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

ARIES

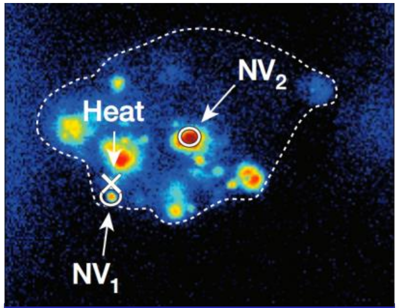
Materials for extreme thermal management: Report from WP17

2nd ARIES Annual Meeting,
Budapest, Hungary -

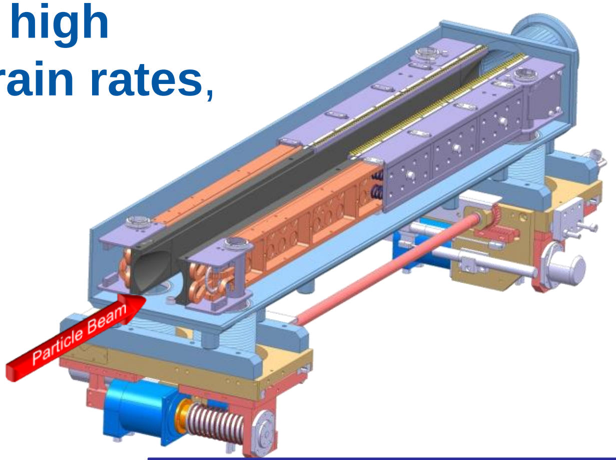
Marilena Tomut (GSI)
on behalf of the ARIES WP17 collaboration

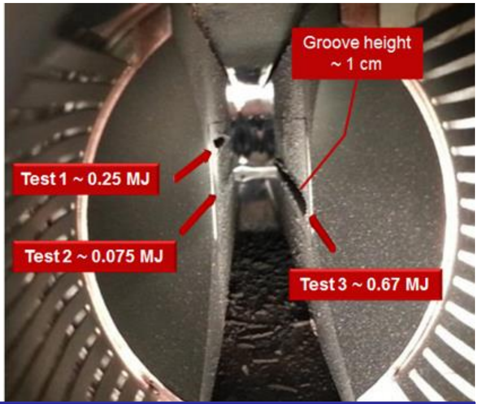
What is Extreme Thermal Management?

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



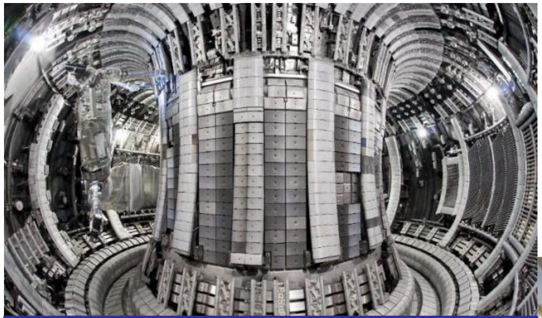
Medical Imaging



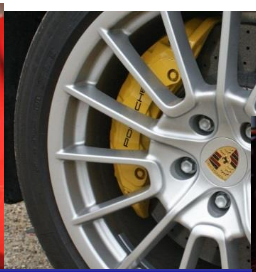


Particle Accelerators (Beam Intercepting Devices)

High temperature Aerospace Applications



Fusion Engineering



Advanced Braking Systems

ARIES

PowerMat in a Nutshell

- Push forward **R&D** of **novel Ceramic Matrix and Metal Matrix Composites** based on graphite and diamond reinforcements with various dopants

- **Simulate** and **test** materials under **extreme thermal shocks** (**particle-** or **laser-beam induced**) and long-term **particle irradiation**

- Investigate **radiation damage** from theoretical, numerical and experimental standpoint

- Identify materials for a broad range of **accelerator applications** (high power collimators, beam targets, beam windows and luminescence screens …)

- Explore **societal applications** in advanced engineering, medical imaging, quantum computing, energy efficiency, aerospace …

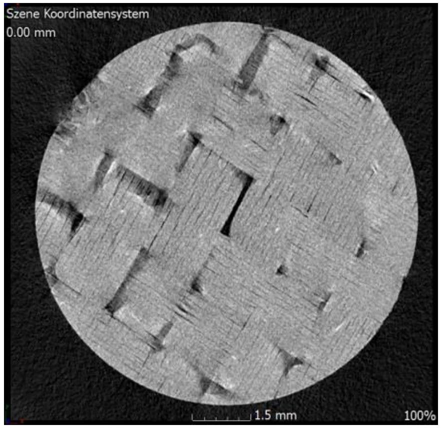
Work Package Organization

- WP17 (**PowerMat**): **6 main beneficiaries**, **1 associate** (**NIMP**)
- **Strong interaction** with **WP14** (**Promoting Innovation**) – Task 14.4
  - **1 beneficiary industry** (**RHP-Technology**), **1 associate industry** (**Brevetti Bizz**) in **Task 14.4** (F. Carra, CERN)
- **JRA** is organized in **5 Tasks**:
  - 17.1: **Communication & Coordination**
    A. Bertarelli, CERN; M. Tomut, GSI
  - 17.2: **Materials development and characterization**
    A. Bertarelli, CERN
  - 17.3: **Dynamic testing and online monitoring**
    L. Peroni, POLITO
  - 17.4: **Simulation of irradiation effects and mitigation methods**
    A. Lechner, CERN
  - 17.5: **Broader accelerator and societal applications**
    M. Tomut, GSI

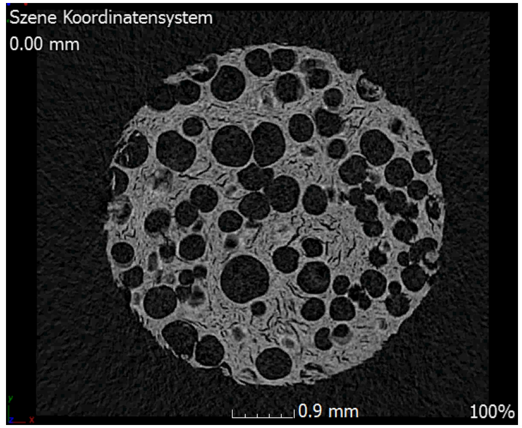
Task 17.2 and 17.3: Characterization of pristine and irradiated graphitic materials for beam intercepting devices

X-ray tomography

2D CFC



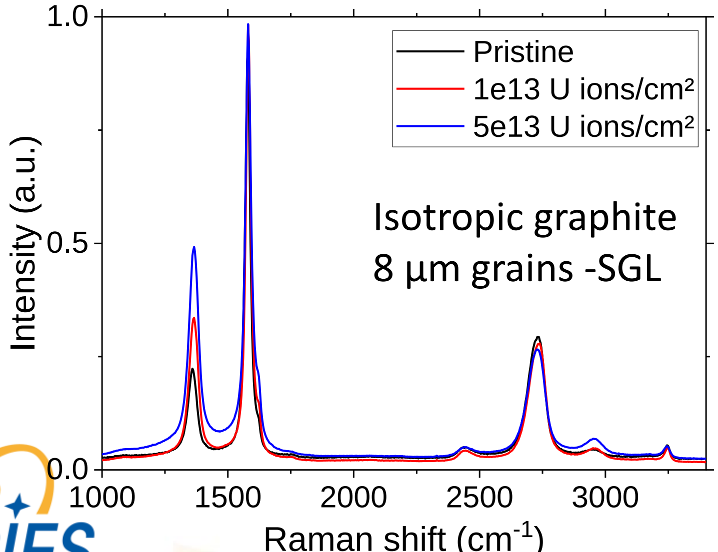
POCO Foam



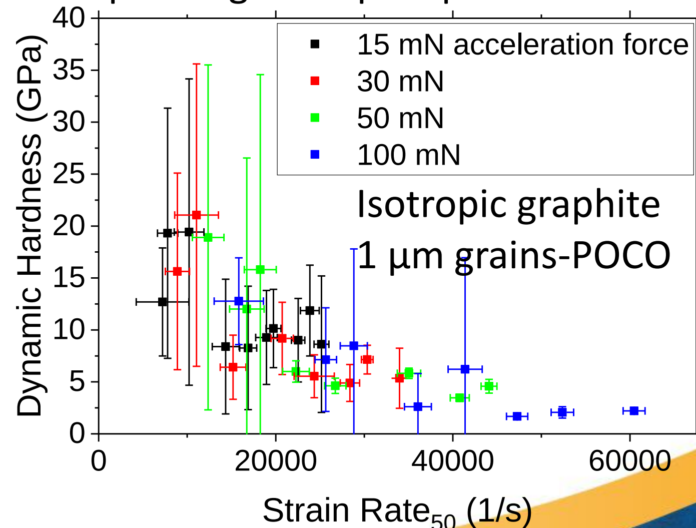
GSI

Nanoindentation, nanoimpact
Fatigue testing
Creep
Poisson ratio measurements
Laser Flash analysis
Thermomechanical analysis
X Ray Diffraction

