A new experiment, the CERN Axion Solar Telescope (CAST) was installed and commissioned in 2002. Its aim is to experimentally prove the existence of an as yet hypothetical particle predicted by theory as a solution of the strong CP problem and possible candidate for galactic dark matter. The heart of the detector consists of a decommissioned 10-m long LHC superconducting dipole prototype magnet, providing a magnetic field of up to 9.5 T. The whole telescope assembly is aligned with high precision to the core of the sun. If they exist, axions could be copiously produced in the core of the sun and converted into photons within the transverse magnetic field of the telescope. The converted low-energy solar axion spectrum, peaked around a mean energy of 4.4 keV, can then be focused by a special x-ray mirror system and detected by low-background photon detectors, installed on each end of the telescopes twin beam pipes. This paper describes the external and proximity cryogenic system and magnet commissioning as well as the first operational experience with the overall telescope assembly.
ABSTRACT

A new experiment, the CERN Axion Solar Telescope (CAST) was installed and commissioned in 2002. Its aim is to experimentally prove the existence of an as yet hypothetical particle predicted by theory as a solution of the strong CP problem and possible candidate for galactic dark matter. The heart of the detector consists of a decommissioned 10-m long LHC superconducting dipole prototype magnet, providing a magnetic field of up to 9.5 T. The whole telescope assembly is aligned with high precision to the core of the sun. If they exist, axions could be copiously produced in the core of the sun and converted into photons within the transverse magnetic field of the telescope. The converted low-energy solar axion spectrum, peaked around a mean energy of 4.4 keV, can then be focused by a special x-ray mirror system and detected by low-background photon detectors, installed on each end of the telescopes twin beam pipes. This paper describes the external and proximity cryogenic system and magnet commissioning as well as the first operational experience with the overall telescope assembly.

INTRODUCTION

Axions made their first appearance in particle physics as a possible solution to the strong CP problem, which can be summarised in the question: why do the strong interactions not violate CP symmetry, since the neutron’s electric dipole moment is at least a factor of $10^9$ smaller than expected? An attractive solution to this invokes a new symmetry, the Peccei-Quinn symmetry [1]. The spontaneous breaking of this new symmetry predicts the existence of a light neutral pseudoscalar particle, the axion. The axion became even more attractive with the realisation that it is one of the most interesting non-baryonic candidates for the omnipresent dark matter. Thus axions may also exist as primordial cosmic relics copiously produced in the early universe.
The experimental axion search is based on the idea that energetic axions might be created continuously in thermal photon-nucleus interactions in the Sun core ($T \sim 15.6 \times 10^6$ K), this being considered as the nearest and brightest potential axion source in the 1-15 keV total energy range.

**WORKING PRINCIPLE OF THE CERN SOLAR AXION TELESCOPE**

The working principle of a solar axion telescope is the inverse Primakoff effect: an incoming axion couples to a virtual photon provided by the transverse field ($B$) of the telescope’s magnet, and is transformed to a real photon which carries the energy and momentum of the original axion. The expected differential axion flux at the earth (FIGURE 1, left) produced by blackbody photons in the solar interior shows a very broad axion spectrum below ~10 keV. The average energy of the emitted solar axions and therefore of the converted photons is ~ 4.2 keV [2].

Hence the main component of the CERN Axion Solar Telescope (CAST) is a decommissioned 10-m long LHC superconducting dipole prototype magnet (FIGURE 2), providing the transverse magnetic field to catalyse the axion-photon conversion. Three different low-background x-ray detectors installed on either end of the beam tubes identify the conversion photons exclusively at times of alignment between the magnet and the core of the sun, providing a unique axion signature. The whole assembly is mounted on a moving platform (-8° to +8° vertical, -40 degrees to +40 degrees horizontal), allowing it to observe the sun for 3.3 hours in total at sunrise and sunset [3].

