Low-Z material R&D application for Beam Intercepting Devices (BID) at CERN

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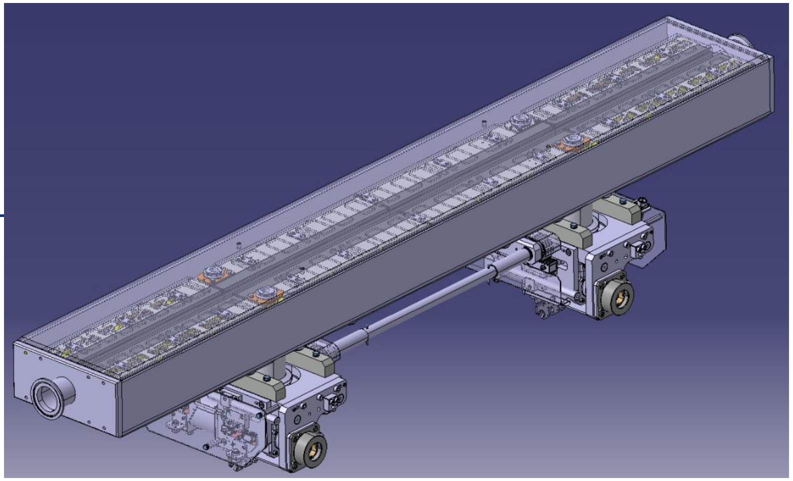
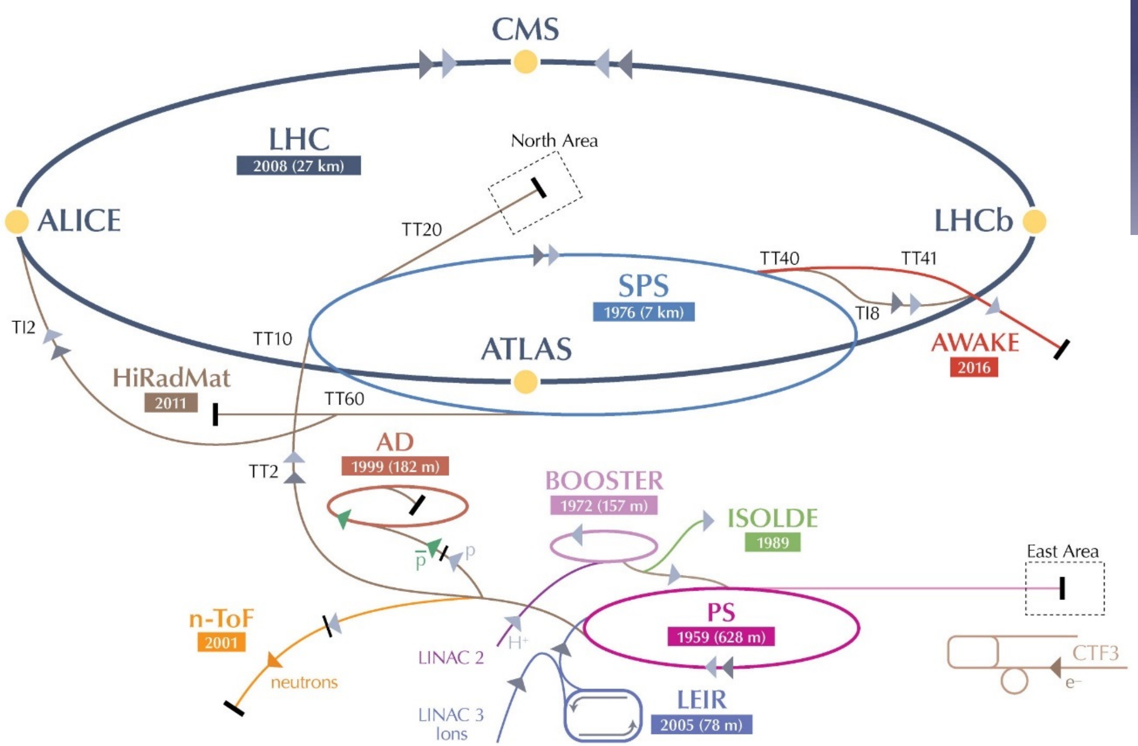
Outlines

- CERN TCDI collimators introduction
- Fast thermal shocks conditions
- Studied Low-Z materials
- Thermo-mechanical simulations description and output
- The High Radiation to Materials (HRM) experiment applied to low-Z materials: description and output
- Material analysis (Micro-tomography, machining, metrology, US measurements…)
- Perspectives for future studies (HRM Phase II)

The TCDI collimators





- 12 passive protection devices: clean the beam halo and dilute beam in case of wrong trajectory
- 2.1m long jaws with a flatness of 0.2mm
- Isostatic graphite / 3D CC material

Principle of collimation

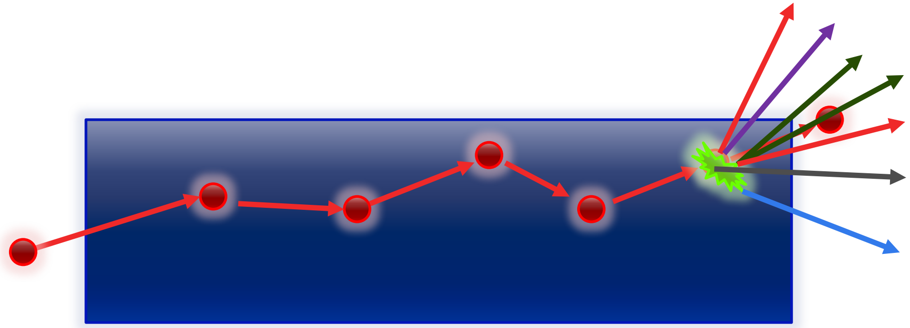
Collimator jaws have to intercept the halo particles before they are lost at the mechanical aperture.

A particle interacting with the collimator material atoms can undergo:

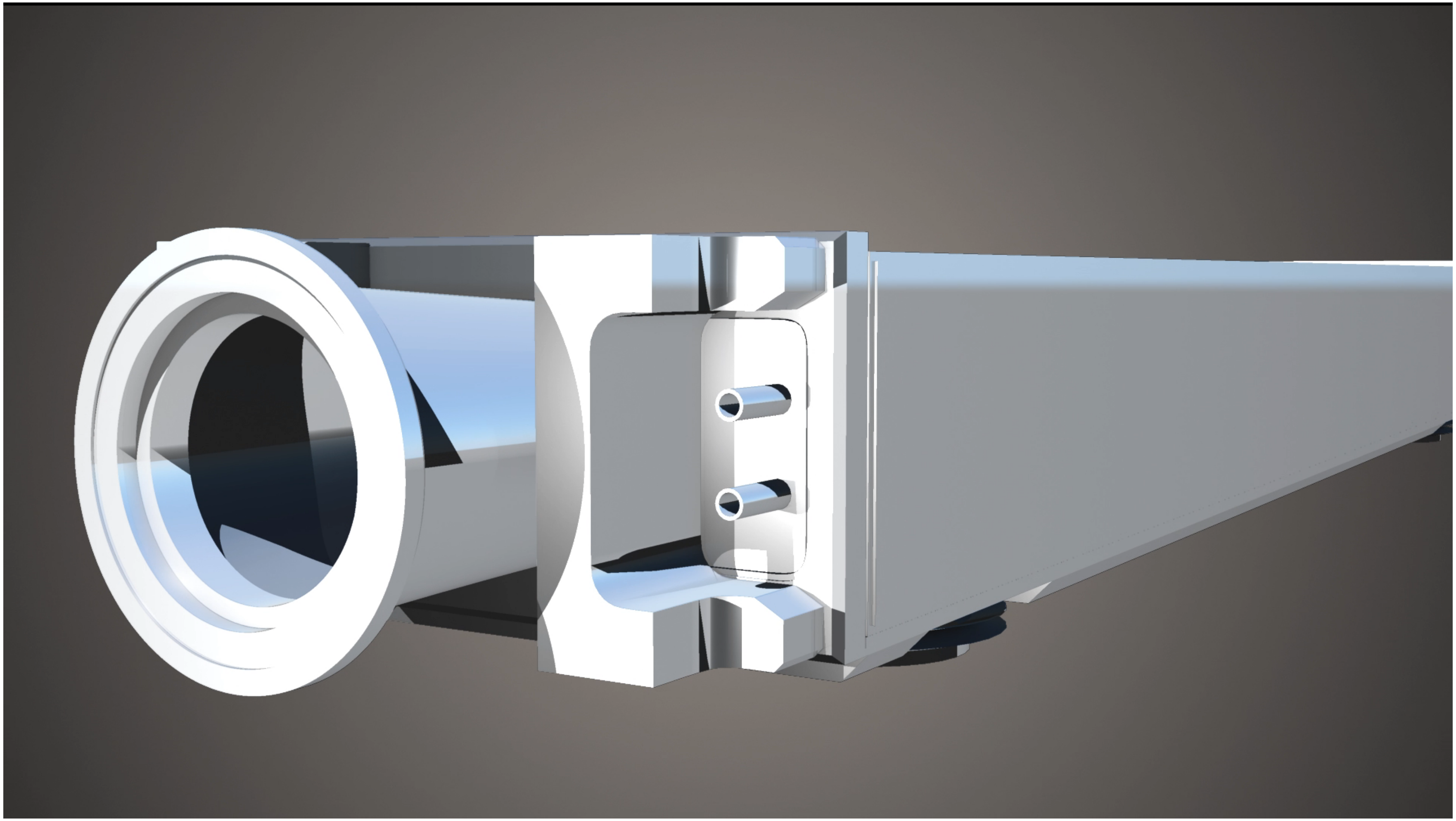
1) Elastic scattering

2) Inelastic scattering

3) Other processes (Single diffractive scattering, ionization, excitation…)



