The ASTAROTH Project - a novel technique for NaI(Tl) crystal cool-down

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INTRODUCTION

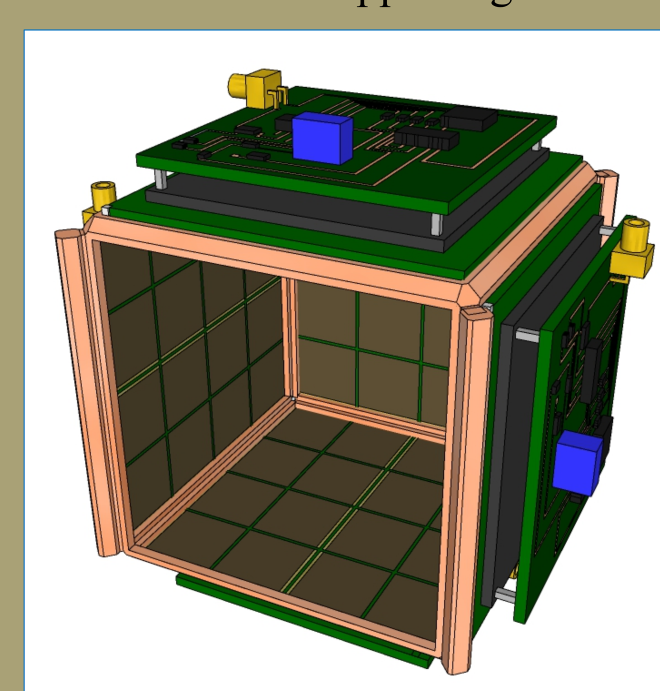
ASTAROTH is an R&D project aiming at improving the physics reach of direct dark matter (DM) detection experiments based on NaI(Tl) scintillating crystals. These are of fundamental importance for testing the DM interpretation of the DAMA annual modulation signal, with the same target and technique [1]. **ASTAROTH proposes a technology development that aims at lowering the detection energy threshold**, making it possible for the first time to observe sub-keV recoils. This would allow disentangling different DM-induced modulation models, thus restricting the parameter space of a surviving DM candidate. ASTAROTH's strategy consists in immersing the target NaI(Tl) crystals in a cryogenic medium and reading them out with Silicon PhotoMultipliers (SiPM) on all surfaces. SiPM feature lower dark noise than PMTs at T<150 K. The chosen cooling medium is liquid Argon (LAr), which can double as veto detector thanks to its excellent scintillation properties. We present here the innovative controlled crystal cooling technique that is being developed for this purpose.

PHYSICS BACKGROUND

A model-independent verification of the DAMA observation requires a new experiment based on NaI(Tl) with ultra-low background, superior sensitivity and low energy threshold.
NaI(Tl)-based detectors, SABRE [2], ANAIS and COSINE, share with DAMA the basic design elements and limitations:

- Limited light collection, ranging from 7 to 15 photoelectrons (phe) per keV.
- Intrinsic high noise and radioactivity of the PMTs.
- Hard to achieve production of very-high-purity crystals with a mass of few kg.

The previous points globally imply **an observable recoil energy higher than 1 keV_{ee}.**
Some of these experiments also exploit an active veto, mainly designed to catch γ's from key backgrounds such as ^{40}K, ^{22}Na. Organic liquid scintillators that are generally exploited for this purpose are becoming increasingly difficult to use, due to stricter safety/environmental procedures.



Top: NaI(Tl) crystal encapsulated in copper cage for SiPM matrices support.
Bottom: Render of the matrices installed on the copper cage

PHYSICS REACH & TECH INNOVATION

ASTAROTH will use high purity cubic NaI(Tl) crystals read on all six surfaces by SiPM matrices, operating at a moderate and tunable cryogenic temperature (87-150K).
On the physics side, this overcomes the limitations of the present generation DM detectors:

- Smaller very-high-purity crystals, easier to produce, can be employed.
- Higher PDE, maximized light collection.
- Lower SiPM dark noise at low temperature (<150 K).
- ASIC readout and digitalization on board provide compactness and fewer (radioactive) components
  → more controlled backgrounds and reduced power dissipation

This will allow accessing for the first time the sub-keV recoil energy region for the observation of a DAMA-like annual modulation signal.
Technologically, the developed light detectors will feature:

- SiPM matrices with area of tens of cm^2, read as a single channel by ad-hoc integrated electronics.
- Single low-radioactivity PCB hosting both SiPM and ASIC.

