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

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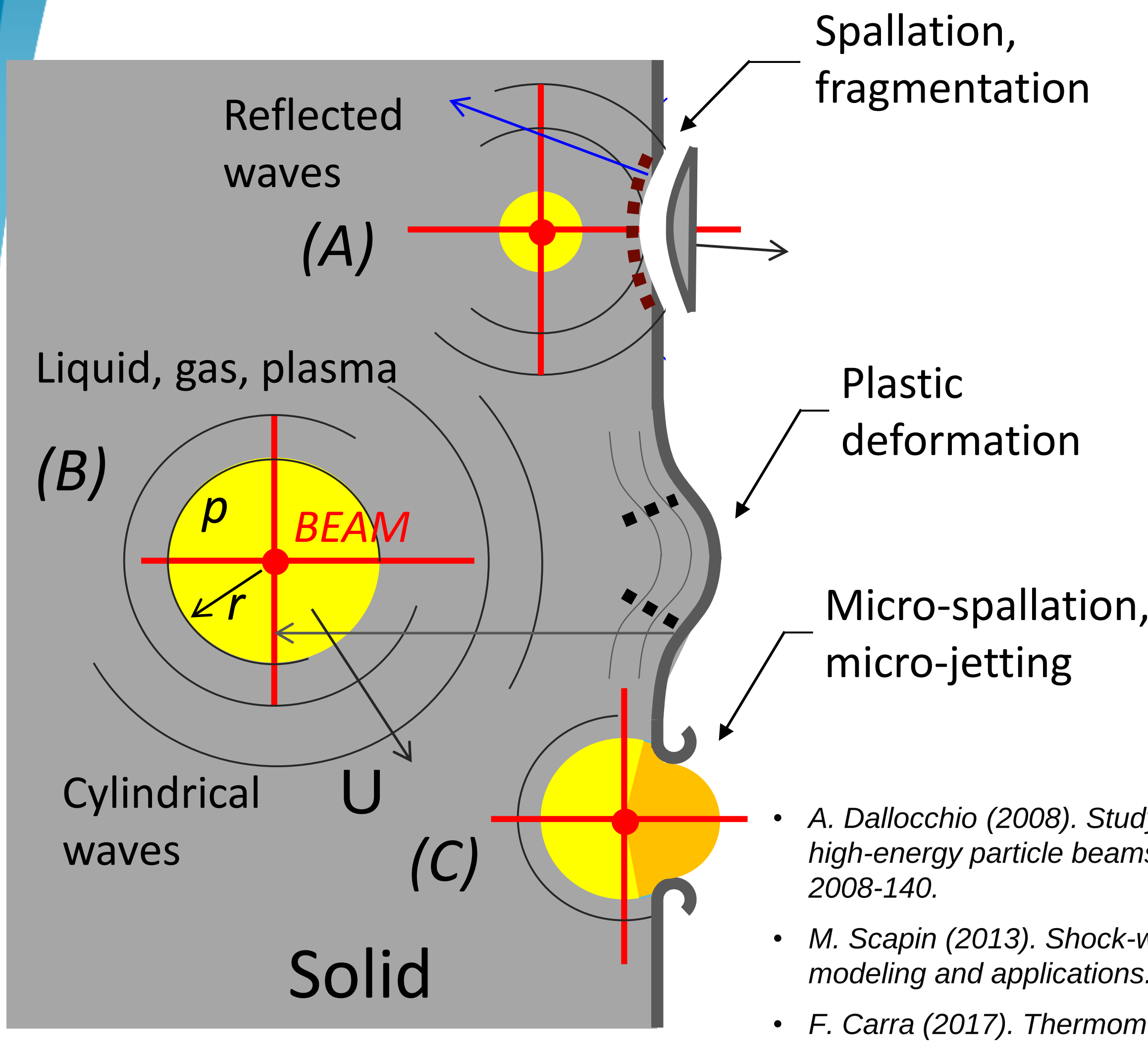
Outline

- Introduction
  - Particle beam – matter interactions
  - Damage mechanisms
- Collimator materials
  - HiRadMat experiments
  - Damage thresholds
- SC magnet components
- ATLAS detectors
- Conclusions

Introduction to beam damage



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

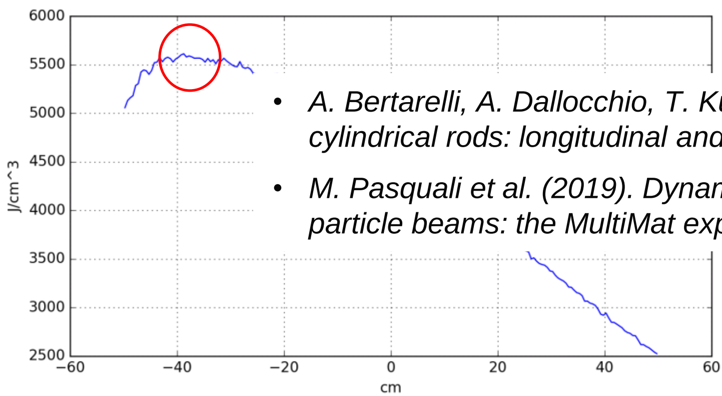
- *A. Dallocchio (2008). Study of thermomechanical effects induced in solids by high-energy particle beams: analytical and numerical methods. CERN-THESIS-2008-140.*
- *M. Scapin (2013). Shock-wave and high strain-rate phenomena in matter: modeling and applications. PhD thesis, 10.6092/polito/porto/2507944.*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

Introduction to beam damage

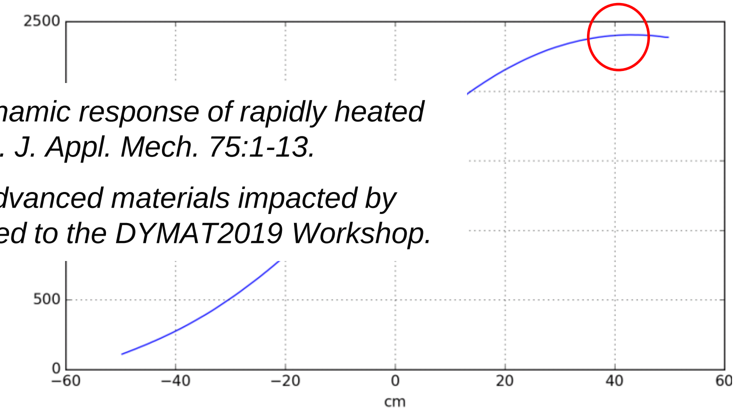
LHC Collimation Project

- 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.*

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

$$\varepsilon_p = f(\alpha T_p) > \varepsilon_{lim} \rightarrow \text{DAMAGE}$$

$$\bar{e}_s = \bar{E}_s / A$$

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

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

HiLumi HL-LHC PROJECT

Collimator damage thresholds

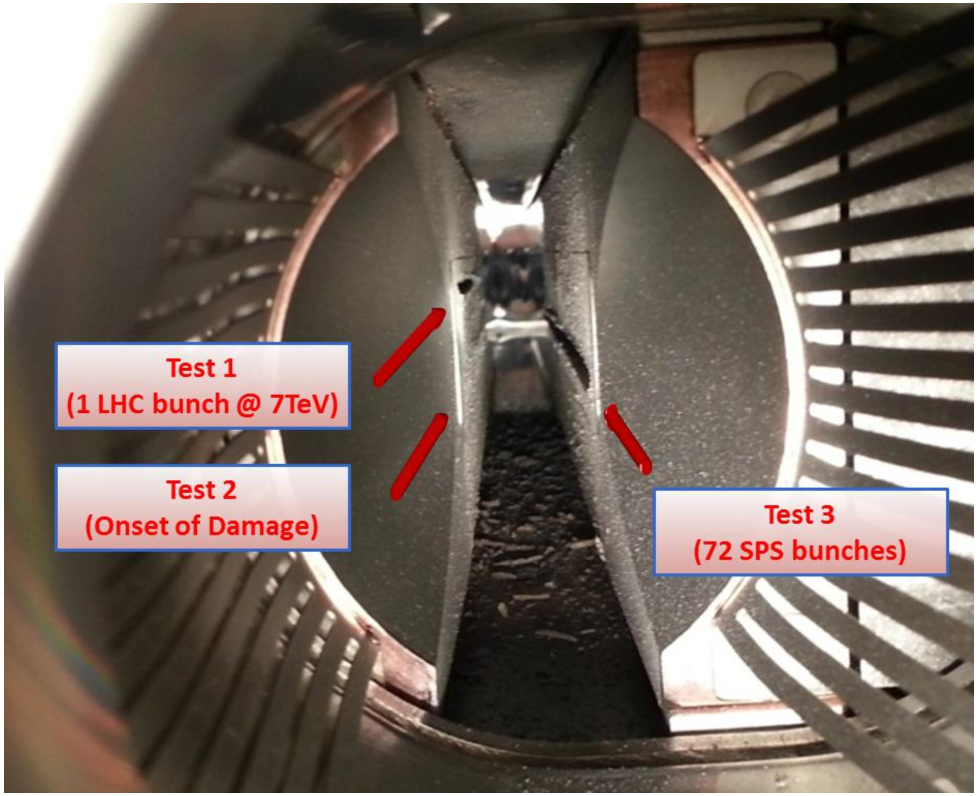
- **Three damage thresholds** defined for collimator materials.
  - Introduced for metallic (ductile) materials see MPP Workshop 2013, Annecy. Extended here to graphitic ones.
  - Defined as a function of the effect on the collimator behaviour.
- **Threshold 1**: onset of damage, with no need to activate 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.

