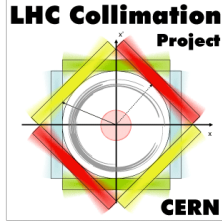# Damage Thresholds for New Collimator Materials, Experiment Detectors and SC Magnet Components

F. Carra (EN-MME), C. Bertella (EP), A. Sbrizzi (EP), D. Wollmann (TE-MPE)
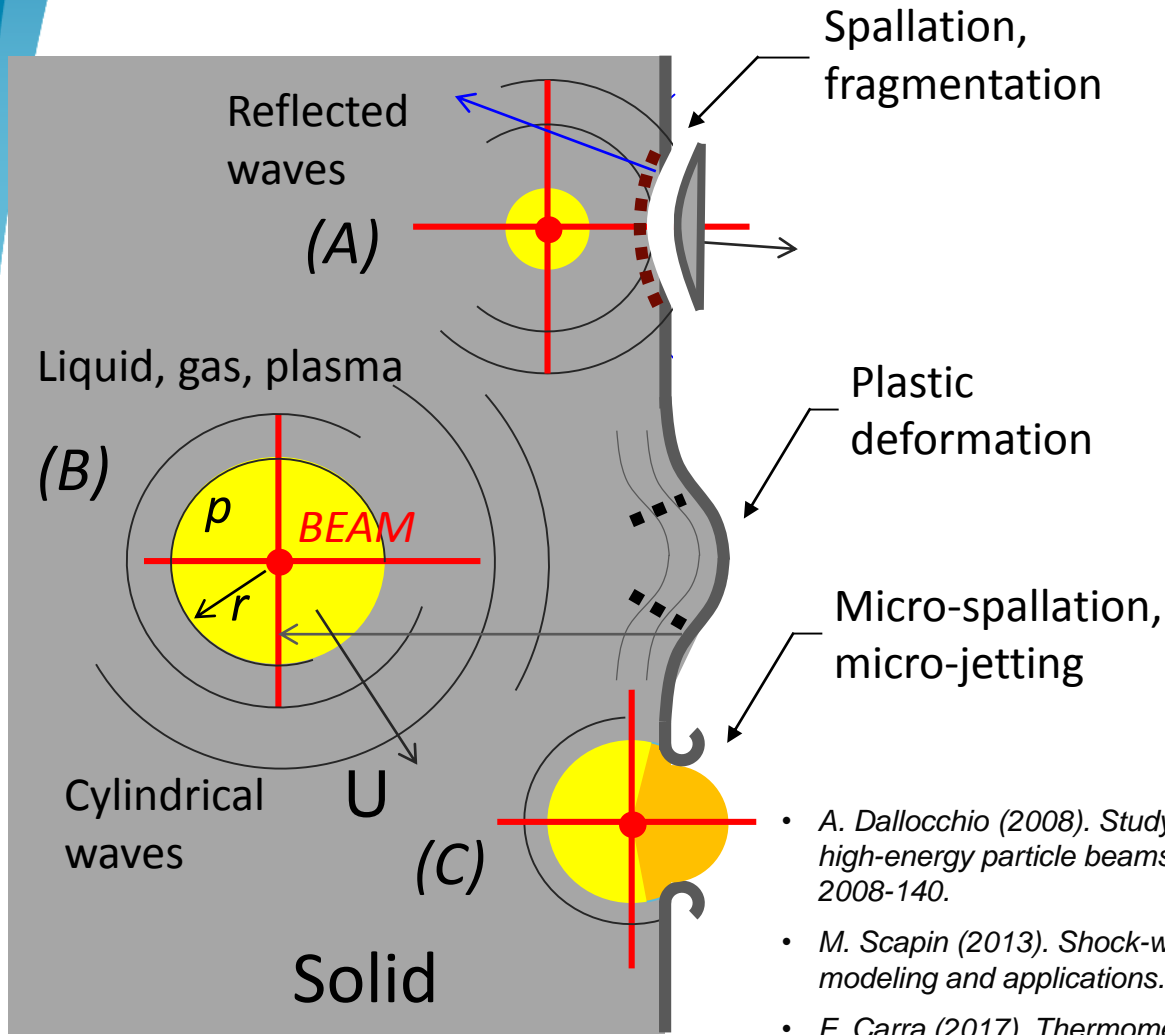With contributions from colleagues of EN-MME, BE-ABP, EN-STI, TE-MPE, EP

MPP Workshop 2019

Chateau de Bossey

May 7th, 2019

Outline

- Introduction

  - Particle beam – matter interactions

  - Damage mechanisms

- Collimator materials

  - HiRadMat experiments

  - Damage thresholds

- SC magnet components

- ATLAS detectors

- Conclusions

Introduction to beam damage

Spallation, fragmentation

Reflected waves

(A)

Liquid, gas, plasma

(B)

p

BEAM

r

Cylindrical waves

U

(C)

Solid

Plastic deformation

Micro-spallation, micro-jetting

Cylindrical spreading loss

- **Far from the impact point**
  - $P \propto r^{-1/2}$ (for spherical: r^{-1})
  - $E \propto r^{-1}$ (for spherical: r^{-2})
- **Close to the impact**
  - Logarithmic singularity

- A. Dallocchio (2008). *Study of thermomechanical effects induced in solids by high-energy particle beams: analytical and numerical methods.* CERN-THESIS-2008-140.
- M. Scapin (2013). *Shock-wave and high strain-rate phenomena in matter: modeling and applications.* PhD thesis, 10.6092/polito/porto/2507944.
- F. Carra (2017). *Thermomechanical Response of Advanced Materials under Quasi Instantaneous Heating.* PhD thesis, https://zenodo.org/record/1414090.

Introduction to beam damage

- Damage is triggered by the energy absorbed by the material
- Two parameters controlling the damage:
  - **Energy density peak** e_p (J/cm^3) → localized effects, the onset of damage, …
  - **Average energy per target section** $\bar{e}_s$ (J/cm^3) → global response of the target, the damage far from the impact, …

Energy density peak (e_p)

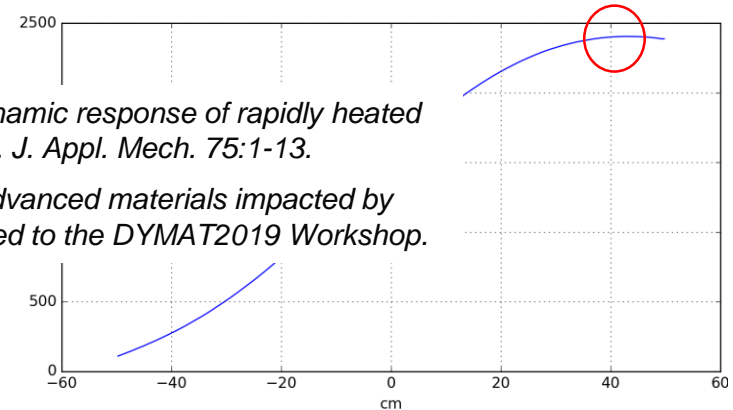**Average energy on the most loaded section ($\bar{e}_s$)**
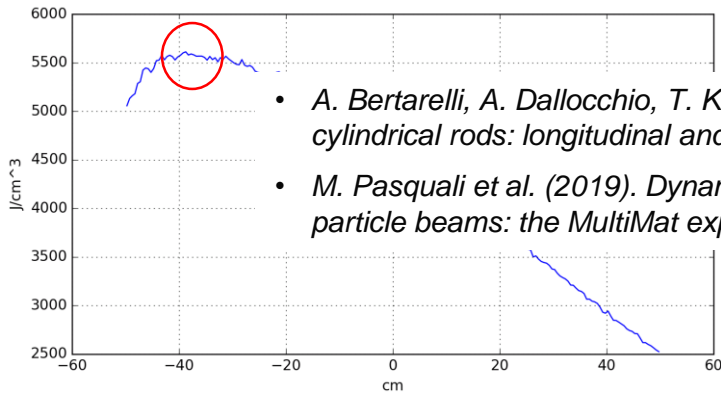
- *A. Bertarelli, A. Dallocchio, T. Kurtyka (2008). Dynamic response of rapidly heated cylindrical rods: longitudinal and flexural behavior. J. Appl. Mech. 75:1-13.*
- *M. Pasquali et al. (2019). Dynamic response of advanced materials impacted by particle beams: the MultiMat experiment. Submitted to the DYMAT2019 Workshop.*

$$T_p = \frac{e_p}{\rho c_p} > T_{lim} \rightarrow \text{DAMAGE}$$

$$\varepsilon_p = f(\alpha T_p) > \varepsilon_{lim} \rightarrow \text{DAMAGE}$$
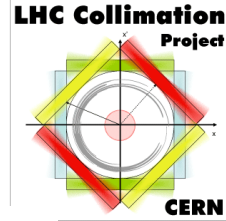
$$\bar{e}_s = \bar{E}_s \big/ A$$

$$\bar{T}_s = \frac{\bar{e}_s}{\rho c_p}$$

$$\varepsilon_s = 2\alpha\bar{T}_s > \varepsilon_{lim} \rightarrow \text{DAMAGE}$$

Collimator damage thresholds

- **Three damage thresholds** defined for collimator materials.

  - Introduced for metallic (ductile) materials see MPP Workshop 2013, Annecy. Extended here to graphitic ones.

  - Defined as a function of the effect on the collimator behaviour.

- **Threshold 1**: onset of damage, with no need to activate the 5th axis.

  - Ductile materials: onset of plasticity.

  - Graphitic materials: crack initiation, local material ablation.

- **Threshold 2**: damage to the surface requiring correction with the 5th axis.

  - Ductile materials: it usually involves heavy plastic deformation and/or ejecta generation.

  - Graphitic materials: pseudo-plastic deformation, internal delamination, important material ablation, …

- **Threshold 3**: damage cannot be corrected with 5th axis anymore.

  - Ductile materials: significant material erosion and plastic deformation in the jaw, no more flat surface close to the impact.

  - Graphitic materials: fracture of the blocks jeopardizing the structural integrity, complete block face delamination with loss of the flatness.
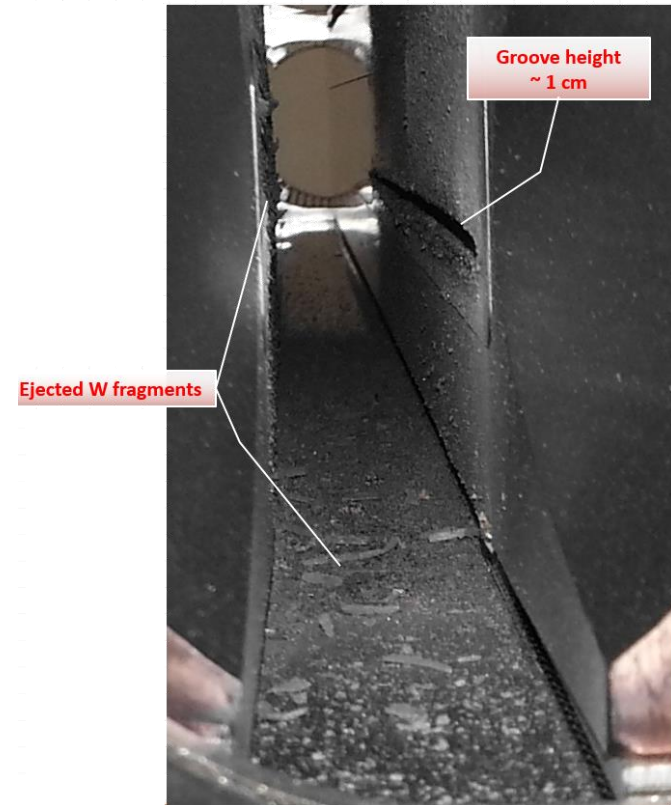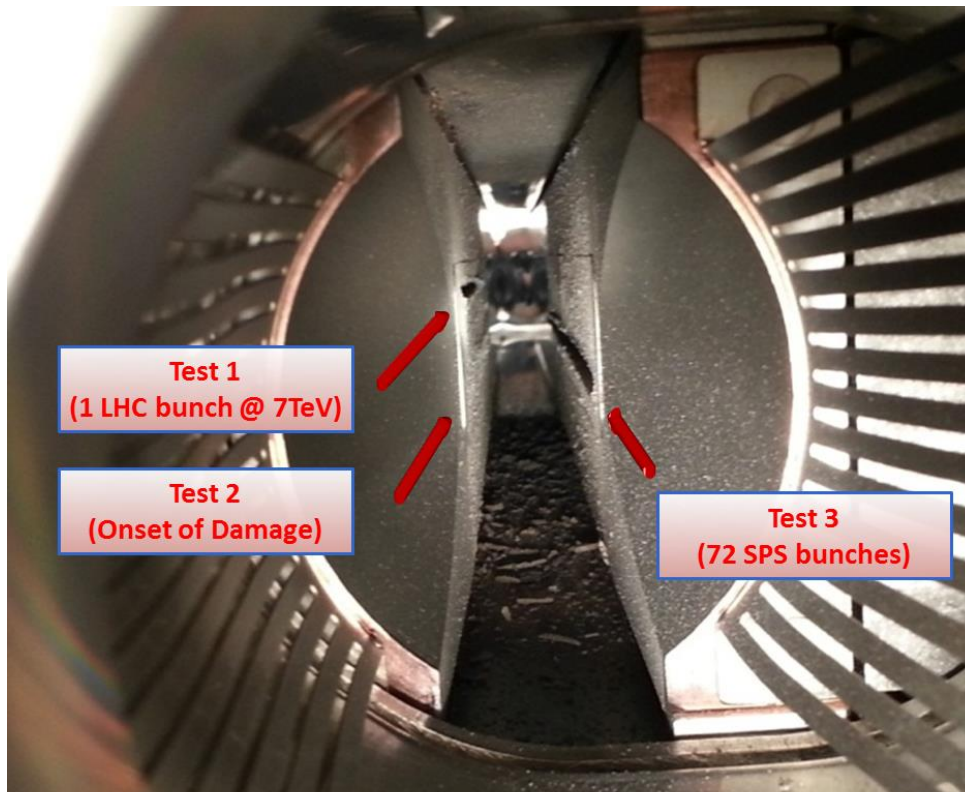
Collimator materials
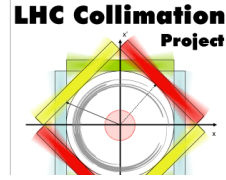
- The evaluation of material response to beam impact is done in two ways:

    - **Numerical simulations** (FLUKA + ANSYS, Autodyn, LS-Dyna)

    - **Experimental tests** (HiRadMat: on full-scale devices or on simple geometry targets)

- The damage thresholds are estimated with a **combination of the two techniques**

- **HiRadMat experiments** on collimator materials and devices:

    - HRMT-09 (2012): TCT collimator (Inermet180)

    - HRMT-14 (2012): collimator material samples (cylinders and half-moons)

    - HRMT-23 (2015): LHC and HL-LHC collimator jaws (CFC, MoGr, CuCD)

    - HRMT-21 (2017): Rotatable collimator (Glidcop) → *see backup slides*

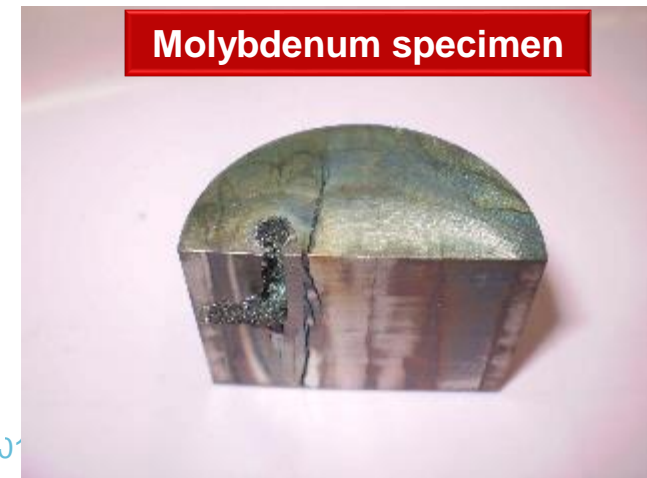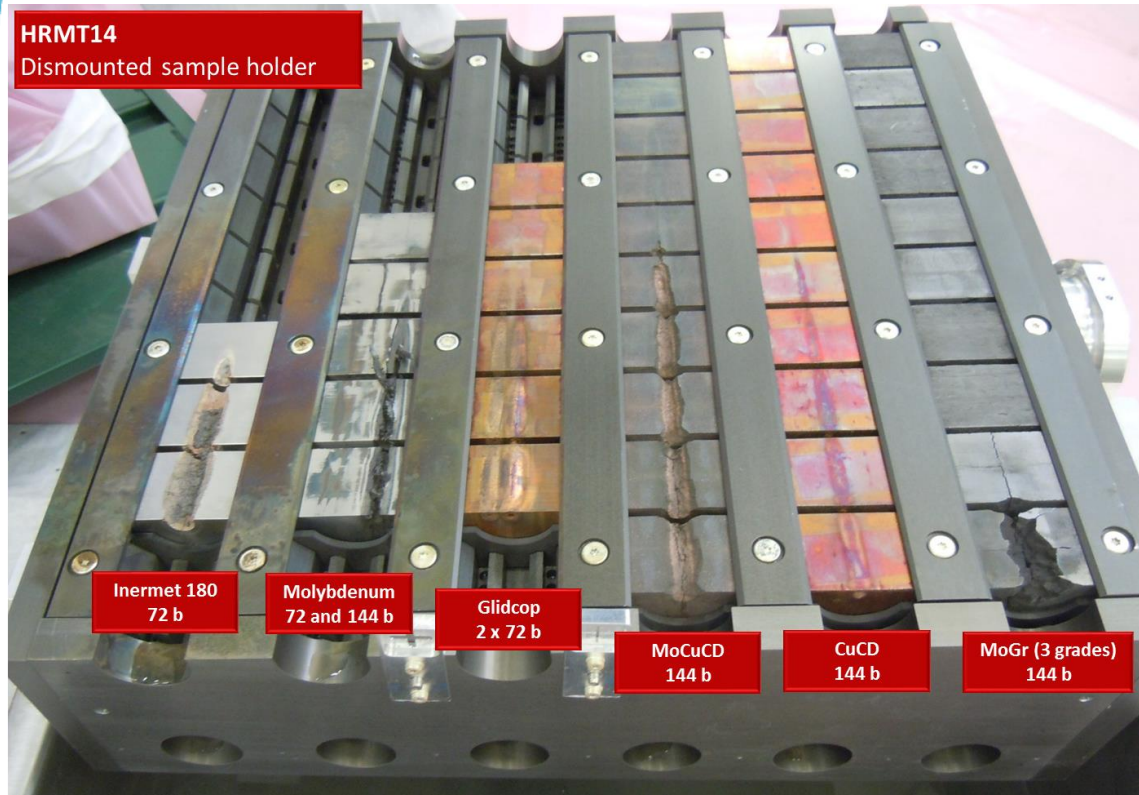   - HRMT-36 (2017): collimator material samples (rods, uncoated and coated)

- Testing of a spare TCT collimator

- Allowed to derive **damage limits for tertiary collimator jaws** (Inermet180)

- Highlighted **additional potential machine protection issues on top of mechanical damage**, due to projection of fragments and dust (UHV degradation, contamination of vacuum chambers, complication of dismounting procedure)

Test 1
(1 LHC bunch @ 7TeV)

Test 2
(Onset of Damage)

Test 3
(72 SPS bunches)

Groove height ~ 1 cm

Ejected W fragments

- *M. Cauchi (2014). High energy beam impact tests on a LHC tertiary collimator at the CERN high-radiation to materials facility. Phys. Rev. ST Accel. Beams 17, 021004.* May 2019

7

HRMT-14 (2012)

- Test of specimens from 6 different materials: Inermet180, Mo, Glidcop, MoCuCD CuCD, and MoGr (very old grade with high density, 5.4 g/cm^3)

- Allowed **characterization of materials of interest for collimators**

- **Tuning of numerical models, with very good benchmarking between measurements and simulations**


HRMT14
Dismounted sample holder

Inermet 180
72 b

Molybdenum
72 and 144 b

Glidcop
2 x 72 b

MoCuCD
144 b

CuCD
144 b

MoGr (3 grades)
144 b

Inermet specimen

Molybdenum specimen

- *A. Bertarelli et al. (2013). An experiment to test advanced materials impacted by intense proton pulses at CERN HiRadMat facility. Nucl. Instr. Meth. Phys. Res. B 308:88–99.*

HRMT-23 (2015)
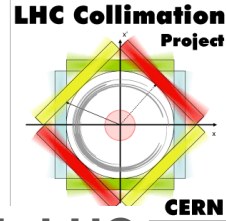
- Test on **three collimator jaws: CFC (LHC design), MoGr and CuCD (HL-LHC design)**
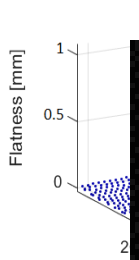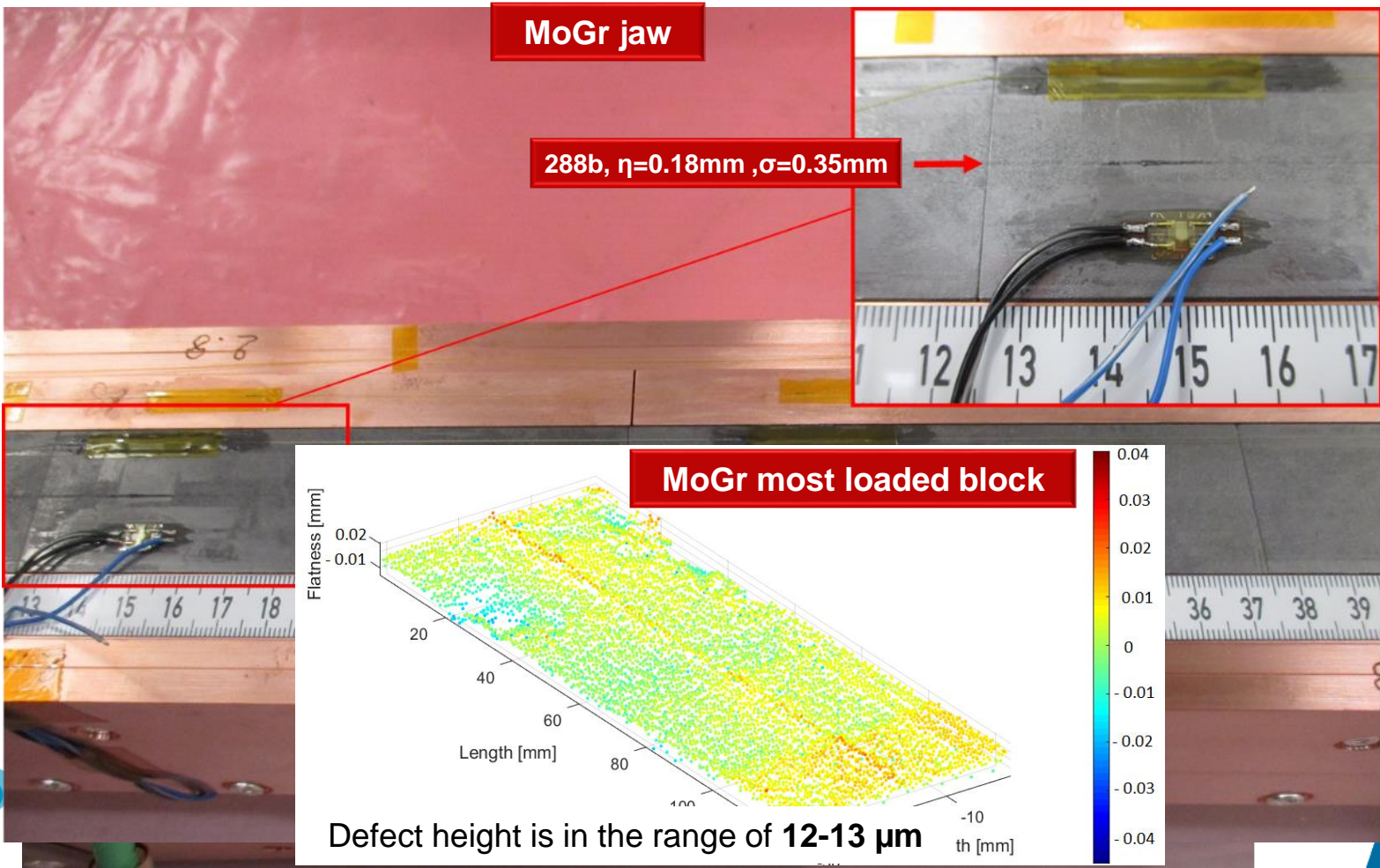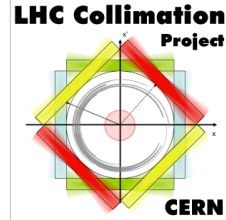

HL design

and CFC: we

CuCD jaw

- *F. Carra (2017). Thermomechanical Response of Advanced Materials under Quasi Instantaneous Heating. PhD thesis, https://zenodo.org/record/1414090.*
- *G. Gobbi et al. (2019). Novel LHC collimator materials: High-energy Hadron beam impact tests and non-destructive post-irradiation examination. Journal of Mechanics of Advanced Materials and Structures.*
- *F. Carra et al. (2019). Mechanical robustness of HL-LHC collimator designs. Accepted in IPAC19, Melbourne, Australia.*

- In the case of CFC and MoGr, minor traces visible after the grazing impacts at 144b and 288b (spallation: onset of damage → *threshold 1*)

- Deeper impacts (even at 288b) → no damage (smaller tensile wave at surface)

- No $\bar{e}_s$-induced damage on downstream blocks

MoGr jaw

288b, η=0.18mm ,σ=0.35mm →

MoGr most loaded block

Defect height is in the range of **12-13 μm**

HRMT-36 (2017)

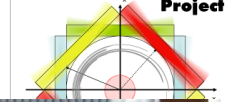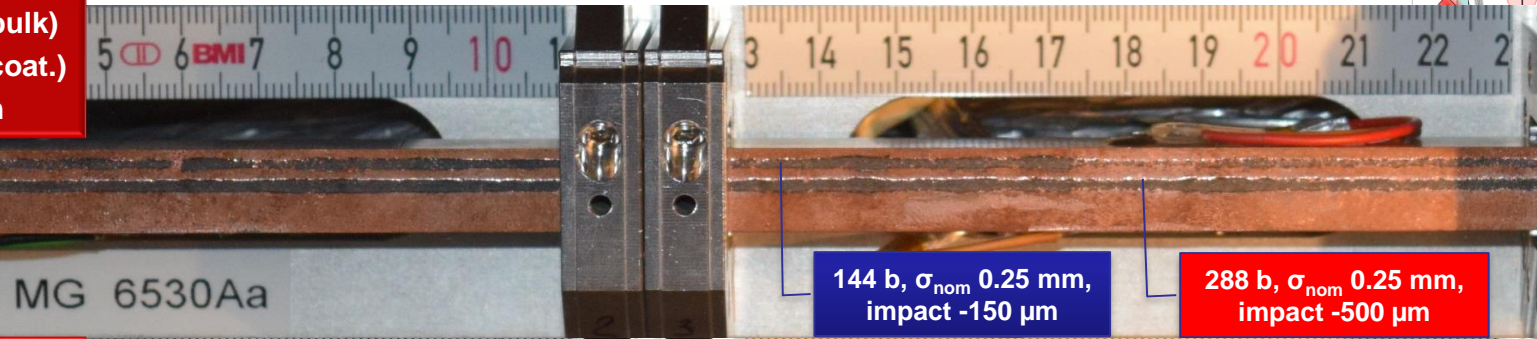| #	Material	Density [g/cm³]	Coated	Coating Material	
1	IT180	18.0	✘		high density
2	Ta10W	16.9	✘		
3	Ta2.5W	16.7	✘		
4	TZM	10.0	✘		
5	CuCD IFAM	5.40	✘		medium density
6	CuCD RHP	5.40	✘		
7	SiC	3.21	✘		
8	MG-6403Fc	2.54	✓	5μm TiN	low density
9	ND-7401-Sr	2.52	✘		
10	MG-6530Aa	2.50	✓	2μm Cu	
11	MG-6541Fc	2.49	✓	8μm Mo	
12	TPG	2.26	✘		
13	TG-1100	2.19	✘		
14	R4550	1.90	✓	2μm Cu	
15	CFC AC150K	1.88	✓	8μm Mo	
16	Ti6Al4V (AM)	1.62	✘		
17	CFOAM	0.40	✘		
18	Al 6082-T651 (UoHud)	2.70	✘		Dedicated setup

