Thermal analysis and cryogenics of the Baby-IAXO magnet

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Abstract. Baby-IAXO is a new helioscope, a demonstration version of the proposed full-size IAXO, the International Axions Observatory. It is currently under design and once installed it will search via the Primakoff effect for axions or axion-like particles (ALPs) originating in the Sun. Axions can transform into photons in the presence of a significant magnetic field, and then be detected. The superconducting magnet for Baby-IAXO comprises two 10 m long racetrack coils, spaced by 0.8 m, operated in a quadrupole configuration and generating an average magnetic field of 2.1 T in the two 700 mm diameter free bores for axion-to-photons decay positioned in between the coils. Cool down and operational cryogenic requirements are handled by a combination of single and double stage cryocoolers. For the cool down of the 18.5 t cold mass within 22 days and for current leads cooling, the use of powerful single stage cryocoolers is of paramount importance. The cooling power is distributed across the cold mass and thermal shield using helium gas flow enforced by cryocirculators. The design of the 10 kA conduction cooled current leads is presented as well, since at 70 K these represent the dominant heat load. The cryogenic system allows for a constant heat load of 1.2 kW at the first stage and 8.5 W at the 4.2 K cold mass. Alternatively, the magnet may be operated in persistent mode, thereby reducing the heat load and the number of cryocoolers. It requires a more complex cooling circuit, implementation of a 10 kA persistent mode switch, and a delicate balance of energizing and operational heat loads.

1. Introduction

Axions and ALPs are hypothetical particles that may convert into photons in the presence of a transverse magnetic field. The most sensitive experiment currently looking for solar axions is CAST, capable of measuring an axion to photon coupling of $g_{ay} < 0.66 \times 10^{-10}$GeV$^{-1}$. The design of IAXO originates from the need to extend the search to particles with a 1 to 1.5 order of magnitude lower $g_{ay}$, which can only be achieved by increasing the sensitivity of the experiment by a factor of $10^8$. The full-size IAXO experiment will reach its target sensitivity by improving its figure of merit, but in particular the magnet’s figure of merit MFOM, set to at least 300 times higher than in CAST [1-3].

Given the very ambitious target of the project, an intermediate scaled down but fully functional demonstrator experiment called Baby-IAXO, is currently designed and start of construction is expected by early 2020. It will serve as a test platform for new technology anticipated for the full-size IAXO. Besides a 24/7 sun tracking system, it needs a higher sensitivity than the current experiments and allows to probe new regions in the $g_{ay}$ versus mass plane. In addition, new design choices will be tested that can lead to an improved magnet figure of merit in the ultimate experiment IAXO.

The IAXO magnet is composed of 8 racetrack coils, 20 m long and in a toroidal arrangement [4]. Using the same configuration in a scaled down demonstrator would neither be cost efficient nor allow to test full-size optics. For this reason, dual racetrack coils in a quadrupole configuration have been
proposed for Baby-IAXO, which allows exercising and qualifying the coil winding and cold mass techniques anticipated for IAXO, as well as providing two Ø 700 mm diameter and 10 m long free bores compliant with the IAXO detector optics. The magnetic field configuration and magnet cold mass layout are shown in Figures 1 and 2, while the magnet properties are summarized in Table 1.

![Figure 1. Magnetic field in the cross section of the magnet in the middle plane. Clearly visible are the two racetrack coils in quadrupole layout enclosing two 700 mm wide bores.](image1)

![Figure 2. 3D-representation of the common coil quadrupole cold mass design of Baby-IAXO. The structure is 10 m long, 1.1 m high and 2.65 m wide.](image2)

In order to have full-time tracking of the sun, a 360° rotation and ±25° inclination system is needed, as shown in Figure 3. This requirement would lead to a rather complex cooling circuit if liquid helium were to be used. Furthermore, the experiment is planned to be housed in the South Hall at DESY, where neither cryogenic infrastructure nor supply of cryogens is available. For this reason, the cooling system of the 20 t cold mass is a dry system fully relying on most powerful cryocoolers.

