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WP4 Managing Innovation: Beam Windows and Composite Materials

I.FAST Final Meeting

22nd October 2025

CERN

M. Tomut (GSI), F. Carra (CERN)

With contributions from WP4.3 & WP4.4 members, CERN IRRAD and FLUKA teams

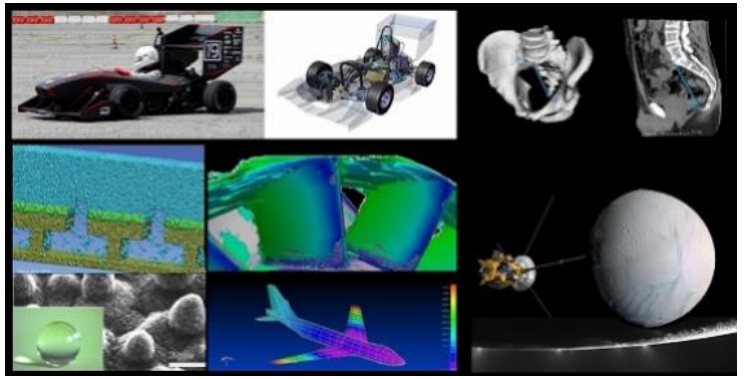
iFAST

Outline

- Task 4.3 – Innovative beam windows for high-power accelerator applications
- Task 4.4 – Carbide-Carbon Materials for Multipurpose Applications
- Results, Outcome, Impact
- Conclusions, lessons learned

WP 4.3 – Innovative beam windows for high-power accelerator applications

- **Beam window**: separating environment at different pressures (vacuum/atmosphere or differential vacuum levels)
- Two technical solutions investigated within WP4.3
  - **Metallic windows** (tantalum, T91 steel, aluminium alloys)
  - **Graphenic windows** (thin graphene membranes)
- Task participants: **GSI (DE), RHP (AT)** and **CERN** + collaboration with **La Sapienza University - DIMA (IT)**



WP 4.3 – Innovative beam windows for high-power accelerator applications

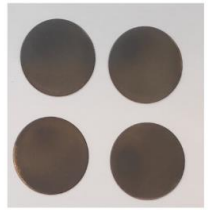
Milestone/Deliverable Number	Title	Lead beneficiary	Type	Dissemination level	Due Date (in months)
MS13	First characterisation of beam windows materials under thermomechanical load and extended radiation damage	GSI	Report	Public	18
D4.3	Manufacturing and testing of two beam-windows prototypes	CERN	Demonstrator	Public	32

Milestone MS13 ***achieved in 2022*** (***link***)

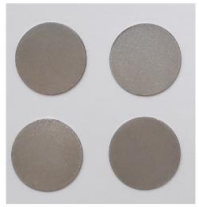
- **Ion irradiation of window foils** of different materials at GSI M-Branch UNILAC → T91 steel, Titanium grade 23, Inconel 718, Aluminium 6082 T6, graphene
- **Online and post-mortem characterization** of mechanical and thermal properties
- **See also Marilena's *talk*** at 2nd IFAST Annual Meeting
- **Scientific production** on top of milestone report (**L. Notari** master thesis, 2 publications→ *see "Scientific Contributions" section at the end*)

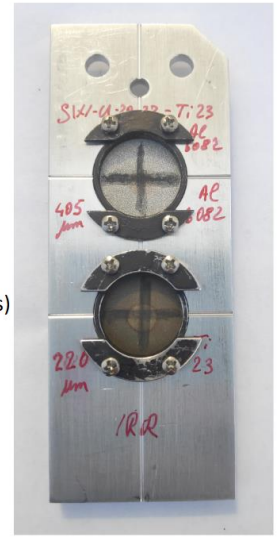
Courtesy of M. Tomut (GSI), L. Notari (La Sapienza)

Titanium Grade 23 (0.22 µm thickness)



Aluminium 6082 T6 (0.405 µm thickness)

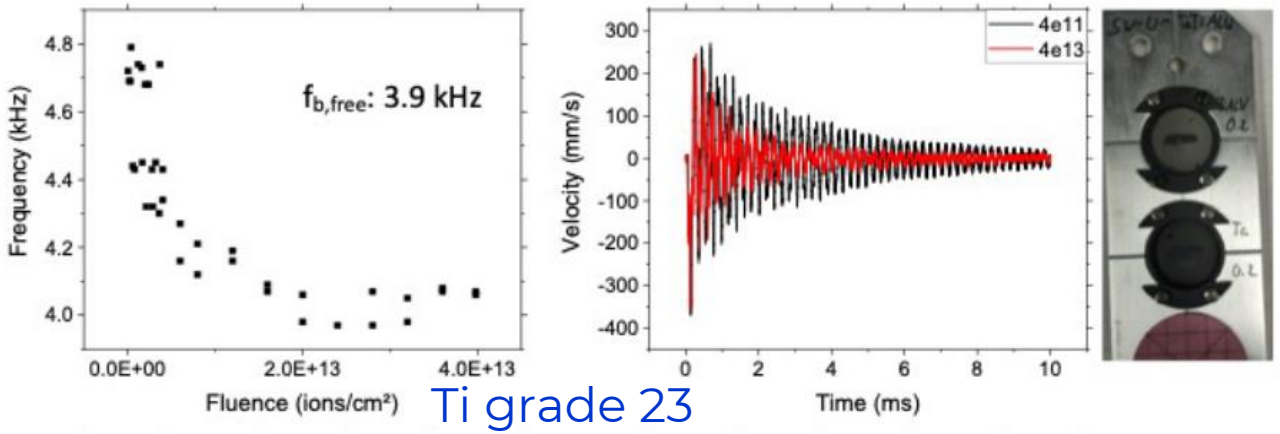




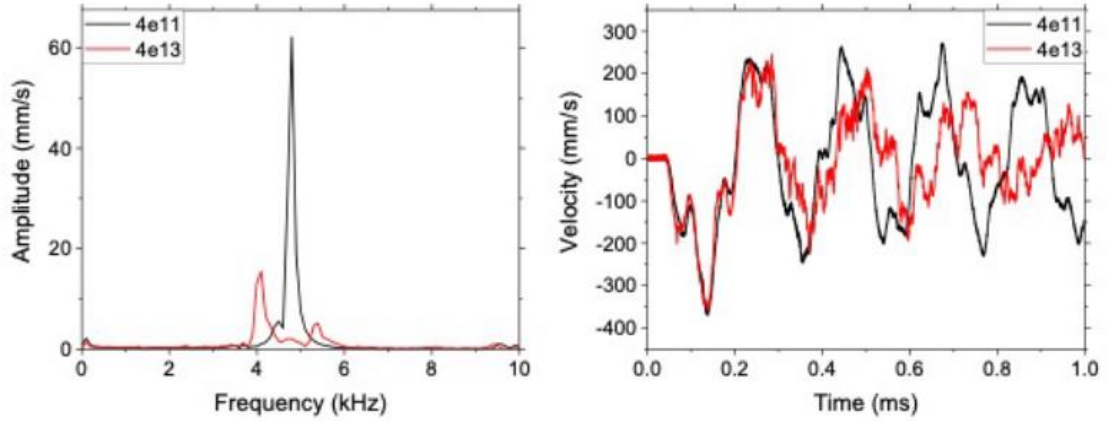
WP 4.3 – MS13 post-irradiation examination

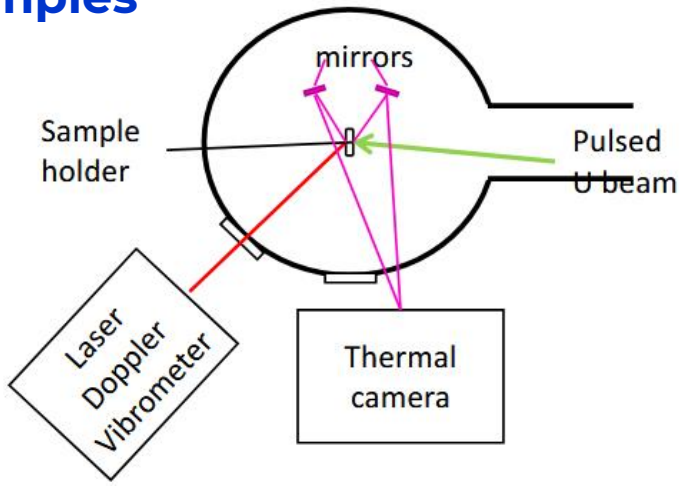
Milestone MS13 ***achieved in 2022*** (***link***): First characterisation of beam windows materials under thermomechanical load and extended radiation damage

LDV monitoring of beam-induced response of MS13 samples

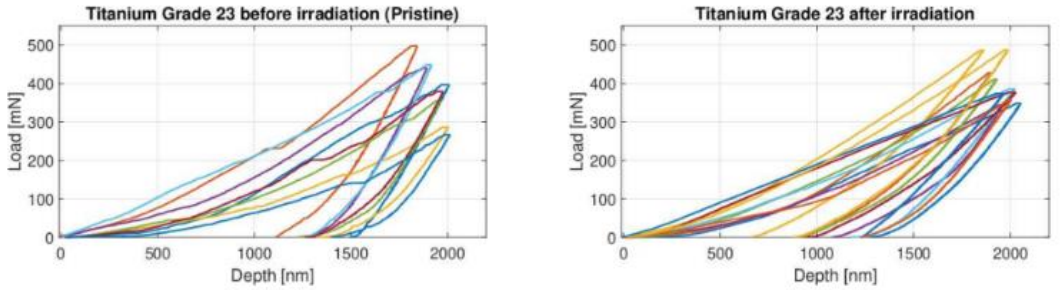


Ti grade 23





Nanoindentation tests of pristine and irradiated Ti



WP 4.3 – Innovative beam windows for high-power accelerator applications

Milestone/Deliverable Number	Title	Lead beneficiary	Type	Dissemination level	Due Date (in months)
MS13	First characterisation of beam windows materials under thermomechanical load and extended radiation damage	GSI	Report	Public	18
D4.3	Manufacturing and testing of two beam-windows prototypes	CERN	Demonstrator	Public	32 → **38**

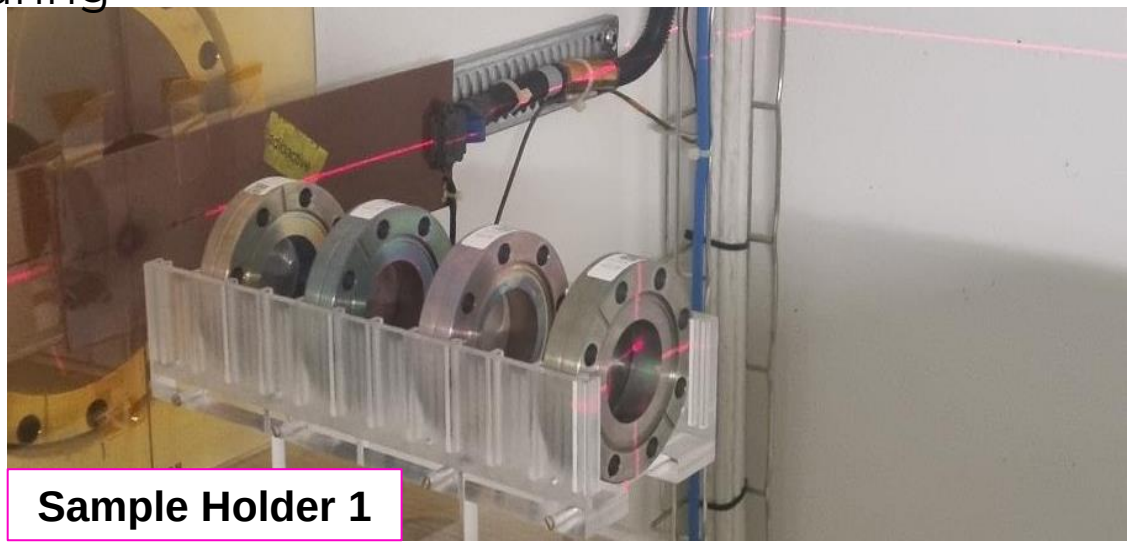
Deliverable D4.3 ***achieved in 2024*** (***link***)