- Test on 16 target stations, including **coated and uncoated material targets (rods)** and electronic devices

- Specimen geometry chosen to:

  - Generate easily detectable **uniaxial signals**

  - **Enhance $\bar{e}_s$ (factor 2-3 above HL-LHC!)** thanks to sample section ~1/10 of collimator jaw section

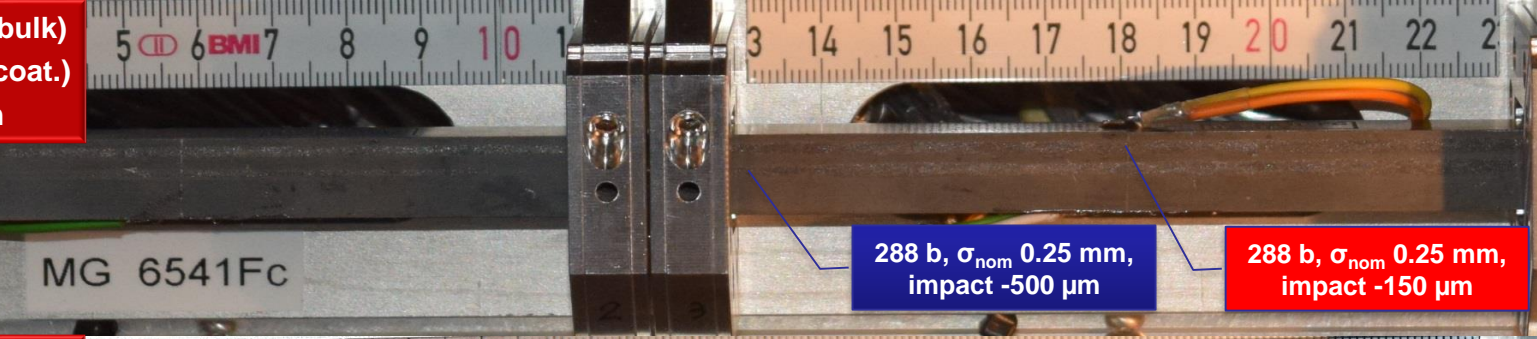 - e_p **enhanced by squeezing the beam** (30-50% above HL-LHC)

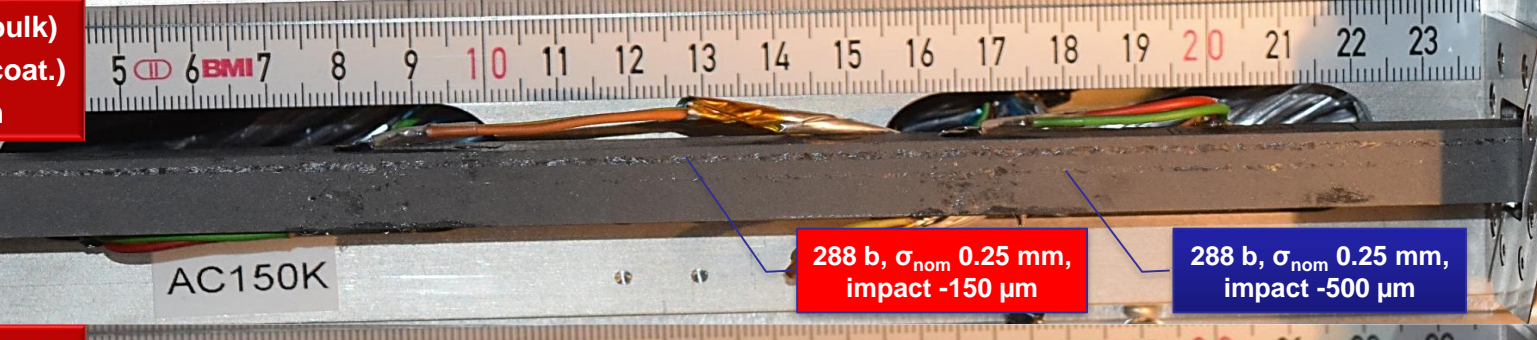F. Carra (CERN), 7 May 2019

HRMT-36 (2017)

LHC Collimation Project
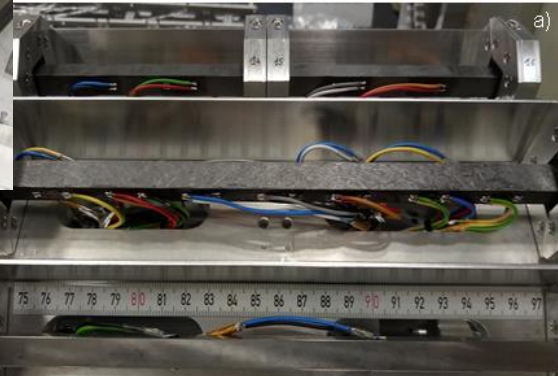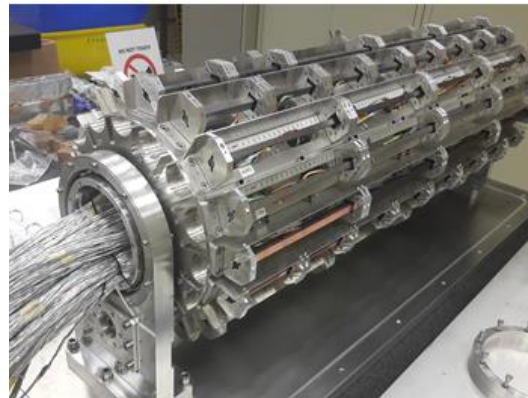
E_{MAX}=7.68 kJ/cm^3 (bulk)
E_{MAX}=15.3 kJ/cm^3 (coat.)
σ_{real} =0.29x0.26 mm

MG 6530Aa

144 b, σ_{nom} 0.25 mm, impact -150 μm

288 b, σ_{nom} 0.25 mm, impact -500 μm

E_{MAX}=6.11 kJ/cm^3 (bulk)
E_{MAX}=13.9 kJ/cm^3 (coat.)
σ_{real} =0.29x0.31 mm

MG 6541Fc

288 b, σ_{nom} 0.25 mm, impact -500 μm

288 b, σ_{nom} 0.25 mm, impact -150 μm

E_{MAX}=3.72 kJ/cm^3 (bulk)
E_{MAX}=14.3 kJ/cm^3 (coat.)
σ_{real} =0.38x0.23 mm

AC150K

288 b, σ_{nom} 0.25 mm, impact -150 μm

288 b, σ_{nom} 0.25 mm, impact -500 μm

Graphite (R4550) with 2 μm Cu + 0.5 μm Ti coating – CO_2 blasting

R4550

144 b, σ 0.25 mm, impact 150 μm

288 b, σ 0.25 mm, impact 150 μm
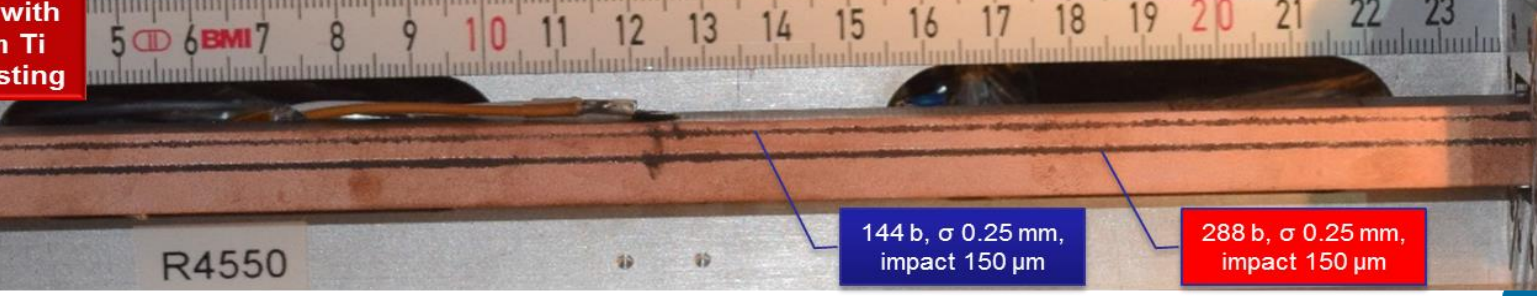
HRMT-36 (2017)
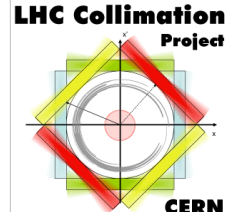
- On top of observing the onset of damage related to e_p **(upstream samples)**, onset of damage related to $\bar{e}_s$ **(downstream)** also identified

- Sample section ~1/10 of collimator block section → increased $\bar{e}_s$
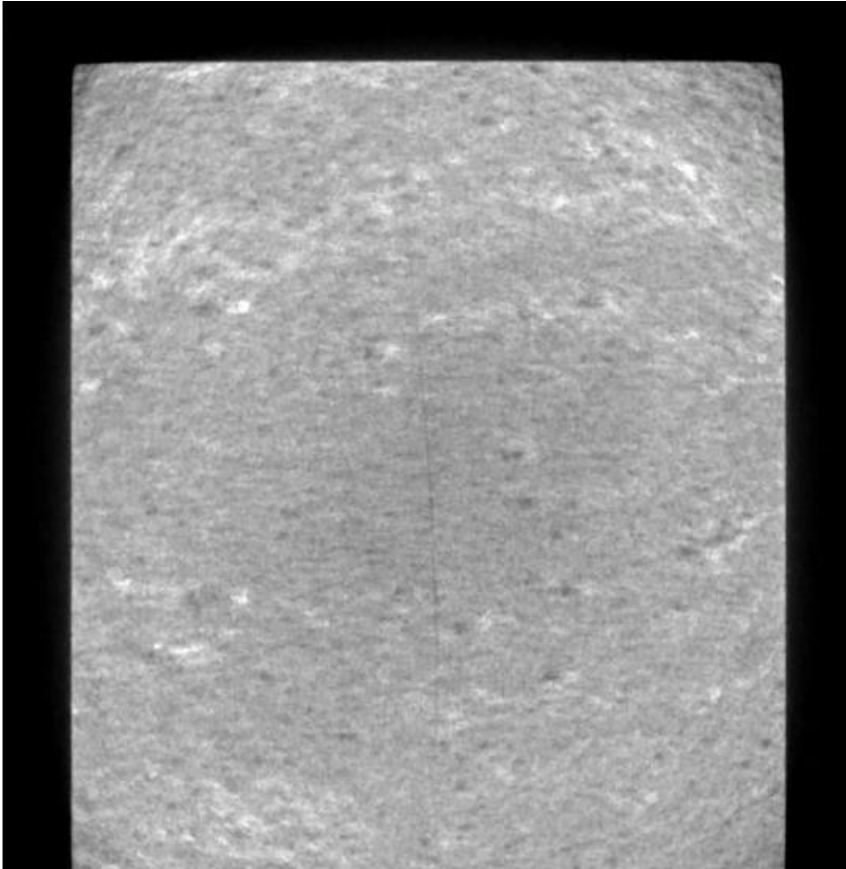
**MoGr sample n. 8
(highest average energy density per section)**

- Appearing on samples with $\bar{e}_s$ 2.5 higher than HL-LHC accidents

- Samples with $\bar{e}_s$ equal to HL-LHC → below onset of damage

- *F. Carra et al. (2017). The "Multimat" experiment at CERN HiRadMat facility: advanced testing of novel materials and instrumentation for HL LHC collimators. J. Phys.: Conf. Ser., Vol 874, Issue 1.*

- *A. Bertarelli et al. (2018). Dynamic testing and characterization of advanced materials in a new experiment at CERN HiRadMat facility. J. Phys.: Conf. Ser.1067 082021.*

- *M. Pasquali et al. (2019). Dynamic response of advanced materials impacted by particle beams: the MultiMat experiment. Submitted to the DYMAT2019 Workshop.*

- *F. Carra et al. (2019). Mechanical robustness of HL-LHC collimator designs. Accepted in IPAC19, Melbourne, Australia.*

# Collimator damage thresholds and accidental scenarios
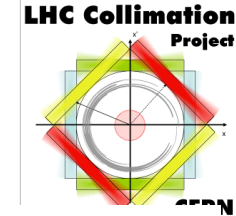
- Damage triggered by e_p (values in the table are in kJ/cm^3)
- For the thresholds not yet observed experimentally, the ">" symbol is used to indicate the most intense peak sustained by the material without reaching that threshold

