

Overview of some CERN High Radiation to Materials experiments and focus on Post Irradiation Examinations

François-Xavier Nuiry, on behalf of all the related experiments
20/12/2018



Outlines

- Overview of some HiRadMat experiments applied to Beam Intercepting Devices
- PIE on 3D CC material (HRMT28)
- PIE on irradiated collimator (HRMT44)
- PIE on Irradiated LHC absorber (HRMT45)

Overview of some HiRadMat experiments applied to Beam Intercepting Devices

- **Response to project requirements for uncharted beam intensities (LIU & HL-LHC requirements)**

- **HRMT28/44** for LIU SPS-to-LHC transfer line collimators (3D CC)
- **HRMT45** for HL-LHC injection dump (TDIS) 2018
- **HRMT35** for coated collimators materials (operational-driven) 2017
- **HRMT18** for crystal collimation 2017

2016 +
2017 +
2018

- **Unknown (non-measured) response of target materials impacted by high intensity & energy proton beams**

- **HRMT42/48** for antiproton target materials (Ta, Ir, etc.) 2017
- **HRMT46** for n_TOF spallation target (pure Pb) 2018
- **HRMT49** for TIDVG5 (polycrystalline Si block)

2017

2018

HRMT-46-48-49

N2 cooled design beam:
Number of pulses: **1500**
Beam p: **440 GeV/c**
Pulse duration: **1.6 ns**
Pulse period: **22.8 s**
Beam size: **4 mm (1σ)**
Intensity: **4e10 ppp**

Reusable tank for future experiments
(it can sustain vacuum even if not required from this specific experiment)

Two independent modules

Motors to align the different targets

Pure Lead cooled down by N2

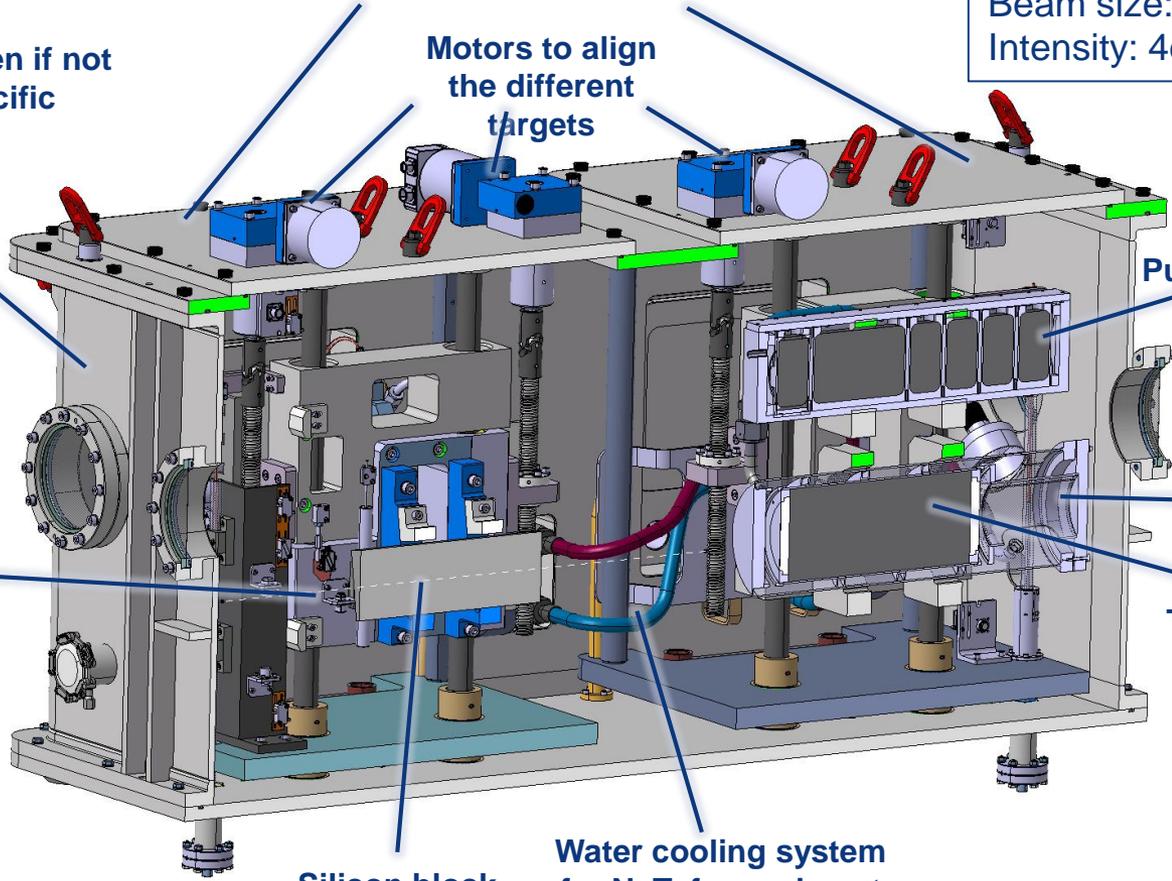
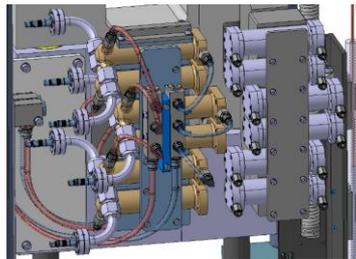
Water vessel

Pure Lead in Ti-6Al-4V container

PROTAD (HRMT48)

Silicon block (HRMT49)

Water cooling system for N_Tof experiment



Courtesy: M. Calviani

HRMT-46 firsts PIE



Pb blocks

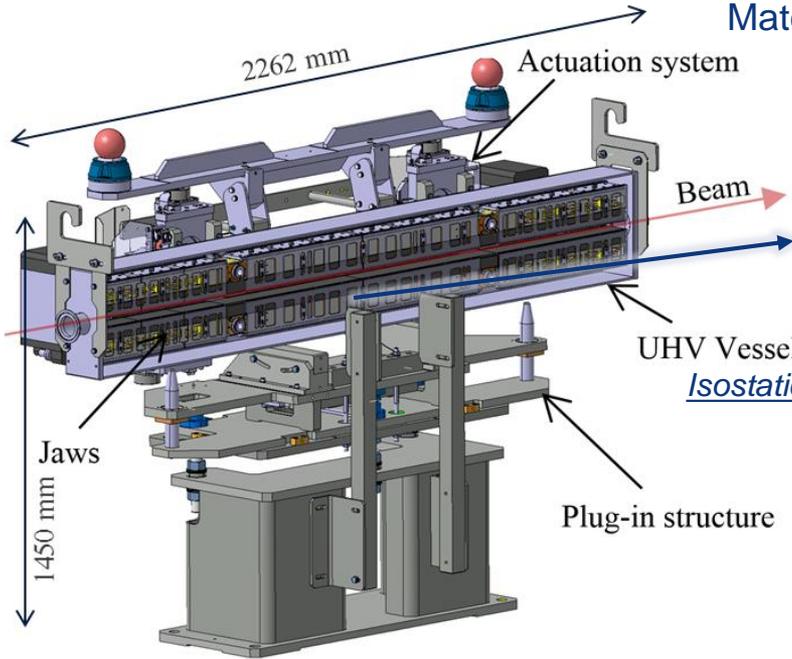
Al-6082
vessel



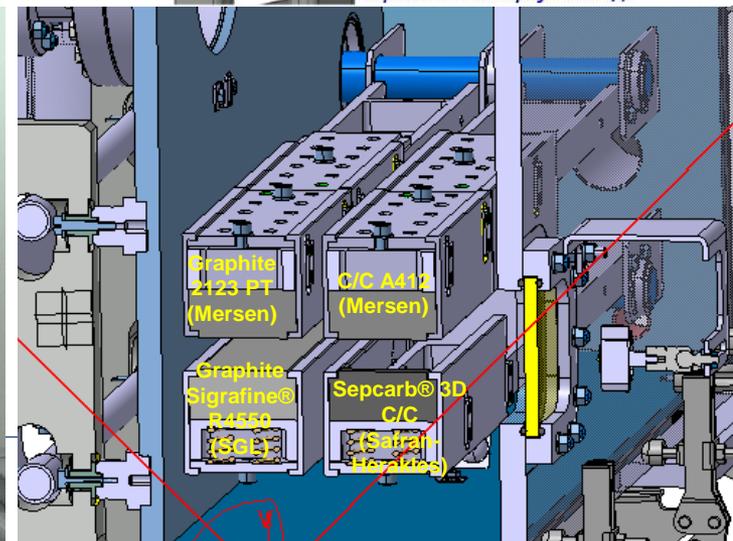
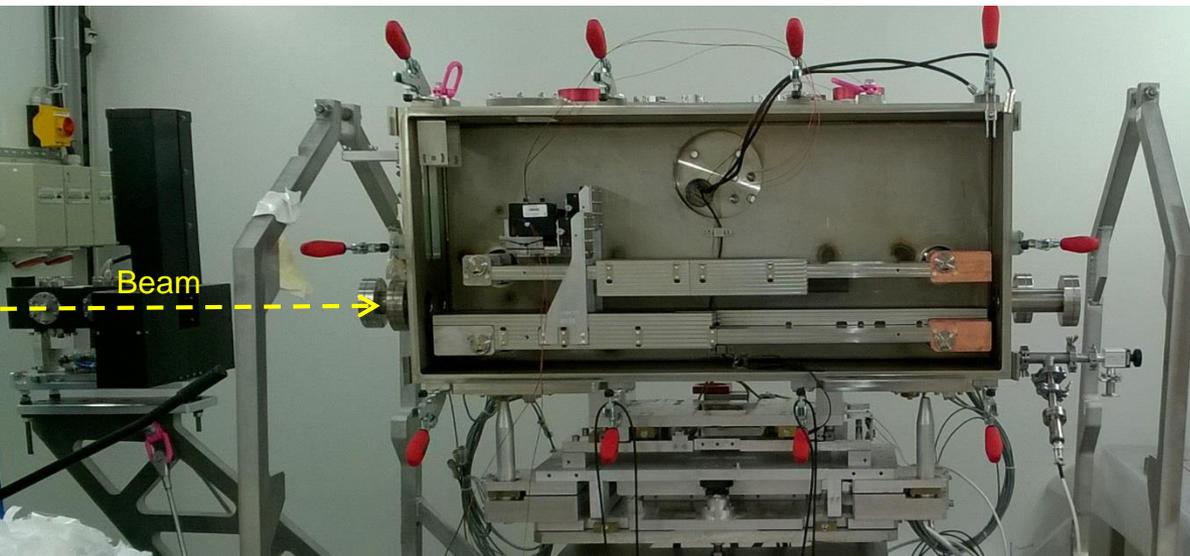
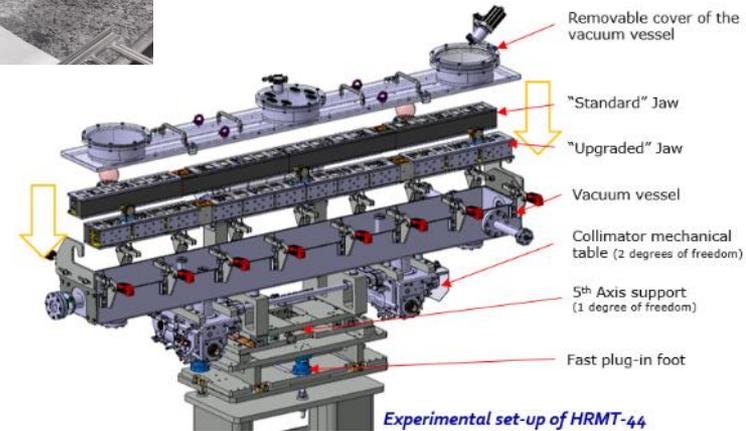
- Neutron tomography with resolution of 25-50 microns ongoing
- High energy X rays are not penetrating enough inside the target

