Low Density Carbon Based Material Testing through High Energy Proton Beams at CERN for BIDs* applications

High Radiation to Material nº28
High Radiation to Material nº35
and 2018 planned experiments

Summary and preliminary outcomes

1st Workshop of ARIES WP17 Power Mat

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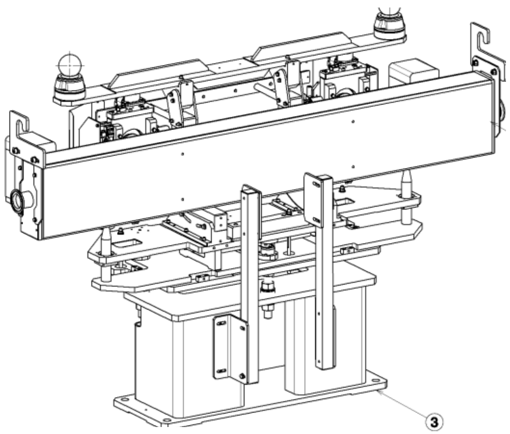
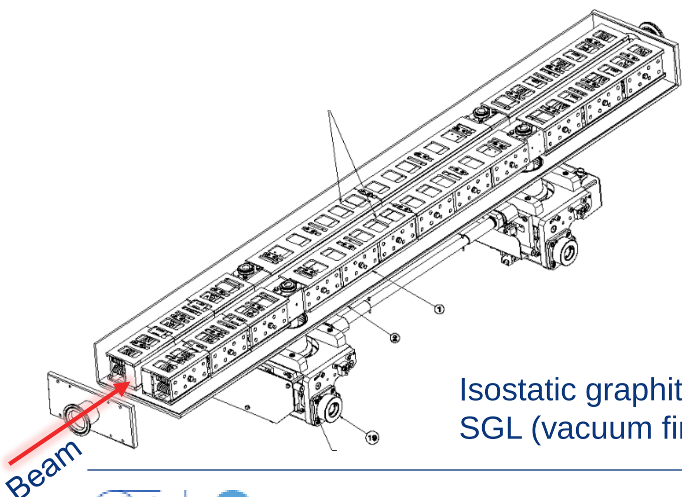
CERN EN-STI-TCD
27/11/2017

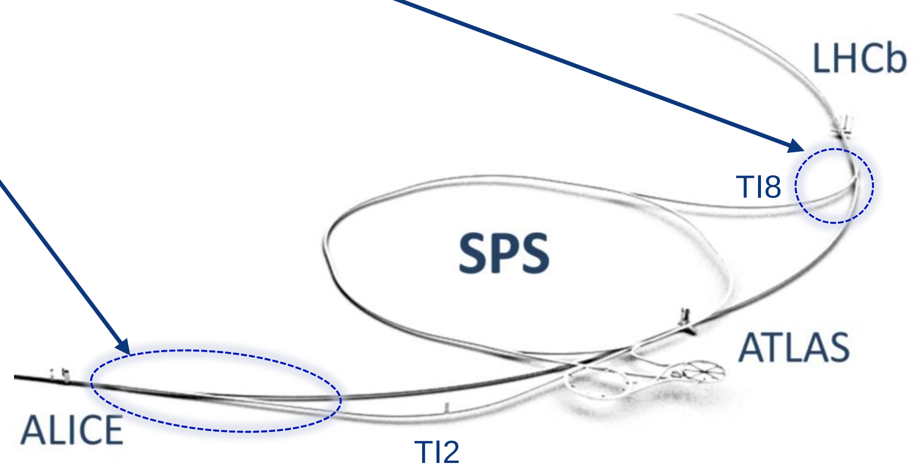
*Beam Intercepting Devices

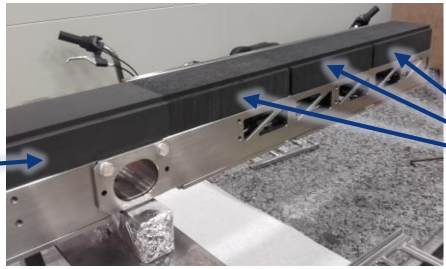
Material Studies in the framework of HL-LHC and LIU projects

6+6 new collimators in Ti2 and Ti8









Isostatic graphite R7550 SGL (vacuum fired)

3D CC (Novoltex PAN fibres) (vacuum fired)

HiRadMat 28

Motivations for HRMT28

1. Assess the Integrity of **Graphite** for TCDIs and TDIs during Run 3 and test an alternative material: **3D CC**. The goal is to reproduce the highest intensity beam that the TCDI and the TDI can see during their life time.

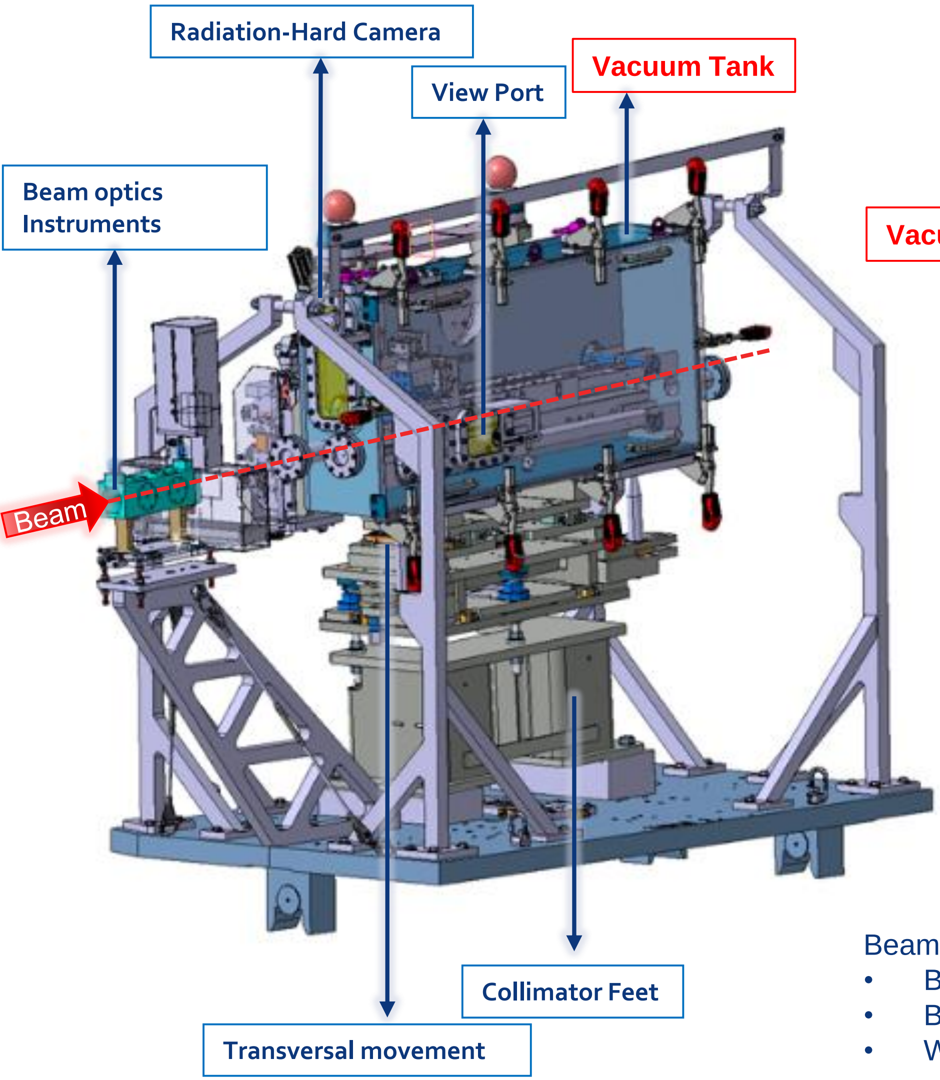
Beam	Intensity	Sig X[mm] × Sig Y[mm]	Max Temperature [°C]	M-C Safety Factor*
Run 3 BCMS	5.76 E13	0.320×0.511	1450	0.8 [~1]
HiRadMat requested beam	3.46 E13 (originally requested 1.3 E11 ppb)	0.313×0.313	1342	0.75 [0.96]
HiRadMat alternative beam (phase II)	2.6 E13	0.25×0.25	1371	[0.97]

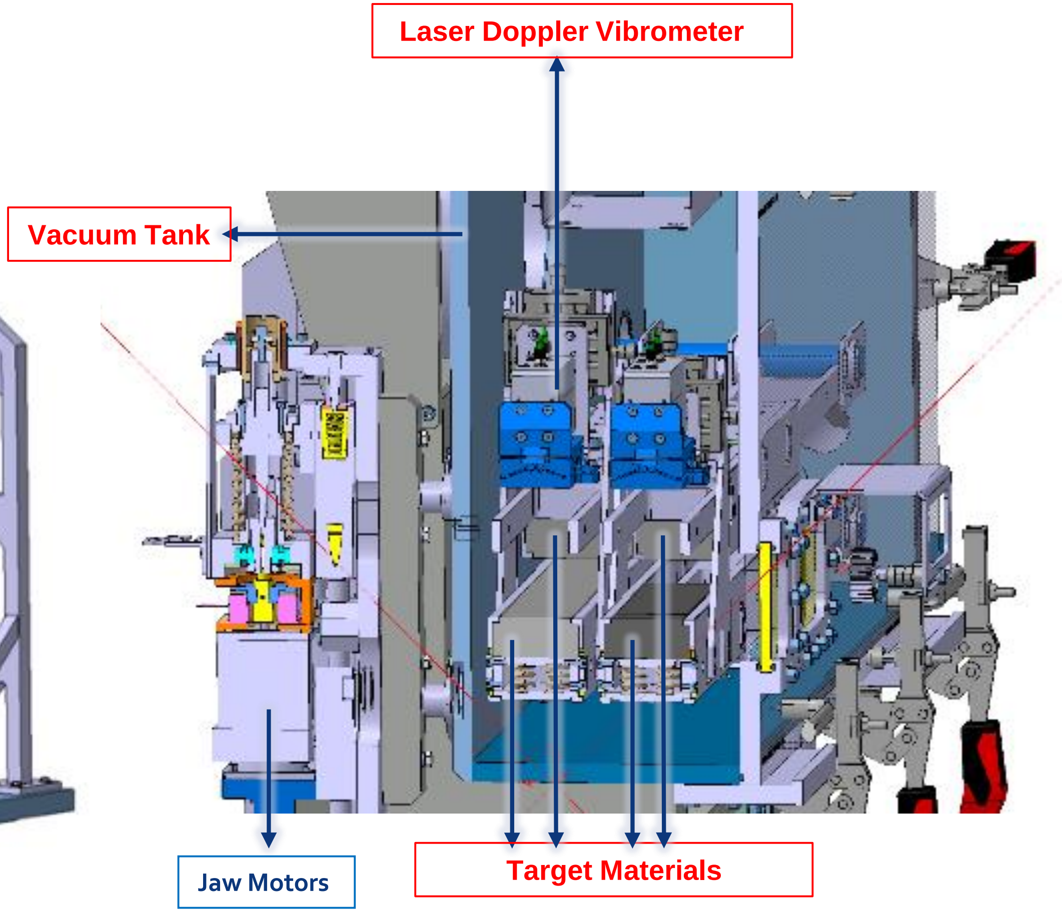
2. Cross-check simulations.

*The Mohr Coulomb safety factors are calculated with a graphite tensile limit of 30 MPa, and the values between brackets consider a graphite tensile limit of 40 MPa which is the value considered by SGL for the R7550 graphite.

