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Materials for Extreme Thermal Management: Report from WP17

ARIES Final Review Meeting

Online Meeting 15.07.2022

Alessandro Bertarelli (CERN), Marilena Tomut (GSI)

WP17 (PowerMat) in a Nutshell

- Identify materials for **accelerator components** (collimators, beam targets, windows and luminescence screens …) withstanding high power impacts and extreme thermal management **(tasks 17.2, 17.5)**
- Develop **novel Ceramic Matrix and Metal Matrix Composites** based on graphite and diamond reinforcements with various dopants **(tasks 17.2, 17.5)**
- **Simulate** and **test** materials under **extreme thermal shocks** (**particle-** or **laser-beam induced**) and **particle irradiation (task 17.3)**
- Investigate **Radiation Damage** from theoretical, numerical and experimental standpoint **(tasks 17.4)**
- Explore **societal applications** in advanced engineering, medical imaging, quantum computing, energy efficiency, aerospace … **(task 17.5)**

ARIES

WP17 (PowerMat) Partners

- WP17: **6 main beneficiaries**, **1 associate** (**NIMP**)
- Strong interaction with WP14: **1 beneficiary industry** (**RHP-Technology**), **1 associate industry** (**Brevetti Bizz**) within Task 14.4

WP17 Coordination

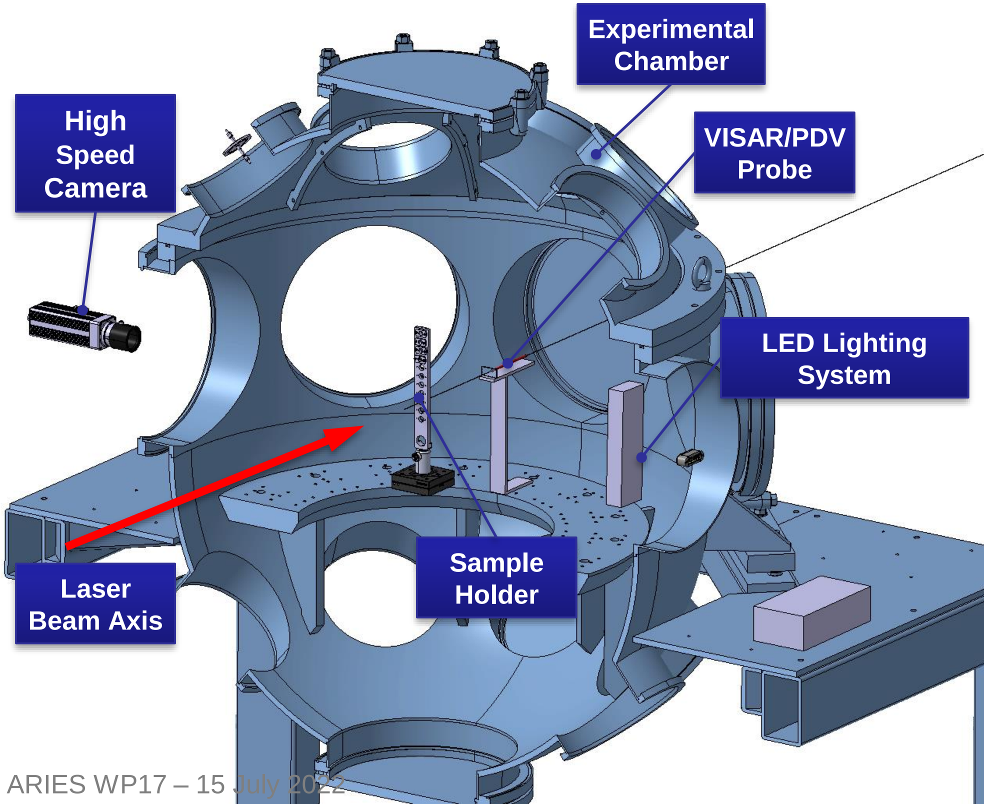
- JRA extended to **December 2021** to allow conclusion of experimental activities delayed because of Covid-19
- All 3 **Deliverables submitted.**
- All 5 **Milestones completed**. MS62-related workshop cancelled because of Covid-19 and **replaced by special issue on "Shock and Vibration" journal**
- **2 additional monographs** in ARIES Editorial Series (vols 59, 60). **4 in total**

Deliverable Number	Deliverable Title	Lead Beneficiary	Type	Dissemination Level	Due date (month)
D17.1	Material Characterization	1 – CERN	Report	Public	12
D17.2	Irradiation effect simulations	1 – CERN	Report	Public	~~44~~ **50**
D17.3	Irradiation test results	23 – POLITO	Report	Public	~~46~~ **54**

Milestone Number	Milestone Title	WP Number	Lead Beneficiary	Due Date (month)	Means of verification
MS58	Organisation of PowerMat kick-off meeting (Task 17.1)	WP17	1 – CERN	6	Agenda, summary report
MS59	Irradiation campaigns at GSI for radiation hardness studies (Task 17.3)	WP17	23 – POLITO	27	Report to StCom
MS60	Irradiation effects analysis (Task 17.3)	WP17	1 – CERN	36	Report to StCom
MS61	Comparative compendium of material developed (Task 17.2)	WP17	1 – CERN	~~40~~ **43**	Report to StCom
MS62	Dissemination of R&D results on novel materials for accelerator and societal applications (Task 17.5)	WP17	12 – GSI	~~46~~ **60**	Report to StCom

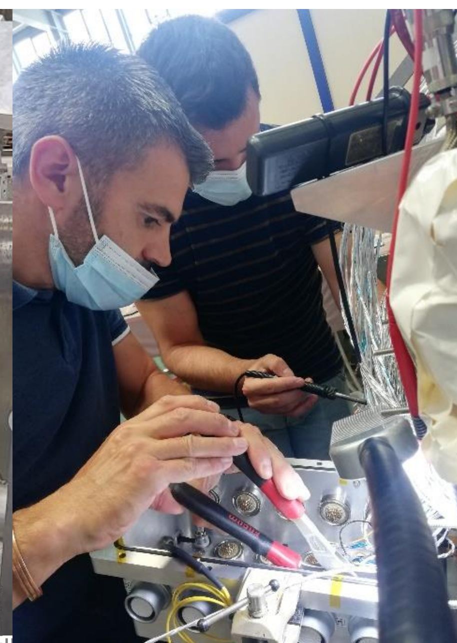
Main Experimental Activities – May ‘21 – April ‘22

- **Main experiments and TNA Contributions** after May 2021
  - HiRadMat experiment at CERN on slender rods (**MultiMat-2**) successfully completed in **September 2021**
  - Novel **Laser experiment** at **GSI-PHELIX** facility successfully completed in **February 2022** (Covid-related postponement)



Task 17.3: Multimat-2 Experiment at HiRadMat

- A modular and reusable platform to **test advanced collimator materials** at **energy densities exceeding HL-LHC values,** complementing first experiment performed in October ‘17 (MultiMat)
- Experiment **successfully completed in September ‘21**, testing 12 different materials (CuCD, MoGr, CrGr, graphite, CFC) and coatings (Mo and Cu)
- **Main goal**: **completing set of constitutive properties** (mechanical response at high strain rates, dynamic strength, internal damping, effects of porosity, anisotropic wave propagation, dynamic behaviour of coatings …) for **recently developed** materials and coatings



