This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.

Carbide-Carbon Materials for Multipurpose Applications

I.FAST 2nd Annual Meeting

20th April 2023

Trieste, Italy

F. Carra (CERN)

On behalf of IFAST WP4.4

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WP4.4 – Objectives and Participants

- Large scale Carbide-Carbon Materials for multipurpose applications (M1 – M48)
  - **Promote the use of carbide-carbon materials (CCM)** in future particle physics facilities and open up the market to commercial applications
  - Thermal conductivity 2-3 times higher than Cu! Stronger, low density
- How?

3x larger volume per sintering cycle

+

1.5x lower sintering temperature material

→

2x Cost Reduction

Higher efficiency

- Who?

nanoker TAKING PROFIT FROM THE SMALL

CERN

CCM Production Cycle

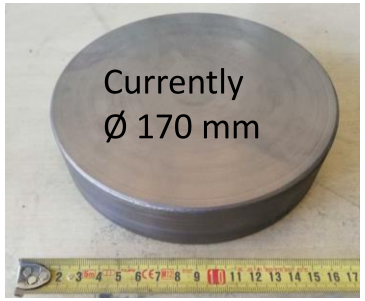
Selection and sieving of the powders

Preparation of the desired composition

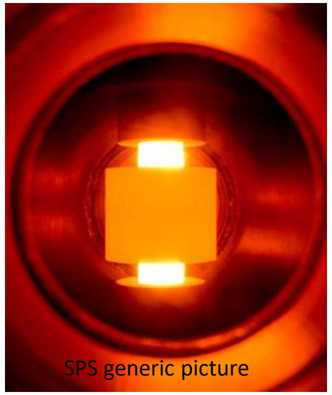
Powder	Vol. %
Graphite	93.9
Mo	5.5
Ti	0.6

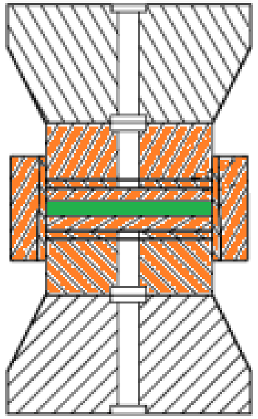
Mixing

Green body preparation



Spark Plasma Sintering (SPS) >25 MPa, >2600 °C

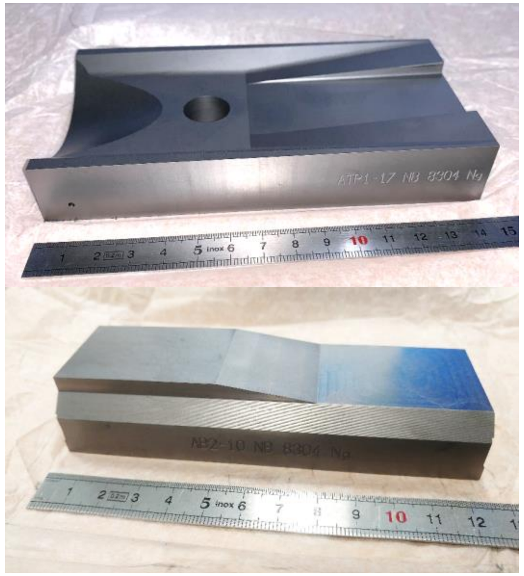




Sintered CCM
Single-use mould elements (graphite)

Stress relieving thermal treatment
0 MPa, >2400 °C

Machining of the pieces



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Deliverables and Budget

Milestone/Deliverable Number	Title	Lead beneficiary	Type	Dissemination level	Due Date (in months)
MS14	Evaluation of a CCM alternative to Molybdenum-Graphite	CERN	Report	Public	16
D4.4	Production of large-size CCM plates	CERN	Demonstrator	Public	24

Milestone MS14 *due date August 2022, achieved in June 2022*

- **Molybdenum-Graphite** (MoGr) is sintered at high temperature
  - Very good from the technical point of view, but…
  - Energy consuming → Expensive! (and not only)
  - Destruction of mould at each cycle → Expensive!
- **Chromium-Graphite** (CrGr) proposed (and produced) as a valid alternative to MoGr
  - Sintered at 2000°C instead of 2620°C
  - Allows saving mould for next cycles

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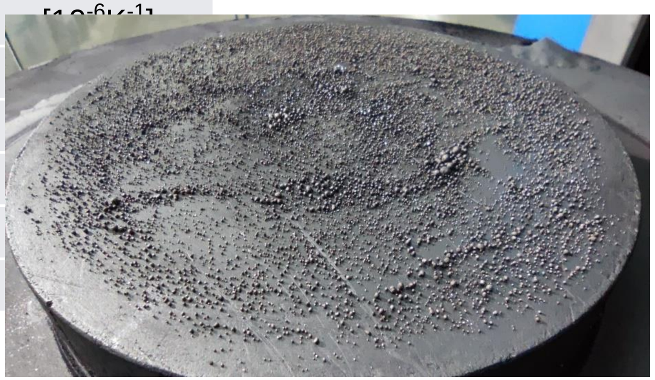
Milestone MS14 – CrGr Characterization

- **Full thermomechanical characterization** done at CERN Mechanical Lab in April 2022
- **Very promising results**, some parameters to be improved during the next years of the project. Mechanical strength increased by a factor of 5 wrt ARIES!

