



# Report from WP17 Materials for Extreme Thermal Management

4<sup>th</sup> ARIES Annual Meeting,  
online – 21 – 22.04.2021

**Alessandro Bertarelli, Marilena Tomut**

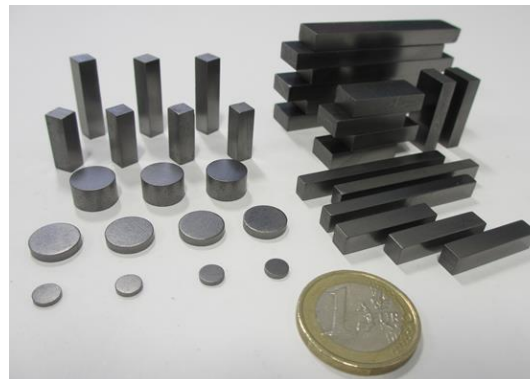
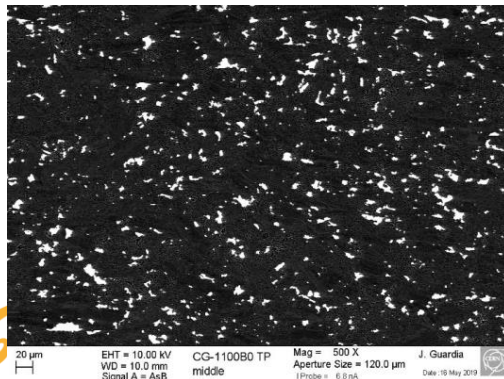
# Task 17.1 – Status and Outlook

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- JRA extended to end of December 2021
- Transnational Activities
  - Irradiation experiment at GSI UNILAC successfully concluded in March 2021 with local staff only due to lockdown. TNA units counted as allocated for an external experiment.
  - New HiRadMat experiment at CERN on slender rods in September 2021, approved by HiRadMat SC and TC. TNA also approved.
  - New Laser experiment at GSI-PHELIX facility on thin disks approved and expected in October 2021. TNA via Laserlab-Europe expected.
- Annual WP Meeting held online in July 2020. Next expected for late-spring / early summer '21

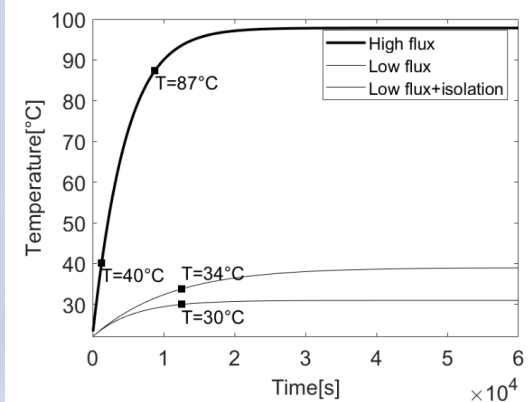
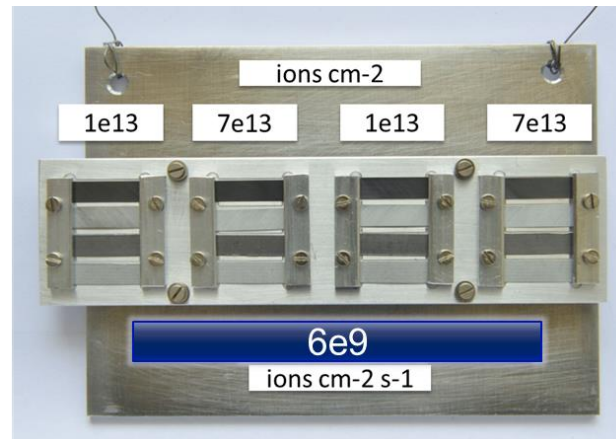
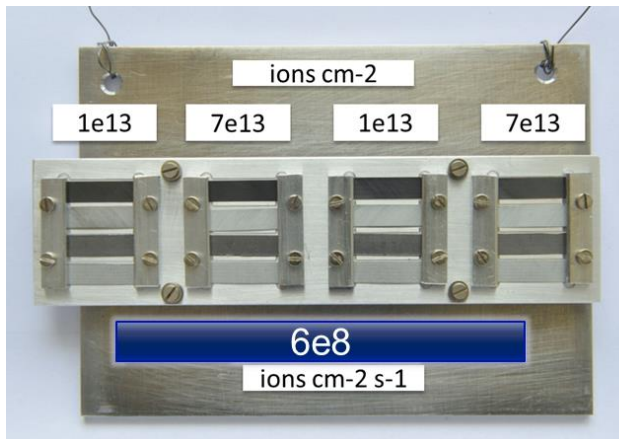
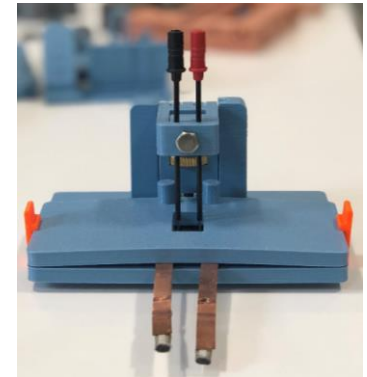
# Task 17.2: Materials development and characterization

