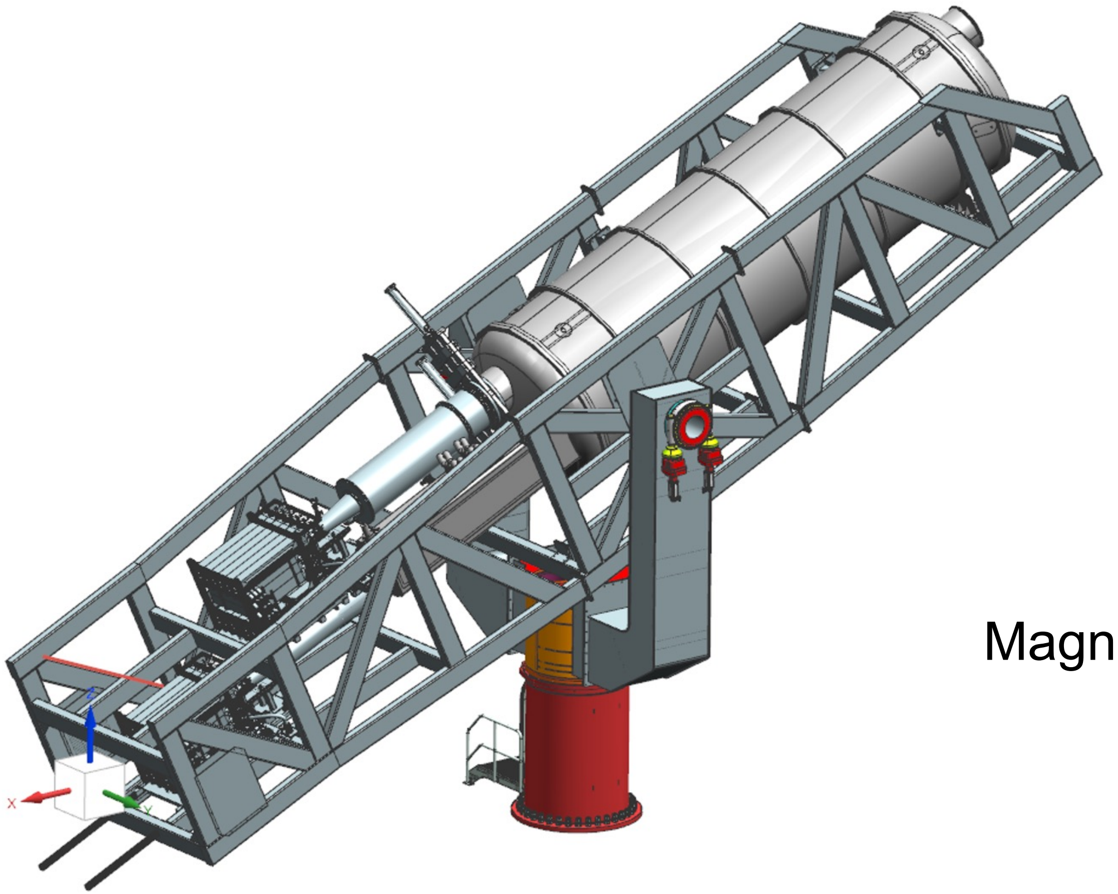
(Baby)IAXO Magnet



Uwe Schneekloth, DESY

SDMW @ CERN
12.09.2022

Magnet design: CERN/ATLAS magnet group

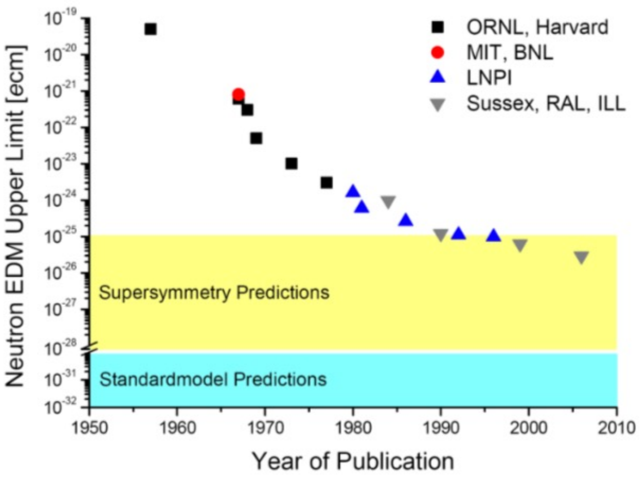
Introduction

Axion Motivation

QCD CP violation

Axion originally proposed to solve Charge Parity violation problem in Quantum Chromo Dynamics (strong interaction)

- QCD Charge Parity violating term
- Expect electric dipole moment of the neutron,
  CP violation phase $\theta \neq 0$,
- Experiment $|d_n| < 3.0\ 10^{-13}$ e fm => $\theta < 10^{-10}$
- New symmetry: $\theta=0$ (Peccei-Quinn 1977), axion (Wilczek)



Dark matter

Standard Model only 15% of matter content in universe. Best motivated candidates those which occur in Standard Model extensions solving also other problems

- Super Symmetry: neutralino
- Strong CP problem: QCD axion

Apart from dark matter, other hints from astrophysics which might be explained by axions

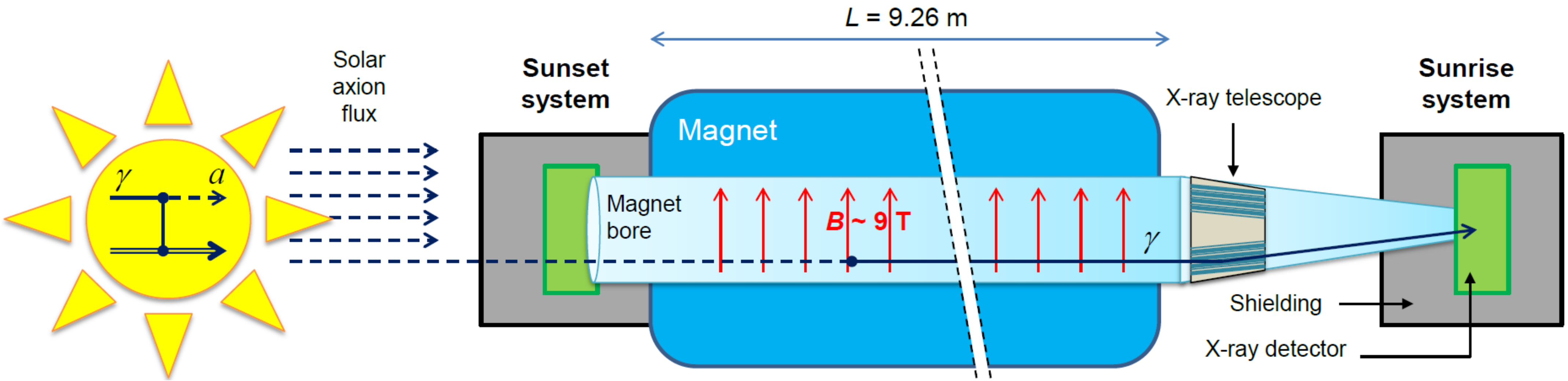
- Excessive energy losses of stars in various stages of their evolution
- Excessive transparency of the universe for TeV gamma ray might be explained by photon - axion conversion

