This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 730871.

Report from WP17 (Materials for Extreme Thermal Management):

- **Last Period Results**
- **Main Achievements and Impact**

5^{th} ARIES Annual Meeting,
CERN Geneva 02.05.2022

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)**

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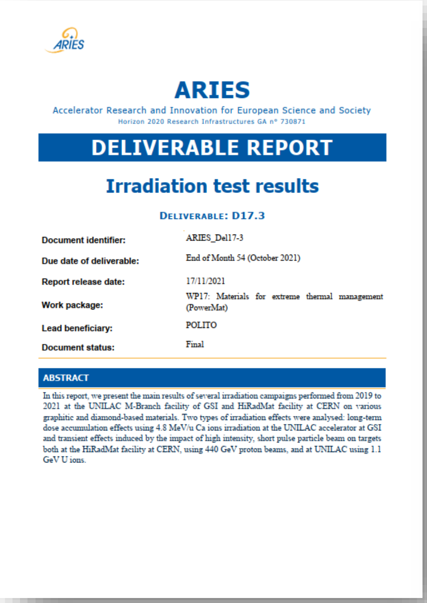
WP17 (PowerMat) Partners

- 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 – May ‘21 – April ‘22

- JRA extended to **December 2021** to allow conclusion of experimental activities delayed because of COVID-19
- Two final **Deliverables submitted (Del 17.2 and 17.3)**
- **MS62** with dedicated **workshop** on R&D **Dissemination** on Novel Materials for Societal application **not held** because of COVID restrictions
- **2 additional monographs** in ARIES Editorial Series (vols 59, 60)
- 7 additional **scientific publications**



ARIES
Accelerator Research and Innovation for European Science and Society
Horizon 2020 Research Infrastructures GA n° 730871

DELIVERABLE REPORT

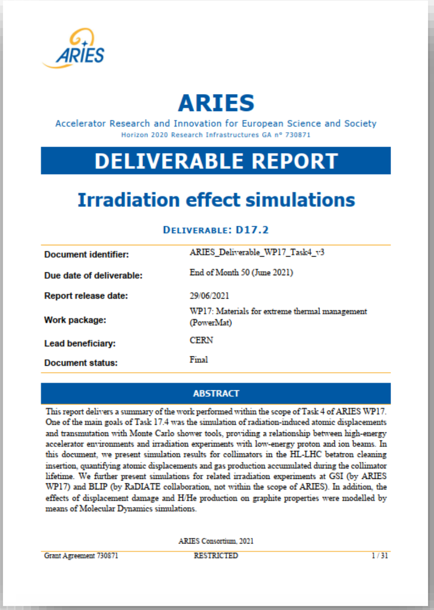
Irradiation test results

DELIVERABLE: D17.3

Document identifier:	ARIES_Del17-3
Due date of deliverable:	End of Month 54 (October 2021)
Report release date:	17/11/2021
Work package:	WP17: Materials for extreme thermal management (PowerMat)
Lead beneficiary:	POLITO
Document status:	Final

ABSTRACT

In this report, we present the main results of several irradiation campaigns performed from 2019 to 2021 at the UNILAC M-Branch facility of GSI and HiRadMat facility at CERN on various graphitic and diamond-based materials. Two types of irradiation effects were analysed: long-term dose accumulation effects using 4.8 MeV/u Ca ions irradiation at the UNILAC accelerator at GSI and transient effects induced by the impact of high intensity, short pulse particle beam on targets both at the HiRadMat facility at CERN, using 440 GeV proton beams, and at UNILAC using 1.1 GeV U ions.



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Horizon 2020 Research Infrastructures GA n° 730871

DELIVERABLE REPORT

Irradiation effect simulations

DELIVERABLE: D17.2

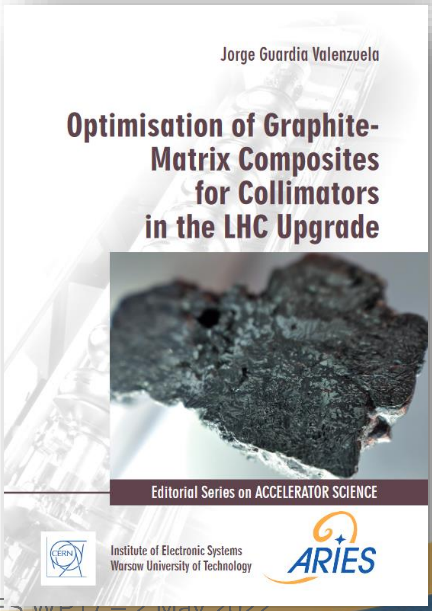
Document identifier:	ARIES_Deliverable_WP17_Task4_v3
Due date of deliverable:	End of Month 50 (June 2021)
Report release date:	29/06/2021
Work package:	WP17: Materials for extreme thermal management (PowerMat)
Lead beneficiary:	CERN
Document status:	Final

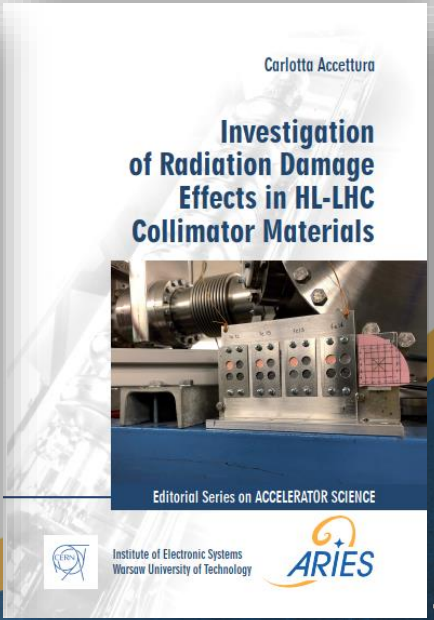
ABSTRACT

This report delivers a summary of the work performed within the scope of Task 4 of ARIES WP17. One of the main goals of Task 17.4 was the simulation of radiation-induced atomic displacements and transmutation with Monte Carlo shower tools, providing a relationship between high-energy accelerator environments and irradiation experiments with low-energy proton and ion beams. In this document, we present simulation results for collimators in the HL-LHC betatron cleaning insertion, quantifying atomic displacements and gas production accumulated during the collimator lifetime. We further present simulations for related irradiation experiments at GSI (by ARIES WP17) and BLIP (by RaDIATE collaboration, not within the scope of ARIES). In addition, the effects of displacement damage and H/He production on graphite properties were modelled by means of Molecular Dynamics simulations.

ARIES Consortium, 2021

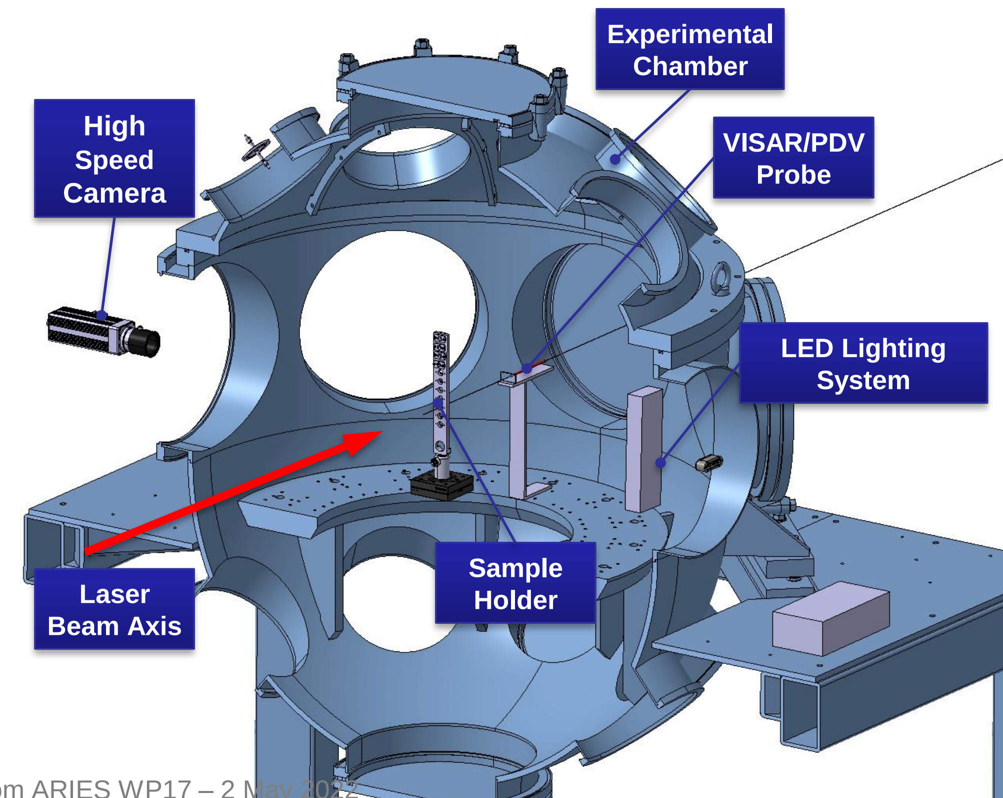
Grant Agreement 730871 RESTRICTED 1 / 31