- Development and optimization of **Molybdenum Carbide – Graphite (MoGr)** composite is **concluded**.
- MoGr specimens prepared for last experiments at **GSI-UNILAC** (ion-irradiation), CERN-HiRadMat (**Multimat-2**) and GSI-PHELIX (Laser irradiation)
- Novel **Chromium – Graphite (CrGr)** composite under development as **lower cost** alternative to MoGr
- 4 different CrGr grades, produced by Brevetti Bizz, investigated in late 2020
- Thermo-physical analyses and microstructural characterization –performed
- **Record high thermal conductivity** -  $739 \text{ Wm}^{-1}\text{K}^{-1}$  at  $20^\circ\text{C}$
- Production of last CrGr plate, delayed because of COVID, is expected in coming months



# Task 17.3: GSI-UNILAC Ion irradiation (2021)

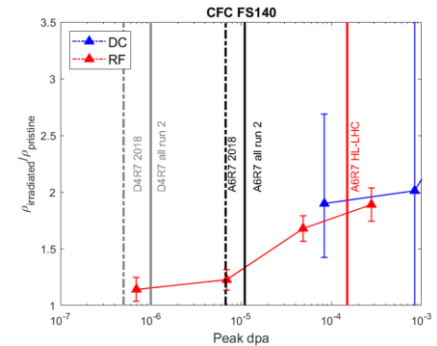
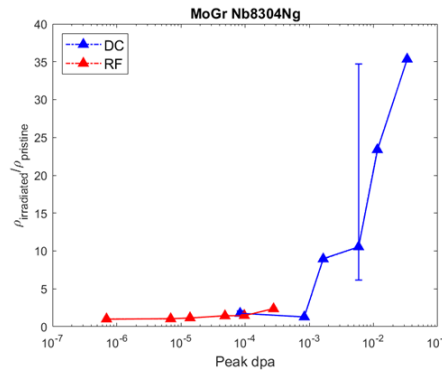
- Experiment performed in March 2021
- 12 shifts completed
  - Ca ions of 4.8 MeV/u
  - 32 samples (New-powders MoGr (Nb8404Ng) and graphite GrR4550, coated and uncoated)
  - Complete thermo-physical characterization before the test (new 3D-printed set-up for electrical resistivity)
  - FEA thermal simulation
  - **Investigation of the dpa rate (using 2 flux)**
  - **Extend the statistic of the results obtained in 2019**
- **PIE planned for spring 2021**





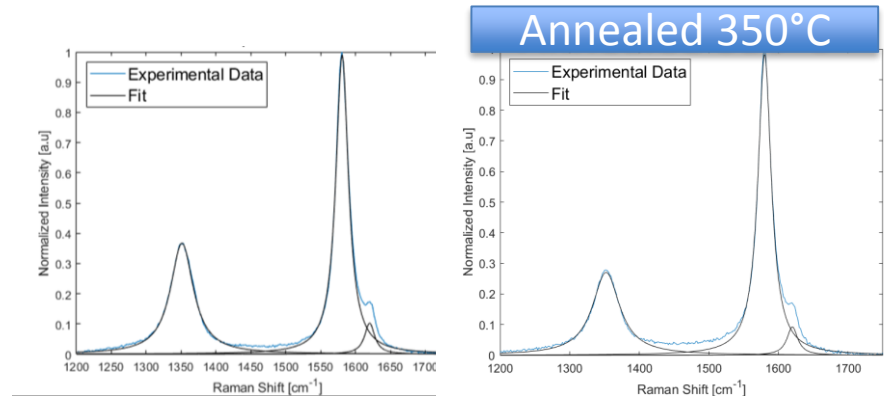
# Task 17.3, 17.4.: PIE of ion irradiation at GSI-2019- updates

- Samples declassified at CERN → easy and faster measurement
- Electrical resistivity measured with two complementary techniques (DC and RF):
  - Evaluate the effect of peak vs average dpa
  - Extract resistivity at dpa corresponding to installed collimator
- Thermal annealing of graphite material and Raman spectroscopy to understand the defect annihilation



Special Joint HiLumi WP2/WP5 Meeting, "Comparison of DC and RF electrical resistivity measurement for ion irradiated samples at GSI "

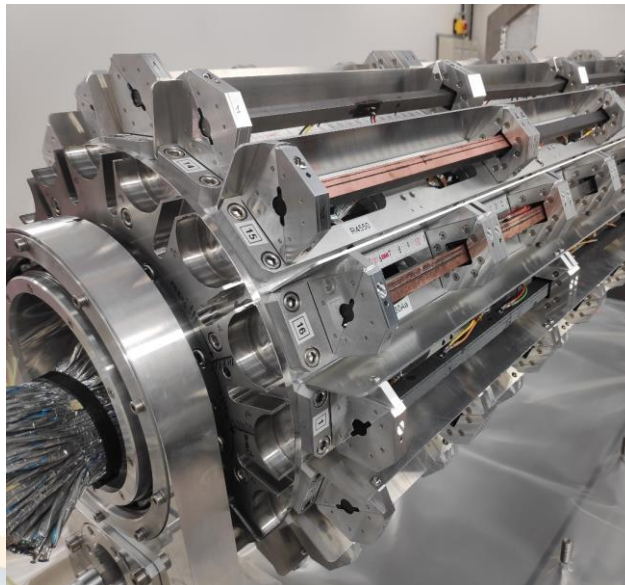
<https://indico.cern.ch/event/992836/?view=nicecompact>



