BabyIAXO Axion Helioscope Superconducting Dipole

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BabyIAXO magnet effort, organization

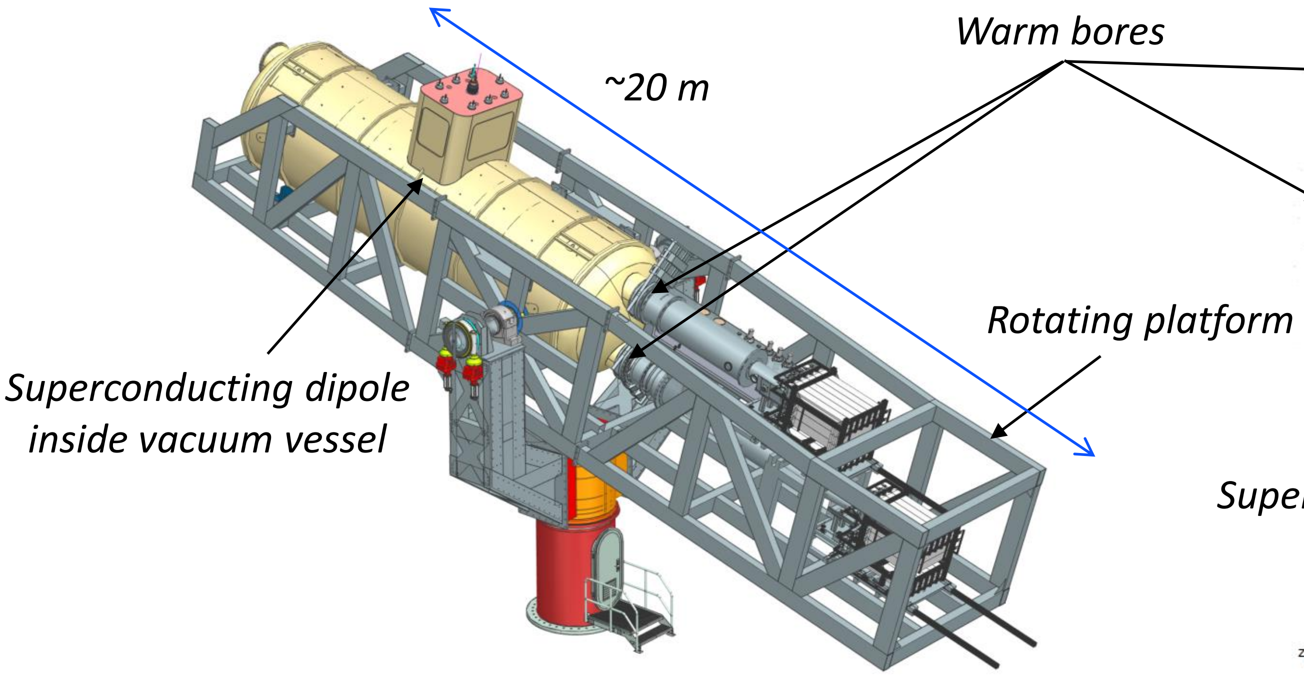
Magnet design

- The magnet conceptual design effort is a collaborative effort, supported by regular CERN-DESY discussions.
- Since October 2023, the design effort is also supported by the Elytt Energy company (team of Julio Lucas). Regular CERN-DESY-Elytt meetings are held to coordinate this ongoing effort.
- Earlier this year, a conceptual design review was organized. Feedback was positive although still homework to do.

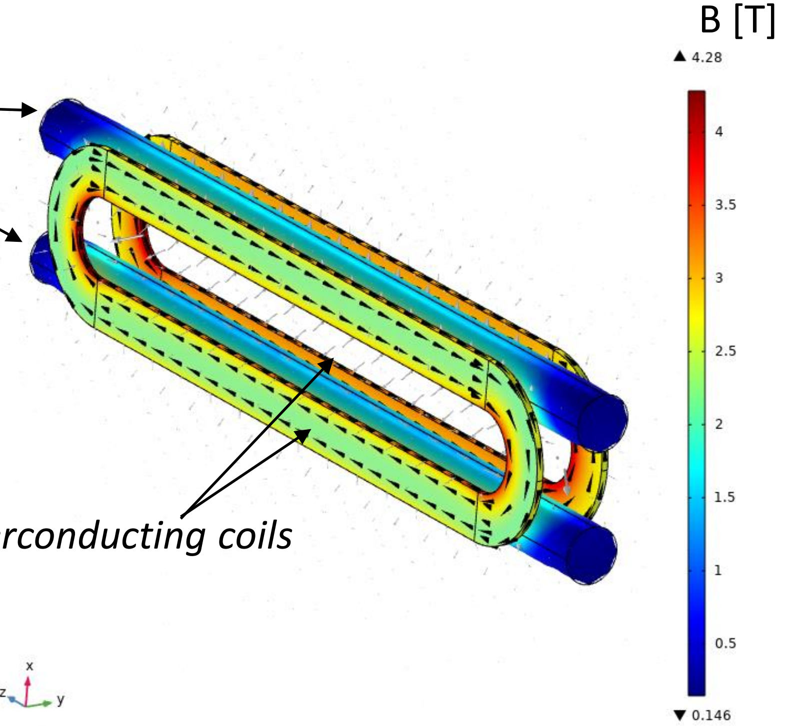
Conductor procurement and qualification effort

- The conductor procurement and qualification effort is a collaborative effort, supported by colleagues of University of Zaragoza and colleagues from the CERN Experimental Physics and Technology departments.