Material	Damage threshold			HL case	
	1	**2**	**3**		**Beam injection error**
CFC	~1.6	*Not observed (> 3.8)*		–	2.6
Graphite	~2.1	*...observed (≫ 4.1)*		–	*Not calculated (> 2.6)*
MoGr		*...served (> 7.7)*	*Not observed (≫ 7.7)*	–	6.1
Inermet	0.6	2.5	15.6	35.6	–
CuCD	≤ 2.5	3.6	*Not observed (> 13.8)*	4.8	–

For coatings: the beam injection error provokes a damage equivalent to threshold 2, but below threshold 3; E_{max} ranging from 12 to 15 kJ/cm^3 depending on the coating material and on the substrate

Collimator damage thresholds and accidental scenarios
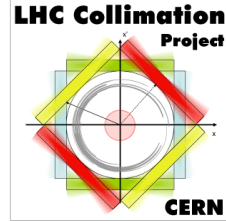
- Damage triggered by $\bar{e}_s$ (values in the table are in kJ/cm^3)

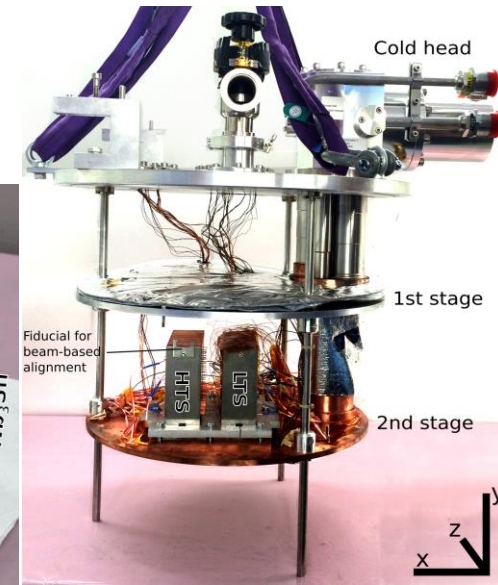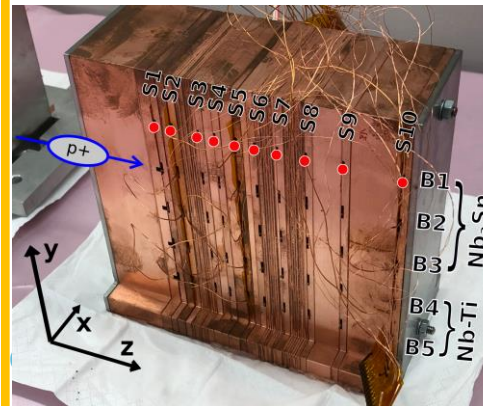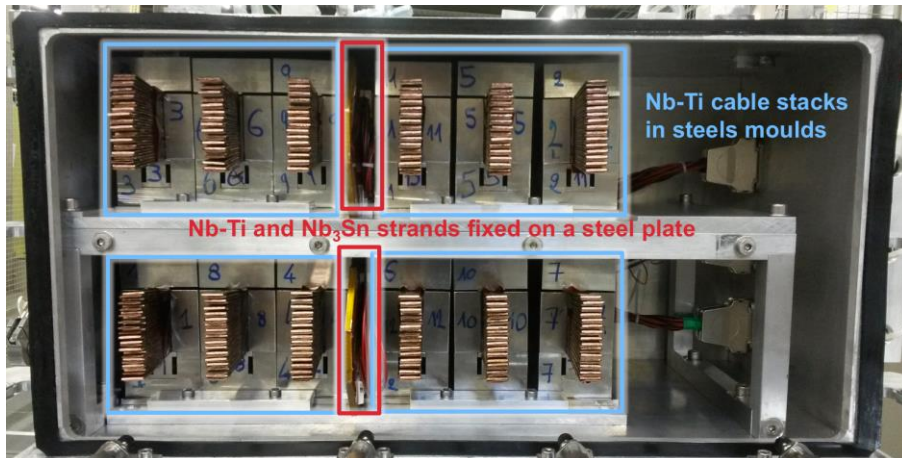| Material	Damage threshold			HL-LHC accidental case	
	1	**2**	**3**	Asy. beam dump	Beam injection error
CFC	*Not observed (>0.27)*	*Not observed ($\gg$0.27)*	*Not observed ($\gg$0.27)*	–	0.10
Graphite	*Not observed (>0.31)*	*Not observed ($\gg$0.31)*	*Not observed ($\gg$0.31)*	–	*Not calculated ($\approx$0.12)*
MoGr	~0.97	*Not observed ($\gg$0.97)*	*Not observed ($\gg$0.97)*	–	0.46

Damage levels on SC magnet components
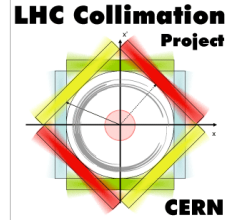
- **Criticality** of injection and dump failures **increases** with increased beam brightness and intensities for HL-LHC, energy deposition up to 100 J/cm^3 expected

- **Study the damage limit** of superconducting magnets components due to **beam impact**
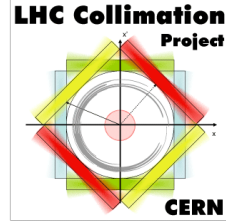
Room temperature experiment (09.2016):
- Nb-Ti & Nb$_3$Sn strands
- Cable stacks with polyimid insulation
- Up to **2.6e12 p$^+$** per shot @ 440 GeV
- Hotspots up to 1150 K reached in strands

Cryogenic experiment @ **4.5 K** (08.2018):
- Nb-Ti, Nb$_3$Sn strands & YBCO tapes
- Shots of **3e12 p$^+$** @ 440 GeV
- Hotspots **up to ~1250 K** reached in strands

Nb-Ti cable stacks in steels moulds

Nb-Ti and Nb$_3$Sn strands fixed on a steel plate

Cold head

Fiducial for beam-based alignment

1st stage

2nd stage

Main results of RT experiment

Polyimid insulation:

- **No degradation** measured after beam impact – temperature up to ~1050 K (2.5 kJ/cm^3)

- **Weakening** of the insulation at the point of the beam impact was observed for **T > 850 K** (1.9 kJ/cm^3)

Nb-Ti strands:

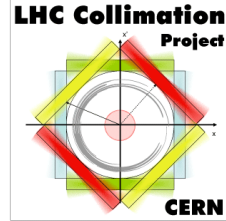- J_c degradation for hotspot temperatures **> 878 K** (2.2 kJ/cm^3)

Nb$_3$Sn strands:

- J_c degradation observed in **all samples** T ≥ 699 K (1.4 kJ/cm^3)

V. Raginel, et al., *First Experimental Results on Damage Limits of Superconducting Accelerator Magnet Components Due to Instantaneous Beam Impact*, IEEE Trans. Appl. SC, Vol 28(4), June 2018

V. Raginel, *Study of the Damage Mechanisms and Limits of Superconducting Magnet Components due to Beam Impact,* CERN-THESIS-2018-090

Observations after cryogenic experiment

- Clear **beam impact marks** on copper blocks of sample holder

- Nb-Ti strands: no visible deformation

- Nb_3Sn strands: **visibly bent** for hotspot temperatures > 700 K (2.2 kJ/cm^3), **cracks** in copper matrix

- YBCO tapes: **partial welding** to sample holder for hotspot temperature > 700 K

Critical transport current (I_c) measurements **ongoing** in collaboration with University of Geneva
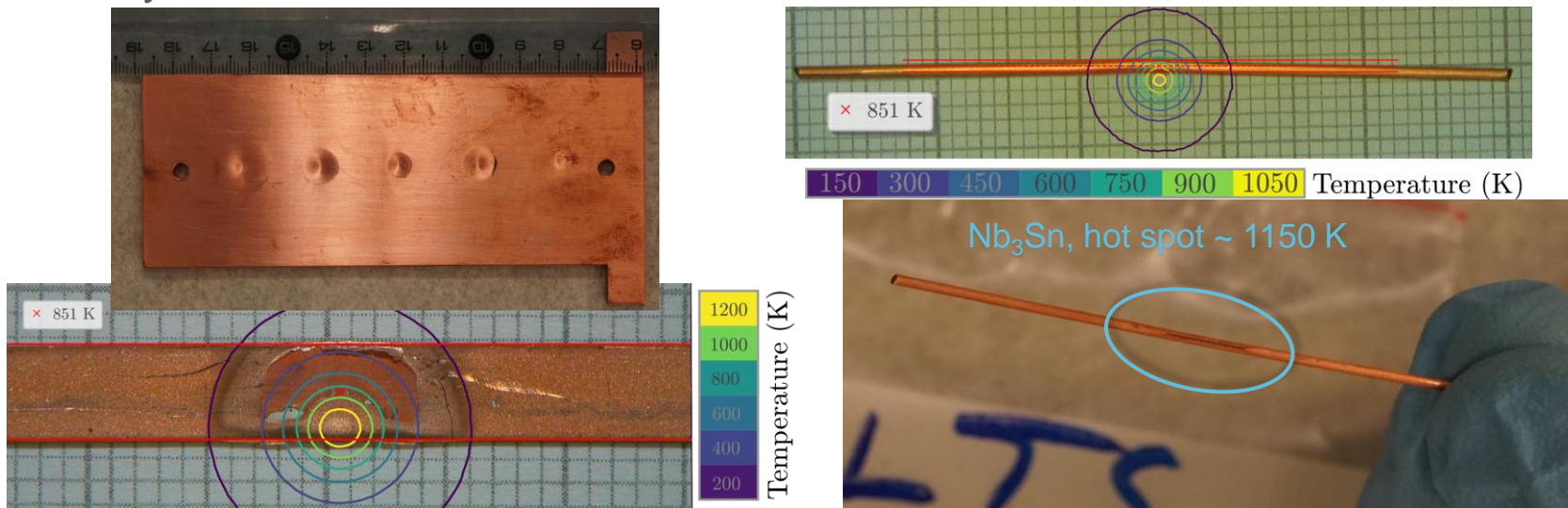

A. Oslandsbotn, A. Will, D. Wollmann, Beam Impact on Superconductor short samples of Nb3Sn, Nb-Ti and YBCO, 2018, EDMS 2068064

A. Will, et al., Beam impact experiment of 440GeV/p Protons on superconducting wires and tapes in a cryogenic environment, Proceedings of IPAC2019, to be published

ATLAS detectors

- ATLAS silicon tracker detectors: designed to sustain high integrated dose over several years of operation at the LHC. The upgrade of LHC to higher luminosity (HL-LHC) calls for new tests.

- HL-LHC failure scenarios: asynchronous beam dump or wrong injection settings.

- Inner tracker (ITk) will be entirely in Si. Latest tests under beam impact performed in July 2018.
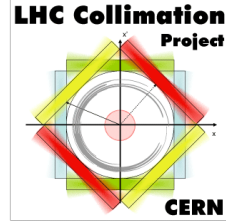

Beam position
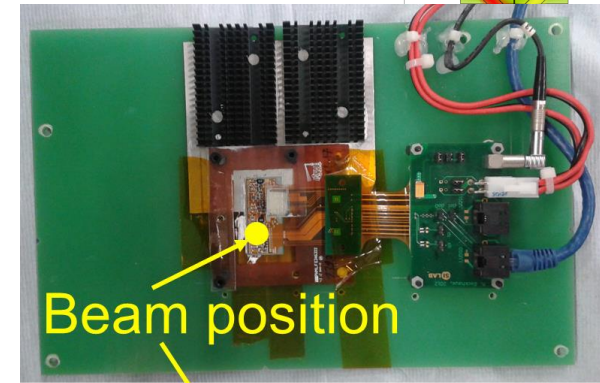
ITK DAQLoad
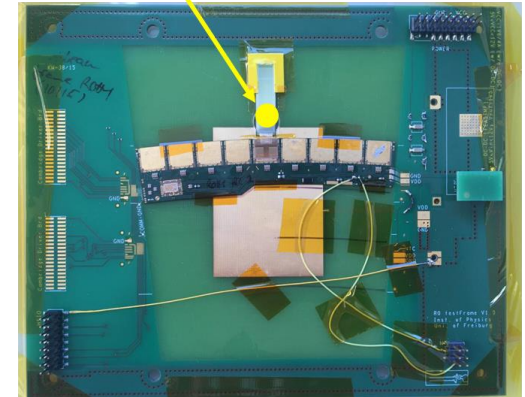
Module	IBL	ITk
Type	n^+-in-n, Planar	n^+-in-p, Low-R
Chip	FE-I4	ABC130
Total Size	2x4 cm^2	0.7x2.6 cm^2
Thickness	200 µm	310 µm
Channel/pitch	2x26680 (50x250 µm^2)	64 (77 µm)
Max. Dose	250 MRad	35 MRad

- ITk strip miniature sensor available for the beam test. ITk Pixel prototype with RD53A not available at that time, used most advance technology IBL.

- Improved cooling system via aluminium and dissipator: T~36℃

ATLAS detectors: IBL results

- Module tested in Stable beam configuration.

- Bulk and surface damage post-irradiation, cause a linear increase of the leakage current with the fluence.

- Monitoring of leakage current after each shot. Increase after irradiation: ~230 µA at 80 V.

- Noise increases around the beam spot in a similar way for the three modules.