## Task 17.3: CERN-HiRadMat Multimat-2

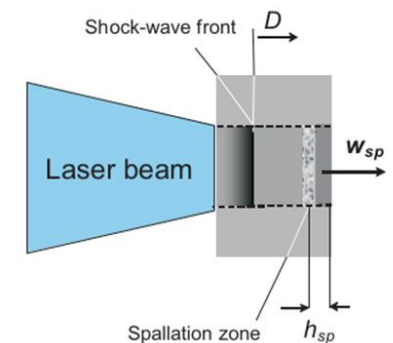
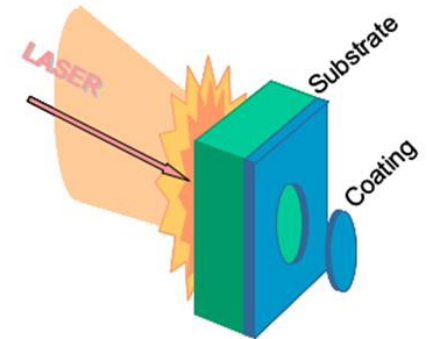
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- Multimat was designed with an **openable tank**, to be re-used for next, similar experiments. **Up to 16 target stations** can be installed under inert gas atm.
- **Same test bench adopted, only replacing the targets**
- **Faster, cheaper!** Bulk of the preparation work will be the local instrumentation on the targets
- Main objective is to qualify latest developed materials (MoGr, CrGr, coatings ...) under HL-LHC beam accident scenarios
- Planned for **September 2021**



# Task 17.3: Laser Experiment at GSI-PHELIX

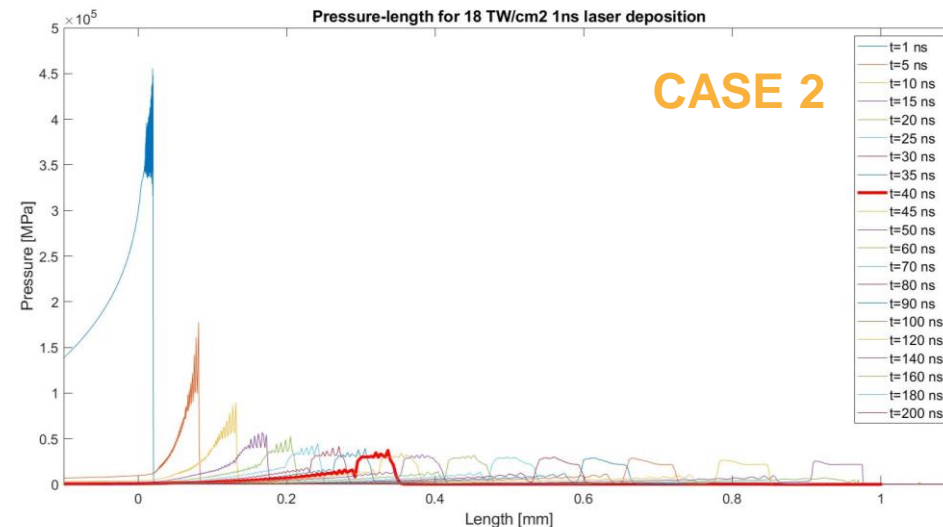
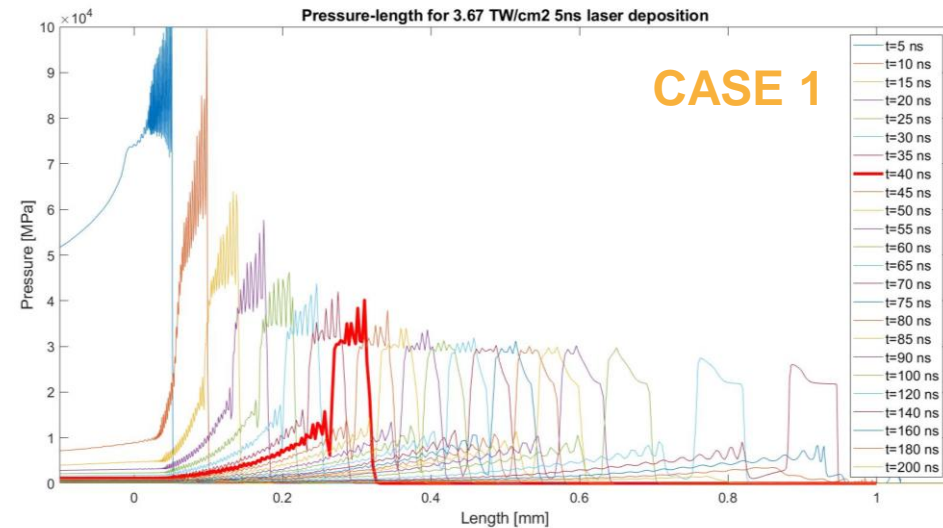
- The experiment aims at testing thin samples (disks or plates) of several materials under intense laser pulses, to reach energy densities beyond HiRadMat, mimicking extreme future scenarios as in FCC-hh (peak energy density  $\sim 50 \text{ kJ/cm}^3$ ):
  - Several grades of MoGr, CrGr, CFC, Graphite, CuCD, Carbon Foams to be tested
  - Back face may be coated (Mo, Cu) to probe thin film adhesion
  - Thickness varying from 0.25 mm to 2.5 mm
  - Cross-section dimension  $10 \div 20 \text{ mm}$
  - In total  **$\sim 40$  specimens**, including  **$\sim 10$  for set-up** and calibration purposes (typically well-known metals as Al and/or Ta)
- Laser parameters
  - Pulse energy ( $E_p$ ): up to 180 J
  - Pulse duration ( $\tau$ ):  $1 \div 5 \text{ ns}$
  - Beam spot diameter ( $d_p$ ):  $1 \div 1.5 \text{ mm}$  (phase plates to be used)
  - Wavelength  $\lambda = 530 \text{ nm}$
- A strong shock wave will be generated in the impacted face, quickly decaying while moving towards the back face, possibly down to the acoustic regime (depending on sample thickness), but still strong enough to generate spallation near the back face
- Preliminary simulations at POLITO and ELI-NP ongoing



