Beam Induced Damage Mechanisms and Their Calculation

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with contributions from
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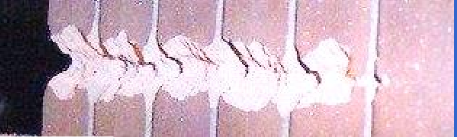
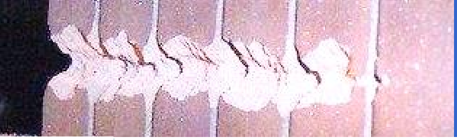


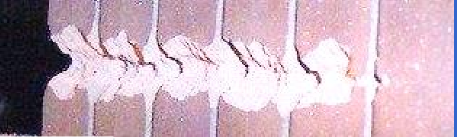
Outline

- Objective and Scope of the Lectures
- Part I: Introduction to Beam-induced Accidents
- Part II: Analysis of Beam Interaction with Matter
- Part III: Design Principles of Beam Interacting Devices
- Part IV: Experimental Testing and Validation



Objectives and Scope of the Lectures

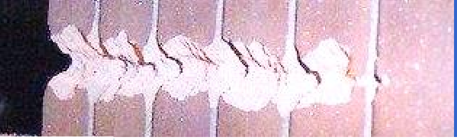
- We deal with **rapid and intense interactions** between **particle beams** and accelerator components (typically lasting **ns** to **μs**). We do not treat here other energy release mechanisms (e.g. of stored magnetic energy)
- Focus on **damage mechanisms** occurring **in the μs scale**. Longer term phenomena (e.g. radiation damage) are not extensively covered
- Mainly treat components directly exposed to interaction with beam (**Beam Interacting Devices**)
- However, **mechanisms extend to any other component** accidentally and rapidly interacting with energetic beams (vacuum chambers, magnets, cavities).
- Mostly treating **isotropic materials**. Principles can be extended to **anistropic** materials with some mathematical complexity
- In **first lecture**, focus is given on the theoretical and thermo-mechanical principles allowing to **analyze the phenomena**.
- In **second lecture**, we deal with the **design of beam interacting systems** treating aspects as figures of merit, intensity limits, advanced materials, testing facilities etc.



Outline

Design Principles of BID

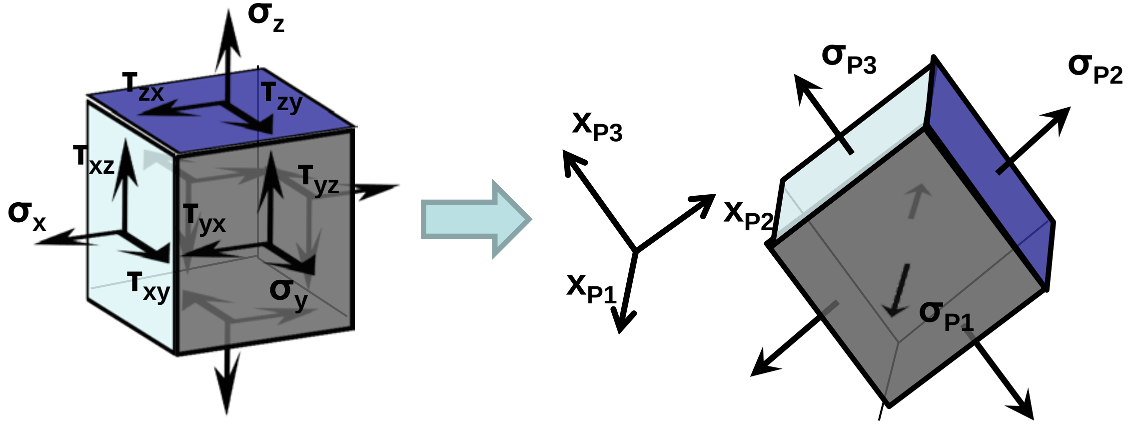
- Objective and scope of the lectures
- Part I: Introduction to Beam-induced Damage
- Part II: Analysis of Beam Interaction with Matter
- Part III: Design Principles of Beam Interacting Devices (BID)
  - Introduction to Failure Criteria
  - Material Selection: Figures of Merit
  - Materials for Beam Interacting Devices
- Part IV: Experimental Testing and Validation



- ✓ Introduction to Failure Criteria
  - ✓ General State of Stress
  - ✓ Failure Criteria: von Mises
  - ✓ Failure Criteria: Stassi – d’Alia
  - ✓ Deformation to Failure

General State of Stress – Failure Criteria

- **Failure Theories** were developed (mostly empirically) to predict failure in case of combined state of stress
- Many theories are based on the **reduction** of the complete 3D stress state to one in which only **normal stress** acts along each of the **3 principal directions**.

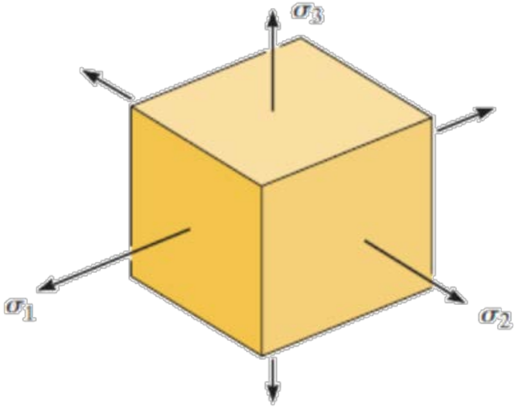


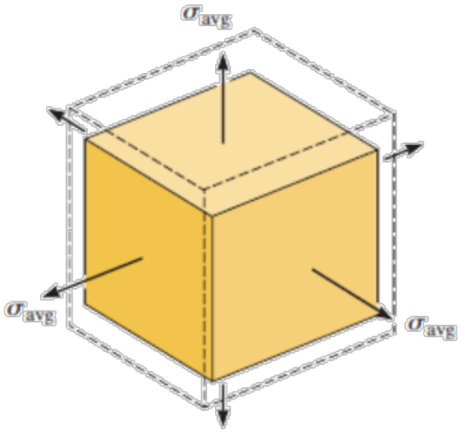
- **No single Failure Theory is suitable to every material under any state of stress and for all conditions**!
- **Safety coefficients** are adopted to protect against the approximation of Failure Criteria and the uncertainties in the state of stress knowledge.

Failure Criteria: von Mises

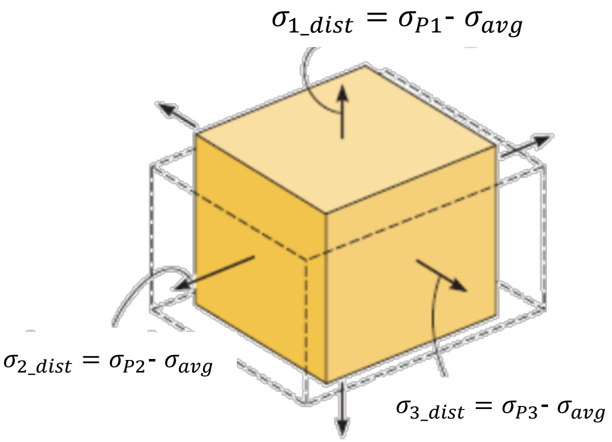
Maximum-distortion-energy theory (or von Mises-Huber Yield criterion)

- Suitable for Ductile Materials. Extensively used.
- **Total Strain Energy** can be considered as the sum of **two parts**, one representing the energy causing **volume change** with no change in shape, and the other representing the energy **distorting** the element.
- Failure (by **plastic yielding**) is assumed to occur when the **Distortion Energy** in the material reaches the same critical value as in a tension test at yielding.

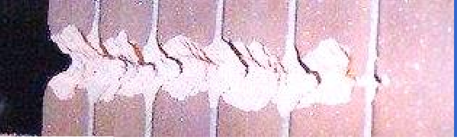




Volume change



Shape distortion



Failure criteria: von Mises and Stassi – d’Alia

Maximum-distortion-energy theory (or Von Mises-Huber Yield criterion)

Resistance condition

$$\sigma_Y \geq \sigma_{EQ} = \frac{1}{\sqrt{2}} \cdot \sqrt{(\sigma_{P1}-\sigma_{P2})^2+(\sigma_{P2}-\sigma_{P3})^2+(\sigma_{P3}-\sigma}$$

Pressure-modified von Mis

- Suitable for Isotr e strengths (e.g. *Grap*

$$k = -\frac{\sigma_{strength\_compression}}{\sigma_{strength\_tension}}$$

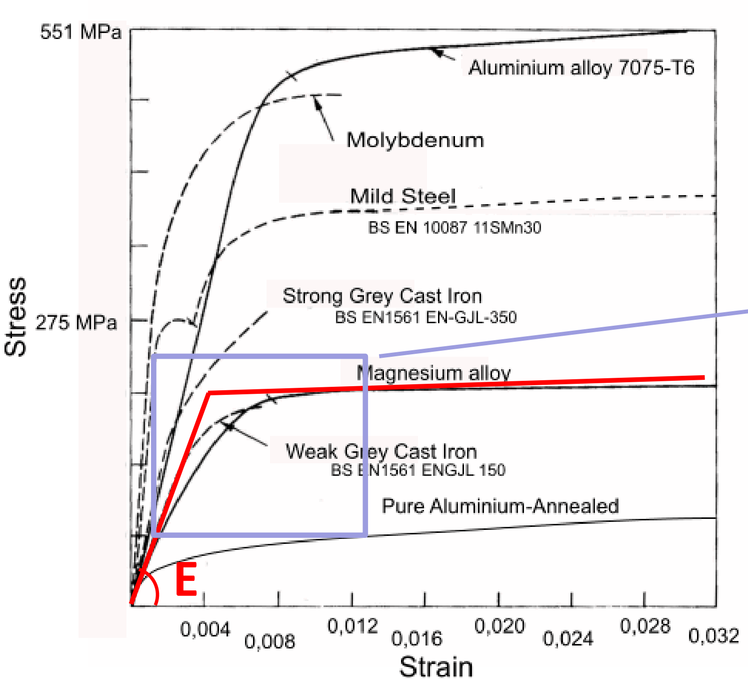
$$P = -\frac{\sigma_{P1}+\sigma_{P2}+\sigma_{P3}}{3}$$

Nota Bene: We’ve seen how many regimes are possible (linear elastic, elasto-plastic, shock), depending on material properties and loading conditions

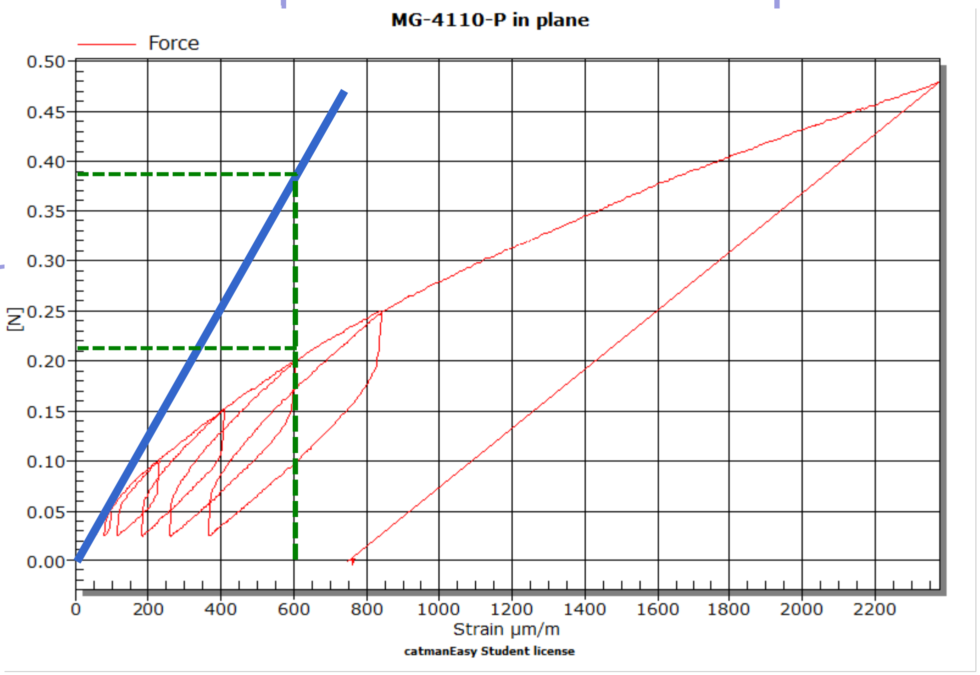
For baseline conditions, seek elastic regime!!

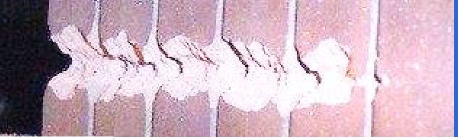
Deformation to Failure

- The linear approximation is a powerful mean to describe the stress-strain relationship.
- For some materials, though, **σ-ε can depart appreciably from linearity**. Examples are: Copper, Aluminum and Magnesium alloys, and particularly **Graphitic materials** …
- For **deformation-driven** problems (e.g. beam-induced energy deposition), **overestimation** can be made when considering tension as the limiting factor
- **Deformation to Failure** is a **more realistic criterion** is such cases!!



Molybdenum-Graphite Force vs. Strain





Material Selection: Figures of Merit

- ✓ Material Selection: Figures of Merit
  - ✓ General Recommendations for Materials
  - ✓ Figures of Merit: Thermomechanical Robustness
  - ✓ Figures of Merit: Thermal Stability
  - ✓ Figures of Merit: Electrical Conductivity
  - ✓ Figures of Merit: Radiation Resistance

General Recommendations for Materials

- The **choice** of a particular material for a BID, as much as for any other system, is driven by the material **performance under different points of view**

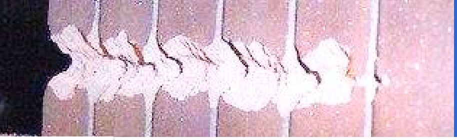
- Such aspects may be **general** for all applications or **component-driven**

  Some component-driven requirements include ...
  Radiation Hardness, Robustness, UHV Compatibility, Industrial feasibility of large components, Possibility to machine, braze, join, coat ..., Cost ...

Q: How to decide amongst a number of materials in the early phase of design?

