EuCARD2 4th Annual Meeting Report on WP11

Collimator Materials for Fast High Density Energy Deposition

EuCARD-2 Annual Meeting, Glasgow, 28 – 30 Mar 2017

Adriana Rossi on behalf of ColMat-HDED

EuCARD-2 is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453

Starting from the end ...

ARIES PowerMat WP17 coordinators

Marilena Tomut (GSI)

Alessandro Bertarelli (CERN)

WP11 Milestones and deliverables

Milestones :

MS69 Irradiation of first samples	M12
MS70 Present results on material damage from irradiation	M24
MS71 Show new material development status	M24
MS72 Present results on material damage from simulation and compare to experiments	M45

Deliverables :

11.1 Result on simulations of new materials and composites	M36
11.2 Report on comparative assessment of beam simulation codes	M40
11.3 Irradiation test results	M46
11.4 Results on characterisation of new materials and composites	M46

Deliverable reports

Grant Agreement No: 312453

EuCARD-2

Enhanced European Coordination for Accelerator Research and Development

Seventh Framework Programme, Capacities Specific Programme, Research Infrastructures, Combination of Collaborative Project and Coordination and Support Action

DELIVERABLE REPORT

IRRADIATION TESTS RESULTS

DELIVERABLE: D11.3

Document identifier:	EuCARD2-Del-D11-3-MT_EQ_FC_AR_AL
Due date of deliverable:	End of Month 46 (February 2017)
Report release date:	27/02/2017
Work package:	WP11
Lead beneficiary:	GSI, CERN
Document status:	Draft

Abstract:

This document presents the results of the irradiation experiments for studies on radiation hardness and on response to proton beam-induced high energy density deposition of the new Molybdenum Carbide - Graphite (MoGr) and Copper-Diamond (CuCD) materials developed within the EuCARD-2 WP.11. The irradiations were performed at GSI, BNL, Kurchatov Institute and at the HiRadMat facility at CERN using ion and proton beams with energies between 35 MeV and 440 GeV.

63 pages

Grant Agreement No: 312453

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DELIVERABLE REPORT

RESULTS ON CHARACTERISATION OF NEW MATERIALS AND COMPOSITES

DELIVERABLE: D11.4

Document identifier:	EuCARD2-Del-D11-4-v1FC_JG_FCv2
Due date of deliverable:	End of Month 46 (February 2017)
Report release date:	20/02/2017
Work package:	WP11
Lead beneficiary:	[Short name of participant e.g. WUT]
Document status:	Draft

Abstract:

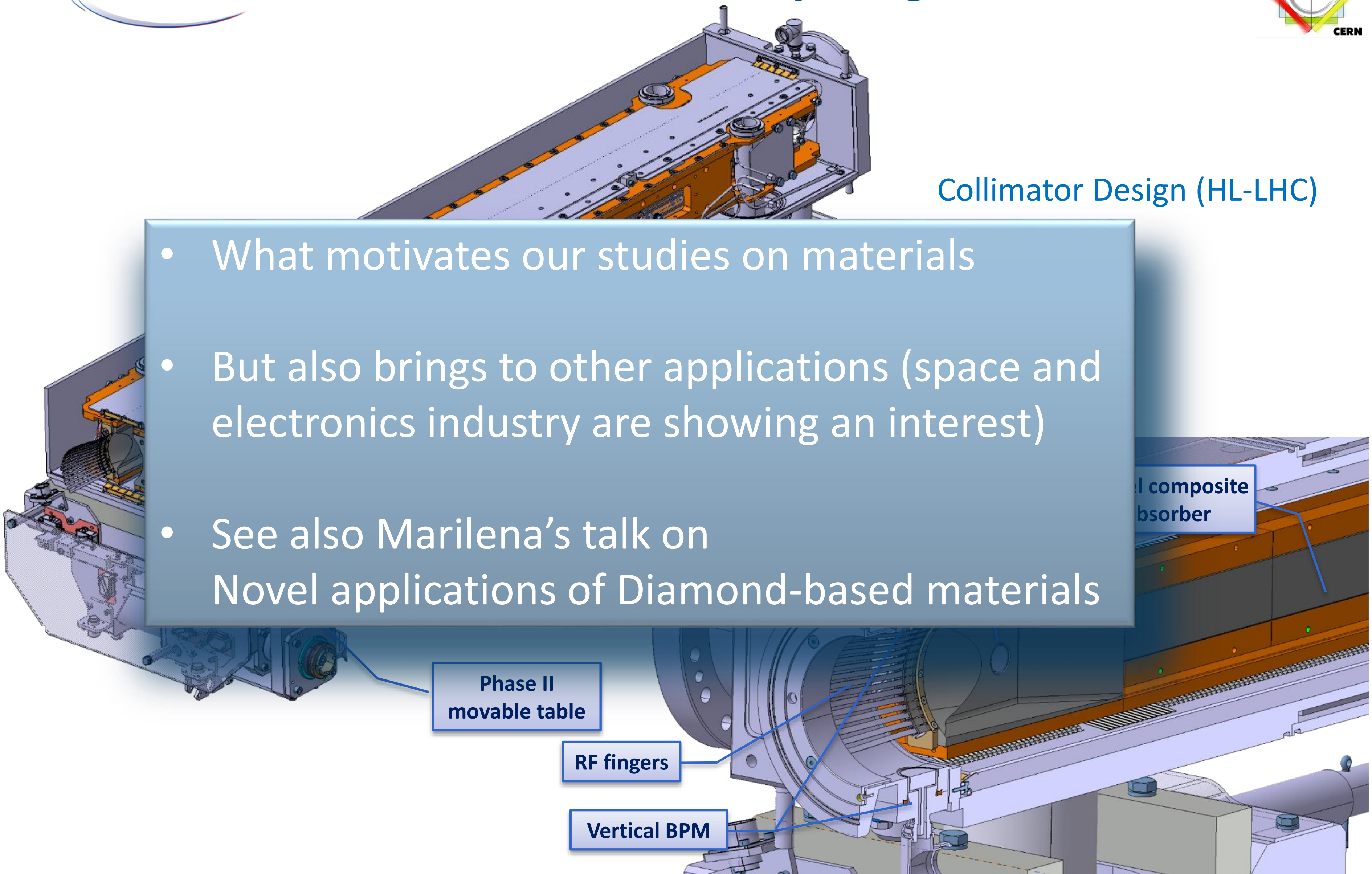
This document summarizes the characterization done on the novel materials developed at CERN for low-impedance and high-robustness LHC collimators. Results of the measurements done at CERN, GSI and Kurchatov Institute are presented.

27 pages

… to continue from the beginning

Beam intercepting devices

Collimator Design (HL-LHC)



- What motivates our studies on materials
- But also brings to other applications (space and electronics industry are showing an interest)
- See also Marilena’s talk on
  Novel applications of Diamond-based materials

