Carbon-based composites for thermal management in collimators

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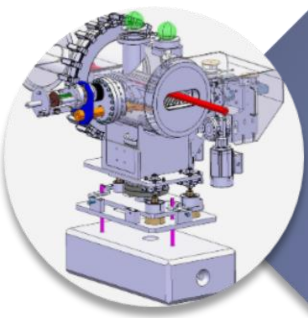
Collimator materials R&D team, Mechanical & Materials Engineering group at CERN, Switzerland

Focused Technical Workshop: Carbon Fibre
Thursday, 29 April 2021 08:30 - 10:30
Organised by the Sweden's official Industrial Liaison Office (ILO)

CERN Mechanical & Materials Engineering (MME) Group : domains of activities

https://en.web.cern.ch/group/MME



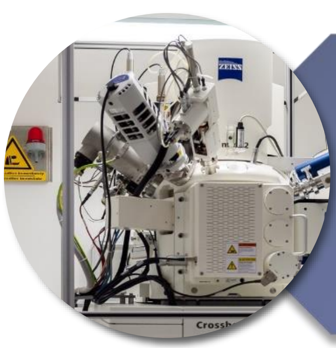
Design, Simulations and Measurements

- **Largest design office at CERN** using computer-aided design (CAD) software: 40 designers (Staff and Industrial Support).
- **Engineering Unit:** Advanced calculations, analyses and numerical simulations.
- **Mechanical Measurements Lab**: stress and strain, pressure, vibration and thermo-physical characterisation (RT – 2000 °C).

Fabrication

- Machining & Maintenance
- Preparation & Subcontracting
- Assembly & Forming

- 4000 m^2 of internal **workshop facilities with state-of-the-art equipment,** 50 technicians (Staff and Industrial Support): CNC machining, sheet metal work & welding, electron beam & laser, vacuum brazing, metallic additive manufacturing.
- **External subcontracting service.**



Materials, Metrology & NDT

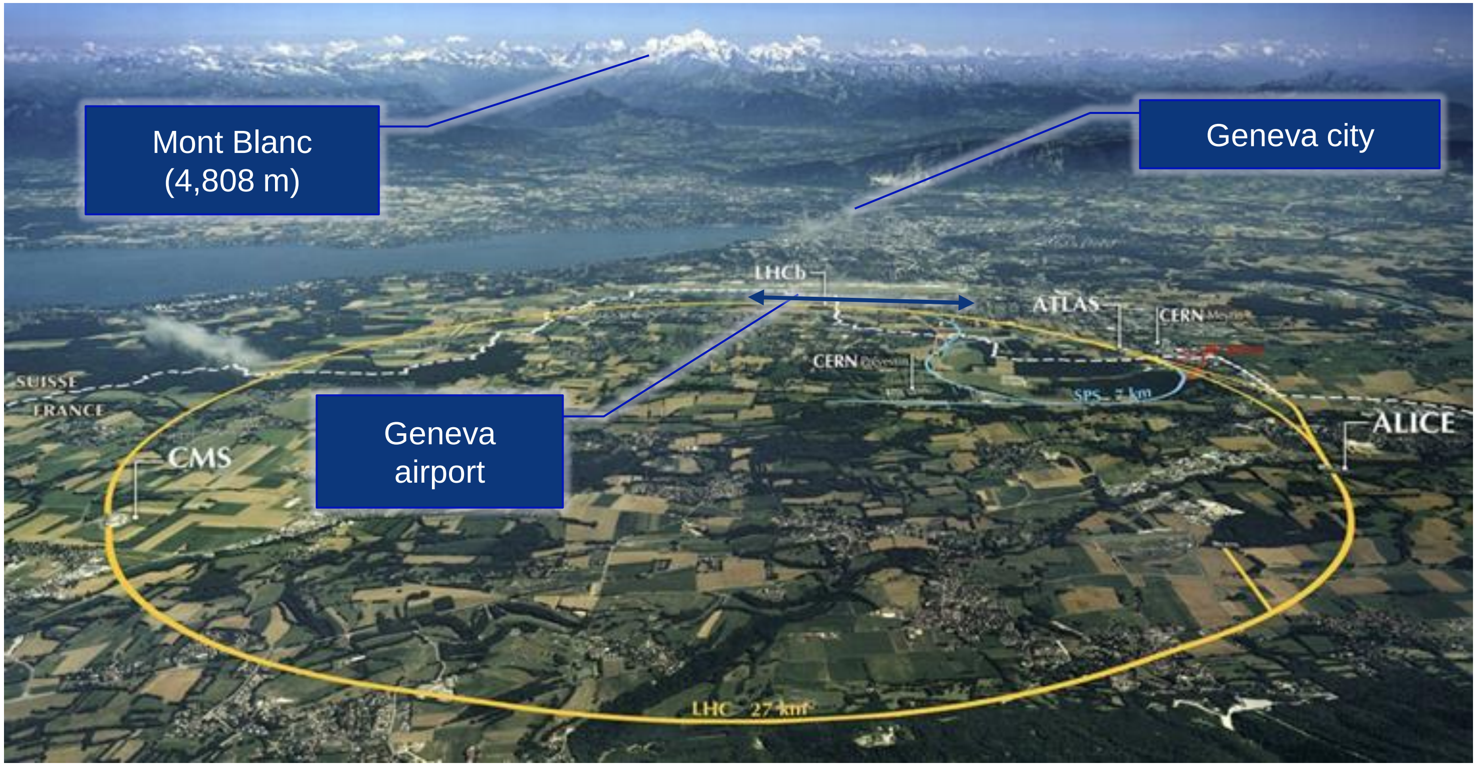
- **Material selection, analysis & metallurgy**: optical microscopy, FIB, SEM, XRD, thin-film characterisation, mechanical testing (4 K - RT) and failure analysis.
- **NDT**: ultrasounds, radiography, micro computed tomography.
- 350 m^2 of **internal metrology facilities**: 3D Coordinate Measuring Machines (CMM)