	Specification		CrGr Plate #1		
Property	∥*	⊥	∥*	⊥	Unit
Density at 20ºC	2.40 – 2.60		2.32		[g/cm³]
Specific heat at 20ºC	> 0.6		0.687		[J/(g·K)]
Electrical conductivity at 20ºC	> 0.75		1.02		[MS/m]
Thermal Diffusivity 20ºC /at 300ºC	> 350/100	> 20/6	470/120	33/9	[mm^2/s]
Thermal conductivity at 20ºC /at 300ºC	> 500/280	> 35/20	750/350	52/27	[W/(m·K)]
Volumetric CTE 20-1000ºC	< 7		6.7		$[10^{-6}K^{-1}]$
Coefficient of thermal expansion 20-1000ºC	< 2.9	< 15	4.0	12.0	
Young's Modulus at 20ºC	35 < E < 75	5 < E < 8	46	3	
Flexural strength at 20ºC	> 60	> 10	58	8	
Flexural strain to rupture at 20ºC	> 2500	> 4000	3280	4200	
Dimensional stability*	< 0.05	< 0.25	-0.05	0.45	

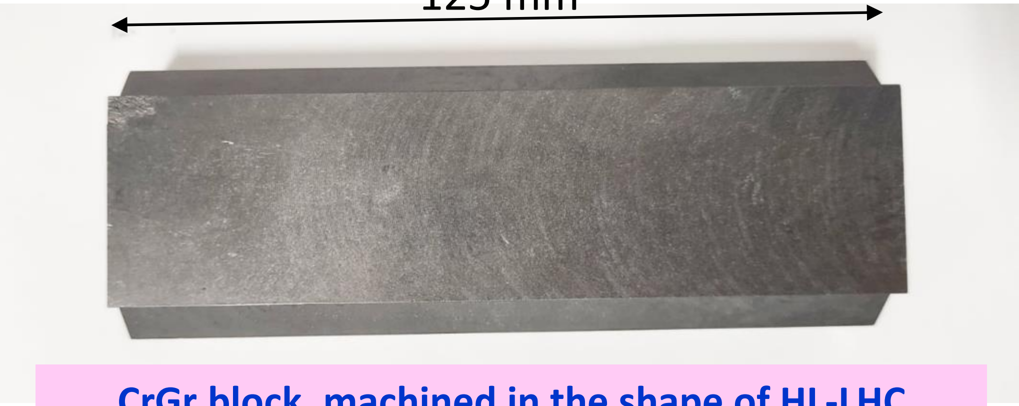


Reusable Mold and Parts → Important Cost Reduction

Additional CrGr Characterization

- **Component of complex shape and tolerances** produced, to prove machinability and test UHV behaviour

