Socio-economic benefits from ESA's Science Core Technology Programme

A report for esa

CASE STUDY: Silicon Carbide

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Building the largest space telescope …

Space science missions are particularly demanding, carrying highly complex instruments and requiring considerable precision and performance to ensure the acquisition of the highest quality of data. ESA's Science missions are only getting more ambitious in their pursuit of pushing the boundaries of our scientific knowledge on the Universe. Therefore, the space observatories developed are becoming larger, and yet their mass needs to be restricted to ensure the feasibility of launch and sufficient mission duration. Materials traditionally used, such as glass-ceramic, are considerably too heavy to meet the stringent requirements of such ambitious science missions.

Silicon Carbide (SiC) was identified as a promising potential solution to this mass/surface challenge. A compound of silicon and carbon, it possesses considerably attractive properties for space, such as:

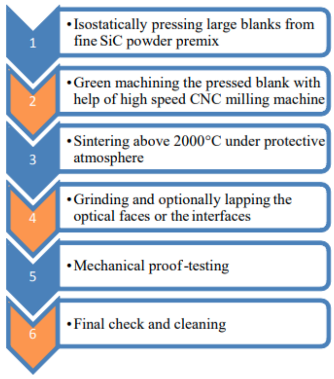
- Its very high specific stiffness, which allows SiC mirrors to maintain a precise shape structure while having a very low mass;
- Its low coefficient of thermal expansion coupled with its high thermal conductivity, which grants it a very broad operating temperature range (4 to 1,570K) and stability against thermal changes; and
- Homogeneous and attractive isotropic characteristics.

The US started working on using SiC for space optics in the late 1970s/early 1980s, developing mirror products such as for the NASA EO-1 mission, but did not maintain development momentum in the following years, in contrast to Europe. ESA meanwhile started working on SiC as a low mass, large surface solution for its next big infrared astronomy mission, HERSCHEL, which required a 3.5m diameter telescope, the largest flown in space at the time when launched in 2009.

… required an innovative product, developed in France …

Through the Science Core Technology Programme (CTP), ESA awarded funding to France's Mersen Boostec for SiC technology scale up, equipment and facilities. The company built off its rich heritage in optics and silicon carbide, initially for terrestrial applications but shifting to space optics following its close technical partnership with Astrium (now Airbus) and with ESA's support.

Mersen Boostec



Bougoin & Lavenac, (2012)

Mersen Boostec had managed to produce sintered SiC (S-SiC), a nearly pure material, which is very homogenous, has low porosity and high mechanical strength, and by working on SiC for ESA, the company inscribed itself in a multinational collaboration for HERSCHEL, which included stakeholders in Finland, Germany, France, Belgium and Spain, most notably Astrium/Airbus.

Through this CTP-funded technology project, **the French company adopted a new approach and developed a disruptive product that is stiff, low density, highly thermally conductive and has a low thermal expansion**, meeting stringent mission requirements for Herschel and many more relevant missions[1].

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[1] Bougoin, M. & Lavenac, J., 2012, *The SiC hardware of the Sentinel-2 Multi Spectral Instrument*, Proceedings of the International Conference on Space Optics (ICSO 2012), CNES, Ajaccio, October 2012

… with potential for significant socio-economic benefits

Mersen Boostec's silicon carbide solutions have been utilised in the space domain for several years now, leading to a variety of socio-economic benefits for the company, its partner Airbus and the wider European industrial landscape. As it continues to develop, enabling more complex space science missions as well as providing solutions to additional terrestrial domains, its impacts will continue to grow.

Creating a wide variety of SiC-based solutions for both space and terrestrial applications

New knowledge and expertise

Mersen Boostec and Airbus have developed new processing and technological expertise through their involvement in the various space science mission instrumentation development projects.

ESA

Developing SiC for Herschel represented a challenge for Mersen Boostec, who previously had focused on making 10cm parts - much smaller than the 3.5m diameter mirror required for the ESA mission. The company therefore had to acquire knowledge around machining and sintering, especially for manufacturing very large SiC parts, as well as having to develop new dedicated equipment and facilities.