# Task 17.3: Laser Experiment at GSI-PHELIX

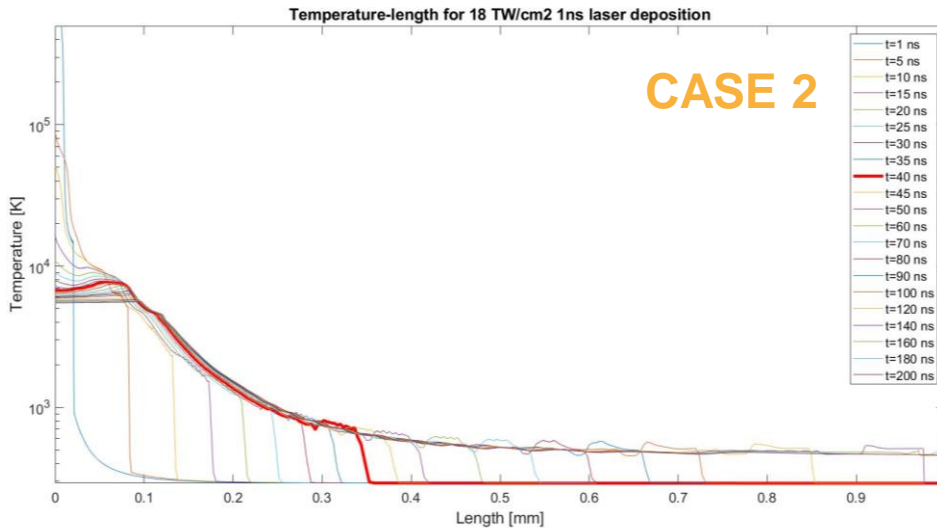
- Pressure simulation with HELIOS code
- 2 cases both with 180 J:
  1.  $I=3.67 \text{ TW/cm}^2$  and 5 ns pulse
  2.  $I=18 \text{ TW/cm}^2$  and 1 ns pulse
- The laser pulse hits the graphite plate at  $x=0 \text{ mm}$
- Peak pressure at the end of the deposition time:
  1. 100 GPa
  2. 450 GPa

After 40 ns both cases show a constant profile pressure with a peak of about 30 GPa, which is the condition that is expected from a shock wave propagating into a solid in a 1-D geometry. This condition is reached in both cases at around 0.3 mm from the front face



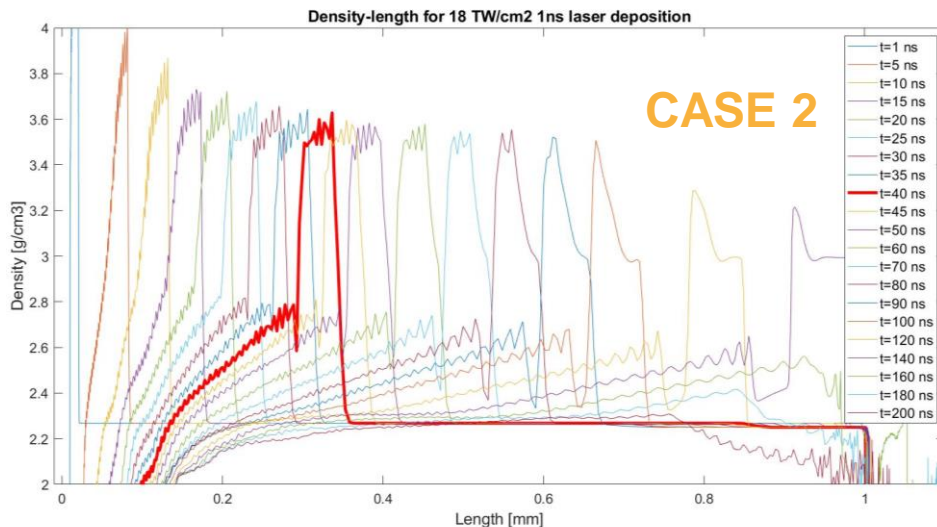


# Task 17.3: Laser Experiment at GSI-PHELIX



- Temperature and density simulation

From the temperature profile plot it can be highlighted that from  $x=0.3$  mm onwards the temperature reached is lower than 1000 K, which is well below the melting temperature of graphite. This evidence ensures that from  $x=0.3$  mm onwards the graphite is still solid.