Outline

- Introduction
  - Collimation technology at CERN
  - Challenges
- Carbide – graphite composite materials for collimators
  - How are they produced
  - Their properties
- Present and future needs

CERN

- European Organization for Nuclear research. Largest high-energy physics laboratory
- The deepest structure and physics of matter are studied with the aid of **high-energy particle beams**
- **Large Hadron Collider (LHC)** is the biggest and most powerful particle accelerator in the world (27km)



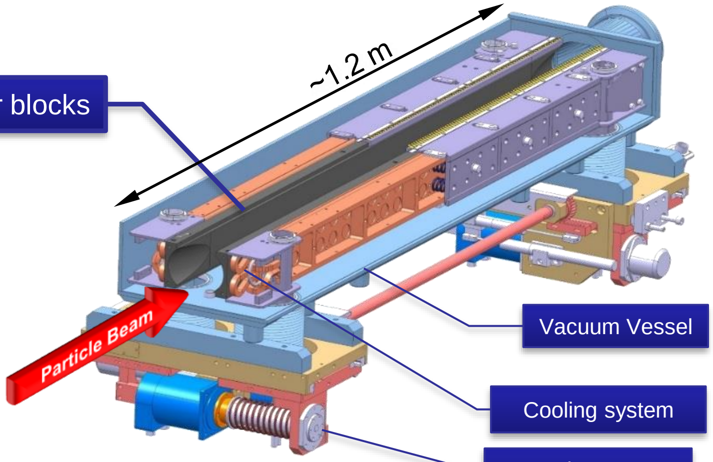
- High luminosity LHC upgrade (HL-LHC) will further increase the total **energy** of the circulating beams

LHC Collimation Project at CERN

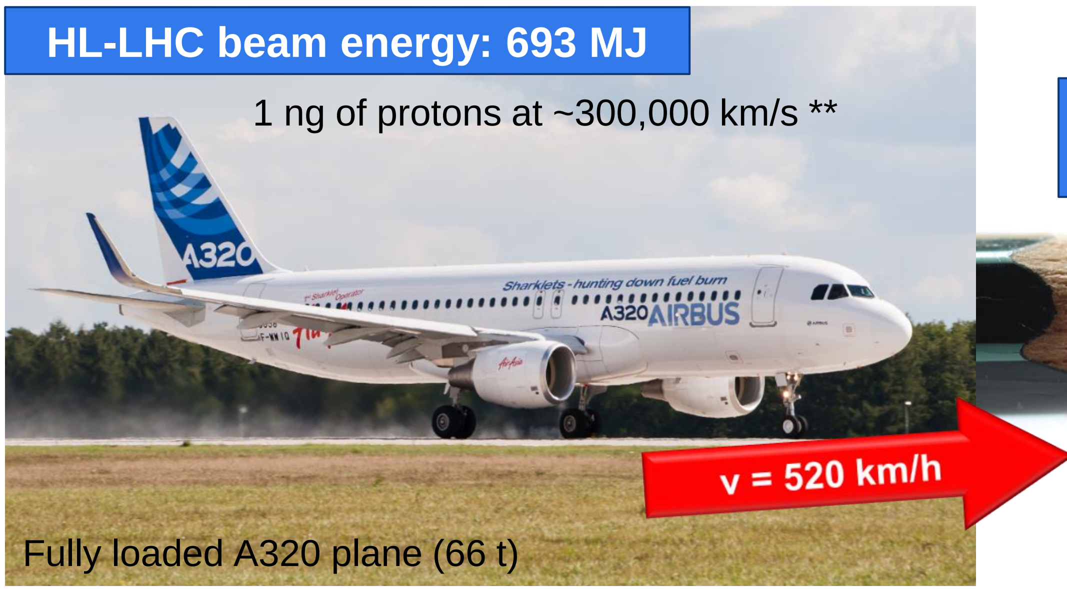
- The **energy** of the circulating particle beams is equivalent to an Airbus A320 flying at 520 km/h, concentrated in the diameter of a pencil lead