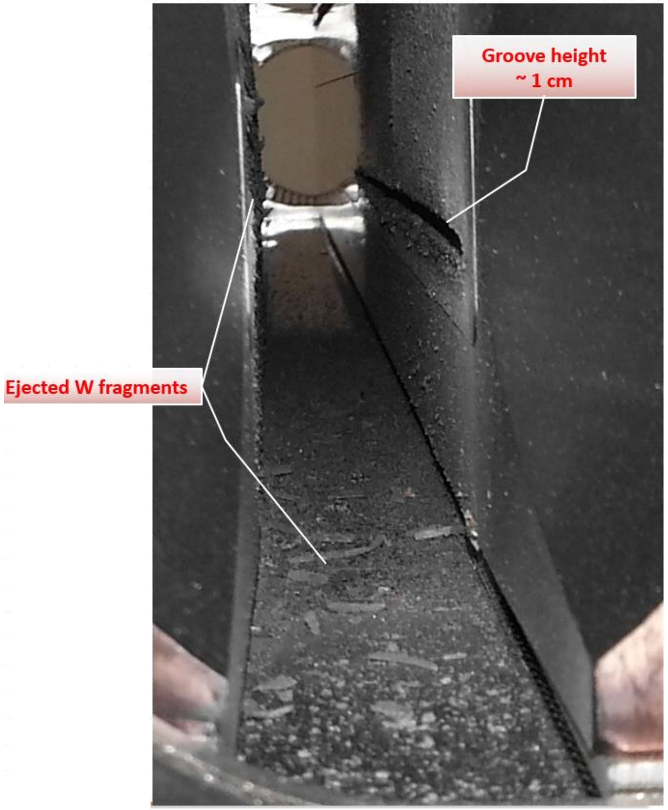
Collimator materials

- 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)

HRMT-09 (2012)

- 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)

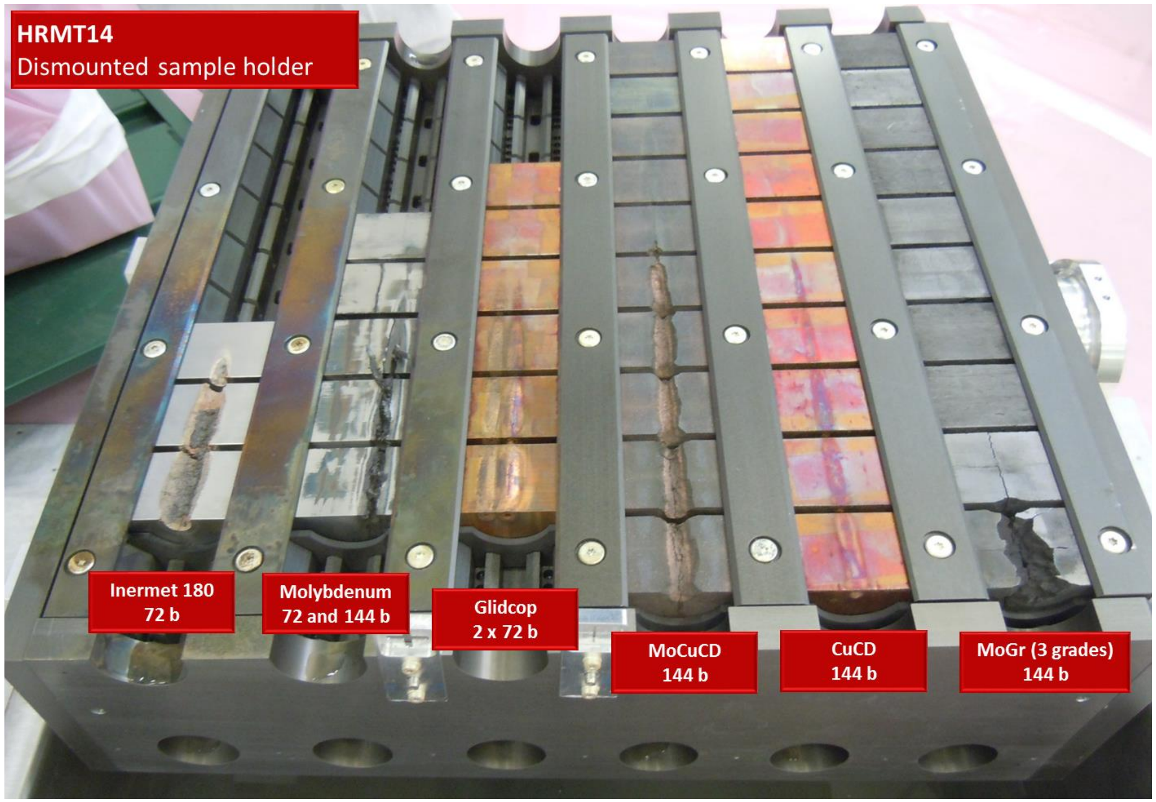


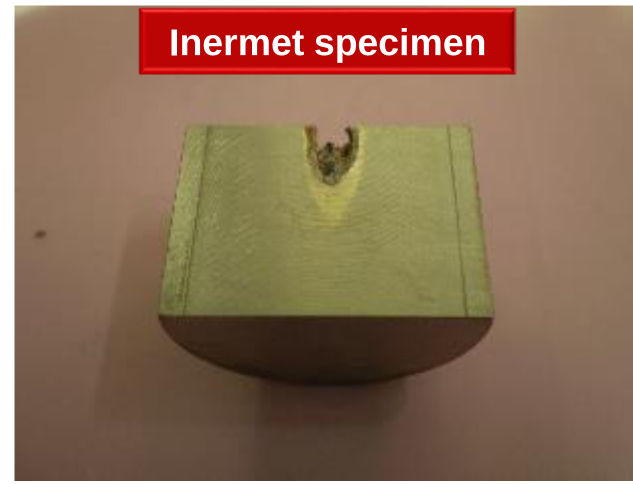


- *M. Cauchi (2014). High energy beam impact tests on a LHC tertiary collimator at the CERN high-radiation to materials facility. Phys. Rev. ST Accel. Beams 17, 021004.*

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**

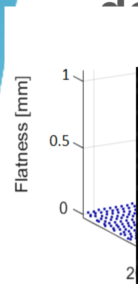




- *A. Bertarelli et al. (2013). An experiment to test advanced materials impacted by intense proton pulses at CERN HiRadMat facility. Nucl. Instr. Meth. Phys. Res. B 308:88–99.*

HRMT-23 (2015)

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



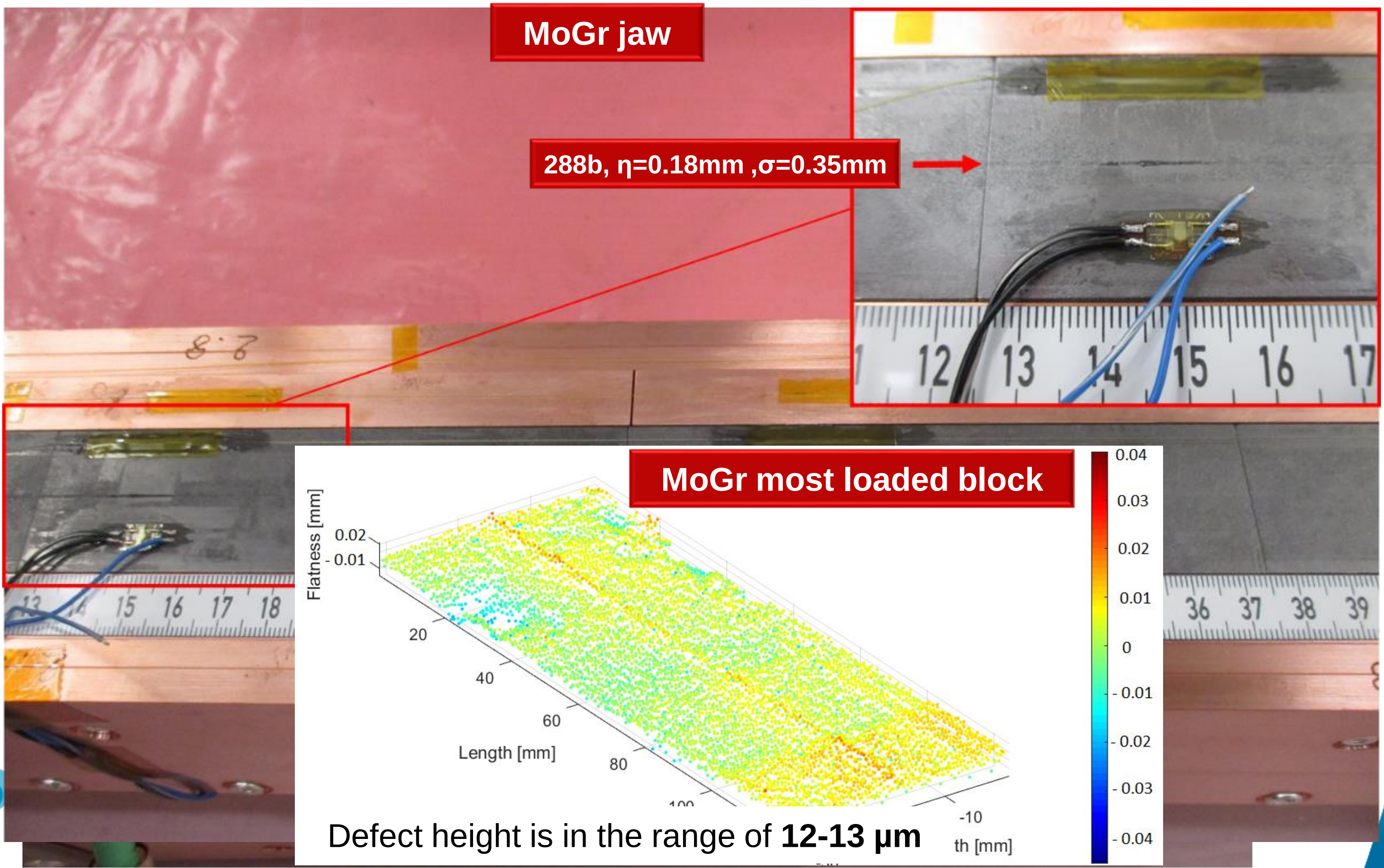
HL design

and CFC: we

- *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.*

HRMT-23 (2015)