Searches for Solar Axions

CAST, CERN Axion Solar Telescope

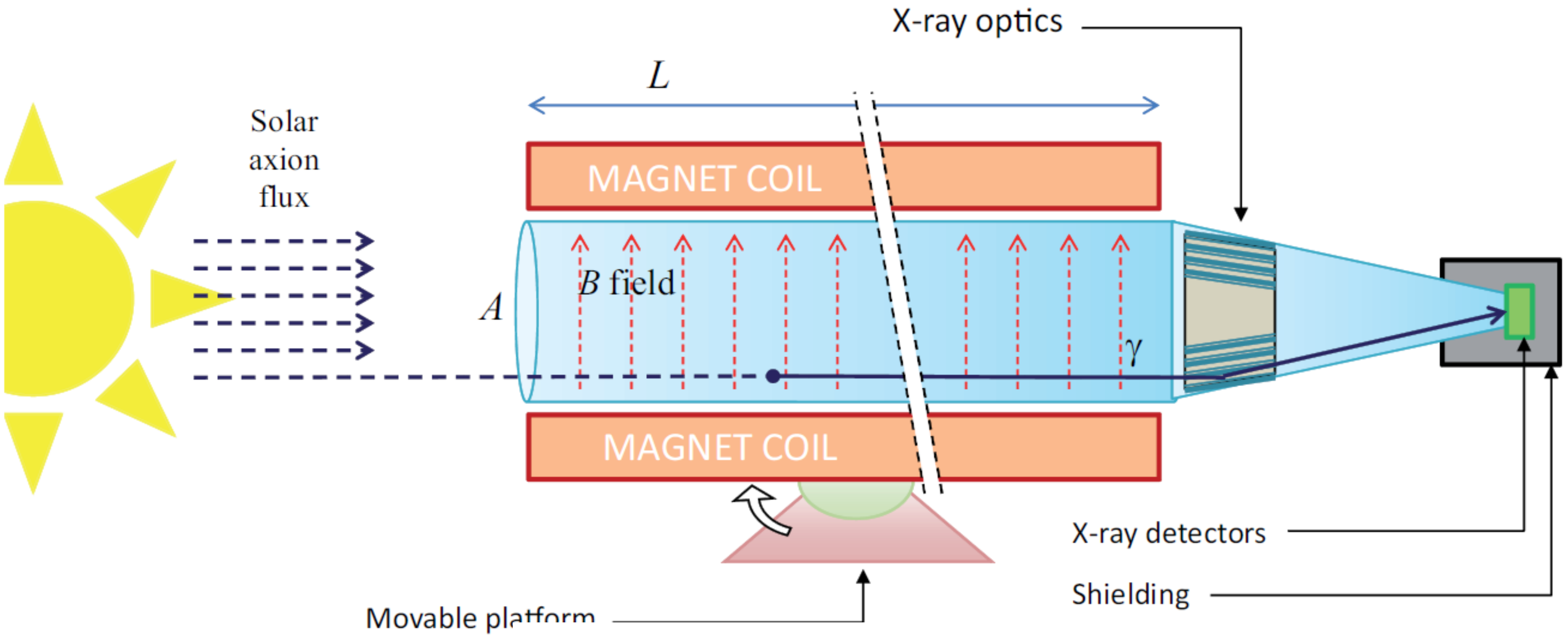
- First helioscope using low background techniques and X-ray focusing
  - Superconducting LHC dipole magnet
  - X-ray detectors
  - Use of buffer gas to extend sensitivity to higher masses (QCD axion band)
- Most sensitive measurements until now

LHC prototype dipole magnet at CERN



Enhanced Axion Helioscope

International Axion Observatory



IAXO conceived as large-scale, realistic enhanced axion helioscope

$>10^4$ better signal to noise ratio than CAST

Sensitive to g_{ag} ~ x20 lower than CAST

Magnet figure of merit

Sensitivity
$$g_{a\gamma}^4 \propto \underbrace{b^{1/2}\epsilon^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2}\epsilon_o^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

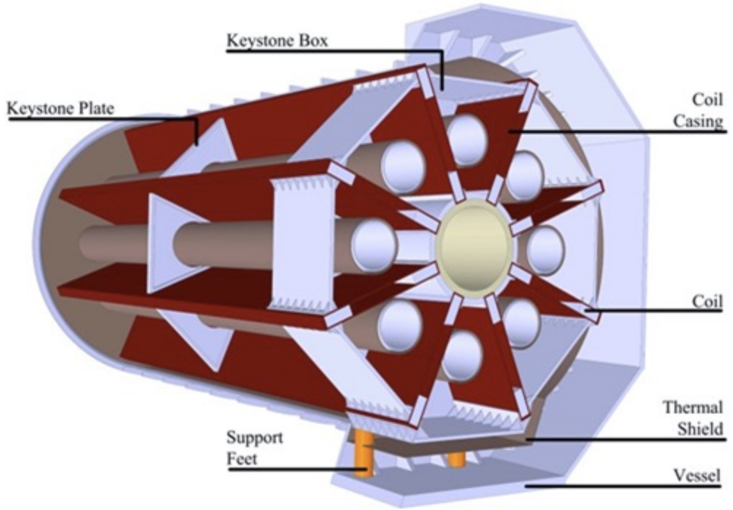
Enhanced axion helioscope: *JCAP1106:013,2011*

International Axion Observatory

IAXO Magnet

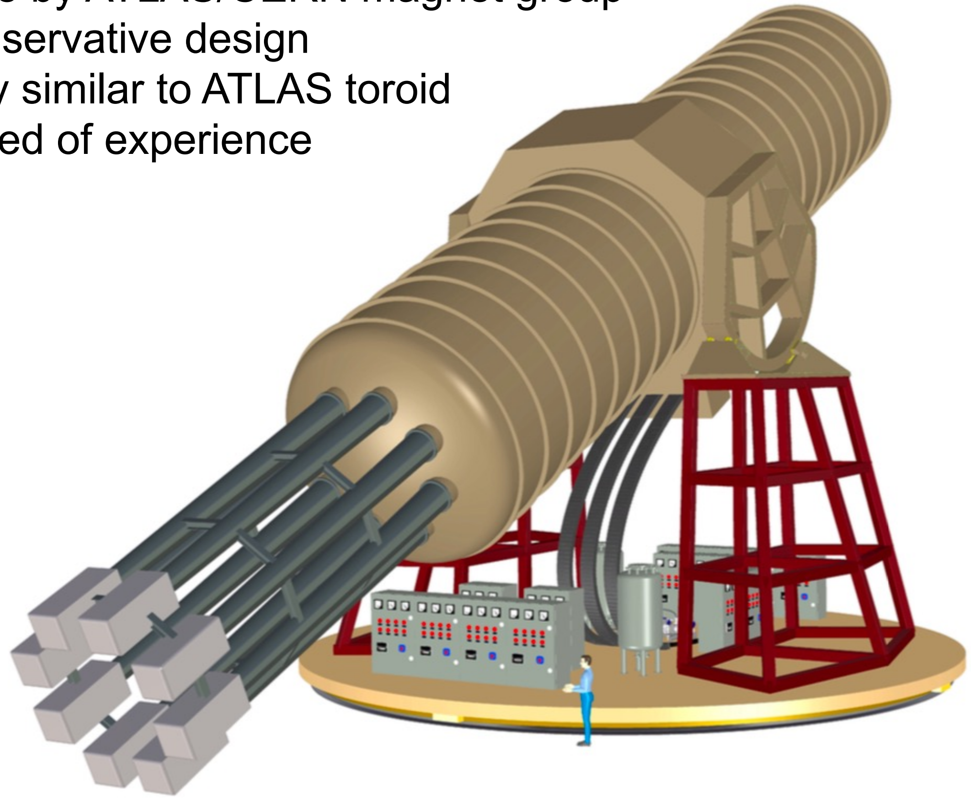
- Large toroidal 8-coil magnet L = ~20 m
- 8 bores: 600 mm diameter each
- 8 X-ray telescopes + 8 detection systems
- Rotating platform with services

