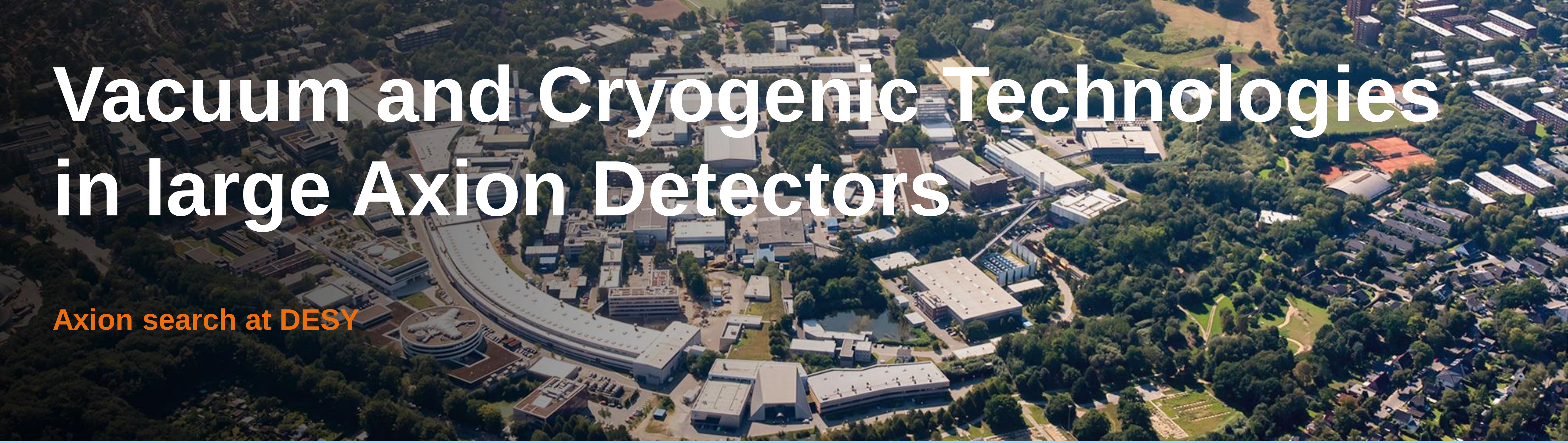


Vacuum and Cryogenic Technologies in large Axion Detectors

Axion search at DESY

Jörn Schaffran

IUVSTA Workshop 109 : APPEC Tech Forum Vacuum & Cryogenics, Maastricht, 24-26 Nov. 2025

HELMHOLTZ

Overview

Agenda

01 Physics

- Introduction
- Motivation
- Overview of the three experiments

02 ALPS II

- Detailed setup (technical concept)
- The magnet
- Other vacuum and cryo-technical requirements

03 BabyIAXO

- Technical requirement
- The magnet
- Bore tube requirements (experimental components) and FAT

04 MADMAX

- Experimental setup
- The magnet
- The prototype cryostat
- Other subcomponents

Summary

- Summary and outlook

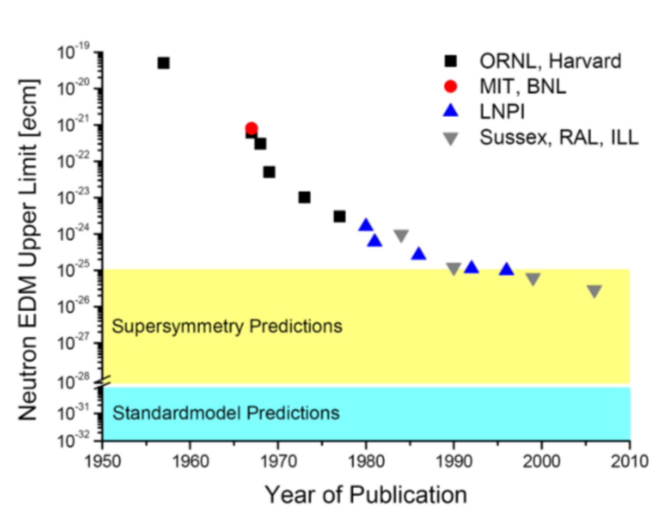
Introduction – Axion search

Axion Motivation

QCD CP violation

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

- QCD CP violating term
- Expect electric dipole moment to the neutron, CP violation phase $\theta \neq 0$,
- Experiment $|d_n| < 3.0\ 10^{-13}$ e fm => $\theta < 10^{-9}$
- New symmetry: θ=0 (Peccei-Quinn 1977), axion (Wilczek)



Dark matter

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

- Hierarchy problem: MSSM neutralino
- Strong CP problem: QCD axion

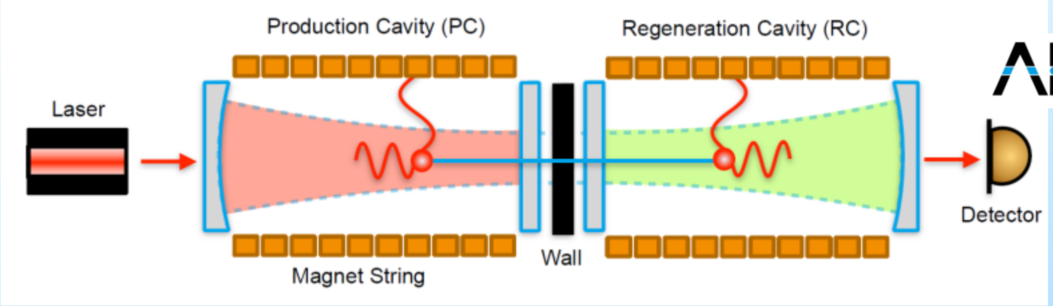
Apart from dark matter, other hints from astrophysics which might be explained by axions

- 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

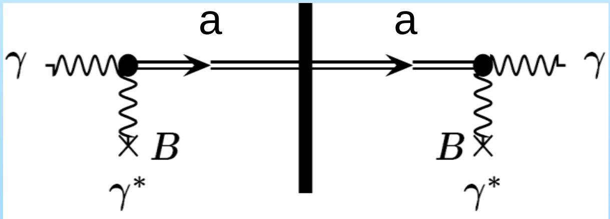
Could solve the CP violation and explain dark matter.