LHC: 362 MJ   HL-LHC: 693 MJ

- Need of a protection system → **Collimators**
- CFC successfully used for LHC baseline but not enough conductive for HL-LHC (resistive wall beam instabilities)
  → **Development of graphite-based composites**



LHC typical collimator Cutaway



Carbon Fibre – Carbon (CFC)

** mass at rest. Speed is ~100 % of c above 1 GeV (E_{LHC}=7 TeV).

Collimation

Video available at the CERN document server: http://cds.cern.ch/record/1750704

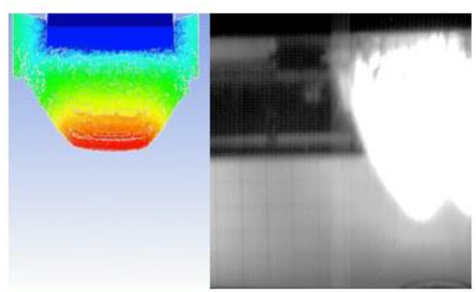
Challenges: collimator material's properties

Extreme environment: thermal shocks (accidental beam impacts), UHV, ionizing radiation, high geometrical stability required…

- ↘ **Density:** balance to limit peak energy deposition while maintaining adequate cleaning efficiency
- ↑ **Electrical Conductivity:** limit resistive-wall impedance (beam instabilities)
- ↑ **Melting/Degradation Temperature:** withstand high temperatures reached in case of accidents
- ↑ **Thermal Conductivity:** maintain geometrical stability under steady-state thermal loads
- ↓ **CTE:** increase resistance to thermal shock induced by accidental beam impact
- ↑ **Ultimate Strength:** improve thermal shock resistance
- ↑ **Specific Heat:** improve thermal shock resistance (lowers temperature increase)
- ↑ **Radiation-hardness:** improve component lifetime under long term particle irradiation
- ↓ **Outgassing Rate:** ensure UHV compatibility

Industrially feasible

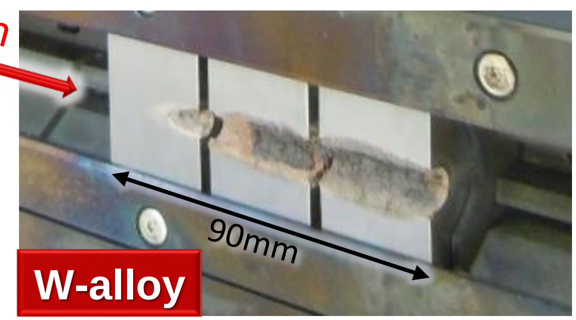
Beam



Before:

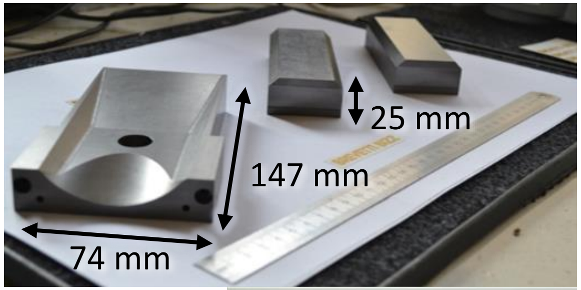
After:

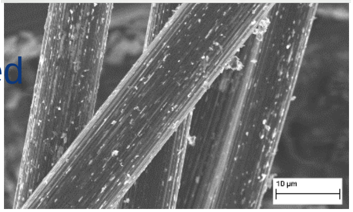
Beam



Carbon-based materials have the best compromise of properties.
CFC not enough electrically conductive

