Status of the BabyIAXO Superconducting Detector Magnet Design

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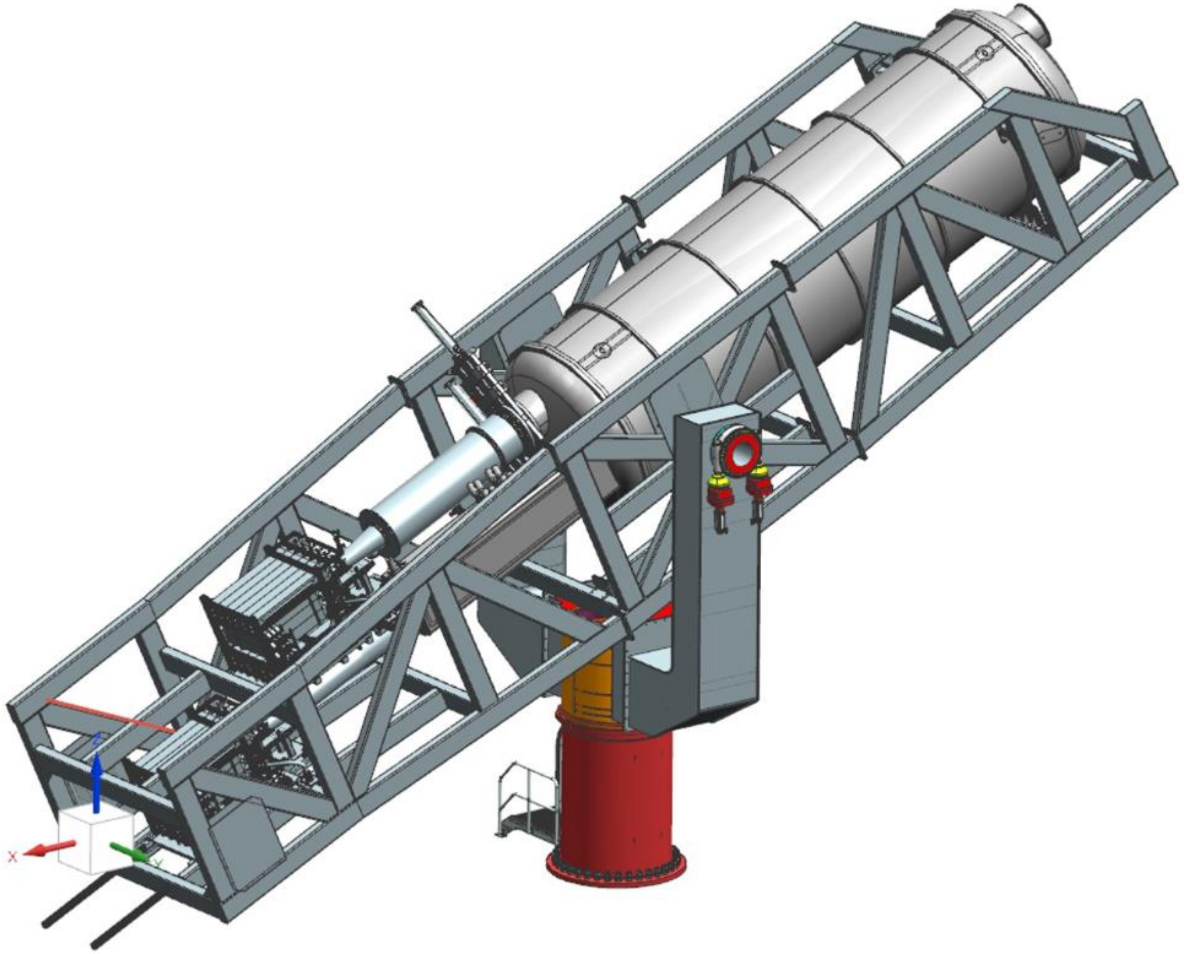
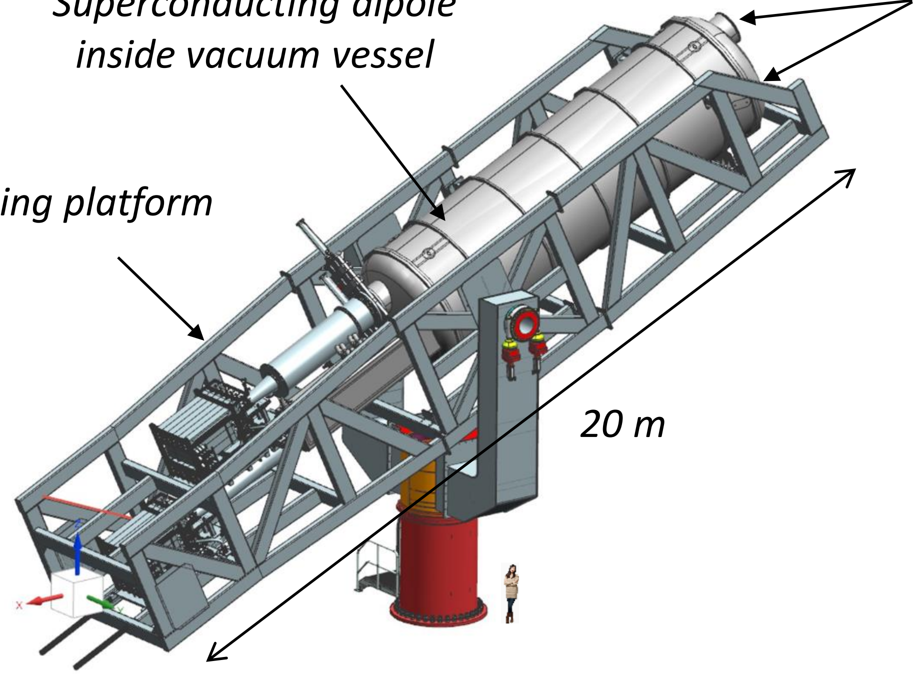
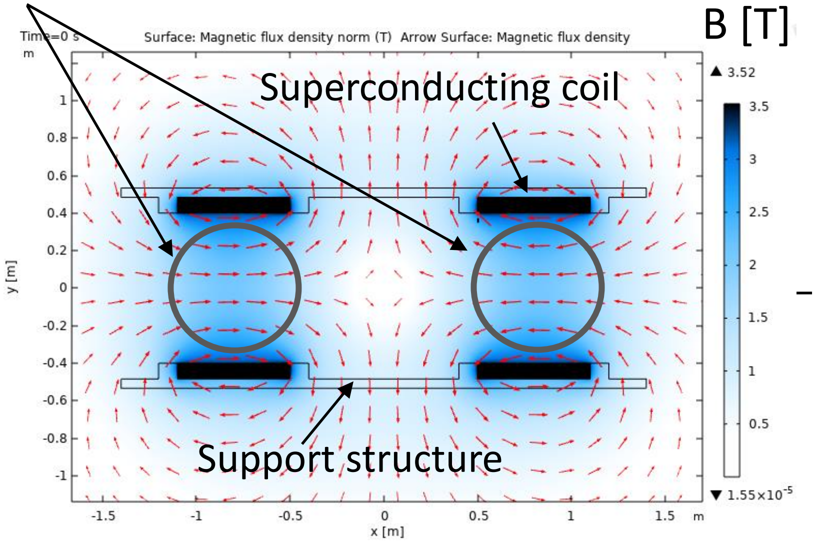
Overview