BabyIAXO experiment, introduction



BabyIAXO experiment, to be hosted at DESY



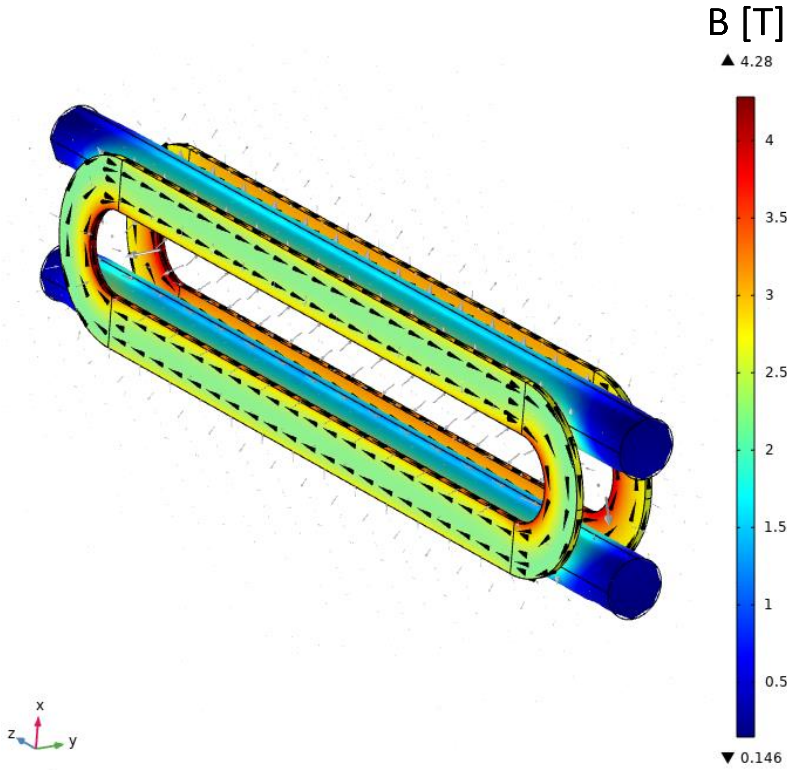
Magnet 3D coil geometry, current direction, and resulting magnetic field

- Searching for axions emitted from the sun.
- Requires transverse magnetic field, for converting axions into photons.
- Sensitivity proportional to length^2, free bore 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.

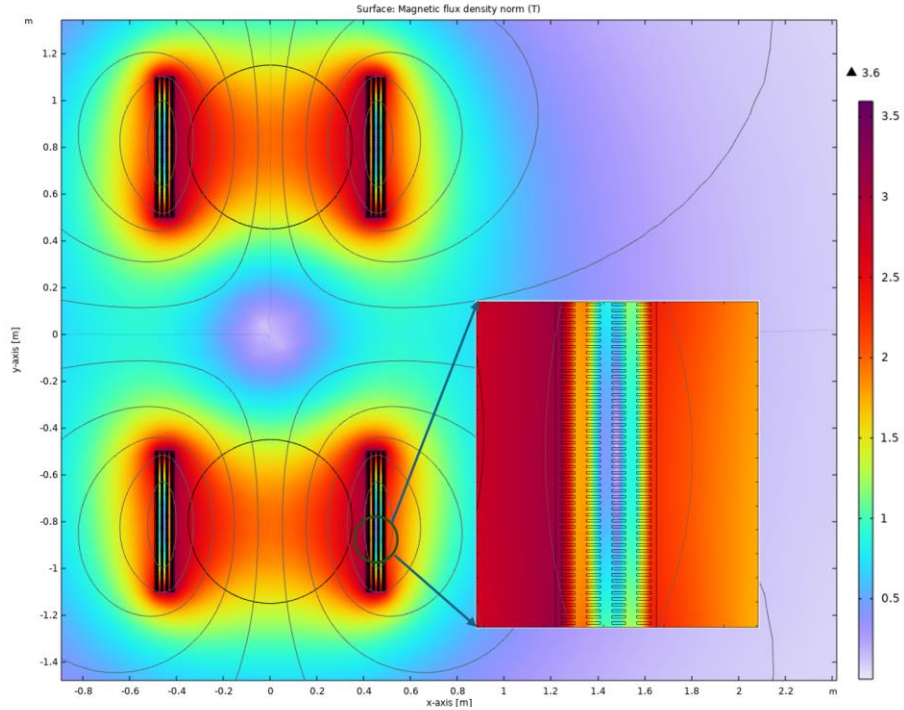
$$\mathrm{MFOM\,(3\text{-}D)} = \int_A \left(\int_L B_\perp(x,y,z)\,\mathrm{d}x \right)^2 \mathrm{d}y\,\mathrm{d}z$$

Magnet-figure-of-merit (MFOM)

Cold mass concept: “Common-coil” geometry



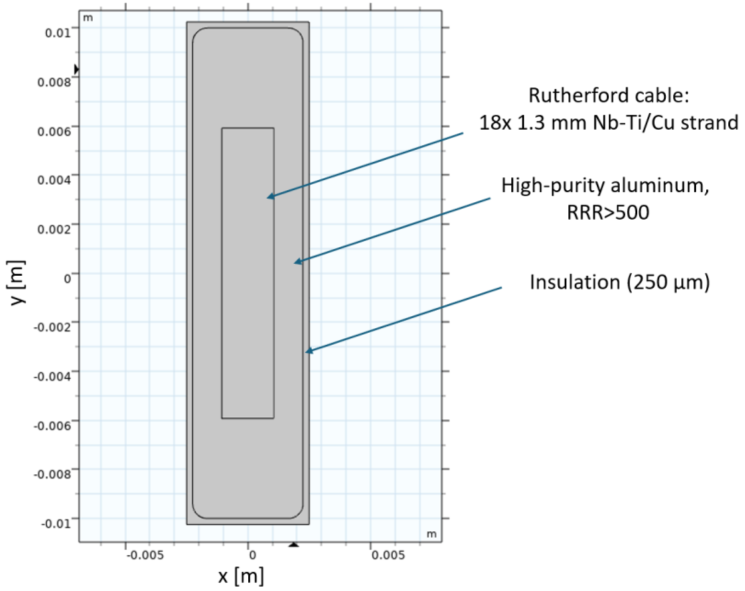
Magnet 3D coil geometry, current direction, and resulting magnetic field



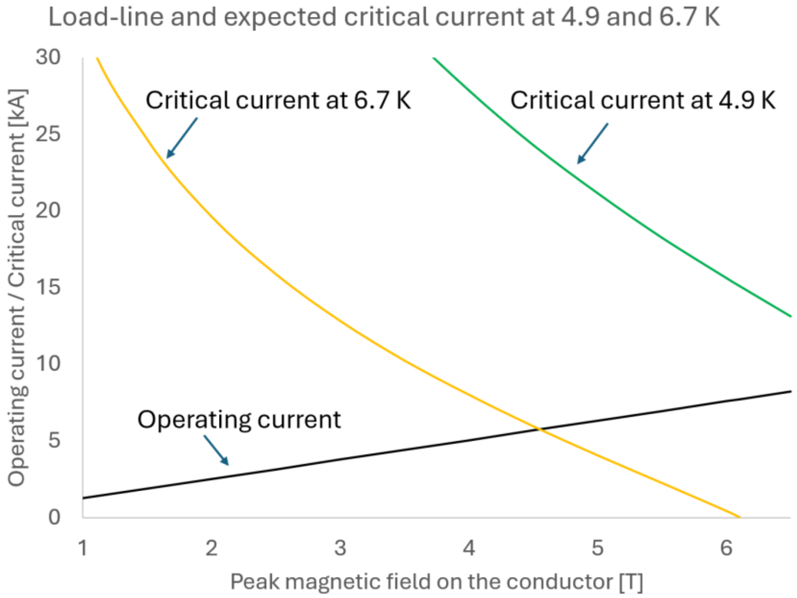
2D cross-sectional figure of the magnet coil geometry, also showing the individual conductors

- Featuring a so-called “Common-coil” geometry, where transverse magnetic fields in the warm bores are being generated by flat race-track coils, and current in the coils on both sides of the cold mass flows in opposite direction.
- Attractive geometry: Flat coils are less complex to fabricate than shaped coils (for example saddle-coils), the force distribution is more homogeneous and thus the risk is lower when compared to alternatives.