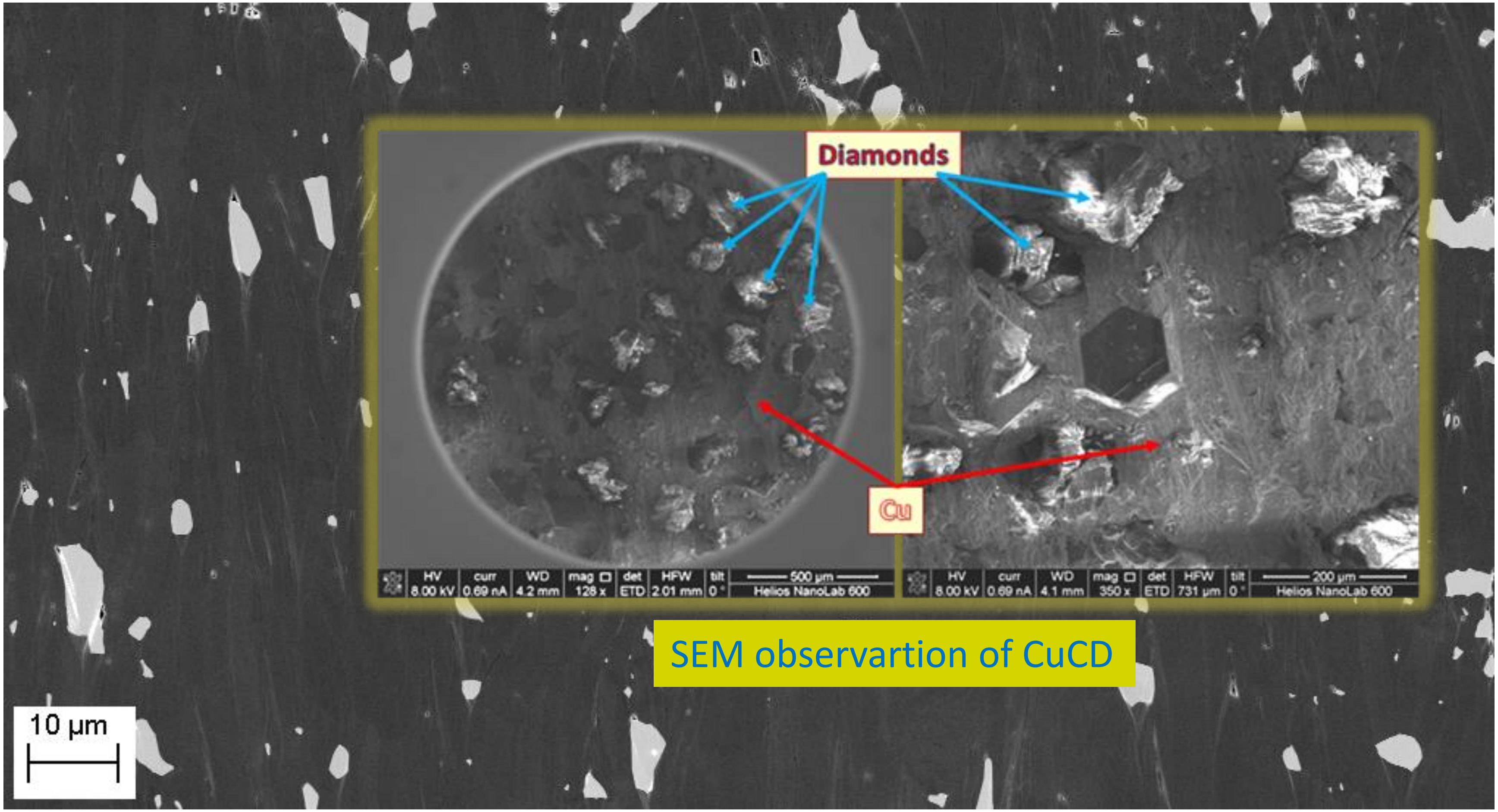
1. **R&D, theoretical studies**: *Jorge. Guardia Valenzuela*, PhD University of Zaragoza
   Structural and compositional analyses for the optimization of graphite-based composites used in the LHC collimation system

2. **Experimental characterization**: *Elena Quaranta*, PhD Politecnico di Milano
   Investigation of collimator materials for the High Luminosity Large Hadron Collider

3. **Simulations**: *Federico Carra*, PhD Politecnico di Torino
   Thermomechanical Response of Advanced Composite Materials under Quasi-Instantaneous Heating

4. **Radiation effects**: Bachelor thesis
   - *Yuan Xu,* TU Darmstadt – Effects of Swift Heavy Ion Irradiation on Molybdenum Carbide – Graphite (MoGR) Composite
   - *Philipp Bolz,* TU Darmstadt – Nanoindentation characterization of ion induced degradation of mechanical properties of carbon materials
   - *Carsten Porth,* TU Darmstadt – Ion-induced microstructural and functional properties changes in Molybdenum-Carbide-Graphite composites
   - *Katja Bunk*, University of Frankfurt – Structural transformation of Molybdenum Carbide – Graphite composites induced by irradiation with Au-ions
   - *Florian Kopietz,* TU Darmstadt – XRD and Raman spectroscopy study of structural transformation induced by irradiation with light and heavy ions in Molybdenum Carbide – Graphite composites

MoGr and CuCD being investigated



Molybdenum-Graphite (MoGr) = composite of graphitic matrix reinforced with molybdenum carbide. Here MG6403Fc cross-section obtained by ion-polishing. Note the graphite planes oriented vertically in the image.

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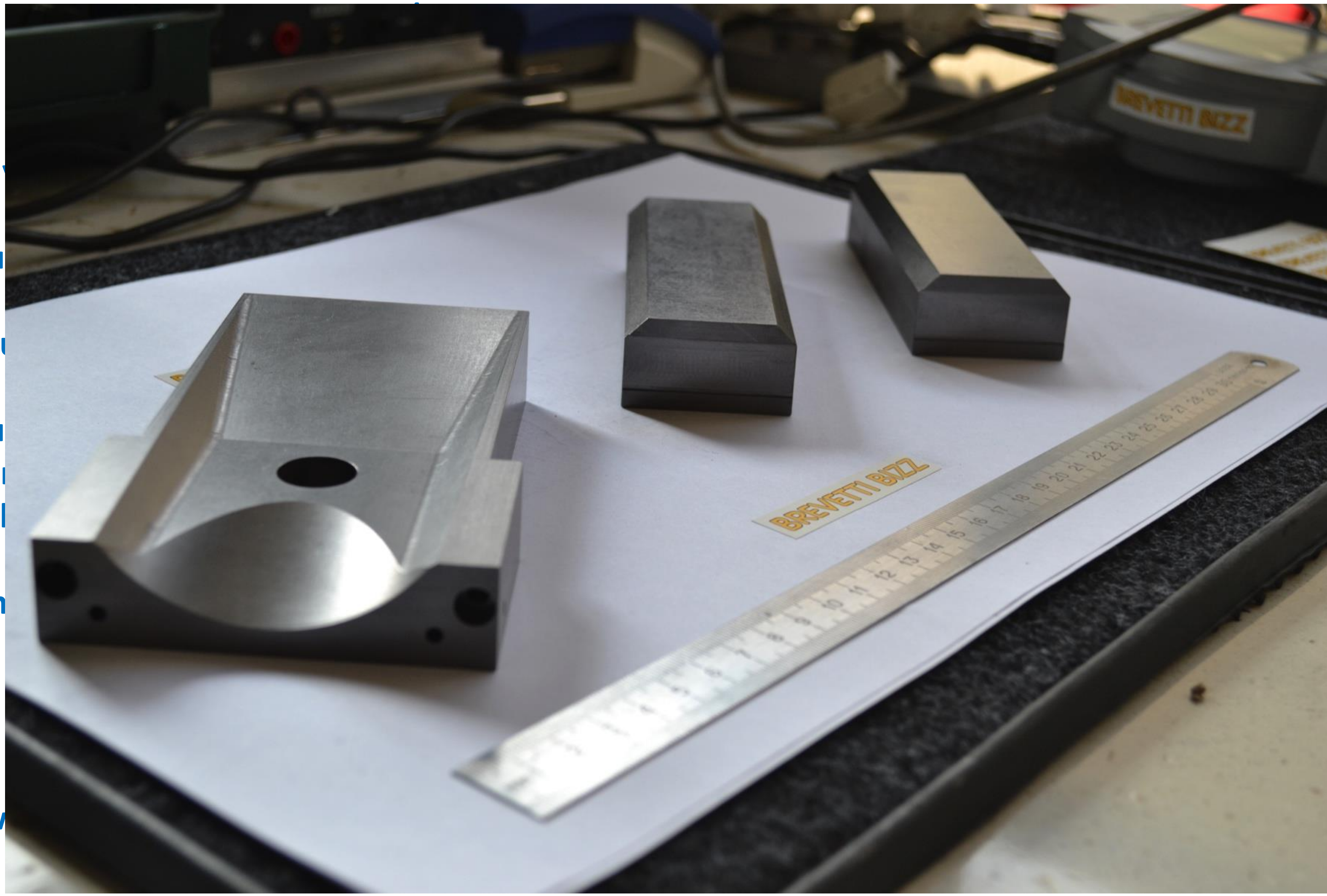
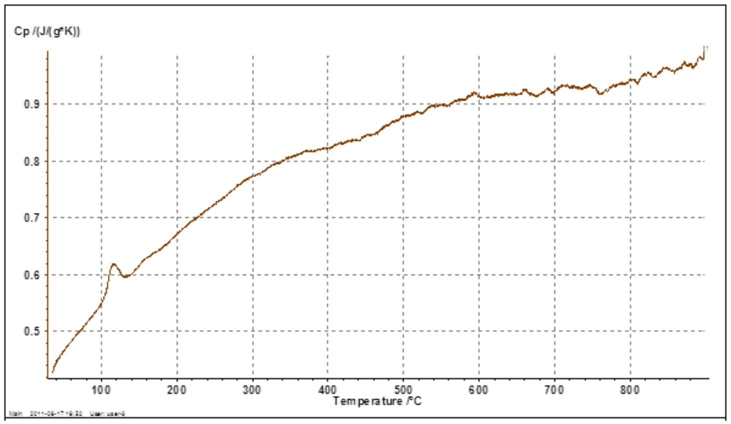
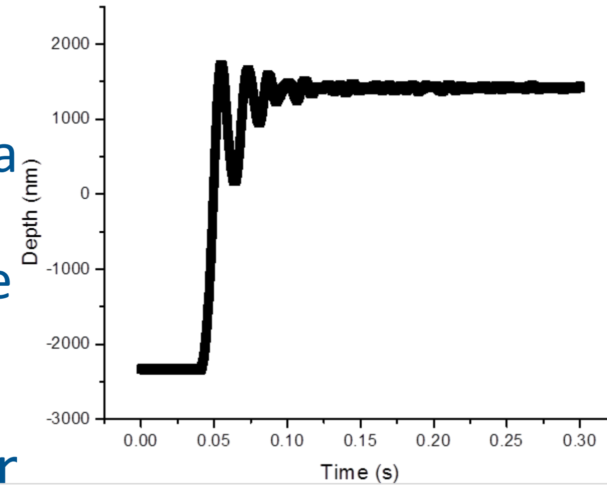