- Relevant parameters can be **turned into** a set of **arbitrary Figures of Merit** (FOMs), allowing to rank materials against a **specific requirement**

IMPORTANT! *Figures of Merit rely on simplified, constant, temperature-independent material properties.*
*They should be used as **indicative, comparative tools** in the design phase and **not for quantitative assessment** of performance!*



Figures of Merit : Thermomechanical Robustness

Thermomechanical Robustness Index (TRI)

$$TRI = \boxed{\frac{\varepsilon_{Adm}}{\varepsilon_{Real}}} \left(\frac{T_m}{\Delta T_q} - 1\right)^m$$

$$\varepsilon_{Real} = \bar{\alpha} \cdot \boxed{\Delta T_q}$$

$$\varepsilon_{Adm} = \frac{\boxed{R_M}}{\bar{E} \cdot (1-\nu)}$$

$$\Delta T_q = \frac{C_R \rho^n}{c_p X_g} \propto \frac{q_d}{c_p}$$

- ***TRI*** is related to the ability of a material to **withstand the impact** of a short particle pulse
- In thermal shock problems, **admissible strain** is the most meaningful quantity as the phenomenon is governed by thermal deformation
- On the other hand, effective **strength** values (**R_M**) are much easier to obtain in literature
- The term in **T_m** (**melting temperature**) provides an indication of the loss of strength at increasing temperature
- **ΔT_q** is a temperature increment related to the energy deposited **q_d** in the material by a given particle pulse.
- Deposited energy is to some extent related to the **Geometric Radiation Length X_g** and material **density ρ**
- **C_R**, ***n***, ***m*** are **arbitrary** coefficients defining the influence of various parameters.

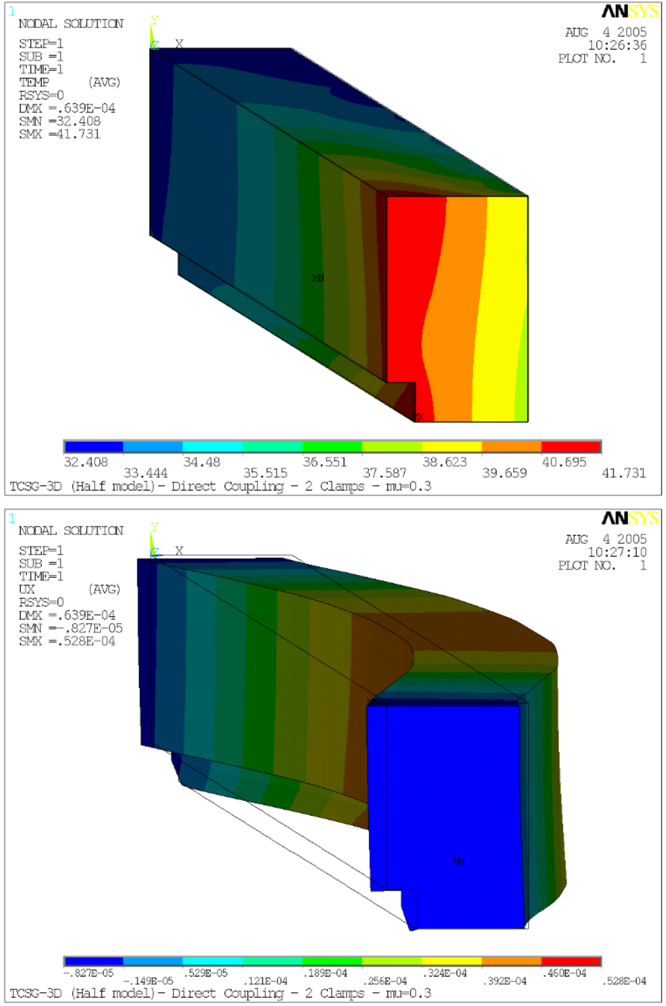
$$TRI = \frac{R_M c_p X_g}{\bar{E}(1-\nu)\bar{\alpha} C_R \rho^n} \cdot \left(\frac{T_m c_p X_g}{C_R \rho^n} - 1\right)^m$$

Thermal Stability Index (TSI)

- Under steady-state or slowly transient heat deposition, ***TSI*** provides an index of the **ability of the material to maintain geometrical stability** of the component.
- It is related to the **inverse of the curvature** of a long structure induced by a non uniform temperature distribution (for given **steady-state particle losses**).
- ***TSI*** is proportional to thermal conductivity and radiation length; inversely proportional to CTE and density …
- For anisotropic materials (e.g. *Carbon-Carbon*, *MoGr*) **weighted average properties** are assumed.

$$TSI = \frac{\bar{\lambda} X_g}{\bar{\alpha} C_S \rho^n}$$

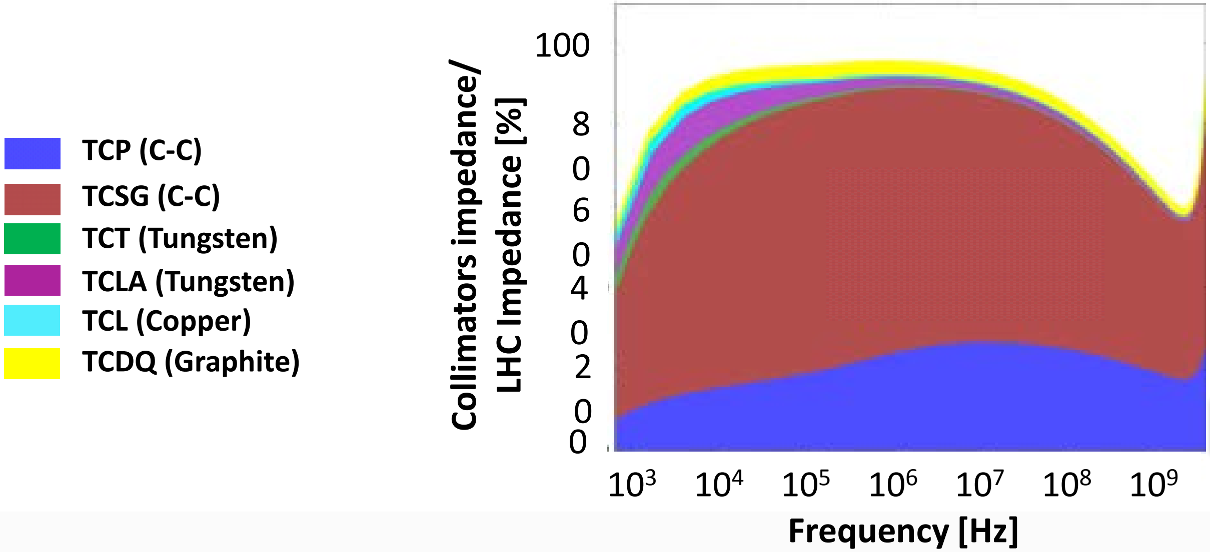
Operating temperature and thermally-induced deflection of a LHC secondary collimator jaw



Figures of Merit : Electrical Conductivity

Electrical Condutivity (γ)

- Components located in accelerator rings (collimators, absorbers, spoilers …) are required to minimize their contributions to **RF impedance** to limit **adverse electromagnetic effects on beam stability**.
- In “classical” regime, **RF-impedance** drastically **increases when beam approaches the “resistive wall”** ($\propto 1/b^3$) ⇨ contributions to impedance are much larger from components sitting close to the circulating beam as BIDs.
- RF-impedance is inversely proportional to electrical conductivity ⇨ **highest electrical conductivity** is sought for materials sitting **closest to circulating beams**!

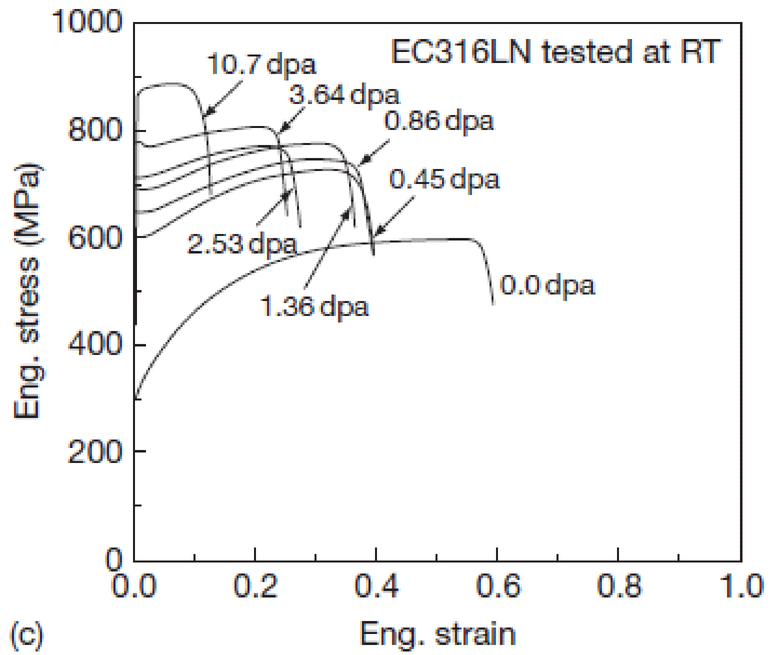


N. Mounet (CERN)

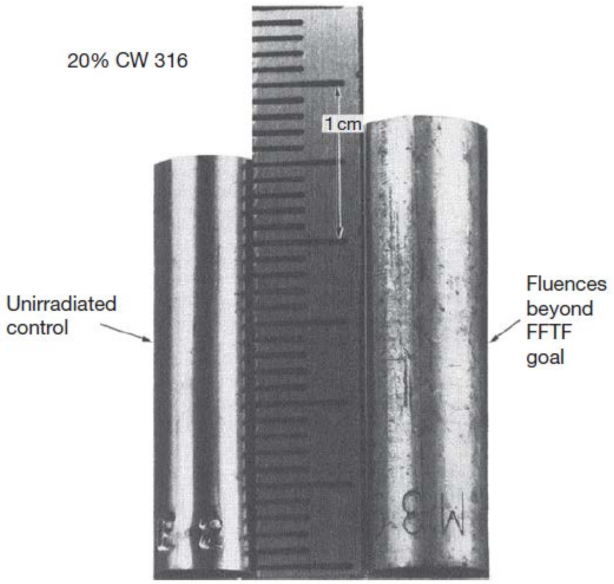
Figures of Merit: Radiation Hardness

- **Irradiation** of materials by energetic particles causes **microstructural defects** (*see N. Mokhov lecture)* which translate into **macrostructural changes** in material properties
- Many of the affected properties directly influence performance
- Such often-radical changes shall be taken into account in the design phase

Embrittlement of 316LN at different dpa levels



‘Comprehensive Nuclear Materials’, Editor-in-Chief: Rudy J.M. Konings, Elsevier

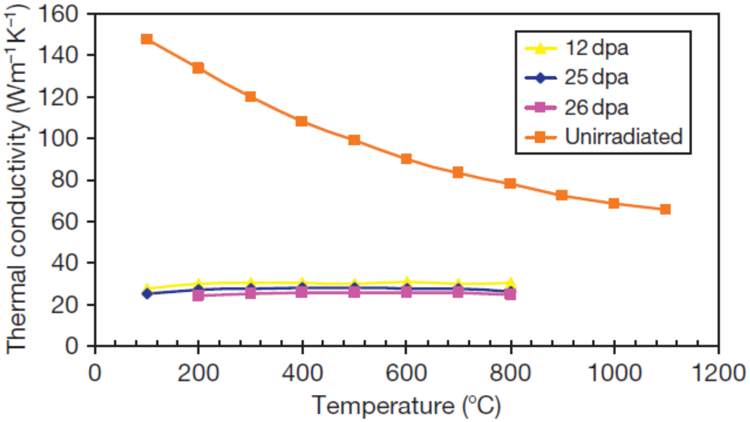


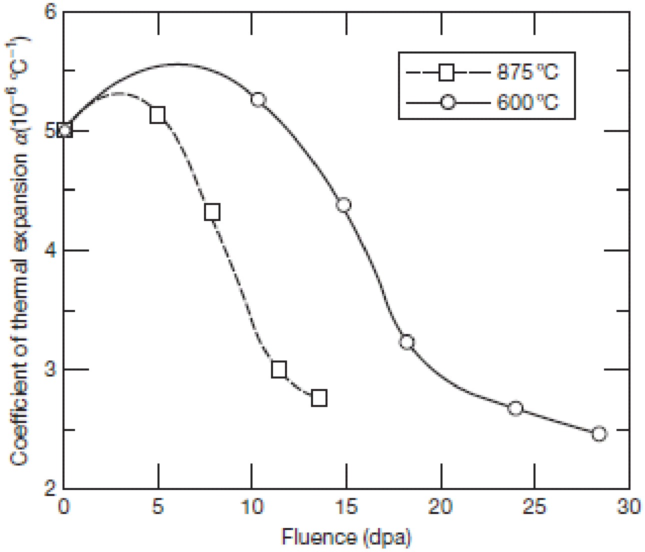
Swelling of 316 pipe after 75dpa irradiation : +33% in volume

Figures of Merit: Radiation Hardness

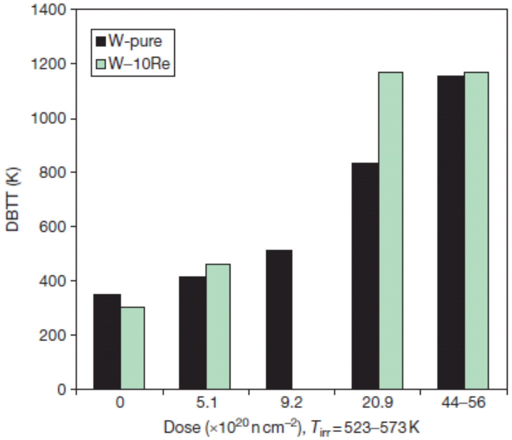
Some more examples for material of interest...