HRM 28 & 44, aim of the experiment

TCDIL Collimator



Materials the TCDIL jaws are made of

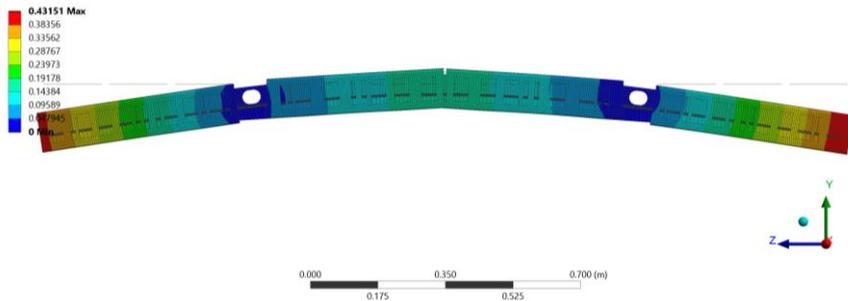


HRMT-44 Online instrumentation analysis

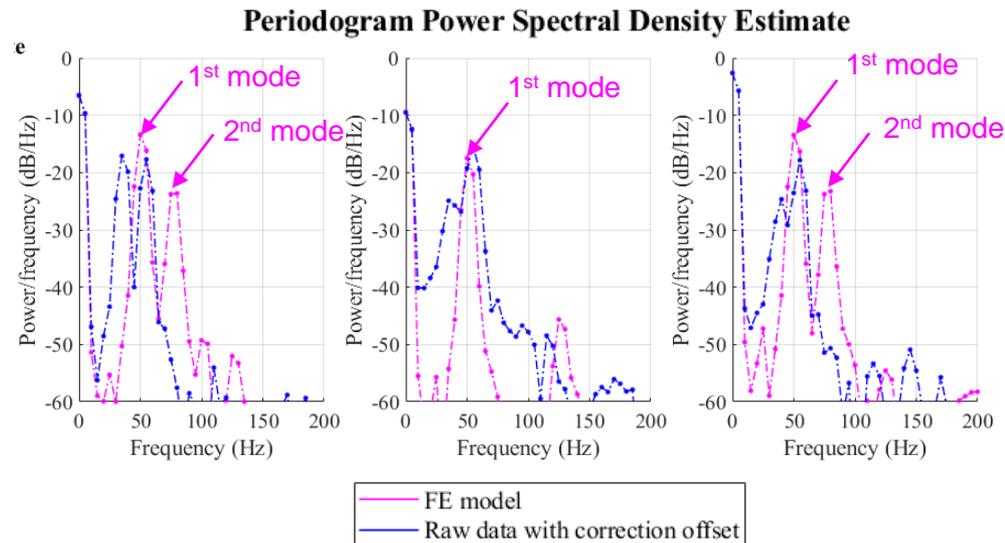
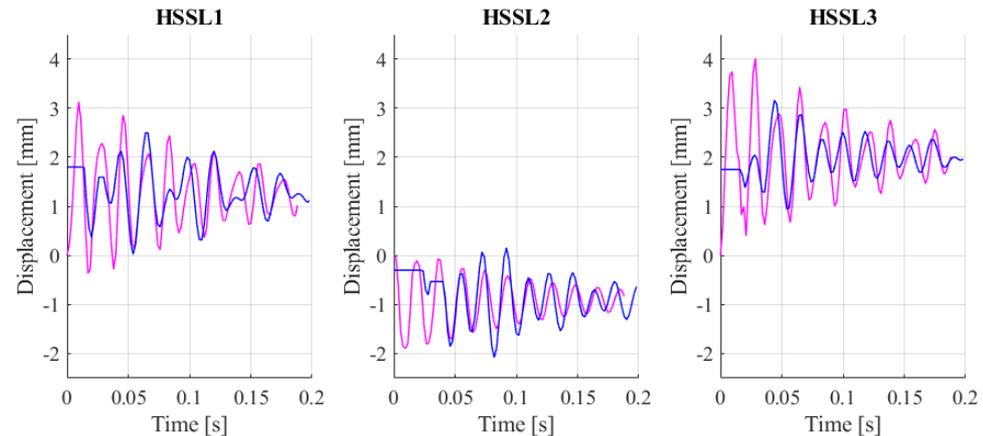
Update of the FE-model and correlation

Numerical/Experimental approach:

- Elastic material models
- Correlation of the damping of the dynamic vibrations by adjusting the friction coefficient of the boundaries $\mu=0.1$
- 1st mode **55Hz** : very good agreement



- 2nd Bending mode **77Hz**: Absent but low amplitude were expected ($P_{77Hz} \propto \frac{P_{50Hz}}{10}$)

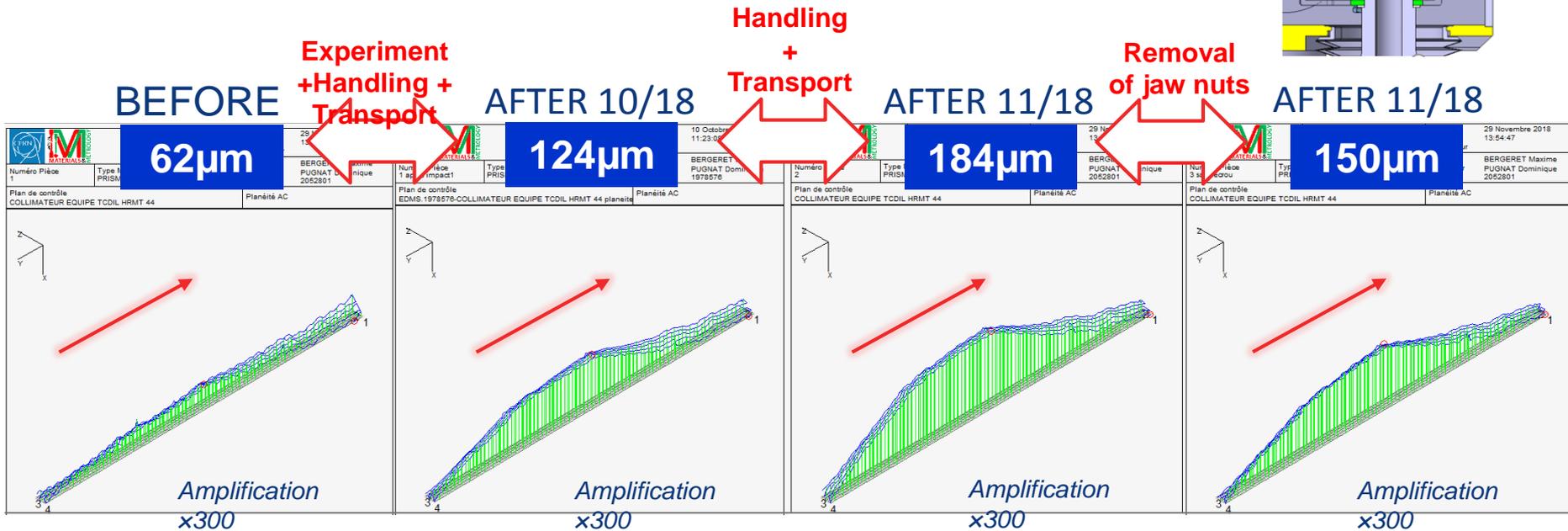
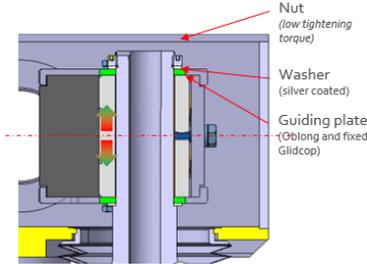


HRMT-44 Post-Irradiation Examination

Metrology of the Jaws before/after impact

Mounted into the vacuum tank

TCDIL-Jaw Standard AC: Flatness



Flatness alteration (Form):

- More **convex form**
- Beam impacts and Transport+Handling influence the flatness with similar range

	Date	04/10/2018
Dose [µSv/h]	Contact	110
	at 10 cm	30
	at 40 cm	8



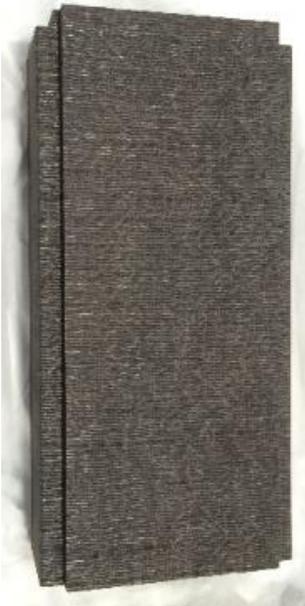
R&D on 3D CC for collimation applications

- 3D Carbon/Carbon composites can be good alternatives to graphite, due to their ability to stop an eventual crack propagation (composite architecture). The material has an high strain to failure.