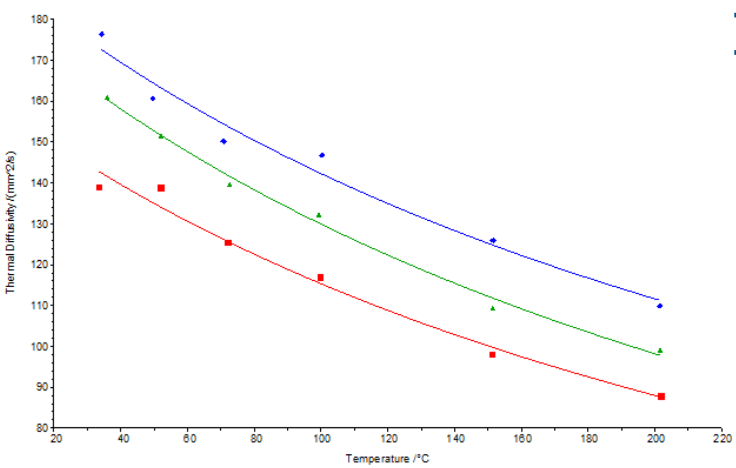
Production sketch

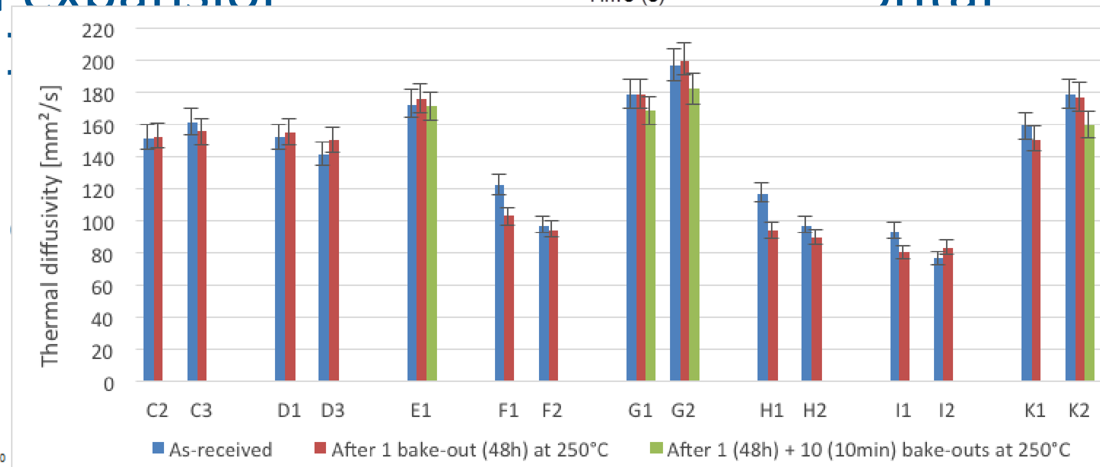
Thermo-mechanical characterisation of materials

- entia … SC
- Lase … A427)
- Coefficient of thermal expansior … ntal









Thermo-mechanical characterisation of materials

Name		MG-6530-Aa		MG-6403-Fc		CuCD
Direction		ǁ	⊥	ǁ	⊥	
Density (g/cm³)		2.505		2.55		5.252
Electrical conductivity (MS/m)		0.905	0.048	0.965	0.071	~10 - 58
Thermal Diffusivity (mm²/s)*	20⁰C	325.4	31.4	465.5	31.3	188.7
	500⁰C	76.9	5.8	79.4	5.9	64.0
Specific Heat (J/g/K)	20⁰C	0.601		0.624		0.340
	500⁰C	1.327		1.304		0.680
Thermal Conductivity (W/m/K)	20⁰C	489.9	47.2	740.1	49.8	337.3
	500⁰C	255.6	19.2	263.9	19.5	228.6
CTE (μm/K) from RT to:	200⁰C	1.65	11.64	2.67	7.93	9.34
	500⁰C	1.78	12.85	2.87	8.86	10.57
	1000⁰C	1.74	15.33	2.82	11.16	-
	1900⁰C	1.76	18.88	2.76	16.30	-
Residual deformation (%)		0.04	0.17	0.00	0.12	0.11
Flexural Strength (MPa)		70.9±3	12±0	58.1±8	10±1	100±11
Flexural strain to rupture (μm/m)		2501±547	7244±1771	2430±498	4344±1010	4245±1702

Overview of irradiation tests on MoGr

BNL (p^{+}, n) | GSI (^{238}U, ^{209}Bi, ^{197}Au, ^{152}Sm, Ca, C ions) | BNL (p^{+}, n)

mid 2013 — Feb. 2014 — July 2014 — mid 2015 — 2016

3th generation

MG 1110-E
(3.7 g/cm^{3})
NOT fully molten
20%v Mo
40%v C-fibers
(long+short)

4th generation

MG 3110-P
(2.67 g/cm^{3})
Fully molten
20%v Mo
40%v C-fibers
(long+short)

5th generation

MG 5200-S
(2.65 g/cm^{3})
Fully molten
7.2%v Mo
46.4%v C-fibers
(long+short)
2 annealing cycles:
- 1150°C
- 1300°C

6th generation

MG 6400-U
(2.63 g/cm^{3})
Fully molten
4.5%v Mo
NO C-fibers
Annealing 1800˚C

MG 6541-Aa
(2.5 g/cm^{3})
Fully molten
4.5%v Mo
0. %v Ti
5%v C-fibers
(short only)
Annealing 1900°C

MG 6530-Aa
(2.5 g/cm^{3})
Fully molten
4.5%v Mo
5%v C-fibers (long only)
Annealing 1900°C

7th generation

MG 6403-Aa
(g/cm^{3})
Fully molten
4.5%v Mo
%v Ti
NO C-fibers

E. Quaranta, CERN

Irradiation campaigns at BNL

- **1^{st} irradiation campaign (2013-2014):**
  - 200 MeV proton irradiation at BLIP (up to 1.1 x 10^{21} p/cm^2)
  - Spallation neutrons from 112 MeV protons at BLIP
  - Tightly focused 28 MeV proton beam at TANDEM

  Irradiated materials:
  - Glidcop AL-15 (SCM Metals, USA)
  - Mo (Plansee, Austria)
  - CuCD (RHP Tech., Austria)
  - MoGr (Brevetti Bizz, Italy), 3^{rd} generation grade

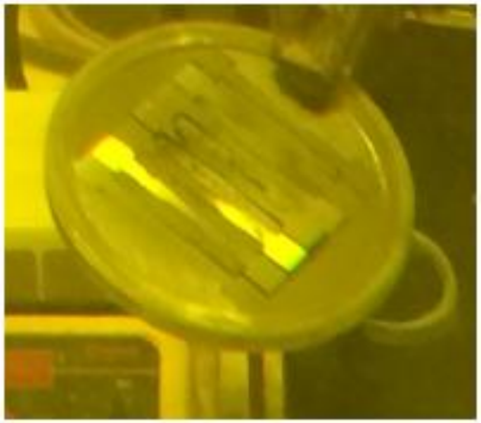
- **2^{nd} irradiation campaign (2016):**
  - 200/160 MeV protons at BLIP (~ 2 x 10^{20} p/cm^2)