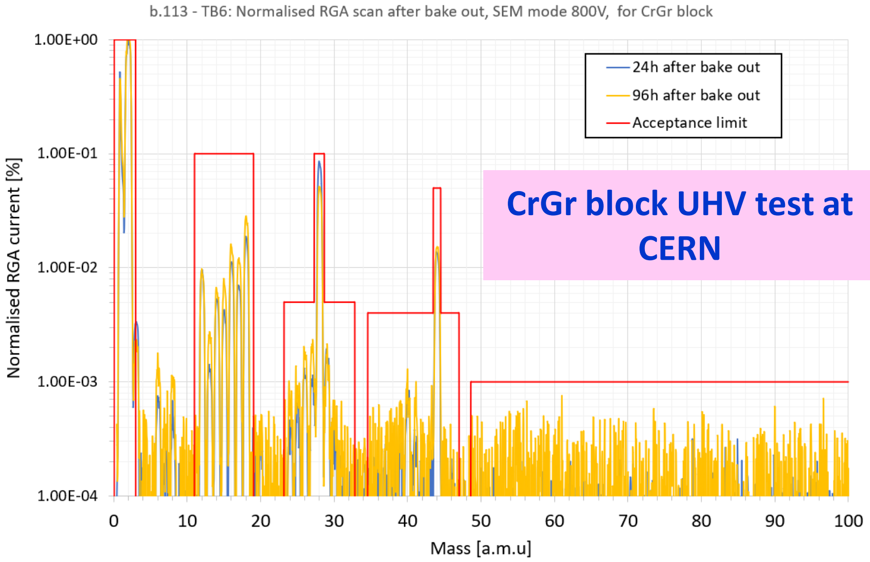
125 mm



CrGr block, machined in the shape of HL-LHC collimator absorber

CrGr block metrology

Tolerance*	Time interval after machining			
	7 days	1 month	2 months	3 months
Flatness of back face [mm]	0.010	0.011	0.011	0.012
Flatness of top face [mm]	0.005	0.011	0.011	0.010
Parallelism of top face wrt back face [mm]	0.022	0.019	0.021	0.038
Position of top face wrt back face [mm]	0.025	0.022	0.021	0.042



CrGr block UHV test at CERN

Material compliant for installation in the LHC!

Courtesy of G. Cattenoz (CERN)

Deliverables and Budget

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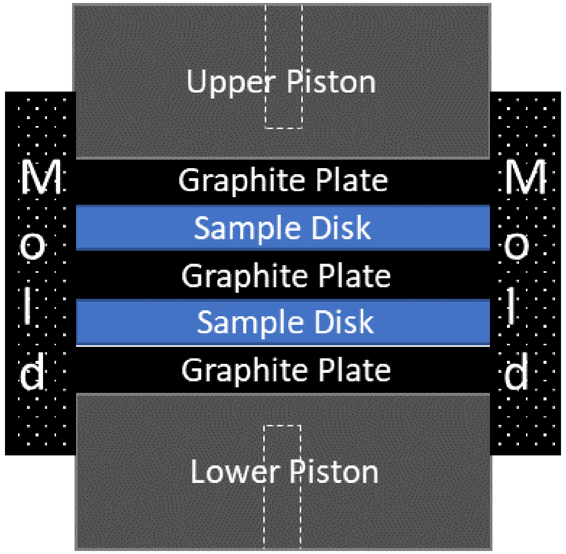
D4.4	Production of large-size CCM plates	CERN	Demonstrator	Public	24

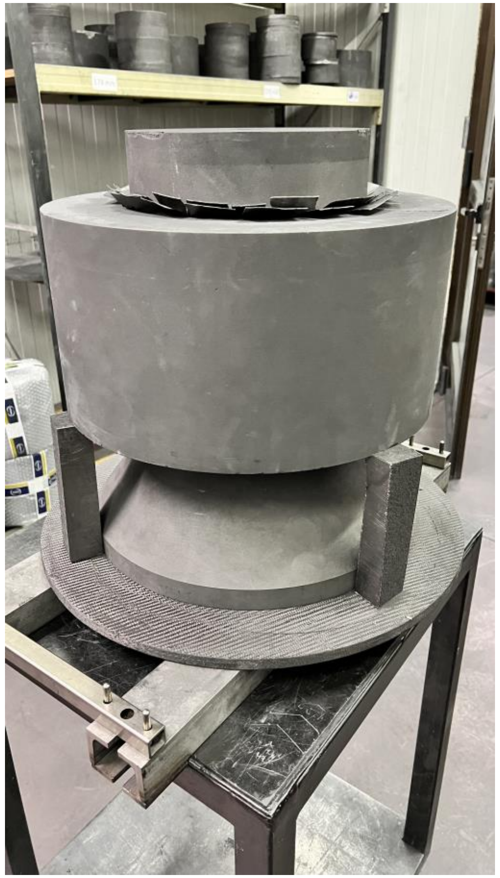
Deliverable D4.4 *due date April 2023, submitted to I.FAST project office 3 weeks ago*