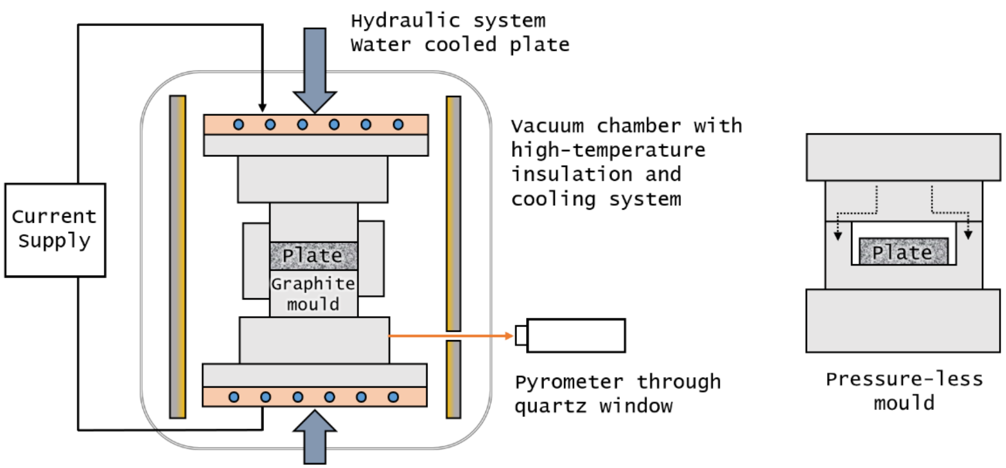
Carbide – graphite composites: MoGr

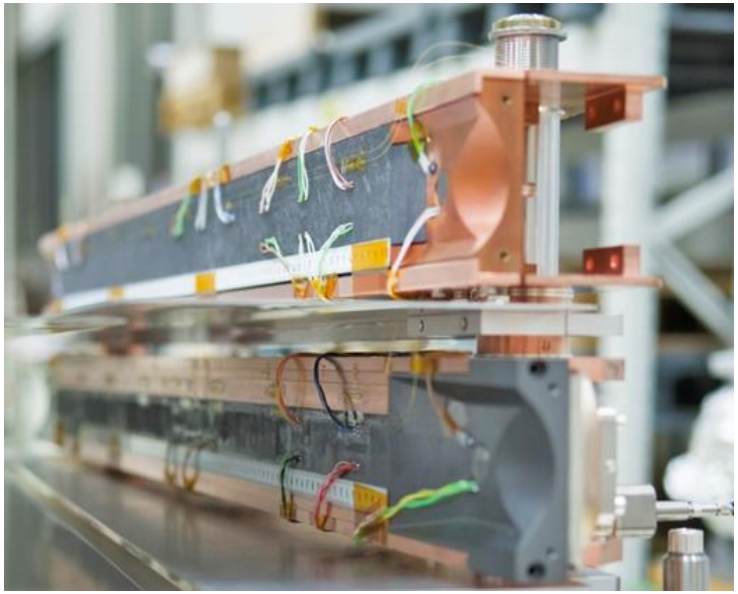




- Co-developed with the SME Italian company Brevetti Bizz
- Production: **spark plasma sintering** (SPS), a variation of hot-pressing
- Powders of graphite (~90-95vol.%), Mo (~4.5vol.%), CF (0-5vol.%) and Ti
- Melting point of the carbide (~ 2600 ºC) reached: **Liquid phase sintering**
- Post-sintering pressure-free thermal treatment. Machined to shape with standard milling
- Typical sintered plate size Ø170x30 mm or 150x100x30 mm. Upscaling being investigated
- R&D project is now **fully industrialized**:

  12 new HL-LHC collimators with MoGr installed. ~360 MoGr blocs produced

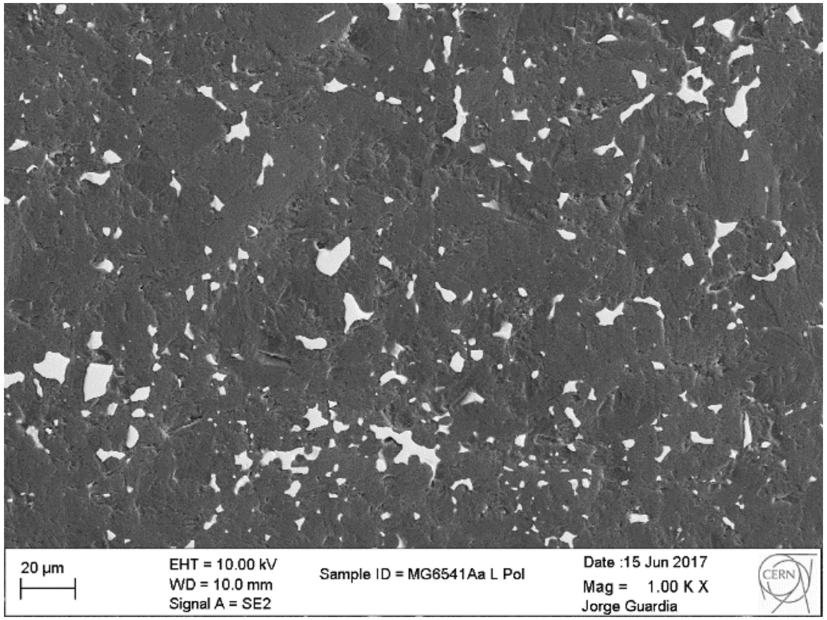




Development and properties of high thermal conductivity molybdenum carbide – graphite composites. J.Guardia et al. Carbon (2018) https://doi.org/10.1016/j.carbon.2018.04.010