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

The High Radiation to Materials experiment nº28: Overview

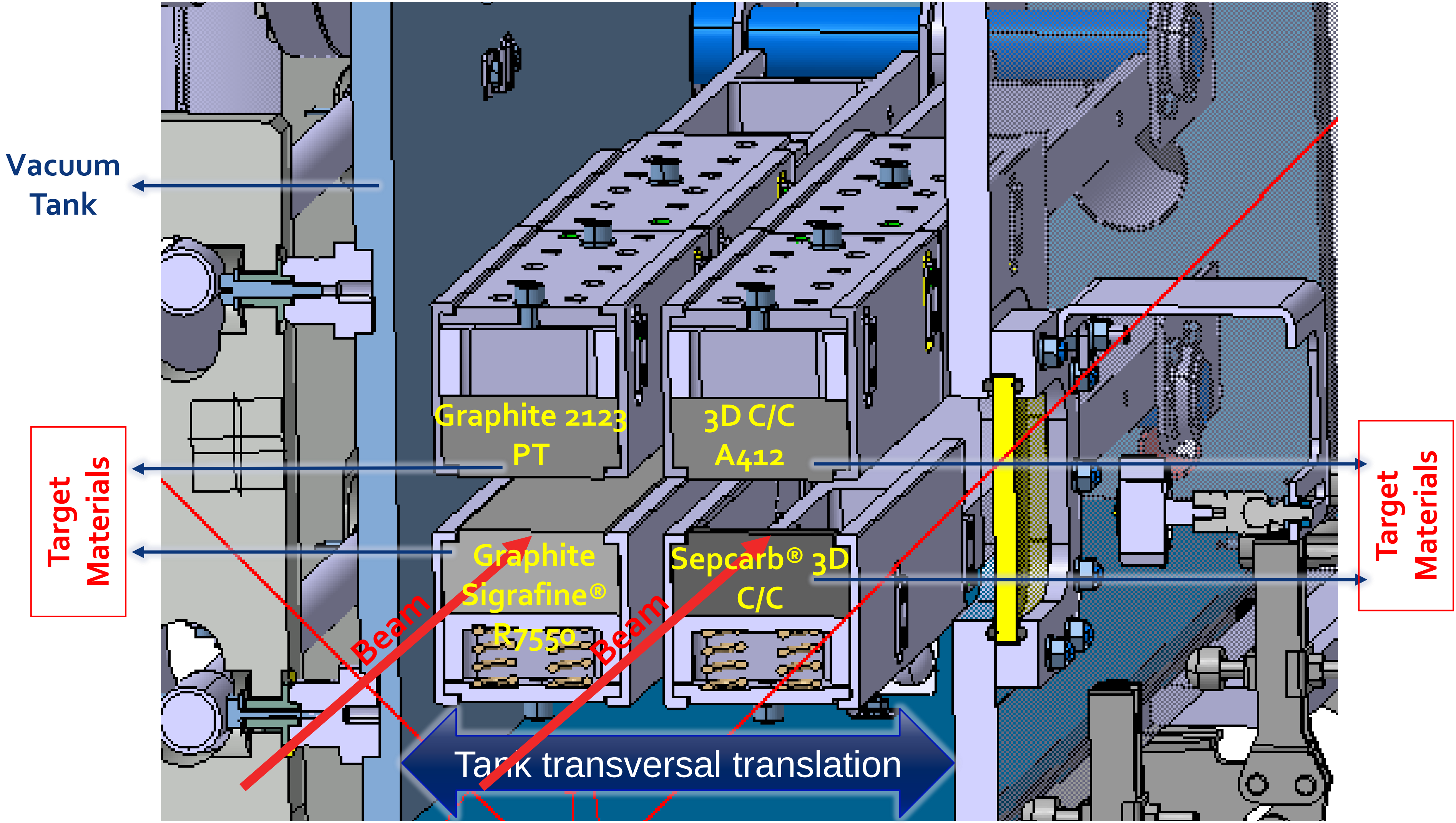




Beam instrumentation:

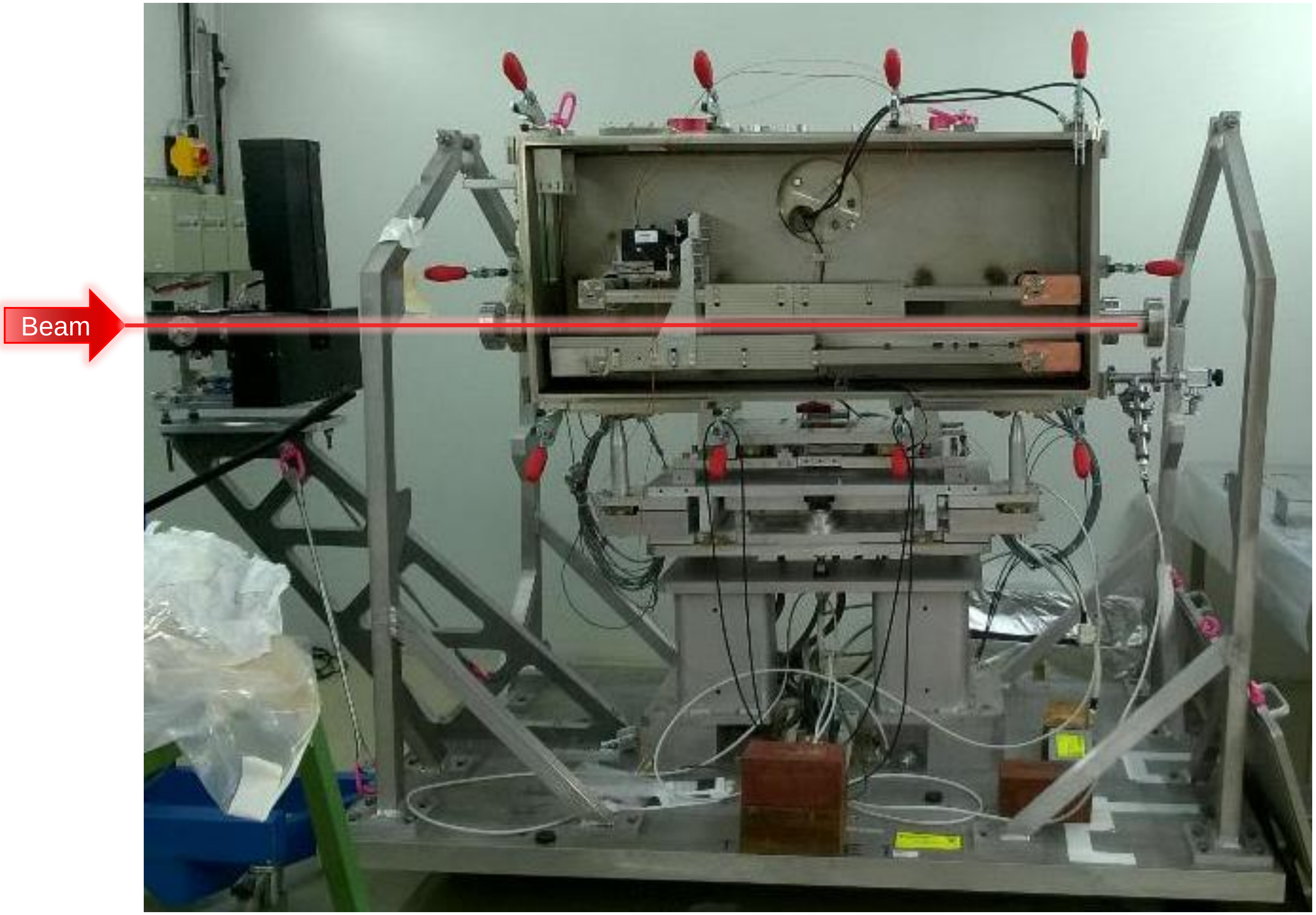
- BTV, working also for high intensity shots
- BPKG (Working only in the horizontal plane)
- Wire scanner (in SPS ring), working for up to 3 batches

The High Radiation to Materials experiment nº28: target material layout



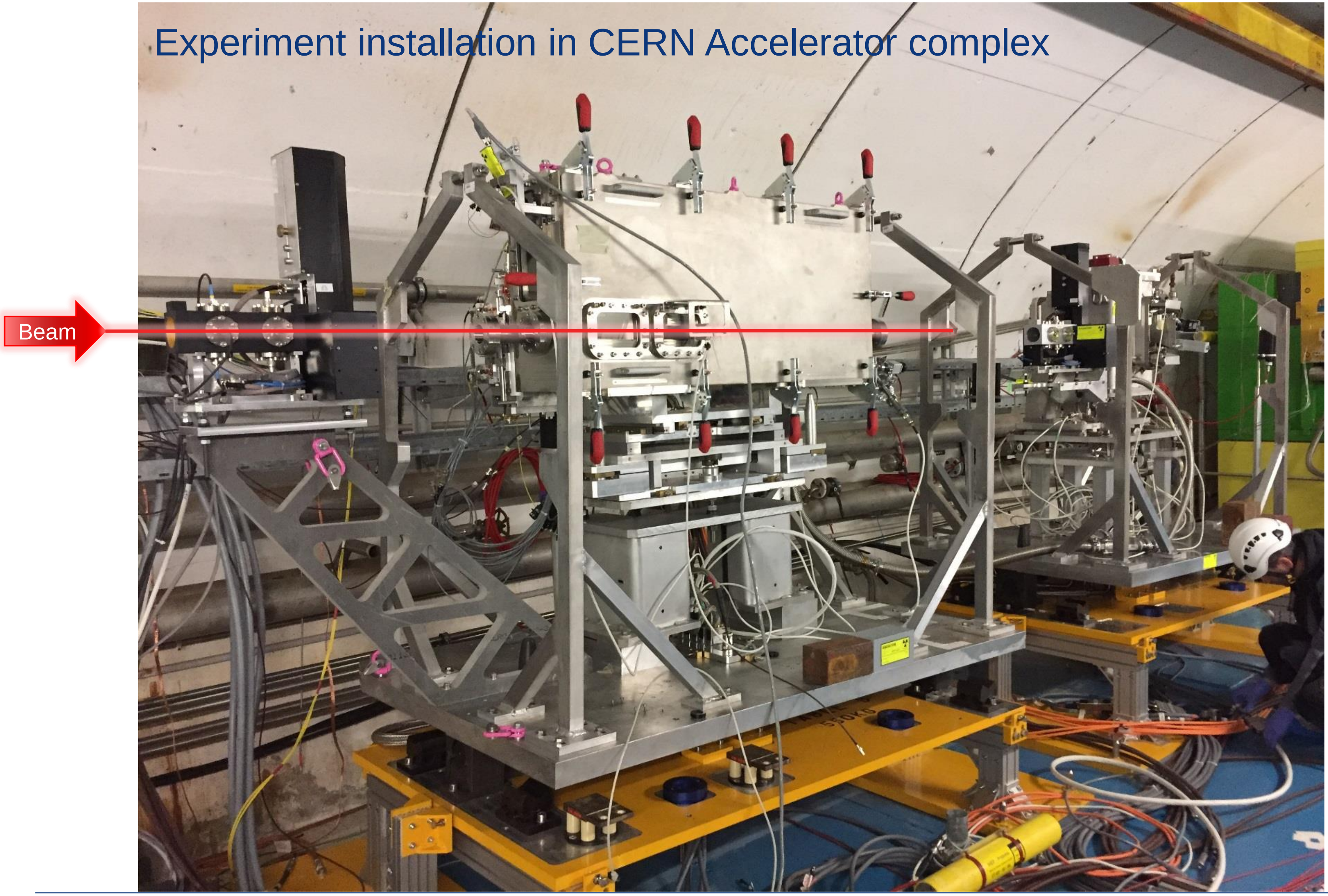
The Experimental Set Up

Experiment preparation in CERN Radioactive Bunker



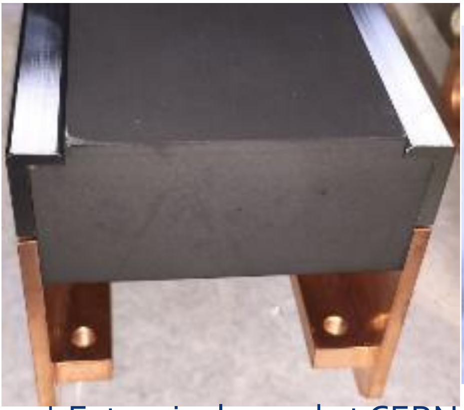
The Experimental Set Up

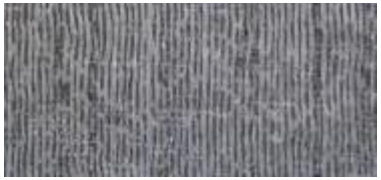
Experiment installation in CERN Accelerator complex

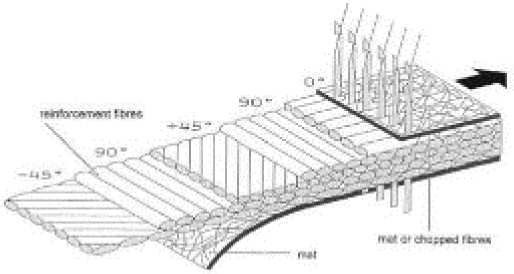


Materials tested

	Isostatic graphite		3D CC	
	Sigrafine® R4550 *	2123 PT	Sepcarb®	A412
Density [g/cm^3]	1.83	1.84	>1.80	1.7
Thermal Conductivity [W. ℃$^{-1}$.m^{-1}]	100	112	Non-Disclosure Agreement	-
Coefficient of Thermal Expansion 10^{-6} [℃-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 [℃]	>2600	2760	3000	-







* Extensively used at CERN

3D CC Material production summary

PAN “White”

Pre-carbonisation

Peroxyded PAN

Getting a wire

Getting a 2D bidirectional peroxyded .