- Introduction
- Winding layout
- The conductor
- Resulting magnet performance
- Quench behavior of the coils
- Current leads
- Cryogenics and heat loads
- Cold mass, coil suspension, and vacuum vessel
- Summary



BabyIAXO experiment, introduction





Cross-section of magnet cold mass with magnetic field

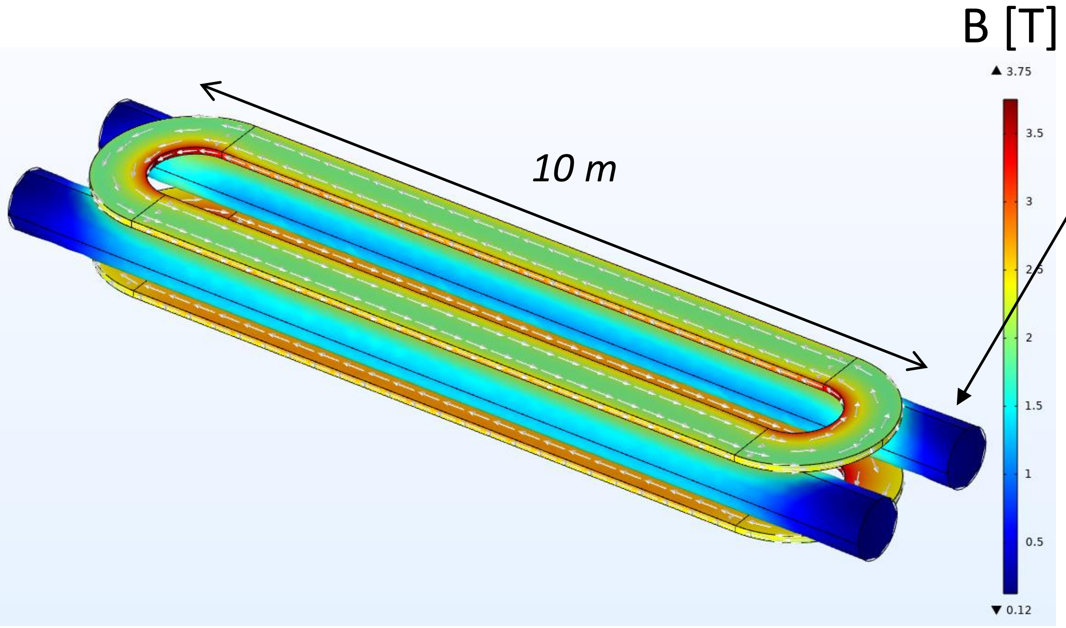
BabyIAXO experiment, to be hosted at DESY

- Searching for axions emitted by the sun;
- Requires transverse magnetic field, for converting axions into photons
- Detector sensitivity proportional to length^2, diameter^2, and magnetic field^2
  → A large and powerful superconducting detector magnet is needed!
- BabyIAXO magnet: About 2 T of transverse magnetic field over a free bore volume of about 8 m^3, i.e. the combined free bore volume of 120 LHC dipoles

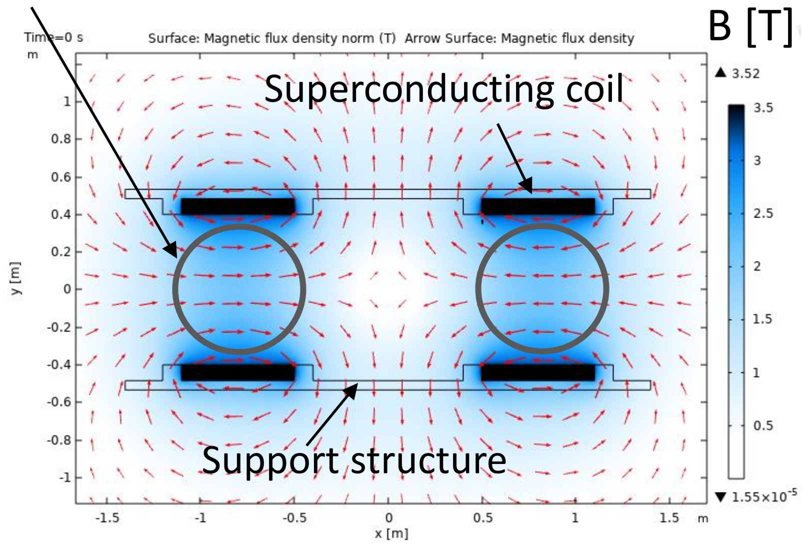
$$\mathrm{MFOM\,(3\text{-}D)} = \int_A \left(\int_L B_\perp(x,y,z)\,\mathrm{d}x \right)^2 \mathrm{d}y\,\mathrm{d}z$$

Magnet-figure-of-merit (MFOM)

Winding layout



Common-coil dipole, with counter-flowing current in two superconducting race-track coils

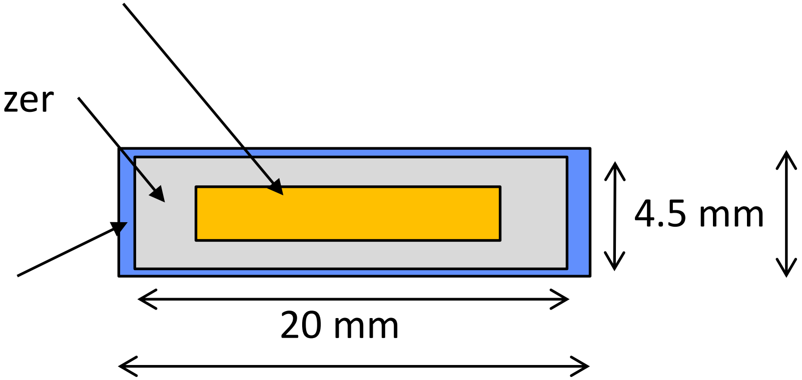


Cross-section of magnet cold mass with magnetic field

Proposed winding layout:

- Common-coil superconducting dipole with a coil length of 10 meters
- Two race-track coils with counter-flowing currents
- Produces a transverse magnetic field over the two 11-meter-long bores with a free diameter of 0.7 m
- To be operated at T ≤ 5 K featuring Nb-Ti-based superconducting coils with about 2 T in the bore

Considered conductor composition and geometry



Rutherford cable: 18 Cu/Nb-Ti strands, 1.3 mm Ø

Pure aluminum stabilizer

Insulation:
Epoxy-impregnated
glass-fiber

Schematic representation

Aluminum-stabilized conductor:

- Rutherford cable comprising 18 Nb-Ti/Cu strands with diameter of 1.3 mm and Cu:non-Cu ratio = 1.08
- Surrounded by pure aluminum, combined dimensions: 4.5 x 20 mm^2
- Epoxy-impregnated glass-fiber insulation:
    - 0.5 mm between neighboring conductors inside a winding layer
    - 1.0 mm between neighboring conductor in adjacent layers

Why an aluminum-stabilized Nb-Ti/Cu conductor?