- Postponed by 6 months (June 2024) due to beam unavailability at GSI in '23
- Alternative solution found → **proton irradiation at CERN IRRAD in Sep-Oct '23**
- Sample material selection **based on results of MS13** in terms of irradiation resistance
- Deliverable completed and submitted in June '24 → **see also N. Vejnovic's *talk* at 4th IFAST annual meeting**

WP4.3 – D4.3 experimental setup, 1st Irradiation Campaign

Deliverable D4.3 ***achieved in 2024*** *(**link**)*: Manufacturing and testing of two beam-windows prototypes → *we actually manufactured* ***8 windows instead of 2***

- **Facility**: IRRAD (PS proton beam, T8 beam-line at the CERN PS East Hall building 157) ***www.cern.ch/ps-irrad***
- **Beam**: protons @24 GeV/c
- **Samples**: thin foils brazed to metallic flange produced by **RHP**
- **Irradiation period** 6th September-11th October 2023
- **Fluence** up to 1.96e16 p/cm^2 over 10x10mm
- **Average dose -** 4.56 MGy (Tantalum)

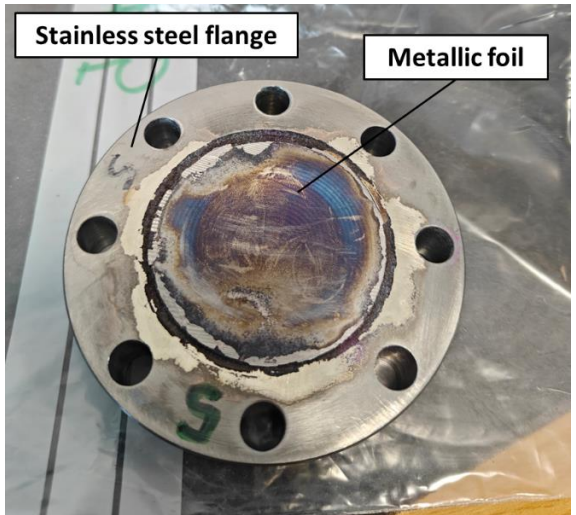


Sample Holder 1

Courtesy of G. Pezzullo, F. Ravotti (CERN)

Sample holder 1

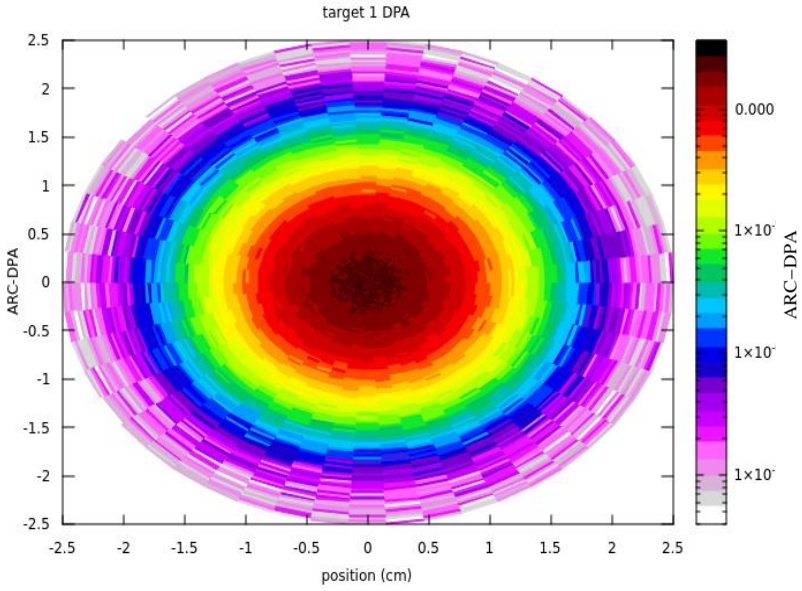
- Sample #7 → **Tantalum**, diameter 50mm, thickness 0.3mm
- Sample #15 → **Tantalum**, diameter 50mm, thickness 0.4mm
- Sample #13 → **T91**, diameter 50mm, thickness 0.4mm
- Sample #10 → **T91**, diameter 50mm, thickness 0.6mm



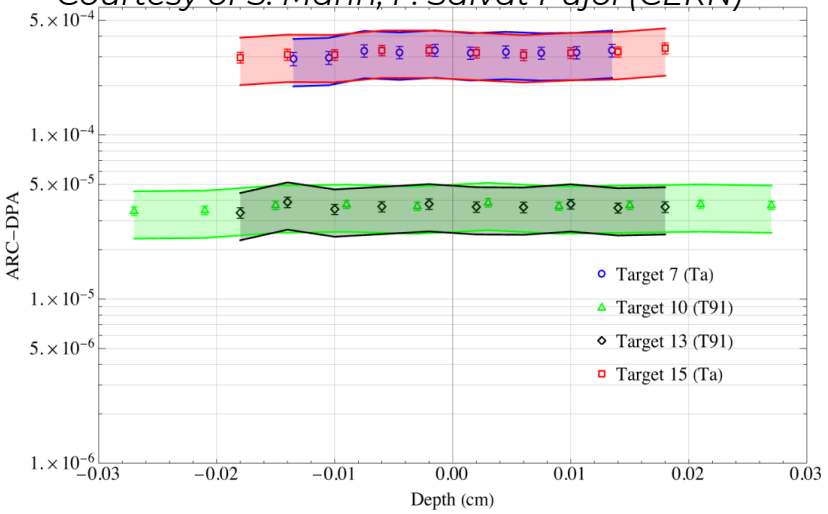
WP 4.3 – D4.3 thermophysical characterizatio, 1st Irradiation Campaign

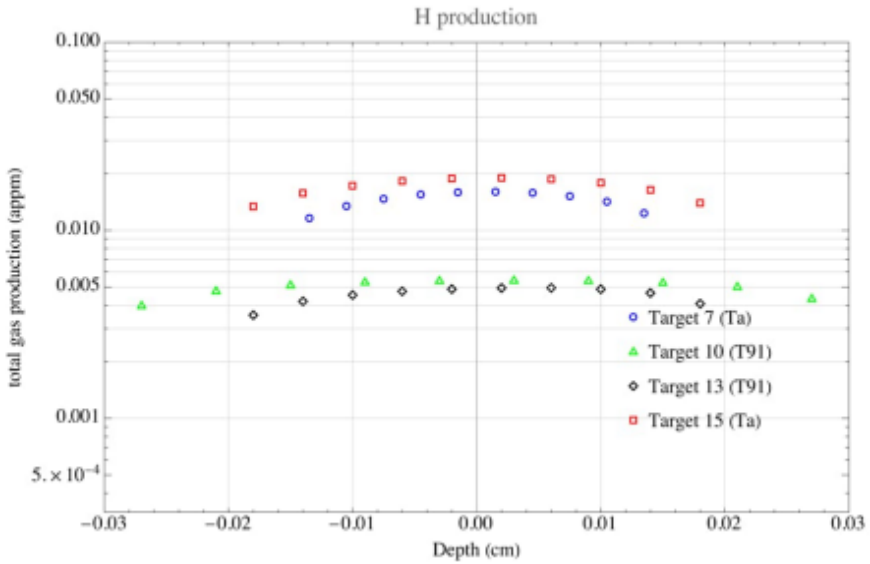
Deliverable D4.3 ***achieved in 2024*** (***link***): Manufacturing and testing of two beam-windows prototypes → *we actually manufactured* ***8 windows instead of 2***

- Change in the thermomechanical properties were correlated to the **estimated displacement-per-atom (DPA) and gas production** (big thanks to the FLUKA team at CERN SY-STI!)
- FLUKA simulations also allow to estimate the **temperature during irradiation** (looks to be close to T_{room})
- Highest level of DPA in Sample Holder 1 **~3e-4 DPA**



Courtesy of S. Marin, F. Salvat Pujol (CERN)

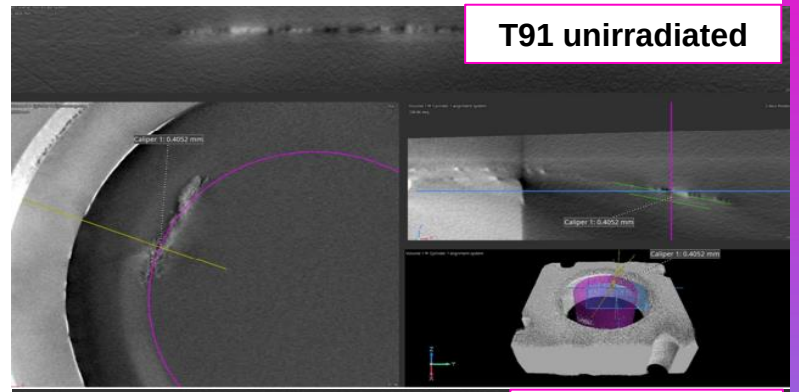


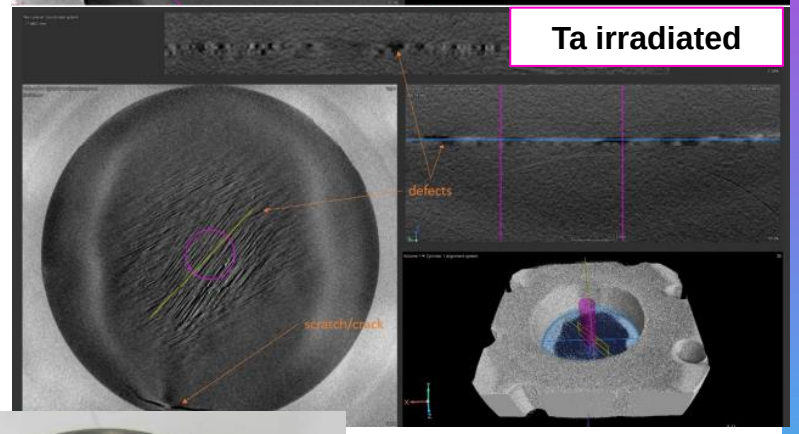


WP4.3 – D4.3 thermophysical characterization

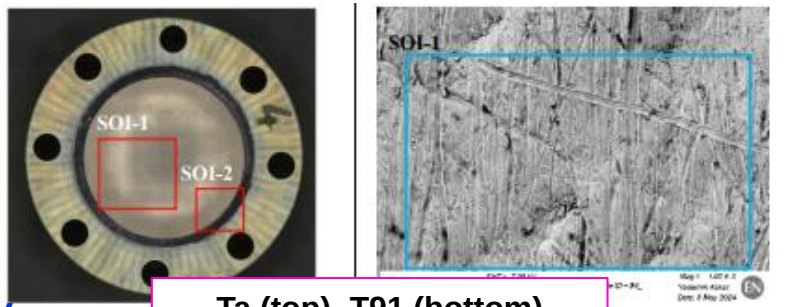
- Extensive pre- and post- irradiation examination
  - Computed micro-tomography
  - Optical microscopy and SEM
  - Electrical and thermal conductivity
  - Dye penetrants at the junction window/flange

Computed micro-tomography

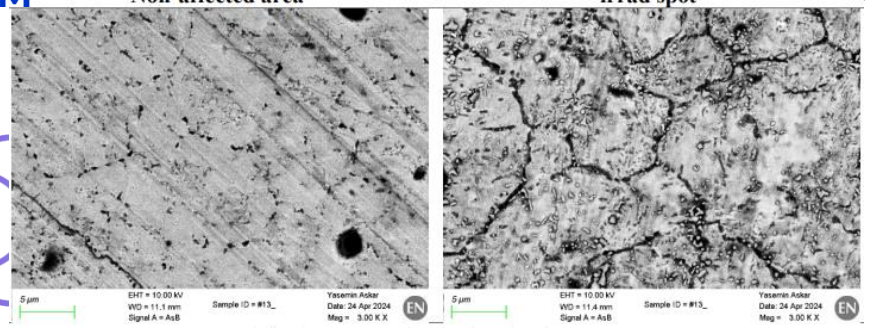




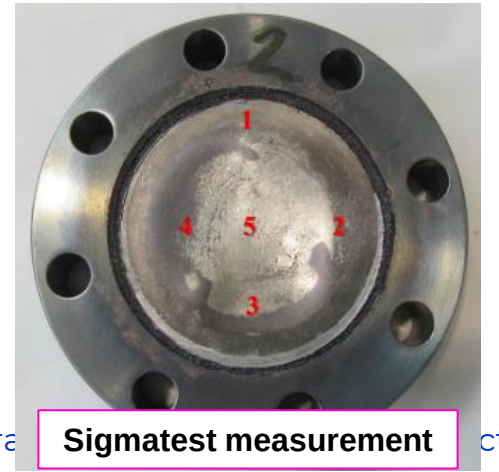
Optical microscopy and SEM



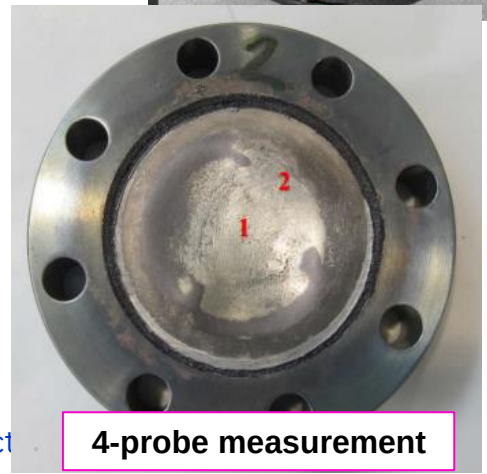
Ta (top), T91 (bottom)