- Limit on the damage threshold from **300·10^{10} p/cm^2 (2006) to 1·10^{13} p/cm^2 (2017/18).**
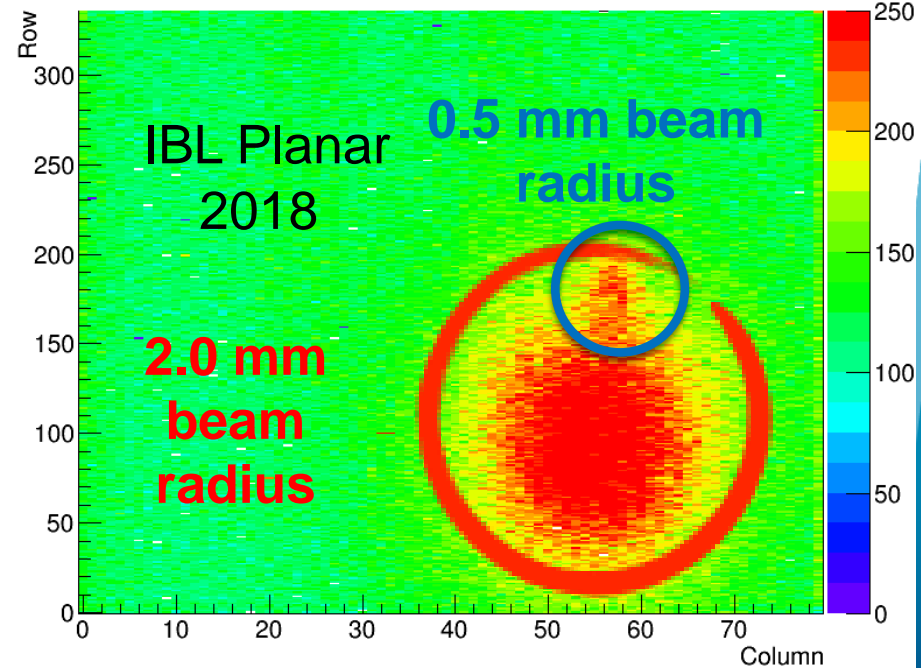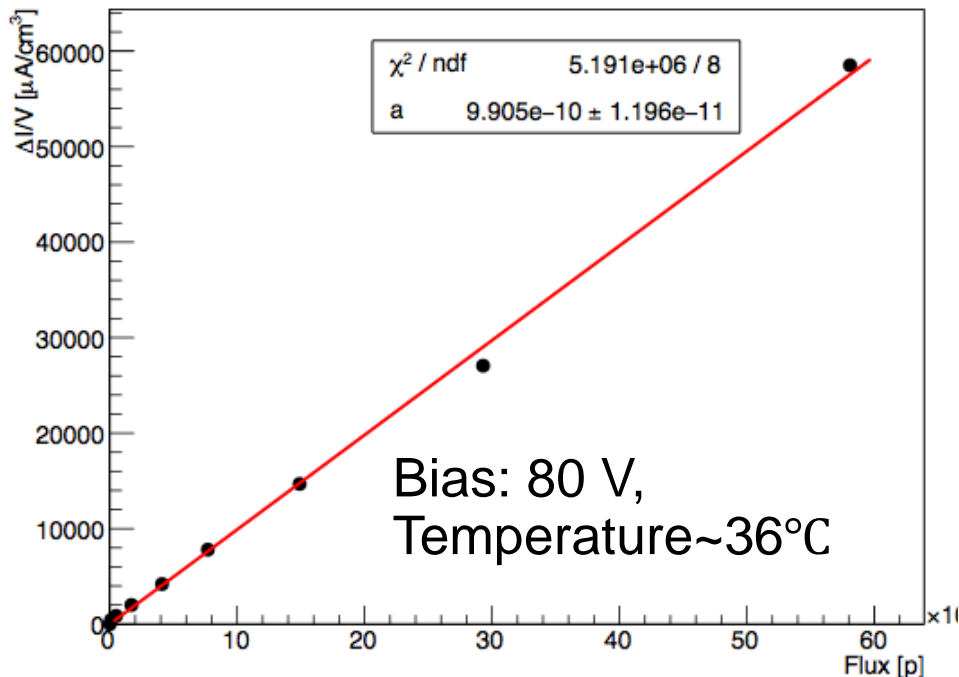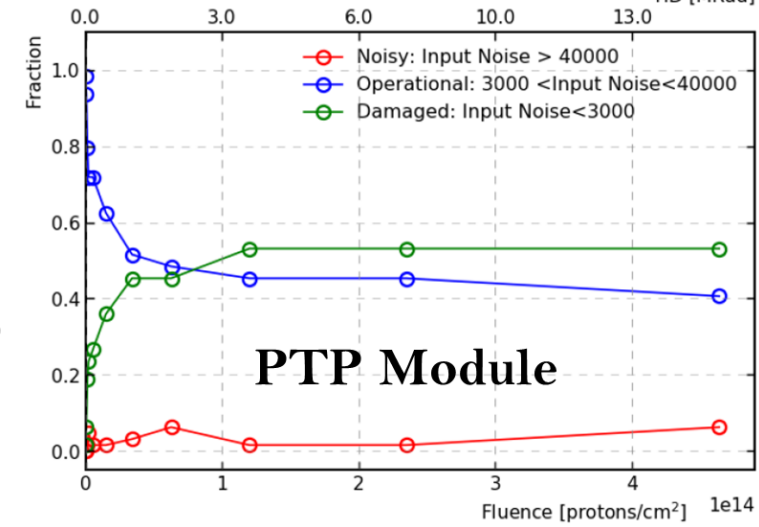
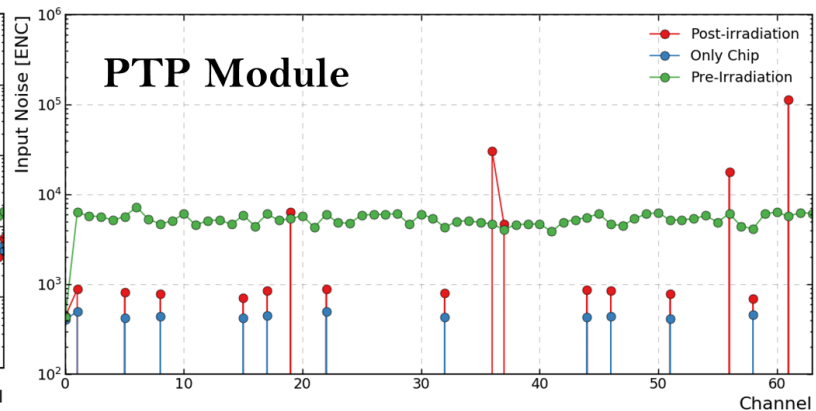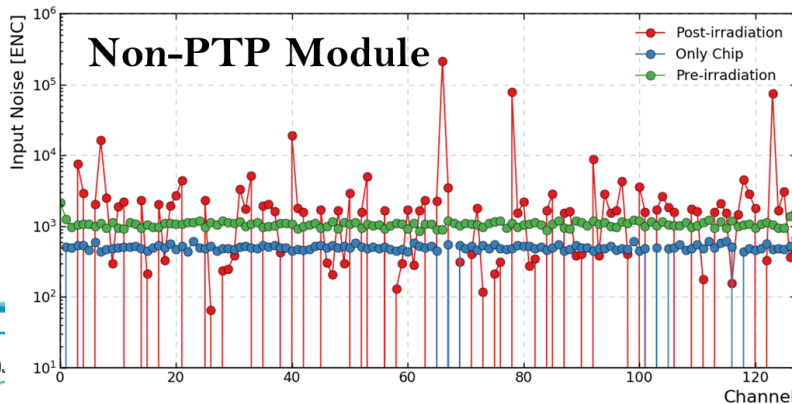# ITK STRIP: Influence on Read-out Electronics
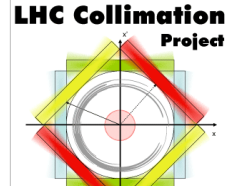
PTP Module:

- Module noise increase concentrated in the first shot
- Stable behavior before $1 \cdot 10^{13}$ proton (3 MRad)
- With increase of the proton fluence, a decreasing number of fully operating channels was observed
- **After about $6 \cdot 10^{13}$ protons (15 MRad) more than 50% of channels have been damaged for the PTP module**


Non-PTP Module:

- Unfortunately, due to connectivity problems during the experiment, the on-line monitoring of this sensor was not possible
- Noise and gain measurements before and after the beam-loss experiment showing typical values for silicon strip modules
- **Apparently no damage of beam-loss on the read-out channels for the non-PTP module**

ITK STRIP: Influence on Read-out Electronics

- After the beam-loss experiment, the sensors were disassembled from the testing modules and characterized
- Typical behavior of irradiated sensors
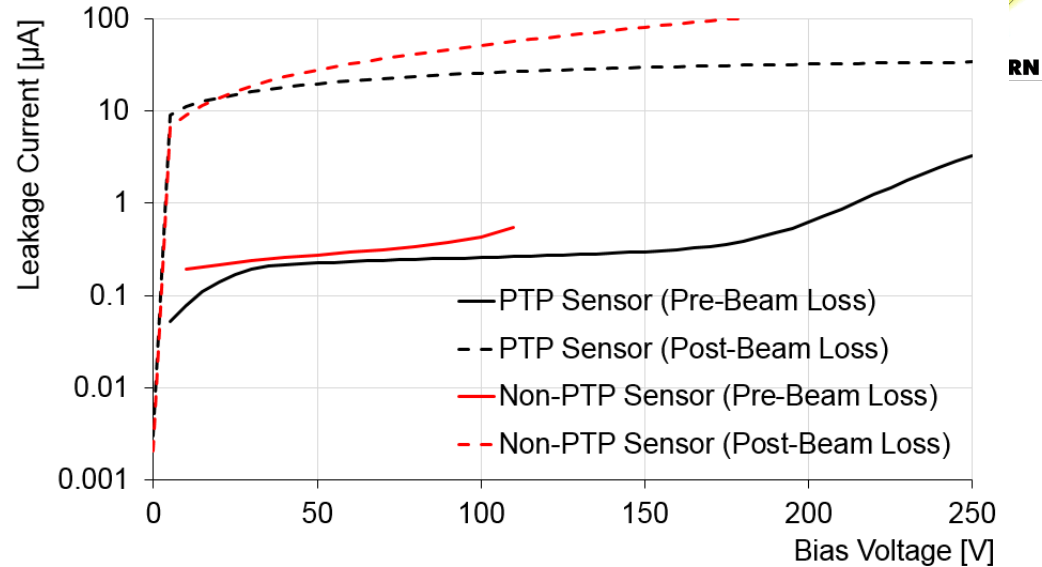
**PTP Sensor**:
- Measured current across oxide and value of coupling capacitance:
  - ✓ Strip current: OK → No electrical continuity across coupling oxide
  - ✓ Coupling capacitance: OK → Expected value, no variation across the sensor

Non-PTP Sensor:
- Measurement of current across oxide showing 70% of strip coupling capacitors broken **Non-PTP strips have not survived the beam-loss experiment**
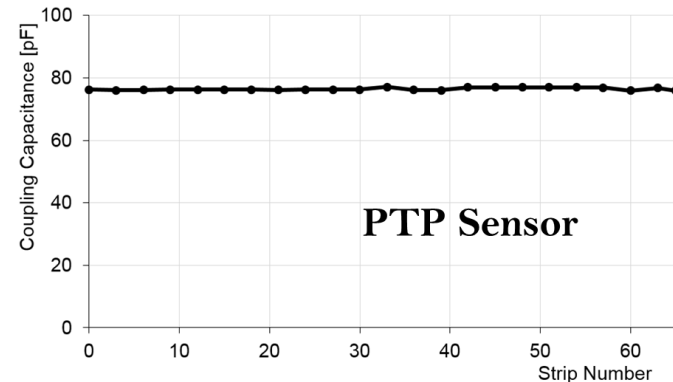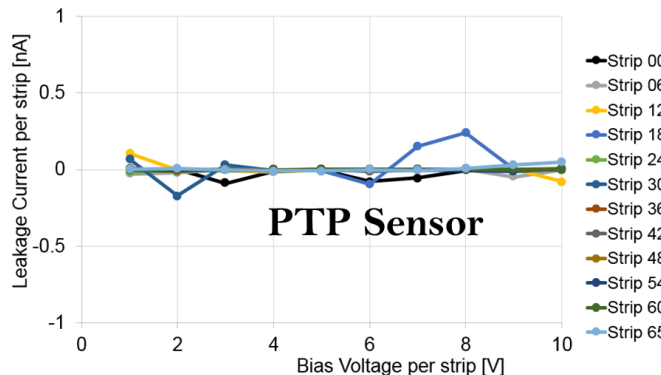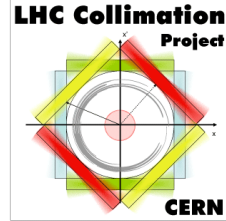
Conclusions
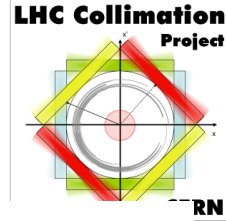
- The damage mechanism in case of particle beam impact on a material is controlled by two parameters: **peak energy density ($\bar{e}_s$) and maximum energy over a longitudinal cross-section (e_p)**

- However, **damage definition changes depending on the application**: it may be related to the thermostructural behaviour (collimators), to the degradation of the relevant electromagnetic properties (SC magnets), or to a loss of electronic functionality (ATLAS detectors)

- Need of performing **experimental tests** (HiRadMat) and, where possible, **numerical simulations**, combining the two methods

- For **collimators**, dedicated tests aimed at simulating similar or higher expected in the accidental scenario.

  - For primary and secondary collimator materials, **thresholds 2 and 3 have never been reached so far**

  - For tertiary collimator materials, **threshold 3 is expected in the case of tungsten under energies lower than the accidental scenario**. In the case of CuCD, threshold 3 is **not reached neither in the accidental scenario, nor experimentally**

Conclusions

- The tests done in 2016 and 2018 to **SC magnet components** allowed:
    - Assessing the damage thresholds for the **insulation**
    - Evaluate the behaviour and damage limits of **different SC solutions: Nb-Ti, Nb$_3$Sn and YBCO**
    - Effects on the **superconducting properties** (I_c) under checking
- Technical solutions for the **ATLAS detectors** also recently tested.
    - Allowed to choose between **different technologies**. For example, highlighted the need of a PTP system.
    - **Updated damage thresholds**, first defined in 2006.