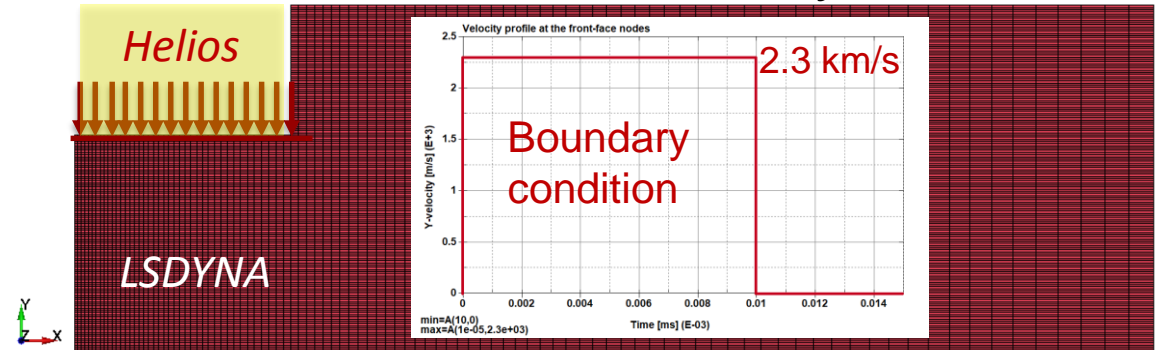


The reference density of graphite is 2.25 g/cm<sup>3</sup> (Table 7833 SESAME)

# Ls-Dyna simulations

- Geometry of the graphite disk takes into account the 0.3 mm of depth at which the LSDYNA solution begins
- Shock waves generated by imposing the y-velocity pulse evaluated from Helios at the interface nodes

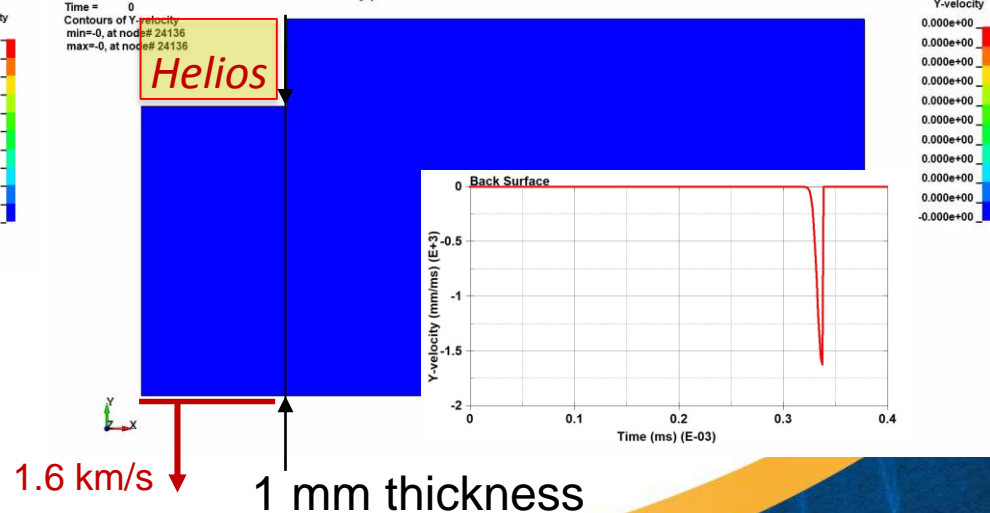
## 2D Axisymmetric model



CASE 1 THICKNESS 0.5mm 2300m/s 10ns velocity profile

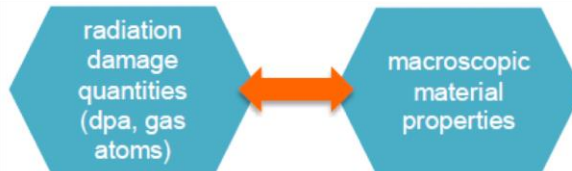


CASE 1 THICKNESS 1mm 2300m/s 10ns velocity profile



# Task 17.4: MD simulation of lattice damage in graphite

## • Study effect on material properties



- Molecular Dynamics (MD): LAMMPS code
- italian High Performance Computing center, (HPC, several CINECA grants)
- Frenkel Pair Accumulation (FPA) method
- New method for injection of gas atoms (H, He, not shown here)

V. Toto, M.Beghi

geometries:  
single grain and  
double grain  
(single boundary)

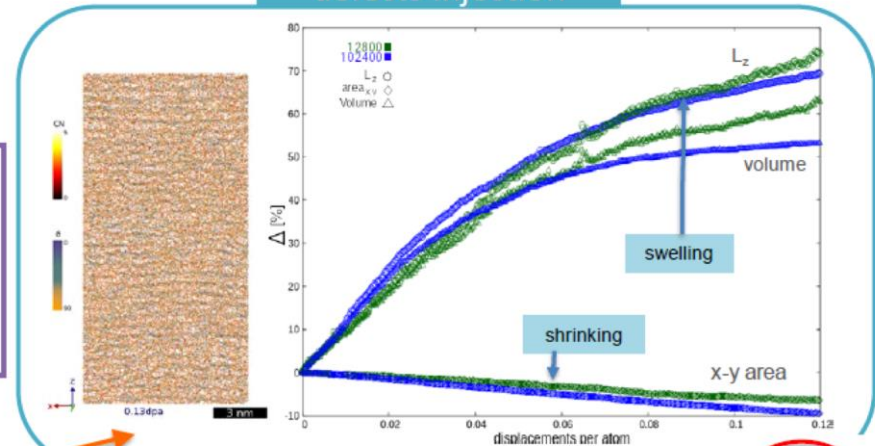
- swelling & shrinking
- reduction of elastic anisotropy

Next steps:

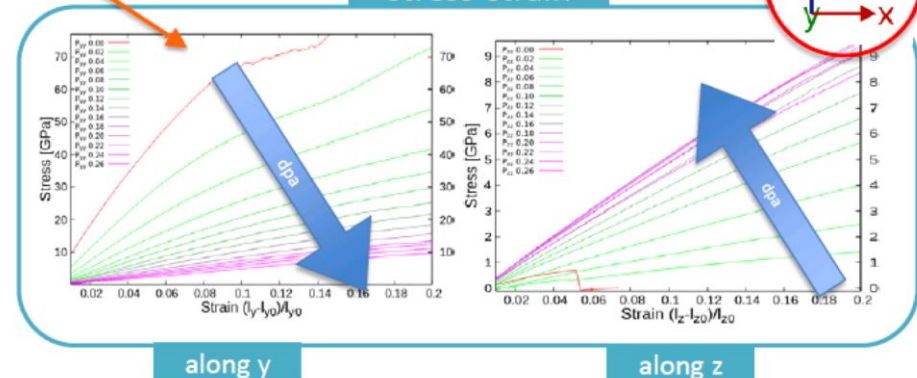
- further analysis of the gas injection methodology
- analysis of the aging of the damaged structure
- analysis of annealing

Bottleneck: computational cost !

### defects injection



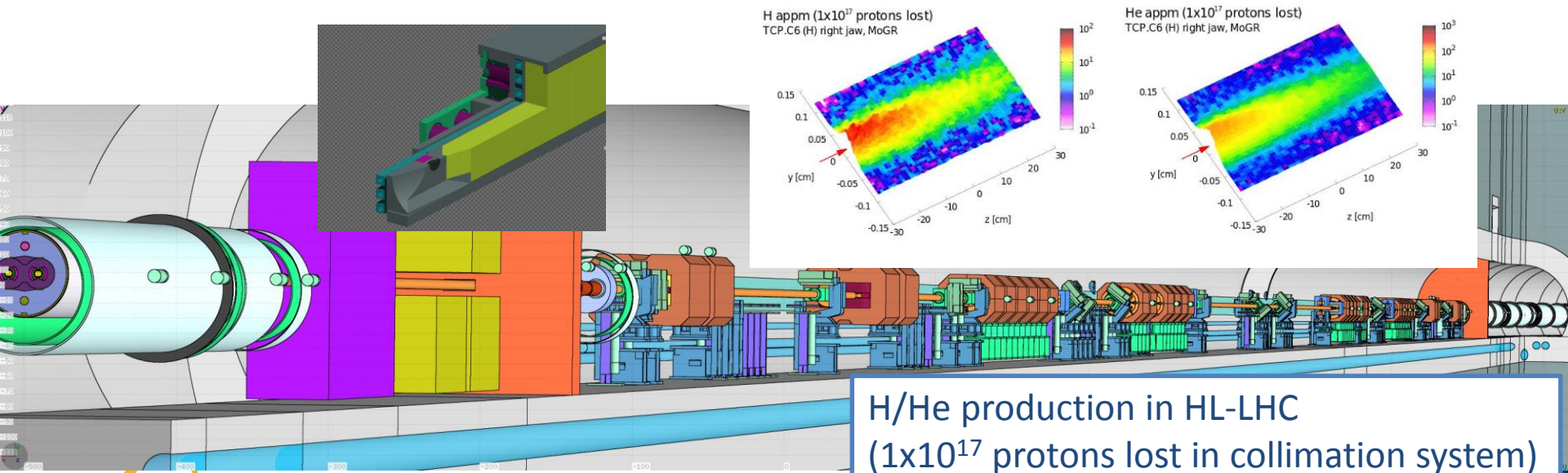
### stress-strain





# Task 17.4: Radiation damage in HL-LHC collimators.

- Completed **displacement damage** and **H/He gas production** studies for collimator bulk materials (MoGR and CfC) and coatings through complex shower simulations
- DPA results and methodology summarized and in PhD thesis (E. Skordis, University of Liverpool and CERN)
- Working on publication (DPA and gas production)

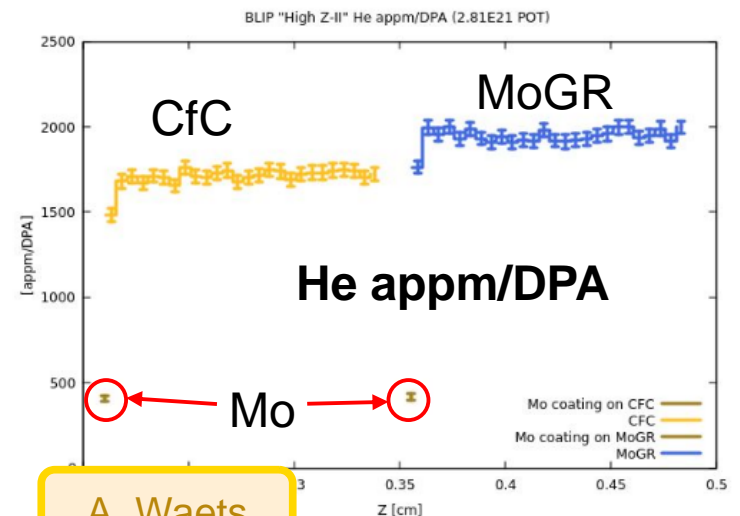
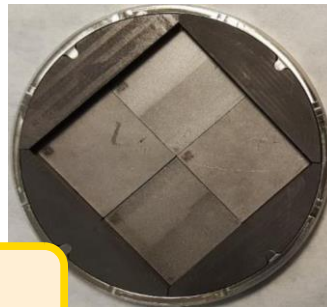
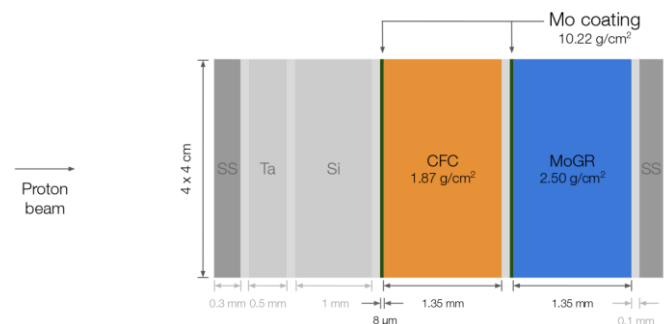