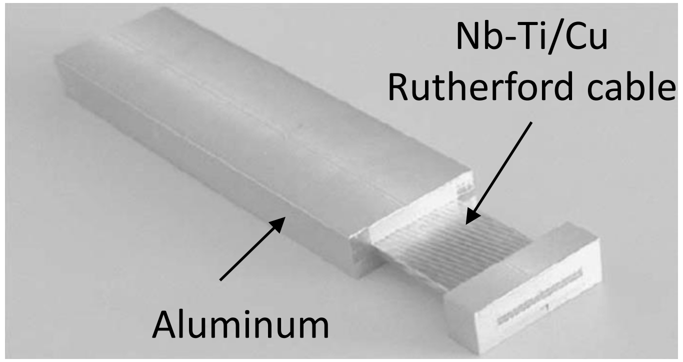
Conductor technology



Conductor geometry



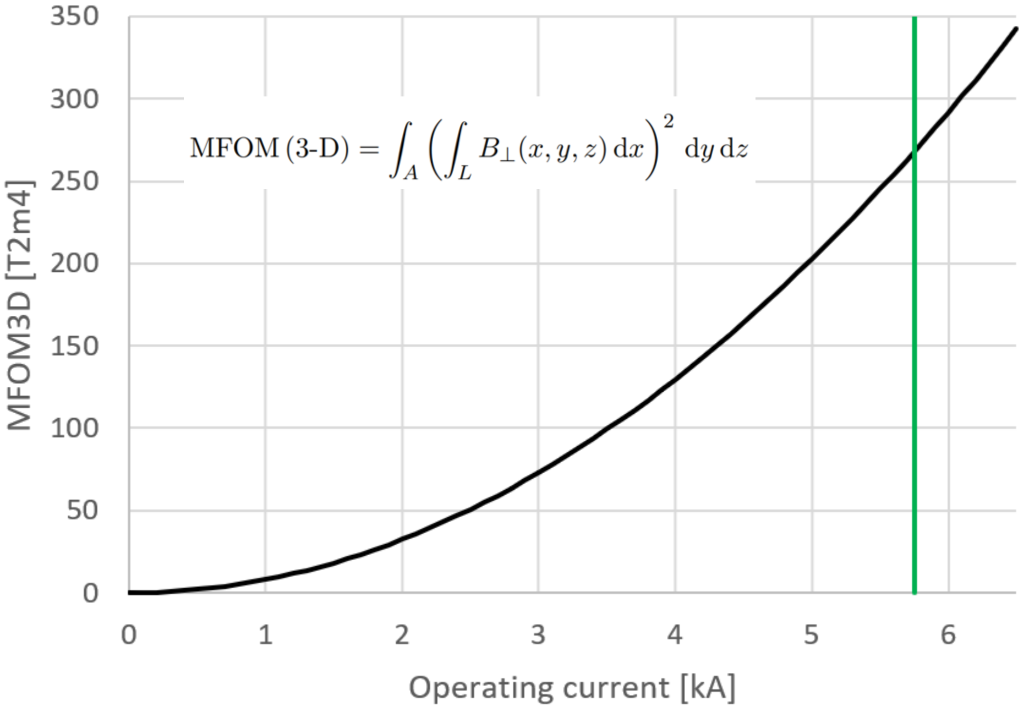
Magnet operating load line



Example of an aluminum-stabilized Nb-Ti/Cu conductor (pull-out sample for CMS)

- The BabyIAXO magnet design features an aluminum-stabilized Nb-Ti/Cu conductor, a “standard” conductor technology, historically widely used in conduction-cooled superconducting detector magnets (more on this later).
- Comprising a Nb-Ti/Cu Rutherford cable (flat cable featuring 18 Nb-Ti/Cu strands with a diameter of 1.3 mm) cladded with high-purity aluminum.
- Considering an operating current of 5.75 kA, and a peak magnetic field on the conductor of 4.54 T, the current-sharing temperature (i.e. the temperature at which the critical current matches the operating current) is 6.7 K, and at the operating temperature the conductor is operated at 62% of the load-line.

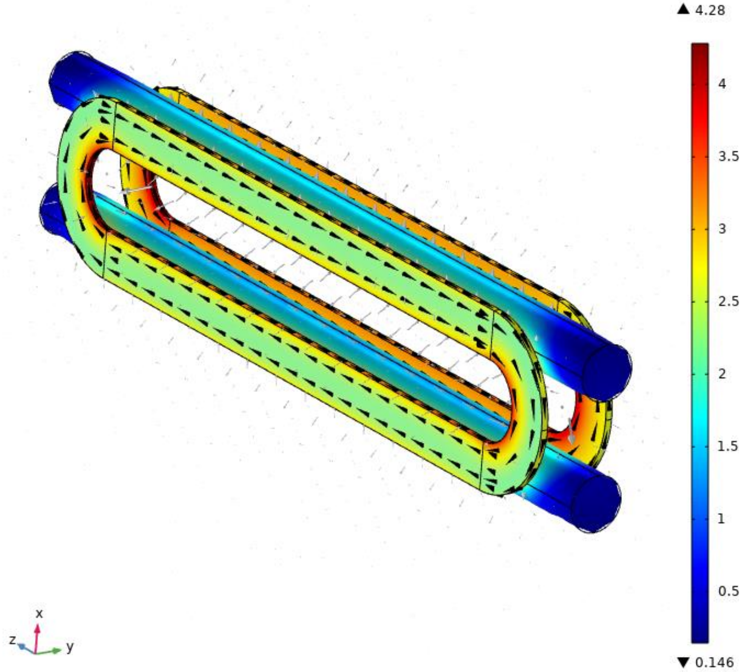
Magnet Figure of Merit



MFOM-3D as a function of current

- Metric for the useful magnetic field component: the so-called Magnet-Figure-of-Merit.
- When powered at the operating current of 5.75 kA, on average, the coils generate 2 T in the warm bores.
- **Resulting Magnet-Figure-of-Merit at 5.75 kA: 268 T^2m^4**