- Conceptual design done at CERN



Magnet design

- done by ATLAS/CERN magnet group
- Conservative design
- Very similar to ATLAS toroid
- Based of experience



[IAXO CDR: JINST 9 (2014) T05002 (arXiv:1401.3233)]

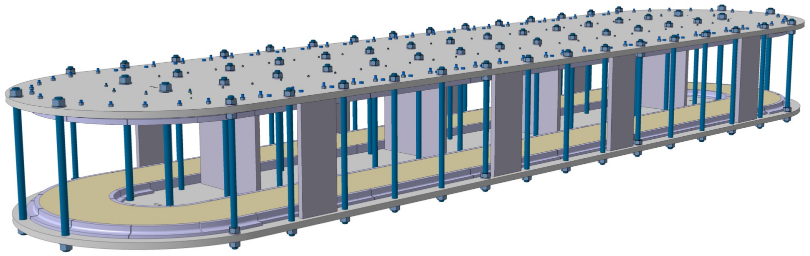
Magnet figure of merit $= B^2 L^2 A$

- CAST 21 $T^2 m^4$
- IAXO 6200 $T^2 m^4$
- BabyIAXO 325 $T^2 m^4$

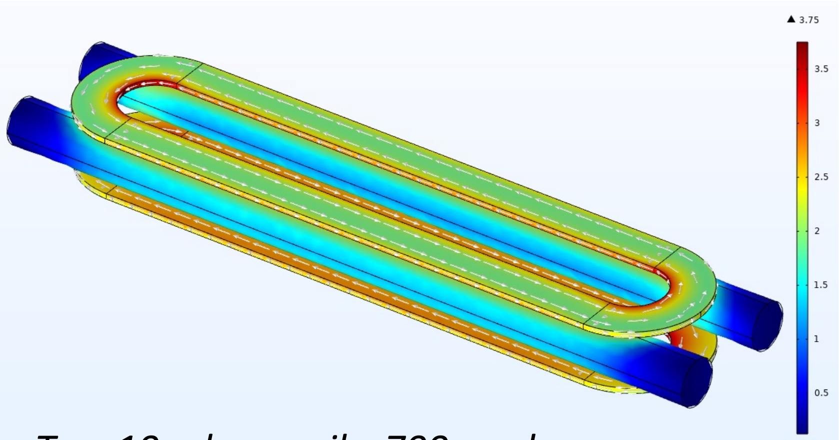
BabyIAXO

Magnet Design

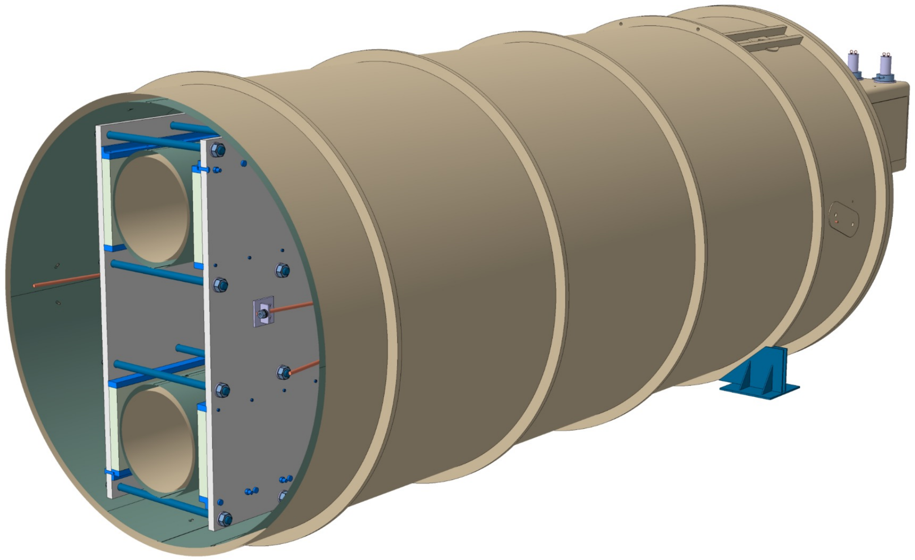
- Prototype for IAXO: BabyIAXO
  - Originally planning to build prototype coil of ½ length
  - Two bores similar to final IAXO bores
  - Detection lines representative of final ones
  - Test & improve all systems
  - Startup activities, again experience and physics results
- Magnet design in progress at CERN



