Advancements in Carbon Nanotube-Based Filters for EUV Solar Coronal Spectroscopy

E. Alaimo, F. D'Anca, F. Fiorentino, U. Lo Cicero, L. Sciortino, M. Todaro,
P. T. Törmä, J. Etula, B. Mikladal, I. Varjos, C. Argiroffi, G. Cozzo, P. Pagano, F. Reale,
P. Boerner, B. De Pontieu, P. Testa, D. Perrone, M. Stangalini, M. Barbera

State of the art and Ongoing Research

Many open questions lie unanswered in the science of solar physics: in particular, the mechanisms heating the solar corona are not yet fully understood [1]. Many missions, with the likes of SDO/AIA, Solar Orbiter/EUI, and Hinode/EIS, were launched to study the EUV solar structures, but none of them reached the spatiotemporal resolution scales required to study some predicted phenomena that have a big role for the coronal heating problem. Sub-arcsecond and sub-10 s spatio-temporal resolution is required to help hone existing theories [2]. This is why the MUSE mission is being developed, also seeing participation by the Italian community approved by the Italian Space Agency, ASI, with contributions by INAF and other Italian universities (PI of the Italian Consortium: F. Reale). Particularly, UNIPA and INAF-OAPA are responsible for the design, procurement, and characterization of thin film filters for use in MUSE (M. Barbera).

Thin films in solar coronal spectroscopy astrophysical space missions are needed for many reasons: firstly, they need to provide a visible and infrared blocking factor of about 10^6; secondly, they need to protect detectors and mirrors from contamination from particles, molecules, atomic oxygen where applicable; then, they have to withstand acoustic and vibrational loads during launch; and finally, they have to ensure a high EUV transmittance, enough to guarantee the missions' requirements. For SDO/AIA, Al or Zr filters were employed, and they successfully met the requirements above [3], although many aspects have arisen in recent years. The development of new generation filters needs to consider state-of-the-art challenges such as the presence of pinholes in polyimide-based filters which might limit the overall optical blocking factor; the diffraction issues caused by very finely spaced meshes, such as those which were used in the case of SDO/AIA [4]. Some filters' deterioration is also very probable during the mission years and as of today, no clear explanation was given for some of these deteriorations [5], and atomic oxygen is a probable culprit for low earth orbit (LEO) missions.

Our research is being conducted in collaboration with AMETEK Finland Ltd, Canatu Oy. We are proposing an innovative technology using carbon nanotubes (CNT) pellicles coated with aluminum or zirconium, supported by a coarse CNT-based mesh. These filters demonstrate high EUV transmittance, resistivity to high temperatures, and scalability, which proves particularly useful considering future missions where having bigger filters might be a priority. The figure below is an example of the general development procedure adopted by our team. European Space Agency (ESA) and ASI are actively supporting our research, respectively, for X-ray Astrophysics and EUV Solar Coronal Physics applications.

We first procured a batch of filters with about 120 nm of Al and 120 nm of Zr deposited on a CNT-based thin film which transmits 55% of light at the 550 nm visible wavelength. We investigated such filters via synchrotron light experiments via XAS (X-ray Absorption Spectroscopy), XPS (X-ray Photoelectron Spectroscopy) at the synchrotron Elettra, Trieste (beamlines BEAR and BACH), and UV-VIS-IR Transmission Spectroscopy in-house at

INAF-OAPA. The initial tests give good results to start studying the filters' material for modeling purposes but suggest that the new batch would need to have more coating. Many more steps will be taken: more manufacturing of thicker samples, standardized vibrational tests collaborating with NASA and Lockheed Martin, detailed studies of PSF simulations for diffraction patterns of the CNT-based meshes, and more experimental synchrotron tests. In conclusion, this research is a remarkable example of how a very novel technology, such as carbon nanotubes, could prove very useful in the context of thin films applied in astrophysical space missions.

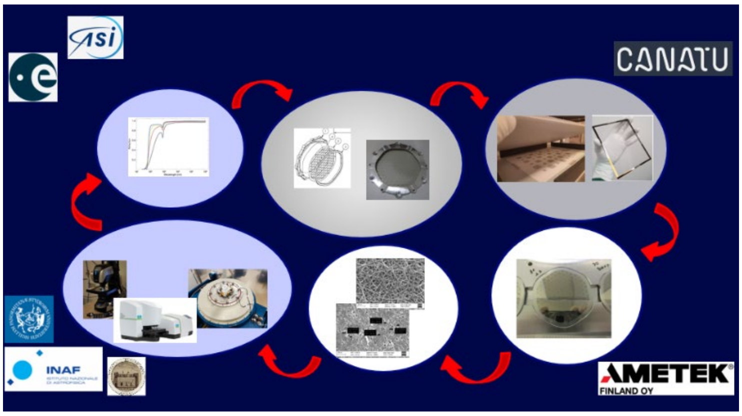

Figure caption: Overview of the Filters Development Process as done by the UNIPA/INAF team, in collaboration with ASI (for EUV space missions) or ESA (for X-ray space missions) and with CANATU and AMETEK companies. From the top left, going clockwise: Filters Design, Hardware Modelling, Carbon Nanotubes growth, Metal coating, Microscopy Control, Space Characterization and Qualification.

Perspectives and Desiderata for Future Heliospheric Missions and Facilities

The prospect of our work is to characterize the CNT-based filters for use in space missions, particularly in their oxide content and in their ability to resist vibrations. In the future panorama of solar physics, many challenges will arise, some of which regard technological aspects that are neither completely understood nor experimentally investigated as of today.

One aspect is easy access to Solar Simulator facilities: the optical blocking power of filters is a crucial piece of information to predict the stray light effects in EUV missions [3] and studying changes in the filters' visible transmittance after some experimental tests, such as contamination due to micro-meteorites, vibration tests, or Atomic Oxygen tests (ATOX), could prove essential in the correct development of the technology.

Another aspect of novel interest would be the development of facilities that would be able to do ATOX tests alongside EUV or UV irradiation, to see synergetic effects that might induce deterioration of the filters [5] in a perfectly realistic LEO environment.

Some facilities allow to study of these effects taken singularly, but it is very hard to study these effects combined and reliably in a single space-grade facility.

References

[1] N. Viall et al. 2021, in Solar Physics and Solar Wind, eds. N. E. Raouafi, & A. Vourlida, 1, 35, DOI: 10.1002/9781119815600.ch2
[2] B. De Pontieu et al. 2022, ApJ 926 52, DOI: 10.3847/1538-4357/ac4222
[3] P. Boerner et al. 2012, Sol Phys 275 41–66, DOI: 10.1007/s11207-011-9804-8
[4] B. Poduval et al. 2013, ApJ 765 144, DOI: 10.1088/0004-637X/765/2/144
[5] C. Tarrio et al. 2023, Sol Phys 298 32, DOI: 10.1007/s11207-023-02112-x