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LHC Collimation Project CERN

ARIES

Report from recent material characterization campaigns and new developments

ARIES WP17 2nd Annual Meeting
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https://indico.cern.ch/event/938208/

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With contributions from Mechanical Measurements Laboratory, Mechanical & Materials Engineering group at CERN

Outline

- CuCD tests
  - Thermal conductivity isotropy
  - High-temperature bending tests
- Updates on graphite-matrix composites
  - Description and results
  - Comparison with MoGr and pure carbon materials
- Conclusions
- Next steps

CuCD composites (Copper-diamond)

Produced by:

CuCD HRMT36 grade

Composition:
- **50vol%** bi-modal **diamond** mixture with mesh size 70/80 and 120/140.
- Matrix: **copper alloy.**
- Theoretical density=6.21 g/cm^3 (CD=3.514, Cu-alloy=8.9 g/cm^3)

Several batches produced for different purposes.
Measured density:
- 3025 (weight+dimensions): ~**5.7 g/cm^3**
- 3434 (weight+dimensions): **5.7 g/cm^3**
- 3434 (Archimedes'): 6.06 g/cm^3 *
- HT-bending (Archimedes): 6.10 g/cm^3 *
- HT-bending (weight+dimensions): 5.1 g/cm^3 **

→Estimated porosity content is ~8 vol%

5.7 g/cm^3 is used for the material model

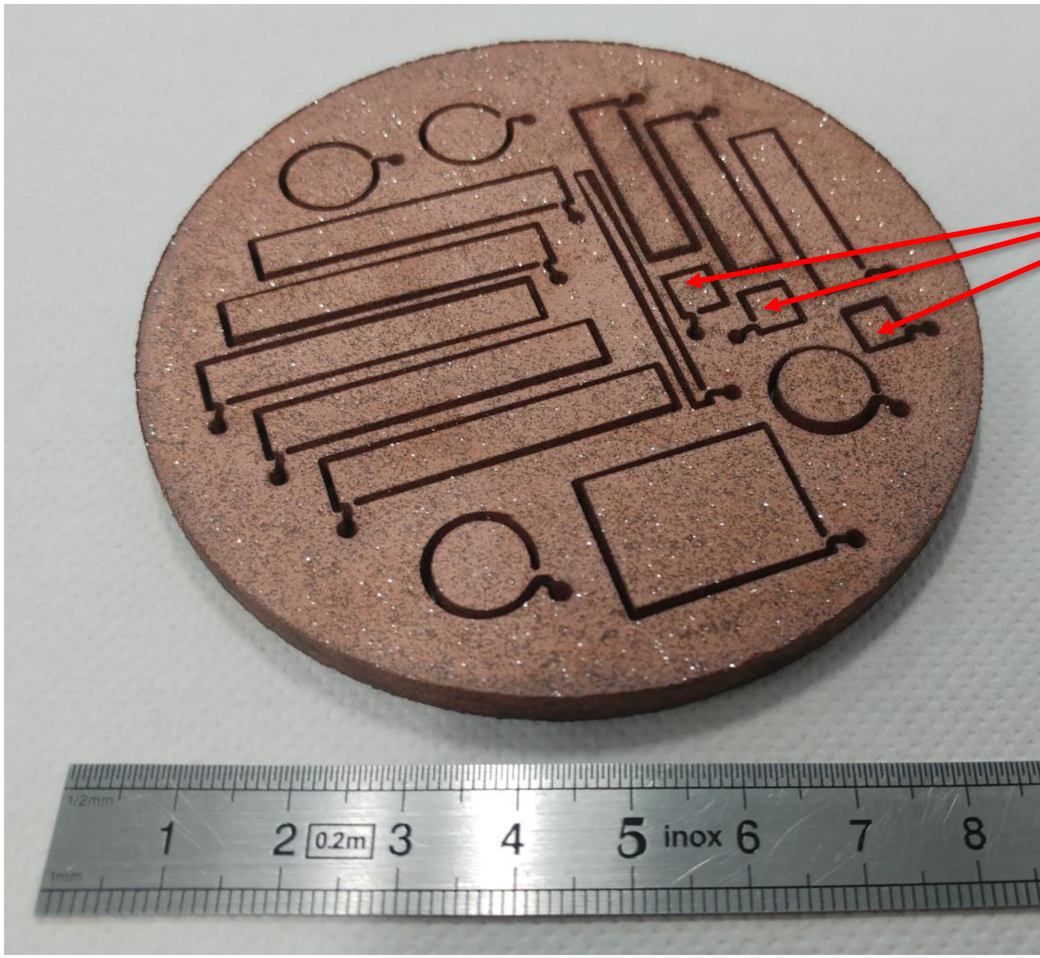
Plate for thermo-mechanical characterization (Mid-2018)


