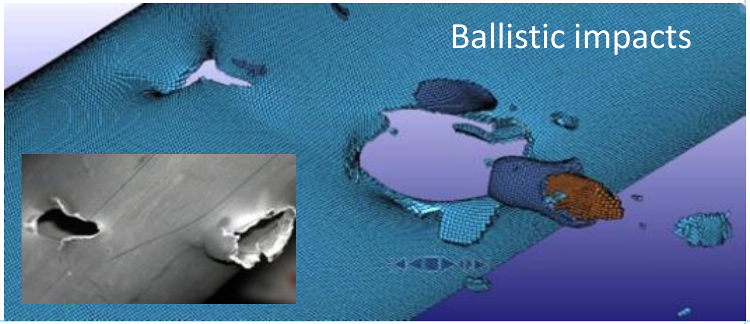
Research activities





High strain-rate behavior of materials: experimental tests and numerical modeling.
Mechanical behavior of advanced materials.
Structural adhesives.

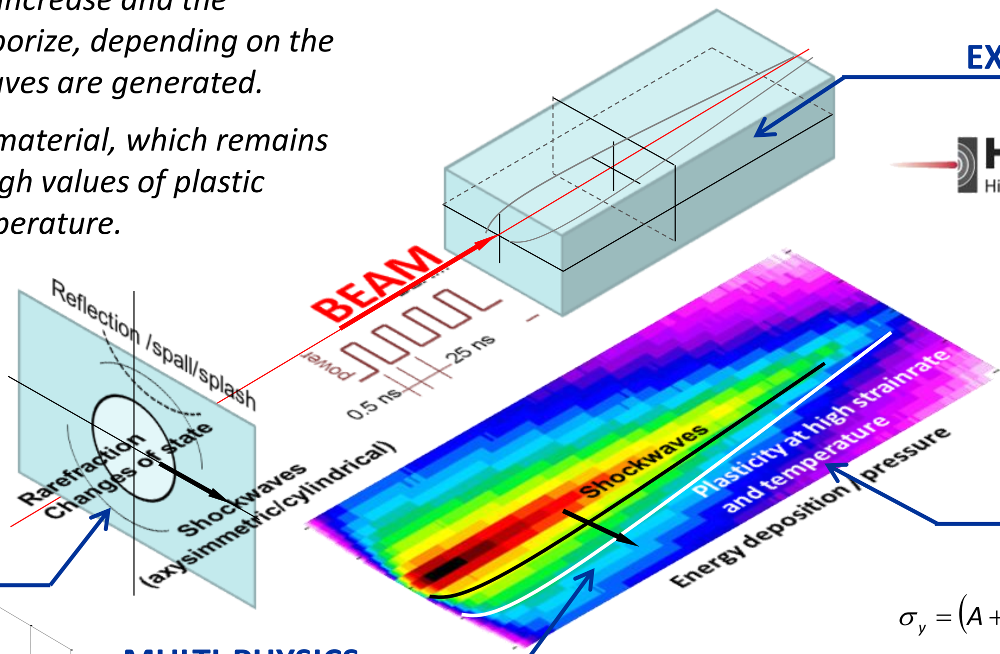




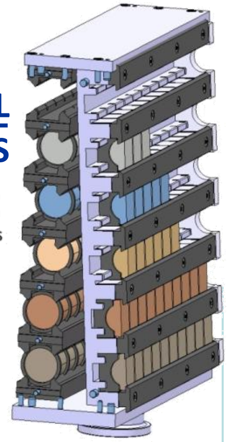
Numerical modeling of structures subjected to ballistic impacts and blast loading.
Shockwaves induced on materials by high energy particle beams.

In the material part closest to the beam, the pressure and temperature increase and the materials could melt or vaporize, depending on the loading condition: shockwaves are generated.

The remaining part of the material, which remains solid, is characterized by high values of plastic strain, strain-rate and temperature.



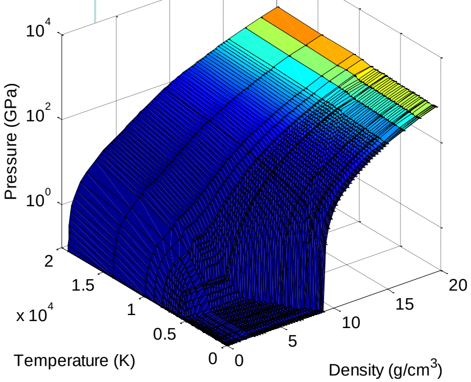
EXPERIMENTAL METHODS



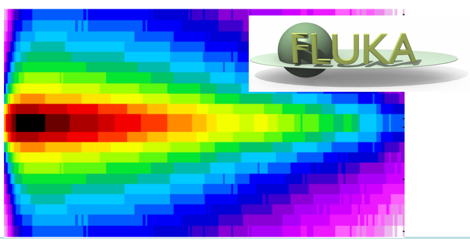
MATERIAL MODELS

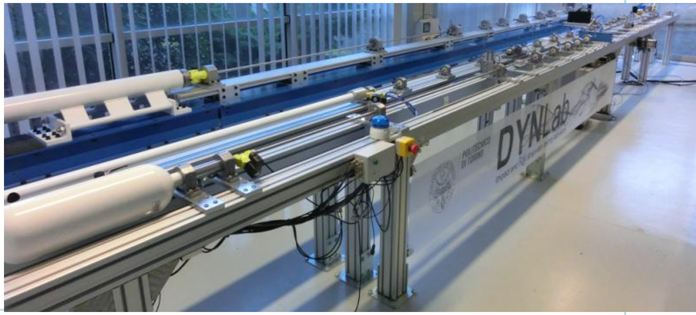
$$\sigma_y = \left(A + B\varepsilon_{pl}^{n}\right)\left(1 + C\ln\frac{\dot{\varepsilon}_{pl}}{\dot{\varepsilon}_0}\right)\left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^{m}\right)$$

EQUATIONS OF STATE

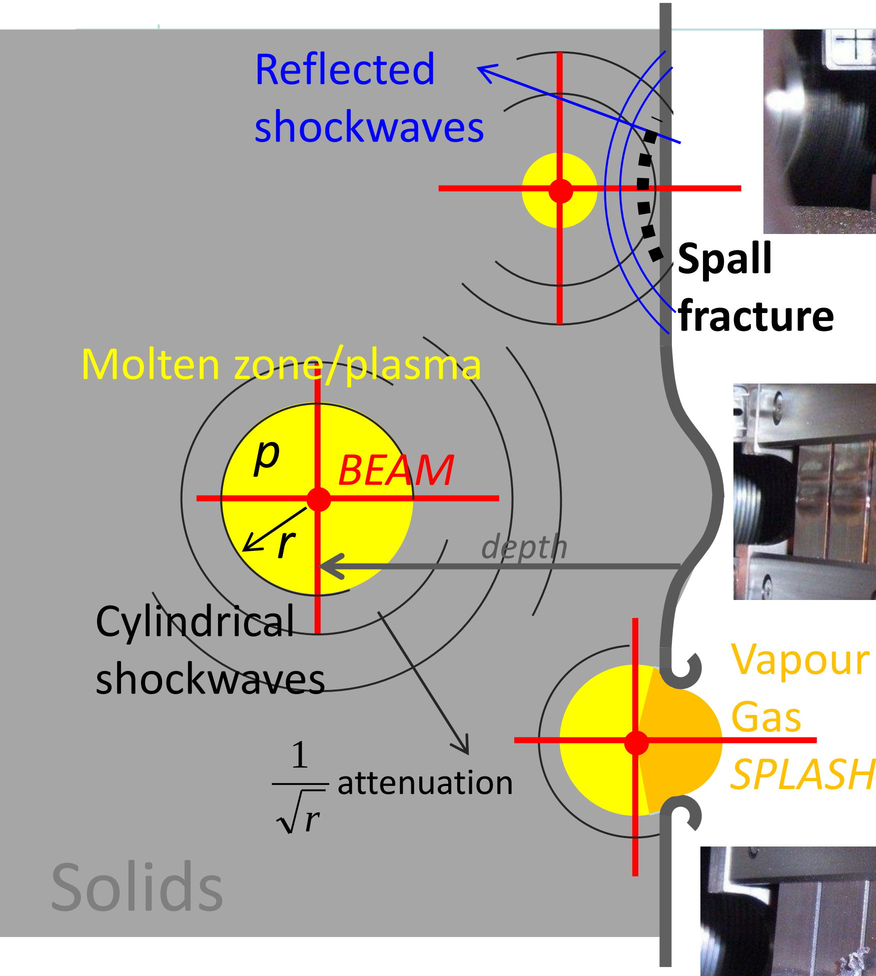


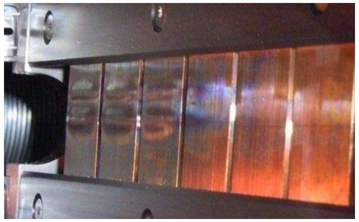
MULTI-PHYSICS SOLUTIONS

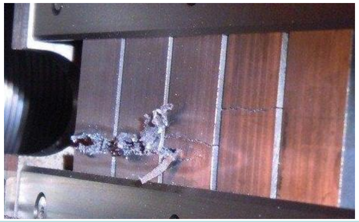




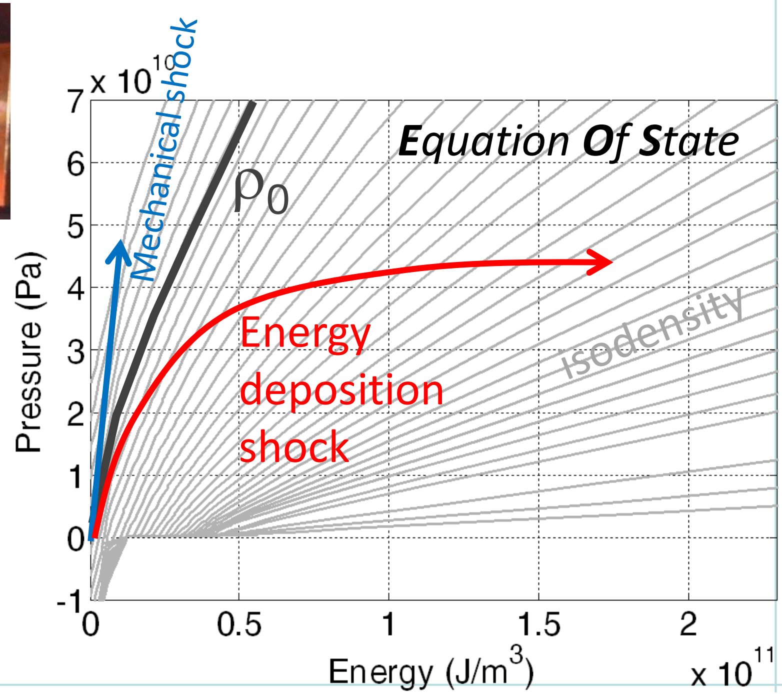
WP8 Work - Scenario





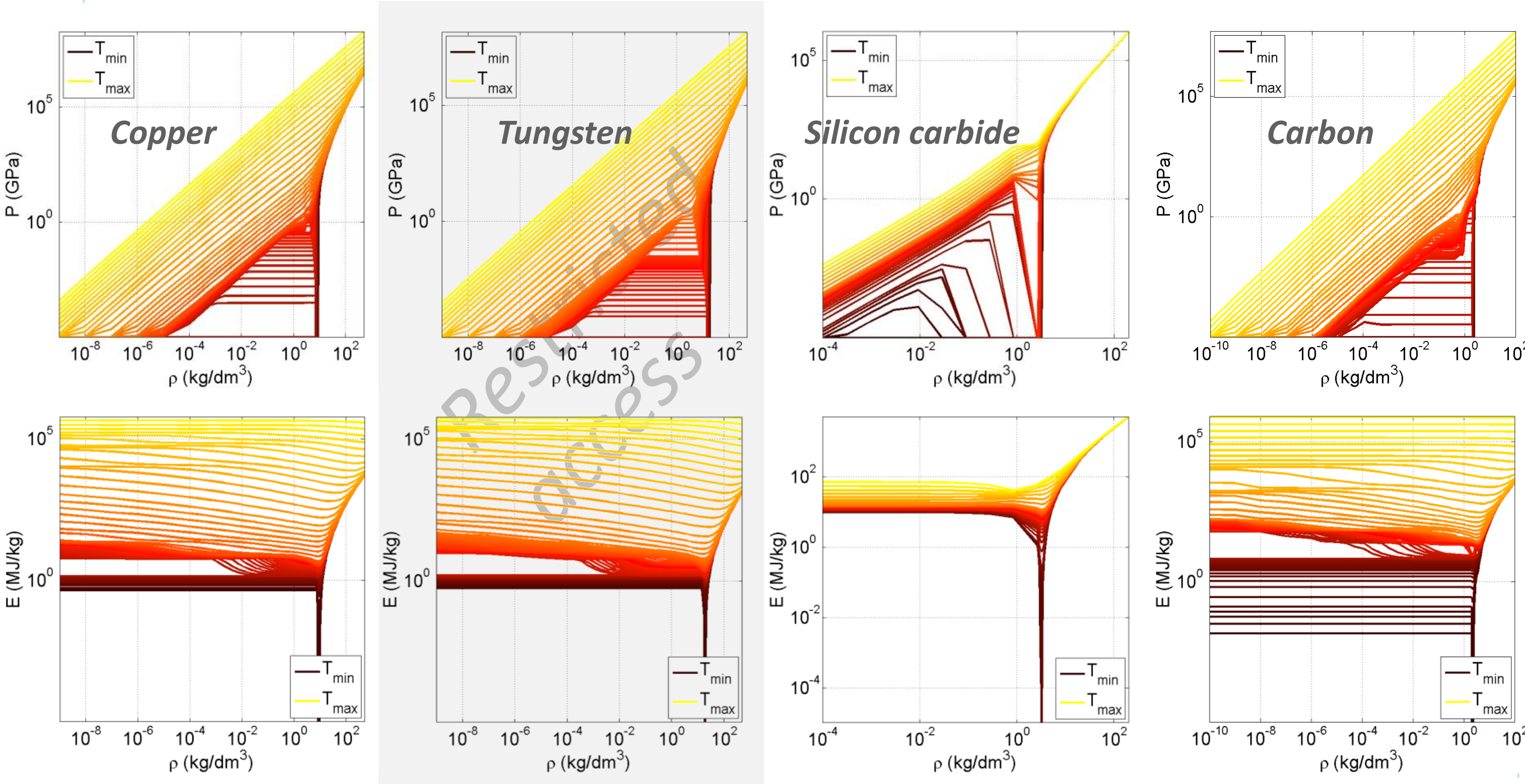


The effects of the particle beam interaction depend on a great number of parameters/conditions (number of bunches, beam intensity, beam size, depth of impact, material physical properties, mechanical behaviour...)