Overview of typical parameters

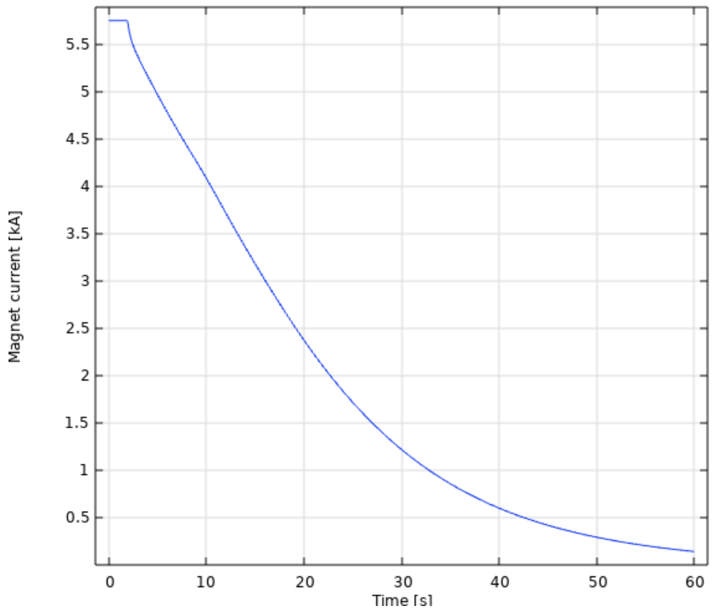


Magnet 3D coil geometry, current direction, and resulting magnetic field

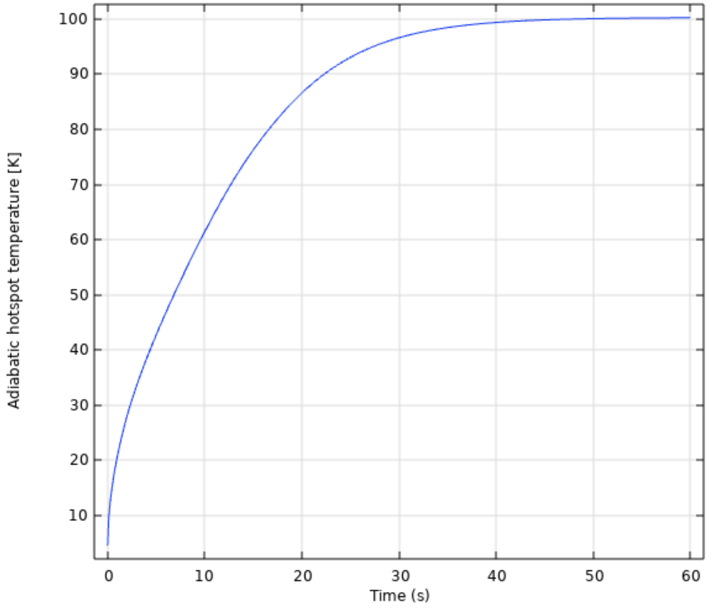
Parameter	Value
Operating current [kA]	5.75
Free bore diameter	0.7
Transverse magnetic field during operation [T]	2.0
Stored magnetic energy [MJ]	51
Inductance [H]	3.1
Cold mass weight [tons]	26
Energy density [kJ/kg]	2.0
Overall coil conductor length, excluding busbars, joints, etc. [km]	19.8
Conductor length per pancake [km]	2.5
Peak magnetic field magnitude on the conductor, including self-field [T]	4.54

- 22 km of aluminum-stabilized conductor is needed.
- When powered at 5.75 kA, the resulting stored magnetic energy is 51 MJ.

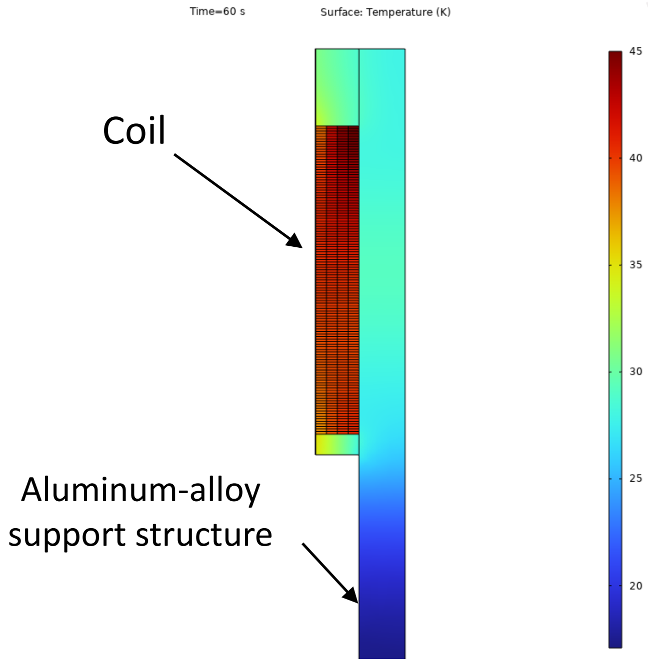
Quench detection and protection



Fast Dump current discharge



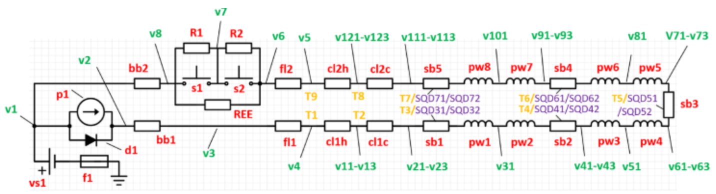
Adiabatic hotspot temperature



Coil temperature after Fast Dump

Conventional approaches are used for magnet quench detection and protection:

- Quenches are detected and validated using inductively balanced voltage taps.
- After quench detection and validation, the magnet is discharged over a redundant energy extraction system, giving 700 V to ground.
- The resulting hotspot temperature is 100 K, while the rest of the coil reaches 45 K. 80% of the stored magnetic energy is dissipated in the dump resistor.