ID: RHP3025 (July 2017), tested in HRMT36 (Oct-2017)


Specimens for high-temperature bending tests (February-2020)

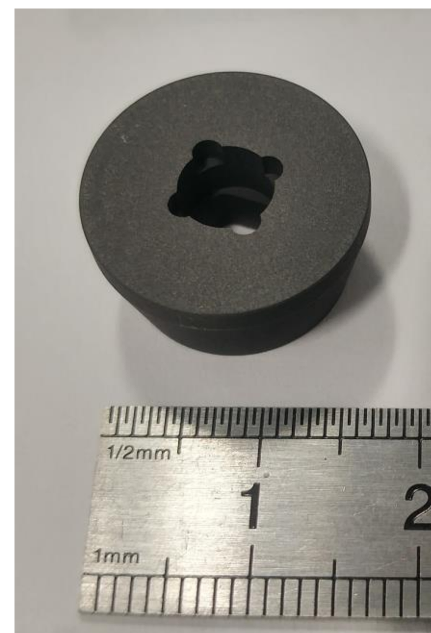
* Large error due to liquid infiltration in open porosity
** Large error due to small sample dimensions

CuCD HRMT36 grade: isotropy

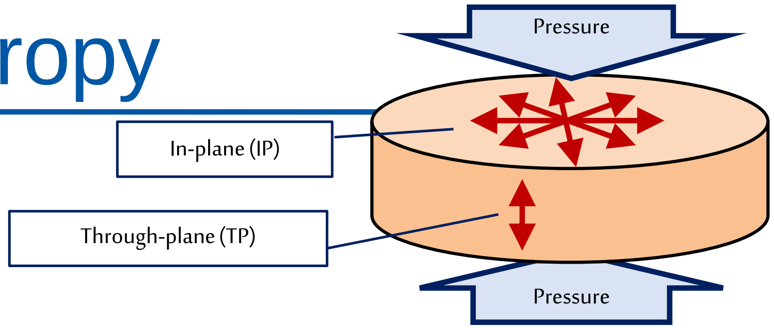


3 samples (4.5x5x5 mm) for
in-plane Laser Flash Analysis tests