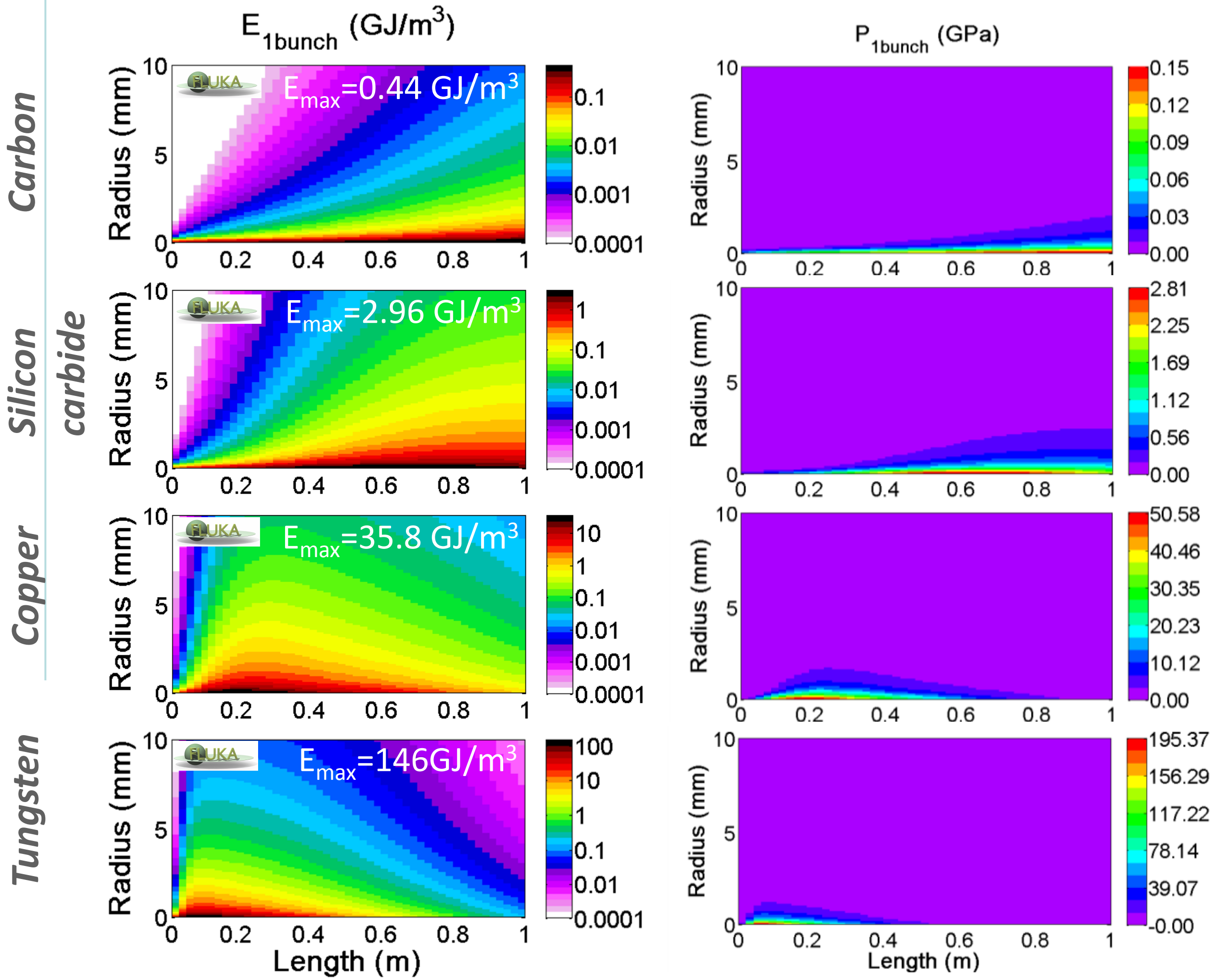


What did we learn in 4 years?

The equations of state of (pure) materials of interest were obtained from SESAME library in tabular form.



WP8 - Equations of state



The FLUKA energy deposition on material is converted in mechanical effects through the EOS.

One 7 TeV protons bunch 1.15×10^{11} protons

The proton energy loss and the maximum position is strongly ”material” dependent

WP8 – From Fluka to mechanical field

Pressure gradients produce plasticity (in ductile material)!

*These models have typically been tested and calibrated with experiments on Hopkinson bars, Taylor cylinders and with high-explosive (HE)–driven shock or compression waves at pressures **up to a few tens of GPa** and strain rates of 10^3 to 10^5 s^{-1}*

Johnson-Cook

$$\sigma_y = \left(A + B\varepsilon_{\mathrm{pl}}^{n}\right)\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\left(1 - \left(\frac{T - T_{\mathrm{ref}}}{T_{\mathrm{melt}} - T_{\mathrm{ref}}}\right)^{m}\right)$$

Steinberg-Guinan

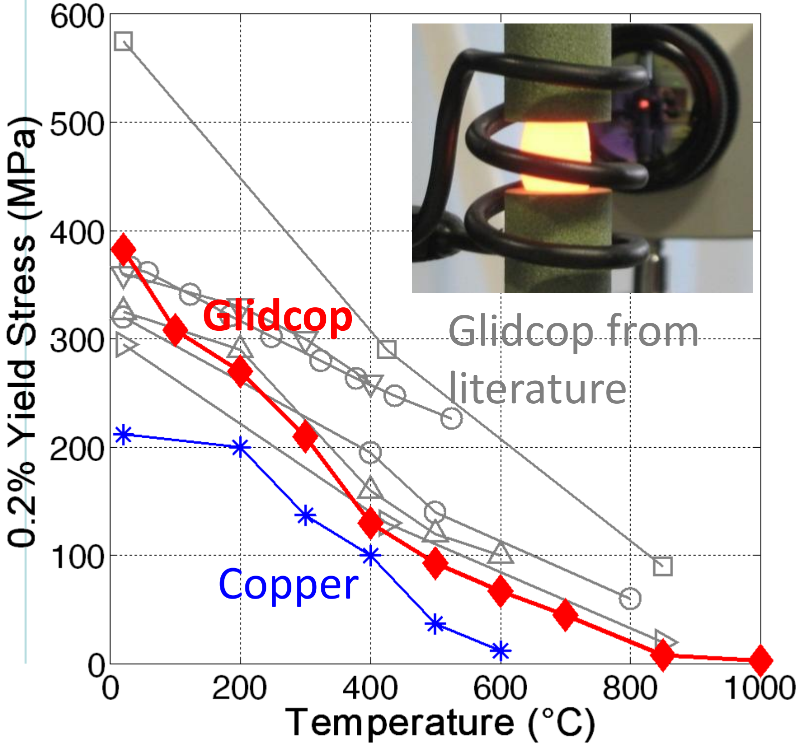
$$\begin{cases} \sigma_y = \sigma_0\left[1 + \beta\left(\varepsilon_{pl,i} + \varepsilon_{pl}\right)\right]^{n} \cdot G/G_0 < \sigma_{\mathrm{MAX}} \\ G/G_0 = \left[1 + bPv^{1/3} - h(T - 300)\right] \\ T_{melt} = T_{m0}\exp\left[2a(1 - v)\right]v^{-2(\gamma_0 - a - 1/3)} \end{cases}$$

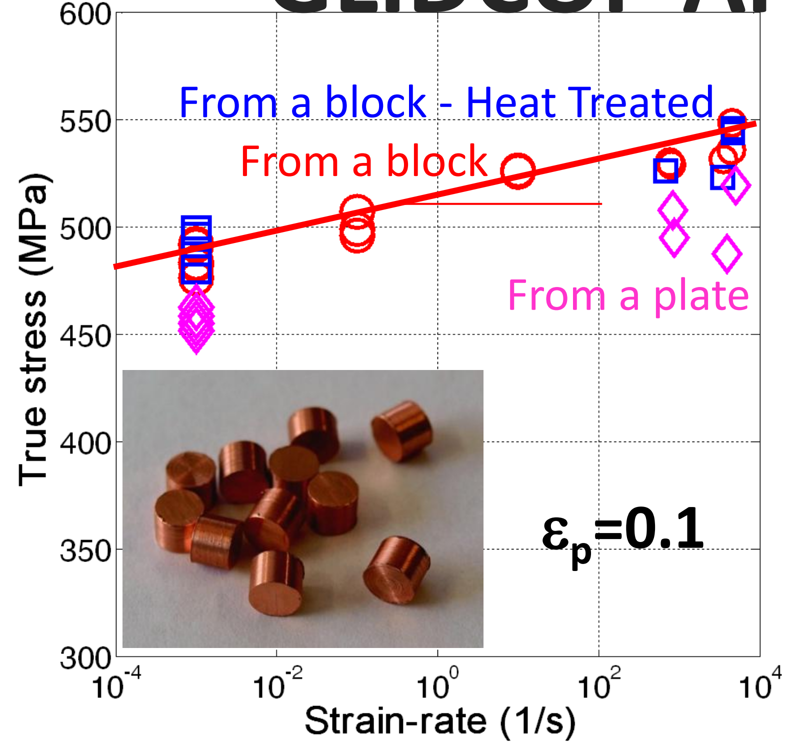
$P_{expected} \sim E_{deposited} > 100$ GPa!

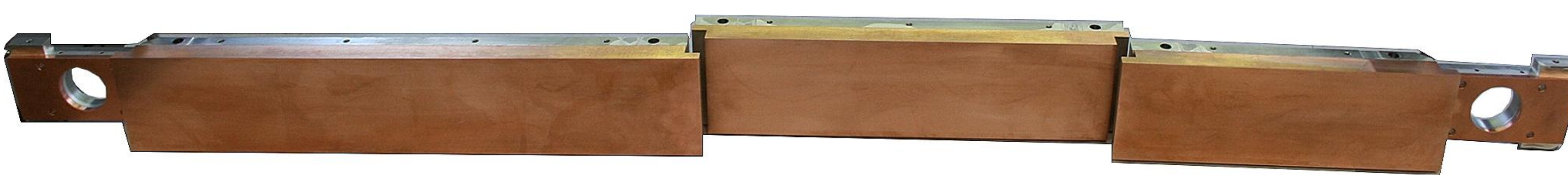
For the future, improvement in the material strength model is a fundamental aspect!

When the temperature reaches the value of the melting temperature the shear strength of the material model becomes zero **and the material starts to be considered like a fluid (pure hydrodynamic behaviour)**

GLIDCOP Al-15

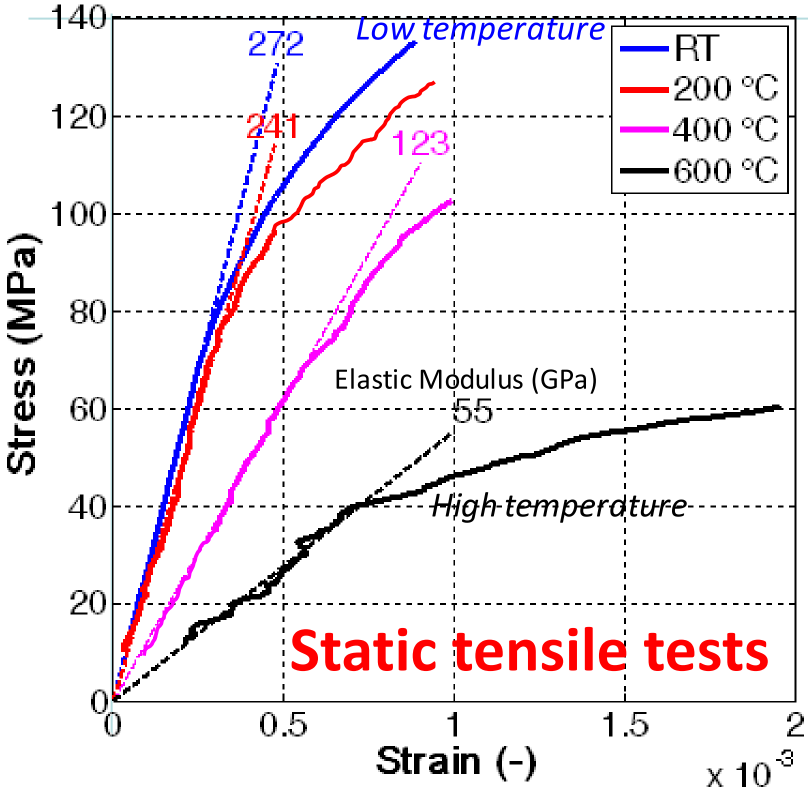


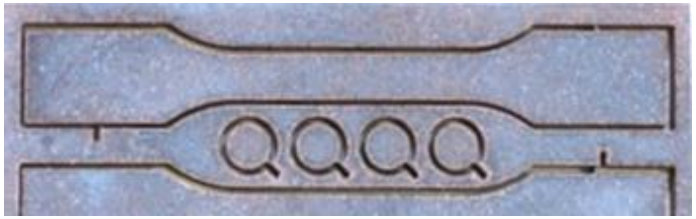


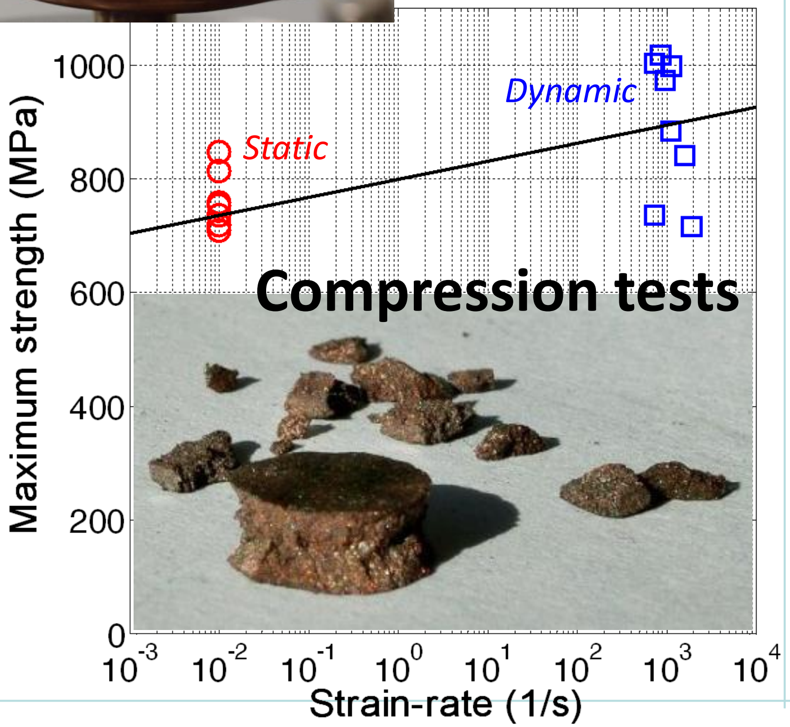


WP8 - Constitutive material models (II)