![Figure 3. Artistic impression of the Baby-IAXO experiment, and its 360° rotation and tilting mechanisms shown at +25° inclination.](image3)

| Table 1. Main design parameters of the Baby-IAXO magnet. |
|----------------------------------------------------------|
| Winding width [mm] | 595 |
| Winding height [mm] | 82 |
| Coil length [m] | 10 |
| Pole gap [mm] | 1000 |
| Gap between coils [mm] | 800 |
| Stored energy [MJ] | 50 |
| Self-inductance [H] | 1.0 |
| Peak magnetic field [T] | 3.2 |
| Current density [A/mm²] | 56 |
| Operating current [kA] | 9.8 |
| Temperature Margin [K] | 2.0 |
| Coil ΔT [K] | 0.2 |
| 3D-MFOM [T·m⁴] | 232 |
2. Heat load by cold mass supports, radiation, and current leads

The cooling capacity of pulse tube cryocoolers is rather limited, especially at 4.2 K, where the currently best performing machines offer 2 W of cooling power [5]. New machines offering 2.5 to 3 W are expected to become available in time for the Baby-IAXO magnet construction. Nonetheless, it is of paramount importance to minimize the total heat load of the system in order to minimize the number of cryocoolers.

2.1. Cold mass suspension structure

The heat transferred through the cold mass support structure is by conduction. It can only be reduced by using materials with better mechanical and thermal properties and applying supports as slender as possible. In order to limit the heat flow to the cold mass, the supports are thermalized at 50 K at 40% of their length. In Table 2 the properties of the most commonly used support materials are shown.

Some of the cold mass supports are limited by the displacement of the cold mass, while others will be stressed to their maximum allowable stress. In order to limit the displacement with the lowest possible heat load, a material with maximum $E/q$ ratio is needed, where $E$ is the Yong’s modulus, $q = \int_{4.5K}^{50K} \lambda(T) \, dT$, and $\lambda$ is the thermal conductivity. Yet, if a rod needs to be used to its full strength, the ratio to maximize is $\sigma_a/q$, where $\sigma_a$ is the maximum allowable stress.

**Table 2.** Properties of most usual materials for cold mass supports of superconducting magnets.

| Material         | $E$   | Thermal contraction | $\sigma_a$ | $q$    | $\frac{\sigma_a}{q}$ | $\frac{E}{q}$ |
|------------------|-------|---------------------|------------|--------|-----------------------|---------------|
| Inconel          | 200   | 0.19                | 710        | 154    | 4.5                   | 1.3           |
| Ti6Al4V          | 114   | 0.14                | 465        | 58     | 8.0                   | 2.0           |
| Permaglas [6]    | 20    | 0.15                | 100        | 8.0    | 12.5                  | 2.5           |
| GFRP uniaxial    | 34    | 0.07                | 135        | 8.0    | 17                    | 4.25          |
| CFRP uniaxial    | 134   | 0.03                | 550        | 7.2    | 75                    | 1.8           |

1 Contraction between 300 and 4.5 K of a support rod thermalized at 40% of its length at 50 K.
2 Worse performance than GFRP between 300 and 50 K.
3 Weak point is the bonding between the fibers and the metal interface.
4 Safety factor of 3 required for composite materials.

Even though composite materials are better for limiting the heat load, they have to be custom made and Permaglas rods [7] can only be found in sizes up to M30. It was decided that composite supports would be considered only when the heat load when using titanium rods was prohibitively high. Thus, the calculations were initially based on using Ti6Al4V.

