Vacuum and Cryogenic Technologies in large Axion Detectors

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Abstract

The large Axion search experiments ALPS II, (Baby)IAXO and MADMAX are either already in operation or planned for installation at DESY. This type of experiment requires the use of magnetic fields, which are typically created using superconducting dipole magnets. In addition, all of these experiments have specific requirements for the experimental setups used in cryogenic and vacuum environments. This talk provides an overview of the experiments and their sub-components operating in cryogenic and vacuum environment, some of which are already operational, while others are still in the planning or testing phase.

Introduction

The existence of Axions and other WISPs is strongly supported by theory and cosmology in order to address unanswered questions beyond the Standard Model of particles physics, as well as to explain the evolution and structure of the universe. Axions were originally proposed to explain charge-parity (CP) conversation in quantum chromodynamics [1]. If they are detected, these particles could provide insight into particle physics at energies much higher than the Large Hadron Collider (LHC) at CERN can reach. Unfortunately, these WISPs interact very weakly, meaning they cannot be detected by accelerator-based experiments. The experiments at DESY in Hamburg will provide unique detection opportunities [2].

Apart from dark matter, other astrophysical phenomena that might be explained by Axions include the excessive energy losses of stars at various stages of their evolution, and the excessive transparency of the universe to TeV gamma rays, which could be explained by photon-axion conversion.

Axion experiments at DESY

Laboratory experiments can be used to search for Axions, with the aim of generating and detecting such particles independently of any astrophysical or cosmological assumptions. Other experiments are carried out in haloscopes, which are sensitive to the dark matter responsible to explains the kinematics of our Milky Way, and in helioscopes, which search for particles emitted by the Sun. DESY covers all these types of experiments – the “light shining to a wall” laboratory experiment ALPS II (Any Light Particle Search), the helioscope (Baby)IAXO (International Axion Observatory) and the haloscope MADMAX (Magnetized Disc and Mirror Axion Experiment). All require vacuum and cryogenic technologies, most of them are innovative and uncommon.

The ALPS experiment

Figure 1 shows a picture of the experiment. A powerful laser beam, operating in a strong magnetic field, propagates towards a wall. If a photon is converted into an Axion (the Sikivie effect), the resulting Axion does not interact with the wall and can pass through it. On the opposite side, the Axion can be converted back into a photon in the presence of a magnetic field and which can then be detected [3]. The sensitivity of the ALPS experiment is given by the Figure of Merit (FoM) $P_\gamma = 1/16 * F_{PC} * F_{RC} * (g_{a\gamma\gamma} * B * l)^4$, driven by the power of the laser light, the magnetic field and its length, realized by the use of 24 old straightened superconducting dipole magnets constructed for the HERA accelerator. Each of the dipoles operates at a temperature of 4.2 K and provides a field of 5.3 T. The powerful laser beam is enclosed within a 125 m long vacuum tube that operates in the UHV regime, providing a nearly particle-free environment. Detection is realized by a heterodyne concept, but further upgrades involving a transition edge sensor (TES) operating at around 20 mK are planned. Currently two dilution refrigerators are in operation for R&D purposes.

Figure 1: The ALPS II experiment at DESY during the construction phase

The BabyIAXO experiment

The IAXO experiment [4] is designed to detect Axions produced in the core of the Sun. BabyIAXO is the first step in proving the feasibility of the final IAXO experiment. Although it is much smaller, it will already allow us to investigate and search in unexplored Axion parameter regions (landscape). Figure 2 provides an overview of the experiment. The Magnet Figure of Merit (MFoM) is crucial to define the relevant experimental sensitivity here and it is given as $MFoM = B^2 * L^2 * A$, mainly driven by a long and strong dipole field with a large aperture, which is needed to convert Axions and detect photons. The superconducting dipole magnet will operate at 6 kA, providing a field of 2.2 T. It is 10 meters long and has two warm bore tubes, each with a diameter of 0.7 meter. It will therefore presently be the biggest dipole magnet in the world. Cooling will be provided by six to eight two-stage coolers operating at 50 K and 4.2 K, one 25 K GM one-stage cooler for the inner shield, and three GM one-stage coolers operating at 50 K for the outer shield and HTS power leads. The coils are cooled using a thermosiphon concept. A helium tank

containing the two-stage cryo-coolers, which are equipped with re-condensers on their second stage, is positioned on top of the magnet. Helium gas bubbles returning to the reservoir are re-liquified here to maintain a constant pressure and Helium level in this closed system. The 25 K/50 K circuits and an additional cooling loop (which is used to cool the magnet down from 300 K to 25 K) are equipped with cryogenic fan units respectively, which operate within a specified temperature range of 300 K to 10 K. Different types of heat exchanger are connected to the cryo-cooler heads here. Research and development for newly designed re-condensers and heat exchangers is ongoing at CERN. The requirements for the vacuum pumps for the isolating vacuum have not yet been finalized, but we expect a large volume with a large surface area (MLI), operation in a magnetic fringe field, and frequent tilting during operation (movement). The magnet itself is in the design phase and is being developed in cooperation with CERN, DESY and the company Elytt (Spain). According to a technical-driven schedule, BabyIAXO could be start up in the year 2030.