Tissue + mat association

Wrapping (cylindrical of flat)

Needling

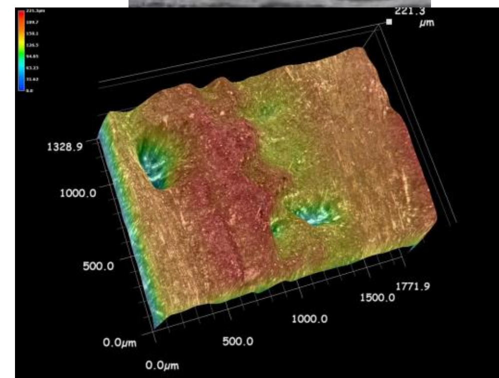
Getting 3D block

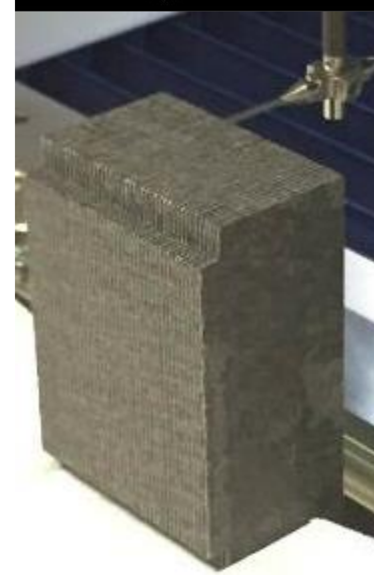
High temperature carbonisation

Densification. Low pressure and High temperature (methane / propane) → Carbon deposition on fibbers and hydrogen removal.

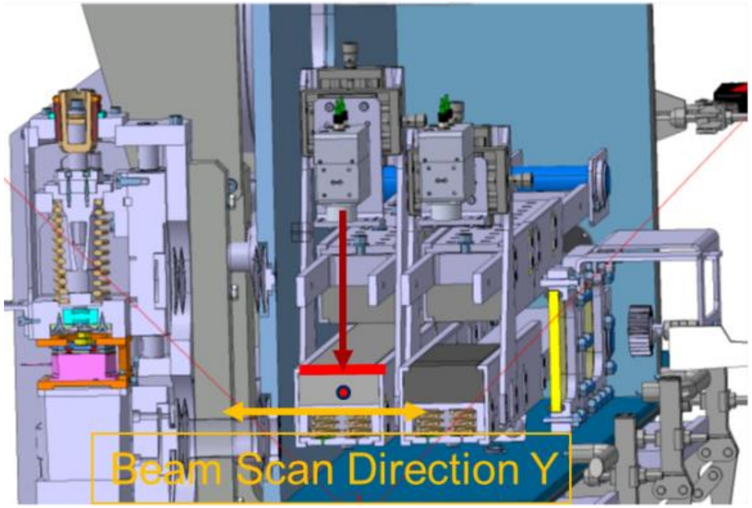
→Very pure Carbon Matrix.

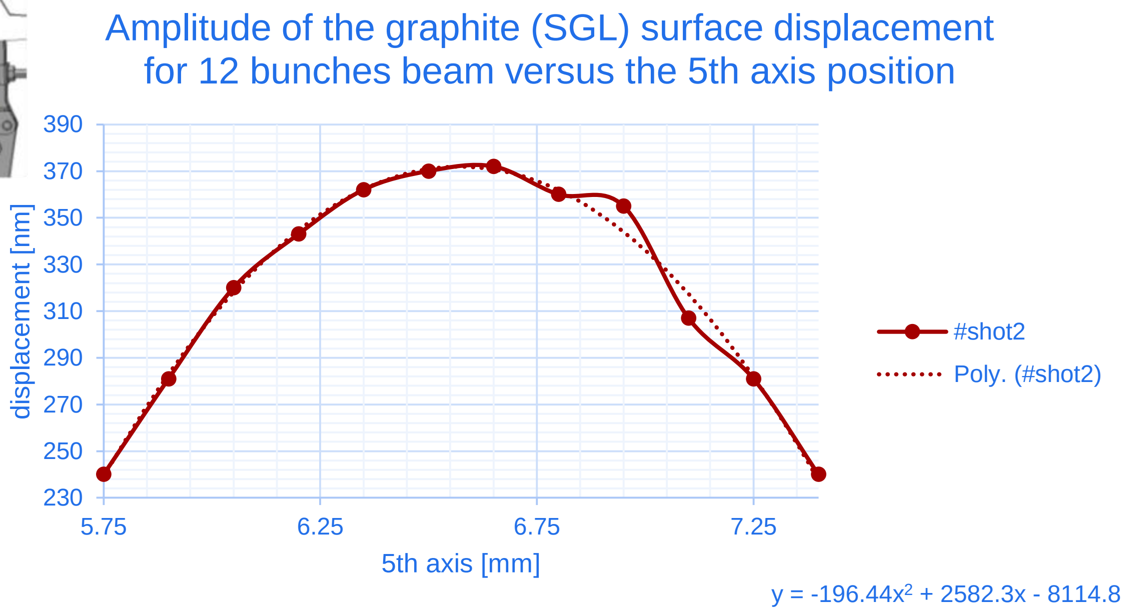
Several densification steps done for CERN.





Optometer alignment with the beam (graphite)





A precise alignment of the LDV with the beam was achieved (better than 0.15 mm)

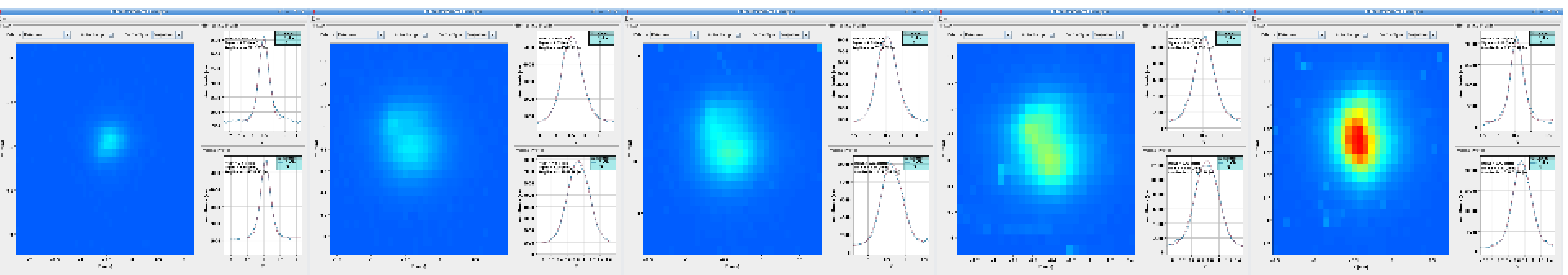
High intensity shot analysis

*under investigations

Target	Time	Intensity	Sigma X (mm)	Sigma Y (mm)	Impact parameter requested	Impact parameter possibly got*
SGL R7550® graphite	19h09min52s	3.23E+13	0.2	0.28	1.5σ	3.3σ

Discussions about the impact parameter

BTV524 OD 0 – 1 bunch *BTV524 OD 0.7 – 12 bunches* *BTV524 OD 1.3 – 72 bunches* *BTV524 OD 2 – 216 bunches* *BTV524 OD 2 – 288 bunches*



3D CC				
Number of bunch	**Screen**	**Filter [OD]**	**H[mm]**	**V[mm]**
1 bunch	**SiC**	0-0 [0]	-0.401	1.070
12 bunches af. Correction	**SiC**	1-0 [0.7]	-0.452	0.868
72 bunches	**SiC**	2-1 [1.3]	-0.463	0.637
216/288 bunches	**SiC**	3-0 [2]	-0.448	0.730
Diff [HIS - 1 Bunch]	**SiC**		-0.047	-0.340

Observed for 3D CC in one direction and for graphite in the other direction!

Jaw surfaces (ASL 3D CC and SGL Graphite)