Task 17.3: Laser Experiment at GSI-PHELIX

- **P219 experiment** goal: **dynamic test** of **thin disks** under **intense laser pulses**, reaching **energy densities** comparable to **extreme accidental scenarios** as in **FCC-hh** (peak energy density **~50** $kJ\ cm^{-3}$)
- **P219 Experiment** at **PHELIX Z6** (**GSI**, Darmstadt) facility successfully completed in **February 2022**
- **48 targets irradiated, Ø10 mm,** thicknesses from **0.75 to 3.5 mm materials** including **MoGr, Graphite, CrGr, CFC (2D, 3D) CuCD, Glassy C, Flex Graphite, C-Foam,Special Alloys, bare** and **Cu- and Mo-coated**
- Experiment **Laser Parameters** (Wavelength $\lambda = 530\ nm$)
  - Pulse energy and duration: **~ 60 J** in **1.5 ns**
  - Beam spot diameter (intensity) : ~1 mm (**~ 5 TW cm**$^{-2}$)
- A **strong shock wave** is generated on the impacted face, quickly decaying while moving towards the back face, but still strong enough to generate **spallation near the back face**
- **Explicit numerical simulations** (CERN, POLITO, ELI-NP) predict the dynamic conditions achieved during the irradiation

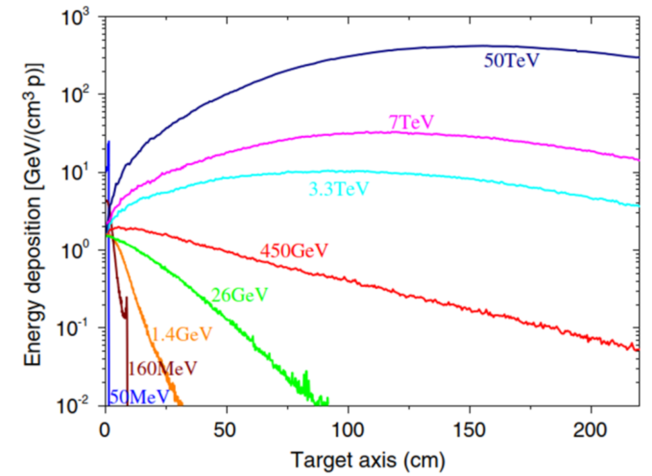
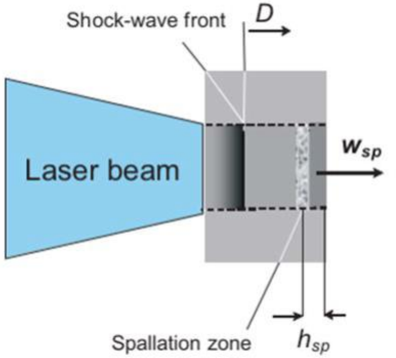
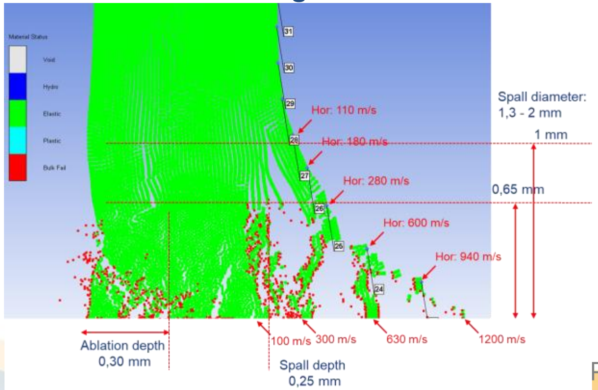
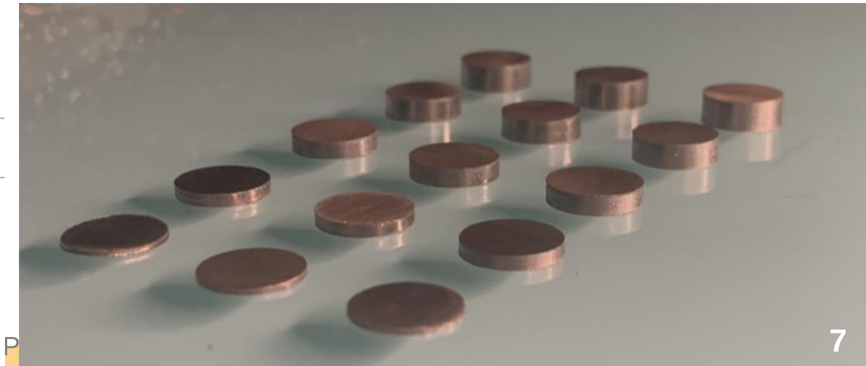


FIG. 14. Energy deposition per incident proton as a function of the depth into the solid graphite target at $r = 0$. The beam size is 0.2 mm for all the presented energies from 50 MeV to 50 TeV.



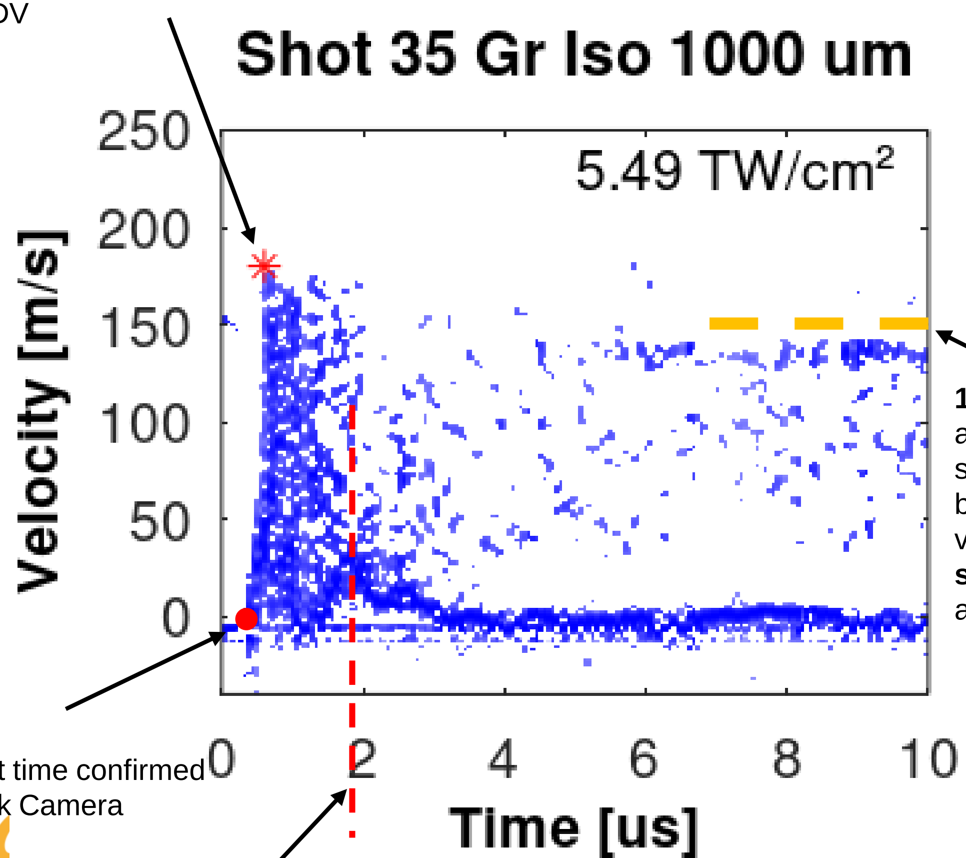




Task 17.3: Laser Experiment at GSI-PHELIX

- **Online Measurements**: PDV vs Shadowgraphy, cross-checking with Streak Camera