Microstructure

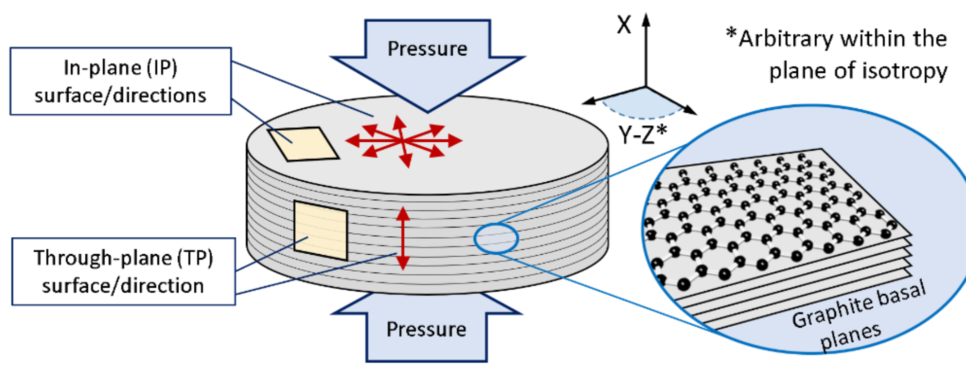
Sintering pressure direction



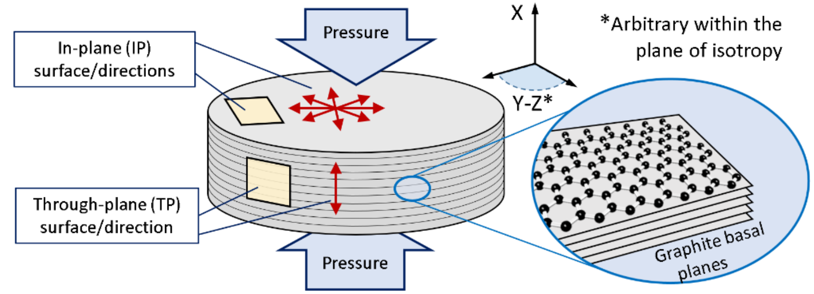
In-plane polished surface

Perpendicular fracture surface

- Carbides: ~5 µm diameter
- Well-connected graphite matrix ~95vol%
- Well-compacted: porosity <0.5 vol.%
- Carbide particles reinforce the graphite, holding together the graphite in the weak direction



Characterization (MoGr)



	In-plane	Through-plane
Electrical conductivity [MS/m]	**~1**	~0.08
Thermal Conductivity [W/(mK)]	**650 – 900**	~50
CTE RT÷200 °C [$10^{-6}K^{-1}$]	**1.7 - 2.7**	8 - 12
Flexural Strength [MPa]	60 – 100	10 - 17
Specific Heat [J/(gK)]	0.6 - 0.65	
Density [g/cm³]	**2.5 – 2.6**	

