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CERN IT-4201 Gr-Mo I-FAST

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I-FAST: Graphite-Metal carbide materials

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BACKGROUND INFORMATION

	MoGr ∥	MoGr ⊥	CFC AC150K ∥	CFC AC150K ⊥	R4550 Isotr.	GLIDCOP Isotr.	INERMET Isotr.	SS-316L Isotr.
$\rho\ [g\,cm^{-3}]$	2.5–2.6		1.89		1.86	8.75	17.94	7.95
$T_m\ [°C]$	2589		3650		3650	1083	1350	1400
$c_p\ [J\,g^{-1}K^{-1}]$	0.6–0.65		0.71		0.71	0.39	0.15	0.45
Z	6.6–6.8		6		6	28.96	67.66	25.5
A	13.5–13.8		12.01		12.01	63.62	166.67	54.7
$\gamma_e\ [MS\,m^{-1}]$	0.9–1.2	0.05–0.07	0.24–0.18	0.03	0.08	53.8	8.7	1.35
$a\ [mm^2\,s^{-1}]$	430–530	28–37	174–227	40	73	106	34	4
$k\ [W\,m^{-1}K^{-1}]$	650–900	45–65	233–304	54	100	365	91	14
$\alpha\ [10^{-6}K^{-1}]$	1.7–2.7	8–12	-0.8	11	4.2	18.5	5.3	15
$R_M\ [MPa]$	60–80	10–12	105–140	10	60	375 (T)	683 (T)	515 (T)
$E\ [GPa]$	60–85	4–5	≈50	5	11.5	128	360	195
$\varepsilon_{adm}\ [\%]$	0.18–0.26	0.45–0.72	0.14–0.2	0.43	0.7	10	3	40
$X_0\ [g\,cm^{-2}]$	39–42		43.0		43.0	13.2	7.2	14.4
$X_g\ [m]$	15–17		22.8		23.1	1.5	0.4	1.8
$\Delta T_q\ [K]$	2.4–2.9		1.5		1.5	57.1	646	40.6
TRI	141–367		1362		3445	6.3	0.6	10.9
TSI	43–73		47		23	0.9	0.1	0.1
RFI	0.9–1.1		0.4		0.3	7.3	2.9	1.2

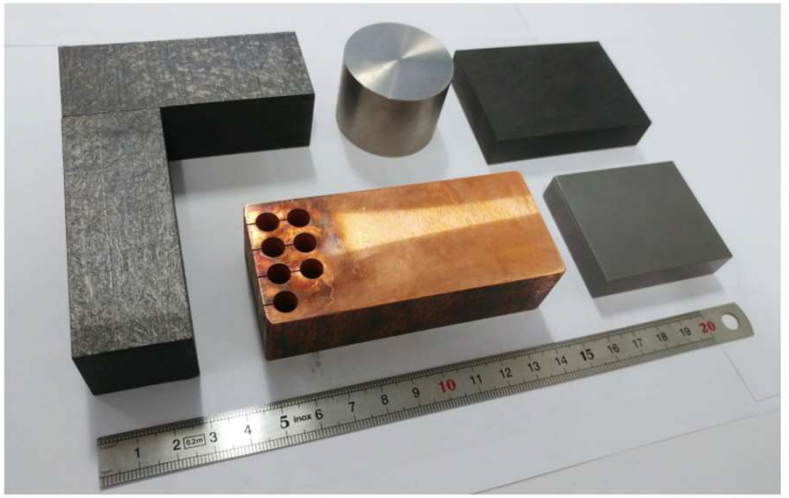

Figure 1.21: Materials currently used in collimator absorber blocks: (left) CFC AC150K, INERMET®180 cylinder (W-alloy), (top right) Graphite R4550 , GLIDCOP® Al-15 (Cu-alloy), MoGr (bottom right).

Information (pictures) from PhD Jorge Guardia Valenzuela:

"OPTIMISATION OF GRAPHITE-MATRIX COMPOSITES FOR COLLIMATORS IN THE LHC UPGRADE"

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Tender IT 4201

MoGr series production for LS2

- Material to equip **10 TCSPMs and 5 TCPPMs** (+20% spare material)
- Total of 360 pieces (blocks + tapered extremities)
- **Contract for uncoated blocks and taperings awarded to Nanoker (ES)**
- Production rate: 0.5 and later 1 batch*/month
- **Conditioning and Acceptance tests at CERN:** thermal treatments, US, metrology, thermophysical and UHV tests
- Technical officer: F. Carra (EN/MME)

- Contract for **coating TCSPM blocks awarded to DTI (DK)**, after successful qualification of samples and, later, of two preseries!
- **Conditioning and Acceptance tests at CERN**: thermal treatments, UHV, adherence, coating thickness and electrical conductivity
- Technical officer: W. Vollenberg (TE/VSC)