- In the experimental tests, in spite of the lower beam stored energy, the expected damage mechanisms was mimicked through squeezing the HRMT beam, changing the sample geometry.
- **However, to completely validate full scale devices and derive upper damage thresholds, it is of paramount importance to perform tests with the nominal LIU/HL-LHC beam stored energy.**

# *Thanks for your attention!*

Backup slides

HRMT-14 (2012)

- Test of specimens from 6 different materials: Inermet180, Mo, Glidcop, MoCuCD CuCD, and MoGr (very old grade with high density, 5.4 g/cm^3)

- Allowed **characterization of materials of interest for collimators**

- **Tuning of numerical models, with very good benchmarking between measurements and simulations**
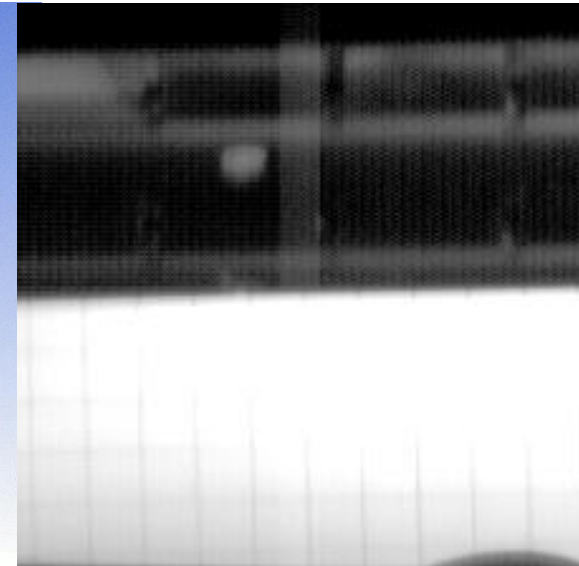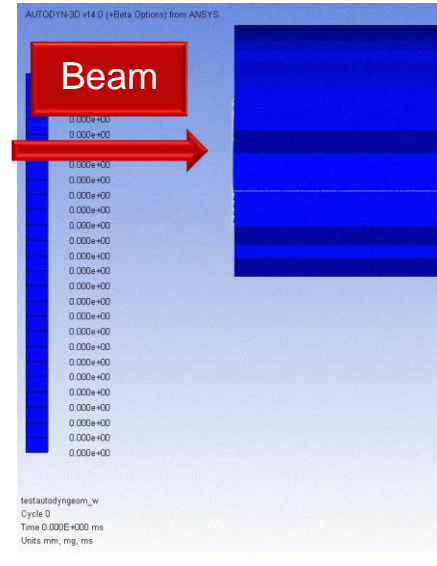
Medium Intensity Samples (Type 1)

- Strain measurements on sample outer surface;
- Radial velocity measurements (LDV);
- Temperature measurements;
- Sound measurements.
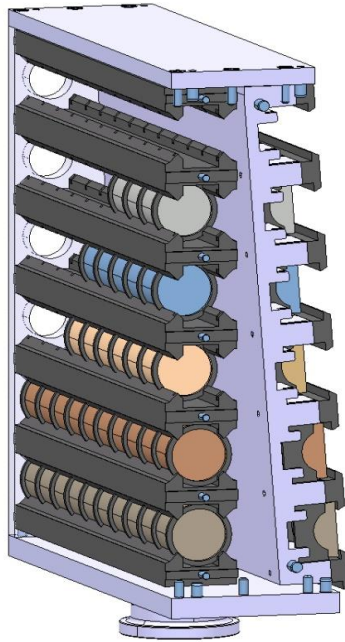
High Intensity Samples (Type 2)

- Strain measurements on sample outer surface;
- Fast speed camera to capture fragment front formation and propagation;
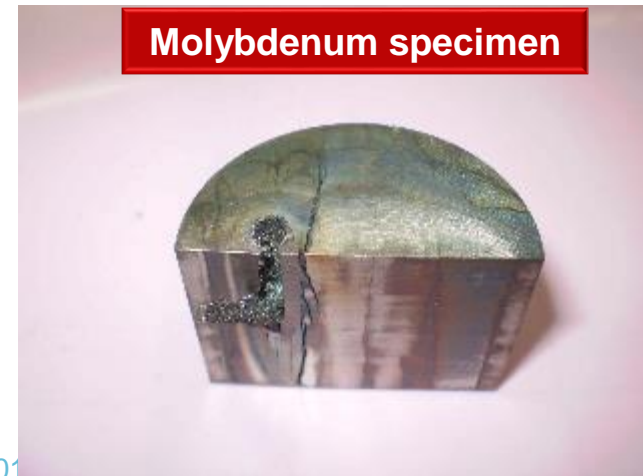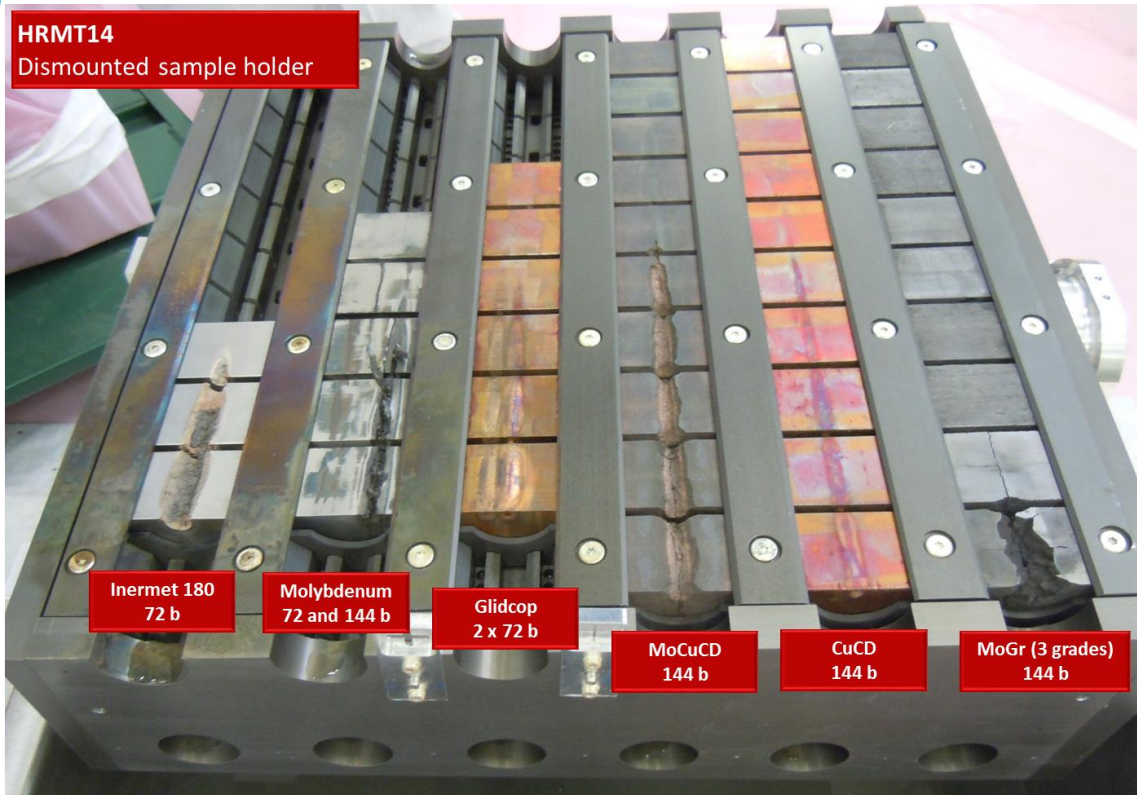- Temperature measurements;
- Sound measurements.

Beam

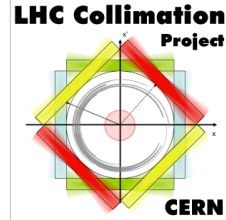| Case	Bunches	p/bunch	Total Intensity	Beam Sigma	Specimen Slot	Velocity
Simulation	60	1.5e11	9.0e12 p	2.5 mm	9	**316 m/s**
Experiment	72	1.26e11	9.0e12 p	1.9 mm	8 (partly 9)	**~275 m/s**

- *A. Bertarelli et al. (2013). An experiment to test advanced materials impacted by intense proton pulses at CERN HiRadMat facility. Nucl. Instr. Meth. Phys. Res. B 308:88–99.*

HRMT-14 (2012)

- Tank opened in **May 2015** in b. 109 (CERN), after 2 ½ years of cool-down

- Activation was low, but **risk of contamination** due to radioactive fragments and powders (mostly Cu and W)

- Non-destructive and destructive testing campaign

HRMT14
Dismounted sample holder

Inermet 180
72 b

Molybdenum
72 and 144 b

Glidcop
2 x 72 b

MoCuCD
144 b

CuCD
144 b

MoGr (3 grades)
144 b

Inermet specimen

Molybdenum specimen

HRMT-21 (2017)

- Test on **SLAC rotatable collimator** (Glidcop)

- **Low-impedance secondary collimator** capable of withstanding 7 TeV failures

- Goals:
  - Demonstrate that the rotation functionality works for the design failure at top energy (Asynchronous beam dump**: 8 bunches @ 7 TeV**)
  - Understand onset of damage for even more demanding scenarios, e.g. LHC injection error: **288 bunches @ 450 GeV**
  - Integrity control of the cooling pipes under both impact and jaw rotation
  - Check the eventual sticking of the jaws in case of ejecta with LHC-type aperture
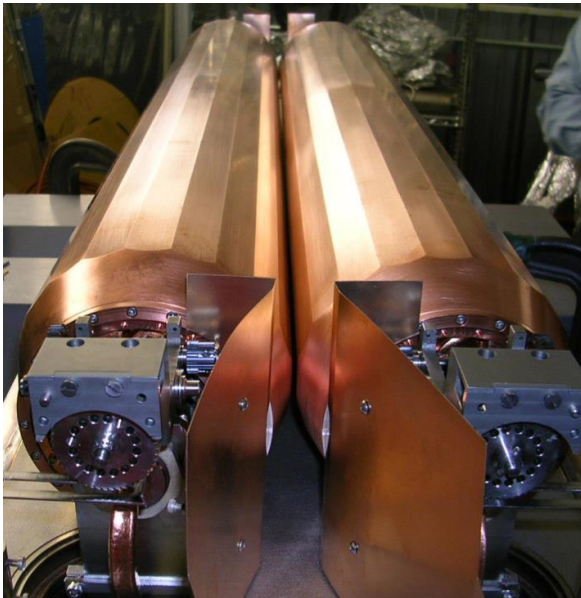
No	Intensity			Beam spot [mm]		Bunch spacing [ns]	Pulse length [us]	
	# bunches	p/bunch	Total	Sigma_x	Sigma_y			
1-25	1	6.00E+10	3.00E+12	0.35	0.35	25	0.025	Alignment
26	6	1.20E+11	7.20E+11	0.35	0.35	25	0.15	Shot #1
Rotation of 1 facet AC (~1.5 hours)								Rotation
27-51	1	6.00E+10	3.00E+12	0.35	0.35	25	0.025	Alignment
52	12	1.20E+11	1.44E+12	0.35	0.35	25	0.3	Shot #2
Rotation of 1 facet AC (~1.5 hours)								Rotation
53-77	1	6.00E+10	3.00E+12	0.35	0.35	25	0.025	Alignment
78	24	1.20E+11	2.88E+12	0.35	0.35	25	0.6	Shot #3
Rotation of 1 facet AC (~1.5 hours)								Rotation
79-103	1	6.00E+10	3.00E+12	0.35	0.35	25	0.025	Alignment
104	36	1.20E+11	4.32E+12	0.35	0.35	25	0.9	Shot #4
Rotation of 1 facet AC (~1.5 hours)								Rotation
105-129	1	6.00E+10	3.00E+12	0.35	0.35	25	0.025	Alignment
130	48	1.20E+11	5.76E+12	0.35	0.35	25	1.2	Shot #5
Rotation of 1 facet AC (~1.5 hours)								Rotation
131-155	1	6.00E+10	3.00E+12	0.35	0.35	25	0.025	Alignment
156	72	1.20E+11	8.64E+12	0.35	0.35	25	1.8	Shot #6
Rotation of 5 facet AC + 1 facet BD (~9 hours)								Rotation
157-181	1	6.00E+10	3.00E+12	0.35	0.35	25	0.025	Alignment
182	144	1.20E+11	1.73E+13	0.35	0.35	25	3.6	Shot #7
Rotation of 5 facet AC + 5 facet BD (~15 hours)								Rotation
183-207	1	6.00E+10	3.00E+12	0.35	0.35	25	0.025	Alignment
208	288	1.20E+11	3.46E+13	0.35	0.35	25	7.2	Shot #8

Total: 9.96E+13 Total: ~31.5 hours

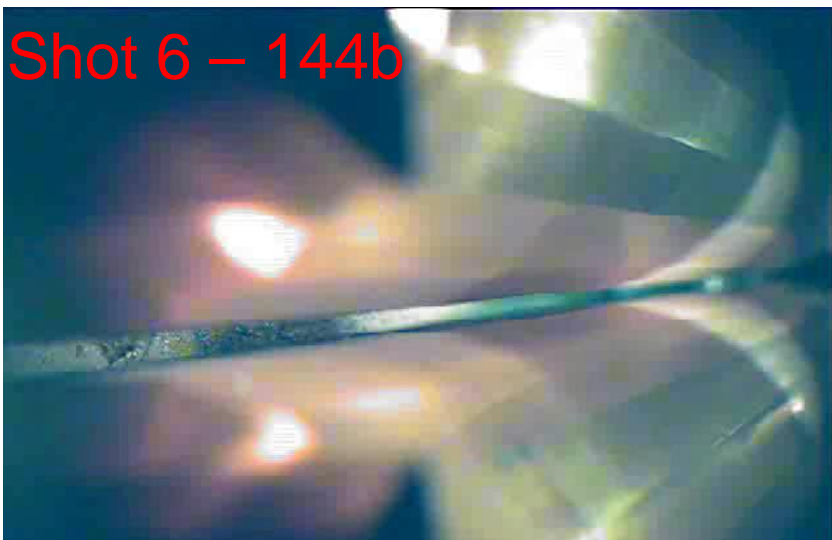**Equivalent total energy**

Onset of plastic damage estimated to be around 2E12p @ 440GeV (141kJ)