CERN Collimators operation: video

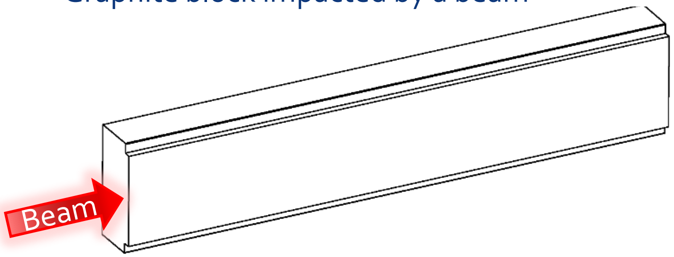


Fast thermal shock conditions

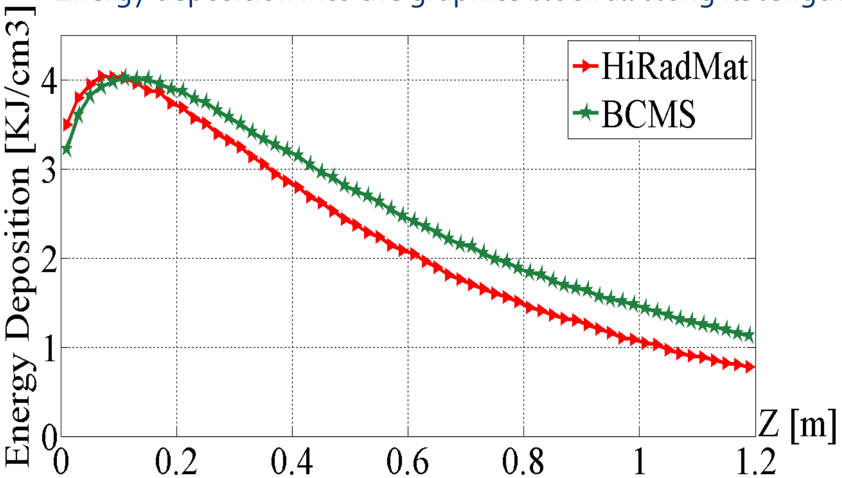
- Beam impacts generate thermo-mechanical stresses
- The developments done so far are applied to the SPS to LHC transfer lines collimators
- The **objective** is to find a material able to withstand the corresponding beam impact

	HiRadMat	HL-LHC Beam (Run 3 BCMS)
N. of Protons per pulse	3.45×10^{13}	5.76×10^{13}
Pulse duration [µs]	7.8	7.8
Sigma X [µm]	313	320
Sigma Y [µm]	313	511
Peak per primary [GeV. cm^{-3}.prim^{-1}]	0.66	0.44

Graphite block impacted by a beam



Energy deposition into the graphite block all along its length



Selection of a suitable material

- The governing factor is the density of the material :~1.8 g/cc

High density → High temperature gradient → High stresses

- A material with an high shock resistance [1] is mandatory:

$$R_T = \frac{K\sigma_T(1-\upsilon)}{\alpha E}$$

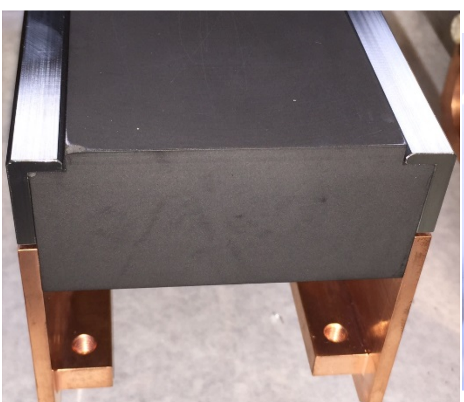
- K is the thermal conductivity [W.m-1.˚C-1];
- σ_T is the tensile limit [MPa];
- α is the coefficient of thermal expansion [˚C-1];
- υ is the Poisson's ratio;
- E is the Young's modulus [MPa].

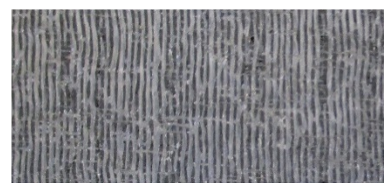
- Other requirements:

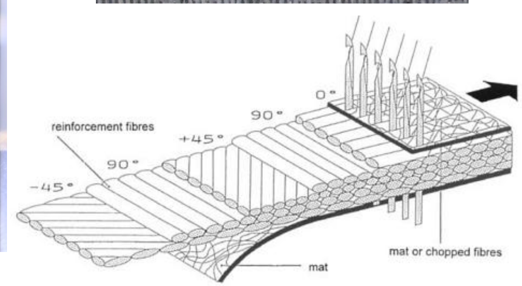
→Easily machinable
→Good radiation hardness properties
→Able to support temperatures up to minimum 1500°C
→Compatible with UHV
→Available on the market

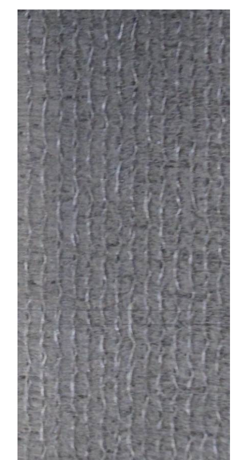
Recently studied low-Z materials

	Isostatic graphite		3D CC	
	Sigrafine® R4550 *	2123 PT	Sepcarb®	A412
Density [g/cm³]	1.83	1.84	>1.80	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 (dynamic)	11.4	Non-Disclosure Agreement	15
Tensile Strength [MPa]	40	35	Different in the 3 directions ~100 (Sepcarb®), 60 (A412)	
MST [°C]	>2600	2760	2700	-









* Extensively used at CERN

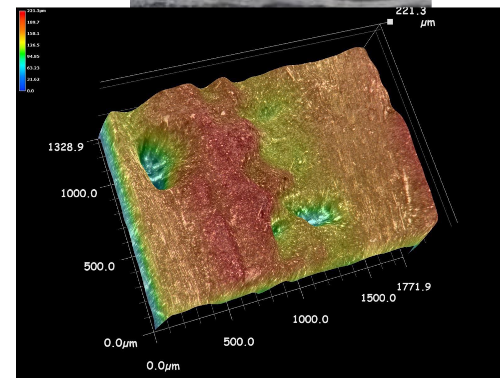
Recently studied low-Z 3D CC

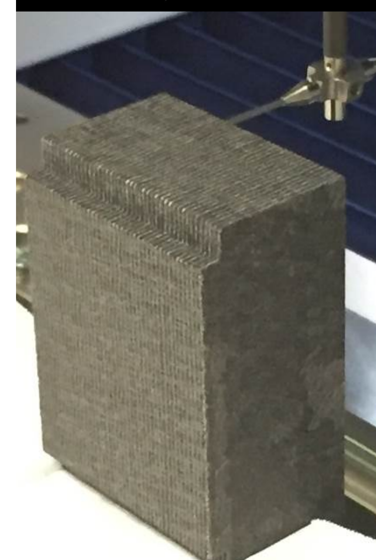
- Sepcarb® 3D CC
- Produced via the CVI process, allowing good mechanical properties up to ~2700ºC
- Material pre-characterisation at CERN:

CTE and specific heat (ASTM E228 and E1269);
Thermal conductivity (LFA: ASTMC714);
Compressive strength (ASTMC695-91), tensile strength (EN658-1);
Impact Excitation Testing to get the Young's modulus (ASTMC1259);

- Qualification for UHV:

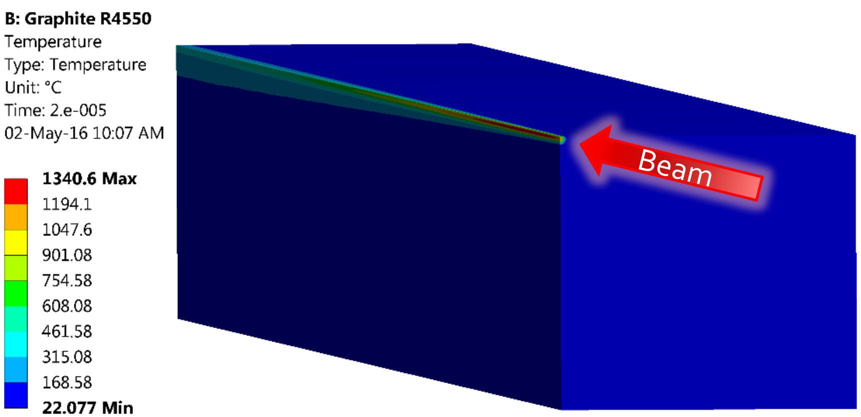
Outgassing: $2.5\ 10^{-8}$ mbar.l.s^{-1} for one collimator.
RGA after bakeout.



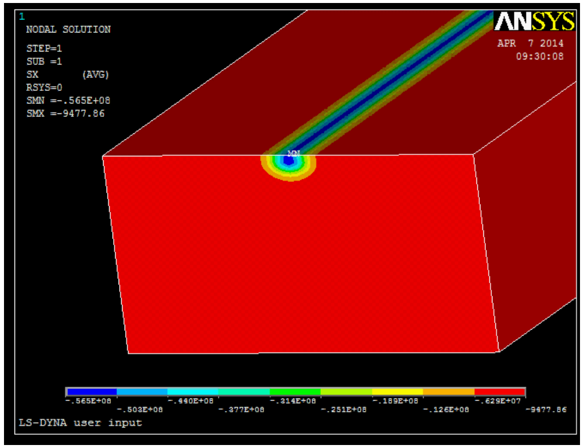


Thermo-mechanical simulations

Temperature gradient due to beam energy deposition



Pressure waves travelling inside the material



Mohr-Coulomb safety factor used for graphite:

$$F_s = \left[\frac{\sigma_1}{\sigma_{Tensile\ \ limit}} + \frac{\sigma_3}{\sigma_{compressive\ \ limit}}\right]^{-1}$$

Mohr-Coulomb Stress Safety tool evaluates maximum and minimum principal stresses at the same locations. Shall be higher than 1 for material survival

Max-Min principal stresses safety factor for both materials:

$$F_{s,t} = \left[\frac{\sigma_{Tensile\ \ limit}}{\sigma_1}\right]$$

$$F_{s,c} = \left[\frac{\sigma_{Compressive\ \ limit}}{\sigma_3}\right]$$

[2]

Shall be higher than 1 for material survival

Thermo-mechanical simulations

	GRAPHITE Sigrafine® R4550	3D C/C Sepcarb®
Max. temperature [˚C]	1348	1280
Max. Principal Stress/ Tensile Strength [MPa]	40.1/40 Is there failure?	SF1: 55 SF2: 5.9 SF3: 8.6
Min. Principal Stress/Compressive Strength [MPa]	-80/-118	SF1: 9.8 SF2: 7.3 SF3: 1.7
Mohr-Coulomb Safety Factor	0.72 (considering a strength of 30MPa)	-