The probability for a coherent axion-to-photon conversion is proportional to $(B \times L)^2$, where $L$ is the length of the magnetic field $B$. The straight-bore twin-aperture LHC dipole prototype used by CAST can produce a magnetic field of up to 9.5 T over a length of 10 m ($B \times L = 95 \text{Tm}$) with an angular resolution of 10 mrad [4], thus making it 100 times more efficient as an axion-photon-converter than the best competing setup at the university of Tokyo ($B \times L = 9.2 \text{Tm}$) [5]. Analyses of the first data taken allowed the reducing of the lower limit for the axion-to-photon coupling constant given by the Tokyo Helioscope considerably (FIGURE 1, right).

The conversion probability is maximised when the axion and photon amplitudes are coherent throughout the detection region. For axions of a given, non-zero mass ($\geq 0.03 \text{ eV/c}^2$) this coherence can be restored by filling the conversion region with an appropriate medium, which has to fulfil two main requirements: the x-ray energy must be far above the ionisation energy of the buffer gas and the absorption length for keV x-rays
has to be larger than the length of the magnetic pipes. Therefore the CAST experimental program foresees an initial running period of 1-2 years with the dipole inner bore under vacuum in order to cover axion masses \( m_a < 0.03 \text{ eV/c}^2 \), while in a second phase the conversion region will be filled with helium and the pressure will be changed in appropriate steps to measure several points for \( 0.02 \text{ eV/c}^2 < m_a < 1 \text{ eV/c}^2 \).

**CRYOGENICS FOR THE SUPERCONDUCTING MAGNET OF CAST**

To obtain the maximum field of around 9 – 9.5 T, the magnet has to be cooled and operated in superfluid helium below 1.9 K. In order to minimize cost and labour, the whole cryogenic infrastructure needed to cooldown the magnet from ambient temperature and to supply it with liquid helium at 4.5 K has been recovered from the cryogenics of the dismounted \( e^+e^- \) collider LEP (helium buffers and gas bags) and one of its former experiments DELPHI (helium liquefier, recovery and purification systems) and adapted for use with CAST. To cooldown and operate the magnet at 1.9 K a new Roots pumping group has been purchased and installed. The main characteristics of the cryogenic system are listed in Table 1.

Cryogenic and electrical feed to the former LHC prototype magnet is done through

![Simplified layout of the CERN Axion Solar Telescope (CAST)](image)

**FIGURE 2.** Simplified layout of the CERN Axion Solar Telescope (CAST)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cryoplant: (ex-DELPHI plant)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressor suction</td>
<td>(MPa)</td>
<td>0.104</td>
</tr>
<tr>
<td>Compressor discharge</td>
<td>(MPa)</td>
<td>1.4</td>
</tr>
<tr>
<td>Nominal throughput</td>
<td>(g/s)</td>
<td>160</td>
</tr>
<tr>
<td>Cooling power at 4.5 K</td>
<td></td>
<td>300 W &amp; 3.5 g/s liquefaction</td>
</tr>
<tr>
<td>70-80 K</td>
<td></td>
<td>2500 W</td>
</tr>
<tr>
<td><strong>Storage:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas storage at 1.4 MPa</td>
<td>(m³)</td>
<td>2440</td>
</tr>
<tr>
<td>Gas bags + buffer at 0.1 Mpa</td>
<td>(m³)</td>
<td>160</td>
</tr>
<tr>
<td><strong>Helium Pumping Group:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suction pressure</td>
<td>(kPa)</td>
<td>1.54</td>
</tr>
<tr>
<td>Discharge pressure</td>
<td>(MPa)</td>
<td>0.102</td>
</tr>
<tr>
<td>Nominal throughput</td>
<td>(g/s)</td>
<td>2.0</td>
</tr>
</tbody>
</table>
the same magnet feed box (MFB) already used with the cryogenic LHC test benches [4], but was adapted to the new cryogenic infrastructure needed by CAST. The modified flow scheme of the MFB as well as its interface via a total of seven flexible transfer lines, needed to connect to the liquid helium supply, gaseous helium pumping group and quench recovery system is shown in FIGURE 3. The flexible lines were designed to allow the movement of the telescope without interrupting its cryogenic operation. Since the x-ray detectors and the focussing mirror system are installed outside the magnetic field on either end of the beam tube, the warm bore inserts (anti-cryostats) originally installed inside the magnet aperture to house measurement equipment were no longer needed and dismounted to decrease the heat load on the superfluid helium bath.