Me-CD





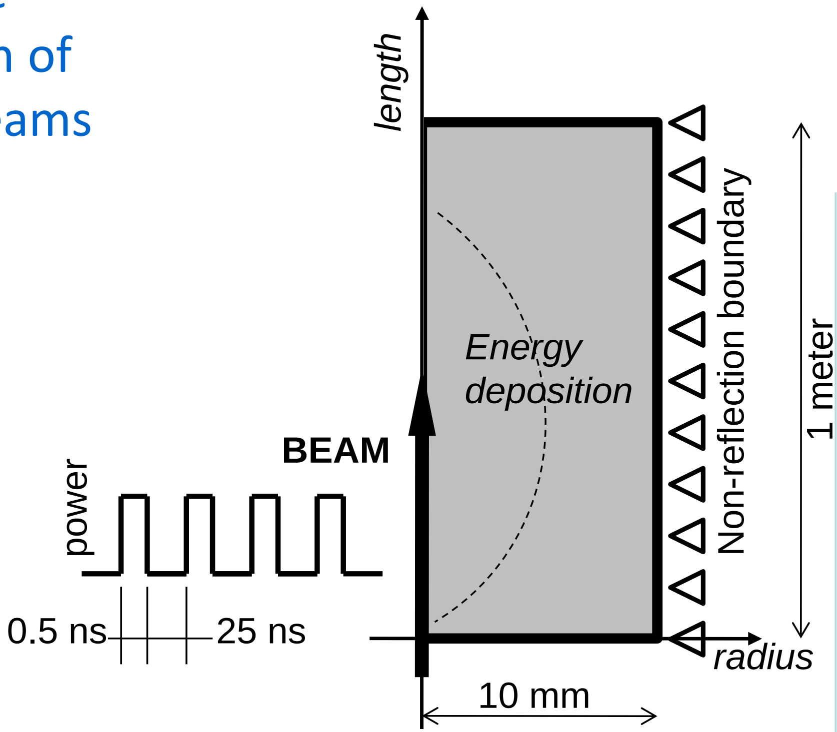


WP8 - Constitutive material models (III)

A strong effort was devoted to the development of an efficient and reliable technique for the mechanical simulation of structures hit by high energy particle beams using a simple approach:

Fluka as input for a FEM hydrodynamic analysis (LS-Dyna)

- ✓ How to pass the energy (FLUKA) to the mechanical model (LSDYNA)?
  THROUGH THE EOS
- ✓ Which type of EOS? LINEAR POLYNOMIAL
  (LOCAL INTERPOLATION OF THE TABULAR EOS FOR EACH ELEMENTS, FOR EACH BUNCH)
- ✓ BUNCH PROFILE: POWER VS. TIME HISTORY



WP8: FEM Simulations (I)

For each element

During the bunch arrival (0.5 ns)

the energy increases along an isochoric transformation and the pressure grows up

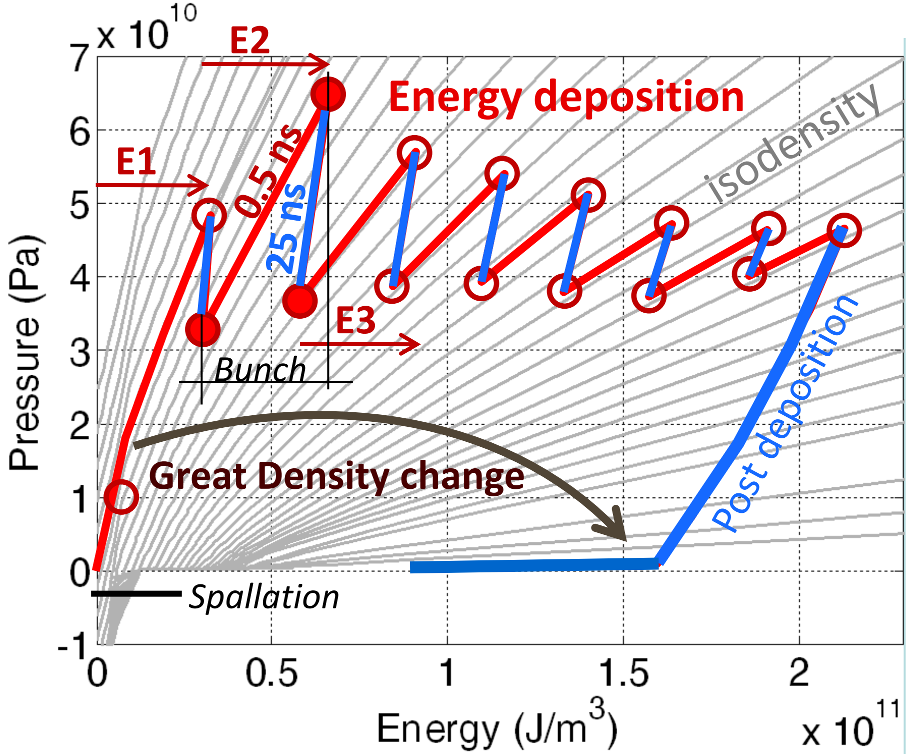
A MATLAB routine calculates the deposition-end condition on the tabular EOS along the isodensity and interpolate the zone around with a polynomial EOS

After the bunch arrival
(25 ns or end of deposition)

the material could expand (lower pressure and density) or compress (higher pressure and density)

The LS-DYNA FEM model calculates the mechanical response of the structures starting from the previous condition with the polynomial EOS

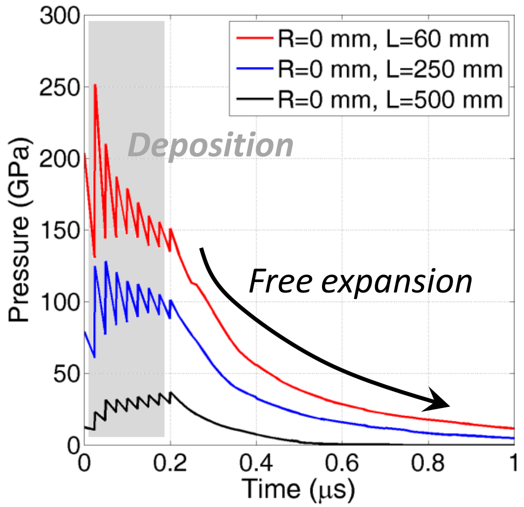
A MATLAB program governs the simulation, performs some calculations and runs the LSDYNA analysis for each bunch

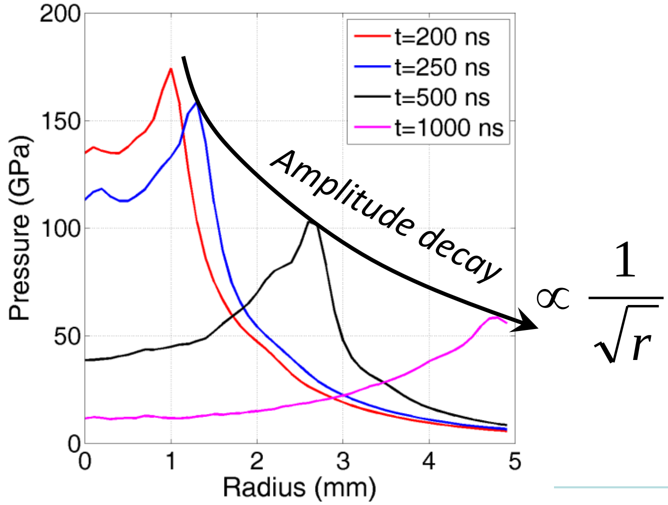


WP8: FEM Simulations (II)

On the axis

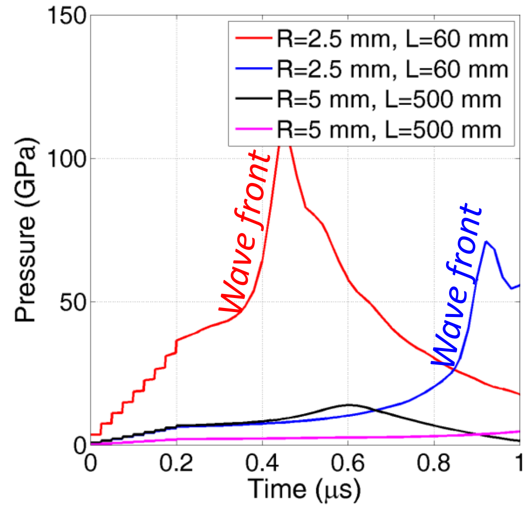
L = 60 mm

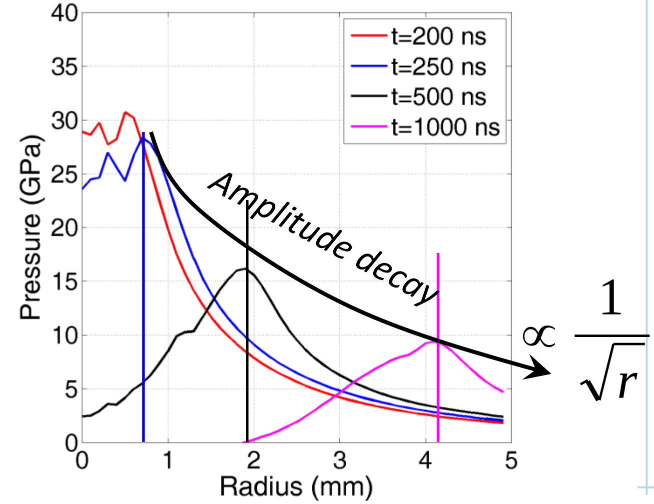




Far from axis

L = 500 mm





WP8: FEM Simulations (III)

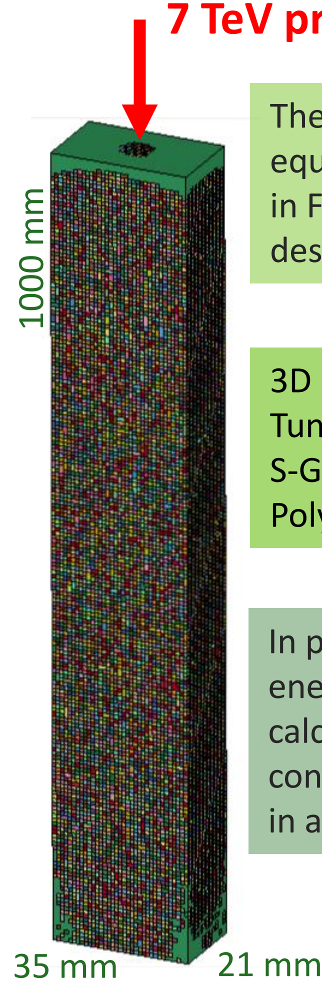
THE ENERGY DEPOSITION IS DENSITY DEPENDENT

At the beginning

- ✓ for FLUKA, define the correct number of primaries to achieve a good precision on the energy deposition, the energy and the thresholds;

For each step

- ✓ take as input the density map resulting from the LS-DYNA calculations;
  - define discrete density levels: each level is an independent FLUKA material (max 500 levels);
- ✓ use a voxel structure to define the regions with different density in the target block;
  - associate to each voxel the corresponding material with the correct density;
  - <u>perform density interpolation in case of mesh deformation (FEM);</u>
- ✓ store the energy deposition for each voxel;
- ✓ **RESTART** a new mechanical analysis (1 or more bunches)



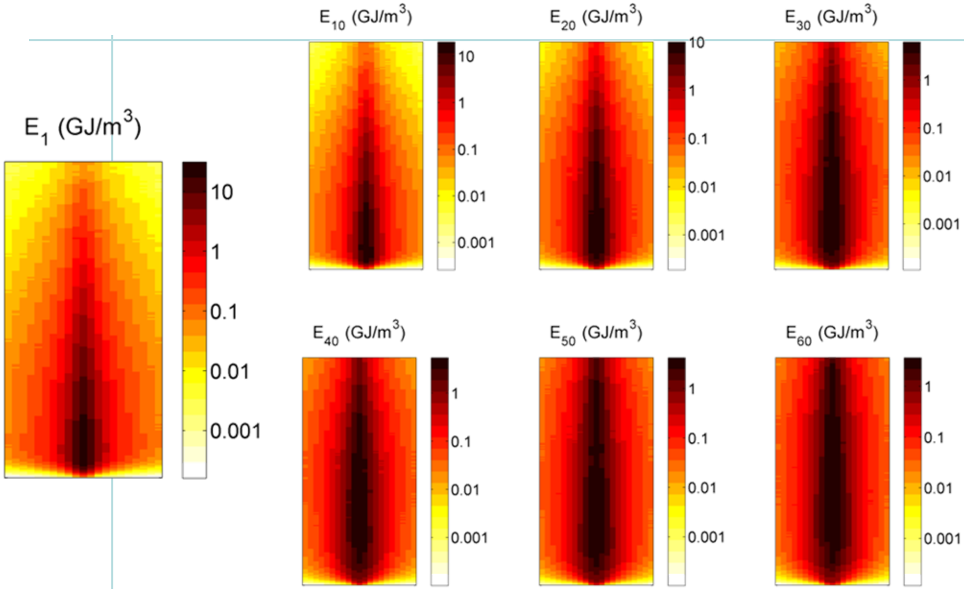
The mechanical model equivalence is obtained in Fluka via Voxel description