- 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

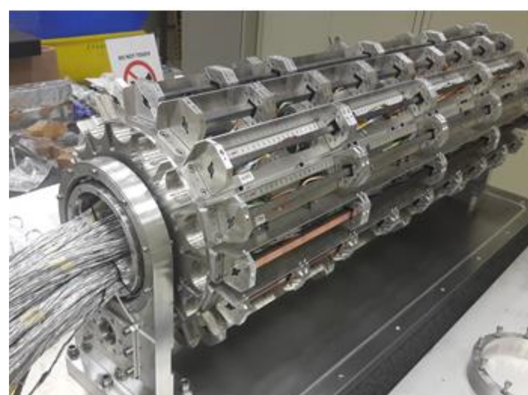


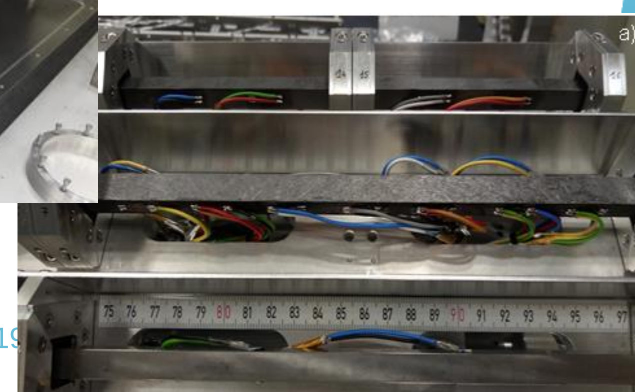
HRMT-36 (2017)

LHC Collimation Project CERN

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



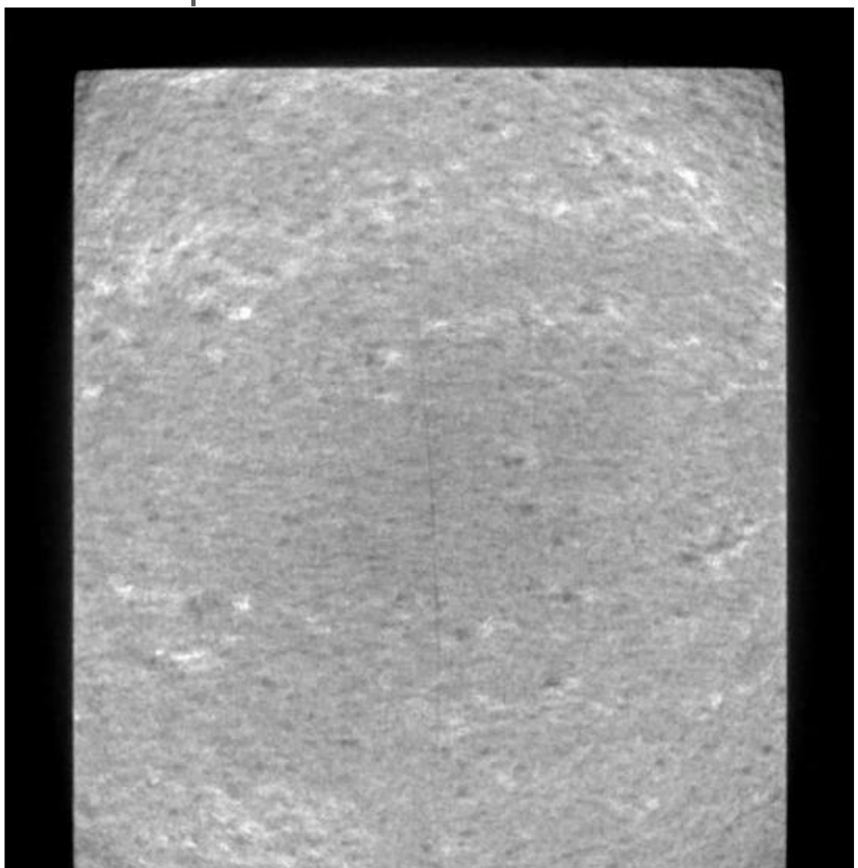


HRMT-36 (2017)


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)

Material	Damage threshold			HL-LHC ...tal case	
	1	2	3	A...	...am ...tion error
CFC	~1.6	*Not observed (> 3.8)*	*Not* [illegible]	[illegible]	2.6
Graphite	~2.1	*Not o*[illegible]	[illegible]*ed* [illegible]*.1)*	–	*Not calculated (> 2.6)*
MoGr	[illegible]	[illegible]*d* [illegible]*.7)*	*Not observed (≫ 7.7)*	–	6.1
Inermet	[illegible]	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)

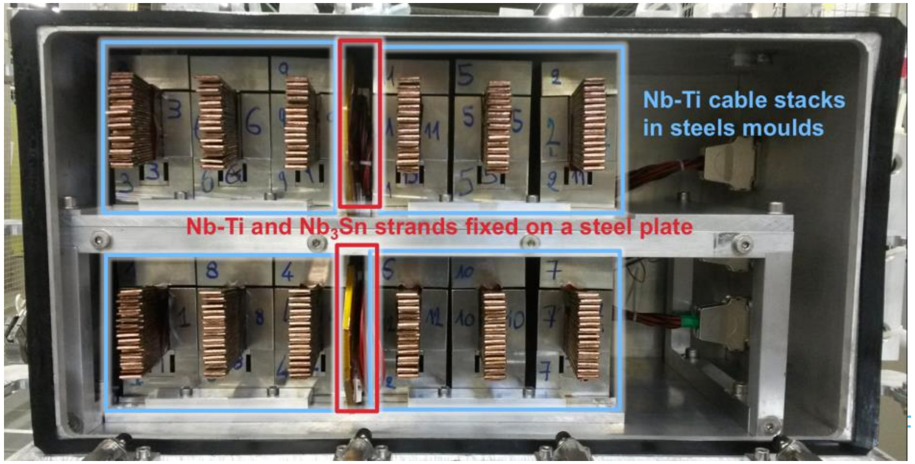
Material	Damage threshold			HL-LHC accidental case	
	1	**2**	**3**	**Asy. beam dump**	**Beam injection error**
CFC	*Not observed (>0.27)*	*Not observed (≫0.27)*	*Not observed (≫0.27)*	–	0.10
Graphite	*Not observed (>0.31)*	*Not observed (≫0.31)*	*Not observed (≫0.31)*	–	*Not calculated (≈0.12)*
MoGr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

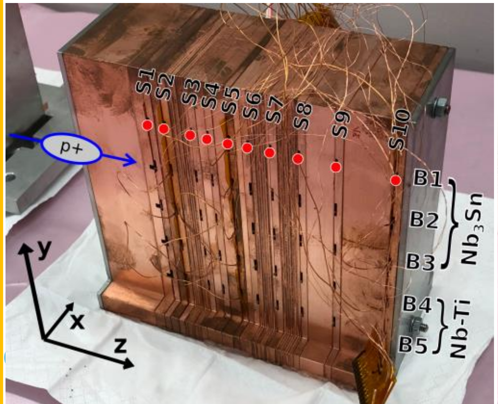
Room temperature experiment (09.2016):

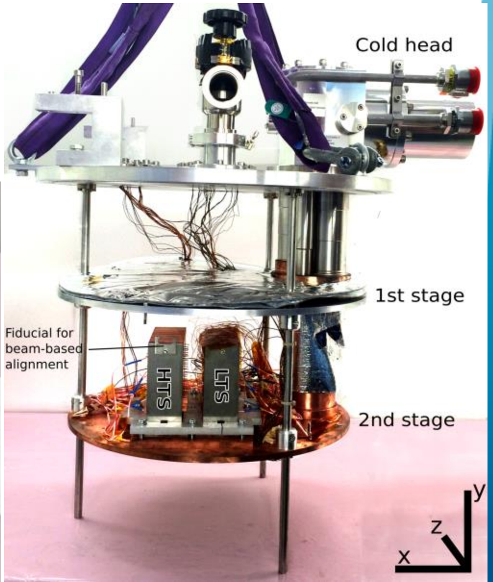
- Nb-Ti & Nb_3Sn strands
- Cable stacks with polyimid insulation
- Up to **2.6e12 p$^+$** per shot @ 440 GeV
- Hotspots up to 1150 K reached in strands



Cryogenic experiment @ **4.5 K** (08.2018):

- Nb-Ti, Nb_3Sn strands & YBCO tapes
- Shots of **3e12 p$^+$** @ 440 GeV
- Hotspots **up to ~1250 K** reached in strands





Main results of RT experiment

LHC Collimation Project CERN

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_3Sn strands:

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

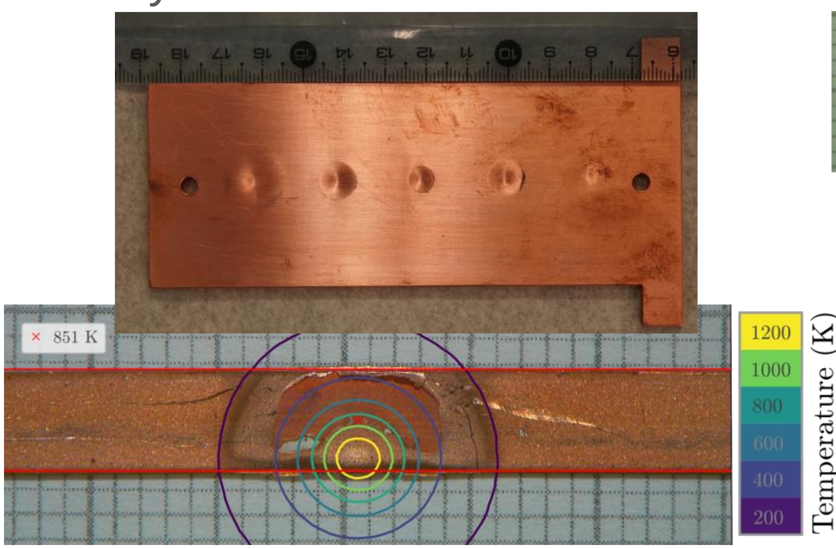
V. Raginel, et al., *First Experimental Results on Damage Limits of Superconducting Accelerator Magnet Components Due to Instantaneous Beam Impact*, IEEE Trans. Appl. SC, Vol 28(4), June 2018