Electrical conductivity measurements



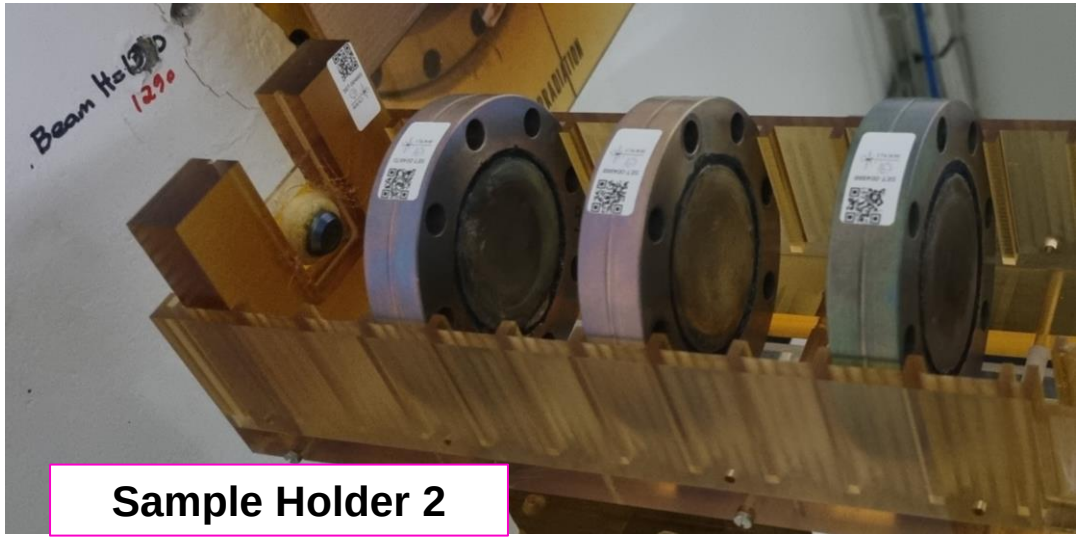
Sigmatest measurement



4-probe measurement

WP 4.3 – 2nd Irradiation Campaign

- As 8 window prototypes were built, a **2nd sample holder was also assembled**
- It was not in the scope of D4.3, but **we still decided to irradiate it at a higher fluence than sample holder 1 (10 times higher)**
- Samples are very radioactive and **cannot be characterized post-irradiation before 1 year**



Courtesy of G. Pezzullo, F. Ravotti (CERN)

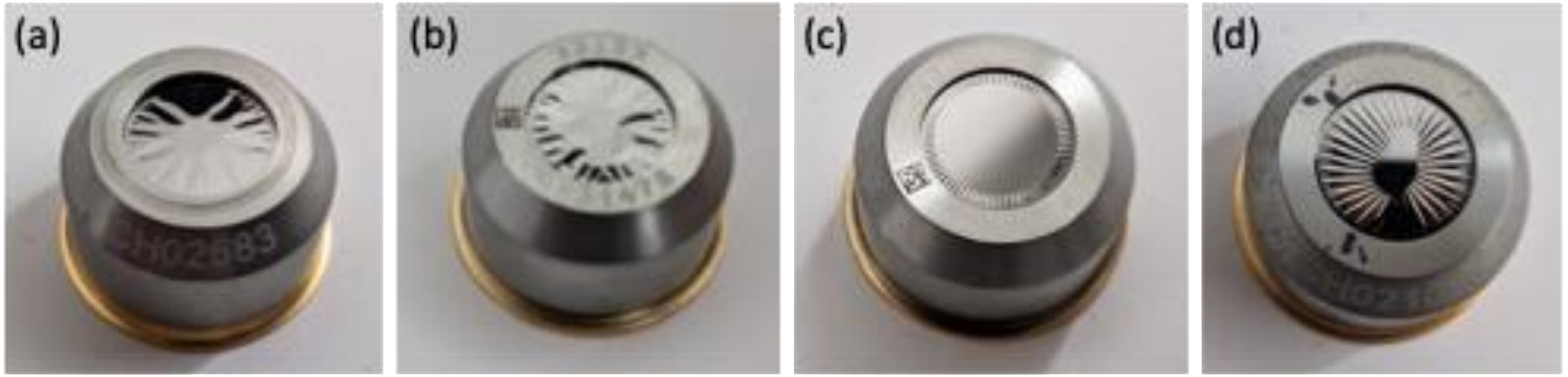
- **Facility**: IRRAD (CERN), ***www.cern.ch/ps-irrad***
- **Beam:** protons @24 GeV/c
- **Irradiation period** March-June 2024
- **Fluence** up to **2.39e17 p/cm2** over 10x10mm
- **Average dose**
  - 43.9 MGy (Tantalum)
- **~3e-3 DPA**

- Sample #8 → **Tantalum**, diameter 50mm, thickness 0.6mm
- Sample #9 → **T91**, diameter 50mm, thickness 0.4mm
- Sample #11 → **T91**, diameter 50mm, thickness 0.6mm
- Sample #10 → **Graphene**, 10x10 mm, thickness 1 um

WP 4.3 – Graphenic Carbon windows

The right material has been found!

Irradiated membranes from KETEK



Pristine

4.8 MeV/u Au
1x 10^{13} ions/cm^2
flux of 2x10^9 i/cm^{2}s

4.8 MeV/u Au
5x 10^{13} ions/cm^2
flux of 2x10^9 i/cm^{2}s

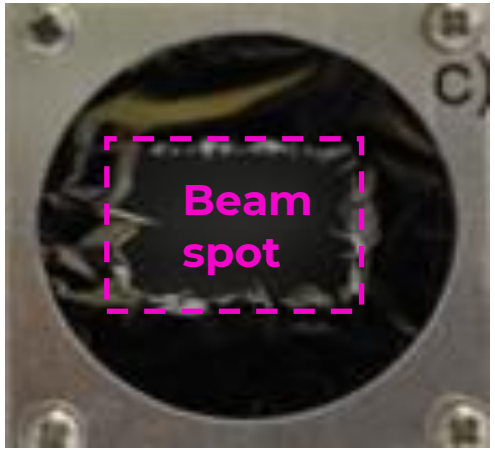
5 MeV/u Ne
6.9x10^{16} ions/cm^2
flux of 6x10^{12} i/cm^{2}s

Irradiation-induced **compaction**

Sample	Beam fluence [ions/cm^{2}s]	Areal density [mg/cm^2] Before irradiation	After irradiation	Change [%]
(b)	10^{13}	0.1932± 0.0003	0.2022 ± 0.0003	2.9 ± 0.2
(c)	5×10^{13}	0.2304 ± 0.0004	0.2375 ± 0.0004	4.6 ± 0.2

K. Botsiou, Master thesis

Irradiated membranes from a US company

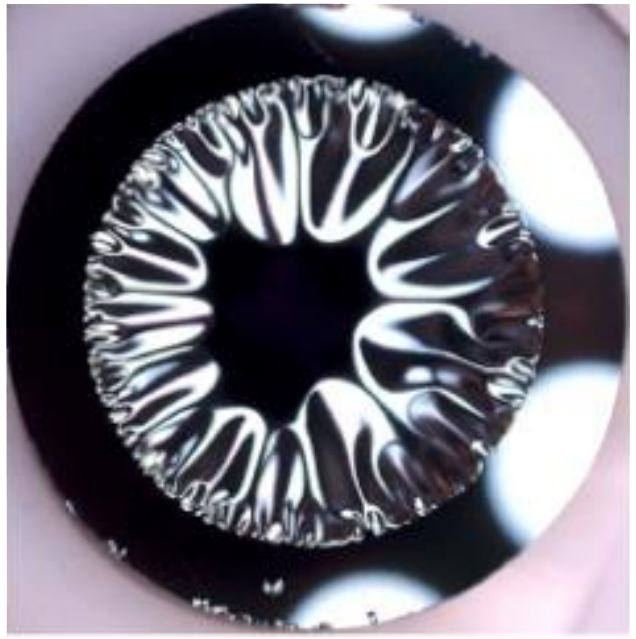


Failure of a graphene platelet-based membrane irradiated with 4.8 MeV/u 5 ×10^{13} U ions/cm^2

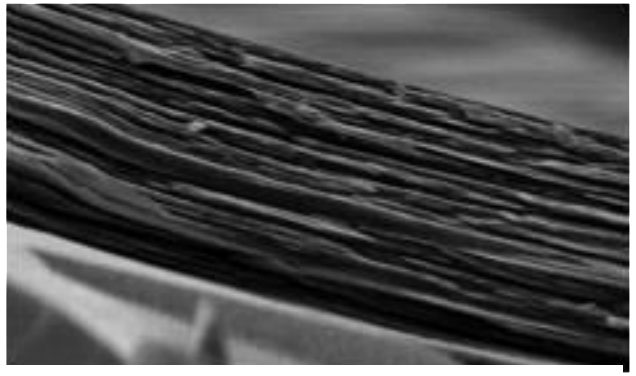
WP4.3 – Graphenic beam windows

- CVD deposition on SIC ensures an intimate bonding with the substrate
- Interconnection of graphemic lamellae –good mechanical properties and radation hardness