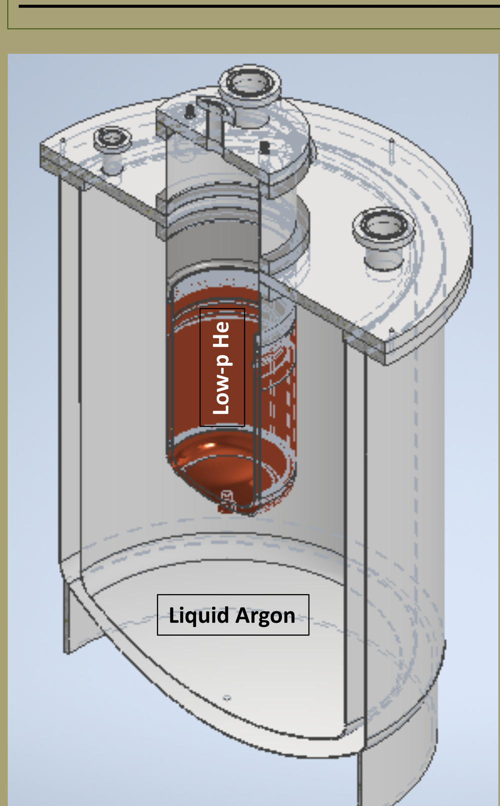
Such device aim at replacing traditional PMTs of a similar sensitive surface with a compact light-weight sensor, featuring unmatched low radioactivity for a wide range of applications.

PASSIVE CRYSTAL COOLING

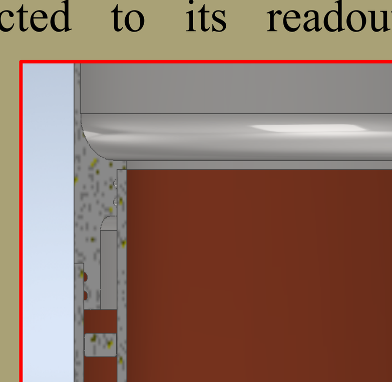
The design of the NaI(Tl) crystals chamber and cooling system is driven by strict requirements, in order to ensure the crystals survival and stable read-out from the electronics:

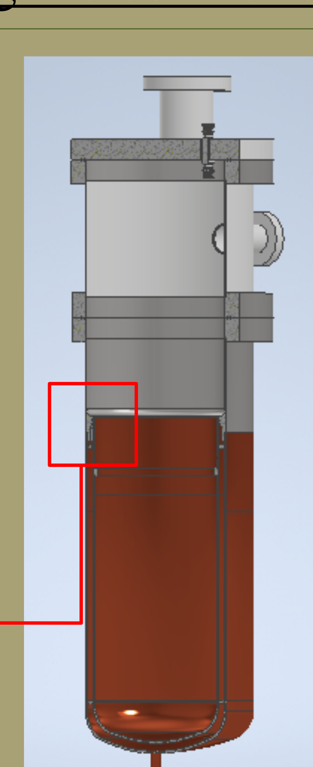
- **Temporal gradient limited to <20 K/h.**
- **Spatial gradients (within crystal) < 1 K.**
- **Temperature stability in time, during data taking, within 0.1 K.**

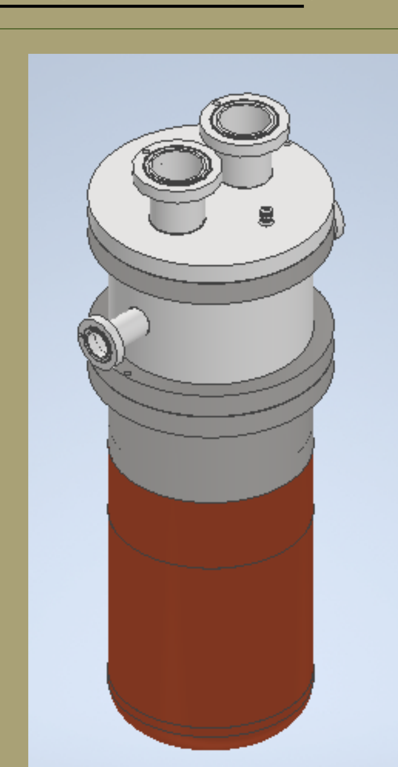
On the physics side, the design is optimized to run the crystal and characterize its yield as a function of temperature, eventually selecting its best working point.
A custom-made dual-wall, vacuum-insulated copper chamber was developed, featuring a specially designed Stainless Steel (SS) thermal bridge between the two walls, and a heater.
The chamber is immersed in a LAr bath (at 87 K) providing cooling power, that gets diffused on the inner wall only by conduction through the SS bridge. This allows cooling the inner volume (and the crystals) down to 87 K. The tunable power heater is then used to raise the temperature in a controlled way up to 150 K and keep it stable.
Low pressure Helium gas fills the inner volume, serving as heat-transfer medium to the crystals, and providing the necessary thermal inertia to ensure the crystals safety. This design minimizes the effects of radiation and convection, maximizing the control on heat transfer.