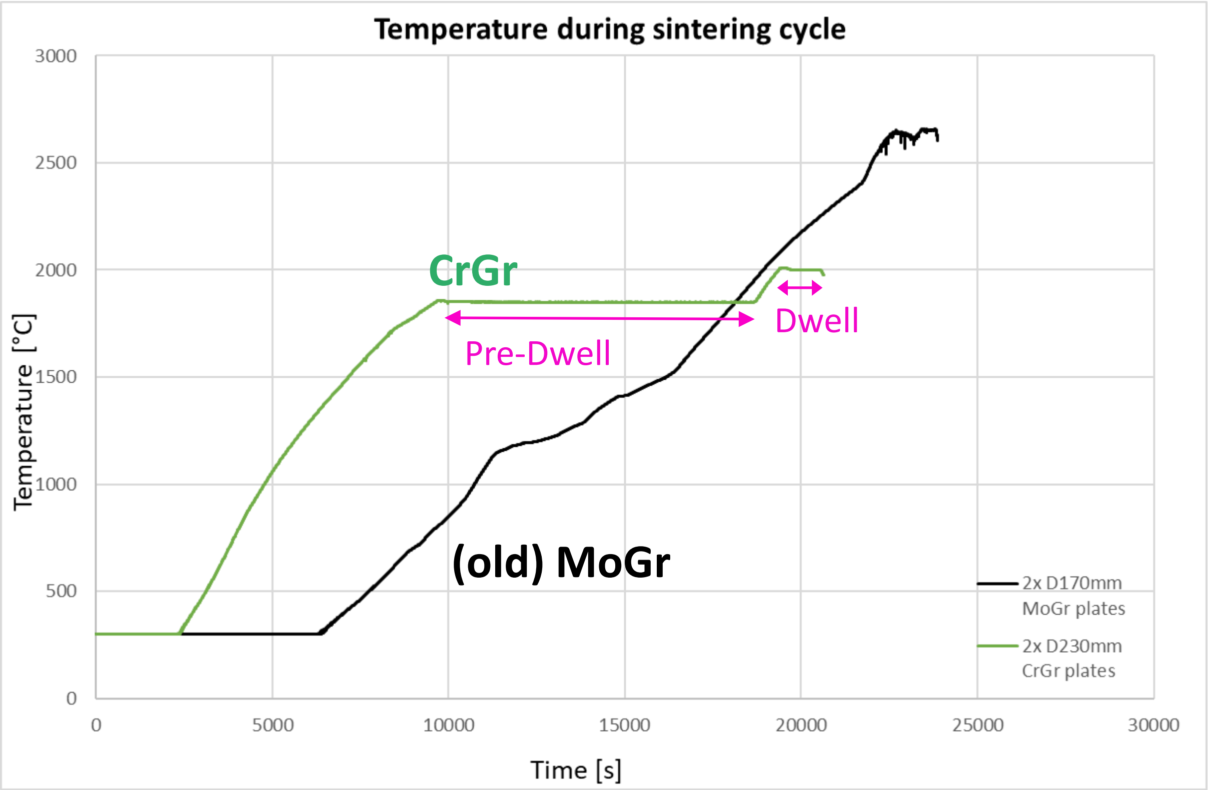
- Produce two large CCM plates (cross section >400 cm^2) in a single sintering cycle
- This means: moving from the sintering of Ø170 mm to Ø230 mm plates → **doubling the cross-section** (and: 2 plates per cycle!)
- Given the good results achieved on CrGr, and the advantages provided over MoGr → **decision to select CrGr as D4.4 baseline material**
- Sintering run: **9th March 2023**

Deliverable D4.4 – CrGr 2xØ230 mm production

- **One single mould** for two Ø230 mm CrGr disks (+ graphite spacers)
- Shorter cycle, lower sintering temperature wrt MoGr