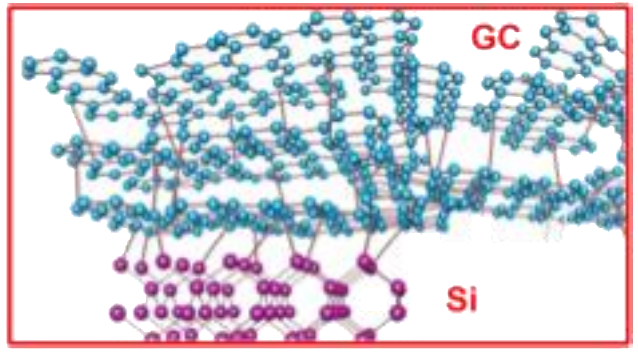
KETEK



GC membrane on Si ring for beam window application

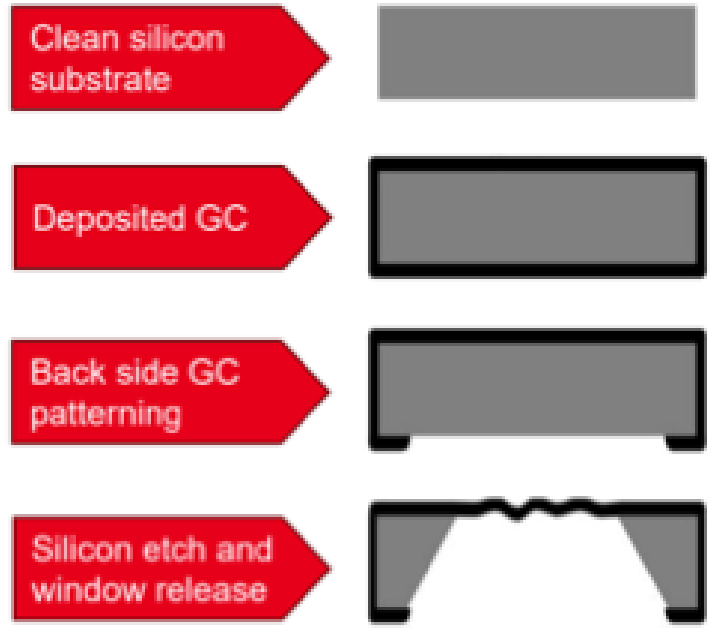


Laminar structure of GC



Strong bonding on Si ring

CVD deposition of GC on Si substrate



2-step etch process of Si substrate

WP 4.3 – Innovative beam windows for high-power accelerator applications

Application of graphenic beam windows as gas targets windows – tests at GSI

1 bar gas pressure

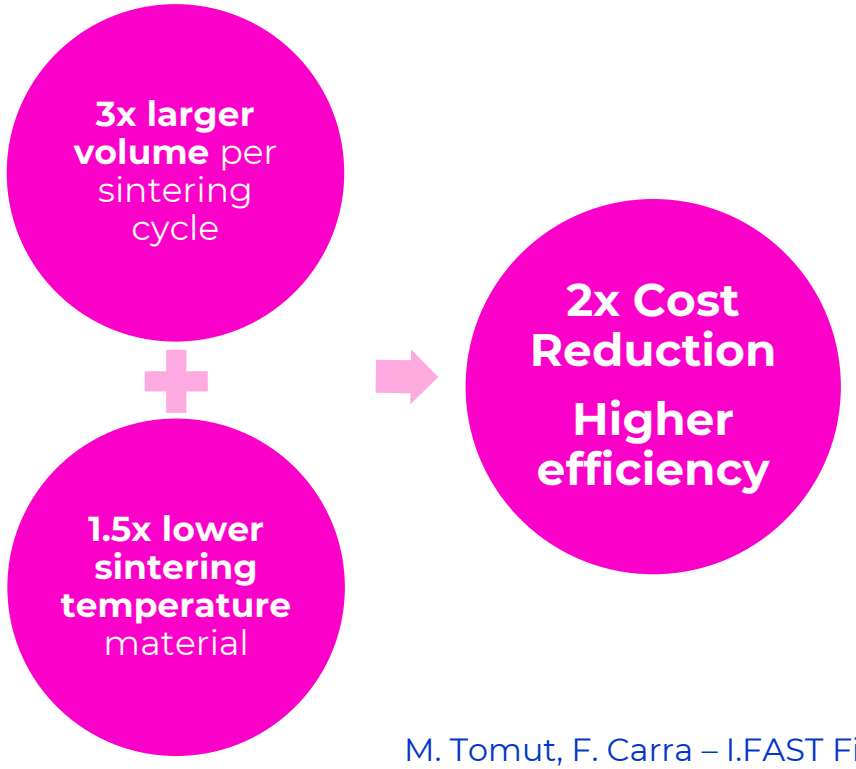
Test with Pb beam up to 280 MeV/u

Filled gases:
Nitrogen
Propene
Argon

Tested at the FRS beamline at SIS-18, GSI, Darmstadt

WP 4.4 – Carbide-Carbon Materials for Multipurpose Applications

- 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 transfer, aerospace light components, fusion, etc.)
  - Thermal conductivity 2-3 times higher than Cu! Stronger, low density
- How?



- Who?

CERN

WP 4.4 – Carbide-Carbon Materials for Multipurpose Applications

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 ***achieved in 2022*** (***link***)

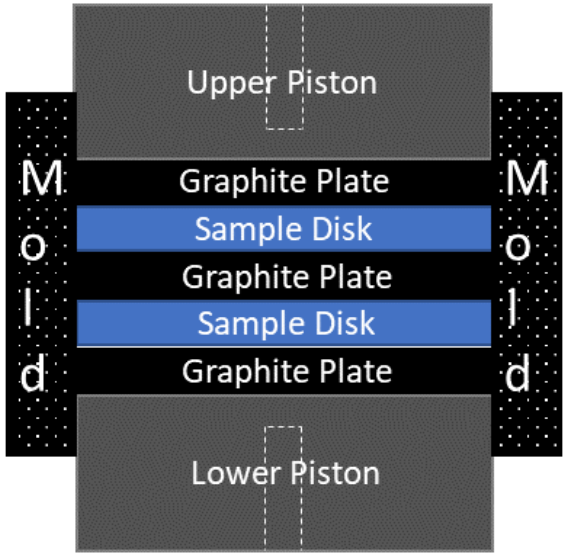
- **Chromium-Graphite** (CrGr) proposed (and produced) as a valid alternative to MoGr
- Presented at the 1st IFAST Annual Meeting (see ***here***)

D4.4 ***achieved in 2023*** (***link***)

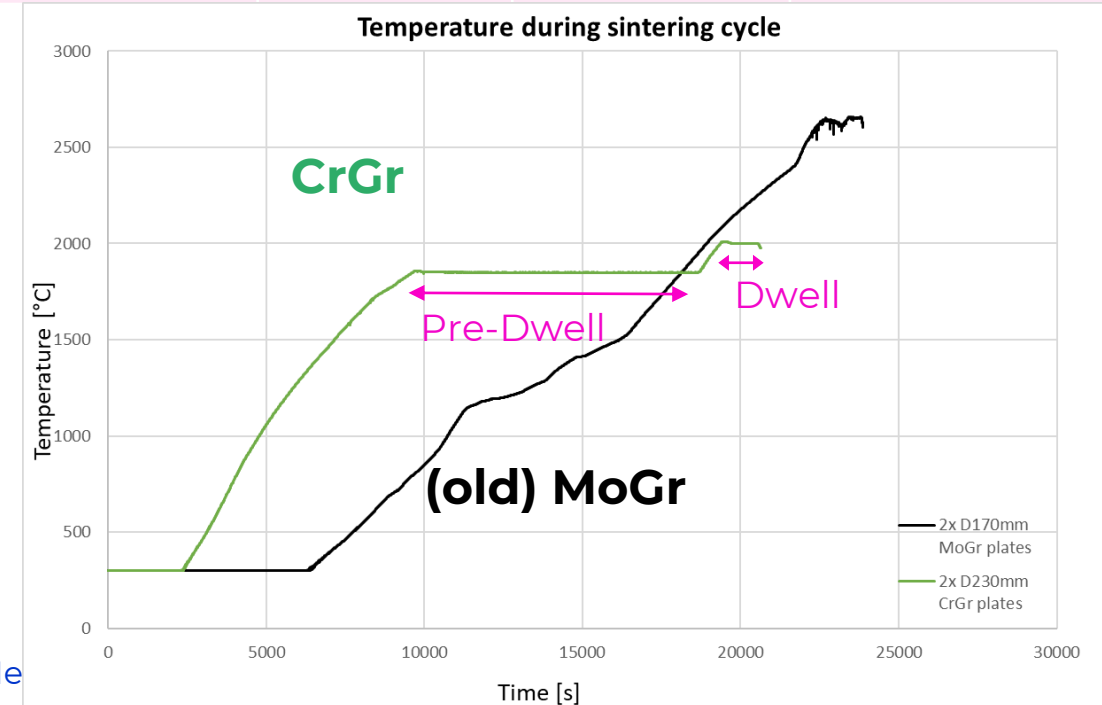
- **Two big (Ø230 mm) Chromium-Graphite disks produced in a single machine cycle** (doubling of disk cross-section, decreasing of the sintering temperature wrt MoGr)
- Presented at the 2nd IFAST Annual Meeting (more details ***here***)

WP 4.4 – D4.4 production energy savings

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



	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%**



WP 4.4 – D4.4 mould and insulation increased lifetime

- **CrGr** lower sintering temperature and closer CTE with graphite mould with respect to MoGr
- This results in the **survival of graphite mould and insulation elements during CrGr sintering**, whereas these components had to be replaced at every MoGr sintering cycle → **lower production cost** (adding to the cost reduction coming from energy savings)

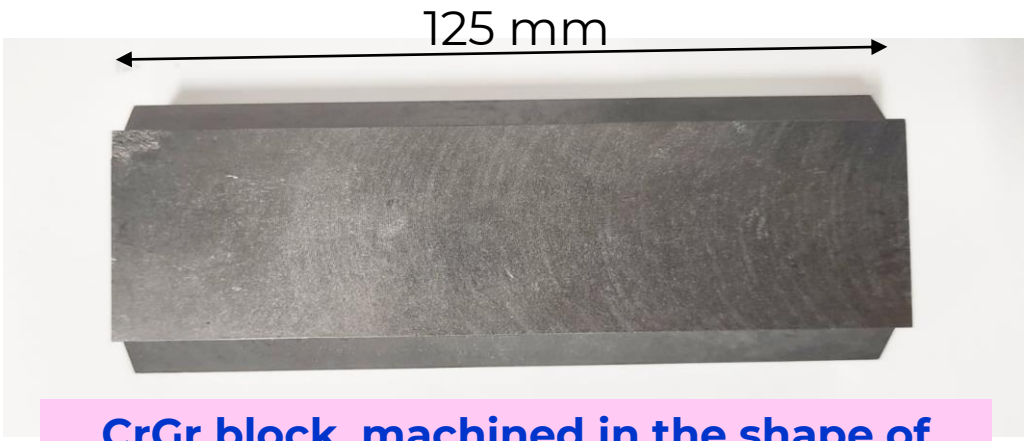
WP 4.4 – D4.4 material characterization

- CrGr produced during D4.4 was **fully characterized from the thermophysical point of view**, and the results were compared to ARIES MoGr and to IFAST specifications
- Further characterization continued also after the deliverable (**fresh measurements September 2025**), examining for example homogeneity of the plate, UHV properties, machining tolerances
- **Production of 1:1 scale prototype** (HL-LHC collimator absorber block)

Property	Specification		CrGr Plate #1 (2022)		D4.4 plates (2024)	
	∥ / IP	⊦ / TP	∥ / IP	⊦ / TP	∥ / IP	⊦ / TP
Density at 20 °C [g/cm³]	2.40 – 2.60		2.32		2.47	
Specific heat at 20 °C [J/(g·K)]	> 0.6		0.687		0.7 ↑	
Electrical conductivity at 20 °C [MS/m]	> 0.75		1.02		1.15 ↑	0.35
Thermal diffusivity at 20 °C / at 300 °C [mm²/s]	> 350/100	> 20/6	470/120	33/9	420/100 ↓	38/10 ↑
Thermal conductivity at 20 °C / at 300 °C [W/(m·K)]	> 500/280	> 35/20	750/350	52/27	700/250 ↓	64/23 ↑
Volumetric CTE 20 – 1000 °C [ppm/K]	< 7		6.7		7.2	
Linear CTE 20 – 1000 °C [ppm/K]	< 2.9	< 15	4.0	12.0	5.0	11.5
Flexural strength at 20 °C [MPa]	> 60	> 10	58	8	96 ↑	22 ↑

WP 4.4 – Additional CrGr Characterization

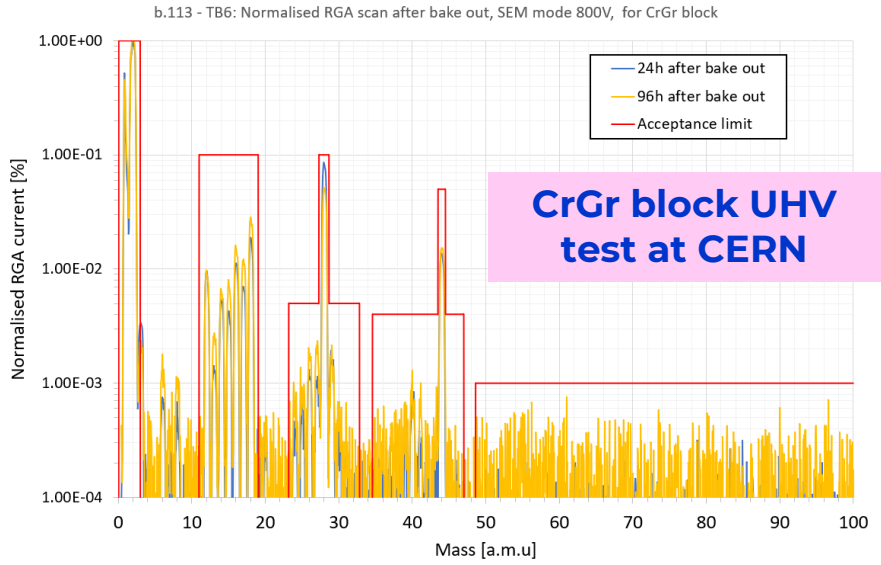
- **Component of complex shape and tolerances** produced, to prove machinability and test UHV behaviour



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!