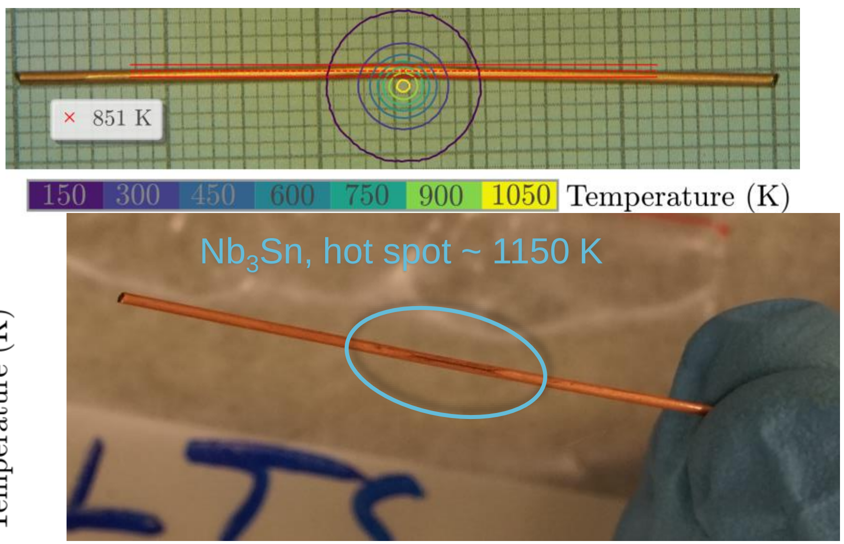
V. Raginel, *Study of the Damage Mechanisms and Limits of Superconducting Magnet Components due to Beam Impact,* CERN-THESIS-2018-090

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



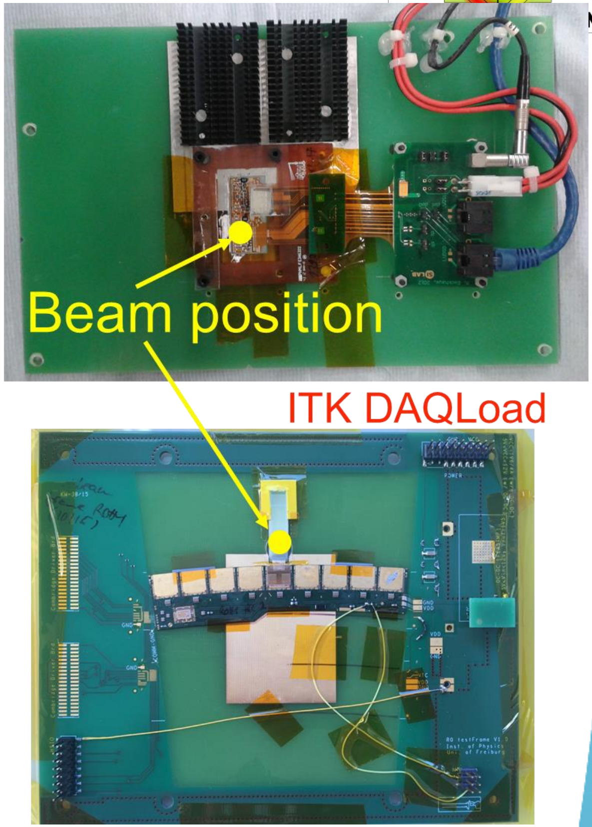


A. Oslandsbotn, A. Will, D. Wollmann, Beam Impact on Superconductor short samples of Nb3Sn, Nb-Ti and YBCO, 2018, EDMS 2068064

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.

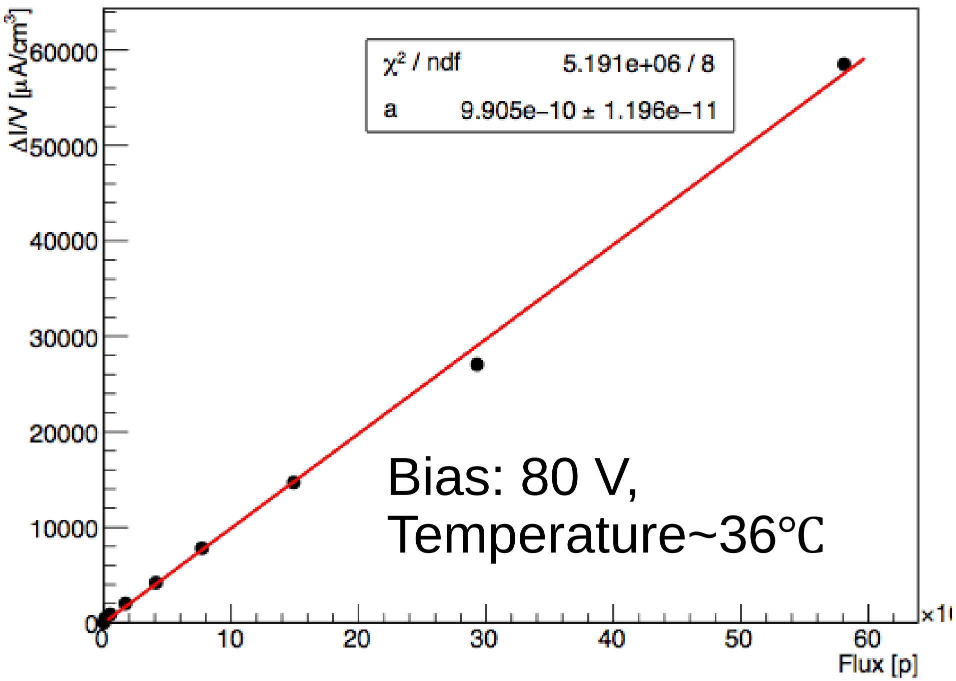


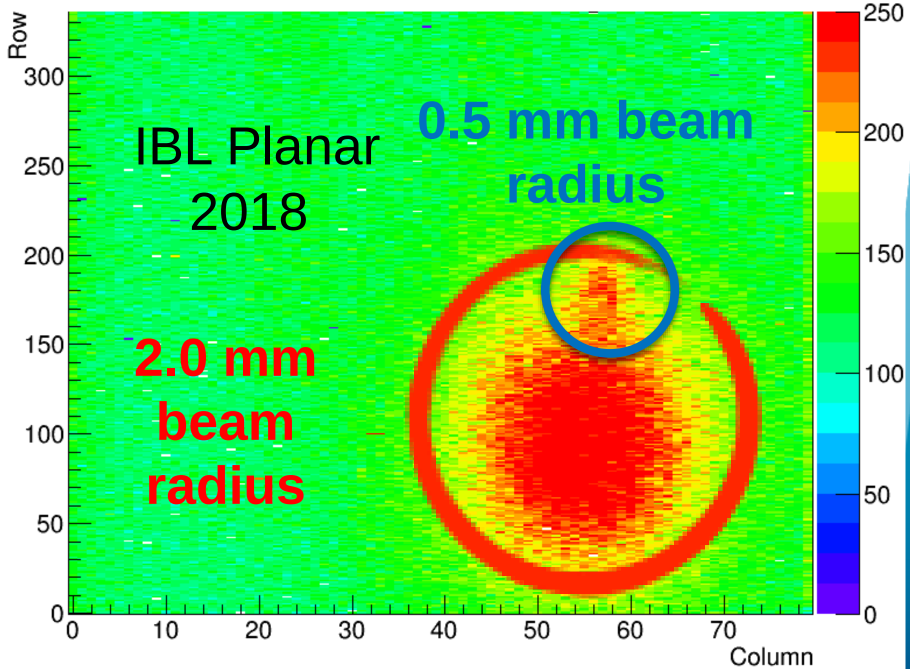
Module	IBL	ITk
Type	n^+-in-n, Planar	n^+-in-p, Low-R
Chip	FE-I4	ABC130
Total Size	2x4 cm^2	0.7x2.6 cm^2
Thickness	200 μm	310 μm
Channel/pitch	2x26680 (50x250 μm^2)	64 (77 μm)
Max. Dose	250 MRad	35 MRad

- 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 **$300 \cdot 10^{10}$ p/cm^2** (2006) **to $1 \cdot 10^{13}$ p/cm^2 (2017/18).**

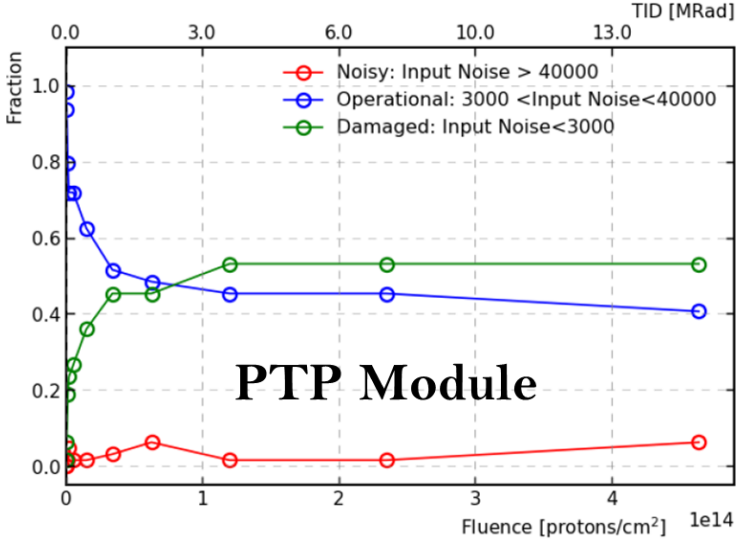




ITK STRIP: Influence on Read-out Electronics

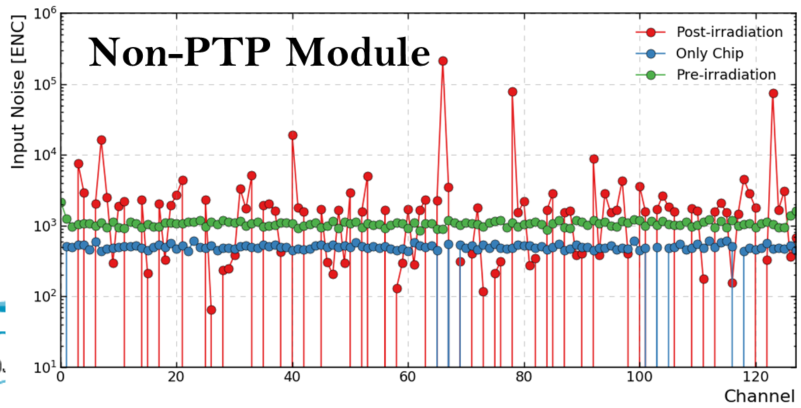
PTP Module:

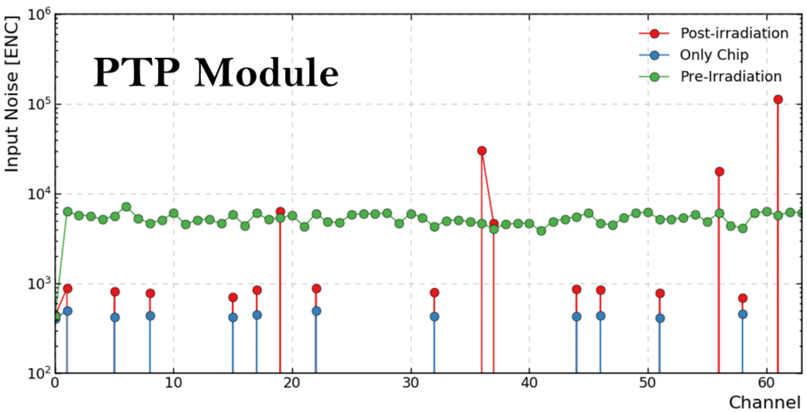
- Module noise increase concentrated in the first shot
- Stable behavior before $1 \cdot 10^{13}$ proton (3 MRad)
- With increase of the proton fluence, a decreasing number of fully operating channels was observed
- **After about $6 \cdot 10^{13}$ protons (15 MRad) more than 50% of channels have been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



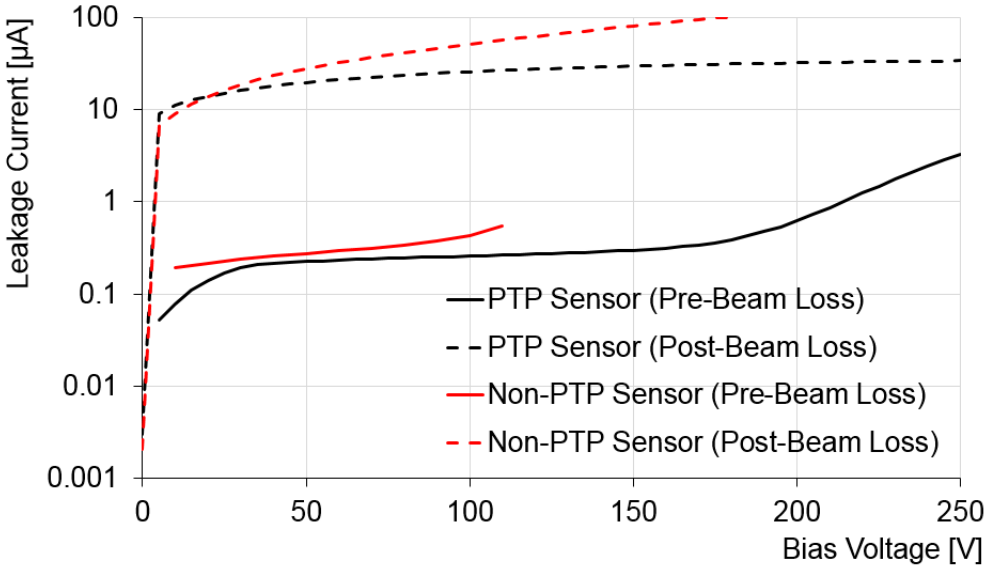
Non-PTP Module:

- 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



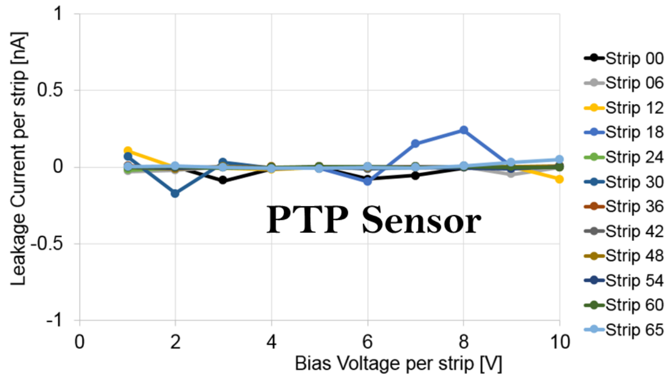
- After the beam-loss experiment, the sensors were disassembled from the testing modules and characterized
- Typical behavior of irradiated sensors

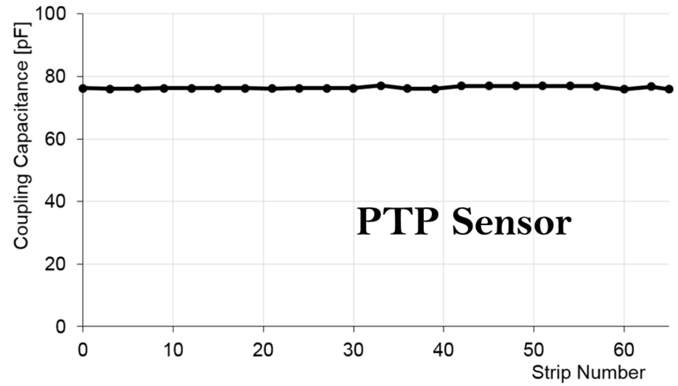
<u>PTP Sensor</u>:

- 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

<u>Non-PTP Sensor</u>:

- 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_3Sn 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!

HL-LHC PROJECT

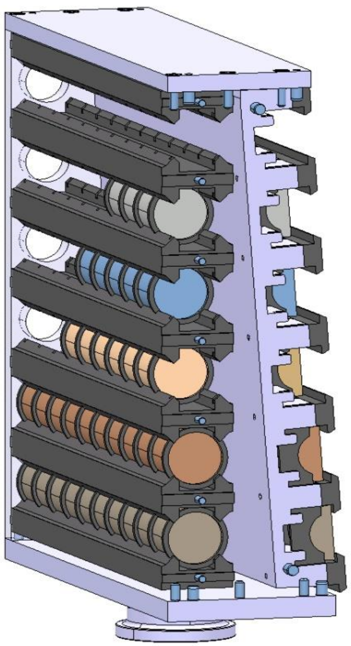
Backup slides

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**

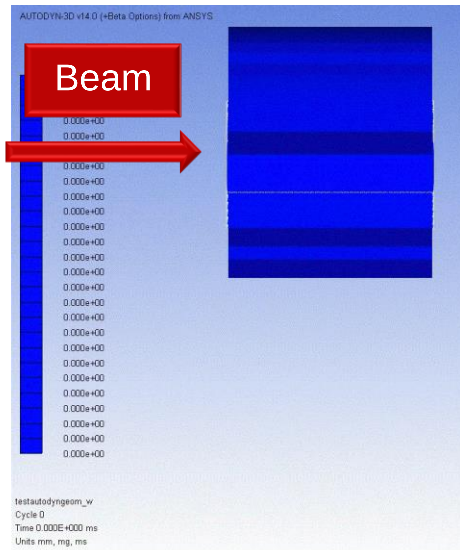
Medium Intensity Samples (Type 1)

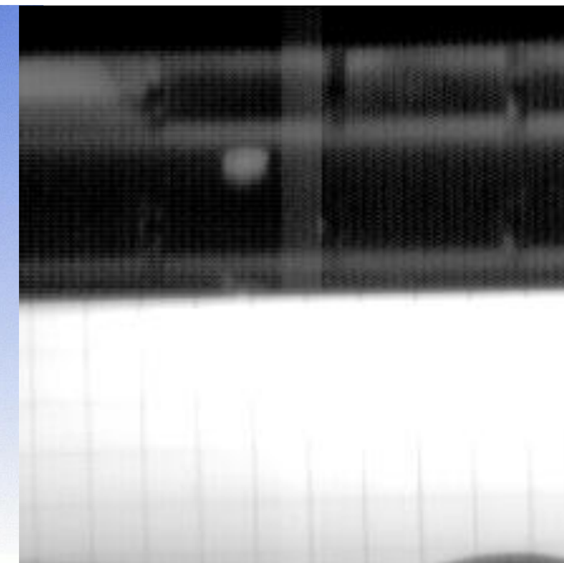
- Strain measurements on sample outer surface;
- Radial velocity measurements (LDV);
- Temperature measurements;
- Sound measurements.



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.