  Irradiated materials:
  - MoGr, 6^{th} and 7^{th} generation grades
  - CFC (current material of LHC primary and secondary collimators)

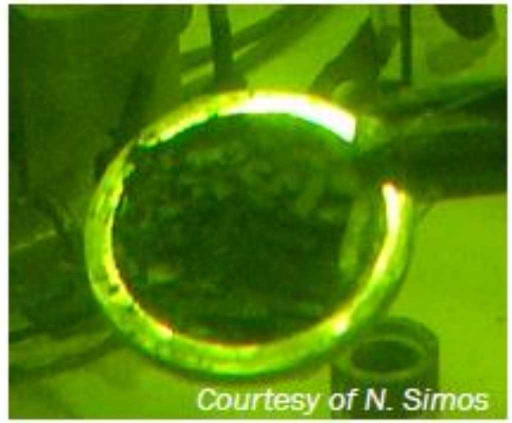
Courtesy of N.Simos (BNL) & E. Quaranta (CERN)

1st irradiation campaign: 2014

Irradiated Mo



Irradiated MoGr



BNL IRRADIATION DAMAGE STUDIES OF THE METAL MATRIX COMPOSITE MO-GR CONSIDERED FOR HIGH LUMINOSITY LHC COLLIMATOR UPGRADE

PROGRESS REPORT

Main Contributors:

N. Simos[1]

P. Nocera[1] and E. Quaranta[1]

Added Contributions from
Stefano Redaelli[3] and A. Bertarelli[3]

[1]Brookhaven National Laboratory, Upton, NY 11973, USA

[2]University of Rome

[3]CERN

DRAFT

Mo, Glidcop and CuCD survived.

MG-1110E seriously damaged at high fluences (1.1×10^{21} p/cm^2)

Open points after 1st irradiation campaign:

- MoGr still not optimised (possible unreleased **internal stresses** from production cycle)? Are the new grades better?
- Fluence **threshold** where structural **damage** start to appear?

Courtesy of N.Simos (BNL) & E. Quaranta (CERN)

First visual inspection after 2nd campaign

Late April 2016:

2 MoGr capsules opened after 1st step in fluence ($\sim 5 \times 10^{19}$ p/cm^2)

June – July 2016:

All capsules opened (max fluence > 2×10^{20} p/cm^2)

- No macroscopic damage of any sample observed after first visual inspection when irradiated capsules where opened remotely in the Hot Cells
- Further micro/macro analyses are planned to assess response of the material to possible irradiation-induced damage.

Courtesy of N.Simos (BNL) & E. Quaranta (CERN)

Irradiation of novel composite - GSI

Ion irradiation: C – U

Energies: 70 MeV – 1 GeV

Fluence: up to 1×10^{14} i/cm^2 ~ 10^{-4} dpa

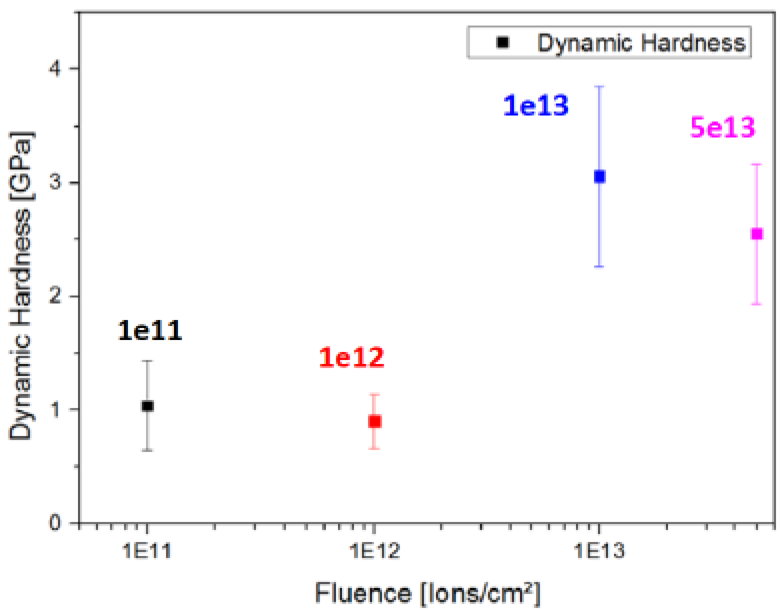
Structural characterization: XRD, Raman

Functional properties degradation:

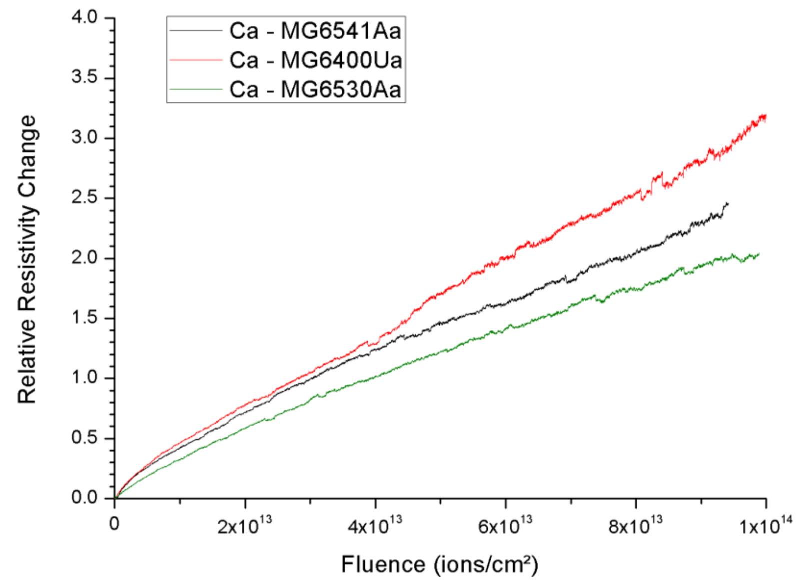
Material optimization

Radiation damage effect on properties degradation

Irradiation induced hardening
– dynamic harness:



Increase of electrical resistivity
- online measurements during irradiation



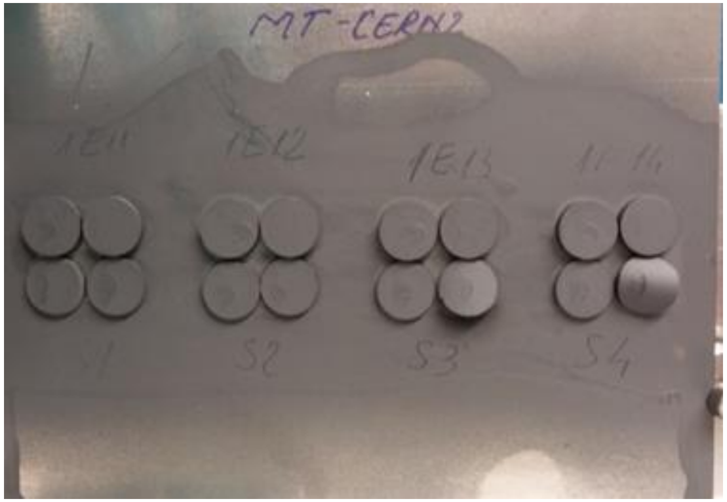
- Hardness and Young's modulus increased with accumulated dose.
- Samples annealed at higher temperatures show less degradation