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)

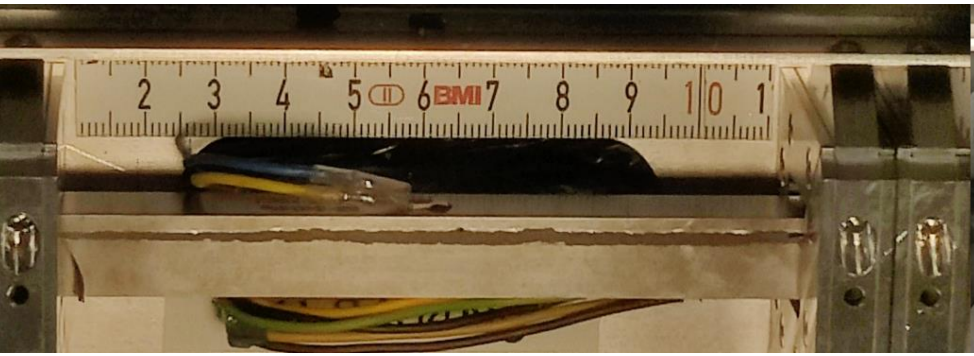


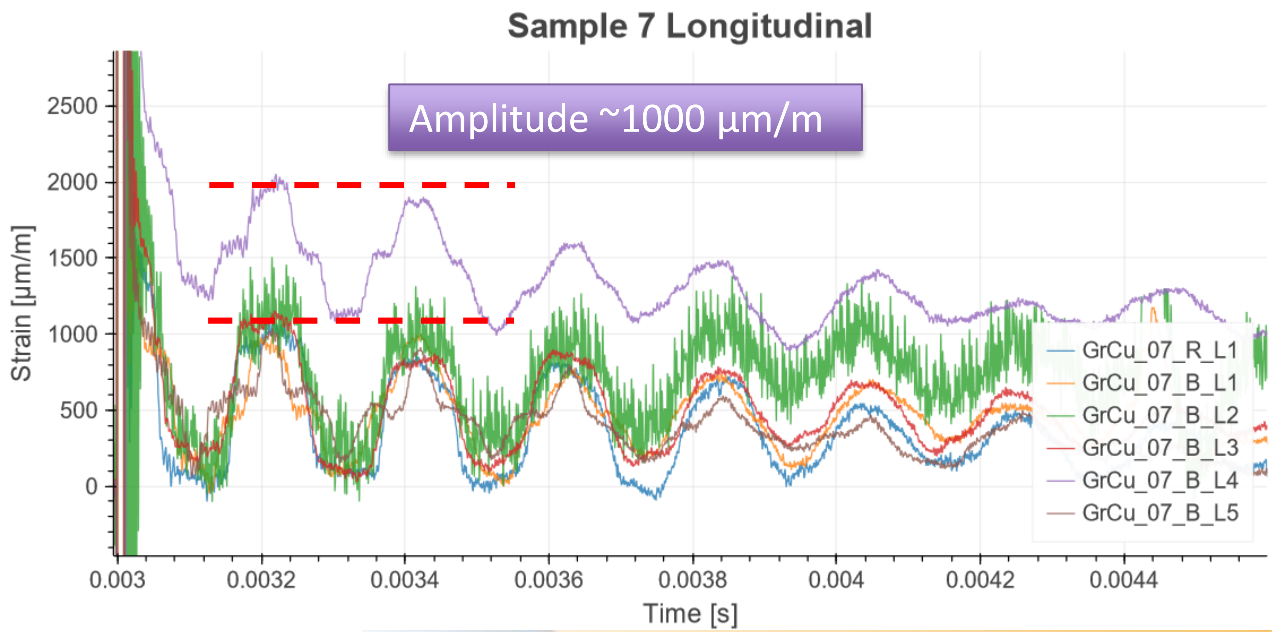
Task 17.3: Multimat-2 Experiment at HiRadMat

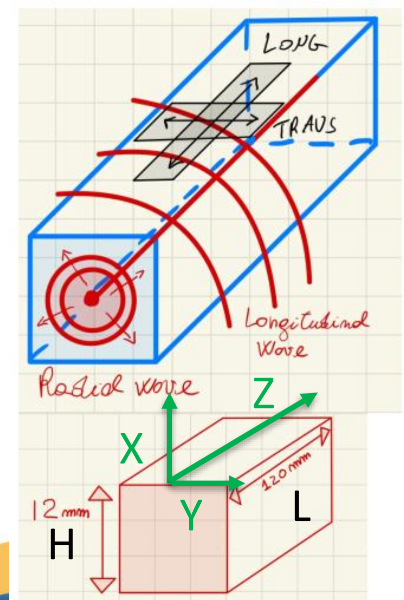
- A modular and reusable platform to **test advanced collimator materials** at **energy densities exceeding HL-LHC values,** complementing first experiment performed in October ‘17 (MultiMat)
- Experiment **held in September ‘21**, testing 12 different materials (CuCD, MoGr, CrGr, graphite, CFC) and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

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)
- Comprehensive set of real-time strain and temperature measurements compared to numerical models, allowing determining dynamic damage threshold







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

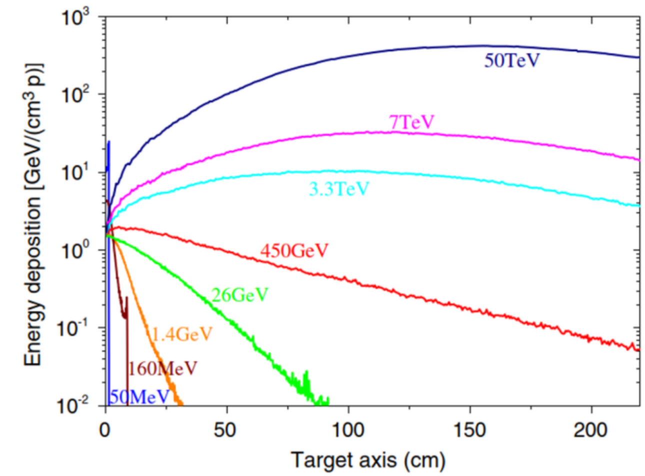
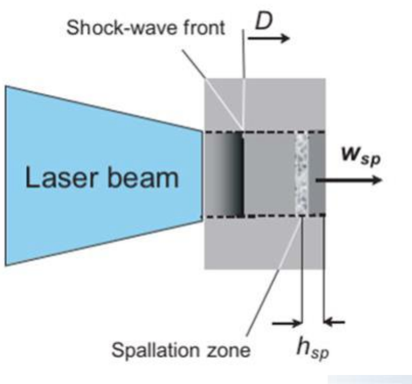
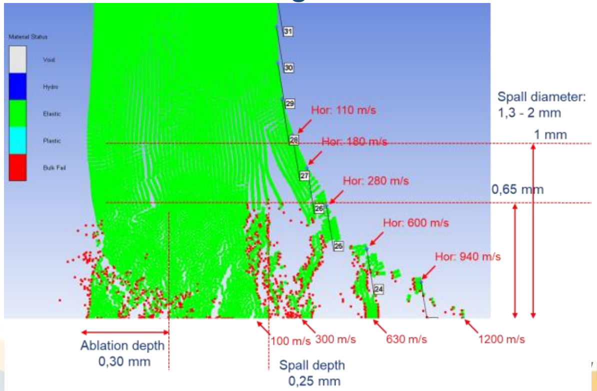
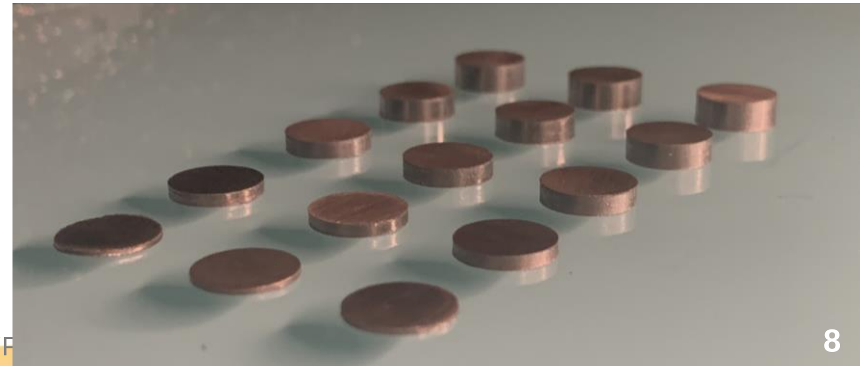