Back face Peak velocity 180 m/s after 0,60 µs from PDV

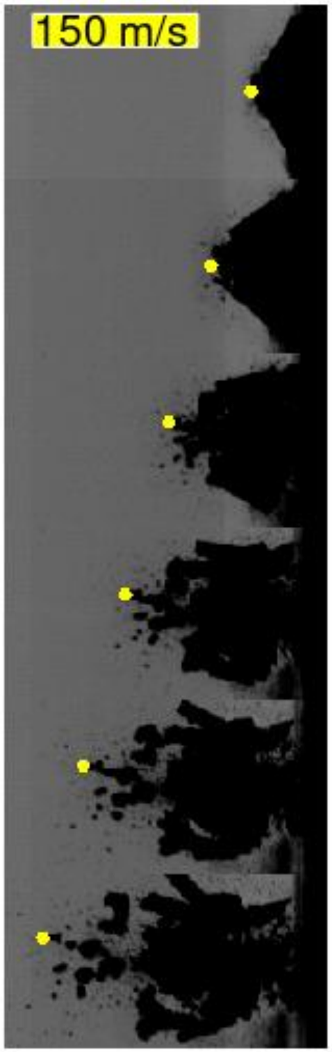


0,32 µs
Breakout time confirmed by Streak Camera

Suspicion of crack at 600 µm below the back-surface
To be checked by tomography

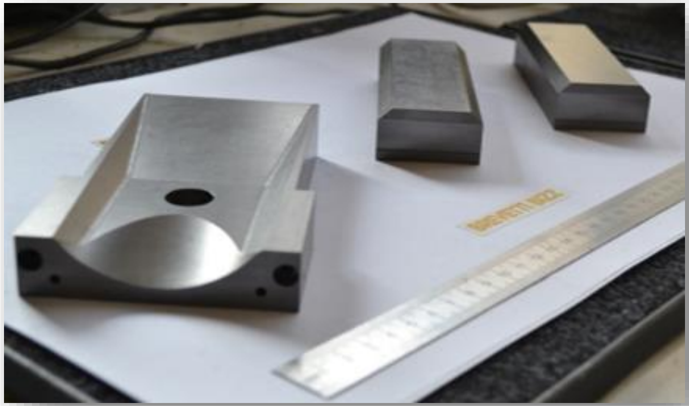
150 m/s debris velocity as measured by shadowgraphy (Difference between peak and debris velocity proportional to **spall strength** in the acoustic approximation)

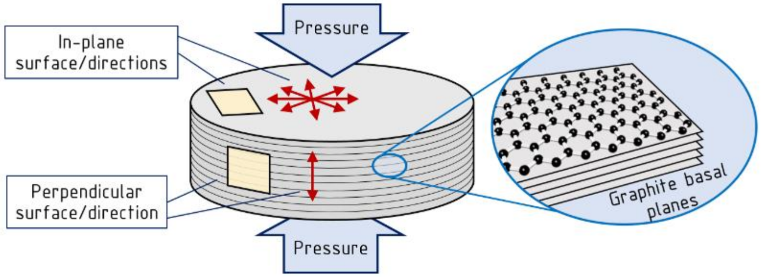
1 frame every 5,4 µs



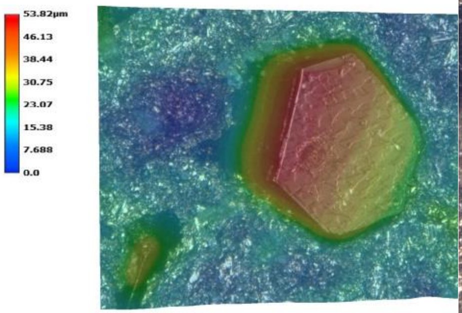
WP17 Main Achievements: Novel Materials

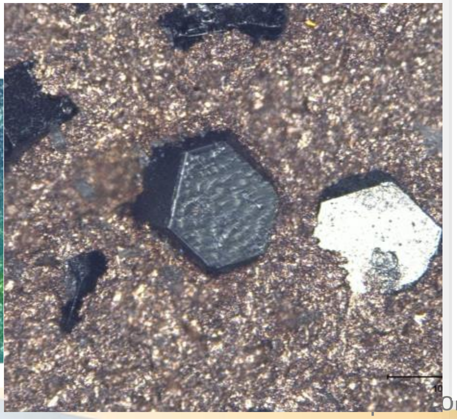
- CERN, GSI, POLITO, BREVETTI, RHP, NIMP
- R&D of advanced materials for **extreme thermal management** applications
- Further **development, optimization, characterization** and **industrialization** of **MoGr (Brevetti Bizz)** and **CuCD (RHP-Technology)**
- **R&D and complete characterization** of 4 grades of first generation **Chromium – Graphite (Brevetti Bizz)** as lower cost, more affordable alternative to MoGr.