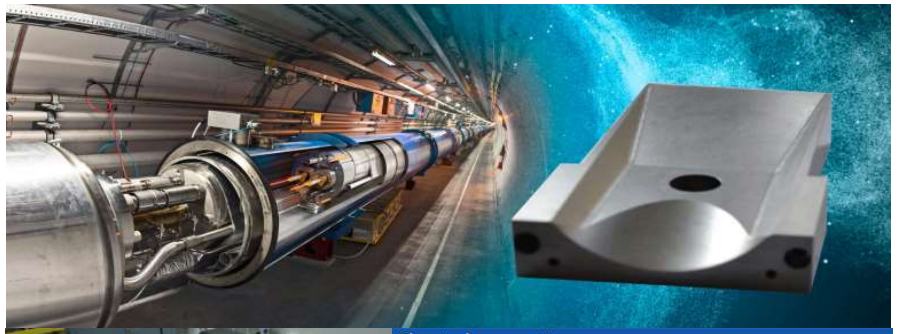
HiLumi HL-LHC PROJECT

1 batch = material to equip 1 collimator*

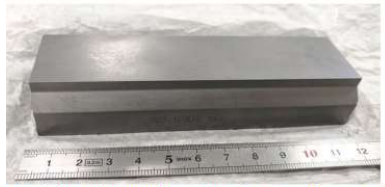
F. Carra (CERN), 2 September 2020

Picture taken from presentation F.Carra (CERN) Sep 2020

GRAPHITE-METAL CARBIDE COMPOSITES



Primary collimator. Picture courtesy of CERN



Block for collimator (position tolerance of 5 micron)

Physical properties		
Parameters	Units	X,Y | Z [*1]
Density	g/cm³	2.57
Flexural Strength	MPa	102.1 | 16.9
Flexural Strain to rupture	µm/m	2580 | 5900
Young Modulus	GPa	69.7 | 5.5
Thermal conductivity (@20ºC/300ºC)	W/m·k	650/310 | 45/23
Thermal Diffusivity (@20ºC/300ºC)	mm²/s	390/110 | 27/8
CTE average (20-1000ºC)	$10^{-6}K^{-1}$	6.5
CTE [*2] (20-1000ºC)	$10^{-6}K^{-1}$	2.4 | 14.7
Specific heat	J/g·K	0.65
Electrical conductivity	MS/m	0.8
Dimensional stability	%	0 | 0.1

All properties measured at 20ºC unless otherwise stated

[*1] XY - Parallel to the grain direction; Z - Perpendicular to the grain direction

[*2] CTE adjustability according to chemical composition

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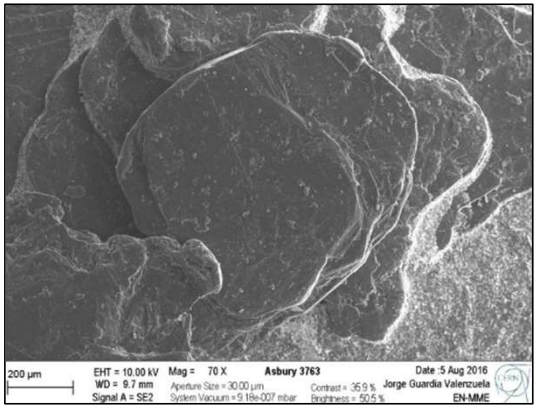
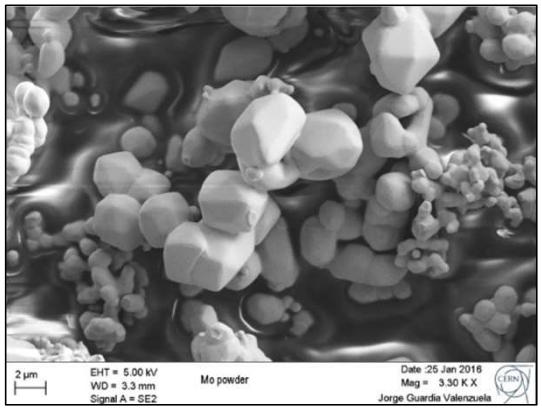
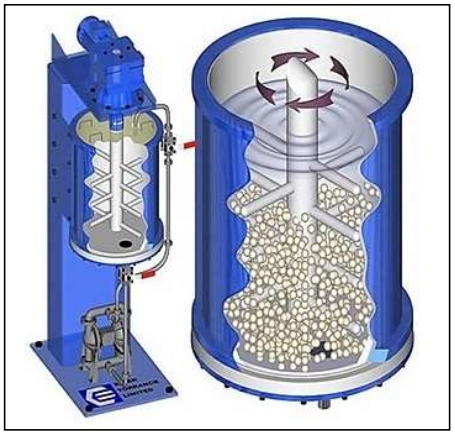