(Almost) no stress relaxation after machining (was an issue for MoGr)

Courtesy of G. Cattenoz (CERN)

SAC recommendations and TRL

- **SAC Feedback from 4th annual meeting** *(not specific to WP4):*
  - Despite modest progress, there remains too little output on the I.FAST website and Zenodo from I.FAST partners, as repeatedly noted by SAC.
  - The SAC suggests assigning dedicated communication liaisons in each WP to ensure regular contributions and alignment with project milestones.

- **Actions:**
  - **N. Vejnovic (CERN)** in charge of WP4 communication (thanks!)
  - ***Article*** on WP4.3 results published on Accelerating News #52 – September 2025
  - Backs up ***article*** on WP4.4 results published on Accelerating News – December 2024

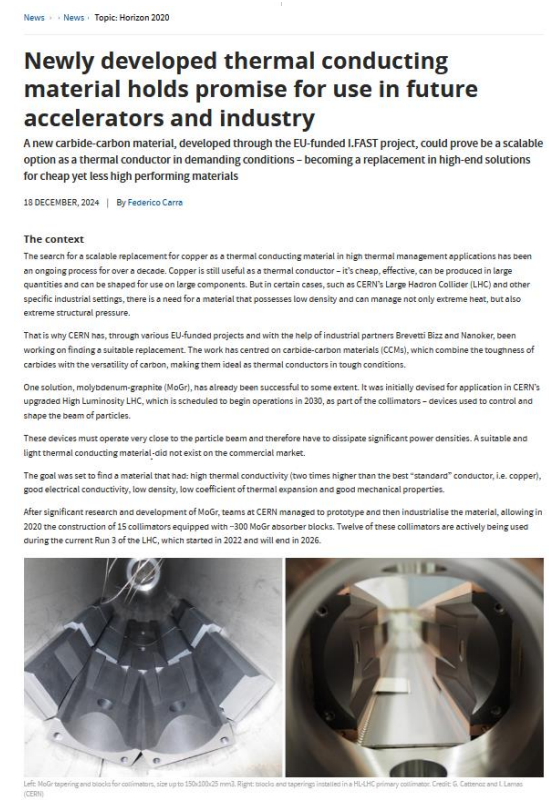
A look at innovative beam window materials for next-generation accelerator facilities

The EU-funded I.FAST project assessed the potential of two new materials to act as beam windows for future accelerators – with promising early results

12 SEPTEMBER, 2025

Sample holder with I.FAST beam windows at CERN's IRRAD facility

Beam windows are a critical part of particle accelerators. As accelerators increase in power and cost, new solutions are needed to find materials that can match the new requirements of future facilities.



News › News › Topic: Horizon 2020

Newly developed thermal conducting material holds promise for use in future accelerators and industry

A new carbide-carbon material, developed through the EU-funded I.FAST project, could prove be a scalable option as a thermal conductor in demanding conditions – becoming a replacement in high-end solutions for cheap yet less high performing materials

18 DECEMBER, 2024 | By Federico Carra

The context

The search for a scalable replacement for copper as a thermal conducting material in high thermal management applications has been an ongoing process for over a decade. Copper is still useful as a thermal conductor – it's cheap, effective, can be produced in large quantities and can be shaped for use on large components. But in certain cases, such as CERN's Large Hadron Collider (LHC) and other specific industrial settings, there is a need for a material that possesses low density and can manage not only extreme heat, but also extreme structural pressure.

That is why CERN has, through various EU-funded projects and with the help of industrial partners Brevetti Bizz and Nanoker, been working on finding a suitable replacement. The work has centred on carbide-carbon materials (CCMs), which combine the toughness of carbides with the versatility of carbon, making them ideal as thermal conductors in tough conditions.

One solution, molybdenum-graphite (MoGr), has already been successful to some extent. It was initially devised for application in CERN's upgraded High Luminosity LHC, which is scheduled to begin operations in 2030, as part of the collimators – devices used to control and shape the beam of particles.

These devices must operate very close to the particle beam and therefore have to dissipate significant power densities. A suitable and light thermal conducting material did not exist on the commercial market.

The goal was set to find a material that had: high thermal conductivity (two times higher than the best "standard" conductor, i.e. copper), good electrical conductivity, low density, low coefficient of thermal expansion and good mechanical properties.

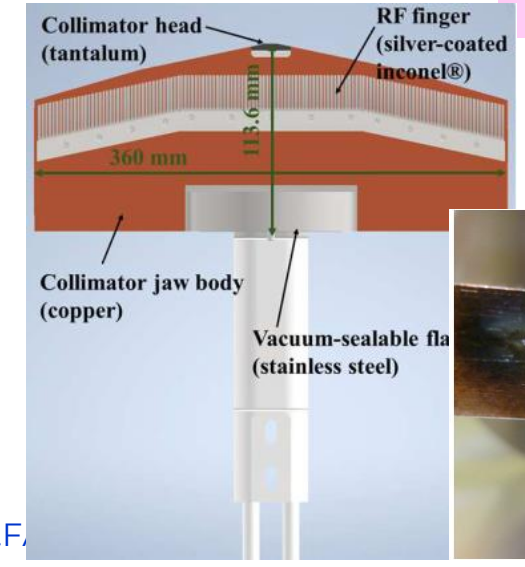
After significant research and development of MoGr, teams at CERN managed to prototype and then industrialise the material, allowing in 2020 the construction of 15 collimators equipped with ~300 MoGr absorber blocks. Twelve of these collimators are actively being used during the current Run 3 of the LHC, which started in 2022 and will end in 2026.

SAC recommendations and TRL

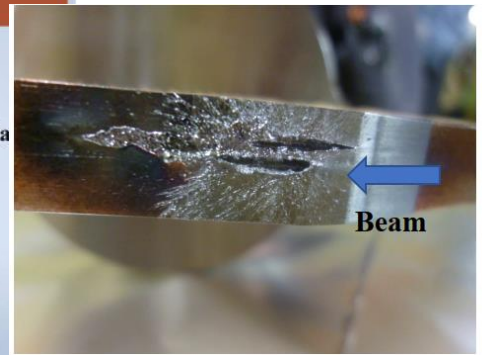
- **SAC Feedback from 4th annual meeting:**
  - The following areas are highlighted as particularly successful:
    - Innovative beam windows for high-power accelerator applications
    - Graphene Carbon windows - identifying optimum materials
    - Promotion of the carbide-carbon materials (CCM) for future particle
  - physics facilities; opening up commercial applications

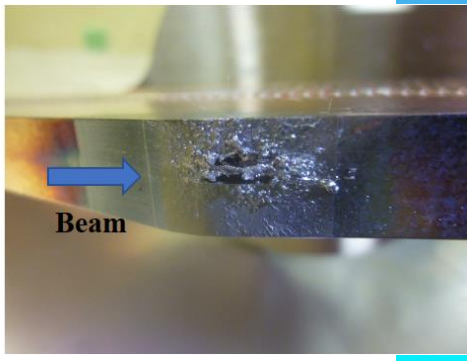
Big MoGr block for KEK studies, courtesy of S. Rivera

- **15 HL-LHC collimators with MoGr already operating** in the LHC, CrGr development can provide cheaper solution
- **KEK collaboration via IFAST**: several material samples sent to KEK, and extensively tested for possible application in SuperKEKB collimators



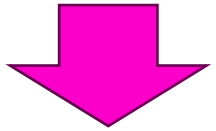
Studies at KEK, courtesy of S. Terui





SAC recommendations and TRL

- **SAC Feedback from 4th annual meeting:**
  - The SAC strongly recommends **extending the advanced accelerator technology development into the next phase of the I.FAST program**. This includes in particular high-field superconducting magnets with HTS and superconducting RF with A15 (Nb3SN and other) superconductors, **additive manufacturing** technology for wider applications, **advanced particle beam accelerations technologies**, and others.



- The I.FAST WP4 team has submitted **two tasks to the new EPITA proposal**, with the goal of consolidating and increasing the TRL of the developed technologies:
  - WP12.1: Carbide-Carbon Materials
  - WP12.2: High-Entropy Alloys via Additive Manufacturing and FAST/SPS

Scientific Contributions

- 2 Master thesis:
  - **L. Notari**, "***Dynamic radiation effects induced by short-pulsed U-ion beams in metallic targets***", Master Thesis, 10.5281/zenodo.7484054
  - **K. Botsiou**, "***Alpha particle energy loss measurements in carbon for improved stopping power values and areal density determination of graphenic carbon foils***", Master Thesis, 2024
- Publications:
  - L. Notari, M. Pasquali, F. Carra, M. Losasso, M. Tomut, "*Materials adopted for particle beam windows in relevant experimental facilities*", Phys. Rev. Accel. Beams **27**, 12 February 2024, 024801, https://zenodo.org/uploads/10964349
  - L. Notari, M. Pasquali, F. Carra, M. Losasso, J. Guardia-Valenzuela, M. Tomut, "*Dynamic response to short-pulsed U-ion beams of material candidates for vacuum beam windows manufacturing*", Helyon, Volume 10, Issue **24**, 30 December 2024, e40707 https://doi.org/10.1016/j.heliyon.2024.e40707
  - K. Botsiou-" *Accurate alpha-particle stopping Power measurements in Graphenic Carbon foils and its application to high-precision, non-destructive areal density determination*" submitted to Scientific Communications
  - F. Carra, "*Newly developed thermal conducting material holds promise for use in future accelerators and industry*", Accelerating News Issue 49, December 2024, https://acceleratingnews.eu/news/issue-49/ifast-ifa/newly-developed-thermal-conducting-material-holds-promise-use-future
  - N. Vejnovic, "*A look at innovative beam window materials for next-generation accelerator facilities*", Accelerating News Issue 52, September 2025, https://acceleratingnews.eu/news/issue-52/ifast-ifa/look-innovative-beam-window-materials-next-generation-accelerator

Conclusions

- **All milestones and deliverables of WP4.3 and WP4.4 completed in due time** (change of D4.3 delivery date agreed early on, and due to GSI irradiation facility unavailability)
- **Highly motivated team mixing up laboratory, academy and industry** → several activities and studies performed in addition to the contractual milestones and deliverables
- **Good scientific dissemination** via online articles and papers on international journals (see next slide)
- The same team (Nanoker, RHP, GSI, Munster University and CERN) **aiming at continuing the fruitful collaboration within future EPITA**

*Big thanks to all the participants and especially to **Marcello Losasso**, who initiated and coordinated the WP4 until his retirement!*

Results, Outcome, Impact –Task 4.3.

Results	**Outcome (1-3 years)**	**Impact (4-5 years)**
Development of an **experimental protocol** for the characterization of beam window materials under **combined thermomechanical loading and extended radiation damage**	· extend applications to materials for beam intercepting devices and fusion	· Extended **material resilience maps** (**dose–temperature–stress**).
Ta, T91 metallic beam windows -brazing solutions and radiation hardness tested ***TRL 6***	· results important for other beam intercepting devices and fusion application • Advanced materials solutions- high entropy alloys- **EPITA**	· Innovative joining solutions for metallic beam windows - **additive manufacturing** combined with **multi-material integration**
Graphenic membrane beam windows ***TRL 6***	· applications for gas and water calibration targets for nuclear physics and medical accelerators	· Larger and thicker graphenic beam windows for extended application in accelerator technology

Results, Outcome, Impact –Task 4.4.