FIG. 14. Energy deposition per incident proton as a function of the depth into the solid graphite target at $r = 0$. The beam size is 0.2 mm for all the presented energies from 50 MeV to 50 TeV.

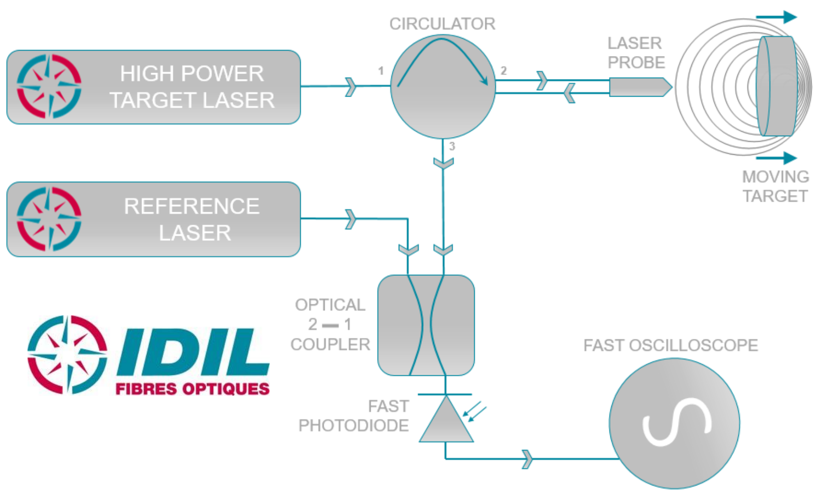


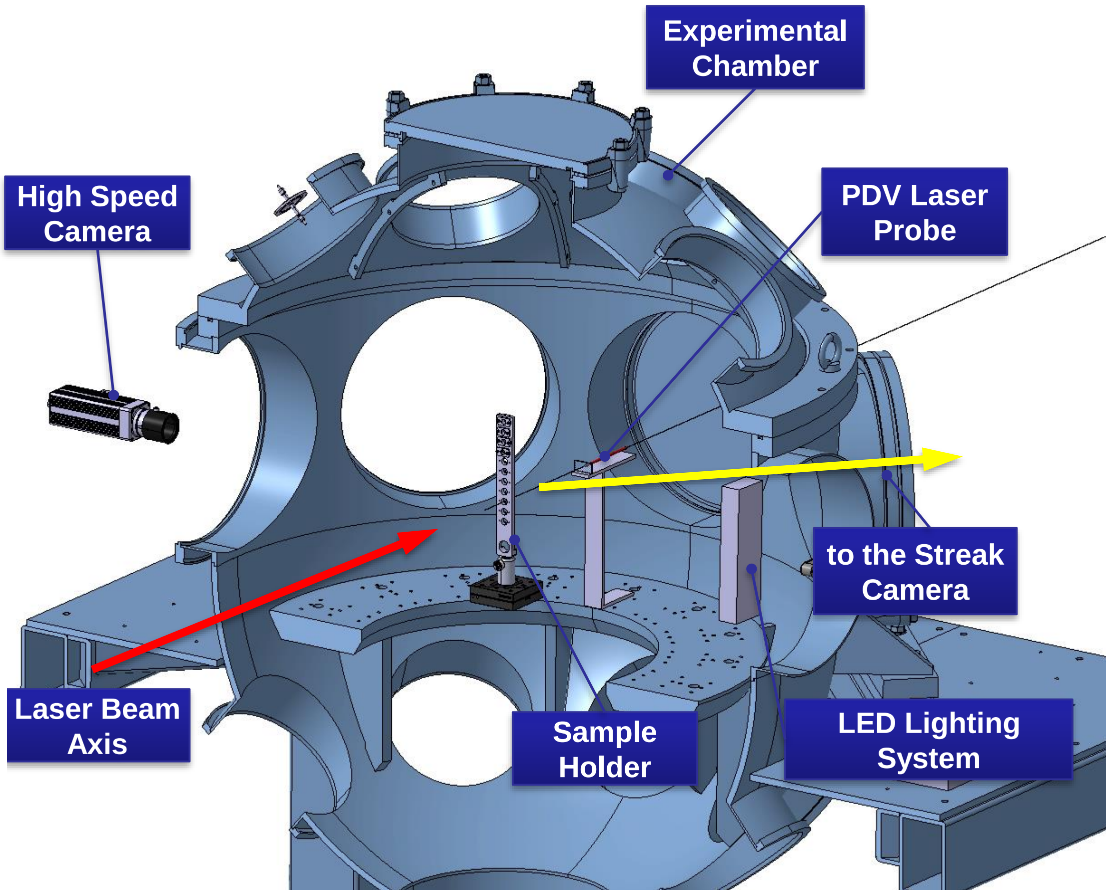




Task 17.3: Laser Experiment at GSI-PHELIX

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

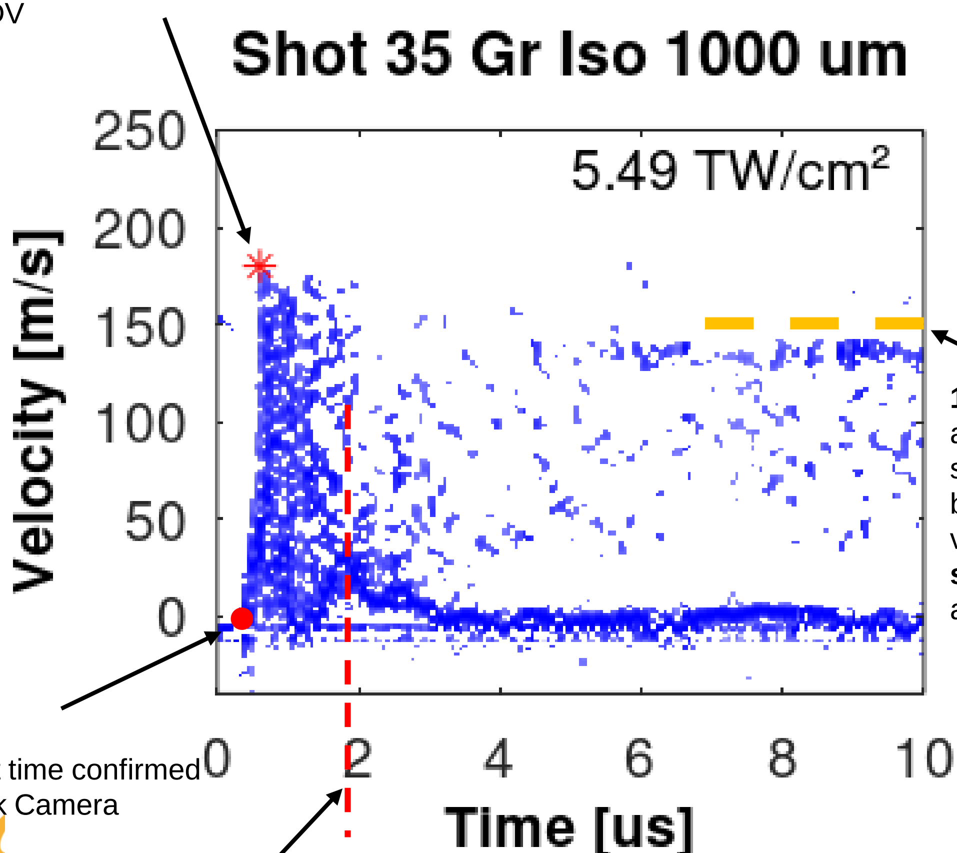




Task 17.3: Laser Experiment at GSI-PHELIX

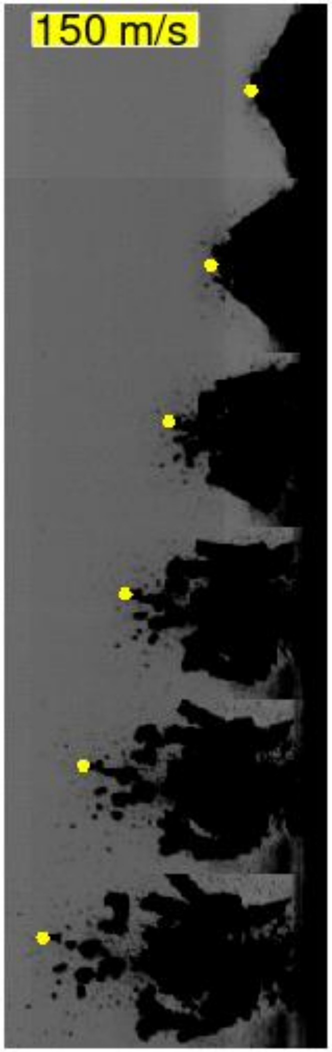
- **Online Measurements**: PDV vs Shadowgraphy, cross-checking with Streak Camera

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



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

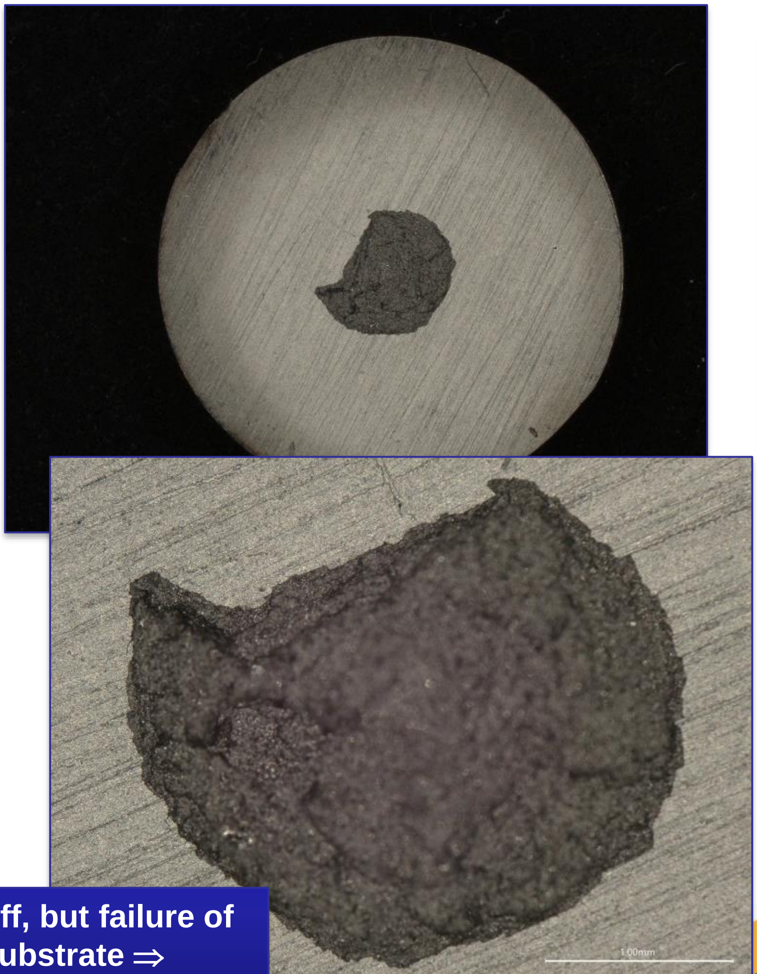


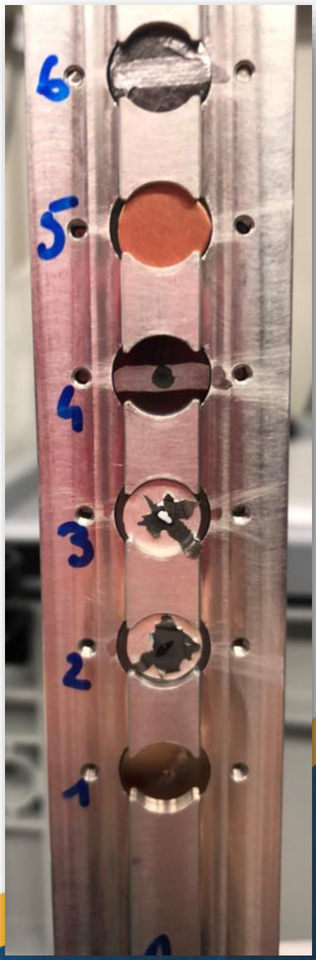
0,32 µs
Breakout time confirmed by Streak Camera