Special graphite sample holder
manufactured for these samples



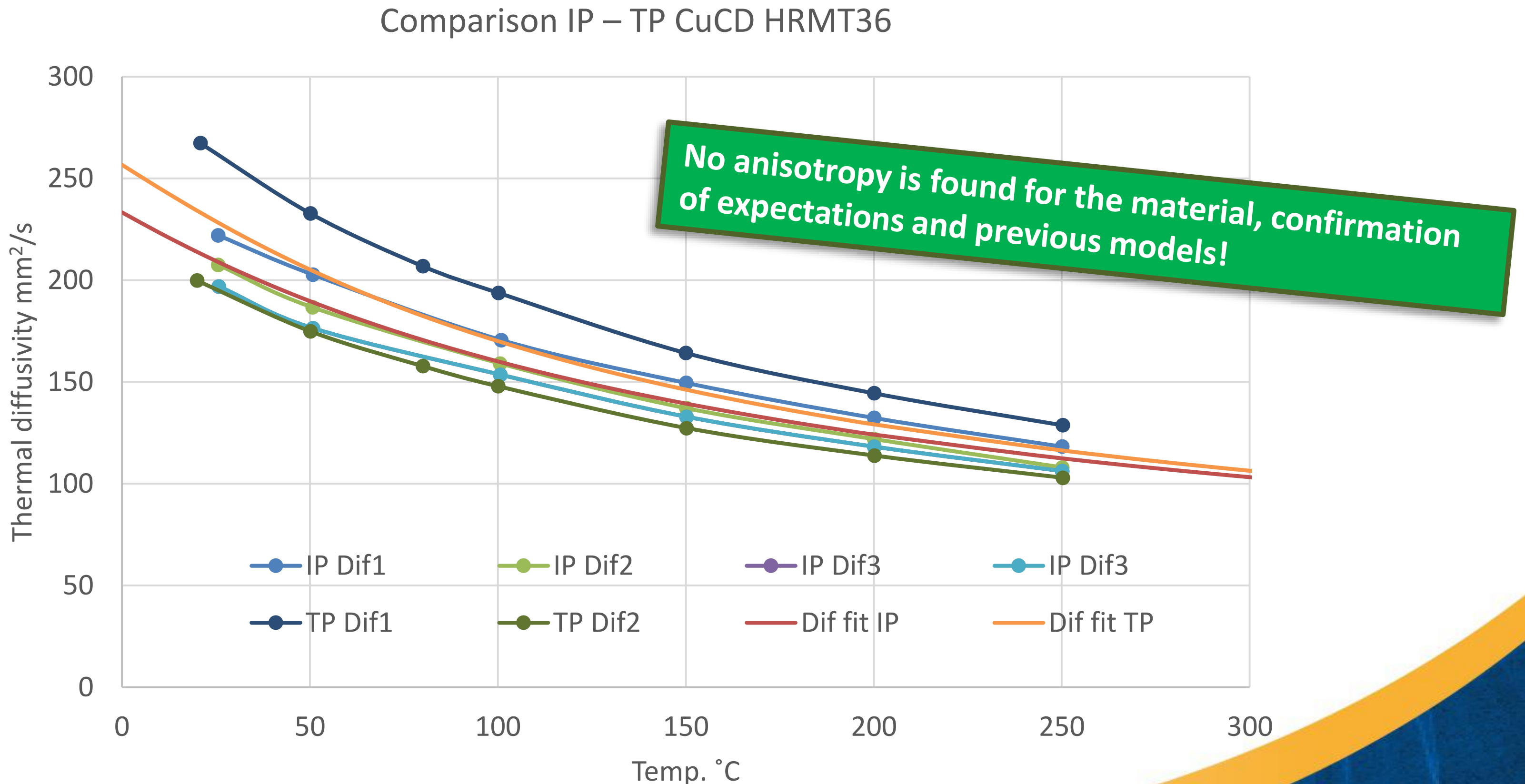
CuCD HRMT36 grade: isotropy



Average (fit) thermal diffusivity results at 20 °C:

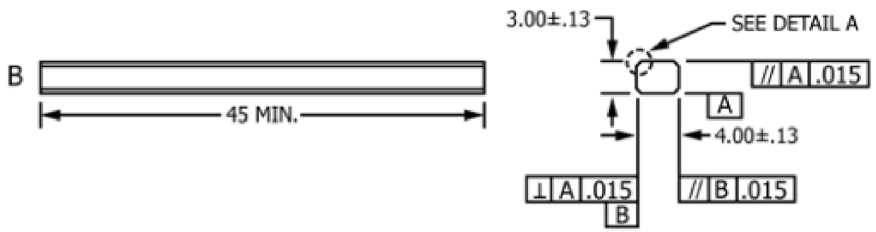
- In-plane: **214** mm^2/s
- Through-plane: **234** mm^2/s

These values are comparable within the test method uncertainty (precise thickness measurement is challenging for this material).