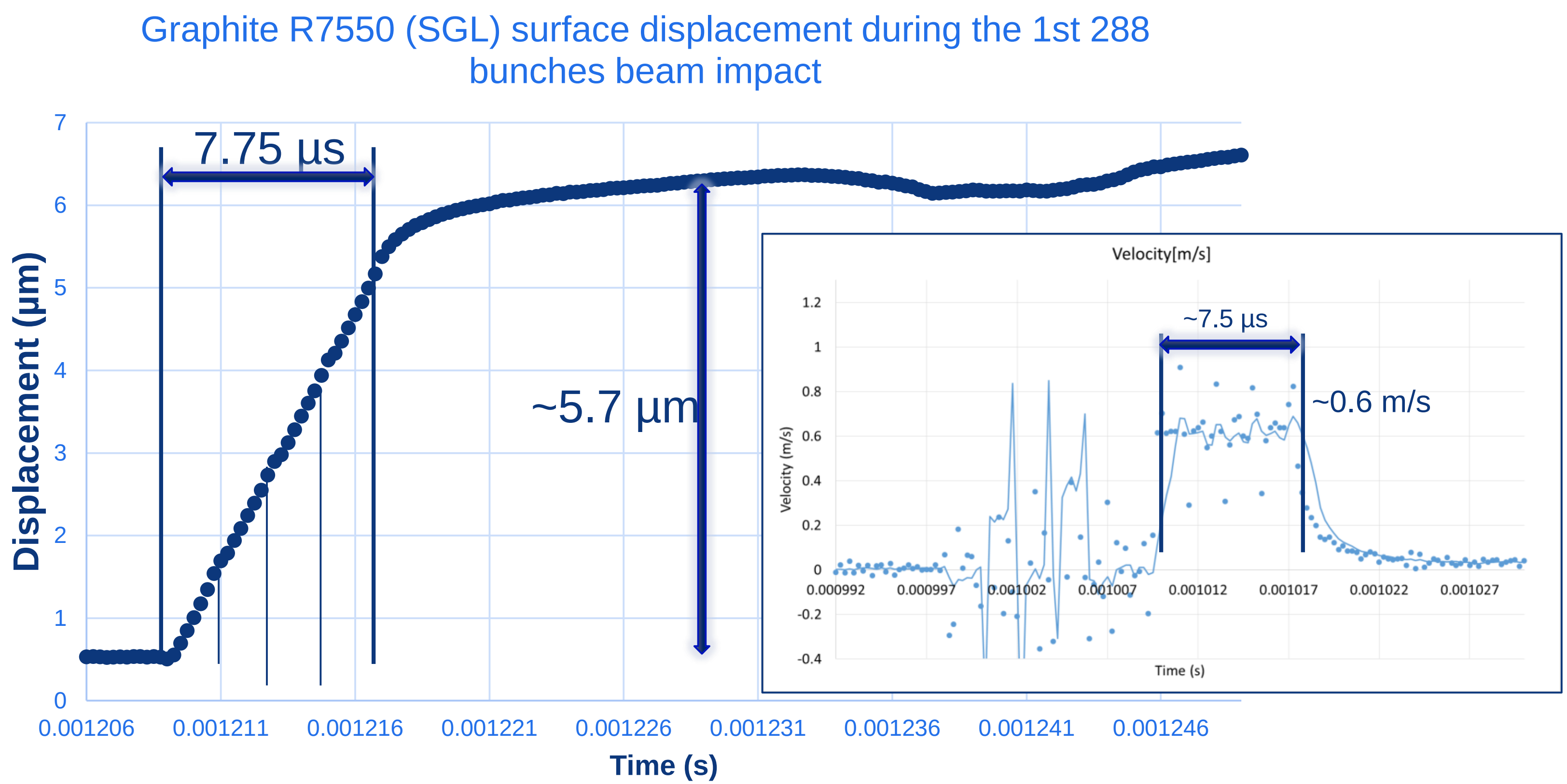
Online pictures

After 2x216 and 2x288 bunches shots on graphite

Before impact on graphite

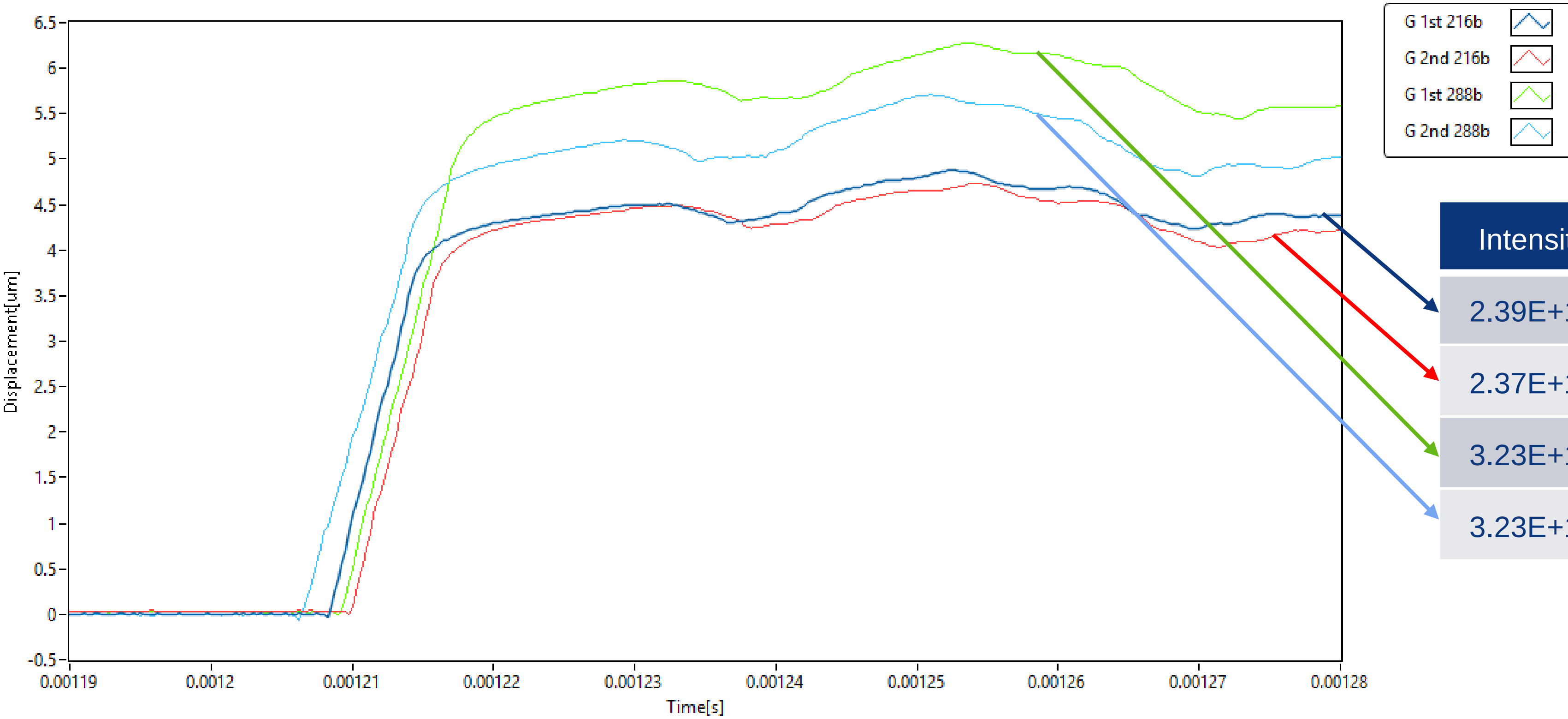
Graphite (SGL) surface displacement when impacted

4.9 kJ /cm3 of peak energy deposition



1. Ramping displacement: The proton beam interacts with the Graphite and continuously deposes energy.
2. Quasi-static step: After the beam passage and regarding the very low time scale, the adiabatic thermal response fixes the thermal-strains. The structural response is quasi-static.

Graphite (SGL) surface displacement for 4 consecutive high intensity shots



Intensity
2.39E+13
2.37E+13
3.23E+13
3.23E+13

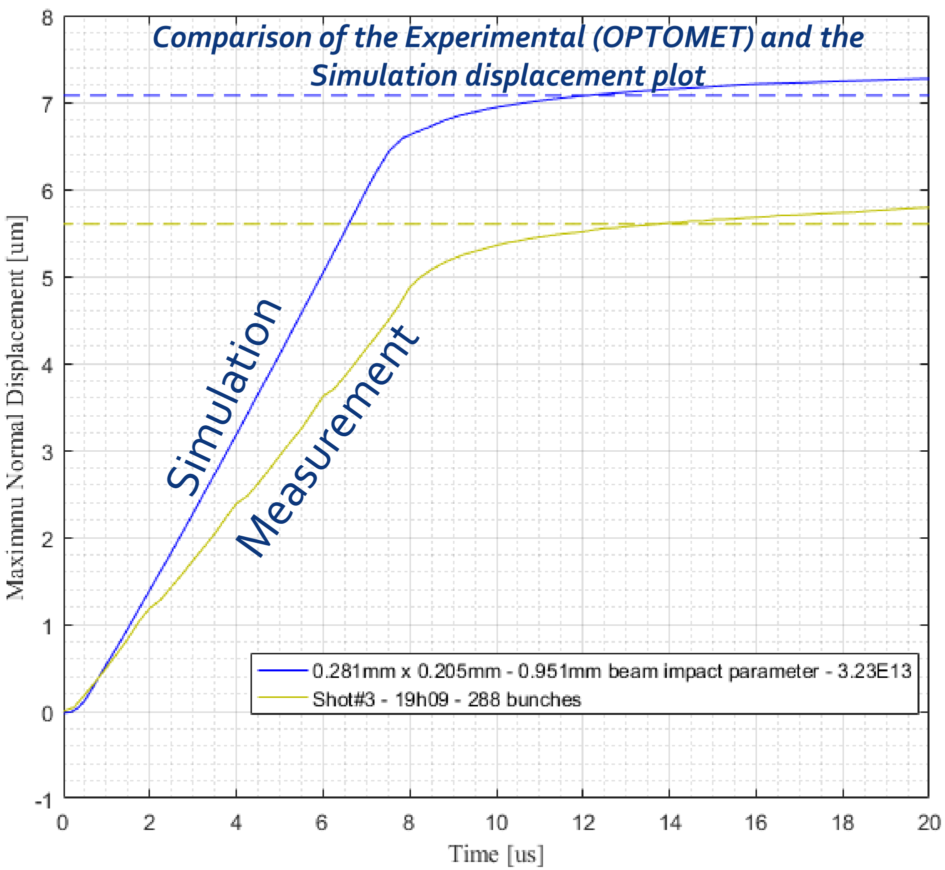
- The very similar (shape) surface displacement curves over time shows that no beam induced damage occurs on the material, shot after shot;
- The amplitude difference for the last two shots can be due to the impact parameter difference (last pulse is 0.3 mm deeper).

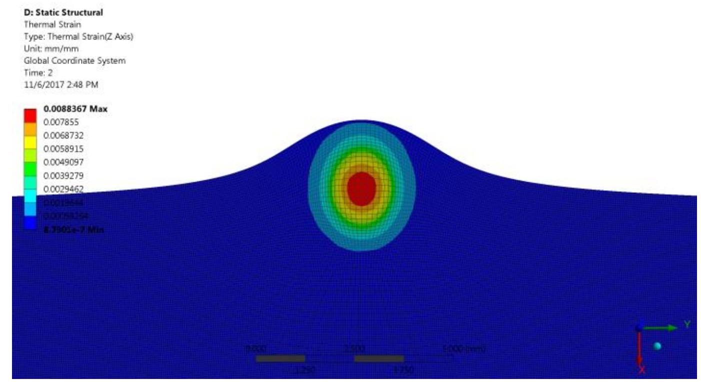
Simulated impacts on R7550 Graphite

Courtesy: Maxime Bergeret EN/STI-TCD CERN

The thermo-structural responses of the material is calculated in ANSYS by importing the FLUKA energy map :

- Peak temperature: **1608°C**
- Bumping amplitude: **7.08µm**





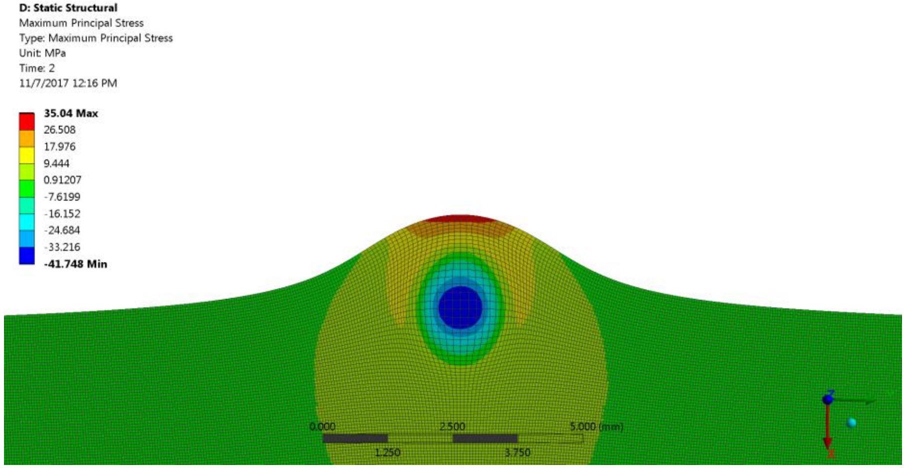
Thermal strain (Scale: X300)

Error between Experimentation and Simulation:

- The curve are very similar with ramping and stepping displacement at the end of the pulse (7.2µs);
- <u>26% Amplitude error.</u>

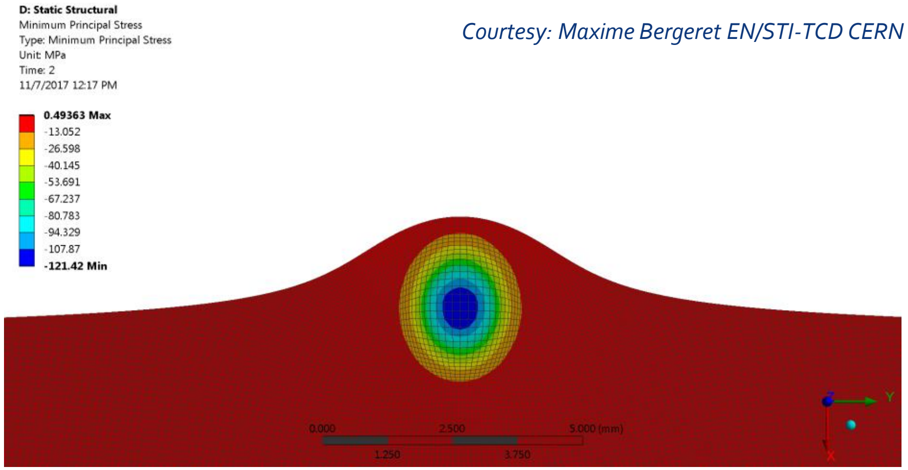
Simulated impacts on R7550 Graphite

	Simulation		Measurement
	1.5σ	3.3σ	Under discussions
Surface displacement	8.20 µm	7.08 µm	~ 5.7 µm
Maximum Principal Stress	67 MPa	35 MPa	-
Minimum Principal Stress	-126 MPa	-121 MPa	-



Maximum principal stress after high intensity shot

Courtesy: Maxime Bergeret EN/STI-TCD CERN



Minimum principal stress after high intensity shot

At room temperature the limits are:

- *Tensile Strength: 38.5MPa (SGL Tensile Tests)*
- *Compressive Strength: 130MPa (SGL Datasheet)*

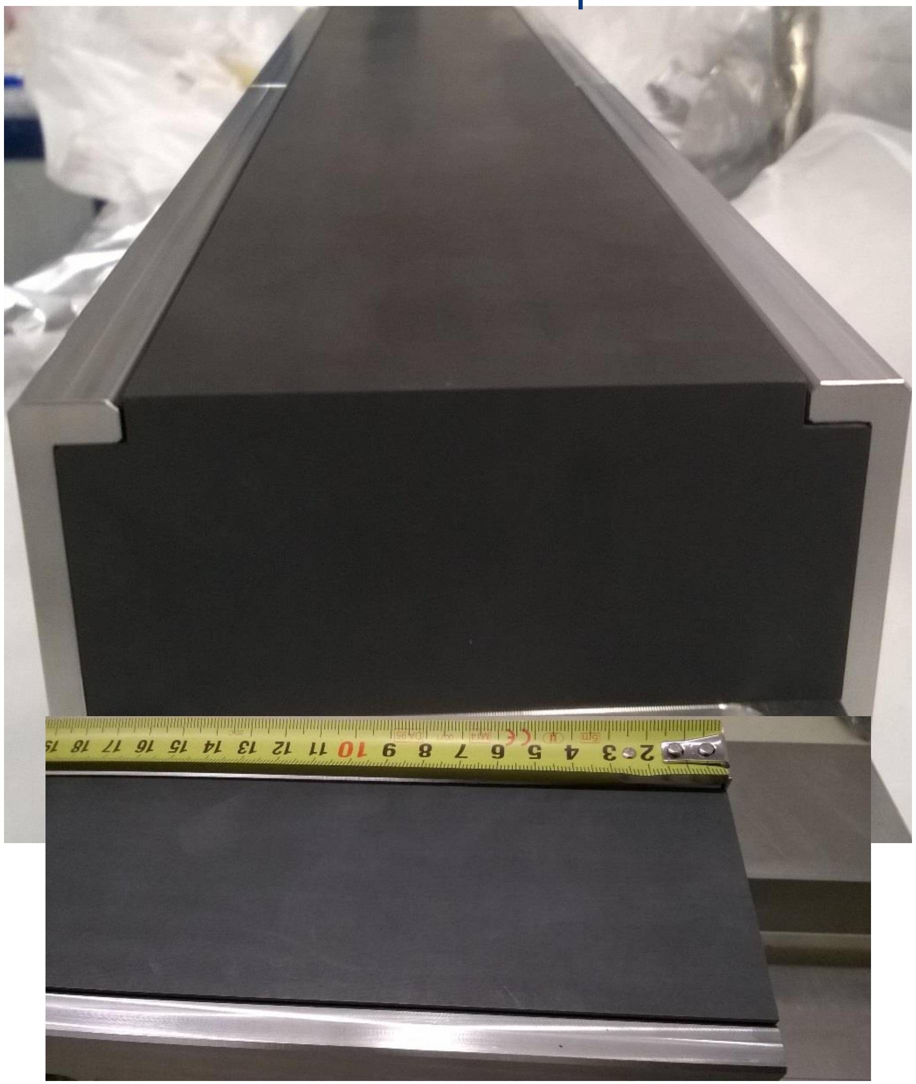
Ongoing studies

Numbers of parameters influence the thermo-structural response and the measured displacements:

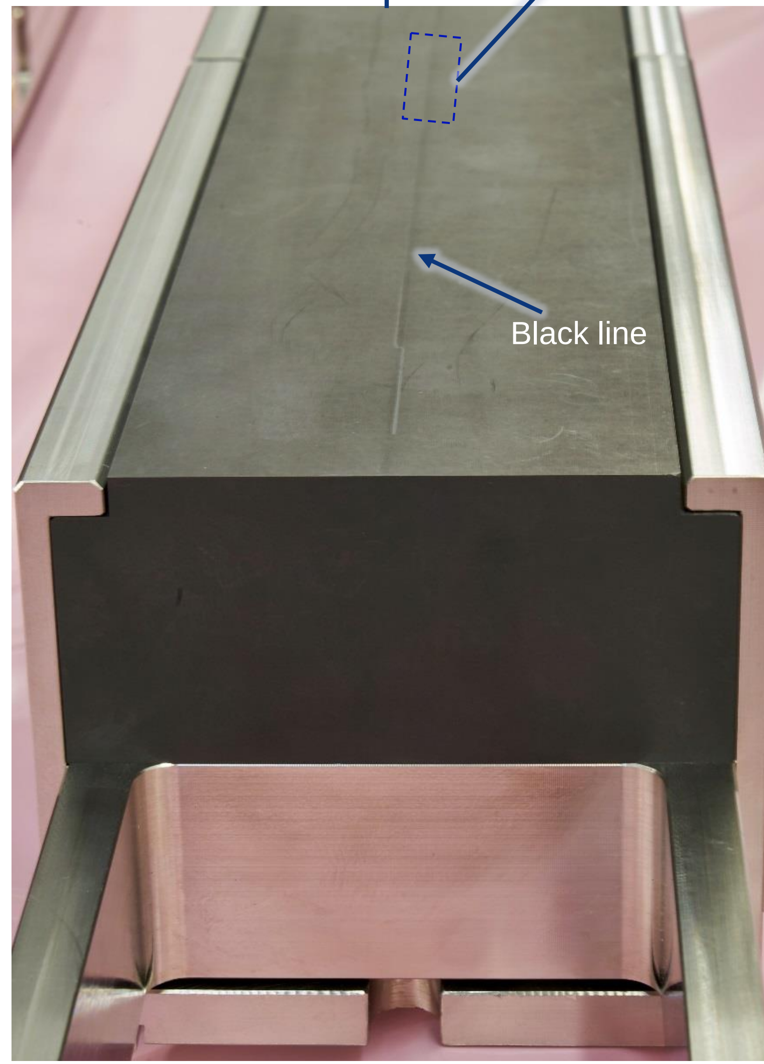
1. **The Material properties implemented into ANSYS, and especially, Cp [J/kg/C]; CTE [/C];**
2. The beam dimensions σ_H ; σ_V *[mm];*
3. The position of the Beam into the Graphite, **Beam Impact Parameter**;
4. The OPTOMET pointing precision, 5th Axis tuning;

Mersen 2123 PT graphite pictures

Before beam impact



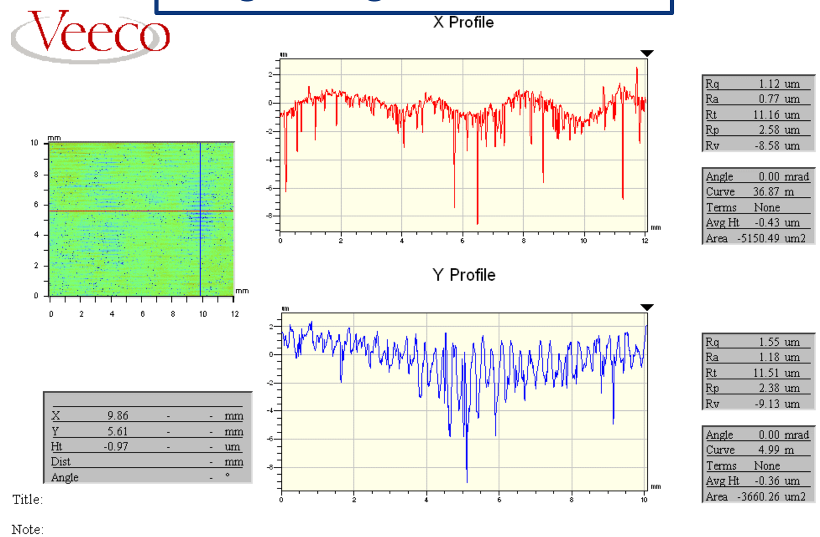
After beam impact



SPSXTCDIL0003_Mersen Graphite→ Veeco Inspection

After impact

Beginning of the block



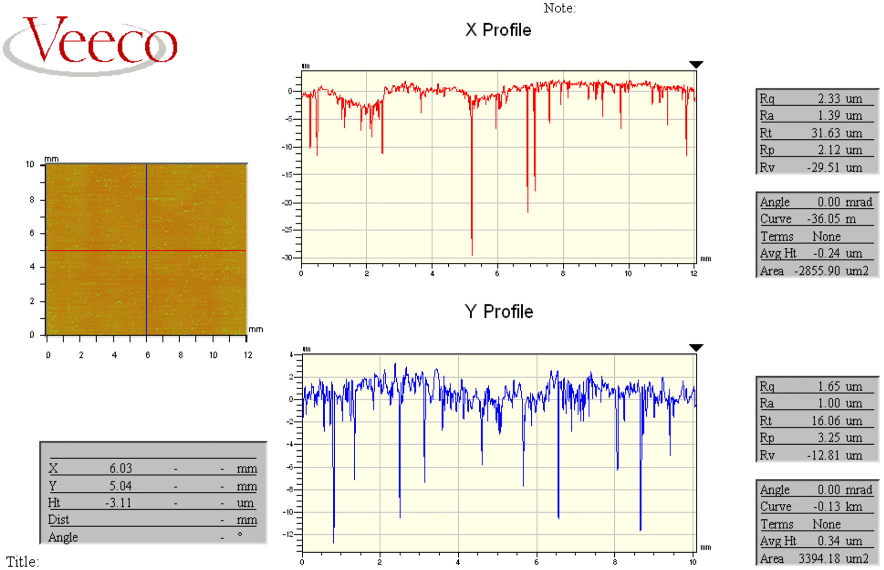
Apparatus used:

Profilometer Veeco NT 3300

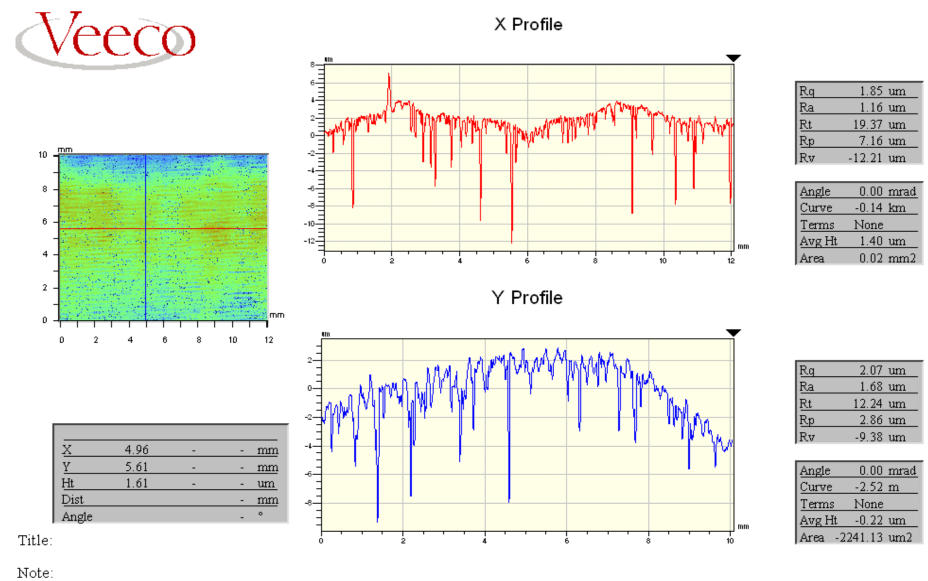
No contact probing system

Courtesy: Stefano Pianese EN/STI-TCD CERN, and CERN EN-MME Metrology lab

Middle of the block



End of the block

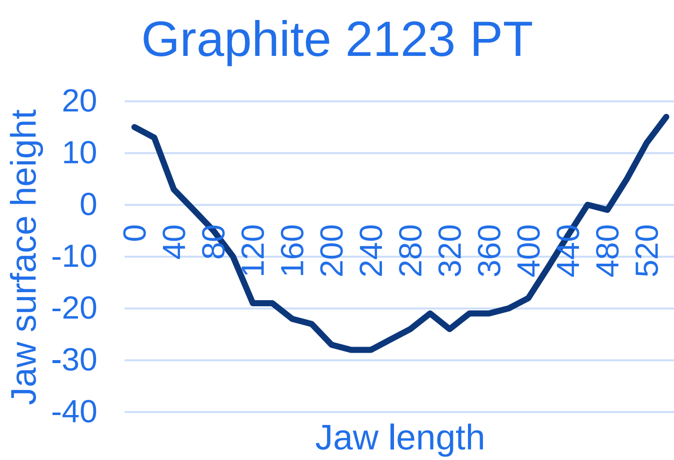


Targets (jaws) metrology measurements (summary)

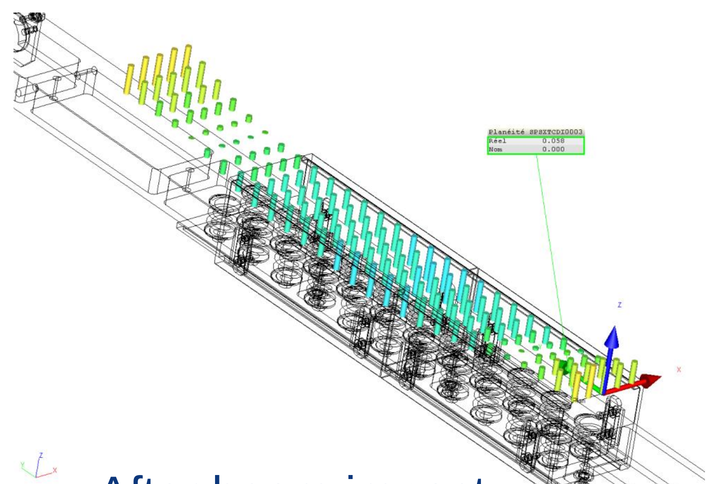
Courtesy: Stefano Pianese EN/STI-TCD CERN, and CERN EN-MME Metrology lab

Jaw flatness measurement before and after beam impact:

Jaw flatness	Graphite Sigrafine® R7550 (SGL)	Graphite 2123 PT (Mersen)	3D C/C A412 (Mersen)	Sepcarb® 3D C/C (Airbus Safran Launchers)
Before Impacts	**80 µm**	**56 µm**	**128 µm**	**44 µm**
After Impacts	**96 µm**	**58 µm**	**82 µm**	**44 µm**
	✓	✓	Bloc movement during handling	✓



Before beam impact

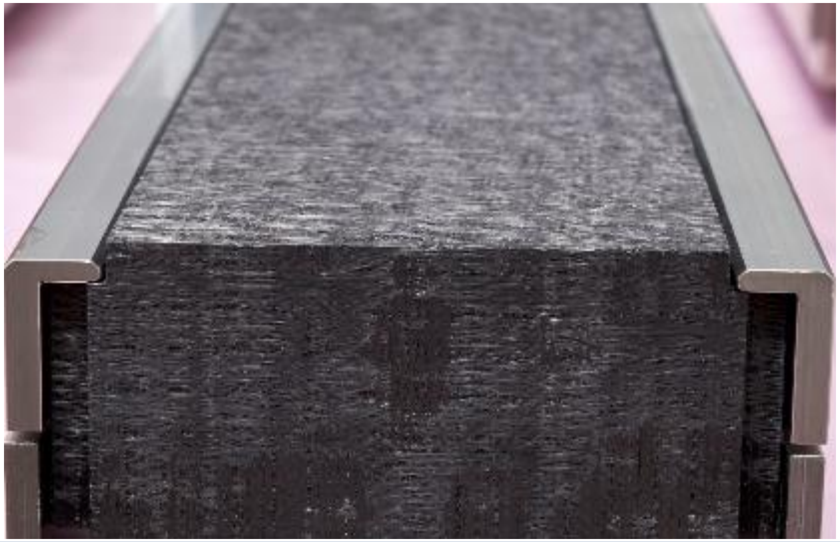


After beam impact

SPSXTCDIL0006_ASL_3D C-C 170 mm → Before and after impact, visual Inspection.