Powering circuit

Novel aspect of the BabyIAXO magnet design: Integrated Cryogenics

Integrated cryogenics:

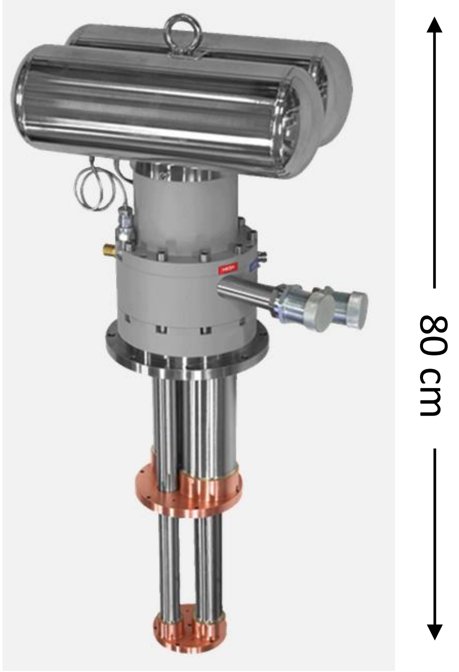
- Using cryo-coolers integrated into the magnet vacuum vessel itself, rather than an external cryogenic plant.

Motivation for integrated cryogenics

- The BabyIAXO magnet will be in an area without a cryogenic plant at DESY → Externally supplied liquid helium is unavailable.
- Located on a rotating platform, complicating the supply of liquid helium to the magnet.

What are advantages / disadvantages of integrated cryogenics using cryocoolers?

- Disadvantage: The design of the magnet and the cryogenic “plant” is combined into one, adding to the complexity of the design (for example considering cryocooler magnetic-field sensitivity)
- Disadvantage: The cooling power and efficiency of cryocoolers is modest (although improving in recent years), and so the magnet design must be compatible with a minimal cooling budget and local space-considerations.
- Advantage: Cryocoolers give modularity and redundancy advantages.
- Advantage: Long cooling lines and associated losses are avoided.
- Advantage: Less overall space is needed.
- Advantage: Cryocoolers themselves do not feature internal liquid helium, and so the overall use of helium (a non-renewable resource) is kept at a minimum.



Example of a cryocooler (PT425)

Elements to be cooled and cooling methods

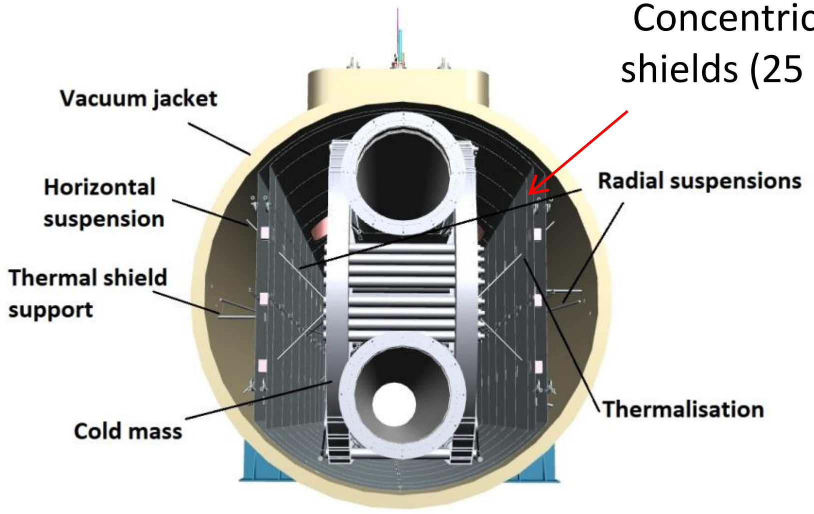
Multiple elements to be cooled:

- Cold mass at T < 5 K → Cooled with liquid helium from phase separator via thermosiphon.

- Two concentric thermal shields, to mitigate low cooling budget at 4.5 K
  - 25 K thermal shield → Cryocooler + helium-gas cooling, circulated with cryo-fan.
  - 50 K thermal shield, intercepting most of the thermal radiation from room temperature → Cryocoolers + helium-gas cooling, circulated with cryo-fan.

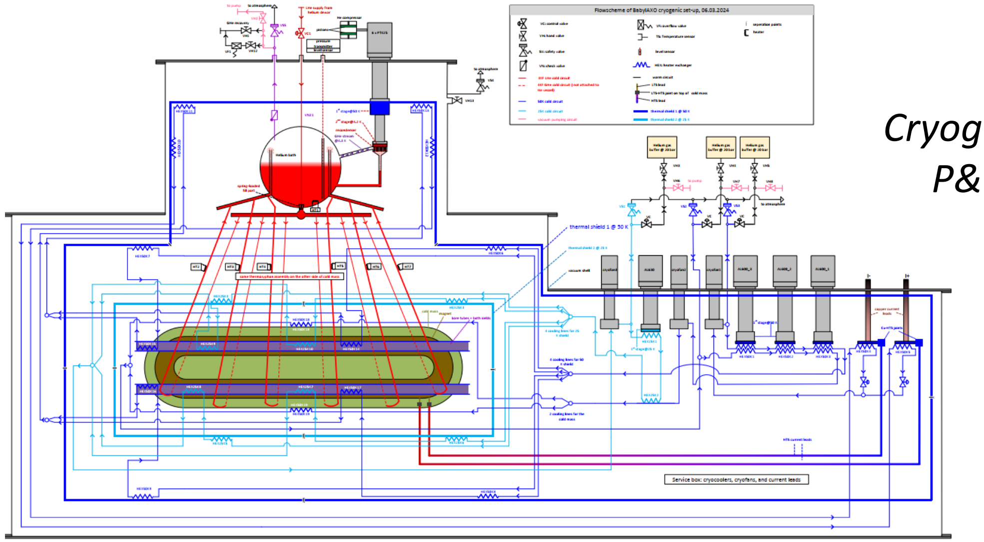
- HTS-based current leads, using 50 K helium-gas cooling loop to intercept heat and limit the heat load onto the cold mass.

- During initial cooldown: Dedicated cooldown circuit, combining cooling power from most cryocoolers to cool the cold mass, pumped to vacuum during regular operation.