The cooling of the magnet in a pressurised superfluid helium bath is performed using a hollow-finger heat exchanger made of copper with a developed area of 1 m². The exchanger is fed with liquid helium drawn from the bottom of the 4.5 K bath and later sub-cooled in a copper mesh heat exchanger before Joule-Thomson expansion to saturation at 1.54 kPa. The heat load to the superfluid helium bath is transported by conduction along the magnet length to the heat exchanger with a nominal capacity of around 50 W at 1.9 K. The 4.5 K saturated helium bath, which intercepts residual heat at the lower end of the 13 kA vapour-cooled current leads, is thermally and hydraulically separated from the pressurised helium II enclosure by two small diameter lambda plates, which allow feed through of the superconducting current bus and instrumentation wiring. An electro-pneumatically-actuated “respirator” valve at the bottom of the 4.5 K bath allows liquid filling and pressure compensation upon density changes between 4.5 K and 1.8 K. Emergency relief and helium discharge after a resistive transition are performed through two DN50 industrial-type cold valves, the first one (opening time of 120 ms) discharging the magnet helium content into the 4.5 K vessel, the latter de-pressurising the

FIGURE 3. Modified flow scheme of the Magnet Feed Box (MFB) for CAST [6]
corresponding liquid helium buffer volume, at 0.17 MPa to the gas bags to limit helium loss. This liquid helium buffer volume is protected in addition by a 0.3 MPa safety relief valve to atmosphere. Ultimate protection of the pressurized helium enclosure relies on a DN50 nickel rupture disk, which has a design pressure of 2 MPa, operates at 1.9 K and is connected to an evacuated pipe closed by a “warm” rupture disk with a design pressure of 0.03 MPa. The vacuum between the rupture disks is monitored using a “helium guard”, pressurised at 0.1 MPa, preventing at the same time any external air inleak, which could affect the cold rupture disk functioning due to a condensed frost layer.

**COMMISSIONING AND FIRST OPERATION OF CAST CRYOGENICS**

**Installation and commissioning**

The installation phase of the CAST cryogenic system started in November 2001 with the dismantling of the former Large Electron Positron collider (LEP) experiment DELPHI (DEtector with Lepton, Photon and Hadron Identification). The cold box which had been mounted underground on top of the DELPHI detector was re-installed in the hall on the surface attributed to the CAST telescope and re-piped to the main helium compressor. Some of the infrastructure (6000 l liquid nitrogen storage tank, helium gas buffers and gas bags) had to be re-arranged in order to allow operation of CAST without interfering with the construction and installation work of the LHC and its experiments. In parallel to the installation of the moving platform and the cryostated former LHC prototype magnet, the MFB was refurbished and the interface of seven semi-flexible helium transfer lines was developed and mounted. The former DELPHI cryogenics process control system was upgraded and the pumping group for the 1.8 K- cooling was installed. The conditioning of the isolation vacuum tank, including an integral leak test against atmosphere and the pressurized helium circuits, was performed from May to June 2002.

The final commissioning and the first cooldown of the dipole magnet started on 20th July 2002 and the system reached 1.8 K continuous operation mode 12 days later. Initially a first test ramp of the magnet current to 3 kA with a provoked fast discharge afterwards

**FIGURE 4.** Process control mimic of the CAST cryogenic system with magnet at nominal current
was done, to verify and improve the automatic quench recovery procedures of the process control system. Then two so called “training quenches” had to be performed before the dipole magnet could be kept continuously excited with the nominal current of 13.4 kA, corresponding to a magnetic field of 9 T (FIGURE 4). During the “training quenches” the magnet current was ramped up to the point where a local resistive transition on the superconductor occurred, which triggered the quench protection system [7]. In order to distribute the resistivity and the associated dumped energy across the whole cold mass during the current switch-off, the quench protection system discharges pre-loaded condensators across heating elements mounted on the superconducting coils. After a full thermal cycle (1.8 K to 300 K to 1.8 K) during the CERN winter maintenance shutdown (from December 2002 to March 2003) another “training quench” at 13.0 kA was necessary before the nominal 9 T magnetic field could be obtained.