3D lagrangian geometry
Tungsten component
S-G model
Polynomial EOS

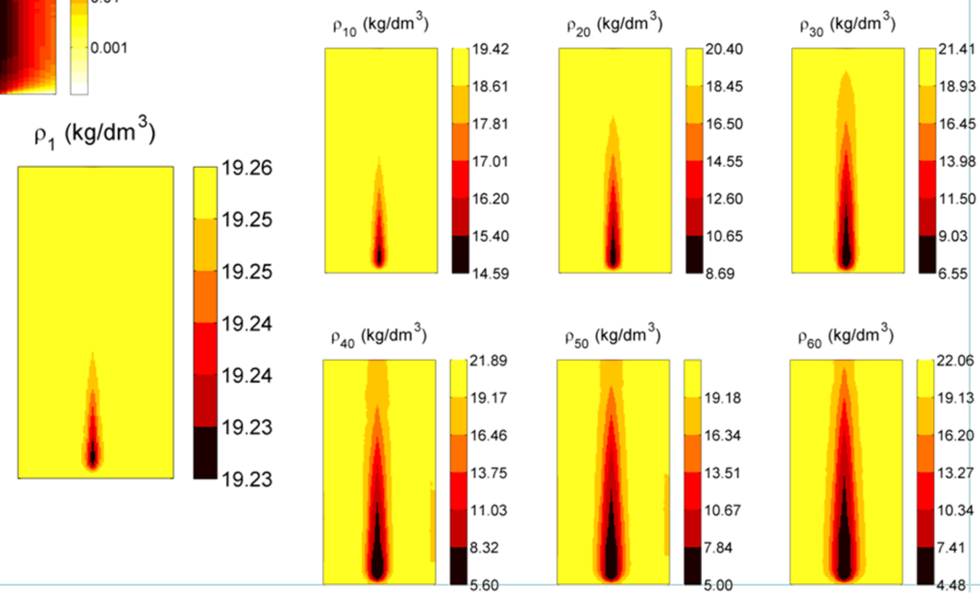
In previous analyses the energy deposition was calculated for the initial condition and then used in a multi-bunch case

FLUKA

WP8: Fluka/LS-DYNA coupling (I)

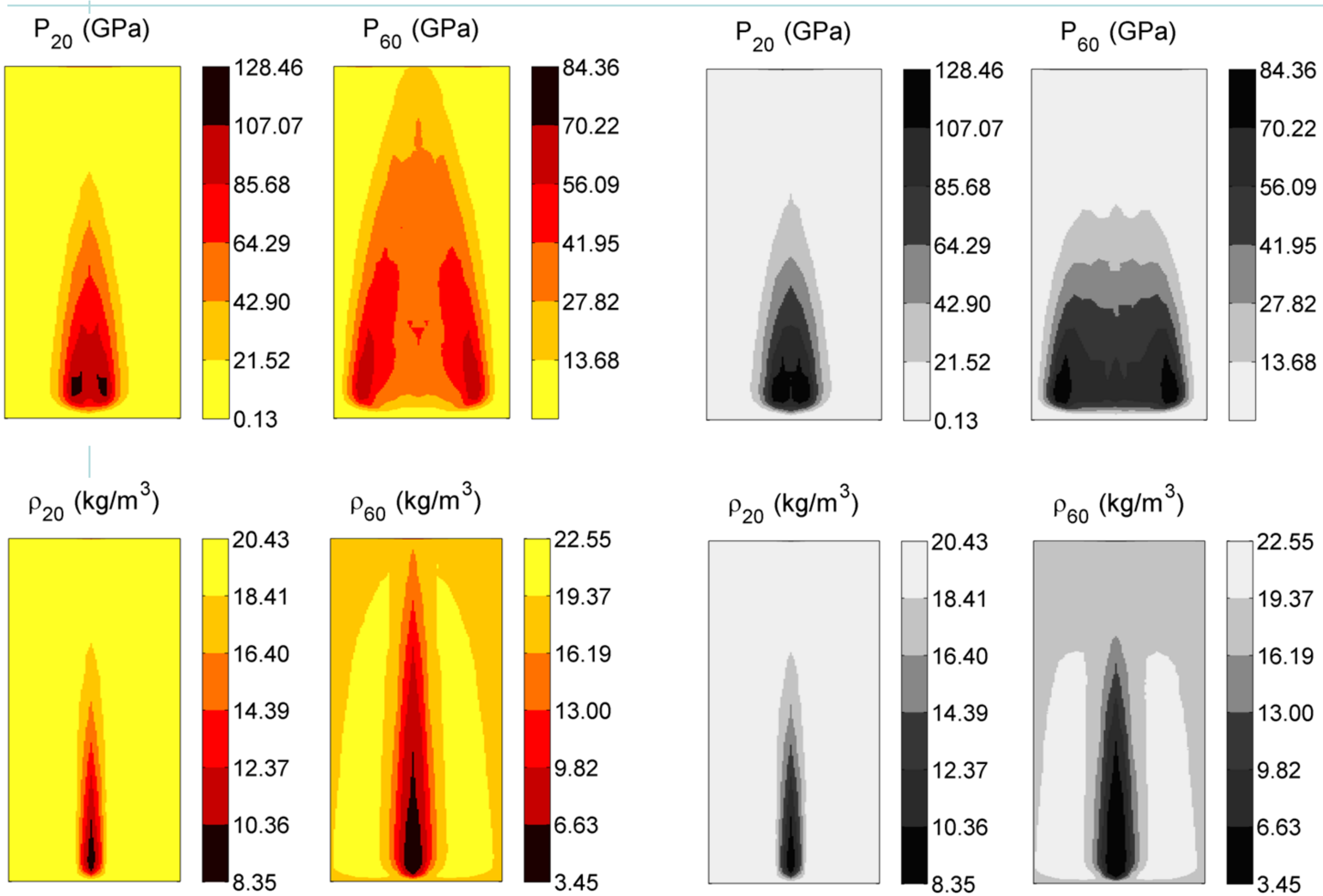


- ✓ The energy distribution changes both in values and shape
- ✓ The material, in which a great amount of energy is deposited, is subjected to a significant density reduction becoming more transparent to the next proton bunch
- ✓ *Tunnelling* effect: the proton beam penetrates more in depth in the material in the axial (*z*) direction and the energy is more diluted over the target



- ✓ The density modification involves higher longitudinal coordinates increasing the number of bunches
- ✓ After 60 bunches the total length of the target experiences a reduction in density in the zone around the beam axis

WP8: Fluka/LS-DYNA coupling (II)



Coupled

Uncoupled

- ✓ The pressure decreases in the region where there is the maximum deposition at the beginning while increases in the longitudinal direction due to the more in depth penetration of the beam.
- ✓ The state in term of pressure is completely defined on the EOS knowing the density and the energy. Considering the same density, the pressure is higher where the energy is higher. The differences between the two cases become more relevant increasing the number of bunches.

WP8: Fluka/LS-DYNA coupling (III)

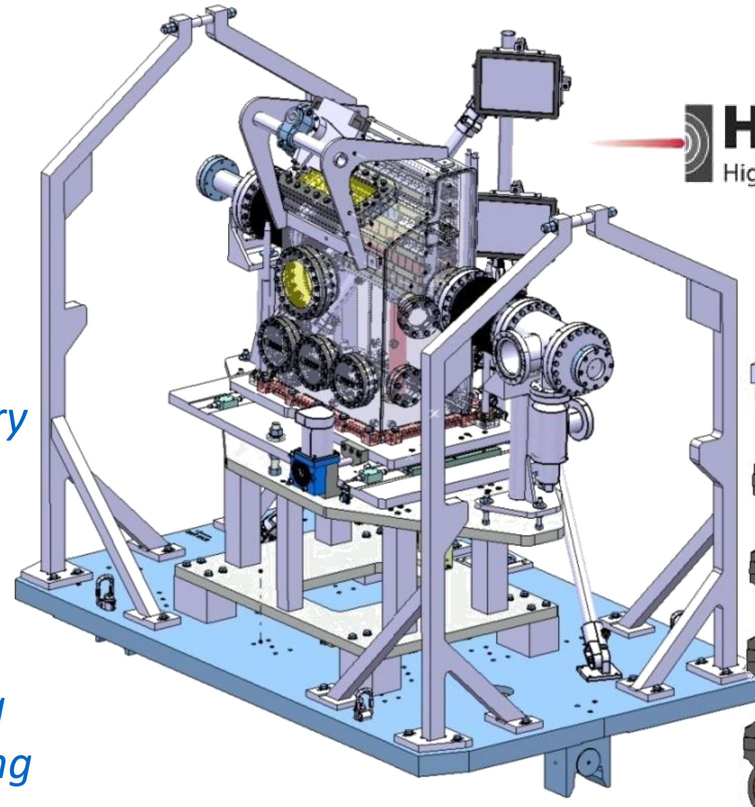
POLITO actively contributed to the concept and development phases of HRMT14 experiments

Impact configuration:

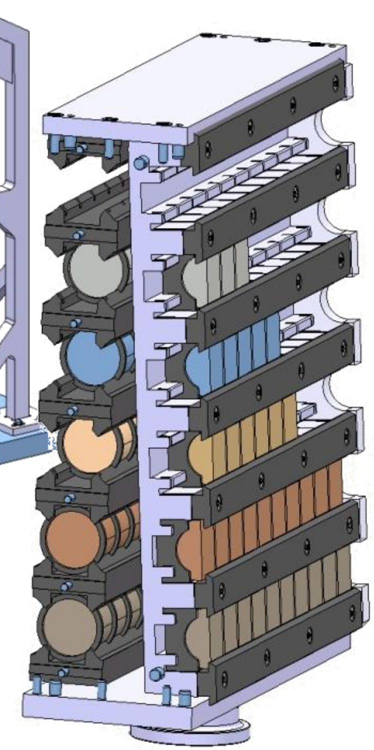
- ✓*Impact condition*
- ✓*Specimen shape and geometry*
- ✓*Boundary conditions*
- ✓*Materials*

Instrumentation:

- ✓*Sensor choice and positioning*
- ✓*Sensor and DAQ benchmarking*
- ✓*Fast camera triggering*
- ✓*Lightening system setup*



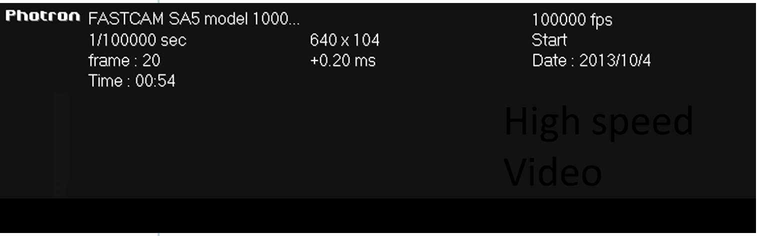
HiRadMat
High-Radiation to Materials



WP8: HiRadMat

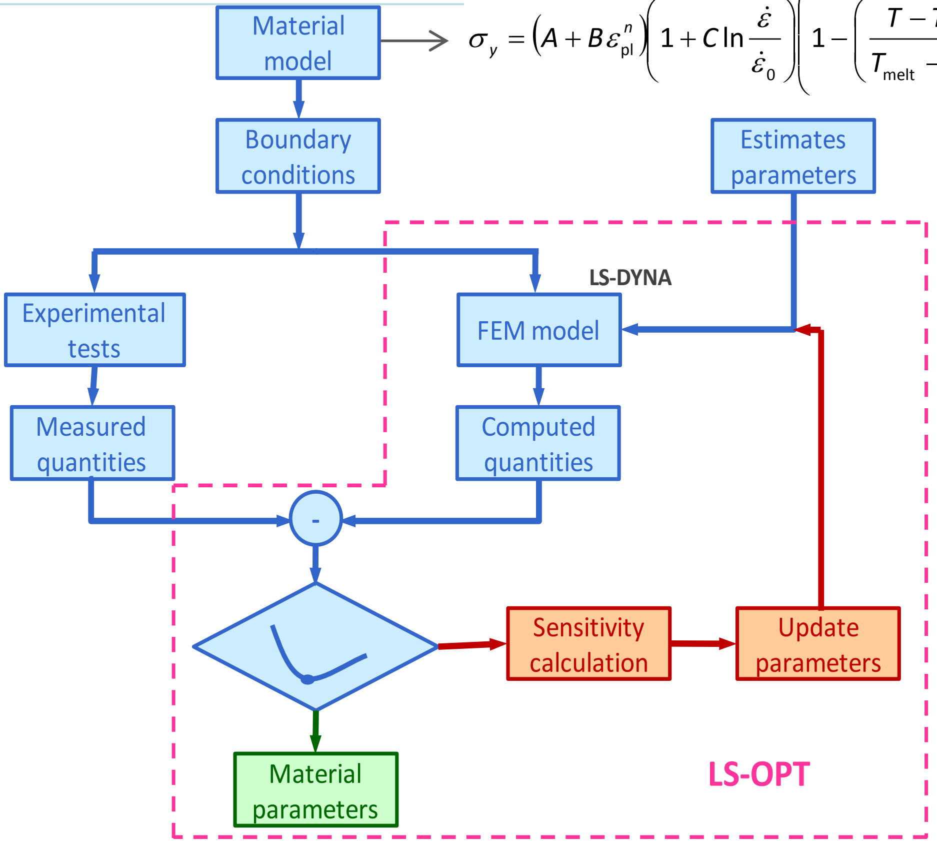
1. Development of strength and failure models for relevant materials (mechanical tests at different temperatures, strains and strain rates)
2. Fracture analysis of composites (brittle) materials
3. Contributions to the development of Equations of State for relevant materials
4. Contribution to multi-material tests in HiRadMat2

Hopkinsons Bars Gas Gun



High temperature dynamic tests

$$\sigma_y = \left(A + B\varepsilon_{pl}^{n}\right)\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\left(1 - \left(\frac{T - T_{ref}}{T_{melt} - T_{ref}}\right)^{m}\right)$$

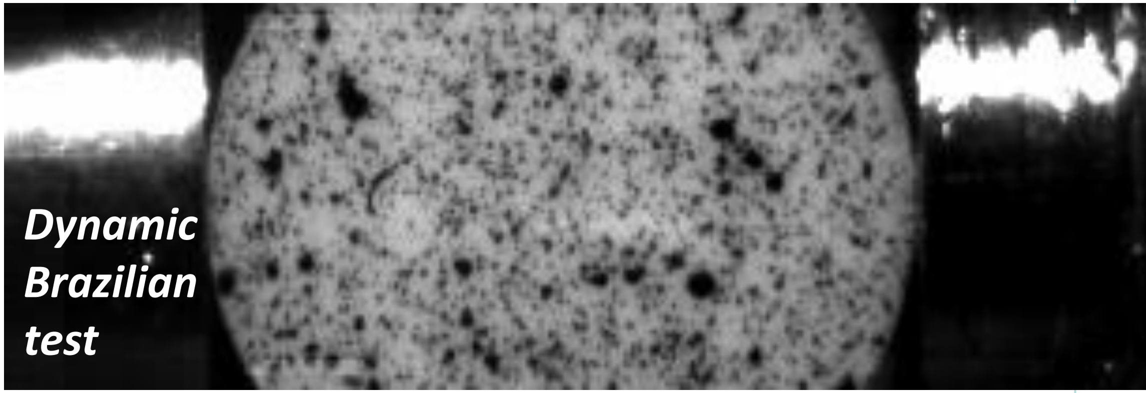


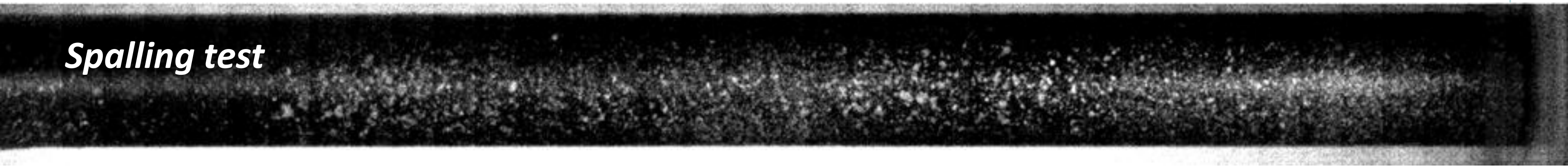
Experimental tests combined with numerical identification techniques of different strength material models in wide ranges of temperatures and strain-rates.