In addition: →Very high service temperature (characterised up to 2750°C);

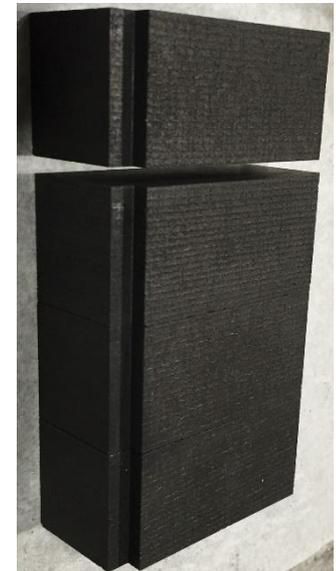
→Materials at least 2 to 3 times higher tensile strength and CTE inferior or equal to the graphite one.

Sepcarb® 3D C/C



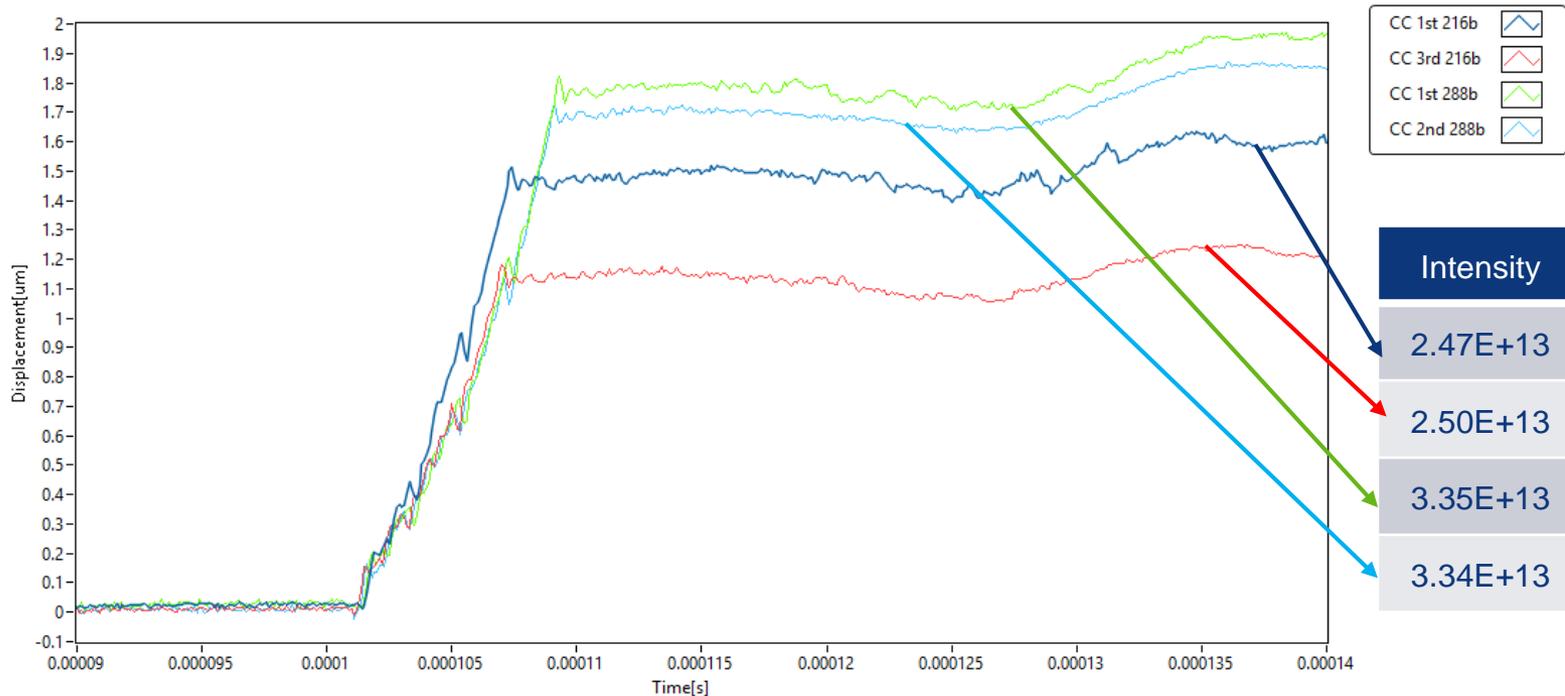
	Sigrafine® R7550	Graphite 2123 PT	Sepcarb® 3D C/C	C/C A412
Density [g/cm ³]	1.83	1.84	>1.81	1.7
Thermal Conductivity W. °C ⁻¹ .m ⁻¹	100	112	Non- Disclosure Agreement	-
Coefficient of Thermal Expansion 10 ⁻⁶ [C ⁻¹]	4	5.6	2	-
Young's modulus [GPa]	11.5	11.4	Non- Disclosure Agreement	15
Tensile Strength [MPa]	30	35	100	60

3D C/C A412



PIE on 3D CC material (HRMT28)

Surface displacement recorded during the experiment, for Ariane group 3D CC



- The very similar surface displacement curves over time is an indicator that no beam induced damage occurs on the material, shot after shot.
- The amplitude difference for the 1st and 3rd shots at 216b can be due to a small spot offset in X.

PIE on 3D CC material (HRMT28)

After Impact

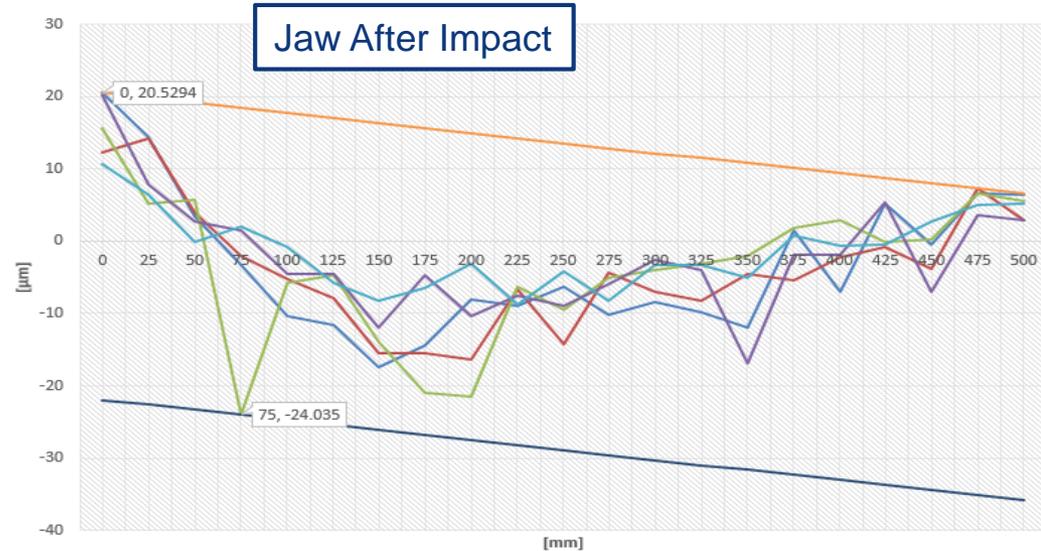
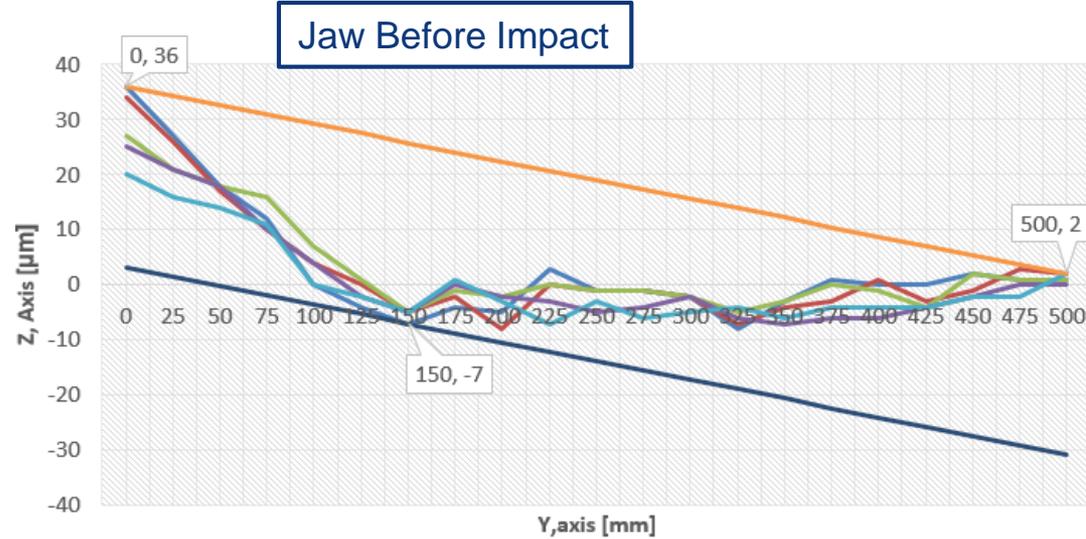
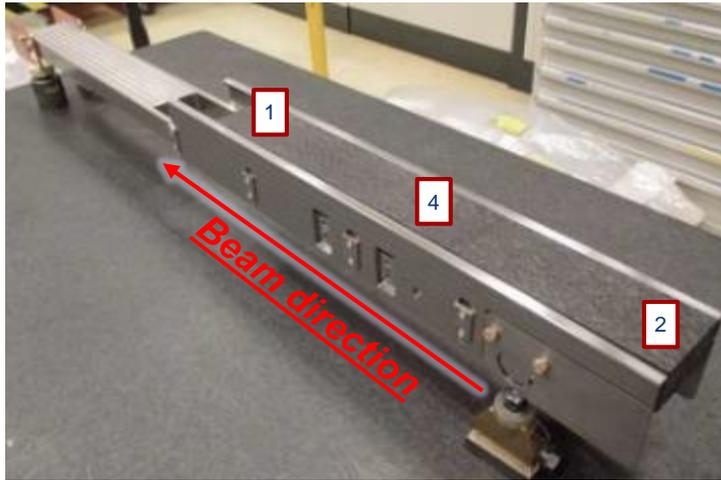
Before impact