Herschel's mirror could not be made in a single piece, instead needing to be cut into 12 segments, which then required Mersen Boostec to braze them together using innovative techniques. Thanks to their SiC solution, Herschel's mirror weighed only 300kg – a comparable glass reflector would weigh nearer 1.5 tonnes. **The mission's mirror resulted in being just a third of the mass of Hubble's main mirror, despite providing twice the observing area**. Additionally, the GAIA mission torus – a stiff and stable optical bench for the GAIA instrument – was made of 19 SiC parts, and facing a large amount of required brazing, Mersen Boostec developed an ultrasound technique with the French Nuclear Agency (CEA) for the detection and cartography of possible voids in the brazed joints, to ensure reliable verification.

Furthermore, Airbus developed several assembly techniques in order to manufacture the large and complex SiC assemblies, including a bolting technique, epoxy bonding and high temperature brazing.[2]

Enabling a European champion

Mersen Boostec's involvement in ESA's Science missions have allowed it to **develop from a small, relatively specialised SME into being a leader in Europe for silicon carbide optical solutions**. Their solutions with Airbus for mirrors higher than 500mm are especially competitive, considering there are not many solutions on the market other than those which are SiC-based. Thanks to the material properties of SiC, such as its low coefficient of expansion (how much it expands for each degree of temperature increase), the design of the instrument can be simplified. This leads to cost savings, as well as time saved for thermal integration of the instrument.

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[2] Castel, D., et. al., 2014. *SiC Technology for space telescope: How to make the impossible.* Available at: https://articles.adsabs.harvard.edu/pdf/2014ESASP.727E..32C

Mersen Boostec and Airbus have also been approached by international actors, seeking to utilise their solutions and know-how in other missions - for example, the United States are exploring the option of having a telescope for a scientific mission to be developed with SiC, since it would require a mirror measuring a diameter of 2.4m. **Overall, there are now 23 full-SiC telescopes operating in space from Mersen Boostec, with another 10 being prepared for launch**, whilst at the same time the company is diversifying its portfolio into other market segments, as outlined below.

New market opportunities

Mersen Boostec has diversified its portfolio beyond the space domain, entering terrestrial markets such as laser scanning mirrors, the semi-conductor industry, and the fine chemicals industry

Boostec recognised the importance of expanding its range of products beyond the space domain in order to grow the company further, especially considering the fact that there can be significant gaps between the implementation of next generation complex space science missions. Therefore, using its unique knowledge in the design and manufacture of silicon carbide parts from its heritage, the company has expanded its targeted markets to develop innovative products for solutions requiring ultra-precision or functionality in extreme environments. **Through this, Mersen Boostec has an opportunity to capture a share of multi-billion euro and fast-growing markets**.

For example, the company provides laser galvo scanning mirrors for the laser scanner industry, producing a range of standard and custom active mirrors from 10 to 200mm apertures with a range of high reflective coating. There is a wide range of market segment opportunities for these high-end scanning mirrors, including for material processing such as welding, cutting, drilling, microlithography and additive manufacturing, as well as for instrumentation, including tracker systems, scanner systems and Lidars, biomedical instruments, and imaging. This has led to successful contracts such as with Velo3D, with whom Mersen has signed a **€1.99 million[3] contract for their SiC mirrors for direct lasers to be used in the Velo3D Sapphire XC 3D printers**.[4]

Mersen Boostec entered the semi-conductor and optomechanical equipment fields by providing SiC ultra-stable structures that are now required by the industry, with high specific stiffness and thermal stability. Its solution can provide high mechanical strength without mechanical fatigue, strong stability over time, and a good chemical inertia, as well as being water- and gas-tight, with no outgassing or moisture absorption. As a material, it supports activities where ultra-precision is required, including semiconductor industry processes, EUV lithography machines, ultra-high vacuums and scientific equipment.

SiC heat exchangers meanwhile can lead to optimised performance for applications in the pharmaceutical and fine chemicals industry, acting as a key solution for processes with high corrosion and for processes which usually demand high service rates, in order to decrease the need for maintenance. Other equipment produced for the chemical industry include Advanced Flow Reactors, specific injection tubes and nozzles for high temperature and abrasive processes, quench rings for high temperature reactors, and specific protection tiles and other parts. Some of the key benefits of using SiC for this equipment are that it has no particle emission and hence no contamination for high purity applications, it allows for easy maintenance, and its heat exchanger is extremely compact.