→ Doubts concerning graphite ability to withstand the beam impact

→ Confidence in the 3D CC Sepcarb® to survive the beam impact

The High Radiation to Materials experiment n°28

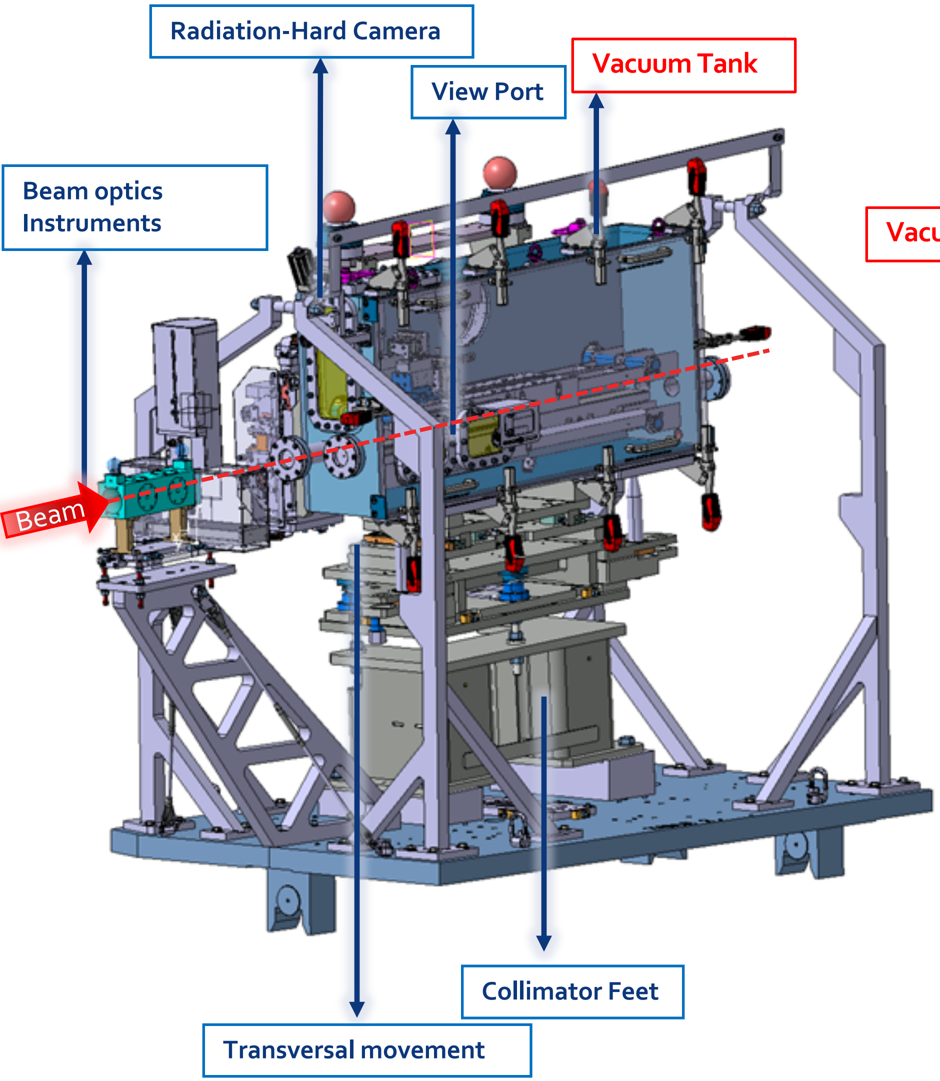
HiRadMat
High-Radiation to Materials

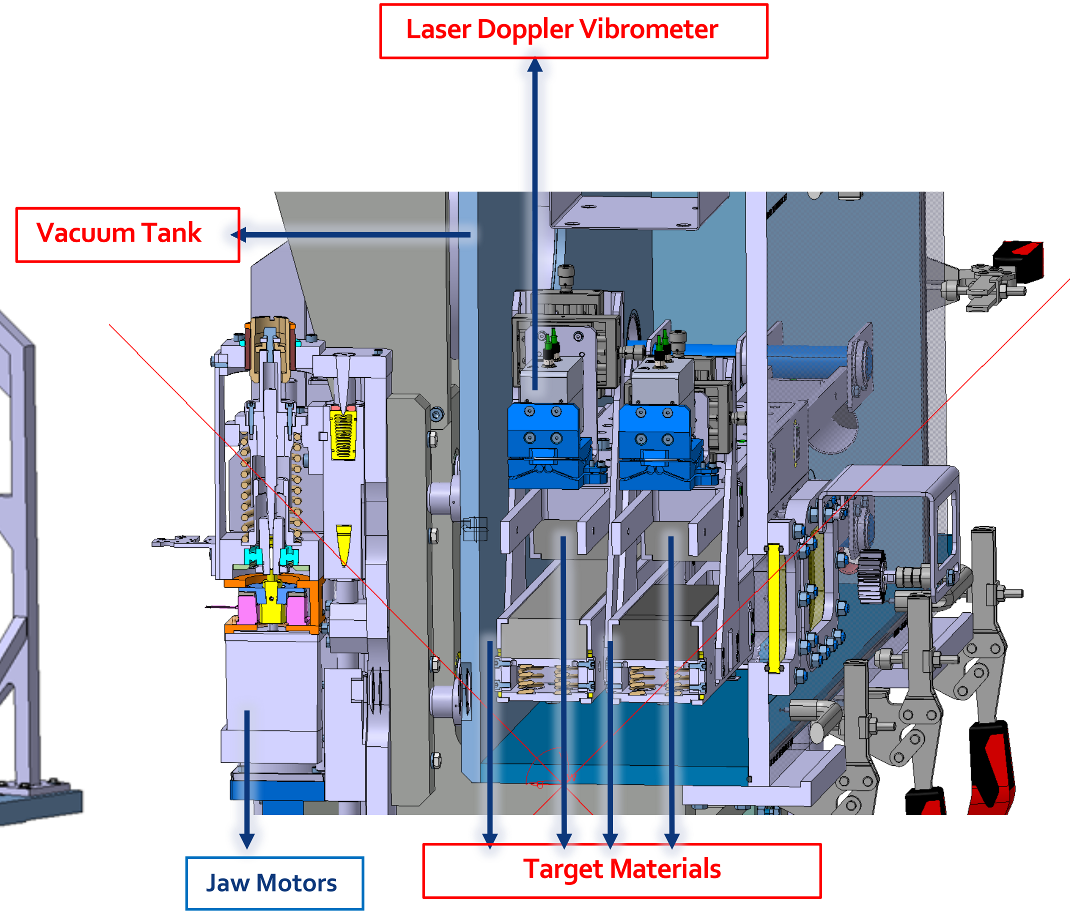
With the transfer lines collimator project the main objectives where to perform:

→Material qualification against beam

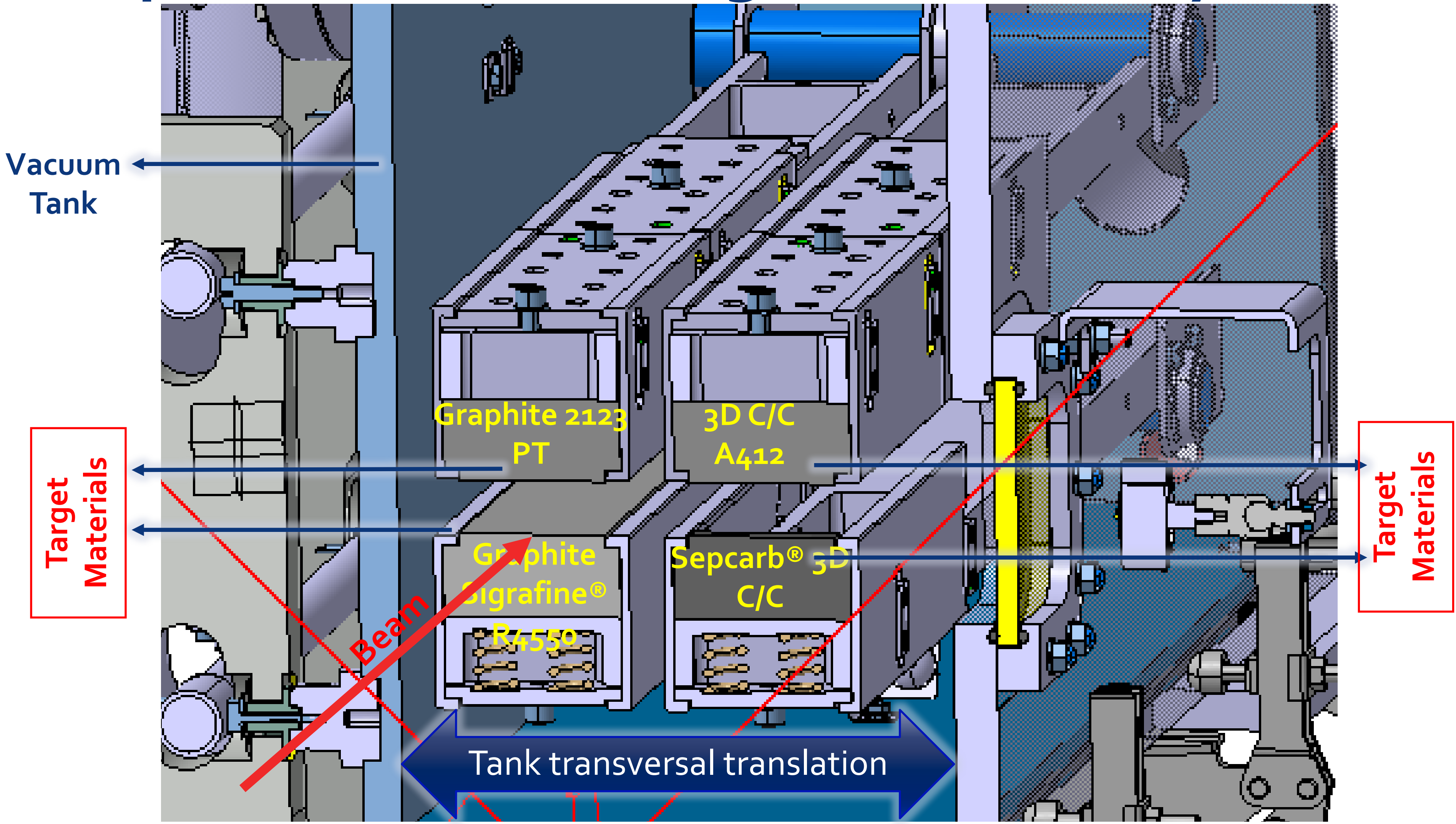
→Simulations cross-check

The High Radiation to Materials experiment n°28: Overview





The High Radiation to Materials experiment n°28: target material layout



The High Radiation to Materials experiment nº28: Pre-irradiation analysis

It is needed to know well the target "state" and "shape" before impact in order to be able to quantify the possible damages involved by the beam impacts:

- Ultrasounds measurements on graphite (CERN):

Detectable defects: 1mm on a 25mm thickness, 2mm on a 50mm thickness.