Suspicion of crack at 850 µm below the back-surface
To be checked by tomography

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

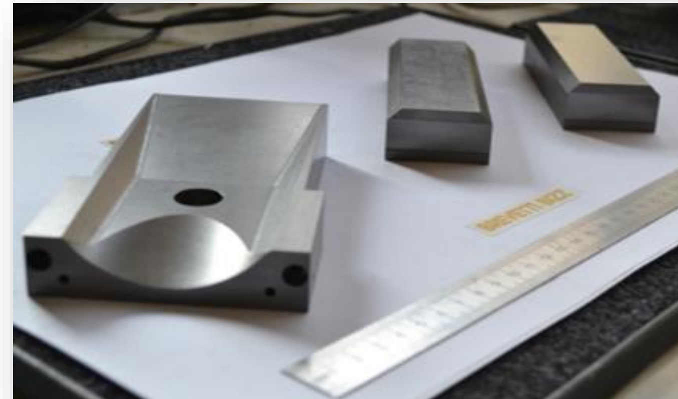


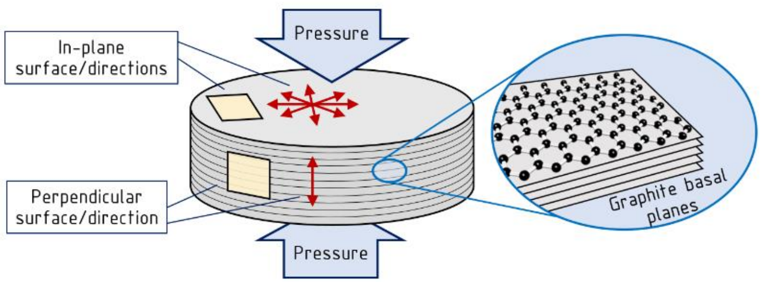


No peel-off, but failure of the substrate ⇒ good adherence

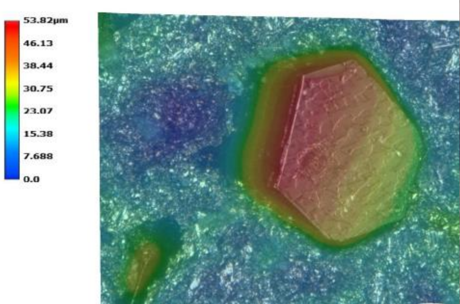
WP17 Main Achievements: Novel Materials

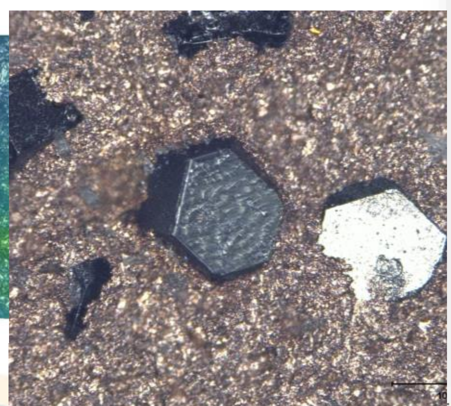
- R&D of advanced materials for **extreme thermal management** applications
- Further **development, optimization, characterization** and **industrialization** of **Molybdenum-Graphite (Brevetti Bizz)** and **Copper-Diamond (RHP-Technology)**
- **R&D and complete characterization** of 4 grades of first generation **Chromium-Graphite (Brevetti Bizz)** as lower cost, more affordable alternative to MoGr