Thermal properties of nuclear grade Graphite



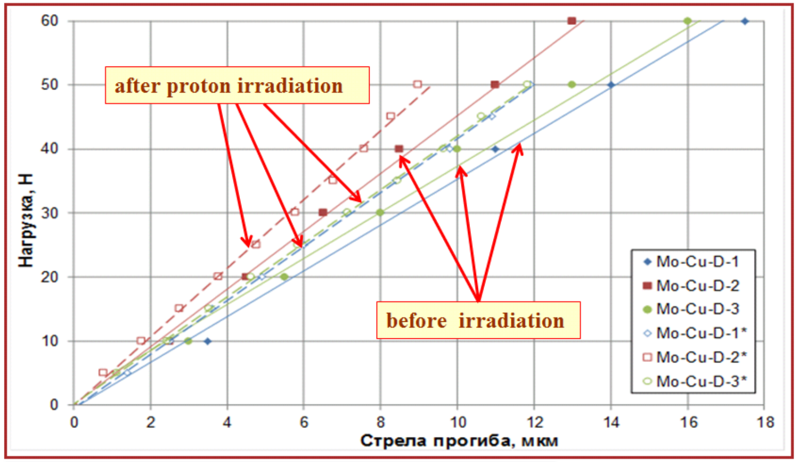


Ductile to Brittle Transition Temperature for Tungsten

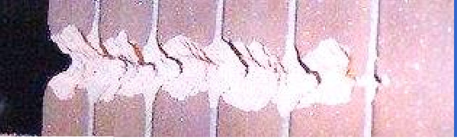


Embrittlement of MoCuCD Composite

Deformation curves for irradiated (*) by 30 MeV protons and unirradiated Mo-Diamond samples for LHC collimator materials

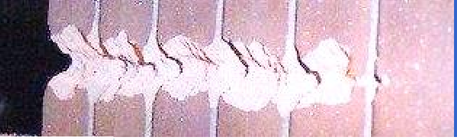


A. Ryazanov (RRC Kurchatov Institute)



Part III: Design Principles of BID

- ✓ Materials for Beam Interacting Devices
  - ✓ Material Requirements
  - ✓ Novel Materials R&D Program
  - ✓ Novel Materials: Copper-Diamond
  - ✓ Novel Materials: Molybdenum-Graphite
  - ✓ Material Comparison



Material Requirements

As seen, maximizing FOMs requires the optimization of a number of material properties …

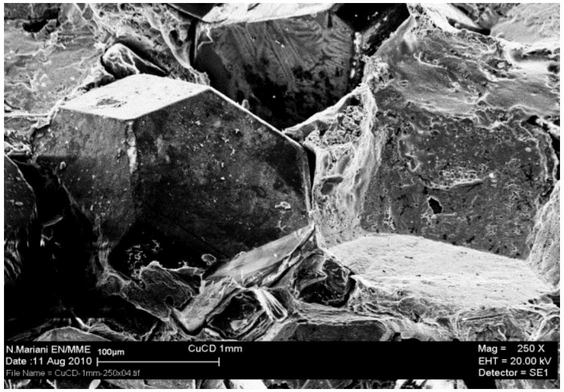
- Maximize **Electrical Conductivity** (γ) to limit RF Impedance
- Maximize **Thermal Conductivity** (λ) to maintain geom… er steady-state losses (**TSI**)
- Minimize **CTE** (α) to increase resistance t… etrical stability (**TRI** and **TSI**)
- Maximize **Melting/Degradati…** igh temperatures reached in case of bea…
- Maximize **Speci…** crease during impacts (**TRI**)
- Maximize… larly ***strain to failure***) to improve thermal shoc…
- Balanc… umber (**Z**) to limit peak energy deposition while maintaini… ing/interaction efficiency (**TRI** and **TSI**)
- Minimize **R… Induced Damage** to improve component lifetime under long term particle irradi… tion

Difficult to combine all requirements in one existing material!

Widespread, on-going efforts in developing novel materials!

Novel Materials R&D Program

- **Extensive R&D program** launched at CERN in partnership with industries and other institutions.
- Aim: explore/develop **composites** combining the properties of **graphite** or **diamond** (low ρ, high λ, low α) with those of **metals** and **transition metal-based ceramics** (high $\boldsymbol{R_M}$, good γ).
- Amongst many investigated materials, most interesting are **Copper-Diamond** and particularly **Molybdenum Carbide-Graphite**.
- Production techniques include Rapid Hot Pressing, Liquid Phase Sintering and Liquid Infiltration.



EUCARD²

Novel Materials: Copper-Diamond

- Developed by RHP-Technology (Austria)

Composition :

- 60%v diamonds (90% 100 µm, 10% 45 µm)
- 39%v Cu powder (45 µm)
- 1%v B powder (5 µm)

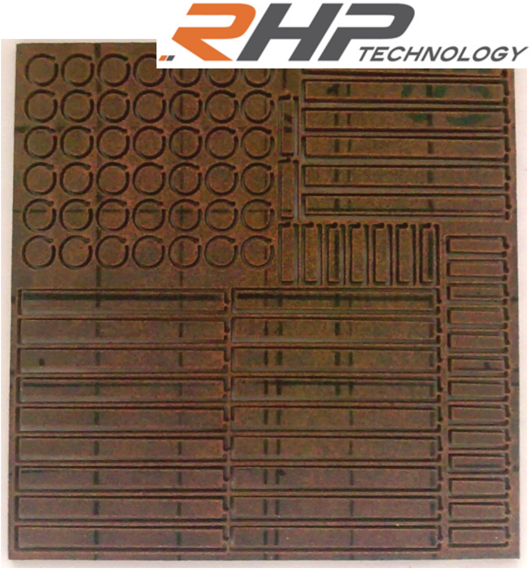
⬆ • No diamond degradation

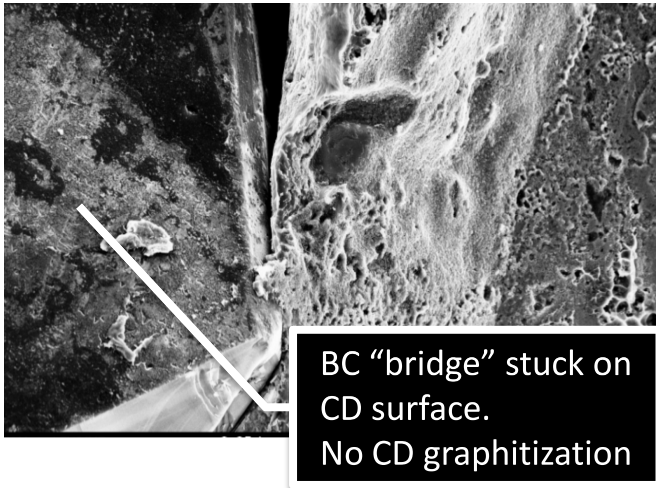
⬆ • Thermal (**~490 Wm^{-1}K^{-1}**) and electrical conductivity (**~12.6 MSm^{-1}**)

⬌ • No direct interface between Cu and CD (lack of affinity). Partial bonding bridging assured by Boron Carbides limits mechanical strength (**~120 MPa**).

⬇ • Cu low melting point (**1083 °C**)

⬇ • CTE increases significantly with T due to high Cu content (from ~**6 ppmK^{-1} at RT** up to **~12 ppmK^{-1} at 900 °C**)



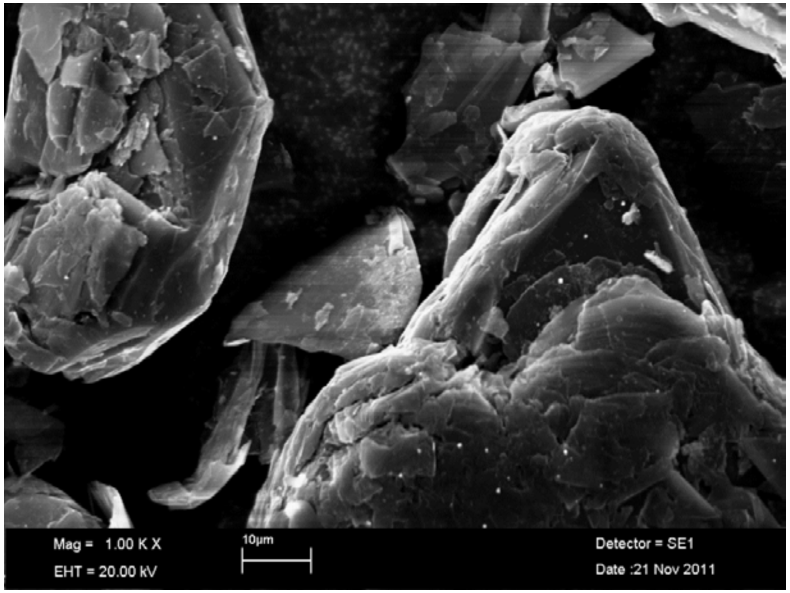


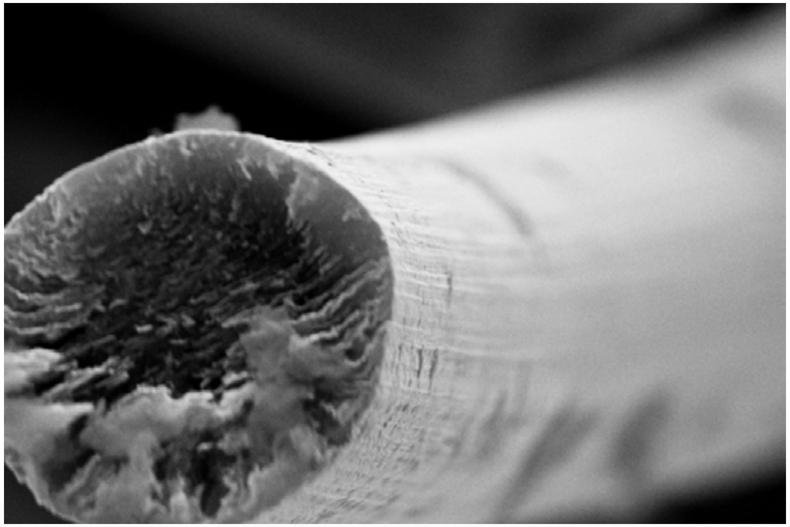
BC “bridge” stuck on CD surface.
No CD graphitization

Novel Materials: Molybdenum-Graphite

- Co-developed by CERN and Brevetti Bizz (Italy)
- Broad range of processes and compositions investigated (Molybdenum, Natural Graphite, Mesophase pitch-based Carbon Fibers).

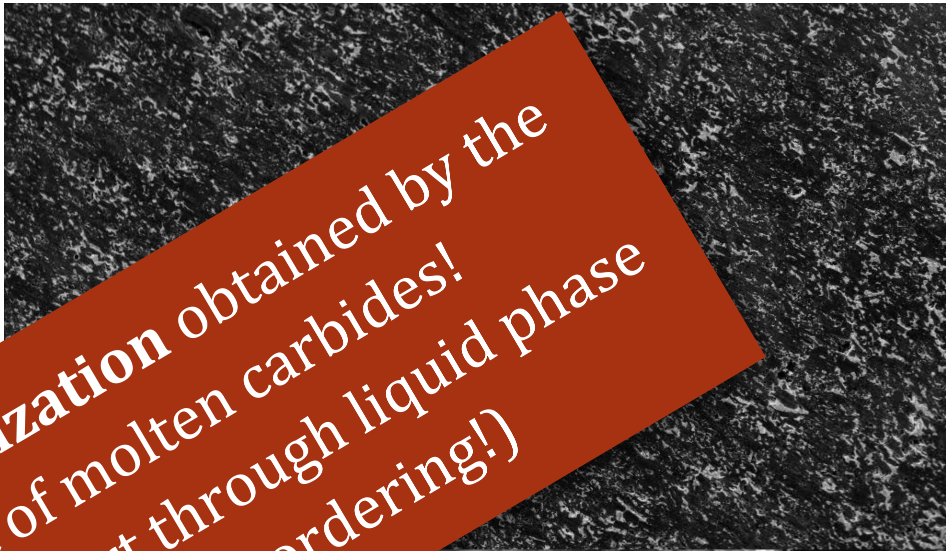
- **Why Molybdenum?**
  - Refractory metal
  - Density lower than Tungsten
- **Why Natural Graphite?**
  - Low CTE (along basal plane)
  - High Thermal Conductivity (along basal plane)
  - Low Density
  - Very High Service Temperatures
  - High Shockwave Damping
  - Low cost
- **Why Mesophase Pitch-based Carbon Fibres?**
  - Increase mechanical strength
  - Contribute to Thermal Conductivity (highly ordered structure)

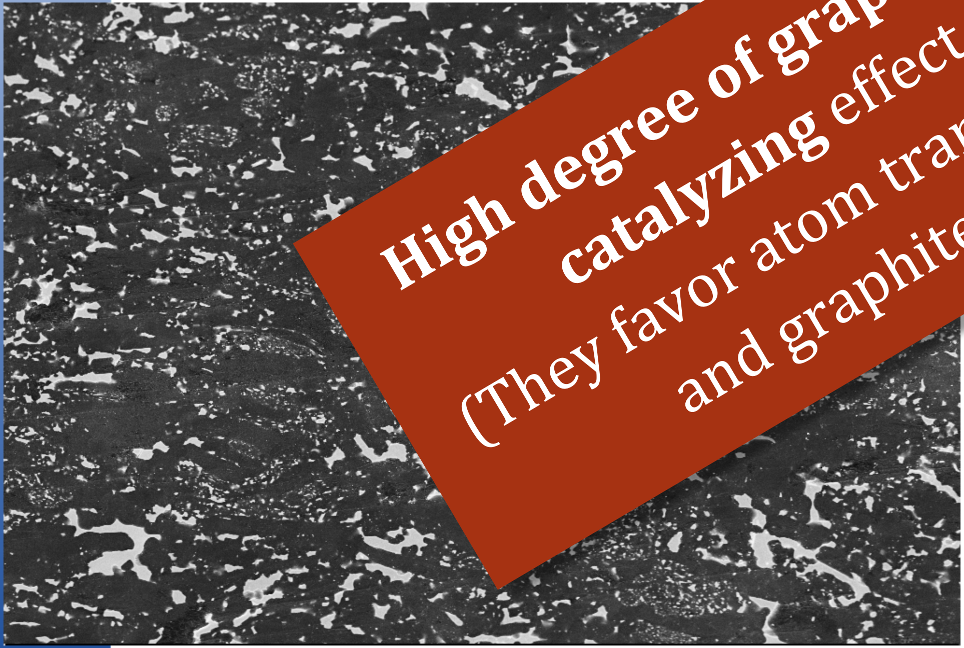


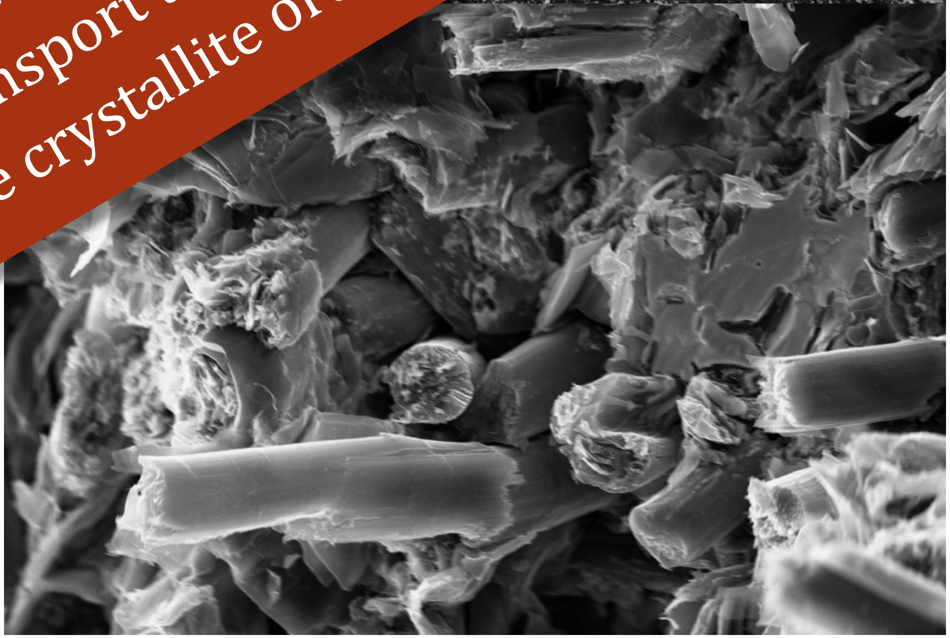


Novel Materials: Molybdenum-Graphite

- Homogeneous distribution of graphite, fibers and fine MoC_{1-x} grains
- Excellent crystalline structure of graphite and Carbon Fibres with highly Oriented Graphene planes
- Strong fiber-matrix bonding