- Microscopy inspection (CERN):

Detectable surface defects: 10µm to 50µm.

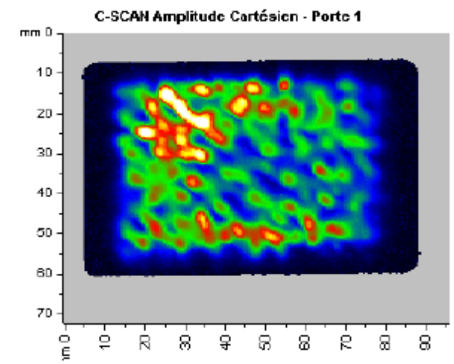
- Metrology (CERN):

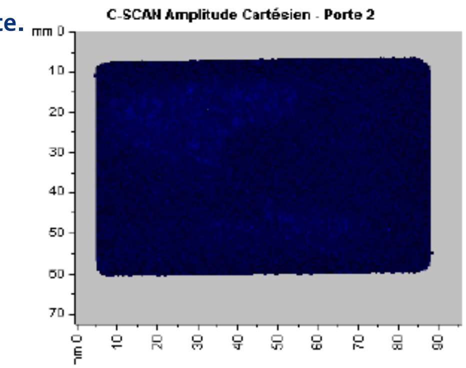
Detectable surface defects: 1µm to 50µm.

- Micro-tomography inspection (ESRF, Grenoble, FR):

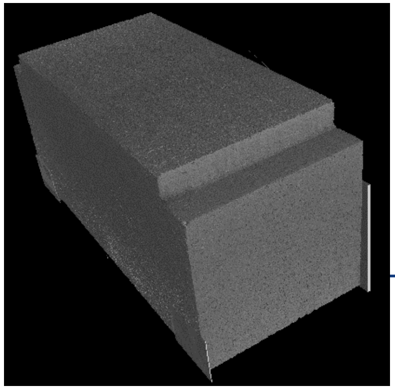
Full 3D scanning of the part.
Detectable defects: about 2×23µm inside the block (Only for 3D C/C).

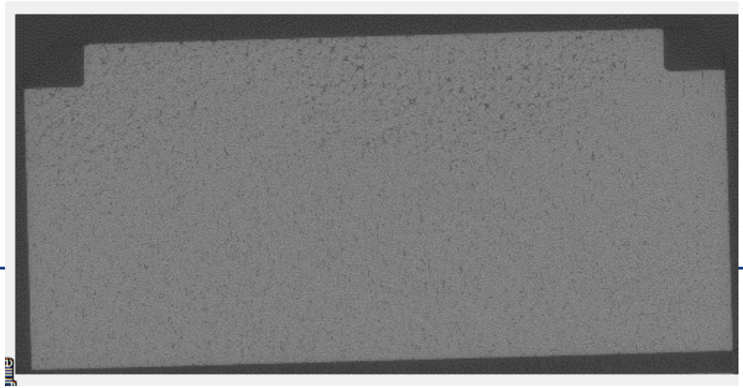
Microscopy Inspection on Graphite.



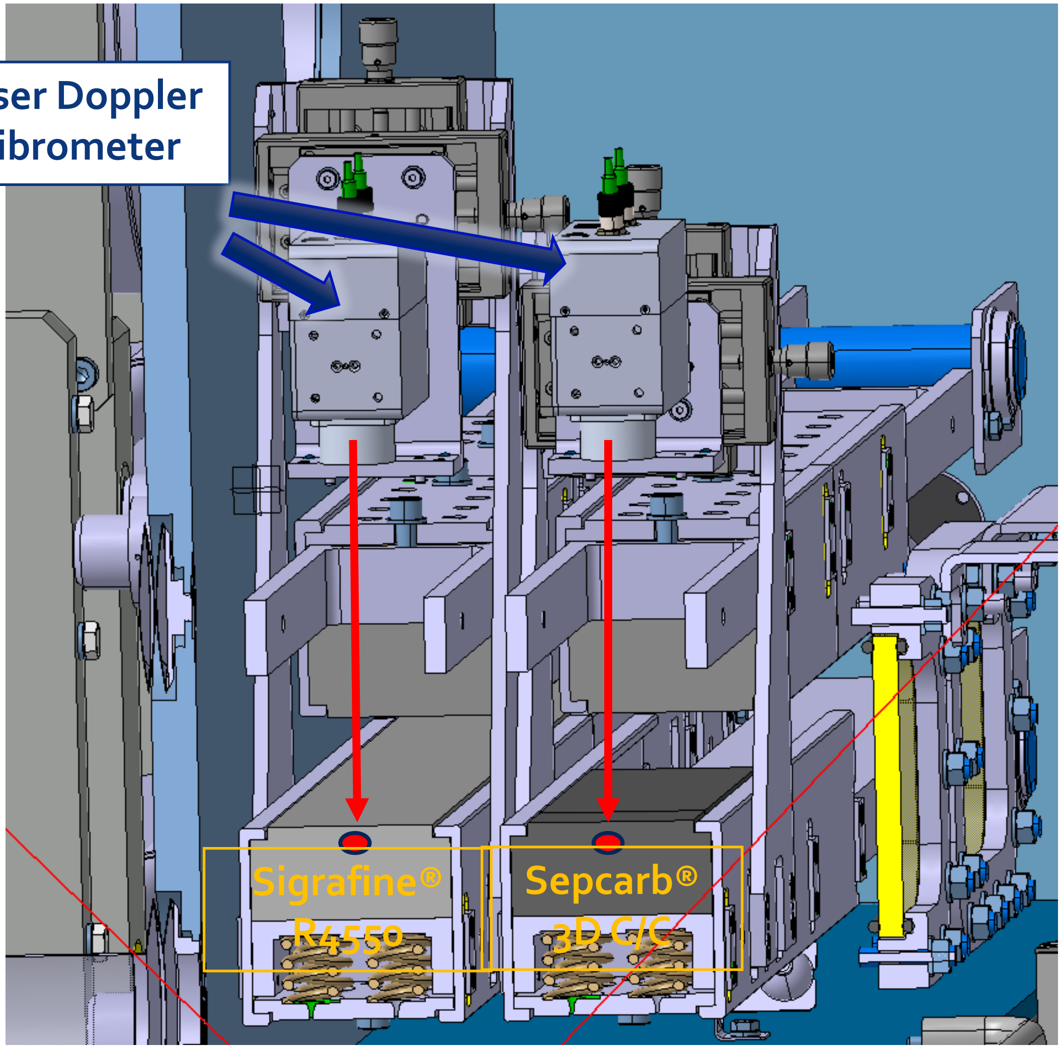


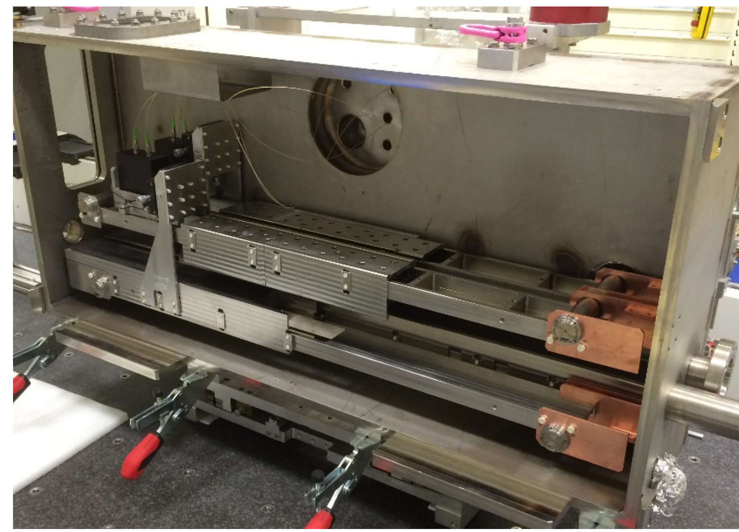
Difference in the intensity of the ultrasound crossing the block. Inhomogeneous material, due to:
- Micro porosity,
- Micro defects smaller than the resolution,
- Grain size.



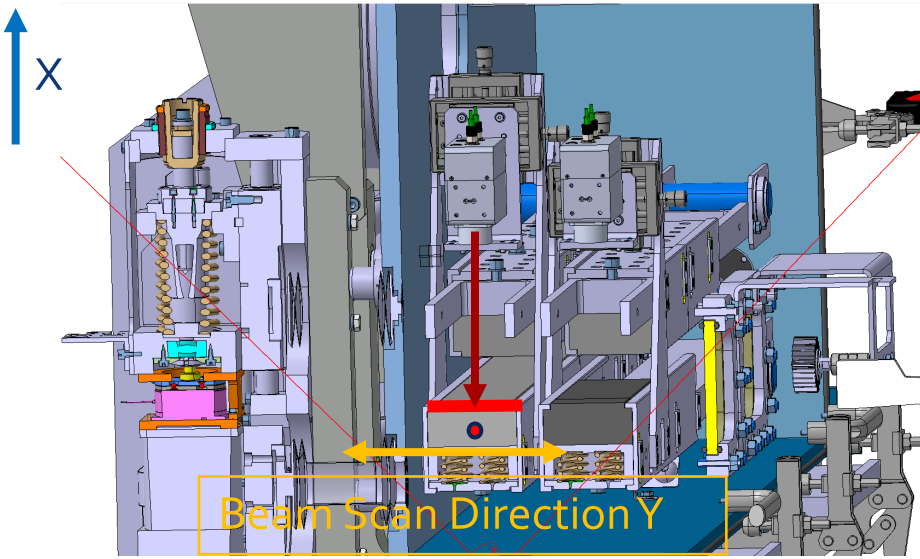


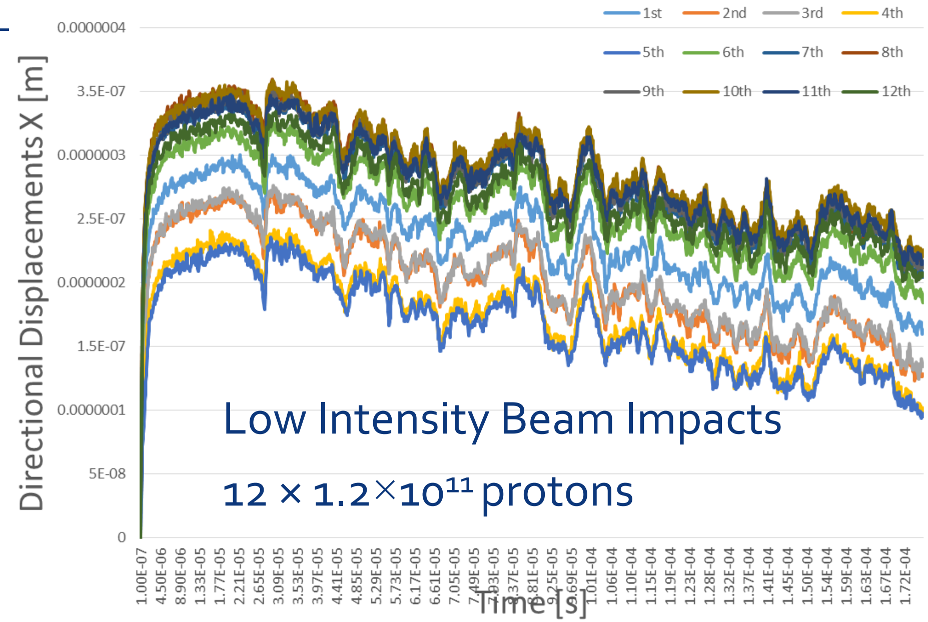
The High Radiation to Materials experiment n°28: online instrumentation