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





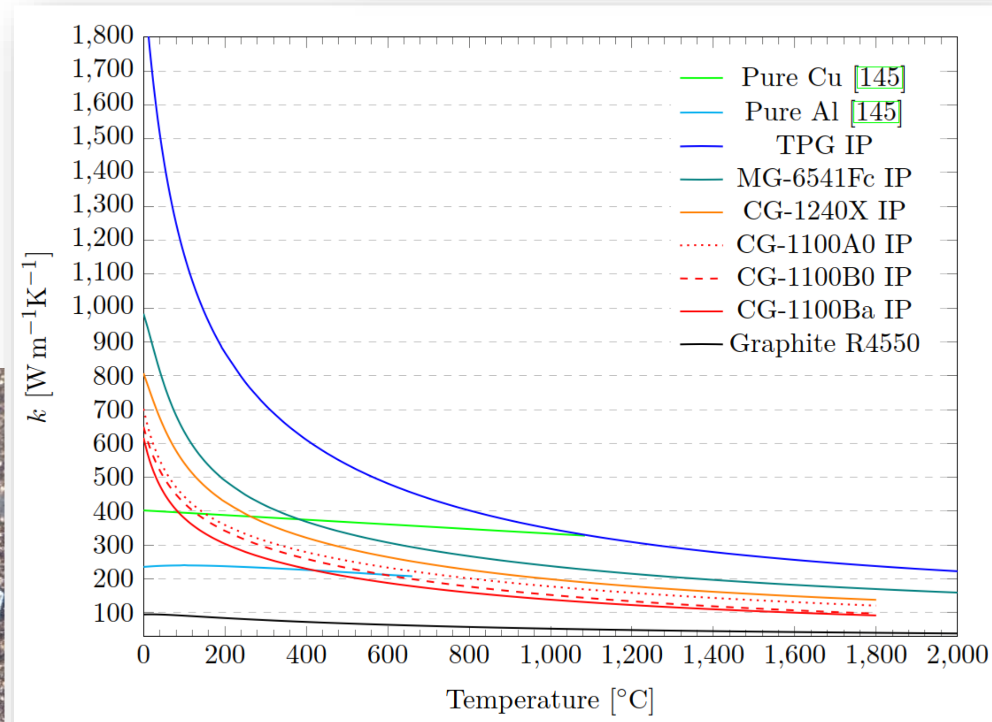
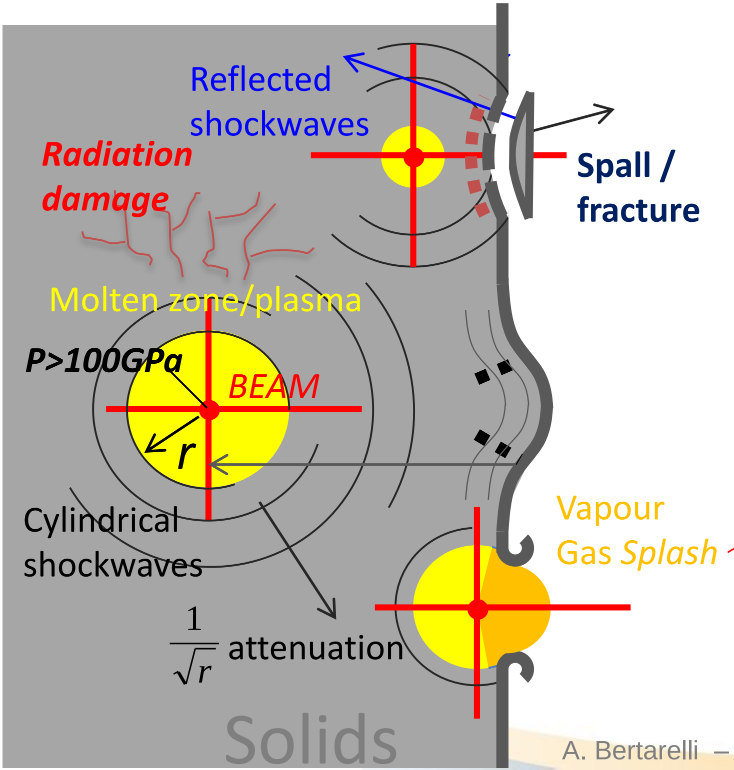
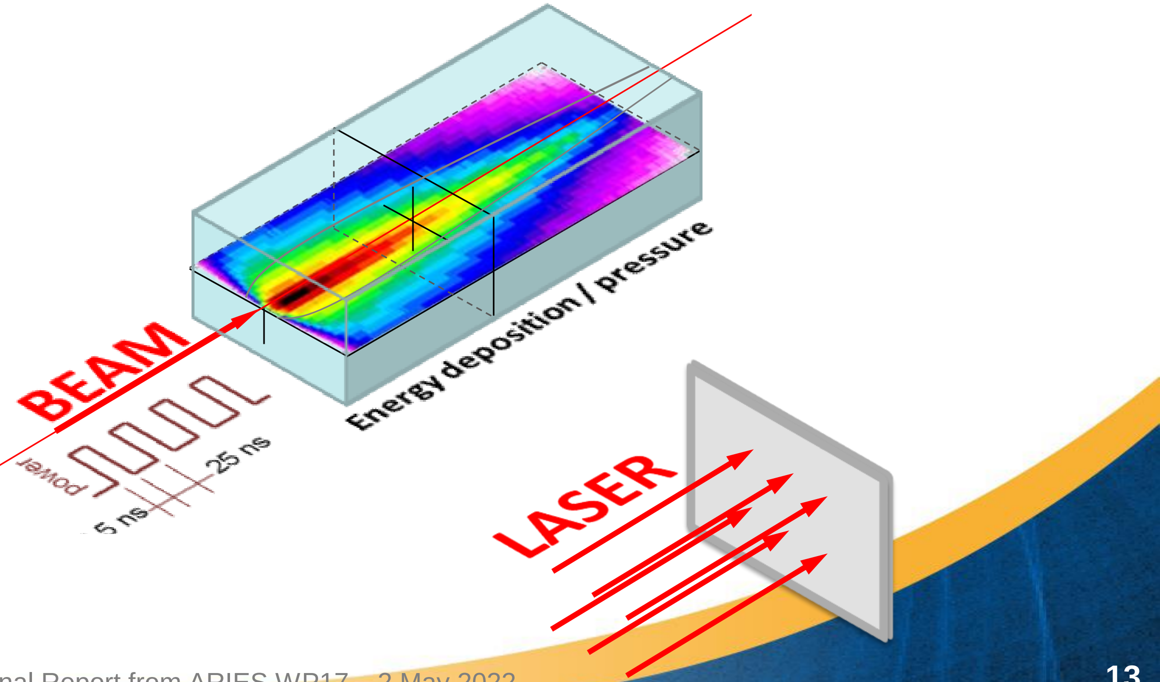


Figure 6.20: In-plane thermal conductivity of the investigated materials.