How to search - Experimental Axion Search Methods

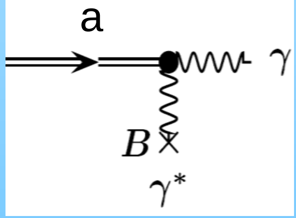
- **Light-shining-through-a-wall (LSW)**
  - Production and detection of axions in laboratory

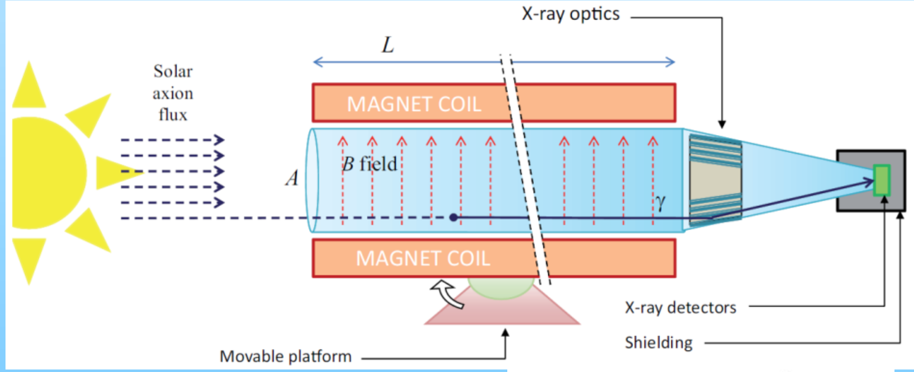


Primakoff effect conversion

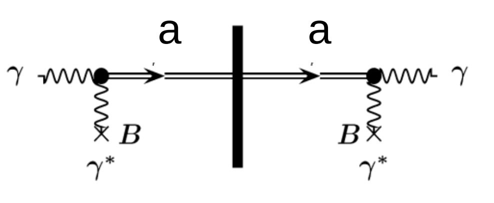


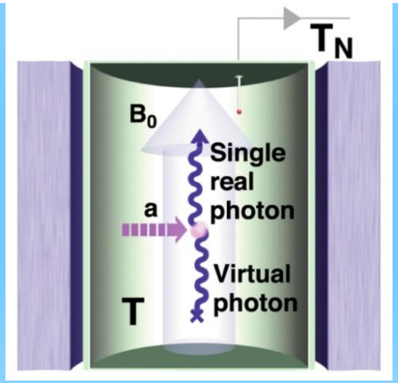
- **Helioscopes**
  - Axion production in sun, detection in laboratory





- **Haloscopes**
  - Axion dark matter production in early universe, detection in lab (microwaves)



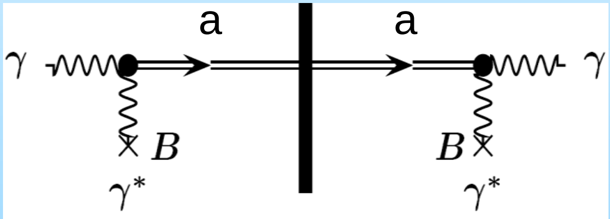


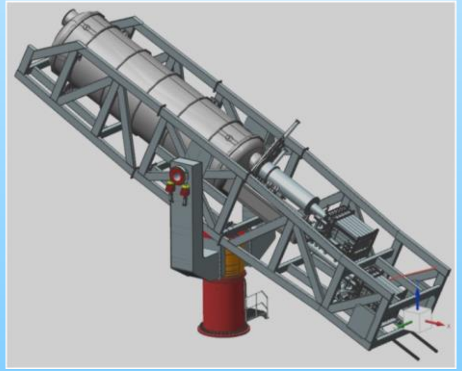
Very complementary axion production and detection Different techniques and systematics

How to search - Experimental Axion Search Methods

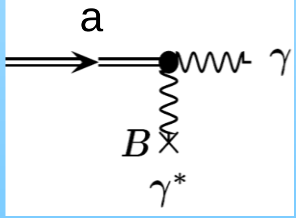
- **Light-shining-through-a-wall (LSW)**
  - Production and detection of axions in laboratory

Primakoff effect conversion

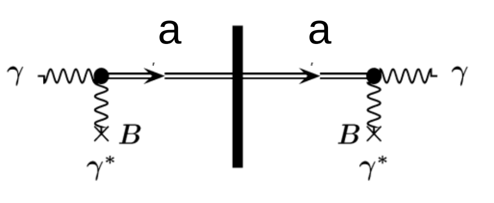


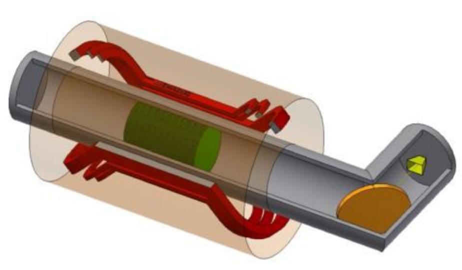


- **Helioscopes**
  - Axion production in sun, detection in laboratory



- **Haloscopes**
  - Axion dark matter production in early universe, detection in lab (microwaves)





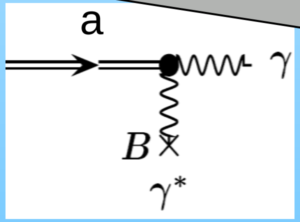
Very complementary axion production and detection Different techniques and systematics

How to search - Experimental Axion Search Methods

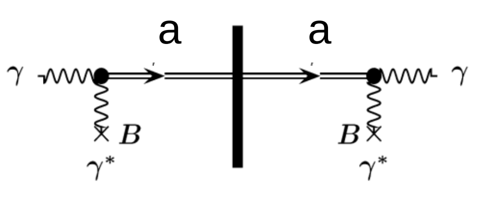
- **Light-shining-through-a-wall (LSW)**
  - l detection of axions in laboratory

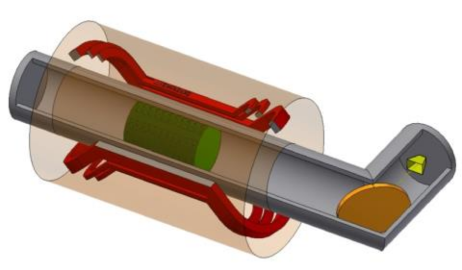
All of these experiments require cryogenic and vacuum techniques.