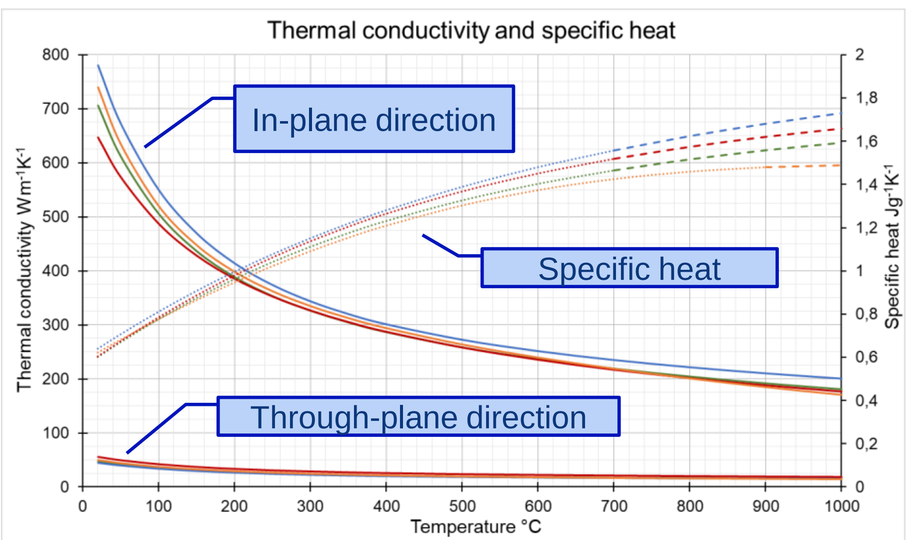
2x Cu

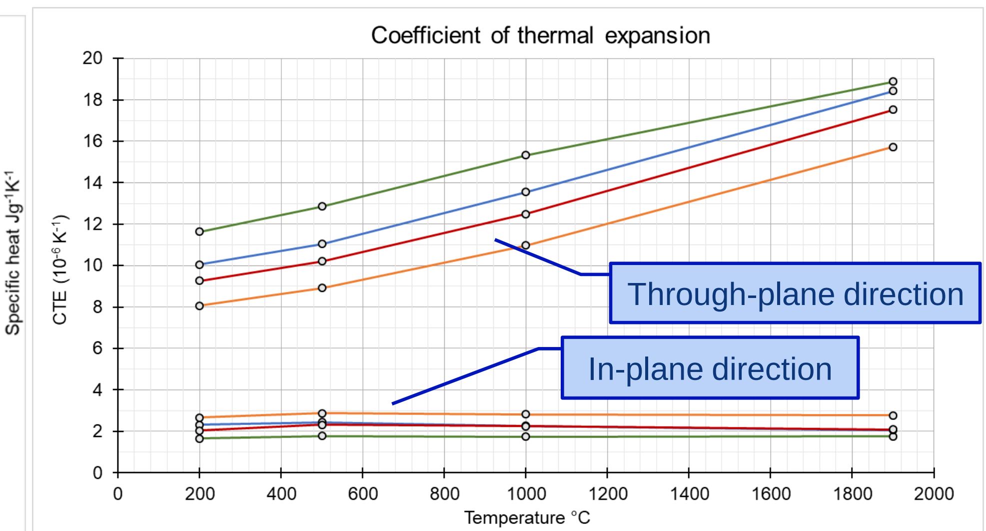
10-15x isotropic graphite

Si

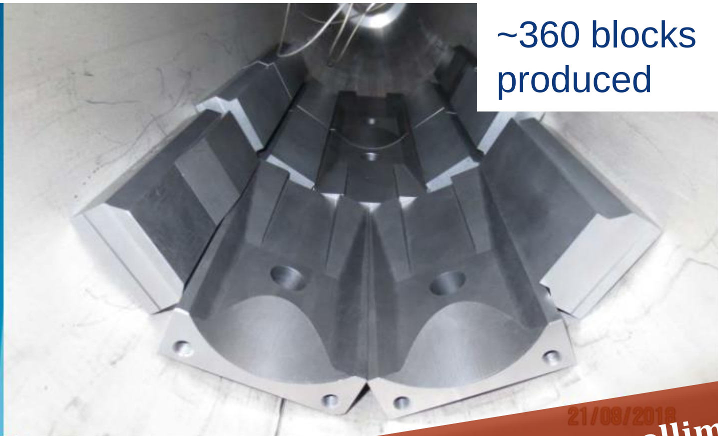
~ isotropic graphite

Al

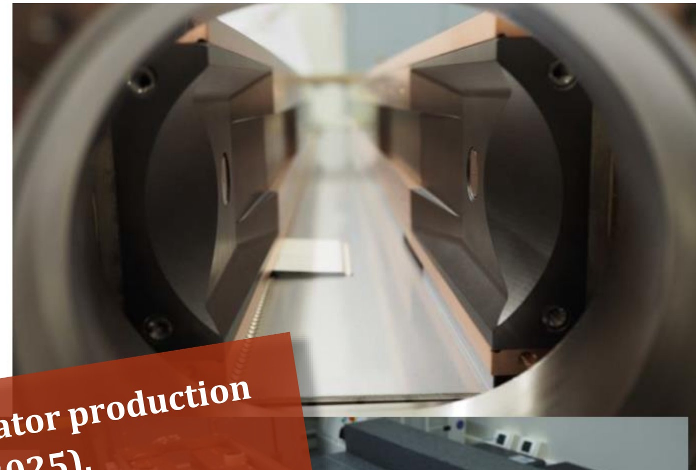


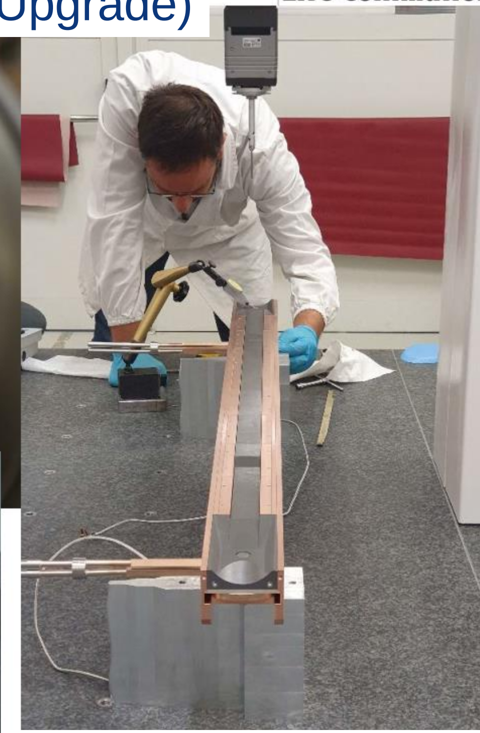


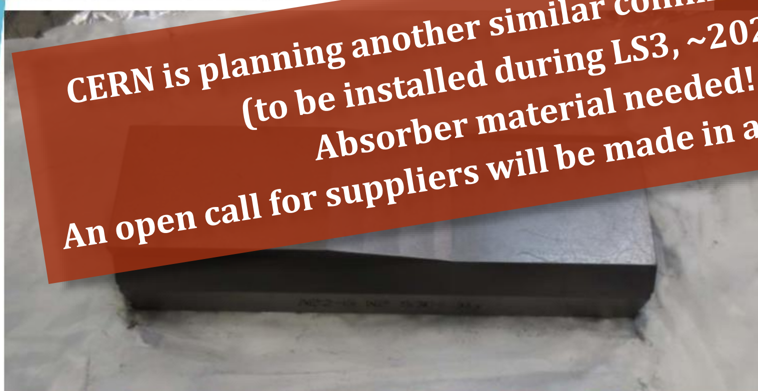
Collimator production for LS2 completed by end-of-2020 (HL-LHC Upgrade)