Development of strength and failure models

Development of experimental techniques suitable to investigate the dynamic behaviour of (brittle) composite materials, for different levels of strength.

Choice and calibration of failure models for this class of materials.



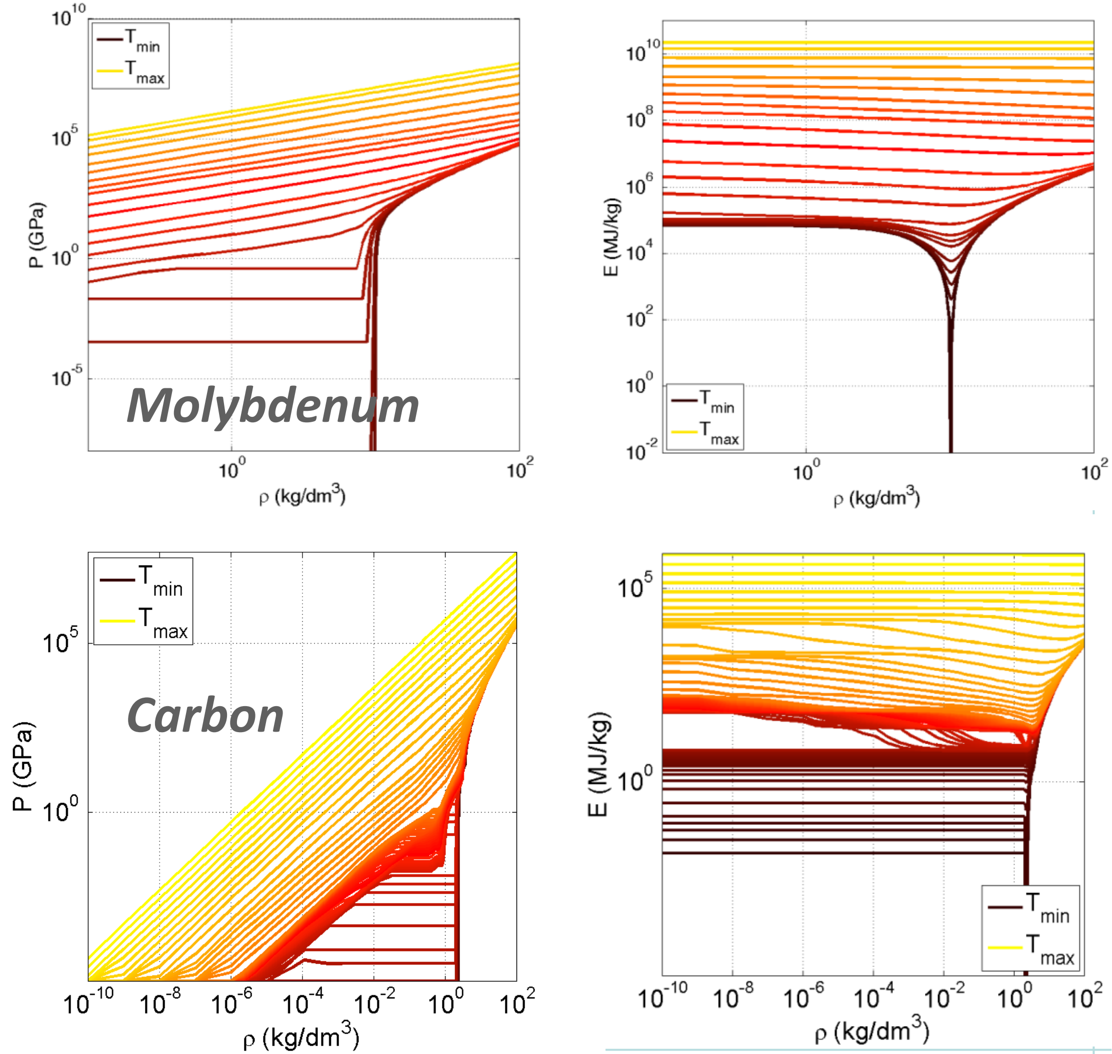


Fracture analysis of composites materials

Due to the mechanical engineering skills in this field, POLITO could not develop a whole EOS for new materials

Main actions could be:

- ✓ Benchmarking and checking of available or developed tables (hydrocodes requirements)
- ✓ Combining existing EOS to obtain EOS for mixture and composite materials (*for example molybdenum-graphite*)



Development of new Equations of State

HRMT14 was a successful and novel series of experiments but some improvements could be considered in the second generation of experiments on materials hit by particle beam:

- ✓ Optimization of the geometry and boundary condition of the specimens (reduction of the dimensions, new geometries)
- ✓ Evaluation of the mechanical quantities to acquire (stress, strain, pressure, velocity, displacements, acceleration…) and with which systems and transducers
- ✓ Optimization of the beam parameters (number of bunches, intensity, size) in function of type of material and required scenario: high number of bunches on cylinder specimen for tunnelling evaluation
- ✓ Evaluation of thermodynamics variable (temperature...)
- ✓ Electromagnetic disturbs/noise reduction

HiRadMat^2
High-Radiation to Materials

Politecnico di Torino: introduction, overview of WP8 work and possible contributions to WP11

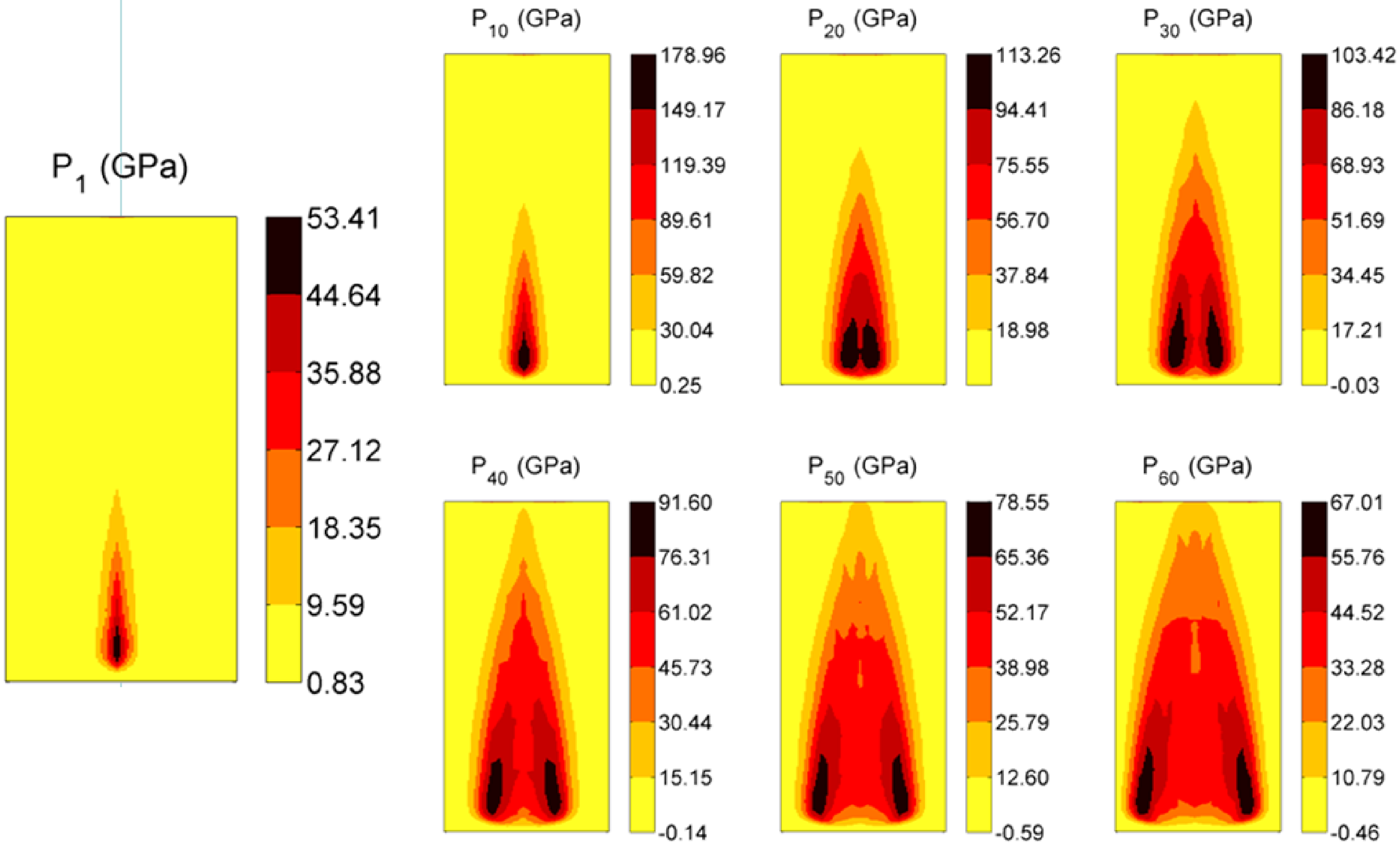
Thank you for your attention

Politecnico di Torino: introduction, overview of WP8 work and possible contributions to WP11

Backup slides

POLITECNICO DI TORINO

Dipartimento di Ingegneria Meccanica e Aerospaziale



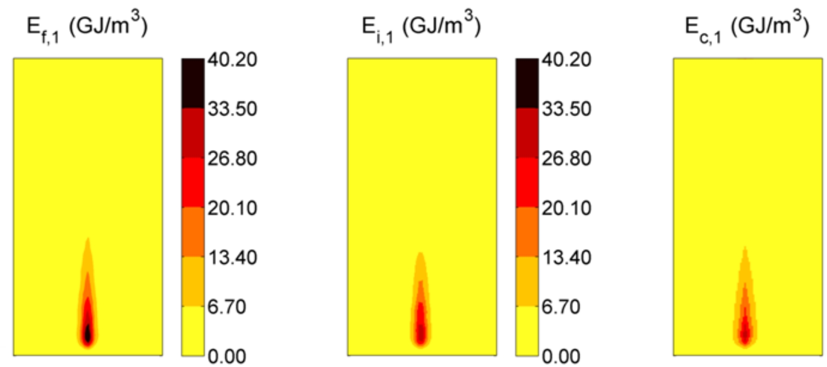
- ✓ The maximum of pressure remains more or less in the same longitudinal
- ✓ The pressure wave starts to travel in the *x* and *y* directions (the pressure wave is cylindrical)

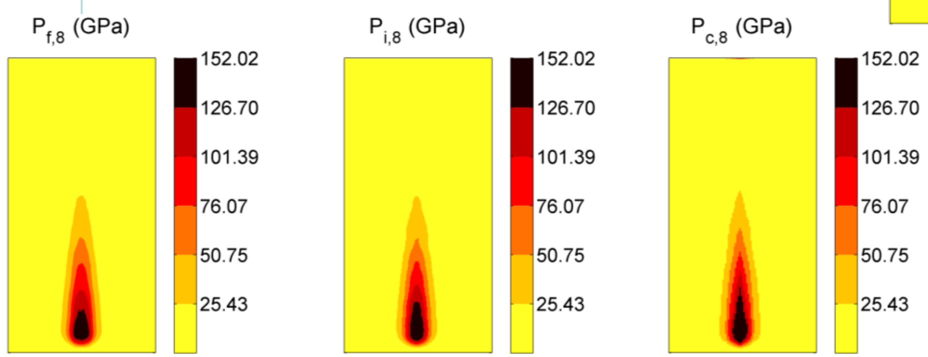
- ✓ The pressure increment, consequent to the next bunches, is reduced in the zone, in which the first bunch deposited a great amount of energy. On the other hand it should increase in the part of the target, in which there is an increment in density