Aluminum-based cold mass support structure



Two 10m long coils, 700mm bores

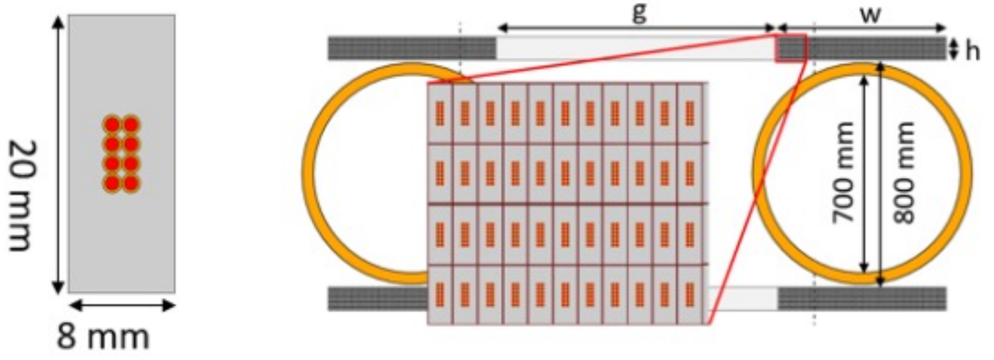


Vacuum vessel, coil suspension, cold mass, and bore tubes

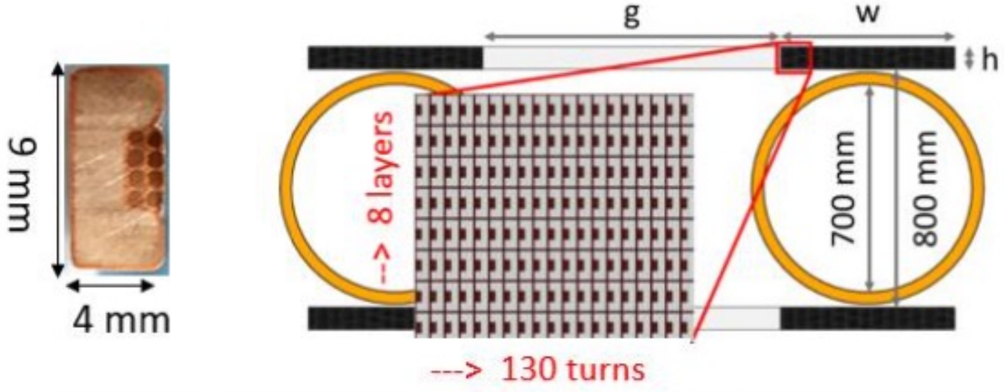
BabyIAXO Magnet

Conductor

- Originally planning to use new conductor similar to PANDA solenoid at FAIR, Rutherford cable with aluminum stabilizer
  - R&D and production in Russia in collaboration with Budker Institute
  - Production delayed. Were however planning to produce long samples this summer.
- Instead, were planning to use conductor manu-factured for MELC experiment at INR Moscow
  - Experiment cancelled in 90ties
  - ~50km of cable available, in-kind contribution
  - Several samples tested at CERN and Univ. of Twente
  - Critical current ~20% lower than specs. Some mitigations considered.
  - Many defects found during respooling last summer
  - Cannot be used for magnet



10 kA type coextruded conductor
(production trials in Russia)
MFOM 3D-2D = 230-330 (based on today's Ic)



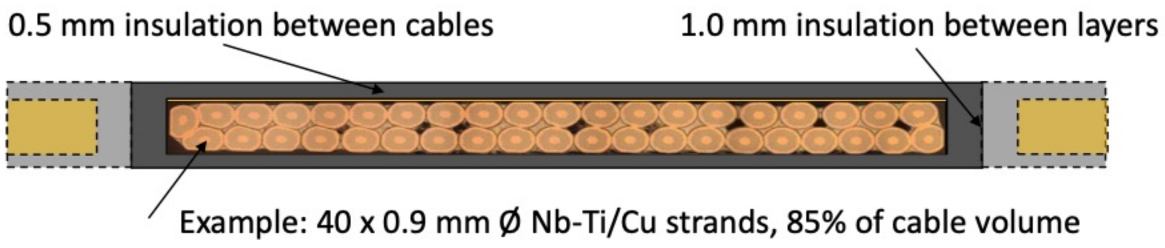
3 kA type cable-in-channel conductor
(available at INR, made medio 1990)
MFOM 3D-2D = 230-330 (based on "promised" Ic)

BabyIAXO Magnet

Conductor Options

Looked at fall back solution, standard Rutherford cable

- Commercially available, does not need R&D, no lead time for qualification, since Al stabilized cable presently not available.



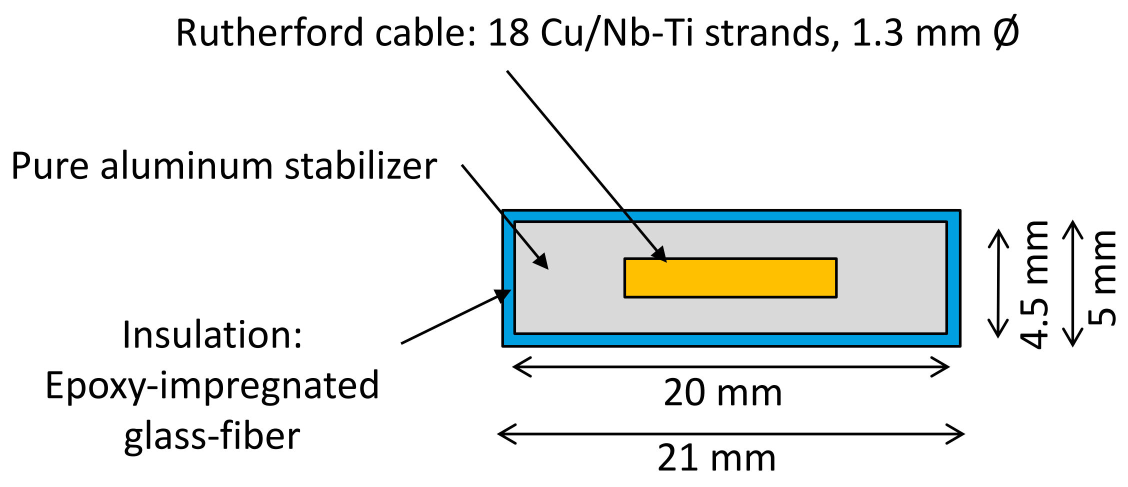
Several, serious issues

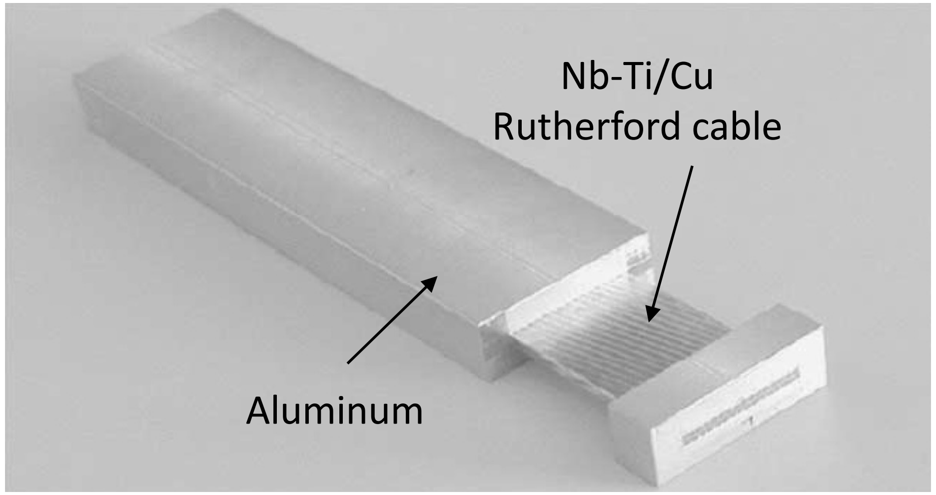
- Very poor electrical, thermal and SC properties (minimum propagation zone) compared to Al stabilized cable (each factor 10)
- Novel approach for detector magnets, expect significant reduction of conductor stability and magnet performance. Has not been used before.
- Incompatible with aluminum support structure (due to mismatch in thermal shrinkage), would have to use stain steel
- Cannot guarantee magnet figure of merit
- Cooling much more challenging
- Dry cooling may not work

=> Back to original conductor type (Al stabilized Rutherford cable)

BabyIAXO Magnet

Conductor Geometry, Present Design





Aluminum-stabilized conductor:

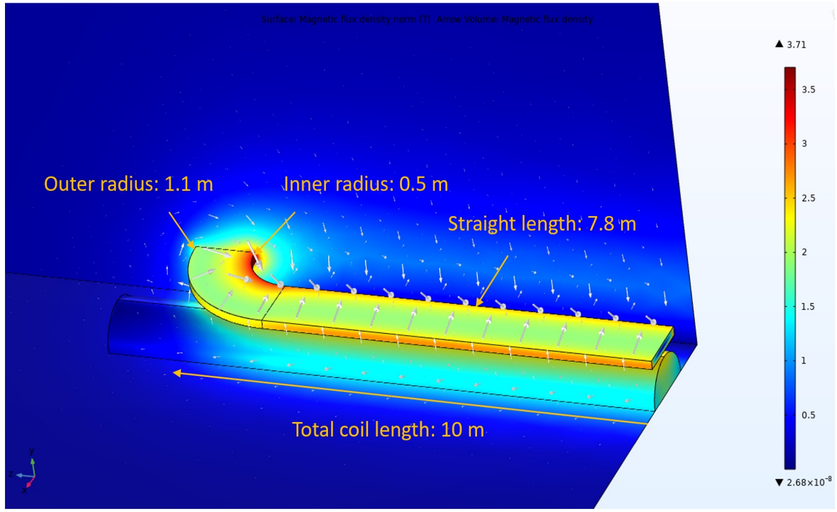
- Rutherford cable comprising 18 Nb-Ti/Cu strands with diameter of 1.3 mm and Cu:non-Cu ratio = 1.08
- Surrounded by pure aluminum, combined dimensions: 4.5 x 20 mm^2
- Epoxy-impregnated glass-fiber insulation:
  - 0.5 mm between neighboring conductors inside a winding layer
  - 1.0 mm between neighboring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

BabyIAXO Magnet

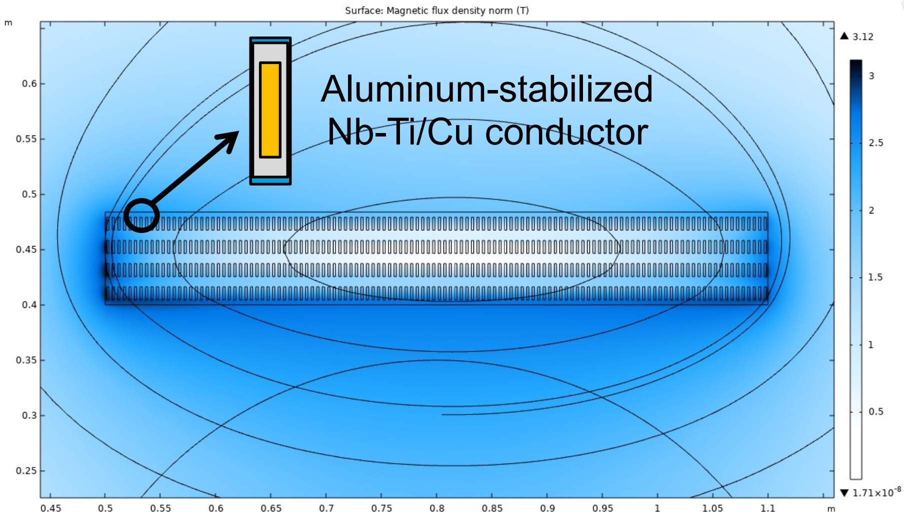
Winding Layout

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

- Need 20 km of conductor + some additional length for busbars, joints, quality control, etc.
- Peak field for 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**



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



Cross-section of the winding

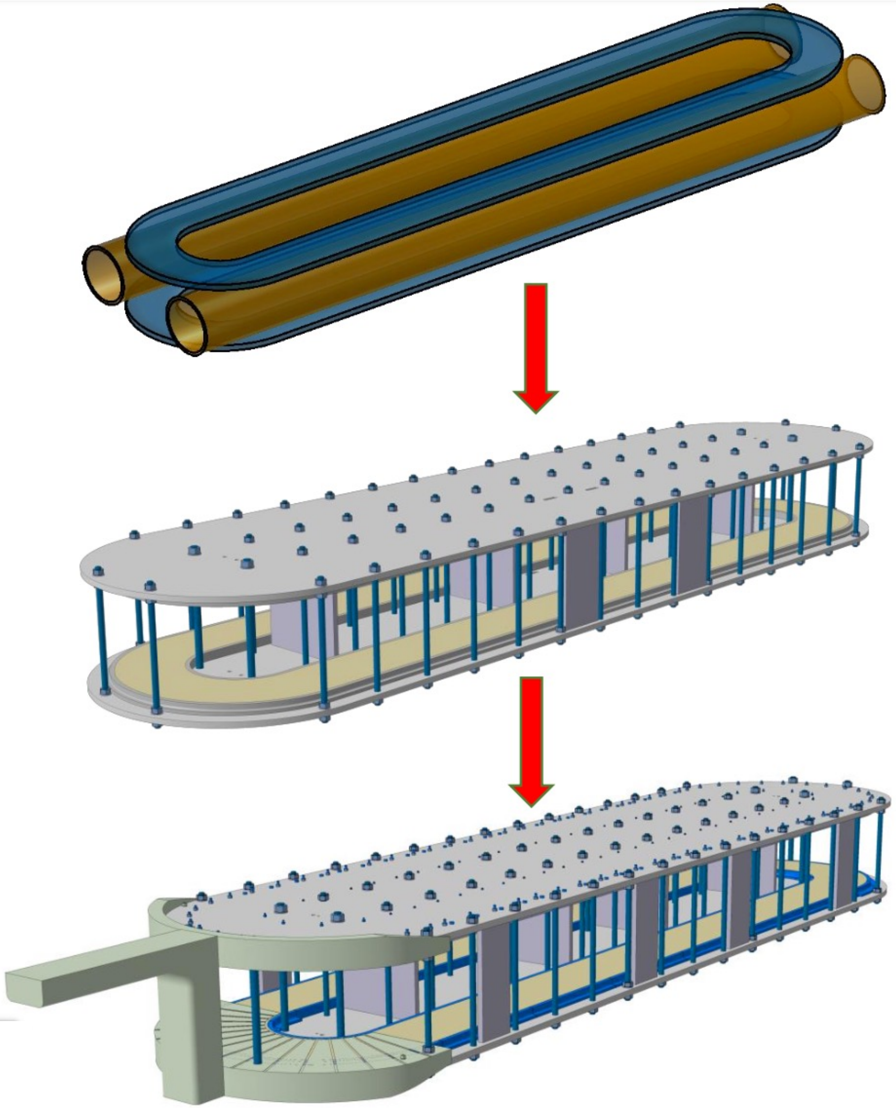
BabyIAXO Magnet

Cold Mass

Adjustments:

- Added stiffening plates.
- Changed plate thicknesses.
- Fine tuned tensile rods, washers, and nuts.
- Added thermal bracket to extract the heat from the cold mass with minimal temperature gradient.
- Completed the design for budget inquiry spec.