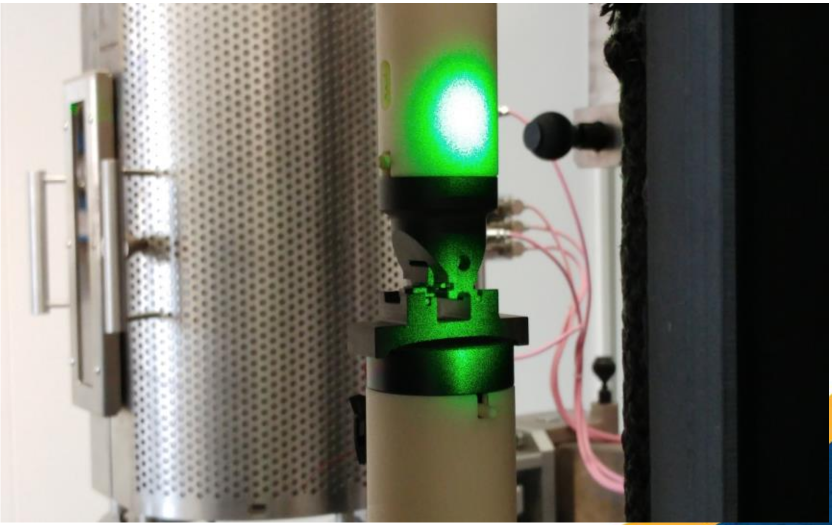
CuCD HRMT36 grade: HT-bending tests

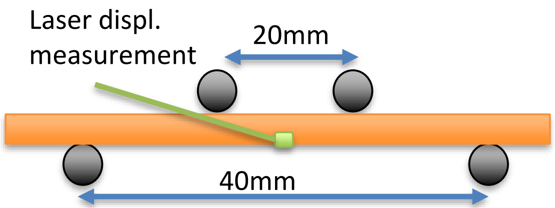
- ***Bending tests at high temperature on the CuCD Multimat grade**: requiring 20 samples with indicative dimensions:*



- **25 rods** prepared by RHP in February 2020 and shipped to CERN
- Most of the samples already tested at the CERN MME laboratory!

- Tests performed with silicon-carbide 4-poing fixture up to 300 °C
- Laser extensometer measuring displacement at the specimen centre (side under traction) → strain
- Challenging strain measurement due to small optical aperture in the furnace



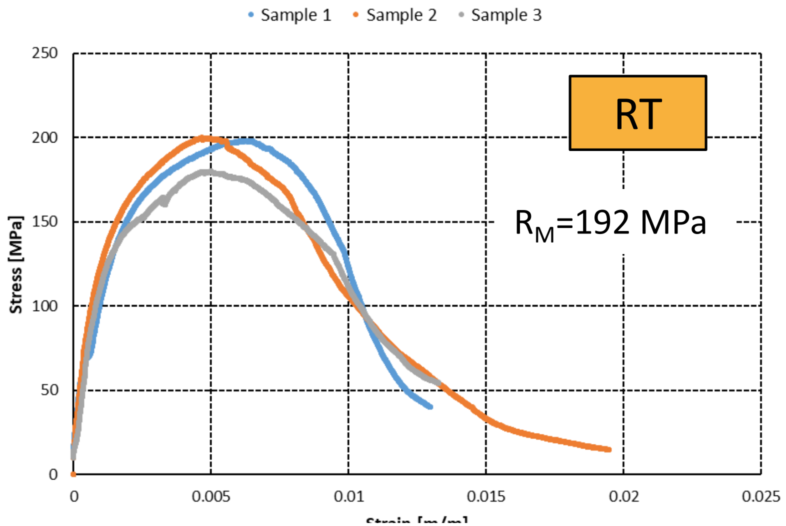


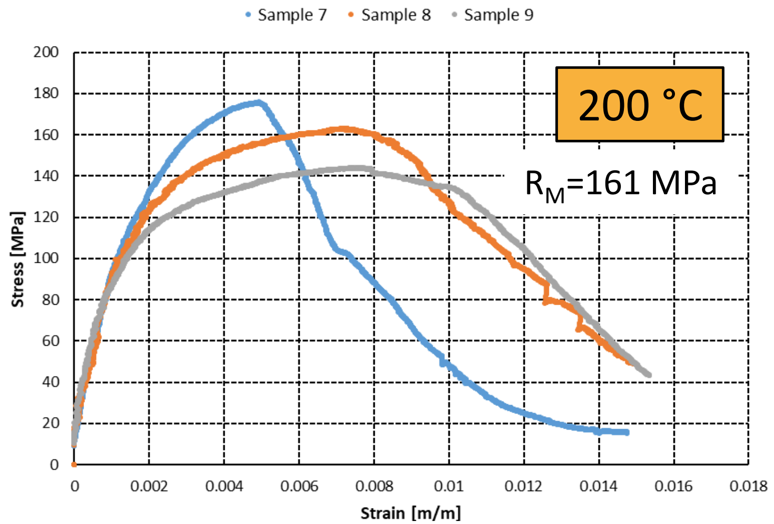
$$\varepsilon = \frac{12h}{3L^2 - 4A^2}x$$