**Table 3.** Forces and momenta transferred through the suspension system to the cryostat. The coordinate system is shown in Figure 4.

| Orientation | $F_x$ [kN] | $F_y$ [kN] | $F_z$ [kN] | $M_x$ [kN.m] |
|-------------|------------|------------|------------|--------------|
| Tilted -25° | -0.71      | 0          | -200       | 73           |
| Horizontal  | -0.7       | 0          | -220       | 87           |
| Tilted +25° | -0.91      | 0          | -220       | 151          |
| Transport   | ±160       | 0          | -180       | 0            |

The Lorentz forces due to the quadrupole field are handled by the coil casing, rods and plates shown in Figure 2. Since these forces are symmetric and cancel out, they are not seen by suspension system
shown in Figure 4. The loads that are transferred to the cryostat, through the suspension system, are the weight of the cold mass in all possible configurations of inclination (± 25°), the acceleration due to transport and the electromagnetic forces between cold mass and the steel support pillar. The supporting pillar and tilting mechanism as shown in Figure 3, are made of magnetic steel, thus causing a pulling force on the cold mass. Given the geometrical arrangement of the supporting rods, it is convenient to represent this force by the equivalent force and momentum generated relative to the magnet’s center of mass. The electromagnetic force is calculated for the magnet’s ultimate current of 12 kA. During transport, the cold mass is locked vertically and transversely in order to prevent too high stress on the rods and for limiting the cold mass deflection, respectively. A summary of the loads transferred through the cold mass suspension system is shown in Table 3. Figure 4 shows the layout of the cold mass suspension rods as well as the results for one of the load cases. The longitudinal and the top vertical suspension rods are the ones that are strength limited (maximum $\sigma_a/q$); whereas the remaining ones are simply used to self-center the magnet or to remove degrees of freedom, thus maximum $E/q$.

The cold mass support structure is designed such that the rods are always in tension, thus preventing buckling failure in the members. The rods are getting in tension during cool down, meaning that they are snug-tightened during installation, which simplifies the assembly procedure. Table 4 shows the heat load and dimensions of each rod.

![Figure 4](image-url)

**Figure 4.** Cold mass support layout and direct stress in the support rods when inclined at +25°. Rods marked in green need maximum $\sigma_a/q$, while the ones in red need to maximum $E/q$.

**Table 4.** Dimensions and heat load of the cold mass suspension system rods.

| Rod Type        | Material | Length [m] | Diameter [mm] | Number of rods | Heat load @50K [W] | Heat load @4.5K [mW] |
|-----------------|----------|------------|---------------|----------------|---------------------|----------------------|
| Vertical rods   | Ti6Al4V  | 1.8        | 16            | 8              | 1.9                 | 90                   |
| Longitudinal    | Ti6Al4V  | 1.6        | 16            | 4              | 1.1                 | 50                   |
| Transverse      | Ti6Al4V  | 2.0        | 16            | 4              | 1.3                 | 40                   |
| Total heat load |          |            |               |                | 4.3                 | 180                  |

2.2. Radiation

Similarly to most modern superconducting magnets, an actively cooled thermal shield in combination with 30 layers of MLI will be used to intercept the radiation coming from the cryostat outer vessel. For the cold mass a single high-quality reflective layer is used. In order to further reduce the heat load at 4.2 K, a thermally floating shield is foreseen around the cold mass with exception of the rather limited space around the bore tubes. Where applied, this shield will reduce the heat flux by a factor of two.
The inner surfaces of the cold mass, where no floating shield is installed, have a heat flux of around 50 mW/m² [8]; while on the outer surfaces, where the floating thermal shield is present, 25 mW/m² are expected. By enclosing the cold mass by thermal shields as shown in Figure 5, most of the MLI installed will be on flat surfaces with no restriction on the packing factor, which simplifies the installation and reduces the effective thermal conductivity. Furthermore, part of the radiation from the bore tubes will be lost as they have direct line of sight between themselves and with the outer shield. The heat loads due to radiation are summarized in Table 5. The heat fluxes assumed are rather conservative, and for that reason a safety margin of only 20% was considered.