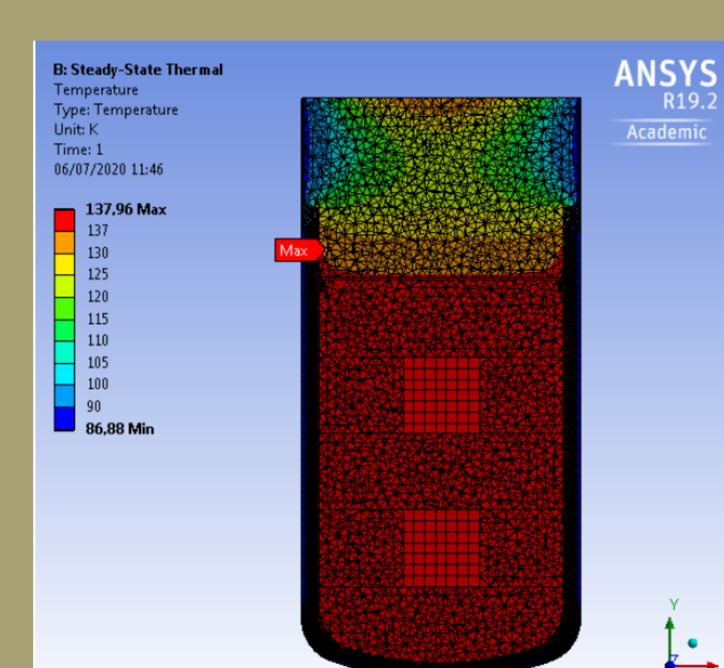


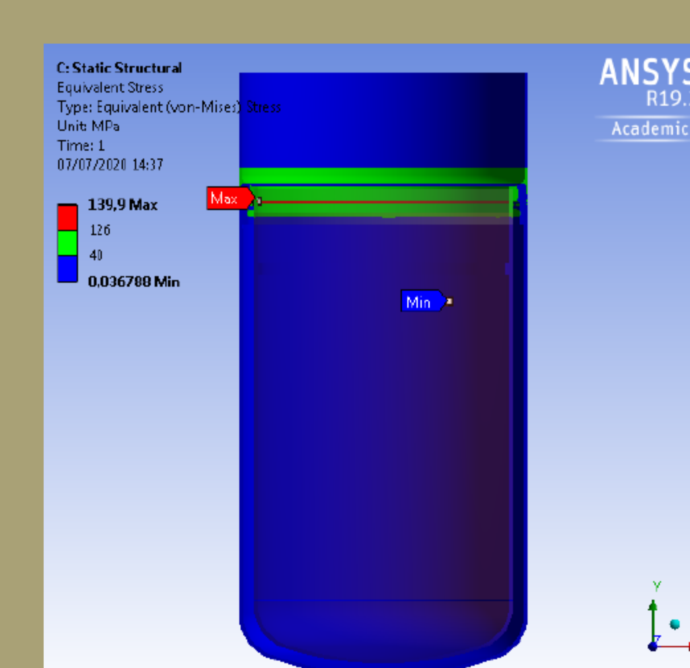
Left: simplified sketch of the ASTAROTH detector. The inner copper chamber, hosting the crystals, is immersed in a LAr bath within a closed dewar.
Right: 3D renders (full and section) of the copper chamber connected to its readout chimney.
Bottom: detail of the SS thermal bridge, brased to the copper cage walls.











Thermal and mechanical FEAs of the ASTAROTH dual-wall copper box, highlighting the optimal temperature uniformity in the main volume (Left) and the stress map in most loaded areas (SS thermal bridge, Right)

SIMULATION OF THE COOLING SYSTEM

Thanks to the Mechanical Service of INFN Milano, the new cooling system was fully simulated and tested with a Finite Element Analysis (FEA), following a two-stage approach.

- **A static thermal simulation** was performed, having as input the LAr cooling power and the power emitted by the heater, to obtain a specific temperature in the inner volume (e.g.: 150 K). This demonstrated that the equilibrium temperature of the chamber is uniform within <0.01 K over the whole volume.
- **A mechanical simulation** was implemented, with the temperature maps obtained in the first stage as input. This highlighted the most stressed areas (the thermal bridge) and allowed developing their design.

OUTLOOK

The ASTAROTH project aims at testing the DM interpretation of the DAMA annual modulation signal. The first steps for the project is to develop a new cooling technique for NaI(Tl) crystals and a compact SiPM-based readout technology. This will allow characterizing the crystals over a wide rage of temperatures, selecting the best working point, to achieve superior sensitivity and ultra-low background.

[1] E.g.: "The DAMA/LIBRA apparatus", DAMA Collaboration, *Nucl.Instrum.Meth.A 592 (2008) 297-315*
[2] "The SABRE project and the SABRE PoP", SABRE Collaboration, *The European Physical Journal C* volume 79 (2019)