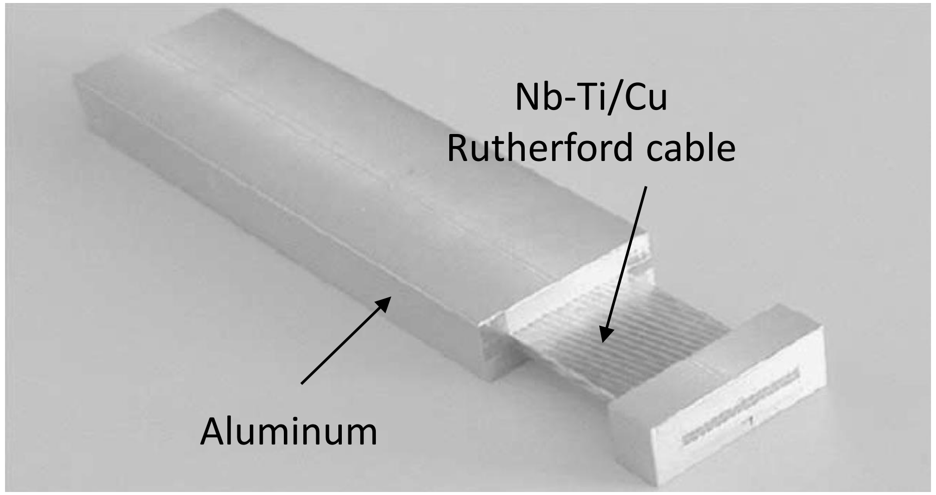
Niobium-titanium:

- Nb-Ti is the most affordable superconductor, for example extensively used for MRI magnets
- It is mechanically ductile and robust, able to handle tensile strains > 1%
- It is the standard work-horse conductor for most superconducting magnets in existence
- But: It does require low temperatures (≤ 5 K) and only allows for a limited magnetic field range

Pure-aluminum stabilizer:

- Very high thermal conductivity, important for conduction-cooled superconducting detector magnets like the BabyIAXO magnet
- Very high electrical conductivity, allows to temporarily carry the current in case of a quench, thus preventing permanent degradation of the magnet
- Very high electrical and thermal conductivity → Increases the amount of perturbation energy needed to quench the magnet → limits the chance of training quenches

The aluminum-stabilized Nb-Ti conductor has been the standard "workhorse" conductor for superconducting detector magnets for decades



Example of an aluminum-stabilized conductor (pull-out sample for CMS)

The conductor: Commercial availability challenge

But: Aluminum-stabilized conductors are presently unavailable!

How did we determine this?

- Organization of a workshop “Superconducting Detector Magnet Workshop”, co-organized by CERN and KEK, was hosted at CERN in September 2022.
- Discussions between world-wide representatives from companies and institutes.
- The aluminum-stabilized conductor was a topic of key interest.
- Result: While R&D are on-going in Russia and China, unfortunately, no commercial availability is foreseen in the few years.
- This is an issue, given that many future superconducting detector magnets consider this conductor type in their baseline.

How to solve the challenge?

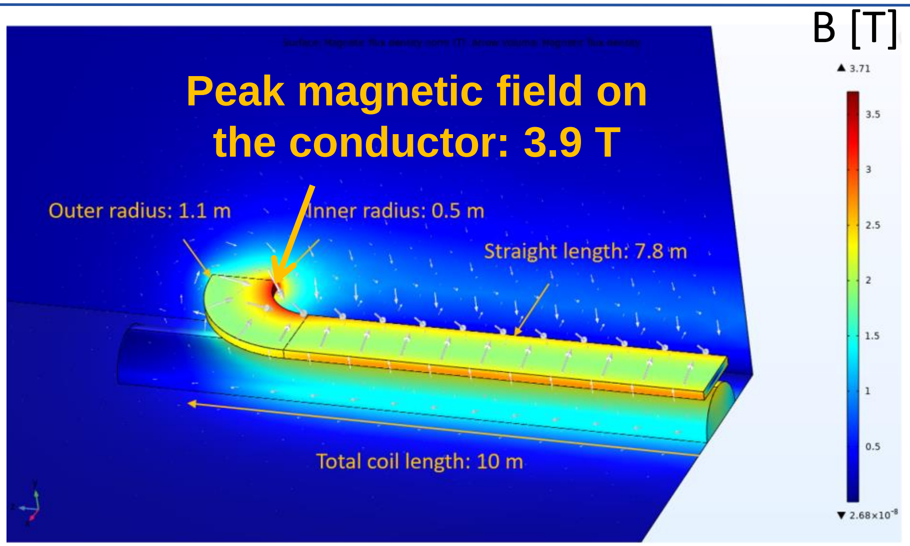
- Currently, an effort is on-going to see if availability may be re-established, featuring a collaboration of various departments at CERN: Experimental Physics (Context: EP R&D WP8), Engineering, and Technology departments, as well as KEK.

Superconducting Detector Magnet Workshop, 12/9/22 – 14/9/22, in hybrid format, with 90 participants (57 on-site, 33 online) from 36 institutes and companies,

https://indico.cern.ch/e/sdmw

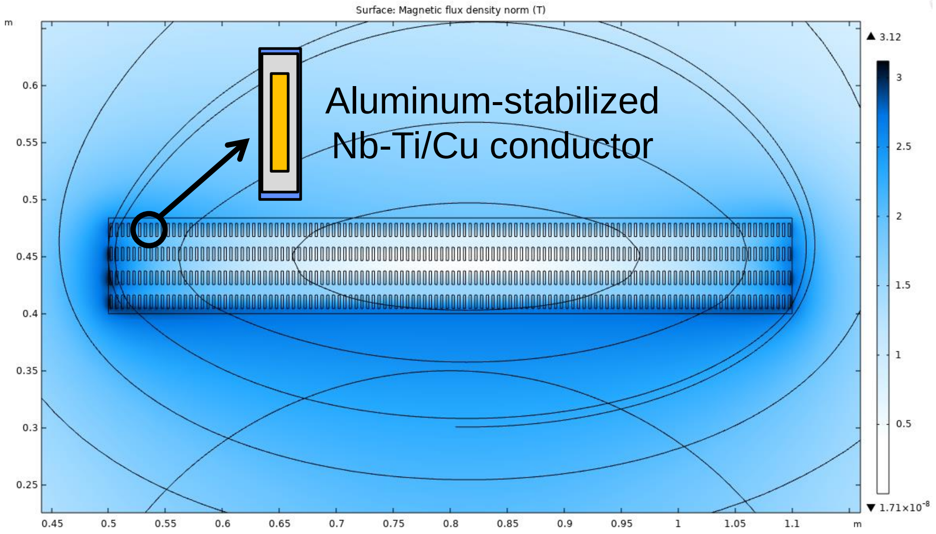
Winding layout

Property	Value
Number of windings per layer	120
Number of layers per coil	4
Number of coils	2
Conductor length, excluding extra lengths for busbars, joints, quality control, etc [km]	20
Inductance [H]	3.1
Nominal operating current [kA]	5
Stored magnetic energy at nominal operating current [MJ]	38
Peak magnetic field at nominal operating current [T]	3.9