Raman spectroscopy



Nanoimpact with varying Strain Rate depending on impact parameters

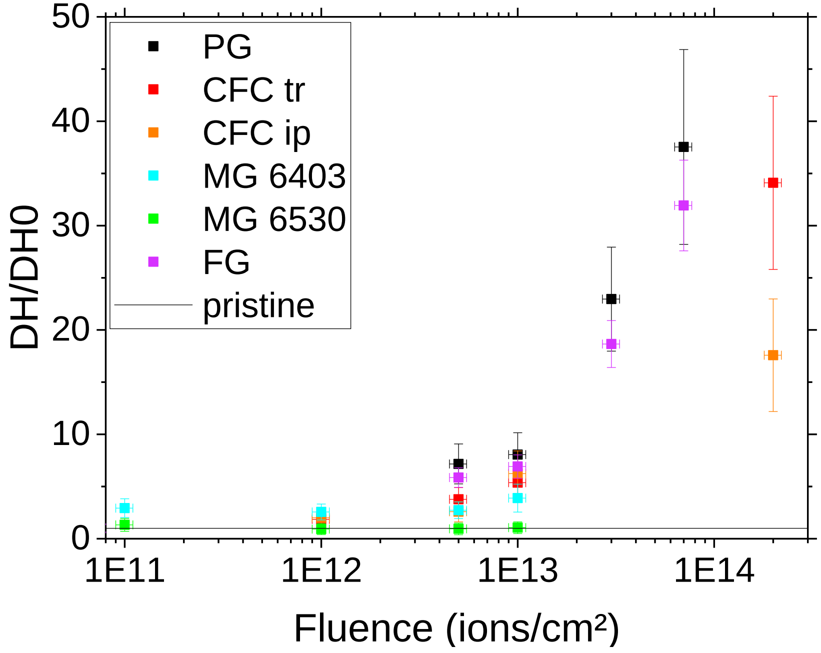


Task 17.3 – Nano-impact response of irradiated graphitic materials

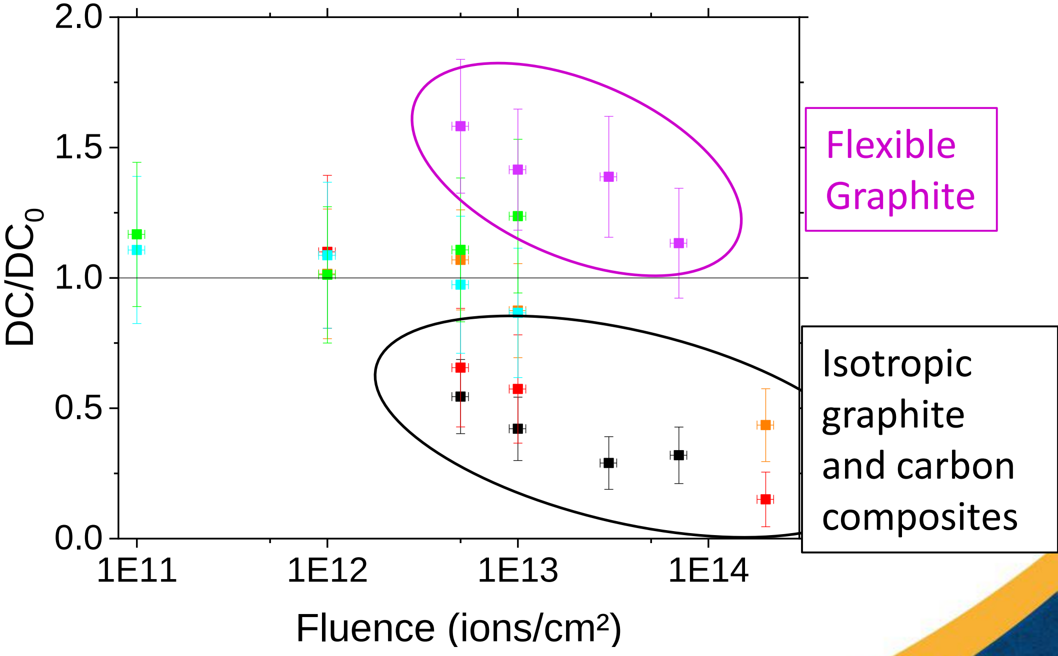
GSI

Irradiation of isotropic graphite, CFC, FG and MoGr
with Au 4.8 MeV/u and 3.6 MeV/u

Relative change of dynamic hardness

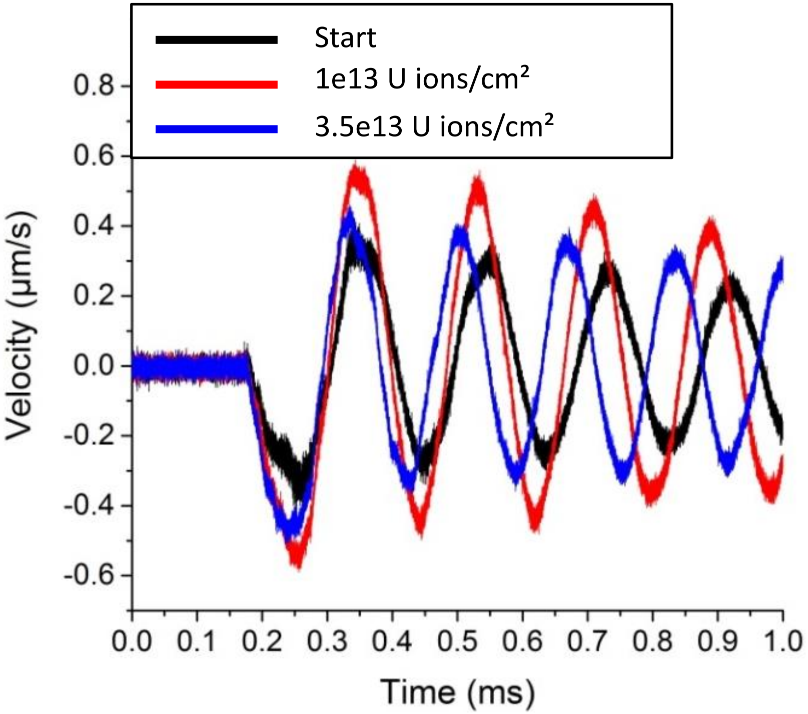


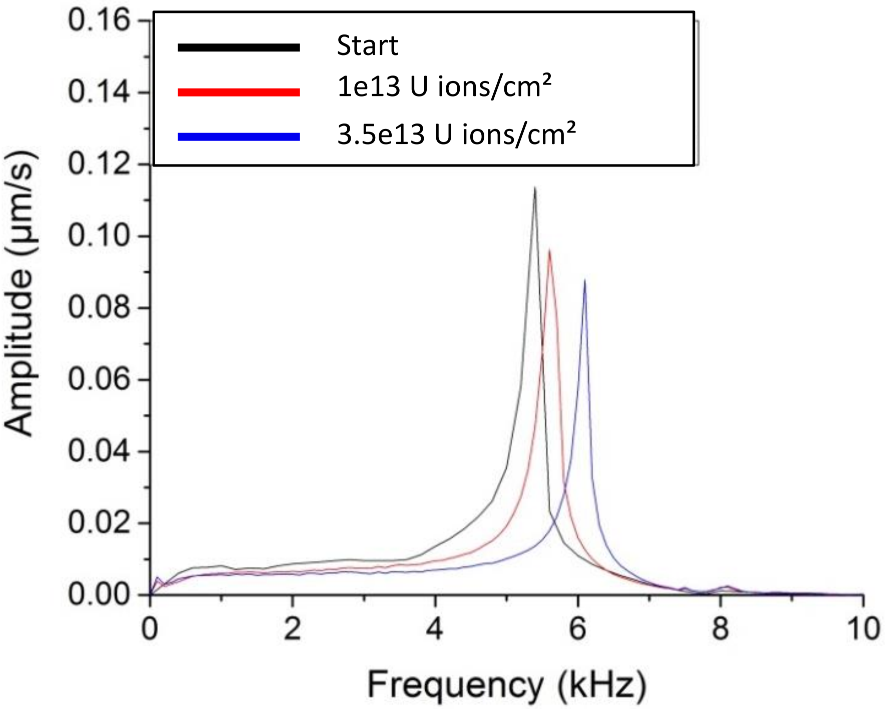
Relative change of damping constant



Task 17.3 – Response of irradiated graphite to beam-induced pressure waves – 4.8 MeV/u U, 100 µs

LDV online monitoring - bending modes of disc targets with does accumulation



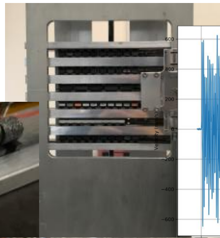


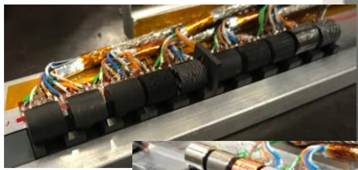
First order bending frequency increases for higher accumulated fluence
Caused by increased Young's modulus in beam spot

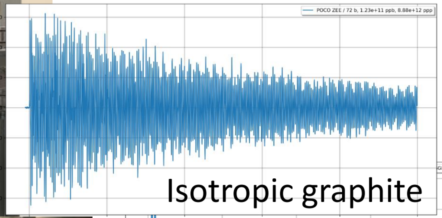
Task 17.3: Dynamic Testing and Online Monitoring @HiRadMat FlexMat experiment- GSI

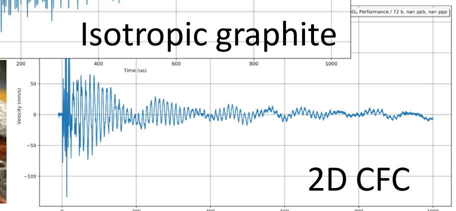
- response to beam induced pressure waves of a broad range of carbon materials and composite targets
- applications for high power targets, beam windows and beam dumps (FAIR & …)