3 blocks 80 X 37 X 170 mm

PIE on 3D CC material (HRMT28)

3D CC, Ariane group



jaw Assembled, Flatness [µm]

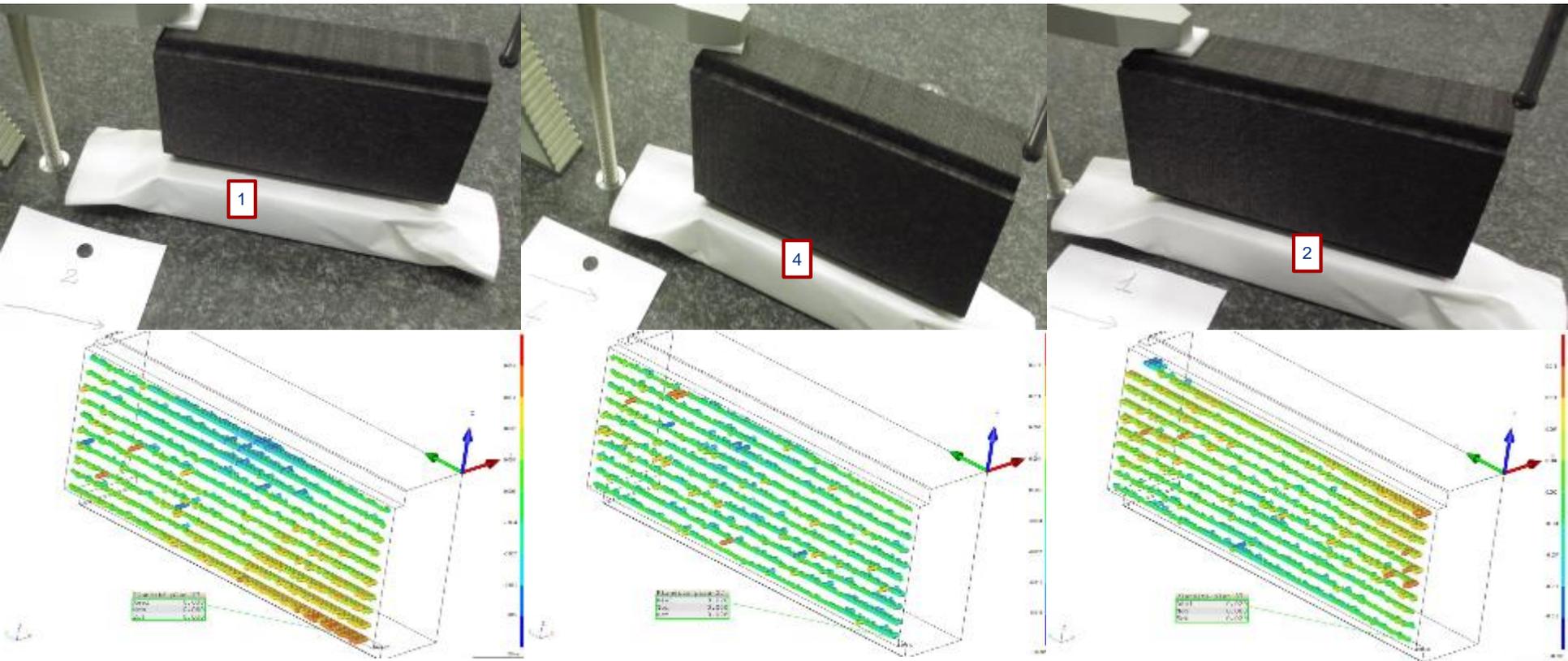
Before Impact

33 µm

After Impact

42 µm

PIE on 3D CC material (HRMT28)



Flatness [μm]	Block #2	Block #4	Block #1
Before impact	26	28	30
After impact	30	26	29

PIE on 3D CC material (HRMT28)

- From the analyses performed so far, no clear “measurement” of beam damages
- **Micro-tomography** analyses have been performed at ESRF, France.



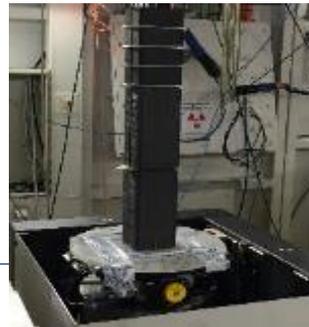
ESRF, high energy source of X-rays

Isotope	After 6 months (Bq/kg)	ESRF limit (Bq)
H 3	8.18E+05	3.70E+07
Be 7	2.51E+06	-
Be 10	7.23E-01	-
C 14	1.62E-03	3.70E+06

AFTER IMPACT

BEFORE IMPACT

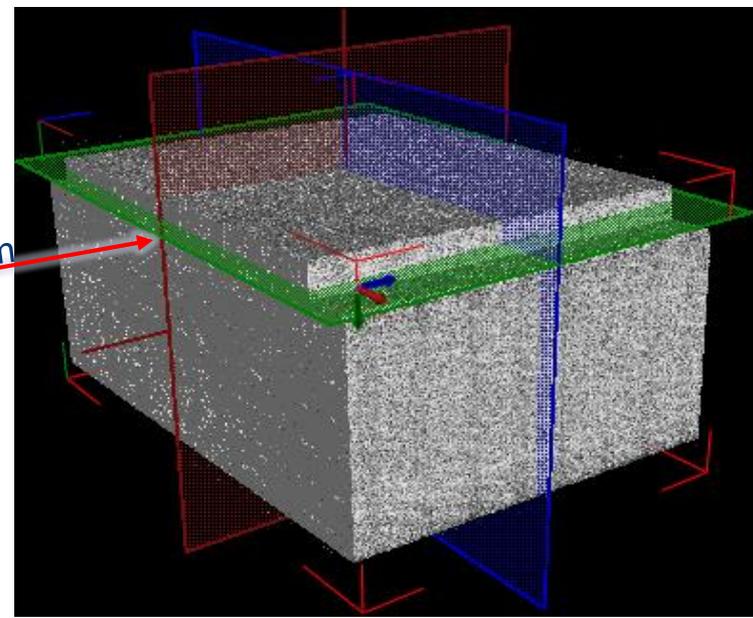
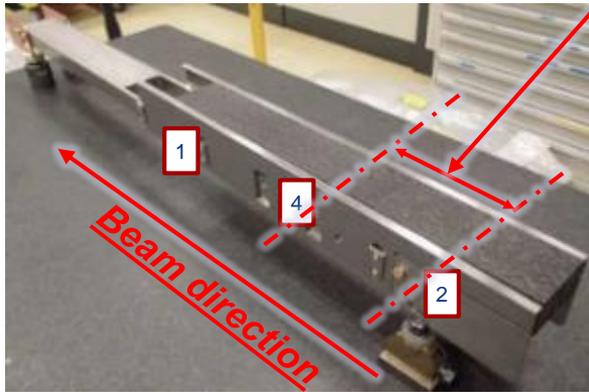
- N. blocks:
 - 4 blocks of 170mm *80mm* 37mm
 - 17 blocks of 35mm *80mm* 37mm
- Optic → 22.5 μm
- No radioactive
- Experimental set-up → blocks stacked as shown.



- N. blocks:
 - 3 blocks of 170mm *80mm* 37mm
 - 12 blocks of 35mm *80mm* 37mm
- Optic → 24.5 μm
- Slightly Radioactive:
 - At contact 12.5 μSv/h
 - At 10 cm 2 μSv/h
 - At 40 cm 0.5 μSv/h
- Experimental set-up → samples tested one by one on the micro-tomography plate

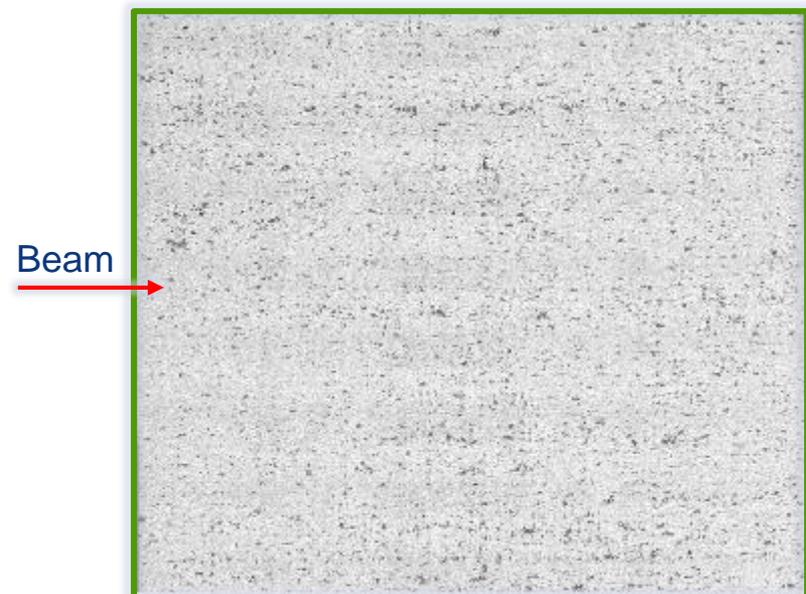
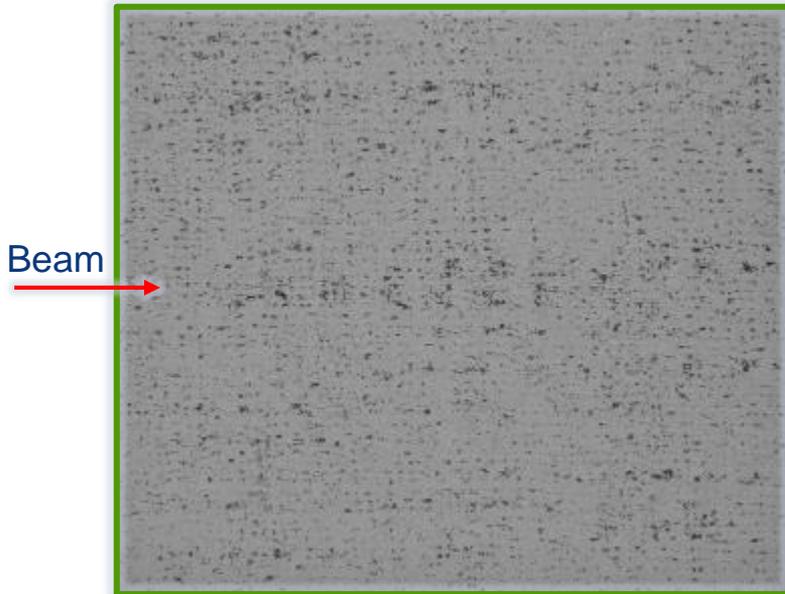
PIE on 3D CC material (HRMT28)

According to the simulations the peak energy deposition is between 50 mm and 250 mm starting from the beginning of the jaw.