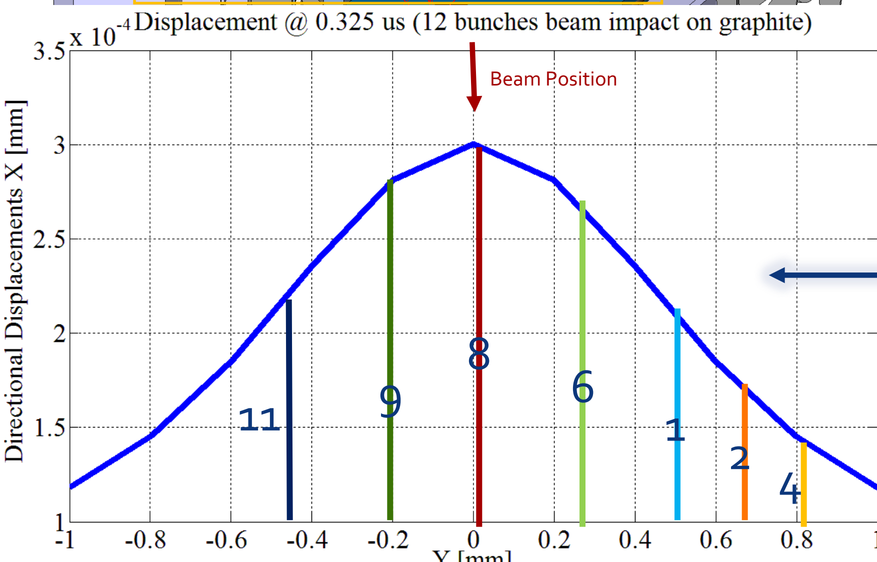




The HRM nº28: Instrumentation alignment







A beam scan was performed to align the LDV with the beam

The HRM n°28: impacts done so far

- Three high intensity beam impacts on the graphite Sigrafine® R4550

  → $3 \times 288 \times 1.2 \times 10^{11}$ protons

- Two high intensity beam impacts on the graphite 2123PT

  → $2 \times 288 \times 1.2 \times 10^{11}$ protons

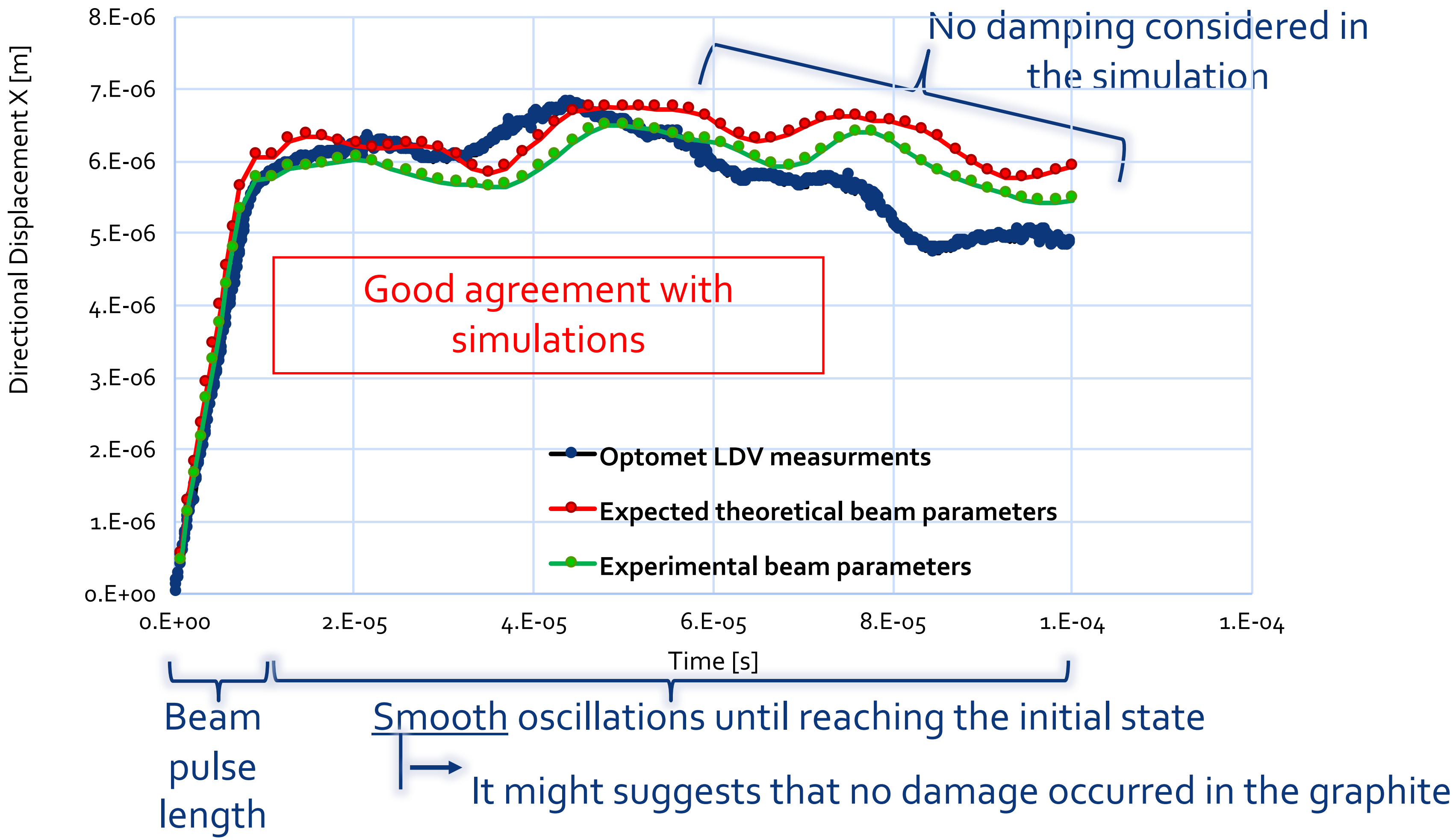
- All the blocks were impacted at 1.5 sigma distance (impact parameter) below the block surface as it is the impact parameter which is expecting generating the highest stress levels in the material [4].

	Beam parameters	Simulation results Max temperature in the graphite
HRM28 experimental beam parameters	σx =400µm, σy =350µm, 288 bunches, 1.24×10^{11}ppb	1097°C
HRM28 expected theoretical beam parameters	σx =313µm, σy =313µm, 288 bunches, 1.20×10^{11}ppb	1348°C

- High intensity beam impacts on 3D CC planned for spring 2017

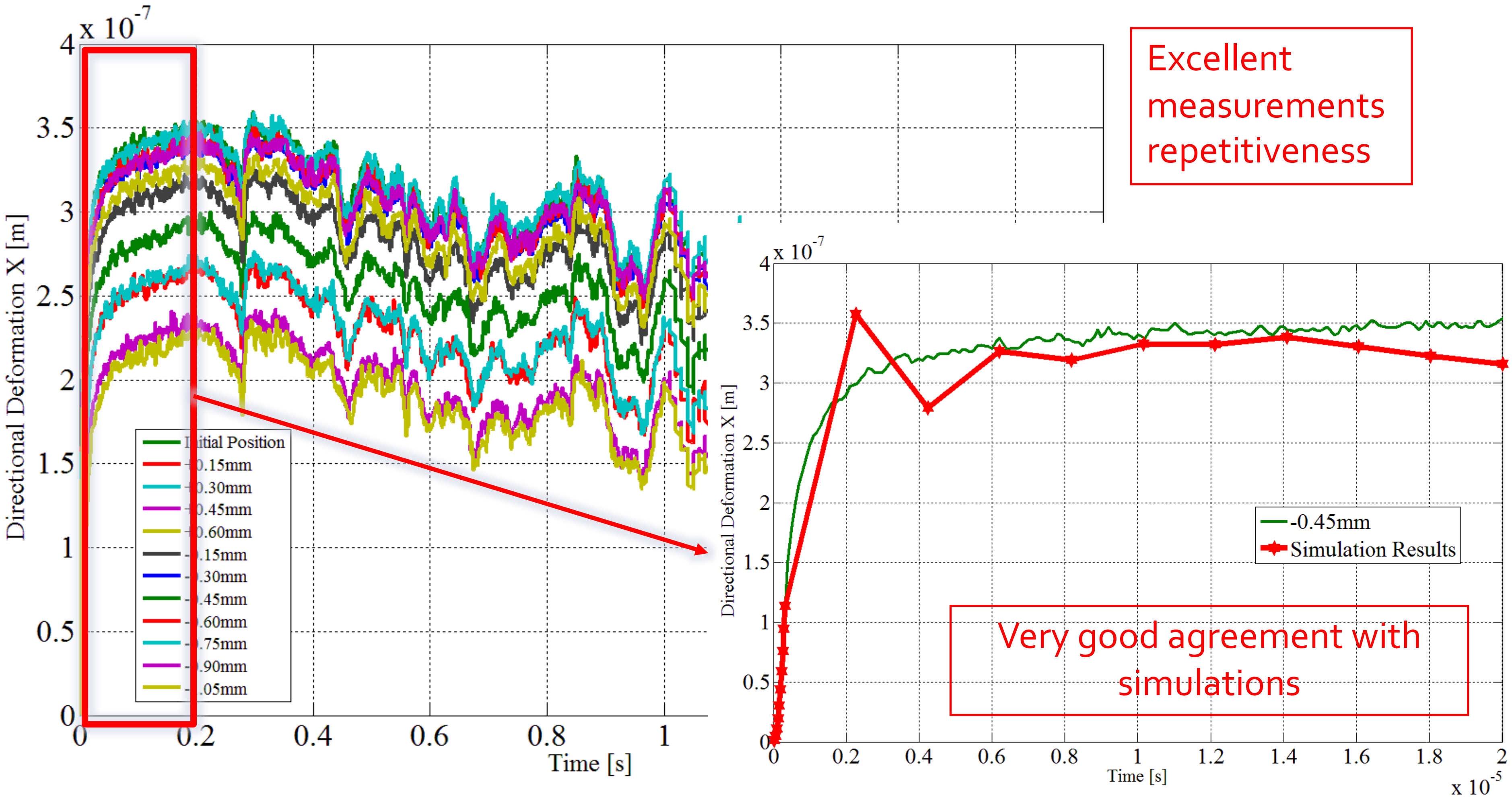
The HRM n°28: results

Graphite surface displacement over time during and after an high intensity beam impact (288 × 1.2×10[11] protons)