  - Axion production in sun,



- **Haloscopes**
  - Axion dark matter production in early universe, detection in lab (microwaves)



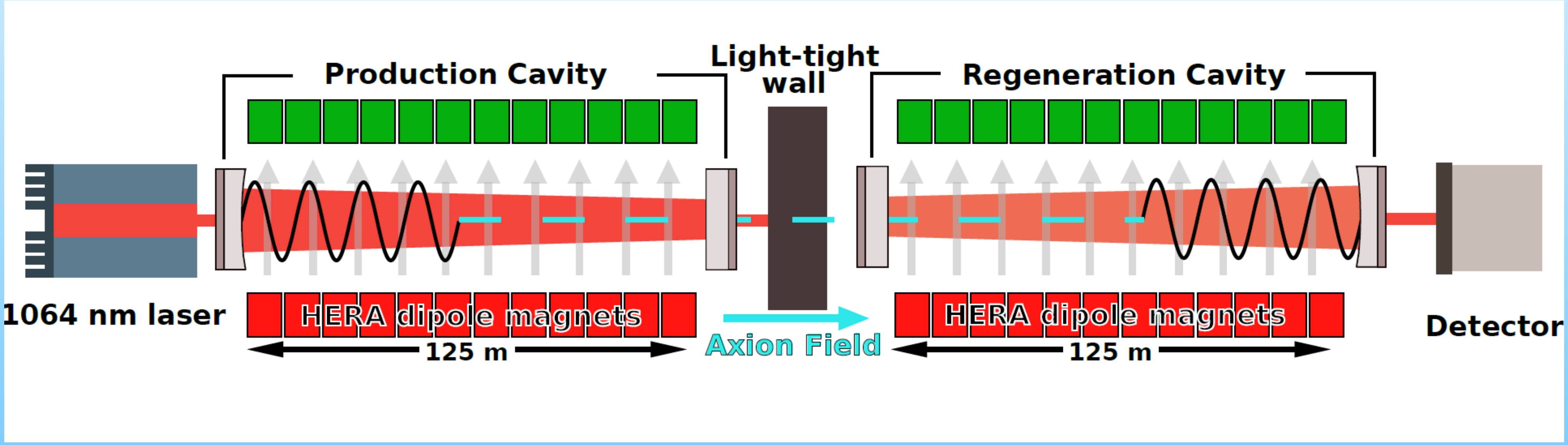


Very complementary axion production and detection Different techniques and systematics

ALPS II - Any Light Particle Search II

Light-through-a-wall

Probing axion-photon couplings model independently.



5 cm

Axion generation 250 m Axion reconversion

Light injection Axion pass the wall Light detection

Any Light Particle Search II

Light-through-a-wall

Probing a

Demands given by the FoM:

Long section of dipole magnets

Strong magnetic field

1064 nr

$$P_{\gamma\to\phi\to\gamma} = \frac{1}{16}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot(g_{a\gamma\gamma}Bl)^4 = 6\cdot10^{-38}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot\left(\frac{g_{a\gamma\gamma}}{10^{-10}GeV^{-1}}\frac{B}{1\,T}\frac{l}{10m}\right)^4$$

Light i

Particle free vacuum space for optics (powerfull laser light)

Any Light Particle Search II

Light-through-a-wall

ALPS II

Techniques:

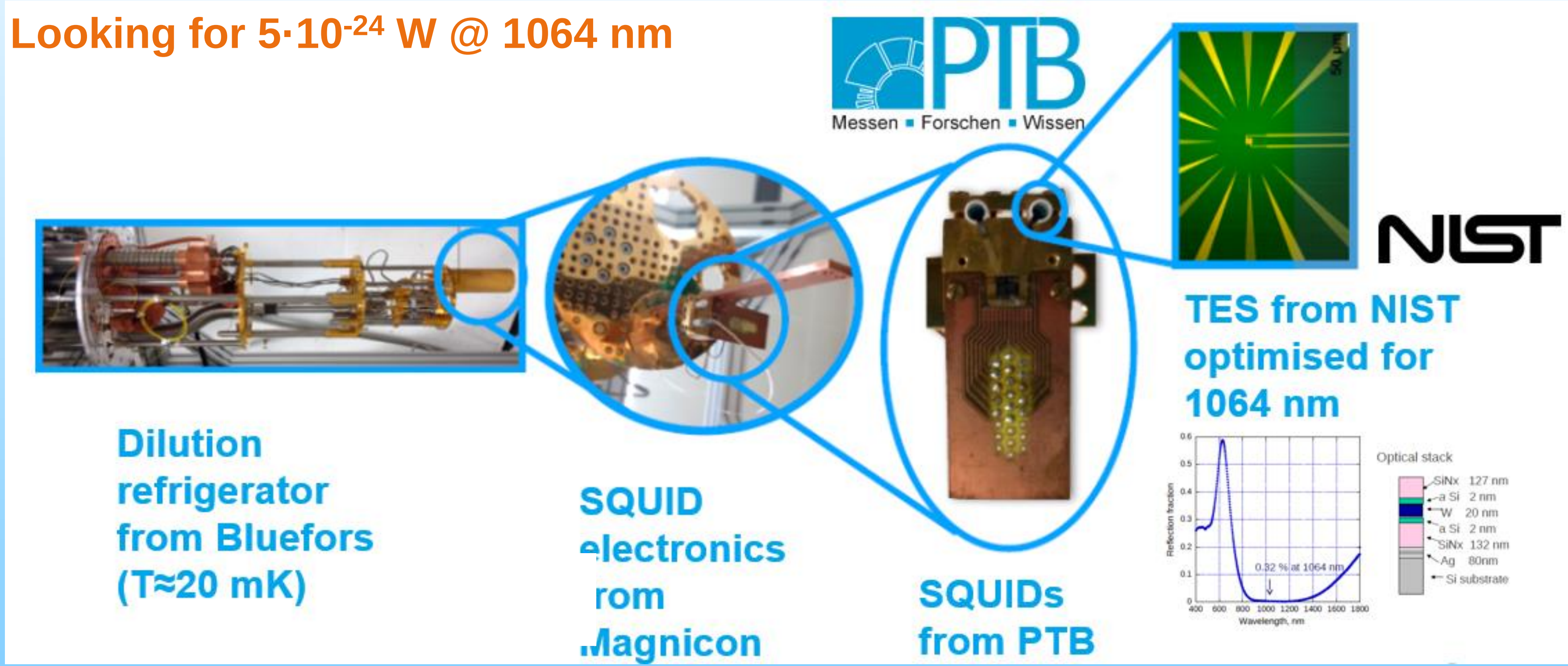
- 24 old HERA dipole magnets operated at 4.2 K and a field of 5.3 T.
- 250 m long vacuum tube @4.2 K and with >5 cm diameter.
- Nearly particle free environment close to the optic components.
- Commissioning successful and first science run done, next will follow 2026.

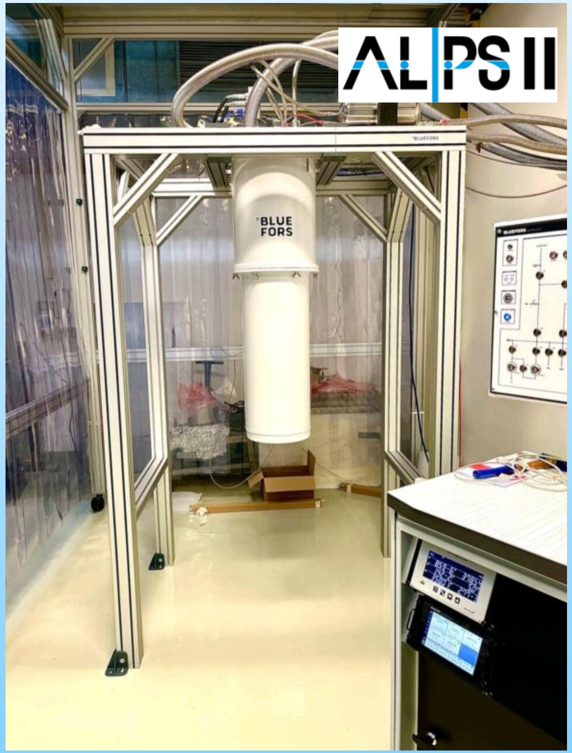
Next steps:

- Upgrade with TES (next slide).
- Vacuum Magnetic Birefringence (VMB).
- GW detection.