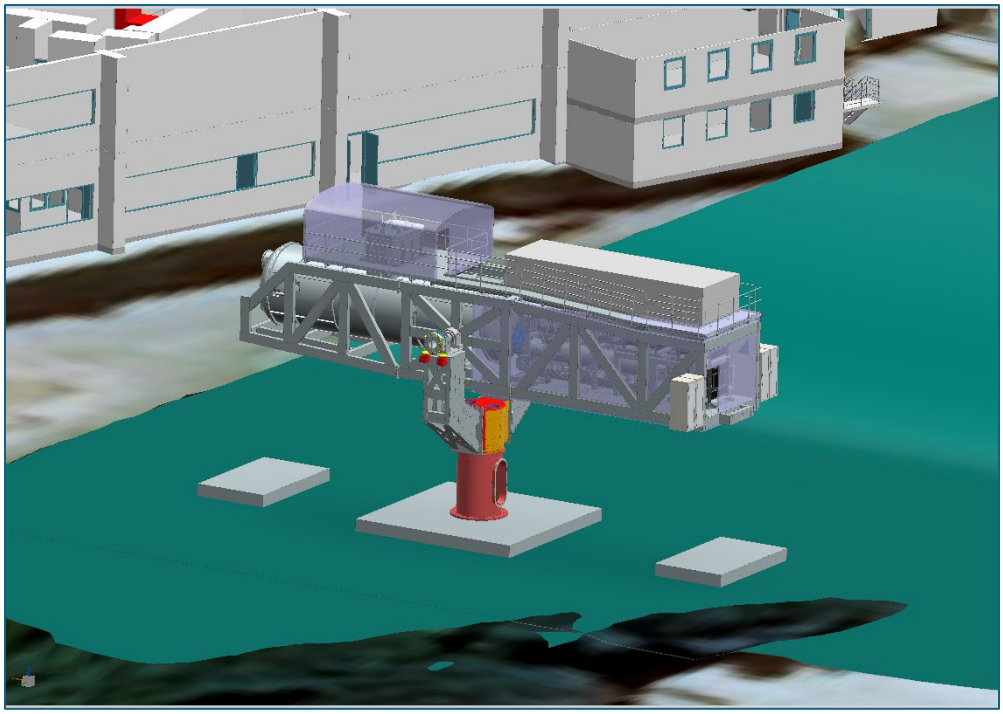

Figure 2: The BabyIAXO experiment

The optics, which are used to focus the X-ray photons onto the detector, are enclosed within a dedicated vacuum tube. This tube, with the X-ray optics inside, is connected to each of the two warm bores, each of which has a volume of 8 m^3. Flexible operation in the range from 1 mbar (helium partial pressure) to 1 E-8 mbar was specified. The two beam tubes have been manufactured and the initial tests have been performed successfully. The complete experimental vacuum system will be equipped with two cryogenic pumps (Edwards), four turbomolecular pumps (Leybold, Spain), nine DN200 and two DN800 gate valves, nine scroll pumps (Pfeiffer Vacuum), and some accessories for operation and control. A leak rate below 1E-09 mbar l/s and hydrocarbon-free operation were specified,

with each hydrocarbon partial pressure three orders of magnitude below the total system pressure.

The MADMAX experiment

A third experiment called MADMAX [5, 6] is planned. In the final MADMAX phase we plan to use a 9 T dipole magnet with a bore diameter of 1.35 m to search for Axions in our surroundings. The MFoM is driven by the squared B-field and the bore cross-section. Up to 80 dielectric disks need to be positioned in a high magnetic field and a cold environment of 4.2 K to amplify the very weak signal from unknown Axion masses (frequencies) to a measurable value (the booster). In collaboration with the company JPE, we have successfully qualified a piezo motor setup in a 5.3 T field at around 5 K using a dipole magnet from the former HERA accelerator [7]. Another development was the manufacture of a cold cryostat to suppress thermal noise in the experimental environment. The cooling system is similar to the one used for the BabyIAXO magnet one. The inner wall of the system is cooled using a double-walled cryostat. Five SHI-RP-182B2S cryo-coolers are located on top, operating in the gas phase of the expansion vessel where the boiled liquid is reliquefied back into the 50-litre bath. The second stages of the cryo-coolers are equipped with heat exchangers and operate at a temperature of 50 K to cool the surrounding thermal shield. A cryo-fan from Absolute System pushes helium through the circuit. The complete cryostat was designed by BNET (Bilfinger) and has already passed the factory acceptance test in the end of 2025. A cold test at Hamburg University is in progress but has not yet been completed. Once commissioned and qualified, the system will be used to install and test the experimental equipment before shipping it to CERN for operation in the 1.6 T Morpurgo dipole magnet to take data with MADMAX booster prototypes.

Figure 3: MADMAX Cryostat

The inner volume, where the booster is located, needs to be operated within a pressure range of 1E-06 to 1E-02 mbar using helium gas for operation in the higher end of this range. For this purpose, we use a turbomolecular pump with a HiScroll from Pfeiffer Vacuum. Figure 3 shows the complete cryostat.

The procurement process for an intermediate MADMAX dipole magnet with a field of around 4 T has begun, with conceptual design planned for completion by 2026. The magnet will be operated in one of the former HERA halls (H1 experiment) at DESY, making use of the existing iron yoke in order to minimize the fringe field in this environment. Preparation of the infrastructure has already begun, for example with the installation of a new sub-cooler box (ACPS – ALPS Cryo-Platform Subcooler), which was specified by DESY and designed by Demaco. It is intended to supply sub-cooled helium at ~4.3 K and a pressure of 3.5 bar to three independent operational experiments. The ACPS has been installed and successfully warm commissioned. The final connections to the HERA transfer line and the warm gas pipes are still pending.

Figure 4: New Sub-cooler box at DESY (ACPS)

Summary

Axion detectors require many different types of cryogenic and vacuum technology. In order to realize novel applications, significant input from industry is needed during the design phases. The three collaborations (ALPS II, IAXO and MADMAX) already have more than ten industrial partners, and some of the projects have been already successfully completed. Further input from industry is planned for the coming years.

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