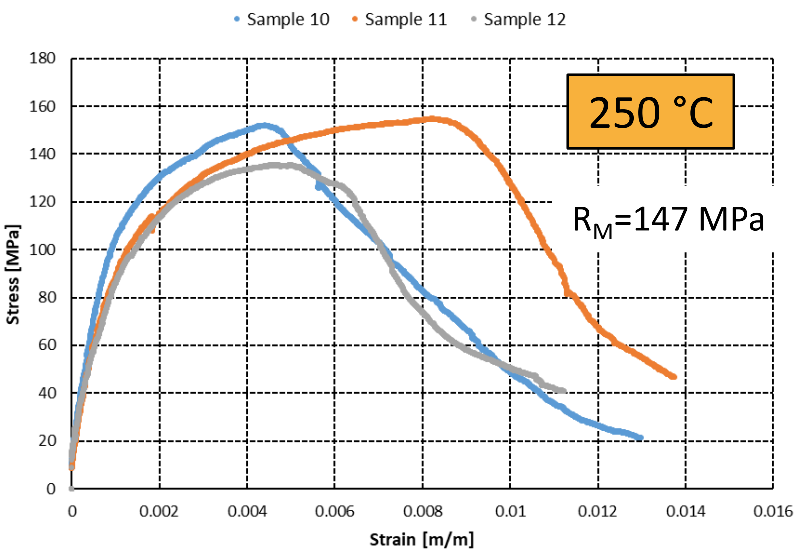
ε= strain
x=displacement
h= thickness= 3 mm
L= outer span = 40 mm
A= (outer-inner span)/2 = 10 mm

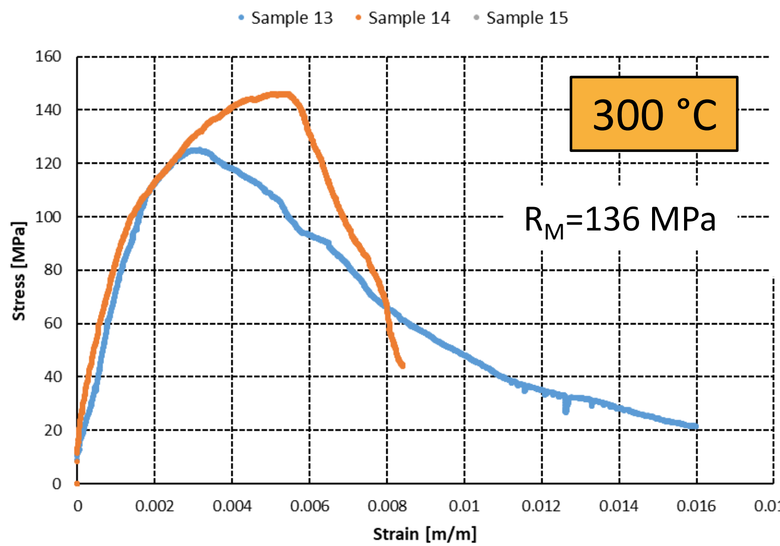
CuCD HRMT36 grade: HT-bending tests

Preliminary results. Analysis & implementation in the material model ongoing.





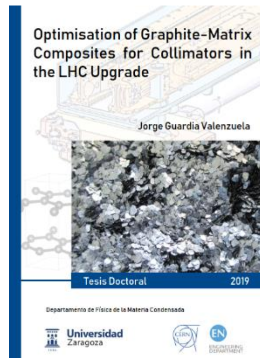




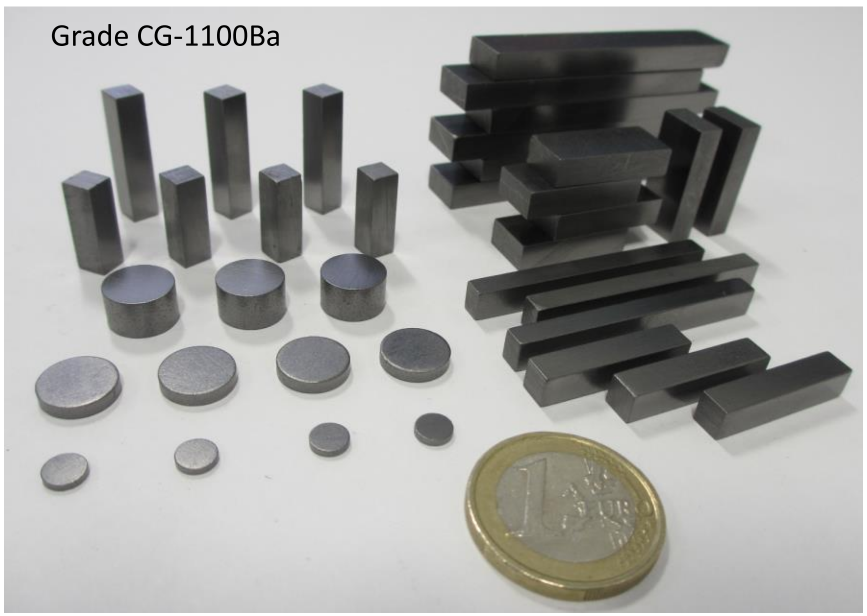
CrGr composites (graphite-matrix)