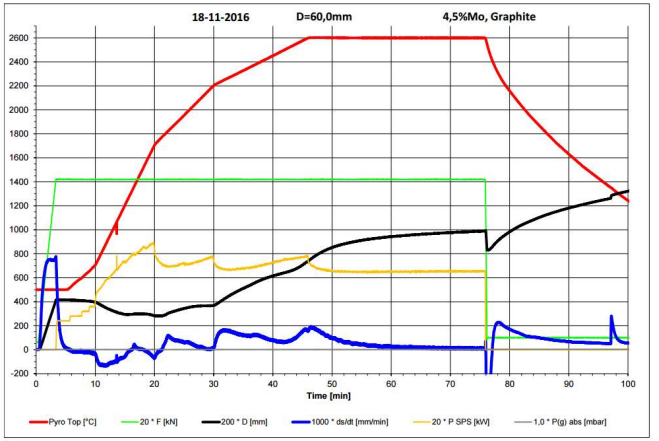
Graphite flakes



Mo powder



Attrition milling



Phase I: SPS, 2650ºC 25 MPa

Phase II: Annealing 2350ºC

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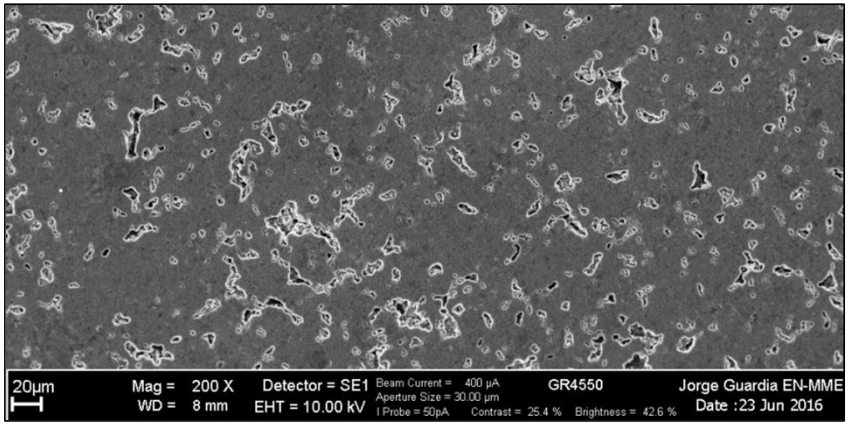
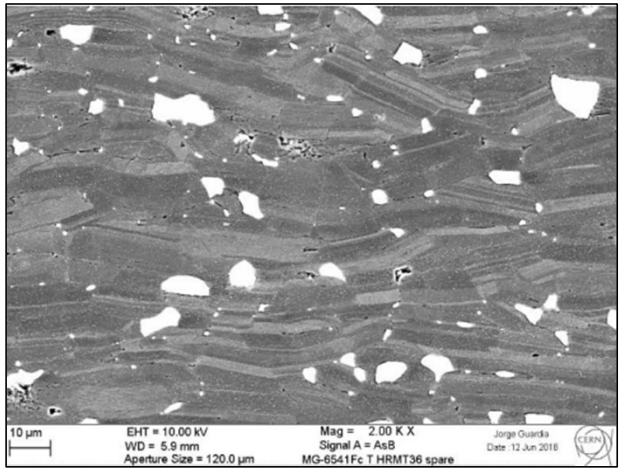
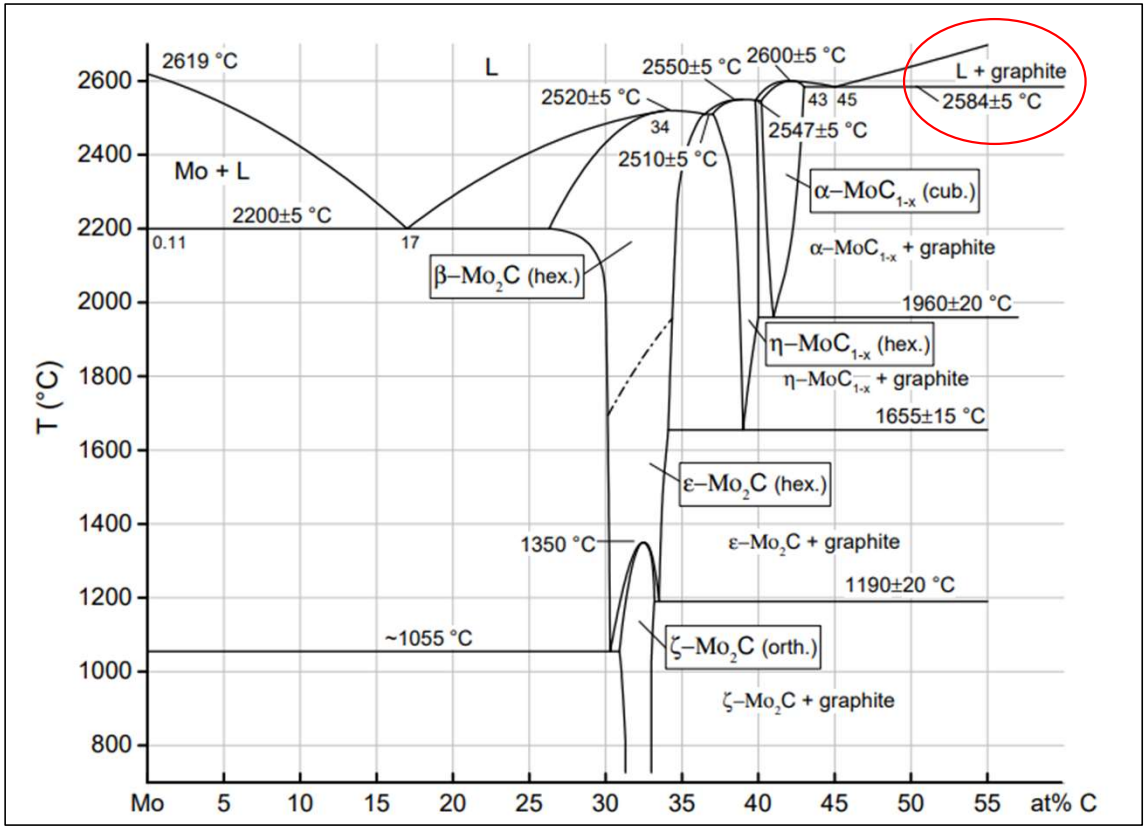