Intermediary shots
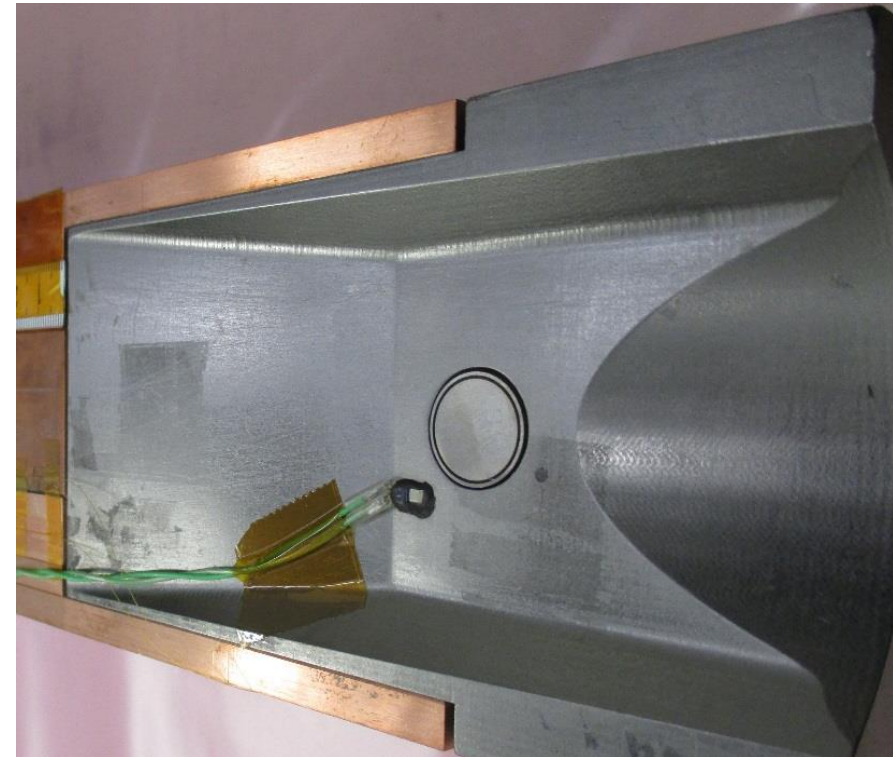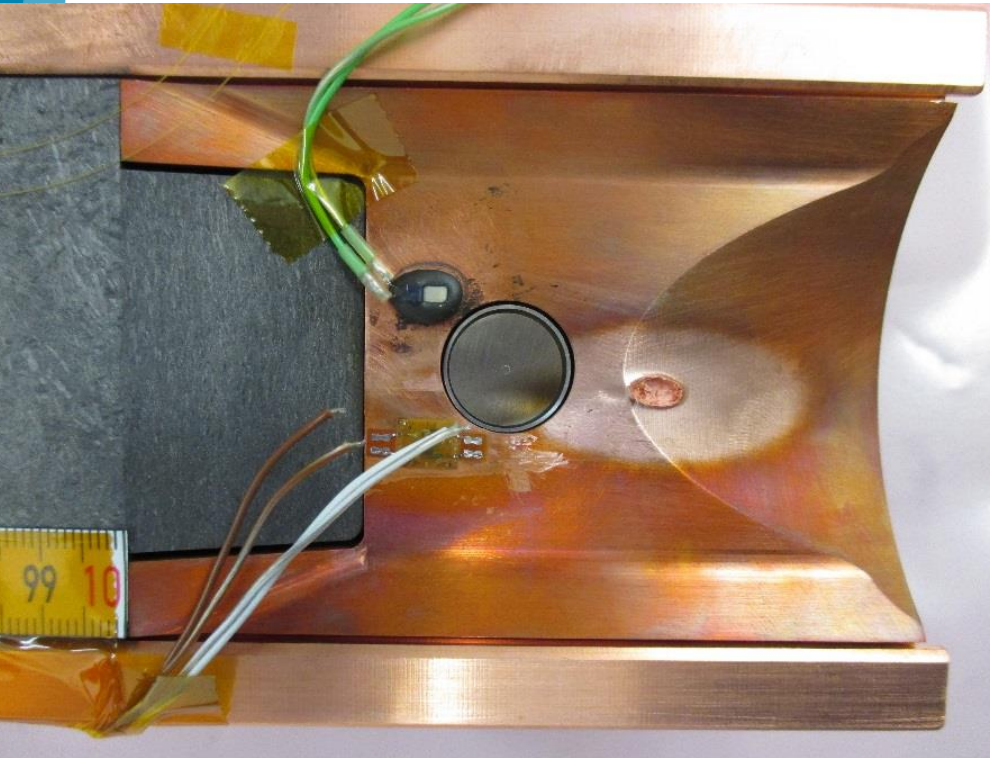
Design failure at 7Tev 15E12p @ 440GeV (1MJ)

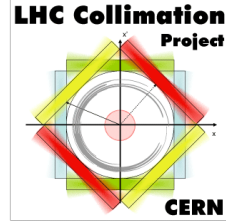**HL-LHC injection error** 3.5E13p @ 440GeV (2.4MJ)

Shot 3 – 24b
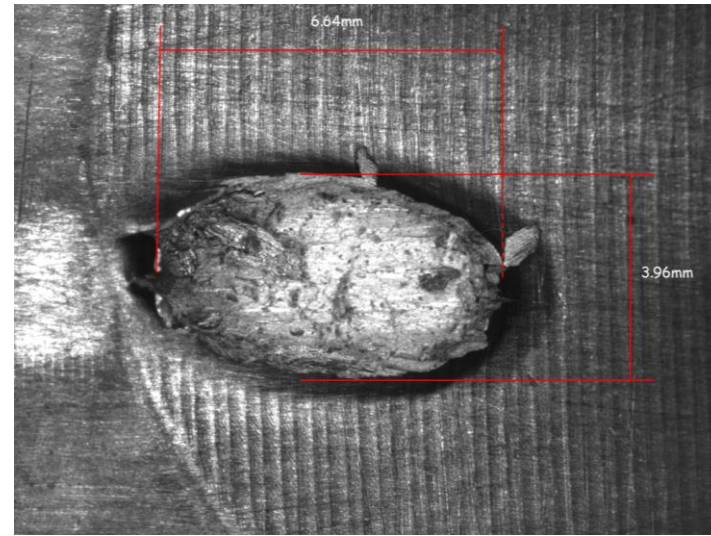
Shot 4 – 48b
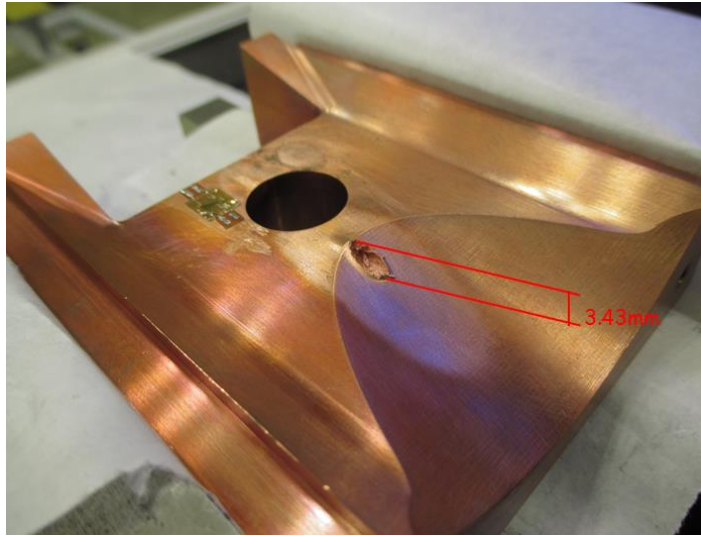
Shot 6 – 144b

Shot 7 – 288b

- *G. Valentino et al. (2019) Design, construction and beam tests of a rotatable collimator prototype for high-intensity and high-energy hadron accelerators.*
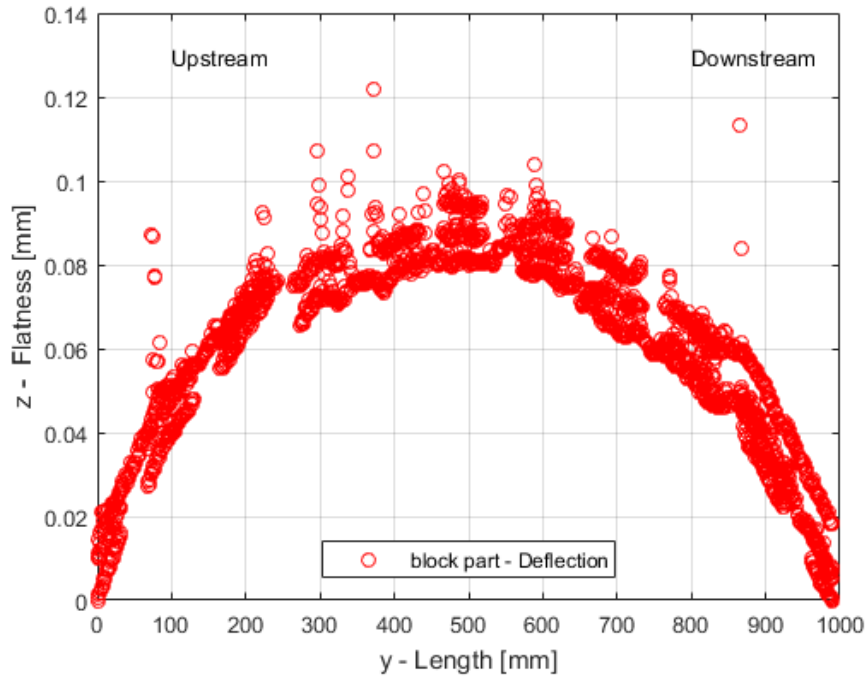
Metrology - Taperings
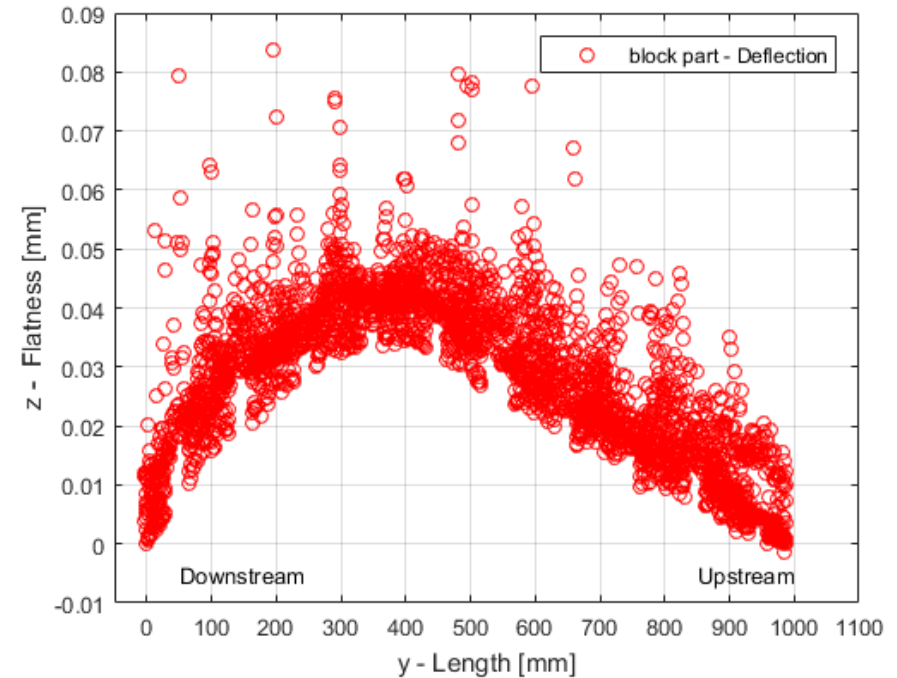