Before impact

After impact

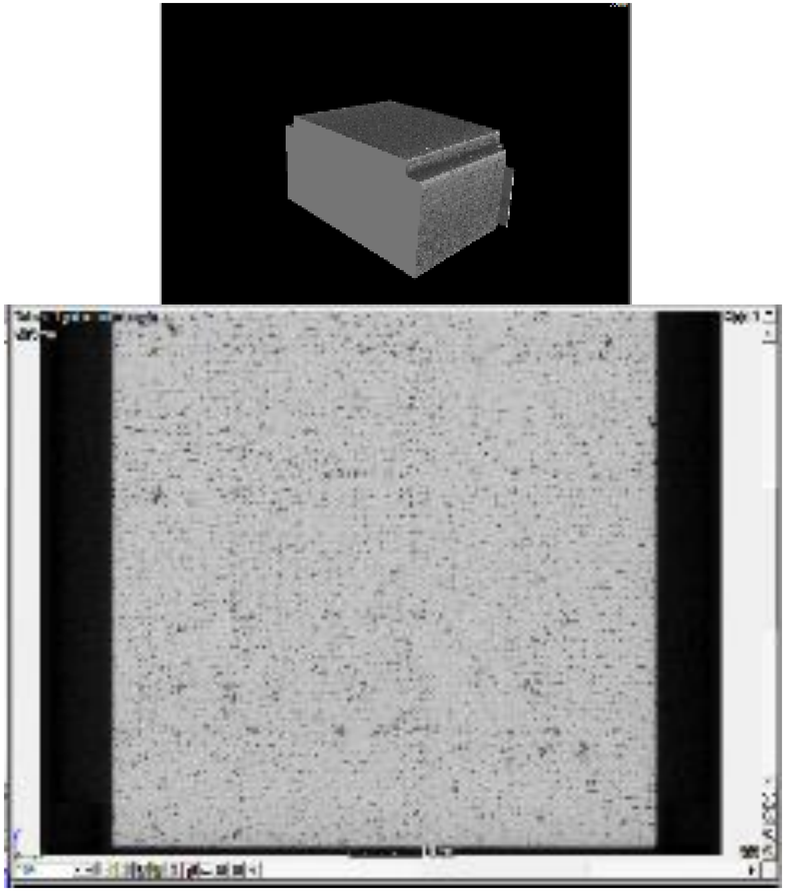


Courtesy: Stefano Pianese EN/STI-TCD CERN

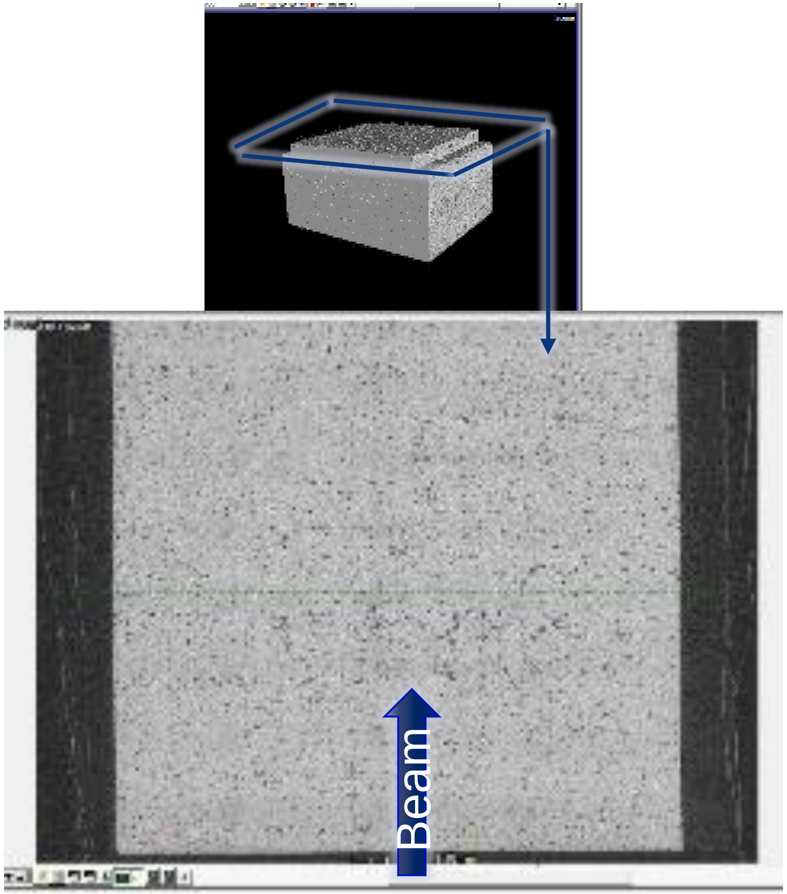
Micro tomography (ESRF collaboration)

Courtesy: Stefano Pianese EN/STI-TCD and MME CERN

Before Impact

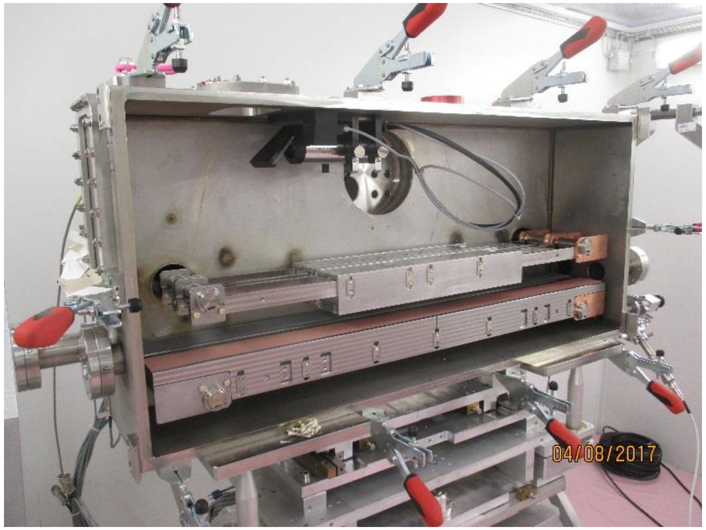


After Impact



The two pictures have been taken at the same location, before and after impact, where the beam has impacted.

HiRadMat 35



HRMT 35 Aim

- Assess the level of damage on the coating that the current TDI (LHC Injection absorber) could face (grazing impact).
- For LS2 collimators, experience on the coating behaviour for different coatings configurations and material subtracts.

After impact

3.5E13 protons per pulse
440 GeV
0.3mm nominal spot size

Graphite with Cu coating

CFC with Mo coating

Graphite with Mo coating

Courtesy: Inigo Lamas EN/STI-TCD CERN

Main outputs

- Graphite coated with Mo and graphite coated with Cu OK
- Tatsuno CFC with Mo coating OK
- Possible materials for secondary collimators
- Actual TDI (Graphite + Cu coating) shall survive the ongoing beams

Summary

- SGL Graphite and ASL 3D CC are undamaged after several high intensity shots;
- SGL Graphite and ASL 3D CC are "*behaving*" as expected by the simulations;
- Metrology is showing the same global shape before and after impact;
- HD pictures are showing no differences between before and after impact, excepted for the 2123PT graphite.
- Micro-tomography of the 3D CC shows no difference before and after impact.
- Simulation results are sensitive with the **spot size**, the **beam impact parameter and intensity**, the **material model.**
- The actual TDI shall survive ongoing beams.

IPAC Paper:
F-X. Nuiry†1, O. Aberle, M. Bergeret, A. Bertarelli, N. Biancacci, R. Bruce, M. Calviani, F. Carra, A. Dallocchio, L. Gentini, S. Gilardoni, R. Illan, I. Lamas Garcia[2], A. Masi, A. Perillo-Marcone, S. Pianese, S. Redaelli, E. Rigutto, B. Salvant,
Design and Prototyping of New CERN Collimators in the Framework of the LHC Injector Upgrade (LIU) Project and the High-Luminosity (HL-LHC) Project

Future Experiments **TCDIL DEEP and TDIS-TZM**

Assess the TDIS and TCDIL jaw flatness for extreme accidental deep impacts in the jaw.

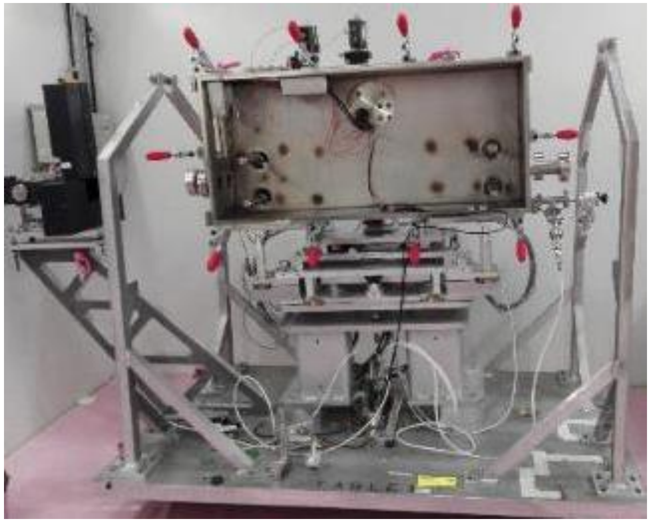
Proposed experiment configuration:

One jaw with the updated design

One jaw with design baseline

Thanks for your attention

Multi-experiment tank



- HRMT 28 Phase I : April 2016
- HRMT 28 Phase II : June 2017
- HRMT35 : August 2017
- Allows to shorten time from one experiment to another one, save money, and reduces radioactive waste.
- *Could be used for other HRMT experiments:*

*Big volume: 545*247*1234 mm^3 with large access;*

LHC Collimator size compatible;

Several vacuum feedthroughs;

5 independent translation axis;

*2*2 beam windows;*

4 view ports.

HRMT 28 in a nutshell

- **4 low density materials** impacted for BID applications;
- About **15 people** involved in the experiment operation itself;
- About **1.12E15** total POT spread over **3 runs**;
- **23 hours spent in the CCC**, aligning the experiment and data acquisition;
- **3 Gb** of collected data;

Residual dose rate	After 9h of cool down	After 44h of cool down
PMIHR02	1 mSv/h	227 µSv/h

Summary of the experiment

13/06/2017 → Impacts on Graphite jaws

Start at 11h00 → Beam Steering done with 12 bunches beams;
14h40 → End of the BBA (1 bunch);
17h13 → End of the Optomet LDV alignment (12 bunches beam);
18h32 → End of high intensity shots test (jaws opens);
19h27 → End of the high intensity shot (216/288 bunches) on the SGL graphite;
19h57 → End of the high intensity shot (216/288 bunches) on the MERSEN graphite.

16/06/2017 → Impacts on 3D CC jaws

Start at 9h46 → Beam Steering done with 1 bunch beam;
12h43 → End of the BBA (1 bunch);
LHC Filling
14h39 → End of the 12 bunches beam for statistics;
15h35 → End of the Optomet LDV alignment tentative (12 bunches beam);
18h00 → End of the Optomet LDV alignment tentative (72 bunches beam);
18h53 → End of high intensity shots test (jaws opens);
19h29 → End of the high intensity shot (216/288 bunches) on all 3D CC jaws.

Summary of the experiment

27/06/2017 → New impacts on 3D CC jaw (ASL)

Start at 9h00 → Beam position checks with 1 bunch and 12 bunches beams. Adjustment of the vertical position of the beam, cross check with BTV;
10h51 → Start of 72 bunches extraction for optomet alignment;
12h47 → End of the Optomet LDV alignment (72 bunches beam);
12h57 → Start of high intensity shots on ASL jaw;
13h13 → End of the high intensity shot (216/288 bunches) on the ASL jaw.