**Cooldown procedure**

The fully automated cooldown of the CAST telescope magnet takes around 6 days and is sub-divided in three phases. Initially the cold mass is cooled from ambient to around 100 K with high-pressure (1.0 MPa) gaseous helium via a progressively closing by-pass of the final Joule-Thompson expansion stage, respecting a maximum temperature gradient of 100 K between the helium go and return of the cold box (FIGURE 5, left graph). Inside the MFB the gaseous helium flow is first sent through the magnet before returning via the MFB helium phase separator to the cold box. At a gaseous helium return temperature of around 80 to 100 K the phase separator of the cold box is filled with liquid helium, which is then transferred by a pressure differential of up to 40 kPa via the MFB to the cold mass. Once the magnet volume is completely filled, the level in the MFB helium buffer starts to rise and then the liquid is directly sent to the MFB buffer controlling a level of 275 mm and a pressure of 0.13 MPa (FIGURE 5, right graph). The thermal shield of the magnet is cooled to a temperature of around 60 K by sending a small part of the gaseous helium flow at the outlet of the first turbine and returning it to the low-pressure return line on the warm side of the cold box.

In the final cooldown phase from 4.5 to 1.8 K, the magnet is isolated from the MFB liquid helium buffer by closing the quench protection valve. Then the two-stage pumping group is started to lower the pressure in the MFB helium heat exchanger down to 1.54 kPA. The helium level is maintained constant by supplying liquid from the MFB helium buffer volume through a Joule-Thomson expansion valve (FIGURE 6). The bath of the

![FIGURE 5. Cooldown phases 1 & 2 of CAST telescope: 300 to 100 K (left), 100 to 4.2 K (right)](image-url)
magnet is becoming superfluid by conduction approximately 3 - 4 hours after the helium heat exchanger in the MFB has passed the lambda point (FIGURE 6).

Quench recovery

The detection of a resistive transition of the magnet at nominal current (13.4 kA) triggers, in addition to the fast discharge of the current, the opening of the quench valve within 120 ms. This re-connects the magnet volume to the MFB liquid helium buffer in order to discharge the entire superfluid helium content (approximately 300 l), which is vaporised in a few seconds. As a consequence the pressure in the MFB liquid helium buffer and the heat exchanger rise rapidly. In order to protect the cryoplant the quench detector signal triggers a stop of the turbines and closure of the liquid helium supply valve, while the gaseous helium return valves are kept open up to a pressure of 0.14 MPa and when the pressure in the MFB buffer volume exceeds 0.2 MPa the discharge valve to the gas bag is opened (FIGURE 7, left graph). If the pressure in the helium recovery collector exceeds 0.12 MPa a mechanical safety devices discharges to atmosphere (FIGURE 7, right graph). The re-start of the automatic cooldown to 1.8 K of the cold mass, which is warmed up to 40 K by the dumped energy, requires a manual acknowledge by the operator and takes around 6 hours.

FIGURE 6. Final cooldown phase of CAST magnet 4.2 to 1.8 K

FIGURE 7. Temperature (left) and level / pressure (right) graphs during a quench recovery of CAST magnet
Operational experience

The CAST cryogenic system has accumulated in total 8000 running hours including the 2002 commissioning and test run. 4000 hours were devoted to physics data taking in 2003 so far. During this period in total 93 hours of downtime have been observed, of which only 5.2 hours (failure rate: 1.3 ‰) were caused by failure of cryogenic equipment and 88 hours (failure rate: 2.2 %) downtime were of non-cryogenic origin. A number of fast discharges of the magnet occurred without any real resistive transition of the magnet. Most were due to voltage trips occurring in the current supply due to the current control loop reacting abruptly to power network instabilities. Fast discharges occurred as well when tuning the quench detection system to try and cope with these instabilities. Subsequently the current supply control loop and the quench detection systems have been improved and the entire system is now working nominally in stable conditions.

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