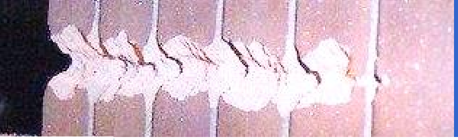




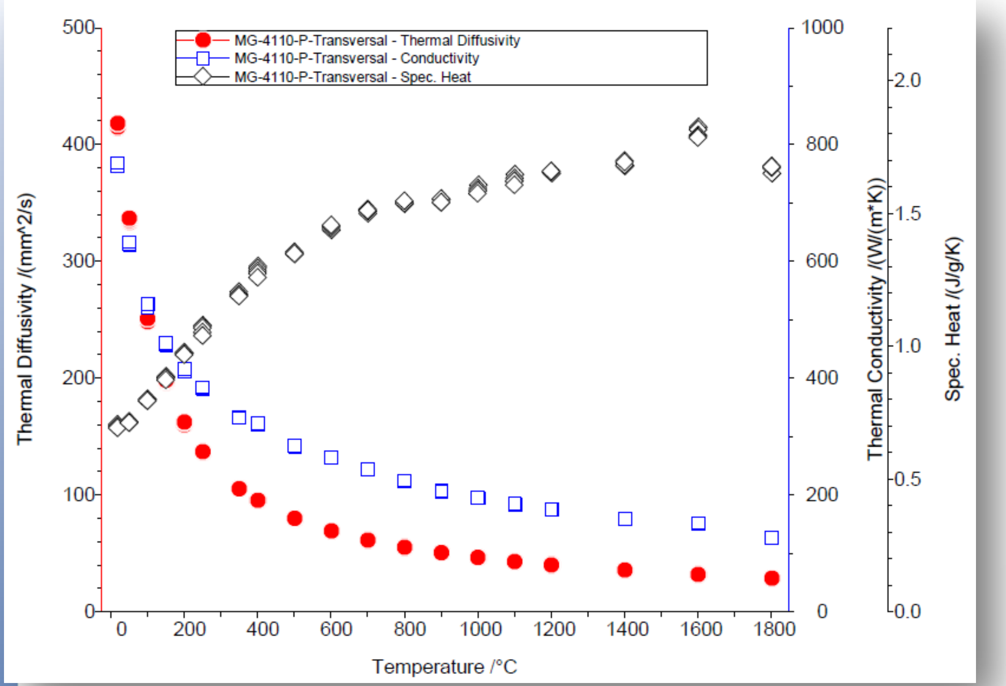


High degree of graphitization obtained by the **catalyzing** effect of molten carbides!

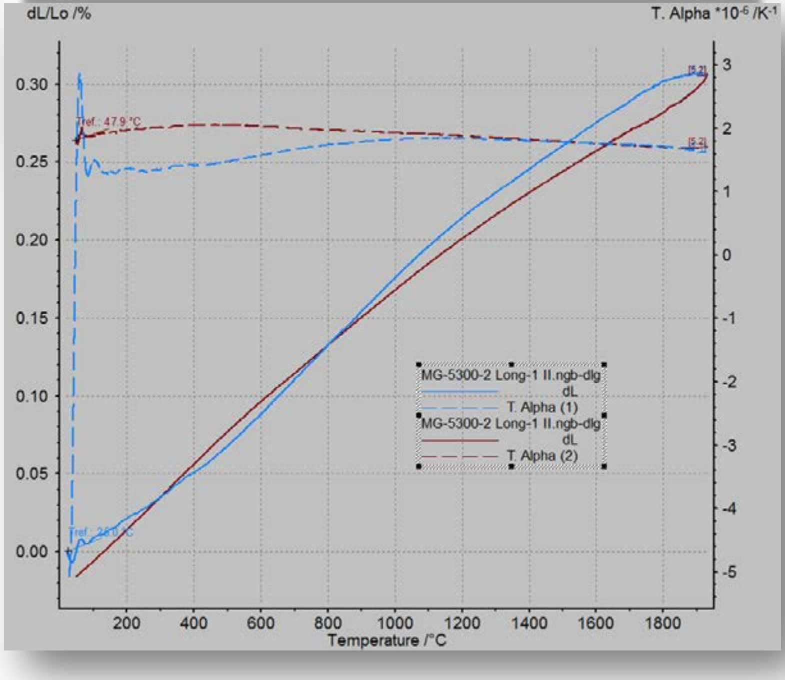
(They favor atom transport through liquid phase and graphite crystallite ordering!)



Molybdenum-Graphite Properties



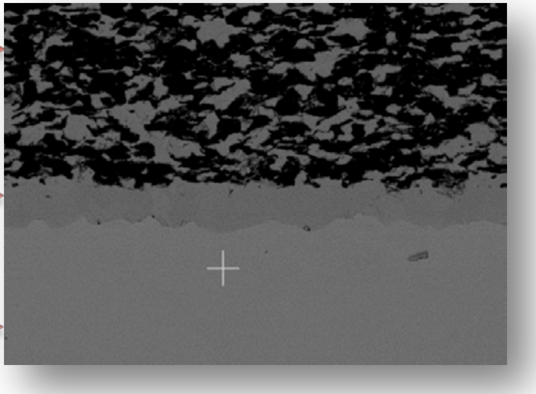
ρ [g/cm^3]	2.5
$\alpha_\perp$ (RT to 1000° C) [$10^{-6}K^{-1}$]	<1.8
$\alpha_{//}$ (RT to 1000° C) [$10^{-6}K^{-1}$]	12
$\lambda_\perp$ (RT) [W/mK]	>770
$\lambda_{//}$ (RT) [W/mK]	85
$\sigma_\perp$ (RT) [MS/m]	1÷18
$\sigma_{//}$ (RT) [MS/m]	0.3
E (Flexural) [GPa]	53
R_{Fl} [MPa]	85



Core:
1.1 MS/m

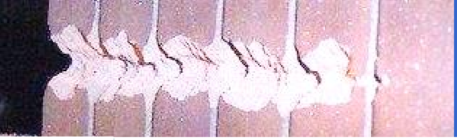
Carbide layer:
1.5 MS/m

Mo Coating:
18 MS/m



FOMs: Material Comparison

Material	Beryllium	Carbon-Carbon	Graphite	Molybdenum Graphite	Copper-Diamond	Glidcop ®	Molybdenum	Tungsten Alloy (IT180)
ρ [g/cm^3]	1.84	1.65	1.9	2.50	5.4	8.90	10.22	18
Z	4	6	6	~6.5	~11.4	~29	42	~70.8
X_g [cm]	35	26	19	17	4.8	1.4	0.96	0.35
c_p [Jkg^{-1}K^{-1}]	1925	780	760	750	420	391	251	150
$\bar{\alpha}$ [10^{-6} K^{1}]	18.4	4.1	5.5	5.0	7.8	20.5	5.3	6.8
$\bar{\lambda}$ [Wm^{-1}K^{-1}]	216	167	70	547	490	365	138	90.5
T_m [°C]	1273	3650	3650	2589	~1083	1083	2623	~1400
$\bar{E}$ [GPa]	303	62.5	12	44	220	130	330	360
R_M [MPa]	*370*	87	*30*	*80*	70	365	660	*660*
ΔT_q [K]	**0.36**	**1.2**	**1.7**	**2.1**	**15.1**	**60.1**	**144**	**745**
TRI [–]	**790**	**1237**	**1101**	**634**	**6.8**	**5.3**	**6.4**	**0.5**
TSI [-]	**17.1**	**44.6**	**10.1**	**69.4**	**9.9**	**0.8**	**0.7**	**0.1**
γ [MSm^{-1}]	**23.3**	**~0.14**	**~0.07**	**~1÷18**	**~12.6**	**53.8**	**19.2**	**8.6**

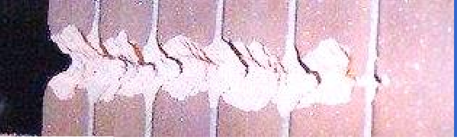


FOMs: Material Comparison

- **The higher the FOM, the better the material … No one-fits-it-all material**!
- **Carbon-based materials** feature **excellent TRI** and **TSI** thanks to low-Z, low CTE, low density, high degradation temperature, high conductivity ….
- **Beryllium** is outstanding under practically all points of view … unfortunately its used is severely limited by its **toxicity**.
- However low electrical conductivity penalizes *C-C* and *graphite* **if RF-impedance is an issue**. In such a case, **MoGr** is the **most promising compromise**, particularly if coated with higher conductivity thin films.
- **Note poor performance of Tungsten Alloy**, also due to the low melting temperature of the **Ni-Cu matrix** required to reduce material brittleness … **it is not pure W**!

Material	Beryllium	Carbon-Carbon	Graphite	Molybdenum Graphite	Copper-Diamond	Glidcop ®	Molybdenum	Tungsten Alloy (IT180)
ρ [g/cm^3]	1.84	1.65	1.9	2.50	5.4	8.90	10.22	18
Z	4	6	6	~6.5	~11.4	~29	42	~70.8
T_m [°C]	1273	3650	3650	2589	~1083	1083	2623	~1400
ΔT_q [K]	0.36	1.2	1.7	2.1	15.1	60.1	144	745
TRI [–]	790	1237	1101	634	6.8	5.3	6.4	0.5
TSI [-]	17.1	44.6	10.1	69.4	9.9	0.8	0.7	0.1
γ [MSm^{-1}]	23.3	~0.14	~0.07	~1÷18	~12.6	53.8	19.2	8.6

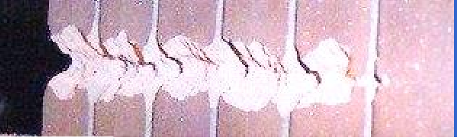
- Objective and scope of the lectures
- Part I: Introduction to Beam-induced Damage
- Part II: Analysis of Beam Interaction with Matter
- Part III: Design Principles of Beam Interacting Devices (BID)
- Part IV: Experimental Testing and Validation
  - Why Experimental Tests?
  - HiRadMat Facility
  - HiRadMat Experiments



Why Experimental Tests?

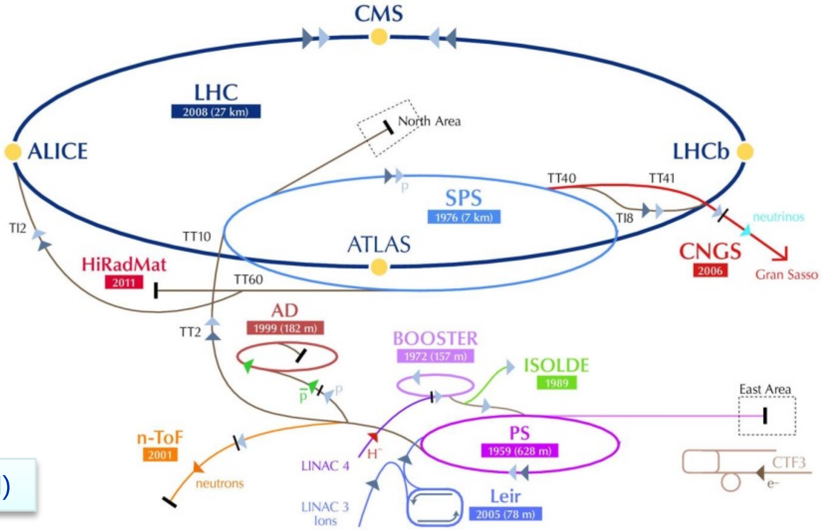
Why is experimental validation important?

- With accidental beam impacts, one enters a relatively unknown territory, that of **high power explosions and ballistics**.
- When **large density changes, phase transitions, fragmentations** are involved, one has to resort to special advanced tools (Hydrocodes).
- These **state-of-the-art wave propagation codes** can be very reliable, provided the **complex material models** required are available and precise.
- Existing material constitutive models at **extreme conditions** are limited and mostly drawn from military research (**classified**). They are often **unavailable** for specific alloys and composites.
- Additional consequences on UHV, electronics, bellows cannot be easily anticipated by numerical simulations.
- Only **ad-hoc material tests** can provide the correct inputs for numerical analyses and validate/benchmark simulation results on **simple specimens** as well as on **complex structures**.
- A **dedicated facility** has been designed and commissioned at CERN to test materials and systems under high intensity pulsed particle beams: **HiRadMat** (High Radiation to Materials).