J.G. Valenzuela et al., Carbon 135 (2018). 72-84





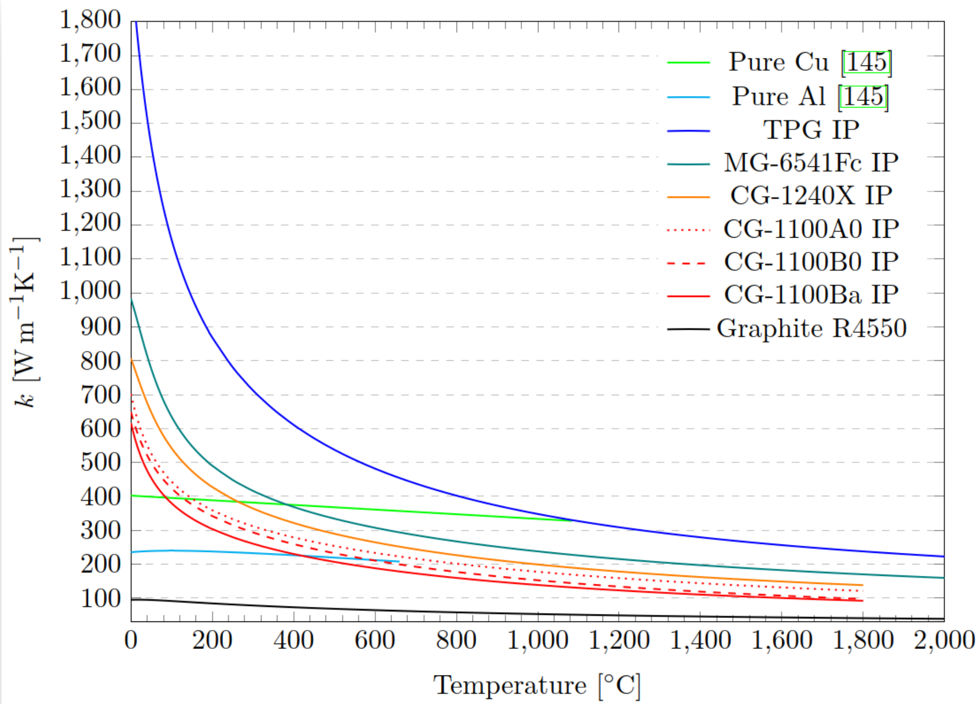
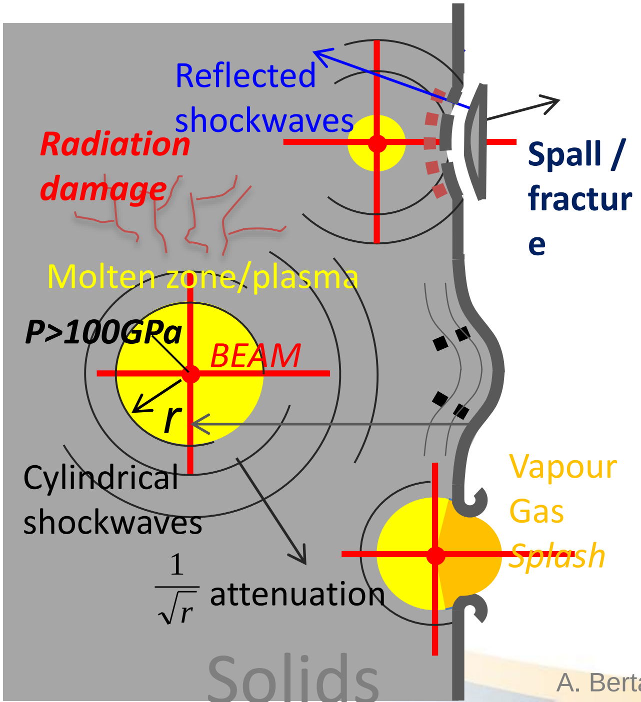
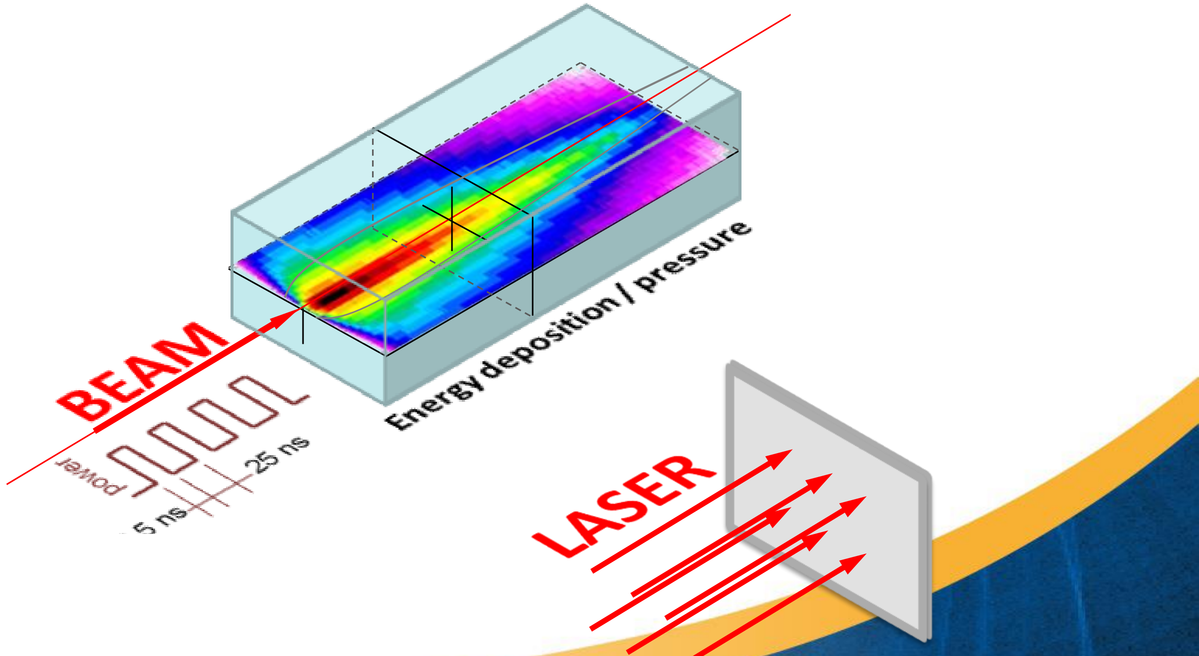


Figure 6.20: In-plane thermal conductivity of the investigated materials.

WP17 Main Achievements: Numerical Methods and Tests

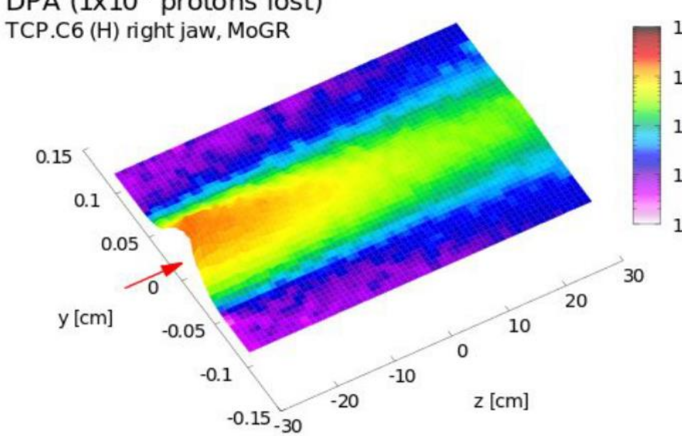
- CERN, POLITO, GSI, UniMalta, ELI-NP, POLIMI
- Development and optimization of **advanced numerical methods** (including **hydrocodes**) to study high energy impacts on materials and components
- **3 experimental campaigns at HiRadMat** (FlexMat, Multimat and MultiMat-2) to test a wide range of materials and coatings to assess their survivability and derive their properties, benchmarking numerical simulations
- A **novel experiment using high power laser** inducing dynamic conditions akin to the ones predicted for accidental impacts in future high-energy accelerators (e.g. FCC-hh)
- **State-of-the-art instrumentation** and **diagnostics** systems developed

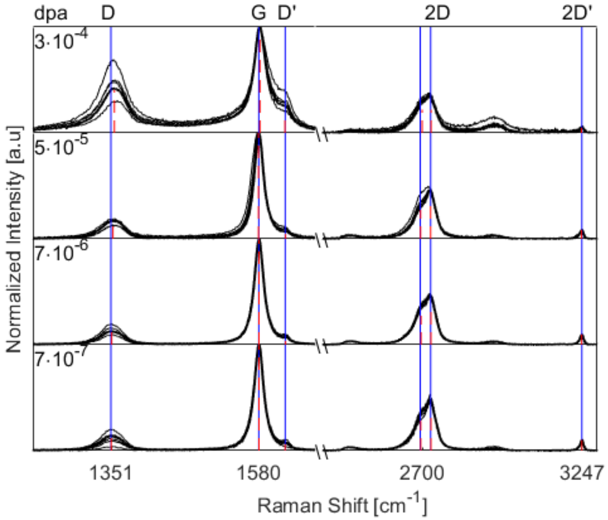




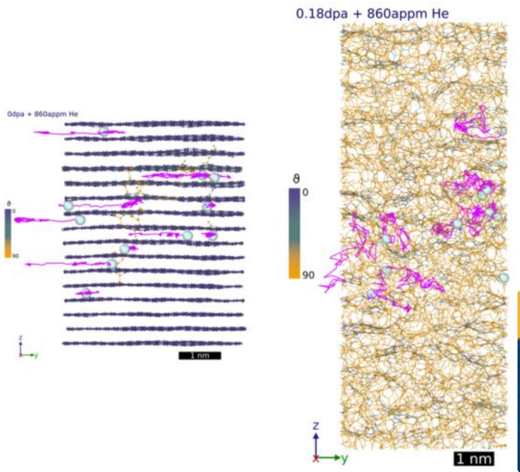
WP17 Main Achievements: Irradiation Simulations and Tests

- CERN, GSI, POLIMI
- Development of a **FLUKA-based simulation methodology** to **compare** the **radiation damage** induced by HE p+ in **HL-LHC** with experiments using **low-energy heavy ions**, by means of the **Displacement per Atom (dpa) indicator**
- **3 ion irradiation campaigns** at **GSI-UNILAC** on several materials measuring the radiation effects on key thermo-physical (e.g. **electrical conductivity**) and mechanical properties as a function of dpa, to predict the **lifetime** of components in high-energy accelerators
- Irradiation of diamonds and diamond/metal-matrix composites to assess their **iono-luminescent response** for luminescence-based applications
- **Molecular dynamics** simulation of lattice damage in graphite





Raman spectra evolution of MoGr MG6541Fc for different dpa levels



Visualization of He atoms unwrapped trajectories in a pristine and damaged MD simulation box