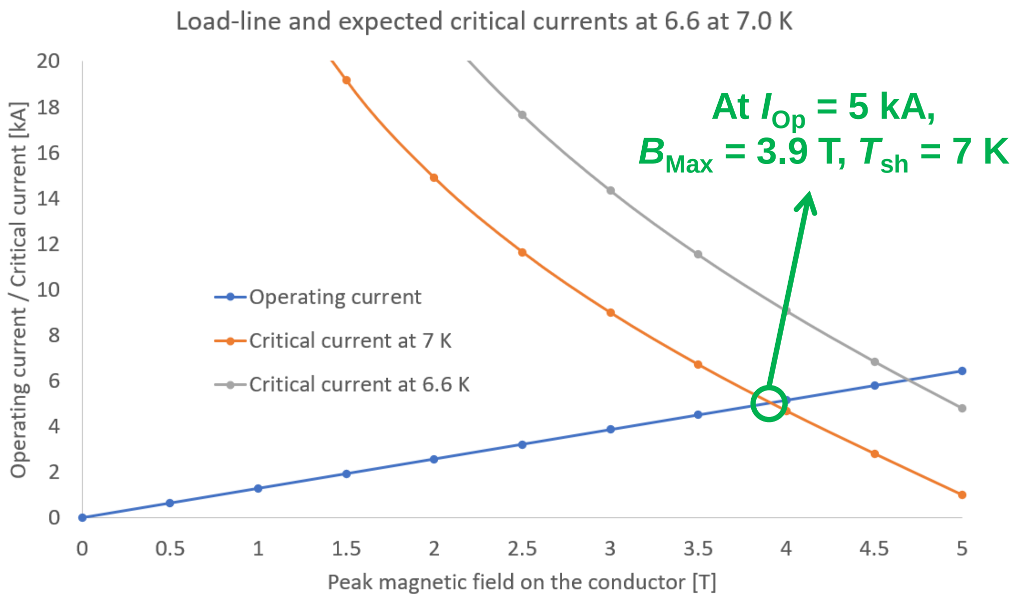
3D Representation of 1/8th of BabyIAXO, homogeneous current density

- 20 km of aluminum-stabilized conductor is needed + some additional length for busbars, joints, quality control, etcetera.
- Peak field in case of theoretical homogeneous current density: 3.7 T (in the turns of the coil)
- Additional self-field contribution due to concentration of current in the center of the conductor: 0.2 T
- **Peak magnetic field in the conductor at the nominal operating current of 5 kA: 3.9 T**



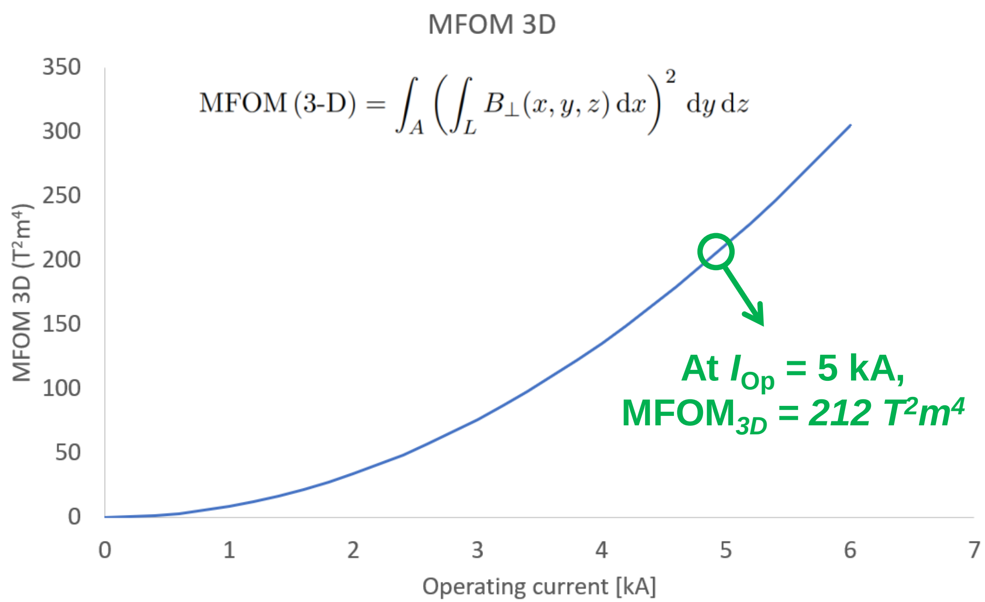
Cross-section of the winding

Implications on Conductor and Magnet Performance



At I_{Op} = 5 kA,
B_{Max} = 3.9 T, T_{sh} = 7 K

Magnet load line and conductor performance



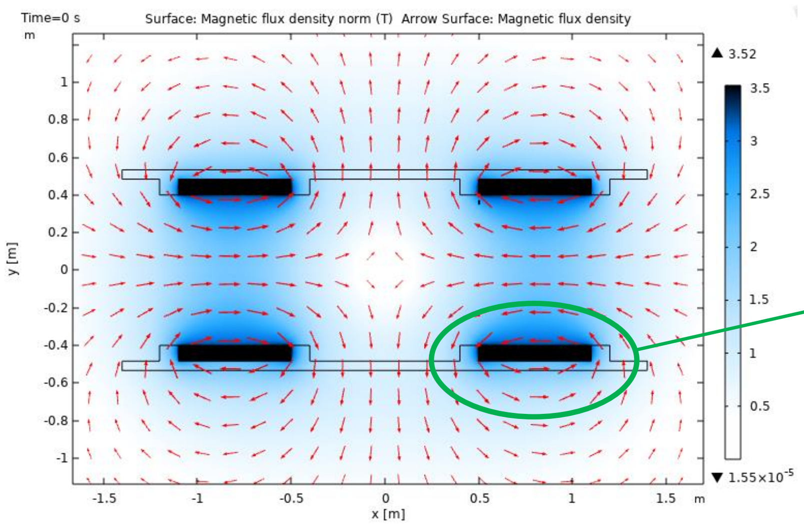
$$\mathrm{MFOM\,(3\text{-}D)} = \int_A \left(\int_L B_\perp(x,y,z)\,\mathrm{d}x \right)^2 \mathrm{d}y\,\mathrm{d}z$$