ALPS II -Transition Edge Sensor (detection)

Looking for 5·10^{-24} W @ 1064 nm





Dilution Refrigerators from Bluefors with superconducting transition edge sensor (TES) for photon counting:

- Base temperature about 20 mK.
- Cooling power at 100 mK about 300 µW.
- One of the cryostats placed in a gray (semi-clean) room ➔ clean room lab planned.
- Different temperature stages.

Baby(IAXO) - physics

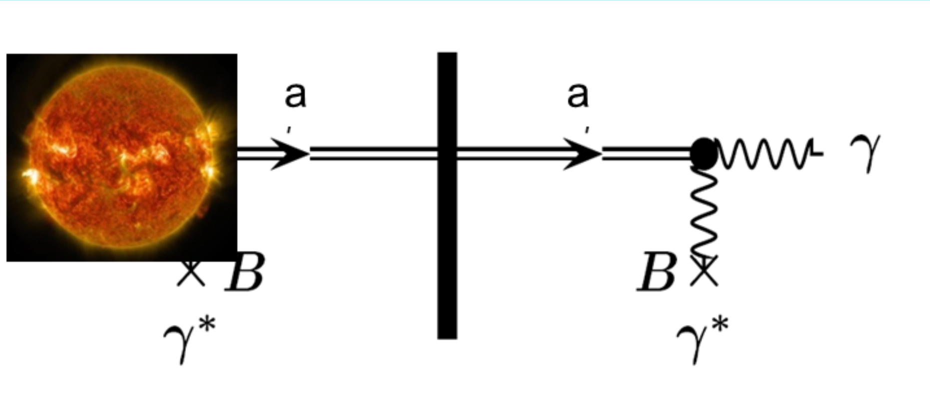
Why do we search an Axion?

Motivation

- Detecting Axions coming from the sun.

How to detect an Axion?

- Axionen are produced in the core of the sun by interaction of photons with the electromagnetic field. Detection by Helioscope.
- Helioscope: a magnet pointing to the sun in order to maximize the Axion flux.



Axions coming from the sun, converted in a photon (Primakoff-Effect) and measured.

BabyIAXO - concept

What do we need?

Realization

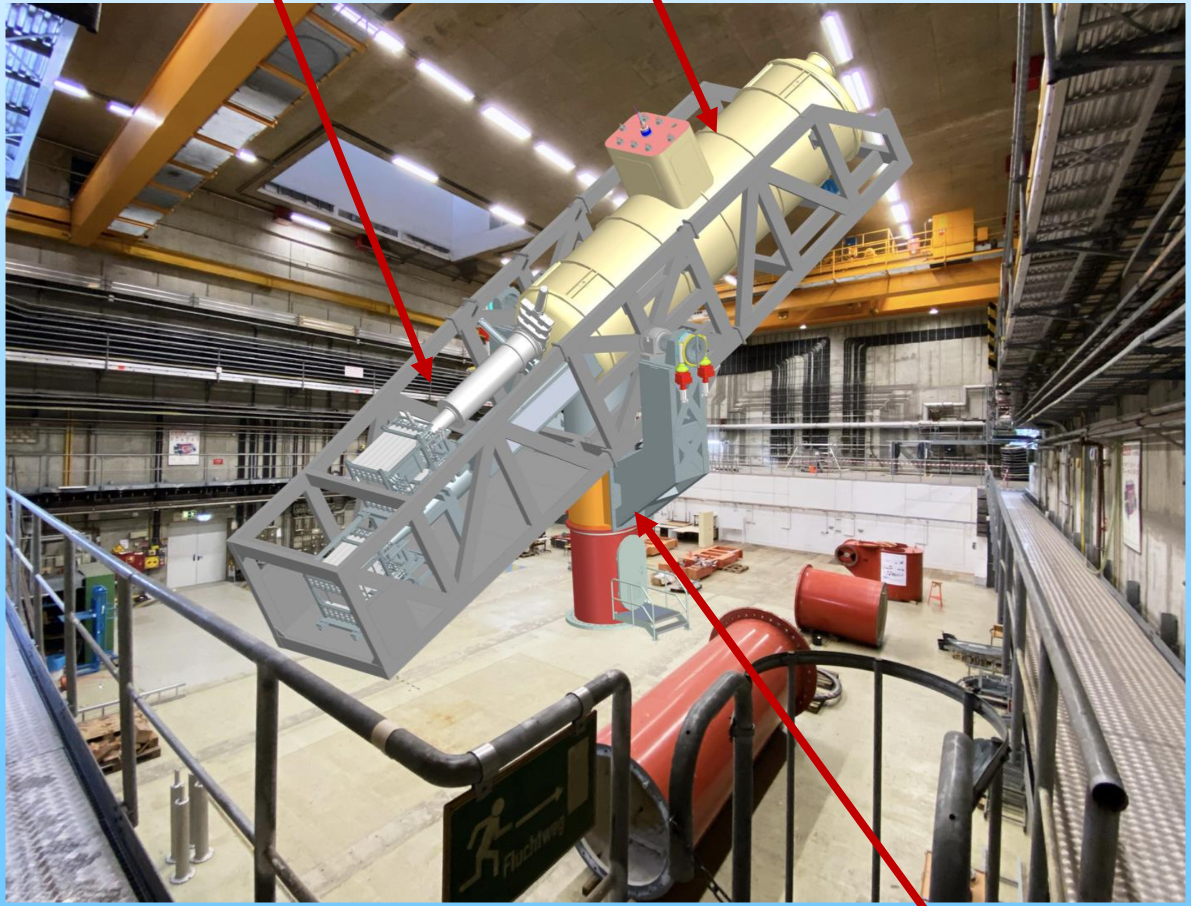
A 10 m long superconducting dipole magnet (2.2 T) follows the sun with its 2 bore tubes (0.7 m diameter each, vacuum) to trap, convert and detect Axions.

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

$\Rightarrow$ Field and bore tube dimensions (length and diameter).

Optics & Detectors

Magnet



Experimental setup

Support und Drive System

BabyIAXO - concept

What do we need?