WP17 Main Achievements: Numerical Methods and Tests

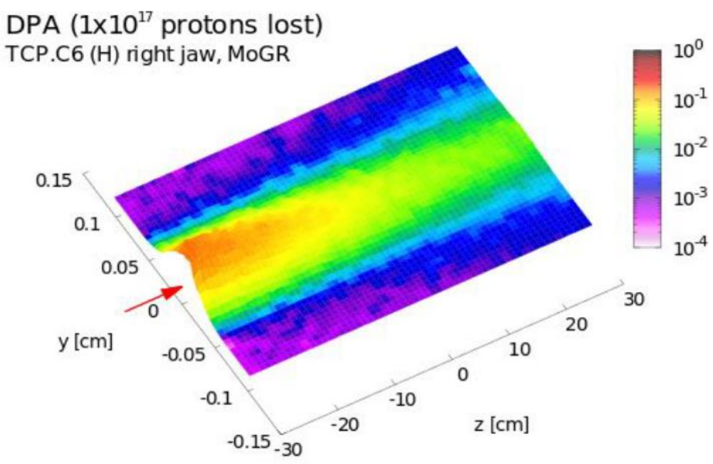
- Development and optimization of **advanced numerical methods** (including **hydrocodes**) to study high energy impacts on materials and components
- **3 experimental campaigns at HiRadMat** (FlexMat, Multimat and MultiMat-2) to test a wide range of materials and coatings to assess their survivability 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

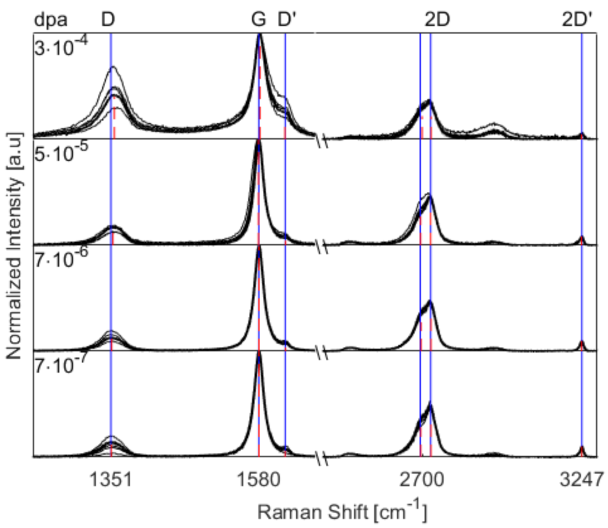




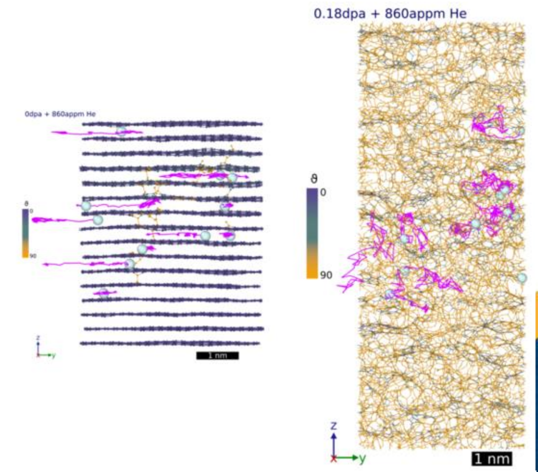
WP17 Main Achievements: Irradiation Simulations and Tests

- 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 level.



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

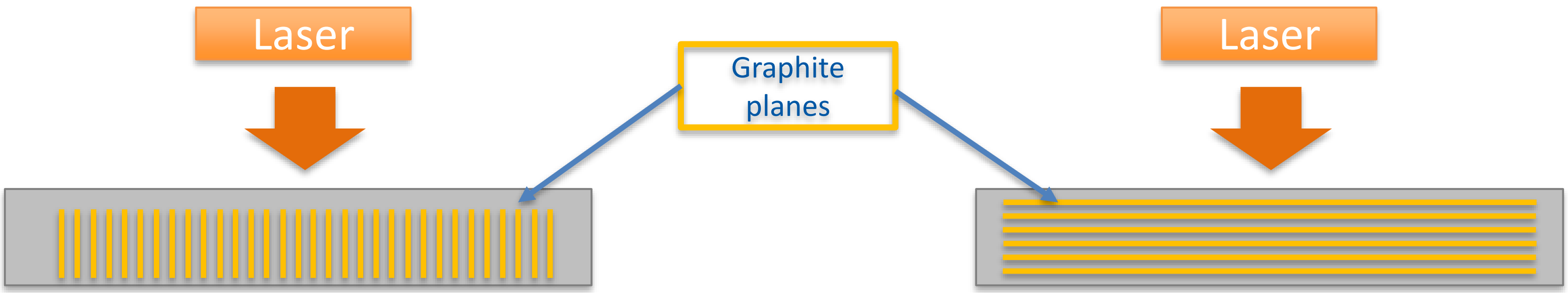
WP17 List of Exploitable Foreground

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

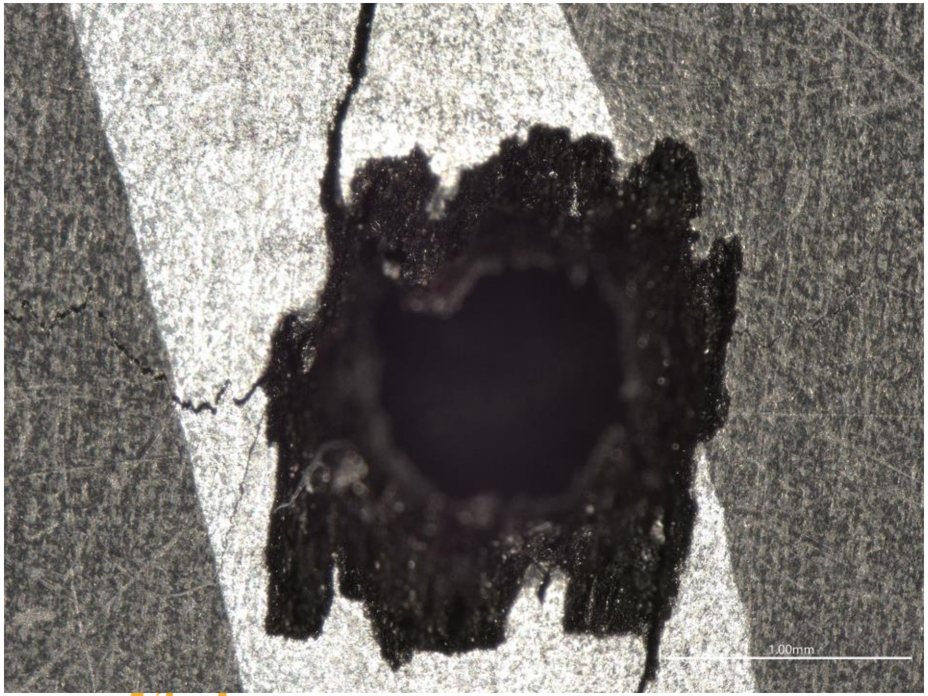
This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 730871.

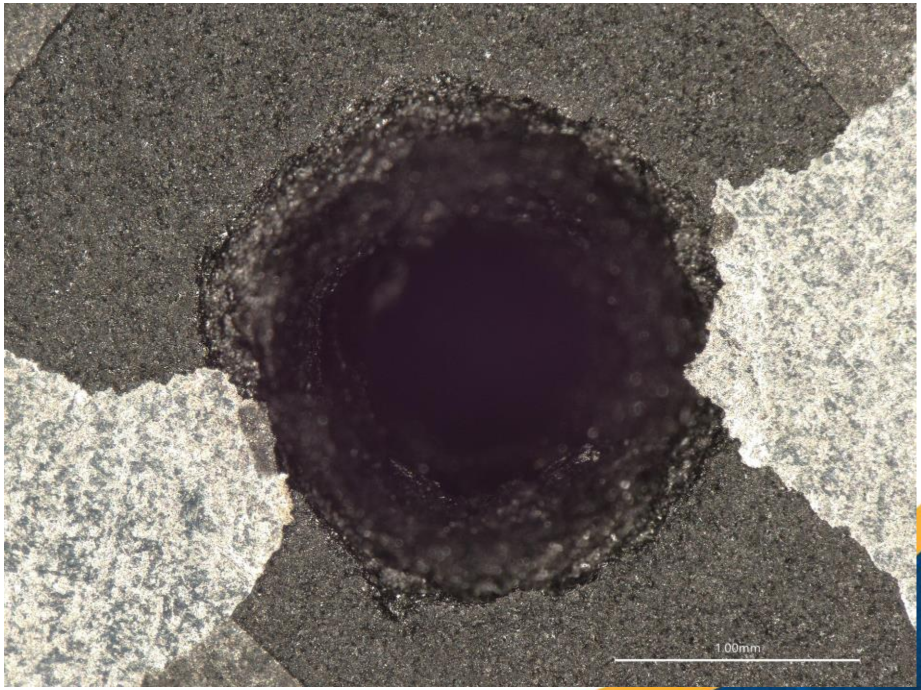
Thank you for your attention!