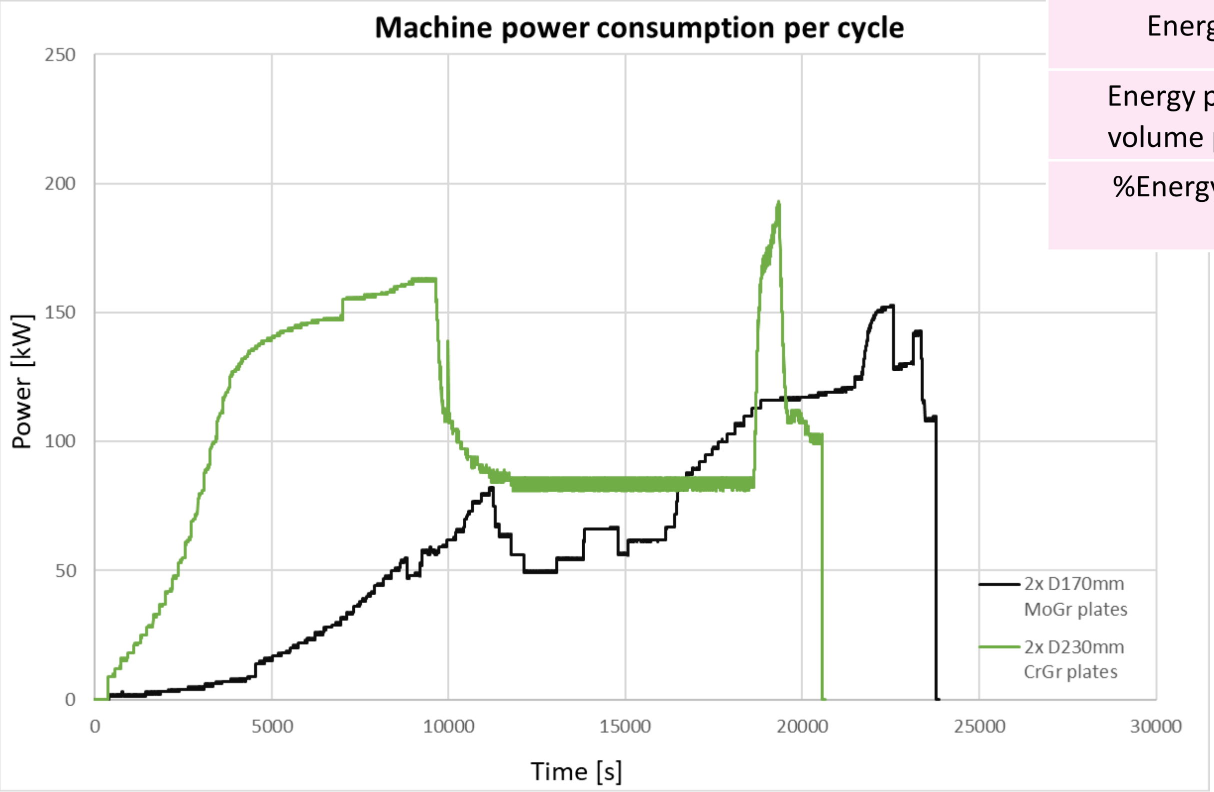


Deliverable D4.4 – CrGr 2xØ230 mm production

- **Energy saving** (similar peak power, shorter time, bigger volume produced)

**estimation*

	2x Ø170 MoGr plates	2x Ø230 CrGr plates	2x Ø230 CrGr plates without pre-dwell*
Energy per cycle [kWh]	408	577	214
Energy per cycle per material volume produced [kWh/cm^3]	0.36	0.28	0.10
%Energy saving per material volume	***Pre-I.FAST baseline***	**-23%**	**-72%**

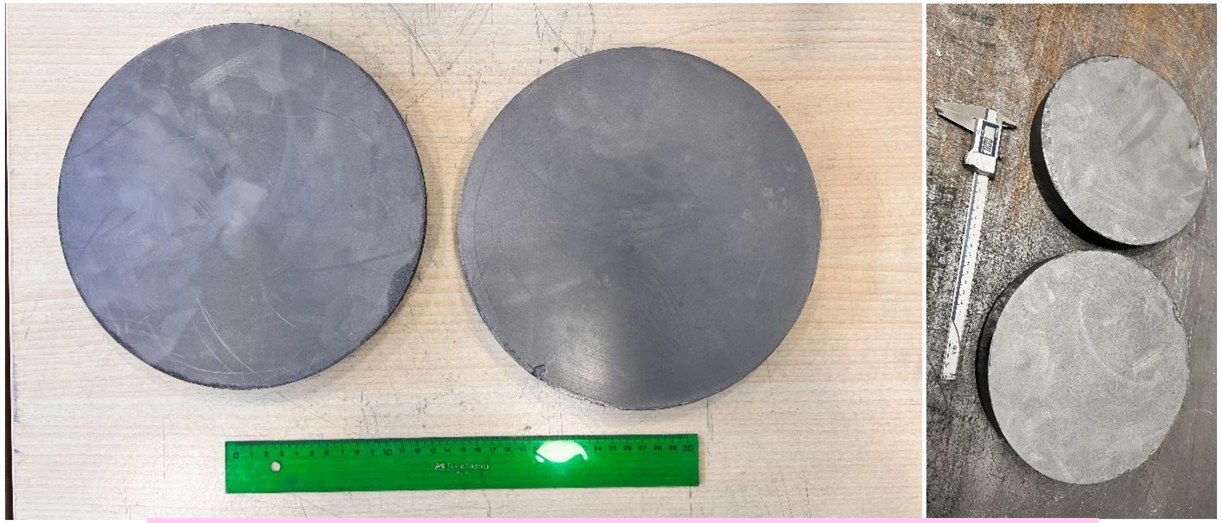


Deliverable D4.4 – CrGr 2xØ230 mm production

- **Mould saving**

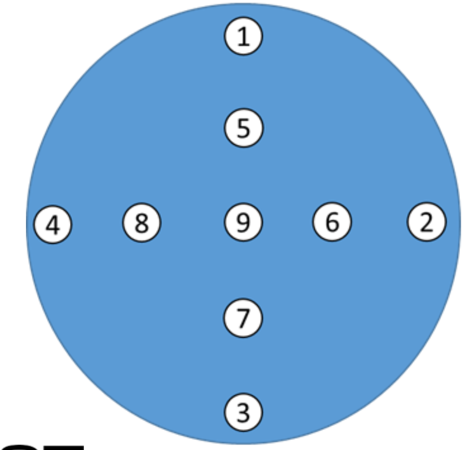
Deliverable D4.4 – CrGr 2xØ230 mm production

- Preliminary characterization at **Nanoker**
- **Very promising** electrical conductivity and compaction (Density)
- **CTE now to be measured at CERN**, to evaluate best annealing cycle (and: can we remove annealing cycle?)