Realization

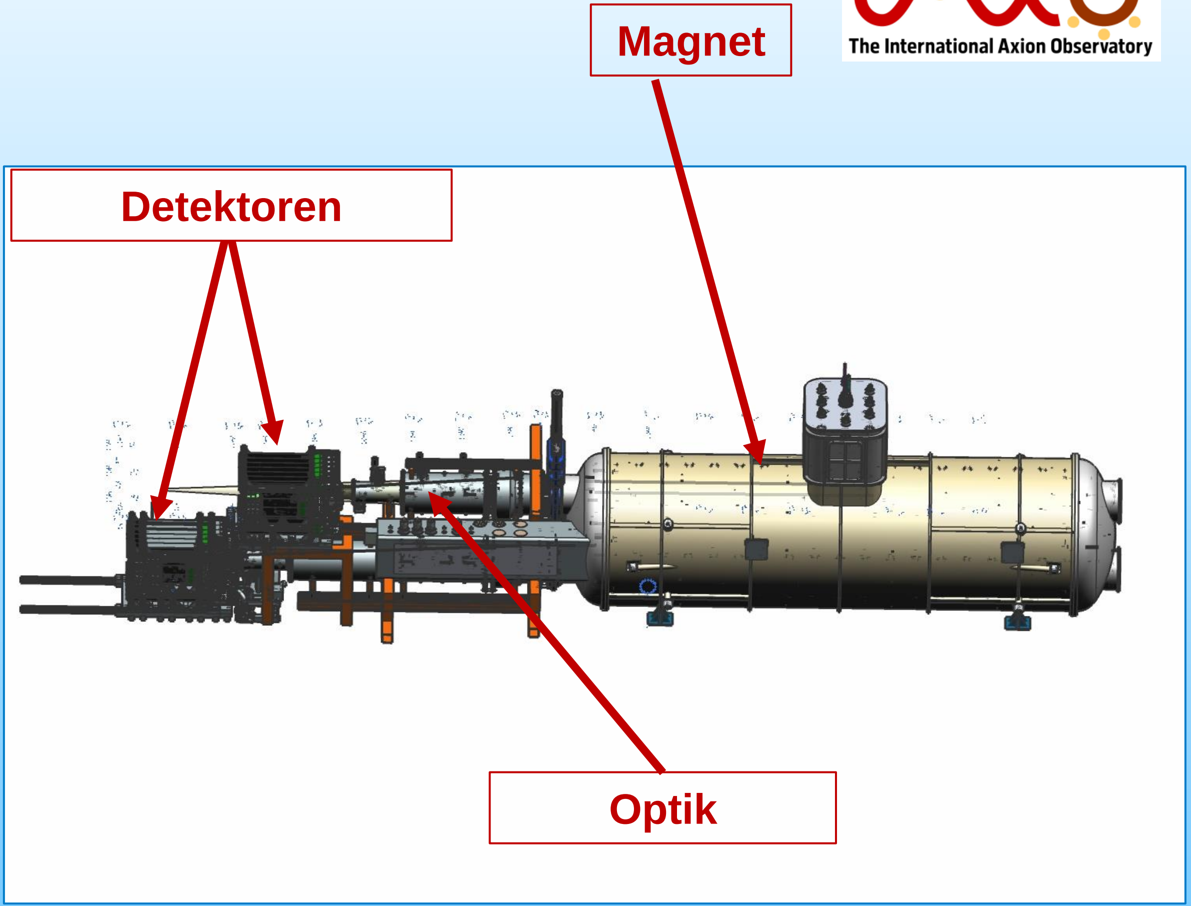
A 10 m long superconducting dipole magnet (2.2 T) follows the sun with its 2 bore tubes (0.7 m diameter each, vacuum) to trap, convert and detect Axions.

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

⇒ Field and bore tube dimensions (length and diameter).

⇒ A lot of conceptional engineering is already outsourced (Elytt, Spain).

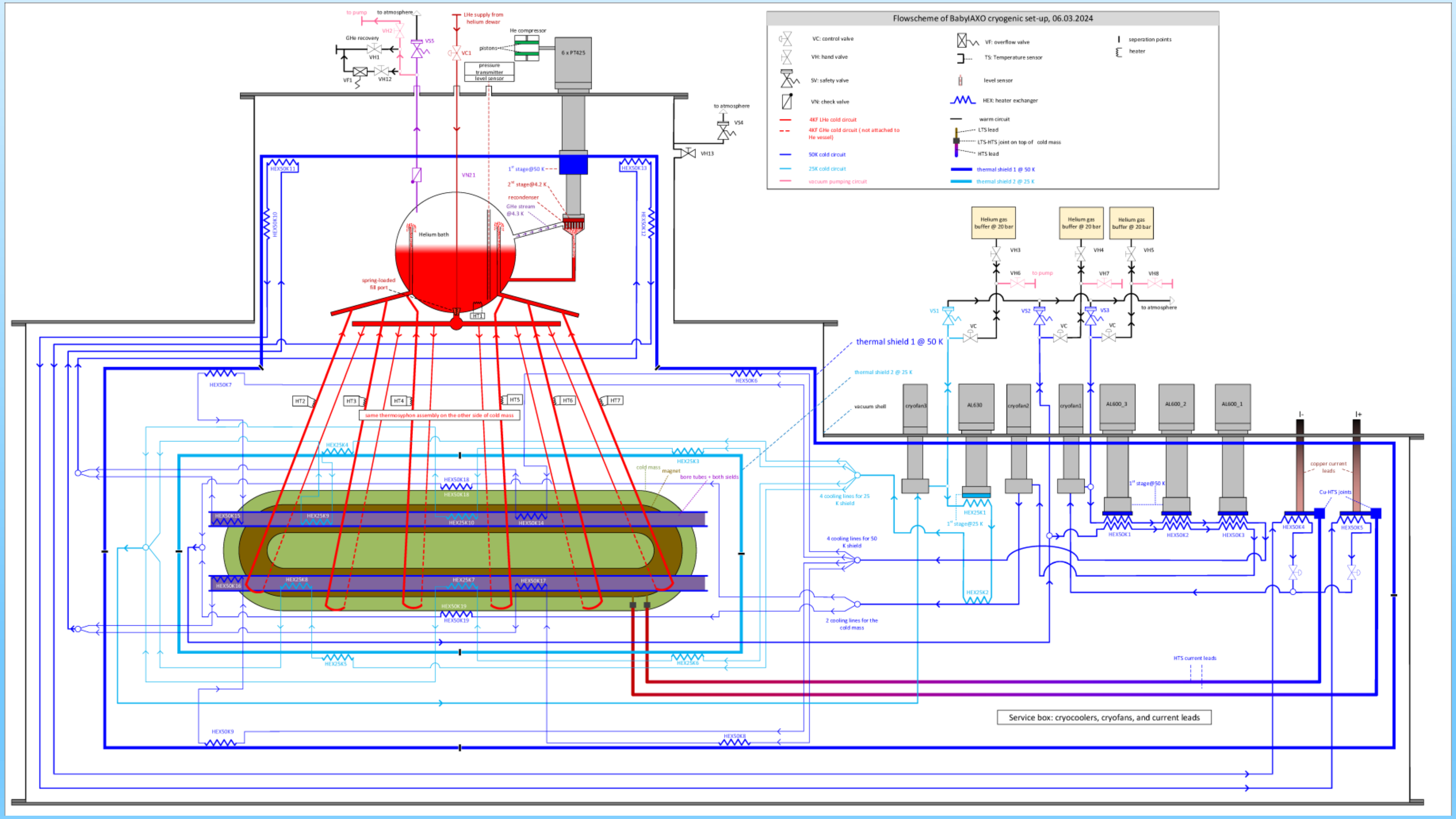
⇒ Next step: tender for TDR and manufacturing.