The company also provides SiC modules for continuous flow reactors in cooperation with Corning SAS, providing a product that is cost-competitive, with a smaller footprint than traditional reactors and a reduced amount of production steps for increased productivity and safety.

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[3] $2.1 million

[4] Mersen, 2022. *Mersen's expertise to support revolutionary metal 3D printing technology of Velo3D*. Available at: https://www.mersen.com/sites/default/files/publications-media/2022-03-pr-en-velo3d.pdf

Finally, Mersen Boostec is working with the European Southern Observatory on their Extremely Large Telescope (ELT) project, a ground-based optical/near-infrared telescope **for which the company will produce the reference structure of the 4th mirror adaptive optic and the 5th mirror**.

Unique collaborative partnership

From early on in the company's development, Mersen Boostec has had a **unique relationship with Airbus**, with both companies attributing their close collaboration as a key aspect of their success for their participation in these mission programmes.

Airbus owns around 5% of Mersen Boostec, and their close relationship has led to effective communication and a work environment where the design of the instrument is made in parallel/collaboration with Mersen Boostec, **acting as partners in the development** rather than simply viewing them as a supplier. This means that when Airbus designs parts of the mission, they ensure that they understand the facility availability, as well as the technological capabilities and constraints, and the cost impact of different designs.

Supporting commercial applications

Thanks to its partnership with Airbus and the technological developments and know-how it has gained through the ESA Science missions, Mersen Boostec has also developed commercial instruments for space segments beyond science missions, including commercial telescope payloads for Earth Observation satellites sold and exported by Airbus.

The skills and lessons learned through designing and implementing payloads for complex missions such as Herschel or Euclid have been translated into these telescope payloads so that they can be made in a simpler, lower-cost fashion, where there is little to no risk in comparison to expensive institutional missions. **The innovative all-SiC payloads allow the technology to ensure short delivery times and to be competitive on the market**.

An example of a commercial payload is **Airbus's own Pleiades Neo constellation**, which is the company's most advanced optical constellation of four identical 30cm resolution satellites for geospatial intelligence. Its use of the latest generation lightweight silicon carbide optical instrument means that it can have a high-quality payload that is more advanced than previous generations, and hence deliver high resolution imagery for a wider range of end users. Airbus and Mersen Boostec further refined the silicon carbide technology and optical instrument design for this state-of-the-art constellation, enabling it to provide better solutions in all resolutions.[5]

Bringing a non-toxic material to market that has a wide range of beneficial properties

Mechanical and thermal properties bringing technological advantages

Sintered-SiC mechanical and thermal properties include having high stiffness, low density, high thermal conductivity and low thermal expansion

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[5] Airbus, 2021. *Breathtaking first images from Pleiades Neo.* Available at: https://www.airbus.com/en/newsroom/news/2021-06-breathtaking-first-images-from-pleiades-neo-0

Mersen Boostec

These properties bring a number of technological advantages for those seeking to utilise the material within their manufacturing process:[6]

- One of the fundamental aspects of sintered SiC's advantages lies with the fact that the material is very homogeneous with very low in-built stresses, and its performance reproducibility from batch to batch supports the development of space instruments. Sintered SiC also has isotropic properties, which is when the material's properties remain the same when tested in different directions, and this helps to facilitate optical payloads dimensioning and behavioural prediction.
- Its low specific density, very high stiffness and a high bending strength allows for optical systems to be produced that are stiff and very lightweight, and hence can be built at a larger scale.
- Sintered SiC has a low coefficient of thermal expansion which, when combined with its very high thermal conductivity, allows for visible quality imaging even in the presence of stressing and changing thermal loads conditions. This means it is a useful material to use for achieving the strict thermos-elastic performances of space optical payloads over a broad operating temperature range, in contrast to composites or glass.
- Sintered SiC provides for stability over time: it is insensitive to space radiations; avoids aging and creep deformation under stress; has no moisture sensitivity, outgassing, or residual stresses; and is resistant to high fatigue, corrosion and abrasion. **These properties therefore make it a stable material that is reliable for long-term space missions.**

Replacing the use of toxic materials

One material that has similar mechanical properties to Silicon Carbide and a heritage of use in space science and exploration missions is Beryllium. Beryllium is a very stiff, lightweight metal that maintains a stable shape, even at extremely high and low temperatures, and this has made it a popular material to use in lightweight precision instruments for certain space missions. For example, NASA has utilised Beryllium for components on the space shuttles, the International Space Station, the Spirit and Opportunity rovers, the Spitzer Space Telescope and other missions.[7] Recently, the agency built the 18 gold-plated hexagonal mirrors on the James Webb Space Telescope out of Beryllium.