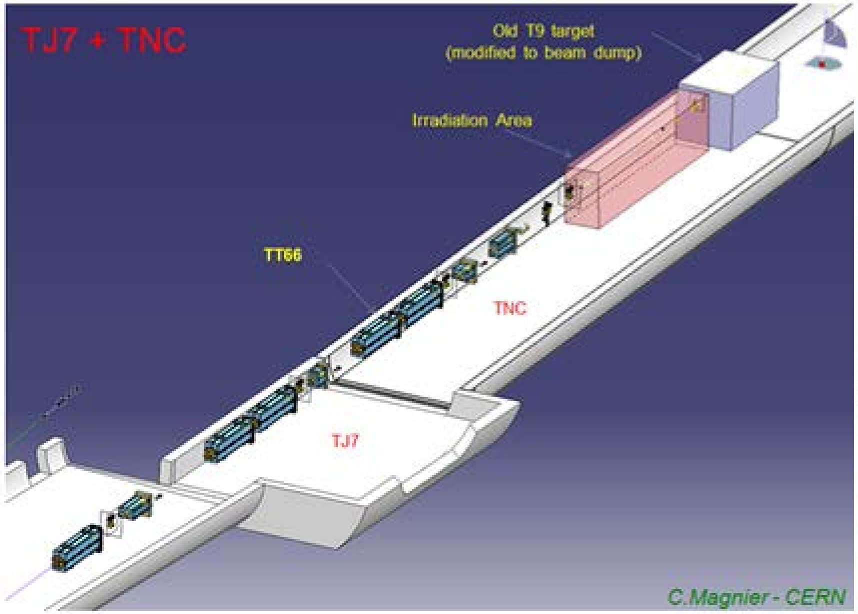


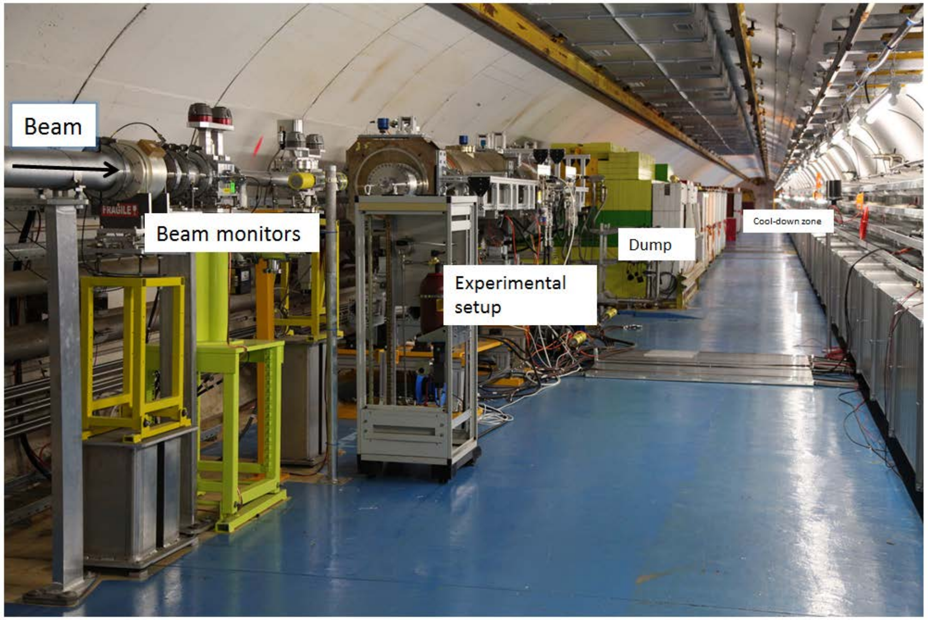
HiRadMat (High Radiation to Materials) Facility

- **Dedicated facility for studying the impact of intense pulsed beams on materials**
  - Material damage
  - Material vaporization
  - Thermal management
  - Radiation damage to materials
  - Beam-induced pressure waves
  - 9 experiments in 2012



A. Fabich, I. Efthymiopoulos (CERN)



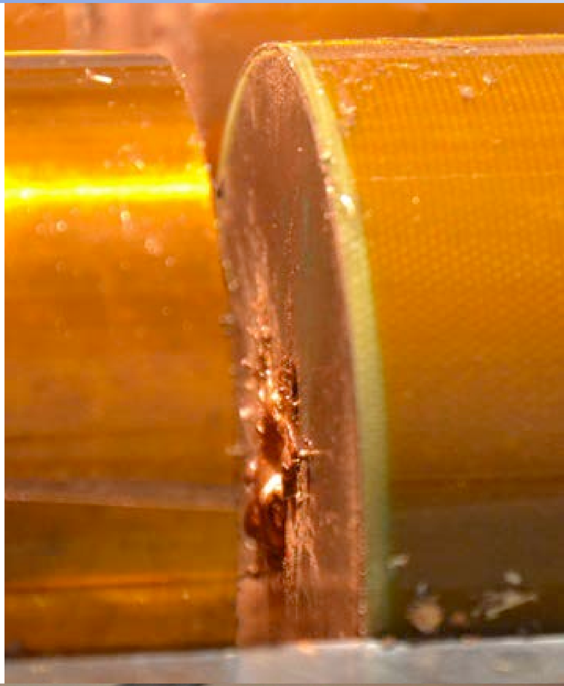


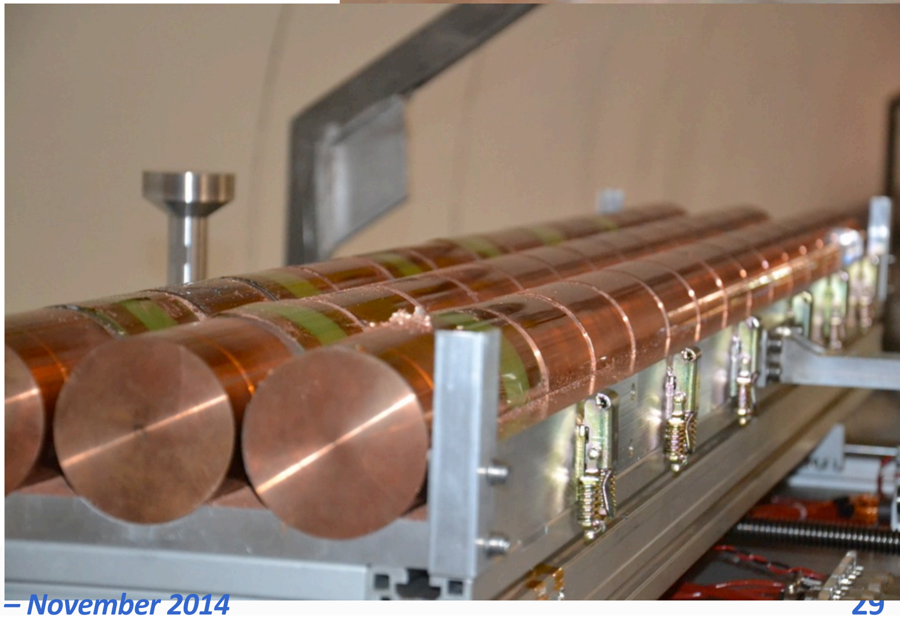
HRMT12 Experiment

- **Experiment Goals**
  - Show damage of SPS beam impacting on target.
  - Benchmarking of hydrodynamic tunneling simulations.

  - **Target**: Copper, 3 x 15 blocks, length 10cm and radius 4cm.

  - Experiment with SPS beam in HiRadMat.
  - 440GeV/c.
  - 108 or 144 bunches with 1.5e11 p per bunch.
  - Bunch trains of 36 bunches.
  - Bunch spacing 50ns.
  - Beam size σ = 0.2 or 2mm.

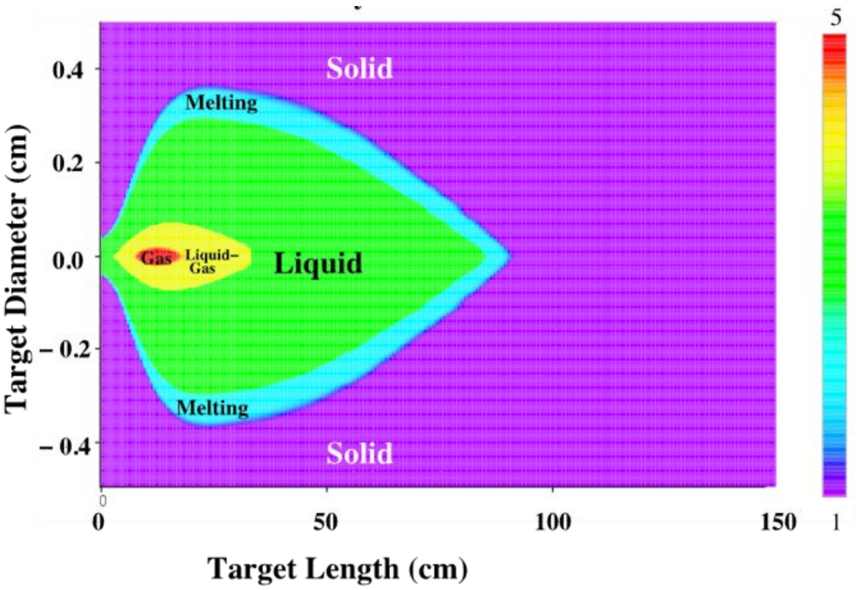




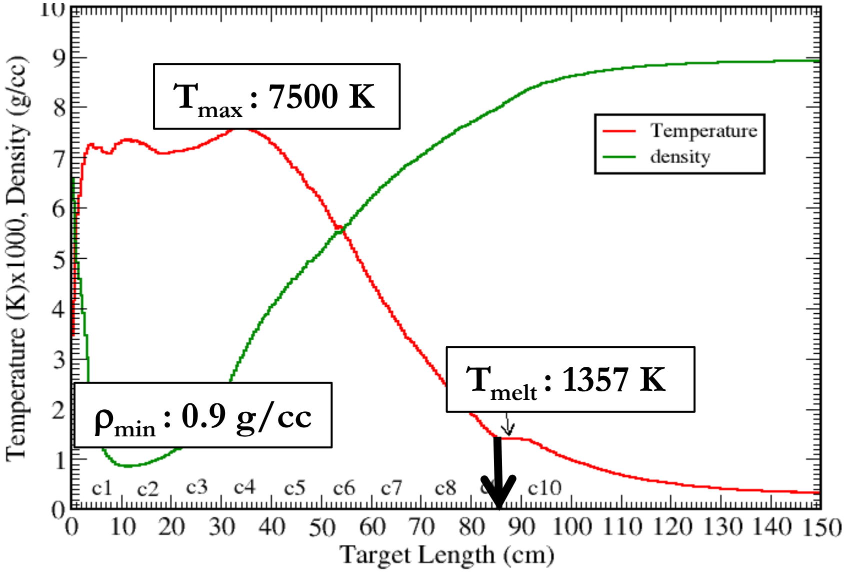
J. Blanco, R. Schmidt *et al* (CERN)