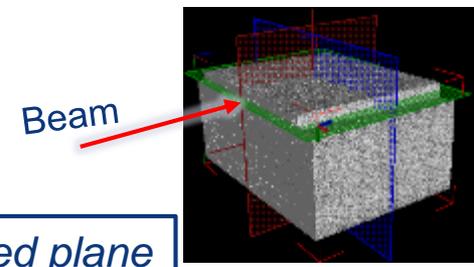


Before impact green plane

After impact green plane

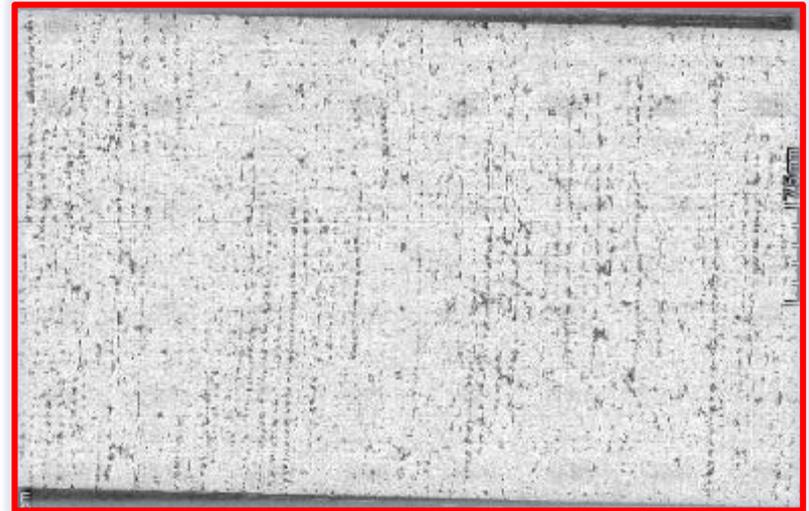
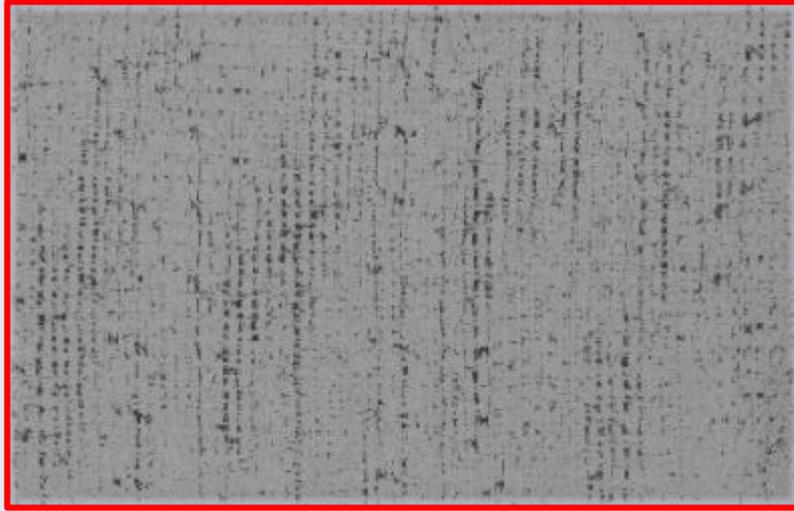


PIE on 3D CC material (HRMT28)



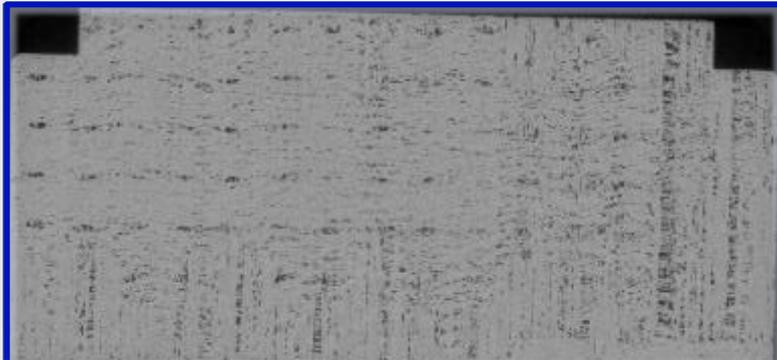
Before impact red plane

After impact red plane



Before impact blue plane

After impact blue plane



Sepcarb® 3DCC from Ariane Group:

After 9 high intensity shots at 216/288 bunches

No surface beam induced damages neither remarkable flatness nor shape differences!

HRMT45 TDIS-TZM

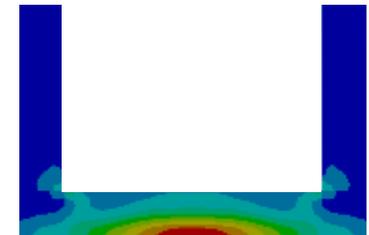
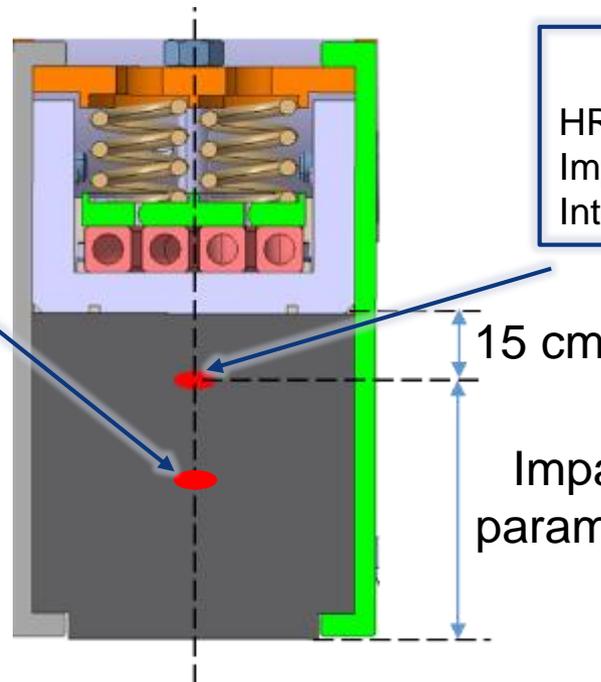
To reproduce a state of temperature/stresses in the back-stiffener comparable to that induced by the worst-case potential impact of the HL-LHC beam:

LHC failure scenario (worst-case)

HL-LHC 320b beam
 Impact parameter: 38 mm
 Intensity: $2.3E11$ ppb (320 bunches)

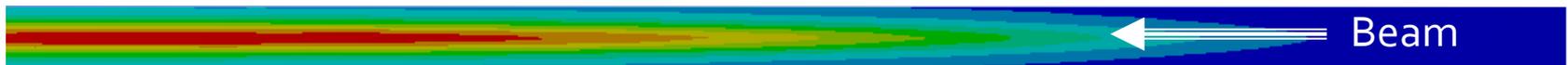
HRMT scenario

HRMT beam
 Impact parameter: 52 mm
 Intensity: $1.2E11$ ppb (288 bunches)



HRMT settings

Max. temp: 235 °C
 Max. stress: 460 MPa
 (Static tensile strength \approx 525 MPa)

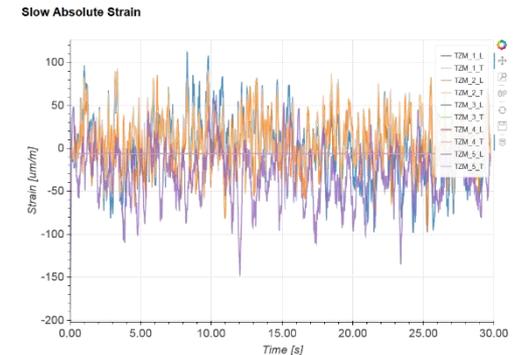
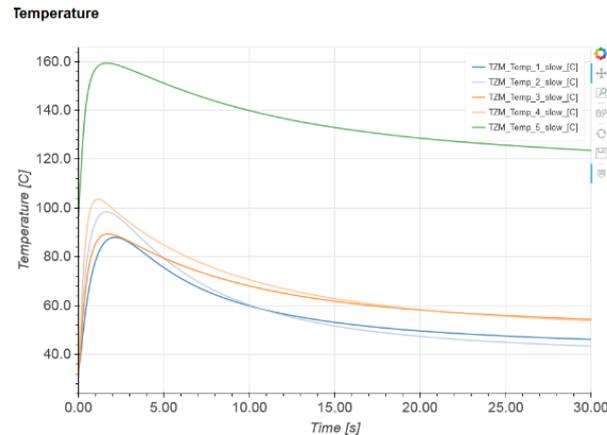


HRMT45 TDIS-TZM

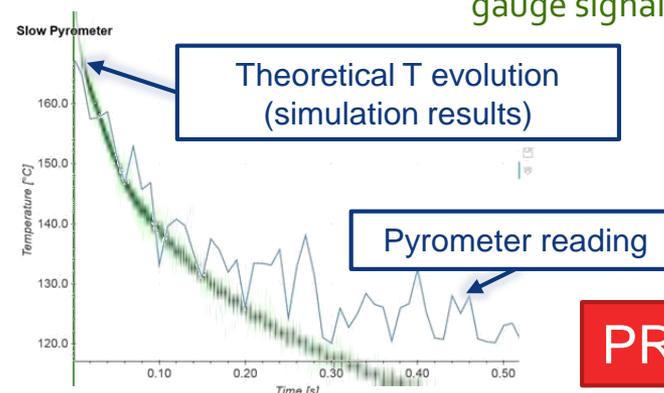
- The experiment took place **end of August 2018** successfully impacting several 288 bunches at top intensity