At I_{Op} = 5 kA,
MFOM_{3D} = *212 T^2m^4*

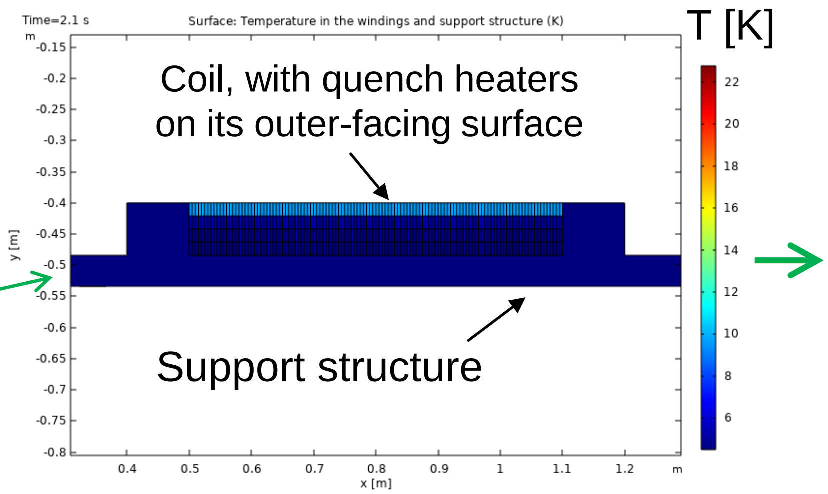
MFOM_{3D} as a function of operating current

- The nominal operating current is defined by the operating temperature (5 K) and a conventional temperature margin (2 K), giving a current sharing temperature of 7 K and a resulting magnet performance MFOM_{3D} of 212 T^2m^4.
- If the construction quality of the magnet and its components is very good, additional performance may be attained beyond the nominal operating current of 5 kA.
- To allow for a possible operating current beyond 5 kA, all components are checked for compatibility with an operating current of 6 kA (which would give MFOM_{3D} at 6 kA = 305 T^2m^4).

Quench behaviour (1/2)



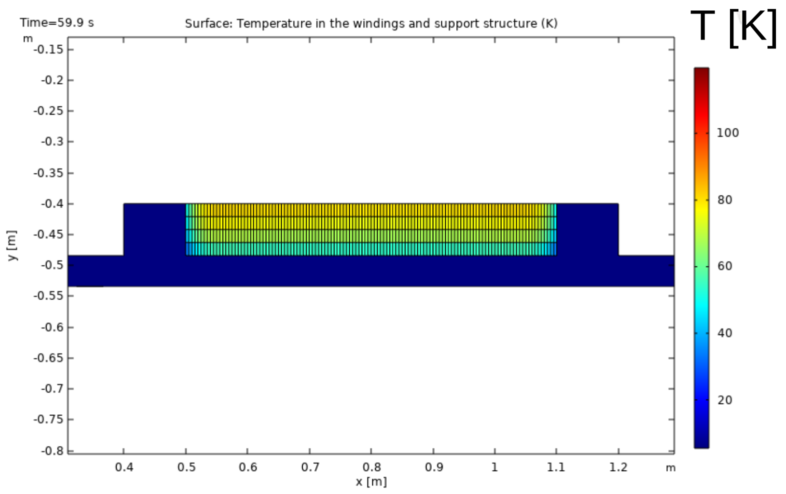
Cross-section of the magnet with magnetic field, at t = 0 s, I_{Op} = 6 kA



Coil, with quench heaters on its outer-facing surface

Support structure

After 2.0 s, the quench is detected and validated, the quench heaters are fired, and the inner-facing layers are quenched

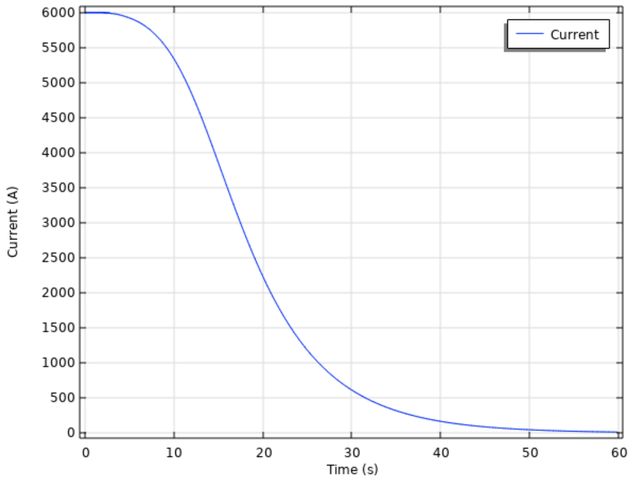


After 60 s, the stored magnetic energy is dissipated over the magnet

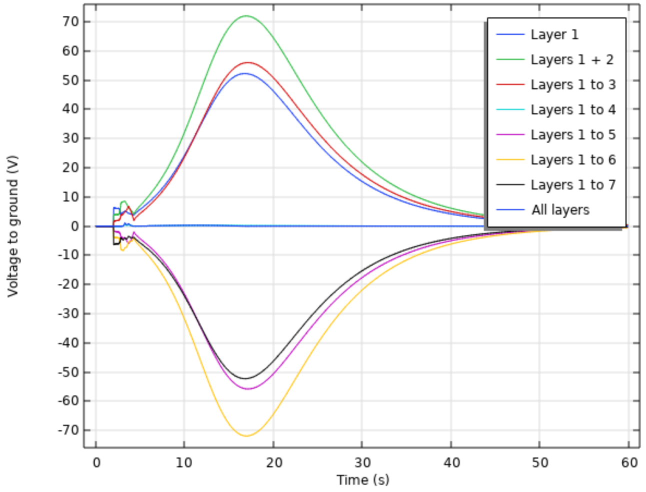
- Superconducting (detector) magnets feature very high current densities, so in case of a sudden local loss of superconductivity (i.e. a so-called quench), the quench must be quickly detected, and the magnet must then be quickly discharged to prevent permanent damage.

- This means for BabyIAXO:
  - Quench detection and validation through the continuous automatic monitoring of voltages over the coils
  - In case of a quench detected: Automatic discharge of quench heaters to quickly induce a controlled normal-conducting zone in the magnet
  - Result: The stored magnetic energy is homogeneously dissipated over a large fraction of the coil windings before permanent damage can occur.