Microestructure of Isostatic graphite



Microstructure of LP Gr-Mo



Phase diagram Mo-C (Equilibrium point)

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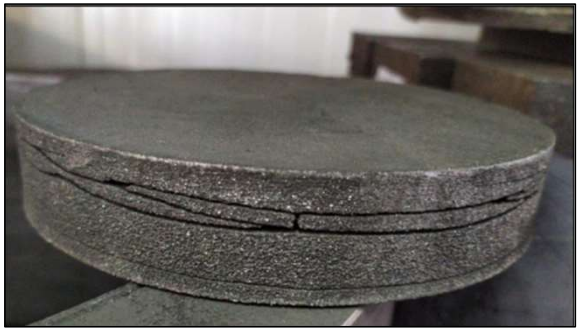
Molten metal-carbide



Generation of defects

(In-plane) CTE Gr-Mo: $2.4 \cdot K^{-1}$
CTE Graphite: $4.2 \cdot K^{-1}$

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Graphite-Molybdenum carbide:

- Expensive material (16-20 €/cc)
  - High consumable cost (mould sacrifice)
  - High energy cost (2650ºC + annealing at 2350ºC)
  - Effect of scale (2 x D175 mm blanks)

I-FAST activities:

- Alternative material to Graphite-Molybdenum
- Reduce the cost of material
  - Lower consumable cost (no graphite sacrifice)
  - Lower energy (reducing sintering Tª)
  - Upscaling (2x D230 mm blanks)

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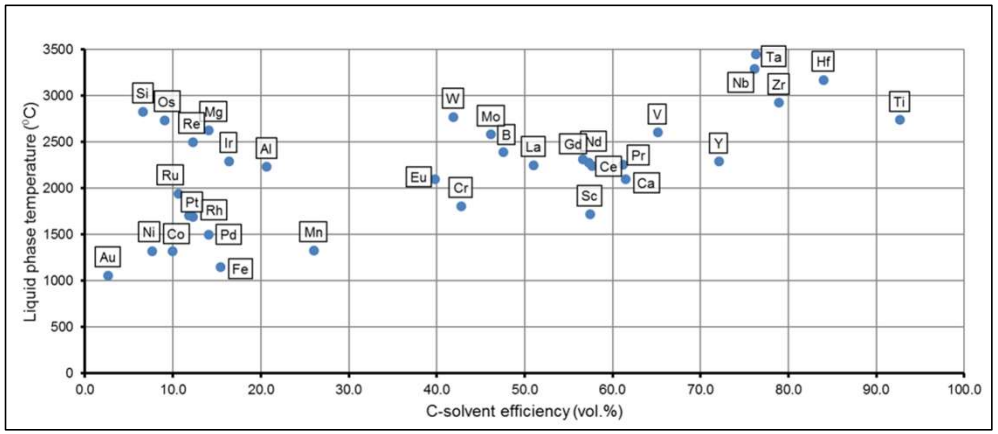
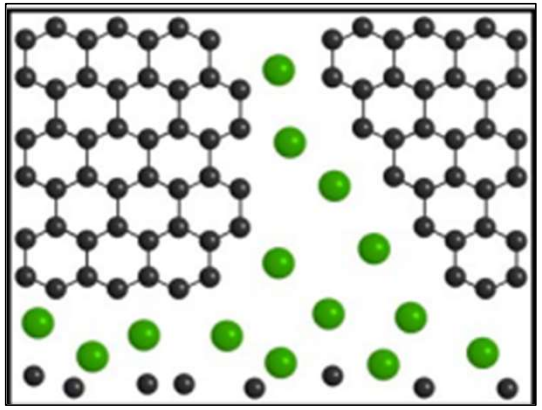