Fracture surface observation: anisotropic materials



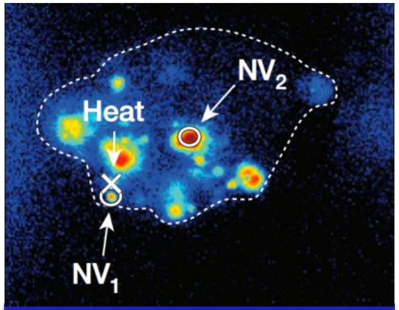
Thickness=0.75mm



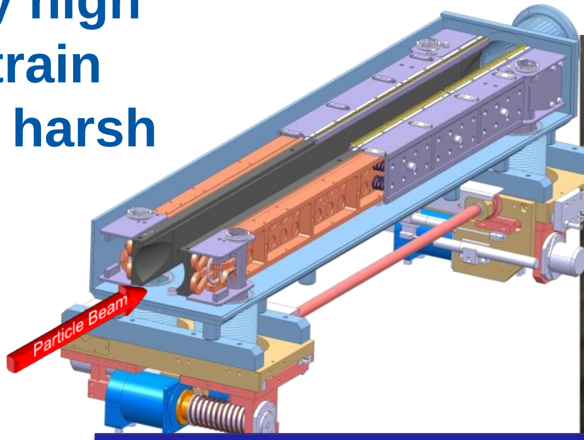


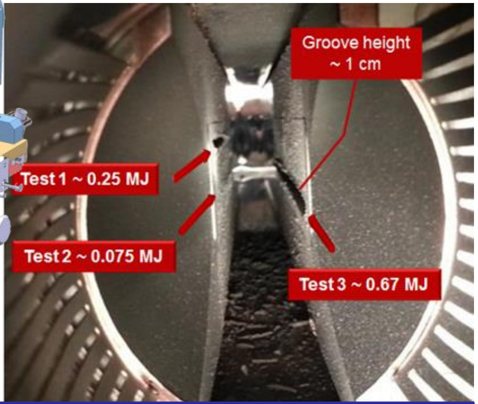
What is Extreme Thermal Management?

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

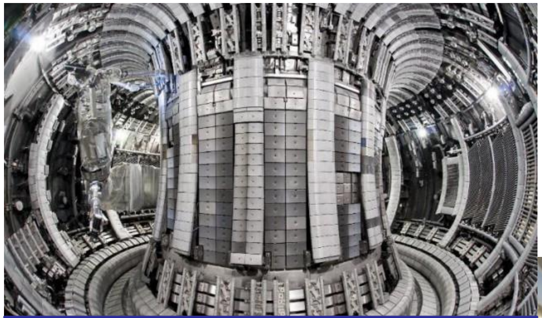


Medical Imaging



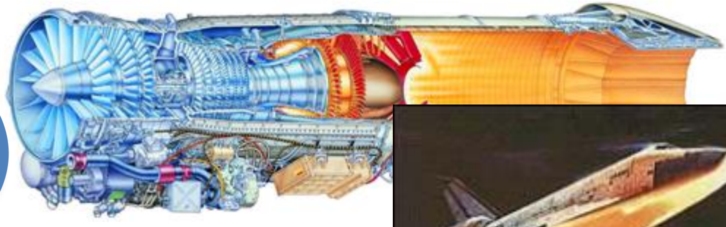


Particle Accelerators (Beam Intercepting Devices)