WP17 List of Exploitable Foreground

Type of exploitation foreground	Description of exploitable foreground (relevant deliverable)	Purpose (How the foreground might be exploited and by whom)	IPR	Potential/expected impact (quantify where possible)	Exploitable product(s) or measure(s)	Sector(s) of application	Timetable, commercial or any other use
INV	Chromium carbide – graphite composite with high thermo-mechanical performance	Development will continue within I.FAST WP4, to improve thermophysical properties	Open	Around 2 times lower cost in future beam intercepting devices for accelerator-driven systems	Absorber elements for collimators & other beam-intercepting devices	Electronics, aerospace, particle accelerators	2024: demonstration of scalability to industrial size
INV	New generation of copper-diamond composites	Material now being installed in HL-LHC collimator prototypes and candidate for series production; also of interest for luminescence screens	Industrial know-how	Material 10 times more robust than the current tertiary collimator absorber material	Absorber elements for collimators & other beam-intercepting devices	Electronics, aerospace, medical, particle accelerators	2022: first-time installation in an HL-LHC collimator
GAK	Numerical / experimental method to study the radiation damage produced by protons on matter by means of ion irradiation	The method will be applied in the incoming I.FAST WP4, in the scope of vacuum window materials	Open	Decrease the duration and cooling time of irradiation tests by a factor of 20 with respect to proton irradiation	Any component subjected to radiation damage	Nuclear plants, fusion, particle accelerators, aerospace, medical	2022: application of the method during the I.FAST WP4 irradiation campaign
technology	Instrumentation system for dynamic tests of structures under particle beam pulses	The system may be used in experimental particle beam facilities to monitor and characterize the equipment; part of the instrumentation system can be adopted also in accelerators during operation.	Open	Measure the dynamic response of materials in harsh environment up to strains of ~0.1, strain rates of 10^4 s^{-1} and temperatures of 300 °C	Measure via strain gauges, optical fibres, laser-Doppler vibrometer and temperature probes	Structure dynamics, particle accelerators, aerospace	As of 2022

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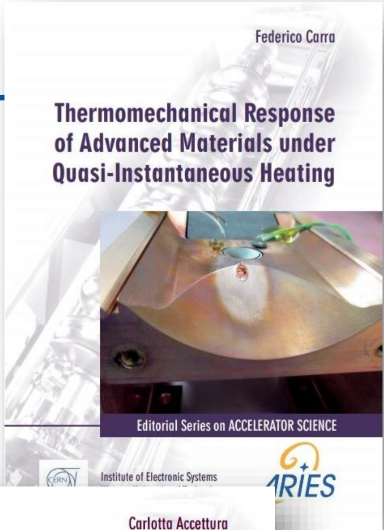
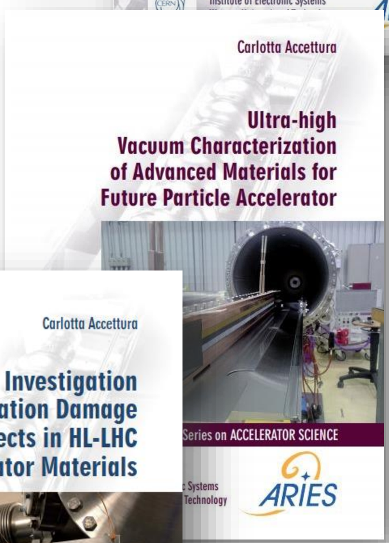
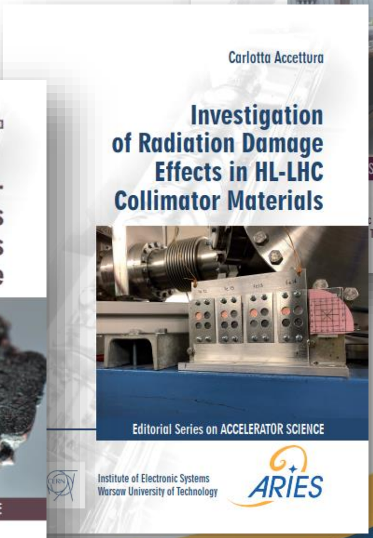
Thank you!

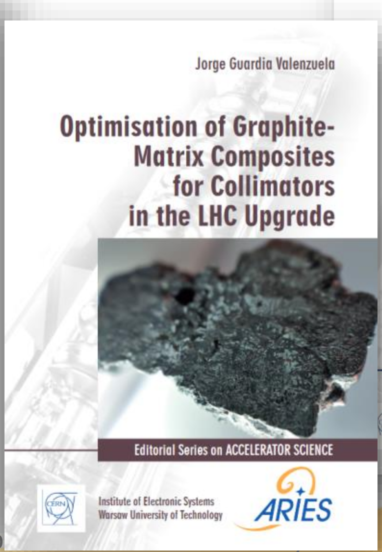
WP17 Outreach: Publications

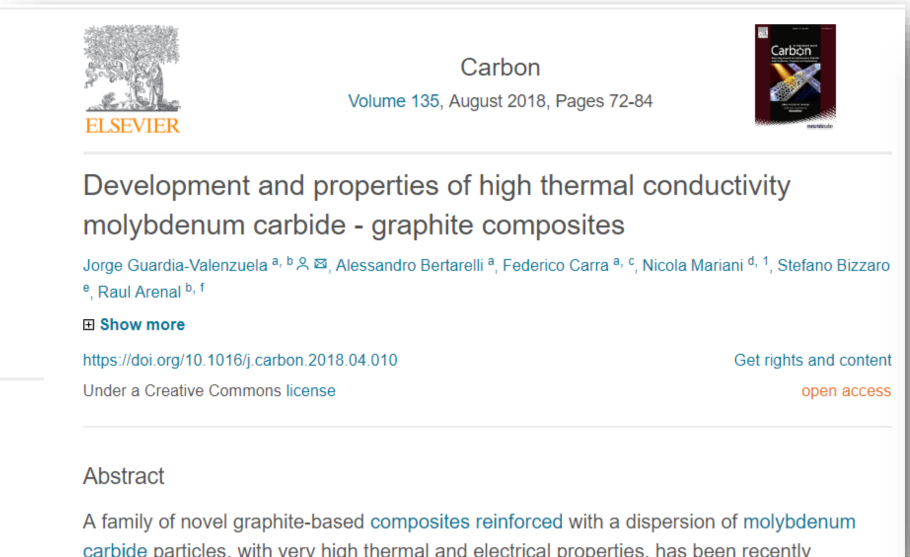
- ~20 PowerMat-related **Articles** and 5 **Theses** (4 PhD and 1 Master) uploaded in **Zenodo**
- 1 **PhD thesis** including **IP-sensitive** content with deferred publication
- Four workshops
- **Open Access** article in **Carbon** journal
- Four volumes in **ARIES monographs** published by WUT
- Special issue on compilation of HiRadMat tests …










ELSEVIER

Carbon

Volume 135, August 2018, Pages 72-84

Development and properties of high thermal conductivity molybdenum carbide - graphite composites

Jorge Guardia-Valenzuela [a, b], Alessandro Bertarelli [a], Federico Carra [a, c], Nicola Mariani [d, 1], Stefano Bizzaro [e], Raul Arenal [b, f]