CrGr composite materials

- Based on the knowledge learnt from MoGr [1], new composite materials have been developed at CERN.
- The main goal is to reduce production complexity with respect to MoGr.
- Several grades of chromium-graphite have been produced
- PhD “Optimisation of graphite-matrix composites for collimators in the LHC Upgrade” (J.Guardia, 2019). Thesis not yet public for IP protection reasons.



Grade CG-1100Ba



Grade CG-1100B0

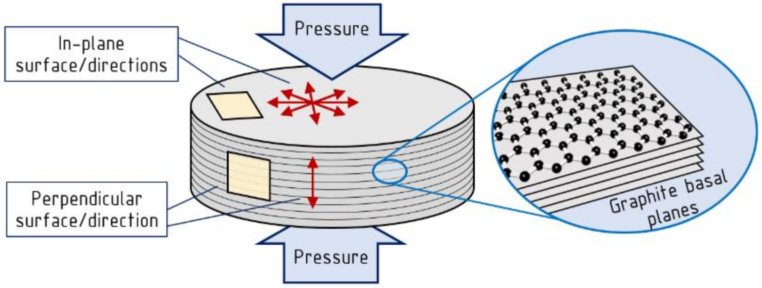
Produced by: BREVETTI BIZZ

[1] Development and properties of high thermal conductivity molybdenum carbide - graphite composites. J.Guardia, A.Bertarelli, F.Carra et al. Carbon 2018, Vol 135. https://doi.org/10.1016/j.carbon.2018.04.010

Grade CG-1240X

- **Best in-plane electrical and thermal conductivities** amongst all CrGr grades.
- **Similar through-plane conductivity** to the other grades.
- Production failure due to the mould breakage → another trial is foreseen.

Comparison table



	MoGr		CG-1100A0		CG-1100B0		CG-1100Ba		CG-1240X	
Direction	**IP**	**TP**	**IP**	**TP**	**IP**	**TP**	**IP**	**TP**	**IP**	**TP**
Density ($g \times cm^{-3}$)	2.5-2.6		2.31		2.21		2.15		2.26	
Electrical conductivity ($MS \times m^{-1}$)	0.9-1.1	0.05-0.07	0.84	-	1.00	0.08	1.01	0.08	1.06	-
Specific heat at 20°C ($J \times g^{-1} \times K^{-1}$)	0.6-0.65		0.677		0.687		0.670		0.714	
Thermal diff. at 20°C ($mm^2 \times s^{-1}$)	430-530	28-37	391	38	378	42	370	37	458	34
Thermal cond. at 20°C ($Wm^{-1}K^{-1}$)	650-900	45-65	612	59	574	64	532	53	739	55
CTE 20-200°C ($x10^{-6}$ K^{-1})	1.7-2.7	8-12	4.2	8.6	2.3	7.9	2.6	8.3	1.8	11.5
Flexural strength (MPa)	60-80	10-12	-	-	31.2	6.6	26.2	5.5	15.0	-
Elastic modulus (GPa)	60-85	4-5	-	-	42.8	3.8	38.7	2.4	~20	-
Flexural strain to rupture (%)	0.18-0.26	0.45-0.72	-	-	0.16	0.42	0.12	0.42	0.24	-

Thanks to the colleagues in the Mechanical Measurements Laboratory at CERN for the comprehensive characterization campaign!