D4.4 2xØ230 mm CrGr plates

Density 2.44 g/cm^3



Conductivity (MS/m)		
Position	Side 1	Side 2
1	1,04	0,74
2	1,02	0,75
3	1,03	0,79
4	1,04	0,78
5	1,08	0,89
6	1,06	0,94
7	1,01	0,88
8	1,09	0,96
9	1,05	1,00
Average	**1,05**	**0,86**

Conductivity (MS/m)		
Position	Side 1	Side 2
1	0,95	0,92
2	0,94	0,93
3	0,94	0,90
4	0,95	0,88
5	0,93	0,91
6	0,93	0,93
7	0,93	0,92
8	0,94	0,91
9	0,92	0,93
Average	**0,94**	**0,91**

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Conclusions and Next Steps

- All milestones and deliverables of I.FAST task 4.4 **have been reached in the first two years of the project**
- However, in the scope of the task objective (reduction of cost of carbon-carbide materials), **several actions are still foreseen in the last two years of I.FAST**:
  - **Complete the in-lab characterization of the CrGr** produced in the scope of deliverable D4.4, and publish the results on an international journal (record achieved in CrGr thermophysical properties and record in a CCM size sintering)
  - Optimize and, if possible, remove production steps related to material **pre-dwell and annealing**
  - Study the machine insulation system to understand if further improvements are needed to **reduce power losses**
  - **Further increase the material volume produced per cycle**: increase the plate thickness (up to 5 cm?) and/or increase the number of plates (up to 4?)
  - Optimize the material composition to **reduce spilling of molten metal**

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Thank you for your attention!

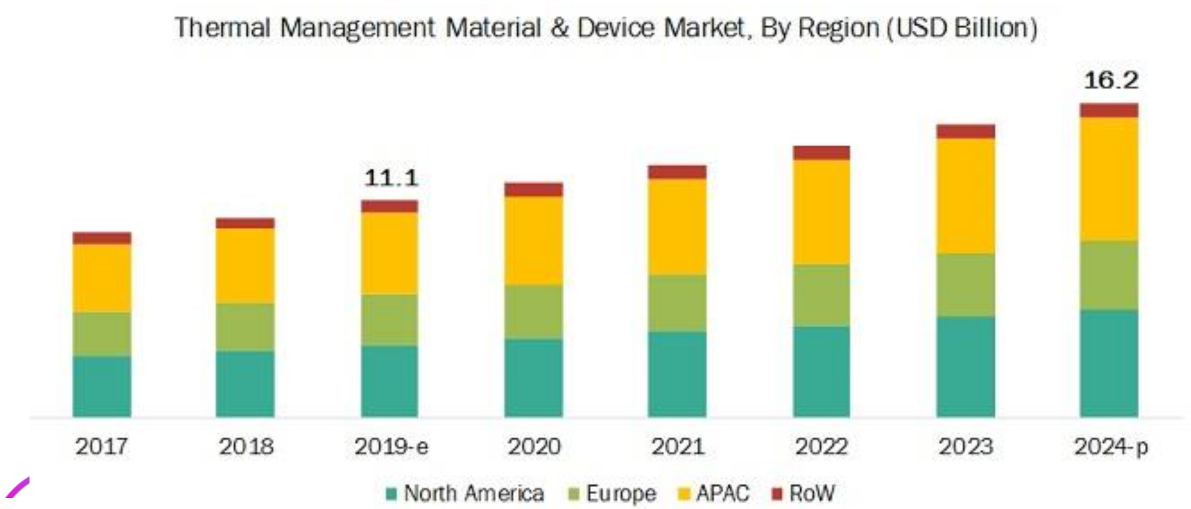
And thanks to the contribution of several people from WP4.4:

C. Accettura, C. Gutierrez, J. Guardia, S. Hoell, M. Losasso, L. Puddu, S. Rivera, O. Sacristan

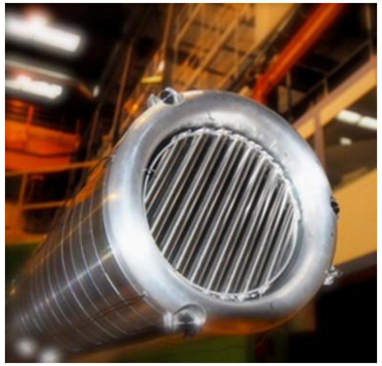
This project has received funding from the European Union’s Horizon 2020 Research and Innovation programme under GA No 101004730.