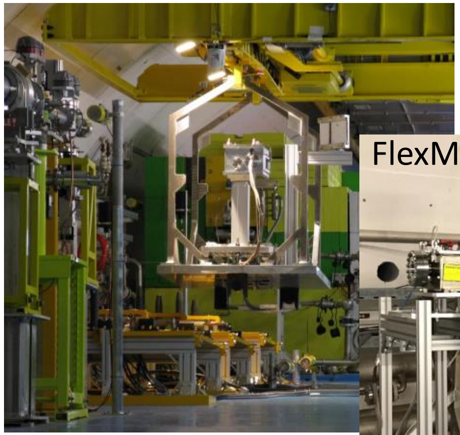
FlexMat - June 2018
HiRadMat@SPS, CERN



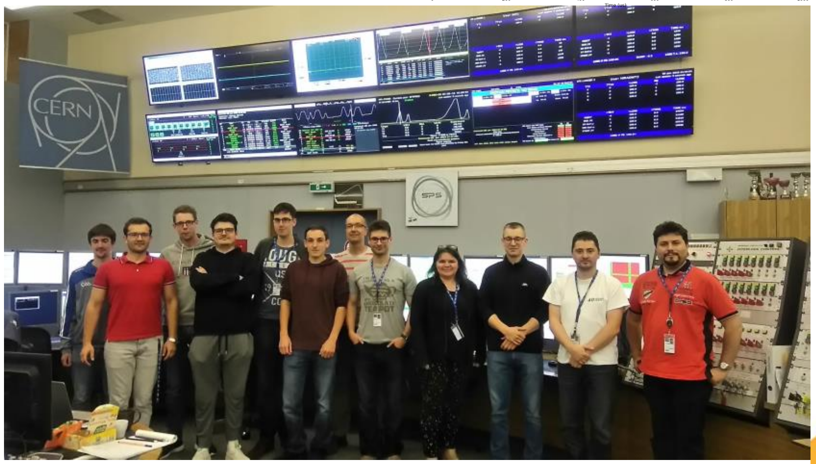








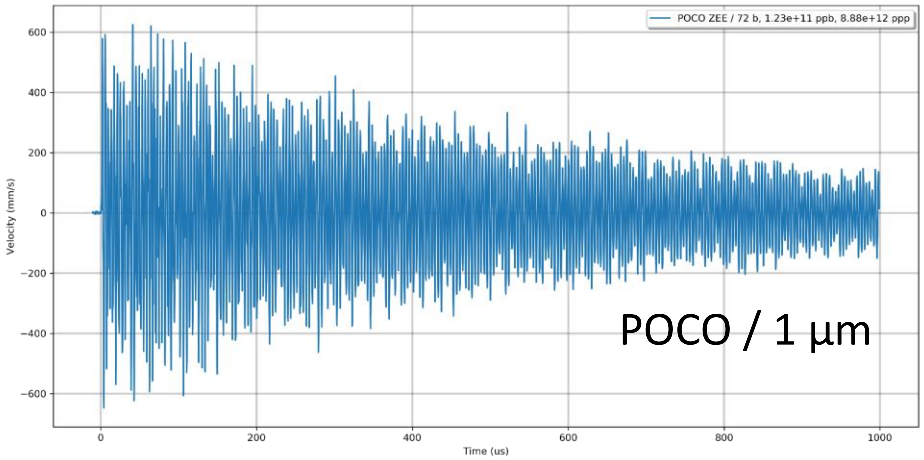
FlexMat mounting in SPS tunnel at CERN

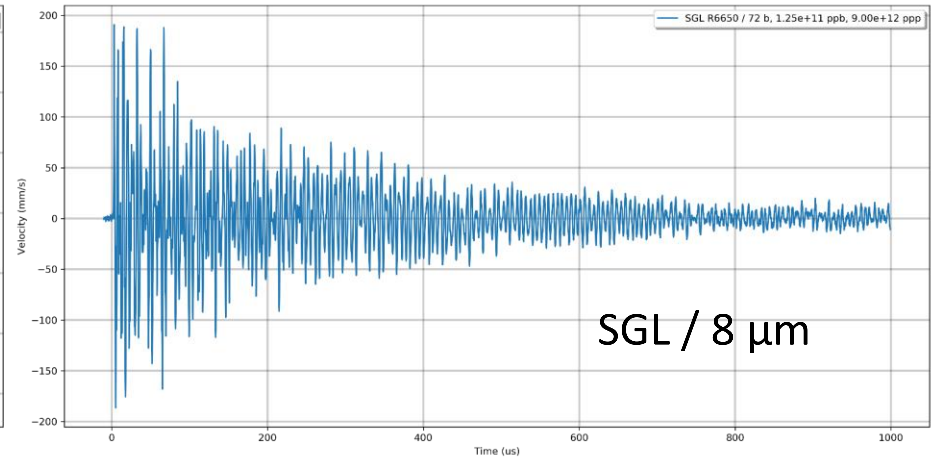


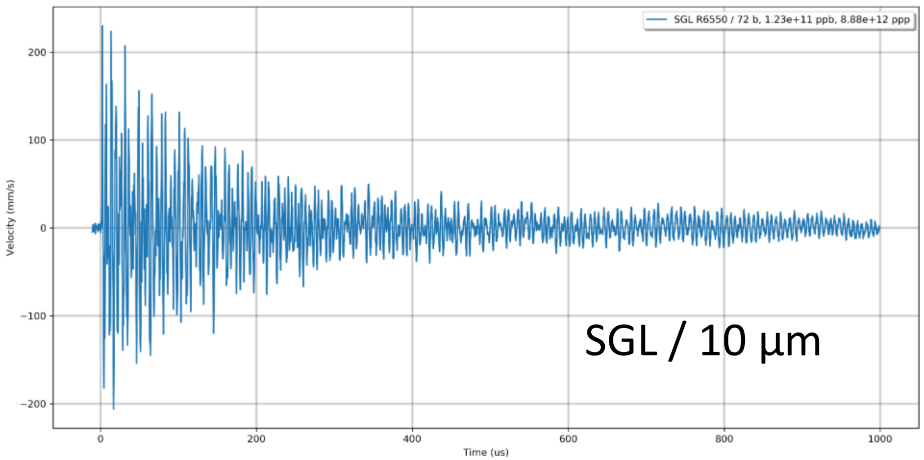
- 283 beam pulses
- total of 1.24E15 pot
- up to 1.3E11 ppb

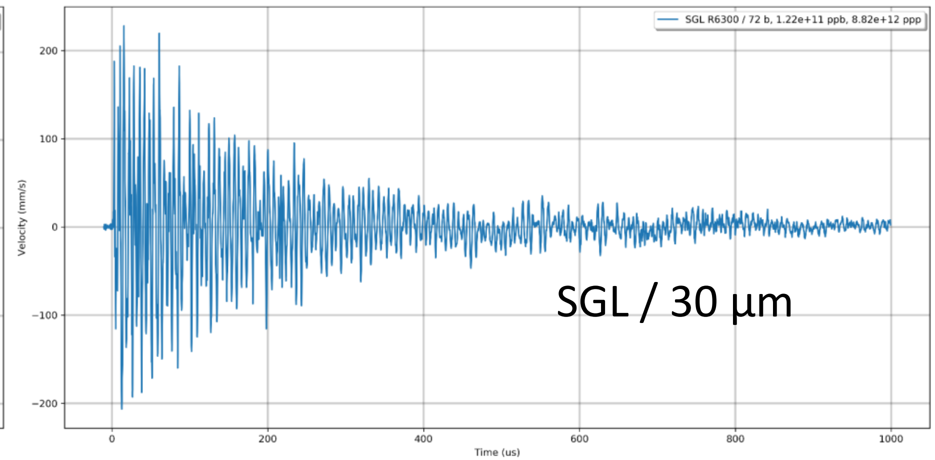
This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 730871.