The HRM nº28: results

Graphite surface displacement over time after an low intensity beam impact (12 × 1.2×10[11] protons)

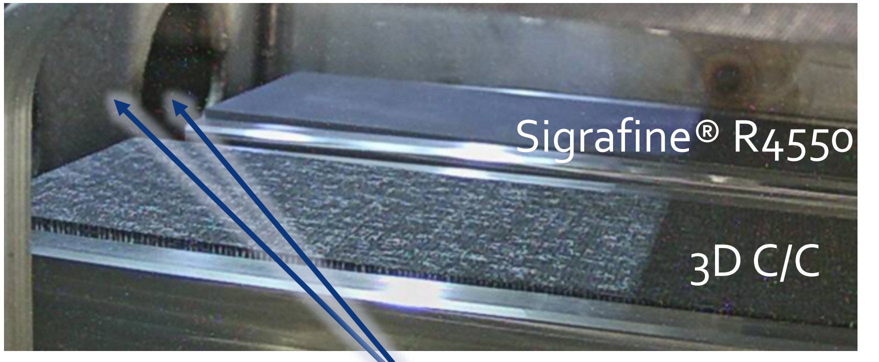


Excellent measurements repetitiveness

The HRM nº28: results

Before beam impact

After two beam impacts

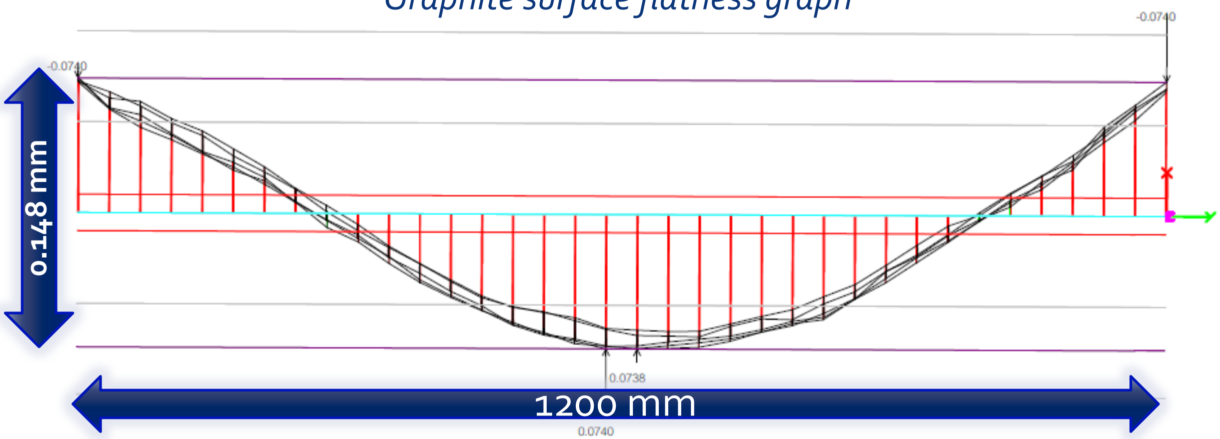


HD camera pixels died

- No visual damage on the graphite after three high intensity impacts (288 × 1.2×10^{11} protons)
- The tensile limit of the graphite is higher with dynamic loads (strain rate: 5×10^{2} s^{-1}) than with static ones (strain rate: 0.5×10^{-4} s^{-1}) [3]