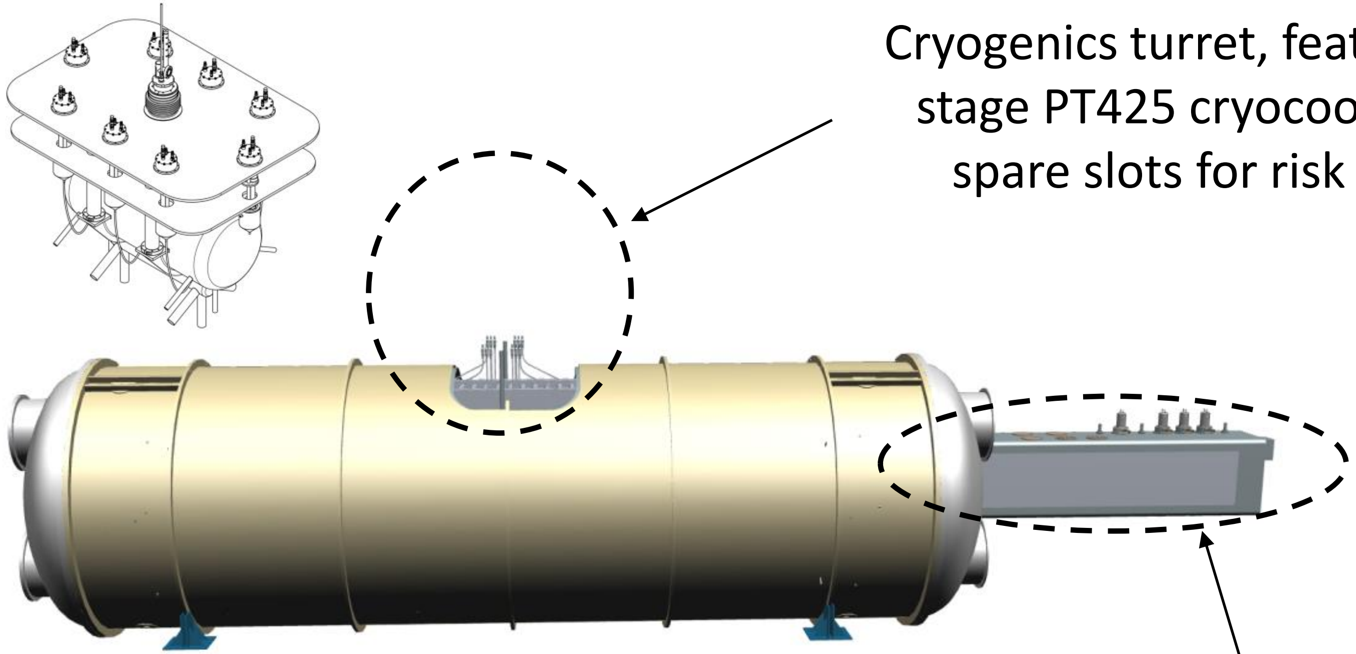
Concentric thermal shields (25 and 50 K)

Cold mass, concentric thermal shields and coil suspension

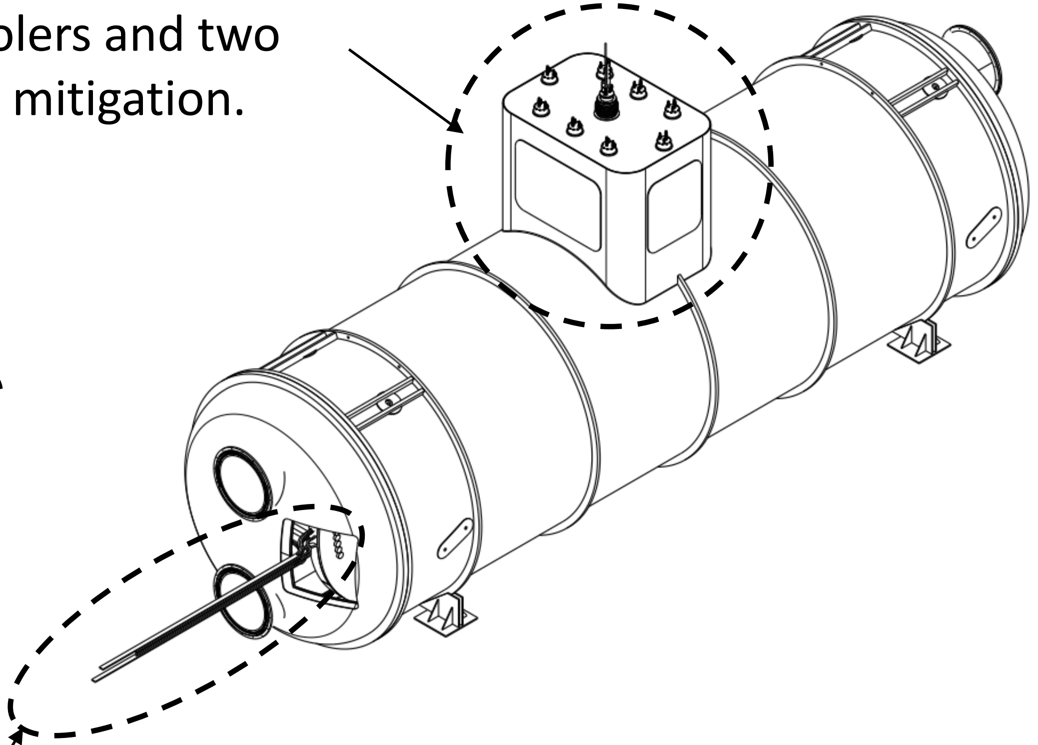


Cryogenics P&ID

Cryogenics layout of BabyIAXO magnet



Cryogenics turret, featuring six two-stage PT425 cryocoolers and two spare slots for risk mitigation.



Two main cryogenic elements:

- Cryogenics turret, providing thermosiphon liquid helium cooling (4.5 K).
- Service box, providing gaseous helium cooling (25 and 50 K).

Service box, featuring three Al-600 cryocoolers, one Al630 cryocooler, and three cryofans for helium gas circulation, as well as HTS-based current leads and vacuum pumps.

Heat loads and available cooling budget

Heat-load type at 4.5 K	Value [W]
Instrumentation	< 1
Conduction cooling through cooldown circuit	< 0.5
Joint dissipation, excluding current leads	0.33
Cold mass suspension	0.32
Thermal radiation onto cold mass	1.0
Thermal radiation onto phase separator	0.6
Current-leads	2x 0.62
Eddy-currents during ramp-up / slow dump	1.6
Sum	**6.6**
Available cooling power at 4.5 K	**14.1**

- Concentric thermal shielding (at 50 and 25 K) to intercept >99% of the total heat load.
- **Conceptual design result: At each cooling stage, sufficient power + margin is available to maintain superconductivity.**
- Looks OK on paper, but how to validate the design?