Results	Outcome (1-3 years)	Impact (4-5 years)
Production of large-size Molybenum-Graphite plates ***TRL 9*** **Installed in 12 HL-LHC collimators**, currently under operation!	• Promote the use of carbide-carbon materials (CCM) in future particle physics facilities for beam intercepting devices	• Reinforced industrial know-how and **European competence in carbon composite manufacturing** • **Enhancing manufacturing competitiveness** in key enabling technologies. • Open up the market to **commercial applications (thermal transfer, aerospace light components, fusion**, etc.) • Consistent with EU green-policy targets through **minimization of environmental impact**
Production of large-size Chromium-Graphite plates ***TRL 4*** **23 to 75 % energy saving** as respect to Mo-Gr	• Continued advancement in radiation hardness studies within the ***EPITA*** project. • About 2 years until market readiness	

Lessons learned

- The assembly process of beam windows, particularly the **bonding of foils to flanges** is the key to mechanical integrity and reliability
- For metallic beam windows, the joining process between the window and flange requires further optimization. **Additive manufacturing combined with multi-material integration** could offer an innovative route to develop advanced and reliable **joining solutions** for such components
- Small and medium-sized enterprises (SMEs) and start-ups are typically **highly motivated to engage in co-innovation and to expand the range of applications they target**
- However, their **limited administrative capacity** and **restricted production resources** often constrain their ability to manage the complex requirements of EU projects and to adapt manufacturing processes to emerging application areas
- *Ongoing **R&D** remains critical for achieving meaningful innovation outcomes; some targeted funding for PhD/postdoc positions would significantly enhance project efficiency and impact*

iFAST

Thank you for your attention!

From: F. Carra, C. Belei, M. Kitzmantel, M. Pasquali, M. Tomut, N. Vejnovic, J. Swieszek, S. Rivera, C. Gutierrez, L. Notari, S. Marin, F. Salvat Pujol, F. Ravotti, G. Pezzullo, I. Aviles, S. Hoell, J. Guardia Valenzuela, C. Accettura, O. Sacristan, L. Puddu, M. Losasso, K. Botsiou, J. Rockstedt, S. Purushothaman, collaborators from RIKEN and I'm probably forgetting someone...

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

SAC recommendations and TRL

- **SAC further (general) suggestions**
  - I.FAST technologies should be critically assessed with regards to a realistic pathway to identified markets and the time scales required.
  - For each technology, it would be good to get idea of technology readiness level (TRL) as not all developments seem to have the same level of market-readiness.

Technology	TRL	TRL definition	Time until market readiness (TRL=9)*	Comments
Ta and T91 beam windows	**6**	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)	**2 years**	Assembly (window + flange bonding) requires optimization and testing at higher does / flux
Molybenum-Graphite	**9**	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)	**–**	Installed in 12 HL-LHC collimators, currently under operation!
Chromium-Graphite	**4**	Technology validated in lab	**2 years**	Based on the experience with MoGr

**in presence of budget and a driving application scenario concretizes*

CCM Production Cycle

Selection and sieving of the powders

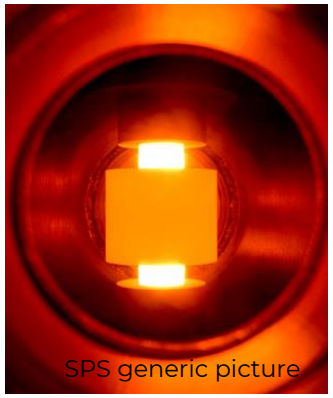
Preparation of the desired composition

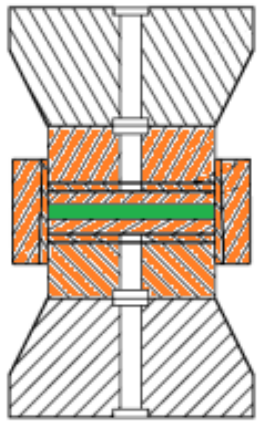
Powder	Vol. %
Graphite	93.9
Mo	5.5
Ti	0.6

Mixing

Green body

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

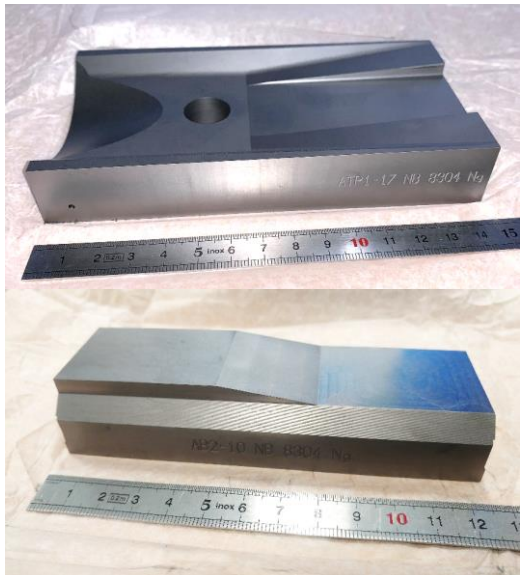




Sintered CCM
Single-use mould elements (graphite)

Stress relieving thermal treatment 0 MPa, >2400 °C

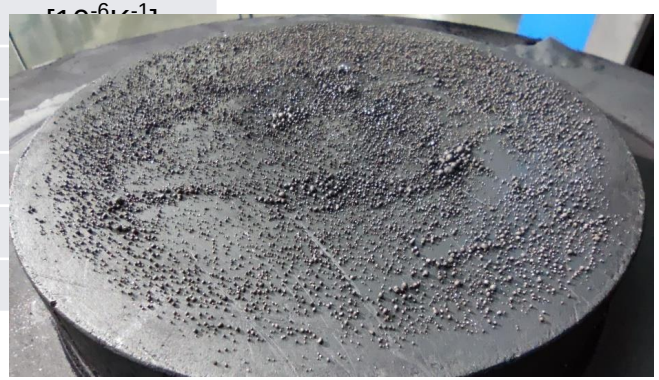
Machining of the pieces



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!

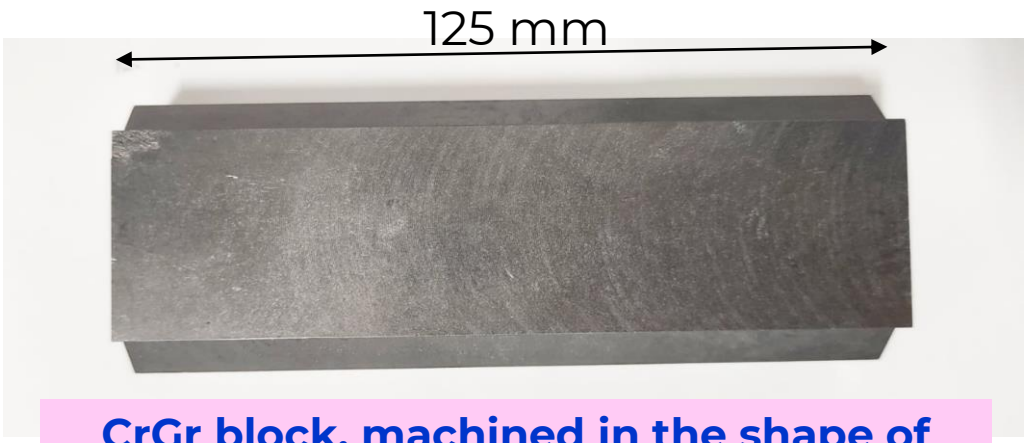
	Specification		CrGr Plate #1		
Property	∥*	⊦	∥*	⊦	**Unit**
Density at 20ºC	2.40 – 2.60		2.32		[g/cm³]
Specific heat at 20ºC	> 0.6		0.687		[J/(g·K)]
Electrical conductivity at 20ºC	> 0.75		1.02		[MS/m]
Thermal Diffusivity 20ºC /at 300ºC	> 350/100	> 20/6	470/120	33/9	[mm^2/s]
Thermal conductivity at 20ºC /at 300ºC	> 500/280	> 35/20	750/350	52/27	[W/(m·K)]
Volumetric CTE 20-1000ºC	< 7		6.7		
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

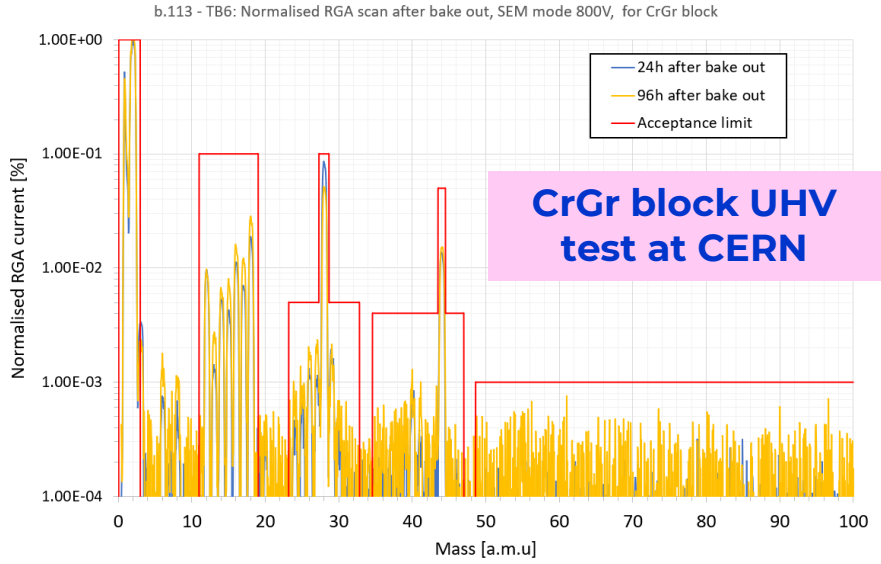
- **Component of complex shape and tolerances** produced, to prove machinability and test UHV behaviour



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

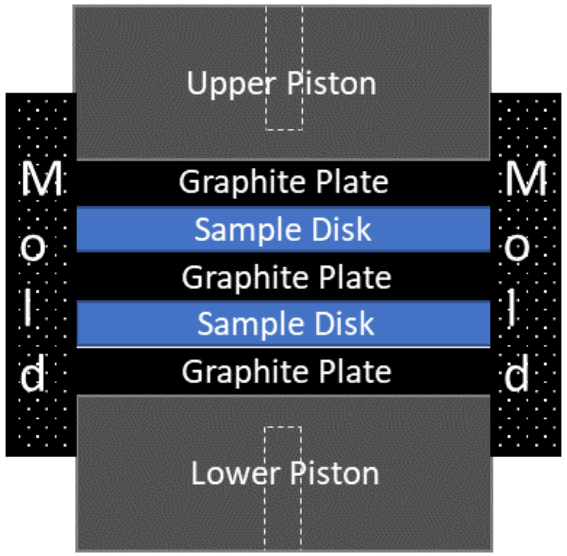
Milestone/Deliverable Number	Title	Lead beneficiary	Type	Dissemination level	Due Date (in months)
MS14	Evaluation of a CCM alternative to Molybdenum-Graphite	CERN	Report	Public	16
D4.4	Production of large-size CCM plates	CERN	Demonstrator	Public	24