COARSE: 1×1×5 mm

INTERMEDIATE: 0.5×0.5×2.5 mm

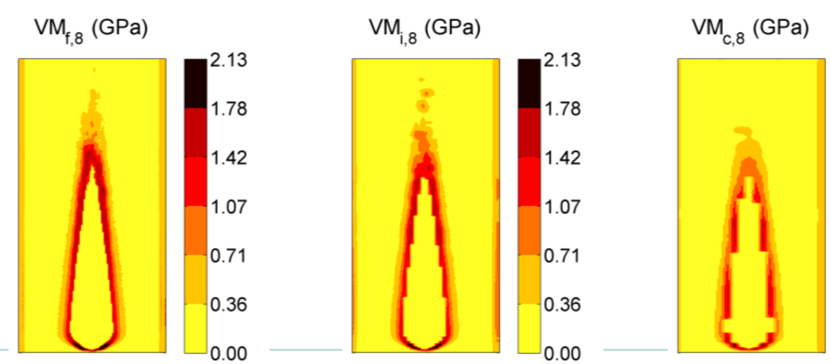
FINE: 0.2×0.2×2.5 mm



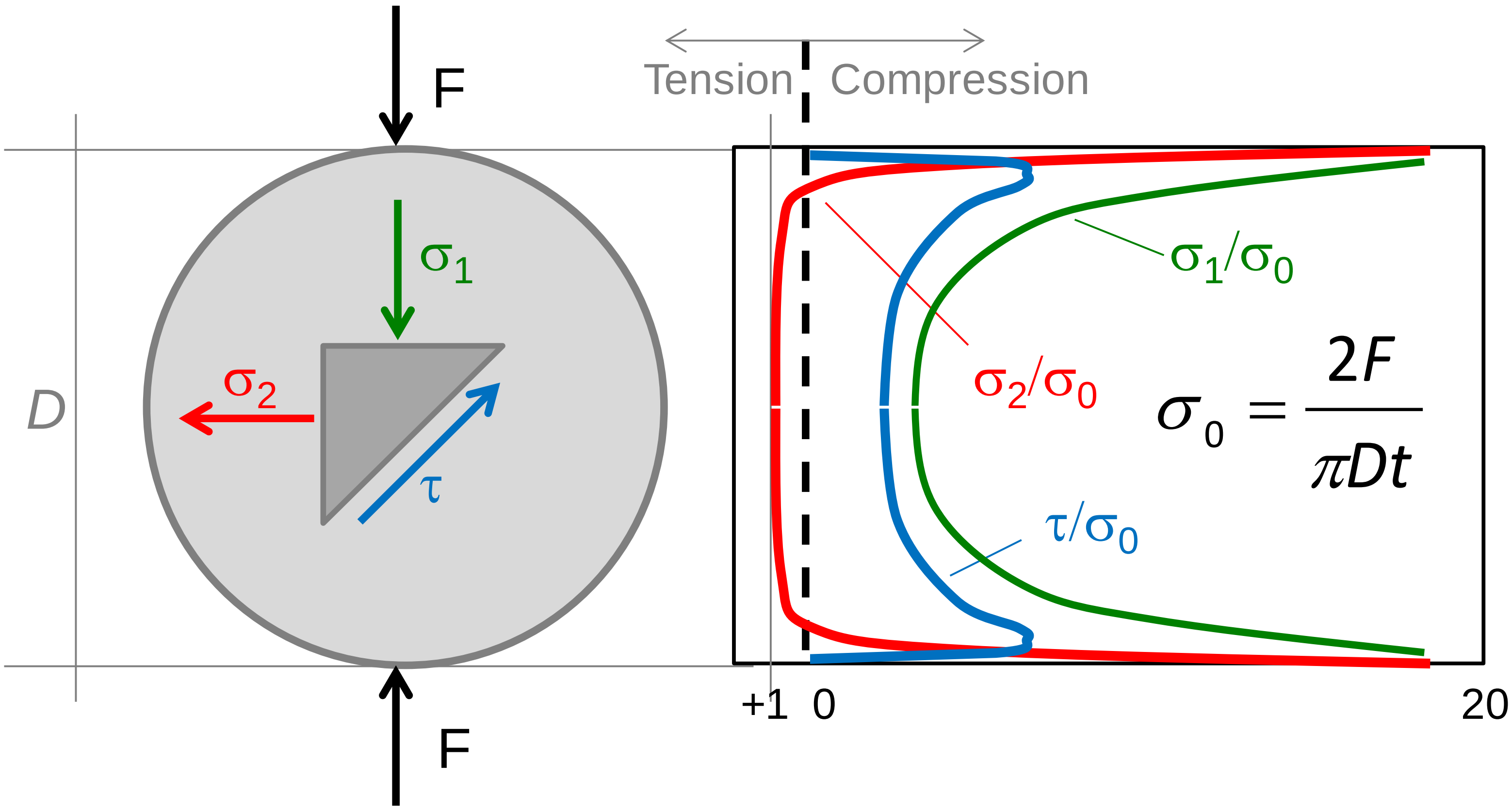


The maximum pressure is lower for the finest case but it is associated to a more significant reduction in density: higher tunnelling effect.
The computational cost is higher in case of the finest mesh

The finest case implies a more in depth penetration of the beam and a more defined and smooth distribution of the quantities over the target.



LS-DYNA/FLUKA: mesh influence

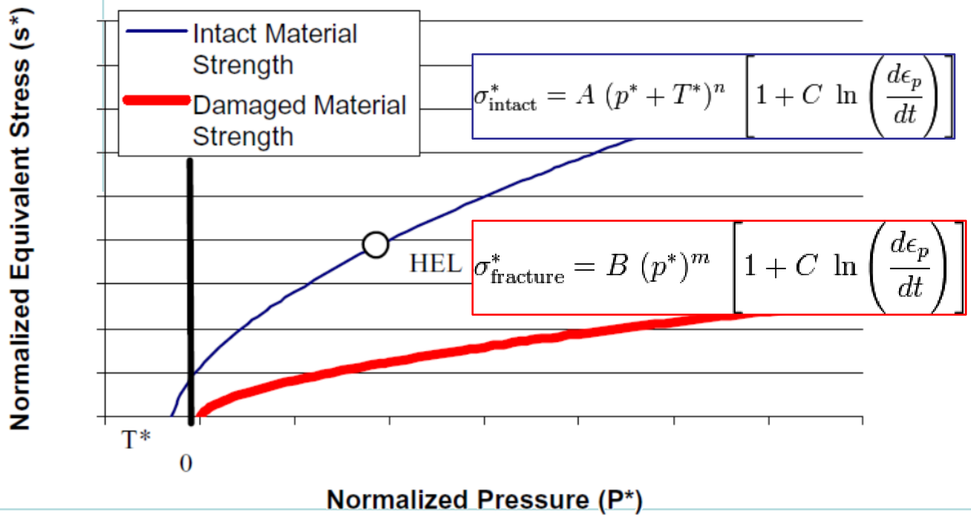


$$\sigma_0 = \frac{2F}{\pi D t}$$

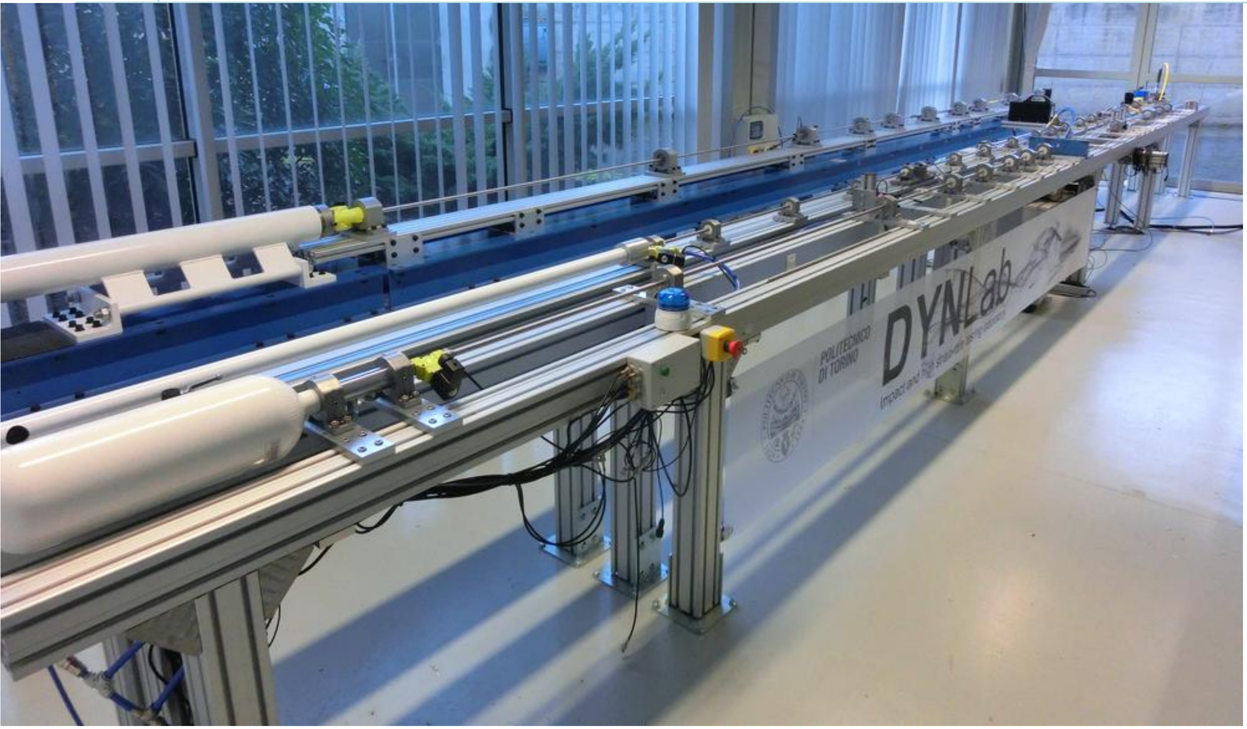
Pressure values (spall) and gradients produce fracture (in brittle material)!

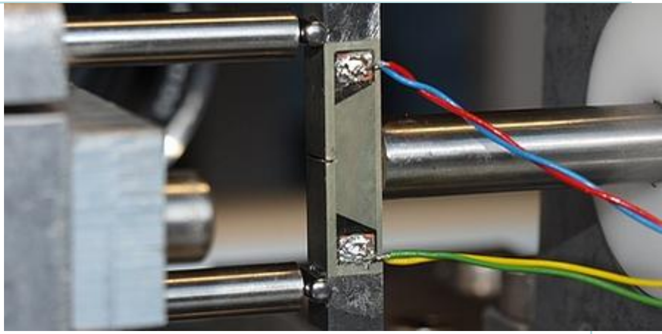
The **Johnson-Holmquist** material model), with damage, is useful when modeling brittle materials, such as ceramics, subjected to large pressures, shear strain and high strain rates.
The model simulates the increase in strength shown by ceramics subjected to hydrostatic pressure as well as the reduction in strength shown by damaged ceramics.

$$\sigma^* = \sigma^*_{\text{initial}} - D\ (\sigma^*_{\text{initial}} - \sigma^*_{\text{fracture}})$$



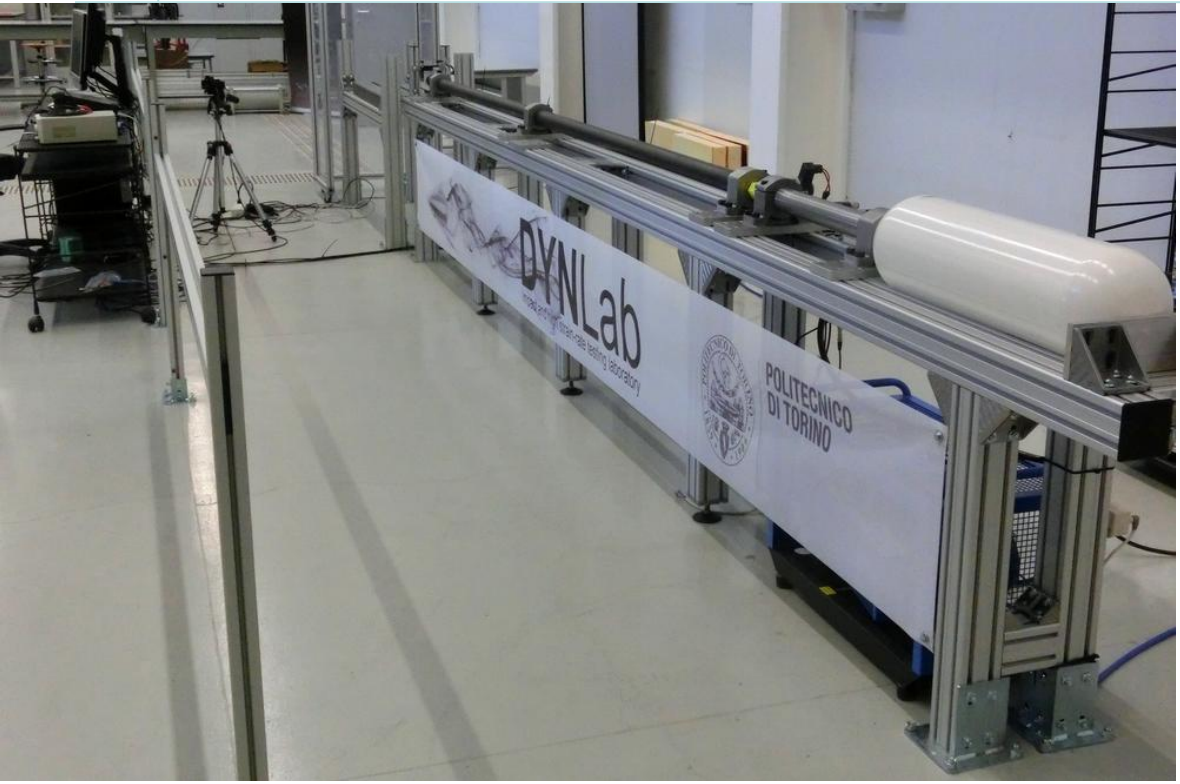
	B4C	SiC	AlN	Al2O3	Silica Float Glass
Reference	[9]	[12]	[10]	[8]	[11]
Density (kg/m^3)	2510	3163	3226	3700	2530
Shear Modulus (GPa)	197	183	127	90.16	30.4
Strength Constants					
A	0.927	0.96	0.85	0.93	0.93
B	0.7	0.35	0.31	0.31	0.088
C	0.005	0.0	0.013	0.0	0.003
M	0.85	1.0	0.21	0.6	0.35
N	0.67	0.65	0.29	0.6	0.77
Ref Strain Rate (EPSI)	1.0	1.0	1.0	1.0	1.0
Tensile Strength (GPa)	0.26	0.37	0.32	0.2	0.15
Normalized Fracture Strength	0.2	0.8	NA	NA	0.5
HEL (GPa)	19	14.567	9	2.79	5.95
HEL Pressure (GPa)	8.71	5.9	5	1.46	2.92
HEL Vol. Strain	0.0408		0.0242	0.01117	
HEL Strength (GPa)	15.4	13.0	6.0	2.0	4.5
Damage Constants					
D1	0.001	0.48	0.02	0.005	0.053
D2	0.5	0.48	1.85	1.0	0.85
Equation of State					
K1 (GPa) (Bulk Modulus)	233	204.785	201	130.95	45.4
K2 (GPa)	-593	0	260	0	-138
K3 (GPa)	2800	0	0	0	290
Beta	1.0	1.0	1.0	1.0	1.0





- ✓ 4 Hopkinson bar systems (tension, compression/bending, miniaturized) with semiconductor straingages and fast data acquisition system (up to 20 MHz)
- ✓ Standard test (tensile, compression), miniaturized tensile, Brazilian test and spalling test (brittle), triaxiality effect (notched specimens), fracture toughness …
- ✓ 2 high speed video cameras (max **1 Mfps**) and one VISAR

Strength and failure models - hopkinson



- Light Gasgun forTaylor test, flyer-plate and ballistic impacts

- 2 high speed video cameras (max **1 Mfps**) and one VISAR

Strength and failure models - gasgun

- ✓ Maxima performances: full resolution **1024 x1024** (7000 fps); maximum frame rate **1000000 f/s** (64 x 16 pixels);
- ✓ Shutter: global electronic shutter up to **369 ns**, frame rate independent
- ✓ Variable Region of Interest (ROI)
- ✓ Capture **12-bit** uncompressed data
- ✓ 20µm pixels ensure best light sensitivity for demanding high-speed or low light applications
- ✓ 8GB memory (standard: 5457 frames or 0.780 s @ maximum resolution)
- ✓ Gigabit Ethernet interface
- ✓ Triggering and trigger delay options programmable and selectable