**Figure 5.** Schematic layout of the actively cooled thermal shield and the floating thermal shield.

**Table 5.** Heat load due to radiation on the thermal shield and cold mass.

|                        | MLI layers | \( q_{MLI} \) [mW/m²] | Area [m²] | \( Q_{MLI} \) [W] | \( Q_{limit} \) [W] (+20% margin) |
|------------------------|------------|------------------------|-----------|-------------------|-----------------------------------|
| Thermal shield @50K    | 30         | 1200                   | ~135      | 165               | 200                               |
| Cold mass @4.5K        | 1          | 25 - 50                | ~130      | 4.9               | 5.9                               |

2.3. **Current leads optimization and cooling**
The use of HTS conduction cooled current leads is the only viable option for a completely dry system. A schematic representation of a current lead is shown in Figure 6. The heat load of the metal section of a pair of leads at nominal current is given by:

\[
Q_{lead} = 2 I \sqrt{2 \int_{60K}^{300K} \lambda(T) \rho(T) dT} = 840 \text{ W.} \tag{5}
\]

When compared to the other heat loads at the 50 K stage, the heat load from the current leads is substantially higher. For this reason, they are cooled independently, as this would allow their operation at 10 to 20 K above the shield temperature. This results in a lower heat load from the current leads and a lower radiation to the cold mass. Moreover, each current lead has a dedicated electrically floating cryocooler, thereby removing the need for an electrical insulator at the cold end, hence decreasing the thermal resistance of the contact, see Figure 7.

If operated above nominal current, the cryocoolers may not be able to keep the end of the lead below 80 K, and in this case the use of a liquid nitrogen heat exchanger is foreseen. The supply of liquid nitrogen will not be continuous, but effected in regular intervals when necessary. This liquid nitrogen heat exchanger, normally not used, serves the extra heat load between 10 kA nominal current and eventually 12 kA ultimate magnet current, but at the same time allows a faster system cool down or it can be activated as back-up for degraded cryocoolers performance if needed. At CERN, a self-protecting
HTS current leads are currently being developed which are expected to reach a heat load below 1 W at 10 kA.

3. Cryogenics

3.1. Cool down

The cooling system of the magnet is shown in Figure 7. Effective cooling of the cold mass may be achieved using a combination of, for example, two single stage GM AL600 and four dual stage Pulse Tube PT420 cryocoolers currently available from the company Cryomech Inc. Each AL600 cryocooler can provide 600 W at 80 K while each PT420 can provide 55 W at 45 K and 2 W at 4.2 K.

![Figure 6. Layout of the HTS current lead for Baby-IAXO. Cooling at the intermediate stage is by two GM cryocoolers. In overcurrent mode, the cryo-coolers are assisted by a liquid nitrogen heat exchanger.](image)

For cooling down the cold mass, a He gas circulator is connected to both single stage cryocoolers through heat exchangers. At room temperature the cooling capacity is 1.8 kW per machine [9]. Furthermore, the cold mass will be linked to the second stage of the four PT420 cryocoolers, which together can output 400 W of cooling power at room temperature [10]. This means that in order to cool down the 20 t cold mass to 40 K, it will take about twenty days. This duration can be reduced if liquid nitrogen is used to assist the cryocoolers during the cool down process. Once 40 K is reached, the thermal link between the AL600 and the cold mass is broken by purging the He gas circuit. From 40 down to 4.2 K the second stages of the PT420 machines remain connected to the cold mass; and it is expected to take less than two extra days to complete the cool down.

The cooling of the thermal shield is managed by a separate He gas circulation circuit, for its cooling power linked to the first stage of the PT420 cryocoolers. At room temperature, 1.8 kW of cooling power is available from the quartet of cryocoolers. As the mass of the thermal shield is about 1 t, the cool down of the shield can be achieved in less than a week. Even though shield cooling can be done faster than for the cold mass, they are controlled for achieving the same rate, this prevents the second stage of the cryocoolers from operating for an extended period at a higher temperature than the first stage.