Component	Mass [t]
Cold mass	17.0
Thermal shield	1.3
Cryostat	15.5
Total	**~ 34 (+ services)**



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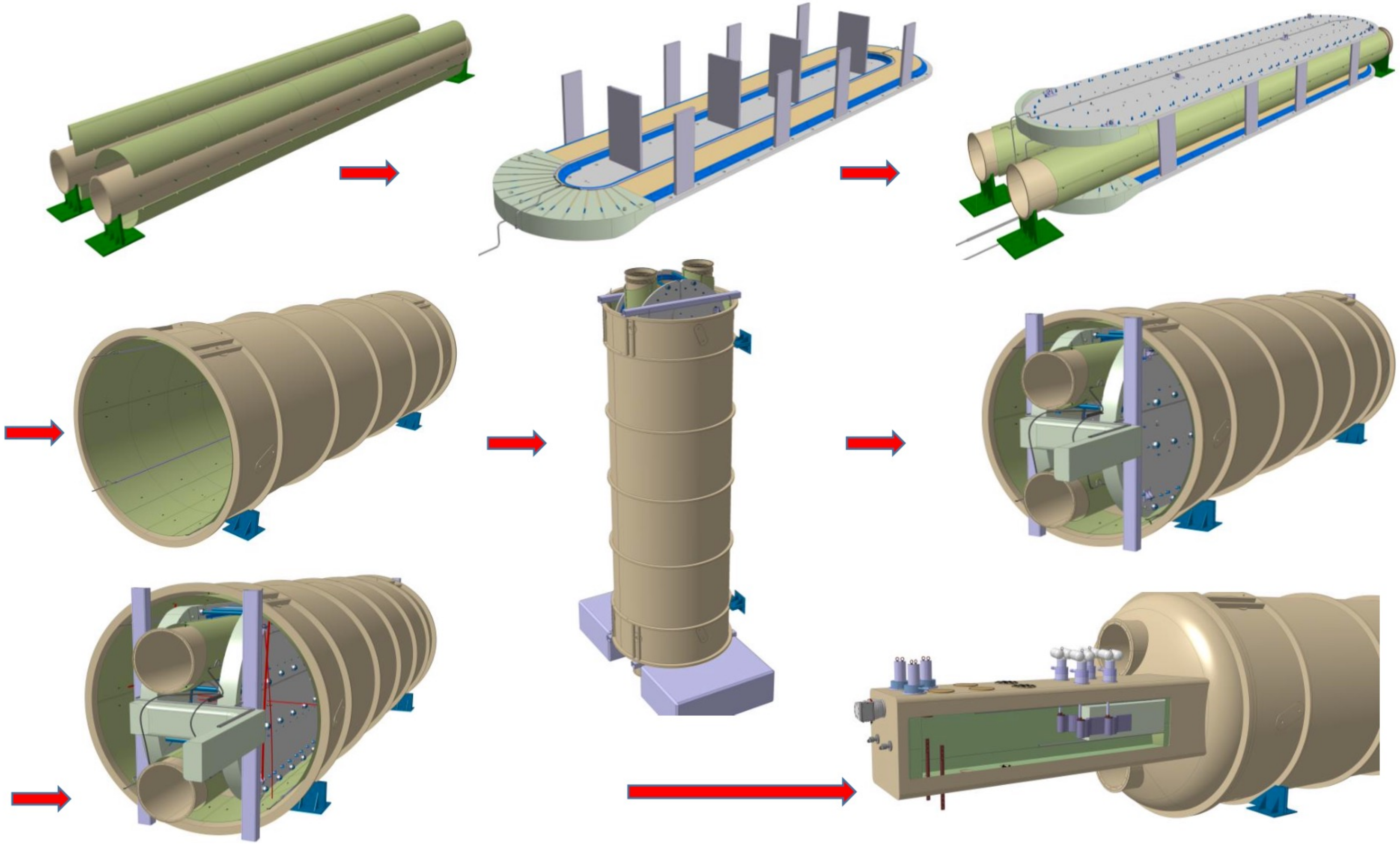
Cold Mass Assembly

In 26 steps:

1. Install thermal shield on bore tubes
2. Install bore tube cooling pipes
3. Install cooling stripes onto the coils
4. Install cooling pipes onto the coils
5. Install positioning plates on coils
6. Bring bore tubes into position
7. Install the other coil
8. Install cold mass rods
9. Connect bore tubes to the cold mass
10. Install thermal bracket
11. Merge pipes into single inlet
12. Install top thermal shield panels
13. Install cooling pipes onto the top
14. Install bottom shield panels
15. Install bottom cooling pipes
16. Install remaining thermal shield
17. Swivel the pressure vessel
18. Insert the coil into the vessel
19. Fix cold mass
20. Swivel assembly into horizontal
21. Install support rods, remove beams
22. Install thermal shield end flanges
23. Install cooling pipes end flanges
24. Close end flanges
25. Install services
26. Close panels of service box.

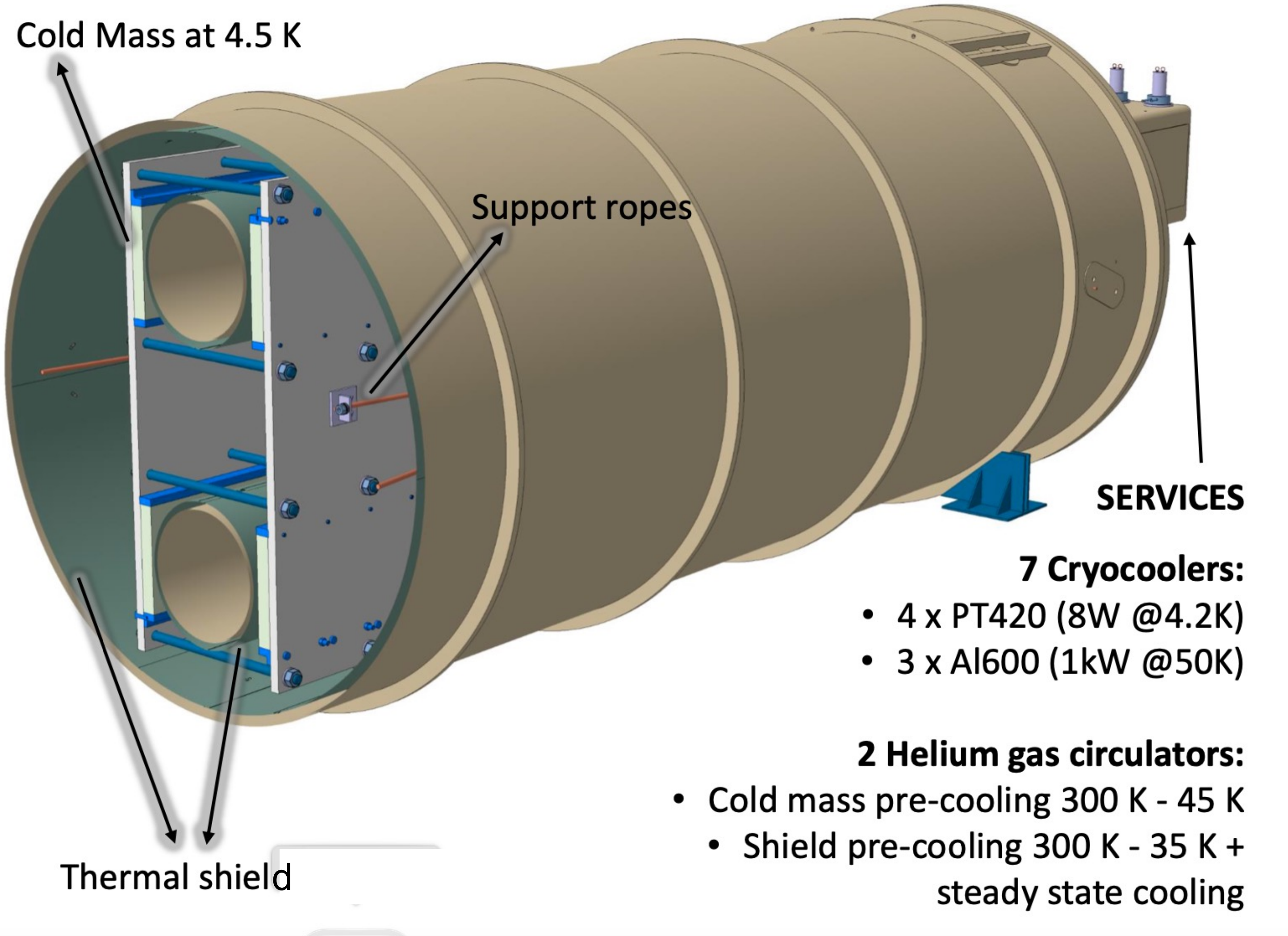


BabyIAXO Magnet

Cryogenic System, original design

Dry cryogenic system:

- Supercritical ^{4}**He** at 20 bar circulates in a **closed circuit.**
- Cooling provided by **mechanical cryocoolers.**
- **Heat transport** from cold mass and shield to cryocoolers **by He gas circuits driven by circulators.**
- Final stage of cold mass cooldown (45 K to 4.5 K) and steady-state cooling by **conduction via thermal links.**
- Thermal shield temperature **lowered from 50 K to ≈35 K.**



7 Cryocoolers:

- 4 x PT420 (8W @4.2K)
- 3 x Al600 (1kW @50K)

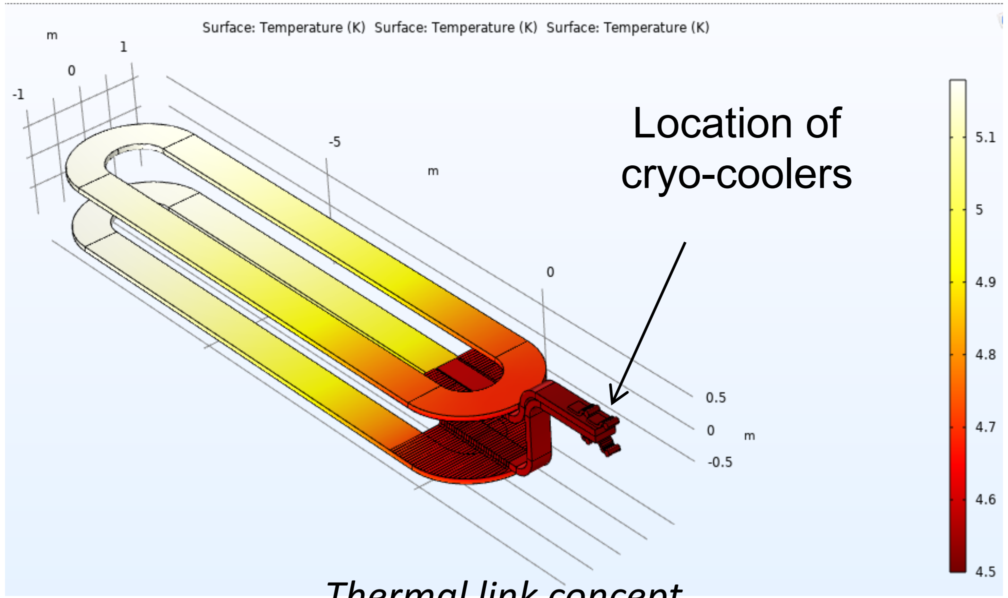
2 Helium gas circulators:

- Cold mass pre-cooling 300 K - 45 K
- Shield pre-cooling 300 K - 35 K + steady state cooling

BabyIAXO Magnet

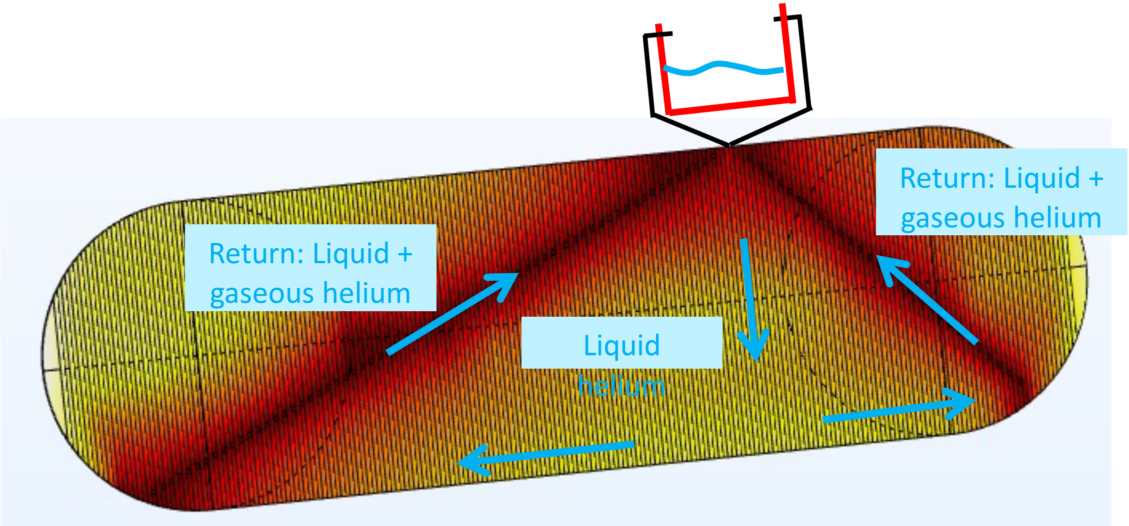
Cryogenics and Head Loads

Temperature gradient over the coils, interfaces, etc, dependent on the heat load



Thermal link concept

Liquid helium, provided by local cryo-cooler helium condensation (or external cryogenics)