Back-stiffener temperature/strain measurement

- 5x PT100 probes + 5x bidirectional strain gauges positioned in contact with each back-stiffener
- Fast response pyrometer pointing to back-stiffener hottest spot:



No permanent deformation in back-stiffener inferred from strain gauge signals

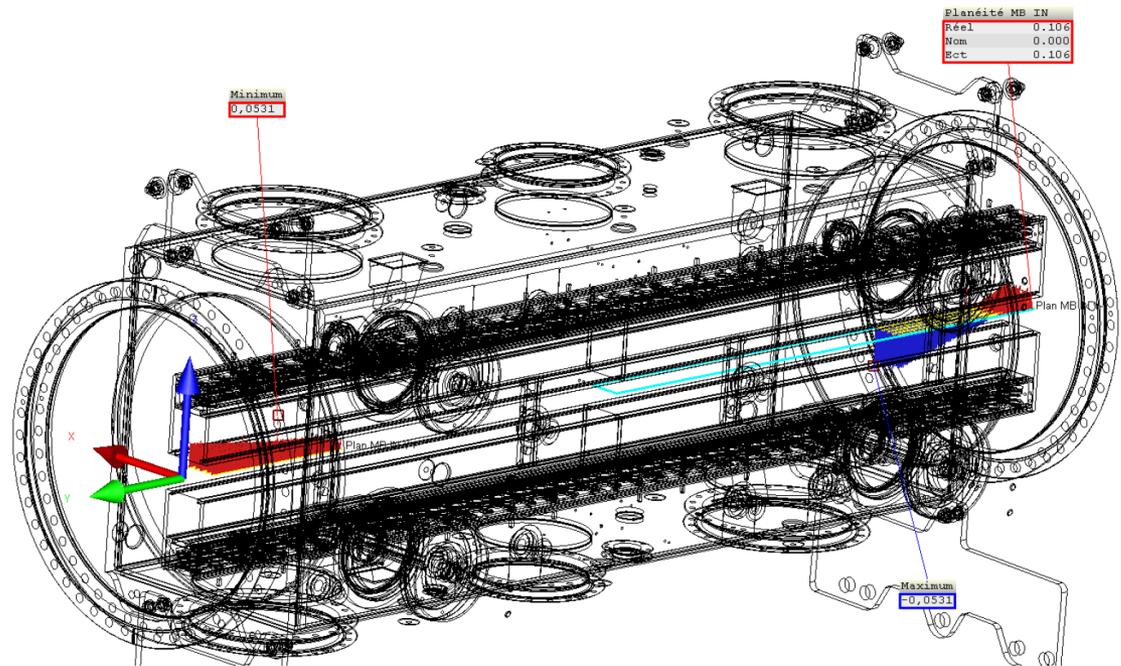
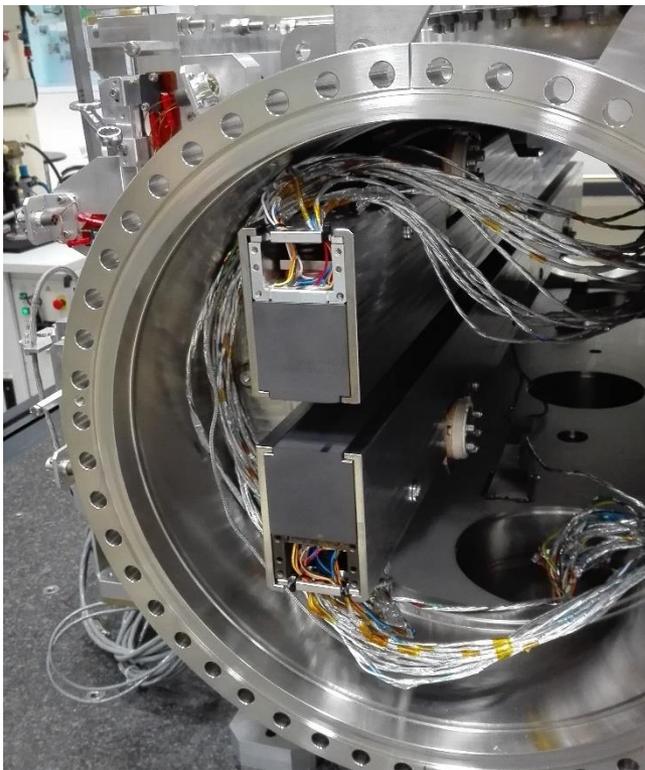


PRELIMINARY

HRMT45 TDIS-TZM

In-tank Jaw flatness control

- Only jaws extremities controlled due to limited sensor arm length entering inside the tank



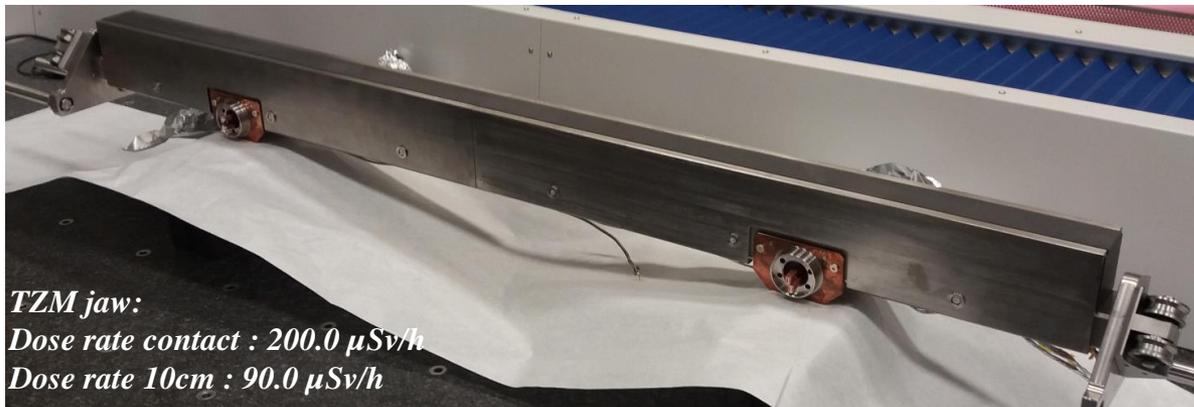
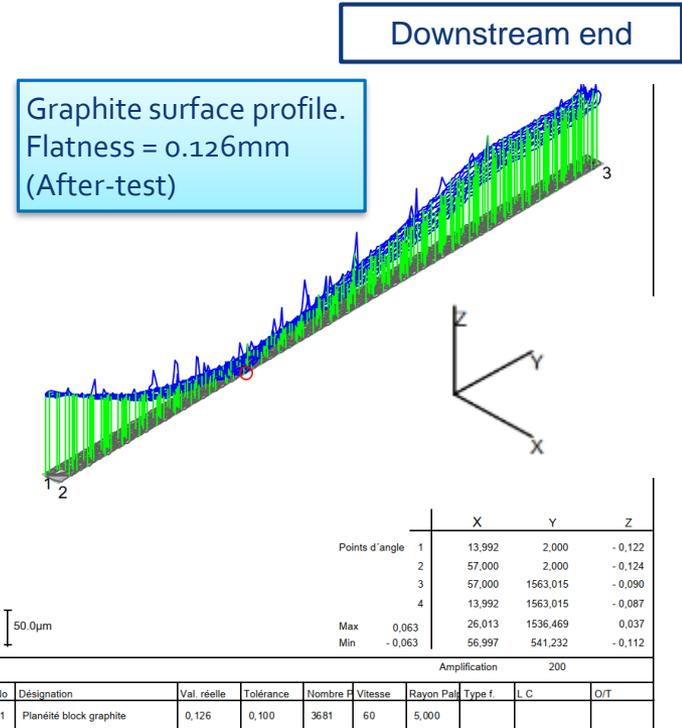
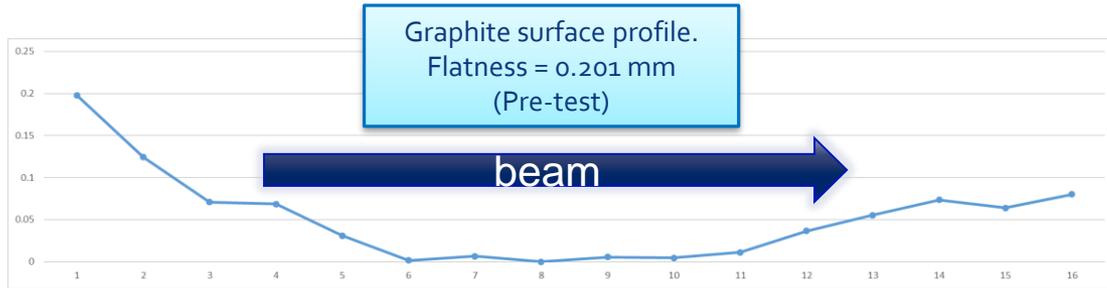
Very small jaw flatness variation observed with respect to the pre-test condition (flatness value \approx 0.1 mm)