Heat-load type at 25 K	Value [W]
Cold-mass suspension	4.6
Thermal radiation onto shield	27
Thermal-shield suspension	20
Thermal interception of instrumentation heat loads	< 5
Cryofan	23
Sum	**80**
Available cooling power at 25 K	**135**

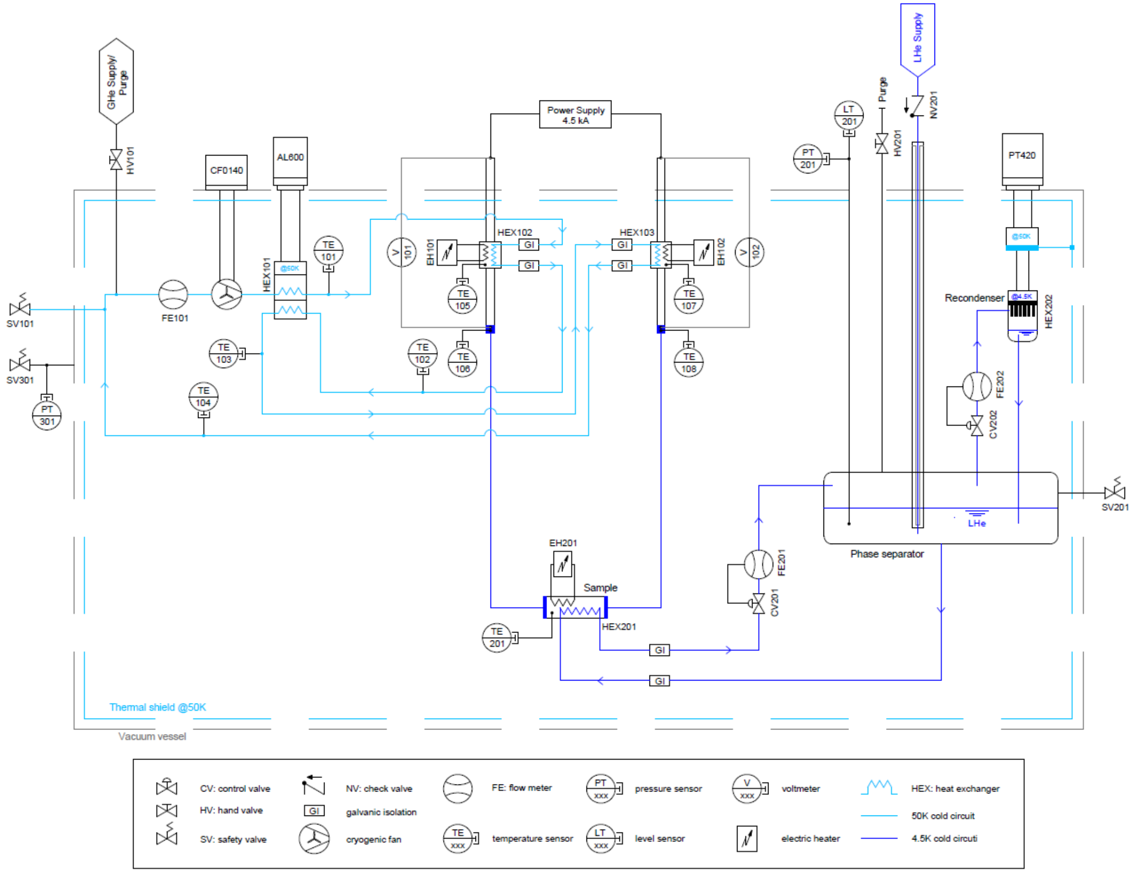
Heat-load type at 50 K	Value [W]
Cold-mass suspension	59
Thermal radiation onto shield	280
Thermal-shield suspension	46
Thermal interception of instrumentation heat loads	< 10
Cryofan	83
Current leads	600
Sum	**1078**
Available cooling power at 50 K	**1470**

R&D efforts on integrated cryogenics

- PhD Research “Novel cryogenic solutions for superconducting detector magnets” by Weronika Gluchowska, in collaboration with Wroclaw University (Prof. Chorowski), and in the context of CERN EP R&D WP8.

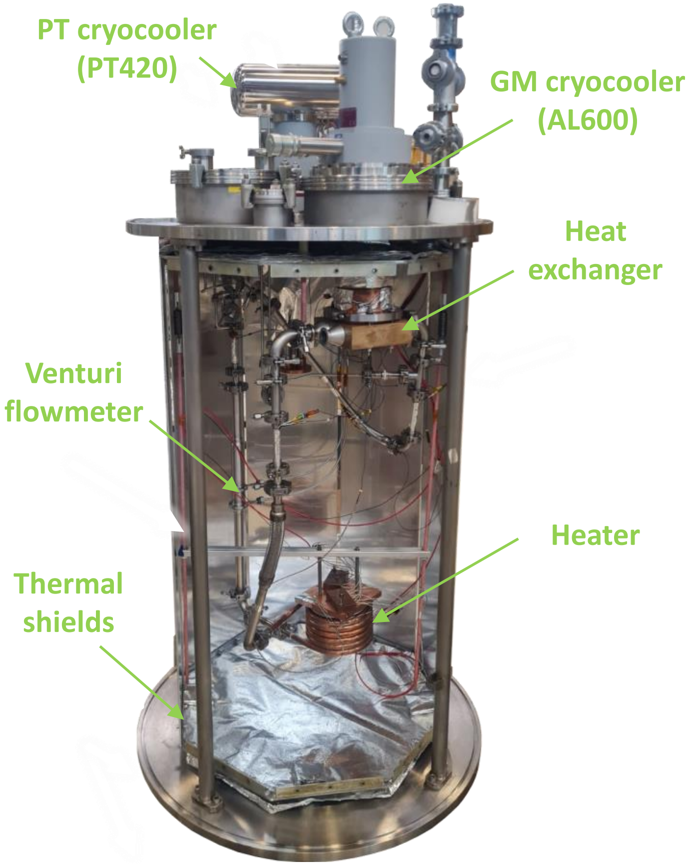
- Demonstrating:
    - Combining helium gas circulation with cryocoolers and HTS-based high-efficiency high-current leads.
    - Featuring local cryocooler-based liquid helium liquefaction and thermal syphon.
    - **Compact Zero-boil-off cryogenics, requiring minimal amounts of helium.**

- Objective: To develop and demonstrate technology for the BabyIAXO magnet and future similar magnets.