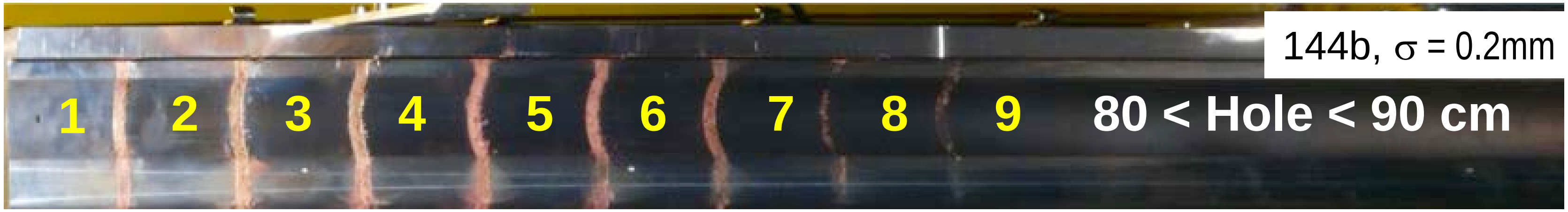
HRMT12 Experiment

- **Comparison test results vs. simulations**

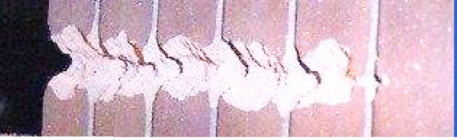


Third target, 144 bunches delivered after 7.85μs



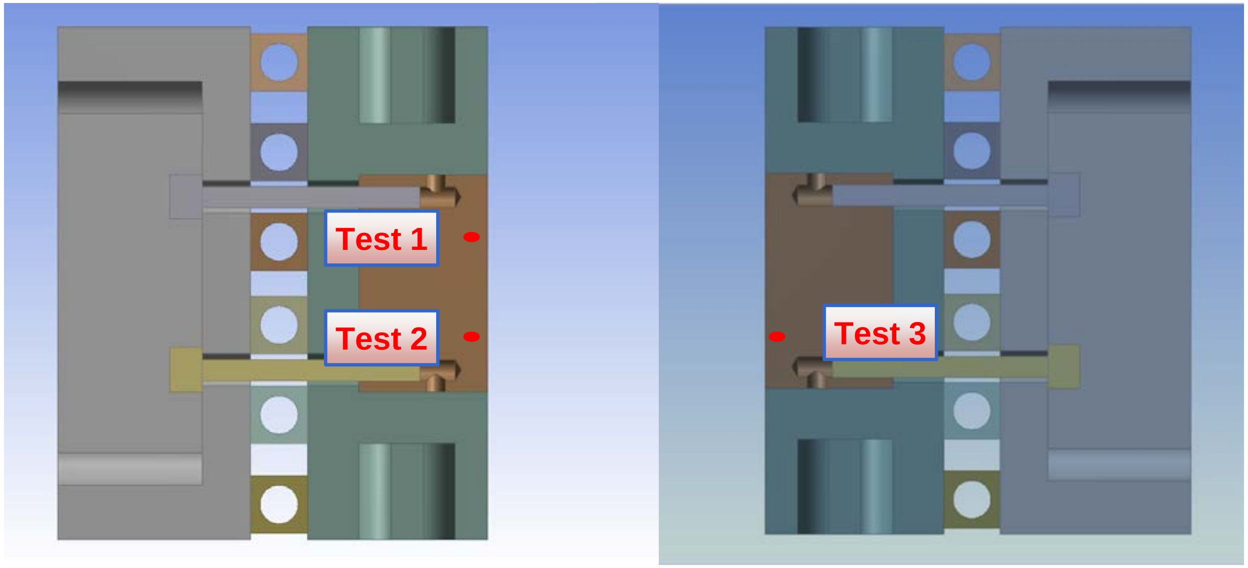


N. Tahir (GSI)
R. Schmidt *et al* (CERN)



HRMT09 Experiment

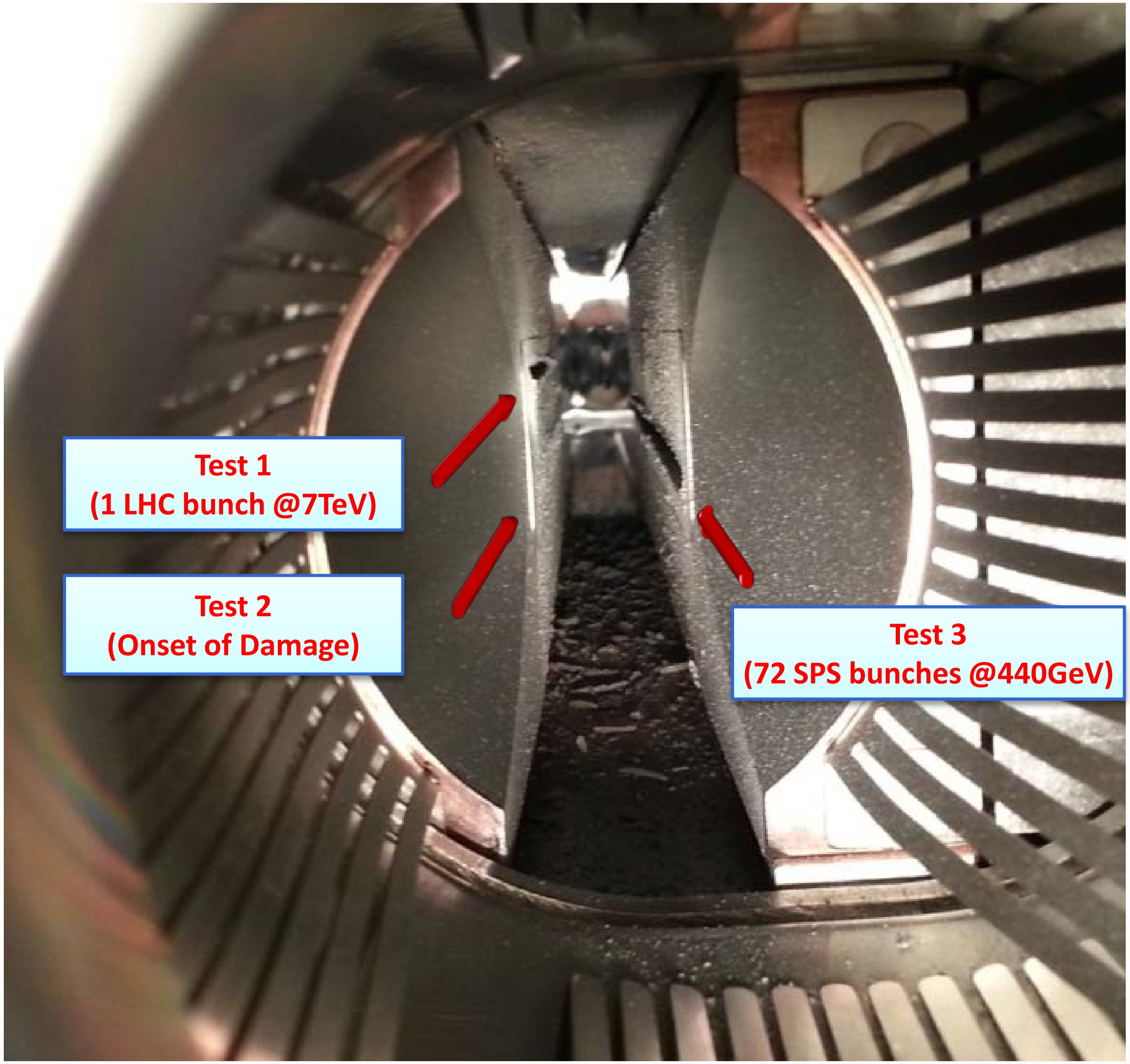
- **Experiment Goals**
  - Integral test under SPS beam of 2 LHC Tertiary Collimator Jaws
  - Beam energy: 440 GeV
  - Impact depth: 2mm



	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 Experiment

- **Post-irradiation visual inspection**



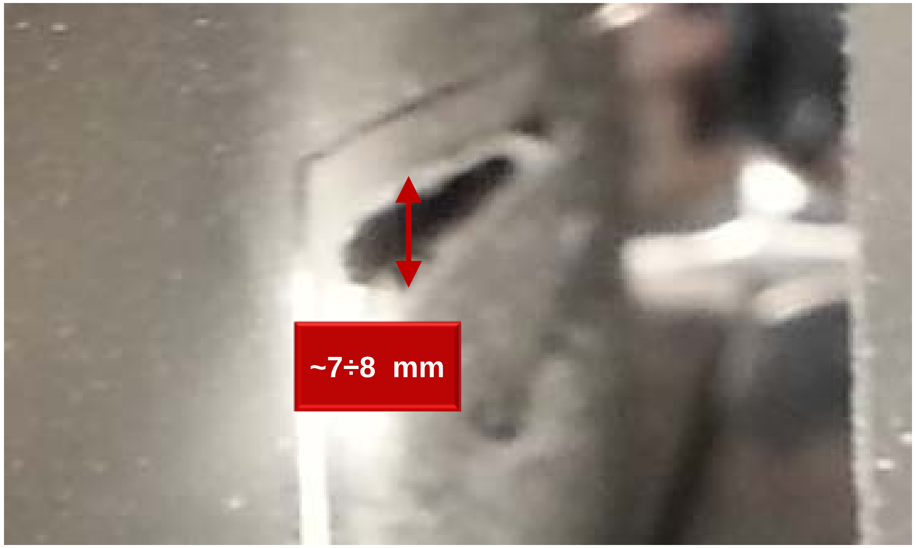
Test 1
(1 LHC bunch @7TeV)

Test 2
(Onset of Damage)

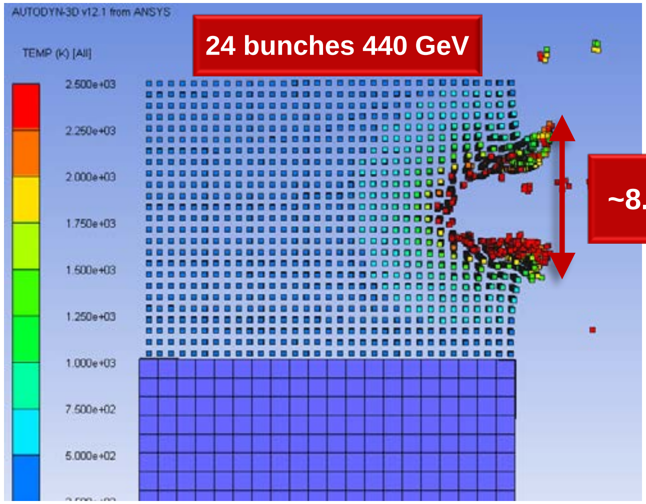
Test 3
(72 SPS bunches @440GeV)

HRMT09 Experiment

- **Analysis of Test 1**
  - Goal: beam impact equivalent to 1 LHC bunch @ 7TeV
  - Intensity 1.5 x 10^{11}p
  - Qualitative damage evaluation
  - Groove height ~ 7 mm, in good agreement with simulations

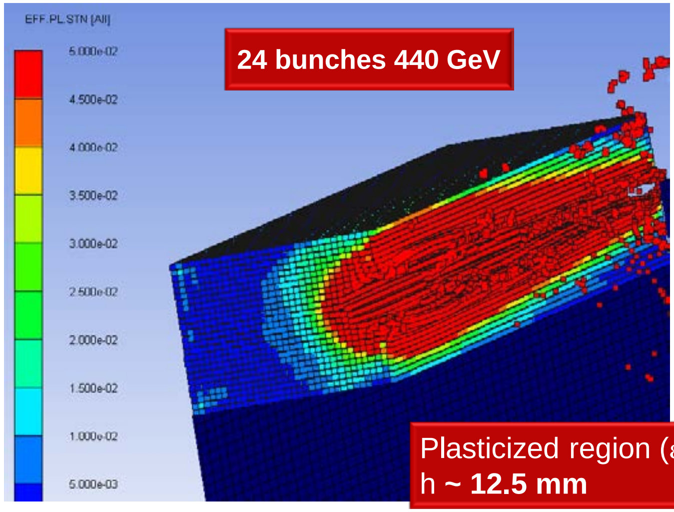


~7÷8 mm



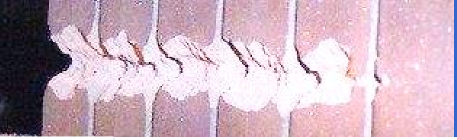
24 bunches 440 GeV

~8.5 mm



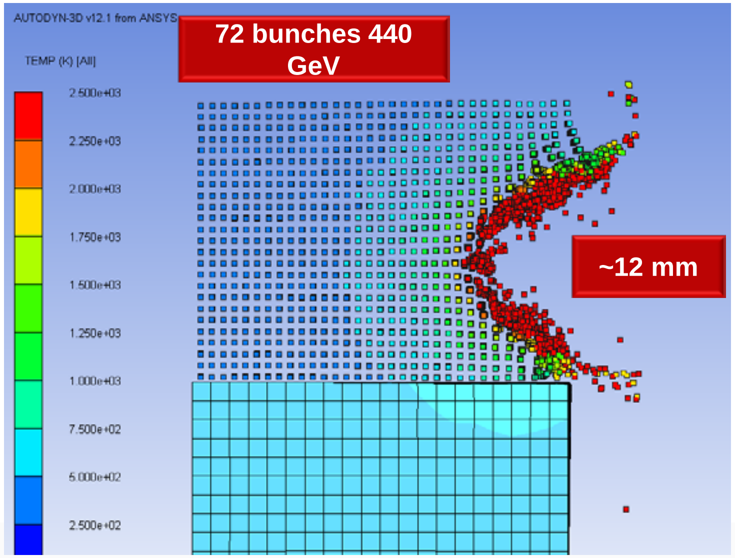
24 bunches 440 GeV

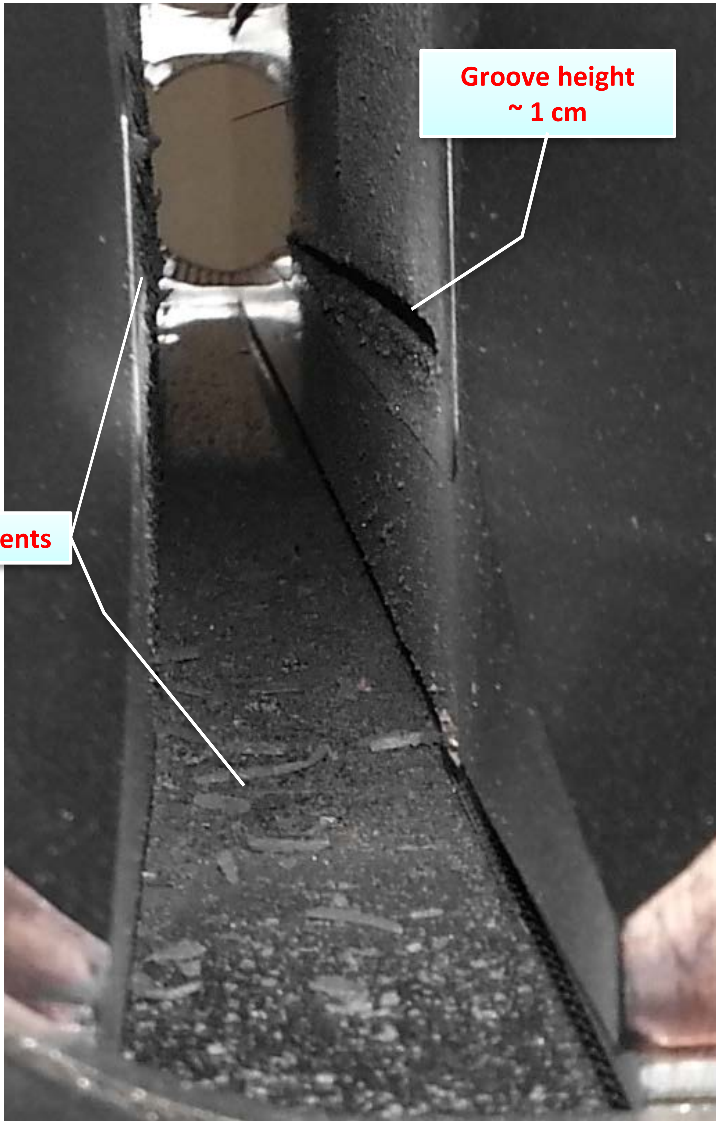
Plasticized region (ε_{pl} > 5%)
h ~ **12.5 mm**



HRMT09 Experiment

- **Analysis of Test 3**
  - Goal: induce severe damage on the collimator (~3 equivalent LHC bunches)
  - Impressive quantity of tungsten alloy ejected (partly bonded to the opposite jaw, partly fallen on tank bottom or towards entrance and exit flanges)
  - Vacuum degraded. Tank contaminated
  - Groove height ~ 1 cm (consistent with numerical simulations)