Liquid phase temperatures

	Min.	Max.	Market [€/g]
Sc	652	804	5-13*
Cr	0.4	2.2	
Mn	1.0	4.3	
Fe	0.04	0.06	0.08 (1 kg)
Co	1.1	7	29.71 (1 kg)
Ni	1.0	6.6	11.67 (1 kg)
Ru	65.4	65.4	7.50
Rh	528	528	86.38
Pd	89	264	38.8
Pt	181	609	25.86
Au	394	529	37.15
Mo	0.5	15	

Prices



Solution - precipitation

Selection of Chromium driven by:

- Liquid phase formation of carbide < 2000ºC
- Low cost of metal poder
- High C-solvent efficiency
  - Promote solution-precipitation mechanism

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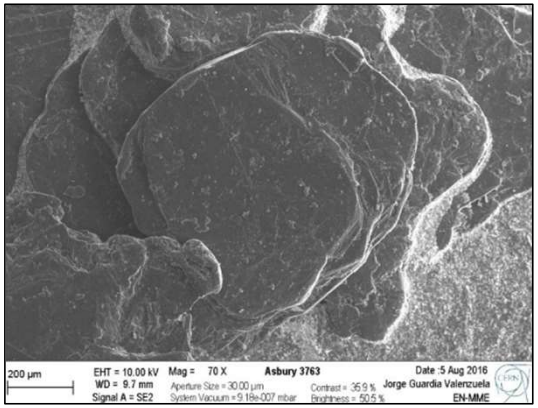
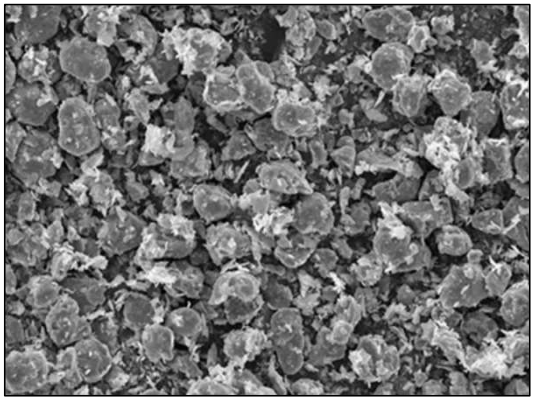
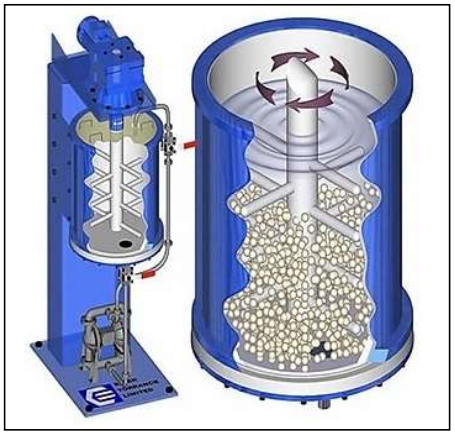