Experimental setup

BabyIAXO

Cryogenics…



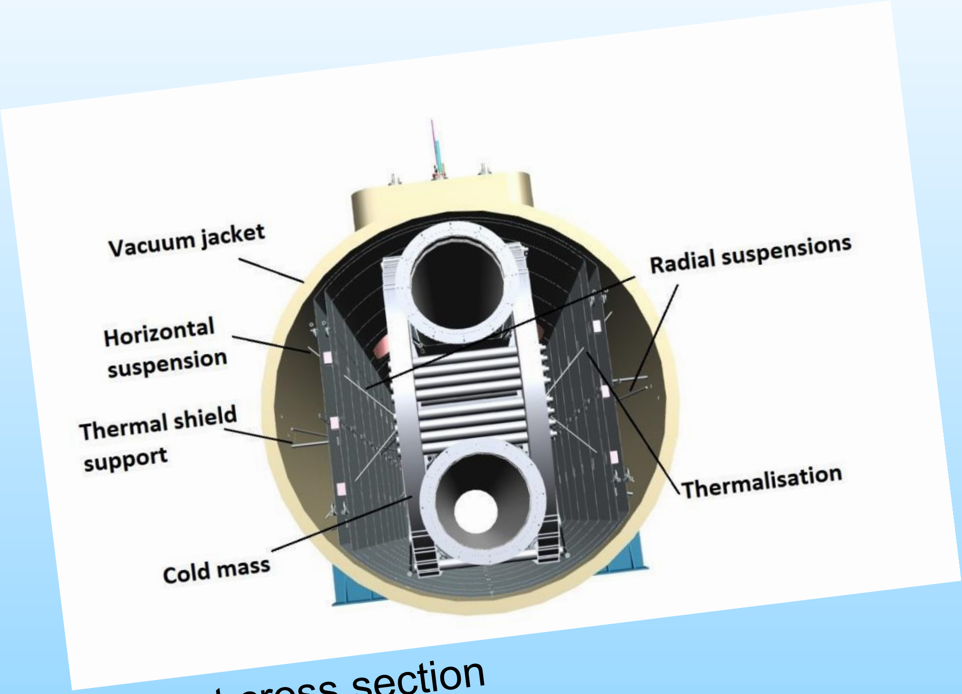
Concept:

- Cooling of cold mass by thermos siphon (recondensing by 6-8 cryo cooler; currently planed with PT425-RM).
- Cold mass is surrounded by two thermal shields operating at T=25 K (1x AL630 cooler) und T=50 K (3x AL600) and Cryofans (supplier not defined yet).
- Additional cooling of leads (HTS) at 50 K (same 3 Als).
- Separate cooling loop for cool down process.

BabyIAXO

Cryogenics…

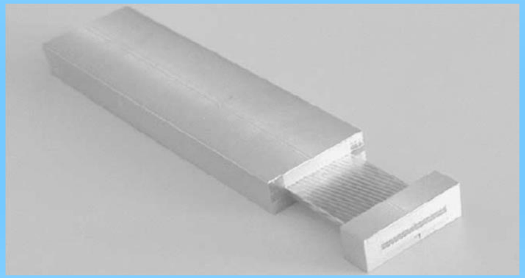
- Magnet design is a cooperation between CERN, DESY and industry (Elytt).
- Conductor design and manufacturing investigated by CERN.
- Cryogenic design by DESY / CERN.
- Vacuum: UZar / DESY and Cadinox.

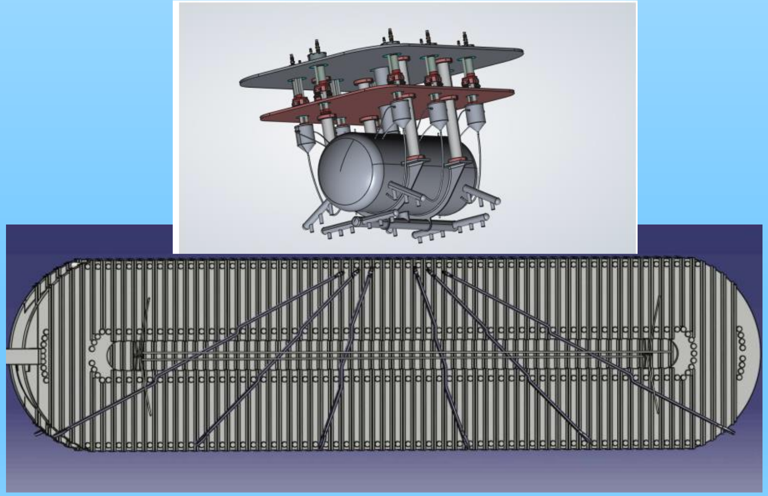


Magnet cross section

Concept:

- Cooling of cold mass by thermo siphon (recondensing by 6-8 cryo cooler; currently planed with PT425-RM).
- Cold mass is surrounded by two thermal shields operating at T=25 K (1x AL630 cooler) und T=50 K (3x AL600) and Cryofans (supplier not defined yet).
- Additional cooling of leads (HTS) at 50 K (same 3 Als).
- Separate cooling loop for cool down process.