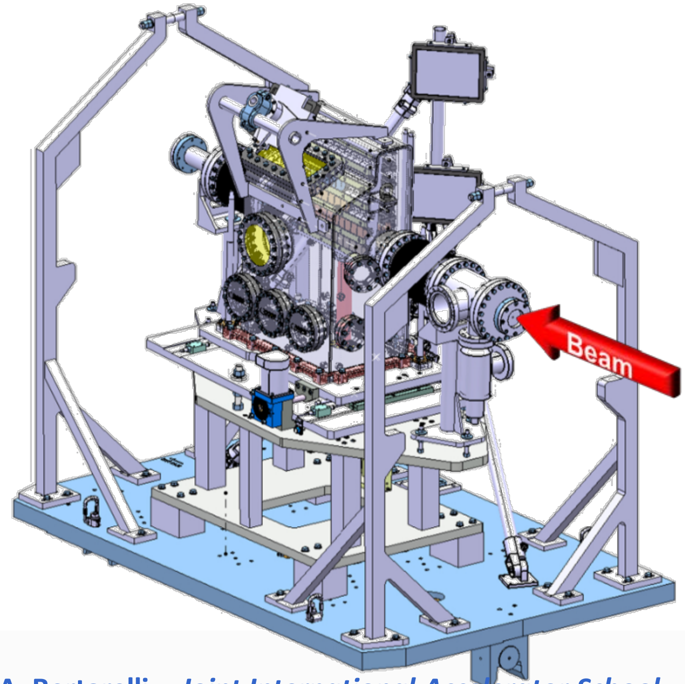


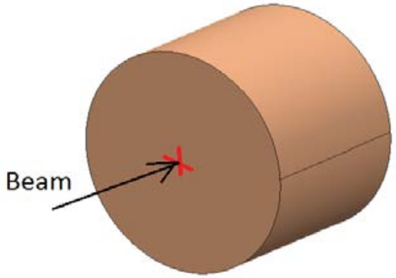


HRMT14 Experiment

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

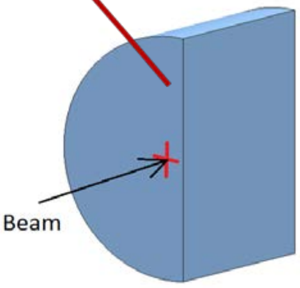
Beam Parameters	
Beam energy	440 GeV
Number of protons per bunch	1.1e11
Bunch Spacing	25 ns





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

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



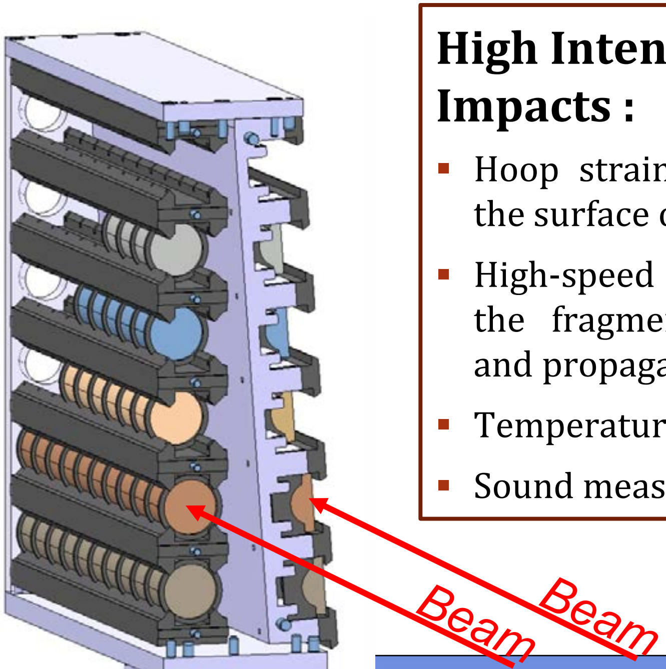
HRMT14 Experiment

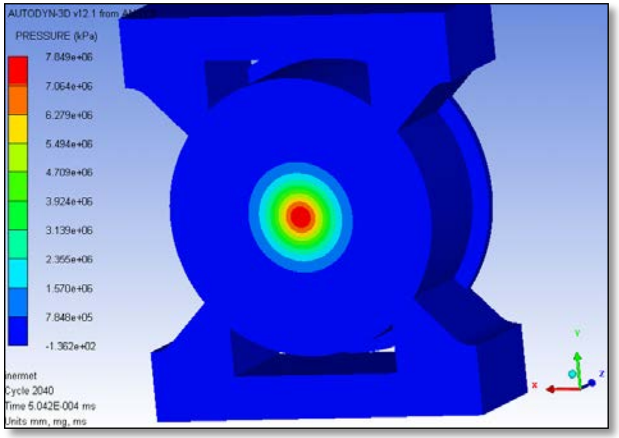
Medium Intensity Beam Impacts :

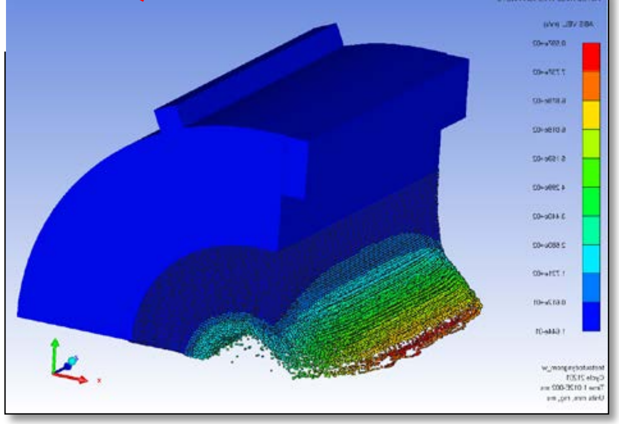
- Hoop strain measurements on the surface of the sample;
- Radial vibration measurements;
- Temperature measurements;
- Sound measurements.

High Intensity Beam Impacts :

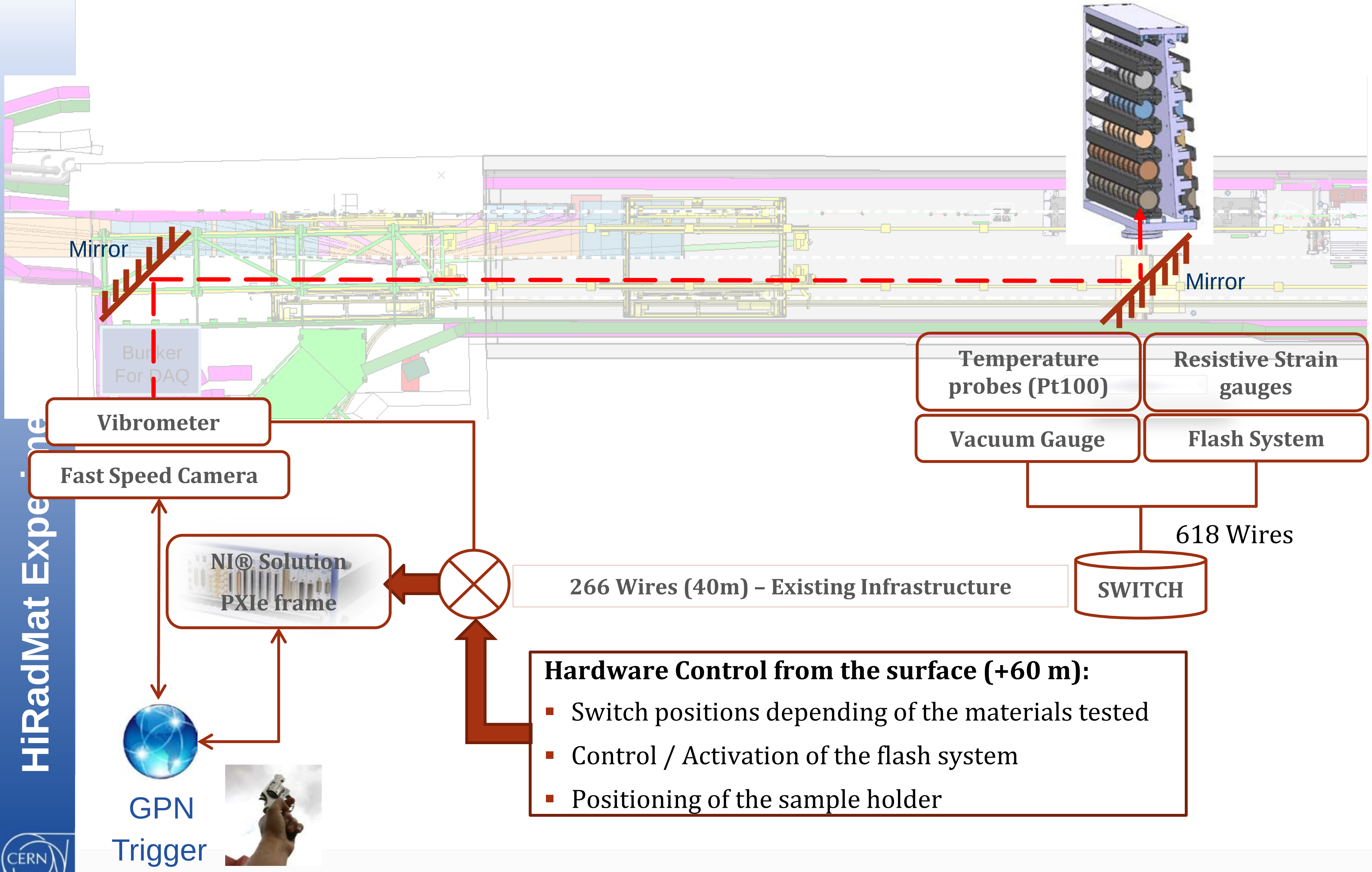
- Hoop strain measurements on the surface of the sample;
- High-speed camera to follow the fragment front formation and propagation;
- Temperature measurements;
- Sound measurements.







HRMT14 Experiment

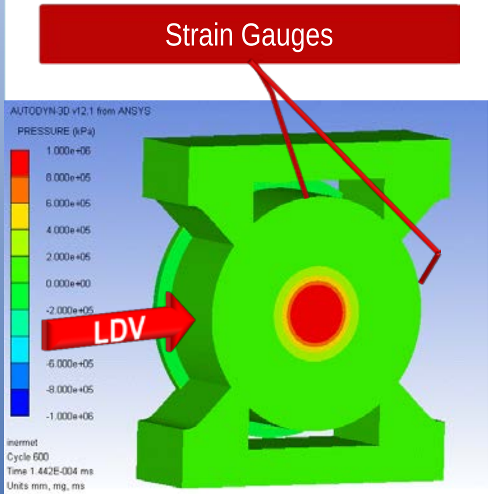


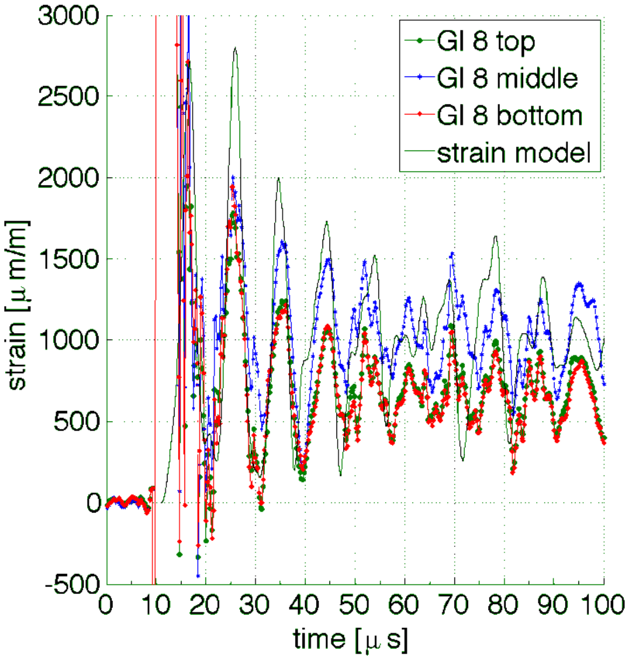
Hardware Control from the surface (+60 m):

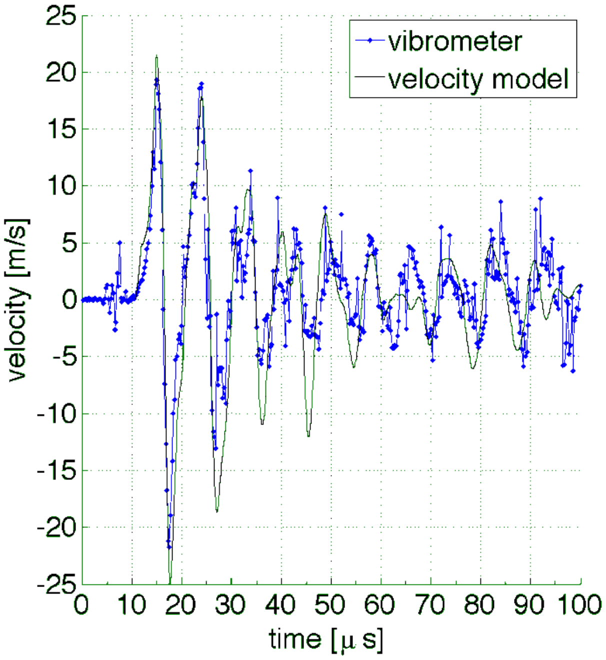
- Switch positions depending of the materials tested
- Control / Activation of the flash system
- Positioning of the sample holder

HRMT14 Experiment

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

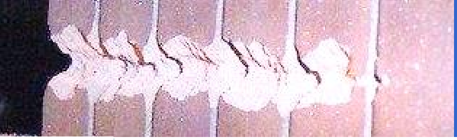






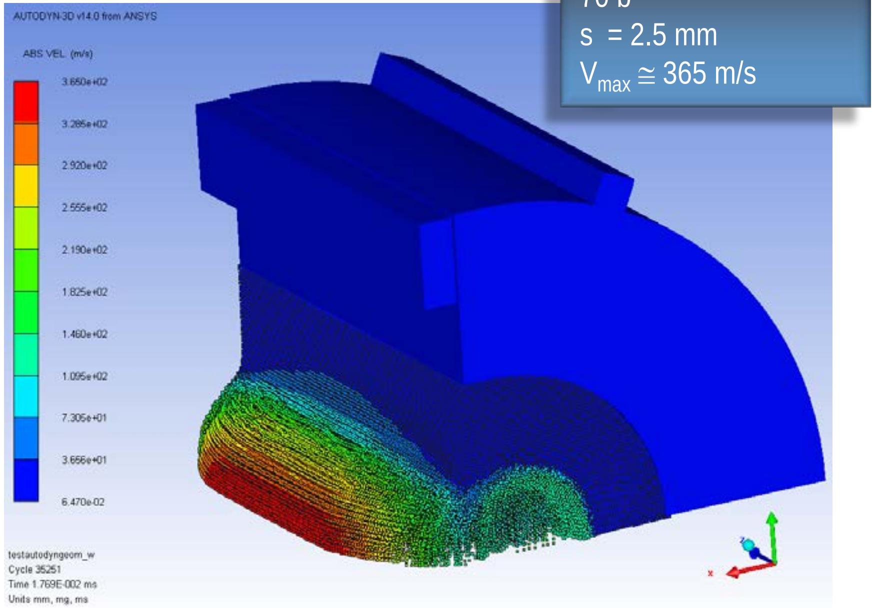
Inermet180
24 b (scraped)