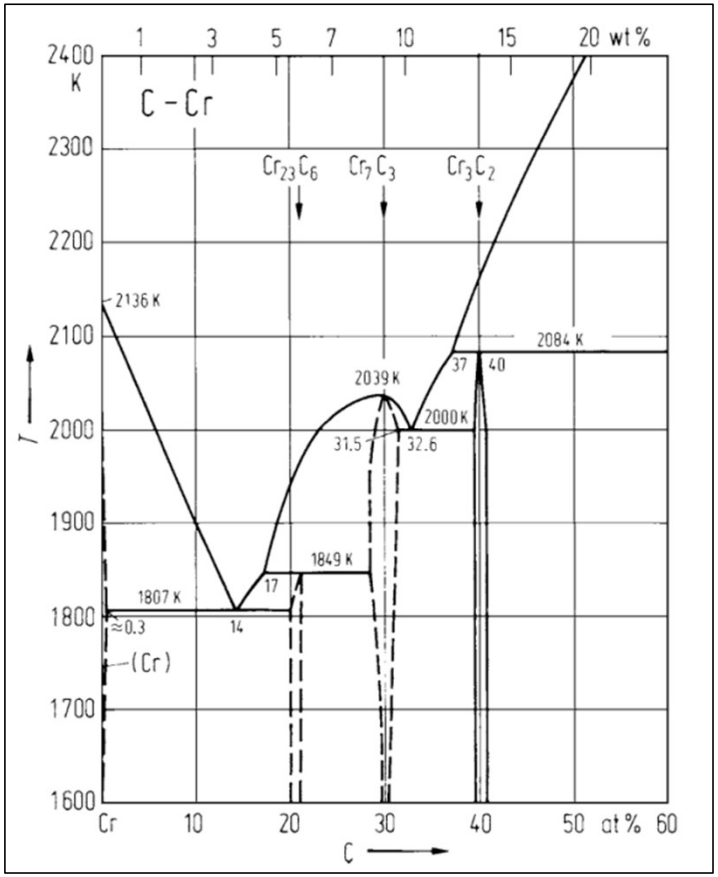
Graphite flakes



Cr powder



Attrition milling



Phase Diagram (liquid pase at 1850 ºC)

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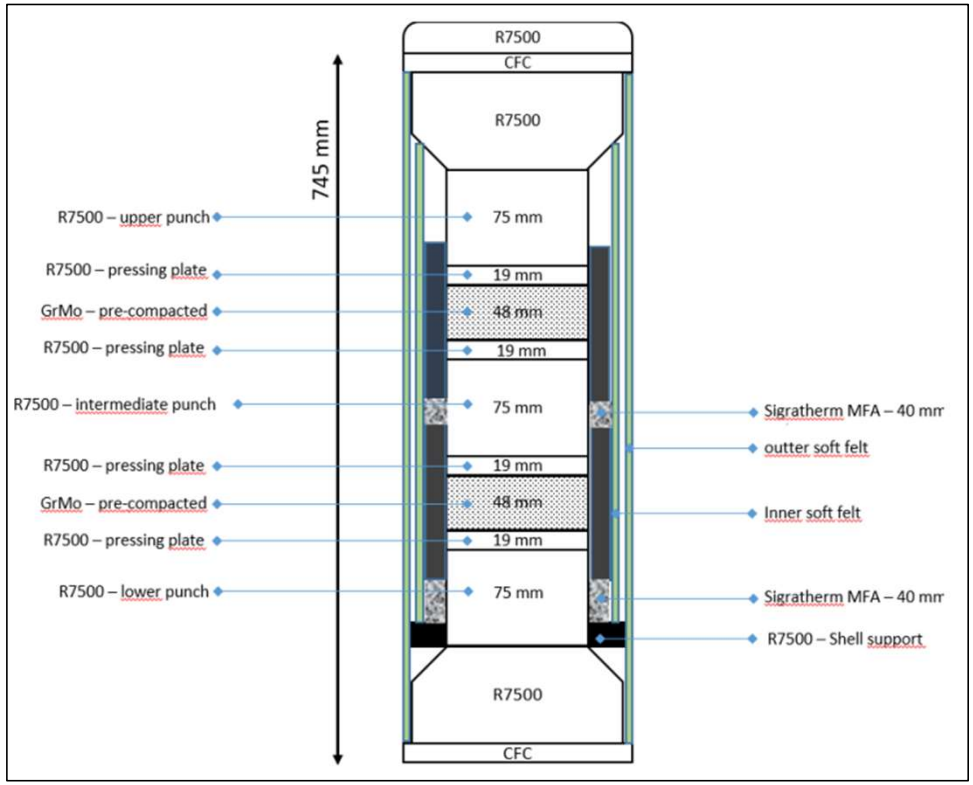

Mould configuration

2x Mould configuration

1º Insulation layer

2º Insulation layer

Mould filling

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Sintering Run	Production period	Plate number	Diameter (cm)	Density (g/cm3)	Electrical Conductivity (MS/m)
#1*	November 2021	Plate #1	170	2.30	1,00 – 1,07
#2*	March 2022	Plate #2	170	2.23	0.75 – 0.76
		Plate #3	170	2.29	0.80 – 0.81
#3 (D4.4)	March 2023	Plate #4	230	2.44	0.86 – 1.05
		Plate #5	230	2.44	0.91 – 0.94