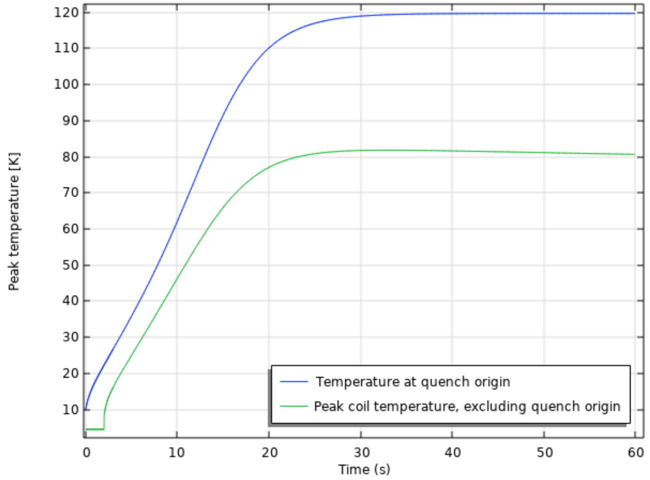
Quench behaviour (2/2)



Current discharge after the quench



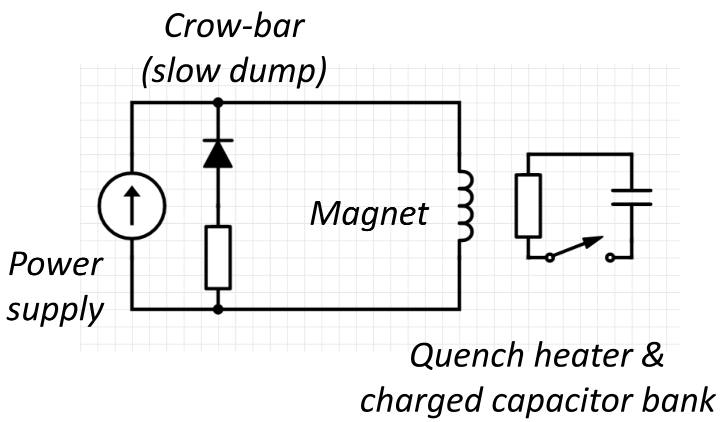
Internal voltages during the discharge



Resulting peak temperatures

The simulation results show that, even at ultimate current (I_0 = 6 kA):

- The resulting temperature at the quench origin is 120 K, and the peak temperature in the coil excluding the quench origin is at 80 K.
- Despite eddy currents, the support structure does not heat up significantly, and so ΔT ≈ 80 K. However, this is acceptable since the linear expansion coefficient of aluminum is low at T < 100 K → Acceptable stresses expected during a quench discharge.
- The internal voltages in the coil stay below 100 V, which looks correct.
- The total voltage over the coil is always (very close to) 0 V, which means that the health and safety risks associated to (exposed) normal-conducting busbars are modest.



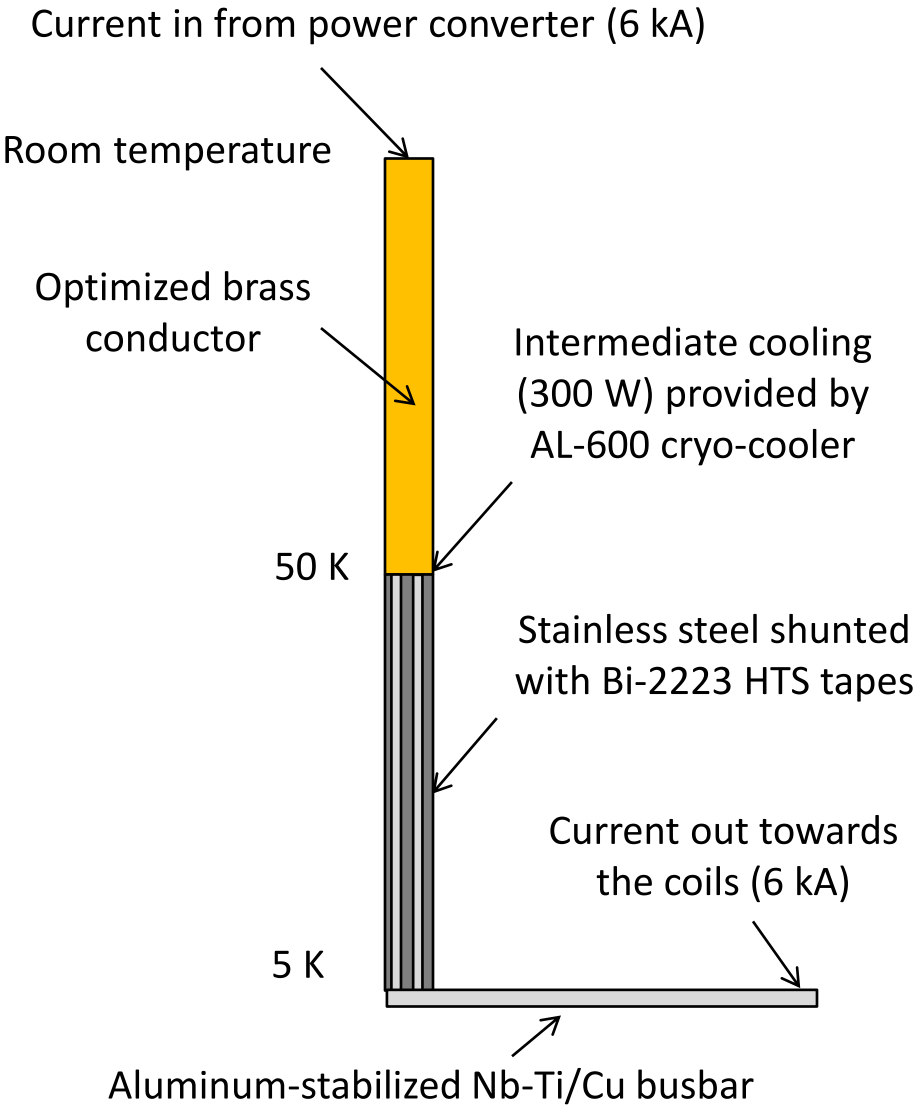
→ This all looks as it should be for a superconducting detector magnet!

Current leads

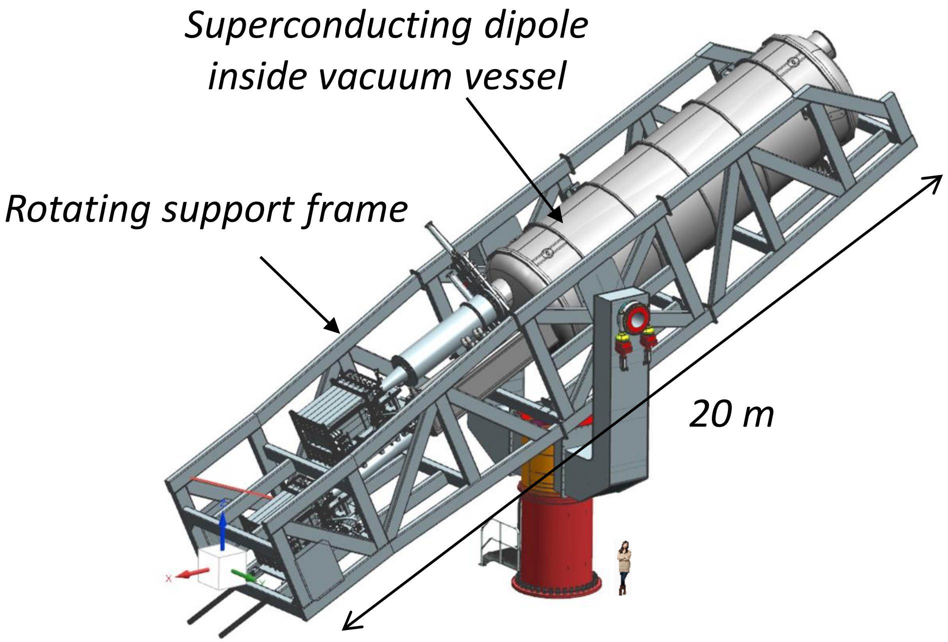
- The current leads allow current to flow from room temperature to 5 K → A thermally efficient design is required to minimize heat load onto the cold mass.