FlexMat results – response of isotropic graphite grades



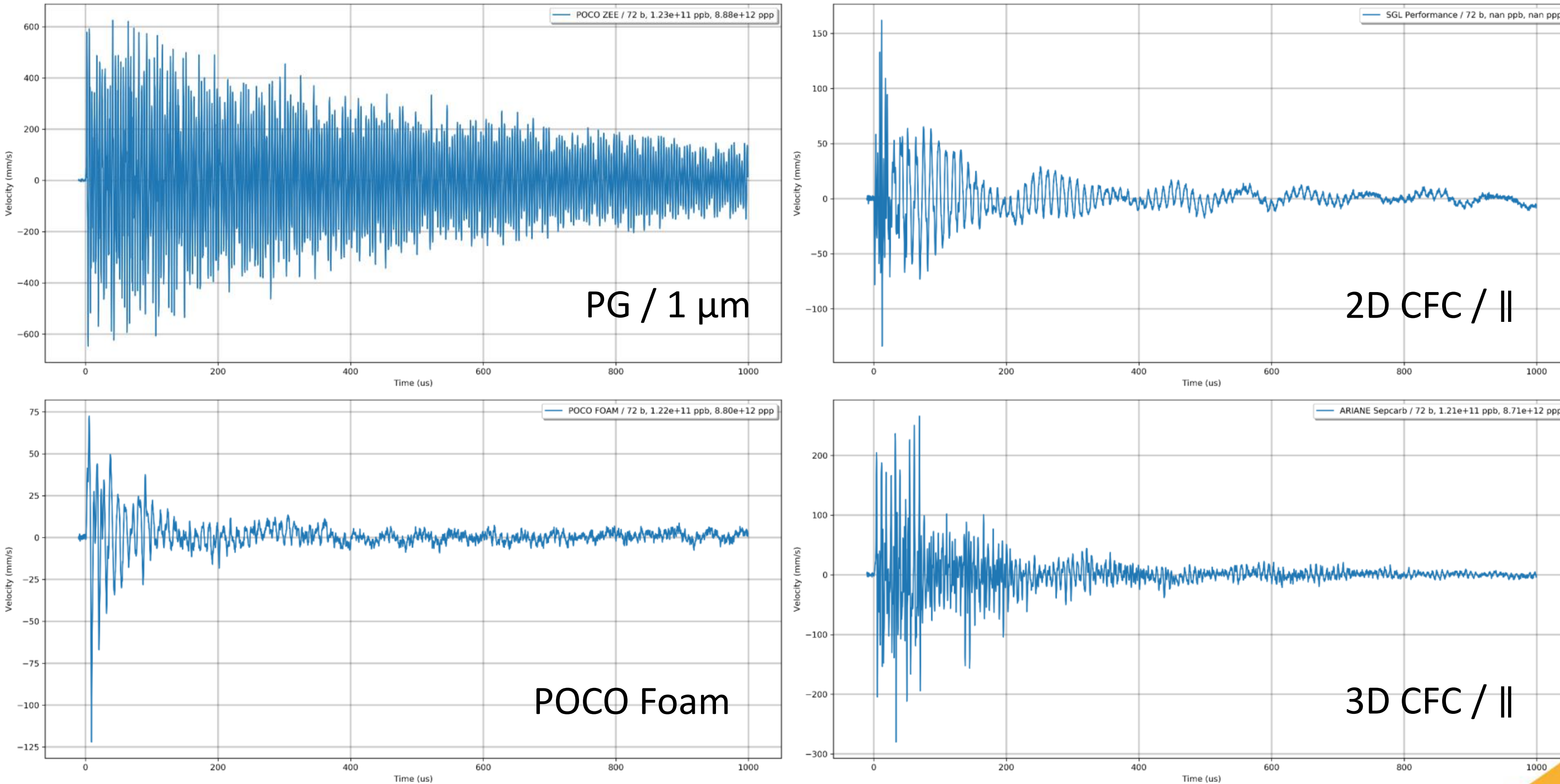






- Polycrystalline graphites with different grain sizes

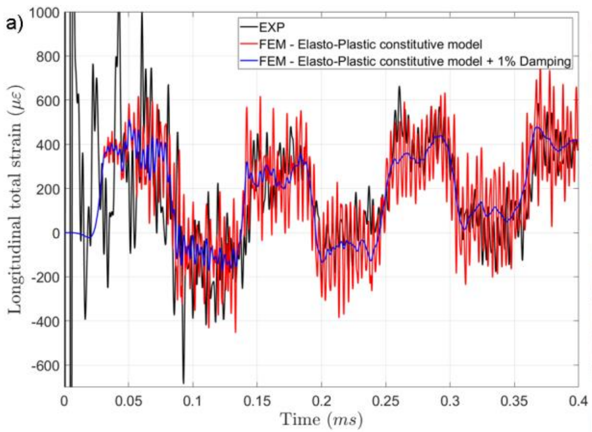
FlexMat results – response of isotropic graphite vs. CFC vs. foam

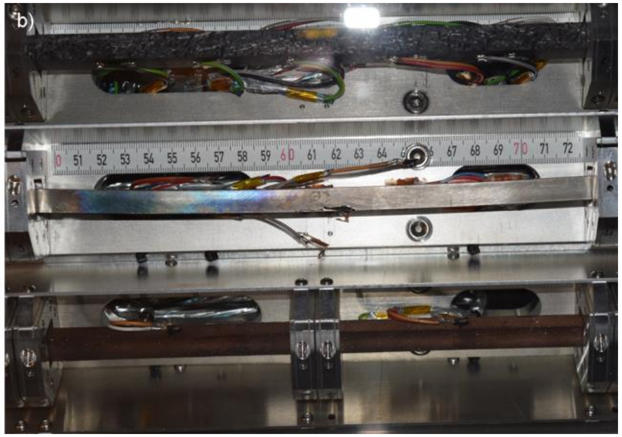


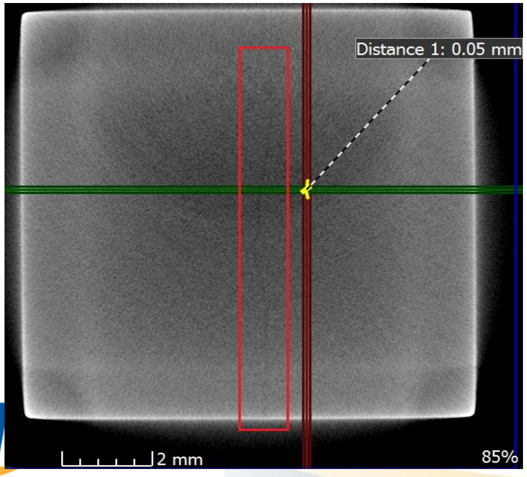
Task 17.3: Dynamic Testing and Online Monitoring @HiRadMat Post-processing of MultiMat Experiment Data

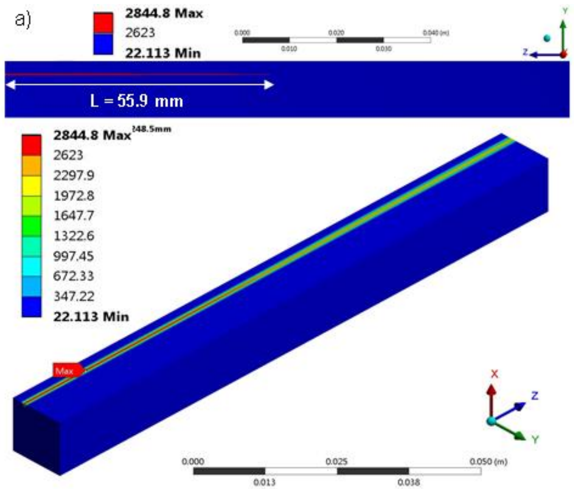
- **478 Pulses**: intensity up to 10 kJ/cm^3
- **Three pulse types**: On/Off-axis, Grazing
- **A number of unknown materials properties already derived**:
  - dynamic constants,
  - damping,
  - viscoelastic parameters,
  - dynamic strength.
- **Post-irradiation tests continuing …**

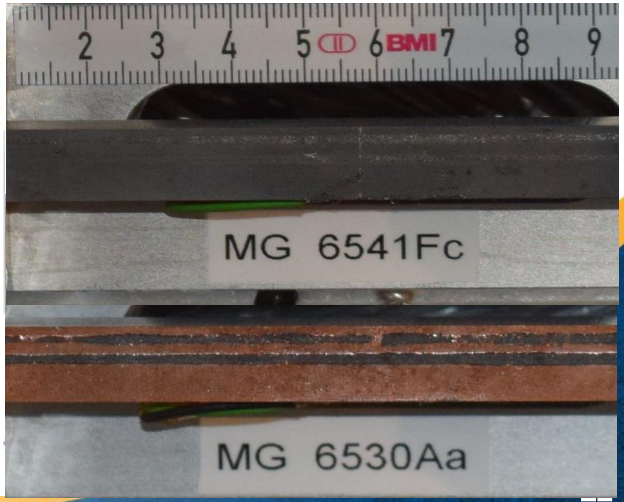
Material	Int. [10^{13} p]	σ(x,y) [mm]	E_max [kJ/cm^3]	E_max HL-LHC (BIE) [kJ/cm^3]	E_max HRMT23 [kJ/cm^3]
MG6541Fc	3.66	0.29×0.31	6.11	5.68	-
AC150K	3.68	0.38×0.23	3.72	2.44	3.16
MG6530	3.99	0.29×0.26	7.68	5.68	5.66
R4550	4.04	0.31×0.27	4.15	-	-









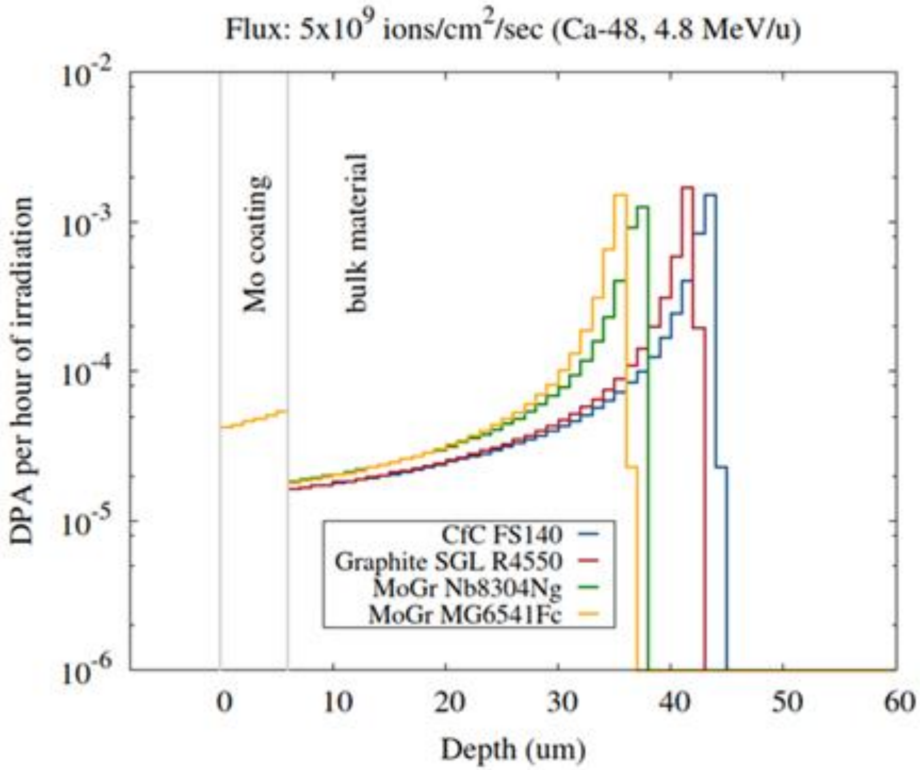


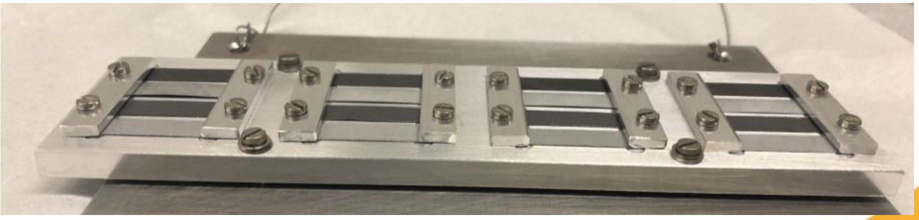
Task 17.3. Ion irradiation at GSI for collimator materials