**values after stress-relaxtion annealing cycle at 1700°C*

Test performed to Cr-Gr in the framework of I-FAST

	Specification		CrGr Plate #1		
Property	**I***	**I-**	**I***	**I-**	**Unit**
Density at 20°C	2.40 – 2.60		2.32		[g/cm³]
Specific heat at 20°C	> 0.6		0.687		[J/(g·K)]
Electrical conductivity at 20°C	> 0.75		1.02		[MS/m]
Thermal Diffusivity 20°C / 300°C	> 350/100	> 20/6	470/120	33/9	[mm²/s]
Thermal conductivity at 20°C / 300°C	> 500/280	> 35/20	750/350	52/27	[W/(m·K)]
Volumetric CTE 20-1000°C	< 7		6.7		[$10^{-6}K^{-1}$]
Coefficient of thermal expansion 20-1000°C	< 2.9	< 15	4.0	12.0	[$10^{-6}K^{-1}$]
Young's Modulus at 20°C	35 < E < 75	5 < E < 8	46	3	[GPa]
Flexural strength at 20°C	> 60	> 10	58	8	[MPa]
Flexural strain to rupture at 20°C	> 2500	> 4000	3280	4200	[µm/m]
Dimensional stability	< 0.05	< 0.25	-0.05	0.45	%

Characterization to Plate #1

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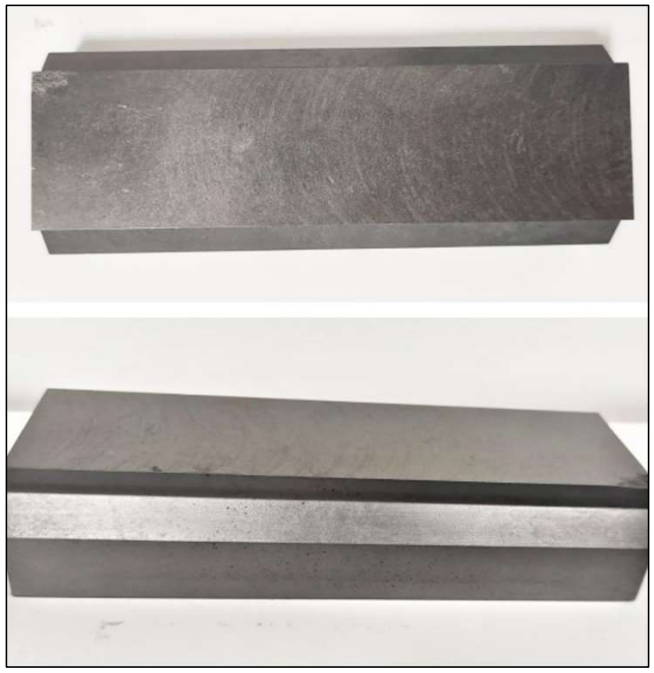


Block Type I machined on Plate #1

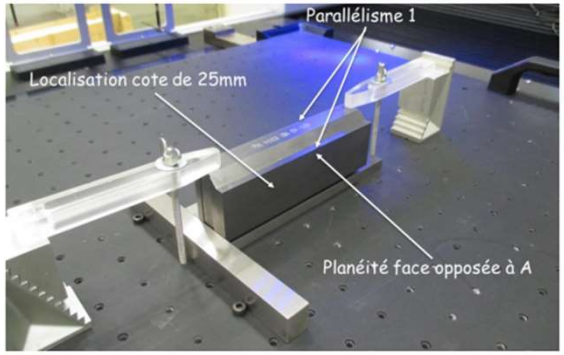


Figure 9 – CrGr absorber block, positioning for metrology measurement at CERN.

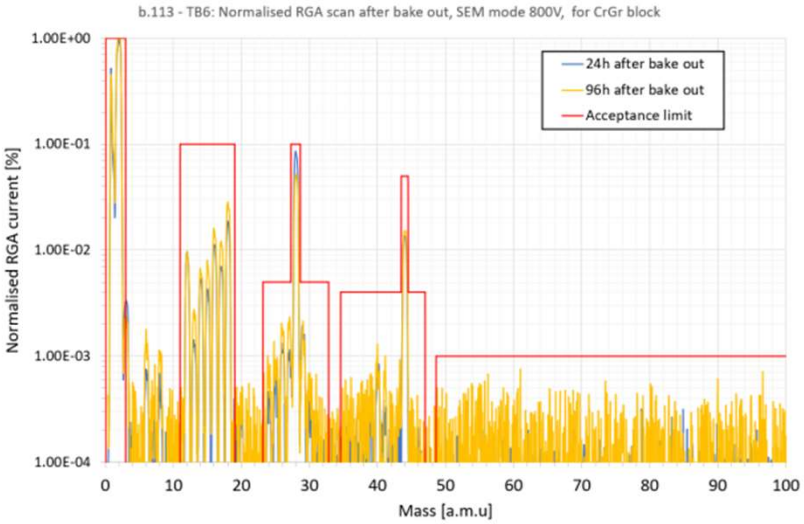
Table 5. Variation of tolerances of the CrGr absorber block after different post-machining time intervals.