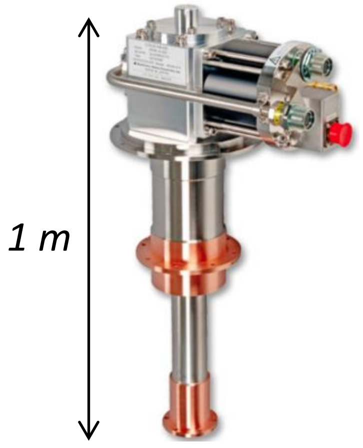
- Solution under investigation:
  - Intermediate cooling at 50 K with one Al-600 cryo-cooler for each current lead, to intercept most of the heat from room temperature
  - 300 K → 50 K: Optimized brass conductor gives about 300 W of heat load at 50 K per current lead for a maximum operating current of 6 kA, to be cooled away by the cryocoolers.
  - 50 K → 5 K: High-temperature-superconducting tapes shunted with a stainless-steel rod
    - Continuous quench detection over the HTS tapes
    - Sufficient stainless steel thermal mass and electrical conductance to survive a quench-heater-induced fast discharge, in-case the HTS tapes quench
    - Longer stainless-steel piece gives lower heat load onto the cold mass, and a heat load well below 1 W per current load looks feasible.

- On-going effort: Soldering trials and definition of geometry



Cryogenics





Cryo-cooler technology

- The detector hall where the experiment is to be installed does not feature a cryogenic plant. Moreover, the magnet is located on a rotating platform, and getting liquid helium to the magnet is a challenge.
- How to keep it cold?
  - Proposed solution: Cooldown of cold mass and intermediate thermal shields with cryocoolers. This is a first for a magnet of this size
  - Compact and modular solution, but with limited cooling power: 6 cryocoolers give a total cooling power of 4.2 K of 14 W.
  - BabyIAXO magnet: 170 m^2 cold mass surface area → 82 mW/m^2 cooling at 4.2 K, for reference: ATLAS Magnets: ~2500 m^2 cold mass surface area → 6 kW gives 2400 mW/m^2 cooling at 4.2 K.
  - **Cold mass has to be kept cold with a minimal amount of cooling power, which is a key challenge for the BabyIAXO magnet design effort.**

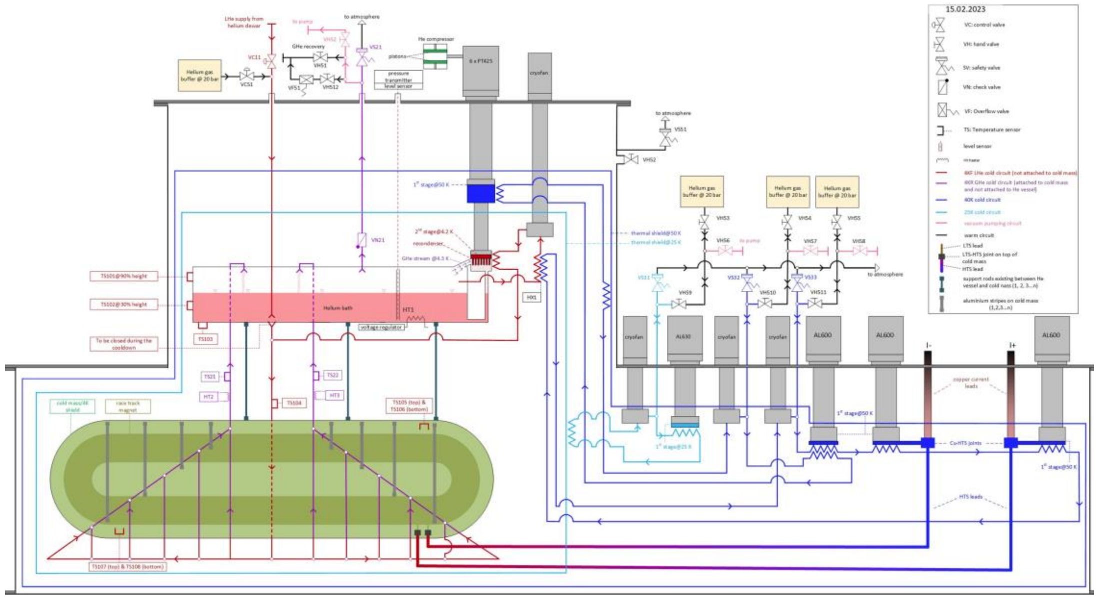
Preliminary cryogenic operational concept (1/2)

How to minimize the heat load onto the cold mass?

- Featuring HTS-based current leads where nearly all heat load is intercepted at 50 K with cryo-coolers (somewhat similar to what is used in the LHC)
- Double concentric thermal shields operating at 50 K and 25 K to minimize the radiation
- Cold mass suspension and instrumentation wiring thermalized to the thermal shields, to minimize the heat load onto the cold mass
- Slow ramp-up and ramp-down (3 hrs) to limit dynamic losses
- A careful accounting of all expected heat loads and losses

How to keep the thermal shields and current leads cold?

- The thermal shields at 25 and 50 K are cooled with helium gas, circulated from the cryocoolers (Al-600 + Al-630) to the shields by cryo-fans (= gas circulation pumps). The 50 K thermal shield also receives cooling from the 1st stage of the six PT425s.
- The current leads are cooled by dedicated cryocoolers (Al-600), intercepting the dissipation and heat load coming from room temperature at 50 K.



Preliminary cryogenic schematic

Preliminary cryogenic operational concept (2/2)

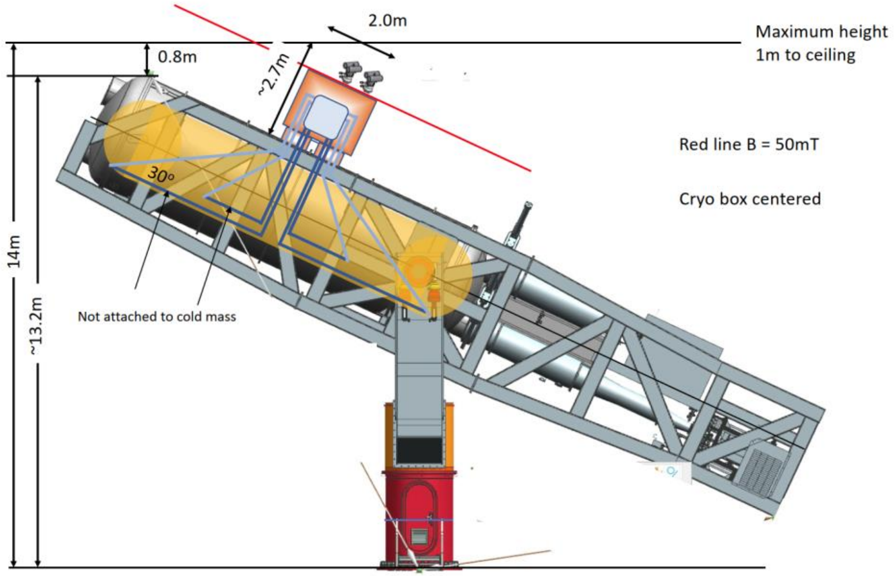
How to keep the cold mass cold?