- Different bulk and coating materials irradiated with Ca ion (4.8Mev/u) at GSI UNILAC (M3) in March 2019
- FLUKA simulation to assess DPA rate and set the destination fluence to reach the DPA level in the coating expected for HL-LHC

	DPA in Mo coating
Ca ions	~$5\cdot10^{-5}$ DPA/h
HL-LHC	$1\div3\cdot10^{-3}$ DPA

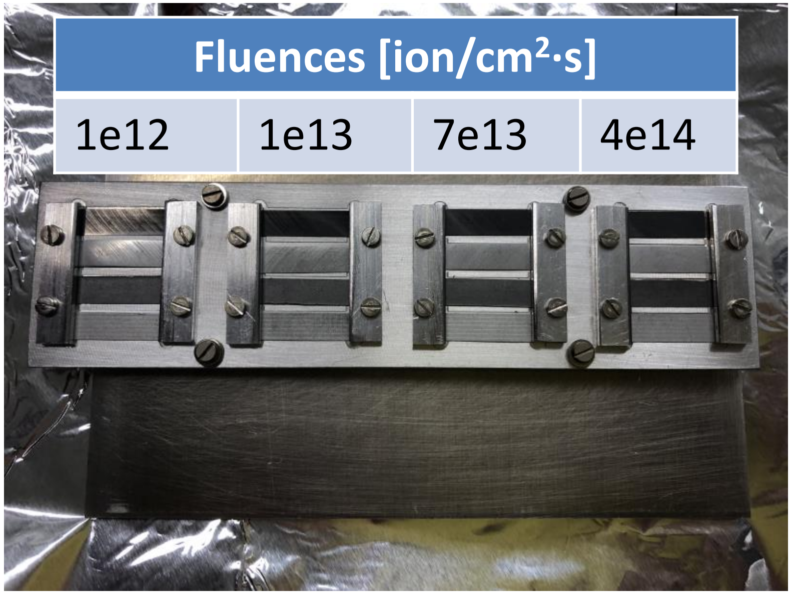
- Sample holders with 4 slits irradiated at different fluences to investigate damage threshold
- Sample geometry optimized for PIE

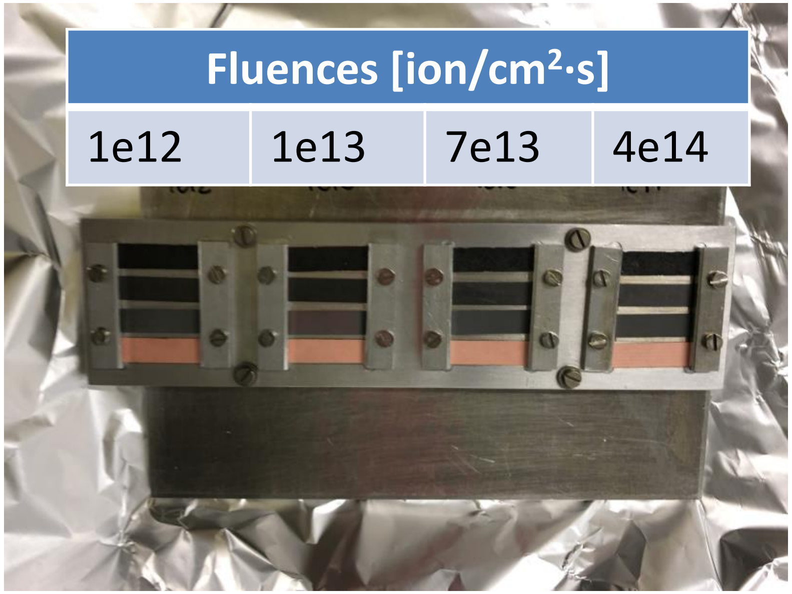




Collimator materials irradiation at GSI-no visible signs of damage at 4 x 10^{14} Ca ions/cm^2, 4.8 MeV/u

- 5 holders (80 samples) irradiated with: MoGr (2 grades), Graphite, CFC, Mo-coated graphite, Mo-coated MoGr, Cu-coated MoGr
- Visual inspection reveals no structural damage of bulks and coatings





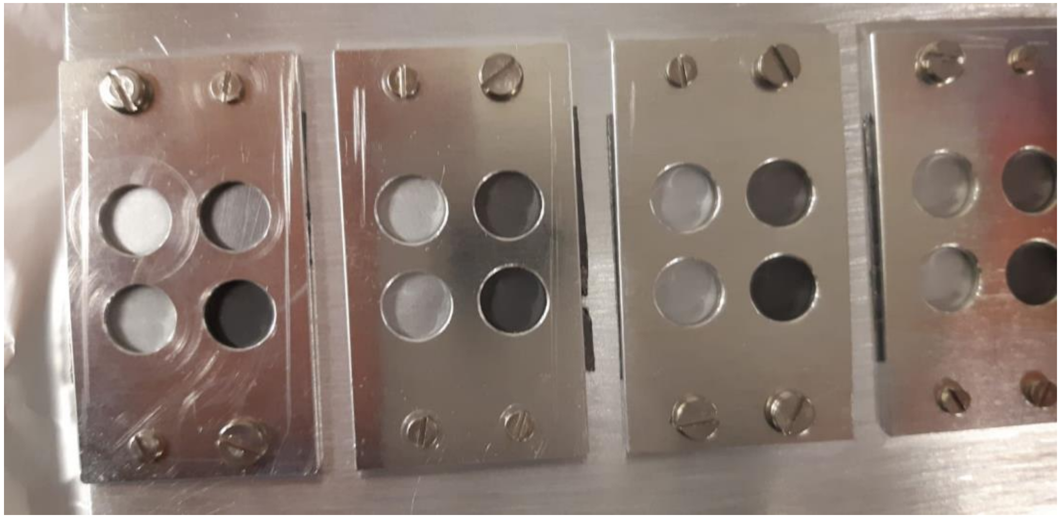
Sample for electrical and thermal conductivity measurements

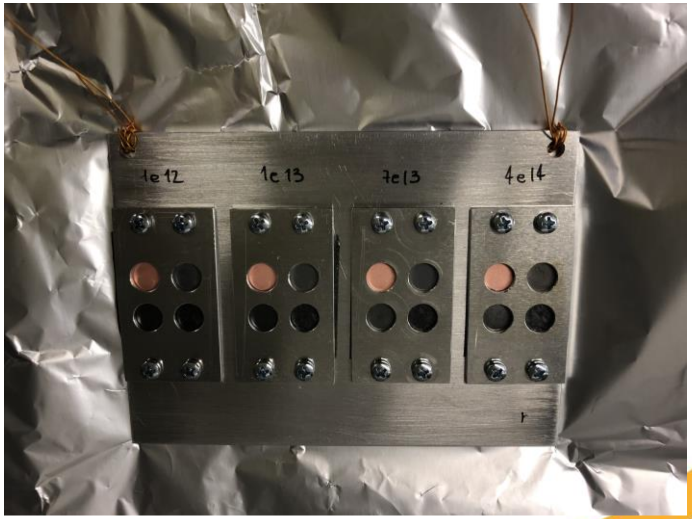
Collimator materials irradiation at GSI-no visible signs of damage at 4 x 10^{14} i/cm^2

- 5 holders (80 samples) irradiated with: MoGr (2 grades), Graphite, CFC, Mo-coated graphite, Mo-coated MoGr, Cu-coated MoGr
- Visual inspection reveals no structural damage of bulks and coatings

Fluences [ion/cm^2·s]			
1e12	1e13	7e13	4e14

Fluences [ion/cm^2·s]			
1e12	1e13	7e13	4e14

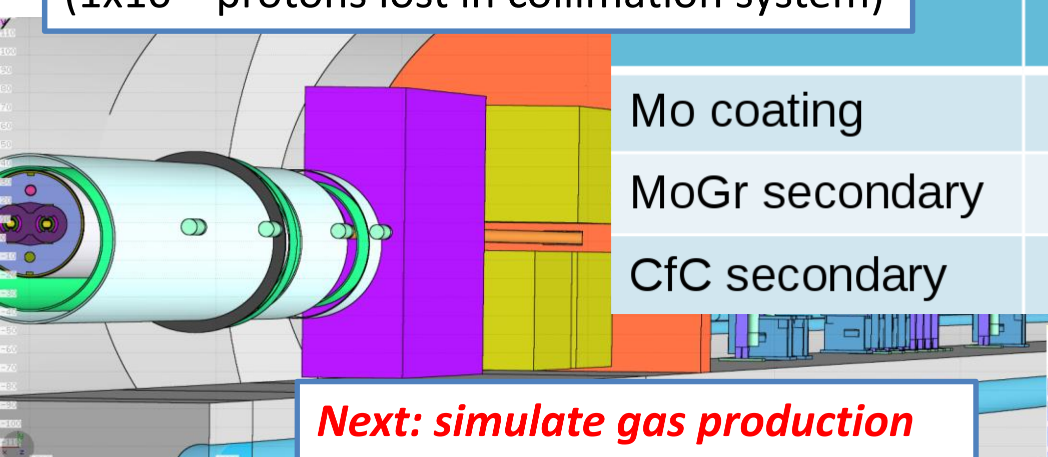


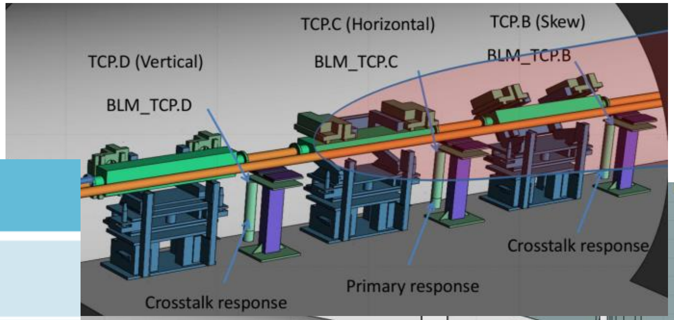


Sample for microstructural and mechanical measurements

Task 17.4 – Simulation of radiation effects

- Assessment of long-term radiation damage in HL-LHC collimators
  - Finalized beam loss predictions for the HL-LHC era based on 2015-2018 Beam Loss Monitor (BLM) measurements - losses are a factor of ~10 less than originally estimated
  - Obtained updated displacement damage estimates for collimator bulk materials and coatings through complex shower simulations