Tolerance*	Time interval after machining			
	7 days	1 month	2 months	3 months
Flatness of "A" face [mm]	0.010	01011	0.011	0.012
Flatness of face opposite to "A" (*i.e. "Beam face"*) [mm]	0.005	0.011	0.011	0.010
Parallelism of "Beam face" with respect to "A" [mm]	0.022	0.019	0.021	0.038
Position of "Beam face" with respect to "A" [mm]	0.025	0.022	0.021	0.042

**with reference to Annex B.*

Dimensional stability

**for installation in LHC collimators*



Outgassing test

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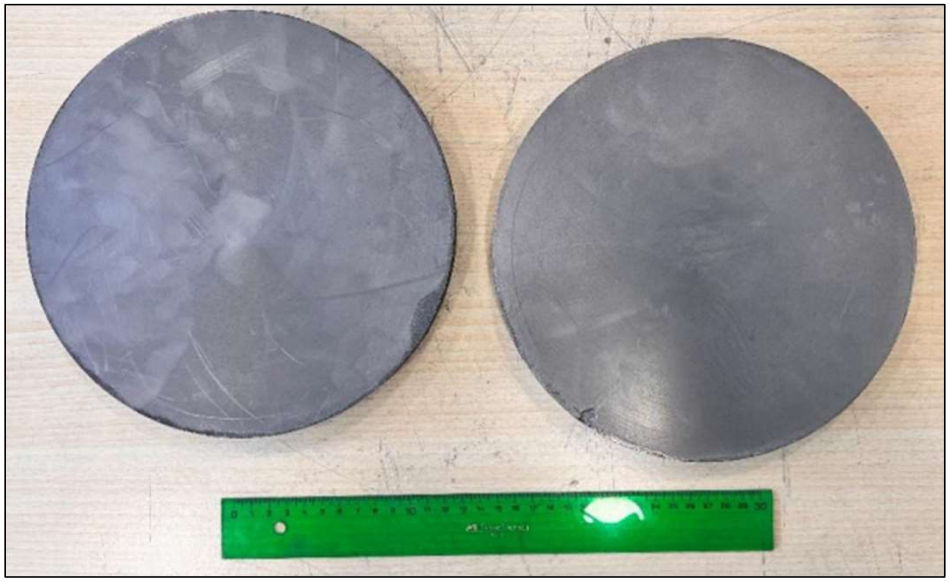
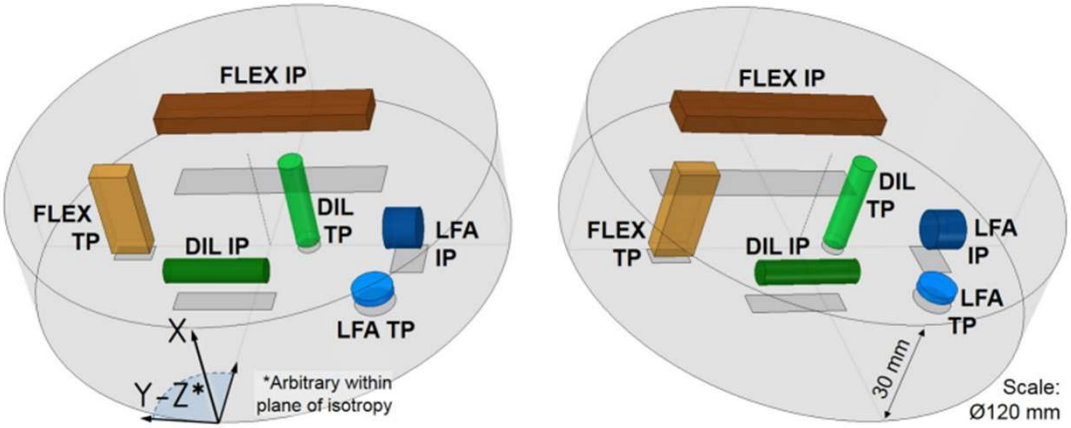


2 blocks of D230 mm Cr-Gr



Characterization in D230 mm (ongoing)

Graphite-Chromium carbide:

- Reduction of cost of material (4-6 €/cc)
  - Lower consumable cost (reusable mould)
    - CTE compatibility between Cr-Gr and Graphite mould and lower Tª
  - Lower energy cost (72% reduction compared to Mo-Gr)
  - Upscaling (2 x D230 mm blanks)
- Material properties (measured in D175 mm)
  - Fulfillment of initial specs (Thermo-physical-mechanical)
  - Dimensional stability.
  - Compatible to be installed in the collimator (Outgassing)

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