- The cold mass is cooled by a thermal syphon, where a Dewar filled with liquid helium is located above the cold mass.
- In the Dewar, liquid helium condensation occurs where cooling power (14 W in total at 4.2 K) is provided by six PT425 cryo-coolers.
- The cooling lines are oriented to respect the maximum angle of rotation (25^{o}), and therefore the minimum angle is 30^{o}.
- A cooling line below the Dewar allows for liquid helium flow.
- Angled cooling return lines allows for a mixture of liquid and gaseous helium to return to the dewar.
- The density difference between the liquid and the liquid/gas mixture gives rise to pressure variations and natural gravity-driven circulation with minimal losses.
- The excess liquid in the Dewar provides temporary cooling in case of a power cut.

How to cool down the cold mass?

- Featuring a dedicated cooling line and cryo-fan, allowing all cryocoolers to be used to cool down the cold mass to ~35 K. This cooling line is pumped out during regular operation.
- The remaining cooldown is done by the thermal syphon

→ Promising preliminary concept that addresses the cryogenic challenge, currently under investigation



Sketch of thermal syphon on top of the magnet

Cryogenic overview of losses and cooling power

Heat loads at 50 K	Expected value [W]
Thermal radiation	262
Coil and thermal shield suspension	12
Cryo-fan	35
Current lead heat loads	609
Total expected heat load	**918**
Available	**1470**

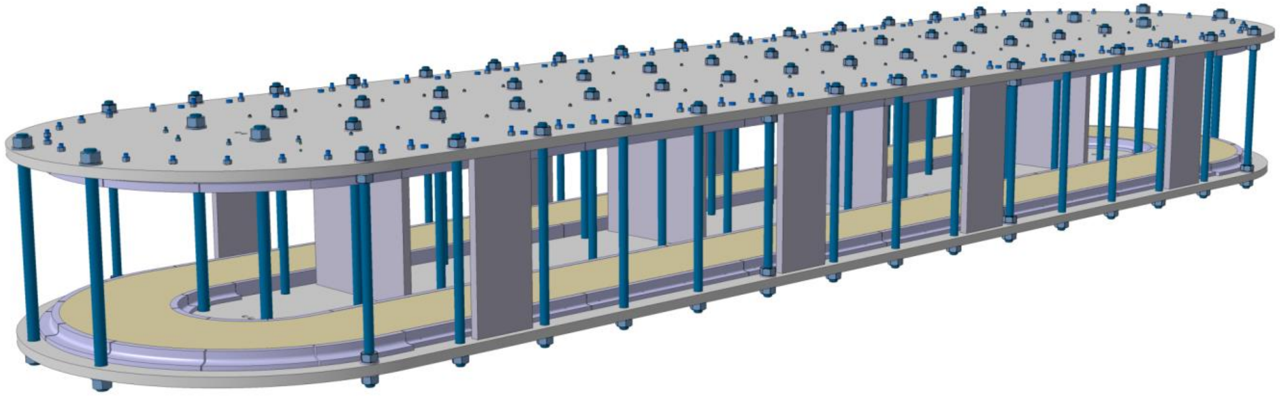
Heat loads at 25 K	Expected value [W]
Thermal radiation	5
Coil and thermal shield suspension	2
Cryo-fan	35
Total expected heat load	**42**
Available	**135**

Heat loads at 25 K	Expected value [W]
Thermal radiation	0.8-4.3
Coil suspension	0.1
Cooling pipe heat loads	0.1
Instrumentation, including heater	1
Current leads	2
Joints	2
Ramping losses (3 hrs)	2
Total expected heat load	**8.0 – 11.5**
Available cooling power	**14.1**

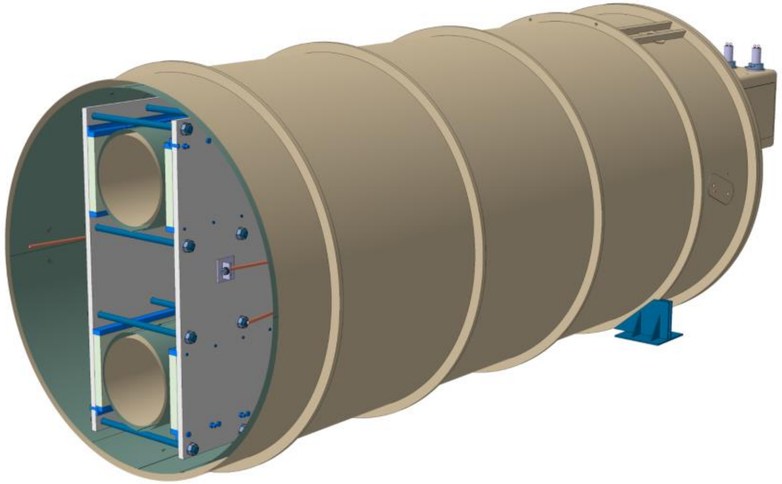
Overview of heat loads

- The preliminary numbers indicate that sufficient cooling power is available.
- This is currently a topic of study, addressed in regular CERN-DESY discussions.

Cold mass, coil suspension, and vacuum vessel



Aluminum-based cold mass support structure



Vacuum vessel, coil suspension, cold mass, and bore tubes

- The coil geometry presented here was optimized to fit in the previously designed preliminary aluminum-based support structure.
- The vacuum vessel design will need to be updated to account for the thermal syphon.
- The cold mass geometry had been frozen due to manpower issues, and this topic is now being resumed.

Object	Weight
Cold mass [t]	17
Thermal shield [t]	1.35
Cryostat [t]	15.2
Total	~34 (+services)

Previously calculated weight estimates

Summary

BabyIAXO experiment:

- Featuring a large superconducting detector dipole, with about 2 T over 8 m3 of free bore volume.
- Design in progress, in a combined CERN/DESY design effort

Key challenges:

- Availability of aluminum-stabilized conductor
  - A workshop was organized to discuss with world-wide colleagues from institutes and industry in Sept 2022
  - Currently, the topic of availability of the conductor topic is being addressed through regular CERN-KEK discussions

- Complex cryogenics featuring cryo-coolers
  - Novel cryogenic design, currently under study
  - The use of cryo-coolers is a first for a magnet of this size

→ Towards a detailed conceptual design