High intensity shots on the 13/06/2017

Target	Time	Intensity	BTV.524 measurements Sigma X (mm)	Sigma Y (mm)	Position in X (mm)	Position in Y (mm)	
SGL R4550® graphite	18h43min28s	2.39E+13	0.44	0.49	-0.22	0.9	
	18h57min04s	2.37E+13	0.43	0.42	-0.29	0.89	
	19h09min52s	3.23E+13	0.42	0.48	-0.3	0.91	
	19h27min28s	3.23E+13	0.43	0.44	-0.23	0.85	Jaw moved by 0.3mm within the beam
Mersen 2123UHP 5® graphite	19h42min40s	2.42E+13	0.49	0.28	-0.3	0.88	
	19h46min40s	2.44E+13	0.52	0.3	-0.33	0.86	
	19h50min40s	3.25E+13	0.4	0.24	-0.29	0.91	
	19h57min04s	3.25E+13	0.38	0.39	-0.32	0.79	Jaw moved by 0.3mm within the beam

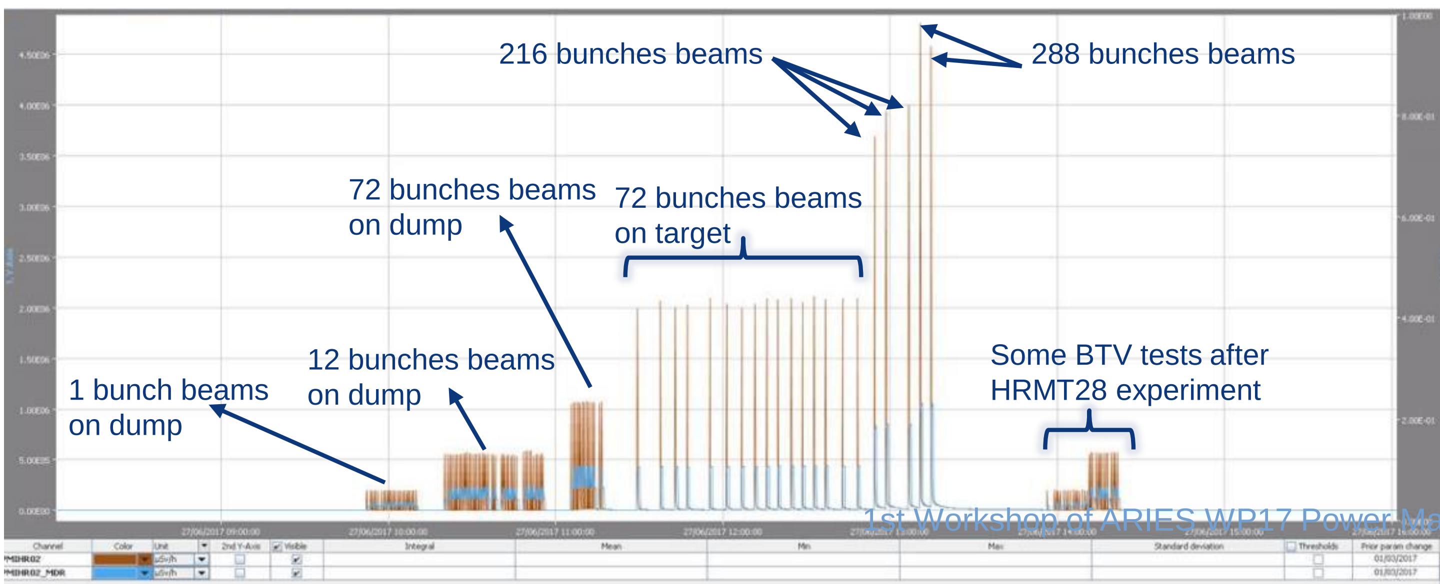
High intensity shots on the 16/06/2017

			BTV.524 measurements			
Target	**Time**	**Intensity**	**Sigma X (mm)**	**Sigma Y (mm)**	**Position in X (mm)**	**Position in Y (mm)**
ASL Sepcarb 3D CC	18h42min24s	2.77E+13	0.29	0.4	-0.32	0.95
	18h52min48s	2.94E+13	0.28	0.4	-0.28	1.02
	19h26min24s	3.82E+13	0.3	0.34	-0.33	0.88
	19h30min24s	3.81E+13	0.36	0.29	-0.36	0.9
Mersen 3D CC	19h00min00s	2.91E+13	0.26	0.38	-0.32	1
	19h04min00s	2.91E+13	0.28	0.34	-0.31	1
	19h20min00s	3.89E+13	0.28	0.33	-0.32	0.92
	19h22min24s	3.77E+13	0.28	0.37	-0.33	0.91

High intensity shots on the 27/06/2017

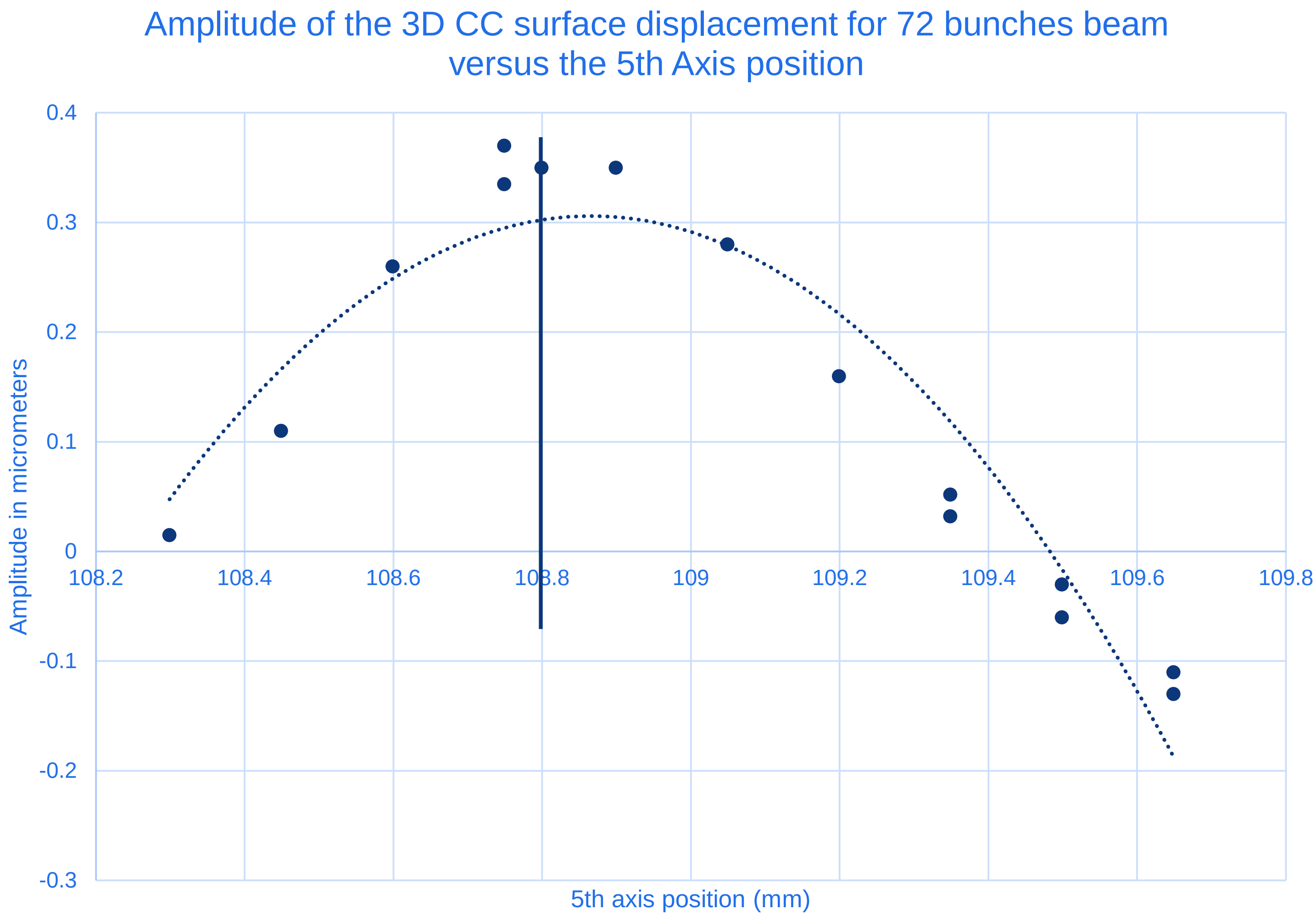
Target	Time	Intensity	BTV.524 measurements Sigma X (mm)	Sigma Y (mm)	Position in X (mm)	Position in Y (mm)	
ASL Sepcarb 3D CC	12h54min02s	2.47E+13	No Signal on BTV				
	12h58min07s	2.49E+13	0.24	0.25	-0.46	0.73	Strange signal on LDV
	13h06min14s	2.50E+13	0.24	0.24	-0.45	0.74	
	13h10min21s	3.35E+13	0.2	0.23	-0.44	0.73	
	13h14min26s	3.34E+13	0.2	0.22	-0.44	0.72	

For this run, a red filter in front of the BTV camera in TT61 has been installed



RP Monitor PMIHR02, showing residual dose rate versus time

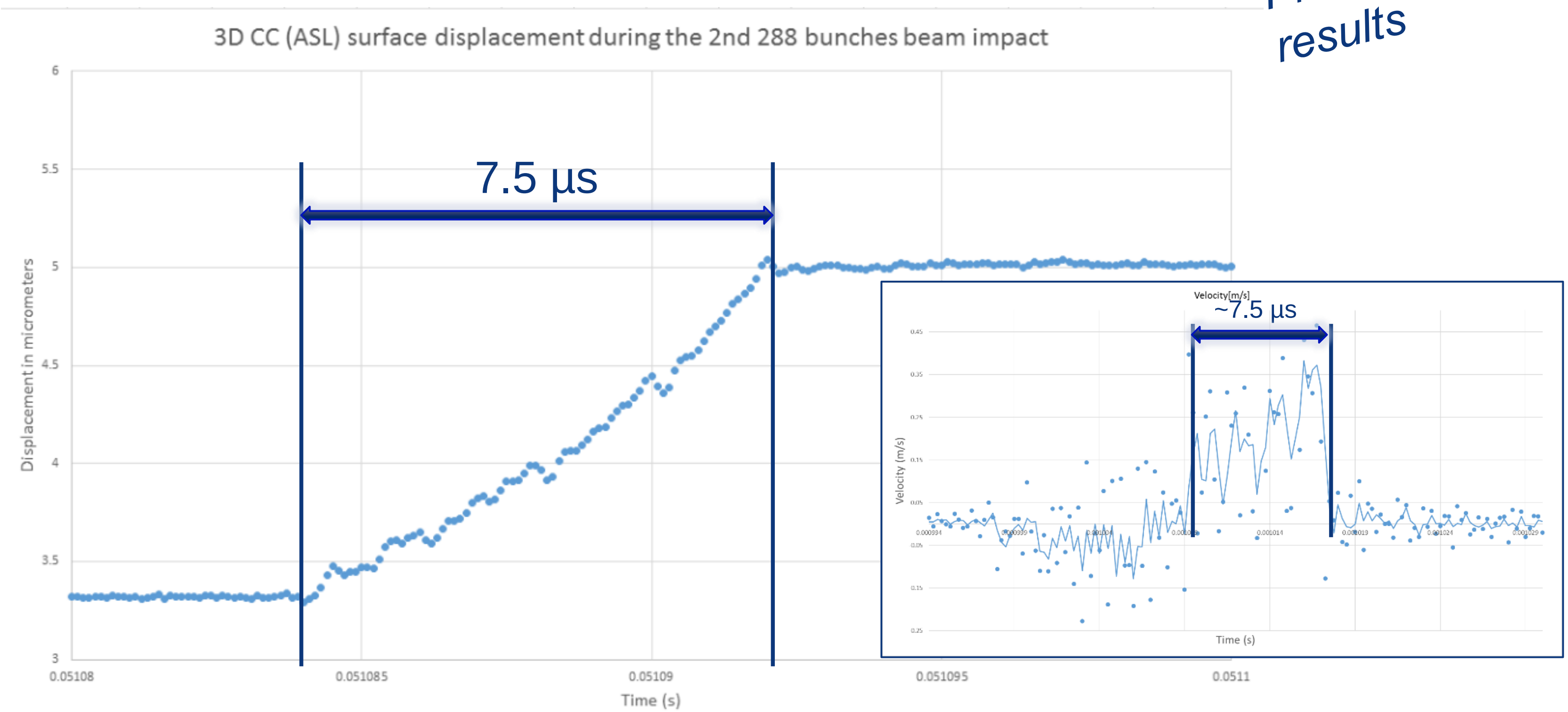
Optometer alignment with the beam (3D CC)



A precise alignment of the LDV with the beam was achieved (better than 0.15mm) ✓

3D CC surface displacement when impacted (LDV 10 MHz)