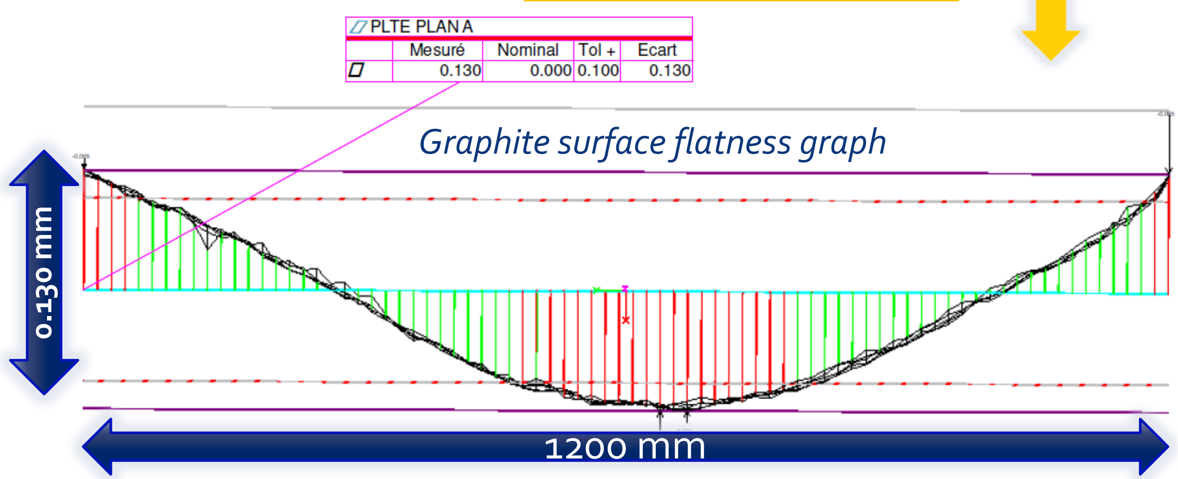
Metrology on Sigrafine® R4550

Graphite surface flatness graph



Before impact

After three impacts



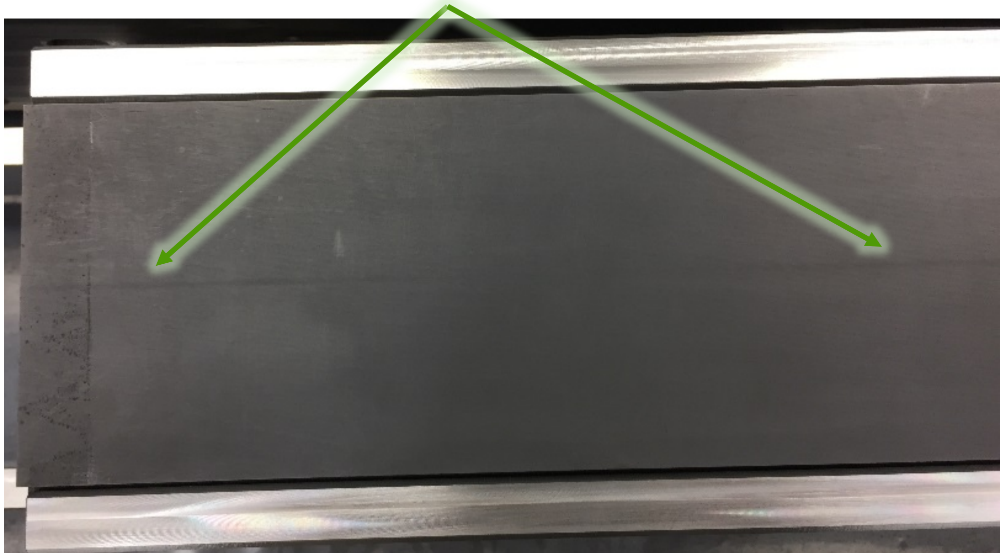
Graphite surface flatness graph

No influence on the graphite global shape

Results for graphite 2123PT

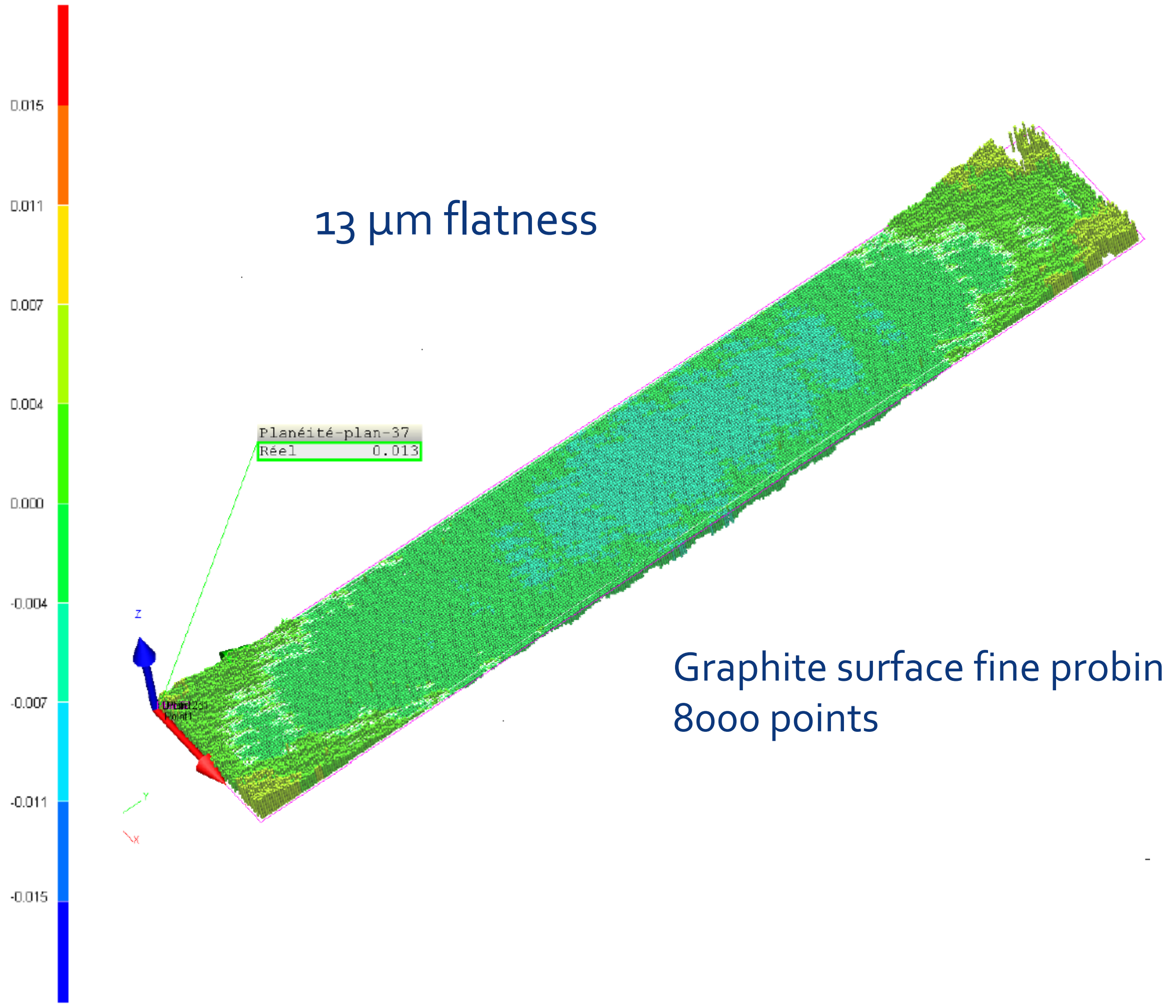
Graphite surface before impact

Graphite surface after impact, presence of a “strip”



Metrology on graphite 2123PT before impact

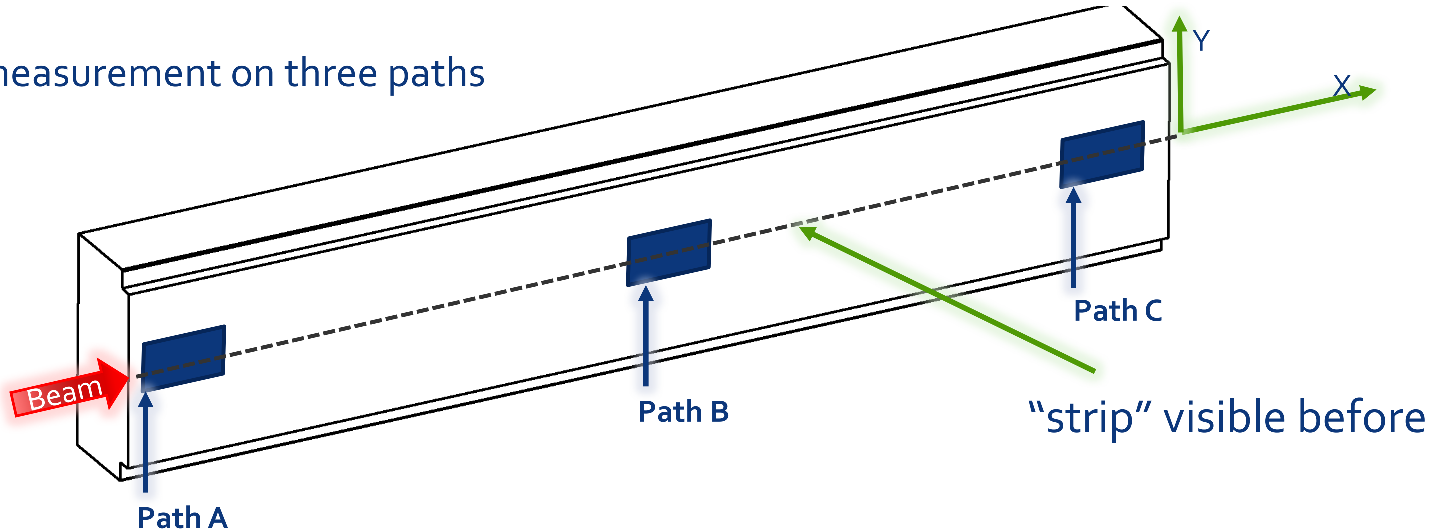
13 µm flatness

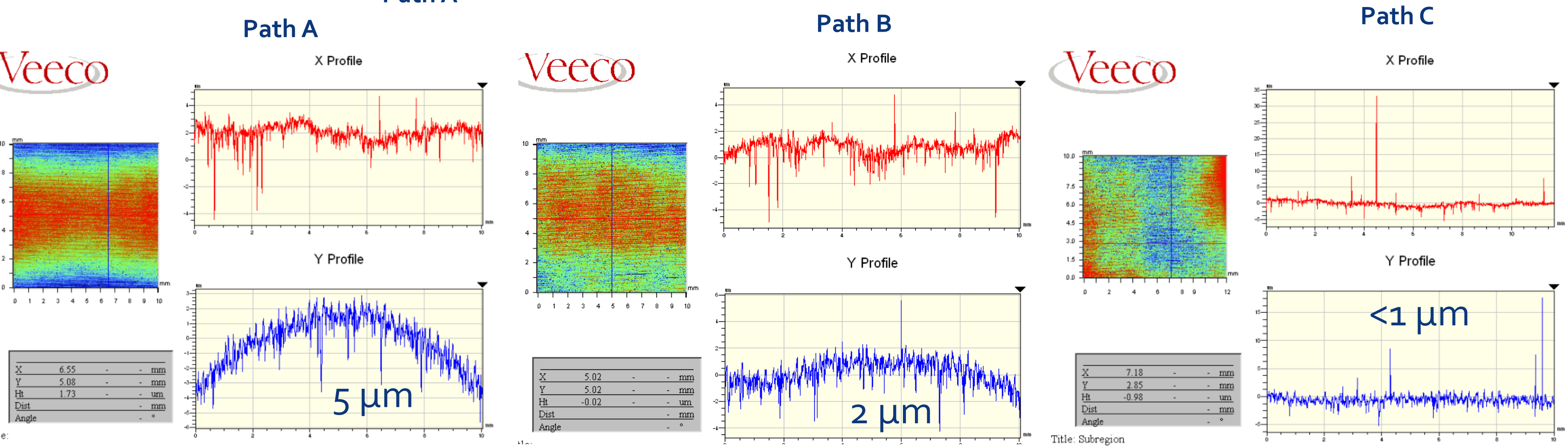


Graphite surface fine probing
8000 points

Metrology on graphite 2123PT after impact

Roughness measurement on three paths





Conclusions

- HRM28 experiment is giving quantitative information about the material behaviour during beam impact.
- This information is in agreement with the ANSYS simulation results performed before the experiment.
- Considering experimental and numerical results from the HRM28 experiment, and its hypothesis, there is no show-stopper with the selection of the SGL R4550® graphite for the TCDI collimators.
- In the framework of further developments, it has been decided to also consider 3D CC, to try to qualify against beam a material which might extend the collimators performance to more stringent beams.

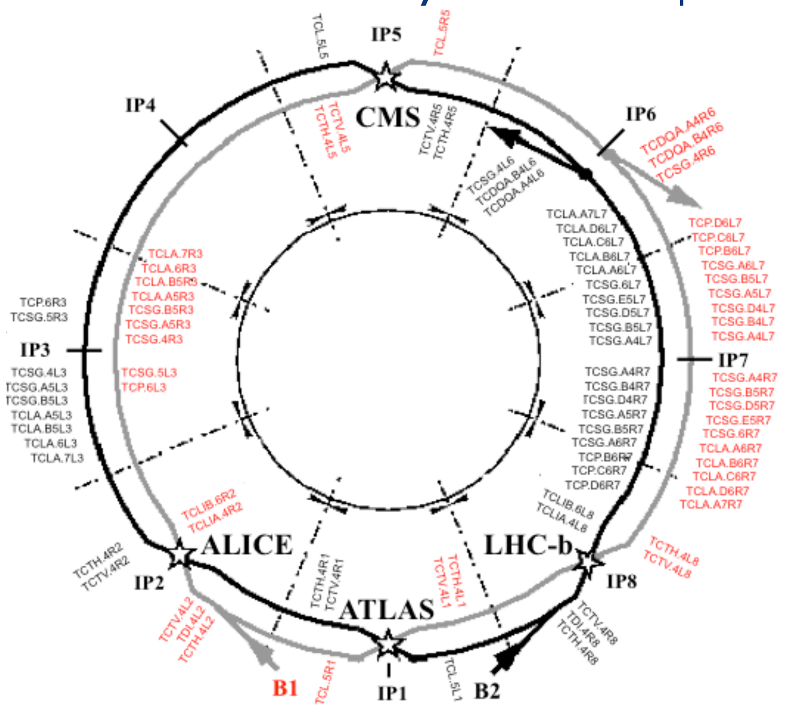
References

- [1] *W.F.Krupke; M.D. Shinn; J.E. Marion; J.A. Caird; S.E. Stokowski (1986). "Spectroscopic, optical, and thermomechanical properties of neodymium- and chromium-doped gadolinium scandium gallium garnet"*
- *[2] Engineering Considerations of Stress, Strain, and Strength by R. C. Juvinall (McGraw-Hill) and Mechanical Engineering Design by J. E. Shigley (McGraw-Hill).*
- *[3] "Investigation of Dynamic Fracture Behaviour of Graphite" Lorenzo Peroni, Martina Scapin, Federico Carra, Nicola Mariani, Departement of Mechanical and Aerospace Engineering, Politecnico di Torino and CERN, Geneva Switzerland*
- *[4] High-Radiation-to-materials technical board, 28th of April 2015, CERN Geneva Switzerland, https://indico.cern.ch/event/388600/*