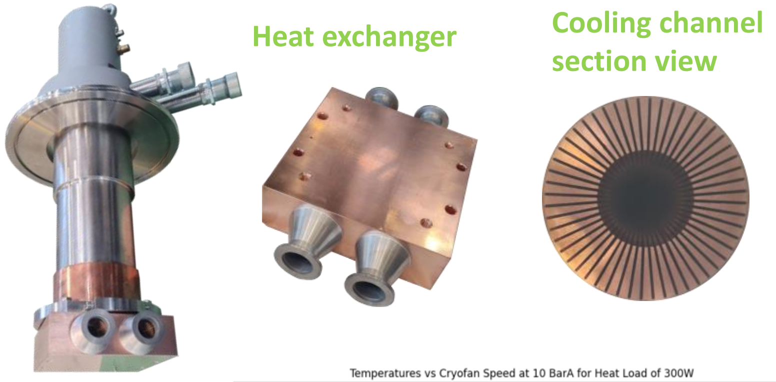


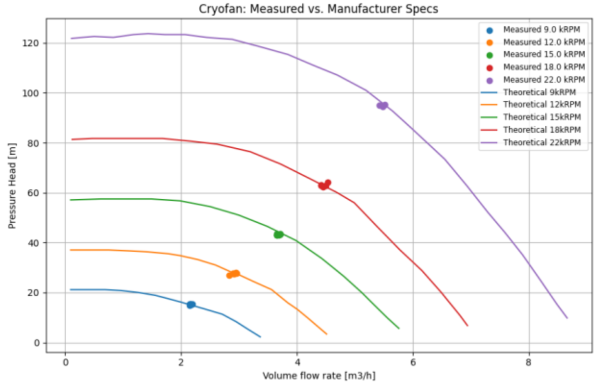
R&D results so far

Experimental installation

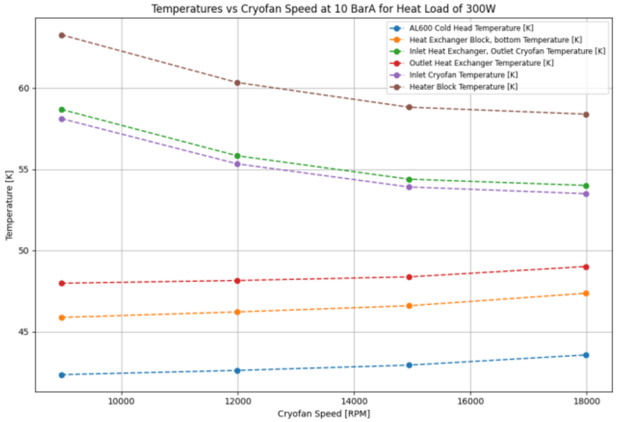


Developed and experimentally demonstrated thermal interface and heat exchanger technology

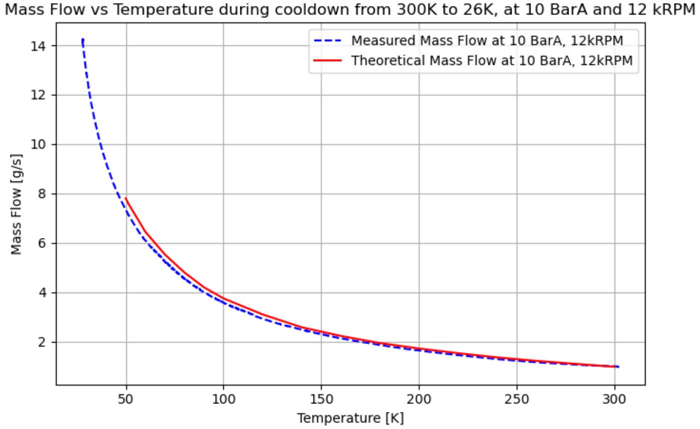




Measurements vs. manufacturer specification



Various experimental observations

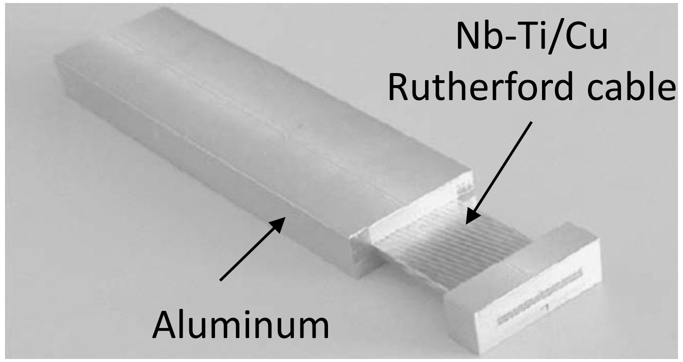


Measured vs. expected mass flow

- First stage of the experiment completed and tested: Cryocoolers + heat exchangers + gas circulators + heaters
  → **Excellent results, showing that the concept works.**
- Next step: Addition of HTS-based current leads in the demonstrator.

Conductor availability

- **Aluminum-stabilized Nb-Ti/Cu: Traditional “workhorse” conductor for conduction-cooled superconducting detector magnets**
- **In recent years**, the companies historically producing this conductor type have **discontinued production**.
- In the context of **CERN EP R&D**, CERN is partnering with industry to produce trial lengths of aluminum-stabilized Nb-Ti/Cu conductor. Industrial partner candidates have been identified and visited, and technical aspects have been discussed and documented.
- A Chinese company has notified us in Sept. 2023 that they are **ready to produce aluminum-stabilized Nb-Ti/Cu conductors commercially.**
  - Samples of a previously produced conductor have been received
  - The IAXO collaboration is in contact with this company and actively possibilities.
- For the BabyIAXO magnet, **Nb-Ti/Cu Rutherford cable** (core of the conductor, ~40% of total needed length) has been ordered
  - Several meetings were held with the manufacturer with support of colleagues from CERN TE-MSC.
  - A visit to the manufacturers will take place in the coming time.



Example of an aluminum-stabilized Nb-Ti/Cu conductor (pull-out sample for CMS)

Summary

- **Design and conductor efforts**
  - Ongoing effort towards a detailed design. The design effort is supported by colleagues from CERN, DESY, and Elytt Energy.
  - The effort to procure a conductor is supported by colleagues from University of Zaragoza, the CERN Experimental Physics department, and the CERN TE-MSC group.

- **Novel cryogenics concept**
  - The BabyIAXO magnet design features integrated cryogenics, where cooling power is provided by cryocoolers.
  - Novel approach, may be very interesting for other future superconducting detector magnets as well.
  - Conceptually studied to ensure sufficient cooling power is available at the different temperature stages.
  - Ongoing effort: Development and demonstration of various associated technologies needed, in the context of CERN EP R&D.

- **Conductor availability, a common issue shared between a variety of superconducting detector magnet projects**
  - The BabyIAXO magnet design features aluminum-stabilized Nb-Ti conductors, a traditional “work-horse” conductor for conduction-cooled superconducting detector magnets.
  - Complication: In recent years commercial availability has been an issue.
  - Therefore:
    - On-going effort to produce trial lengths of conductor in the context of CERN EP R&D.
    - In the last year, commercial availability has been re-established by a vendor, and this option is now under active investigation.