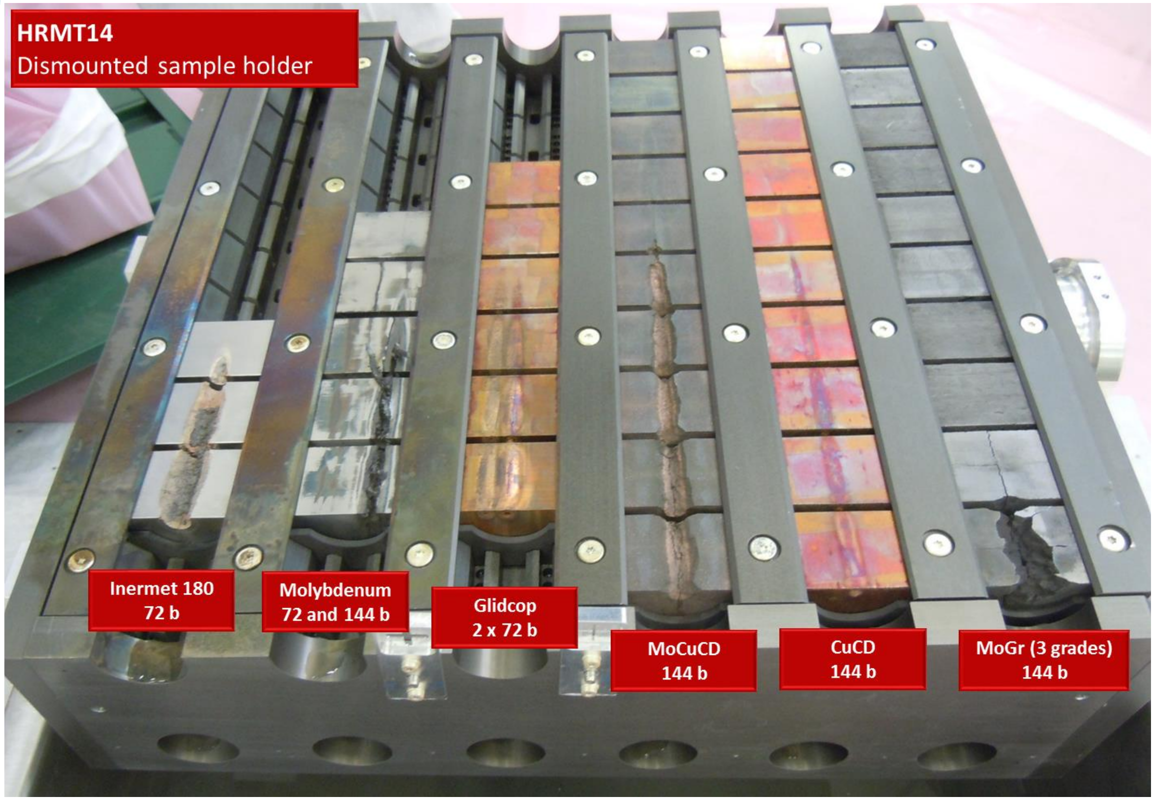


Case	Bunches	p/bunch	Total Intensity	Beam Sigma	Specimen Slot	Velocity
Simulation	60	1.5e11	9.0e12 p	2.5 mm	9	316 m/s
Experiment	72	1.26e11	9.0e12 p	1.9 mm	8 (partly 9)	~275 m/s

- *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.*

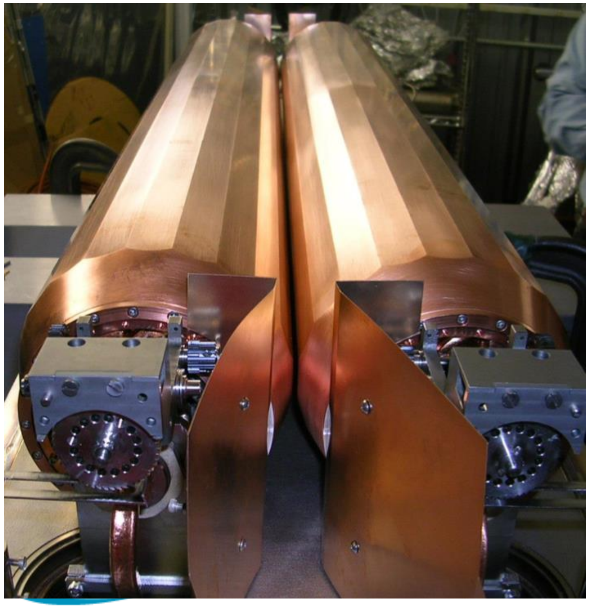
HRMT-14 (2012)

- 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



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



Beam Pulse List

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

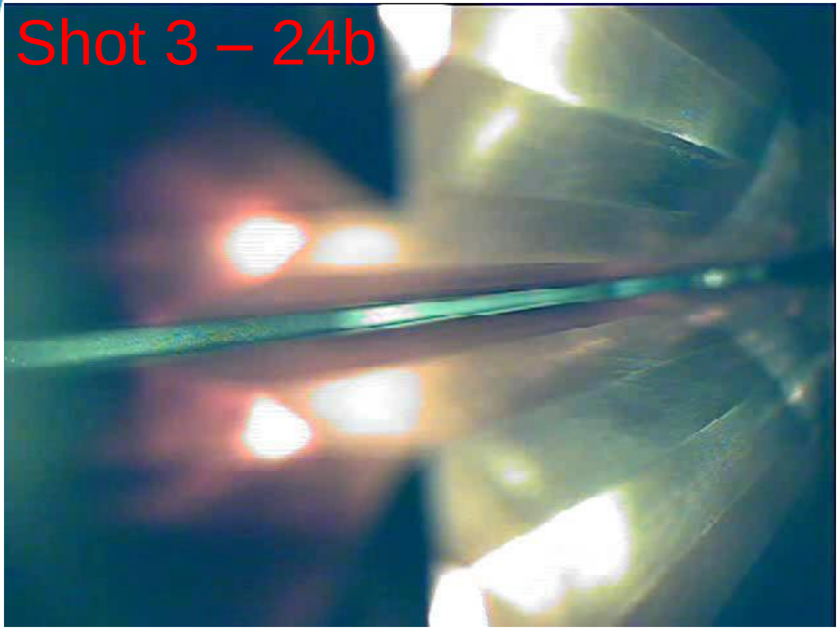
Onset of plastic damage estimated to be around 2E12p @ 440GeV (141kJ)

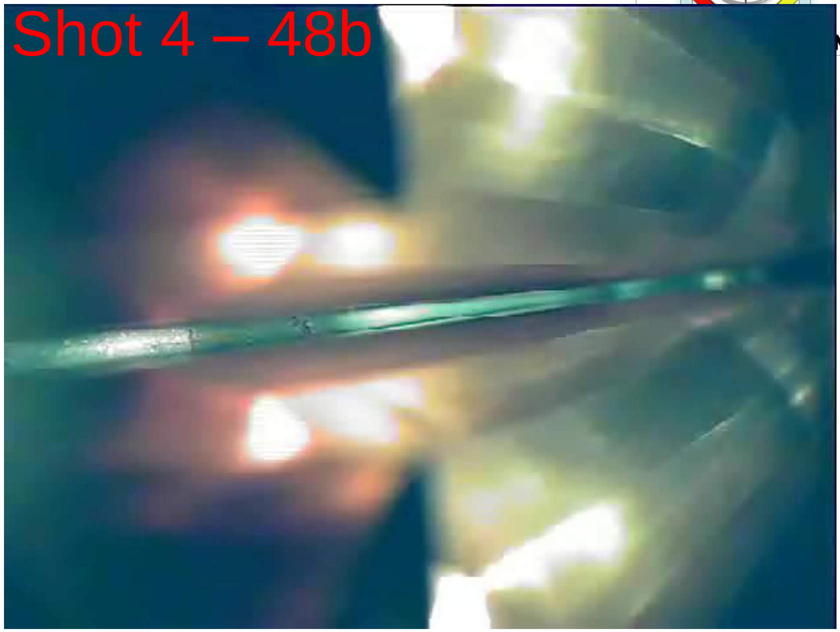
Intermediary shots

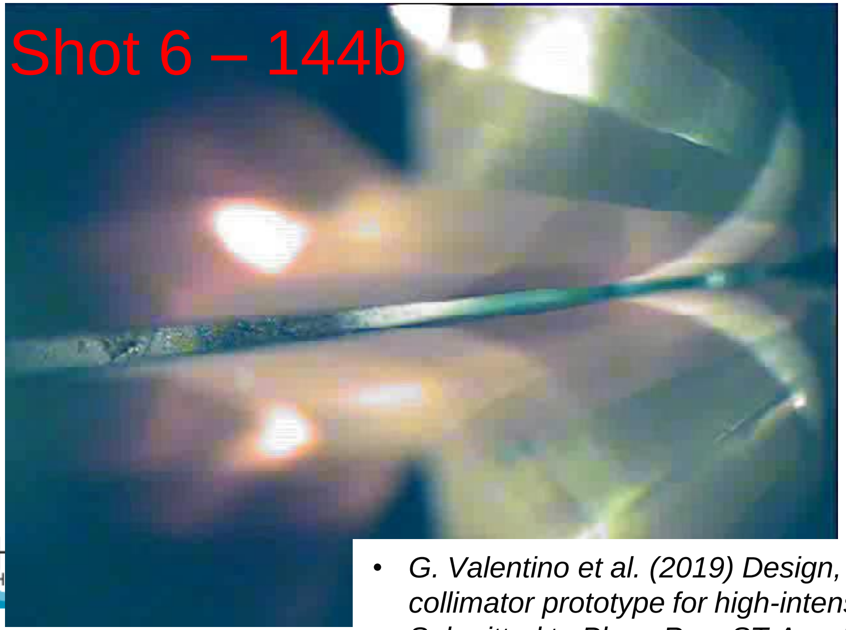
Design failure at 7Tev 15E12p @ 440GeV (1MJ)

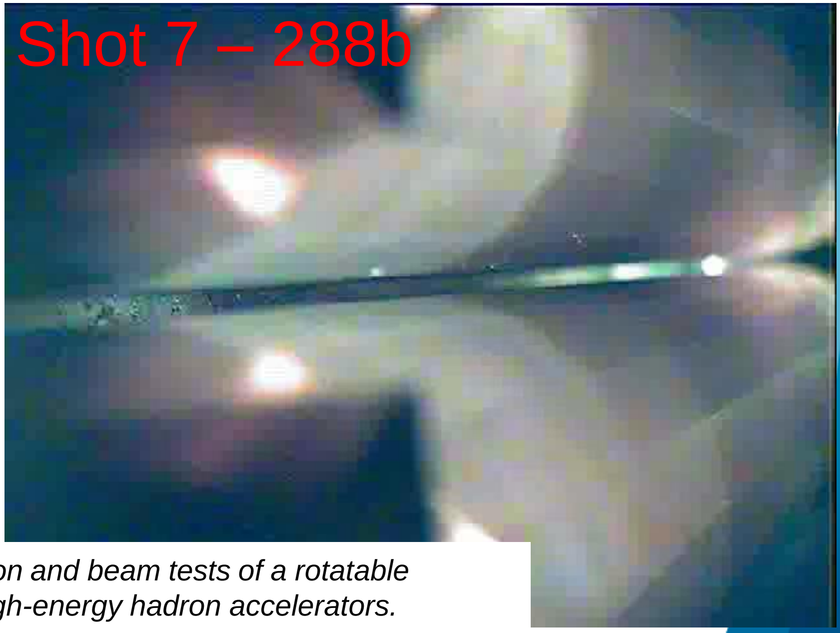
HL-LHC injection error 3.5E13p @ 440GeV (2.4MJ)