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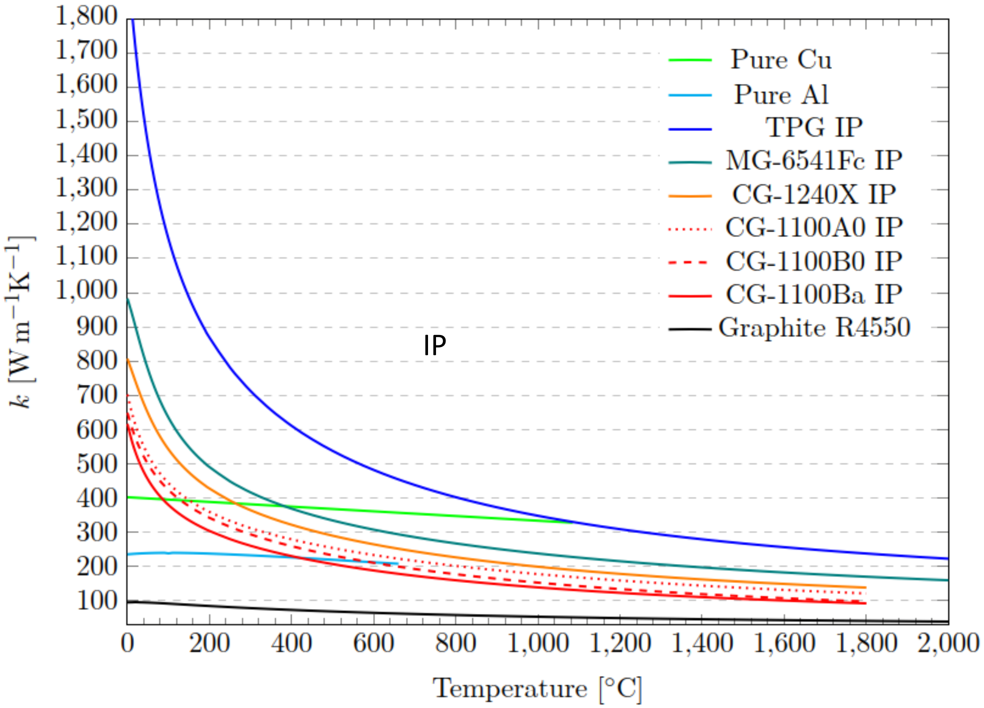
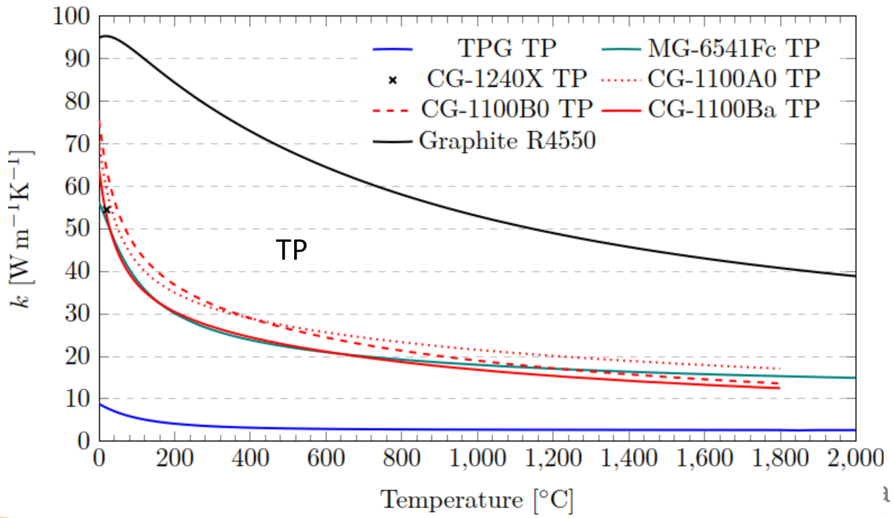
Thermal conductivity comparison



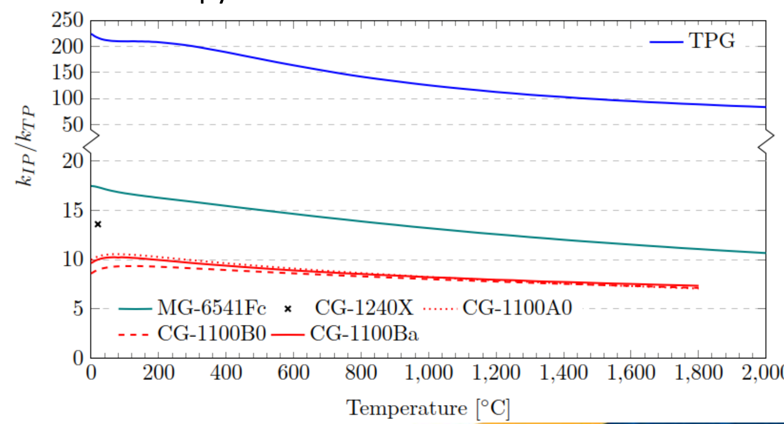
CrGr materials are less anisotropic than MoGr or PG

k of CG-1240X is just slightly lower than best MoGr produced so far

Note that the composites have higher k than copper in its usable range → thermal management