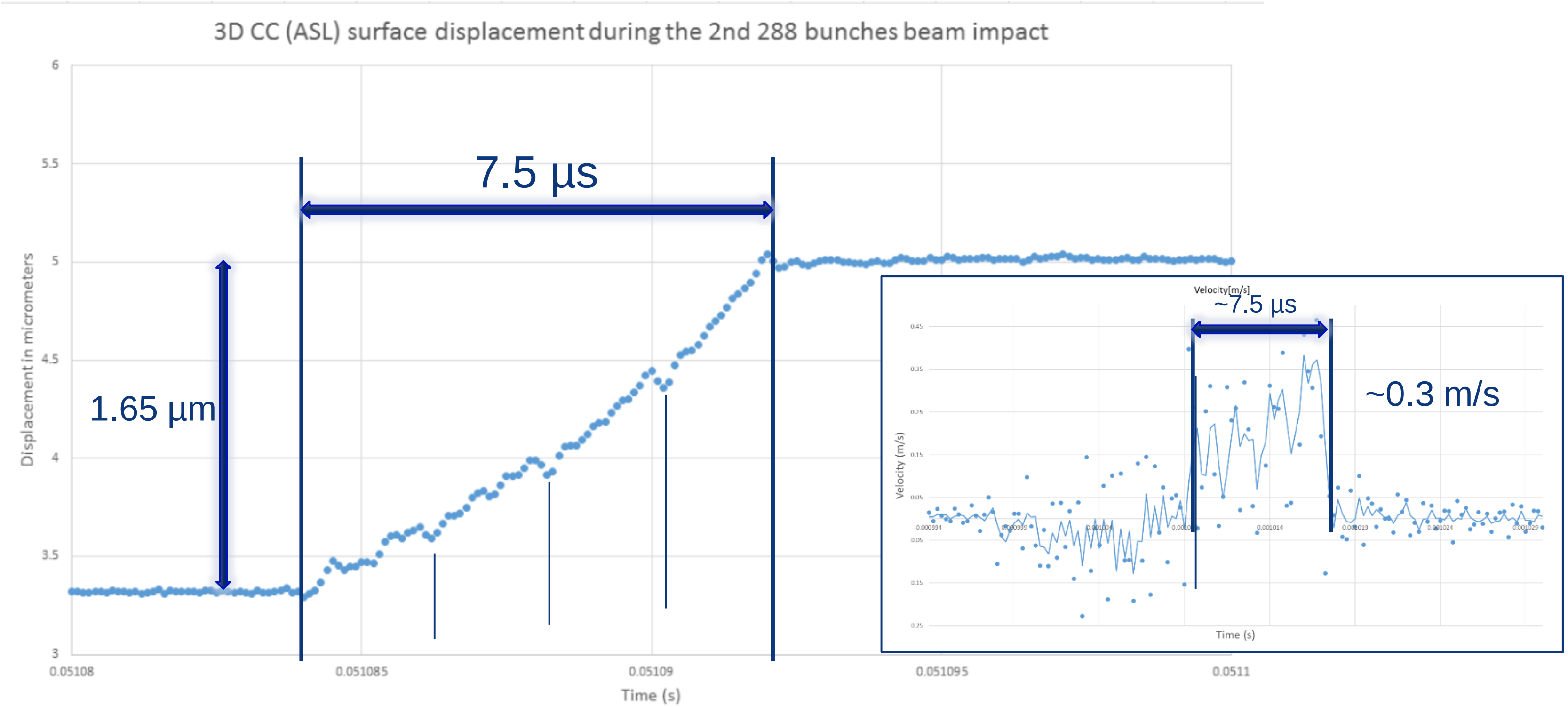
Preliminary results



Quick analysis:

- Correct bunch length ✓
- Expected magnitude of the surface displacement ✓

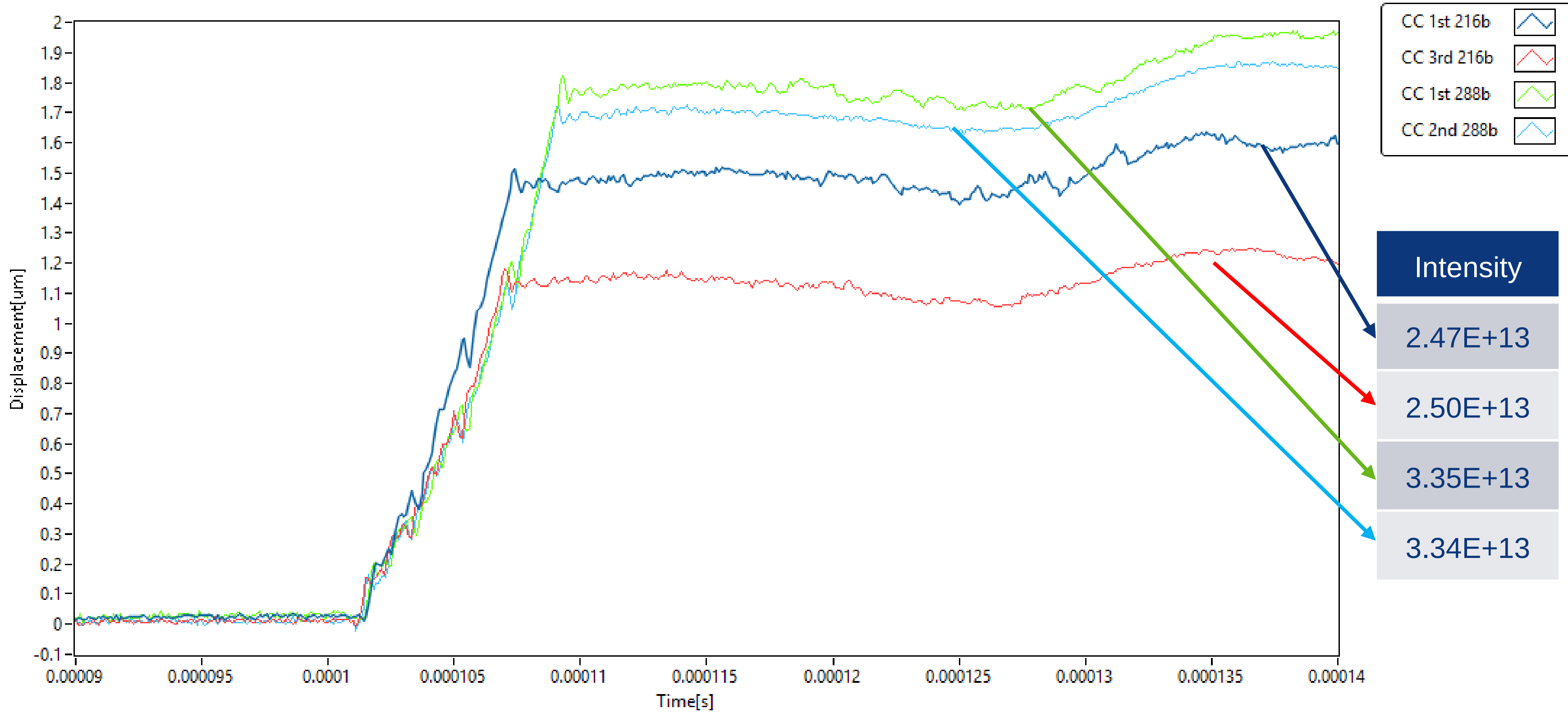
3D CC surface displacement when impacted (LDV 10 MHz)



Quick analysis:

- Correct bunch length ✓
- Expected magnitude of the surface displacement ✓

3D CC (ASL) surface displacement for 5 consecutive high intensity shots (LDV interface 10 MHz), 27-06-2017 (one 216 b shot not recorded)



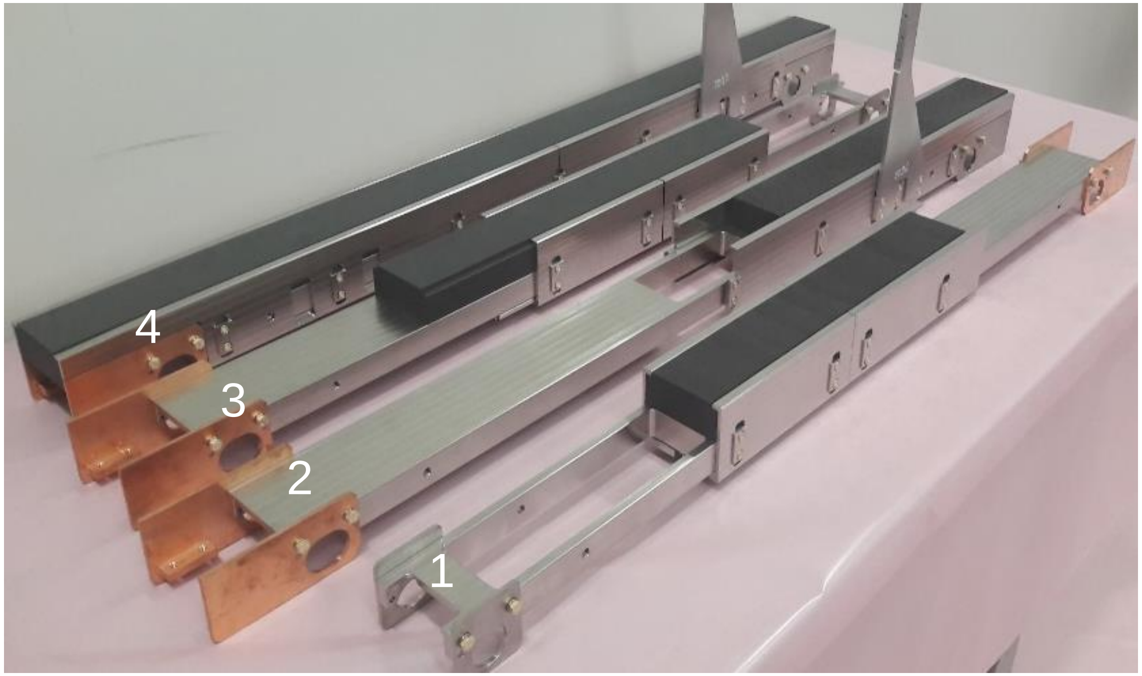
- The very similar surface displacement curves over time are is an indicator that no beam induced damage occurs on the material, shot after shot.
- The amplitude difference for the 1st and 3rd shots at 216b can be due to a small beam spot jitter in X.

Experiment dismantling in 867/R-P58

Installation in a fully cleaned bunker

The opened vacuum vessel with jaws removed

Targets (jaws) dismounting in 867/R-P58



RP measurements on the 25.07.17 at 16h45

1 / contact: 320 µSv/h, 10 cm: 70 µSv/h, 40 cm: 25 µSv/h

2 / contact: 370 µSv/h, 10 cm: 73 µSv/h, 40 cm: 27 µSv/h

3 / contact: 280 µSv/h, 10 cm: 52 µSv/h, 40 cm: 15 µSv/h

4 / contact: 280 µSv/h, 10 cm: 63 µSv/h, 40 cm: 17 µSv/h

High intensity shots on the 13/06/2017

Target	Time	Intensity	BTV Sigma X (mm)	BTV Sigma Y (mm)	BTV Position in X (mm)	BTV Position in Y (mm)		Calculated Sigma X (mm)	Calculated Sigma y (mm)	Position in X (mm) BPKG	Impact parameter expected
SGL R4550® graphite	18h43min28s	2.39E+13	0.44	0.49	-0.22	0.9		0.203054	0.232736	Meaningless because BPKG not perfectly aligned with BTV524	
	18h57min04s	2.37E+13	0.43	0.42	-0.29	0.89		0.208802	N/A		
	19h09min52s	**3.23E+13**	0.42	0.48	-0.3	0.91		**0.205414**	**0.280867**		??
	19h27min28s	3.23E+13	0.43	0.44	-0.23	0.85	Jaw moved by 0.3mm within the beam	**0.204648**	**0.286383**		**1.5 σ**
Mersen 2123UHP5 ® graphite	19h42min40s	2.42E+13	0.49	0.28	-0.3	0.88		0.192967	0.283735		
	19h46min40s	2.44E+13	0.52	0.3	-0.33	0.86		0.197366	0.285878		
	19h50min40s	3.25E+13	0.4	0.24	-0.29	0.91		N/A	0.275063		
	19h57min04s	3.25E+13	0.38	0.39	-0.32	0.79	Jaw moved by 0.3mm within the beam	0.195948	0.276492		

High intensity shots on the 16/06/2017

Target	Time	Intensity	BTV Sigma X (mm)	BTV Sigma Y (mm)	BTV Position in X (mm)	BTV Position in Y (mm)	Calculated Sigma X (mm)	Calculated Sigma y (mm)	Impact parameter expected	
ASL Sepcarb 3D CC	18h42min 24s	2.77E+13	0.29	0.4	-0.32	0.95	0.200881	0.388974		
	18h52min 48s	2.94E+13	0.28	0.4	-0.28	1.02	0.194461	0.283627		
	19h26min 24s	3.82E+13	0.3	0.34	-0.33	0.88	0.203367	0.293693	**1.5 σ**	
	19h30min 24s	**3.81E+13**	0.36	0.29	-0.36	0.9	**0.19739**	**0.288927**	**1.5 σ**	
Mersen 3D CC	19h00min 00s	2.91E+13	0.26	0.38	-0.32	1	0.20366	0.256023		
	19h04min 00s	2.91E+13	0.28	0.34	-0.31	1	0.191674	0.279542		
	19h20min 00s	3.89E+13	0.28	0.33	-0.32	0.92	0.194497	0.298098	**1.5 σ**	
	19h22min 24s	3.77E+13	0.28	0.37	-0.33	0.91	0.204685	0.295752	**1.5 σ**	