H/He production in HL-LHC  
( $1 \times 10^{17}$  protons lost in collimation system)



# Task 17.4.: Irradiation of HL collimator materials @BLIP

- Irradiation carried out by **RaDIATE collaboration** (M. Calviani et al.)
  - MoGR and CfC samples irradiated in RaDIATE target box (CERN2 capsule) in 2018 → in total  $2.81 \times 10^{21}$  protons on target
  - Proton beam with 181 MeV: sizable H/He production → appm/DPA comparable to future HL collimators (as shown by FLUKA studies)
- **Post irradiation examination (PIA)** in industry jointly planned by RaDIATE, HL-LHC WP5 and ARIES WP17 – after some COVID-related delay, **capsule has been opened and analysis is ongoing**



# Task 17.5.: Irradiation of High Entropy Alloys



*Colaboration with WWU Münster on novel compositional complex alloys for high dose applications*

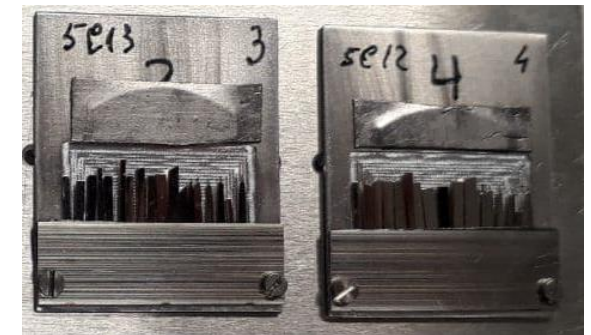
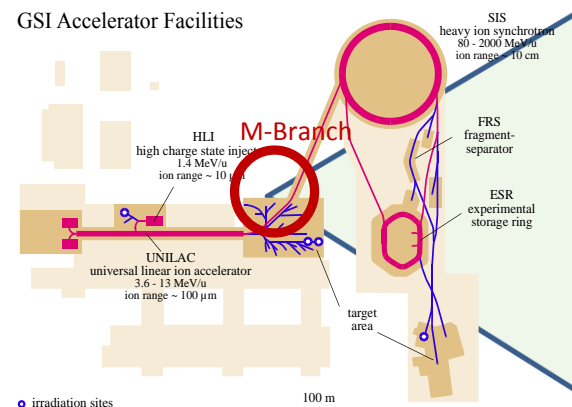
At M3 beamline,  
UNILAC accelerator,  
GSI, Darmstadt

$^{197}\text{Au}^{26+}$ , total energy 946 MeV

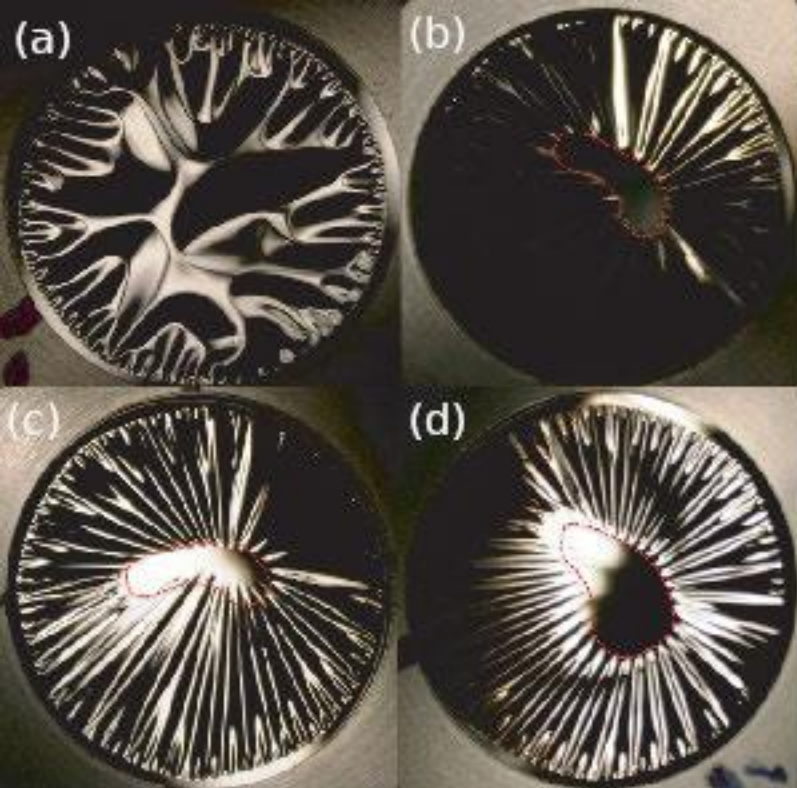
Accumulated fluences:  $5 \times 10^{12}$  and  $5 \times 10^{13}$  ions/cm<sup>2</sup>  
- at a flux of  $2 \times 10^9$  ions/cm<sup>2</sup> s