Total intensity:
2.7e12 p
σ ≅ 1.4 mm

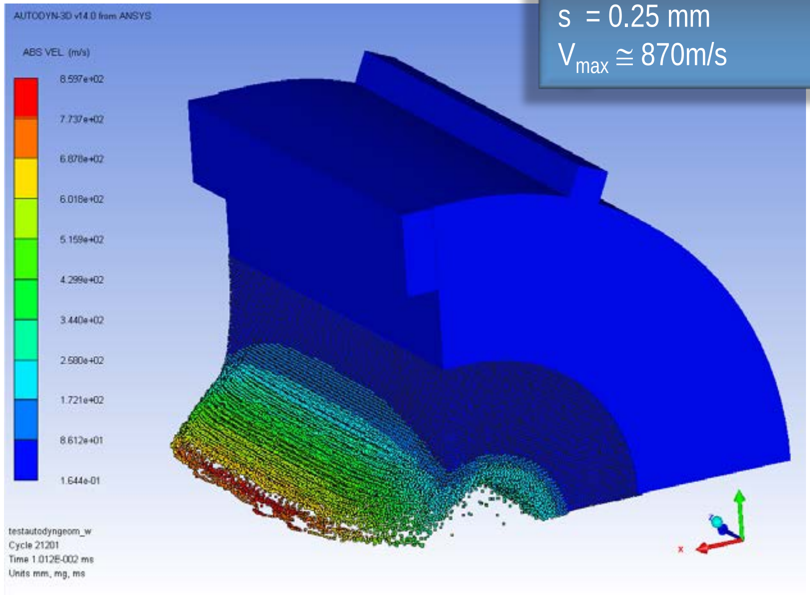


HRMT14 Experiment

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



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

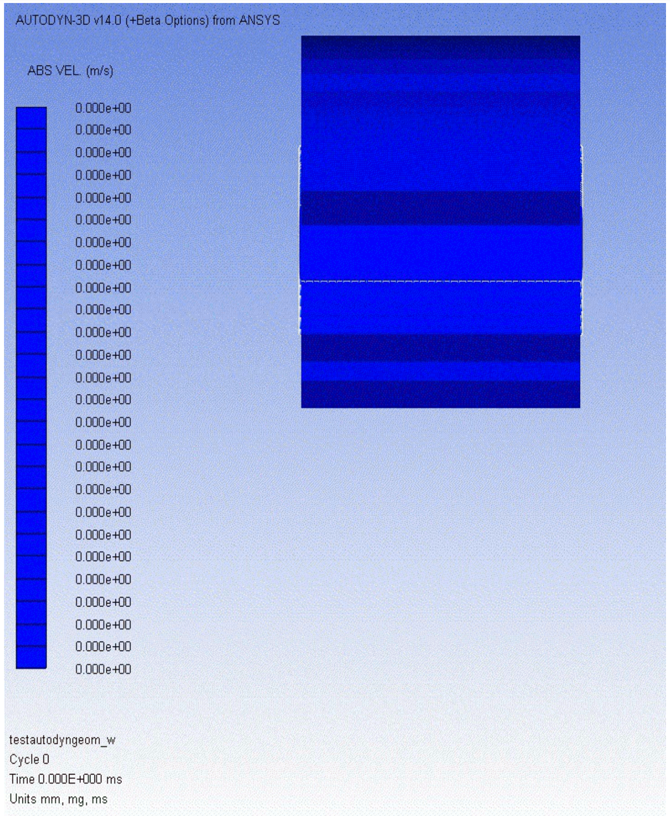


Inermet180
60 b
s = 0.25 mm
$V_{max} \cong$ 870m/s

HRMT14 Experiment

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

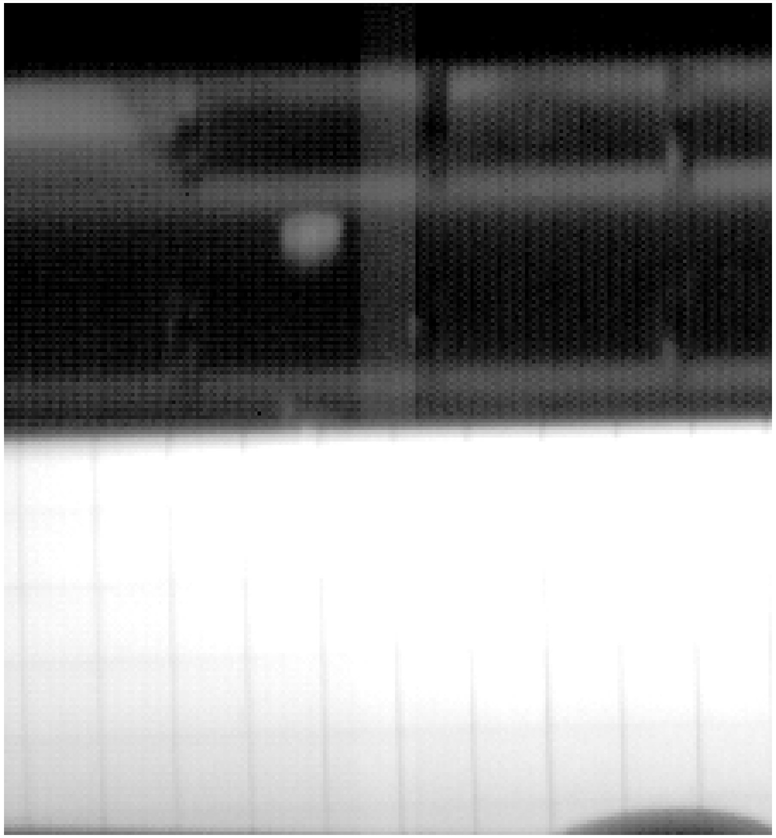
Beam



AUTODYN-3D v14.0 (+Beta Options) from ANSYS

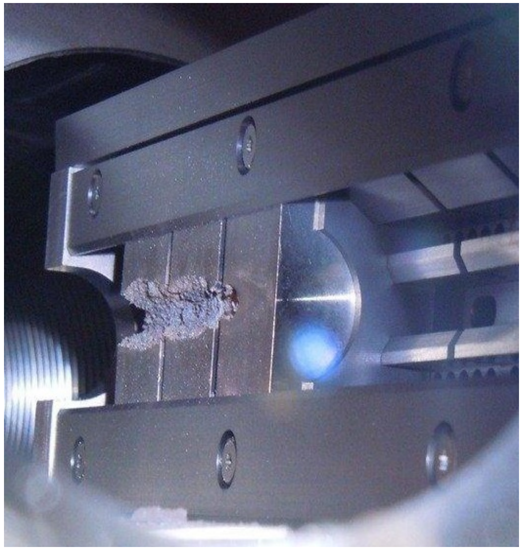
ABS VEL. (m/s)

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

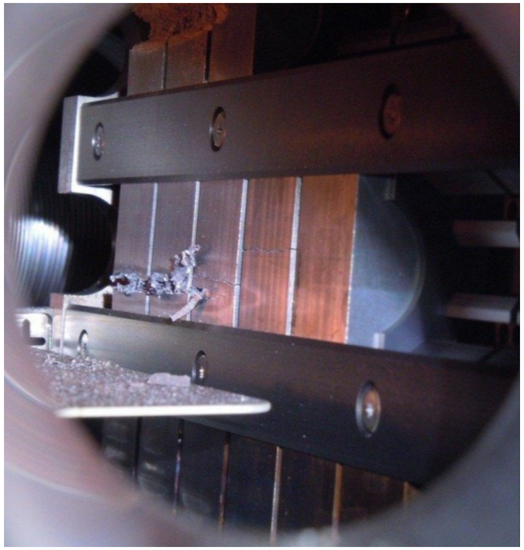


Case	Bunches	p/bunch	Total Intensity	Beam Sigma	Specimen Slot	Velocity
Simulation	60	1.5e11	9.0e12 p	2.5 mm	9	316 m/s
Experiment	72	1.26e11	9.0e12 p	1.9 mm	8 (partly 9)	~275 m/s

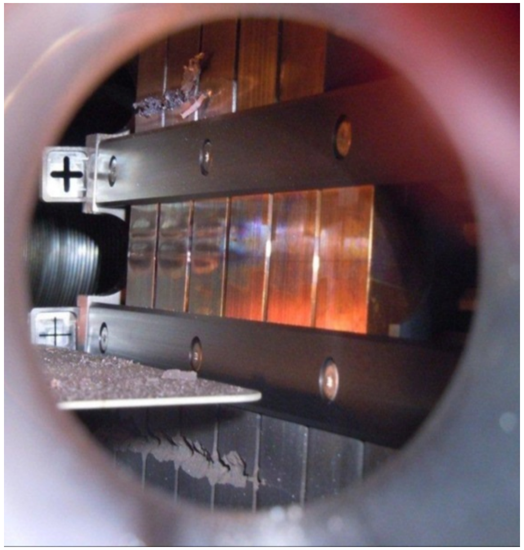
HRMT14 Experiment



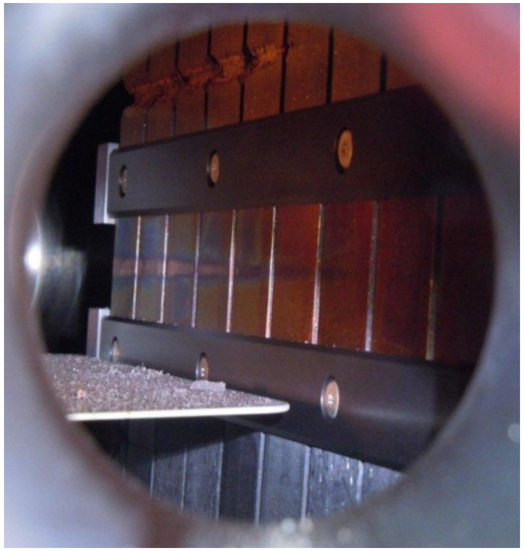
Tungsten Alloy, 72 b



Molybdenum, 72 & 144 b



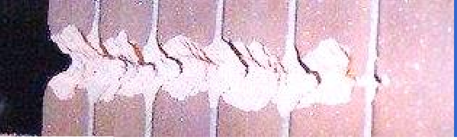
Glidcop, 72 b (2 x)



Copper-Diamond
144 b

Molybdenum-Copper-Diamond 144 b

Molybdenum-Graphite (3 grades)
144 b



Final Remarks

- High energy particle accelerators handle beams with **extremely high destructive potential** in case of interaction with matter (several hundreds **MJ** can be released in few **μs** ⇨ **TW** power scale)
- The analysis of beam-matter interaction involves several disciplines and requires a **multiphysics approach**
- When interaction phenomena do **not** lead to extensive **changes of density** or **phase transitions**, material response can be analysed with a good degree of approximation by **thermoelasticity principles**
- **Otherwise**, advanced nonlinear tools (**hydrocodes**) must be invoked: these numerical codes rely on complex **material constitutive models** encompassing the full range of states of matter
- A number of indicative **Figures of Merit** can help in the material selection process in the early design phase of systems exposed to beam interaction
- **No material fits all requirements!** However, a new generation of **metal-** and **ceramic-matrix composites** with **diamond** or **carbon** reinforcements is showing promising results, in particular **Molybdenum Carbide – Graphite**
- Only **dedicated**, **carefully designed experiments** in **ad-hoc facilities** (e.g. HiRadMat) can benchmark advanced numerical simulations and provide the **final validation** for systems potentially exposed to interaction with highly energetic beams


That's all Folks!

Homework Problem

A **L=100 mm** long target rod with circular cross-section of radius **R = 2.5 mm** made of **isotropic graphite** is impacted at its center by a train of **n_b = 288** proton **bunches**. Each bunch has a population of **$n_p = 1.5 \times 10^{11}$ protons**. Bunches are separated by **t_b = 25 ns**.

The following material properties are uniform and can be assumed temperature-independent: density **$\rho = 1.85$ g/cm^3**, thermal conductivity **λ = 70 W/mK**, CTE **$\alpha = 4 \times 10^{-6}$ K^{-1}**, Young's Modulus **E = 10.5 GPa**, Poisson's ratio ν = **0.15**.

Assuming that the energy deposition profile is **uniform** in the longitudinal direction, with an **axially symmetric** Gaussian distribution (standard deviation **0.6 mm)** and a peak deposited energy density per proton of **$q_p = 2.46 \times 10^{-11}$ J/g**, do the following:

1. *Calculate the peak energy density* q_{dMax} *and peak power density* $\dot{q}_{dMax}$ *at the target center deposited during the impact.*
2. *Write the distribution of the energy* $q_d(r)$ *deposited on the target cross-section during the impact. Calculate the total deposited energy per unit length* Q_d.
3. *Assume a reasonable average value for the specific heat* c_p, *whose evolution with temperature is given in the plot below. Justify your choice.*
4. *Determine the thermal diffusion time and verify if the heat deposition can be considered "instantaneous".*
5. *Based on your conclusions on previous question, determine the initial temperature distribution on the cross section, its maximum value and its final uniform value (assuming an adiabatic problem)*

Homework Problem

6. *Assuming that the rod is restrained at both its ends, determine, at the time of maximum stresses, the quasistatic radial, circumferential and axial stresses at the center and on the outer rim of the rod.*
7. *Given that, in reality, the rod is free to axially expand, calculate the period of axial stress waves.*
8. *Determine the maximum value of the dynamic axial stress to be superposed to the quasistatic stresses calculated at step 6.*
9. *Draw an approximate plot of the dynamic axial stress at mid-rod as a function of time. Comment on the time structure of the stress curve.*
10. *Calculate the maximum total axial stress on the outer rim.*