HRMT45 TDIS-TZM

Preliminary results

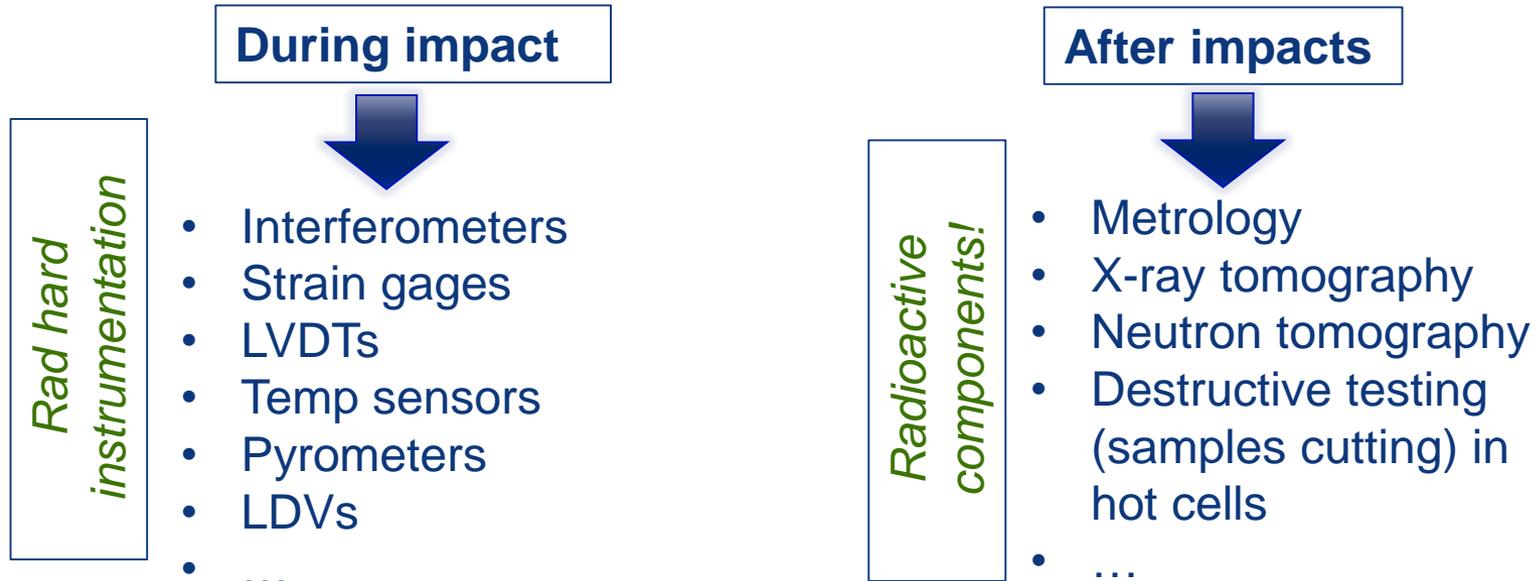
Off-tank TZM Jaw flatness control

- Similar surface profile compared to pre-test condition. Lower flatness deviation has been measured though (0.126 vs 0.201 mm). Same effect observed in upper jaw (aluminum back stiffener).



Conclusions

- Many different HiRadMat experiments performed
- Extremely useful information for accelerator operational devices
- Beam impacts on materials are analyzed:



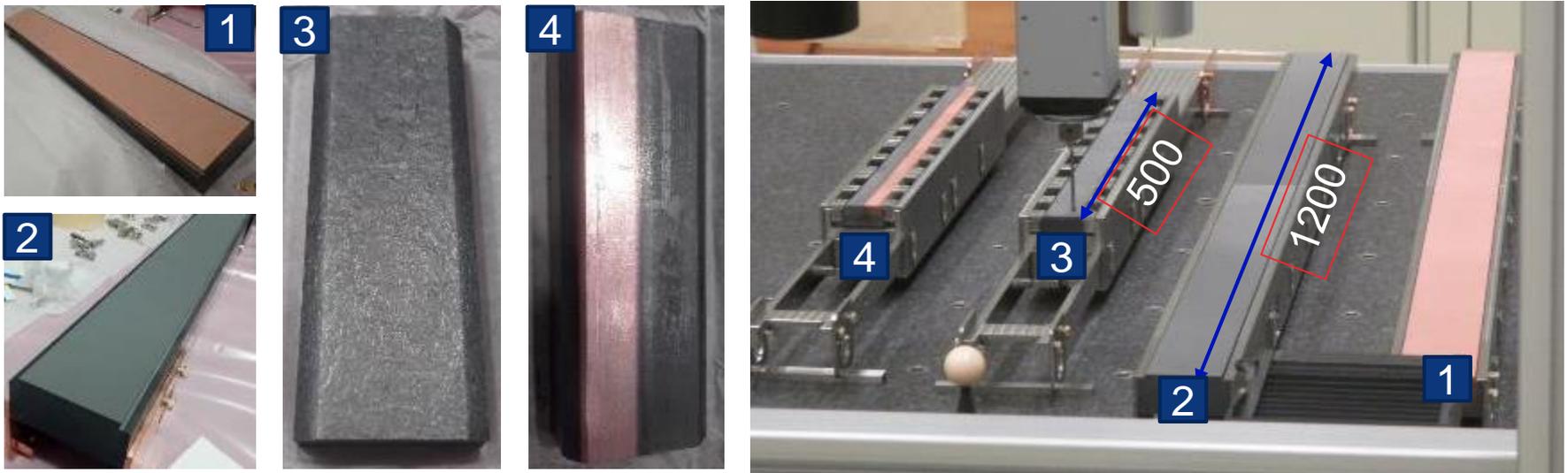
Thanks for your attention

Overview of some HiRadMat experiments applied to Beam Intercepting Devices

- HRMT28: Irradiation of low-Z carbon based materials for Beam intercepting devices
- HRMT35: Irradiation of coated low-Z absorbing materials for the Target Dump Internal (TDI) and SiC-SiC irradiation
- HRMT44: High energy beam impacts on new TCDIL (CERN collimators)
- HRMT45: High energy beam impacts on new TDIS (LHC injection absorber)
- HRMT48: Prototyping of new AD target design made of high density materials (tantalum and iridium)
- HRMT46: N-Tof
- HRMT49: Polycrystalline silicon material study in the framework of the TIDVG project

HRMT-35 TDIS-LHC Collimators coated jaws

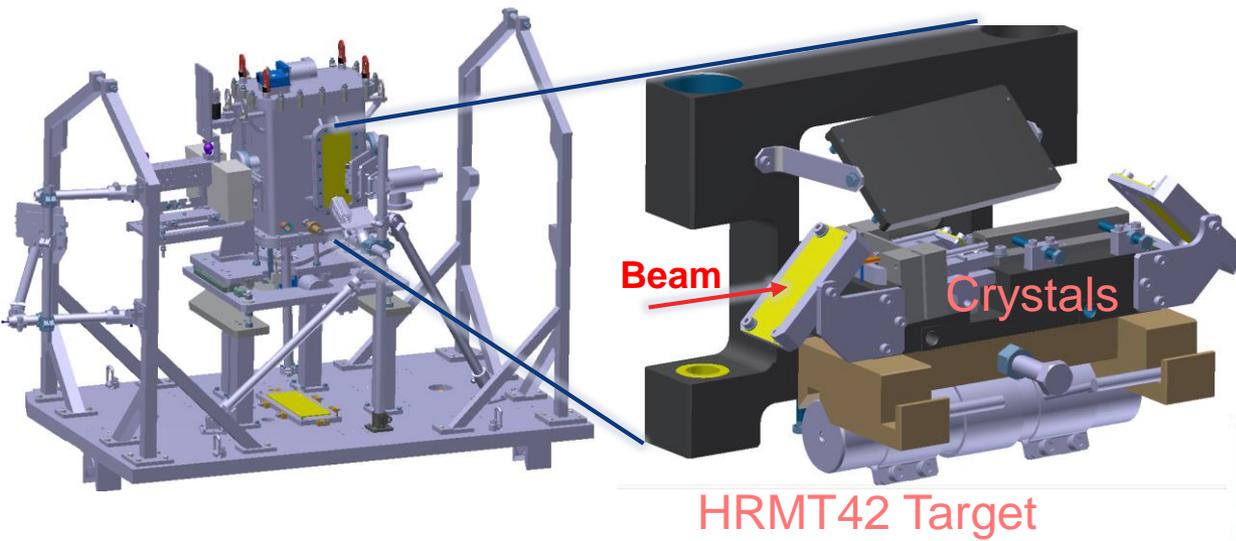
- Four different absorbing materials and coating configurations:
 1. **SGL Graphite R4550 TDI coating configuration with Cu-coating;**
 2. **SGL Graphite R4550 TDI coating configuration with Mo-coating;**
 3. *Tatsuno 2D CFC in a TCPPM/TCSPM configuration with Mo-coating;*
 4. *Molybdenum Graphite (MoGr) with Mo and Cu coating*



Courtesy: I. Lamas Garcia

HRMT18/42 Experiment

- Two experiments shared experimental setup
- Re-using experimental setup of HRMT27



HRMT42 Target

Instrumentation

- 1x RadHard Camera
- 1x HD Camera
- 1x LDV OptoMet pointing at the HRMT-42 target

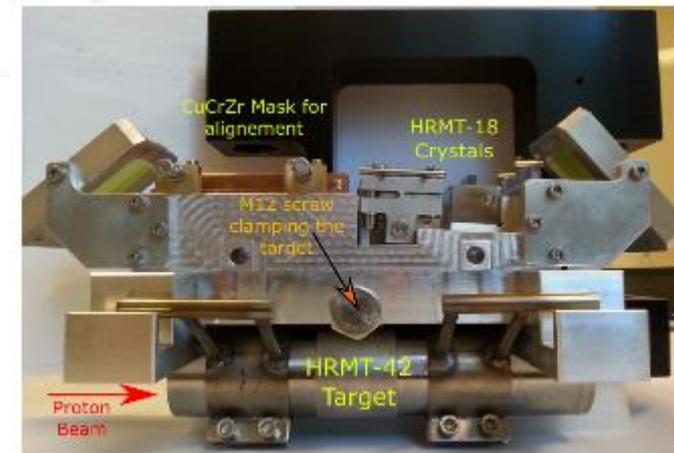
Executed during W17 2017

HRMT-18 crystal collimation

Experimental verification of Si Crystals robustness under accidental impact of LHC beam.