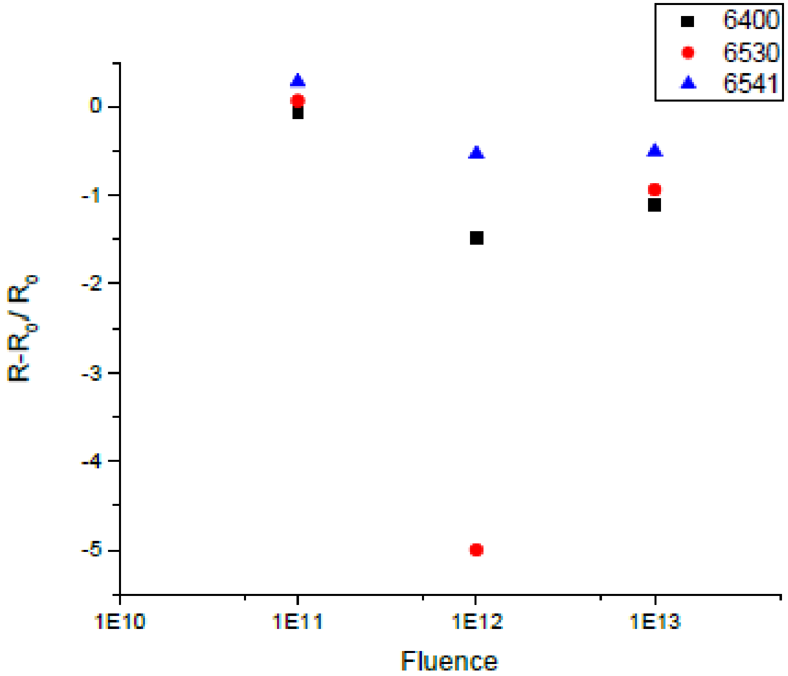
- Defect accumulation results in gradual resistivity increase
- Presence of carbon fibers reduce material's resistivity degradation

Irradiation induced deformation and mitigation

- Macroscopic bending was observed around 5×10^{12} Au ions/cm²

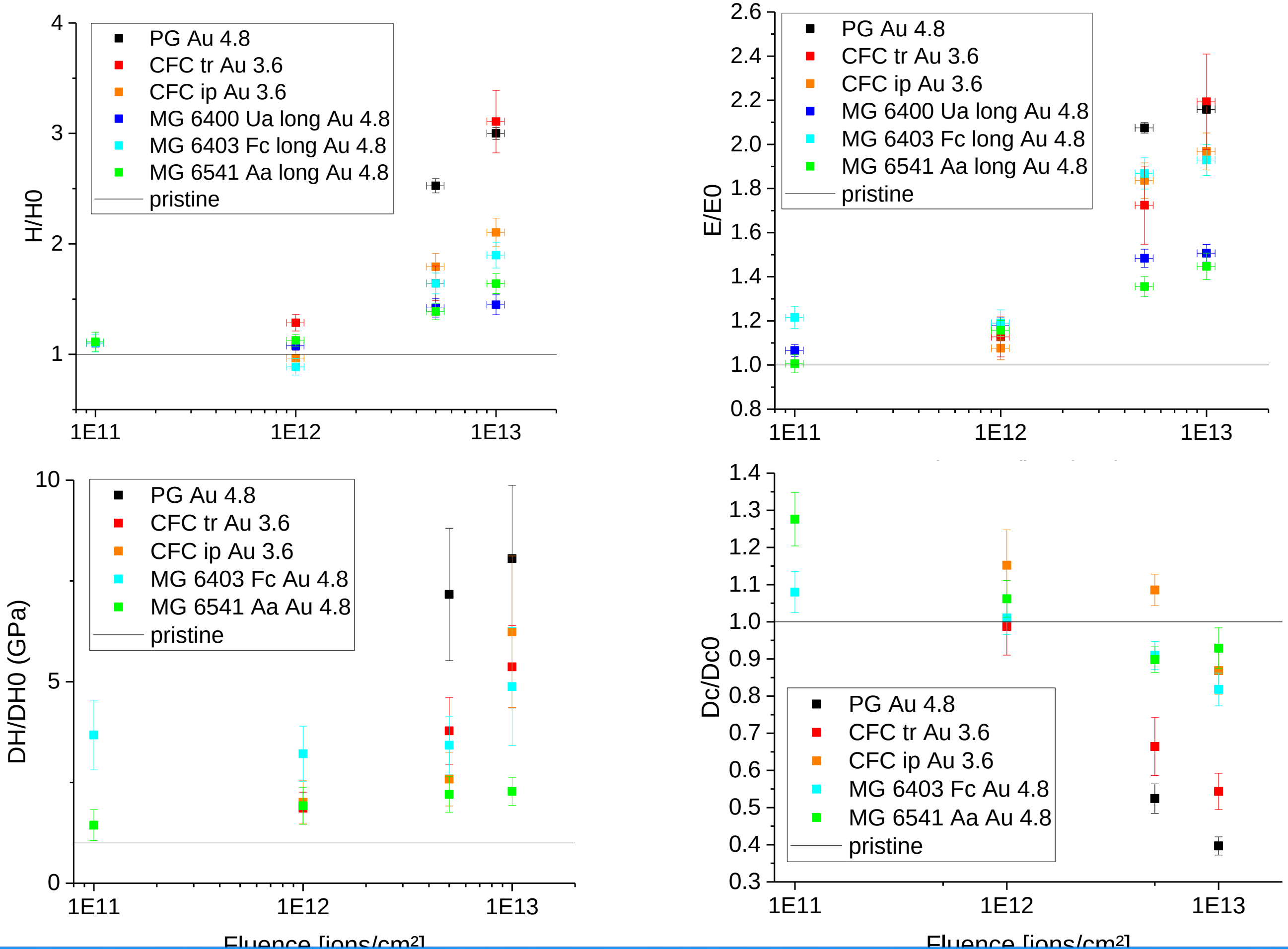
- Optimization of the material to avoid swelling and deformation





Irradiation induced hardening- latest measurements

- MoGr – better behaviour than isotropic graphite and CFC

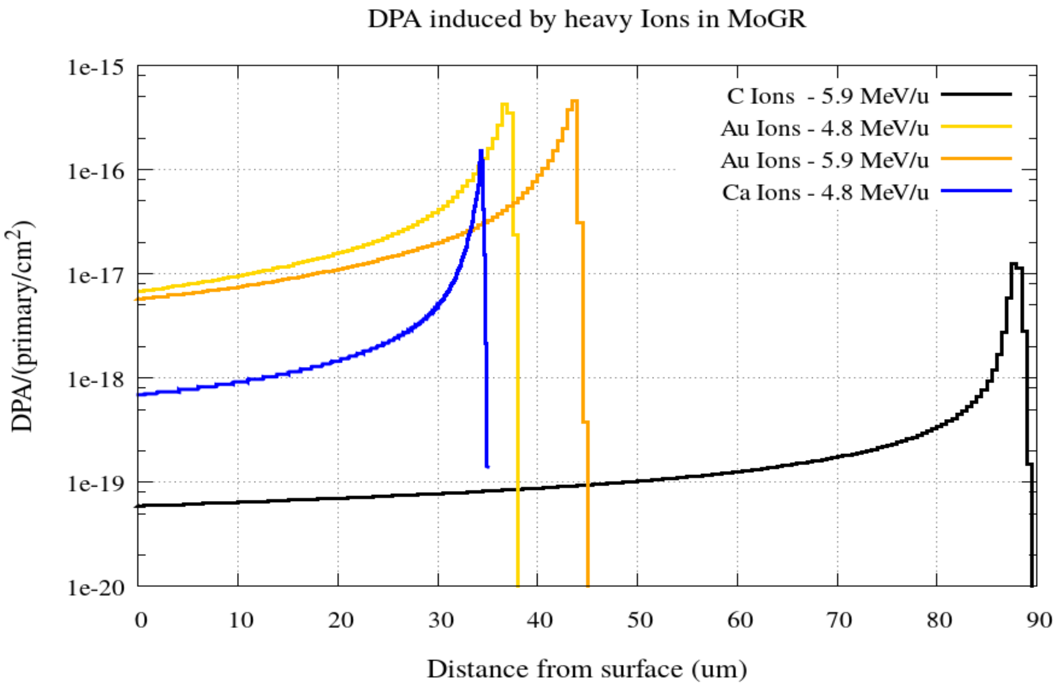


D11.3 Irradiation tests results

FLUKA simulations

MoGr (6400, 6530, 6541)