Motivation

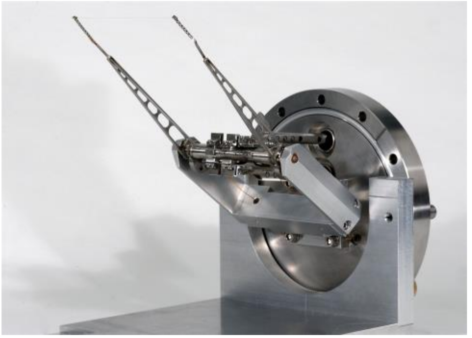
- **Increasing worldwide request for thermal management materials** (high thermal diffusivity and specific heat, low density)
- **Cost still high**: CCM are limited to high-end applications (nuclear energy, particle physics, aerospace, …)
- Decrease of energy consumption, improvement of production cycle **efficiency and sustainability** are also a must
- In particle physics: very interesting for **beam-intercepting devices and beam instrumentation, beam windows, etc.**



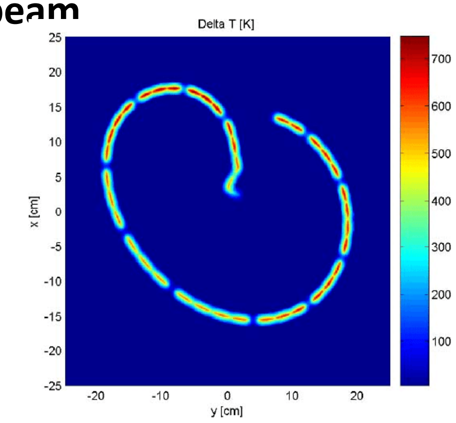
Expected figures for the development of the thermal management market in the next years, source: https://www.marketsandmarkets.com/Market-Reports/thermal-management-market-155049228.html



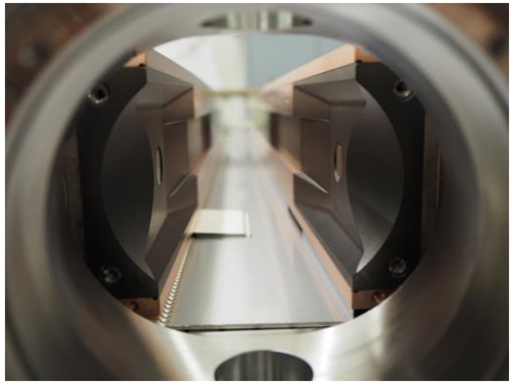
Targets



Beam wire scanners



Dumps



Collimators

Year 1 activities – Technical Specification

- Definition of the **minimum thermophysical properties** for a use in HEP beam-intercepting devices and in thermal-management applications

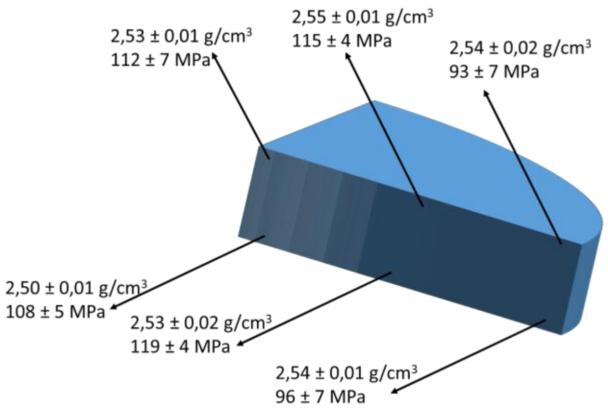
	Specification		
Property	**∥***	**⊥**	**Unit**
Density at 20ºC	2.40 – 2.60		$[g/cm^3]$
Specific heat at 20ºC	> 0.6		[J/(g·K)]
Electrical conductivity at 20ºC	> 0.75		[MS/m]
Thermal Diffusivity 20ºC /at 300ºC	> 350/100	> 20/6	[mm^2/s]
Thermal conductivity at 20ºC /at 300ºC	> 500/280	> 35/20	[W/(m·K)]
Volumetric CTE 20-1000ºC	< 7		$[10^{-6}K^{-1}]$
Coefficient of thermal expansion 20-1000ºC	< 2.9	< 15	$[10^{-6}K^{-1}]$
Young's Modulus at 20ºC	35 < E < 75	5 < E < 8	[GPa]
Flexural strength at 20ºC	> 60	> 10	[MPa]
Flexural strain to rupture at 20ºC	> 2500	> 4000	[µm/m]
Dimensional stability*	< 0.05	< 0.25	%