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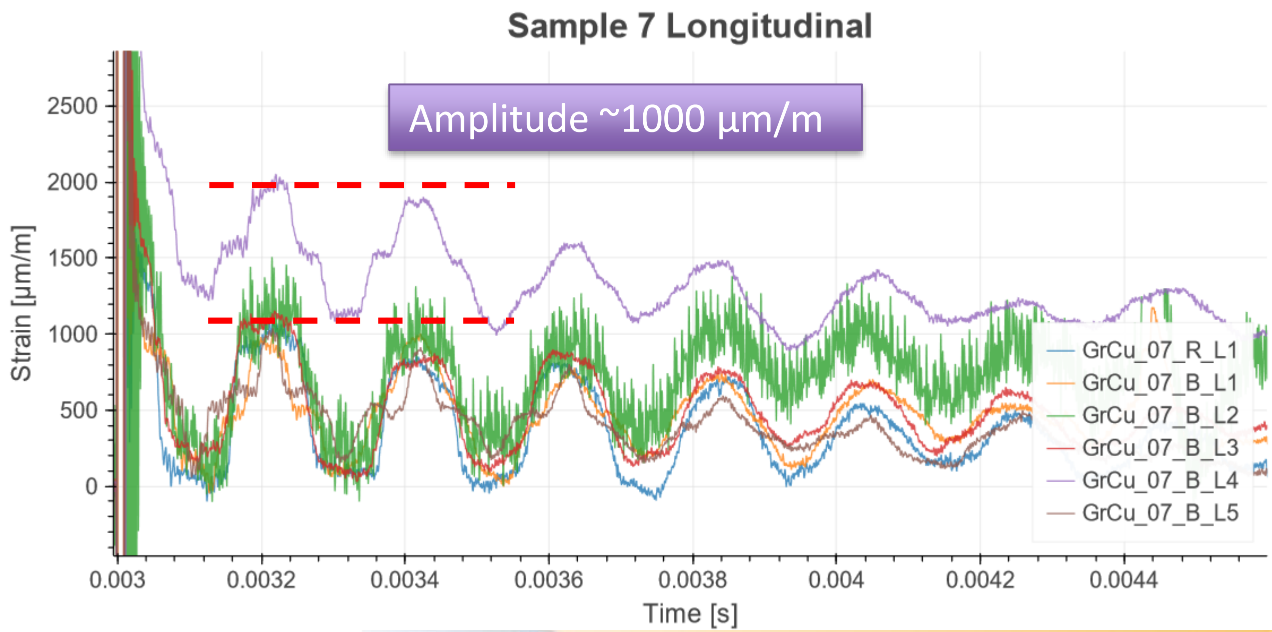
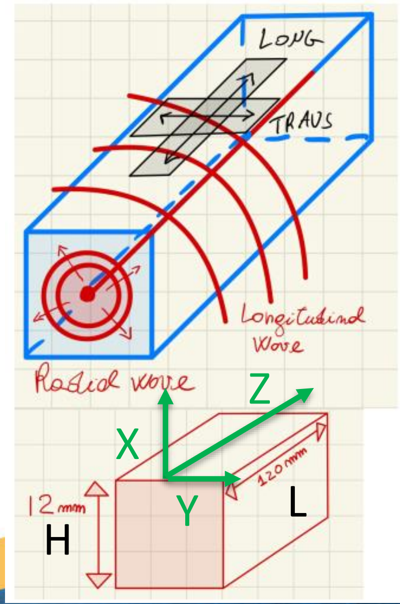
Abstract

A family of novel graphite-based composites reinforced with a dispersion of molybdenum carbide particles, with very high thermal and electrical properties, has been recently

Task 17.3: Multimat-2 Experiment Results

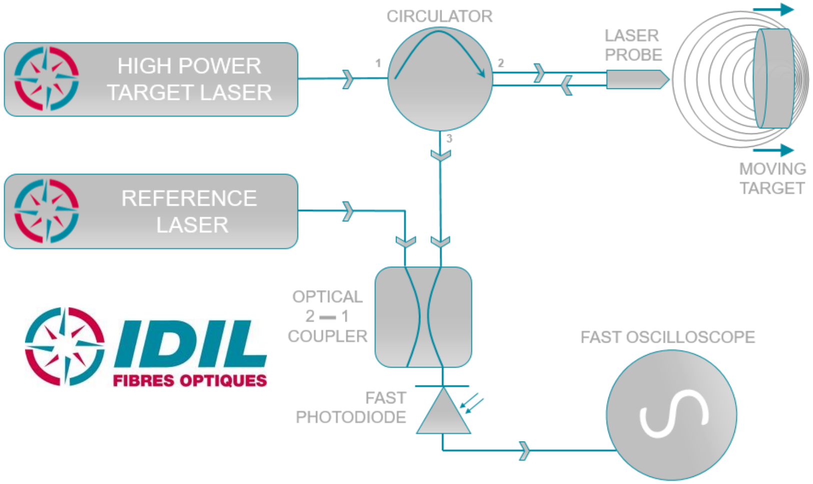
- No signs of fracture on bulk materials, including in CuCD. Coatings damage proportional to material density and deposited energy (higher on MoGr compared to lighter Graphite)
- Extensive set of online strain measurements compared to numerical models and allowing determining dynamic damage threshold





Task 17.3: Laser Experiment at GSI-PHELIX

- **Online Diagnostics**
  - **High Speed Camera** for Shadowgraphy - POLITO
  - **PDV** probe (**Photonic Doppler Velocimetry**) – Commercial rental (IDIL)
  - **Streak Camera** – GSI