E. Skordis

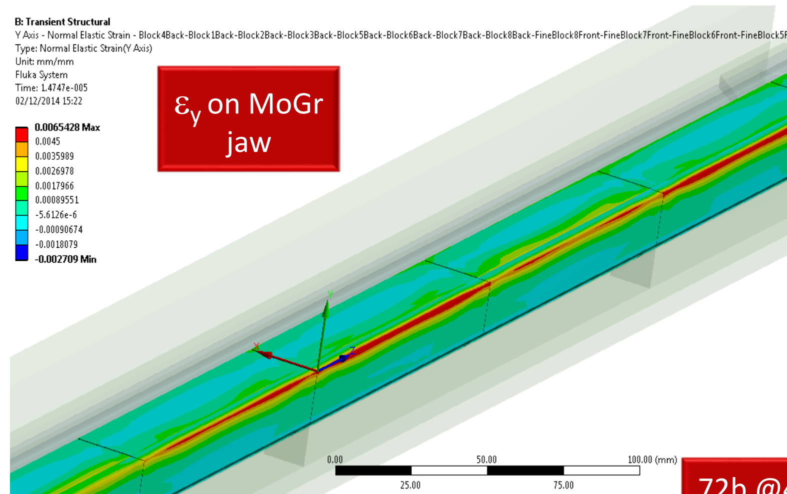


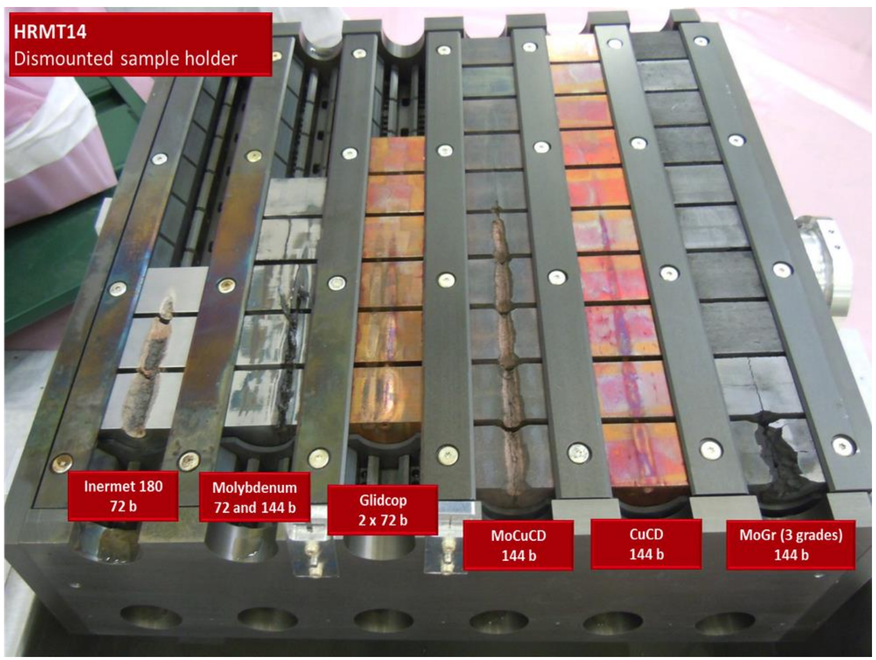
These simulations studies provide a link between DPA values achieved in the experiments and the DPA expected in LHC collimators

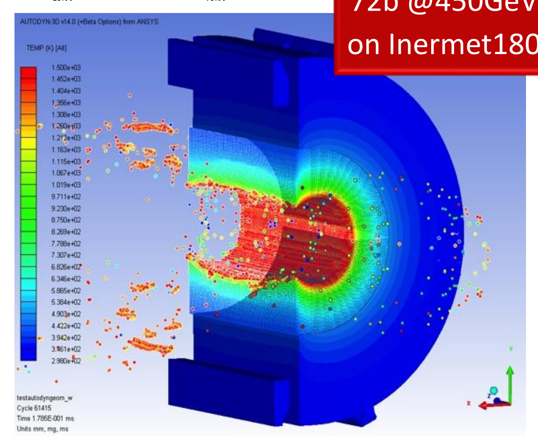
HiRadMat tests (440GeV p^+)

2012 HRMT-14: test of specimens from 6 different materials, including novel composites

- Allowed characterization of materials of interest for collimators
- Tuning of numerical models, with very good benchmarking between measurements and simulations





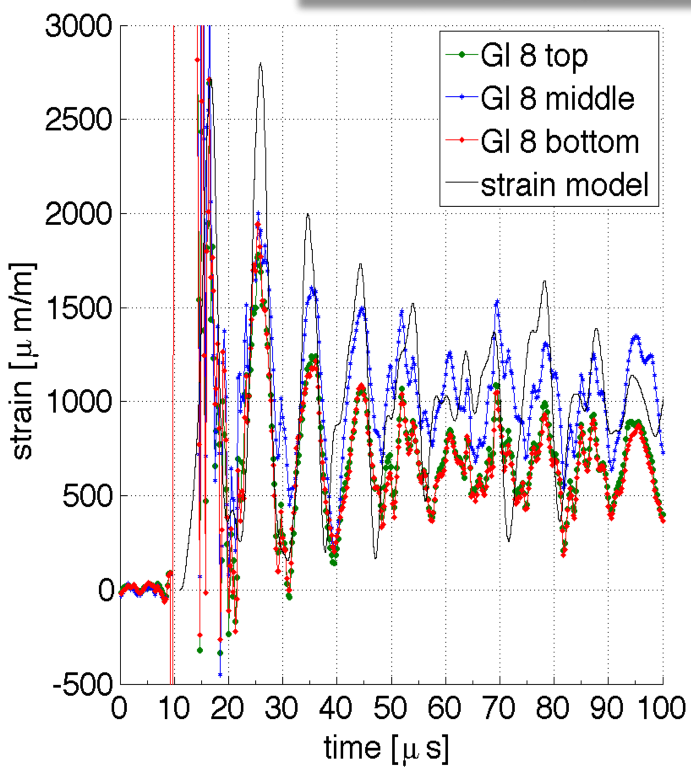


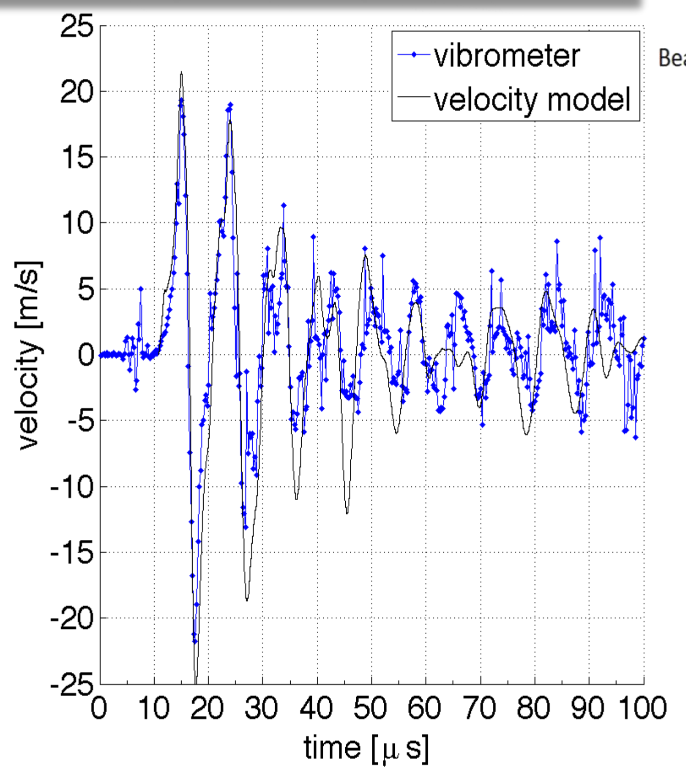
HRMT-14: Material Sample Holder

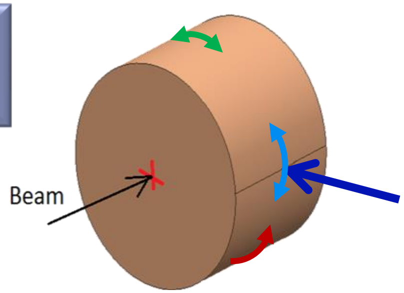
2012: test of specimens from 6 different materials, including novel composites

- Allowed characterization of materials of interest for collimators
- Tuning of numerical models, with very good benchmarking between measurements and simulations