Downstream **Glidcop tapering** of CFC jaw **locally melted**

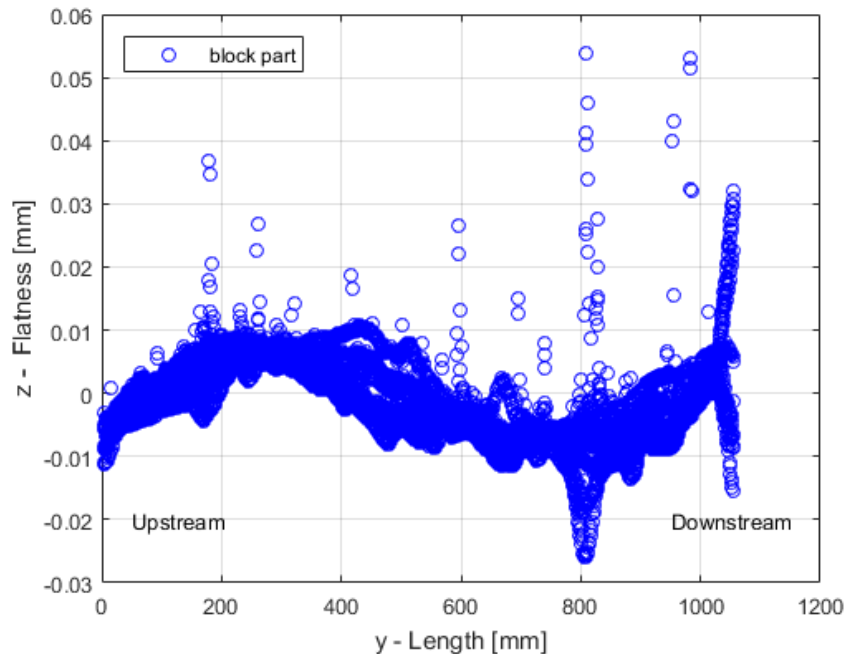**MoGr no damage detected**

Metrology – MoGr and CuCD jaws

Plastic deformation? Yes → most likely due to a cumulative effect of successive shots with energy equal/above the accidental case scenario
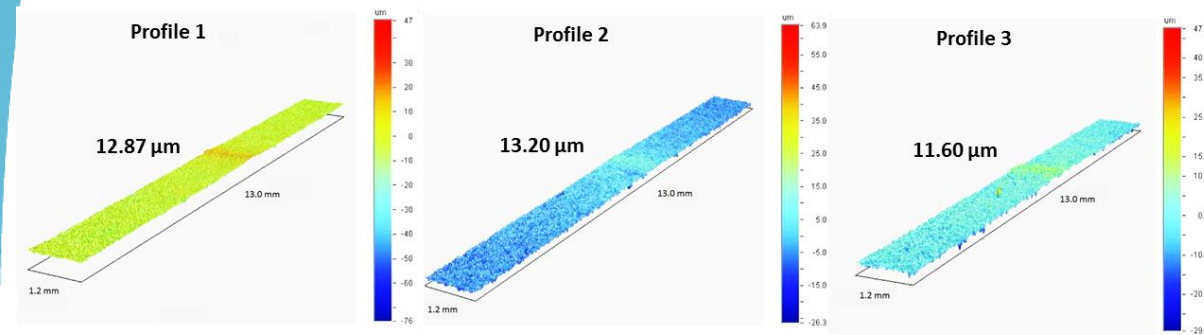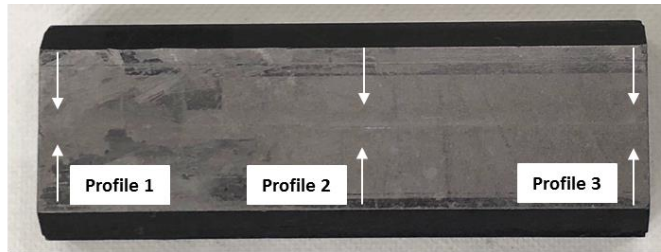
Metrology – CFC jaw housing

Flatness within the machining tolerance → CFC lower energy absorption

3D topography - MoGr

Block 2

- No spallation takes place → pseudo-plastic expansion

- Defect height is in the range of **12-13 µm** and localized in tenth of mm width region

- Surface roughness 1.5 µm →considered as mean error of the height measurements

Computed tomography - MoGr

Block 2

CARBIDE AGGLOMERATE
d = 2.30 mm

CRACK d = 1.73 mm

Block 1

VOID d = 2.49 mm
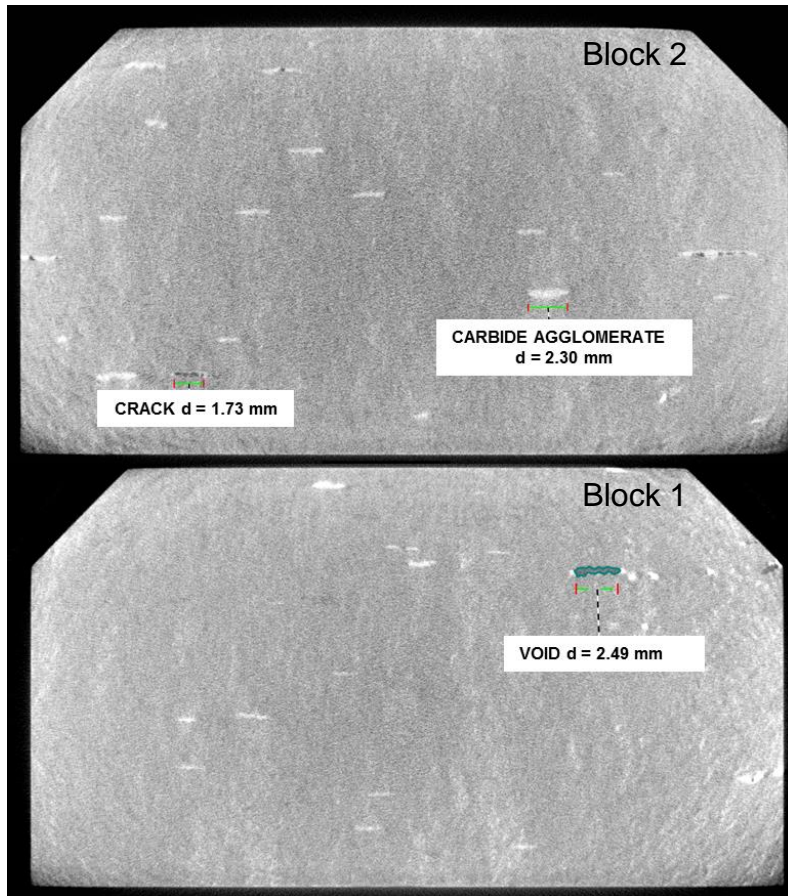
- No internal damages detected

- Agglomerate of molybdenum carbides with disk shape, dimensions few mm

- Small cracks or voids appear in correspondence of carbide agglomerates randomly distributed in the bulk → not attributed to beam effect

Production process not optimized yet at the time of the experiment

Computed tomography - MoGr
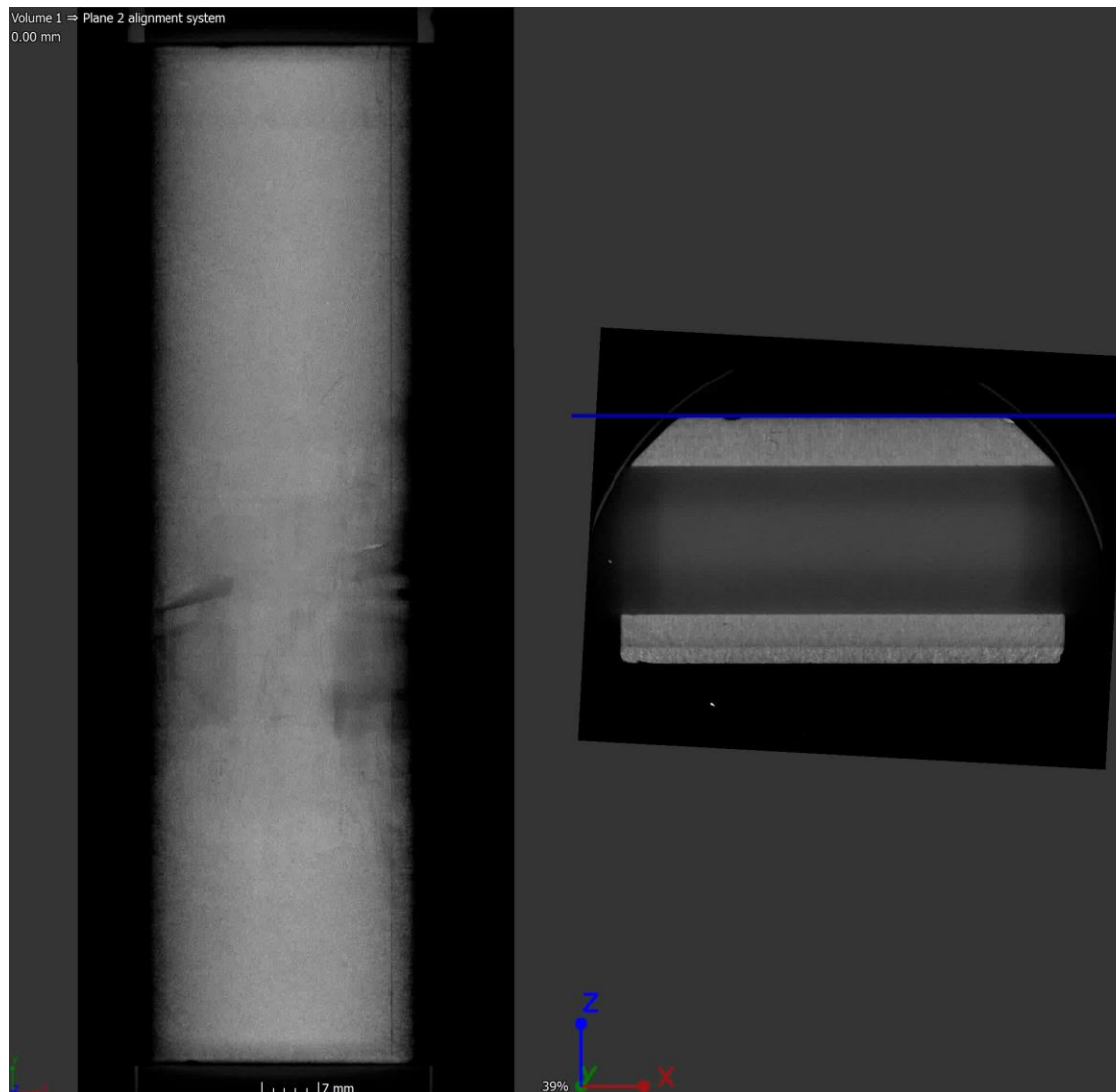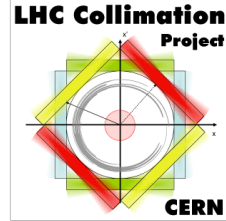

- Last block

Useful links and literature

- **MoGr production management**:
  - EDMS CERN-0000186962

- **Procedures for UHV compatibility of MoGr**
  - Vacuum firing on uncoated MoGr, EDMS n. 2050564
  - Surface preparation and vacuum firing on MoGr to be coated, EDMS n. 2067775
  - Thermal treatment on MoGr post-coating, EDMS n. 2083915

- **Irradiation studies on materials**:
  - Summary of irradiations at BNL and Kurchatov Institute for MoGr and CuCD: Eucard-2 deliverable D11.3: "Irradiation tests results", 2018
  - MoGr irradiation with ions at GSI:
    - "Heavy ion induced radiation effects in novel molybdenum-carbide graphite", GSI Scientific report , 2015
    - "Present results on material damage from irradiation", Eucard-2 milestone MS70, 2015
    - "Radiation induced effects in MoGr composites", Eucard2 WP11 meeting, Malta, 2016
  - CFC irradiation at Kurchatov Institute: "The effects of high-energy proton beams on LHC collimator materials", Kurchatov final technical report, 2008

Thermomechanical tests
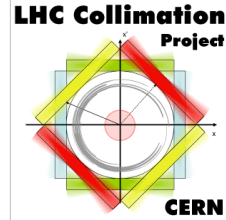
Property	Specification		Unit	Batch 2	
	$\parallel^*$	$\vdash$		$\parallel^*$	$\vdash$
Density at 20ºC	2.40 – 2.60		[g/cm³]	2.59	
Specific heat at 20ºC	>0.6		[J/(g·K)]	0.65	
Electrical conductivity at 20ºC	>0.90		[MS/m]	1.02	
Thermal Diffusivity 20ºC /at 300ºC	>390/120	>25/8	[mm^2/s]	407/115	17/5
Thermal conductivity at 20ºC /at 300ºC	>500/300	>35/25	[W/(m·K)]	705/333	29/15
Coefficient of thermal expansion 20-1000ºC	<2.9	<15	[$10^{-6}K^{-1}$]	2	16.3
Young's Modulus at 20ºC	35<E<70	5<E<8	[GPa]	85	5.2
Flexural strength at 20ºC	>60	>10	[MPa]	89	13.7
Flexural strain to rupture at 20ºC	>2500	>4000	[µm/m]	1450	4100
Dimensional stability	<0.05	<0.25	%	0	0.03

Figures of merit	Baseline	Batch 2
TRI	160	255
TSI	38	68
RFI	0.95	1.01

Thermomechanical tests
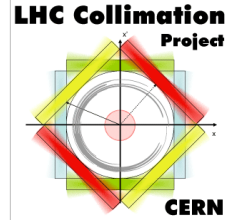
Property	Specification		Unit	Batch 2	
	$\parallel^*$	$\vdash$		$\parallel^*$	$\vdash$
Density at 20ºC	2.40 – 2.60		[g/cm³]	2.55	
Specific heat at 20ºC	>0.6		[J/(g·K)]	0.63	
Electrical conductivity at 20ºC	>0.90		[MS/m]	0.85±0.03	
Thermal Diffusivity 20ºC /at 300ºC	>390/120	>25/8	[mm^2/s]	340/95	29/8
Thermal conductivity at 20ºC /at 300ºC	>500/300	>35/25	[W/(m·K)]	527/306	47/25
Volumetric CTE 20-1000ºC	<7		[$10^{-6}K^{-1}$]	5.8	
Coefficient of thermal expansion 20-1000ºC	<2.9	<15	[$10^{-6}K^{-1}$]	2.5	12.4
Young's Modulus at 20ºC	35<E<70	5<E<8	[GPa]	67.4	5.2
Flexural strength at 20ºC	>60	>10	[MPa]	70.3	13.7
Flexural strain to rupture at 20ºC	>2500	>4000	[µm/m]	2000	4100
Dimensional stability	<0.05	<0.25	%	0.02	0.2

Figures of merit	Baseline	Batch 2
TRI	160	266
TSI	38	59
RFI	0.95	0.95