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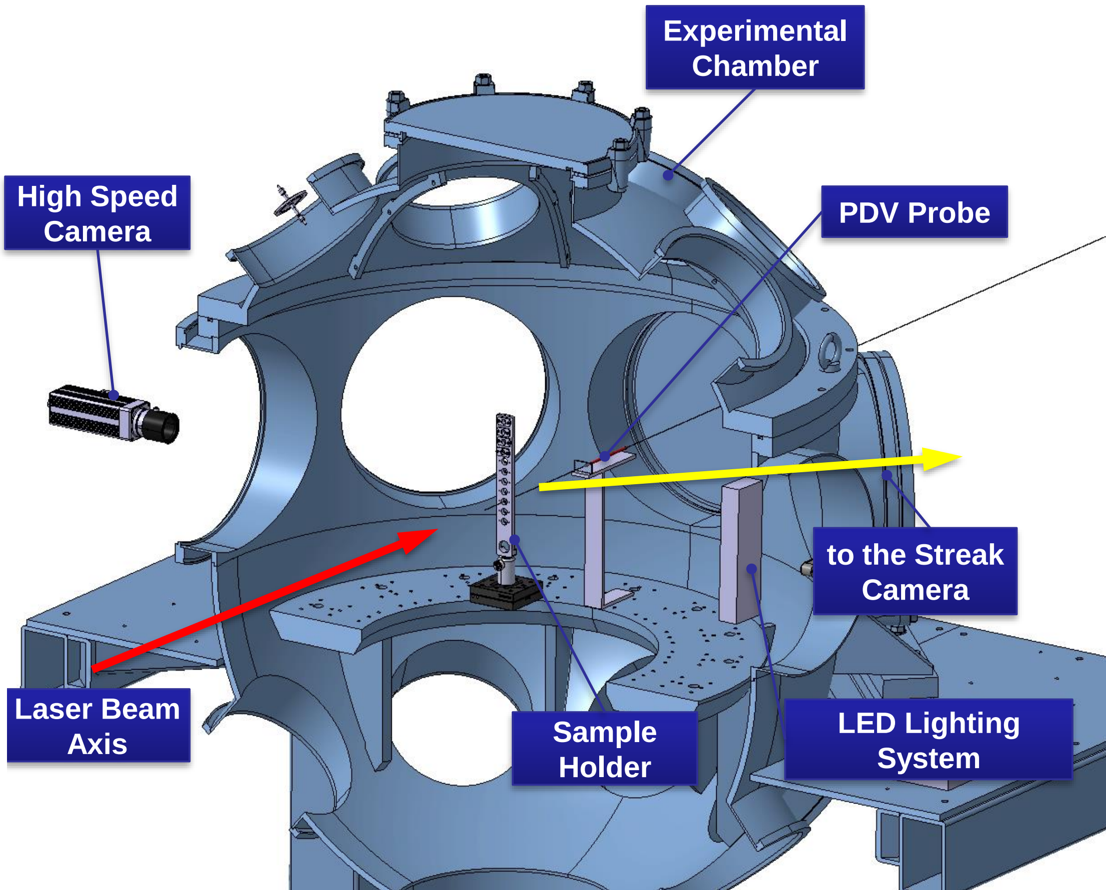
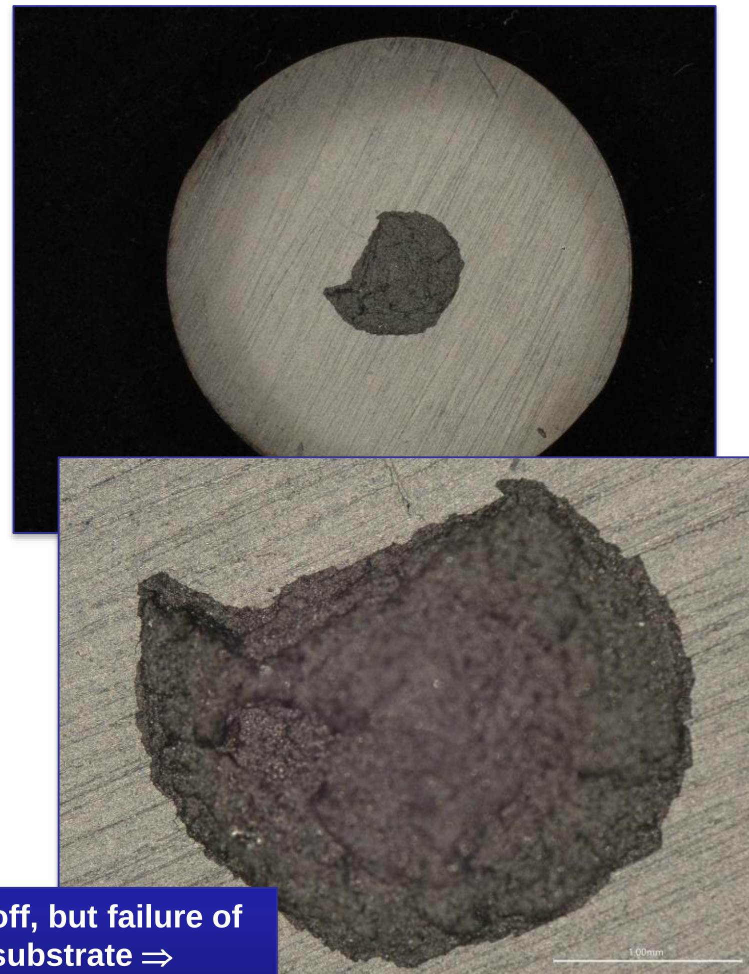
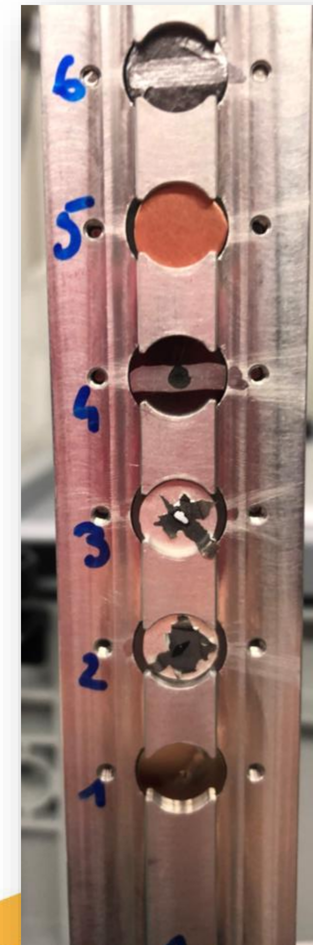


Task 17.3: Laser Experiment at GSI-PHELIX

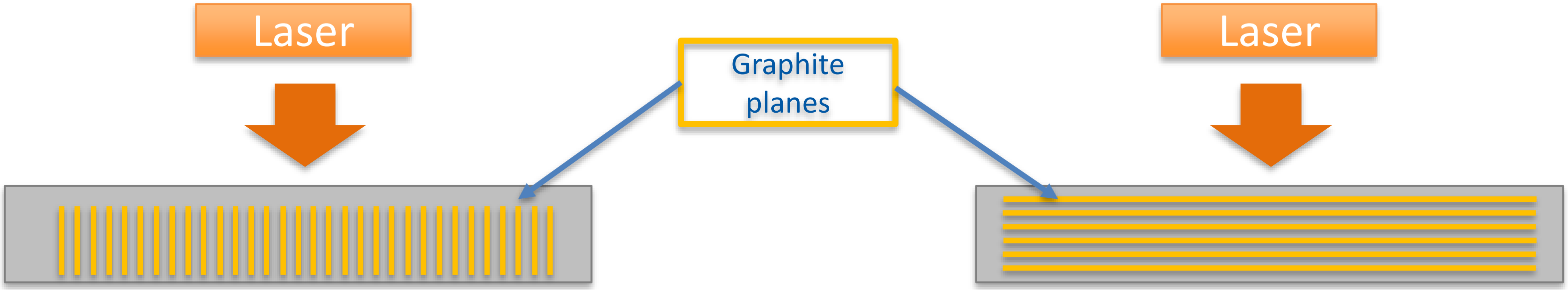
- **Post Irradiation Examination**: first visual observations to be followed by microscopic inspections ⇒ Cu- and Mo-coated 1.5-mm MoGr targets example