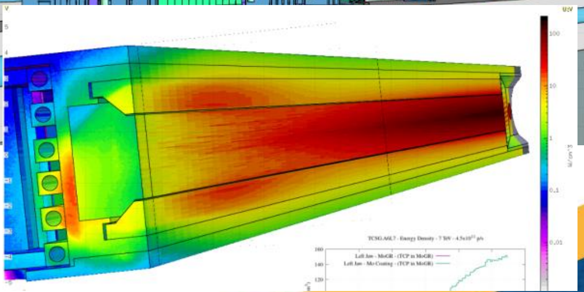




Displacement Per Atom (DPA) in HL-LHC (1x10^{17} protons lost in collimation system)

	DPA
Mo coating	$1\cdot10^{-3}$
MoGr secondary	$4\text{-}5\cdot10^{-4}$
CfC secondary	$1\text{-}2\cdot10^{-4}$

Next: simulate gas production (H, He) in collimator materials – activity started



E. Skordis

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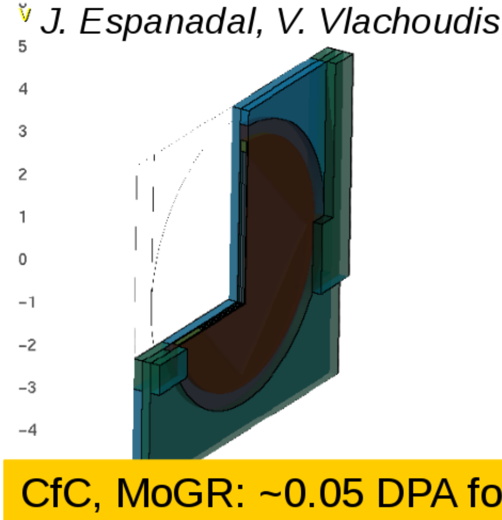
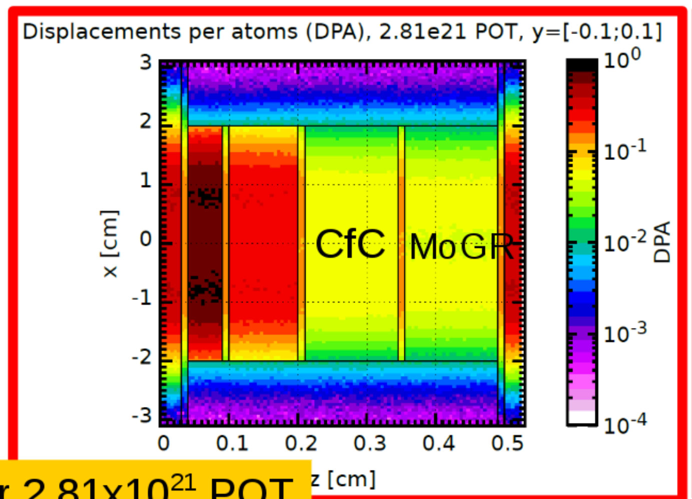
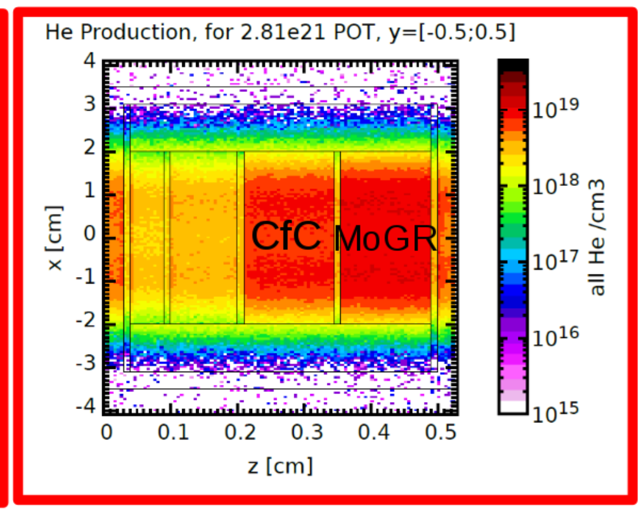
Task 17.4 – Simulation of radiation effects

- Irradiation of HL-LHC collimator materials at BLIP by RaDIATE collaboration
  - MoGR and CfC samples irradiated in RaDIATE target box - in total 2.81×10^{21} protons on target achieved in Phase 3 run (2018)
  - DPA and gas production (H, He) calculations with FLUKA by CERN colleagues (and with MARS by US collaborators within RaDIATE collaboration
  - Post irradiation examination jointly planned by ARIES WP17 and RaDIATE







CfC, MoGR: ~0.05 DPA for 2.81×10^{21} POT

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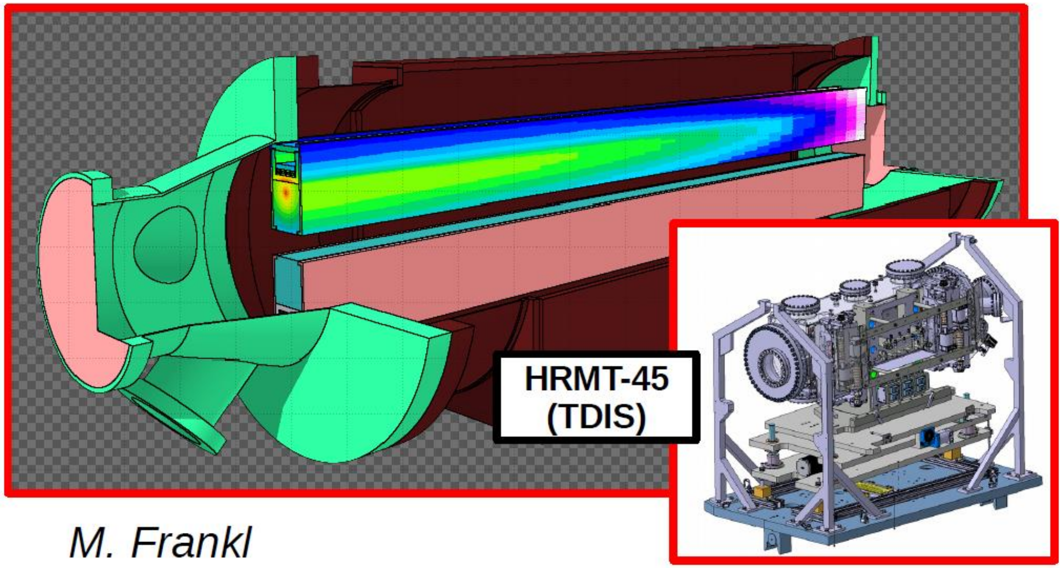
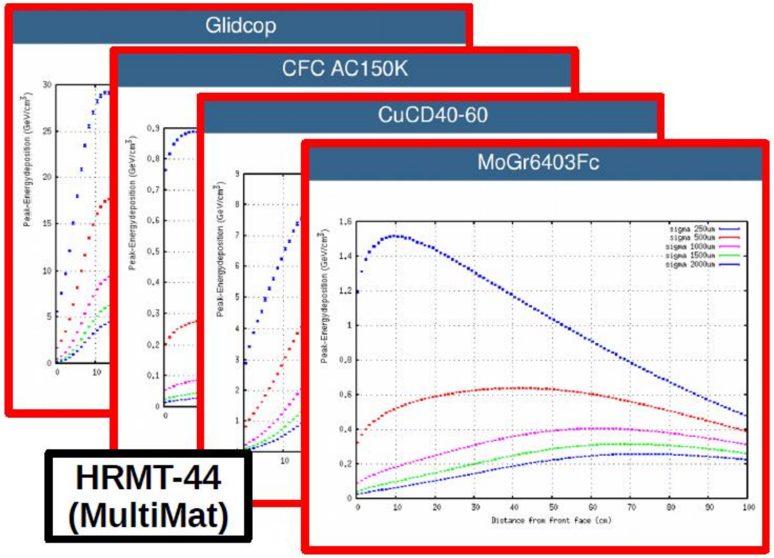
Task 17.4 – Simulation of radiation effects

- Carried out energy deposition studies for several HiRadMat tests
  - Coated Graphite and MoGR collimators (CERN EN/STI group, HRMT-35)
  - MultiMat (CERN EN/MME group, HRMT-36)
  - SPS-LHC transfer line collimator (CERN EN/STI group, HRMT-44)
  - HL-LHC injection protection collimator (CERN EN/STI group, HRMT-45)