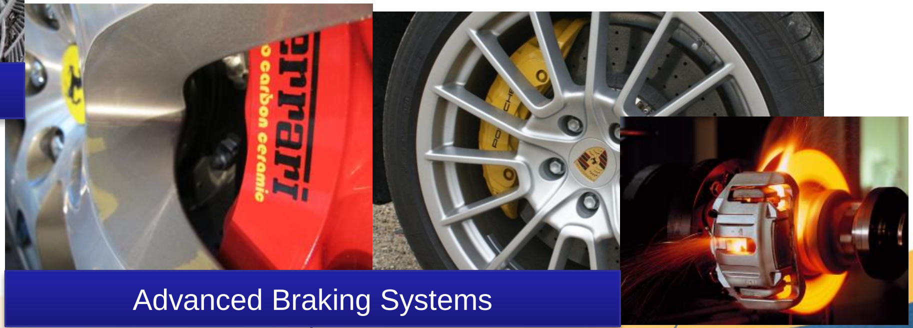


Fusion Engineering

ARIES



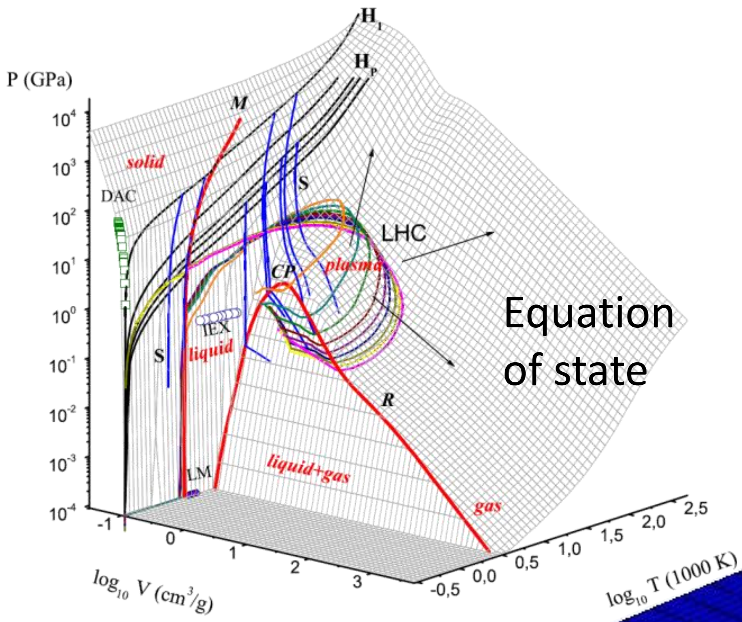
High temperature Aerospace Applications



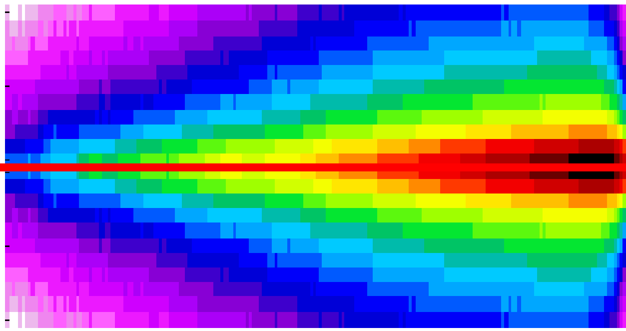
Advanced Braking Systems

ARIES

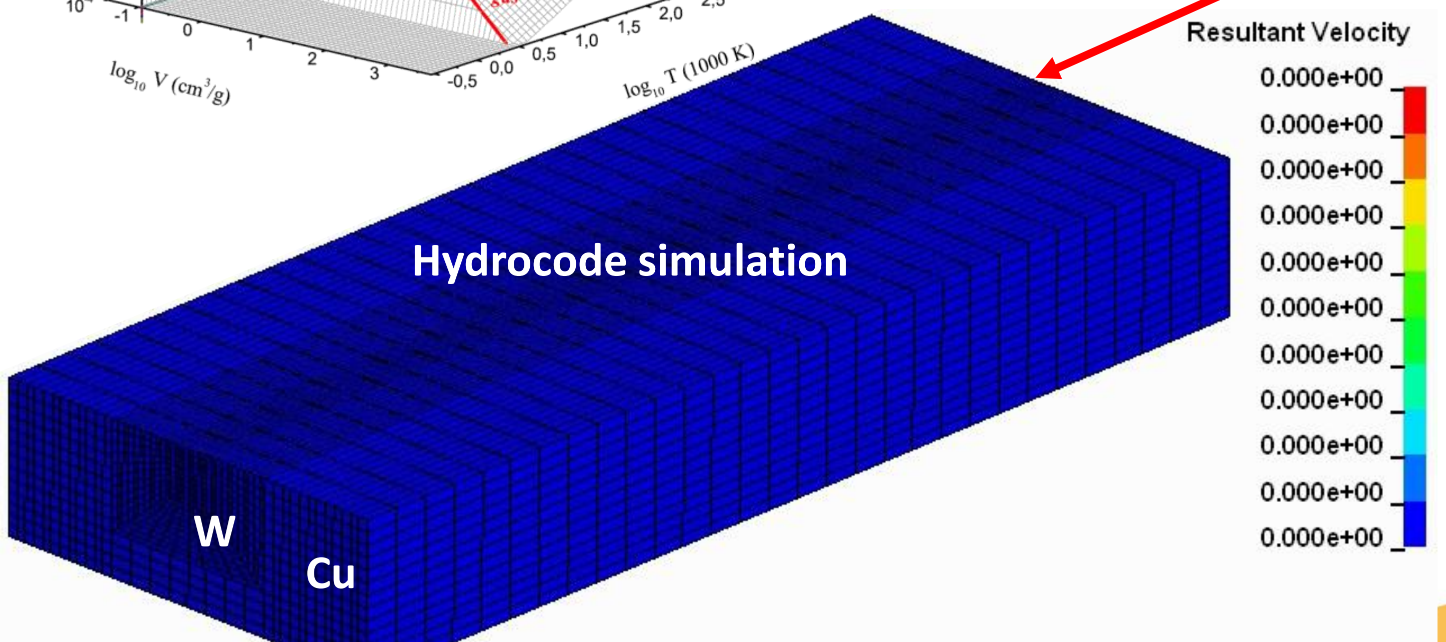
Hydrodynamic simulations: EOS, spall strengths for new materials



Energy deposition



Particle beam



Diagnostics: High Speed Scan System

Velocity measurement based on Doppler effect and optical interferometry
Provided by IDIL Fibres Optiques

IDIL FIBRES OPTIQUES

- 5U Rack (Height: 225 mm, Length: 430 mm, Depth: 445 mm)
- 1 Mainframe, 2 channels on demo module
- Touch screen to command the mainframe and the slots
- 1 Photonic Doppler Velocimetry (PDV or Heterodyne velocimetry) channel
- 3 Velocity Interferometer System for Any Reflector (VISAR) channels
- In-chamber Probe to Rack connection via Optical Fibre line, with dedicated feedthrough. **Any such flange available**? Checking Marilena's proposal …

ARIES

Diagnostics: Oscilloscope for HSSS

- Oscilloscope provided by CERN (Tektronix B MSO64-10) – 10 GHz, 4 channels (3 VISAR, 1 PDV)
- Does PHELIX/GSI have a similar system in house?

Model overview

Table 2: Oscilloscope

	MSO64B	MSO66B	MSO68B
FlexChannel inputs	4	6	8
Maximum analog channels	4	6	8
Maximum digital channels (with optional logic probes)	32	48	64
Bandwidth (calculated rise time)	1 GHz (400 ps), 2.5 GHz (160 ps), 4 GHz (100 ps), 6 GHz (66.67 ps), 8 GHz (50 ps), 10 GHz (40 ps) Derate 10 GHz Bandwidth at 0.05 dB/5 ℃ above 23 ℃. Derate 8 GHz Bandwidth at 0.02 dB/5 ℃ above 23 ℃		
DC Gain Accuracy	50 Ω: ±2.0% 4 at >2 mV/div (±2.0% at 2 mV/div typical, ±4% at 1 mV/div typical) 50 Ω: ±1.0% 5 of full scale at >2 mV/div, (±1.0% of full scale at 2 mV/div typical, ±2% at 1 mV/div typical) 1 MΩ: ±2.0% 4 at >2 mV/div (±2% at 2 mV/div, ±2.5% at 1 mV/div typical and 500 µV/div typical) 1 MΩ: ±1.0% 5 of full scale at >2 mV/div, (±1.0% of full scale at 2 mV/div typical, ±1.25% at 1 mV/div and 500 µV/div, typical)		
ADC Resolution	12 bits		
Vertical Resolution Note: Vertical resolution specified based on the number of channels used.	8 bits @ 50 GS/s; 10 GHz on 2 channels 8 bits @ 25 GS/s; 10 GHz on 4 channels 12 bits @ 12.5 GS/s (High Res); 5 GHz on 4 channels (8 bits @ 12.5 GS/s; 5 GHz on >4 channels) 13 bits @ 6.25 GS/s (High Res); 2 GHz on 4 channels (12 bits @ 6.25 GS/s (High Res); 2 GHz on >4 channels) 14 bits @ 3.125 GS/s (High Res); 1 GHz on 4 channels (13 bits @ 3.125 GS/s (High Res); 1 GHz on >4 channels) 15 bits @ 1.25 GS/s (High Res); 500 MHz on 4 channels (14 bits @ 1.25 GS/s (High Res); 500 MHz on >4 channels) 16 bits @ ≤625 MS/s (High Res); 200 MHz on 4 channels (15 bits @ 625 MS/s (High Res); 200 MHz on >4 channels) 16 bits @ ≤312.5 MS/s (High Res); 100 MHz on >4 channels		
Sample Rate	50 GS/s on 2 analog / digital channels (20 ps resolution); 25 GS/s on 4 analog / digital channels (40 ps resolution); 12.5 GS/s on > 4 analog / digital channels (80 ps resolution)		
Record Length	62.5 Mpoints on all analog / digital channels, (125 Mpoints, 250 Mpoints, 500 Mpoints on all channels optional; 1 Gpoints on up to four channels with 500 Mpoints on all channels for MSO66B and MSO68B instruments)		
Waveform Capture Rate	>500,000 wfms/s (Peak Detect, Envelope acquisition mode), >30,000 wfms/s (all other acquisition modes)		
Arbitrary/Function Generator (opt.)	13 predefined waveform types with up to 50 MHz output		
DVM	4-digit DVM (free with product registration)		
Trigger Frequency Counter	8-digit frequency counter (free with product registration)		

Diagnostics: High Speed Camera

- High Speed Camera: Photron SA5, provided by POLITO
- Expected frame rate: 150-200 kfps
- Shutter: 369 ns
- Lighting: VIC Single Ultra-Bright LED Module Model 900170
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Model 900170R Single Ultra Bright Module

with Model 900670 Dual Video Flood Sync

AC Powered Controller

- Performance examples:
  - 1,024 x 1,000 pixels @ 7,500 fps
  - 512 x 512 pixels @ 25,000 fps
  - 256 x 256 pixels @ 87,500 fps
  - 128 x 128 pixels @ 262,500 fps
  - 128 x 24 pixels @ 775,000 fps
- Variable Region of Interest (ROI)
- Capture 12-bit uncompressed data
- 20μm pixels ensure best light sensitivity for demanding high-speed or low light applications
- Equivalent ISO light sensitivity 10,000 (monochrome), 4,000 (color) measured to ISO12232 S sat
- Phase lock to IRIG/GPS
- Composite and SDI video output for real time monitoring during set up, recording and playback
- Optional remote keypad control with integrated viewfinder
- 8GB, 16GB or 32GB memory options
- Gigabit Ethernet interface