**The dimensional stability shall be ensured after the following thermal cycle: heating of the specimen up to 1950ºC with a ramp of 5ºC/min. Cooling of the specimen down to room temperature with the same ramp.*

Year 1 – Increase of volume per cycle

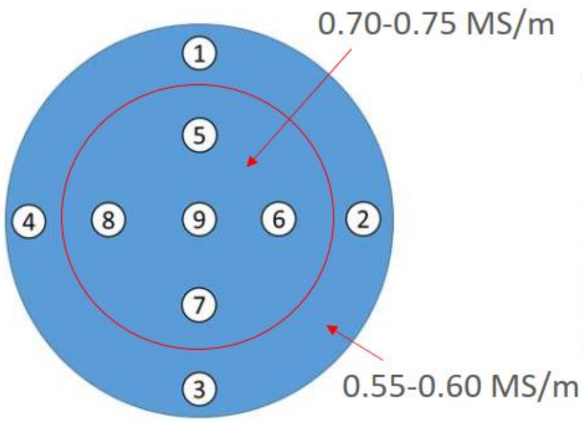
- **Molybdenum-Graphite** (sintered at 2640°C)

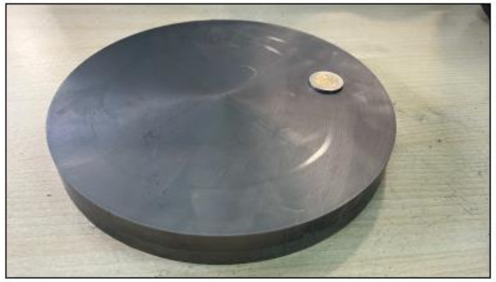
2 plates produced with 230 mm Diameter (2x bigger section than before IFAST)



Disk (230 mm diameter)	Density (g/cm^3)	Electrical Conductivity (Mean values on each side) (MS/m)
Plate #1 (p=26 MPa)	**2,53**	**0,6 – 0,63**
Plate #2 (p=40 MPa)	**2,60**	**0,65 – 0,68**
Specification	**2,3 ÷2,6**	**>0,8**

Lower electrical conductivity values than in the 170 mm diameter disks





Pre-compaction of the green powder:

Maximum Applied Force Uniaxial Hydraulic Press ~ 900 kN

- 170 mm Ø → 40 MPa → 2,00 g/cm^3
- 230 mm Ø → 21 MPa → 1,65 g/cm^3

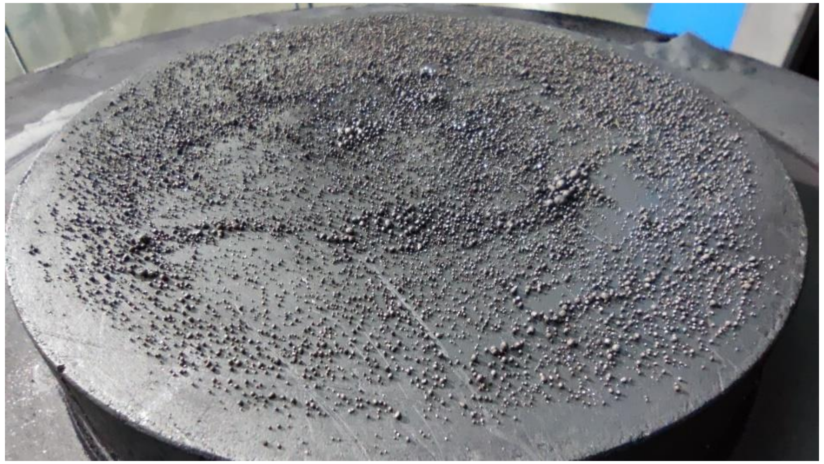
Next: <u>increase the metal content</u>, together with the higher sintering pressure

Year 1 – Decrease of sintering Temperature

- **Chromium-Graphite** (sintered at 2000°C – 1.3x lower T)
- Concept proposed by **Jorge Guardia** within ARIES WP14 & WP17, technically was not demonstrated yet (very poor mechanical properties)

3 plates produced with 170 mm Diameter

Disk (170 mm diameter)	Density (g/cm^3)	Electrical Conductivity (MS/m)
Plate #1	2,30	1,00 – 1,07
Plates #2 & #3	2,30	0.75/0.81
Specification	2,3 ÷2,6	>0,8



Reusable Mold and Parts → Important Cost Reduction

- **Plate #1 produced in a single plate per cycle**, very promising properties, decision for full characterization at CERN
- **Plates #2 and #3 double-plate per cycle**, losing a bit in conductivity → composition and cycle to be optimized

Year 1 – CrGr Characterization