3.2. Stationary operation

The cryogenic system has to extract the heat loads that are summarized in Table 6. The He gas circulation circuit used to cool the shield is dimensioned to extract the heat arriving at the 50 K level with the exception of the heat input from the current leads.

The normal conducting current leads are kept at 60 to 70 K level by two GM cryocoolers that are connected directly to the current leads without using a galvanic insulator. This is made possible by...
having a sliding interface between the heads of the cryocoolers and the cryostat, thus compensating for any mismatch in thermal contraction. Besides, the cryocoolers need to be electrically floating to prevent the current leads from being shorted. When operating above nominal current, the back-up LN2 heat exchanger eventually used to speed up the cool down, is then used to prevent the temperature of the current leads from drifting to above 80 K.

One of the issues limiting the maximum operating current is the peak temperature in the coil. The high-purity aluminium used as stabilizer for the superconducting cable has a thermal conductivity of about 1600 W/(m K) at 4.5 K, thus making it possible to maintain a temperature gradient $\Delta T$ of less than 0.2 K over the coil simply by conduction.

**Figure 7.** Sketch of the cryogenic solution, arrangement of six cryocoolers for cold mass and leads, He gas cryocirculator for distributing the cold and simplified piping layout of Baby-IAXO.

### 3.3. Optional persistent mode operation

An alternative cooling scheme, see Figure 8, adjusted to a possible persistent mode operation of the magnet was studied as well. In this mode, after energising the magnet, the persistent mode switch short-circuits the coil terminals thereby eliminating the current flow in the current leads. This mode of operation has several advantages, the main one being that the magnet can be charged in a stationary position where after the bus bars can be disconnected. Temporary rigid bus bars can then be used instead of more complex flexible ones allowing 360° rotation.

Secondly, the heat load from the current leads is drastically reduced, as now during stationary operation there is no Joule heating in the current leads. Since there is current flowing in the leads only when energizing the magnet, they can be optimized for this case and generally made slimmer. This may result in a higher temporary heat load during magnet charging, but a substantially lower one during many months of stationary operation. The current lead optimized for persistent mode shows 40 to 50% less cross section than the stationary current carrying leads presented in section 1.4. This results in a reduced heat load of about 260 W at 50 K during stationary operation.

The lower overall heat load at 50 K level allows the cryocoolers to operate at a lower temperature, and consequently allows to reduce the number of cryocoolers. Also the cool down time is reduced.

From a cryogenics point of view the persistent mode of operation is more complex, as it requires several heat exchangers connected to the GM cryocoolers. This complexity comes from the fact that during ramping up of the magnet, the extra heat load needs to be sent to the shield. Consequently, the
50 K cooling circuit needs to be shared by all cryocoolers. Lastly, in order to implement this mode of operation, a reliably operating persistent mode switch for 12 kA has to be developed and qualified.

![Figure 8](image-url) Sketch of cryogenic solution, arrangement of cryocoolers for cold mass and leads, He gas cryocirculators for distributing the cold and simplified piping layout of the Baby-IAXO magnet system, now optimized for persistent mode operation.

4. Conclusion
The Baby-IAXO detector magnet is being designed to have as many similarities as possible with the proposed full-fledged IAXO detector magnet, however, when it comes to the cooling strategy, the location foreseen for Baby-IAXO does not allow for an identical approach. The cool down and operation of the 18.5 t cold mass is based on using four pulse tube double stage and two GM cryocoolers, whose combined cooling power is enough to cover the heat loads of 8.5 W at 4.5 K and 1250 W at 50 K. As back-up for underperforming or aged cryocoolers, as well as for allowing a 20% above-nominal current operation, a liquid nitrogen heat exchanger is envisioned. An optional cooling scheme based on persistent mode operation is proposed as well.

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