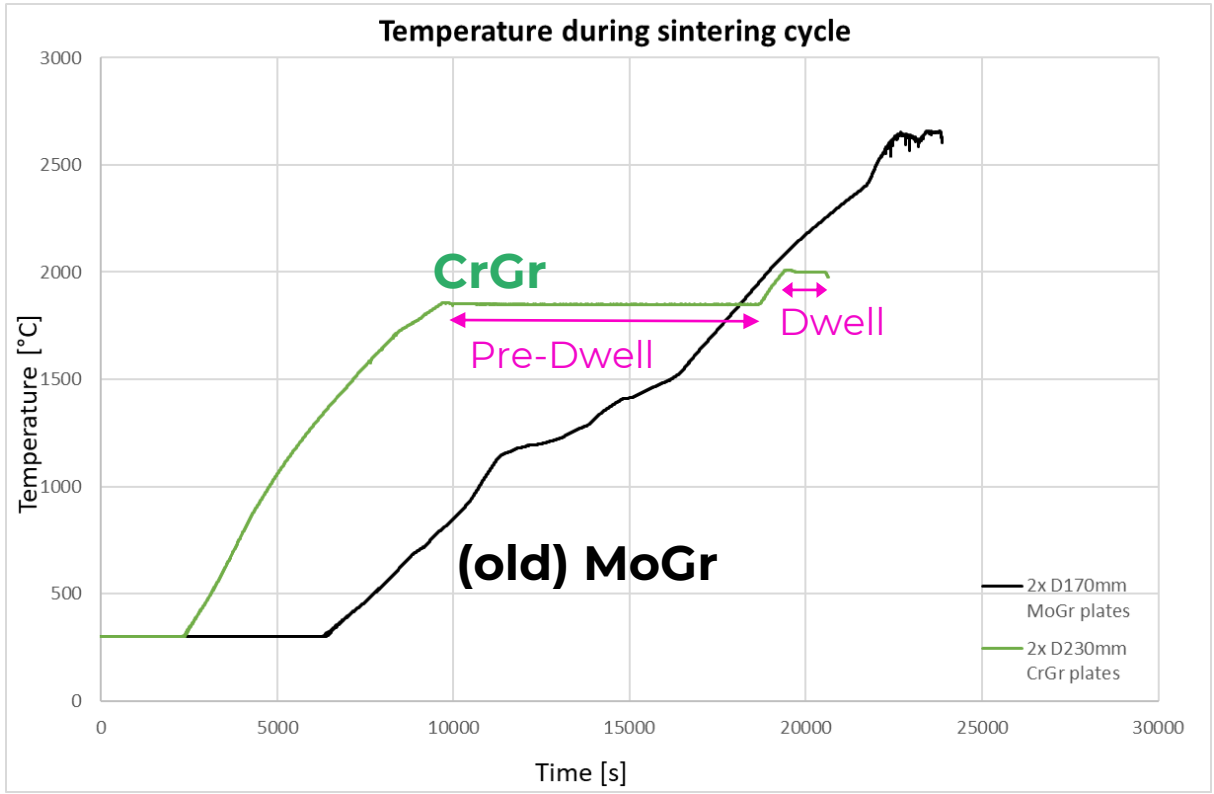
Deliverable D4.4 *due date April 2023, submitted to I.FAST project office 3 weeks ago*

- 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



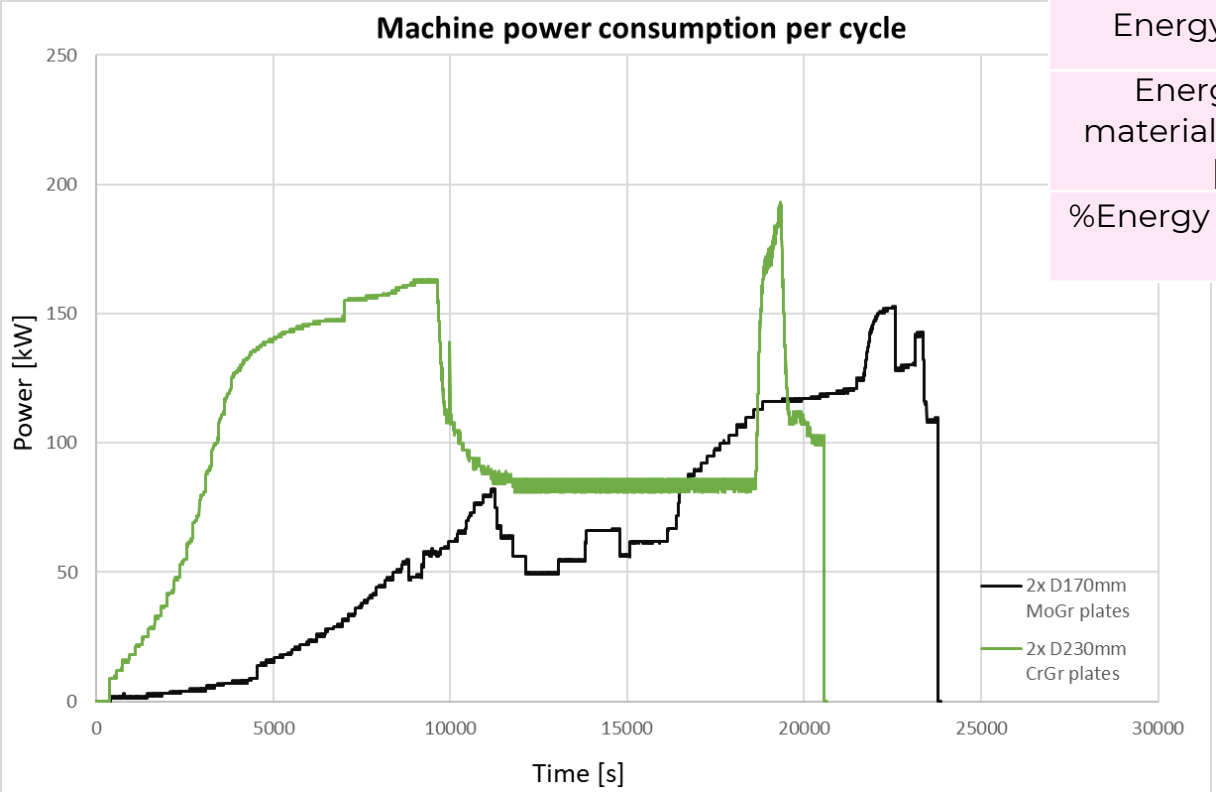


Deliverable D4.4 – CrGr 2xØ230 mm production

- **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/cm³]	0.36	0.28	0.10
%Energy saving per material volume	***Pre-I.FAST baseline***	**-23%**	**-72%**

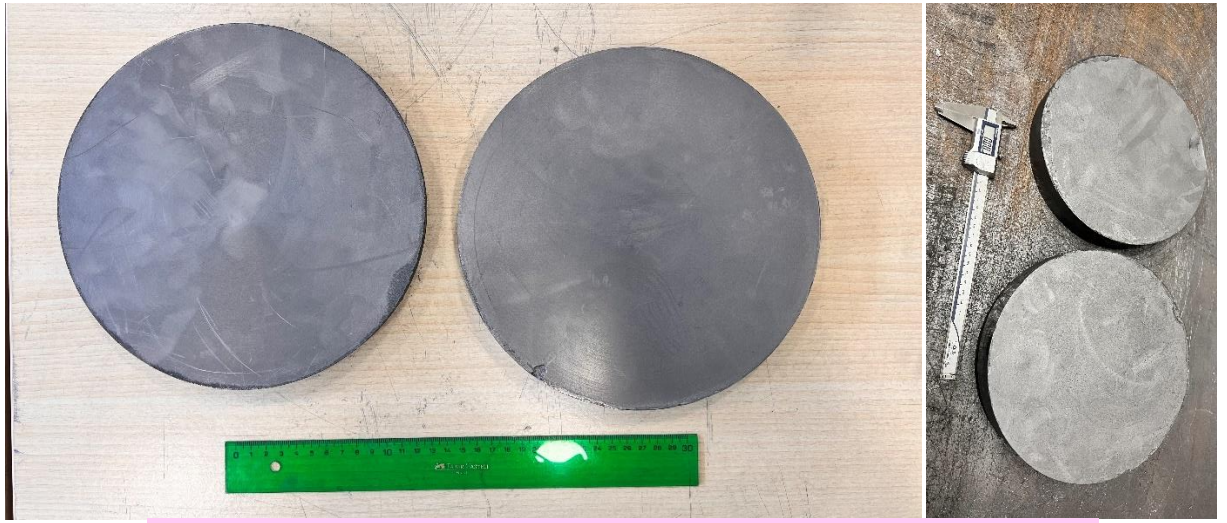


Deliverable D4.4 – CrGr 2xØ230 mm production

- **Mould saving**

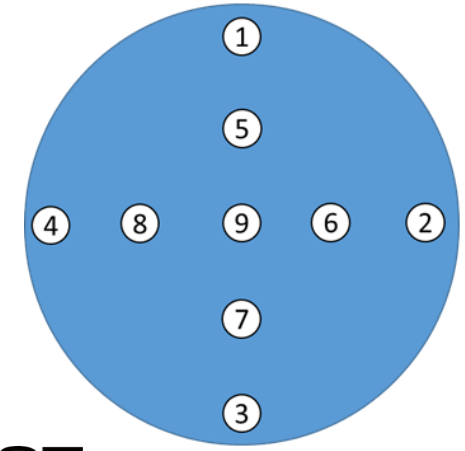
Deliverable D4.4 – CrGr 2xØ230 mm production

- 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**

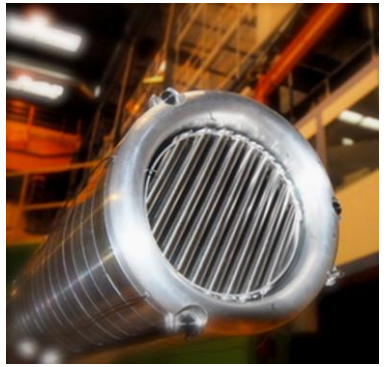
Conductivity (MS/m)		
Position	Side 1	Side 2
1	0,95	0,92
2	0,94	0,93
3	0,94	0,90
4	0,95	0,88
5	0,93	0,91
6	0,93	0,93
7	0,93	0,92
8	0,94	0,91
9	0,92	0,93
Average	**0,94**	**0,91**

Conclusions and Next Steps

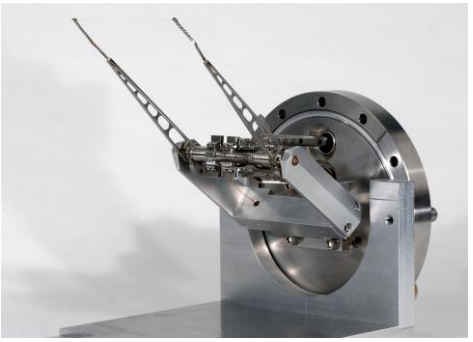
- All milestones and deliverables of I.FAST task 4.4 **have been reached in the first two years of the project**
- However, in the scope of the task objective (reduction of cost of carbon-carbide materials), **several actions are still foreseen in the last two years of I.FAST**:
  - **Complete the in-lab 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**

Motivation

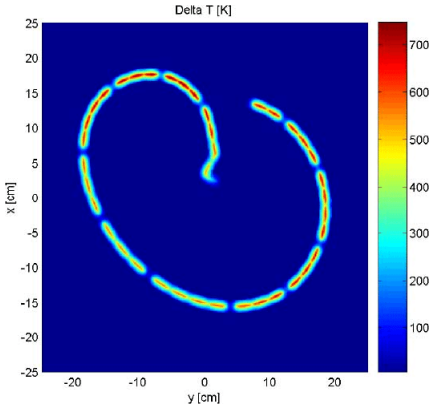
- **Increasing worldwide request for thermal management materials** (high thermal diffusivity and specific heat, low density)
- **Cost still high**: CCM are limited to high-end applications (nuclear energy, particle physics, aerospace, …)
- Decrease of energy consumption, improvement of production cycle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



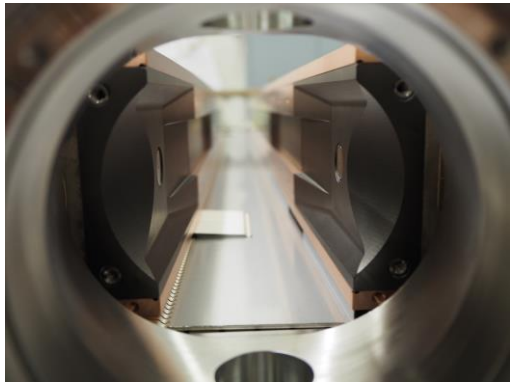
Targets



Beam wire scanners



Dumps



Collimators

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

Year 1 activities – Technical Specification

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

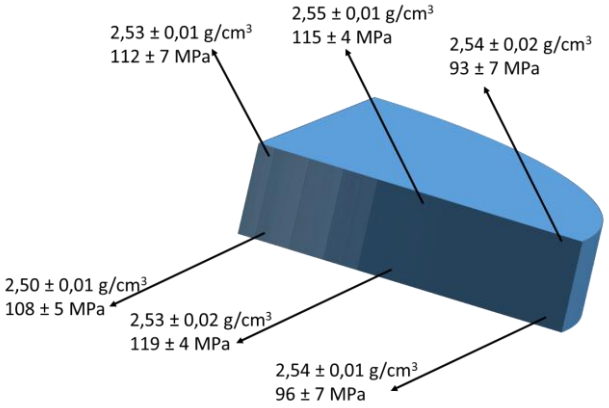
	Specification		
Property	**∥***	**⊦**	**Unit**
Density at 20ºC	2.40 – 2.60		[g/cm³]
Specific heat at 20ºC	> 0.6		[J/(g·K)]
Electrical conductivity at 20ºC	> 0.75		[MS/m]
Thermal Diffusivity 20ºC /at 300ºC	> 350/100	> 20/6	[mm^2/s]
Thermal conductivity at 20ºC /at 300ºC	> 500/280	> 35/20	[W/(m·K)]
Volumetric 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