HRMT-21 (2017)



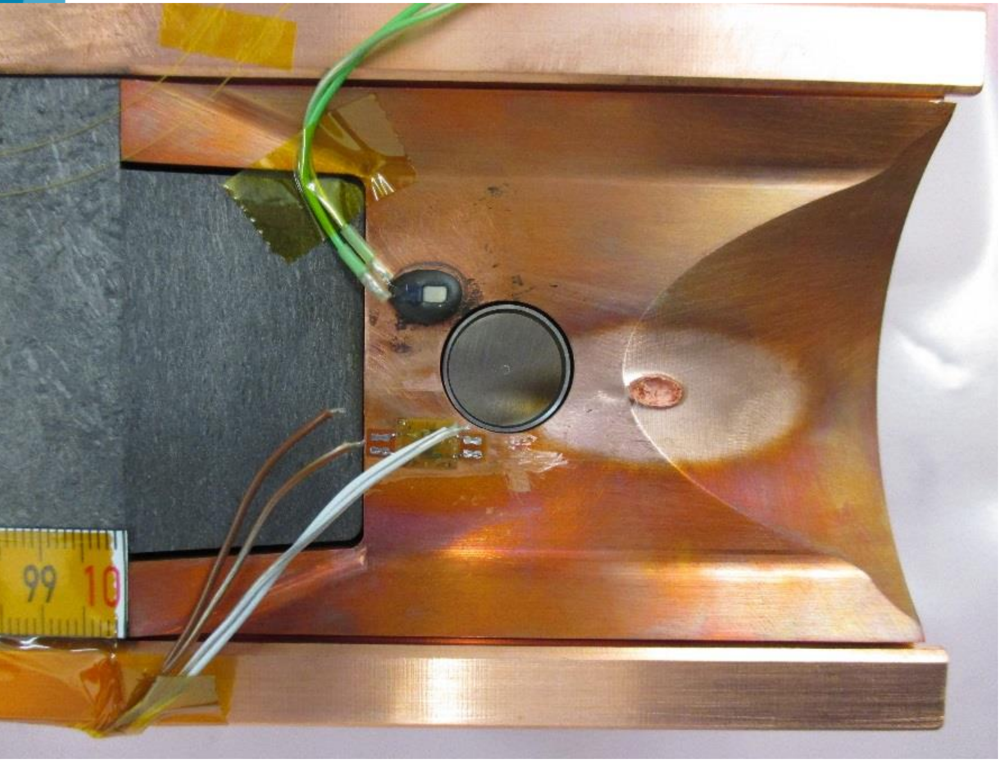




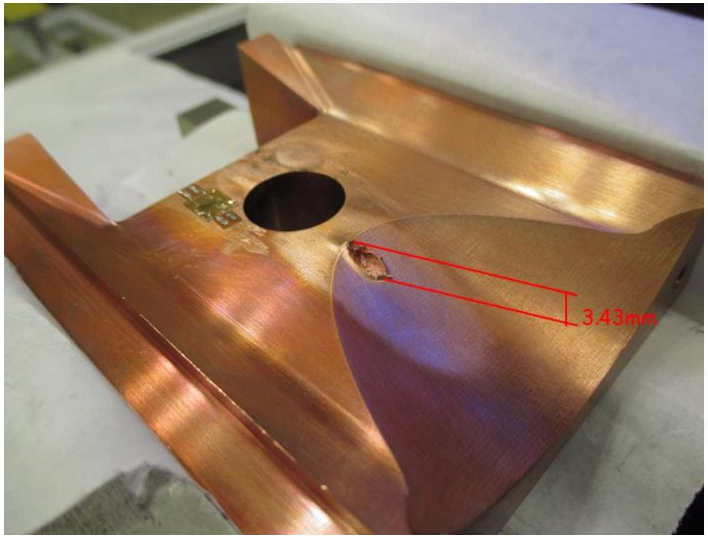


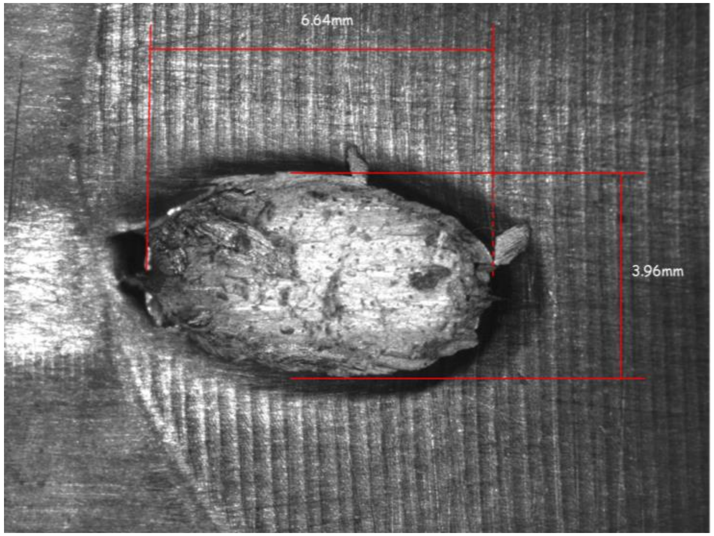
- *G. Valentino et al. (2019) Design, construction and beam tests of a rotatable collimator prototype for high-intensity and high-energy hadron accelerators.*

HRMT-23 (2015)