The disadvantage of this material however is that Beryllium is toxic to humans, with workplace exposures to dust or fumes from Beryllium and Beryllium compounds potentially leading to severe health issues such as cancer or chronic beryllium disease, which is an autoimmune response that causes damage to lungs.[8] Therefore, strict workplace practices must be put in place to prevent the risk of exposure to people.

Conversely, **Silicon Carbide has the benefit of being a non-toxic material, able to replace Beryllium in industries such as in laser processes, as well as being suitable for space missions** requiring materials of high stiffness, light weight and the ability to withstand extreme temperatures whilst remaining stable. Therefore, the more SiC is used as a cost-efficient replacement for Beryllium, the more steps can be taken towards having safer work environments.

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[6] Breysse, J., Castel, D., and Bougoin, M., 2012. *All-SiC telescope technology at EADS ASTRIUM: Big step forward for space optical payloads.* International Conference on Space Optics – ICSO 2012.
[7] EarthObservatory, 2021. *Digging Beryllium for James Webb.* Available at: https://earthobservatory.nasa.gov/images/148574/digging-beryllium-for-james-webb
[8] Geology.com, 2022. *Uses of Beryllium*. Available at: https://geology.com/usgs/beryllium/

Positioning Europe as a leader in large-scale SiC solutions for space science missions

Enabler of space science missions

Mersen Boostec's SiC has been an enabling technology for multiple highly complex space Science missions such as Herschel, GAIA and EUCLID, providing a solution without which the missions would not have been able to proceed.

The Herschel Space Observatory had a mission objective to study the cool Universe at infrared to submillimetre wavelengths, seeking to understand the formation of stars and galaxies across the history of the universe and how they interact with interstellar medium. Its main mirror measured 3.5m in diameter, which was four times larger than any previous infrared space telescope ever flown in space at the time.[9] The complexity of the mission objectives and the sheer size of its mirror required the use of a material with properties such as SiC, which provided a solution that was stable, low in mass yet large in size as needed.

GAIA is a mission that is charting a three-dimensional map of the Milky Way, providing the positional measurements for around one billion stars, and in the process exploring the composition, formation and evolution of the galaxy.[10] In a similar fashion to Herschel, GAIA's mission objectives required a payload platform that was mechanically and thermally ultra-stable, meaning that SiC's low thermal expansion coefficient and high thermal conductivity made it an ideal material for the mission.

Additional missions where Boostec® SiC material has been utilised include the Atmospheric Laser Doppler Instrument (ALADIN) telescope on the ADM-AEOLUS mission for measuring wind profiles for climatology and meteorology users, and one of the telescopes for Rosetta's Osiris cameras, where the lightweight properties of SiC allowed for the small size of the telescope, and thus the precision of the Osiris instrument for locating landing sites for the Philae lander could be increased.[11] Mersen Boostec also made a major technological contribution in building components for the Near Infrared Spectrograph (NIRSpec) instrument on board the James Web Space Telescope (JWST), which was developed by Airbus for ESA, as part of the wider NASA, ESA and CSA collaboration for the JWST mission.

Looking to the future, the EUCLID mission is due to be launched in 2023, with a mission goal to investigate dark matter distribution, the history of the Universe's expansion, and insights learned regarding the nature of dark energy. The high requirements of the mission have led to its mirrors and structures of the payload module instruments to be made predominantly of SiC material, which will provide the needed lightweight, stiffness, strength and dimensional stability.[12]

Increasing European competitiveness

Whilst the United States started working on using SiC for space optics in the late 1970s/early 1980s, the country did not push ahead in continuous research and development of the material, hence falling behind Europe in terms of advancement. Today, US companies can make optics for space missions, but they do not have the same brazing technology as in Europe, which is the metal-joining process whereby a filler metal is usually melted and flowed into the joint to combine the two items together. With Boostec® SiC, the brazing technique consists of adding a silicon alloy between two sintered SiC pieces, with the end result that the braze material has a matching