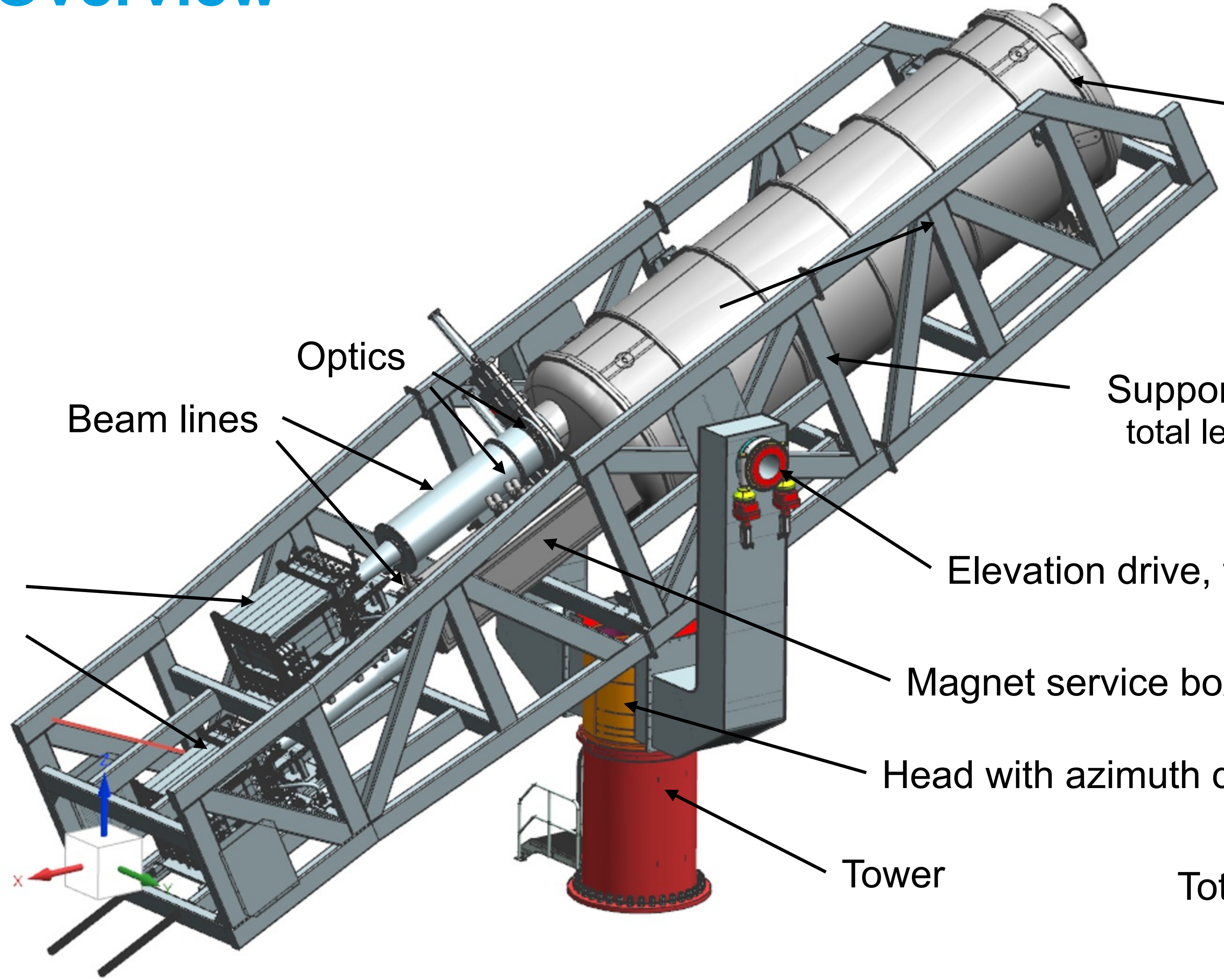


Thermal siphon concept

Cryogenics of the BabyIAXO magnet is very challenging, due to absence of external liquid He plant

- Baseline cooling concept: Cooling with cryo-coolers, which give very limited cooling power at 4 K, so **minimizing the losses and heat loads onto the cold mass and thermal shield is critical** and achieving thermal homogeneity in the magnet is a significant technological challenge
- Two options under consideration: Thermal link and thermal siphon concept

BabyIAXO Overview

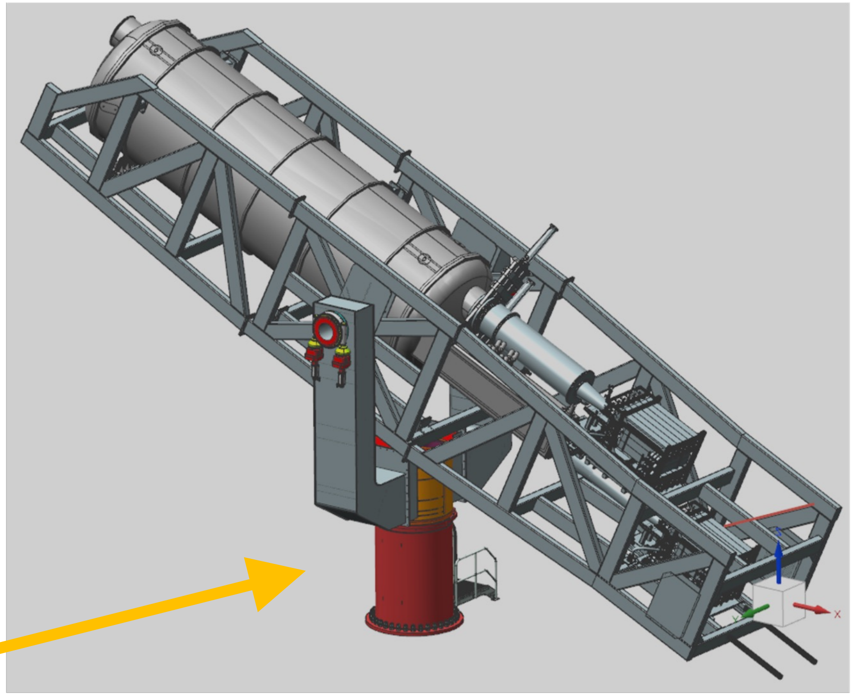


Total mass ~126t

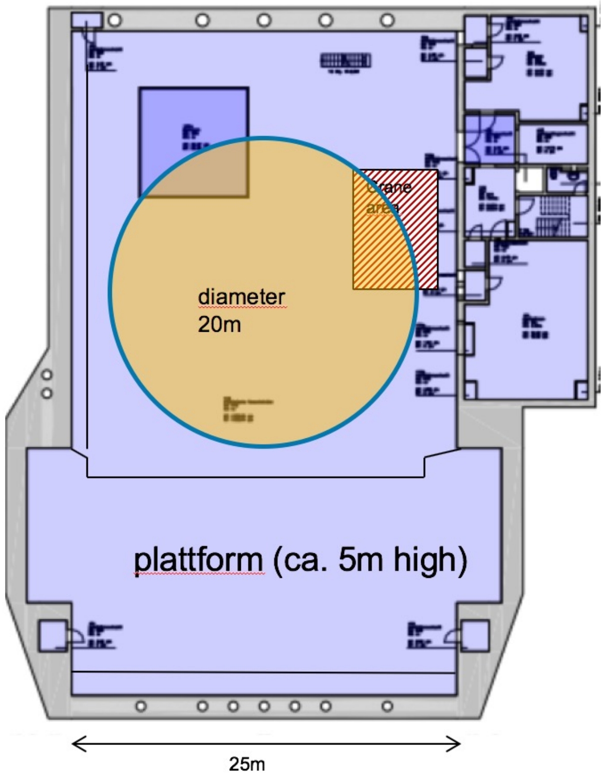
BabyIAXO

Support and Drive System

CTA MST prototype in Berlin



Site: HERA South Hall
at DESY



Going use MST prototype positioner for BabyIAXO

- Size, weight and tracking specs very similar
- MST prototype disassembled in February, shipped to Hamburg in May 2020

Conclusions

- Design of BabyIAXO, prototype of IAXO helioscope, quite advanced
- Essential parts of structure and drive system already exist. Almost ready to start ordering others parts
  - Support & Drive System Optics, vacuum system and detectors should be ready in a few years

- Magnet unfortunately delayed due to conductor issues
- Urgently need aluminum stabilized conductor for the magnet

Thanks to M. Mentink (CERN) for providing slides