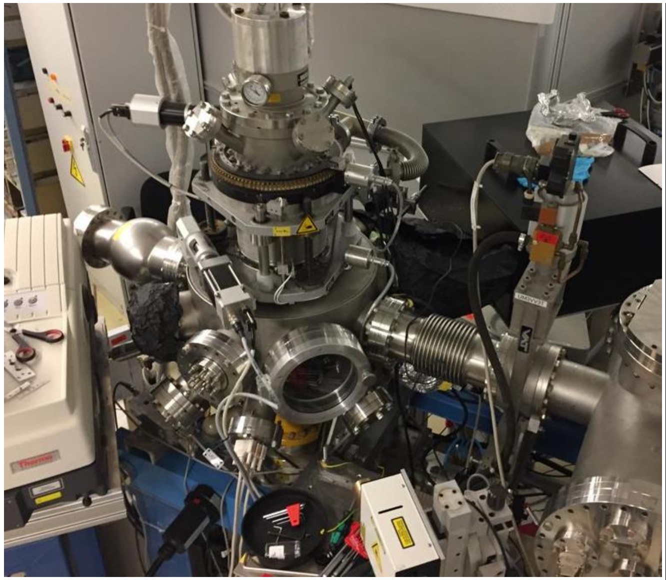




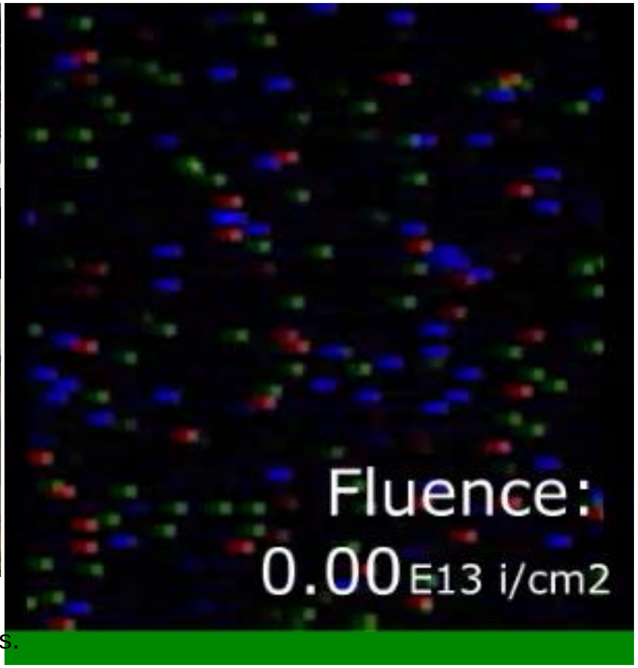
M. Frankl

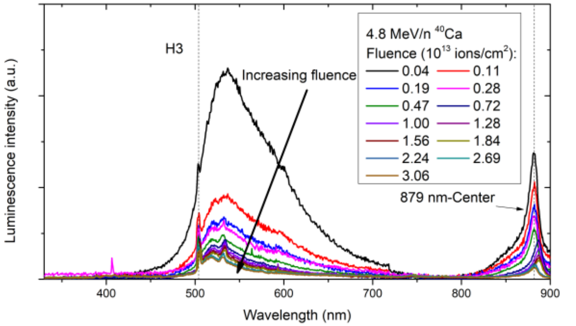
Task 17.5 - Broader accelerator and societal applications

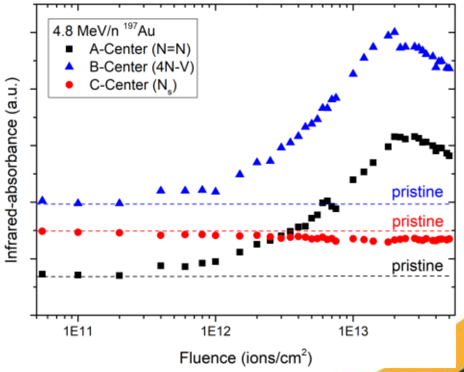
- Irradiation of diamonds and diamond/metal-matrix composites for luminescesnce applications at GSI - UNILAC
- High intensity and high fluence irradiation with: 4.8 MeV/n Ca, Sn, Xe and Au
- Various on-line experiments: Ion-beam induced luminescence, Raman and FTIR spectroscopy



M3-branch at UNILAC: Multi-purpose UHV chamber with cryogenic sample holder and various spectrometers.

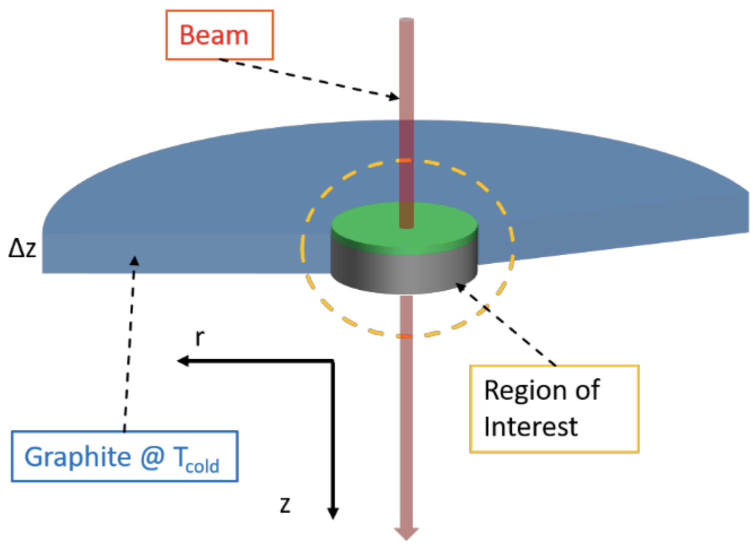






Task 17.5 - Broader accelerator and societal applications

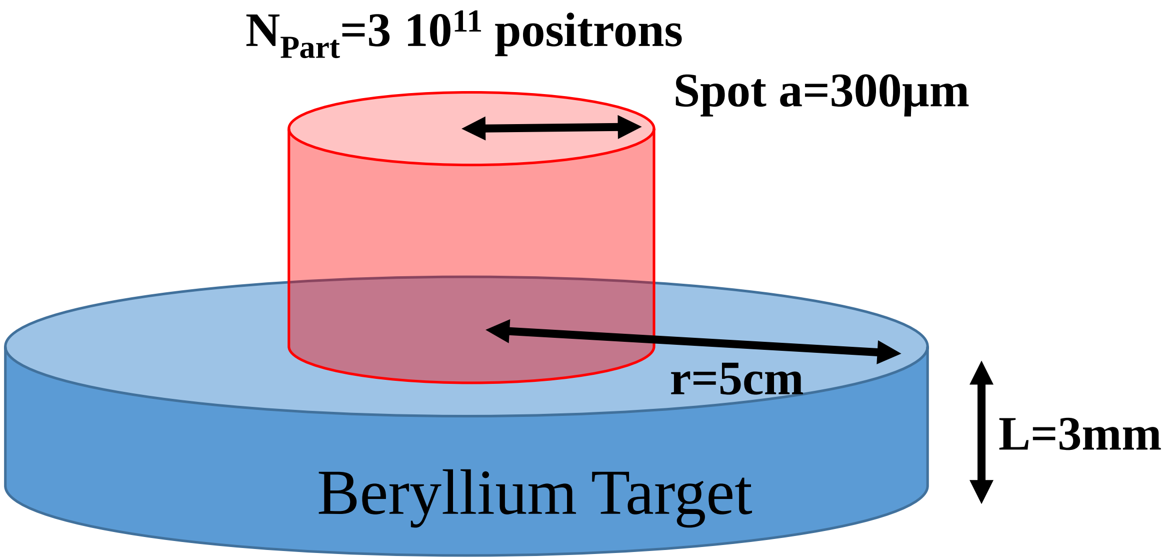
- Irradiation of highly oriented pyrolytic graphite for applications to thin targets for NUMEN experiment
  - measurement of the cross sections of Double Charge Exchange reactions for several couple of ion projectile-target, in order to provide helpful data to study the nuclear matrix elements of the neutrino-less double β-decay- intense ion beams on thin targets (D. Calvo- INFN, Torino)

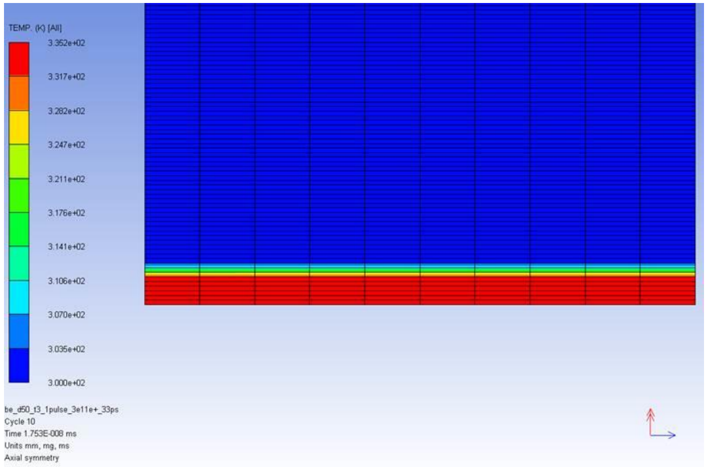


F Pinna *et al* 2018 *J. Phys.: Conf. Ser.* **1056** 012046

Post-irradiation measurements on degradation of thermal conductivity of target materials