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[9] European Space Agency, 2022. *Herschel Overview.* Available at: https://www.esa.int/Science_Exploration/Space_Science/Herschel_overview

[10] European Space Agency, 2022. *GAIA Fact Sheet.* Available at: https://sci.esa.int/web/gaia/-/47354-fact-sheet

[11] UKSPACE, 2014. *Silicon Carbide Rosetta landing site.* Available at: https://www.ukspace.org/silicon-carbide-rosetta-landing-site/

[12] Bougoin, M. et al., 2019. *Full-SiC EUCLID's very large telescope.* Proc. SPIE 11180, International Conference on Space Optics – ICSO 2018, 111801P (12 July 2019)

coefficient of thermal expansion (CTE) as sintered SiC, the brazing joint can be very thin, and the overall process is non-reactive, meaning the SiC material is not 'attacked'.[13] By lacking a similar SiC-focused technological process, US companies are limited in the size of silicon carbide components that they can manufacture, and in terms of maturity of solution, the optical products are usually less than 1m in diameter for sizing, and not so lightweight or complex. Additionally, US competitors often propose the mirror component but not the entire telescope made of SiC, since this was a concept developed by Airbus and Mersen Boostec. The US have since recognised the importance of SiC for space applications, and the fact they must push for advancement to reach Europe's level in terms of development, even approaching the two companies to investigate if SiC would be feasible for the James Webb Space Telescope, although at the time the material was not mature enough.

Unlike the US, China has had success in using this technology to make large payloads such as mirrors and other instruments. However, these activities are for their own space missions, and so they are not competitors for export.

Therefore thanks to Boostec® SiC, **Europe has a unique technology and can offer the best version of this technology than was ever available in the past**. However, countries such as China, Korea, Japan and the US are now making huge effort to use this technology, and so **it is important for Europe to look ahead for further development**.

Expanding European non-dependence

The Boostec® SiC material not only provides Europe with increased competitiveness, but also feeds into the expansion of European non-dependence for developing, accessing and using core technologies. As stated, Silicon Carbide is a mission-enabling material, providing a way to build complex missions such as Euclid, which would not have been feasible 20 years ago.

This also allows ESA, Airbus and the wider European landscape to use a European-based material as an alternative to other solutions, such as Beryllium, which is only processed in commercially viable quantities from the United States, China and Kazakhstan.[14]

Would these benefits have been realised without ESA?

ESA

ESA funding was instrumental for this technology development and its applications for science missions, as **it funded technology maturation through 'valley of death' TRLs (i.e. 4-6)**. ESA mission and technology development contracts also represented the large majority of Mersen Boostec's revenue in the early years of its development, meaning the company would likely not have survived without its participation on flagship science missions. ESA funding, notably around Herschel, was critical in strengthening the relationship between Mersen Boostec and Astrium/Airbus, which today still benefit from this deep technological partnership, in and beyond the space industry.

> "Without ESA funding, Boostec would not exist. It was instrumental in our business for funding and development of Silicon Carbide."
>
> *Michel Bougoin, Mersen Boostec*

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[13] Breysse, J. et al., 2019. *All-SiC telescope technology at EADS ASTRIUM: Big step forward for space optical payloads*. Proc. SPIE 10564, International Conference on Space Optics – ICSO 2012, 1056442 (30 August 2019)

[14] Beryllium.com, 2022. *Sources of Beryllium*. Available at: https://beryllium.com/about-beryllium/sources-of-beryllium

… plus further development and benefits to come

Looking to the future, European stakeholders such Mersen Boostec and Airbus aim to maintain their leadership in the domain, as **international competition is rising fast**. To achieve that, they need to ensure that they sustain their competitiveness through pursuing further developments in improving SiC production processes, notably the efficiency of polishing techniques.

This will continue improving Mersen Boostec and Airbus' positioning for multi-year contract opportunities when new science missions are being proposed and developed. Additionally, new developments and improvements around SiC will also enable Mersen Boostec to seize larger market shares in the expansion of its growing terrestrial applications, which are now a core aspect of the business's revenue percentage.

Overall, **maintaining and increasing competitiveness and leadership would support revenue, employment, and skills and capabilities** at Mersen Boostec and Airbus, with an overall **strengthening of the French/European supply chain**.