Specifications: Partial Frame Rate / Recording Duration Table

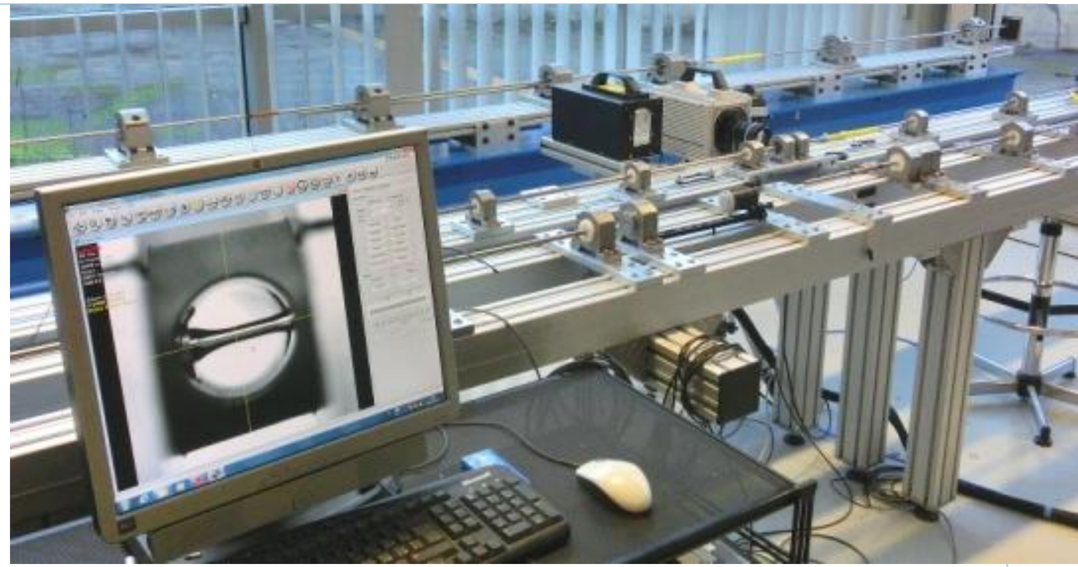
FRAME RATE (fps)	MAXIMUM RESOLUTION Horizontal	MAXIMUM RESOLUTION Vertical	MAXIMUM SHUTTER SPEED	RECORD DURATION (12-BIT) TIME (Sec.) 8GB	16GB	32GB	64GB	FRAMES 8GB	16GB	32GB	64GB
1,000	1,024	1,024	1 µs 1/1,000,000 sec	5.46	10.92	21.84	43.68	5,457	10,918	21,841	43,686
2,000	1,024	1,024		2.73	5.46	10.92	21.84	5,457	10,918	21,841	43,686
4,000	1,024	1,024		1.36	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5,000	1,024	1,024		1.09	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7,000	1,024	1,024		0.78	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7,500	1,024	1,000		0.75	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
9,300	1,024	800		0.75	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10,000	1,024	744		0.75	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
15,000	960	528		0.75	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
20,000	832	448		0.77	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
30,000	768	320		0.78	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
50,000	512	272		0.82	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
75,000	320	264		0.90	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
100,000	320	192		0.93	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
150,000	256	144		1.03	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
300,000	256	64		1.16	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
420,000	128	64		1.66	3.33	6.66	13.31	698,538	1,397,589	2,795,690	5,591,893
525,000	128	48		1.77	3.55	7.10	14.20	931,384	1,863,452	3,727,587	7,455,857
775,000	128	24		2.40	4.81	9.62	19.24	1,862,769	3,726,904	7,455,175	14,911,715
930,000	128	16	369 ns 1/2,712,000 sec	3.00	6.01	12.02	24.05	2,794,154	5,590,357	11,182,762	22,367,573
1,000,000	64	16		5.59	11.18	22.37	44.73	5,588,309	11,180,714	22,365,525	44,735,146

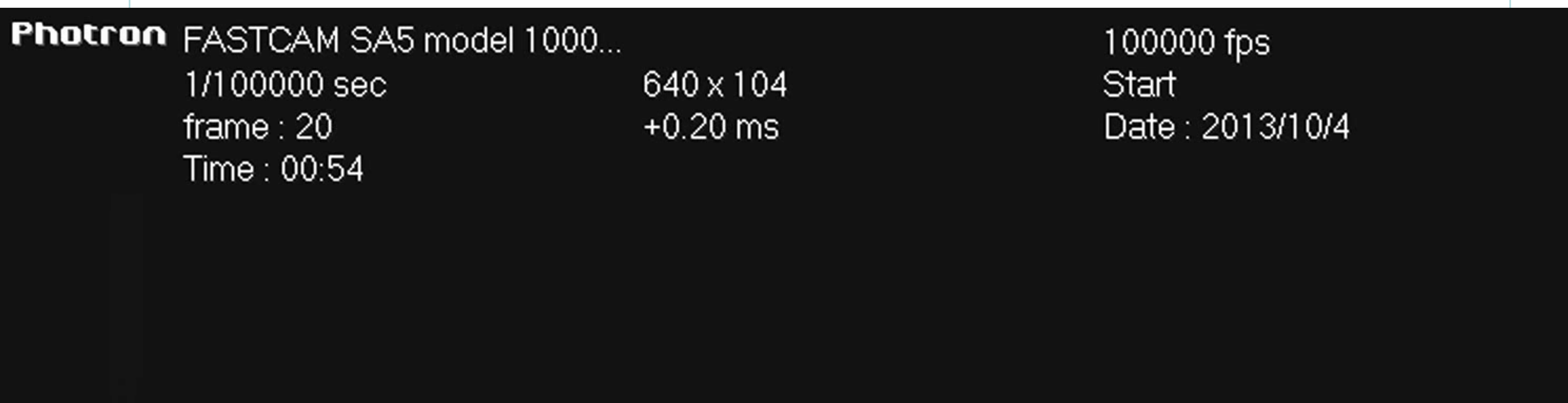
OPTION SUBJECT TO EXPORT LICENSE CONTROL RESTRICTIONS WHERE APPLICABLE

Accordingly with EUCARD2 improvement process of all testing facilities a new high speed camera was acquired

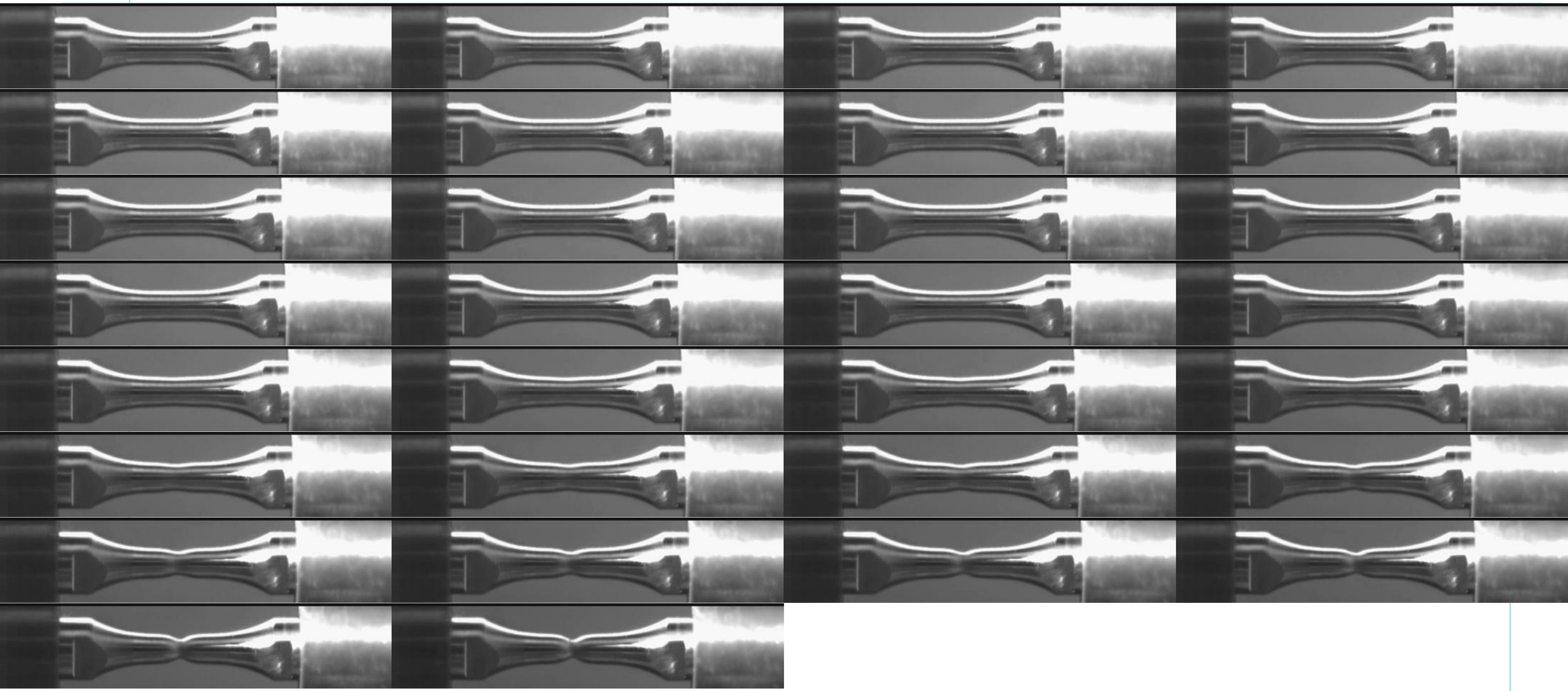
High speed camera (I)

Video acquisition could be synchronized with data acquisition systems (which generates trigger) and lightening system (flash light)
The time between trigger and full light illumination is about **20 μs**

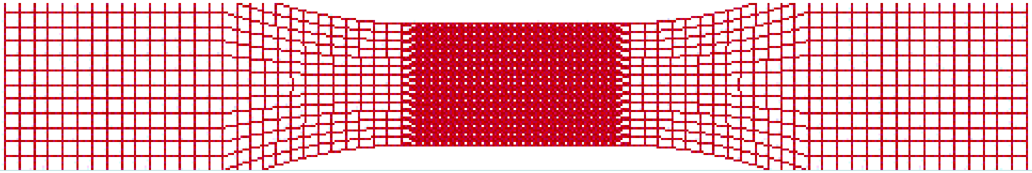




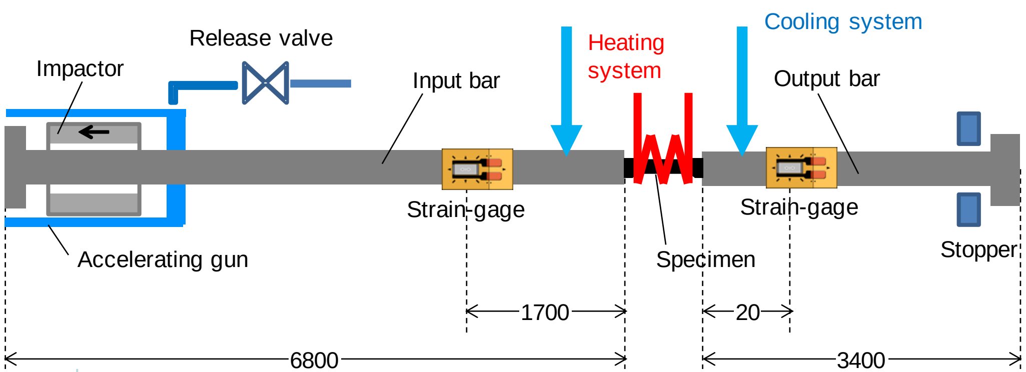
High speed camera (II)

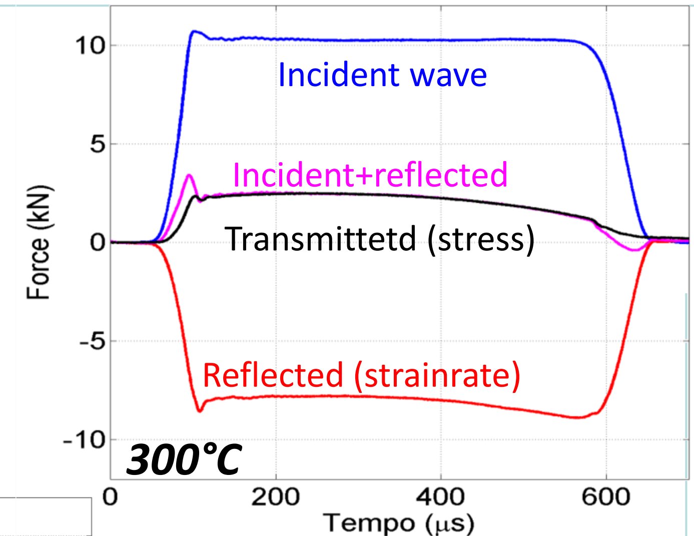


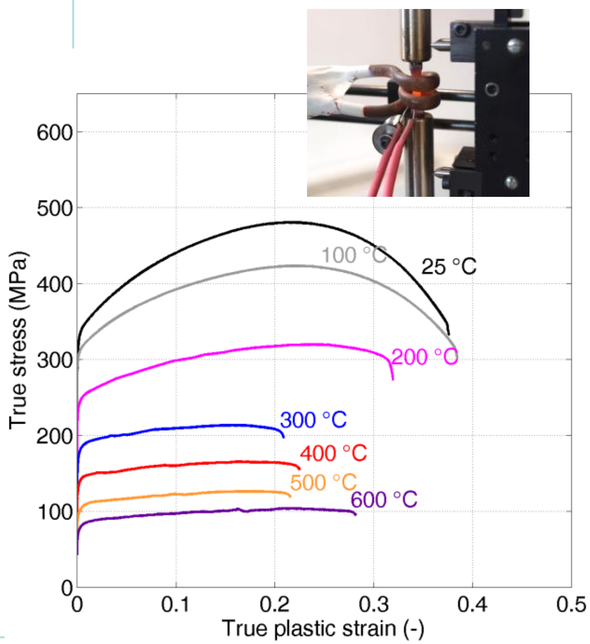
A great number of high resolution images are avaliable for FEM comparison and image analysis