Al stabilized conductor


Siphon cooling

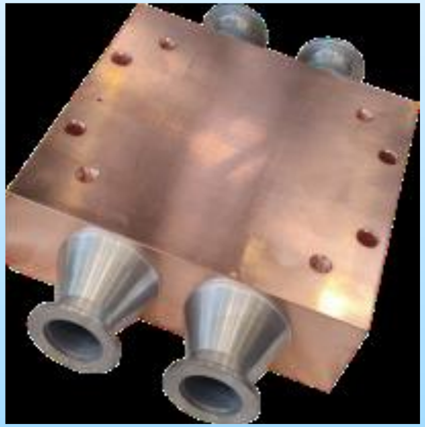
BabyIAXO

Cryogenics… accessories

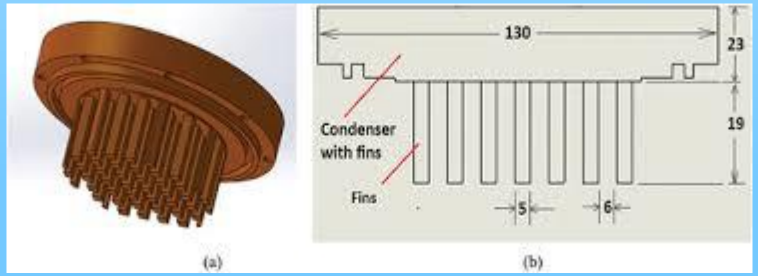
PT425-RM

CRYOMECH

AL630



Heat exchanger



Recondenser

Cryofans

Concept:

- Cooling of cold mass by thermo siphon (recondensing by 6-8 cryo cooler; currently planed with PT425-RM).
- Cold mass is surrounded by two thermal shields operating at T=25 K (1x AL630 cooler) und T=50 K (3x AL600) and Cryofans (supplier not defined yet).
- Additional cooling of leads (HTS) at 50 K (same 3 Als).
- Separate cooling loop for cool down process.

BabyIAXO

Vacuum… UHV and partial pressure operation compatible

<u>Beamtube vacuum design finalized and some main parts already ordered:</u>

- 2x cryo pump (DN200, S_{N2} = 1200 l/s) => ordered
- 4x turbomolecular pump (DN200, S_{N2} =1250 l/s) => ordered
- 9x DN200 gate valves => ordered
- 9x SCROLL pump (KF25 or KF40, S_{N2} =12-15 m^3/h) => ordered
- Accessories like gauges, 2x DN800 gate valves, flow control, etc. => open
- Tubes, etc. => partly open

BabyIAXO

Vacuum… UHV and partial pressure operation compatible

The International Axion Observatory

Beamtube vacuum design finalized and some main parts already ordered:

- 2x cryo pump (DN200, S_{N2} = 1200 l/s) => ordered
- 4x turbomolecular pump (DN200, S_{N2} =1250 l/s) => ordered
- 9x DN200 gate valves => ordered
- 9x SCROLL pump (KF25 or KF40, S_{N2} =12-15 m^3/h) => ordered
- Accessories like gauges, 2x DN800 gate valves, flow control, etc. => open
- Tubes, etc. => partly open

Demands on isolating vacuum not finalized yet:

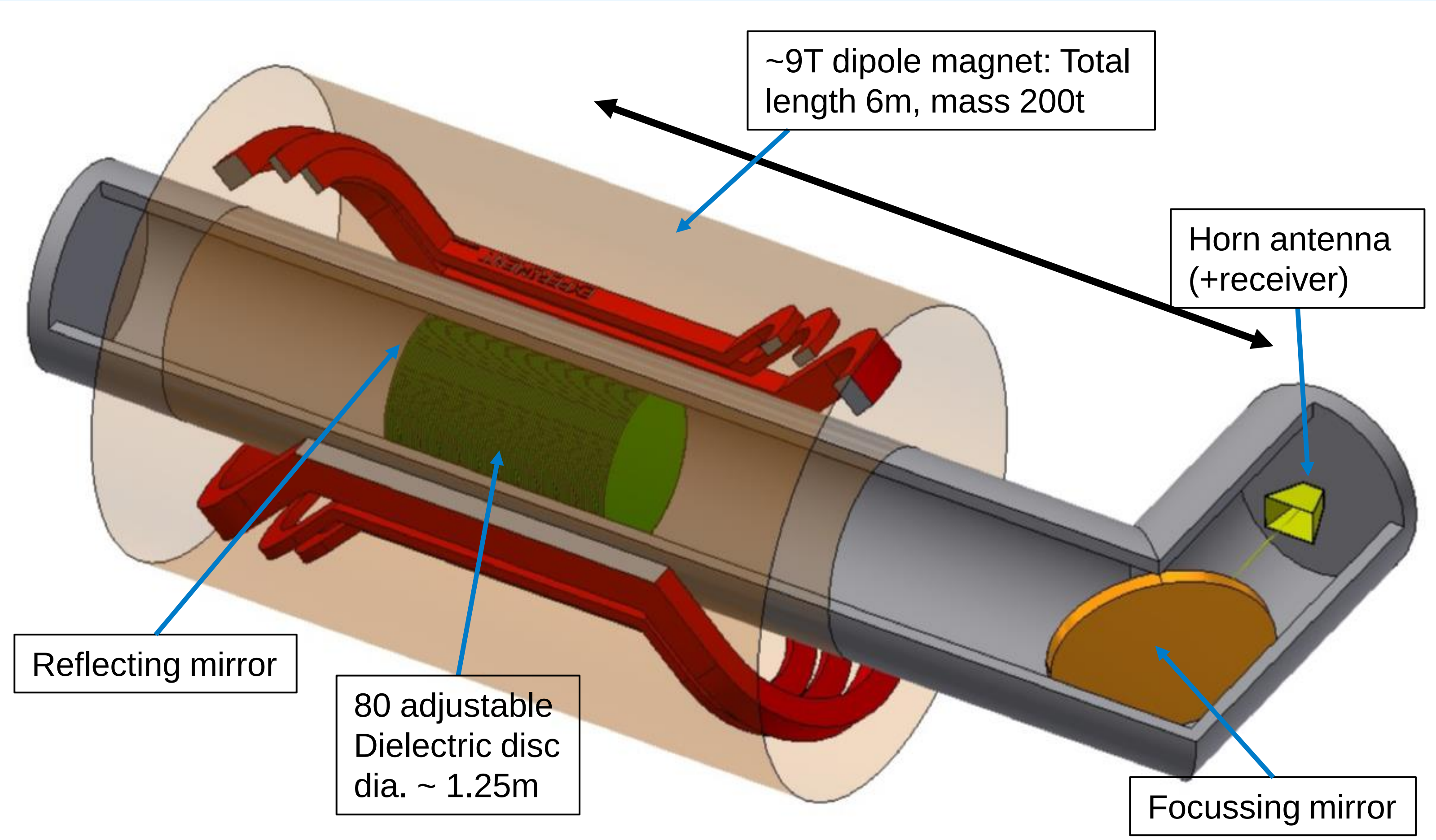
- Big surface (MLI)
- Big volume (3.3 m x 11 m)
- Partly magnetic fringe field
- Horizontal and vertical movement
- Cryostat(s)

$\Rightarrow$ **Specification not finalized.**

Magnetized Disc and Mirror Axion Experiment

Haloscope - Searches for Dark Matter Axions around us

Large aperture strong dipole magnet to host the “booster” (dielectric disks).