~360 blocks produced

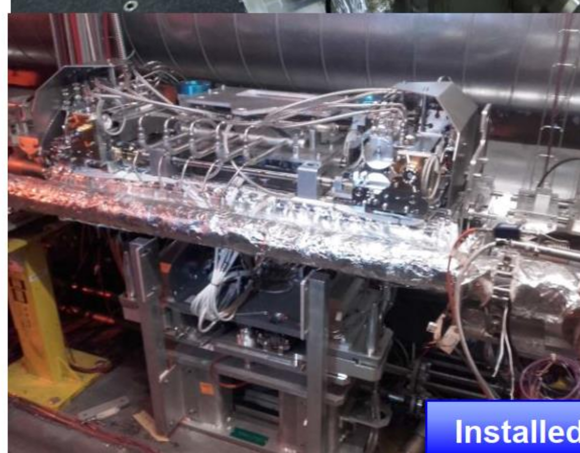






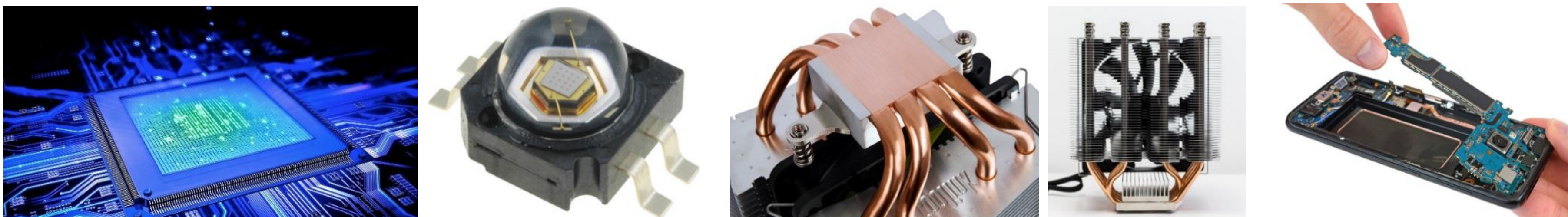
CERN is planning another similar collimator production (to be installed during LS3, ~2025).
Absorber material needed!
An open call for suppliers will be made in a couple of years.

Strong collaborative effort from colleagues all around CERN (EN-MME, EN-STI, TE-VSC, BE-ABP) and industrial partners

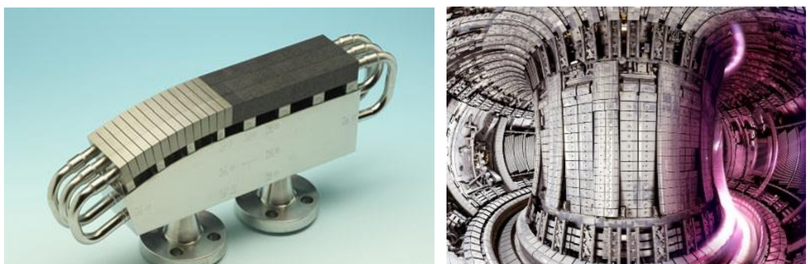


Assembled and installed collimators: courtesy of I. Lamas

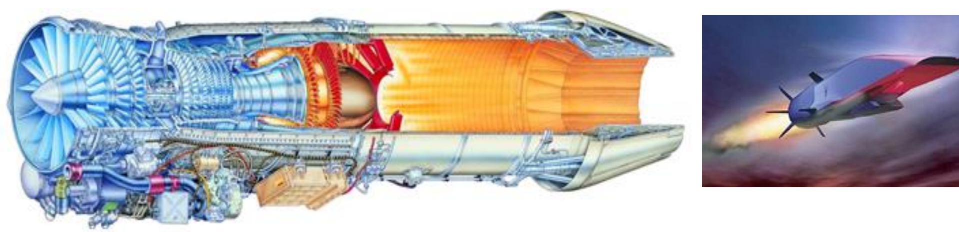
Knowledge transfer: Thermal management applications



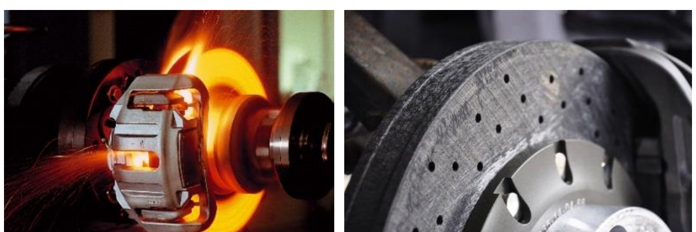
Thermal Management for High Power Electronics



Fusion Engineering



High temperature Aerospace Applications



Advanced Braking Systems

Energy Applications

Any application needing:
- High thermal conductivity
- Low weight (low density)
- Low thermal expansion
- High temperatures*