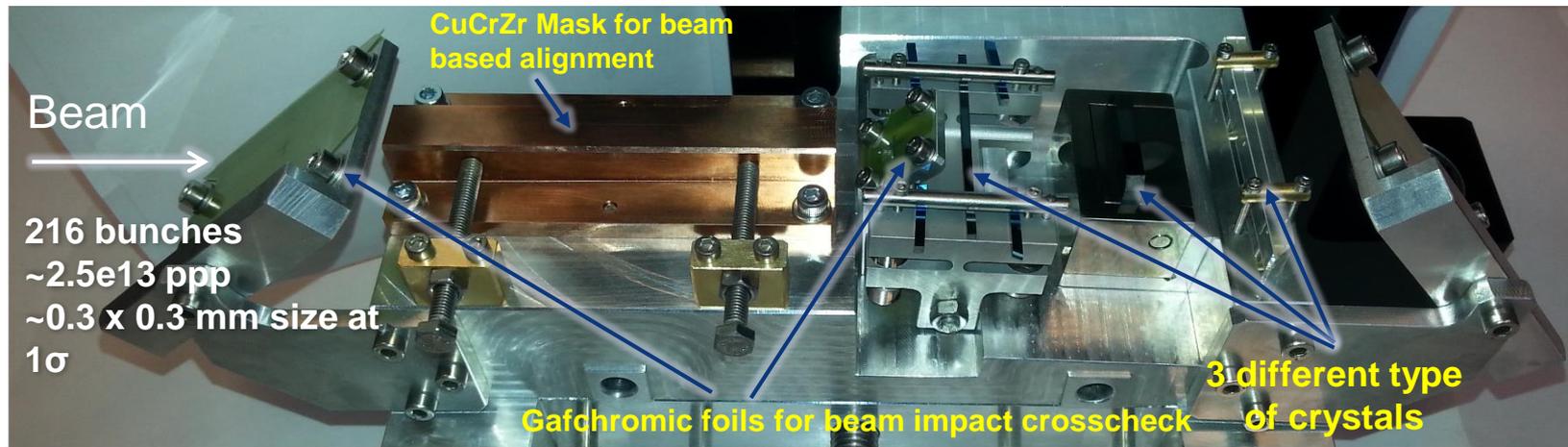
HRMT-42

Irradiating a first up-scaled prototype a proposed core and matrix for the new AD-Target design



HRMT18 setup and first PIEs

The Setup

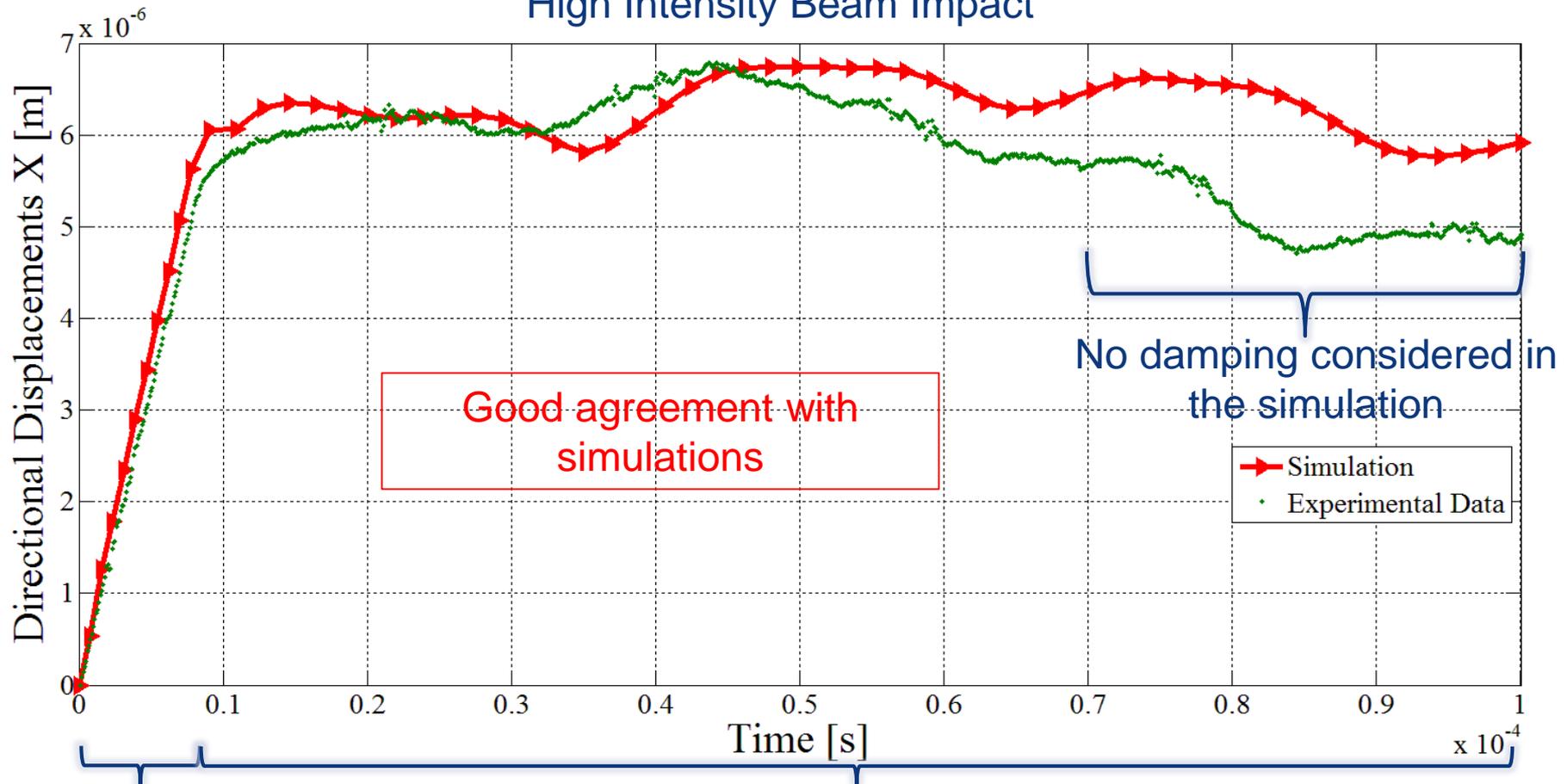


PIEs and Post Irradiation Performance Results

- The 3 crystals do not show **any macroscopic damages** after the **irradiation** (visual inspection)
- The two silicon bent crystals for LHC collimation purposes have been tested with the beam in H8 showing the **same bending angle** and the **same channeling efficiency** as before the irradiation

The High Radiation to Materials Results

High Intensity Beam Impact



Good agreement with simulations

No damping considered in the simulation

Simulation
Experimental Data

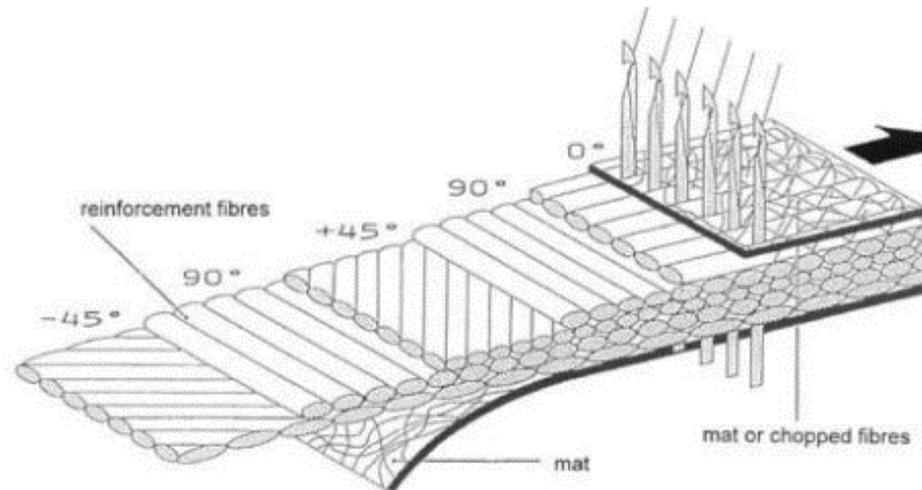
Beam pulse length

Smooth oscillations until reaching the initial state

It suggests that no damage occurred in the graphite

R&D on 3D CC for collimation applications

- 3D CC is highly orthotropic (3 main directions)
- Originally → Poly Acrylo Nitrile fibres: pre-oxidized PAN carbon precursor fibre staples are positioned atop a pre-oxidized PAN carbon precursor fabric. The preform consists of a stack of layers of this dual-layer material.
- As each layer is added, a needling head with hundreds of hook-fitted needles passes over the dual-layer material and punches the pre-oxidized PAN fibre staples through the fabric layers, transferring the staples perpendicularly and through the fabric layers, forming the third direction of reinforcement.
- Now, ASL is also producing 3D CC with standard carbon fibre grades.
- The link between fibres is then done via Chemical Vapor Infiltration, which is allowing getting the final requested density (1.8 g/cc for CERN).



R&D on 3D CC for collimation applications

- Available pre-characterisation :

Tensile strength, strain at failure, and Young's modulus, from room temperature to 2750°C, tested according to EN-658-1;

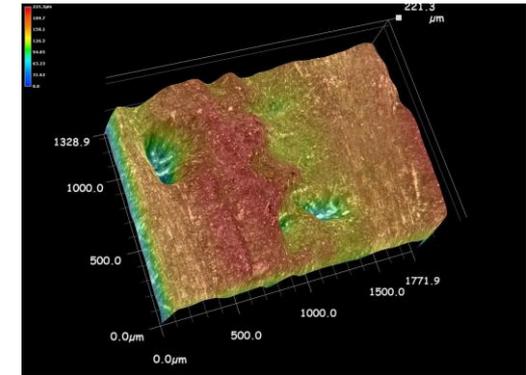
Compression strength, from room temperature to 2750°C, tested according to EN-658-2;

+ shear measurements, diffusivity and dilatation measurements over a wide range of temperature, as well as UHV characterisation...

→Very good machining ability



- Microscopy gives good results
- X-rays not adapted
- Ultrasonics gives incoherent results
- Microtomography is a success



Courtesy: TE-VSC

Material	Outgassing rate bakeout [mbarl/s]	RGA Baked	Outgassing rate Unbaked [mbarl/s]	RGA Unbaked	
				< 50 amu	> 50 amu
3d CC Heracles	2.5·10 ⁻⁸ ✓	✓	1.35·10 ⁻⁵ ✗	✗	✓
Graphite Mersen	2.0·10 ⁻⁸ ✓	✓	6.0·10 ⁻⁶ ✓	✓	✓
3d CC Mersen	8.0·10 ⁻⁸ ✗	✓	2.0·10 ⁻⁵ ✗	✓	✓
Graphite SGL	3.8·10 ⁻⁹ ✓	✗	1.7·10 ⁻⁶ ✓	✓	✗

Next objective:
High strain rate testing at
high temperature !