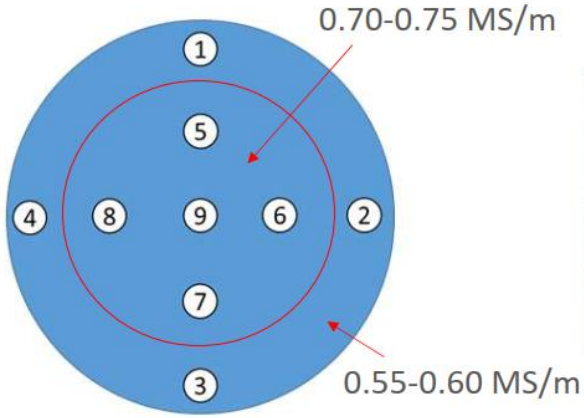
- **Molybdenum-Graphite** (sintered at 2640°C)

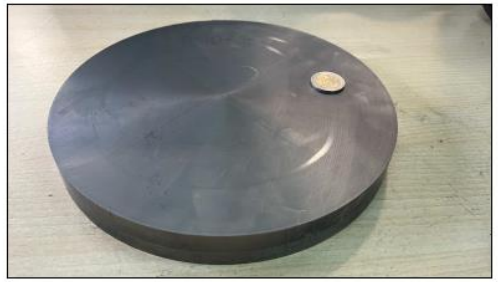
2 plates produced with 230 mm Diameter (2x bigger section than before IFAST)



Disk (230 mm diameter)	Density (g/cm³)	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/cm³
- 230 mm Ø → 21 MPa → 1,65 g/cm³

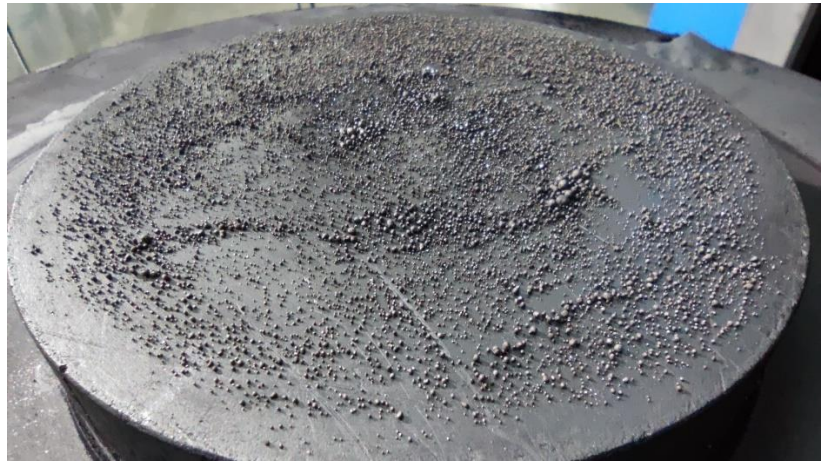
Next: increase the metal content, together with the higher sintering pressure

Year 1 – Decrease of sintering Temperature

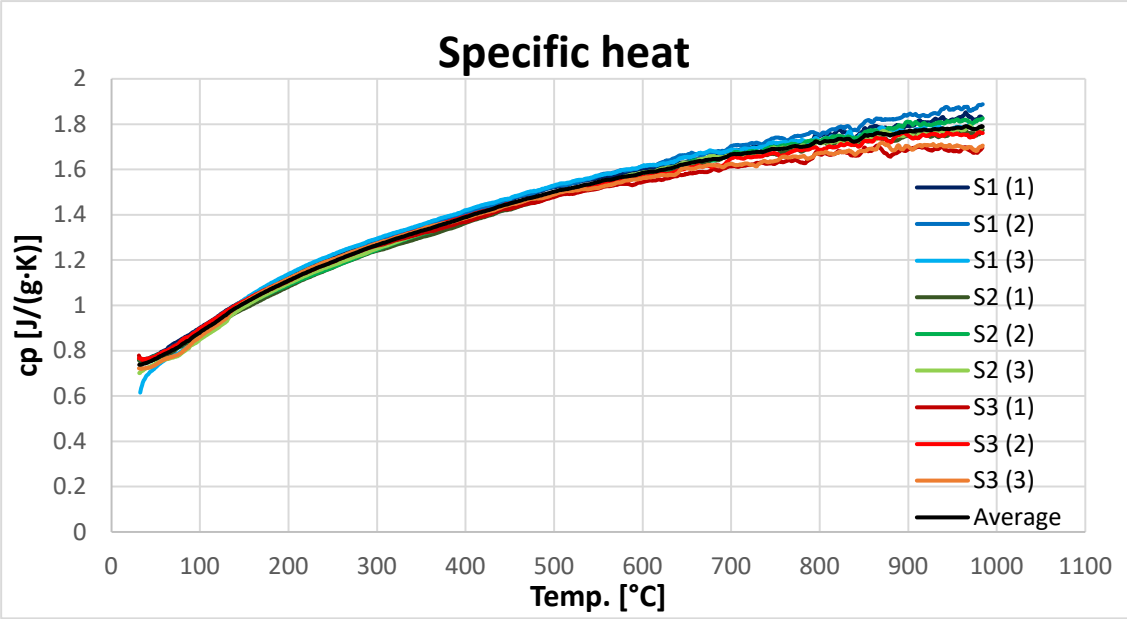
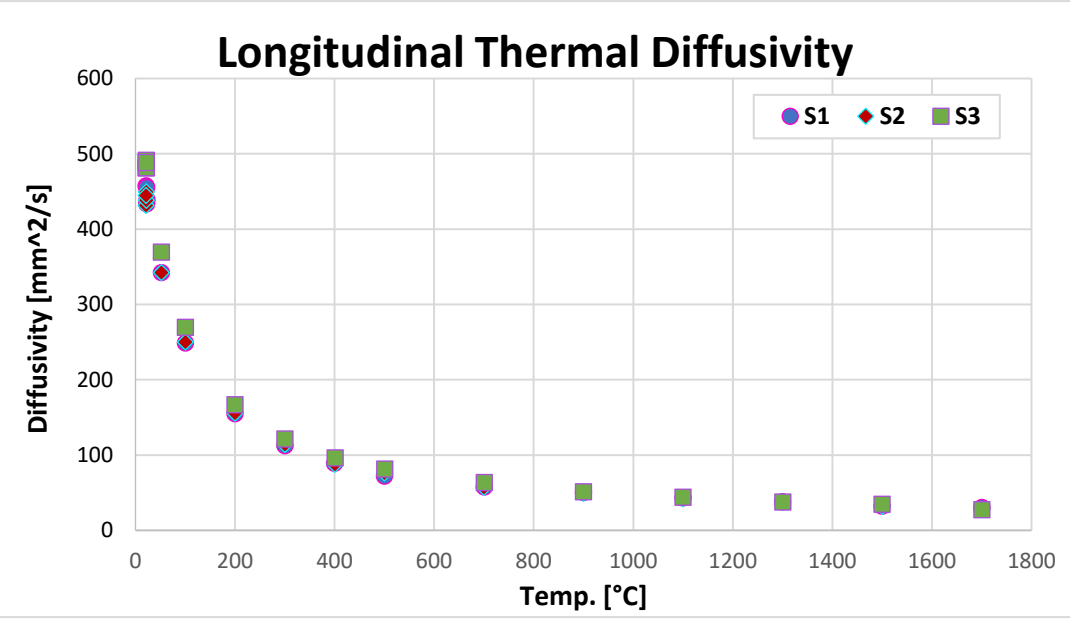
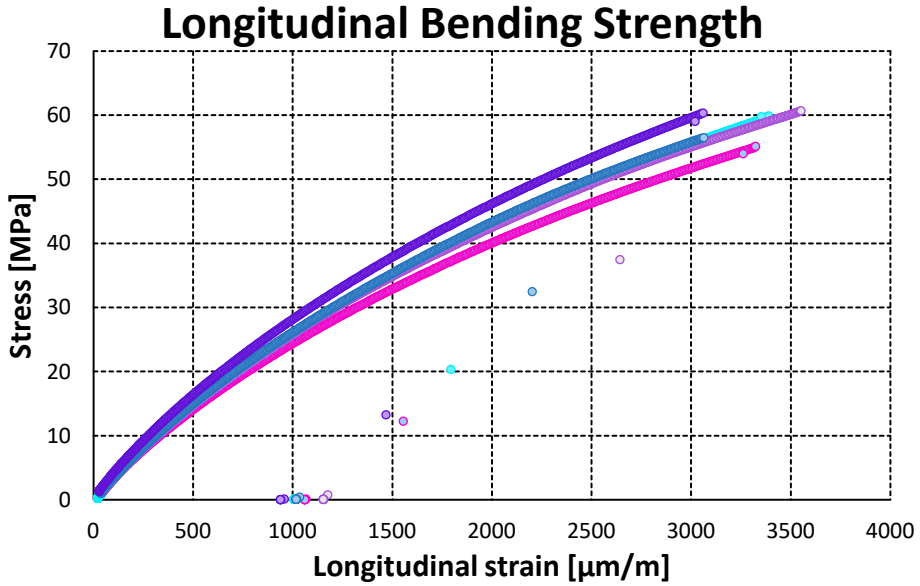
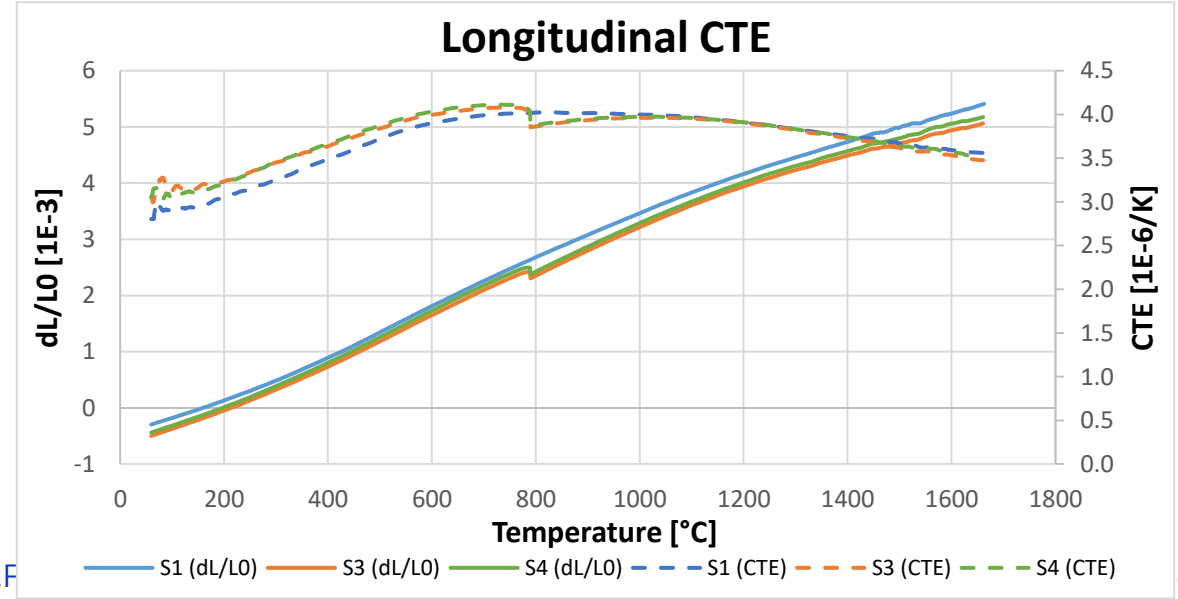
- **Chromium-Graphite** (sintered at 2000°C – 1.3x lower T)
- Concept proposed by **Jorge Guardia** within ARIES WP14 & WP17, technically was not demonstrated yet (very poor mechanical properties)

3 plates produced with 170 mm Diameter

Disk (170 mm diameter)	Density (g/cm³)	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