Magnet figure of merit: B^2 x A
⇒ strong dipole field
⇒ Large disc diameter

Main goal:
9 T dipole magnet with 1.35 m warm bore.

Next step:
4-5 T dipole with 0.6 m warm bore diameter

Site: HERA Hall North next to ALPS II at DESY

Magnetized Disc and Mirror Axion Experiment

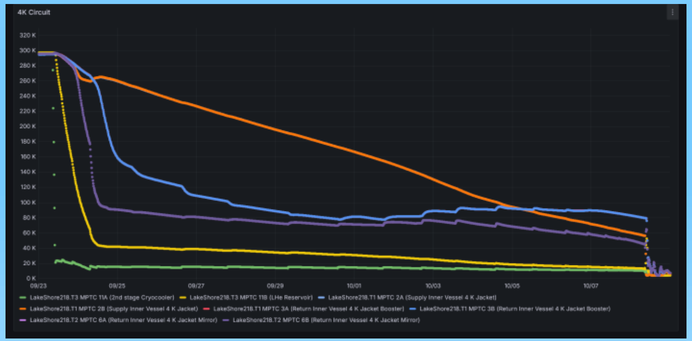
Cryostat to reduce system temperature (noise)

<u>Cooling concept:</u>

- Cold wall at 4.2 K is needed.
- Intermediate solution of double walled cylinder and thermos siphon.
- Phase separator with 5 cryo-cooler (SHI-RP-182B2S; 1.5 W/36 W)) and re-condensers.
- Thermal shield at 50 K with cryofan (Absolut System).
- Operation in vacuum and gHe partial pressure (1E-2 mbar)
- Goal: operation in a CERN dipole with 1.6 T field.

<u>Status:</u>

- Successful (warm) FAT April 2025.
- Currently commissioning on DESY campus (SHELL, UHH laboratory).
- Cool down successful, next step: check final close cycle operation.



Magnetized Disc and Mirror Axion Experiment

Experimental preparation (DESY: HERA North hall)

New sub-cooler distribution box 2024 (ACPS):

- Distributes helium at 4.2 K and 3-4 bar for 3 independent experiments.
- Successful FAT at DEMACO in May 24.
- Installation at DESY in mid of 2024.
- Warm SAT in July 24 .
- Status: wait for final connection on warm gas management.

DEMACO

Magnetized Disc and Mirror Axion Experiment

Moving disks: motors

Mechanical demonstrator with (warm and cold test):

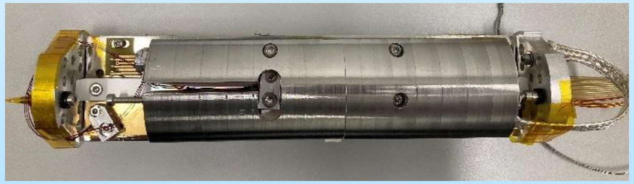
- One 200 mm sapphire disk in titanium ring + mirror.
- Three JPE piezo motors on self-built carriages.
- Piezo controller system for driving a disk with three motors.
- Cryo interferometer for displacement measurement.

Successful piezo motor tests
in cryogenics & inside ALPS II magnet
→ **Motor works in 5.3 T field and at 5 K**

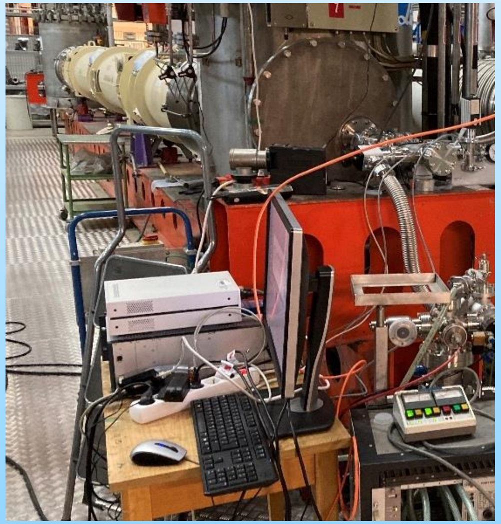
E. Garutti *et al* 2023 *JINST* **18** P08011 (arxiv:2305.12808)

Networking to find a suitable motor working in cryogenic and magnetic environment was done here (APPEC Technology Forum 2018)

Setup single motor test

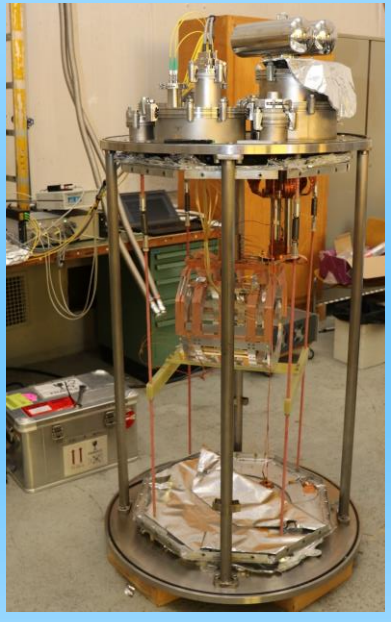


ALPS-II magnet test stand

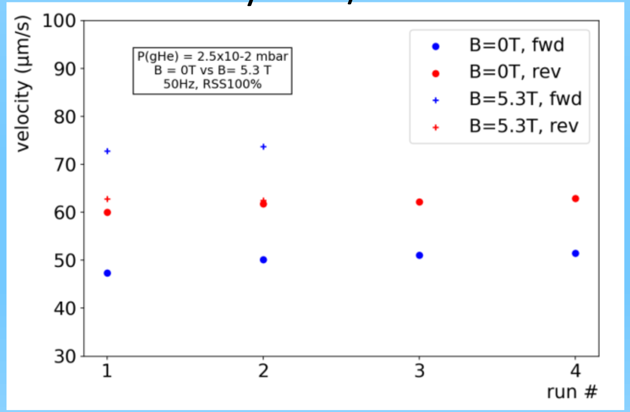


Driven by innovation

Add. test at CERN Cryolab



Motor velocity with/without B Field



Summary

Moving disks: motors

- A lot of cryogenic and vacuum applications are needed.
- 3 strong collaborations also in exchange with other collaborations from Axion community.
- Already strong input from industry during the design phase.
- New and unique technical developments with industry partners.

⇒ How to improve: setting up a cryolab at DESY to test new applications and make cooling concepts more economic.

⇒ Additional funding is needed or maybe collaboration with industry?

Bedankt!

Vielen Dank!

Thank you!

Kontakt

Deutsches Elektronen-Synchrotron DESY

www.desy.de

Jörn Schaffran
ALPS
Joern.schaffran@desy.de