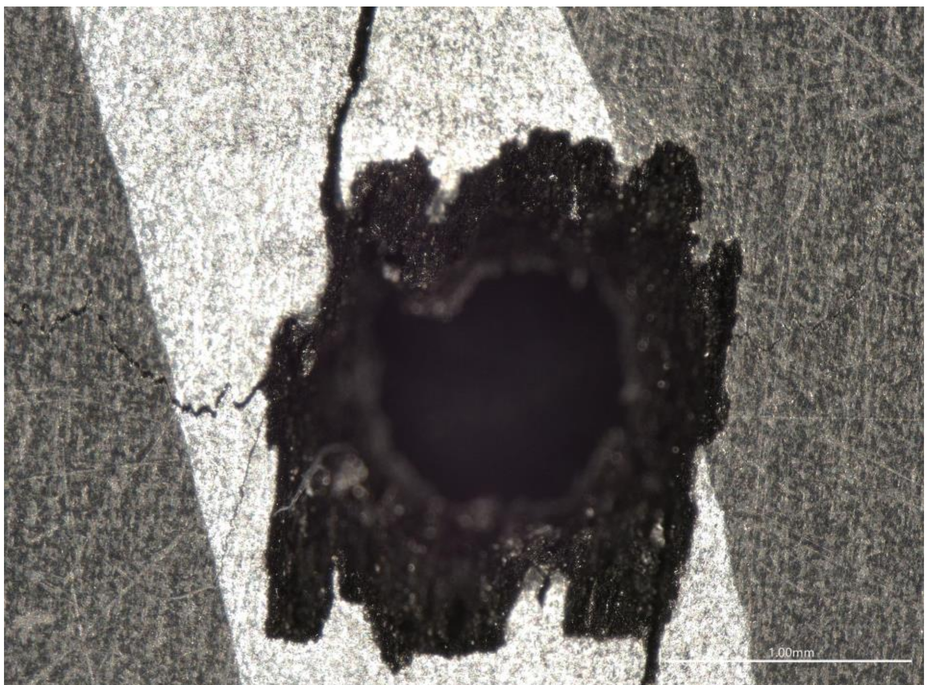


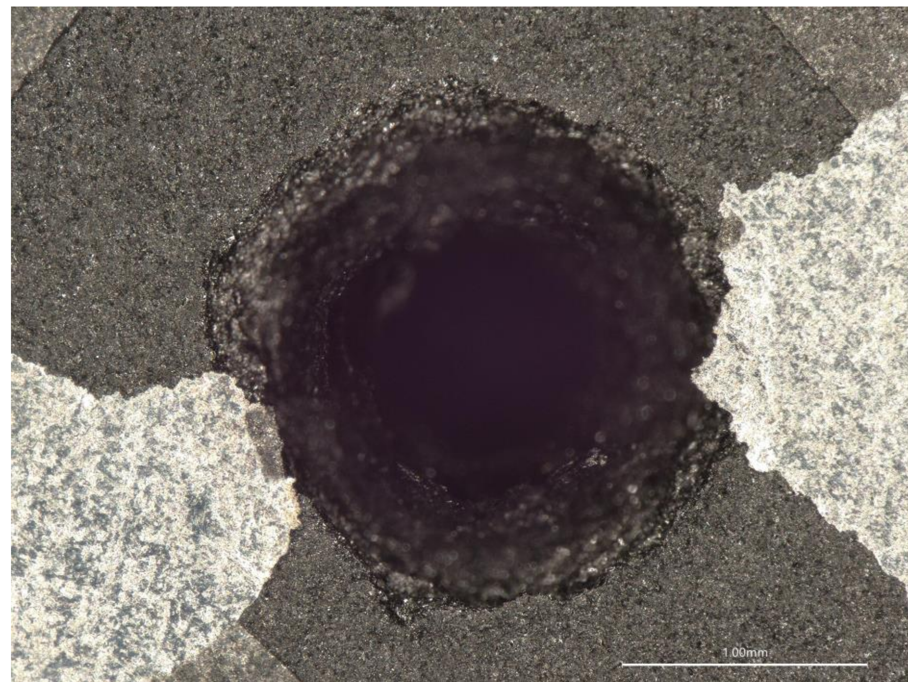
No peel-off, but failure of the substrate ⇒ good adherence

Fracture surface observation: anisotropic materials



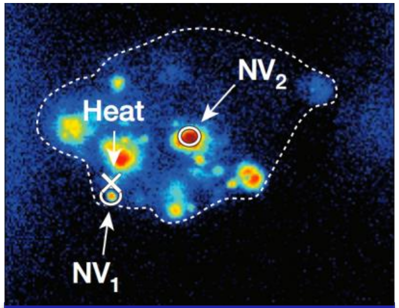
Thickness=0.75mm



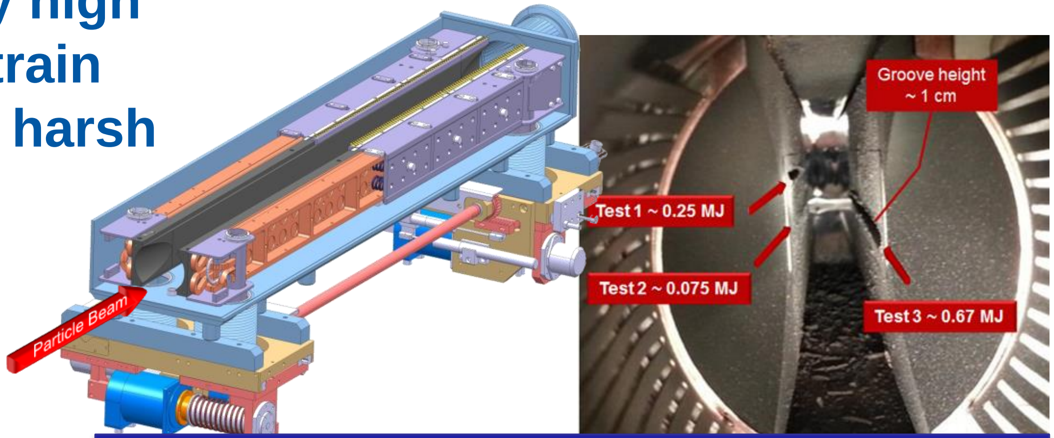


What is Extreme Thermal Management?

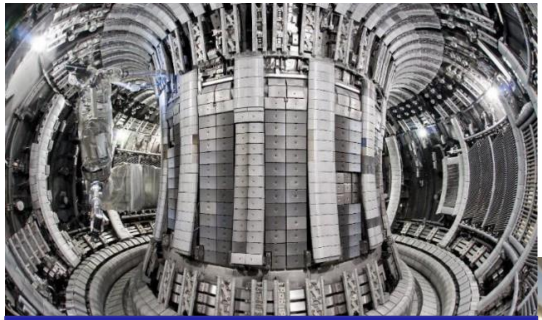
- Applications dealing with **very high temperatures**, **pressures**, **strain rates**, **particle irradiation**, in **harsh environments** …



Medical Imaging



Particle Accelerators (Beam Intercepting Devices)

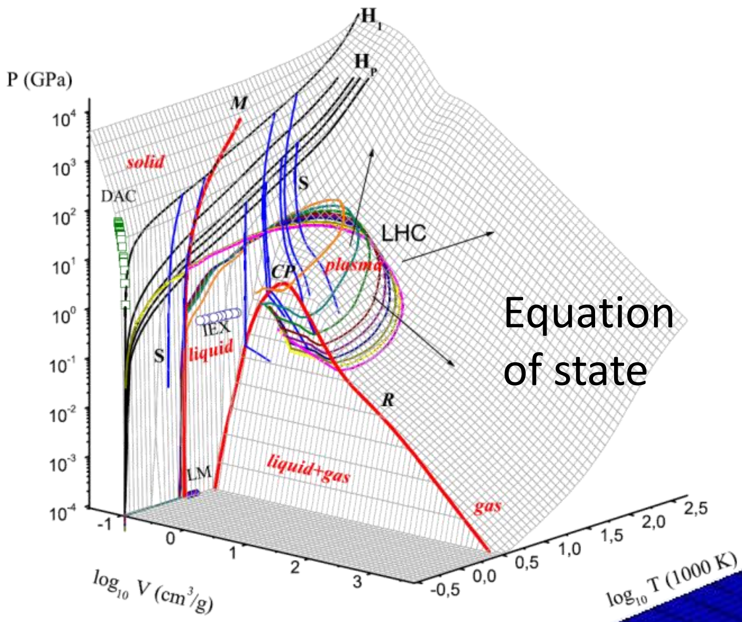

Fusion Engineering


High temperature Aerospace Applications

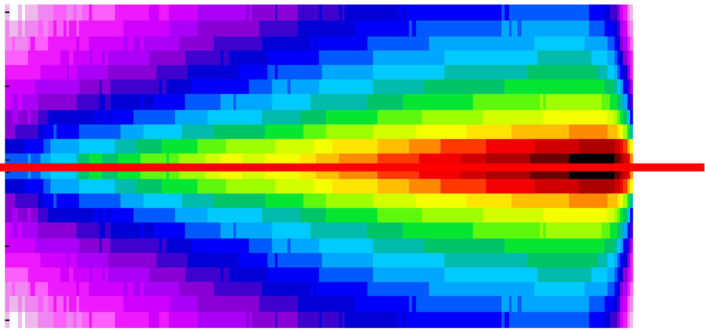

Advanced Braking Systems

ARIES

Hydrodynamic simulations: EOS, spall strengths for new materials



Energy deposition



Particle beam