Irradiation conditions:  
ambient temperature and 50 K

GSI Accelerator Facilities



Irradiation holders



ive beam windows for high-power accelerator

ster, RHP

months

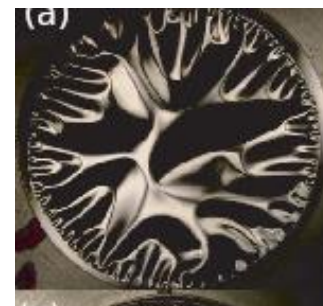
w-density R&D  
taking place

etek

TG1100 grades

will be irradiated

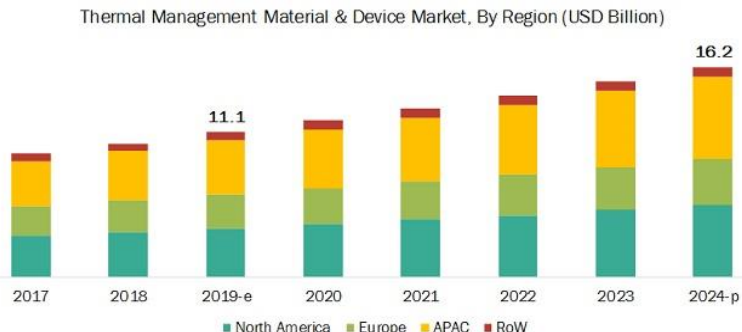
- 6 samples per each of the three grades, 10x10x0.2÷0.5 mm (final thickness ~0.35 mm).
- The shortest dimension corresponds to the through-plane direction
- The samples were sent from Nanoker company to GSI on 13/04/2021





# IFAST - WP4 task 4.4 (May 2021-April 2024)

- **IFAST WP4.4 – “Large scale Carbide-Carbon Materials for multipurpose applications”** naturally follows the R&D and industrialization phases for the carbide-carbon materials.
- Production plan already agreed with Nanoker.
- First items will be two upscaled NB-8404Ng plates (Ø230 x 30 mm)
  - Acceptance tests will be carried out on the upscaled material. Tests planned for June-September 2021.
- Further testing (including springback, UHV, etc.) planned for October-December 2021
- R&D on alternative CCMs and characterization to be done in parallel during 2021
- If the material is OK, next step is the upscaling of the thickness dimension (to Ø230 x 45 mm)





# Milestones

Milestone number <sup>18</sup>	Milestone title	WP number <sup>9</sup>	Lead beneficiary	Due Date (in months) <sup>17</sup>	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 materials developed (Task 17.2)	WP17	1 - CERN	40 <b>M 43</b>	Report to StCom
MS62	Dissemination of R&D results on novel materials for accelerator and societal applications (Task 17.5)	WP17	12 - GSI	46 <b>M 51</b>	Report to StCom

# Deliverables

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<b>Deliverable Number<sup>14</sup></b>	<b>Deliverable Title</b>	<b>Lead beneficiary</b>	<b>Type<sup>15</sup></b>	<b>Dissemination level<sup>16</sup></b>	<b>Due Date (in months)<sup>17</sup></b>
D17.1	Material characterization	1 - CERN	Report	Public	12
D17.2	Irradiation effect simulations	1 - CERN	Report	Public	44 <b>M 50</b>
D17.3	Irradiation test results	23 - POLITO	Report	Public	46 <b>M 54</b>

# WP17 Outreach: Publications in the last 12 months

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- **Accepted:**

- *Thermomechanical Characterisation of Copper Diamond and Benchmarking with the MultiMat Experiment*, Shock and Vibration, 2021
- *Design and Construction of an Instrumentation System to Capture the Response of Advanced Materials Impacted by Intense Proton Pulses*, Shock and Vib., 2021
- *Direct formation of nitrogen-vacancy centers in nitrogen doped diamond along the trajectories of swift heavy ions*, Appl. Phys. Lett., 2021
- *TEM analysis of radiation effects in ODS steels induced by swift heavy ions*, NIMB, 2021

- **Submitted:**

- *Dynamic radiation effects induced by short-pulsed GeV U-ion beams in graphite and h-BN targets*, Shock and Vibration
- *Dynamic Response of Graphitic Targets with Tantalum Cores Impacted by Pulsed 440-GeV Proton Beams*, Shock and Vibration
- *Calcium ions irradiation test on materials for High-Luminosity LHC collimators: Experiment description and outcome*, PRAB

- **Theses:**

- Portelli M, PhD thesis submitted for examination at the University of Malta: 'Numerical Modelling of Advanced Materials Subjected to High-Energy Particle Beam Impacts'
- Toto V. master's thesis at POLIMI on Molecular Dynamics simulations of graphite

# Conclusions and Outlook for the next 8 months

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- ARIES-WP17 greatly contributed to development, characterization, beam testing and beam effects simulations for a series of advanced materials for high power accelerators and thermal management applications; some of them produced in series and adopted for HL-LHC collimators
- Potential for Knowledge Transfer exists: actively working with WP14 (Promoting Innovation) and KT group at CERN
- COVID-19 pandemic has jeopardized some experimental activities planned for years 3 and 4 which will be finalized within the 8 months extension for this WP
- All deliverable and MS achieved so far
- Remaining D17.2- M50, D17.3- M54 and MS62 – M51 will be delivered in time
- Substantial outreach, including articles, theses and workshops
- WP activity continuing (at smaller scale) as tasks 3 and 4 in WP4 of I-FAST





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Nuclear Physics

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