Glidcop Sample – Slot#08
72 b (scraped), Total intensity: 4.66e12 p, σ ≅ 1.3 mm

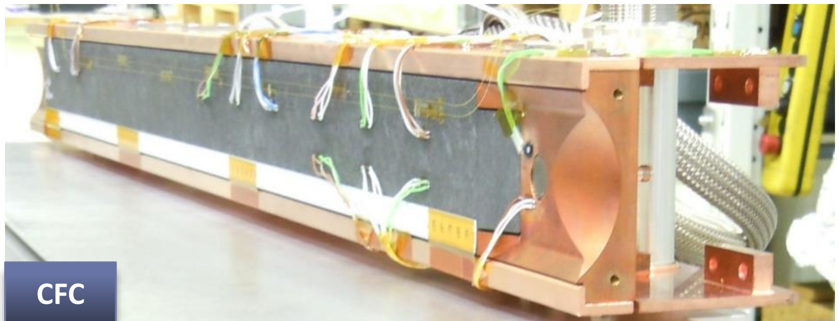


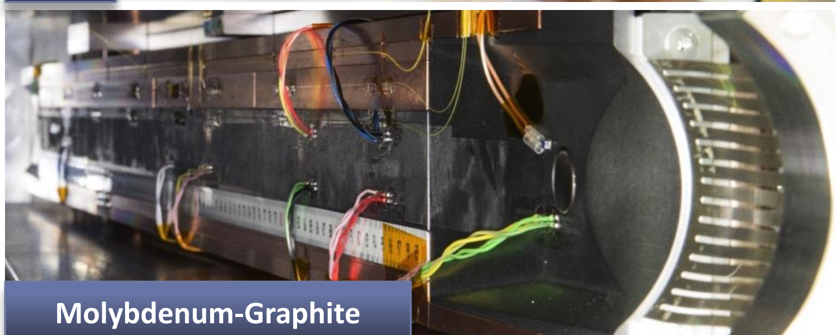




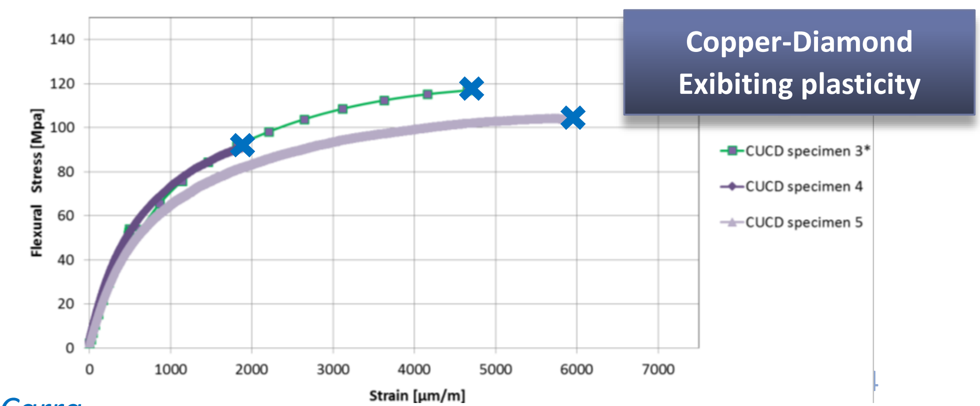
HRMT23 and Material Modelling

- July 2015: proton beam impacts on three LHC and HL-LHC jaws (CFC, MoGr, CuCD)



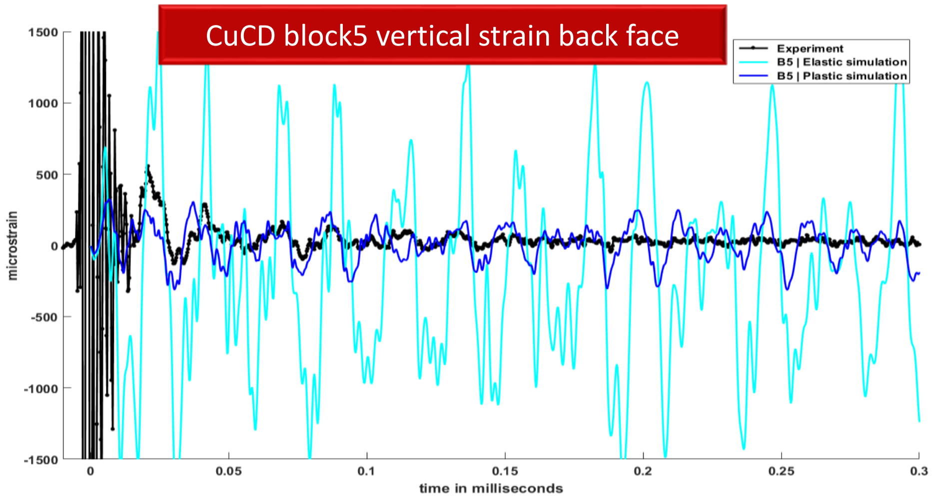


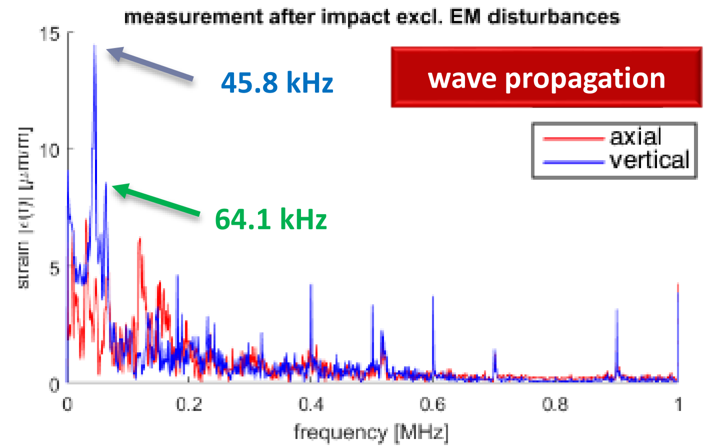
Elastic Constants	CFC	MoGr	CuCD
E_x [GPa]	2.8	7.1	160.5
E_y [GPa]	57.5	74.0	160.5
E_z [GPa]	93.0	74.0	160.5
G_{xy} [GPa]	3.5	4.3	75.1
G_{xz} [GPa]	6.4	4.3	75.1
G_{yz} [GPa]	10.6	31.3	75.1
ν_{xy}	0.11	0.13	0.07
ν_{xz}	0.10	0.13	0.07
ν_{yz}	0.10	0.19	0.07

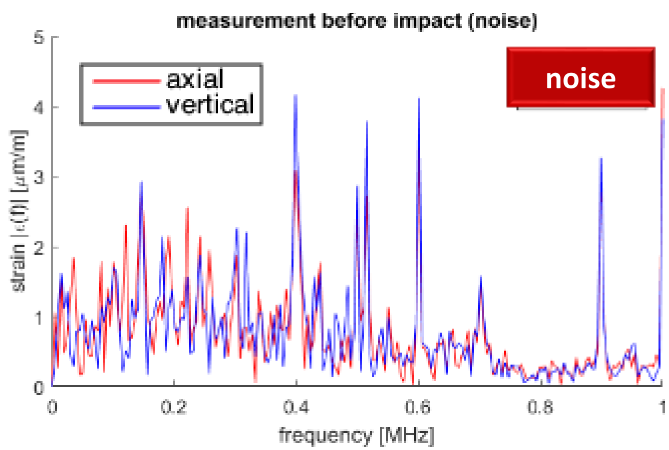


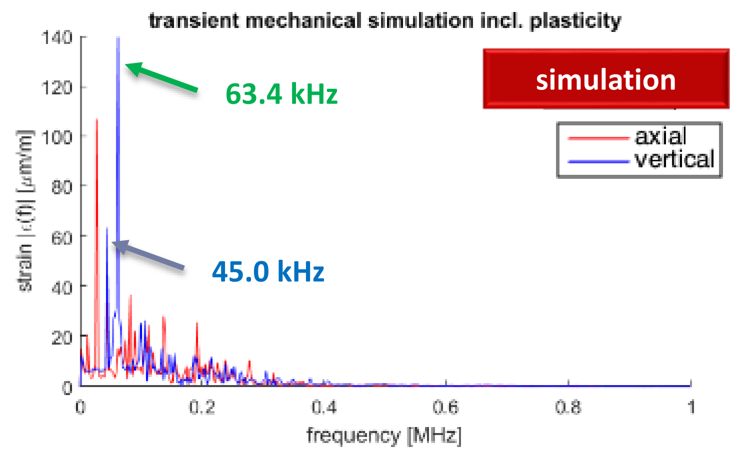
CuCD Modelling

- HRMT shot #124: **CuCD 24 bunches**, σ 0.61 mm, impact 5σ
- Pseudo-plasticity of the material taken into account!