Knowledge transfer group at CERN
http://kt.cern/

*In inert atmosphere can withstand >2000 °C. In air ~500 °C

Conclusions

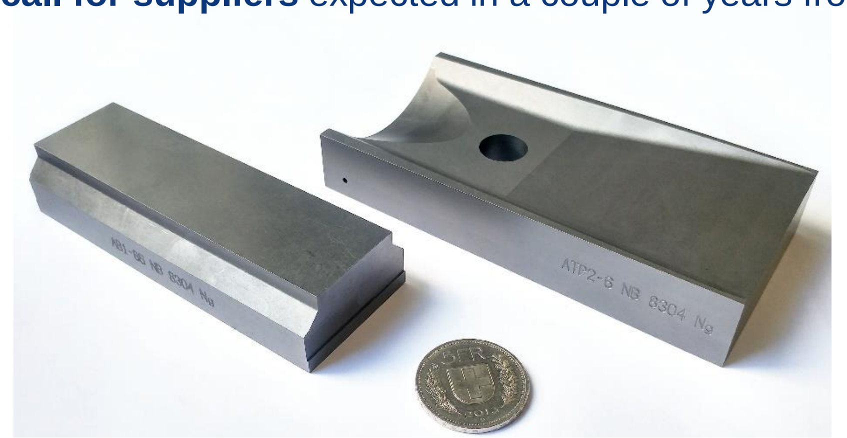
- A family of **graphite-matrix** composite materials containing **molybdenum carbide** particles (MoGr) has been successfully developed for CERN HL-LHC collimators → now fully industrialised

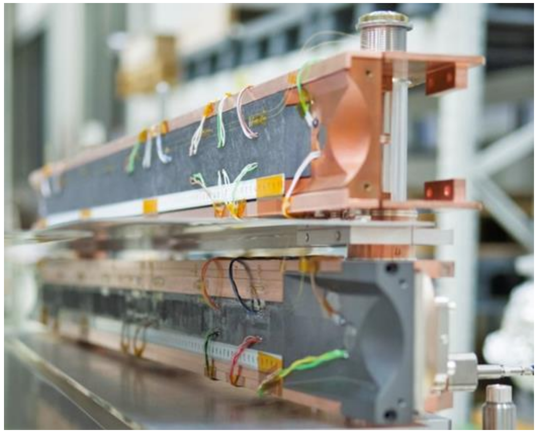
- Produced by **spark plasma sintering** assisted by **molten metal-carbon liquid phase**

- Material of interest for other **thermal management applications** such as electronics or aerospace

  - Low $CTE_{20\text{-}200\ °C}$: $\sim 2.5\times10^{-6}\ K^{-1}$ (≈Silicon)
  - High thermal conductivity: up to 900 $W\ m^{-1}K^{-1}$
  - Low density: $\sim 2.5\ g\ cm^{-3}$
  - Electrical conductivity: $\sim 1\ MS\ m^{-1}$
  - Tailorable properties

- CERN is planning to install another set of upgraded collimators by ~2025 (for LS3)
  - Absorber **composite material** with properties in the range of those from MoGr **will be required**
  - **Open call for suppliers** expected in a couple of years from now





Acknowledgements

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- S. Sgobba and colleagues from the **Metallurgy Lab** at CERN
- **Knowledge Transfer (KT)** group at CERN

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Thank you for your attention!

Backup slides

Comparison table

	MoGr		CFC AC150K		Graphite R4550	Glidcop AL-15 (Cu)	IT180 (W-alloy)	SS-316L
Direction	**In-plane**	**Through-plane**	IP	TP	Isotropic	Isotropic	Isotropic	Isotropic
Density ($g \times cm^{-3}$)	**2.5-2.6**		1.89		1.86	8.75	17.94	7.95
Electrical conductivity ($MS \times m^{-1}$)	**0.9-1.1**	**0.05-0.07**	0.18-0.24	0.03	0.08	53.8	8.7	1.35
Specific heat at 20°C ($J \times g^{-1} \times K^{-1}$)	**0.6-0.65**		0.71		0.71	0.39	0.15	0.45
Thermal diff. at 20°C ($mm^2 \times s^{-1}$)	**430-530**	**28-37**	174-227	40	73	106	34	4
Thermal cond. at 20°C ($Wm^{-1}K^{-1}$)	**650-900**	**45-65**	233-304	54	100	365	91	14
CTE 20-200°C ($x10^{-6}$ K^{-1})	**1.7-2.7**	**8-12**	-0.8	11	4.2	18.5	5.3	15
Flexural strength (MPa)	**60-100**	**10-17**	105-140	10	60	375 (Tens.)	683 (Tens.)	515 (Tens.)
Elastic modulus (GPa)	**60-85**	**4-5**	~90	~5	11.5	128	360	195
Flexural strain to rupture (%)	**0.18-0.26**	**0.45-0.72**	0.14-0.2	0.43	0.72	27 (Tens.)	3 (Tens.)	40 (Tens.)