Metrology - Taperings



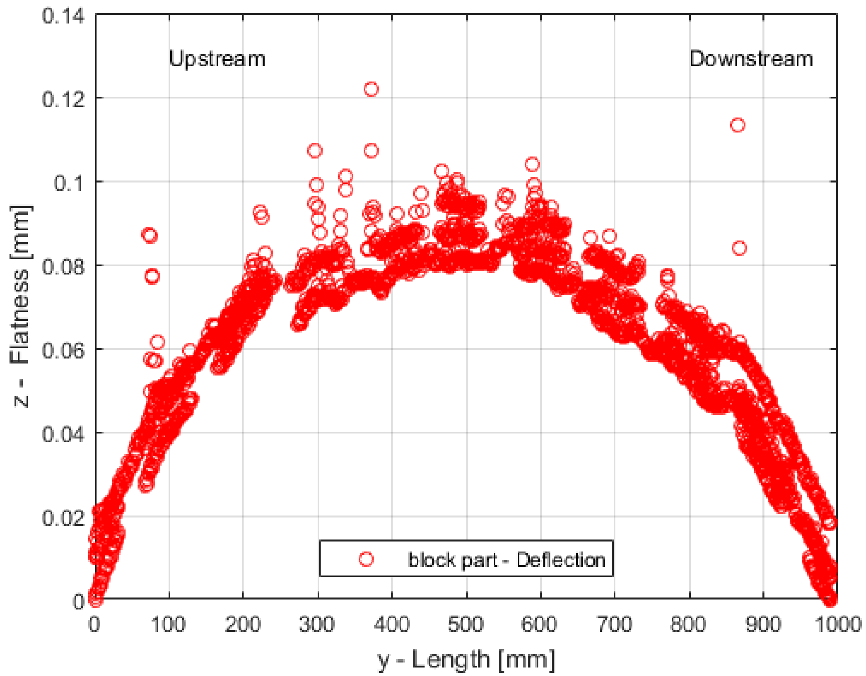


Downstream **Glidcop tapering** of CFC jaw **locally melted**

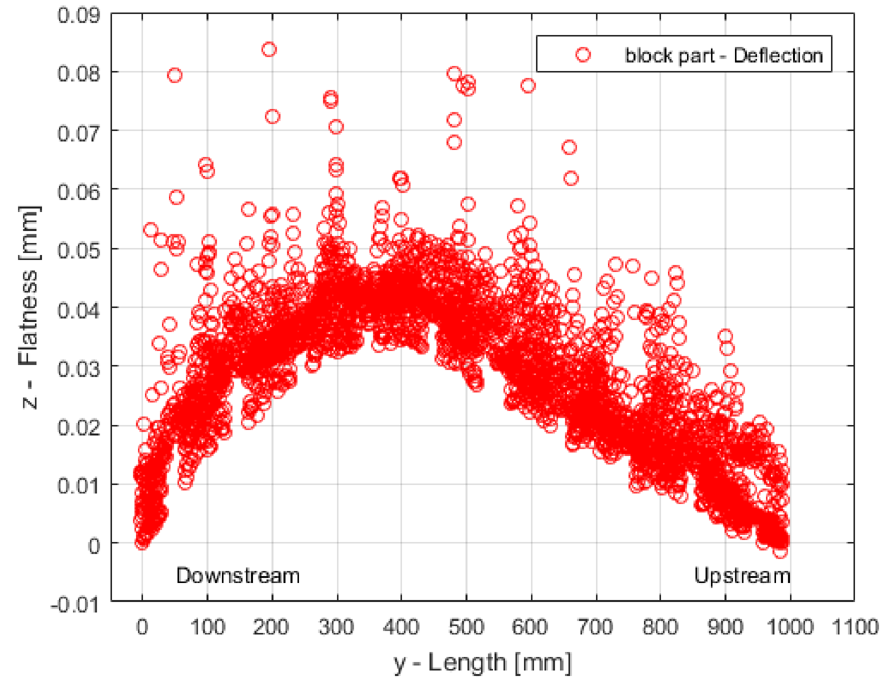
MoGr no damage detected

Metrology – MoGr and CuCD jaws

MoGr → **~80 µm**



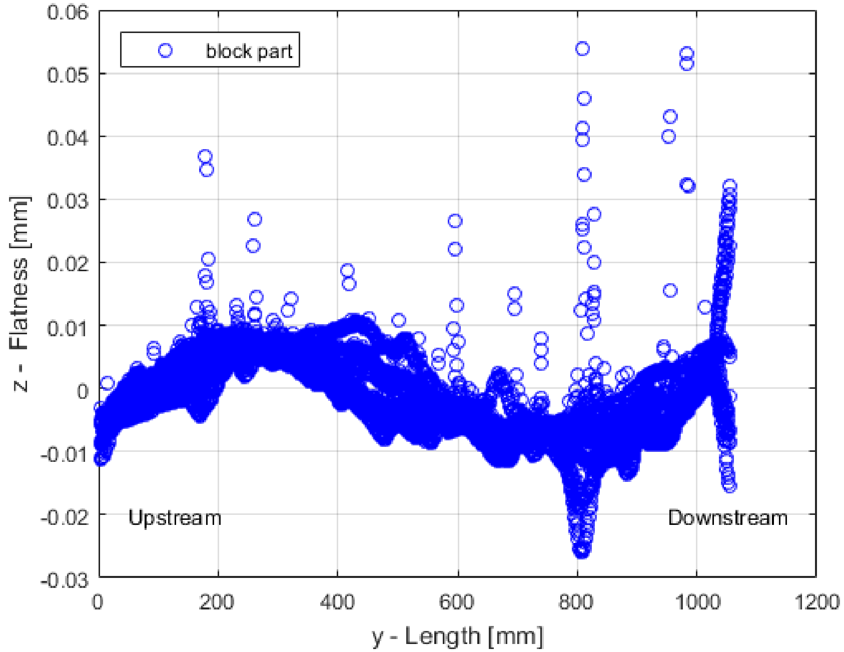
CuCD → **~50 µm**



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

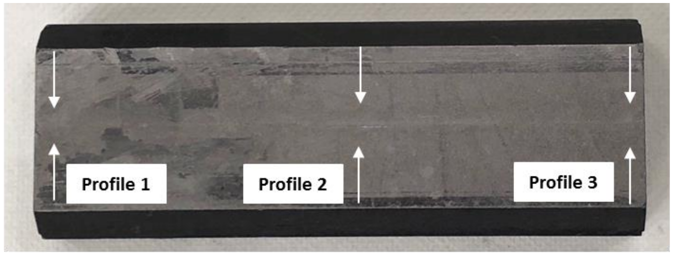
CFC → **~20 µm**

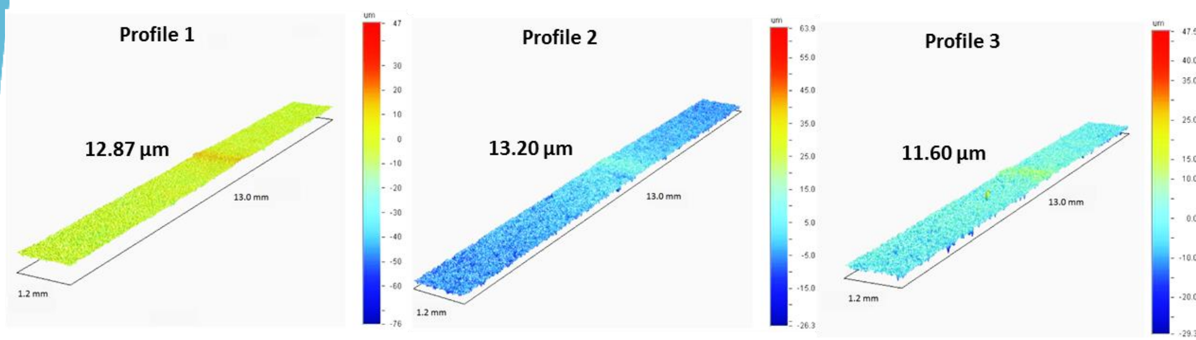


Flatness within the machining tolerance → CFC lower energy absorption

3D topography - MoGr

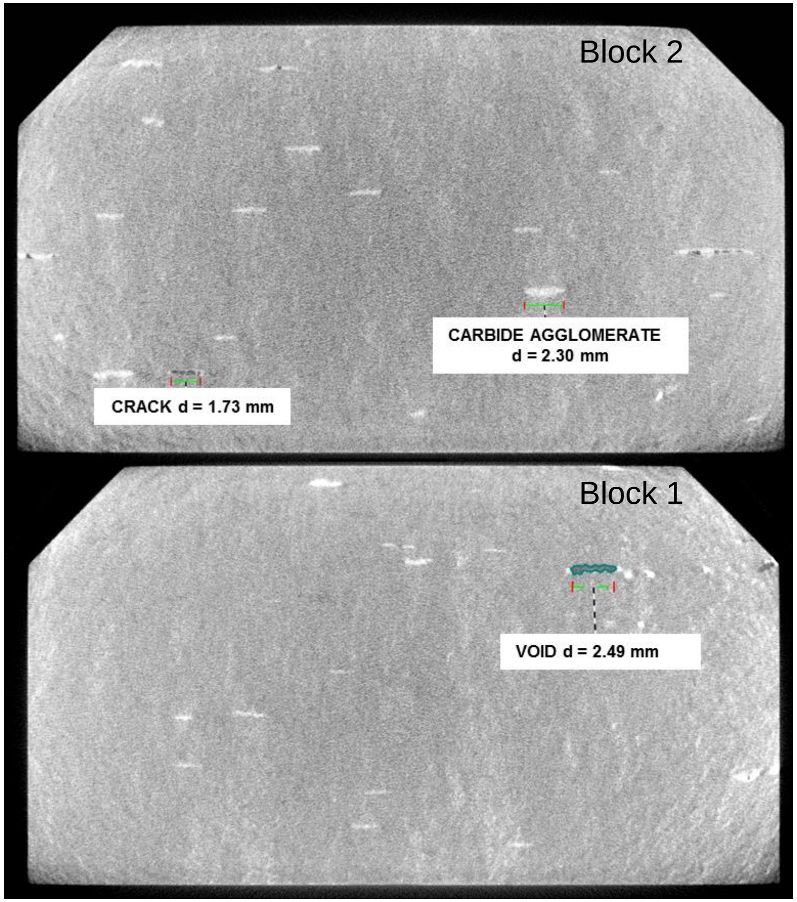
Block 2





- 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

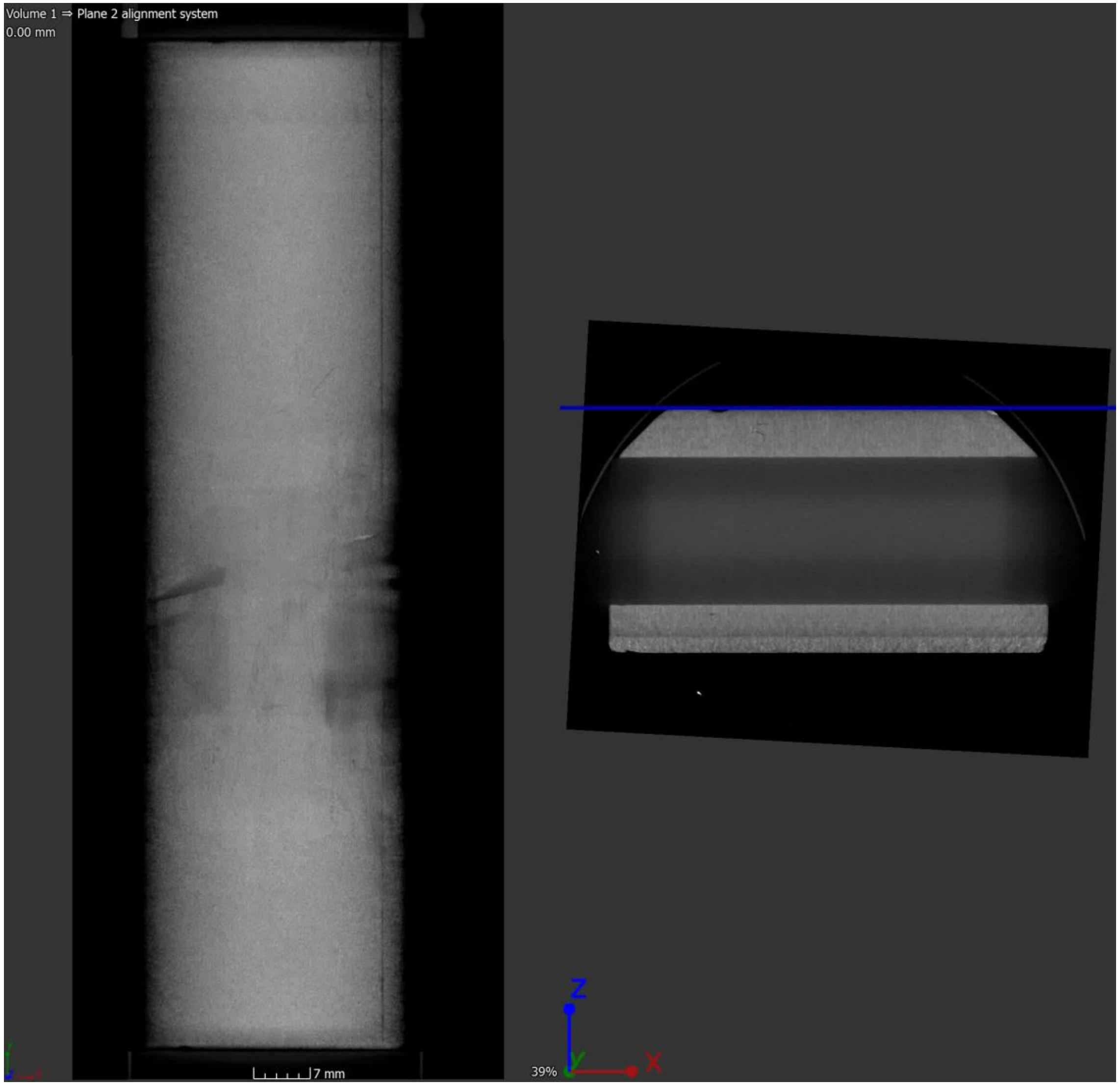


- No internal damages detected
- Agglomerate of molybdenum carbides with disk shape, dimensions few mm
- Small cracks or voids appear in correspondence of carbide agglomerates randomly distributed in the bulk → not attributed to beam effect

↓

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

LHC Collimation Project CERN

	Specification			Batch 2	
Property	**II***	**⊦**	**Unit**	**II***	**⊦**
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

LHC Collimation Project CERN

Property	Specification			Batch 2	
	II*	⊥	Unit	II*	⊥
Density at 20ºC	2.40 – 2.60		$[g/cm^3]$	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