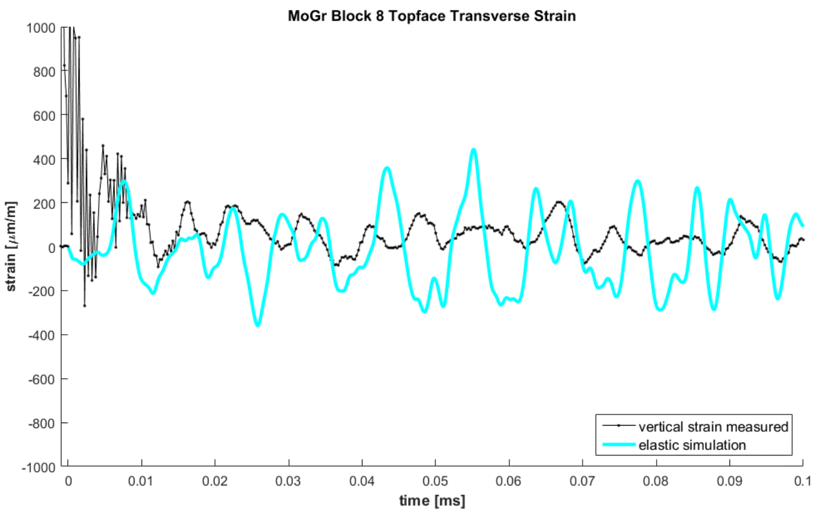


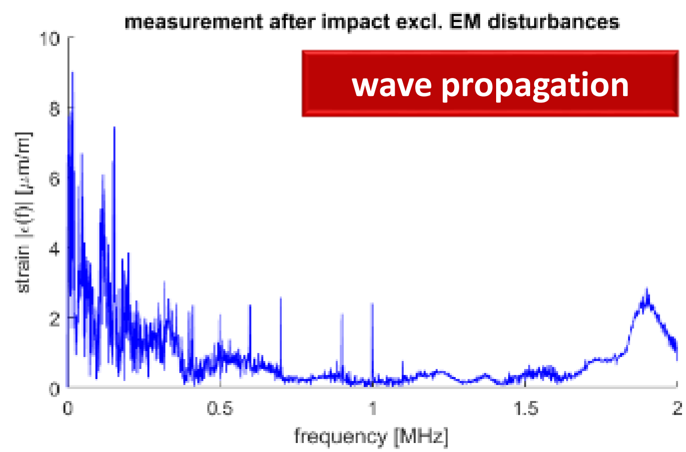


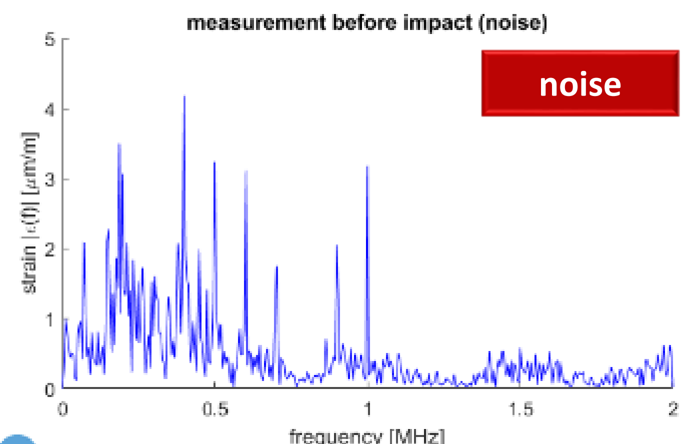
- Why observed decrease in amplitude with time? **Damping**?

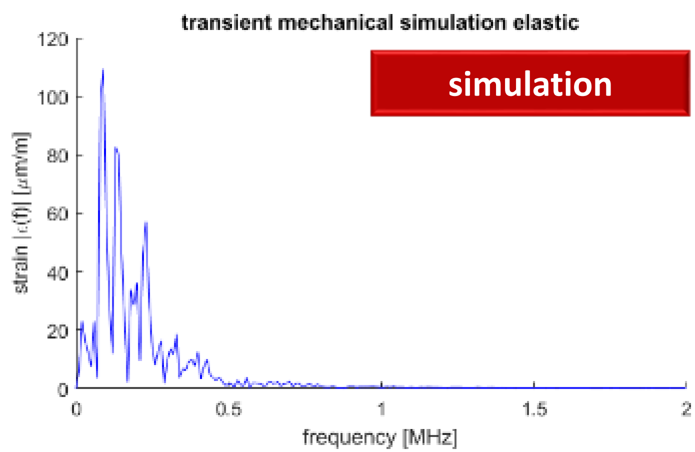
MoGr Modelling

- HRMT shot #200: **MoGr 24 bunches**, σ 0.6 mm, impact 5σ
- Orthotropic elasticity simulated up to now, can evolve into **orthotropic viscoelasticity** (similarly to what done on isotropic graphite with L. Peroni, M. Scapin for DAMAS 2013)









Halo cleaning simulations with advanced collimator materials

- SixTrack material DB updated with new composites materials.

Main simulation parameters:

- Energy: 7 TeV
- Beam 1, Hor. halo
- Statistics: 6.4 x 10^6 SixTrack particles
- Nominal 7 TeV optics and post LS1 LHC layout
- All **CFC** secondary collimators in IR7 replaced by new materials: **MoGr**, **CuCD**, **Inermet180**.

Note: the high-Z Inermet180 is not part of any LHC upgrade plan, due to its limited robustness. It was included in the study for comparison.

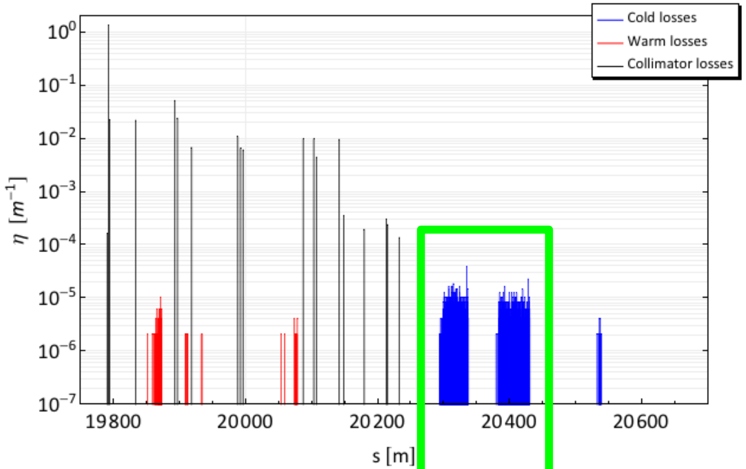
Collimator settings at 7 TeV [σ]		
IR7	TCP	6
	TCSG	7
	TCL	10
IR6	TCSG	7.5
	TCDQ	8
IR3	TCP	15
	TCSG	18
	TCL	20
IR1/5	TCT	8.3
IR2/8	TCT	25

IR7 DS → highest loss location

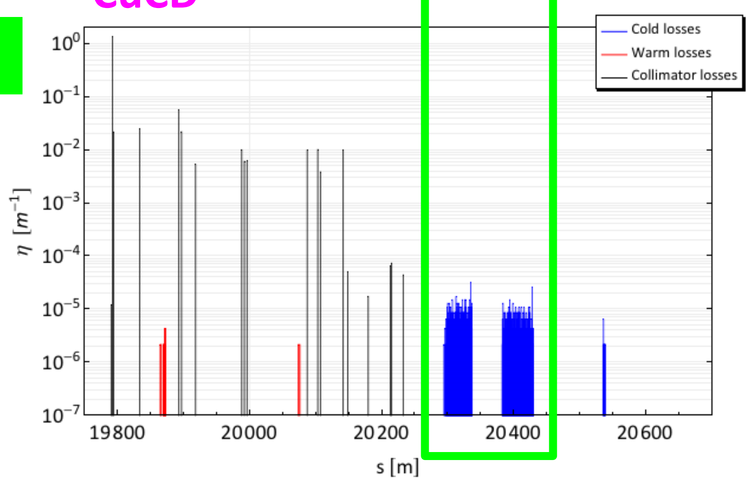
Not largely affected by TCSG materials, losses dominated by single diffractive events in primary collimators.

Courtesy of E. Quaranta

CFC



CuCD



Summary

- It's been a very intense 4y programme executed magnificently by all collaborators
- Tangible results that are promising both for accelerator applications and beyond
- A collaborative team built over the years

Thank you
and thanks
the WP11 collaboration