Anisotropy ratio:



Reference graphitic materials

Purely oriented graphite: very weak TP properties

Direction[1]	Gr. R4550 Isotropic	PG (TPG) $\parallel$	PG (TPG) $\perp$	CFC (AC150K), orthotropic Z	Y	X
ρ $(g\,cm^{-3})$	1.83	2.26		1.89		
c_p $(J\,g^{-1}K^{-1})$	0.715	0.69		0.712		
γ_e $(MS\,m^{-1})$	0.08	2.5*	0.0009	0.24	0.18	0.03
a $(mm^2\,s^{-1})$	73	1095	5	227	174	40
k $(W\,m^{-1}K^{-1})$	95	1710	8	304	233	54
α RT–200°C^2	4.2	-0.9	29.3[3]	-0.4	-0.2	10.7
α RT–1000°C^2	5	~0.4	~29.5[3]	0.5	0.5	11.4
RD (%)	-0.01	-0.02	0.01[3]	0.001	0.002	0.07
R_M (MPa)	61.2±3	25.5±0.4	-	139.6±.1	104.2±3	10.3±.3
ε_{adm}	0.72±0.04	0.08±0	-	0.14±0.01	0.20±0.04	0.43±0.03
E (GPa)	11.5	~65	-	110.2	75.4	3.1
G (GPa)	4.6	-	-	21.5	4.3	3.3

[1] In-plane ($\parallel$)/through-plane ($\perp$) or Cartesian directions.

[2] $(10^{-6}\,K^{-1})$.

[3] From specimen TP4, measured only up to 600 °C. α RT–1000°C is extrapolated.

* By eddy-current method on the surface, otherwise by four-wire method (average).

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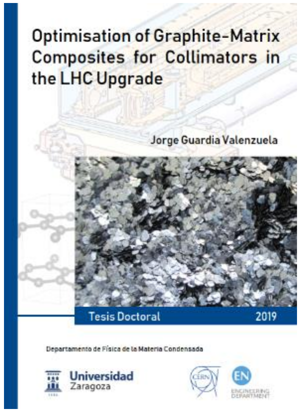
Summary

- CuCD thermal conductivity isotropy tests completed: no relevant anisotropy found.
- CuCD high-temperature bending tests completed. Analysis ongoing.
- New graphite-matrix composite grade produced. Excellent thermal and electrical conductivities found. Mechanical properties to be improved.
- PhD thesis “Optimisation of graphite-matrix composites for collimators in the LHC Upgrade” by J.Guardia was completed in 2019. MoGr and CrGr material families were investigated.



Next steps

- Complete CuCD high-temperature bending test campaign to implement the test results in the material model.
- Repeat production of CG-1240X promising grade, which experienced mould breakage during sintering.
- Investigate other additions to reinforce the graphite matrix of CrGr materials.

On behalf of the materials R&D team, thanks to our industrial partners and to the colleagues in the Mechanical Measurements Laboratory!!

BREVETTI BIZZ

RHP TECHNOLOGY

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 730871.

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Thank you for your attention!

CuCD HRMT36 grade (density of 3434 batch)

Measurements

	1	2	3	4	5	6		average	
Thickness (mm)	4.97	4.96	4.91	4.96	4.93	4.9		4.938	mm
a (mm)	20.1	20.13	20.21					20.147	mm
b (mm)	15.28	15.24	15.21					15.243	mm
Mass (g)	8.5887	8.589	8.5888					8.589	g
							volume	1.517	cm3
							density	5.663	
								5.7	**g/cm3**

Comment on the accuracy of this method:

- With an estimated error of 0.1 mm in the geometry, the range of density goes from 5.49 to 5.85 g/cm^3.
- Because of the microstructure (protruding diamonds) it is expected that the measured volume is overestimated, therefore the real density is likely to be on the high side (higher than the result 5.663 g/cm^3). The value is therefore rounded to 5.7 g/cm^3.

Estimated porosity content is around 8 vol%

Marcus' proposal: use a thin Vaseline/paraffin coating and measure the volume with the Archimedes' method, as in http://dx.doi.org/10.1016/j.jallcom.2009.10.040