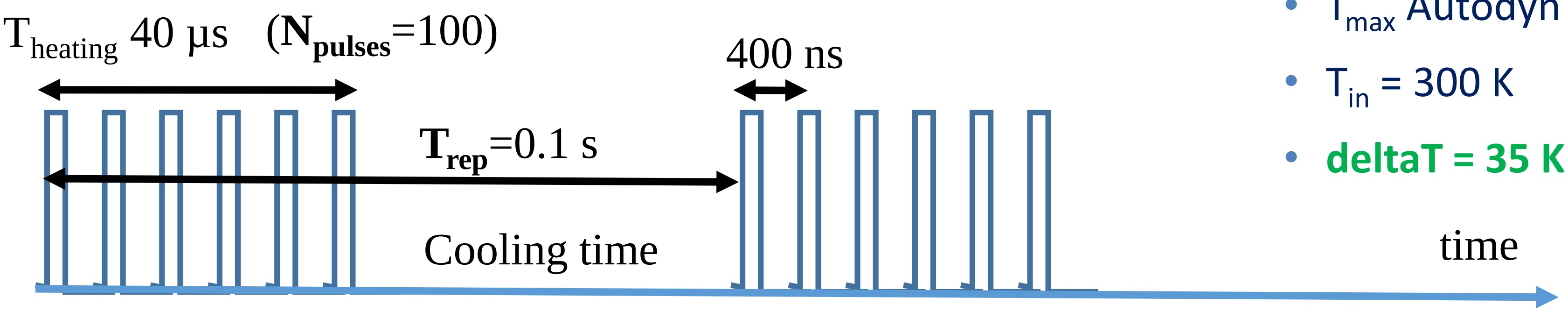
Thermomechanical response of the LEMMA beryllium target (CERN, PoliTo)





First simulations done with Autodyn (1 bunch)

- T_{max} Autodyn = 335 K
- T_{in} = 300 K
- **deltaT = 35 K**

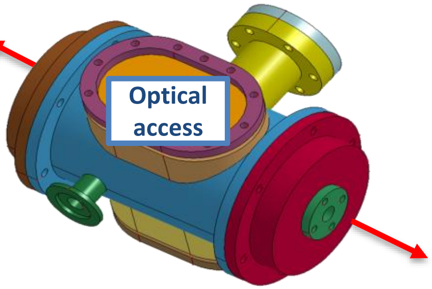


For steady state → moving to ANSYS (no change of phase, long times – minutes!

What's next in PowerMat

- Data analysis of GSI FlexMat experiment at HiRadMat (GSI)
- Fracture mechanics and high strain-rate tests. POLITO

-Vacuum chamber for Hopkinson bar apparatus



- Milestone month 27: report on irradiation test at GSI
- Investigations of properties degradation of materials irradiated at GSI

for collimator, high power targets and beam windows

- Prepare for high power laser beam test

at ELI-NP and laser driven proton beams

impact at PHELIX-GSI

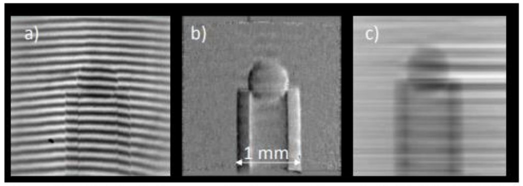


Figure 41 – Talbot X-ray deflectometry of plastic tube and sphere at 17 keV (Ref. [182]): a) Moire fringe image. b) Areal electron density gradient image. c) Areal electron density obtained by integration of the gradient. The artifacts in the density image are due to the use of 1-D Talbot gratings.

- Simulate gas production: H, He in collimator materials
- Experimental aproach of high energy combined gas production and radiation damage effects in HL-LHC collimators and targets by He implantation and low energy ion irradiation
- A special issue with the title: "Shockwave Generation in High Energy Particle Impacts" in Journal "Shock & Vibrations"

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Thank you!

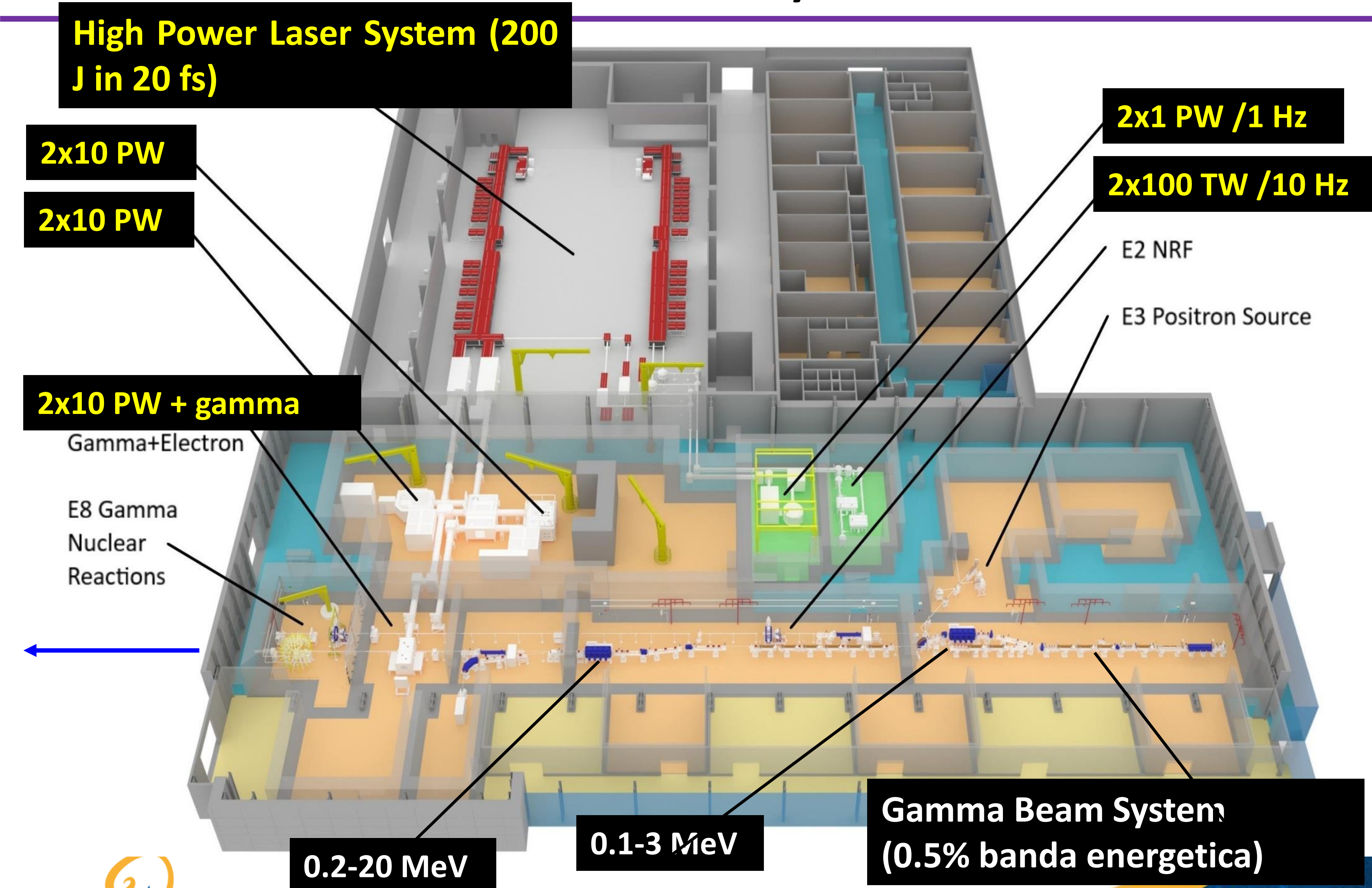
What is MultiMat Experiment

- Experiment at **HiRadMat** performed in October 2017
- Al vessel hosting under inert gas a **rotatable barrel** equipped with **16 target stations**, each one embarking up to 8 slender specimens
- **18** different **materials tested**, ranging from ultra light C foams to W heavy alloys
- MoGr, CFC and graphite **coated** with **Mo**, **Cu**, **TiN**
- Platform reusable in future HiRadMat tests

Main objectives

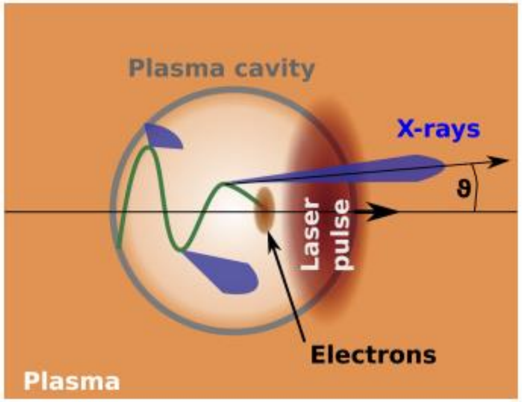
- Acquire **material dynamic responses** and derive **constitutive models** to benchmark complex numerical simulations
- Test materials and coatings with beam brightness beam
- Exploit sample geometry to exceed some **stress components induced by HL-LHC high intensity accidents**

ELI-NP facility

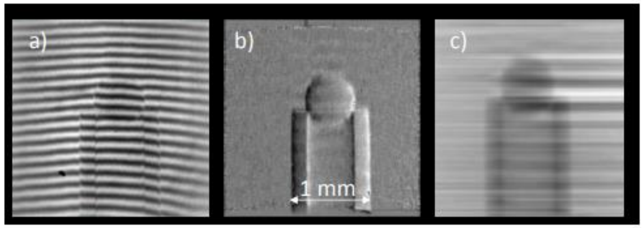


10 PW amplification demonstrated in March 2019

E5 experimental area



[Kohler et al, 2016]



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[D. Stutman, Appl Opt, 2015]

- Vacuum enclosures under manufacturing. To be installed starting October 2019
- 0.37 FTE hired at ELI-NP working on developments of online diagnostics:
  - X ray phase contrast probe used as backlighter
  - Betatron X ray emission from LWFA
  - Diagnostic provides very high sensitivity of solid plasma densities
  - 2 laser pulses, 25J 25fs, one beam for laser induced shocks/particle beams, second for probing