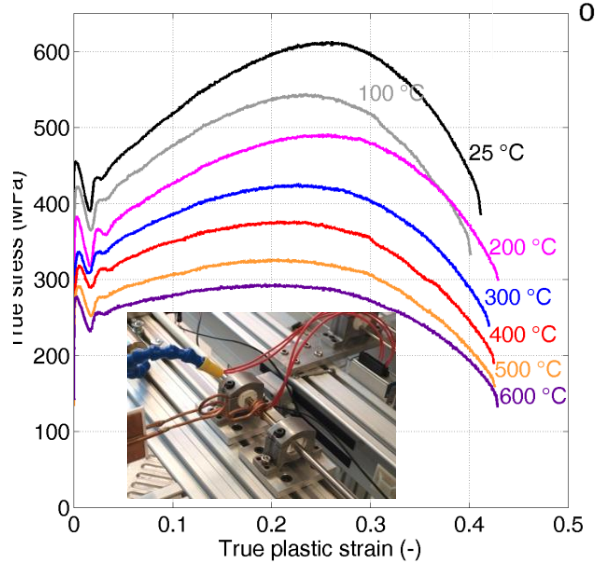


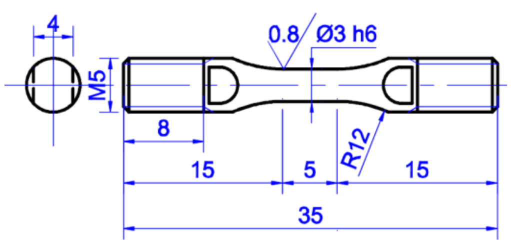
High speed camera (III)



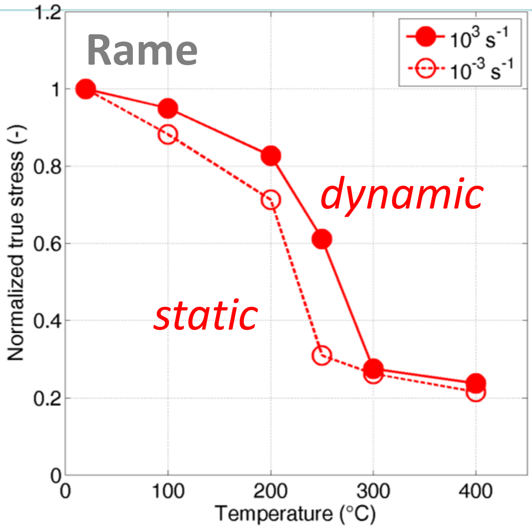


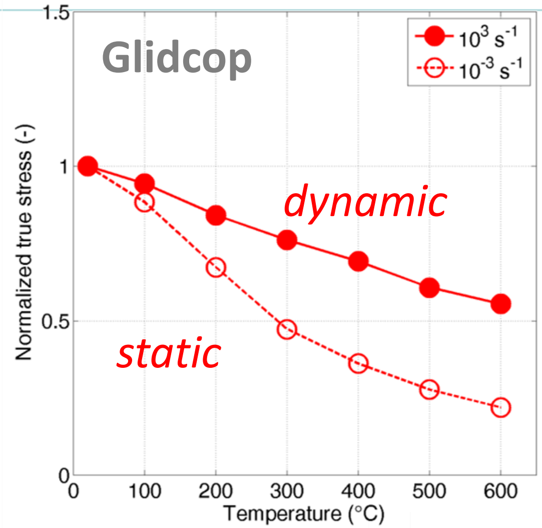


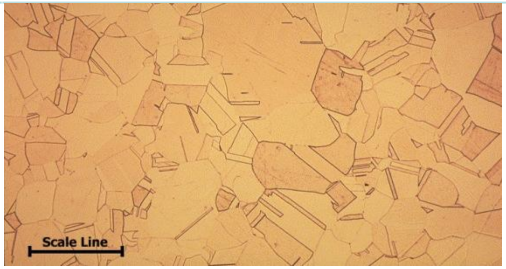


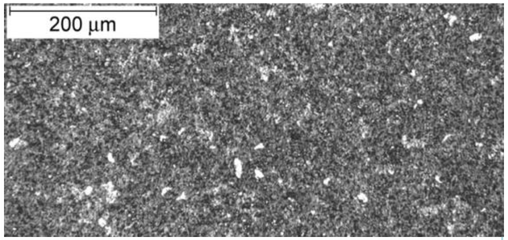


Strain-rate & temperature (I)

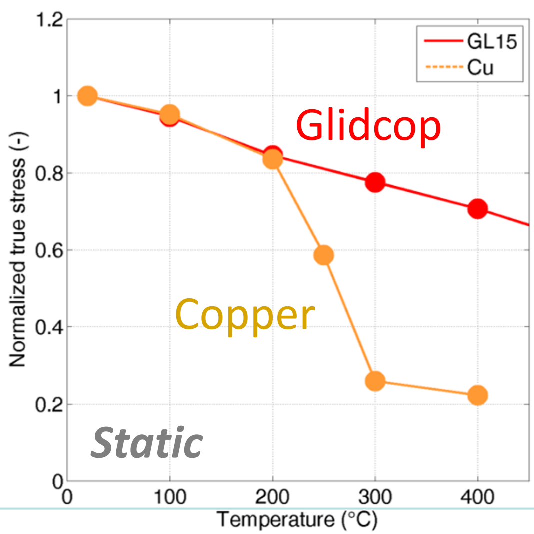


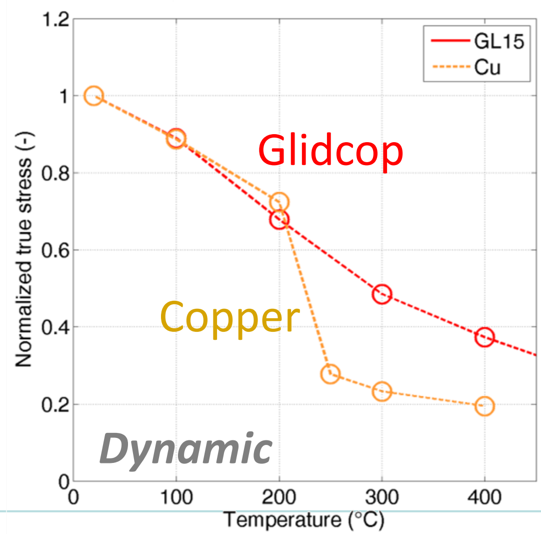




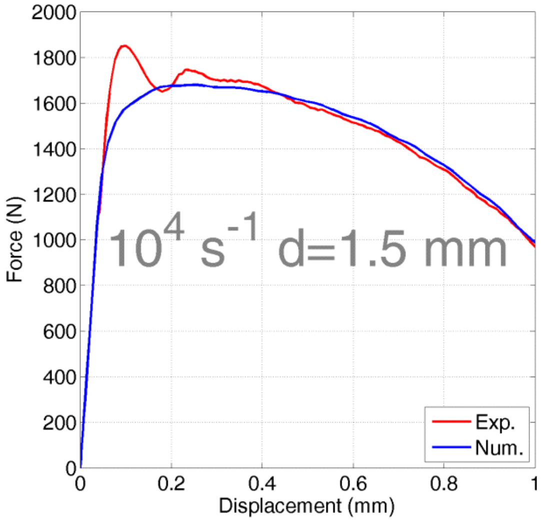


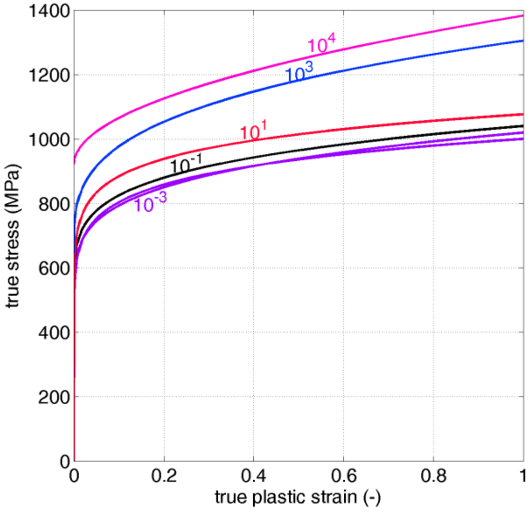
ε =10%

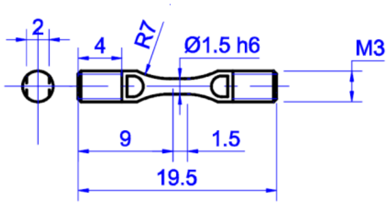


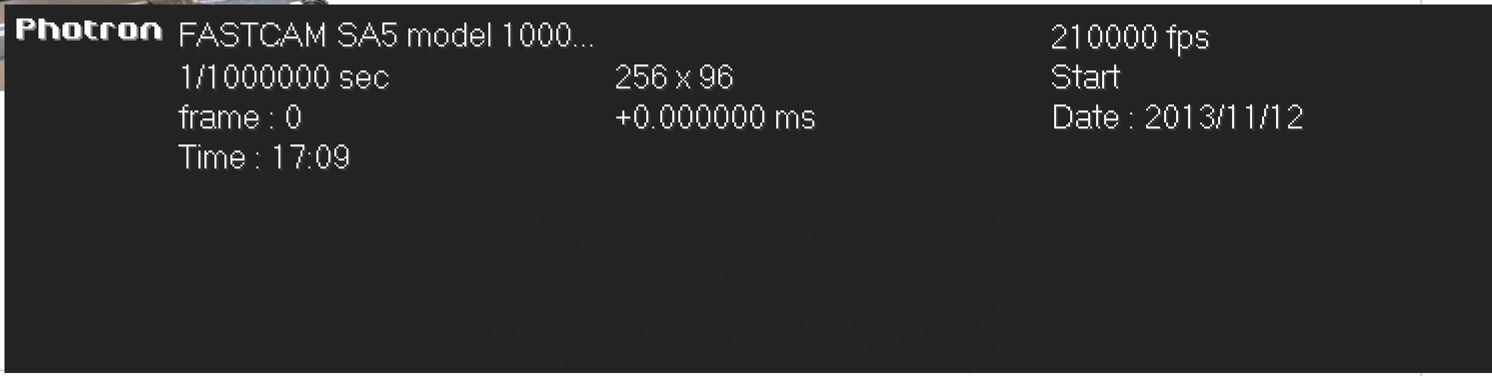


Strain-rate & temperature (II)

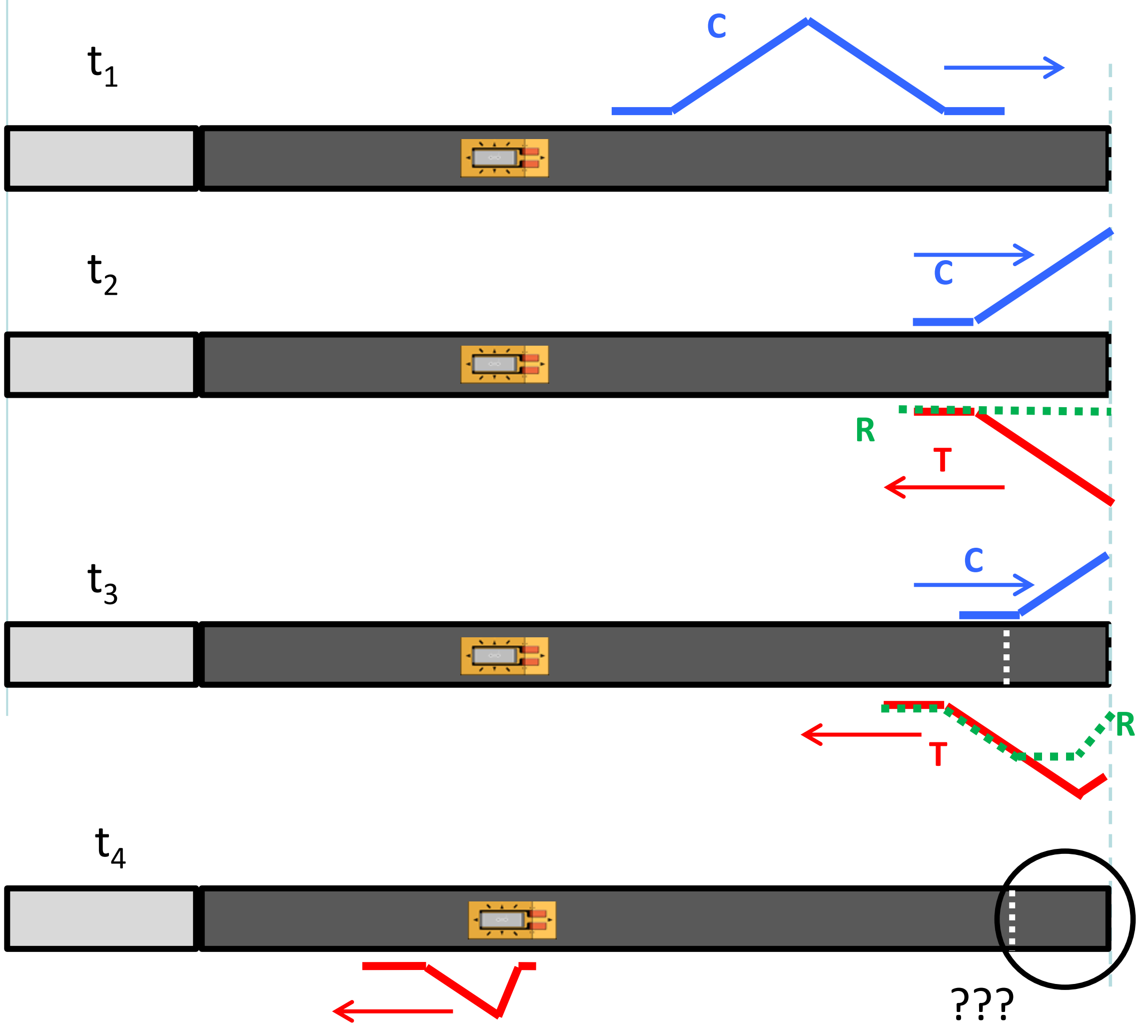








Ultra high strain-rate ($10^4 s^{-1}$)



The compressive wave (**C**) of length L is transmitted into the specimen and travels until reaching the free surface

At the free surface the compressive wave is reflected back as tensile wave (**T**), which grows in amplitude: when **T** = **C**, the resultant **R** = 0 and the specimen is completely unloaded.

When the resultant **R** = **T** – **C** reaches the ultimate stress of the material, it generates a fracture surface.

The wave travelling inside the left main fragment is limited in amplitude by the ultimate stress of the material, and cannot generate other fractures (unless inhomogeneities are present). Further fracture could occur in the right fragment.

SHPB Spalling test