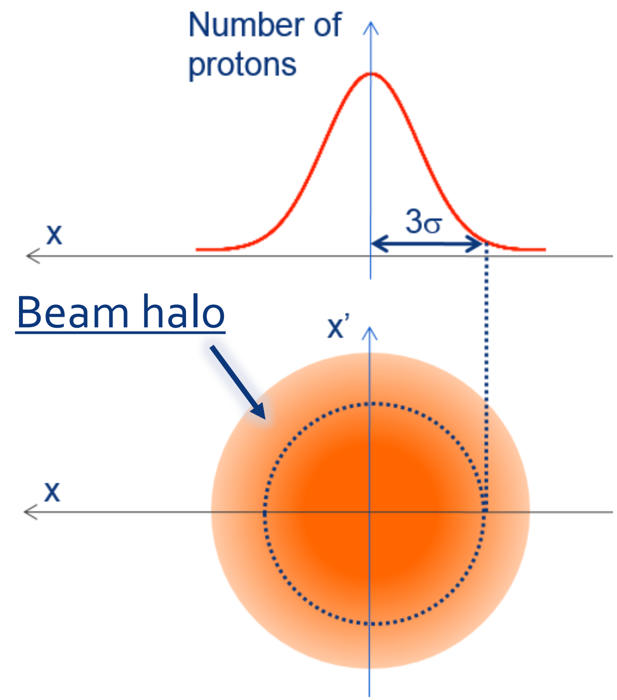
- https://espace.cern.ch/hiradmat-sps/Wiki%20Pages/Home.aspx
- http://lhc-collimation-project.web.cern.ch/lhc-collimation-project/default.php

Appendix: The CERN LHC Collimation system

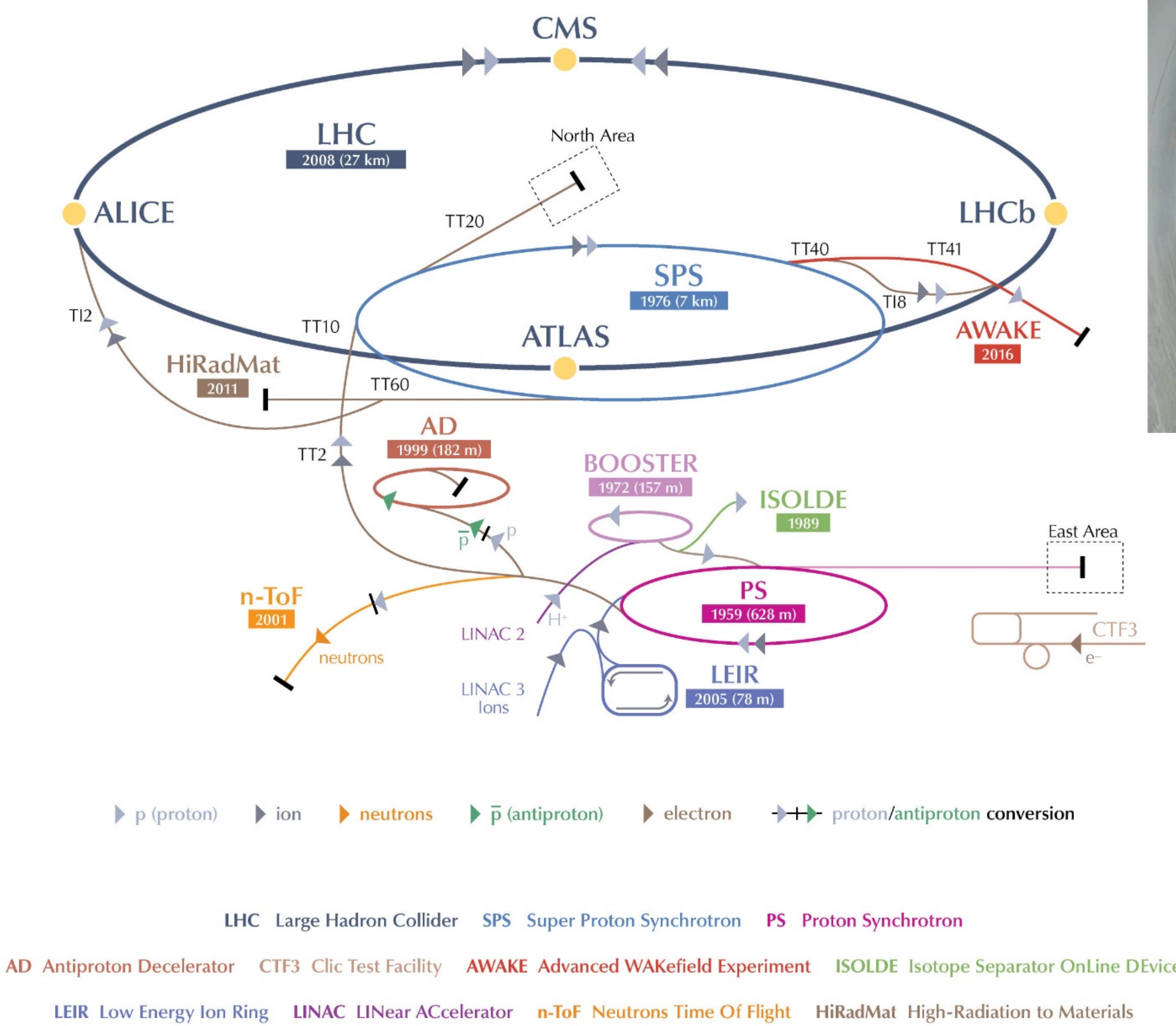
- The high luminosity performance of the LHC relies on storing, accelerating, and colliding beams with unprecedented intensities.
- Tiny fractions of the stored beam suffice to quench a super-conducting LHC magnet or even to destroy parts of the accelerators.
- The energy in the two LHC beams is sufficient to melt almost 1 ton of copper!
- The **LHC collimation system** aims at protecting the accelerator against beam losses.

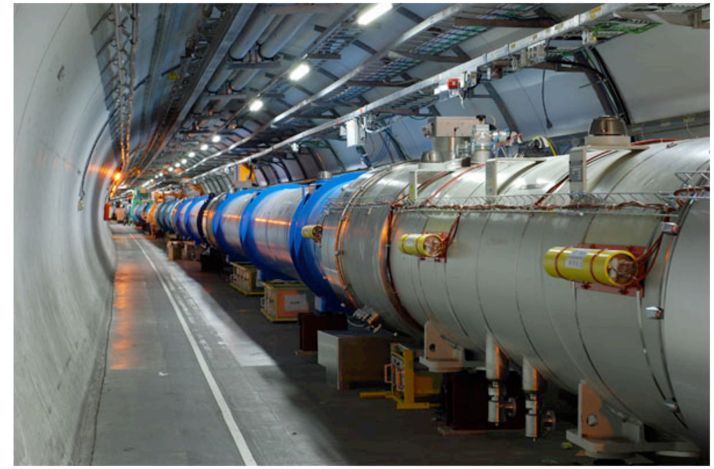


The halo particles diffuse outwards and can be lost at the mechanical aperture of the machine
➔ these particles can induce quenches in superconducting magnets



The CERN’s accelerator complex



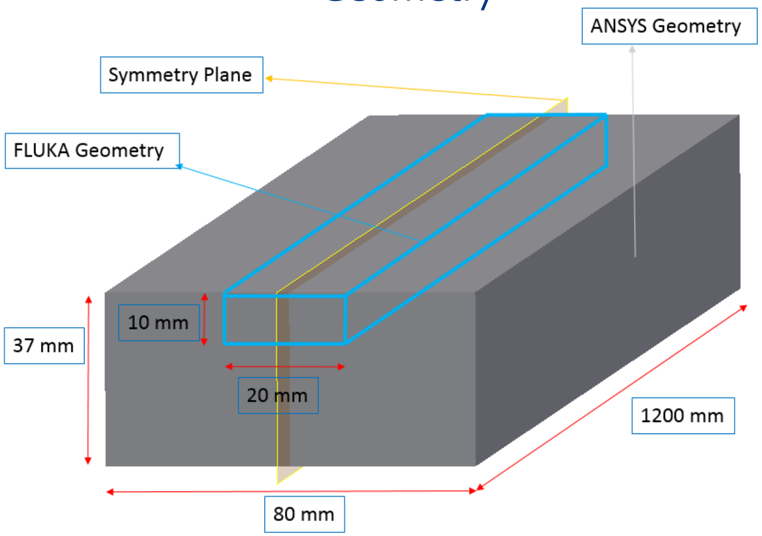


LHC in a nutshell:

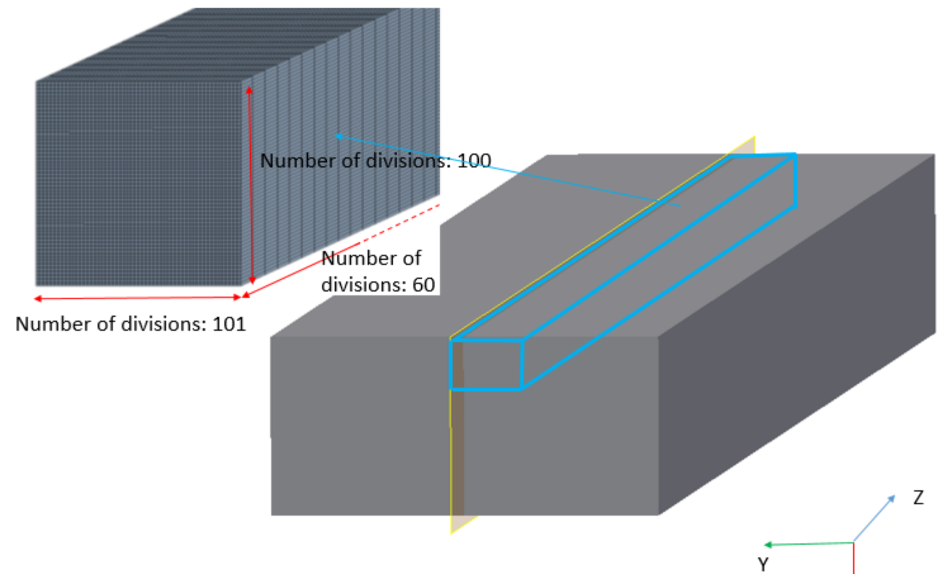
- Main aim: discovering the Higgs Boson, (particle predicted by the standard model to explain mass of the particles, and super-symmetric particles)
- Circular accelerator (27km circumference, 100m underground)
- Project approved in December 1994
- First circulating beam on Sept the 10th of 2008
- 1232 superconducting dipoles

Thermo-mechanical simulations (ANSYS®)

Geometry



Finer mesh on the impacted area



- *Transient Thermal Analysis*
  - Density [$\rho = \rho(T)$]
  - Thermal conductivity [$K = K(T,X,Y,Z)$]
  - Specific heat [$Cp = Cp\ (T)$]

- *Transient Structural Analysis*
  - Coefficient of thermal expansion [$\alpha = \alpha\ (T,X,Y,Z)$]
  - Elasticity [$E\ (T,X,Y,Z)$, $\upsilon\ (T,X,Y,Z)$, $G\ (T,X,Y,Z)$]

Linear elastic material models (temperature and direction dependent) have been adopted